FRONTIERS FOR DISCOVERY IN

HIGH ENERGY DENSITY PHYSICS

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Preface

In January, 2004, a nationally-constituted High Energy Density Physics Task Force was commissioned by the National Science and Technology Council's Interagency Working Group on the Physics of the Universe to prepare a report that summarizes the compelling research opportunities of high intellectual value in high energy density physics. These opportunities for discovery include the broad scope of this highly interdisciplinary field that spans a wide range of physics areas including plasma physics, laser and particle beam physics, nuclear physics, astrophysics, atomic and molecular physics, materials science and condensed matter physics, intense radiation-matter interaction physics, fluid dynamics, and magnetohydrodynamics. Building on recent National Research Council reports and advisory committee reports commissioned by the U. S. government, the Task Force devoted four months to the information-gathering process in preparation for the Workshop on High Energy Density Physics held in Gaithersburg, Maryland on May 24 – 26. The present report constitutes the final output from the deliberations and discussions at the Workshop. Specifically, the Task Force has identified fifteen principal science thrust areas/areas of research in high energy density physics and has developed compelling questions of high intellectual value that motivate the research. For each question, a Scientific-American-level narrative is provided that frames the intent of the question and the motivation for the research. Finally, for each research thrust area a description is provided that summarizes in more detail (a) the principal scientific objectives and milestones; (b) the research tools and facility requirements; (c) the time line and resource requirements to achieve the primary objectives (assuming an approximate ten-year time horizon); (d) the identification of opportunities for interagency cooperation, where appropriate; and (e) a delineation of references to key reports and studies.

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CHAPTER 1

Introduction and Executive Summary

Now is a highly opportune time to identify the compelling research opportunities of high intellectual value in high energy density physics. High energy density physics is a rapidly growing field that spans a wide range of physics areas including plasma physics, laser and particle beam physics, nuclear physics, astrophysics, atomic and molecular physics, materials science and condensed matter physics, intense radiation-matter interaction physics, fluid dynamics, and magnetohydrodynamics. New astrophysical observatories have enabled studies of high energy density physics on the stellar and even galactic scales, and new laboratory facilities are allowing contolled and precise investigations of matter under extreme conditions.

Three recent reports commissioned by the U.S. government do an excellent job in defining the field of high energy density physics and in identifying the exciting scientific research frontiers. These are:

1. *Connecting Quarks with the Cosmos: Eleven Science Questions for The New Century* (National Academies Press, 2003);
2. *Frontiers in High Energy Density Physics - The X-Games of Contemporary Science* (National Academies Press, 2003); and
3. *The Science and Applications of Ultrafast, Ultraintense Lasers: Opportunities in Science and Technology Using the Brightest Light Known to Man* (Report on the SAUUL Workshop, June 17-19, 2002).

In January, 2004, a nationally-constituted High Energy Density Physics Task Force was commissioned by the National Science and Technology Council's Interagency Working Group on the Physics of the Universe (Appendix A) to prepare a report that delineates the compelling research opportunities of high intellectual value in high energy density physics. These opportunities for discovery span the broad scope of this highly interdisciplinary field. Building on the substantial reports listed above and recent advisory committee reports, the Task Force devoted four months to the information-gathering process in preparation for the Workshop on High Energy Density Physics held in Gaithersburg, Maryland on May 24 – 26 (Appendix B). The present report constitutes the final output from the deliberations and discussions at the Workshop.

In this report the working definition of 'high energy density' refers to energy densities exceeding 10^{11} Joules per cubic meter (J/m^3). Equivalently, this energy density corresponds to pressures exceeding 1 megabar (Mbar), electromagnetic wave intensities exceeding 3×10^{15} Watts per square centimeter (W/cm^2), or static magnetic fields exceeding 500 Tesla (T). Table 1 and Figure 1 illustrate the characteristic physical parameters corresponding to energy densities of 10^{11} Joules per cubic meter, and a simple 'map' in density – temperature parameter space that illustrates the wide range of high energy density conditions accessible in astrophysical systems and laboratory experiments.

Energy Density Parameter (u) Corresponding to ~10^{11} J/m^3	Value
Pressure	1 Mbar
Electromagnetic Radiation	
Electromagnetic wave (laser) intensity I (u~I)	3×10^{15} W/cm^2
Blackbody radiation temperature T (u~T^4)	5×10^6 K (400 eV)
Electric field strength E (u~E^2)	1.5×10^{11} V/m
Magnetic field strength B (u~B^2)	500 T
Particle Beams	
Current density (J) for a beam of (KE=) 30 GeV electrons (u~J*KE)	100 kA/cm^2
Current density for a beam of 100 MeV ions (m=10m_{proton}, Z=1) (u~J(m*KE)$^{1/2}$)	4 MA/cm^2
Plasma Pressure	
Plasma density (n) for a temperature (T) of 1 keV (10^7 K) (u~nT)	6×10^{20} cm^{-3}
Plasma density (n) for a temperature (T) of 1 GeV (10^{13} ^{o}K) (u~nT)	6×10^{14} cm^{-3}
Ablation Pressure	
Laser Intensity (I) at 1μm wavelength (λ) (u~$(I/\lambda)^{2/3}$)	4×10^{12} W/cm^2
Blackbody radiation temperature T (u~$T^{3.5}$)	8×10^5 K (75 eV)

Table 1. *Equivalent parameters corresponding to an energy density of 10^{11} J/m^3. This is the energy density of matter at a pressure of 1 Mbar (one million atmospheres). Also shown are the parameters corresponding to an equivalent energy density in the electromagnetic field energy of a laser pulse or a blackbody radiator, the kinetic energy of intense particle beams, and the thermal energy of hot plasmas. The final two entries in the table correspond to an ablation (recoil) pressure of 1 Mbar caused by an external laser or blackbody radiator that impinges on a solid-density target.*

In Figure 1, the 10^{11} J/m^3 threshold definition of high energy density should be regarded as a *guideline* rather than a sharp boundary. As evident from Figure 1, the density – temperature space spanned by high energy density physics is vast, and includes many astrophysical objects, many physics regimes, and can be accessed by a wide variety of laboratory facilities. In all cases, the high energy density conditions are those of extreme states of matter.

It is not the purpose of this report to reconstruct the eloquent prose and scientific motivation for research in high energy density physics that are presented in the three reports identified earlier in this Chapter. Rather, building on these substantial reports, the Task Force has focused its efforts on providing a clear and concise delineation of many of the compelling research opportunities and thrust areas in this rapidly developing field. During the information-collection process, for convenience, the Task Force divided its activities into the following four major research areas:

1. High energy density physics in astrophysical systems;
2. Beam-induced high energy density physics (Relativistic Heavy Ion Collider, heavy ion fusion, high-intensity accelerators, etc.);

3. High energy density physics in Stockpile Stewardship facilities (Omega, Z/ZR, National Ignition Facility, etc.); and
4. Ultrafast, Ultraintense Laser Science.

While this constitutes a convenient categorization of research activities for purposes of preparing this report, and in many respects reflects the present organization of this emerging field of physics as funded by several federal agencies, the corresponding research areas are most remarkable because of their common physics issues and intellectual challenges that are characteristic of matter under high energy density conditions. As one example, understanding the fundamental properties of warm dense matter is one important aspect of each of these four major research areas. Warm dense matter consists of extreme states of matter that are neither in a 'cold, condensed-matter' state, nor in a 'hot, plasma' state, but rather somewhere intermediate. Warm dense matter is typically a strongly-coupled, many-body charged particle system with energy density exceeding 10^{10} J/m^3 , conditions that are extremely difficult to study analytically and by numerical simulation. Many astrophysical systems (e.g., brown dwarfs, and giant planets) and laboratory experimental conditions fall into this regime. Intense ion, electron and photon beams can be used to create these extreme conditions in the laboratory, and the fundamental materials properties can be probed experimentally and studied theoretically. The research instruments and techniques described later in this report, either individually or in combination, can create these extreme states of matter. This is but one example of the interesting high energy density physics that can be explored with laboratory facilities that currently exist, or are planned.

An exciting aspect of the field of high energy density physics is that it intellectually unifies physical regimes that are separated by orders-of-magnitude in density - temperature parameter space as well as research communities that are separated by traditional discipline boundaries. The four areas described above in fact reflect the fusing of four different physics communities (and funding bases) into an integrated scientific enterprise. Such a fusing of research capabilities and intellectual interests provides many new opportunities for scientific discovery identified in this report. In addition, there are strong indications of latent research opportunities that are not so explicitly delineated. For example, the potential benefit of co-locating facilities such as intense particle or laser beams and light sources offers exciting new possibilities. One type of driver could be used to create and the other to probe new and fundamentally different states of matter. The cross-fertilization of the plasma physics and nuclear physics communities may also lead to new ideas for how to diagnose the fundamental properties of quark-gluon plasmas, and even what questions to ask. Thus the potential benefits of an integrated approach to the field of high energy density physics are sure to surpass the considerable promise that each of the sub-fields have already begun to demonstrate separately.

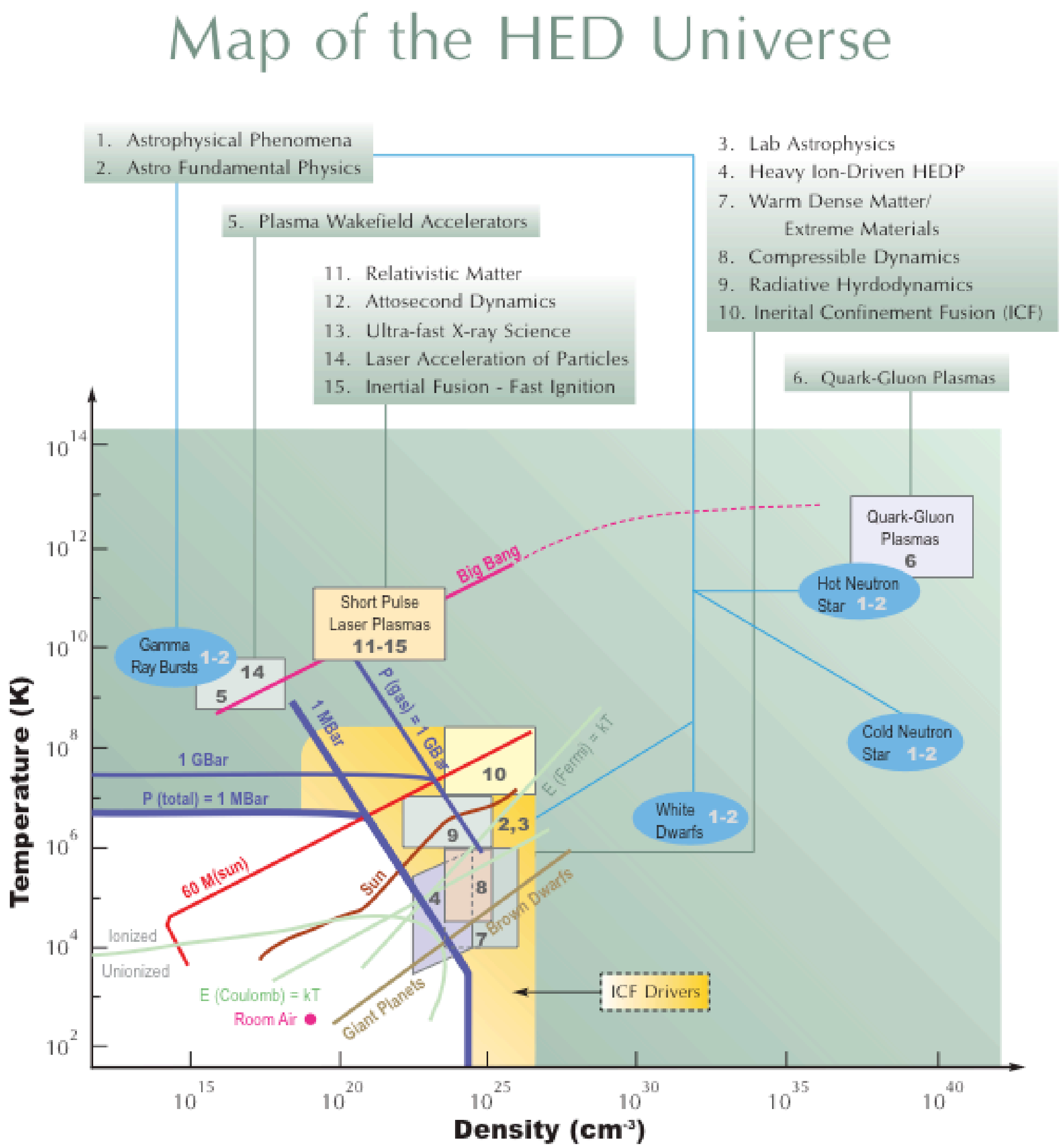

Figure 1. Map of the high energy density physics regime in the density - temperature plane. High energy density as defined in this report corresponds to matter under the extreme conditions in the region above and to the right of the 1 Mbar (heavy blue) curve. The numbered boxes correspond to the 15 science thrust areas identified in this report and show a representative parameter regime for each of these thrust areas.

Subsequent chapters of this report are organized according to the four topical areas identified above. For each topical area, the Task Force has identified the principal science thrust areas/areas of research and has developed compelling questions of high intellectual value that motivate the research. For each compelling question, a Scientific-American-level narrative is provided that frames the intent of the question and the motivation for the research. Finally, for each thrust area a four-page narrative is provided that describes in more detail (a) the principal scientific objectives and milestones; (b) the research tools and facility requirements; (c) the time line and resource requirements to achieve the primary objectives (assuming a ten-year time horizon); (d) the identification of opportunities for interagency cooperation, where appropriate; and (e) a delineation of references to key reports and studies.

For completeness, we list below the principal science thrust areas and compelling questions of high intellectual value identified in this report for each of the four topical areas. The numbering scheme is the same as in Figure 1 and in Chapters 2 – 5.

High Energy Density Physics in Astrophysical Systems

Thrust Area #1 – Astrophysical phenomena

What is the nature of matter and energy observed under extraordinary conditions in highly evolved stars and in their immediate surroundings, and how do matter and energy interact in such systems to produce the most energetic transient events in the universe?

Thrust Area #2 - Fundamental physics of high energy density astrophysical phenomena

What are the fundamental material properties of matter, and what is the nature of the fundamental interactions between matter and energy, under the extreme conditions encountered in high energy density astrophysics?

Thrust Area #3 – Laboratory astrophysics

What are the limits to our ability to test astrophysical model and fundamental physics in the laboratory, and how can we use laboratory experiments to elucidate either fundamental physics or phenomenology of astrophysical systems that are as yet inaccessible to either theory or simulations?

Beam-Induced High Energy Density Physics

Thrust Area #4 – Heavy-ion-driven high energy density physics and fusion

How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition conditions?

Thrust Area #5 – High energy density physics with ultrarelativistic electron beams

How can the ultra high electric fields in a beam-driven plasma wakefield be harnessed and sufficiently controlled to accelerate and focus high-quality, high-energy beams in compact devices?

Thrust Area #6 – Characterization of quark-gluon plasmas

What is the nature of matter at the exceedingly high density and temperature characteristic of the Early Universe?

Does the Quark Gluon Plasma exhibit any of the properties of a classical plasma?

High Energy Density Physics in Stockpile Stewardship Facilities

Thrust Area #7 – Materials properties

What are the fundamental properties of matter at extreme states of temperature and/or density?

Thrust Area #8 – Compressible dynamics

How do compressible, nonlinear flows evolve into the turbulent regime?

Thrust Area #9 – Radiative hydrodynamics

Can high energy density experiments answer enduring questions about nonlinear radiative hydrodynamics and the dynamics of powerful astrophysical phenomena?

Thrust Area #10 – Inertial confinement fusion

Can inertial fusion ignition be achieved in the laboratory and developed as a research tool?

Ultrafast, Ultraintense Laser Science

Thrust Area #11 – Laser excitation of matter at the relativistic extreme

How do many-body systems evolve in a light field under extreme relativistic conditions where an electron is accelerated to relativistic energies and particle production becomes possible in one optical cycle?

Thrust Area #12 – Attosecond physics

Can physical and chemical processes be controlled with light pulses created in the laboratory that possess both the intrinsic time- (attoseconds, 1 as = 10^{-18} s) and length- (x-rays, 1 Å) scales of all atomic matter?

Thrust Area #13 – Ultrafast, high-peak-power x-rays

Can intense, ultra-fast x-rays become a routine tool for imaging the structure and motion of "single" complex bio-molecules that are the constituents of all living things?

Can nonlinear optics be applied as a powerful, routine probe of matter in the XUV/x-ray regime?

Thrust Area #14 – Compact high energy particle acceleration

How can ultra-intense ultra-short pulse lasers be used to develop compact GeV to TeV class electron and or proton/ion accelerators?

Thrust Area #15 – Inertial fusion energy fast ignition

Is it possible to make controlled nuclear fusion useful and efficient by heating plasmas with an intense, short pulse laser?

An important theme that characterizes all of the research areas described in subsequent chapters is the need for a range of facilities to provide a cost-effective national research program. Both specialized facilities and a set of facilities of different sizes are required. The specialized facilities are optimized to study one or more of the science thrust areas and compelling questions identified in this report. We therefore conclude this chapter with an example that illustrates this facility requirement as it pertains to high energy density physics studies on Stockpile Stewardship facilities, and facilities used for research in Ultrafast, Ultraintense Laser Science. For example, a range of facilities is essential to perform experiments at increasing energy/current in order to develop experimental and diagnostic techniques before carrying out experiments on the larger facilities such as the National Ignition Facility (NIF) or the Z/ZR facility, where operating costs are high. This range of experiments will also help to validate the simulation capabilities, physics understanding, and target fabrication techniques, and ensure the success of the limited number of experiments possible on the largest facilities. It is unlikely that experimental run time would be awarded on the largest facilities in the absence of concept demonstrations on the smaller facilities. An effective facility usage plan would attract additional high quality researchers to the field, thereby increasing the number of trained scientists and benefiting the field of high energy density physics in the long term.

To avoid redundancy and to make effective use of existing and future facilities, it is important that the range of facilities have well-planned opportunities for user access. In this context, user access includes facility (shot) time, infrastructure support, including diagnostics, target fabrication, travel, etc., and on-site staff and expertise to aid in the experiments. There also needs to be a clear mechanism for selecting research proposals for facility run time. The site, rather than the user should provide the cost of the operating the facility. The potential users include, but are not limited to, university faculty members and their students and postdoctoral research associates.

An additional requirement is that straightforward user access to the research facilities should be facilitated. In many cases graduate students and postdoctoral research associates are foreign nationals and they should also have access to the facilities. Mechanisms should be developed for allowing open scientific collaborations between academic scientists and scientists at the National Nuclear Security Administration (NNSA) laboratories and facilities, consistent with national security priorities. Many researchers who are foreign nationals subsequently become U.S. citizens and contribute substantially and uniquely to areas of important national need.

The need to foster the field of high energy density physics in the United States and to have an integrated national plan to make effective use of high energy density facilities from the small scale to the large scale leads to the following three recommendations pertaining to the area of laser-driven high energy density physics:

1. Access to kJ-class facilities is essential to develop the scientific basis, experimental techniques, diagnostics, and simulation capabilities, including access by foreign nationals. If the present facilities cannot support this, either because of over-subscription, site access, or cost issues, then a new kJ class laser facility should be constructed and operated with user access at an open site.

2. A nationally integrated plan should be developed for user access to OMEGA/EP, Z/ZR, and NIF, including about 15% of the shot time, the use of staging facilities, and including infrastructure support.

3. Funding opportunities, from multiple agencies, to develop collaborations organized along the scientific thrust areas described in this report should be provided. Memoranda of Understanding (MOUs) among the various agencies are required to allow ready access to facilities developed and supported by different agencies.

This is an illustrative set of recommendations, and recommendations in other research thrust areas can be found throughout the remainder of the report.

Finally, the Task Force strongly reaffirms the Findings and Recommendations made in the three reports identified earlier in Chapter 1. These three reports and the concomitant Findings and Recommendations should be used in combination with the present Task Force report in formulating an integrated national research plan for high energy density physics.

CHAPTER 2

High Energy Density Physics in Astrophysical Systems

2.1 Introduction

The core question of high energy density physics – how does matter and energy behave under conditions of extreme temperature, pressure and density, and how do matter and radiation interact under such extraordinary conditions? – has its core roots in astrophysics. For example, the work of Chandrasekhar (published in 1930) revealed the role played by degenerate matter in governing the evolution of highly evolved stars, ultimately leading to an understanding of remarkable stellar objects such as white dwarfs and neutron stars. Since then, the remarkable diversity and extremes of physical conditions in astrophysical systems has driven much of the early work in high energy density physics, resulting in a bridge between astrophysics and laboratory physics, especially in the areas of high energy density materials and radiation hydrodynamics. Furthermore, this bridge – or connection – is increasingly strengthened by the modern advent of large-scale simulations, which are now reaching a stage in which sensible efforts to directly model laboratory fluids and plasmas, without recourse to 'fitting parameters', can now be accomplished.

With this background in mind, we have organized our discussion of high energy density astrophysics into three thrust areas:

1) Astrophysical phenomena;
2) Fundamental physics of high energy density astrophysical phenomena; and
3) Laboratory astrophysics.

These themes are now part of a relatively recent change in our thinking about the interplay between astrophysics and the rest of physics – that is, recognition that exploration of the same physics by looking on the largest possible scales of the universe and the smallest scales – from the early universe, before recombination, to the quark-gluon plasma produced by modern relativistic heavy ion accelerators – has become a touchstone of some of the most exciting research in modern physics and astrophysics[1]. The "core question" posed at the beginning of this section exemplifies this commonality; and in the following discussion, we examine in more detail how the physics of the very small and the very large find a common home in high energy density (astro)physics.

Our decision to discuss high energy density astrophysics via thrust areas largely defined by the method of investigation, rather than by scientific topic, is based on two distinct aspects of this field that differ significantly from the other areas of high energy density physics covered in this report. First, the diversity of topics in which high energy

[1] See NRC Report *Connecting Quarks with the Cosmos* (National Academies press, 2003)

density physics plays important roles is so broad that attempts to abstract these into a short list of scientific thrusts have proved to be difficult – and, in our view, deceptive – because the profound diversity of science is then hidden from view, and key topics necessarily given short shrift. Second, astrophysics remains in many ways a deeply observational (as opposed to experimental) science, in which the kinds of controlled laboratory experiments that physics is normally associated with are not feasible. Hence we organize the discussion according to the nature of the science approach; and explicitly discuss specific instances of the astrophysics involved as examples – we make no efforts at, nor claim, completeness in this latter regard,

Finally, we note that the compelling questions in the science of high energy density astrophysics identified in this report, and the recommendations this report makes for addressing these questions, follow from, and build upon, several recent larger efforts that review the current status of astrophysics and provide prioritized listings of research programs and missions. These include the 2000 NRC Survey of Astronomy and Astrophysics (National Academies Press, 2001), Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century (National Academies Press, 2003), and The Physics of the Universe (National Science and Technology Council, 2004). The astrophysics section of this report is not intended to supplant these earlier reports, nor to revise their priorities, but instead to call attention to the special opportunities that now exist for progress on astrophysical problems that fall within the domain of the newly emerging subfield of high energy density physics. Interagency cooperation is particularly important for rapid scientific progress in this quintessentially interdisciplinary area.

2.2 Astrophysical Phenomena

As a general matter, astrophysical phenomena are typically characterized by non-dimensional "control parameters" (viz., Reynolds numbers, Rayleigh numbers, and the like) that lie far beyond our direct experience in terrestrial laboratories, and our ability to directly simulate such phenomena on modern state-of-the-art computers. Furthermore, we typically carry out astrophysical experimentation by remote sensing, that is, by using photons or other emissions from astrophysical sources that arrive at Earth, as opposed to in situ probing of the astrophysical systems. As a result, astrophysicists must infer the physical conditions in distant astronomical objects, using rules for physics developed on the basis of our terrestrial experience. Finally, the observed astronomical phenomena are typically so complex, and our understanding of such complex systems is sufficiently primitive, that astronomers and astrophysicists build "models" for these celestial phenomena that resemble in many ways models built by engineers in order to describe systems which physics and the other natural sciences are not as yet able to describe fully from first principles. That is, astrophysical models are often not unique (that is, more than one model may account for the observed data, and further observations – usually motivated by competing model predictions – need to be carried out), and are characterized by free parameters, which encapsulate those aspects of the model that are not yet understood from first principles. Thus, in some ways, one can regard astrophysics also as "astroengineering", with the connection to physics often made (as in engineering) by the driving need to explicate those aspects of models that can (or at times, must be) understood from first principles.

2.2.1 Motivating Intellectual Question

> *What is the nature of matter and energy observed under extraordinary conditions in highly evolved stars and in their immediate surroundings, and how do matter and energy interact in such systems to produce the most energetic transient events in the universe?*

This question is a composite of many subsidiary questions – such as for example, what is the nature of neutron stars, and do quark stars exist? What is the explosion mechanism for Type Ia supernovae, and why are they "standard candles"? What is the explosion mechanism for Type II (core collapse) supernovae? What are gamma ray bursters, and how do they "work"? How do cosmic accelerators work and what are they accelerating? How do accretion disks "work" and how are they connected to the origins of jets? – each of which is deserving of a chapter on its own.

These questions exemplify what astrophysicists call (the aforementioned) "modeling", e.g., the use of existing physics theory – or extrapolations of existing theory – to build models describing particular astrophysical systems. These systems include some of the most extraordinary objects in the universe: from pulsars "in the small" to quasars "in the large", from supernovae in our galaxy to gamma ray bursters at cosmological distances; these objects are central actors in some of the deepest questions of astrophysics – how were the elements heavier than lithium synthesized? What is the age and size of the Universe? What is the Universe made of? What is the ultimate fate of the Universe? A major challenge for astrophysics is to distinguish between competing models for a given astronomical phenomenon or object; this is an area of research in which the use of numerical simulation and laboratory experiments can play critical roles. Furthermore, the kinds of phenomena encountered in astrophysical systems in which high energy density physics plays important roles often challenge the limits of our understanding of "established" basic physics – consider the possible origins of particles with individual energies above 10^{19} eV, or the acceleration and collimation of highly relativistic beams over distances ranging from tens to millions of light years – and thereby drive the greater understanding of basic physical processes.

2.2.2 Research Opportunities

Scientific Objectives and Milestones

Given the wealth of astronomical phenomenology, it is only possible to provide a snapshot of the excitement currently characteristic of high energy density astrophysics; we therefore limit ourselves to only two illustrative examples of astrophysical phenomena of current interest, both of which are easily encapsulated by a core question. In the following, we describe the astronomical context of these questions, and delve into some scientific challenges and opportunities, as well as the hoped-for milestones, flowing from these questions.

What are gamma ray bursts, and how do they "work?" The gamma ray burst (GRB) paradigm is a historically rich and intriguing one that has excited astrophysicists and physicists over the past three decades. Episodic controversies have embroiled this field, usually as a result of new observational data, and these have driven thought on the paradigm and lead to an explosive growth in the interest in these enigmatic sources over the last decade. Within the realm of high energy density astrophysics, there are three focal issues that are central to the burst phenomenon. The first of these concerns the nature of the progenitors for gamma ray bursts, and how they initiate such powerful transient emission. Current perspectives focus on massive stars undergoing core collapse supernova explosions, for which there is mounting spectroscopic evidence in the optical afterglows of bursts. These events possess the requisite energy to power gamma ray bursts, and also the heavy elements inferred in the burst environs from X-ray afterglow observations. The understanding of these Type II supernovae themselves is the focal point of additional compelling questions, for which the burst phenomenon provides additional topical motivation.

The second aspect of the gamma ray burst phenomenon that intrigues the science community is why their blast waves are of finite angular extent. This contributes to a greater paradigm of why mass outflows in astrophysical systems are so frequently collimated, with characteristics such as apparent superluminal motion and structured ejection from the compact centers of extragalactic quasars and galactic microquasars. The mechanism for angular confinement remains a mystery. While collimation imposed by matter or radiation pressure from geometrical structures surrounding a jet is a possibility, an alternative scenario is that magnetohydrodynamical confinement is acting. This could be in a dynamic system such as a supernova explosion, or more steady and connected to a rotational driver such as a neutron star or black hole. Recent progress in magnetohydrodynamic analyses of supernova shells have suggested that collimation should be common, but the analysis of the problem realistically requires more ingredients, principally matter and its interactions, and general relativity, in a high energy density environment. Accordingly, a dramatic increase in computational capabilities is highly desirable. Key issues include the extent to which Poynting flux can act alone in effecting collimation, as opposed to needing assistance from other matter or radiation sources, whether the angular confinement is modest and if it intrinsically possesses non-radial components, and whether outflows must commonly be accompanied by accretion disks, the subject of additional compelling questions, addressed immediately following.

The principal dissipation mechanism in relativistic outflows in gamma ray bursts is not understood. Ejected matter from the central source is only observed in its dissipative phase, where the energy is converted into radiation. The resultant emission is non-thermal in character, and requires relativistic beaming in order to escape the compact environment without attenuation, a property that is also evinced by other luminous, compact regions such as jets in active galaxies. The nature of this dissipative conversion is a crucial issue. While electromagnetically-dominated models have gained popularity recently in the gamma-ray burst paradigm, the leading candidate theory is that coherent or diffusive acceleration of particles in the environs of a plasma shock is extremely efficient, and persists to ultrarelativistic energies before radiative dissipation kicks in. Successful models of this acceleration mechanism have principally been based on analytic or kinetic-type simulations, and can predict efficient generation of non-thermal populations. Full plasma (particle-in-cell) simulations have made substantial progress, but are still limited by speed and memory issues and therefore are constrained by small energy ranges, very modest spatial and temporal scales, restrictively small ion/electron mass ratios, and reduced dimensionality. Critical physics can be lost by imposing such expedient restrictions. The most crucial questions are how coherent is the field structure near the shock, what is the efficiency of acceleration and the energy distribution of electrons, how rapid does the acceleration proceed, what is the radiation emission mechanism, and can such structures generate ultra-high energy cosmic rays? A substantially increased investment in computational resources will lift some or most of these restrictions to plasma codes, thereby enabling rapid progress in our understanding of the burst radiation zone.

How do cosmic accelerators work and what are they accelerating? This is one of the "eleven science questions for the new century" posed by the aforementioned NRC report, *Connecting Quarks and Cosmos*. Physicists have detected ultra high energy cosmic rays (UHECR) with energies beyond 10^{20} eV, but there is as yet no identifiable site within the local super cluster of galaxies with distance less than 50 Mpec that can be linked to the production of these UHECRs. This poses an acute challenge to both the mechanism and the nature of these UHECRs, particularly in light of the well-known Greisen-Zatsepin-Kuzmin (GZK) cutoff, which limits the possible distance likely candidate particles could have traversed through the cosmic microwave background. What physical mechanisms and what astrophysical environments can propel these particles to such exceedingly high energies? The aforementioned gamma ray bursters are a possible cosmic accelerator site, but there are also other candidate sites such as the active galaxies. There exist many cosmic particle acceleration models and mechanisms, including the popular "diffusive shock acceleration" mechanism, which is a variant of the celebrated Fermi mechanism. Although these models invoke a rather diverse spectrum of physical processes, they invariantly rely on the assumption of very high energy density astrophysical settings such as extremely high density relativistic plasma outflows or jets. Analogous to other examples in this section, progress in this subject will also rely on the interplay between large scale computer simulations, scalable and controlled laboratory experiments, and (of course) astronomical observations.

How do accretion disks and jets `work,' and how are they connected to each other? Accretion disks are formed by the infall of matter onto compact objects such as stars or black holes. If the matter has angular momentum (and in any real system it will), then close to the central object the matter will form a rotationally-supported disk. The rate at which matter accretes through the disk onto the central object is controlled by the rate of outward transport of angular momentum. In the past ten years it has been understood that in most cases this transport is controlled by magnetohydrodynamic (MHD) turbulence driven by the magnetorotational instability (MRI), a powerful linear magnetohydrodynamic instability present in the accretion flow itself. In order to understand the observed properties of accretion disks (their luminosity and spectrum), and their evolution (their time-variability, and the rate at which mass is accumulated at the center), it is vital to understand the nonlinear regime of the magnetorotational instability in a wide variety of astrophysical disks. Moreover, accretion disks appear to be the source of powerful, collimated outflows and jets in every system they occur (from disks around newly forming stars to disks around supermassive black holes in the core of active galaxies). Thus, understanding the mechanism that produces astrophysical jets is intimately tied to understanding the dynamics of accretion disks.

Since it is not possible to construct an accretion disk in the laboratory, and since the multidimensional, nonlinear evolution of magnetohydrodynamic turbulence is difficult to study analytically, numerical MHD methods have emerged as a powerful tool for the study of disks. Adopting the ideal magnetohydrodynamic approximation (in which the resistivity of the plasma is assumed to be negligible), current magnetohydrodynamic codes running on modern architectures can evolve local patches of an accretion disk at moderate resolutions (256x256x256 grid points in 3-D) for hundreds of orbits. These computations reveal the dependence of the magnetic stress that drives accretion on the fundamental parameters such as the net magnetic field strength and the vertical thickness of the disk. Reassuringly, the total stress measured in the simulations is in good agreement with values inferred from observations of a variety of astrophysical systems. In addition, the nonlinear regime of the magnetorotational instability has been studied using computational methods in non-ideal magnetohydrodynamics (including both Ohmic dissipation and the Hall effect), in disks in which radiation pressure dominates the gas pressure (appropriate to the conditions expected in the inner regions of disks around black holes), and in disks around rotating black holes in full general relativity (using the Kerr metric).

While recent progress is encouraging, there remain many important issues in accretion disk research. Some require more advanced computational capabilities before they can be addressed. For example, global models of thin accretion disks that span many decades in radii represent a difficult multiple length- and time-scale problem that would be best tackled using nested grids. Calculations of this type hold the most promise for understanding how the internal dynamics of accretion disks affect the generation of magnetohydrodynamic outflows. Similarly, global models of radiation dominated disks require more robust numerical algorithms for treating both the optically thin upper layers of the disk (above the photosphere), as well as the optically thick, turbulent midplane. Accelerating the development of numerical algorithms will almost certainly accelerate our understanding of these problems. However, progress in other areas requires a better description of poorly understood physical mechanisms. For example, the processes that lead to dissipation of the magnetohydrodynamic turbulence driven by the magnetorotational instability at microscopic scales currently are not understood. Various plasma wave damping mechanisms are plausible. However, a predictive theory of the radiative efficiency of accretion requires a detailed accounting of how much turbulent energy is dissipated in the electrons, and how much in the ions. Similarly, for very diffuse accretion flows the particle mean free paths may be large compared to the size of the disk, and a magnetohydrodynamic description will not be appropriate. In this case, kinetic plasma effects can change the properties of the magnetorotational instability (such as the growth rate and saturation amplitude), and might may lead to entirely new instabilities (for example, the anisotropic viscosity in a long mean-free-path plasma can lead to viscous instabilities in a rotationally supported disk). Studies of these new kinetic magnetohydrodynamic regimes in accretion flows require entirely new methods, and may benefit from interaction with high energy density physics experimental efforts.

Resource Requirements

To the extent that astronomy and astrophysics remain a quintessential observational science, the core requirements remain the need for forefront observational tools, e.g., both ground-based and space-based observatories spanning the broad wavelength regimes characterizing photon emission from astrophysical systems, as well as means for detecting and quantifying other types of emissions such as high energy particles (e.g., cosmic rays). Since these are discussed (from both the science and the practical implementation perspectives), and ranked, by the NAS/NRC decadal studies for astronomy and astrophysics, we defer to these reports as discussed at the beginning of this chapter. Here we only call attention to the fact that one of the key missions for understanding the nature of dark matter, namely the Joint Dark Energy Mission (JDEM), is an excellent example of the potential for interagency collaboration on a forefront scientific question, in this case involving the Department of Energy and the National Space and Aeronautics Administration.

In contrast, the growing role for numerical simulations has not made comparable impact as yet in earlier studies. With the advent of the DOE National Nuclear Security Administration's Advanced Scientific Computing Alliance program of centers of excellence in forefront computations (involving at least two university-based centers in which issues of high energy density physics are prominent), the DOE Office of Science "Scientific Discovery Through Advanced Computing" (SciDAC) program (which supports several major efforts in high energy density astrophysics, in collaboration with various disciplinary programs within the Office of Science), and the NSF Physics Frontier Center program (which also supports university-based centers focusing at least in part on problems related to high energy density physics), the needs for such work, and the possible impacts of this type of research, are now becoming much more widely appreciated. The key point is that the complex and multifaceted nature of astrophysical phenomena (multifaceted both in terms of the phenomenology and in terms of the variety of physical processes involved), and the highly nonlinear nature of the physical interactions, have meant that analytical theory is severely hampered in its application; and that laboratory "proxy" experiments can typically only approach aspects of the full complex problem posed by these phenomena. Hence, it is only numerical simulations that provide any hope to be able to understand these phenomena as integrated, complex systems. The scale and range of needed activities, and their estimated costs, coincide closely with the needs for simulations in the laboratory astrophysics case; and we therefore defer the details of this discussion to Section 2.3.2.

2.3 Fundamental Physics of High Energy Density Astrophysical Phenomena

2.3.1 Motivating Intellectual Question

What are the fundamental material properties of matter, and what is the nature of the fundamental interactions between matter and energy, under the extreme conditions encountered in high energy density astrophysics?

This question – as in the previous case – is a proxy for a plethora of subsidiary fundamental physics questions that grow out of the observed astronomical phenomena – for example, what is the equation of state of degenerate and partially degenerate matter, at high and ultra-high densities, and at low and high temperatures? What are the opacities of complex matter at high densities and temperatures? How does matter behave in the presence of extremely large ($>10^9$ gauss) magnetic fields? How are superstrong magnetic fields ($>10^{12}$ gauss) generated and dissipated? Why is the departure from local thermodynamic equilibrium conditions so common in astrophysics? Such questions go to the heart of the fundamental physical processes governing matter and radiation at high energy densities: the equation of state (EOS) describes the connection between density, temperature, and pressure for matter, the opacity marks the degree of interaction between matter and radiation; and magnetic fields are a ubiquitous feature of virtually all astronomical objects – from stars and planets to the universe at large – whose interaction with matter and radiation can lead to highly energetic, transient phenomena. Often, astrophysical model building call upon physical processes – such as the dissipation of magnetic fields – which are beyond our current understanding; and it is the role of high energy density physics to attack such questions by using a combination of theory, simulations, and laboratory experiments. In such cases, it is commonplace for the fundamental physics problem to take on a life of its own, that is, to become intrinsically interesting, quite apart from the astrophysical motivation[2].

2.3.2 Research Opportunities

Scientific Objectives and Milestones

As in the case of astrophysical phenomena, the research opportunities in the basic physics end of high energy density astrophysics are so varied that it is not sensible to provide a detailed account – and a partial account may leave the incorrect impression that there is a consensus as to the relative rank-ordering of "importance" of specific problems. For this reason, we also content ourselves here with an illustration of what this thrust area involves, making no pretense whatsoever of completeness. Furthermore, it should be noted that the possible connections between basic (astro)physics and laboratory

[2] For example, the problem of 'fast reconnection', that is, the dissipation of magnetic fields such that the dissipation rate is independent of the microscopic resistivity of a plasma, first arose in the context of explaining the short time scales associated with solar flares; but has subsequently become a problem of central interest to terrestrial plasma theory, simulation, and experiment.

astrophysics have been traditionally very deep – they were key elements in the his development of atomic and nuclear physics, as well as of quantum mechanics itself – and we see a similarly close connection in the case of high energy density astrophysics. In addition, the role of numerical simulations is a key element in the basic physics end of high energy density astrophysics, a point made in more detail, and with more context, immediately below.

High energy densities in astrophysics usually occur in systems with high mass density. The Big Bang is an archetypal example. At early times, the universe was exceeding dense and optically thick. Matter and energy were then closely coupled and in thermodynamic equilibrium. Likewise, the interiors of supenovae represent states of matter almost in thermal equilibrium. However, we also commonly observe systems far from equilibrium, often involving relativistic particles – jets emerging from black holes, winds from neutron stars, shock waves driven into the surrounding interstellar medium by supernovae (including gamma ray burst sources) all are examples where the state of matter is far from equilibrium, often not even possessing a well defined kinetic temperature. Paradoxically, such configurations occur as a consequence of gravitational collapse, whose consequence can be outflows and explosions with exceedingly high energy/particle and with physical conditions varying on time scales too short to allow relaxation to local thermodynamic equilibrium. The inner regions of accretion disks around relativistic compact objects often have the same character. The free energy available from outflow and infall then can drive systems with low mass density but high energy/particle into states far from thermal equilibrium, leading to acceleration of high energy particles (including cosmic rays, both normal and ultra-high energy), as well as non-thermal radiation that allows us to characterize these systems by remote sensing.*torical*

Such matter forms a dilute (albeit highly energetic) plasma, that is, a dilute gas of electrons, ions, and positrons. Numerical methods are at present the only viable way of studying the dynamics of these plasmas. Using numerical simulations, much progress has been made in recent years in understanding a variety of important problems, including the structure and evolution of accretion flows around compact objects (neutron stars and black holes), and the decay rate and fluctuation statistics of compressible magnetohydrodynamic turbulence. Almost without exception, such advances have used multidimensional magnetohydrodynamic codes. However, for problems involving particle acceleration, the magnetohydrodynamic approximation is insufficient. Examples include the dynamics of very dilute accretion flows, the dynamics of turbulent plasmas near the energy dissipation scale, magnetic reconnection and the structure and particle acceleration properties of collisionless shock waves, both non-relativistic and relativistic. In order to address fundamental problems in these areas, one must move beyond the magnetohydrodynamic approximation, and consider particle kinetics. A full time-dependent and multidimensional numerical solution to the Boltzmann equation is intractable in most circumstances, thus novel methods are required.

Advances in large-scale computing have made this an opportune moment to tackle questions of collisionless magnetic reconnection and the properties of collisionless shocks. The wealth of information accumulating from observations of these phenomena in space give the opportunity to test computational modeling against experiment, and the improvements in X-ray, gamma ray and radio observations of nonthermal phenomena in astrophysical systems urgently require improved results from kinetic models of the physical processes, embedded in macroscopic models of the astrophysical systems. One obvious immediate objective is to characterize the physics of relativistic shocks, so as to put their role as accelerators of high energy particles on a sound footing and apply that knowledge to understanding the emission from the jets emerging from black holes (in active galactic nuclei, microquasars and the gamma ray bursters discussed in the previous section), as well as to the emission from the relativistic winds emerging from neutron stars. A second, almost as immediate, objective is to extend recent advances in the understanding of reconnection to relativistically strong magnetic fields and to relativistic, electron-positron plasmas, and to apply the results to flaring phenomena in neutron stars and high temperature accretion disks.

Resource requirements

The study of kinetic phenomena in collisionless, astrophysical plasmas will advance primarily through advances in simulation. The most important requirements are breakthroughs in algorithms, which will allow simulation of the multiple length and time scales that appear in magnetic reconnection, for example, and in the coupling of the reconnection phenomenon to the macroscopic flows that drive it. Especially important to the particle acceleration problem in reconnection and in shocks is the ability to increase the range of particle energies that can be resolved in kinetic models – in particle codes, this requires major increases in the number of particles that can be contained in a simulation, which in turn requires improvements in algorithms that allow the use of parallelization. In multi-scale problems like reconnection, algorithms that allow coupling between the kinetic and fluid scales need development.

People are the resource most needed to support these advances. To further that goal, support for moderate scale groups ("Centers") in which researchers (permanent staff, graduate students, postdocs and senior visitors) with expertise in multiscale algorithm design (applied mathematics), high performance computing (computer science), plasma physics (theoretical or experimental) and astrophysics can interact over extended periods to advance the state of the art in these problems. As discussed further in Section 2.3, certain aspects of the science – such as algorithm development – may well be best carried out in the context of more traditional university-based single-investigator programs; hence, the present focus on "centers" should not detract from the need to maintain a healthy single-investigator program.

Attention must also be given to the computer hardware required for large-scale simulation. When the physical problems include a variety of coupled physical processes (e.g., particle-in-cell simulation of the plasma dynamics coupled with transfer of radiation emitted and absorbed by the plasma particles), experience suggests that massive parallelization of algorithms using computers constructed from off-the-shelf hardware may be less effective than moderate parallelization used on computers constructed from a smaller number of special purpose processors. Furthermore, the development process (as opposed to production calculation) is often best served by the use of smaller-scale dedicated clusters that allow guaranteed, regular access without the need for extensive resource planning.

2.4 Laboratory Astrophysics

2.4.1 Motivating Intellectual Question

What are the limits to our ability to test astrophysical model and fundamental physics in the laboratory, and how can we use laboratory experiments to elucidate either fundamental physics or phenomenology of astrophysical systems that are as yet inaccessible to either theory or simulations?

One of the most exciting areas of astrophysics is the growing effort to connect astrophysical phenomena and the related fundamental physics to the laboratory; these efforts have become especially notable in the area of interest to this report, e.g., high energy density astrophysics. The motivation underlying these efforts focuses on four different aspects of the high energy density physics-astrophysics-laboratory connection:

(a) High energy density astrophysics and laboratory physics share a common interest in establishing the fundamental properties of matter and energy – equations of state, opacities, transport properties such as conductivities and viscosities – under extraordinary physical conditions. This kind of connection has been long-established – and has been enormously fruitful – in areas both inside and outside of the high energy density physics regime; thus, plasma spectroscopy had its origins in the interaction between astrophysicists and laboratory physicists in the mid to late 19th century, an interaction which continues to be active and productive to this date. In the high energy density case, this connection has grown out of the realization that the new generation of laser and particle beam-driven high energy density facilities offer the possibility of exploring physical conditions in the laboratory that bear a great resemblance to physical conditions found in some astrophysical systems. As a result, there are a variety of concrete new links between astrophysics and the laboratory, including the use of particle accelerators to calibrate air shower experiments, that address some of the most pressing new questions of modern astrophysics.

(b) Astrophysicists want to explore astrophysical phenomenology under controlled laboratory conditions in order to build our intuition in (highly nonlinear) unusual circumstances. For this purpose, it is not necessary for the physical conditions (e.g., density, temperature, pressure) to be similar in the astrophysical and laboratory settings – what is required is that similar nonlinearities operate in the systems under study. Ongoing attempts to understand magnetic field generation in plasmas – relevant to both field generation in white dwarfs and neutron stars and to field generation in laser-driven high energy density plasmas – exemplify this class of research.

(c) Astrophysicists seek to directly connect laboratory phenomena/physics to astrophysical phenomena/physics, wherever possible. Under certain conditions, the evolution of astrophysical systems can exhibit asymptotic behavior that is relatively independent of certain control parameters (such as the Reynolds number). In such cases, it is possible to re-scale the evolution equations so that they apply to both the astrophysical system and an appropriately designed laboratory experiment; the recent work on shock propagation in inhomogeneous media, relevant to both laser-driven capsules and Type II (core collapse) supernovae, is a good example of such an interaction.

(d) Astrophysicists look towards the laboratory as a means of developing and validating instruments, diagnostic techniques, and simulation codes to be used for studying astrophysical problems. There is already a rich history of interactions in instrumentation areas related to detector and plasma spectroscopy; and we have already mentioned above the strong interactions on plasma diagnostics connecting astrophysics to the laboratory. More recently, serious efforts have been started in the use of numerical simulation codes developed for astrophysical studies to examine phenomena in laser-driven and pulsed power-driven high energy density plasmas; such studies aim both to validate the simulation tools and to use laboratory results to drive the development of additional capabilities of the simulation tools.

In all these cases, the as-yet unanswered question is: what are the limits to our knowledge of the physics of matter under extremes of temperature, density, and pressure? The aim of laboratory astrophysics is, in part, to help establish these limits; and, in particular, to serve as a 'Rosetta stone' for astrophysical observations and theory, that is, to help build the physicist's and astrophysicist's intuition about physical processes which are not encountered under normal terrestrial circumstances, and which are sufficiently complex and nonlinear that theory and (numerical) simulations alone are incapable of providing sufficient guidance for understanding.

Given the intellectual excitement underlying the above-mentioned motivations for laboratory astrophysics, it is crucial to remember that laboratory astrophysics has its historical roots in a seemingly more prosaic (albeit at least equally important) role, namely establishing the fundamental properties of matter and energy, as well as studying the details of the interaction between radiation and matter. Thus, the roots of modern atomic physics and quantum mechanics are to be found in important measure in the early 19^{th} Century efforts in atomic spectroscopy targeted at the Sun, and the realization that these astronomically-derived spectra may be connected at a deep level with the emission and absorption spectroscopy carried out at that time in the laboratory setting. Similar issues arise today – can one hope to understand fundamental material properties – such as equations of state and opacities – needed for astronomical purposes by studying similar or analogous physical systems in the laboratory?

Now, the extraordinary physical conditions encountered in astrophysical systems lead to the immediate problem that replication of similar conditions in terrestrial laboratories is often difficult, and much of the time downright impossible. There are three distinct and complementary ways of dealing with this problem, each of which is limited by distinct constraints that prevent ready application to the entire density-temperature domain encountered in astrophysical systems.

- Pushing the frontiers of attainable plasma properties. One of the grand challenges of laser and particle-driven plasma science is to push the frontiers of achievable plasma densities and temperatures. As can be seen from the ρ-T diagram in

Chapter 1, existing and planned laser and pulsed power facilities are, or will be, entering high energy density physics regimes which are common to astrophysical fluids, including especially conditions similar to those present in the interiors of giant gaseous planets and brown dwarf stars. A key question is what physical constraints exist that place ultimate limits on the boundaries of this achievable ρ-T domain.

- Scaling. It has been argued that microscopic processes such as viscosity may play only negligible roles in controlling the dynamics of processes on large spatial scales; if such arguments hold, then it becomes possible to non-dimensionalize the governing evolution equations in such a way that experimental results from laboratory experiments can be re-scaled to astrophysical system dimensions. While such arguments have found extensive application in hydrodynamics, there are serious questions whether they can be extended to magnetohydrodynamic problems, primarily because in the latter case, inverse cascades may back-couple dynamics on the small scale to dynamics on large spatial scales. It will be very important to study concrete examples in which such inverse cascades occur, and to investigate the validity of scaling arguments in such cases.

- Analogies. There are a number of circumstances in which one can neither hope to replicate astrophysical conditions in the laboratory, nor have any confidence in possible scaling behavior; in such instances, laboratory experiments can nevertheless be invaluable in teaching us about the range of behaviors one can encounter for problems exhibiting similar nonlinear interactions. Examples of this sort include laboratory studies of magnetic dynamos and of magnetized accretion disks; in both cases, the values of the governing astrophysical and laboratory control parameters are vastly different, and scaling arguments are dubious in the extreme. One can nevertheless ask whether certain behaviors are universal, e.g., relatively independent of the values of the control parameters but sensitive to the nature of the governing nonlinearities of the physical systems. For example, in the case of magnetic dynamos, one can ask whether particular magnetic field generation processes, such as the “alpha-effect” first recognized in the case of the solar magnetic dynamo, exist under more exotic physical conditions.

It is not uncommon in astrophysics to find that the system under study cannot be understood with any degree of certainty by use of either theory or numerical simulations. This is especially the case for instances in which both magnetic fields and turbulence play important roles. Thus, formal theoretical attacks on (magneto)turbulence have been largely unsuccessful. Similarly, direct numerical simulations of (magneto)turbulence largely miss the turbulent element (because fully developed fluid turbulence is as yet beyond the ability of current generations of simulation tools); attempts to model the unresolved scales remain at present highly controversial. Similar difficulties arise in problems related to radiation hydrodynamics, such as in the Type II supernova context. In such cases, laboratory experiments of proxy systems can be the only recourse. Thus, it is relatively straightforward to bring laboratory plasmas into a turbulent state; and laboratory studies of problems in which radiation hydrodynamics plays an important role have been carried out. These examples only illustrate what has already been done; similarly, one can illustrate by example where the frontier areas are. One frontier is the development of experiments in which fully collisional magnetized plasmas become turbulent (in the hydrodynamic sense); the challenge is to design experiments in which the magnetic Reynolds number is sufficiently high that one can sensibly speak of magntoturbulence. A related area is the study of magnetic field generation under high energy density physics conditions. Theoretical developments have gone well beyond the traditional mean field theories; and numerical simulations are now playing a much more important role. However, laboratory attempts to study field generation in fully collisional systems have been largely confined to liquid metal experiments, in which the magnetic Reynolds number is painfully low (by astrophysical standards); the consequent small Prandtl number of these experiments thus mean that they are largely studying field generation in a regime fundamentally different from that encountered in condensed stars (whose Prandtl number is very large). Similar concerns arise in the design of experiments modeling accretion disks (e.g., magnetic Couette flows), and new types of experimental innovations will be called for in order to better connect such laboratory and astronomical "systems".

2.4.2 Research Opportunities

Scientific Objectives and Milestones

The scientific objectives and milestones for high energy density laboratory physics are linked to successful exploration in the laboratory context of the great variety of physical processes and models discussed above. The list of possible science objectives for laboratory astrophysics is as vast as the range of possible problems studied by astrophysicists; we therefore confine ourselves here only to a select few examples. Therefore, without attempting to be exhausting, such objectives and milestones include

- Validation of various computational methods for radiation hydrodynamics and magnetohydrodynamics. The milestones are experimentally validated numerical simulation schemes that have been shown to replicate a broad range of high energy density physics experiments within well-defined error bounds.

- Exploration of magnetic field generation and dissipation under high energy density conditions. This objective includes the generation of magnetic fields in laser-driven plasmas ("battery" effect) and magnetic dynamos; the study of magnetic Couette flows (as proxies for magnetized accretion disks); and the study of magnetic field reconnection in an high energy density physics context (addressing the question of whether "fast reconnection" can take place under such conditions). The associated milestones are the demonstration of dynamo action in a laboratory plasma setting that resembles the expected conditions in astrophysical systems where dynamo action is expected; and the demonstration that the magnetorotational instability can effectively transport angular momentum in a laboratory proxy experiment of accretion disks.

- Determination of the equations of state and opacities relevant to conditions found in the context of compact stars. The associated milestones are validated equation of state tables that are both internally thermodynamically consistent and agree within stated error bounds with available high energy density data; as well as similarly validated opacities as a function of frequency and plasma properties.

- Validation of cosmic particle acceleration models and mechanisms. Associated milestones include the validation of the diffusive shock acceleration and other alternative acceleration mechanisms using high energy density particle beams as simulators for the relativistic outflows, as well as the validation of computer codes that simulate these highly nonlinear processes.

Resource requirements

The above-listed selected objectives can in part already be addressed in the context of existing high energy density physics facilities, such as the OMEGA laser facility at the University of Rochester, the Nike laser facility at the Naval Research Laboratory, the pulsed power facility at the Z-pinch at Sandia National Laboratories, as well as at linear particle accelerators such as exist at the Stanford Linear Accelerator Center (SLAC). As discussed in latter chapters of this Report, a number of new facilities of similar type, but with far greater capability – such as the National Ignition Facility (NIF) – will come on line over the next decade; and we expect that current efforts at existing facilities will be able to take advantage of the greater capabilities of these new facilities. Furthermore, we note that certain types of facilities are likely to play major roles in high energy density astrophysics, but may not be primarily (or at all) viewed from this perspective. A good example is the internationally-funded Large Hadron Collider (LHC) at CERN, the next forefront particle accelerator for the international high energy physics community that will in the future devote a substantial amount of facility time (of order one quarter) to nuclear – as opposed to high energy – physics research. This research will focus in part on the production of a quark-gluon plasma, a topic that is already of considerable experimental and theoretical interest as a result of recent work at the Relativistic Heavy Ion Accelerator (RHIC) at Brookhaven National Laboratory. Similarly, particle beams produced at accelerators can be used to drive free electron lasers that in turn can produce extremely high energy x-ray beams for probing high energy density matter; the Linac Coherent Light Source (LCLS) at SLAC is an example of such a facility.

Since the existence of these facilities in question is largely dependent on circumstances that have little to do with astrophysics, we will not discuss the associated resource requirements in this section. Here we only discuss those resource requirements that are peculiar to high energy density astrophysics, and are separate from the facilities themselves.

Establishing a connection between astrophysics and laboratory experiments in high energy density physics involves two distinct efforts, that is, on the experimental and theoretical fronts. First, on the experimental front, the design of appropriate experiments involves simulation tools and expertise that are not widely available to the astrophysics community. One solution is to identify one or more research groups or "centers" that have the responsibility for providing and maintaining the necessary community simulation/design tools for producing the requisite experimental devices (viz., hohlraums); similar groups or "centers" may also be established to assist in the fabrication of the necessary experimental devices. Such "centers" may exist either at universities or national laboratories; the former may be preferable because one can then be relatively confident that the barriers between classified and unclassified research are not compromised. Given the novelty of this research area, new initiatives in experiment diagnostics will be needed; as well as programs to actually build new diagnostic instruments. Such initiatives and programs will have to have a significant university component since a key element of this new field will be the training of the needed new researchers – and university settings are clearly the appropriate solution to the workforce development aspects. Such university-based efforts may well arise in settings other than large collaborative research centers – instrument development has been well-known to also thrive in the context of individual investigator operations.

On the theoretical front, the key missing elements are the production forefront simulation tools – the numerical simulation codes – capable of studying high energy density physics problems. At present, no group external to the national laboratories is charged with the development and maintenance of one or more community codes capable of such simulation tasks. (Such codes could also naturally serve as design tools for the production of, for example, hohlraums.) For reasons similar to those just discussed, such groups or "centers" are best located at universities. Furthermore, it should be noted that while construction of community codes may require marshalling substantial efforts at "centers of excellence", the development of new algorithms, or of new methods for modeling phenomena, have in the past been primarily carried out within the context of individual investigator programs. For this reason, the present focus on critical-mass centers of excellence should not be construed as a bias against individual investigator efforts – quite the contrary.

2.5 Overview of High Energy Density Astrophysics Resource Requirements

In the previous sections, we have commented on the specific resource requirements necessary for significant advances in astrophysical phenomenological and basic physics research, as well as in laboratory astrophysics. However, it is easy to lose sight of the fact that the science in question is often actually carried out by individuals who span these distinct methodologies of carrying out high energy density astrophysics; and that it behooves one to consider the necessary resource requirements from the larger perspective; and in particular, to spell out the financial implications flowing from the support of research groups that are to carry out the research activities discussed above.

Thus, in either the experimental or theoretical cases, the costs associated with the creation and maintenance of the research groups necessary to carry out the 'community service' aspects can be estimated by considering existing efforts of similar scales at universities. The two examples that may serve as prototypes are the ASCI/Alliance Centers of Excellence (which are currently funded at levels of approximately $4M-4.5M/year); and the NSF Physics Frontier Centers (which are funded at roughly similar levels). If a "center" is assumed to roughly split its activities equally between community service and research (the latter is essential to maintaining a vibrant atmosphere conducive to keeping the community codes state-of-the-art), one can envisage a rough split of \$1.25M/\$1.25M between these two activities, i.e., a total center cost in the range of \$2.5M per year per center (i.e., at the low end of the cost spectrum for NSF Frontier Centers). In addition, the program will need a healthy variety of individual investigator efforts, ranging from algorithm development and physical model construction to actual high energy density laboratory astrophysics studies; if we envisage a steady-state program of roughly 40 individual investigators, each of which has a postdoctoral fellow and graduate student participating, and an annual budget per investigator of \$200K, then the individual investigator program would cost roughly \$8M per year. It is of course critical to emphasize that these costs do not include the expenses related to the construction and operation of the critical tools – the experimental and computational infrastructure – necessary to carry out this research.

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CHAPTER 3

Beam-Induced High Energy Density Physics

3.1 Introduction

The interaction of intense beams of electrons or ions with matter can lead to a plethora of high–energy density phenomena. Furthermore such beams are themselves high-energy density systems. In this chapter we consider three thrust areas:

1) Heavy-ion-driven high energy density physics and fusion;
2) High energy density physics with ultra-relativistic electron beams; and
3) Characterization of a quark-gluon plasma produced by collisions of heavy ion beams.

These three thrust areas cover an extremely broad range in the density-temperature "map of the HED universe." In the heavy ion-driven high energy density physics area the key scientific issue is the compression of nanosecond-pulse heavy ion beams that will be suitable for creating and studying the fundamental properties of high energy density matter and eventually fusion. The second thrust area uses ultra-relativistic electron beams, currently the most intense sources in the laboratory, giving power densities on the order of a petawatt per square micron. The interaction of such intense beams with plasmas has opened a new opportunity: ultra-high gradient acceleration and focusing of charged particles. The third thrust area is the exploration of the plasma-like matter formed in the collision of two super-intense heavy-ion beams: this quark-gluon plasma state once existed briefly following the Big Bang. The major opportunity here is to explore the nature of matter at exceedingly high density and temperature as it may have existed at the earliest times after the birth of the Universe.

While the research thrust areas described in this chapter cover a broad range in the density-temperature 'map of the HED universe', it should be emphasized that these are three illustrative examples of research thrusts in beam-induced high energy density physics, and are not intended to cover the entire range of possible opportunities for scientific discovery in this area.

3.2 Heavy-Ion-Driven High Energy Density Physics and Fusion

Accelerators producing appropriately tailored energies of intense heavy ion beams can provide a useful tool for creating uniform high energy density matter to study the strongly-coupled plasma physics of warm dense matter in the near term, and for inertial fusion in the longer term. Both fusion and high energy density physics applications of heavy ion beams require understanding the fundamental physics limits to the compression of ion beams in both space and time before they reach the target, as well as a basic understanding of collective beam-plasma interaction processes and beam energy deposition profiles within the dense plasma targets. This thrust area focuses on the beam and target physics knowledge base needed over the next ten years for future heavy ion beam applications to high energy density physics and fusion. The emphasis during the first five years is on determining the physics limits to heavy ion beam longitudinal compression and transverse focusing upstream of the target, and during the second five year period, an increased effort is planned for beam-target interaction physics and target diagnostic development for high energy density physics. This heavy ion high energy density physics thrust would also make significant contributions towards heavy-ion-driven inertial fusion.

3.2.1 Motivating Intellectual Question

How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition conditions?

Heavy ion beams have a number of advantages as drivers of targets for high energy density physics and fusion. First, heavy ions have a range exceeding the mean-free-path of thermal x-rays, so that they can penetrate and deposit most of their energy deep inside the targets. Second, the range of heavy ion beams in dense plasma targets is determined primarily by Coulomb collisions with the target electrons. The ions slow down with minimal side-scattering, and their energy deposition has a pronounced peak in the rate of energy loss dE/dx that increases with the beam ion charge state Z. These properties make heavy ions an excellent candidate for high energy density physics studies, where thin target plasmas would be uniformly heated by locating the deposition peak near the target center. The primary scientific challenge in exploiting these desirable properties in the creation of high energy density matter and fusion ignition conditions in the laboratory is to compress the beam in time (by 1000 times overall, requiring 10-100 times more longitudinal bunch compression than present state-of-the-art) to a pulse length that is short compared to the target disassembly time, while also compressing the beam in the transverse direction (by 10 times) to a small focal spot size for high local deposition energy density. Proposed new experiments compressing intense ion beams within neutralizing plasma would significantly extend the beam current into high-intensity regimes where the beam would not otherwise propagate in the absence of background plasma, and where beam-plasma collective effects with longitudinal and azimuthal magnetic focusing fields have not been previously explored.

A basic understanding of the collective processes and nonlinear dynamics of intense, high-brightness, heavy ion beams, and a determination of how best to create, accelerate, transport, compress and focus these beams to a small spot size are critical to achieving the scientific objectives of heavy ion fusion and ion-beam-driven studies of warm dense matter. Most of the kinetic energy of heavy-ion beams is in the directed motion of the beam particles, but a small fraction is in random kinetic energy, characterized by the effective temperature of the beam particles. Plasma electrons can be used to neutralize much of the repulsive space charge that resists the beam compression in time and space, but the beam temperature ultimately limits the smallest achievable spot size and pulse duration after the space charge forces are removed from the beam inside plasmas. To minimize the beam temperature, and thereby maximize the energy deposition in the target, the beam dynamics must be controlled with high precision throughout the entire dynamical trajectory, using accurately positioned and tuned confining magnets, carefully tailored accelerating fields, and final charge neutralization techniques that do not degrade the beam quality.

There are key synergistic relationships of the research on intense heavy ion beams to understanding the nonlinear dynamics of intense charged particle beams for high energy and nuclear physics applications, including minimization of the deleterious effects of collective processes such as the two-stream (electron cloud) instability, and the use of a charge-neutralizing background plasma to assist in focusing intense beams to a small focal spot size (plasma lens effect).

3.2.2 Research Opportunities

Target and Accelerator Requirements: A recent sub-panel of the Fusion Energy Sciences Advisory Committee [1] reports "*Inertial fusion energy capabilities [laser, accelerator and z-pinch drivers for fusion energy] have the potential for significantly contributing to high energy density physics and other areas of science. For example, isochoric heating of substantial volumes to uniform, elevated temperatures should be achievable using heavy ion beams…Moreover, the rapid turnaround capabilities envisioned for inertial fusion energy drivers could accelerate progress in HEDP science by enabling a wide community of users to conduct "shot-on-demand" experiments with data rates and volumes far exceeding those obtained on large systems that currently require long times between shots."* As indicated by the scientific question and supporting narrative for heavy-ion-driven high energy density physics and fusion, the primary scientific challenge is to compress intense ion beams in time and space sufficiently to heat targets to the desired temperatures with pulse durations of order or less than the target hydrodynamic expansion time. For low energy ions (in the few to tens of MeV range), requirements to study strongly-coupled plasma properties in the warm dense matter regime are: target foils of thickness a few to tens of microns, 1 to 20 Joules (in a single beam), 0.5 to 10 eV temperature, 0.2 to 2 nanosecond final pulse duration, and 0.5 to 2 mm-diameter focal spot size. Target diagnostics for high energy density physics studies should have spatial resolution small compared to the focal spot size, temporal resolution small compared to the target hydrodynamic expansion time after heating, and energy deposition measurement accuracy better than 3%. For x-ray production in inside indirect-drive fusion targets, ion beams must heat foam layers 1-100% that of solid-density with 50 to 200 kJ per beam (many beams), 200 eV target radiation temperature, 5 to 10 nanosecond final pulse duration, and 4 to 10 mm-diameter focal spot size. For high energy density physics studies, ranges of ions with 0.2 to 1 MeV/u should be larger than the target thickness, with the deposition peak centered in the target in order to achieve maximum uniformity inside the target for accurate measurements of the heated plasma properties, and to allow analysis of transmitted ion energies and charge states as a diagnostic. Hydrodynamic codes with a capability for calculating energy deposition from a distribution of incident ion energies and angles should evaluate changes in observable target properties for different equation-of-state models. For fusion, radiation transport is a key additional target code capability that is required. Ion ranges with 10 to 20 MeV/u should be less than the target radiator thickness, but larger than the mean free path of the target x-rays so that the peak ion deposition can occur inside the radiation case (hohlraum) surrounding the fusion fuel capsule.

The minimum pulse length and focal spot radius depend on the final longitudinal and transverse effective temperatures, respectively, accumulated from all non-ideal effects experienced by the ion beam as it travels from the source through the accelerator, and through longitudinal compression and final focus onto the target. Accelerators for both high energy density physics and fusion must initially inject sufficiently bright (low temperature) beams, accelerate the heavy ions to the desired energy range, and then longitudinally compress and radially focus the beams onto the target with minimal growth in the longitudinal beam temperature (much less than a factor of 10 to allow overall axial bunch compression by a factor of 100 or more), and with minimum transverse temperature growth (much less than a factor of 10 to allow radial focusing by more than a factor of 10).

Scientific Objectives and Milestones: Advances over the past several years include: (i) high current ion sources and injectors (0.1 to 1 A of potassium) have been shown to have adequate initial beam brightness (sufficiently low transverse and parallel temperatures) to meet the above requirements at injection; (ii) negligible beam brightness degradation has been observed in transport of 200 mA potassium ion beams through electric quadrupole focusing magnets; and (iii) more than 95% of potassium beam space charge has been neutralized with pre-formed plasma over ~ 1 meter lengths without deleterious beam-plasma instabilities. Over the next five years, before beam-on-target experiments begin, the research will address the key remaining beam physics issues necessary to meet the accelerator requirements described above. These fall into four scientific areas:

(1) ***High brightness heavy ion beam transport*** in magnets, particularly to understand limits on beam-channel wall clearance (aperture fill) imposed by gas and electron cloud effects, together with beam matching and magnet non-linearities.

(2) ***Longitudinal compression of intense ion beams,*** particularly to understand limits on longitudinal compression within neutralizing background plasma, and the effects of potential beam-plasma instabilities over distances longer than 1 meter.

(3) ***Transverse focusing onto targets***, particularly to understand limits on focal spot size set by chromatic aberrations due to uncompensated velocity spreads from upstream longitudinal compression, and beam temperature growth from imperfect charge neutralization.

(4) ***Advanced beam theory and simulation***, particularly developing, optimizing and validating multi-species beam transport codes that can predict self-consistently the beam loss with gas and electron clouds, and developing integrated beam simulation models required to analyze source-to-target beam brightness (temperature) evolution.

After the beam physics issues identified above are favorably addressed over the next five years, emphasis will be placed on the fifth scientific thrust area:

(5) ***Beam- target interactions***, particularly to understand beam deposition profiles within thin foil targets and the potential uniformity of isochoric heating, accounting for target and beam ion charge state conditions, including development of accurate beam deposition and laser-generated x-ray target diagnostics, and extension of integrated beam simulation models from source *through* target.

These scientific areas will be pursued with an overall 10-year objective of providing the beam and target physics knowledge base for a future ~$50M-class heavy-ion accelerator-based high energy density physics facility for achieving 1-10 eV solid-density plasmas by isochoric ion heating with uniformity and diagnostic resolution adequate to discriminate the predictions of various *ab initio* theories for strongly-coupled plasmas. Successful achievement of this objective will address the Office of Management and Budget/Office of Fusion Energy Sciences 10-year measure for inertial fusion energy/high energy density physics: *"With the help of experimentally validated theoretical and computer models, determine the physics limits that constrain the use of inertial fusion energy drivers in future key integrated experiments needed to resolve the scientific issues for inertial fusion energy and high energy density physics"*. In addition, such an accelerator-driven high energy density physics facility would represent an important step towards the long-term objective of heavy-ion-driven inertial fusion.

Research Tools, Facility Requirements, and Milestones: Several specific facility requirements with intermediate two-year and five-year milestones (for experiments and modeling) are required to measure progress towards the 10-year objective. These include:

Two-Year Science Goals (FY06):

A2: Intermediate experiments to assess the physics limits of neutralized ion beam compression to short pulses. Measure the parallel and transverse temperature of a high perveance ion beam (space-charge potential / kinetic energy larger than 10^{-4}) before and after longitudinal compression by a factor of ten in neutralizing background plasma, and before and after pre-bunching of initially nonneutral ion beam in an acceleration-deceleration system. This series of experiments and modeling is needed to design integrated experiments combining neutralized drift compression and final focusing.

B2: Intermediate experiments to develop a predictive capability for gas and electron effects. Compare measured and calculated effects of gas and electron clouds on beam temperature as a function of beam aperture fill factors initially in transport lines with four magnets (quadrupoles and solenoids). This series of experiments and modeling will provide the scientific basis for future experimental upgrades.

Five-Year Science Goals (FY09):

A5: Integrated beam experiments on neutralized compression and focusing onto targets. Compare the measured and simulated focal spot beam intensity profiles in integrated experiments with beam current and energy upgraded from that used in A2, with a goal of 1 eV temperature in targets (a temperature corresponding to the high energy density threshold level of 10^{11} J/m^3 at solid density). This series of experiments and modeling of compression and focusing will provide the physics basis for a future heavy-ion high energy density physics facility.

B5*: *Demonstrate predictive capability for gas and electron effects for a heavy-ion high energy density physics facility. Compare measured and calculated effects of gas and electron clouds, in combination with beam matching and magnet errors, assuming B2 results warrant an upgrade to longer lattice transport experiments. This series of experiments and modeling is essential to determine the magnet apertures of quadrupole and solenoid transport options for a future heavy-ion high energy density physics facility.

Figure 3.1 gives a timeline with milestones and resource requirements.

Opportunities for Interagency Cooperation: Several opportunities exist for scientific cooperation between the heavy-ion-driven high energy density physics/fusion thrust area sponsored by the Office of Fusion Energy Sciences (OFES) and other federal agencies. These include:

1. Office of Basic Energy Sciences (OBES), with the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory, in common areas of need for data on wall secondary electron production and gas desorption induced by beam loss [2], and in multi-species particle-in-cell simulation models of the impact of gas and electron clouds on the beam, including two steam instabilities [3, 4]. This area may be critical to the achievement of full average beam power and neutron production in the SNS.
2. National Nuclear Security Agency (NNSA), with the Proton Storage Ring (PSR) and Dual Axis Radiographic Hydro Test facility (DARHT) at the Los Alamos National Laboratory [3, 4], in common areas of modeling multi-species gas/electron effects including two-stream instabilities (PSR), and in efficient computational techniques with multi-species modeling of electron beam neutralization from gas and ions backstreaming from the targets (DARHT).
3. Collaborations with the high energy and nuclear physics accelerator communities on joint development of advanced computational tools are important to predict and control electron cloud effects, beam halo production and associated losses, including use of Adaptive Mesh Refinement techniques [5] and nonlinear perturbative (δf) particle simulation techniques [3] developed for modeling heavy ion experiments. Sharing these computational tools can greatly increase the range of intense beam physics problems that can be modeled for a variety of scientific applications.
4. Within strongly-coupled plasma regimes of high energy density physics, scientific progress would benefit from comparisons of equation of state and constitutive properties data obtained using heavy ion isochoric heating with similar data obtained using other future high energy density physics drivers, including lasers, Z-pinches, and X-ray free electron lasers (XFELs)[6].

Figure 3.1: **Timeline and Resource Requirements for Heavy-Ion Driven HEDP/fusion**

Science Areas	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15
High Brightness Beam Transport	4 quadrupoles 4 solenoids		Upgrades (larger and more magnets)			Upgrades of injectors and diagnostics to further reduce beam temperature					
Longitudinal Beam Compression	10x compression		100x compression with 10x focusing			Active beam correction experiments to explore potential 1000x compressions					
Focusing onto Targets	Large plasma source		Plasma lens and time dependent corrections			Advanced focusing experiments e.g., induced self-pinching					
Beam-Target Interactions			Target design and fast beam diagnostics			Beam energy loss and deposition profiles, target T_e (t) n_e(t) diagnostics and modeling					
Advanced Theory and Simulations	Source to target models					Source through target models					
Estimated resource needs	**$12 M/yr**		**$14M/yr**			**$16M/yr**					

2yr Milestones:
A2: 10x neutralized compression
B2: Gas/electron limits in 4 magnets

5yr Milestones
A5: 100x neutralized compression and focusing
B5: Gas/electron predictive capability for HEDP accelerators

10yr Objective:
Beam and target physics knowledge base for heavy-ion-driven HEDP user facility

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3.3 High Energy Density Science with Ultra-relativistic Electron Beams

Ultra-relativistic particle beams with energies greater than one billion electron volts are some of the highest energy density sources available today. Not surprisingly, the discovery potential using such particle beams containing hundreds of amperes of current, is rich and challenging. Indeed, the measurement of such short bunches, phase-locking them to micro-scale structures with femtosecond accuracy and focusing of beams containing petawatts of power to nanometer spot sizes are some of the great challenges at the forefront of beams physics. In addition to particle physics, such beams will allow access to new regimes in the fields of plasma physics, particle astrophysics and quantum electronics. Here we give one example in the area of plasma physics.

When such beams are propagated through plasmas, some of the beam energy can be left behind in the form of a wakefield oscillation. The electric fields of such a wakefield are extremely large and can, in turn, be used to accelerate a second ultrarelativistic particle beam to even higher energy or to focus the beam to a smaller spot size. The ability to generate and control these fields and to precisely manipulate the positions of particles with respect to these fields is a major opportunity in Beam-Driven High Energy Density Science. It could lead to an entirely new paradigm for building future particle accelerators of ever-increasing energy.

3.3.1 Motivating Intellectual Question

Can the ultra high electric fields in a beam-driven plasma wakefield be harnessed and sufficiently controlled to accelerate and focus high-quality, high-energy beams in compact devices?

It is recognized that accelerator based physics will continue to be critical for unraveling the most fundamental scientific questions of our time. Yet this discovery potential will reach a dead end unless breakthrough accelerator technologies can be perfected so that accelerator-based particle physics can continue beyond the electron equivalent center of mass energy of 1 TeV.

The Plasma Wakefield Acceleration scheme(1) is one such promising advanced accelerator concept. In this scheme an ultra-relativistic particle beam is used to drive a high-gradient wakefield in plasma. This wakefield, in turn, accelerates a second trailing bunch containing fewer particles to a higher energy than that in the drive bunch. The plasma wakefield accelerator thus acts as a transformer increasing the voltage of the trailing beam at the expense of current. Using state-of-the art technology accelerating gradients of 20-50 GeV/m are achievable.

The Plasma Afterburner concept(2) proposes to significantly increase the energy of an existing linear collider by placing two, tens of meter long plasma wakefield accelerator sections just before the interaction point a linear collider. In order to obtain the necessary luminosity, the accelerated bunches have to be focused to a tighter spot size. Specially designed plasma lenses are needed to accomplish this.

Much progress has been made in understanding the science behind this conceptually simple scheme. (3) The ultra-relativistic beams needed to drive such wakefields are some of the most intense high energy density drivers with peak intensities exceeding 10^{21} W/cm^2, directed kinetic energy densities exceeding 10^{11} J/cm^3 and energy per plasma particle greater than 1 MeV. Using such beams, both electrons and positrons have been accelerated using meter scale plasmas. Accelerating gradients of tens of GeV/m have been demonstrated in recent experiments over roughly 10-cm length of plasma. Plasmas have also been shown to focus both ultrarelativistic electrons and positron beams.

Many high energy density physics questions must be answered before the Plasma Afterburner concept is ready for a full-scale prototype demonstration. The initial results are promising but the afterburner plasmas will have density-length products that are two to three orders of magnitude greater than in the current experiments. Will the drive and the trailing beams propagate stably through such dense long length plasmas? Will the head of the drive beam continuously erode away? Will the positron beam emittance be preserved? Can the optimally shaped and phased drive and trailing bunches be crafted and aligned with tens of nanometer accuracy needed to obtain a high beam quality?

To answer these and other questions within a decade a focused research effort will be needed that leverages off an existing linear collider facility. Taking the Plasma Wakefield Acceleration scheme from a series of proof of principle experiments to a prototype for a future Energy Doubler for a linear collider is indeed a grand challenge in beam physics.

3.3.2 Research Opportunities

The latter half of the twentieth century has witnessed remarkable advances in our understanding of the elementary constituents of matter. This has been achieved through the construction or ever more powerful and ingenious particle accelerators. As we enter the new century, the continuing advance in this field is threatened because accelerators at the energy frontier have become too big and too expensive for any one nation to build. New technologies must be invented for building accelerators if we are to unravel the most fundamental questions of our time.

Fortunately, there are many new ideas for generating, accelerating, focusing, and cooling charged particles that could lead to an entirely new paradigm for constructing a future accelerator more cost effectively. Many of these are based on recent breakthroughs in laser, plasma, nano-science, superconducting, and other fields. Can these ideas be converted into a practical machine capable of doing physics at the energy frontier?

One concept that utilizes an ultrarelativistic particle beam as a source of free energy to power an accelerating structure in a plasma has shown tremendous promise. This scheme is known as the Plasma Wakefield Accelerator (PBWA).(1) In this scheme, a high energy particle (drive) beam, usually electrons, is propagated through a plasma where it excites a high-gradient wakefield. A second trailing beam that is appropriately phased with respect to the drive beam extracts energy from the wake and thus gains energy. The compelling question is therefore, *"can the ultrahigh electric fields in a beam-driven plasma wakefield be harnessed and sufficiently controlled to accelerate and focus high quality, high energy beams in compact devices?"* to make the concept of a Plasma Afterburner(4) feasible for significantly increasing the energy of a linear collider.

There are numerous opportunities in the area of HEDS with ultra-relativistic beams as they relate to developing the PWFA scheme to the next level. Specifically, what are the key scientific issues that must be addressed before a full scale 100 GeV on 100 GeV prototype of a PWFA could be demonstrated using plasma afterburner sections added to an existing e^+-e^- collider?

In the next section we outline a ten-year research plan aimed at answering the above compelling question. The beam and the plasma parameters needed to meet the scientific objectives that are summarized below are given in Table 3.2. The drive beam and the trailing beam is assumed to have an initial energy of 50 GeV, only because such a beam currently exists at SLAC and could for a relatively modest investment of funds be made suitable for carrying out the program that is outlined here.

Drive Beam Energy	50 GeV
Number of Particles in Drive Beam	$3x10^{10}$
Trailing Beam Energy	50 GeV
Number of Particles in Trailing Beam	$1x10^{10}$
R.M.S, Bunch Length of Drive Beam	45 μm
R.M.S. Bunch Length of Trailing Beam	10 μm
Spacing Between Bunches (variable)	0-150 μm
R.M.S. Spot Size of the Bunches	1-3 μm
Plasma Density	$2x10^{16}$ cm^{-3}
Plasma Uniformity	5%
Average gradient	16 GeV/m
Transformer ratio	1-1.2
Energy Spread	5-10%
Length of Accelerating Sections	3 m

Table 3.2: A Non-Optimized set of beam and Plasma Parameters assumed in the Scientific Objective plan.

Scientific Objectives and Milestones

1. *Shaped Drive and Trailing Bunches.* Can appropriately shaped (drive and trailing) electron and positron bunches with a variable spacing and the necessary charge be generated to excite the wakefield and extract the energy from it?
2. *Beam Loading and Emittance Preservation.* Can one demonstrate relatively efficient beam loading of the wake and obtain a reasonable energy spread of the trailing beam? Can the emittance of the trailing beam be preserved or even improved?
3. *Large Transformer Ratio.* Transfer ratio is the ratio of the useful accelerating field to the peak decelerating field. For a symmetric drive beam this ratio is less than 2. Can transformer ratios of greater than 2 be obtained by shaping the drive beam? This may make it possible to add more than twice the drive beam energy to the trailing beam.
4. *Plasma Production.* Will field ionization by the drive beam itself be able to produce dense plasmas that are several meters in length ? In particular is it possible to generate hydrogen plasmas or is a low ionization potential element such as Li necessary?
5. *Head Erosion and Transverse Instabilities.* Will such bunches propagate through these plasmas without head erosion and transverse hosing type instabilities? If the beam is not matched to the plasma it may undergo up to 100 betatron oscillations. Will such a beam lase an excessive amount of energy to synchrotron emission?.
6. *Separation of the Drive Beam and Trailing Beam.* How will the drive beam be dumped without affecting the trailing beam? At the end of the afterburner section the drive beam energy will be reduced to a few GeV from the initial energy. The trailing beam energy will be increased from initial value (say 50 GeV) to at least twice (10 GeV) and perhaps even higher energy.
7. *Optimal Positron Acceleration.* Is a hollow channel necessary for getting a high quality positron beam? How will such hollow channels be produced? Will the positron beam propagation be stable in a hollow channel? Will the positron beam emittance be maintained in such a structure?
8. *Positron Acceleration on Electron Wakes.* Can and should the positron beam be accelerated on the wake produced by an electron beam?
9. *Radiation Losses.* Is matched beam propagation of the trailing beam necessary to minimize radiation losses and "hosing instabilities"?

10. Plasma Lenses for Focusing. Can high demagnification plasma lenses be demonstrated to focus the accelerated beam to less than 0.1-micron size? How will such beam sizes be measured? Are plasma lenses inherently abberated for positron beams?
11. Backgrounds. Will backgrounds be an issue for the detectors because of the proximity of the plasma sections and the lenses to the interaction point?
12. Simulations. Can the Plasma Wakefield Accelerator be modeled in its entirety-using particle in cell simulations?

Research Tools and Facility Requirements

Not all these questions can be answered using a single existing facility. There is only one laboratory in the U.S.A. that has the GeV class electron and positron beams that are needed to answer many of these questions: the Stanford Linear Accelerator Center (SLAC). The SLAC linac can provide 20-50 GeV beams of electron and positron that, with relatively modest facility modifications, can be used to answer Questions 3-8 above. To answer Questions 1,2 and 9 a dedicated facility is necessary with electron energy in the 1 GeV range, and with the ability to produce shaped drive and trailing bunches with needed charge and emittance. SLAC currently has plans for a 30 GeV facility (SABRE) for multiple constituencies including HEDS.[4] Questions 10 and 11 can be addressed through computer simulations. Question 11 in particular will require substantial computational and manpower resources.

Science Areas	YR 1	YR 2	YR 3	YR 4	YR 5	YR 6	YR 7	YR 8	YR 9	YR 10
High Energy Beamline	Construction ($ 10 M/one time)						Positron beam compressor ($2M)			
1 GeV Beamline	Construction ($10 M/one time)		Beam characterization, emittance improvement							
High Energy Experiments		Plasma production		Head erosion and hosing instability		Electron energy doubling expt.		Positron acceleration expts		
1 GeV Experiments		Production of shaped (drive and trailing) bunches			Beam loading and emittance preservation			Large transformer ratio experiments		
Theory & Computation	Parallelized PIC code			Beginning to end Simulations of the Energy Doubler						
Estimated Resources	$ 4 M/year			$ 6 M/year				$ 9 M/year		

Figure 3.2. Timeline for research on the various key scientific objectives.

Resource Requirements

At the present time HEDS related experiments are being done on a "piggyback" basis to high-energy physics experiments at the Stanford Accelerator Research Center. Most of the HEDS work is done in the Final Focus Test Beam (FFTB) which allows experiments to be carried out using both electron and positron beams. The FFTB facility is scheduled to be converted into the Linac-based Coherent Light Source (LCLS) also known as the X-ray Free Electron Laser project starting mid 2006. This will mean that an alternate high-energy beam line that can provide compressed beams of both electrons and positrons in the 30-50 GeV energy range will be needed to continue much of the work described in this section. While such a facility can only be built at SLAC at the present time, much of the work on electron beam-driven HEDS could be carried out using a lower energy (~1 GeV) beam that has a two pulse with variable separation capability.

The rough cost of both of these beam lines is on the order of $10 M each. There is an opportunity for 2-3 collaborations dedicated to HEDS related work on these facilities. Assuming each collaboration is funded at a level of $3/yr this will mean a research program at $6-9 M/year in this area. The timeline for research is shown in Fig. 3.2.

Opportunities for Interagency Cooperation

As mentioned earlier, the R & D program on high energy density science using ultra-relativistic beams is highly interdisciplinary. Much of the basic expertise needed to make the necessary progress resides in U. S. universities, which are also the source of training of future talent that will be needed to keep the field vigorous. There is at present a modest scale Advanced Accelerator R & D program supported by the Doe's Office of Science that supports largely university and some national laboratory groups. The NSF is contemplating an Accelerator Science R& D program that would support university researchers. This presents a unique opportunity at this time to capitalize on the opportunities in HEDS with ultra-relativistic beams. The infrastructure needed to do meaningful research in this field exists and at national accelerator facilities such as those at SLAC, Cornell, Brookhaven and Fermilab. It is vital to bring together the intellectual resources of the university groups and the infrastructure resources of the national laboratories. Time has come to support medium to large-scale multi-group partnerships involving university and national lab investigators using multi-agency funding.

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3.4 Characterization of Quark-Gluon Plasmas

During the first 10 microseconds following the Big Bang, the temperature of the universe was so high that ordinary hadrons such as protons and neutrons could not form. Instead, the dominant form of matter was unbound quarks and gluons in a state referred to as quark-gluon plasma.

Such a plasma interacts via the strong interaction, rather than electromagnetic, but is expected to manifest many of the same features as classical plasmas, such as screening and collective effects.

The extraordinarily high temperature of the epoch just after the Big Bang, approximately 2 x 10^{12} K (200 MeV in energy units), is achievable today only via accelerator-based experiments which collide heavy nuclei at very high energies. The energy density of this kind of matter far exceeds that of normal nuclear matter, and indeed of other plasmas currently accessible. Consequently, its study represents a major opportunity in the field of High Energy Density physics. The existence and properties of this new phase of matter may have important cosmological implications and play a role in understanding the interiors of neutron stars.

The study of the physics of quark gluon plasmas has been identified as a scientific priority in the National Academy Reports “Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century” [1] and “Frontiers in High Energy Density Physic -The X-Games of Contemporary Science” [2]. The tools required to characterize the properties of this novel type of plasma have been reviewed by the Nuclear Science Community; this scientific thrust was identified as a high priority in the Nuclear Science Advisory Committee Long Range Plan for Nuclear Physics [3].

3.4.1 Motivating Intellectual Questions

- *What is the nature of matter at the exceedingly high density and temperature characteristic of the Early Universe?*

- *Does the Quark Gluon Plasma exhibit any of the properties of a classical plasma?*

The primary scientific goal of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is to demonstrate that, at sufficiently high temperatures, matter does in fact exist as a quark-gluon plasma. Experiments can probe this form of matter inside the fireball created when two massive nuclei collide at high energy by carefully examining a subset of the thousands of particles that emerge from the collision. Present estimates based on the striking initial results from RHIC indicate an energy density near 2 x 10^{30} J/cm^3, exceeding that of ordinary nuclear matter by two orders of magnitude, and more than a factor of 10 above the threshold estimated for quark-gluon plasma formation. While the lifetime of the fireball is only about 1.5-3 x 10^{-23} sec, precision probes of the plasma state generated early in the collision iby high momentum transfer scattering of quarks and gluons in the incoming nuclei have ample time to map the evolution of the matter.

The quarks inside both ordinary hadrons and in the quark-gluon plasma interact predominantly via the strong interaction. The strong force between two quarks originates from the exchange of massless particles known as gluons, just as the electromagnetic force between two ordinary charged particles originates by the exchange of massless photons. However, unlike photons, which are electrically neutral, the gluons themselves carry the “charge” of the strong interaction. Furthermore, this charge, referred to as “color”, comes in three varieties, commonly labeled as red, blue and green. These essential differences between Quantum ElectroDynamics (QED) or ordinary charges and the Quantum ChromoDynamics (QCD) of the strong interaction are responsible for the existence of free charges in QED, but have been shown to cause quarks to be confined within hadrons in QCD.

Nonetheless, under conditions of extremely high energy density and temperature, quarks and gluons can form a plasma analogous to the "classical" electromagnetic plasma of ionized gases. QCD predicts screening of the color charges in a quark gluon plasma, just as charge is screened in a classical plasma. However, unlike a classical plasma, in which the masses of the electrons and the ions introduce various length scales, the dimensionless nature of QCD implies that all such length scales in the quark-gluon plasma are proportional to the inverse temperature 1/T times various powers of the QCD coupling constant g(T). For instance, current estimates suggest that (using color charge rather than electric charge), the Coulomb coupling parameter, i.e. the ratio of the potential energy of the neighboring particles to their kinetic energy, for such a system is significantly greater than 1.0, perhaps even reaching 10. Indeed, high quark interaction rates within the plasma are required to drive the large collective motions observed. To find the properties of this new kind of plasma, it is important to determine the temperature, collision frequency, thermal conductivity, color dielectric properties, radiation rate, radiative-absorptive coefficients and opacity of the quark-gluon plasma. This extensive program of essential measurements will require more than an order-of-magnitude increase in the collider luminosity, as well as enhanced detection and triggering capabilities for the experiments. Such enhancements will allow measurement of thermal radiation, collision rates of rare heavy quarks, Debye screening properties of the plasma, and investigation of energy transport. Theoretical determination of quark-gluon plasma properties will require large computational resources, both for static lattice solutions of QCD to probe the strongly coupled regime and for detailed models of the of the collision dynamics which combine quantum evolution of the initial state, hydrodynamic descriptions of the resulting matter, and transport equations to describe the produced particles.

3.4.2 Research Opportunities

The first 3 years of RHIC operations has produced a wealth of data and spurred a tremendous amount of theoretical work. The initial measurements have clearly established that the matter produced at RHIC shows strong collective behavior, and that densities of order 100 times normal nuclear density have been achieved. Lattice gauge calculations solving the QCD equations at finite temperature, though limited by available computing resources, have provided new insights on the behavior of quarks and gluons near the quark-gluon phase transition where the coupling is not weak. Hydrodynamic simulations of heavy ion collisions have been carried out and compared to bulk phenomena observed in the data to extract the pressure generated and to begin probing the equation of state. Energy transport in the medium has been studied both experimentally and theoretically. This provides a first glimpse of the density of colored objects from which high momentum quarks or gluons scatter, and how the energy they radiate spreads through the system.

However, we have at this point only a limited amount of information about the properties of the matter produced in the collisions. We do have compelling evidence that the matter is strongly coupled, even at very high temperature, which implies that the properties are not those of a weakly interacting nearly ideal gas of quarks and gluons. Instead, the matter produced at RHIC more nearly resembles a warm dense plasma than an ideal one. Consequently the job ahead is to characterize the properties of the medium, and to understand from those properties the precise nature of the quark-gluon plasma formed at RHIC, by combining the broadest possible spectrum of measurements to characterize the physical parameters of the quark-gluon plasma state.

Scientific Objectives

The first approach is to ***run the current suite of experiments with different beam energies and beam combinations***. Such data are important to address several long predicted quark gluon plasma signatures, and their energy density, gluon density, and volume dependence. Initial steps in this direction were begun with a short exploratory measurement in 2004, but a complete and systematic set of observations with corresponding proton+proton comparison data sets remains for future investigation.

Within the limited set of energies and beam combinations studied to date, observables currently measured with reasonable statistical sensitivity include the collective flow pattern for a variety of hadrons such as pions, kaons, protons, and lambda particles. The extent to which these various species share a common velocity traces the evolution of pressure and energy density in the late stages of the collision. Even more useful is the anisotropy in the azimuthal distribution of these particles, since it reflects the initial geometrical anisotropy in off-axis collisions, and therefore is sensitive to pressures in the early phase of the collision. Important confirming evidence for extraordinarily high densities in the initial state is provided by the extinction pattern of the highest momentum particles ("jets"). Here again the dependence on particle masses, and the differing behaviors for mesons and baryons, provide strong indications of the underlying quark and gluon dynamics. Collisions of deuterons on gold nuclei were measured as a control experiment. Such collisions maintain the initial conditions of nucleons bound into a nucleus, but do not create a significant volume of high energy density matter. As can be seen in the figure, all four RHIC experiments show that high transverse momentum (p_T) particles are not extinguished in this case.

The recently completed long Au+Au run should provide definitive data on the detailed behavior of such phenomena which will allow tomographic analysis with respect to the reaction plane. Fully characterizing the plasma, however, will require upgrades of experiments and the facility to provide much higher luminosity.

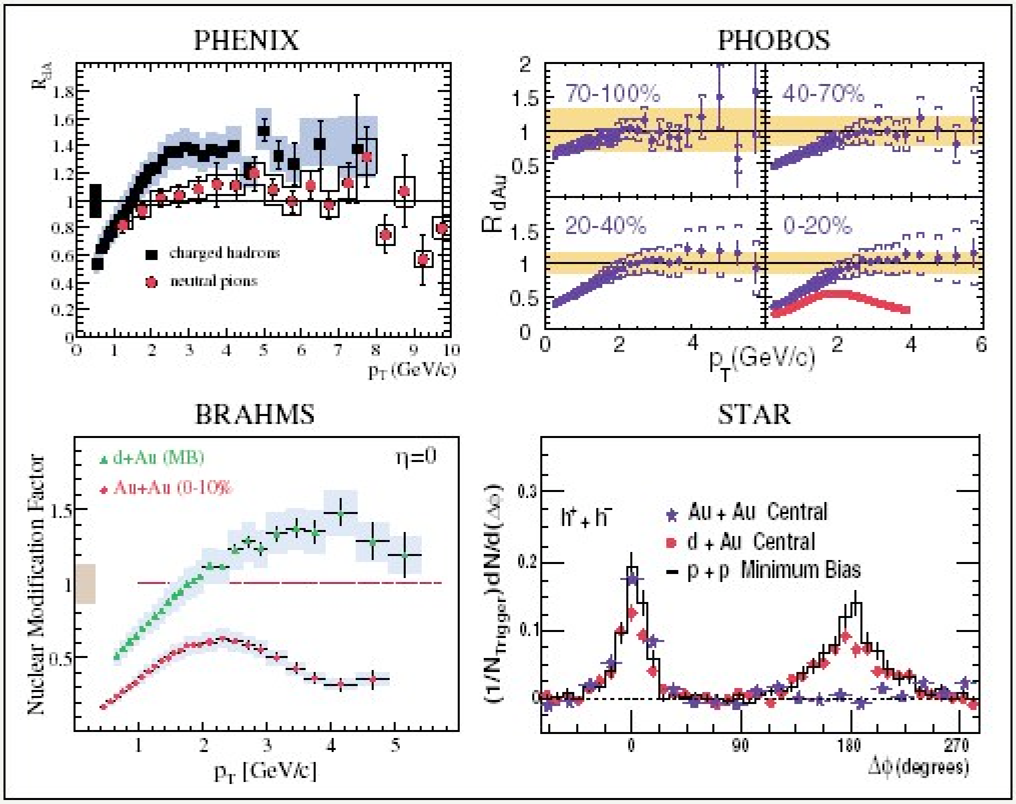

Figure 3.3.1. Left panels show the ratio of particle production as a function of momentum transverse to the beam in d+Au collisions to that in p+p collisions, from the PHENIX and BRAHMS experiments at RHIC. PHENIX shows all charged particles compared to neutral pions, while BRAHMS compares d+Au to head-on Au+Au collisions. Upper right: the same quantity measured by PHOBOS in impact-parameter selected d+Au collisions. Lower right: two particle correlation between high momentum particles, as a function of relative azimuthal angle from STAR. The extinction of jets in central Au+Au collisions is illustrated by the blue stars near 180 degrees.

The primary strategy for ***quantitative analysis of quark-gluon plasma medium properties relies on rare probes***. There are two principal channels in which rare probes offer tremendous benefits. The first uses photons, which emerge from the quark-gluon plasma without further interaction and therefore carry information related to the temperature at the earliest and hottest stages of the plasma. High momentum photons can be used to tag high momentum-transfer scatterings, so that a study of the recoil particles provides a direct measure of the medium transport properties. These processes are suppressed by a factor of 1/137 for real photons, and by the square of this factor when observed via virtual photons that appear as e^+e^- or $\mu^+\mu^-$ pairs. The disadvantages resulting from the reduced rates of electromagnetic probes can be offset by significantly increasing the luminosity of RHIC to provide access to these clean plasma diagnostics.

Heavy flavor production is another rare process with unique abilities to probe plasma properties. The large masses of charm and bottom quarks introduce new scales in the plasma, thereby overcoming the scale-free nature of a plasma containing only light quarks, in which all lengths are proportional to the inverse temperature. As an example, there is an extensive literature investigating the ability of ***bound charmed quark states to***

probe (color) Debye screening lengths in the quark-gluon plasma. Recent developments investigating the production of such bound states via coalescence, and quantifying the temperature dependence of their binding, have only increased the impetus for measuring these states at RHIC. The production of open charm, in which a charm quark is bound with a light quark, is also of great interest, again due to the large mass scale it introduces. Theoretical calculations show that massive quarks should have a significantly reduced energy loss when traversing the plasma. ***The extent to which the heavy quarks participate in the collective flow shared by all light quark species*** is another important handle on the thermalization process. The characteristic feature shared by both open charm and bound charm-anticharm production is that the expected rates are small, with the analogous studies in the bottom sector suppressed by an even larger factor. Nonetheless, the tremendous analyzing power of these channels argues again for a significant luminosity increase in order to perform quantitative studies of these important signals.

Research Tools and Facility Requirements

All projections and studies for both RHIC and RHIC II have demonstrated the necessity to operate the facility at least 27 weeks per year, and preferably 32 weeks, to achieve both the desired physics goals and the economy of scale in avoiding start-up and shut-down end effects. Over the next 3-4 years, runs of this length with the current accelerator capabilities will allow the experiments to collect data with a variety of beam energies to search for threshold effects and the energy dependence of the gluon density and pressure developed in the collision. It is critical, furthermore, to scan an additional 1-2 beam species to measure precisely the volume and density dependence of the observables. This will provide confidence in the interpretation of the observed results and calibrate the theoretical underpinning required to extract plasma properties from the measured data.

Detector upgrades to the two large experiments, PHENIX and STAR, are necessary to take full advantage of the accelerator capabilities. Modest upgrades will allow the experiments to make measurements of quantities which we already see are vital, but which are currently limited by detector performance and background rejection. PHENIX requires a silicon vertex tracker to measure displaced vertices from semileptonic decays of charmed mesons and a hadron-blind detector to reject electron pairs in the low invariant mass region arising from 3-body decays of neutral pions. STAR requires a time-of-flight barrel to allow identification of 95% of the hadrons produced at velocities half way between those of the two beams.

Additional RHIC runs of full energy Au+Au and d+Au collisions of a year's duration will be needed once these initial detector upgrades are in place. The Au+Au run will utilize the upgraded detector capabilities for open charm, identified hadrons, and background rejection under the low mass lepton pairs. A long d+Au run is necessary to provide comparison data for these measurements as well as extend the statistical precision and reach in momentum for rare processes beyond that attained in 2003.

Upgrade of the RHIC facility to increase the luminosity by an order of magnitude will be necessary for full characterization of the plasma properties using sensitive internally generated probes of small cross section. The luminosity upgrade requires overcoming the growth of beam size due to intra-beam scattering by cooling the beams with a high intensity cold electron beam. This upgrade is the accelerator component of what is known as "RHIC-II"[4]. The outstanding performance of RHIC in the recently completed Run-4 is in accord with these projections, and gives confidence in the quantitative studies that form the basis for the RHIC-II proposal.

Both of the large detectors, STAR and PHENIX, will require additional upgrades to take advantage of the higher luminosities. These upgrades, which will complete the RHIC II project are currently in the conceptual design stage, in many cases based on results from an aggressive and ongoing R&D program. STAR's upgrade options include a micro-vertex detector, data acquisition upgrade, enhanced forward tracking, and a fast, compact TPC (with GEM readout) to handle the increased luminosity. PHENIX is developing hadron-blind detectors, forward calorimetry and forward silicon tracking, an inner fast TPC for tracking inside the magnetic field, as well as a greatly enhanced muon trigger Additionally, a new initiative has been started to study the option of a new detector in addition to the above upgrades. These upgrades, as well as the RHIC luminosity upgrade must be preceded by continued research and development work to develop and demonstrate technical solutions to the challenging problems they pose.

Timeline and Resource Requirements

In the near term (the next 1-3 years), the two detector upgrades which enhance the experimental capabilities utilizing the current accelerator need to be completed. The costs estimated for these are approximately $5M for the STAR time-of-flight system, and $6M for the PHENIX Silicon Tracker. Both of these upgrades rely additionally on financial and in-kind contributions from other countries, particularly China and Japan. In addition, an upgrade of the ion source feeding the RHIC collider complex will be necessary. The aging Tandem Van de Graaf accelerator must be replaced by a modern electron beam ion source (EBIS), to reduce risk of catastrophic failure which could cost a large fraction of the running time and to reduce regular operational costs. The estimated cost for this new ion source is $17.5M. There is an additional suite of smaller scope detector upgrades, which will also extend the physics reach of the two large detectors. However, these are foreseen to be built utilizing capital equipment funds foreseen for regular upgrades of the RHIC complex.

In the longer term, construction for the RHIC II project is envisioned for the period 2009-2015. This focuses on the major upgrades of both accelerator and experiments described above. Over the period of these five years, construction and commissioning of electron beam cooling for the RHIC is planned, with a requirement of $53M to complete. This is also the timescale for the major detector upgrades, at a cost of $100M.

Figure 3.3.2 gives a timeline and resource requirements for characterization of quark gluon plasma.

Figure 3.3.2: **Timeline and Resource Requirements for Characterization of Quark Gluon Plasma**

Science Areas	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14
Energy, volume dependence of gluon density, polarized protons	Operate RHIC, detector R&D				Operate RHIC					
	Upgrade ion source									
Heavy quark probes of QGP; Plasma radiation	Modest detector upgrades									
Screening length, short wavelength probe, gluon bremsstrahlung & thermalization					RHIC II: Electron cooling for 10X RHIC luminosity					
					RHIC II: Major detector upgrades					
	$6.4M/year				$8.83M/year					
	$3.7M/year				$16.7M/year					
Estimated resource needs	**$10.1 M/year**			**$6.4M/yr**	**$25.5M/year**					

3yr Milestones:
lighter species, d+Au collisions
polarized p+p collisions
construction of vertex detector
& time-of-flight upgrades

4yr Milestones
complete EBIS ion source
Au+Au with upgraded detectors
Complete R&D for electron
cooling, major detector upgrades

10yr Objective:
Complete RHICII facility to
characterize quark gluon
plasma screening length,
opacity, thermalization

Opportunities for Interagency Cooperation

The science in this section falls under the stewardship of NSF and DOE. The DOE Nuclear Physics office is the steward of Brookhaven National Laboratory and supports operation of the RHIC accelerator complex. The detector components, computational infrastructure, operating grants for the community utilizing RHIC and Grid computing developments are supported by both DOE and NSF. Analysis of the data and evaluation of theoretical models to extract plasma properties from measured quantities require large-scale simulation. This is an area where additional interagency cooperation, possibly involving other agencies, could have significant impact. Additionally, there may be opportunities to investigate High Energy Density physics within the RHIC beams themselves.

References

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CHAPTER 4

High Energy Density Physics on Stockpile Stewardship Facilities

4.1 Introduction

The hallmark of the NNSA high energy density (HED) experimental facilities is their ability to generate "macroscopic" amounts of matter in extreme conditions of density and temperature, and allow the properties of that matter to be measured, "statically" and dynamically. The unique regimes that can be accessed span cold and dense to hot and turbulent through relativistically energetic. Matter can be squeezed until the bound electronic orbitals become unrecognizably distorted, heated until it radiates profusely, shocked so strongly that material flows evolve to turbulence in fractions of a microsecond, and imploded to such extreme conditions that nuclear reactions dominate the energetics. Such conditions are fascinating, both from a fundamental physics perspective, and through applications, such as inertial confinement fusion and laboratory astrophysics. For example, the conditions in the deep interiors of planets and stars can be created and important properties, such as equations of state and opacities, measured. The turbulent dynamics of exploding stars (supernovae) can in part be recreated in a scaled sense, and examined in close-up detail. Rare, multi-hit nuclear reaction rates relevant to the enduring problem of nucleosynthesis of the heavy elements can possibly be probed. These frontier research opportunities are summarized in a set of four compelling questions:

1. What are the fundamental properties of matter at extreme states of temperature and/or density?
2. How do compressible, nonlinear flows evolve into the turbulent regime?
3. Can high energy density experiments answer enduring questions about nonlinear radiative hydrodynamics and the dynamics of powerful astrophysical phenomena?
4. Can inertial fusion ignition be achieved in the laboratory and developed as a research tool?

These questions, and opportunities to address them, especially on NNSA facilities, will be discussed in this chapter. Much of this frontier science potential, however, will never be realized unless (1) a new generation of creative young scientists is exposed to this field, and trained in its techniques; and (2) a coordinated U.S. funding and facility access structure is developed that embraces this cross-disciplinary new branch of science. The NNSA has already made progress in this area with the NLUF program on

Omega and the recent expansion of the NNSA Academic Alliances Program. This progress should be applauded and built on. This leads to the following recommendations.

1. To foster this emerging new field of science in the U.S. requires the ability to interest and train students. This in turn requires experimental facilities where the students can have wide and extended access to learn and develop experimental techniques, try out new ideas, even if not fully refined, and (3) pursue extended research over 3-4 yrs leading to a thesis and graduation. This style of student training in the U.S. currently happens on small (~ mJ or J), "table top" lasers. There is only very limited student access to kJ-class lasers and MA-class Z pinches, which form the training ground for future scientists on the big NNSA facilities. There are even fewer students exposed to a handful of experiments on large lasers (> 10 kJ) and Z-pinches (> 10 MA), such as OMEGA and Z, respectively, due to the very high cost and extremely limited access. The relevant existing facilities in the U.S. are listed in Table 1 below, and those hosting a user program in Table 2. The only official user program on any pulsed HED facility in the U.S. is the National Lasers Users Facility (NLUF) program, which allocates 15% of Omega laser time for this purpose. Omega, however, is a major world-class facility, and is not suitable for the type of hands-on, "move the laser optics around" type of training needed. An appropriate mid-scale, ~kJ class facility dedicated to university research does not exist in the U.S. at present.

Laser energy; pulsed power current	0.1 – 10 J	10 – 100 J	~1 kJ; ~1 MA	10 – 50 kJ; 5-20 MA	~2 MJ; ~30 MA
Current facilities	Hercules (U. of Mich.); L'Oasis (LBNL); JanUSP, Comet, USP (LLNL); Thor (U. Texas-Austin)		Trident (LANL); Janus (LLNL); Z-beamlet (SNLA); Nike (NRL); Neptune (UCLA); COBRA (Cornell U.); Zebra (U. Nevada-Reno);	Omega (LLE); Saturn, Z (SNLA)	
Future facilities		SNLA-PW, Texas-PW		Omega/EP	NIF; ZR

Table 4.1: HED experimental facilities in the U.S., either existing or currently under construction.

Laser energy; pulsed power current	0.1 – 10 J	10 – 100 J	~1 kJ; ~1 MA	10 – 50 kJ; 5-20 MA
Current facilities	none	none	none	Omega (15%)

Table 4.2: Existing HED experimental facilities in the U.S. that have an official user program.

The opportunities to foster the HED physics field would be significantly enhanced if there were at least one kJ-class (mid-scale) laser facility in the U.S., possibly coupled with a short pulse laser, with significant access for university groups and students. This could be on an existing facility; there are several such lasers located at national laboratories. In this case, the issue of wide and extended access for university students (U.S. and foreign) would need to be addressed. Or this could be a new facility constructed for this purpose at a location where access (both facility and site) for students was not an issue. Enhanced access by academic groups to the larger NNSA facilities would also be of considerable benefit.

2. There would be considerable benefit to national coordination of the resources and facility time, including staging, for the basic science use of the NNSA HED facilities. Such coordination could be achieved, for example, by an HED Inter-agency Planning Board formed from DOE SC/NNSA/NSF/NASA. Staging here means that initial ideas get tried, tested, and developed on smaller facilities. The next stage would be demonstration and further development on the existing big facilities, such as Omega and Saturn. Only the most refined and well developed ideas requiring the highest energies would be awarded time on the largest facilities (NIF and ZR) for "culmination tests and experiments".

3. Opportunities for discovery class science could be enhanced, potentially, by combining or reconfiguring facilities. Examples might be (a) combining a shockless and shock compression capability on next generation x-ray free electron laser facilities or light sources, to dynamically infer sub-micron microstructure; and (b) adding petawatt lasers on the larger NNSA facilities to allow the most HED extreme states of matter to be created and probed.

In the following, we describe four broad categories of HED physics possible on the NNSA facilities: (1) fundamental material properties, (2) compressible dynamics, (3) radiative hydrodynamics, and (4) inertial confinement fusion. In each area, we highlight the science frontiers accessible, and describe the scientific opportunities possible, with appropriate additional national investment.

4.2 Materials Properties

Imagine taking a microscopic parcel of matter only fractions of a millimeter in extent, and subjecting it to an enormously high pressure, many times larger than that found at the center of the earth. Then imagine conducting a series of carefully controlled laboratory experiments on this parcel, to determine its fundamental properties: compressibility, opacity, conductivity, viscosity, ionization potential, specific heat, sound speed, and so on. Further imagine doing all of this in the fleetingly brief interval of time of a few nsec (10^{-9} sec, i.e., a billionth of a second) or less. What to the uninitiated hints of science fiction is the routine work of the scientists pursuing high energy density (HED) physics. To create the extreme conditions of density and temperature in the samples being studied requires the world's largest HED experimental facilities, such as the Z-

Machine and the OMEGA Laser that are now in operation, and even more capable near-future systems, the National Ignition Facility laser and the Linac Coherent Light Source. To make high accuracy measurements of the fundamental properties of matter in sub-nanosecond time scales requires new, ultrafast, high-sensitivity diagnostics and detectors. The end result is pioneering research into frontier science, with relevance from the cores of imploding inertial confinement fusion capsules to the centers of the planets and the stars. Several examples from this field are discussed in this section.

4.2.1 Motivating Intellectual Question

What are the fundamental properties of matter at extreme states of temperature and/or density?

To illustrate the scope of this question we highlight four areas of the HED regime.

1) **Warm dense matter** is a particularly intriguing subset of the HED regime, as it refers to a no-man's land where matter is neither solid, fluid, nor plasma, but some heretofore unexplored state that challenges description. Were it in some obscure region of phase space never accessed by experiments, one might be tempted to leave this particular area of *terra incognita* alone. However, warm dense matter occurs commonly in every laboratory experiment in which a plasma is created very quickly from a solid. Examples are numerous, with the most obvious being the density–temperature track of inertial fusion targets, laser produced plasma sources, and shock heated systems. It also occurs on astronomical scales in the cores of giant planets, making our understanding of the evolution of these objects incomplete. Warm dense matter refers, on the one hand, to states from near-solid density to much greater densities with temperatures comparable to the Fermi energy. On the other hand, it also refers to those plasma-like states of matter that are too dense and/or too cold to admit to standard solutions used in plasma physics. This is the region where plasmas become strongly coupled and theories based upon only two particles interacting at a time fail. Warm dense matter, therefore, defines a region between condensed matter and plasmas. Experimentally, the study of warm dense matter has proven difficult, as the isolation of samples in this regime is complicated. Indeed, although every density-temperature time history that starts from the solid phase on the way to becoming a plasma goes through this regime, attempts to isolate warm dense matter for study have proven to be a major challenge.

2) **Matter at extreme pressures:** Matter undergoes enormous changes in its strength, hardness, and density when submitted to either static or dynamic high pressures at temperatures varying from near absolute zero to thousands of degrees Kelvin in a shock, ramped compression wave, or laser heated diamond anvil cell. Compressions to densities as high as 10-15 times that of conventional matter are commonly achieved. X-ray and other techniques can be used to measure the bulk modulus, shear modulus or strength, strain rate, and structure as a function of pressure and temperature. Nature has provided us with metastable high-energy phases such as diamond, conceived at high pressures and temperatures in the core of the earth. New metastable states possible with high energy

density materials, such as the long-sought metallic atomic hydrogen, are achievable goals of HED physics.

3) **Radiative properties in extreme magnetic fields:** Observations show that white dwarf stars can have surface magnetic field strengths up to 10^9 Gauss and models for neutron star crusts and pulsar atmospheres require fields greater than 10^9 Gauss. Strong magnetic fields arise in the laboratory as well. In laser plasmas and pulsed-power experiments, magnetic fields typically exceed 10^6 Gauss. The magnet fields can significantly modify radiative properties in these HED regimes. Indeed, the motion of atoms in a strong magnetic field affects their structure to the point that radiative transitions become so broad that the radiation from a neutron star will have no standard features, causing changes in the opacities. Furthermore, the strong magnetic fields can change the very nature of the way electrons and ions interact so that the time evolution of these systems is greatly modified.

4) **Hot dense matter** refers to the regime of high temperatures and densities, e.g., 10^7 K and 100 g/cm^3, similar to those found at the center of the sun. Under these conditions, our ability to simulate the radiation outflow that leads to the solar radiation we observe is enormously challenging. For the case of simultaneous high temperature and high density, we need to understand how high density affects the atomic properties. At the extreme densities of the stellar interior, the number of hydrogen atoms per cm^3 is $6x10^{25}$, so that on average there is only 0.25 Å (1 Å is 10 billionths of a cm) between atoms, which is smaller than the distance from the hydrogen's proton to the first stable electron orbit. Clearly the electron could not remain in a stable bound orbit around the proton, independent of temperature. The complete description of the radiative properties of the elements in a stellar interior at these densities is a substantial challenge. Conditions that approach this regime can be produced in intense short pulse laser experiments and in the core of inertial confinement fusion implosions.

4.2.2 Research Opportunities

The HED regime for material properties separates naturally into two broad categories. The first is the high temperature regime in which the dense matter does not show effects of order; this includes the imploding core in an inertial confinement fusion capsule and the hot dense matter ejected during ultrafast energy deposition in a solid. The second regime is one in which the matter shows short and/or long-range order, i.e., warm dense matter. This covers materials at near-solid densities with temperatures above the Fermi temperature and extends to dense plasmas with temperatures such that there exists strong coupling, meaning that the kinetic energy of the particles does not exceed the electrostatic energy between two adjacent plasma particles. The difficulty presented by warm dense matter arises theoretically from the fact that in this regime there are no obvious expansion parameters, as the usual perturbation expansions in small parameters used in either condensed matter studies [θ = temperature/(Fermi energy)] or plasma kinetic theories [Γ = (potential energy)/(kinetic energy)] are no longer valid. Furthermore, density-dependent effects, e.g., pressure ionization, become increasingly important as the environment surrounding the ion or atom starts to impinge on internal lattice or atomic structure. Here we include the measurement of the properties of materials relevant to understanding the interior structure of the earth and small planets. For this discussion the study of material properties is separated into four areas.

1) Equation of State: In simplest terms, an equation of state attempts to describe the relationship between temperature, pressure, density, and internal energy for a given substance or mixture of substances. This definition does not illuminate the incredible complexity of the problem of calculating the equation of state of HED matter.
2) Radiative Properties: The properties of absorption and emission in the HED physics regime can be constructed by a) determining the equation of state, b) combining this with knowledge of the spectral characteristics of the ion, atoms, molecules, or solids, as these are effected by the finite temperature dense medium, and then c) piecing the various components together using a model for the HED environment.
3) Strength of Materials: The study of the stress and strain on materials at extreme conditions forms an area of investigation of substantial interest. Here the emphasis is on measuring the material properties of a sample, such as its strength, bulk modulus, and shear modulus, at high pressure, with a large applied shear stress. Perhaps even more fundamental is the determination of its structure and phase at high pressure.
4) Dynamic Properties: The material properties discussed in **1**, **2**, and **3** above are defined for materials in equilibrium. However, there are situations where equilibrium states are not accessed as the time scale required to reach equilibrium is incommensurate with the dynamics of the system under investigation. This leads to an added level of complexity as the time dependence of the property under investigation must then be tracked and the various state variables, such as temperature and/or density, must be measured for these non-equilibrium states.

1) Principal scientific objectives / milestones / timelines

a. Short pulse lasers

There are many short pulse laser facilities with a broad range of capabilities, and these facilities can be expected to increase in numbers in the next few years. However, a definitive Equation of State experiment, meaning that it produces data with sufficiently small uncertainties to be competitive with, for example, the lower energy density work on gas-guns, has been lacking. The relatively small energy of the short pulse lasers used so far translates into a small heated volume on a short time scale, leading to rapid changes and large gradients. The first milestone for these systems for material properties would be quantitative measurements with well-defined error estimates of an equation of state to prove the technique's value. This could be performed in three years with a concerted effort. Similar arguments apply to opacity measurements. On the other hand, the measurement of surface phenomena, such as reflectivity, seems quite possible now.

Harmonic conversion into the x-ray regime could provide a probe for HED material properties experiments of great value. Indeed the difficulty of synchronization of two disparate x-ray sources (e.g., a next generation light source and a short pulse laser) may be overcome if and when the short pulse lasers can provide both the x-ray probe and the creation mechanism for the HED matter. The development of a facility with this capability is likely to take at least five years.

The coupling of short pulse lasers with larger scale facilities provides a very attractive path for performing material properties experiment. The timeline for this is dictated by the schedules of the larger scale facilities. Such a capability could be operational in ~2 yr after a commitment to proceed is made.

b. High energy lasers

High-energy lasers, such as Omega and the initial stages of the NIF, can provide material properties now. The development of equation of state data has proven somewhat difficult, as the quality of the data must be high enough to constrain the theoretical/modeling efforts of theorists. The highest-pressure work must wait for the full NIF in about 4 years. On Omega, experiments to develop techniques for shocks and radiative properties can be performed now at lower energy densities, for example experiments in the 10 to 50 eV regime with x-ray probing. Techniques can be perfected in the next three years, in time for measurements in equilibrium conditions at > 100 eV at the NIF. Thus, HED opacity and equation of state experiments will commence on the NIF around 2009, giving a robust test bed radiation environment at > 100 eV in ~2012, with material properties data really starting to flow at that time.

In addition, laser facilities have a unique capability to make absolute equation of state measurements. Such experiments are considerably more difficult, and significant effort will be required to reduce the uncertainties in such measurements. But the value of having the ability to make absolute equation of state measurements at very high pressures, independent of models, relative comparisons, and assumptions, is very high, and should be a capability that gets developed to maturity. Only by having such alternate techniques can subtle systematic uncertainties of measurements in these new regimes of HED parameter space be brought to light.

c. Pulsed power machines

Pulsed power machines, particularly the Z machine at Sandia, have made remarkable progress over the past few years in providing a valuable complement to the high-energy lasers in the production of equations of state and opacity data. In particular, pulsed power facilities enable larger samples and longer time scales. The strength of these facilities is in making accurate material measurements, especially equation of state and opacity measurements. The magnetic flyer and shockless compression techniques have been developed into mature capabilities. Over the next few years, pulsed power facilities are expected to generate equation of state data at pressures up to 10 Mbar off-Hugoniot and up to 40 Mbar on-Hugoniot. These facilities would benefit from expanded diagnostic suites, and the radiation-driven experiments for material properties research need more development. The opacity experiments complement lasers by providing lower temperature, lower density, but longer duration environments very relevant, for example, to stellar envelope conditions.

d. High Energy, high intensity charged particle beams

Beam facilities, such as SLAC and RHIC, could be used to generate matter in the HED regime over relatively large volumes as the energy of the beams is effectively transferred to bulk matter. An intense ion beam heats matter in a completely distinct manner from lasers, potentially allowing access to much larger regions of the HED phase space. To date the ion beam facilities do not produce sufficient beam energy to heat samples large enough to be interesting to the temperatures required. Pursuing this approach for HED material properties studies would require a substantial effort to fund an intense, possibly heavy, ion beam source to create states in the HED regime. This research is currently planned for the GSI Darmstadt, Germany facility upgrade and for the LBNL heavy-ion-driven HEDP facility. As such we can assume that 8 years will be the minimum to develop an HED material properties effort in the U.S. Experimental programs to develop techniques for this novel capability will be greatly assisted by collaborative work planned for 2005 at the PHELIX laser facility that will work in conjunction with the ion beam machine at GSI.

e. X-ray light sources

Third generation x-ray light sources which currently are limited to ~100 ps duration pulses at MHz repetition rates have been used to perform several studies in the warm dense matter regime. Since the light source has low intensity per bunch, a short pulse laser is necessary to create the heated sample that is then probed by the x-rays. The next evolution of this capability will occur in 2 years when the upgraded source at the ALS will have sub-picosecond bunches, thereby allowing studies of material properties with time resolution in the 100 fs regime.

Next generation x-ray light sources will be free-electron laser based and will have sufficient energy to both create and probe warm dense matter up to perhaps 10 eV. Coupled with high-energy lasers one could also probe HED plasmas at higher temperature and provide a method to pump and probe dynamic effects in these higher temperature dense plasmas. The initial phase of the LCLS, the x-ray free electron laser to be constructed at SLAC, will start operation in 2009. Experimental programs to develop techniques for this novel facility will be greatly assisted by collaborative work planned for the ultraviolet free electron laser (VUV-FEL) starting in 2005 at DESY in Hamburg, Germany. In addition the development of short pulse x-ray sources at short pulse laser facilities will be critically important to develop techniques and should start as soon as possible.

f. Small-scale facilities

There are two generic small-scale technologies, diamond anvil cells and small long pulse lasers, that are ready for use in the study of matter at extreme conditions. A new small pulsed-power shockless-compression driver is also being built at WSU to exploit this unique capability at a higher shot rate and lower cost than on Z. All of these have distinct advantages for research, as they can be easily implemented (and currently exist) at universities, providing direct contact with the manpower resource generation. First, the rapid development of techniques based on diamond anvil cells has been important in determining the equation of state in materials under extreme pressures in static conditions. When the diamond anvil cell is laser heated, conditions in the warm dense matter regime have been accessed, raising the possibility of performing both dynamic and static experiments to obtain a deeper understanding of the equation of state. In the case of small long-pulse lasers, one can create strongly coupled plasmas with novel sample configurations. In both cases the increased number of experiments and the low cost per experiment, coupled to the university location, leads to high scientific productivity and efficient training for HED physics research.

2) Research tools and facility requirements

The most important facility requirement for research in the HED physics regime, as in all experimental research, is access. Many of the facilities discussed here are large and costly on a per shot basis. Thus, the ability to obtain shots over a sufficiently long time to pursue a high quality research program, while obtaining the money to develop sample fabrication capability, is crucial. Furthermore, instrumentation costs for the larger facilities can be onerous for single investigators, so provisions will be required to defray or rationalize the costs through collaborative planning. On smaller facilities, such as the < 1 Joule scale short pulse lasers, the per shot costs can be low but a substantial investment will be required to develop robust, sub-ps, x-ray diagnostics.

a) High-Energy Lasers: (OMEGA and NIF)
These facilities can generate HED matter in several ways. First direct illumination of a sample can efficiently generate high-temperature high-density plasma. Second, using indirect illumination these lasers can generate sufficiently intense x-ray sources that can then be used to heat matter from 10s to 100s of eV, spanning the HED regime and creating equilibrium environments. Third, these lasers can be used to drive shocks to extremely high pressures ($P > 100$ Mbar) that can be used to study the equations of state of HED material.

b) Pulsed Power machines: (Z and Saturn)
Facilities of this type produce immense amounts of x-ray power on somewhat longer time scales than the high-energy lasers. The energy can be used to create radiation environment for studies of equilibrium systems as well as shocks. Indeed, the longer time-scales and increased energies of these facilities are complementary to those of the high-energy laser facilities, allowing distinct approaches to HED regimes with overlapping conditions as well as broadening the region of phase space that can be accessed.

c) Particle beam facilities: (RHIC, SLAC, LBNL)
Very high energy beams of ions (RHIC), the electron beam (SLAC), and the LBNL heavy-ion driver potentially could provide an alternate means for generating HED matter. Due to their long penetration depths, they could be used to volumetrically heat matter, provided the beams are sufficiently intense. This indicates yet another potential avenue to create HED matter to assist in covering the regimes of interest.

d) Short Pulse Lasers:
These lasers are much more prevalent, as the facility costs are smaller and the shot rate is higher. These facilities have been a driving force for many innovative experiments in the HED regime. However, progress in the area of material properties requires data quality that is high, resulting in the need for concerted efforts in this direction. In addition, multi-MeV electron and light ion beams can be produced via laser plasma acceleration

mechanisms, and these beams can be used for the creation and study of HED material properties.

e) X-ray Free Electron Lasers: (LCLS)

These devices are at the intersection of laser and x-ray light source technologies. The laser-like qualities can be used to both pump and probe plasma created either by an optical laser or by the x-ray free electron laser itself. The short pulse width (100 fs), intense photon numbers (10^{12}), short wavelength (~ 1Å), and repetition rates of 120 Hz make these facilities most intriguing. The coupling of these facilities with short pulse and/or high-energy lasers will provide an exciting capability for the study of the HED regime that offers great promise.

f) X-ray-Light Sources: (ALS, APS, SPPS)

The x-ray light sources have proven extremely useful in providing a probing source for matter that has been put into the HED regime by optical laser pumping. These experiments are currently limited to time resolution of > 1 ps due to the length of the x-ray pulses, and therefore require the use of ultra-fast x-ray streak cameras for short time measurements. In the near future an advance on this standard 3rd generation light source will be available with 100 fs duration pulses. Thus prototyping experiments can be performed at these facilitates with the emphasis on heating and shocking crystals to determine the compressibility and phase, for example.

3) Resource requirements

To determine a coherent plan for the effort of material properties studies across the entire phase space covered in the HED regime is beyond the scope of this report. On the other hand, one can form a plan that shows how the various experimental components of a plan would work together for a subset of the total regime and use that to estimate the level of effort required. We take as an example a coordinated effort to explore the warm dense matter component of the HED regime to measure the equation of state. We assume that short pulse lasers will work in tandem with a large-scale facility that could be a high-energy laser, an x-ray free electron laser, or an ion beam machine. Further, we note that the cost for doing this at any of the facilities will be roughly similar since the cost of the large scale facility is *not* included. However, once the infrastructure investment is made, developing the technique on another facility will be substantially less expensive.
The need to have a supporting theoretical effort has not been discussed here but since the regime is new, one requires both guidance from and interaction with the theorist who will use the data and analyze the experiments. The costs for capital (Cap) and small cost expenditures (Small) are estimates, as are the number of full time researchers (FTE) required.

CATEGORY	YEAR	1	1	1	2	2	2	3	3	3	4	4	4	5	5	5	Sum	Sum	Sum
	Sub-category	Cap	Small	FTE	Cap	Small	FTE	Cap	Small	FTE	Cap	Small	FTE	Cap	Small	FTE	Cap	Small	FTE
Instruments																			
	Fourier Domain & X-ray Interferometry (FDI)		15	1	45	10	1.25		5	1							45	30	3.25
	Thomson Scattering (TS)							10	15	1	10		1		5	1	20	20	3.00
	Detectors	25	10	0.25	25	10	0.25	25	10	0.25	25	10	0.25	25	10	0.25	125	50	1.25
	XUVSpectrometer	20	5	0.25													20	5	0.25
	X-ray Spectrometer											2	0.25		2	0.25		4	0.50
	XUV Streak Camera	100	5	0.5		5	0.25										100	10	0.75
	Xray Streak Camera										50	5	0.5	50	5	0.5	100	10	1.00
	100 fs Streak Camera development	100	20	1	100	20	1		20	1							200	60	3.00
Experiments - test and prepare																			
	Short Pulse Laser x-ray source development		25	1.5		20	1		20	1.5								65	4.00
	Absoprtion spectroscopy					10	2		10	1		10	1		10	1		40	5.00
	Determine gradients					15	0.75		15	0.75		15	0.75		15	0.75		60	3.00
	Light Source calibrations		5	0.25		5	0.25		5	0.25		5	0.25		5	0.25		25	1.25
Perform experiments																			
	Implement target chamber	75	20	1	75	10	1		15	0.5		15	0.5		15	0.5	150	75	3.50
	test diagnostic complement					5	0.5		5	0.5		5	0.5					15	1.50
	timing studies					20	0.25		5	0.5		5	1					30	1.75
	Experiment: FDI/heating/absorption					10	1		10	1		10	2		10	2		40	6.00
	TS using x-rays								10	0.75		10	0.75		10	0.75		30	2.25
Theory and Analysis																			
	Rad-hydro simulations		18	0.5		18	0.5		18	0.5		18	0.5		18	0.5		90	2.50
	Condensed matter (CM) EOS			0.25			0.5		10	1		10	1		10	1		30	3.75
	CM Optical properties			0.25			0.5			1			0.5			0.25			2.50
	Strongly Coupled Plasma EOS			0.25			0.5		10	1		10	1		10	1		30	3.75
	SCP Optical properties			0.25			0.5			1			0.5			0.25			2.50
TOTAL		320	123	7.25	245	158	12	35	183	14.5	85	130	12.25	75	125	10.25	760	719	56.25

Table 4.3 indicating the timeline and costs in relative units to field an experimental effort *with no other funding* for the study of Equation of State. The units of cost (Cap) and (Small) are $1000 and the units for manpower (FTE) are person years.

The table is built from experience derived implementing material property studies "from scratch" at large NNSA facilities. The total is ~10 FTE/yr for ~5 years. The concept of bringing a completely new effort to fruition on the larger scale facilities requires substantial effort offline, as the facility will have numerous activities scheduled and offline development of instrumentation and techniques is essential.

4) Opportunities for interagency cooperation

There are two obvious areas for interagency cooperation. First, the NNSA facilities, most particularly NIF but also the Z machine and it successors, as well as the Omega laser can provide unparalleled capability for the development of research into the realm of HED science. With the possibility of access, one can foresee use from researchers that derive their funding from NSF, NASA, DOD, and other areas of DOE. As the study of material properties covers a wide range of topics, it is expected that these agencies could fund the research on NNSA facilities.
The second obvious area is the use of 3rd generation and 4th generation light sources, the province of OBES in DOE, by other communities from within DOE, NSF, NASA, and DOD. The future x-ray free electron laser is an excellent case study, as this facility will have both a light source and laser and as such will be unique. The implementation of a

short pulse and high-energy lasers at the x-ray free electron laser will permit material properties studies through a broad swath of the HED physics regime.

5) References

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c) LCLS: "The First Experiments – Plasma and Warm dense matter" (see LCLS website)
d) TESLA XFEL: http://tesla.desy.de/new_pages/TDR_CD/PartV/fel.html – section 2 "Scientific Applications of XFEL Radiation"
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4.3 Compressible Dynamics

When the full power (~10^{13} W or 10 trillion watts) of a large HED experimental facility is trained onto a ~millimeter size tiny sample for a few billionths of a second, the result is nothing short of dramatic. Pressures of 100's of millions of atmospheres, that is, a hundred times greater than the pressure at the center of the earth, can compress and shred even the strongest materials (such as hardened steel). Subsequent accelerations of $10^{13}g_0$ (10 trillion times the acceleration of gravity at the surface of the earth) exceed those found on the surface of a neutron star. Under such conditions, the action, albeit microscopic and brief, is astronomically intense. These are the HED conditions created and probed in the compressible dynamics thrust. Experiments can probe an individual physics issue, such as the transition to turbulence in a high energy density flow; or address integral problems in compressible dynamics, such as the role of turbulence and turbulent transport in scaled astrophysical jets. Just as high-energy lasers have enabled HED hydrodynamics to be studied at large Mach number (flow-velocity/sound-speed) and Reynolds number, Z-pinches allow HED magneto-hydrodynamics to be studied at large Mach number, magnetization, and magnetic Reynolds number. A revolution in the ability to isentropically (constant entropy) compress materials provides a method to access HED conditions at high densities and much lower temperatures than those accessed by shock waves. This will, in turn, contribute to an improved understanding of planetary interior conditions from their surfaces to their cores and of inertial confinement fusion implosions.

4.3.1 Motivating Intellectual Question

How do compressible, nonlinear flows evolve into the turbulent regime?

Astrophysics is replete with examples of high Mach number shocks interacting with heterogeneous background material, a situation that can lead to instability development and turbulence. The ZR and NIF facilities will provide enough energy (pressure-time) to generate flows that should become turbulent. High-resolution radiographic diagnostics can be applied to provide the data required to accurately assess the fidelity of hydrodynamic code calculations. Validated codes and scaled experiments can then be used to understand astrophysical situations with much greater confidence.

Astrophysical jets are a fundamental signature of the star formation process; they are highly collimated with Mach numbers of 10 or more. High Mach number hydrodynamic jets can be produced in HED facilities and the advanced radiographic capabilities now available allow the flows to be imaged in great detail. More could be drawn from these experiments if spectroscopic or tracer techniques could be developed to allow the flow velocity field and mass transport to be determined. Recent work with Z-pinches indicate the Lorentz force can be used to compress material to form jets which have many of the scaled parameters of astrophysical jets. A major challenge is to measure and control the entrainment of magnetic fields in the jets themselves. These jets, with or without entrained magnetic fields, can be directed to interact with background plasmas and fields. In addition, the measurement of the current distribution in a Z-pinch itself is a remaining grand-challenge of laboratory HED plasmas. The advent of highly collimated proton beams and bursts of x-rays from ultraintense lasers may make deflectometry and other probing techniques such as Faraday rotation possible to estimate the magnetic field distributions.

Plasma jet experiments on HED facilities may also be able to address issues related to turbulence and turbulent transport such as might be taking place in the accretion disks around black holes. Recent experiments with high resolution backlighting have shown the transition to a nonlinear, chaotic flow for jets on Omega and Z. The next generation of HED facilities will enable even more propagation distance so an even greater likelihood of the development of turbulence. The challenge for laboratory experiments is to reach regimes of dimensionless parameters that are relevant to the astrophysical situation, and then to characterize this turbulence so that codes and models used to calculate accretion disk phenomena and jets can be validated. Moreover, transport coefficients such as viscosity are critical and must be measured in unmagnetized and magnetized plasmas. Such measurements will help in understanding the energy flow from the magnetic field into radiation in the highest power Z-pinch experiments as well.

4.3.2 Research Opportunities

High energy density facilities provide unique environments to study compressible dynamics. Controllable high pressures, timescales ranging from tens of femtoseconds to hundreds of nanoseconds, high strain rates and variable degrees of magnetization are all realizable on modern HED facilities. State-of-the-art imaging, diagnostics and precision target fabrication that are now available at all large NNSA HED facilities enable compressible dynamics experiments that can truly test modern computational capabilities and potentially lead to an understanding of this extremely complex area of physics. Compressible dynamics covers spatial scales ranging from atomic (nanometers) through microscopic (microns) to macroscopic (centimeters), ending in astronomical scales (light years) in the case of protostellar jets. This full range of spatial scales enters into the following discussion of fundamental and applied physics issues in high energy density compressible dynamics that can be investigated now and in the near future using HED facilities.

1. Principal scientific objectives and milestones

In the next five years, a compressible dynamics program can make very valuable contributions to our understanding of planetary formation, protostellar and galactic jet evolution, and material behavior in extreme environments. Examples of key scientific objectives are:

1) The propagation of hydrodynamic and magnetized jets into the turbulent regime
2) The measurement of magnetic fields in these jets and other laboratory high energy density plasmas
3) The characterization of high Mach number shocks interacting with homogeneous and heterogeneous media
4) Development of radiographic imaging diagnostics to enable high resolution imaging of high Mach number and turbulent flows.

Achieving the above objectives will begin to answer the compelling questions in this arena. Building on this work, and with the advent of ZR, NIF and Omega EP, the compressible dynamics community should have major breakthroughs in the 2009 to 2014 timeframe such as:

1) Using experiments and simulations (with 3D MHD codes) of highly turbulent flows with non-magnetized and magnetized plasmas, to answer fundamental questions relating to the propagation of protostellar and intergalactic jets, such as:

- why and how do they stay so well collimated?
- are they and do they need to be magnetized?
- where do the currents flow?

2) Diagnose the interaction of high Mach number shocks over long distances with heterogeneous media to test and validate models of supernovae explosion dynamics.

The objectives listed above are examples of what can be achieved. As a stronger community is developed to use HED facilities, one can only imagine the frontier science that will be done and the answers to major scientific questions that will be provided. We can move astrophysics and planetary science from predominantly observational to being a dynamic interaction between theory, experiment, and simulations. The ability to do scaled compressible hydrodynamics experiments relevant to astrophysical flows and dynamics is a new benefit to science, emerging as a result of the HED facilities.

2. Research tools and facility requirements

To meet the requirements for a robust dynamic compression program, we envision a hierarchy of facilities. Nationally, having many experiments devoted to HED science is essential, but it is hard to imagine many shots on the larger facilities due to their high costs and complexity. So the smaller facilities can be used when appropriate, and as platforms to develop techniques and diagnostics to ensure the success of the larger scale experiments.

The Z (ZR), NIF and Omega facilities will be required to meet the demands of the highest pressure dynamic compression experiments, e.g. compressing materials to the pressures of planetary interiors, and to generating hydrodynamics flows, jets and shocks that can be diagnosed well into the turbulent regime and have the most favorable scaling to astrophysical phenomena. NNSA should be prepared to support shots and laboratory staff to provide access to these world class facilities. It is critical to have scientific partners from the laboratories that are experts in the various facilities involved in the research. A model for these partnerships will be discussed later. Also, NNSA should view the needs of the HED basic science community in planning their target fabrication needs. Some of these needs may be very challenging and unique from programmatic mission needs and may require new target fabrication technologies.

The community must also develop the appropriate diagnostics that will make full use of the experimental platforms. Some examples of grand challenge diagnostics are listed below:

1. Measuring turbulent flow with micron resolution over many mm flow lengths, including the mapping of flow velocities
2. Measuring the current and magnetic field distributions in compressed Z-pinches and in magnetized jets.

The smaller laser and pulsed power facilities in the community are ideal locations to develop many of the needed diagnostics and experimental techniques. The MAGPIE pinch facility at Imperial College, as one example, has shown how small facilities can make very relevant measurements to the physics of astrophysical jets. The technique of dynamic diffraction of shocked crystals in laser experiments was first demonstrated on Janus (LLNL), and further developed on Janus and Trident (LANL), both medium scale lasers. Some of the medium scale university facilities are still sponsored primarily by NNSA, which should be continued, both as training grounds for future HED scientists and to provide facilities that other agencies can support. Also, some medium scale facilities are under utilized. For example, NNSA should explore collaborations with other agencies to make the Saturn pulsed power facility available to the broader HED community. Over the next 10 years, various government agencies should collaborate to combine some of the different technologies, e.g. lasers and pulsed power, or gas guns/lasers/pulsed power with synchrotrons, to exploit the synergies of these facilities.

3. Timeline and resource requirements

Near Term (2004-2008)

For the next five years, we recommend that dynamic compression experiments become a focus area for small to medium scale laboratory experiments on NNSA HED facilities. Key facilities, for example, could include:

- Omega laser
- Enhanced academic use capability for Janus, Trident, Z-beamlet laser facilities
- The Texas SSAA Center for High Intensity Laser Science
- The NNSA suite of ultra-short pulse and planned high energy PW lasers
- The ~1-MA z pinch facilities at Cornell, UNR, and Imperial College
- The small, shockless compression drivers planned at Sandia and WSU
- Gas guns at WSU

These facilities can be used to achieve some of the scientific milestones discussed above, and to develop diagnostics for future even higher energy density experiments. Some of this work is already planned through the existing NNSA program. We recommend that this program should grow over the next five years, in particular, to allow wide and extended university use. In addition, other funding agencies should take the opportunity to expand their support in this area to complement NNSA's. A valuable contribution, as an example, would be the formation of an academic funding program where new groups could apply for small grants to develop ideas that could then translate into well thought out future proposals. This would encourage the infusion of new talent into this area, resulting in fresh looks at HED problems. In this time frame, planning activities for ZR and NIF need to commence.

Longer Term (2008-2014)

After 2008, it would be ideal if 15% of shots on NIF, ZR, and Omega were being devoted to basic science in the HED arena to augment the continued program on the smaller scale facilities. This would represent a commitment to HED basic science of approximately 20 M$/yr (facility + target cost). The distribution of shots between the different HED areas should be based on merit and match to facility. This will require a facilities-coordinated selection committee. The compelling questions and proposed goals discussed in this report could motivate experiments on these premier NNSA facilities.

We recommend that each facility have a Basic Science User program that supports the experiments, diagnostics, target fabrication and technical staff. The National Laser Users Facility at the OMEGA laser provides a current example of such a program. The NNSA academic alliances program should continue to provide a funding framework for the universities, and the other agencies (NSF, DOE's Office of Science, and NASA) should support parallel HED programs.

4. Opportunities for interagency cooperation

NNSA and other basic science agencies should collaborate on funding an expanded compressible dynamics program to achieve the following goals:
A new-blood program to encourage new HED researchers. In particular, it would be advantageous to attract fluid dynamicists, condensed-matter scientists, and astrophysicists into studying HED compressible dynamics problems.
Cooperative funding where NNSA funds experiments on NNSA facilities in conjunction with NSF, Office of Science, or NASA funding for the participating academic groups should be developed.
NNSA, BES, and the Office of Basic Science could collaborate on bringing small-scale HED platforms to synchrotrons and x-ray free electron lasers.
Once US collaborative programs have been established, the US community could look for similar collaborations with other countries with established HED interests, e.g. UK, France, Russia, Japan, and Germany.

5. References

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4.4 Radiative Hydrodynamics

Radiative hydrodynamics as a scientific endeavor can conjure up images of esoterica, but the basic idea is easy enough to envision: hydrodynamics (material flow) in the presence of radiation. One example familiar to all is the flash of light (radiation) followed by the peal of thunder (hydrodynamic blast wave) during a thunderstorm. In this particular example, the radiation and hydrodynamics are not coupled. Now imagine the case where they are coupled. The situation can exist where the radiation source follows along with (rather than outrunning) the shock wave, in a glowing thunderbolt. This natural *son et lumiere* is what a radiative shock might look like on a grand scale. Found throughout astrophysics, radiative shocks, and more generally radiative hydrodynamics are one of the primary mechanisms that make the universe glow. On a laboratory scale, creating coupled radiative hydrodynamics, such as radiative blast waves, requires high energy densities, which is the natural domain of HED experimental facilities. The underlying science of radiative hydrodynamics, though simple in concept, is exceedingly complex in practice, and spans settings from the very common place (peals of thunder) to the very exotic (accreting, massive black holes at galactic centers). The potential for using HED facilities to explore scaled versions of these complex dynamics is the topic of the discussion below.

4.4.1 Motivating Intellectual Question

Can high energy density experiments answer enduring questions about nonlinear radiative hydrodynamics and the dynamics of powerful astrophysical phenomena?

The vision of a scaled astrophysical testbed for radiative hydrodynamics is by equal measure compelling and difficult. The key to developing a properly scaled radiative hydrodynamics testbed, lies in reproducing several key dimensionless quantities, such as Reynolds number (inertial/viscous forces), Peclet number (convection/conduction), and Mach number [(flow velocity)/(sound speed)], the ratios of the radiative cooling time to the plasma lifetime and plasma optical depth scale to the system size. Once these parameters have been reproduced, then the potential exists for examining in a scaled laboratory setting, some of the most violent and extreme phenomena known in the universe. A few examples follow.

In an equilibrium photoionized plasma, the photoionization rate is balanced by the radiative recombination rate. Theory and models exist, but laboratory data is badly needed. An interesting application of photoionized plasmas is found in astrophysics. Roughly 50% of the x-ray sources in the observable universe are due to accretion-powered objects. Accretion converts gravitational potential energy of infalling matter into x-rays that interact with the surrounding accretion disk, generating x-ray emissions from a photoionized plasma. Laboratory experiments in relevant regimes are possible on large HED facilities, allowing the models used to interpret the astrophysical observations to be tested and "calibrated" under relevant conditions. Such experiments could lead to a firmer understanding of the dynamics in the vicinity of accreting compact objects such as neutron stars and black holes.

Radiation flow in the presence of large hydrodynamic velocity gradients is a classic problem in coupled radiative hydrodynamics. The absorption probability of photons traversing a "parcel" of plasma depends on the atomic physics and on the velocity gradients, due to Dopper shifts of the absorber relative to the emitter. A very important application of this phenomenon is in the light curve (luminosity versus time) of supernovae. Due to the explosion, there is a very strong velocity gradient. Hence the rate of heat trapped inside that leaks out as radiation versus time depends sensitively on understanding this radiation flow problem. Scaled experiments addressing this modeling problem may be possible on HED facilities, and would lead to an improved understanding of the observables from supernovae.

A strong shock wave is a formidable force. When it encounters obstructions in its path, it compresses, heats, distorts, and ultimately shreds the obstruction, while passing through it. If radiation is introduced into this dynamics, the shock compression and heating can lead to strong radiative emissions that cool the shocked material, leading to a full radiative collapse. This is predicted to trigger new dynamics and instabilities. The enhanced compressions due to radiative collapse of shocked, localized clumps in molecular clouds can trigger star-burst galaxies, that is, a galaxy with a whole series of stars, perhaps hundreds, lighting up simultaneously like a string of Christmas tree lights turning on. Being able to create scaled laboratory conditions to test the models and simulations of this effect would greatly benefit the field of astrophysics.

Ablation front dynamics supplies the fundamental "thrust" that drives inertial confinement fusion capsules to implode. Ablation front dynamics and energetics also underlie areas of laser medicine and laser cosmetic surgery, tattoo removal being one common example. Although widespread in use and application, modeling ablation front phenomena is remarkably difficult, due to the interplay between the incoming intense photon flux, exiting ablation plasma exhaust, strong shock launched forward into the sample, and potential radiative preheat moving ahead of the shock. One very impressive incarnation of ablation (photoevaporation) front dynamics is the famous pillars in the Eagle Nebula. Questions as to their origin depend on whether or not they are due to directional ablation-front hydrodynamic instabilities, or an ionization-radiation instability, or some combination of both. With the ability to create models of these effects, and to produce scaled experimental testbeds for these models on HED facilities, we are in a unique position to made real headway on unraveling the cause of the pillars in the Eagle Nebula, and in other similar, radiatively driven molecular clouds, such as the Horsehead Nebula.

4.4.2 Research Opportunities

A defining feature of current and future high energy density experimental facilities such as lasers or Z-pinches is their ability to create and probe a wide variety of radiative-hydrodynamic conditions. Examples include photoionized plasmas, radiation-dominated plasmas, radiative shocks, supersonic radiation flow in static or expanding plasmas, and ablation (photoevaporation) front dynamics. These examples, found both in HED laboratory settings and in astrophysics, will be discussed further below. For convenience, their characteristic parameters, suitable facilities, and timelines suggested for their investigation are summarized in Table 4.4 at the bottom.

2. Principal scientific objectives/milestones/timelines

a. Radiation-Dominated Hydrodynamics

The prodigious outburst of x-rays generated by the Z-Machine magnetic pinch facility or in laser-driven hohlraums can be used as scaled surrogates to the x-rays emitted as matter falls inward towards the "surface" of an accreting neutron star or black hole. These x-rays then pump the surrounding medium, corresponding to the conditions ~10^3-10^4 km from the accreting compact object (neutron star or black hole). In this low-density setting, radiation dominated conditions imply that the ionization and recombination rates are purely radiative, with collisional rates being negligible in comparison. Partially scaled laboratory experiments are possible on existing facilities such as Z/ZR over the next ~5 years, and fully scaled experiments should be possible on NIF in ~5-10 years. Typical parameter regimes correspond to temperatures and densities of ~100 eV and 10^{-4}-10^{-5} g/cm^3. These experiments will allow measurements of the temperature, density, ionization balance, radiative recombination spectra, and detailed line shapes in a radiatively dominated, photoionized plasma. This allows calibration of astrophysical, photoionized plasma models that are used to interpret the x-ray spectral data being recorded by x-ray observatories in space, such as the Chandra mission, to probe the immediate surroundings of massive black holes at the center of galaxies.

In the turbulent, radiative dynamics much nearer to the "surface" of an accreting compact object (within 1-2 km), the situation is extremely violent and harsh. The temperatures, densities, and magnetic field strengths are enormous. Radiation dominance at high density means that the plasma is optically thick, and the pressure is dominated by radiation pressure. Under these conditions, a wide variety of new instabilities and overstabilities are theoretically predicted. Whether any or all of them play a role in the dynamics observed in such systems, as matter funnels down past the "point of no return" into black holes, will take much more refined simulations, models, observations, and experimental guide posts. The potential for experiments is only starting to be explored, but the extraordinary ability to focus macroscopic amounts of energy into microscopic volumes in nanosecond or even picosecond time intervals on large laser facilities and Z pinches make this possibility fertile for consideration. It seems conceivable that rapidly evolving flows, even turbulent flows, could be created on future HED facilities over the next ~10 years, possibly in conjunction with multiple high energy petawatt lasers used as "heater beams", in which the pressure is dominated by radiation pressure. Typical parameters here correspond to temperatures $> \sim 1$ keV, densities of 10-100 g/cm^3, and magnetic field strengths > 10^9 Gauss. Questions vastly outnumber answers in understanding the dynamics thought to occur in such a setting. Any experimental data addressing aspects of these conditions would be scientifically very valuable. The research in this section would be very well aligned with the NASA Chandra mission, and with any future x-ray observatory, space missions.

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b. Radiation Flow and Material Opacities

In rapidly evolving systems, such as supernova explosions, there are strong gradients in temperature, density, and velocity. There are prodigious amounts of heat flow, in addition to the hydrodynamic flow. These two are coupled, making simulations difficult and uncertain. When the temperatures are high enough, the heat flow is dominated by radiation transport and opacity obstructs this heat flow. One current, very high impact, compelling question is the role played by opacities and radiation flow in a strong velocity gradient in determining the shape-luminosity correlation of Type-1a supernovae. These supernovae serve as standardized candles and are used to determine the expansion rate of the universe. Measurements of the opacities of materials under scaled conditions relevant to Type Ia supernovae would be highly beneficial. The issue is that photons emitted by a given atomic transition at one location in the plasma are absorbed at a different location by atoms that are strongly Doppler shifted, due to the large velocity gradient. This coupling of the radiation flow to the hydrodynamic flow adds enormous complexity to an already difficult problem. The shape-brightness correlation of the supernova light curve is thought to be due to details of the opacities and radiation flow through such a rapidly expanding plasma. This hypothesis could be checked by a concerted program of experimental measurements and large-scale simulations of these expansion opacities on the ZR and NIF facilities in ~5 years, and would have an enormous impact on firming up the fundamental science upon which the discovery of the accelerating universe is built. Typical parameters correspond to temperatures and densities of ~100 eV and 10^{-4}-10^{-5} g/cm^3 in a rapidly expanding plasma (velocity gradients of ~5 x 10^9 cm/s/mm, such that the frequency shifts over one optical depth are significant). Such research would be well coupled to two new NASA supernova projects: the Supernova Acceleration Probe observatory (in space) and the Nearby Supernova Factory observatory (ground based).

c. Radiative Shocks

Very strong shocks and very high Mach number flows invariably enter the regime of coupled radiative hydrodynamics. Colliding galaxies, supernovae, high Mach-number protostellar jets ejected during star formation, photoionized plasmas around accreting massive black holes, star-burst galaxies, and dynamic hohlraums on HED facilities all play host to radiative hydrodynamics. Theoretical models and computer simulations for radiative hydrodynamic systems abound, but they suffer from large uncertainties due to the complexity of the physics involved and the lack of experimental checkpoints. One compelling question in astrophysics is whether shock impact of localized clumps in molecular clouds can trigger star formation, through convergence of strongly radiative shocks. For example, a supernova shock or bow shock from a passing intergalactic jet incident on a clumpy molecular cloud could trigger a whole sequence of star formation events. Another question relating to radiative shocks is whether, in supernova remnants, thin shell instabilities and overstabilities, collectively referred to as Vishniac instabilities, lead to the observed distorted, sinewy shape of many supernova remnants, or does this shape trace its origin back to nonuniformities in the SN explosion itself. Experiments on existing HED facilities over the next ~5 years could play a key role in answering these questions. Example parameters correspond to post-shock conditions of ~100 eV temperatures and a few x 10^{-1} g/cm^3 in a strongly shocked, high-Z gas target.

d. Photoevaporation Front Hydrodynamics

Ablation fronts form a class of radiation-hydrodynamic flows of broad scientific interest. Referred to as a photoevaporation front in astrophysics, the conditions are thought to be prevalent in star-forming regions buried deep within dense molecular clouds. They are also critically important in the compression of an inertial confinement fusion target. A particularly impressive example in astrophysics can be found in radiatively driven molecular clouds. The dynamics are strongly affected by hydrodynamic instabilities growing at the ablation front. A number of questions emerge when the incident radiation is directional (not isotropic or diffuse). An understanding of these "directional hydrodynamic instabilities" has broad impact, both on laboratory experiments and in astrophysical settings. One of the most notable examples is the Eagle Nebula, popularly referred to as "pillars of creation".Radiation incident on the dense cloud surface from two nearby bright young, UV stars triggers photoevaporation (ablation) pressure on the cloud surface. This launches a strongly radiative shock that compresses the cloud and subsequently accelerates it away from the stars. Theoretical considerations show that several aspects of this radiative dynamics can be scaled to the laboratory for close-up scrutiny. Typical parameters correspond to ~50-100 eV radiation temperatures and densities of a few x 0.1 g/cm^3. Answering whether the Eagle Nebula columns are due to directional ablation front hydrodynamic instabilities or an ionization-radiation instability, or some combination of both is a question that can possibly be addressed on existing HED facilities over the next ~5 years.

3. Research tools and facility requirements

The research tools required are the HED experimental facilities listed in Table 4.4. This table also gives the regimes these facilities are required to access, to achieve the scientific objectives listed. The primary facilities required are the large HED facilities, such as Omega, Saturn, Z/ZR, and NIF. A subset of this work could be carried out on stand-alone ultraintense laser facilities, and other smaller HED facilities. Another subset of the research requires that some of the large HED facilities be equipped with petawatt-class lasers, to serve as heater beams, and as sources of ultraintense magnetic fields.

4. Resource requirements

The resource requirements are access to facility time, high quality targets, and funding to support university students. (1) A commitment for facility time on an ongoing basis is essential for meaningful research of this nature to make progress. It takes 3-5 years for any worthwhile scientific question to be pursued to a significant conclusion on these types of facilities. This is also, coincidentally, the typical time for graduate students to complete an experimental Ph.D. degree. Research time for these pursuits, therefore, needs to be considered in these time units. (2) Currently, the single biggest impediment to basic research on large HED facilities is the limited supply of high quality targets, without which the research conducted will likely not be world class. Given the investment of the overall operation, doing anything less than world-class science makes little sense. (3) Finally, one of the greatest benefits to emerge from basic science on the HED facilities is the training of talented, next generation, young scientists, to carry this field into the future. This requires a stable source of funding to cover the costs of students from start to finish through their Ph.D. degrees.

Table 4.4. Parameters, facilities, and timelines for the Radiative Hydrodynamics Thrust.

Phenomenon	Temperature	Density	Facility	Timeline
Photoionized plasmas	20 – few x100eV	10^{-3}-10^{-5} g/cm^3	Saturn, Z/ZR, NIF	Present - 2014
Radiation dominated dynamics	~200 eV – few x 1000 eV	1-100 g/cm^3	NIF, Z/ZR, Omega + petawatts, other ultrahigh intensity lasers	2009-2014
Expansion opacities	20 – few x100eV	10^{-3}-10^{-5} g/cm^3	ZR, NIF	2009-2014
Radiative shocks	~100 eV	~0.1 g/cm^3	Omega, Z, Nike, smaller HED facilities, Saturn	Present - 2008
Photoevaporation front dynamics	50-100 eV	~0.2 g/cm^3	Omega, Z, Saturn	Present - 2008

5. Opportunities for interagency cooperation

Given the natural overlap between astrophysics and HED experiments in radiative hydrodynamics, there are many opportunities for interagency cooperation. DOE/NNSA is the natural funding agency for the design and execution of experiments on the HED facilities. NASA should sponsor the simulations using astrophysical models and codes, and future observations linking the HED experiments to the astrophysical phenomena. In areas where fundamental theory is required, such as in the generation of ultrastrong magnetic fields on ultraintense lasers, NSF and DOE/OFES should have a contribution.

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4.5 Inertial Confinement Fusion

Achieving thermonuclear ignition in the next 10 years is one of the grand challenges of high energy density physics. Imagine taking the output of the entire global power grid for a few billionths of a second and focusing it with a large laser onto the surface of a hollow capsule no bigger than the head of a pin. Next, imagine filling the capsule with isotopes of hydrogen (deuterium and tritium), then sitting back to watch the action. The capsule responds by imploding at velocities of up to 300 km/s, that is, at speeds approaching 0.1 percent of the speed of light! At peak compression, the temperatures and densities at the center are of order 10^8 kelvin (10 keV) and 100 g/cm^3, with pressures approaching 100 Gbar (~10^{16} P). These conditions mimic those found at the center of the Sun. If the capsule ignites (in the thermonuclear sense), the outcome is a "microsun," for a very brief moment, ~0.1 nsec (10^{-10} sec) spewing forth a miniexplosion of ~10^{19} neutrons and He nuclei from nuclear fusion. While the main reason that this is a grand challenge for mankind is the possibility that fusion will be a major energy source for future generations, such conditions can also be exploited for understanding thermonuclear reaction rates in dense, highly screened plasmas relevant to stellar interiors, and nucleosynthesis of the heavy elements, relevant to supernovae. The pursuit of this "controlled astrophysics in the laboratory" is the routine business of the inertial confinement fusion program in the United States.

Inertial confinement fusion ignition requires that an enormous range of HED physics and technology, including materials properties, compressible hydrodynamics, and radiative hydrodynamics (the topics of the previous 3 sections), be harnessed to ~10 psec, ~10 micron precision. Laser-driven ignition experiments on the National Ignition Facility, currently under construction at Lawrence Livermore National Laboratory, will begin in 2010. A variety of advanced concepts are being explored to increase the probability of achieving high gain by ~2015, which is a prerequisite for considering fusion as a potential future energy source.

4.5.1 Motivating Intellectual Question

Can inertial fusion ignition be achieved in the laboratory and developed as a research tool?

Fusion is the power source of the stars. Inertial confinement fusion ignition on earth has been demonstrated with nuclear weapons. A grand challenge of high energy density physics is to demonstrate ignition in the laboratory in a controlled manner. Inertial confinement fusion is the largest high energy density research area presently being pursued. In inertial confinement fusion, energy from a laser, heavy ion beam or pulsed power machine is coupled to the surface of a spherical pellet containing a deuterium-tritium ice layer. The outer region is heated causing the material to stream away from the surface. This causes the remainder of the shell to be accelerated inwards in a manner identical to the way that the hot exhaust from a rocket causes it to be accelerated. The imploding shell compresses and heats the remaining fuel. If the temperatures and densities are high enough (~100,000,000˚C, 1000 times liquid), the fuel will ignite and a propagating fusion reaction "burn wave" will release thermonuclear energy. The goal is to produce more energy than is used to produce the implosion. This leads to longer range, technically more challenging question, "*Can thermonuclear ignition lead to the power source of the stars being used for economic energy production on earth through inertial fusion energy?*" The primary scientific milestone is to demonstrate inertial confinement fusion ignition.

Inertial confinement fusion research in the United States is almost entirely supported by the NNSA at the present time, with a current plan to begin ignition experiments in 2010 using the National Ignition Facility, a 1.8 MJ, 192 beam laser system currently under construction at Lawrence Livermore National Laboratory. For the NNSA, ICF research and the achievement of ignition contribute to its mission of maintaining the reliability and surety of the U.S. nuclear weapon stockpile without the need for testing. Achieving the ignition milestone will lead to further research aimed at maximizing the thermonuclear yield, and this will, in turn not only benefit the NNSA's missions, but also contribute to scientific goals, such as (1) allowing the use of the intense flux of thermonuclear particles to study fusion physics relevant to nuclear weapons and astrophysical objects, including supernovae; and (2) reducing the driver energy to optimize inertial confinement fusion for energy production.

Conventional inertial confinement fusion, as it is currently being pursued in NNSA laboratories, is analogous to processes that take place in a diesel engine. Diesel fuel is injected into the cylinder and compressed. When it reaches appropriate conditions, it self-ignites, releasing its stored energy. There is a new idea in inertial confinement fusion that works more like a gasoline engine relying on an external spark to ignite the fuel after it is compressed. In this concept, called "fast ignition," a high-energy driver is used to compress the fuel, but an additional extremely high power (petawatt) laser system is incident on the target, converting its energy into fast particles that subsequently heat a small region of the dense fuel, causing it to ignite. This concept offers the possibilities of higher gain than conventional inertial confinement fusion and less expensive drivers for economical fusion energy production. Research in this area is in its infancy, and can be summarized with an additional grand-challenge question. *Will the "fast ignition" concept for inertial confinement fusion lead to higher target gains for the same driver energy investment?*

Each of NNSA's three major compression facilities (OMEGA, Z/ZR, and NIF) are adding, or planning to add, high energy petawatt laser systems to complement their compression systems. NNSA's primary mission for these petawatt lasers is to provide advanced radiographic capability to further understand the conditions created by the HED drivers. They could also be used for fast ignition research. Currently, the largest fast ignition project is in Japan.

4.5.2 Research Opportunities

The inertial confinement fusion program has one overarching goal, the achievement of inertial confinement fusion ignition and moderate gain in the laboratory. A simple definition of ignition in an inertial confinement fusion system is that the energy produced by fusion reactions exceeds the energy delivered to a fusion-fuel-containing target to initiate reactions. Moderate gain implies an output energy a factor of ~10 times the energy required to initiate the reactions. Fusion ignition is demonstrated every day as the power source of our sun and the stars. It has also been demonstrated in inertial confinement fusion systems in the explosion of thermonuclear weapons. It has, however, never been demonstrated in the laboratory. The achievement of inertial confinement fusion ignition and gain in the laboratory will be a major breakthrough, in and of itself, and would lead to a number of research opportunities:

- Studies in support of the nation's Stockpile Stewardship Program;
- Development of high yield ignition targets that could be used to study the origin of heavy atoms in the universe;
- Highly screened nuclear reaction rates relevant to stellar cores
- Development of high gain targets that could be used for inertial confinement fusion energy production.

The first experiments to demonstrate ignition are likely to be carried out on the National Ignition Facility (NIF) starting in 2010. The NIF will be a 192 beam, ~1.6 MJ (million joules), ultraviolet laser system when it is completed in ~2008. It is predicted to achieve ignition in both indirect-drive (x-ray illumination with conversion of the laser light into x-rays in a gold can (hohlraum)) and direct-drive illumination (where the lasers are incident directly on the surface of the target). In either case, the target will consist of a spherical shell enclosing a frozen DT ice layer. Compression of this target will lead to conditions more extreme than those found in the sun, allowing thermonuclear ignition to be achieved.

A number of national laboratories and universities are collaborating to develop the physics of inertial confinement fusion ignition. The two largest facilities supporting this effort at present are the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics and the Z pulsed power facility at Sandia National Laboratories. The OMEGA laser has 60 ultraviolet laser beams arranged in the symmetrical shape of a buckyball (vertices on a soccer ball). It produces 30 kJ (thousand joules) of ultraviolet light. While its primary mission is the development of direct-drive ignition, it has also been configured to support x-ray drive inertial confinement fusion experiments and other high energy density experiments. The Z pulsed power facility can be configured to produce up to 1.8 MJ of soft x-rays that are being used to drive implosions. While neither OMEGA nor Z is expected to produce fusion ignition, they are providing the bulk of the physics basis for ignition plans on the NIF.

Smaller facilities such as the NIKE laser at the Naval Research Laboratory, the Trident laser at Los Alamos National Laboratory, the pulsed power facilities at Cornell University, and numerous other sites are providing additional physics input to inertial confinement fusion research. These sites also provide additional education and training of young scientists moving into this field.

Achieving ignition and gain of at least 10 with the NIF is a high priority for the NNSA. This goal of the inertial confinement fusion program underlies the support of virtually all of the research in this area, including at LLNL, LANL, SNL, UR-LLE, and NRL. In addition, General Atomics provides target fabrication support. Additional NNSA funding is provided to University-based users through the Stewardship Sciences Academic Alliances and the National Laser User Facility programs.

Once ignition is achieved on the NIF a number of new research avenues will open up. As discussed above, these include supernova physics, fusion energy, and fast ignition. These areas are only moderately funded at best and will require additional resources to take full advantage of the exciting scientific potential offered. We are unaware of any funding that is directed towards astrophysical uses of ignition.

The successful demonstration of inertial confinement fusion ignition can be expected to invigorate the study of the feasibility of inertial confinement fusion for fusion energy production. The current research efforts are supported by OFES at a moderate level and, over the past few years, through a congressional mandate to NNSA, the High Average Power Laser Program (HAPL). The OFES support is primarily in the area of heavy ion beam fusion, while the HAPL program supports development of laser-based inertial confinement fusion. The HAPL program is developing two high repetition rate lasers (Electra at NRL and Mercury at LLNL), each of which is a prototype of a module that might be used to develop a full-scale high repetition rate inertial confinement fusion laser system for energy production. It also supports research in target design and a variety of reactor issues, including target injection and optical materials. These programs are making good progress, but are subject to an annual congressional mandate, as NNSA's policy is not to fund research relevant to energy production and the OFES funding cannot currently cover the entire program.

As discussed previously, a relatively recent development within the inertial confinement fusion program is the concept of fast ignition. The concept separates the compression and heating phases of an inertial confinement fusion implosion and has the potential to develop higher inertial confinement fusion gains for the same laser energy or reduce the overall energy threshold for inertial confinement fusion ignition. It requires the coupling of a high-energy petawatt laser systems to inertial confinement fusion compression facilities. The NNSA is funding the construction of the OMEGA EP, a two beam, 2.5 kJ (each) high energy petawatt laser system that will be coupled to the OMEGA laser system at the University of Rochester. In addition, high energy petawatt capability is being developed for the Z machine at SNL and the NIF at LLNL, at least partly with institutional funds. NNSA's primary mission for its high energy petawatt laser capability is to provide advanced backlighting capabilities to its compression facilities that allow diagnostics of the extreme states of matter created on the three facilities. NNSA has stated that its mission does not include fast ignition. There is some funding for fast ignition through OFES. This funding primarily supports experiments on the world's existing high energy petawatt laser systems, Gekko at ILE-Osaka, Japan, the LULI Petawatt at Ecole Polytechnique in France and the Vulcan high energy petawatt laser system at the Central Laser Facility in Great Britain. As high energy petawatt laser systems are developed in the United States, research opportunities will be greatly expanded.

As described above, NNSA provides the primary support for ignition research with OFES providing addition funding for fast ignition and energy applications (not part of NNSA's program). There is little or no funding for applications of ignition. A limitation of this funding scenario, in addition to the overall level, is the concentration of the funding in the National inertial confinement fusion participant laboratories. Both OFES and NNSA provide some funding to universities, the latter through the SSAA Program. Thus, while the facilities have strong funding, a major requirement is the development of university infrastructure to enable education and training of new young scientists to support the nation's goals in this area. Experimental time on the major NNSA facilities is available through the National Laser Users Facility on OMEGA and will be through the programs that are being developed to provide external use opportunities on NIF and Z/ZR. The funding for these programs is not currently planned to be at a level that realistically supports external use. For example, to develop experiments for the NIF, preliminary experiments will be required on OMEGA and Z to validate the designs. There is no national mechanism for achieving this. There is also limited support for the target fabrication and numerical simulation capabilities to design the optimal experiments. NSF, NASA, and DoD have little, or no, role in developing these opportunities at the present time, but certainly could.

The imminent achievement of ignition on the NIF and the development of high energy petawatt capability on OMEGA, Z/ZR, and the NIF will provide a multitude of advanced and highly visible research opportunities. Currently the United States is not ready to take advantage of them. Increased resources for universities, a coordinated national effort, and interagency collaboration will be required to take advantage of these world-leading opportunities.

Specifically, if OFES and NNSA were to develop a cooperative program, the uses of ignition for energy development and the development of fast ignition would be greatly facilitated. This is a natural avenue for collaboration between these two agencies. The potential scientific uses of ignition are limited only by scientists' imagination. This is a fertile, but currently ignored, opportunity for collaborations among NNSA, OFES, NSF, DoD, and NASA. There are many physics issues that could be developed with the extreme HED conditions created by ignition.

In summary, ignition science will be developed and understood on NNSA facilities during the next few years and ignition is expected to be achieved on the NIF in less than 10 years. The question for the nation is whether we will be able to take advantage of the opportunities that this achievement will engender. This requires developing the resources and experience now! It is, therefore, important that U.S. government funding agencies that are not mission-oriented toward stockpile stewardship consider providing funding to enable basic science as well as research on the NNSA facilities that is motivated by applications other than inertial confinement fusion. For example OFES should invest in fast ignition research on the high energy petawatt facilities that will soon be on line at OMEGA and Z-Beamlet, while NSF and/ or NASA should invest in some of the laboratory astrophysics research ideas that can be addressed by the NIF when a gain of 10 or more is achieved, and the requisite preparatory research on Omega, Z/ZR, and other supporting facilities. Development of experiments for the NIF will require significant exploratory research on OMEGA, Z/ZR, and other facilities to effectively use that very limited resource.

In all of these areas, the funding must cover student and investigator support, access to the facilities, including travel, and sufficient computational and target fabrication support to produce high quality science. The funding also needs to be sufficiently stable to develop and sustain university-based programs. These experimental programs would cost, $~1 million/yr over 3 years each, but the payoffs would be immense.

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CHAPTER 5

High Energy Density Science with Ultrafast, Ultraintense Lasers

5.1 Introduction

Recent science opportunities with ultrafast, ultraintense lasers (UULs) have stemmed from recent rapid advances in ultrashort pulse laser technology. Using the technique of chirped pulse amplification, it is now possible to construct "table-top" scale lasers with peak powers of many trillions of watts (TW), pulse durations well under 100 femtoseconds (10^{-13} s) and focused intensity well over 10^{19} W/cm^2. The large scale application of chirped pulse amplification has now enabled construction of lasers with peak power at 1000 TW, or one petawatt. The first petawatt laser was demonstrated in the late 1990's at Lawrence Livermore National Laboratory on the now decommissioned NOVA facility. Currently there are a number of petawatt class lasers under construction around the world. The unprecedented light intensity attainable with these lasers provides extremely unique opportunities in high energy density physics research.

The UUL working group has isolated six frontier opportunity areas, five of which are described in this chapter and a sixth area is discussed in the chapter on NNSA facilities. The HED science areas discussed below include:

1) Laser excitation of matter at the relativistic extreme;
2) Attosecond physics;
3) Ultrafast, high peak power x-rays;
4) Compact high energy particle acceleration;
5) Inertial fusion energy fast ignition; and
6) Warm and hot dense matter (described in chapter 3).

In addition to these science opportunity areas, the UUL working group has come upon a number of findings:

I. Facility needs of the UUL community
While all modern UULs are based on a common technology, namely chirped pulse amplification, a range of short pulse laser designs with pulse energy ranging from .001 J to 1000 J are needed to exploit all the opportunities presented. With limited resources, the portfolio of lasers which could be supported should span a wide range of pulse energies and pulse widths. The working group assessed the needs presented by the science opportunities discussed in the following sections. Table 5.1 presents a potential portfolio of facilities that illustrate the range of lasers which can be used to make progress in the six UUL science areas.

	Relativistic plasmas	Attoscience	Ultrafast x-rays	Particle Acceleration	Fast Ignition	Warm/Hot dense matter
kW class kHz fs lasers ~1-10 mJ/pulse		•	•			
Table top multi-TW lasers ~1 J/pulse	•		•	•		•
100 TW class rep rated lasers ~3-10 J/pulse	•		•	•		•
Compact fs PW ~30 J - 30 fs	•	•	•	•		•
Single shot PW ~100J – 1 kJ	•		•	•	•	•
High energy PW lasers at implosion facilities ~1-10 kJ	•			•	•	•
High energy SPL(>1 J) SPL at accelerator based light sources ~1 – 100 J			•			•

Table 5.1: Suggested national portfolio of UULs. A "•" represents an important application area for such a laser. A "•" represents an application area where such a laser will make a significant impact.

One of the significant findings of the working group was that, at least in the context of petawatt-class lasers, the facilities currently under construction in the United States will be an adequate set of petawatt UULs for the next five to seven years. Instead of further investments in laser facility construction, a long range commitment to operating and making these lasers available to a wide range of science driven users will be a better use of resources in the coming years. One area of laser development where significant investment is still needed, however, is in high *average* power UULs, such as kW class 1-10mJ, femtosecond lasers. The range of petawatt-class lasers currently under development nationwide is illustrated in figure 5.0.1. Here the phase space of lasers as a function of laser energy and pulse duration is plotted and maps the laser parameters needed for some application areas. The plot also shows the major petawatt class laser facilities under construction in the US. This illustrates that a complementary set of lasers are being developed which span the wide range of possible pulse energies and durations.

II. The need for a change in mode from single PI to mid-scale efforts in the UUL community

As the discussion of frontier laser facilities indicates, the state of the art in UUL technology is at the petawatt peak power level and kW average power level. With these new trends in high intensity laser research, traditional single investigator efforts will no longer be adequate to exploit many opportunities. While single investigator research efforts will remain a core aspect of innovation in this field, the lasers needed to conduct research at the frontier are beginning to extend beyond the realm of feasibility of traditional single investigator efforts. Exploiting the new science opportunities will require a new mode of organization. This coordinated approach will be needed to determine just what facilities are needed and to make those that are constructed available to a wide research community. This will require a different mode of research than has been traditional for the high field community, a mode where "mid scale" facilities (i.e. those larger than a table top but smaller than the major ICF facilities like NIF, Z and Omega) play a much more prominent role.

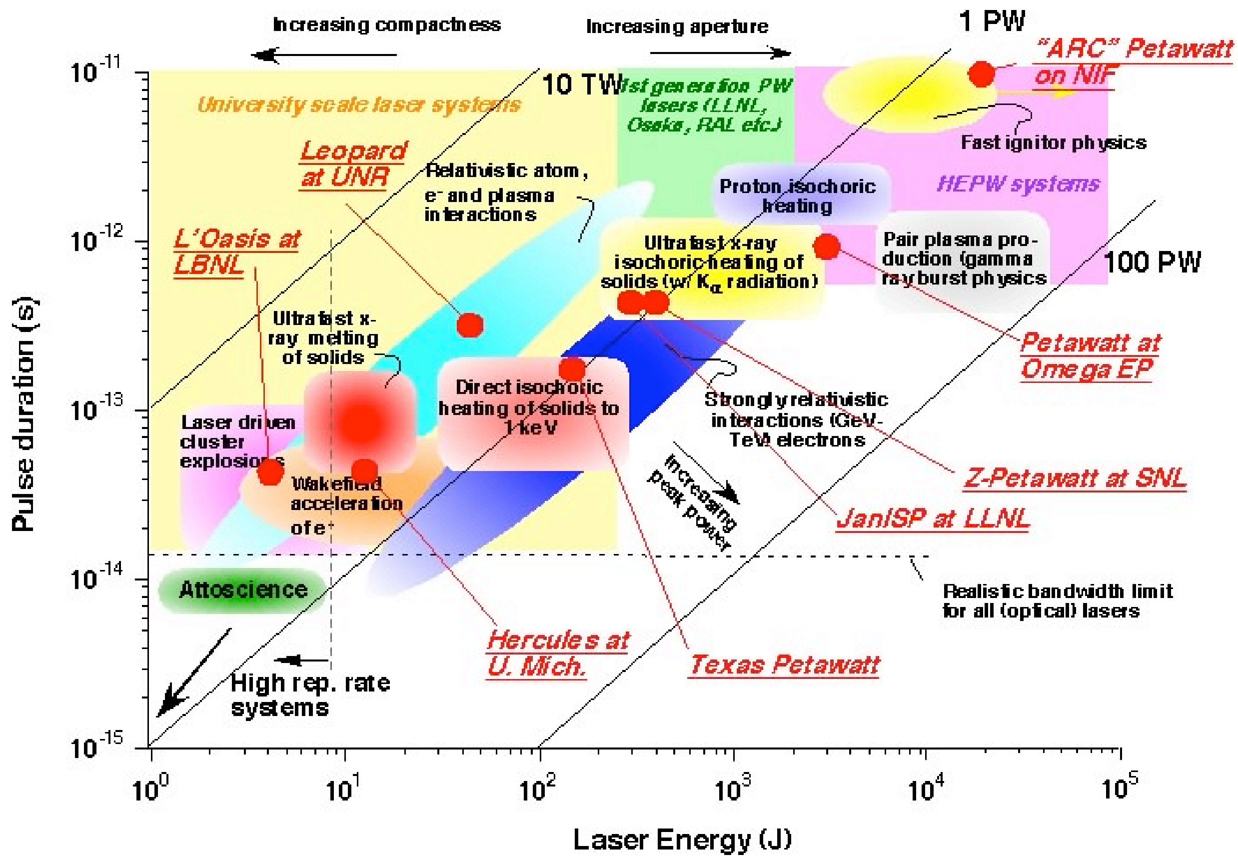

Figure 5.0.1 A pulse energy/pulse duration "phase space" plot of major petawatt class laser facilities being built in the US overlayed on applications. The solid lines designate constant peak laser power.

III. Computational high intensity laser science – the need for massively parallel processing

Computational work is now at the heart of much of the research opportunities discussed below. This indicates that, along with a support for laser facilities, support for computer processing power will be needed to make the greatest progress.

IV. Exploitation of NNSA, DOE SC and NSF facilities

It is clear that maximum progress in UUL based HED science can be made if all of the agencies consider using facilities already under development by NNSA, DOE SC and NSF. This may require agencies to fund experiments on facilities traditionally supported by another agency. For example, many of the petawatt class lasers under development are funded through the NNSA. However, many of the science opportunities of potential interest on these machines may lie in the mission space of the Office of Science or the NSF. Conversely, the large-scale ultrafast fourth generation light source under development by the Office of Science, the Linac Coherent Light Source at the Stanford Linear Accelerator Lab, may be ideal for NNSA applications.

One proposal for how this might be achieved is illustrated in figure 5.0.2. Through the establishment of a cross agency, national High Energy Density Physics Network, the facilities currently under development can be best utilized. This network would be coordinated by an Inter Agency Planning Board which will have representation from the NNSA, the DOE Office of Science, the NSF, NASA and perhaps ultimately AFRL. The network would be structured so that the "mid scale" facilities would not only enable frontier HED science but would also serve as a proving and training ground for scientists which will ultimately conduct experiments at the large NNSA facilities such as NIF Z and Omega. The "mid-scale" facilities absence from the portfolio of US science is a critical missing link for exploiting HED physics opportunities. At the base of the network is the community of single investigators which can use the various resources distributed nationally throughout the network both at other universities and the national laboratories.

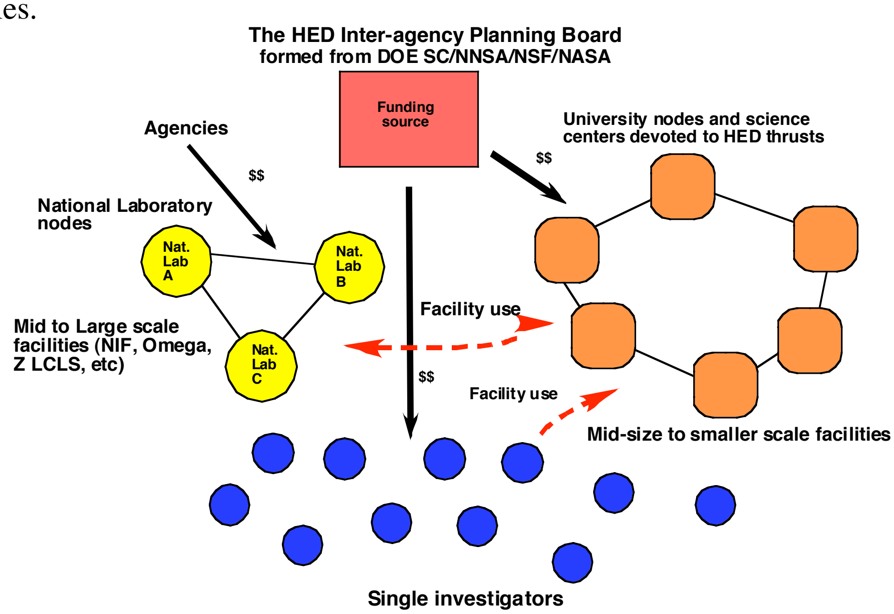

Figure 5.0.2: Schematic of a national network in HED science.

5.2 Laser Excitation of Matter at the Relativistic Extreme

The combination of high energy density drivers (lasers and z-pinches) with high energy petawatt laser systems can be used to create conditions and states of matter that are typically inaccessible in the laboratory. These environments, characterized by ultra-strong magnetic fields (10^9 G and higher) and relativistic energies ($U_p > m_e c^2$), exist only in astrophysical objects and nuclear weapon explosions at present. At intensities between 10^{16} and 10^{20} W/cm^2, the electron's interaction with photons, other electrons, ions and nuclear matter is altered. Above 10^{23} W/cm^2 however, critical tests of quantum electrodynamics – light-light scattering and particle creation – become possible. The ability of a high energy density driver to compress matter and a high energy petawatt laser to heat, or, otherwise transform the target, has the potential to expand significantly, our understanding of relativistic collective dynamics that supports fundamental phenomena observed in the most extreme environments in the universe. Unlike accelerators, ultraintense laser excitation promises the possibility to study in the lab many body systems and macroscopic amounts of matter at the relativistic extreme

5.2.1 Motivating Intellectual Question

- *How do many-body systems evolve in a light field under extreme relativistic conditions where an electron is accelerated to relativistic energies and particle production becomes possible in one optical cycle?*

Super-intense, relativistic laser beams carry light waves with electric field strengths far greater than the internal fields binding electrons to the nucleus. At sufficiently high intensity, not only are atoms literally ripped apart by the huge forces of the light beam, but the liberated electrons themselves acquire an energy which approaches or exceeds their rest energy. Unlike our usual way of describing matter irradiated by light, at these intensities, special relativity must be accounted for in describing the interaction. Exotic relativistic issues come into play including retardation effects, the production of enormous magnetic fields, and plasmas with electrons whose mass varies with time.

At high intensities, where free electrons can be accelerated to relativistic energies in one optical cycle, the orbits of bound electrons in ions will be distorted severely, and the magnetic field of the light will participate in the electron and ion dynamics. Furthermore light-light scattering will become important. As a result, we expect that atomic physics will take on very different character to what we usually think of how an atom acts. Indeed, the optics of such relativistic matter will differ from traditional optics as the change of mass of an electron oscillating at these relativistic velocities introduces a nonlinearity, akin to that usually found only in specially designed nonlinear optical media. This phenomena represents a new era of "relativistic nonlinear optics" with applications that could be a widespread as traditional nonlinear optics has demonstrated over the previous 30 years. Furthermore, the acceleration of many electrons to such high velocity results in the production of truly enormous magnetic fields, with strengths perhaps as mush as a million times higher than a typical household refrigerator magnet.

Again, how matter behaves in such an extreme environment as that present in such a large magnetic field is an open question.

Our understanding of this kind of relativistic matter is only now developing as theories of such many body, relativistic systems are very difficult to formulate. Yet a deeper understanding is important as such matter is thought to rest at the heart of some of the most energetic and enigmatic objects in the universe. So the use of these intense lasers to create laboratory examples of extreme states can shed light on some of the large mysteries of the cosmos. For example, these fundamental relativistic effects play a role in the plasma dynamics associated with cosmological objects such as neutron stars, black holes, pulsars and gamma ray bursts. It is believed that relativistic plasmas exist near black holes and produce copious amounts of anti matter. The use of intense lasers may ultimately allow us to study even these exotic conditions.

5.2.2 Research Opportunities

A detailed understanding of relativistic electromagnetic fields and particle dynamics is central to a vast array of problems ranging from fundamental questions in QED to the properties and dynamics of dense plasmas in intense magnetic fields to the development of new technologies. The threshold for relativistic electron dynamics occurs when $U_p > m_e c^2$ (large ponderomotive energies). Theoretical studies suggest that well below these thresholds (nonrelativistic regime), a new counter-intuitive venue exists where the ionization rate decreases monotonically with increasing intensity – *adiabatic stabilization*. Stabilization, which would affect dynamics in radiation-dominated environments, has been the subject of extensive theoretical study in the nonrelativistic regime. Above threshold ($U_p > m_e c^2$), the nature of stabilization is predicted to change because of longitudinal drift (associated with non-negligible magnetic fields), the effective mass of the electron and retardation effects. The differences above and below threshold provide an opportunity both to probe details of relativistic dynamics experimentally and to develop realistic and reliable models. We point out that while stabilization is consistent with relativistic calculations, current calculations have all been done below $U_p = 2\ m_e c^2$, the pair production threshold for the oscillating electron. Lacking relativistic manybody models, it is unknown how stabilization would change when the pair production channel is open. Experiments are with pulse energies in the 0.01 to 1 petawatt range a required to frame theoretical concepts.

When the photon energy exceeds the rest energy of the electron, relativistic dynamics should come into to play as well. It is not clear if the electron can keep up with the field as the frequency increases, however. What happens above the $2m_e c^2$ limit? Where does the single-particle Dirac wavefunction break down? What new features appear when both $h\nu$ and U_p exceed $2\ m_e c^2$? These are some of the questions that need to be addressed both experimentally and theoretically. Exploiting Lorentz boosts available at heavy ion (RHIC) and electron (SLAC) accelerators, high frequency interactions with atoms and electrons would be possible.

At low frequencies, where the laser has essentially no direct affect on nuclear states, theoretical studies have shown that a strong enough field will enhance β-decay rates. The enhancement, due to an increased phase space into which electrons or positrons are ejected, is coupled to Volkov solutions to the Dirac equation. As with atomic states, direct modification of nuclear states should be possible, especially at high frequencies, at higher intensities. Where is this threshold, how are nuclear processes altered when both $h\nu$ and U_p exceed 2 $m_e c^2$ and what happens when the intensity exceeds 10^{23} W/cm^2 (the limit for direct pair production) are just some of the questions that need to be considered. Petawatt-class lasers and beyond will be required for these studies.

Focused petawatt-class lasers produce large quantities of electrons accelerated to relativistic velocity and these can produce ultra-strong magnetic fields. Magnetic fields of ~700 MG, for example, have been measured in laboratory experiments with a single ~0.5 kJ Petawatt laser beam. Multi-kJ petawatt lasers will produce gigagauss fields and future lasers will avail higher fields. Petawatt lasers at high energy density driver facilities will provide an opportunity to create unique states of matter and to study novel plasma dynamics responsible for fundamental astrophysical phenomena such as gamma-ray bursts, highly polarized gamma rays and photon bubbles. As an example, the decay of super-strong magnetic fields (> 10^{14} G) is thought to power soft gamma-ray repeaters in neutron stars. The interpretation of such phenomena requires an understanding of the physical properties of dense plasmas in intense magnetic fields. Wake-field accelerated electron beam pulses exiting a target foil plasma generated with high magnetic fields (10^8 Gauss) resembles conditions of the atmospheric plasma at a neutron star surface with magnetic fields exceeding 10^8 Gauss. The atmosphere of a neutron star may consist of condensed matter (molecules, metal grains forming droplets) and QED effects (e.g. vacuum polarization) may be important. The strong magnetic fields change the properties of atoms, molecules and condensed matter. The plasma emission and absorption spectra relevant to neutron star atmospheres will be affected significantly.

High-energy petawatt laser beams interacting with matter create intense particle beams that, in turn, can heat a compressed plasma to high temperatures, generate extreme magnetic field strengths, or create copious amounts of anti-particles (positrons). The copious production of anti-particles may allow the creation of electron-positron plasmas that may hold the key to gamma-ray bursts. There are a variety of question that could be addressed including: Can intense bursts of thermal electron-positron plasmas be created and studied in the laboratory? Can relativistic jets and shocks be generated from such an electron-positron fireball in the laboratory? Are the dynamics of such relativistic jets and shocks fundamentally different from those of their nonrelativistic counterparts? Can conditions relevant to radiation-dominated black hole or neutron star accretion disks be generated and investigated?

Probing the environments established by short-pulsed high magnetic and electric fields is possible via ion beam deflection, spectroscopy of hyperfine-structure/Zeeman splitting and level shifts (higher order Stark effect) and field ionization. Faraday rotation (rotation of polarization plane of linear polarized wave traversing a magnetized dielectric medium) and harmonic generation of photon beams could also be observed. The atomic structure of high Z atoms/ions in strong magnetic fields could be studied in magnetically confined plasmas with laser spectroscopy (e.g. Landau levels) or via spectroscopy of the Zeeman/hyperfine splitting in fast (MeV to GeV) highly ionized atoms interacting with an (short pulsed) ultra-high magnetic field (10^8 Gauss). The dynamics of atomic structure, level population, shifts and decay can be used to infer the high field conditions in the time domain. Particle acceleration mechanisms, known to be of crucial importance in cosmological objects such as supernovae remnants, pulsars, and black holes with extreme field conditions exist, could be explored in the strong electric and magnetic fields in dense plasmas produced by intense laser pulses. Intense, relativistic electron beams lead to synchrotron radiation, inverse Compton scattering, bremsstrahlung, and recombination transitions. Each of these elementary radiation processes show distinct photon polarization features that could be exploited to probe our understanding of relativistic particle dynamics under the presence of ultra-strong electro-magnetic fields.

Research Tools and Facility Requirements: Three types of centers are required to explore the scientific forefronts of relativistic laser-atom and laser-electron physics. The specialized facilities necessary for studying threshold relativistic dynamics would house 10-100 TW laser systems. The same facility would also house petawatt class systems and beyond to explore manybody QED issues. Centers investigating the fundamental physics at extreme interaction energies or exotic matter are also needed. A unique Center concept would be to collocate a petawatt-class laser at a relativistic particle source (RHIC, SLAC). This would allow access to deeply bound ions (highly stripped) and the relativistic energies would provide a Lorentz boost in intensity and time dilation in the particles frame. Finally, to focus on relativistic plasma investigations petawatt-class laser systems would be need at the nation's stockpile stewardship drivers (OMEGA, Z, and the NIF). Centers would benefit from a broad intellectual pool of scientists and engineers, both in experiment and theory, sharing a common goal of addressing the complex integration of advanced concepts. Such Centers would profit not only from local expertise but a network of external users.

Timeline and Resource Requirements: In the next half-decade these facilities will become available for the study of extreme states of matter research.

Opportunities for Interagency Cooperation: The physics investigations sketched in this section fall under the stewardship of NSF, DOE, NASA and NNSA. The NNSA's large high energy density facilities are adding or planning to add high-energy petawatt laser capability. To study the compelling physics issues will require cooperation and involvement of all four communities and a workforce larger than the staff of NNSA's laboratories, with the resources to develop the personnel and techniques to take advantage of the facilities. This is a clear opportunity for collaboration. In particular, NNSA needs to develop a realistic strategy to bring a broader community into these problems of wide interest. Without the development of a broad research community, the opportunities presented will be missed. The development of this community requires the training of scientist as well as the resources required to develop the appropriate numerical and experimental techniques.

5.3 Attosecond Physics

The new millennium witnessed the culmination of a decade of work where the measurement and manipulation of sub-femtosecond or *"attosecond"* processes (1 as = 10^{-18} s) became possible in many research laboratories throughout the world for the first time. These UV/XUV light pulses are generated either by nonlinear frequency conversion of an ultra-short infrared pump pulse or Fourier synthesis of broad bandwidth radiation. The physics of the generation of these pulses is based on nonlinear, nonperturbative (intense field) laser-atom interactions. The crucial element for all attosecond pulse generation is the control of the spectral phase necessitating both analysis and synthesis of laser pulses and the XUV radiation they generate. The scientific importance of breaking the femtosecond barrier is obvious: the time-scale necessary for probing the motion of an electron(s) in the ground state is attoseconds (atomic unit of time ≡ 24 *as*). The availability of such attosecond pulses would allow, for the first time, the study of the time-dependent dynamics of correlated electron systems by freezing the electronic motion, in essence exploring the structure with ultra-fast snapshots, then following the subsequent evolution using pump-probe techniques. The explicit dynamics of excited states of atoms could be followed characterizing, for example, processes like autoionization or non-adiabatic transitions during atomic collisions. These pulses also would allow investigations of the dynamics of bond breaking and formation during chemical reactions. Such studies would lead ultimately to developing new more fundamental methods for the complete quantum control of electron dynamics. Although the scientific impact is unquestionable large, the realization of these sources pose significant challenges.

5.3.1 Motivating Intellectual Question

- *Can physical and chemical processes be controlled with light pulses created in the laboratory that possess both the intrinsic time- (attoseconds, 1 as = 10^{-18} s) and length- (x-rays, 1 Å) scales of all atomic matter?*

In stop-action photography, the speed of the shutter or the flash of a strobe light freezes a moving body on film. If the photograph wishes to stop the motion of a speeding car on film, a shutter speed of a millisecond (1/1000th of a second) will suffice. Any exposure time longer than this will smear the image of the car on the film. Harold Edgerton (1903-1990) at MIT pioneered the use of fast strobe light photograph to study the motion of even faster objects. Using a fast flash of light in place of a mechanical shutter, Edgerton was able to freeze events on the microsecond (1 billionth of a second) timescale. His photographs of a bullet penetrating a balloon or the beautiful symmetry of a *splash* caused by a single drop of milk have achieved the stature of modern art. Edgerton's photographic technique goes beyond artistic beauty and is also a widely used scientific probe of the motion of moving bodies. For instance, the real-time photography of a controlled car collision coveys vital information for safety and performance engineering.

Obviously Nature contains different timescales for motion and consequently needs different "tools". Consider the motion of a single H_2O molecule in a filled water glass.

The molecule is tumbling on a picosecond (1 ps = 10^{-12} s) timescale. On a faster timescale (down to 10^{-14} s), the atomic nuclei of hydrogen and oxygen of the water molecule also vibrate and bend relative to each other. Scientists have studied this motion in depth since the late nineteenth century by unraveling the mysteries contained in the molecule's spectrum of emitted light. But the last quarter of the twentieth century has seen a revolution in time-resolved spectroscopy, with the advent of ultra-fast laser pulses. Not unlike Edgerton, scientist now had a super-fast shutter.

Using the technique of 'pump–probe' laser spectroscopy, the experimentalist is able to initiate (pump) and watch (probe) the motion of molecules in real time with a resolution of a few femtoseconds (1 fs = 10^{-15} s). This has not only resulted in a direct measure of how molecules move during a chemical reaction but, perhaps more importantly, it has opened up a new school of thought that views the quantum world in terms of moving 'wave packets', representing the evolution of quantum-mechanical amplitudes and phases. In 1999, Ahmed Zewail was awarded the Nobel Prize in Chemistry for his seminal contributions to this field of femtochemistry.

Although the application of femtosecond light pulses is still a vibrant scientific tool, they cannot freeze every aspect of atomic motion that is relevant in the structure of matter, just as a slow shutter fails to capture the details of the moving body. The frontier in ultra-fast spectroscopy is the study of the motion of electrons bound inside the atom, in orbits close to the nucleus. This new scale is defined by the time it takes the electron in the first Bohr (innermost) orbit of the hydrogen atom to complete one turn around the proton. The period of this orbit — 24×10^{-18} s, or 24 attoseconds — is at least a factor of a hundred shorter than the duration of the shortest laser pulse.

The beginning of the new millennium witnessed the first observation of light with durations in the attosecond timescale, the shortest bursts produced in the laboratory. Although at its infancy, the emergence of attosecond pulses could have as profound an effect on understanding electron motion (i.e., the ability to probe the dynamics of correlated electron motion and of bond formation and destruction), as femtosecond pulses had on molecular dynamics. This, in fact, will allow the most fundamental characterization of the behavior of all phases of matter and usher in a new discipline in science, attophysics.

5.3.2 Research Opportunities

Ultraviolet optical pulses less than one femtosecond long have now been produced, opening the field of attosecond science and technology (1 attosecond ≡ 10^{-18} s). Realization of attosecond pulses would provide the shortest electromagnetic pulses known to man. These sources constitute the first direct probe acting on timescales characteristic of the evolution of electronic wave functions in atoms and molecules, essential freezing all motion. The development of this capability will have tremendous impact in many disciplines of physics, chemistry and material science. Fundamental questions concerning the stabilization of atoms and ions against photoionization, the evolution of complex wave packet states, electron transfer in the condensed phase, and fast electronic processes in solids could be addressed in the time-domain. Furthermore, the ability to control electronic motion, which is the basic component in the structure of any material, allows the possibility of producing new states of matter and new materials.

Attosecond science is enabled by technological advances in the ability to sculpt precisely the electromagnetic field. Control of the intensity (number of photons), phase and wavelength open many new, challenging areas for study. Ultra-high power pulses can be used to generate intense, ultra-short pulses with wavelengths from the visible to x-rays through a variety of processes such as harmonic generation, x-ray lasers and other non-linear processes. These pulses can be used to drive coherent quantum processes in regimes where the underlying dynamics can be directly followed.

Attosecond probing of the quantum dynamics of atoms, molecules and condensed materials can be accomplished using pulses generated by the interaction of short, high-energy laser pulses with a non-linear medium. In essence by making photons from photons, specific pulse lengths and wavelengths, both substantially shorter than those of the incident laser pulse, can be produced. Although these processes tend to be inefficient, the understanding of laser-atom interaction dynamics achieved over the past decade has led to orders-of-magnitude improvements in conversion efficiencies and pulse duration. Computer control of pulse generation can achieve optimization through feedback loops in the production of a desired product state. These studies have led to many advances in nonlinear optics and in the ability to guide electron-photon and electron-electron interaction dynamics.

Studies of complexity in simple quantum systems is an enormously important research area as the understanding acquired can be extrapolated to even more complicated dynamical processes. The flexibility of the coherent pulses created using high-energy sources offers the capability to completely represent the dynamics of the processes of interest. The freedom available in selecting the wavelength, pulse shape and energy and the high repetition rates and large bandwidths will allow the continuous examination of any quantum dynamical process. Attosecond pulses can be used to freeze and probe evolving electronic charge distributions, providing a series of snapshots of the state changes as they progress. This provides a completely new window on the interaction dynamics of electrons that in turn drive the changes in structure in multi-atom systems. A simple example for addressing this challenge would be to probe the dynamics of internal conversion within a molecule that lead to a new electronic configuration and structure of the molecular system. A direct probe of the localized crossing of the molecular potential energy surfaces can thus be achieved.

Attosecond pulse research includes pump-probe studies of excitation and subsequent evolution of quantum-dynamical processes; quantum control of state populations and therefore structural evolution; and direct probing of electron correlation. Investigations of multiphoton core-hole (hollow atom) production can provide simple, yet detailed pictures of the correlated electron responses by following the subsequent relaxation dynamics.

Finally, the field of attoscience, combined with techniques from control of quantum systems using shaped light pulses should enable scientists to control the evolution of electron wavefunctions in high fields. Very practical applications such as the design of more efficient and shorter wavelength x-ray sources might be expected to ensue from this research.

Research Tools and Facility Requirements: Attosecond science will be enabled by a wide variety of approaches and facilities. To date, progress has been made by small research groups working in small collaborations, and much work remains to be done by such small groups of experts. Centers will enable the exploration of new regimes in attosecond science, such as the generation and application of very high energy attosecond pulses, or exploration of attosecond physics in relativistic regimes. Such experiments have not been feasible to date. The specialized facilities required for these experiments would be 10-100 TW laser systems for studying attosecond pulses in the relativistic regime and high repetition rate, high average power TW-class lasers for hyperfast (attosecond) pulse generation. These Centers would benefit from a broad intellectual pool of scientists and engineers, both in experiment and theory, sharing a common goal of addressing the complex integration of advanced concepts. Such Centers would benefit not only from local expertise but a network of external users. Collocation of some Centers near major DOE light source facilities will enhance current capabilities and provide a knowledge base well aligned with the missions of major facilities.

Timeline and Resource Requirements: A variety of funding sources ranging from funding for small scale sources, large scale facilities, individual small grants, mini-consortia or networks, and large scale centers, will be needed to explore these scientific frontiers and to maintain international competitiveness. The area of attoscience is fast-moving and already emerging – therefore it is important that funding in this area start immediately.

2005-2006: Establish working XUV attosecond light sources based on high harmonic generation, metrology and experimental end-stations.
2005-2010: Investigate schemes for pushing the attosecond frontier into the x-ray regime.
2007-2012: Initiate a science-driven program in attophysics on complex electronic dynamics.
2006-2009: short-pulsed petawatt enables investigations of attosecond pulse generation in the relativistic regime.

Opportunities for Interagency Cooperation: Attosecond pulse generation, and the science it enables, defines an emerging area of optical physics with goals that are aligned with Basic Energy Science's (BES) desire to maintain leadership in ultra-fast x-ray science. Attosecond light pulses offer a leap in time-scale beyond those being pursued on large-scale accelerator-based facilities. These tabletop sources will open new avenues of science while complementing and directly contribute to the efforts at the large-scale facilities. Parallel efforts on tabletop and accelerator sources could someday merge and give rise to new vistas in the optical sciences. The physics and application of attosecond generation also provides a unique opportunity for NSF funding. Centers based on high average-power tabletop sources and a multi-institutional network of users will provide NSF a cost effective means for maintaining international competitiveness in this forefront interdisciplinary science.

5.4 Ultrafast, High-Peak-Power X-rays

In the latter half of the twentieth century x-rays have become a powerful and routine probe for determining the structure of matter. The start of the new millennium could trigger a renaissance in x-ray sources and the science it enables. At the heart of this resurgence is the development of x-ray sources, dubbed 4^{th} generation sources, that emit intense bursts of light. In addition, novel laser-based sources are being developed that can provide a compact platform for x-ray science in comparison to large-scale synchrotrons. These novel sources include high harmonic generation, Thomson scattering from electron beams, betatron radiation from electron beams in plasma, and K-shell emission from solids and culsters, The impact of these sources on science is significant since the changes in the structure of matter can now be probed in real time. The genesis of ultra-fast x-ray could have a more diverse impact on multiple disciplines of science than ultra-fast lasers had on chemistry, which produced a Nobel Prize in chemistry in 1999. Soon dynamic studies and single molecule imaging of complex biological molecules will be possible. The emergence of these sources will also allow the study of the intense laser-matter interaction in a new realm. Application of nonlinear optics in the x-ray regime will enable new spectroscopic probes of matter and nanoscale resolution. Unlike any current capabilities, the inner shell electrons will react to the high frequency field while the high intensity will quiver the valence shell. Furthermore, some of these sources may have the ability to produce light pulses with both the atomic length (Angstrom) and time (attosecond $\equiv 10^{-18}$ s) scales. These would be an unprecedented probe of matter that "sees" both the molecular framework and the motion of the electrons.

5.4.1 Motivating Intellectual Questions

- *Can intense, ultra-fast x-rays become a routine tool for imaging the structure and motion of "single" complex bio-molecules that are the constituents of all living things?*

X-rays are a special type of light that can penetrate matter and reveal details not visible to the human eye. Almost everyone has experienced the medical applications of x-rays for uncovering broken bones or dental decay. However the application of x-rays have had an even more profound affect on society by uncovering the basic structure of matter. X-rays were an essential tool that revealed the double helix structure of DNA, the fundamental molecular code of all living things. Today national facilities known as synchrotrons provide x-rays for a plethora of scientists in biology, chemistry, material science, medicine and physics. Unlike other current days tools, x-rays allow the researchers to "see" more directly the position and type of atoms that make up the complex architecture of a macromolecule. Without this extraordinary tool many of the modern day marvels that impinge upon everyday life due to advances in material and the biological sciences would not exist.

However there is a limitation imposed by current day x-rays sources. For one, the intensity or brightness of the x-ray sources are weak compared to other well-known light sources like lasers. This would be analogous to taking a photographic in a dimly lit room, although the photo could be aesthetically pleasing in reality a great deal of the detail of the object is obscured. The architecture and the role these complex bio-molecules play in biology are contained in the details. In order to circumvent this "lightning" limitation, scientists must generate a large quantity in a very specific arrangement of these bio-molecules in order to get a good enough picture. In fact, only a small fraction of the bio-molecules relevant to life have had their structure determining and researchers spend countless years just trying to make enough proper sample for any one bio-molecule.

The future promises to bring extraordinary x-ray sources that are so bright that pictures of bio-molecules can be taken of a "single" molecule. The implications are that every bio-molecule can have their structure determined without the costly need in resources and time for complex synthesis of viable samples. One large-scale facility currently being constructed is the x-ray free-electron laser (X-FEL) at SLAC. The basic idea is that the X-FEL brightness is sufficient to illuminate properly only one bio-molecule, and from that single picture the architecture and makeup of the constituent atoms can be determined. This alone would be an extraordinary goal but the X-FEL holds an additional promise. Unlike current synchrotron x-ray sources, the X-FEL light will also produce a very short (ultra-fast) burst of x-ray light. In fact, the burst is shorter than the movement of the atoms making up the bio-molecule. Consequently not only will the X-FEL allow scientists to determine the architecture but also watch the architecture change with time. In biology, many of these complex molecules are microscopic motors or machines who can change their shape and as a result their biological function. The extraordinary characteristics of the X-FEL light will allow us to watch these machines in action.

- *Can nonlinear optics be applied as a powerful, routine probe of matter in the XUV/x-ray regime?*

In 1905 Einstein showed that matter exposed to light can be excited by the absorption of a single quanta or photon. This work earned him the Nobel Prize in physics in 1921 for the discovery of the linear photoelectric effect. This description of light-matter interaction was sufficient for describing the majority of laboratory observations made in the first half of the twentieth century but in 1960 a reformulation of this basic principle occurred with the invention of the laser. Lasers provided the scientists with light sources with unprecedented brightness and special characteristics. The laser was so bright that scientists found that exposing matter to it could not only result in absorption of one quanta of light but also many quanta all at once. This observation was the genesis of the field of nonlinear optics and its impact on science was recognized by the 1981 Nobel Prize in physics for Bloembergen and Schawlow. For the past forty years nonlinear optics has developed into an important tool for scientists in all facets of science and medicine. For instance, by combining two laser photons together, scientists have developed new types of microscopes, with higher spatial resolution than possible with a conventional microscope. New, highly sensitive methods for chemical sensing also rely on combining many photons together as they interact with matter. Unfortunately current laser technology has limited the application of nonlinear optics to visible or near-visible wavelengths. Traditional nonlinear optics is limited to low laser powers and intensities so as to avoid damaging the optical medium.

At ultrahigh laser power and intensities, however, new x-ray sources are being developed based on the nonlinear optics associated with free electrons. These free electrons can be those in an electron beam, or those in a plasma produced from ionizing a gas, cluster, or solid. For the case of an electron beam, this could use conventional RF technology or novel laser-plasma acceleration. Betatron radiation from electron beams in plasmas can provide a novel source of short-pulse, hard x-rays. Free electrons can emit short pulse x-rays by Thomson scattering from an intense lasers or by recombination with nuclei. Free electrons interacting with ultra-intense lasers and can extend the field of nonlinear optics, for the first time, into the x-ray regime. Just as with the invention of the laser, this advance could signal a new vista in nonlinear optics impacting both fundamental and applied science.

5.4.2 Research Opportunities

The genesis of fourth generation light sources capable of producing intense, ultra-fast burst of x-ray radiation ushers in a new realm in x-ray science. The technical advances are coming from both laboratory-scale terawatt-class ultra-fast lasers and large facility accelerator-based free-electron lasers. The intensity gives the experimentalist access to an unexplored realm of the light-matter interaction enabling for the first time x-ray nonlinear processes, non-perturbative atomic response and possibly single molecules x-ray imaging. The ultra-fast capability of these sources broadens the power of x-rays from just a probe of static molecular structures and moves it into the time domain. Equally compelling is that these sources will revolutionize ultra-fast science by defining a new record in pulse duration down to the atomic time-scale (attosecond $\equiv 10^{-18}$ s), surpassing current femtosecond sources by three-orders of magnitude. Ultimately a new vista in x-ray science can emerge with light pulses with the atomic length-scale for probing structure and the atomic time-scale for watching the electronic motion.

This emergence of this technology will have a broad impact on many facets of science[1,2] including materials, chemistry, biology and high-energy density physics. The coupling of these abilities with ultra-intense, ultra short laser sources will provide a powerful probe and unique driver in HEDP. Modern ultra-intense, ultra short laser can create extreme material states, corresponding to solid density materials at a few eV energy and 10-100 G's of pressures. Creation of materials in this "warm dense matter" (WDM) regime is of fundamental interest since materials in this regime falls in between "standard" condensed matter and "plasma" descriptions of mater. The creation of WDM material, together with the use of ultra-short x-rays to probe their initial properties, will provide important experimental data for developing "equation-of-state" description of highly excited materials. Importantly, the subsequent evolution of WDM material (which occur upon expansion of these states as associated with ablation) will provide an important opportunity for studying phase transitions kinetics. WDM states typically correspond to materials driven to the "supercritical fluid" regime of a phase diagram. The subsequent relaxation upon expansion promises an important opportunity to study materials in the vicinity of liquid-gas (L-G) critical points. Here a material can be driven to the spinoidal region of the L-G phase space where a homogeneous material phase is unstable and phase transition kinetics are not well understood. Further metal-insulator transitions can be expected to occur upon expansion of a supercritical fluid. Time resolved x-ray spectroscopy offers a novel technique to study the relative rates of spatial (Wilson-Bloch Mechanism) separation and electron correlation (Mott-Hubbard Mechanism) effects in metal-insulator transitions. Ultra short pulse, high power fluxes of E > 10 keV x-ray photons are essential for the imaging of high energy density plasmas. These plasmas range from those that will be produced on the National Ignition Facility (NIF), to those of the x-ray source itself. Since these plasmas evolve on fast timescales ~ 100 fs and achieve densities many times that of solid materials, both coherent and incoherent x-rays will be needed: Incoherent x-rays will make possible < 100fs time-resolved backlighting measurements (radiography) and coherent x-rays will permit interferometry, yielding plasma structural information on unprecedented time and space scales. Although there are current efforts using high intensity, short pulse lasers to provide short pulse x-rays for materials studies, virtually no progress has been reported on understanding the x-ray pulse structure. Since this pulse structure is determined by the laser-driven plasma dynamics itself, it is important to measure and understand the very plasmas that are creating the x-rays. A thorough understanding of the roles of resonance absorption and laser acceleration (wakes versus. direct ponderomotive acceleration) in generating the hot electrons for target impact will be aided by imaging of the plasma density structure through backlighting with auxiliary short pulse x-rays.

At lower excitation, ultra short x-rays can play a unique role in probing transient structural dynamics in systems of chemically and biochemical importance. Transition state chemistry (understanding intermediate chemical structures) is an important scientific frontier as evidenced by the 1999 Nobel Prize in chemistry, awarded for the use of visible light to probe the transition state. Visible light, however, provides only indirect information regarding structure and obtaining direct structural information via x-ray diffraction and absorption represents an important scientific frontier in the study of chemical and biochemical reactions. Furthermore, if the time-scale of these intense x-ray sources is short enough (≤ 5 fs), it maybe possible to image[3] "single" complex macromolecule, e.g. proteins, thus circumventing the need for crystallization. Recently, two groups[4,5] reported the formation of attosecond light pulses in the UV/XUV spectral region. Although at its infancy these two reports open a new field of research at the atomic time-scale called attophysics. Furthermore, there does not exist any fundamental barrier for implementing these schemes at shorter wavelengths, e.g. x-rays. Attosecond physics has the potential for providing the first direct probe of electronic motion in atoms and molecules. Attosecond pulses could have as profound an effect on understanding electron dynamics (i.e., the ability to probe the dynamics of excitation, autoionization and other correlated electron motion and of bond formation and destruction), as femtosecond pulses had on molecular dynamics. This, in fact, will allow the most fundamental characterization of the behavior of all phases of matter.

Nonlinear optics in the short wavelength regime could explore a number of important fundamental questions. For example, the process of kicking electrons out of inner shells of atoms (inner, K- and L-, shell photoionization) has been studied extensively in the high frequency, weak-field limit using conventional x-ray sources. However an intense x-ray beam can promote multiple inner shell photoionization via multiphoton excitation. The production of multiple inner shell vacancies is a direct result of electron correlation and would provide unique information than that available from other studies such as heavy ion impact. An important consequence of multiple inner shell vacancies is the possibility of creating population inversions that may be exploited as gain medium for x-ray lasers. Short wavelength nonlinear optics, for example, could be exploited for producing more exotic forms of light, e.g. sculpted x-ray pulses, and even shorter wavelengths.

As a second example, it would be possible to probe the response of matter when the light intensity is very high and the wavelength is so short (or the frequency so high) that the electron can no longer follow the oscillating electromagnetic field. Calculations suggest that the ground state of atoms will become greatly distorted, responding essentially to the cycle-averaged potential field. These new exotic structures have been studied extensively theoretically with the surprising result that the system becomes more immune to ionization as the intensity increases. Experimental verification of this atomic *stabilization effect* is awaiting the creation of sufficiently intense, coherent short wavelength sources. Exotic structures are predicted to occur in multi-electron, and multi-atom systems. Their electron- and photoemission properties will differ very dramatically from those being studied presently with longer wavelength lasers.

• ***Research Tools and Facility Requirements:***
The research tools for advancing ultra-fast x-ray science can be categorized into laboratory-scale laser-driven and accelerator-based facilities. Although different in physical scale, the technical complex for each does require the resources and infrastructure of a facility concept. The laboratory-scale x-ray sources can be located at university or national laboratories Centers while the accelerator-based sources require a national laboratory environment.

Laboratory Scale Centers: These x-ray sources are produced by state-of-the-art ultra-fast laser systems. In all cases, the laser systems should be capable of driving the x-ray source of interest and initiate some physical or chemical process, e.g. plasma formation. Two main categories of laser driver will be needed for different classes of experiments. For experiments requiring high brightness, hard x-rays low repetition rate multi-terawatt or petawatt class lasers are needed for driving incoherent x-rays from gases, clusters, solids, or electron beams. Novel electron beam technology can be used based on laser-plasma acceleration. High-average power (100 W) ultra-fast (5 fs) sources are better suited for experiments requiring the shortest time-structure, coherence and high duty cycle. Furthermore, attosecond sources would not only need the characteristics of the high average power lasers but would greatly benefit from the development of drive lasers operating at wavelengths longer ($\lambda > 1$ μm) than existing CPA titanium sapphire or glass laser systems. In this case the recent advances for arbitrary wavelength operation of optical parametric chirped pulsed amplifiers (OPCPA) becomes a very attractive alternative.

Facility Scale Centers: In recent years, the generation of multi-gigawatt x-ray pulses have become a near reality with the development of single-pass free-electron laser (FEL) concepts. Depending upon the X-FEL scheme fully coherent femtosecond pulses with extreme peak powers can be generated. Two projects are underway in the US and Germany. The LCLS, located at SLAC, will be operational in 2009 and capable of producing 10 GW output at 15-1.5 A. The pulse duration of the LCLS will be sub-femtosecond (≤ 200 fs) but potentially as short as a few femtoseconds. The TESLA X-FEL in Germany has similar specifications to the LCLS but a slightly delayed construction schedule. Both these projects will produce unprecedented x-ray intensity exceeding current sources by many orders (10^5) of magnitude.
Collocation of High-Powered Lasers: To maximize the impact on HEDP science the accelerator-based X-FEL should have synchronized terawatt-class, or possibly petawatt-class, lasers located at these facilities. The high-powered lasers could form plasmas that could be probed by the ultra-fast x-ray beam or the laser could interact with the primary high peak current electron beams. The barrier towards increased utilization has been a cultural difference between the electron- and optical based communities. Establishment of autonomous laser center(s) collocated with accelerator-based facilities could significantly enhance the scientific agenda of these facilities, as well as independent scientific contributions.

• ***Timeline***.
2005-2007: Begin exploratory investigations on existing ultra-short x-ray venues e.g. SPPS at SLAC and addressing critical issues for LCLS operation, e.g. timing & x-ray optics.
2008-2010: Demonstrate the viability for nonlinear x-ray optics.
2008-2012: Initiate a science program in for addressing single molecule imaging. and x-ray nonlinear optics.

• ***Opportunities for Interagency Cooperation:***
Intense ultra-fast x-rays will provide extraordinary opportunities for interdisciplinary collaborations and thus a natural circumstance for interagency collaboration. The LCLS X-FEL project is under the auspices of DOE/BES but the project could impact the science thrust of DOE/NNSA, DOE/OFES, NSF and NIH. A Thomson x-ray source based on scattering from a laser-plasma accelerated electron beam has interest to both DoE/BES and DoE/HEP. A Center focused on the production and application of attosecond x-ray pulses would impact both NSF and DOE/BES science mission. While laser-driven x-ray sources located at NIF or LLE will be relevant to NSF, DOE/NNSA and DOE/OFES.

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5.5 Compact High Energy Particle Acceleration

Current UULs can accelerate particles to relativistic velocities. They can do this directly with the strong fields associated with high focused intensity, or through the creation of fields in plasmas. Great promise now exists of the acceleration of particles by lasers in both cases. Wakefield accelerators have demonstrated electron beams from gaseous targets with energies in excess of a 100 MeV and similar energies have been observed in the acceleration of protons from thin solid targets irradiated at relativistic intensity. Acceleration gradients in excess of 100 GeV/m (3-4 orders of magnitude beyond conventional RF accelerator technology) have been achieved but only over mm distances. Extending the acceleration length to cm or greater distances raises the possibility of a future class of compact high-energy accelerator for university scale research. If the acceleration length could be scaled to meter or greater distances laser-plasma acceleration could be the basis of a future ultra-high energy accelerator (>1TeV).

5.5.1 Motivating Intellectual Question

- *Can ultra-intense ultra-short pulse lasers be used to develop compact GeV to TeV class electron and or proton/ion accelerators?*

Particle accelerators have broadly impacted many branches of science and technology from the esoteric to practical. For example particle accelerators are currently being used in particle physics, material science, structural biology, nuclear medicine, fusion research, transmutation of nuclear waste, cancer therapy, and food sterilization. The ultra-high electric fields generated with UULs can accelerate charged particles to super-fast speeds in ultra-short distances. Unfortunately, these fields are transverse to the direction that a relativistic particles moves, so there is a limit to how much energy can be gained. However, these fields can be coupled to a plasma wave whose electric field is longitudinal. This will lead to a new generation of compact, highenergy, short pulse and low emittance accelerators. Given the impact of previous accelerator technologies, this new form of particle accelerator could ultimately have far-reaching consequences.

Laser driven plasma acceleration has provided the largest recorded terrestrial acceleration gradients, ~300 GeV/m, which are 3 to 4 orders of magnitude above the breakdown fields in conventional accelerators. However, these gradients have only been achieved over a fraction of a mm. Extending the acceleration distance by guiding the laser over several 100's of Rayleigh lengths or at least a cm is a major challenge. In laser driven acceleration of electrons a high peak power (Terawatt to 1 Petawatt) short pulse (10's to 100's of femtoseconds) are focused into a gas or preformed plasma . The radiation pressure of the laser drives up space charge plasma waves. The radiation pressure is ~10 Gbar while the energy density of the plasma wave corresponds to pressures in the 1-10 Mbar range. Furthermore, injecting electrons into the space charge wave and accelerating them while maintaining a small energy spread and small emittance is also a great challenge. These compact accelerators can accelerate bunches of electrons with nano-Coulomb's of charge and with dimensions of 5 μm^3. If such a bunch has an energy of 1 GeV this corresponds to an energy density of 10^{16} J/m^3 or 100 Gbar. Generating such a bunch via the fields of the plasma wave is a tremendous challenge because of the fields of the bunch can greatly modify the wave itself.

The plasma waves used to accelerate electrons are too fast to trap and accelerate the slower protons and ions. Therefore, a different mechanism needs to be used to transfer the fields of the laser to the plasma. When accelerating protons or ions, a petawatt class laser with a pulse length as long as 1 ps is shone on a solid surface. The laser rapidly ionizes and heats the plasma electrons to MeV temperatures or 100 Gbars of pressure. The electrons therefore leave rapidly causing the ions to explode or expand due to Coulomb forces. Such an explosion can produce ion energies near 100 MeV per nucleon. Futhermore, the radiation pressure of the laser launches high Mach number ion acoustic shocks across the target which can trap and accelerate protons to 10's of MeV. Controlling these processes to produce 100 MeV to 1GeV protons or higher Z ions is a great challenge.
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5.5.2 Research Opportunities

• *Introduction*

Historically, breakthroughs in particle accelerator technology have been the foundation for numerous innovations in science and technology. Medical x-ray machines, microwave ovens, televisions and air-traffic-control radar were all once unfamiliar terms describing uncommon technologies. Today's gigantic atom- and electron-smashing accelerators at SLAC, Fermilab, RHIC and CERN are perhaps the last of a generation of billion-dollar particle accelerators that are used to elucidate the inner working of the cosmos and the very building blocks of matter itself. This science has traditionally been an area of American leadership, richly rewarded with Nobel Prizes, and through the acknowledged trickle-down of knowledge and expertise, has provided numerous other advantages to America's economic and intellectual well-being. American science has long claimed leadership in the fundamental understandings of matter in the cosmos, and ourselves in it. The technologies and science discussed here may well be central to the US maintaining this position. Furthermore, given the impact of previous accelerator technologies, this new form of particle accelerator could ultimately have far-reaching consequences.

• *Relativistic electron acceleration*

Laser-driven electron acceleration is advancing past the stage of initial discovery and demonstration to the stage of detailed scientific understanding, optimization, development and deployment. Until very recently, most experiments have operated in the so-called self-modulated laser wakefield regime where the laser pulse length is long compared to the plasma period. In these experiments, a high power laser pulse is focused into a neutral gas. The peak laser intensity typically is on the order of 10^{19} W/cm^2, exceeding the ionization threshold in gases such as hydrogen or helium by several orders of magnitude. When the laser pulse propagates through the ionized gas (plasma), it can become amplitude modulated and drives up large amplitude plasma density oscillations. These large amplitude plasma waves propagate with phase velocity close to the speed of light and can trap and accelerate electrons to multi-MeV energies in distances on the order of a millimeter. The electron beams emerging from these plasma-based accelerators typically contain nano-Coulombs worth of charge (10 billion electrons per pulse) with femtosecond (10^{-15} s) duration, but unfortunately with 100 % energy spread.

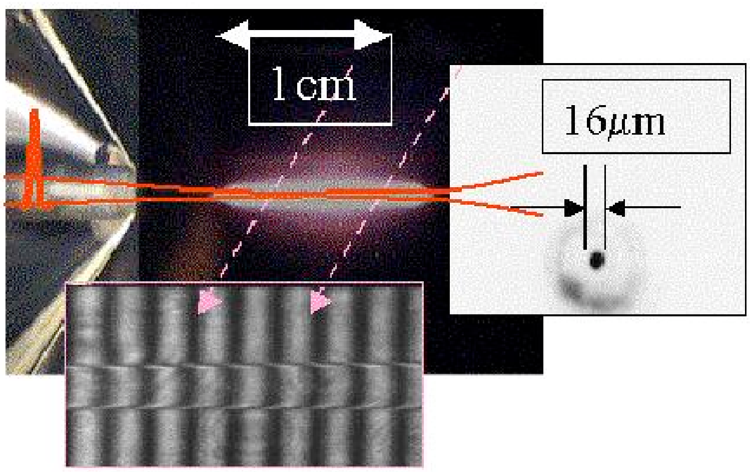

Figure 5.4.1: Luminescence from a fully ionized helium channel formed when a Nd:YAG laser pulse is focused by a conical axicon lens to a 1.5 cm line (left top). This channel is similar to that first demonstrated at the U. of Maryland. Bottom image is a transverse interferogram of the channel and the image to the right is the mode profile. [Courtesy of the University of Texas].

The main challenges that need to be met to generate a 1 GeV electron module are controlled trapping and acceleration of the electrons to minimize the electron energy spread and laser guiding and plasma channels to extend the acceleration distance.. Electron energies up to 350 MeV have recently been reported but the beams had 100 % energy spread. A combination of acceleration distance, pump depletion and dephasing of the electron with respect to the plasma wave typically limit the maximum energy achieved. To increase the acceleration distance requires laser guiding in a plasma channel (Figure 5.4.1). Development of such methods is going on at several universities and national labs and is key in the development of a GeV electron acceleration module.

Very recently preformed channels have been produced and shown to guide laser pulses at relativistic intensities over macroscopic distances. Electron bunches at the 100 MeV level with %-level energy spread containing > 100 pC charge were observed to emanate from these channels under appropriate channel and laser conditions. This demonstration presents an important milestone towards the development of a multi-GeV laser based accelerator. The femtosecond electron bunches also offer the possibility to produce intense femtosecond x-ray pulses as well as coherent terahertz radiation, intrinsically synchronized with intense laser pulses and electron bunches.

To carry out these experiments, several temporally synchronized laser pulses are used. Simulations indicate that the main laser pulse should have peak power on the order of 25 -100 TW for acceleration of 10^9 - 10^{10} electrons to 1 GeV energy. High repetition rate systems (> 10 Hz) are required to allow rapid exploration of parameter regime. This implies average laser power on the order of 100 W or more. For such systems, laser diode pumped amplifiers need to be developed and is actively being pursued by several groups in the US, Europe and Japan.

• ***Pulsed high-energy protons and heavy ions***

Recent experiments with ultra-high intensity laser pulses interacting with thin film targets have shown that a beam of high-energy, (MeV), collimated protons can be produced. In the simple configuration of these experiments these protons, originating from hydrogenous material on the front and rear sides of the target, are accelerated by Coulomb attraction to the relativistic electrons generated in the primary laser plasma interaction. The forward-going ultra-short burst of collimated protons produced has an energy that increases with laser intensity, so far reaching energies of ~ 50 MeV (Figure 5.4.2), and the conversion efficiency to protons increases also with laser intensity (so far reaching ~10%). Moreover the proton emittance can be less than 0.006π mm-mrad, a100-fold improvement over conventional technology. This unique source of protons already complements conventional accelerator-based proton sources. These have higher energy, approaching GeV's, but the duration of the laser generated particles is much shorter, and their fluence orders of magnitude higher. These sources we can see many near- and intermediate-term improvements, which will likely lead to practical applications.

•Scientific Objectives and Milestones:

A useful goal for laser-plasma accelerator research which will still provide a broad HEDS research plan is to generate mono-energetic GeV electron ($\Delta E/E<20\%$, nC of charge and a normalized emittance of 10π mm-mr) or positron/ion beams. Here a ten year focused research program with clear milestones is being proposed that will address the key issues associated with producing a prototype GeV stage. It should be stressed that the proposed research is at the forefront of HEDS, laser-physics, plasma physics, ultra-fast diagnostics, and high-performance computing. If the key questions can be answered this will lead to a compact tool for university scale science in fields ranging from chemistry to solid state physics and biology and medicine. It will also indicate path towards realizing a 100 GeV or higher laser wakefield accelerator for high energy physics.

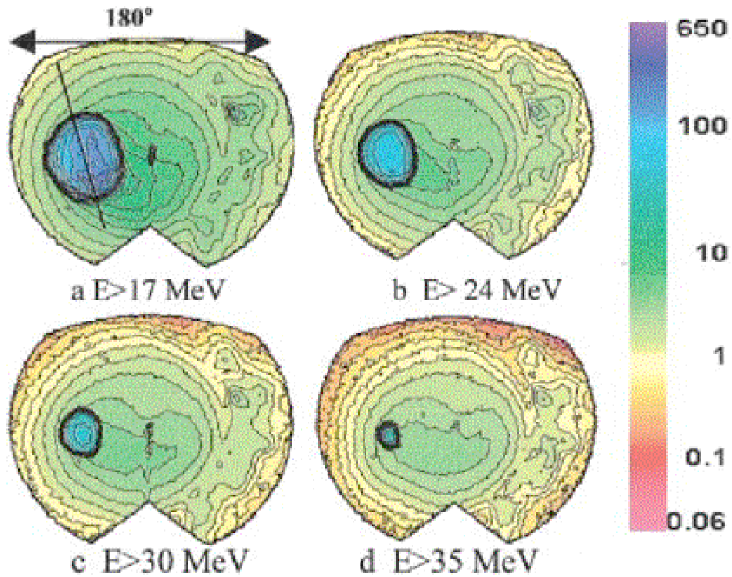

Figure 5.4.2: Data from the LLNL Petawatt laser showing well collimated, multi-MeV proton beams accelerated at the back surface of a target. The high-energy proton beam is uniform and with low emittance. These sources show promise in many applications from medical ion beam cancer therapy to the production of short-lived radionuclides. [Figure from Snavely et al. Phys. Rev. Lett. 85, 2945 (2000).]

• Key HEDS Research Areas and Questions:

To achieve this goal will require addressing the following questions:

1) **Guiding laser pulses for cm to m distances:**
   Can channels be generated at the appropriate density over a cm to m distances? What is the best way to generate a channel? Will lasers be stable to hosing type instabilities in realistic channels? Can high-intensity lasers be coupled into the channels. Another option is to use a higher power laser and focus it to a larger spot size so the vacuum Rayleigh length is large, and have the back of the pulse self-focus. Can such a process be controlled?

2) **Injecting electrons into miniature accelerating structures:**
   Can one control the evolution of the laser such that it can produce a wake that locally self-injects electrons which lead to mono-energetic beams? Can one use another laser(s) to locally inject electrons into a desired bucket? Can one use an external source of electrons?

3) **Beam loading:**
   When 10 pC to nC or more of charge is accelerated, substantial beam loading will occur. Can mono-energetic beams still be produced when there is substantial beam

loading? Will the trailing beam be susceptible to hosing over cm distances? Will there be a coupled laser–bunch head-tail instability? Accelerating positrons is very different in the blowout regime than accelerating electrons. How can a ~nC of positrons be accelerated while maintaining low emittance?

4) **Taming the laser:**
To achieve high efficiency the laser must create a wake over pump depletion distances. What are the tolerances on the quality of the laser beam? Will the laser disperse over pump depletion distances? Can this be controlled by using pulse shaping in real and/or frequency space?

5) **Staging:**
To extend the energy of electrons to 10GeV may require staging multiple laser-plasma accelerator sections together. How to take the bunch from one stage into another and how to phase the multiple lasers will be a great challenge.

6) **Understanding the mechanisms of ion acceleration:**
To date there has been numerous experiments that demonstrate the production of ~50 MeV protons. However, the exact acceleration mechanism and source of these protons is clear. Some experiments indicate that the energetic ions come from the front of the target and propagate through existing on the rear side. Other experiments show that the ions originate from the rear surface. Both scenarios may be occurring simultaneously. Understanding what determines the acceleration mechanism and designing optimized targets is a major research enterprise. Another research question is can the proton/ion acceleration mechanism be staged?

7) **Shock acceleration**:
As the laser power and focused intensity increases the laser-solid interaction will launch high-mach number ion acoustic shocks. A key question is how this depends on the laser intensity, the pre-pulse, and the plasma composition.

8) High-fidelity modeling:
Although in concept the acceleration of electrons and ions by laser-plasma interactions is rather simple, the details are complex and highly nonlinear. To date no predictive nonlinear theory exists. Therefore, to make advances in laser-plasma acceleration will need accurate computer simulation tools. Due to the highly kinetic phenomena of laser-plasma acceleration, particle based models will be essential. Developing particle based models that are efficient and that can model the full scale of experiments in three dimensions will be a great challenge.

• Research Tools and Facility Requirements:
Not all these questions can be answered using a single existing facility. Some facilities can answer a particular question, but to make the most rapid progress the efforts should be housed in centers. The centers will be made of a network of sites, with there own tabletop laser, which are geographically located near designated high end user facilities. For electron acceleration the centers need expertise in channel guiding, particle injection,

ultra-fast particle and photon diagnostics, and high-performance computing together with access to state-of-the-art laser facilities. The facilities should include 10TW, 100TW, as well as 1PW systems. The high-end systems should be at user facilities at strategically located Universities or National Laboratories. For proton/ion acceleration, the centers need expertise in plasma physics, target design and fabrication, diagnostics, nuclear physics, and high-performance computing together with state-of-the-art laser facilities. For the electron acceleration the quality of the laser beam is critical while for the ion acceleration the ability to control the prepulse could be important. For ion acceleration the laser energy and pulse lengths should be an order of magnitude higher while the peak power should be comparable.

• ***Opportunities for Interagency Cooperation:***
The physics and science described above has implications for advanced accelerators and novel high-brightness light sources; and it involves new basic physics of high-intensity laser-plasma interactions as well as provides a unique opportunity for a close coupling between sophisticated and well diagnosed experiments and high-fidelity simulations. Therefore, there are clear opportunities interagency cooperation between NSF-Physics, DOE-HEP, DOE-BES, DOE-FES, and DOE-ASCR.

• ***Timeline and Resource Requirements:***

Science Areas	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15
Laser construction	Several 10TW and several 100TW class lasers		Upgrade of several lasers to the 100 TW and PW levels. These sites will be designated as user facilities.			Upgrade one or two of these sites to the 10 PW level and support the operation of existing facilities					
Channel guiding to 1GeV	Self-trap to 100's of MeV and demonstrate all optical injection		Self-trap and/or all optical injection to 1GeV			Guide PW class lasers over 10cm to 1m distances					
Staging			Demonstrate staging			Demonstrate multiple staging					
Produce mono-energetic beams	100+MeV ions		.1 to 1GeV monoenergetic ion beams			Using 10 PW class lasers to generate >GeV ions Using PW to 10PW lasers to generate 10GeV electron beams					
Advanced Theory and Simulations	Full scale modeling And development of reduced models Dedicated computing resources					Real time feed back And Dedicated computing resources					

Figure 5.4.1: Timeline for advanced laser acceleration research.

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5.6 Inertial Fusion Energy Fast Ignition

At the ultrahigh intensities now achievable with the current generation of ultrafast, ultraintense lasers the enormous electric fields can accelerate electrons to very high energy (many millions of electron volts). Ultrafast, ultrahigh intensity laser production of fast electrons is currently a promising candidate to aid the ignition of an imploded inertial confinement fusion (ICF) pellet by externally heating the fusion fuel. Initial results from Japan and elsewhere are promising. While the prospect of achieving fusion gain high enough for viable energy production is extremely challenging with conventional ICF, fast ignition with ultraintense lasers holds the promise to achieve the necessary high gain by adaptation of the current generation of ICF facilities now under construction to generate ultra short pulses of high energy .

Fast ignition works by utilizing an ultrafast intense laser in conjunction with a more traditional plasma compression facility such as a large laser or energetic Z-pinch. Unlike traditional hot spot ignition, in which both the plasma compression and subsequent heating of the inner core of lower density fuel are both achieved with the radial implosion drive, fast ignition decouples compression and heating. A large implosion machine first assembles the fuel and then the intense laser heats some of the fuel to initiate a propagating fusion burn. The great advantage of fast ignition is that it relaxes the requirement of symmetry on the implosion and the need to create a hot spot in the center of the fuel. This ultimately could result in ignition with a substantially reduced implosion drive energy and the achievement of a commensurate increase in fusion efficiency. This improvement in efficiency could have a profound impact on the possibility of ICF as a fusion energy source.

5.6.1 Motivating Intellectual Question

- *Is it possible to make controlled nuclear fusion useful and efficient by heating plasmas with an intense, short pulse laser?*

The idea of controlled nuclear fusion as a source of inexpensive, clean energy has been a dream for many decades. Incredible progress toward this goal has been made since the Second World War in both approaches to the problem, magnetic confinement fusion and inertial confinement fusion. In the inertial confinement fusion approach, fusion is achieved by imploding a small pellet containing the fusion fuel of deuterium and tritium to high density and, in the process, heating some small core of the pellet to a temperature high enough to initiate fusion in the entire pellet. The result is the creation of a tiny "star" whose fusion energy can be harnessed for the production of electricity.

The scaling of this approach to a fusion energy yield that would make it viable as an economically useful energy source has, however, proved difficult. The traditional approach to achieving fusion ignition in this way, which has yet to be demonstrated but will be achieved with the large multi-beam National Ignition facility laser presently under construction at Lawrence Livermore National Laboratory, requires a large of amount of energy to achieve the very symmetric implosion that is needed to achieve fusion conditions. Such a large implosion machine is a great impediment to making ICF a viable energy source.

A new technique, that of fast ignition (FI), may hold the promise for reducing the size of the implosion machine needed for ICF to reach energy yields of interest for power production. If successful, FI would greatly enhance the possibility of ICF as an energy source. In FI, the fusion fuel is compressed by a laser or an x-ray producing Z-pinch in the usual manner. However, the fuel is then heated by injecting a very intense, ultrafast laser into the side of the heated pellet. The injected intense laser pulses create a powerful beam of high-energy particles (either electrons or protons) that heat a small chunk of the plasma to conditions sufficient to ignite fusion in the rest of the compressed pellet. At present, this alternate ignition approach is speculative as the physics of how energy is deposited at these intensities is not well understood. However, success in this approach would make fusion energy based on ICF a much more likely prospect.

5.6.2 Research Opportunities

• *Introduction to the fast ignition concept and principal scientific objectives*

Ignition with inertial confinement fusion is central to defense interests and is the major goal of the multi-billion dollar laser, the National Ignition Facility (NIF) being constructed by NNSA at LLNL. Inertial Fusion Energy (IFE) is a potential long-term solution to providing a secure energy supply, free from global warming consequences. New opportunities arising from the development of ultra-intense lasers promise to provide both a lower energy threshold for ignition and a higher energy gain in the fusion burn. The fast ignition concept, in which fusion fuel (deuterium – tritium ice) is first compressed and then ignited by a high intensity laser pulse could realize these promises.

The fast ignition concept is illustrated in figure 5.5.1. Unlike traditional hot spot ignition, in which both the plasma compression and subsequent heating of the inner core of lower density fuel are both achieved with the radial implosion drive, fast ignition decouples the compression and heating. A high-energy implosion driver, such as the NIF, the Omega laser or the “Z” Z-pinch machine, compresses the fuel by direct or indirect drive. A short, intense mulit-petawatt laser pulse then heats the fuel at maximum compression for efficient thermonuclear burn. The success of this technique would make inertial confinement fusion less sensitive to the symmetry of an implosion and relaxes the requirements on the drive laser. The great attraction of fast ignition is that the requirements of the fuel compression phase are greatly relaxed relative to conventional ICF because there is no requirement to produce a central hot spot. The symmetry of the drive, the drive pressure and the sphericity of the target can be relaxed. New aspects, such as the development of implosion around a cone to provide a path for the igniter beam may facilitate this concept.

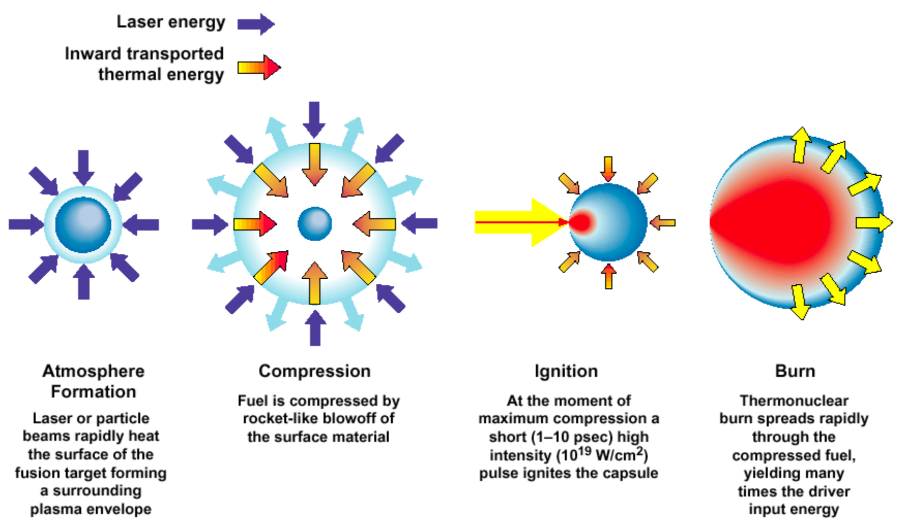

Figure 5.5.1: Fast ignition concept for fusion energy research.

• Principal physics and engineering issues facing fast ignition

The coupling of ultra-short pulse lasers to the compressed core of an ICF implosion is the central issue in fast ignition. UULs couple to the external regions of a compressed target, near the critical surface (where the laser frequency is equal to the local plasma density). This can be 100's of µm from the high-density region where ignition occurs. The UUL energy is converted to energetic electron or ion beams that penetrate to the high-density region. The physics is novel and has great intrinsic scientific interest. There are many unresolved questions about the coupling, and it is not clear how much of the UUL energy can be coupled to the core. For example, understanding the divergence and energy deposition physics of an intense electron beam is essential to validating the FI concept. Full-scale fast ignition with 300×-energy gain at 1MJ drive energies is estimated to require an igniter laser delivering about 100kJ in 20 ps. In principle this could be accomplished with relatively minor modifications to existing of planned ICF facilities like Z, Omega or even the NIF.

Recent experiments in Japan have given a strong impetus to fast ignition by showing that the efficiency for transferring short pulse laser energy to the ignition hot spot can be >20% (R. Kodema et al. *Nature* **412**, 798 (2001)). The Japanese experiment used a novel target design to allow efficient injection of the intense heating laser pulse (illustrated in figure 5.2). Their experiments demonstrated a 1000× enhanced thermo-nuclear burn in a laser driven implosion in which the compressed fuel was irradiated with a 300J ultraintense laser pulse.

The basic physics supporting fast ignition is undergoing vigorous investigation worldwide. The most significant work is being carried out using laser facilities capable of a large number of shots at picosecond pulse energies in the range 10 – 500 J and powers of 100 TW to 1 PW. The essence of the research is to understand the key physical phenomena in fast ignition. It is convenient to describe these phenomena in the order of their occurrence, as the igniter laser pulse approaches the fast ignition fuel.

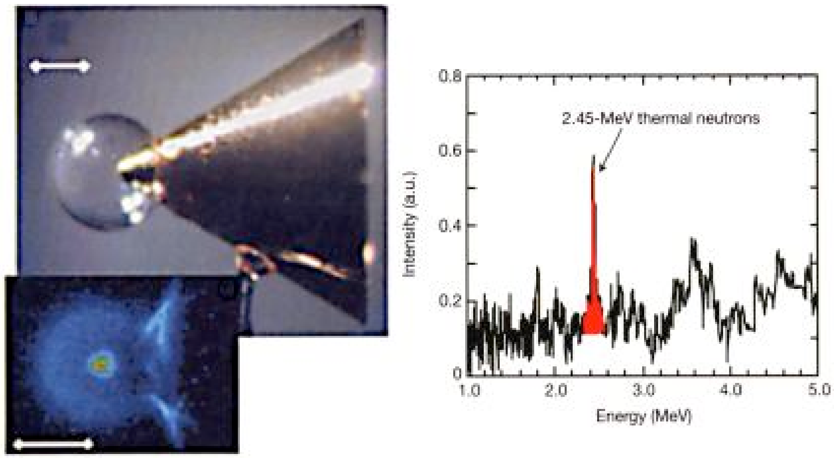

Figure 5.5.2: University of Osaka (Japan), results on fast ignition with a cone target. Shown are the target (top left), x-ray pinhole camera image of the implosion (bottom left) and the neutron spectrum resulting from the injection of the short pulse laser. An enhancement of fusion neutrons by a factor of 1000 was observed when a high intensity short pulse laser was shot down the copper cone (seen at left) at the time of peak compression of the spherical target.

Interaction with sub-critical density plasma in the relevant relativistic intensity regime (up to 10^{20} Wcm^{-2} for fast ignition) is the initial process that occurs as the ignition laser meets low density plasma either in a laser formed channel or in a cone inserted into the implosion to provide a path for the igniter beam. Three-dimensional(3-D) particle in cell (PIC) simulations give a numerical model of the relativistic self focusing, parametric coupling to plasma waves, and particle acceleration. Experimental diagnostics provide evidence to challenge the models. While this phase of FI has benefited from the most research, more work is required to understand it fully. At this stage the laser is strongly absorbed at its critical density and the transfer of its energy to a beam of multi- MeV relativistic electrons must be understood. The transfer efficiency, the energy spectrum and directionality of the electron source can be modeled with 3-D PIC methods and measured experimentally. Results depend on laser pulse duration and intensity and the atomic composition of the plasma (D-T in a channel configuration or Au in the cone scheme). More extensive studies are needed to give a firm basis for fast ignition target design.

The transport of relativistic electrons is probably the most challenging problem in fast ignition. In electron ignition, the electrons create the ignition hot spot directly. Electron beam propagation is the central problem. The complexity is evidenced by the fact that the electron current is of the order of giga amps and exceeds the Alfven current limit by a factor of about 10^6. A cold electron return current must cancel the beam current and it induces a strong Ohmic electric field, which can limit the penetration of the beam. The Curl of the E field induces a growing azimuthal B field, up to a limit at which the net current is equal to the Alfven limit. The B field acts to guide or focus the electron beam. The opposed beam current and cold return current is subject to ‘ two stream’ instabilities, notably the Weibel like filamentation instability. As the electron beam passes through material interfaces and boundaries, index of refraction changes lead to surface currents and additional B field sources. The plasma heats up and its conductivity changes. The self-consistent interplay of these phenomena is the essence of the electron transport problem.

• ***Research Tools and Facility Requirement:***

The development of integrated fast ignition experiments, combining fuel compression and igniter pulse heating, requires large-scale facilities. Presently the largest high-energy petawatt laser facilities are, or will shortly include, three in Europe and one Japan. These are 0.5 kJ, 1 PW lasers alongside long pulse laser compression or ion beam facilities. They are either in operation or will operate with in the next two years. NNSA is currently carrying out technical R&D and developing designs and plans to adapt major driver facilities (the OMEGA laser at LLE, the NIF at LLNL and the Z/ Zbeamlet facility at SNL) for high-energy petawatt operation. Construction of these large, high energy petawatt lasers will be a part of the NNSA program in high energy density physics and inertial fusion. The NNSA program will be a significant enhancement relative to the currently available capabilities overseas and therefore will provide flagship facilities for testing fast ignition with igniter pulse energies from 1 to 10 kJ from about 2006 onwards. Japan will also transition to an approximately 10 kJ PW capability upon completion of its FIREX construction project, and Europe may also provide facilities at this level.

These facilities will enable experiments that measure the achievable heating of the ignition spark at energy levels an order of magnitude lower than are required for full scale fast ignition . They will provide the quantitative basis for decisions on precisely what facility capabilities will be needed to go to full-scale high gain ignition . The feasibility of fast ignition and the possibility of designing the required driver and target are also critically dependent on the development of an understanding and numerical modeling of the relevant complex physical processes. The problem challenges the current capabilities of the most powerful tera-flop computers. It requires the development of new kinds of numerical models, particularly hybrid PIC codes. Crucial to progress are experiments designed to develop physical understanding and to benchmark numerical models.

After the proof of principle phase there will be an opportunity to decide whether and how to adapt for example the NIF for a full scale fast ignition demonstration . This will likely entail a 100kJ short pulse capability obtained by by adaptation of twenty or more of the 192 beams of the NIF.

• ***Timeline and Resource Requirements:***

The time line for major milestones in fast ignition could follow this schedule with appropriate funding:

2004-2006: Perform studies of implosion dynamics on fast ignition relevant targets at the operational implosion facilities (Omega, and Z)

2005-2007:	Conduct experimental campaigns on smaller scale PW and 100 TW facilities to understand fundamental physics issues such as hot electron transport
2006-2007:	NNSA program completes construction of petawatt lasers at Z Omega and NIF which will provide the capability for integrated fast ignition experiments
2007 - 2010:	Conduct integrated implosion and PW injection experiments
2012 ?	Execute an integrated research experiment (IRE) on fast ignition at NIF

• ***Opportunities for Interagency Cooperation:***

This area of research represents an ideal opportunity for cooperation between the NNSA and the DOE Office of Science, Office of Fusion Energy Science. The principal implosion facilities for ICF have been developed by the NNSA in large part in support of the stockpile stewardship program. However, fusion energy falls out of the mission space of the NNSA and fast ignition is not, at the present, part of the NNSA program. With OFES participation in the science aspects of fast ignition, coupled with the large investment in facilities made by the NNSA, a great opportunity now exists.

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APPENDIX A

Charge to National Task Force on

High Energy Density Physics

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January 13, 2004

Professor Ronald C. Davidson
Plasma Physics Laboratory, MS-17
Princeton University
P.O. Box 451
Princeton, NJ 08543-0451
Fax: 609-243-2418

Dear Professor Davidson:

In response to the emerging opportunities[3] for significant advances at the interface of physics and astronomy and the need for interagency coordination to optimize the federal investment in the affected areas, the Interagency Working Group on the Physics of the Universe (IWG-POU) was chartered under the National Science and Technology Council to develop a coordinated plan and set priorities. The emerging field of high-energy-density physics (HEDP) was identified as an area with significant promise, and the IWG-POU recommended that the relevant agencies work together to "develop a science driven roadmap that lays out the major components of a national HEDP program, including major scientific objectives and milestones and recommended facility modifications and upgrades."

This activity requires the vision and judgment of the HEDP community, so the agencies are establishing an HEDP Task Force for this purpose. We are very pleased that you have agreed to chair this task force, and we lay out some of the objectives in this charge.

The HEDP Task Force is charged to develop a science driven roadmap that lays out the major components of a national HEDP program. The central motivations are to (1) identify the main streams of research that help define HEDP, (2) identify for each the main scientific questions that drive the research, (3) articulate scientific objectives and milestones that the HEDP is expected to accomplish, (4) identify the highest priority requirements for the near term and further steps needed establish priorities for the long term, (5) identify for each stream of research the frontier facilities and infrastructure required for effective progress, and (6) discuss the need for interagency coordination in HEDP.

Recent workshops and reports[4] have made significant contributions to defining the emerging field of HEDP, and the Task Force is expected to build upon these studies rather than make an effort to reproduce all the information contained therein. The main

[3] Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century, National Research Council, 2003
[4] The Science and Applications of Ultrafast, Ultraintense Lasers: Opportunities in Science and Technology Using the Brightest Light Known to Man, Report on the SAUUL Workshop, June 17-19, 2002; Frontiers in High Energy Density Physics: The X-Games of Contemporary Science, National Research Council, 2003

motivation for the additional effort is to stress the scientific questions that drive the field and the scientific goals and milestones that may be used to chart progress. Of course, the nature and specificity of the goals and milestones must suit the frontier nature of the field; but we are challenging the community to identify and articulate potential or expected outcomes as clearly as possible to help inform possible future investment in the field. Likewise, it is important for the Task Force to address the issue of priorities, for example by identifying priorities for the near term, including particularly ripe and important scientific opportunities as well as critical near term funding needs. It is understood that HEDP is a young field and that the first task is to define the field and provide some sort of roadmap that characterizes how the field may be expected to evolve. Nevertheless, it is important to begin the discussion of priorities to the extent possible within the limited timeframe and scope of the Task Force's charter. Should further steps be necessary to arrive at more meaningful prioritization, provide a description of those steps.

In order to define broadly the main streams of research opportunity in HEDP, the Task Force is asked to organize a major workshop to respond to the present charge. The workshop report is expected to contain appendices addressing the main streams of research, with a front part of no more than 30 pages that summarizes the response of the HEDP community to the charge. As we have discussed, the anticipated timeframe for the workshop is March-May 2004 with a final report due August-September 2004.

The agency representatives participating in the planning and coordination of the HEDP program are grateful to you for your willingness to lead this important activity.

Sincerely,

Signed copy sent 1-13-04

Joseph L. Dehmer
Director
Division of Physics

On behalf of the IWG-POU-HEDP:

Anne Davies, DOE-OFES
Francis Thio, DOE-OFES
Robin Staffin, DOE-OHEP
David Sutter, DOE-OHEP
Dennis Kovar, DOE-ONP
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Barry Schneider, NSF-PHY
Jill Dahlberg, NRL
John Gillaspy, NIST
John P. Looney, OSTP
Michael Holland, OSTP

APPENDIX B

High Energy Density Physics Workshop

May 24-26, 2004
Gaithersburg, Maryland

Agenda

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High Energy Density Physics Workshop
May 24-26, 2004
Gaithersburg, Maryland

Monday, May 24

8:00 – 8:30 AM	***Attendee Registration, Coffee***
8:30	Charge from the Interagency Working Group - Joe Dehmer
8:50	Task Force Approach and Goals of Workshop – Ron Davidson
9:20	Report from Working Group on HED Astrophysics I –Robert Rosner
9:40	***Break***
10:30	Report from Working Group on HED Astrophysics II-Matthew Baring and Fred Lamb
11:00	Report from Working Group on HED in NNSA Facilities I-Bruce Remington, Richard Lee and Paul Drake
11:40	***Lunch***
1:00 PM	Report from Working Group on HED in NNSA Facilities II-Bruce Remington
1:40	Report from Working Group on HED with Beams I-Chan Joshi and Barbara Jacak
2:30	Report from Working Group on HED with Beams II-Grant Logan
3:00	***Break***
3:20	Report from Working Group on HED with Ultra-Short-Pulse Lasers I-Todd Ditmire
4:00	Report from Working Group on HED with Ultra-Short-Pulse Lasers II-Louis DiMauro
4:40	Public Comment
5:30	***Adjourn***

Tuesday, May 25

8:00 – 8:30 AM	***Attendee Registration, Coffee***
8:30-9:00 AM	Guidelines, Organization and Meetings of Breakout Groups-Ron Davidson
9:00 AM	HED Astrophysics - Bob Rosner
9:10	Laboratory HED - Bruce Remington
9:20	Beam-Induced HED - Chan Joshi
9:30	Ultra-Short-Pulse Laser HED - Todd Ditmire
9:40	Breakout Group Organization
10:20	***Break***
10:40	Breakout Group Discussion
12:00 PM	***Lunch***
1:00	Breakout Group Discussions and Report Preparation
3:00	***Break***
3:20	Breakout Group Discussions and Report Preparation
5:00	***Adjourn***

Wednesday, May 26

8:00 – 8:30 AM	***Attendee Registration, Coffee***
	Summary Reports from Working Groups
8:30 AM	HED Astrophysics Summary Report – Robert Rosner
9:20	Laboratory HED Summary Report – Bruce Remington
10:10	***Break***
10:30	Beam-Induced HED Summary Report – Chan Joshi

11:20	Ultra-Short-Pulse Laser HED Summary Report – Todd Ditmire
12:10 PM	***Lunch***
1:15	Task Force discussion of plans for Final Report Preparation – Ron Davidson and Tom Katsouleas
3:00	***Adjourn***

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