An Overview of High Energy Density Plasma (HEDP) Research in the U.S. Fusion Energy Sciences Program

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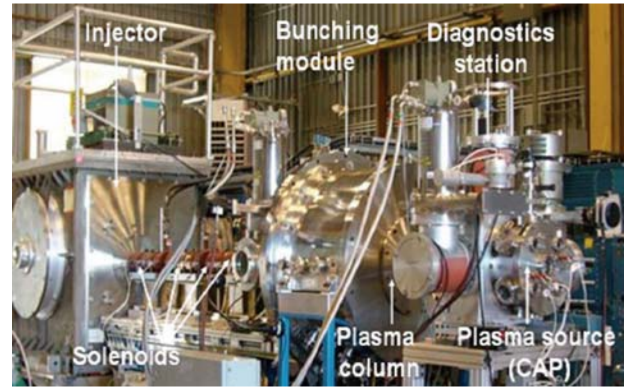
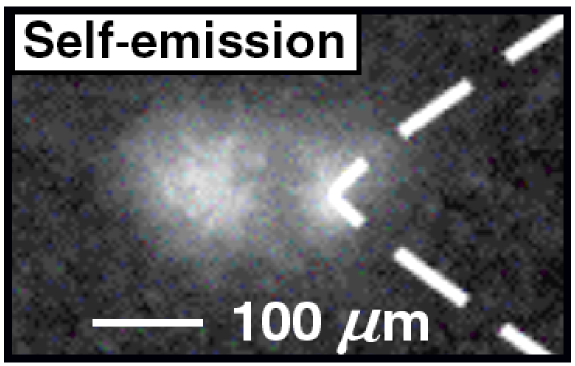
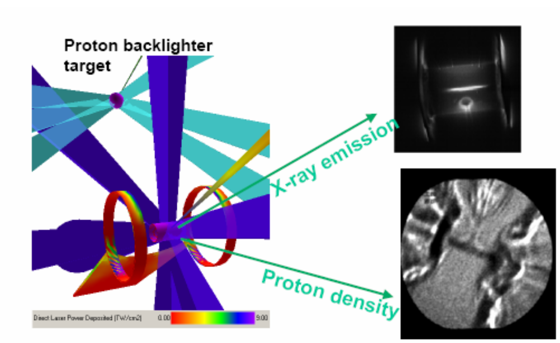
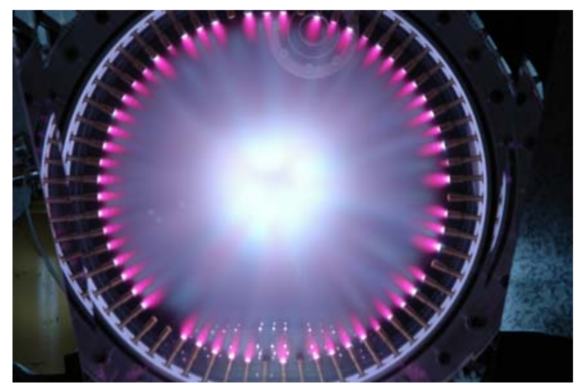
Office of Fusion Energy Sciences (OFES), USA

Presented at the Fifth International Conference in Inertial Fusion Science and Applications, Kobe, Japan, Sept 2007









The scientific themes that underpin current OFES research in HED plasmas are ….

- ***Developing the physics basis of fusion energy by studying HED plasmas***
- ***Create, probe, and control new states of HED plasmas***

- Present program sponsors research in:
  - Fast ignition and laser-plasma interactions
  - Magneto-inertial fusion
  - Heavy ion beam science
- We have plans to expand the program to include
  - Laboratory astrophysics for the study of:
    - Astrophysical jets, gamma ray bursts, accretion disks, white and brown dwarfs, interiors of giant planets, supernova remnants, HED magnetic reconnection

Research is focused on the science motivated by the technical challenges of inertial fusion energy ….

- Beyond NIF, and assuming success on NIF, for inertial fusion energy, the challenge in the nutshell is to produce ***ignition*** with ***sufficient gain***, repetitively for a few Hz, with targets and drivers at ***reasonable cost***.
- In Central-Hot-Spot (CHS) inertial fusion, ignition requires that the heating power into the hot spot exceeds the rate of heat loss from the hot spot
- Increasing heating power to the hot spot by *pdV* heating in <u>conventional</u> Central-Hot-Spot ICF requires increasing implosion velocity
- Increasing implosion velocity has two bad consequences:
  - Lowers fusion gain (fusion yield/driver energy)
  - Increases In-Flight-Aspect-Ratio (IFAR), making the implosion more susceptible to Rayleigh-Taylor instabilities
    - Compromises on the choice of in-flight adiabat, which further compromises on peak areal density and fusion gain
- LPI or RPI (radiation-plasma interaction) further complicates the choice of the cryogenic ablator
- Implosion velocity is a critical design parameter in optimizing an IFE system
- Any physics approach that can lower the implosion velocity and still produce ignition will relax the design constraints

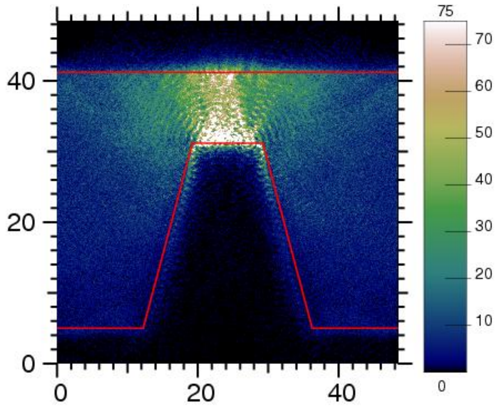
Lowering implosion velocity is one way to enable attractive IFE systems ….

- One approach to lower implosion velocity is to use a second ultra-intense pulse of energy for ignition
  - Decouples the ignition from fuel assembly
  - **Fast ignition, impact ignition, shock ignition**
- Another approach is to suppress the electron thermal conduction from the hot spot using an ultrahigh magnetic fields
  - **Magneto-Inertial Fusion**

In fast ignition, the U.S. is pleased to be a strong partner in the world-wide effort ……

- We have strong collaborations with Japan and the United Kingdom
  - We are interested in collaborating with FIREX-1 and HiPer
- Broadly based domestic research web in support of the international effort
  - University (Rochester, Ohio State, UC-Davis, UC-San Diego, Nevada-Reno, MIT, Texas-Austin)
  - National Laboratory (LLNL, SNL, LANL, PPPL)
  - Industry (GA, Voss, HyperV)
- Develop core scientific capabilities in support of fast ignition research
  - Modeling – hydro, PIC, hybrid, LPI
  - Diagnostic development
  - Target development & fabrication

Jim King - adjusting Cu-K_{α} imager at RAL



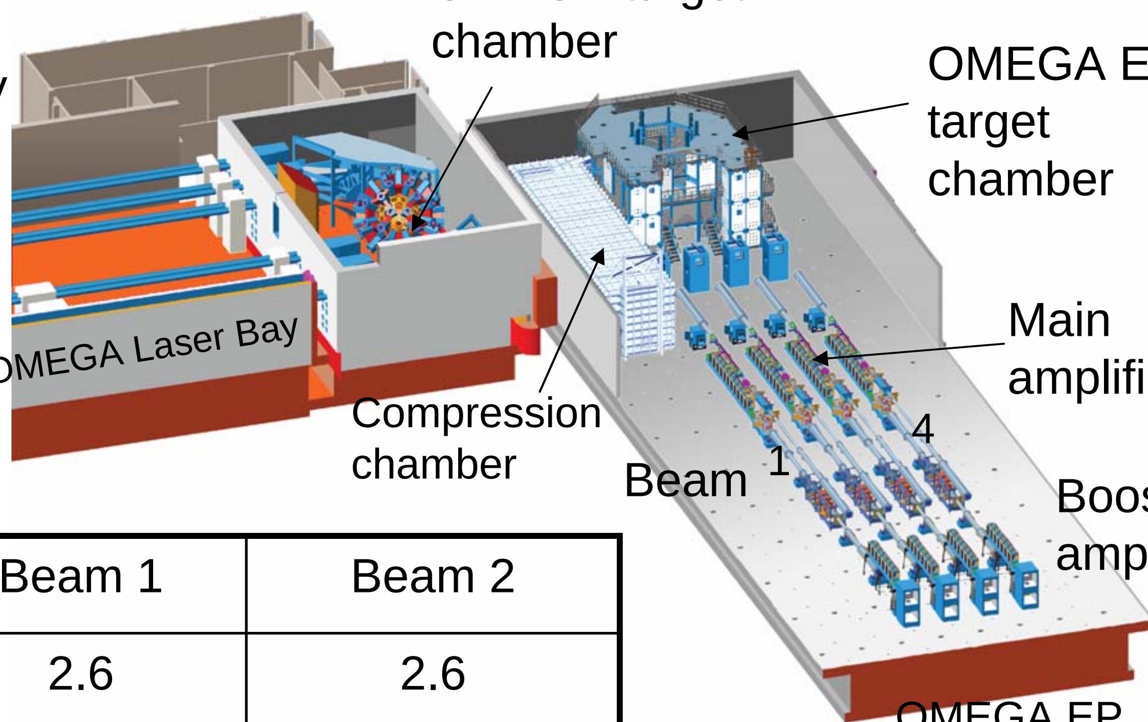
We are also developing our domestic experimental infrastructure and capabilities ….

- The OMEGA EP facility at the University of Rochester is coming on line in 2008.
- The Jupiter/Titans dual-beam PW laser facility is operational at Lawrence Livermore National Laboratory
- The Tridents laser facility is operational at the Los Alamos National Laboratory (2 long 200 J each, 1 short 0.25 PW, 250 J)
- Texas Petawatt at the University of Texas at Austin
- Z-petawatt at Sandia National Laboratory
- NIF-ARC PW lasers (12 kJ initially, up to 80 kJ max.)

OMEGA EP will be our main facility for Fast Ignition in the next several years

- Four beamlines
- Two long-pulse UV only
- Two can either be HEPW or long pulse UV

Beam 2 can produce 2.6 kJ in 10 ps when propagating on a separate path



	Beam 1	Beam 2
IR energy (kJ)	2.6	2.6
Pulse duration at full energy (ps)	10 to 100	80 to 100
Focusing (diam)	>80% in 20 μm	>80% in 40 μm
Intensity (W/cm^2)	3×20^{20}	2×10^{18}

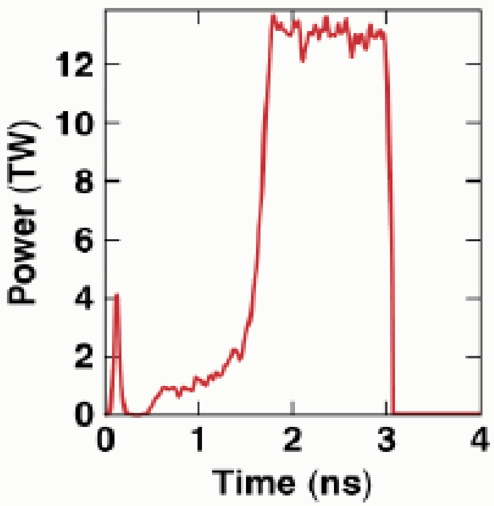
Working with our international partners, we are working towards testing the FI concept …..

- Our aim is to develop fully the scientific knowledge base to enable design of ignition-class FI experiments in the next 5 years
- Develop low-velocity, low-adiabat fuel assembly
  - Large fuel mass, stable implosion, uniform density, minimal hot-spot
- Unravel the physics of ignitor energy creation and transmission
  - Electron and ion fast ignitor
- Develop modeling capability for designing integrated FI
- Program strategy and milestones
  - Develop scientific knowledge base to enable design of Q ~ 0.1 integrated FI experiment (2010)
  - Field integrated FI experiments and demonstrate Q ~ 0.1 (2012)
  - Design and field ignition class experiments on NIF (2015)

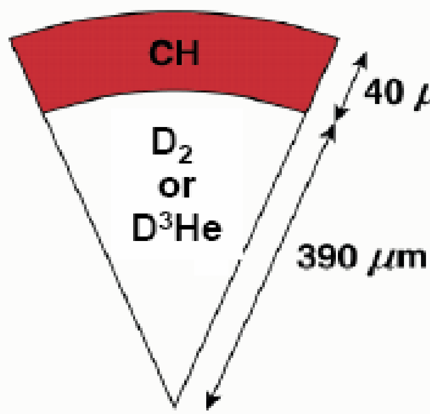
Slow implosions with low adiabat were tested on OMEGA D-^3He fusion proton energy loss measured the high ρR

$E_L \approx 20kJ$ P≈25-34atm $\alpha \approx 1.3$ $V \approx 2 \cdot 10^7 cm/s$

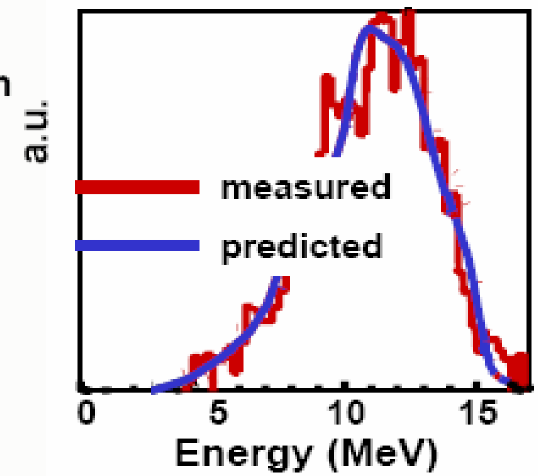
Laser pulse



Target



Secondary proton spectrum



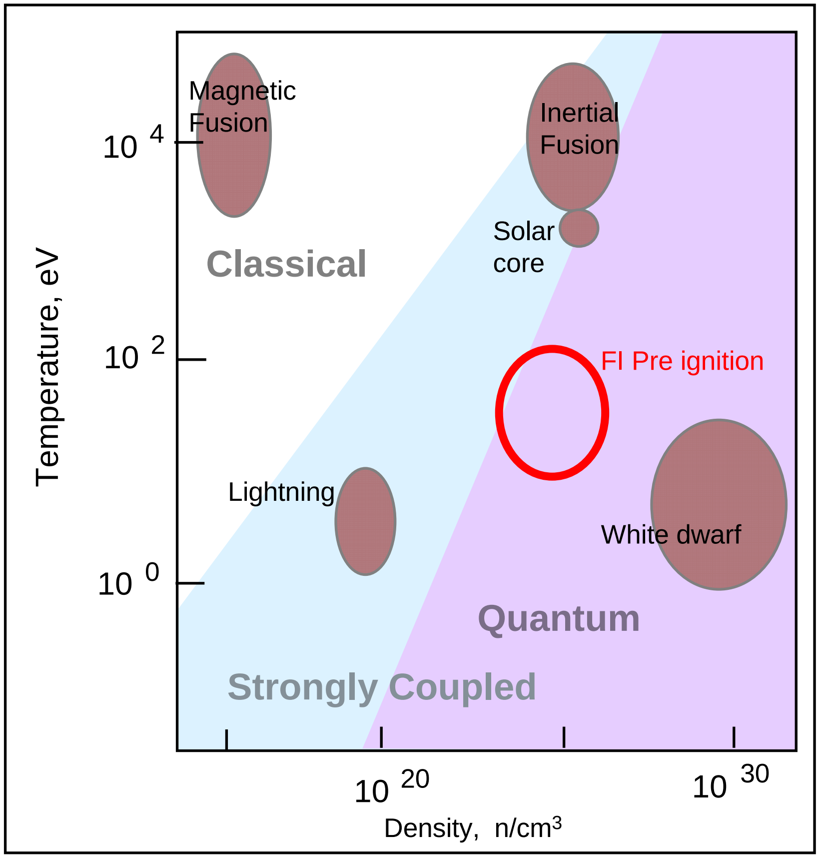
- Peak ρR is $0.26 g/cm^2$, the highest ρR to date on OMEGA
- Empty shells would achieve $\rho R \approx 0.7 g/cm^2$ and stop 4MeV electrons

Warm (CH) thick-shell cone-target implosions in '08

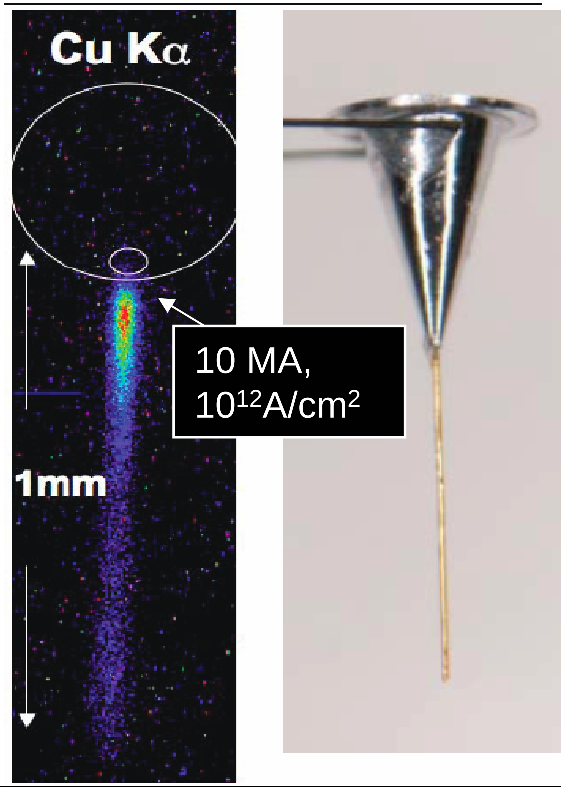
C. Zhou, W. Theobald, R. Betti, P.B. Radha, V. Smalyuk, *et al*, Phys. Rev. Lett. 98: 025004 (2007)

We are developing a predictive understanding of the igniter physics – energy transmission

- We do not yet have predictive capability for the transport of relativistic electrons in dense plasmas against an adverse density gradient
- New regimes in the parameter space of high energy density plasmas
  - Equation of states
  - Transport properties
    - Electrical, thermal
    - In the presence of magnetic fields
  - Beam and plasma instabilities
    - Weibel instabilities
- Experiments are required to guide and benchmark the codes



Experiments to develop and benchmark the codes include ………

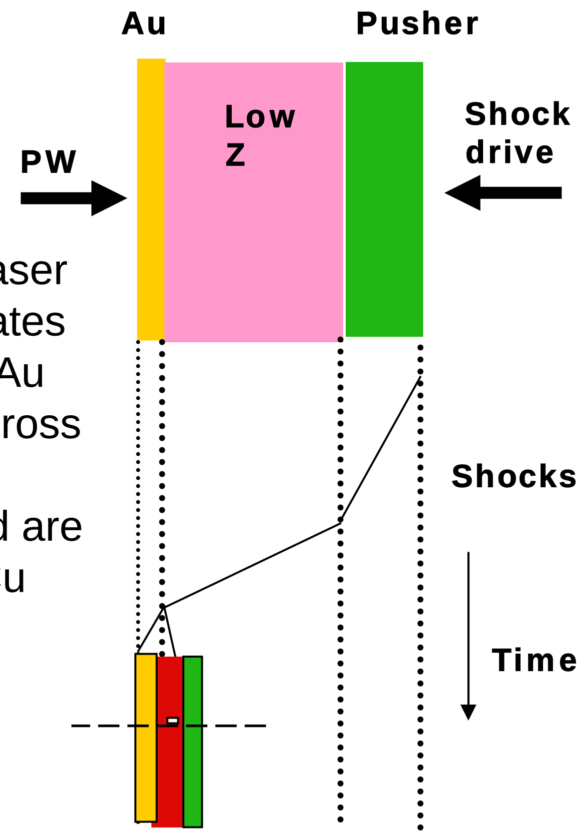


Cone-wire experiment to study relativistic electron transport in dense plasmas

Understand transport in cold metal OK - need to extend work to hot plasma

Shock driven foam experiment emulates FI cone tip at stagnation
- Explores the bottle-neck issue

- 50 J 1 ps laser pulse generates electrons in Au
- Electrons cross the Au/CH interface and are counted in Cu



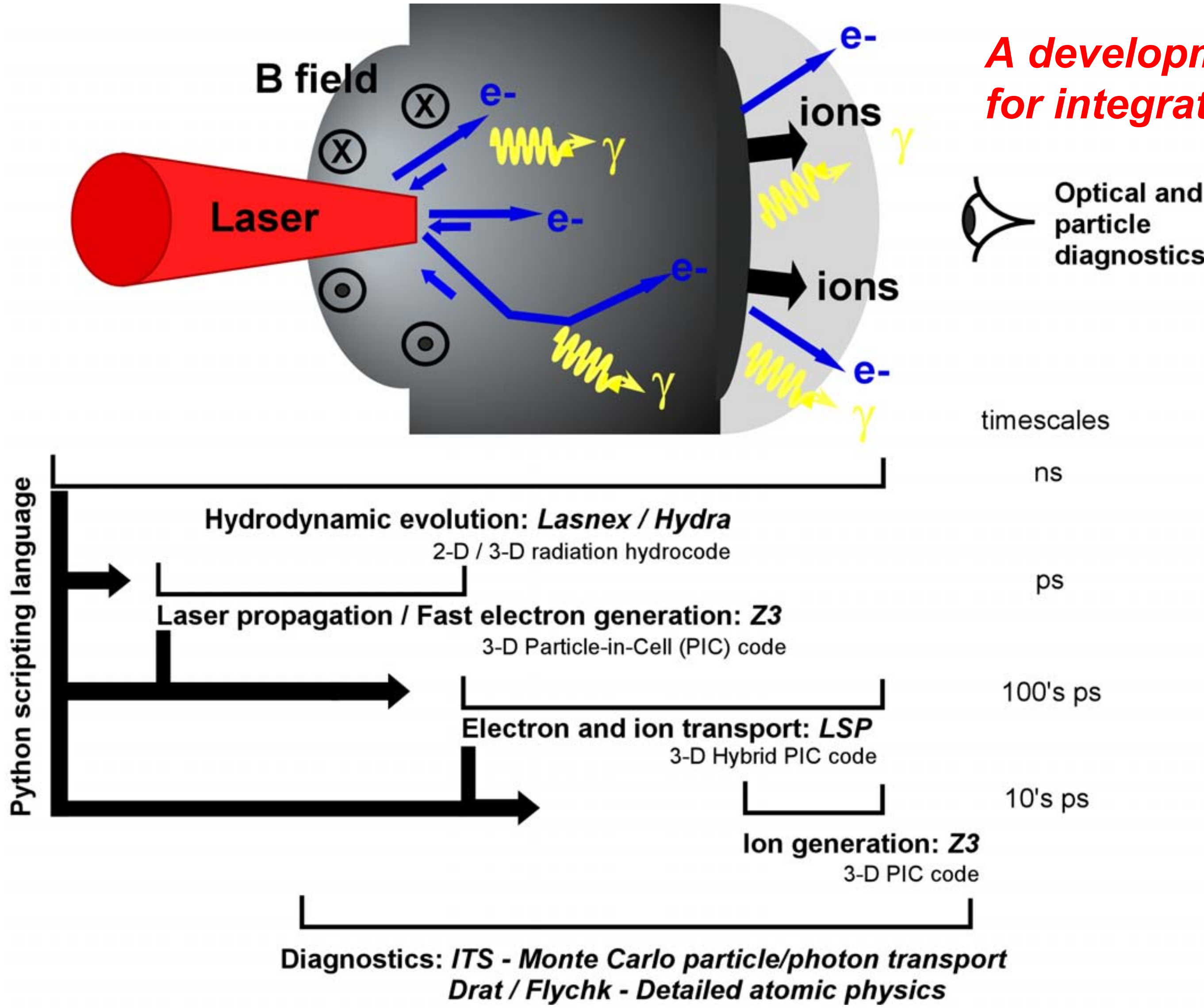
300 J, 1 ns

Accelerates Al/Cu flyer plate

Compresses foam to 1 g/cc

Heats it to 20 eV

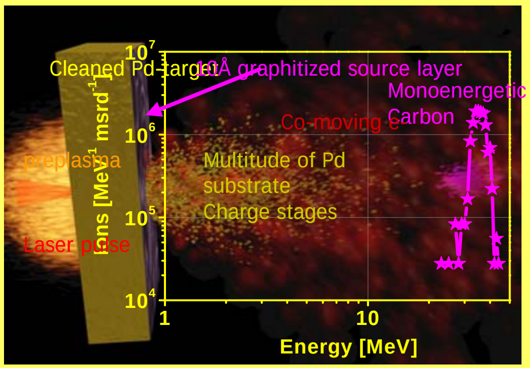
Integrated modeling capability is needed for designing the next generation of FI experiments



A developmental code for integrated modeling

In ion fast ignitor research, beam focusing and photon-ion energy conversion efficiency need to be characterized

At Los Alamos National Laboratory Trident Laser Facility, laser-driven mono-energetic ion acceleration was first demonstrated

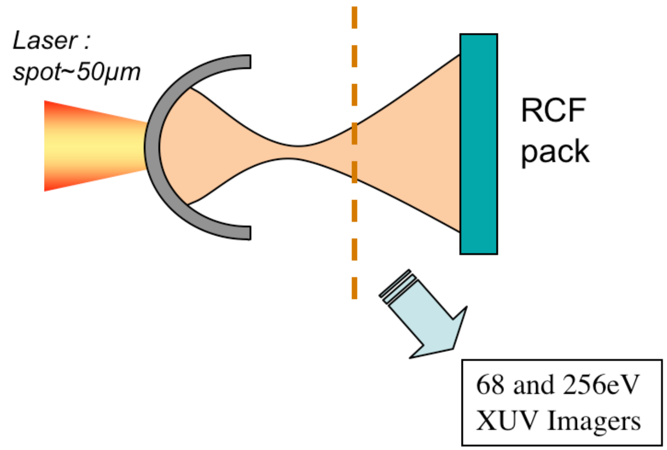


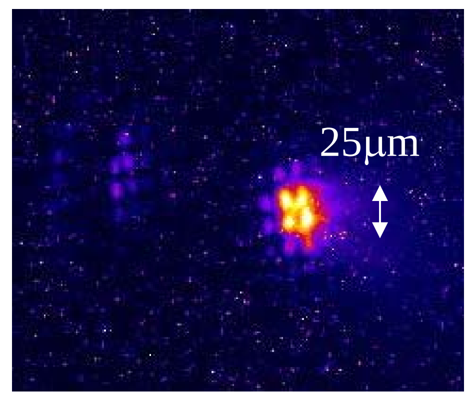
1st experimental demonstration of laser-driven, mono-energetic ion acceleration[1]:
Carbon 6+, 3 MeV/amu, 10^9 particles, ~1kA, longitudinal emittance 10^{-6} eVs

With maxwellian energy distribution:
Range of species: H, Be, C, O, F, Ni, S, Pd, Pt
MeV/amu ion energies, up to 10^{13} ions per pulse[2].

[1] Hegelich et al., Nature 439, p441 (2006).
[2] Hegelich et al., Phys. Plasmas, 12, 056314 (2005).
[3] Flippo et al., PRL, submitted Feb. (2007)
[4] Yin et al., Phys. Plasmas 14, 056706, (2007)

At Lawrence Livermore National Laboratory Titans laser facility, focusing of laser-driven proton beam is being explored

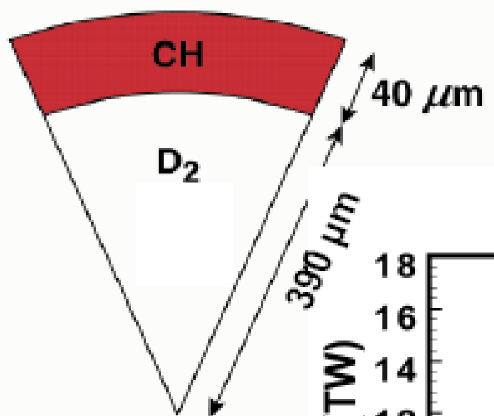




256eV XUV

The shock ignition concept has been tested on OMEGA

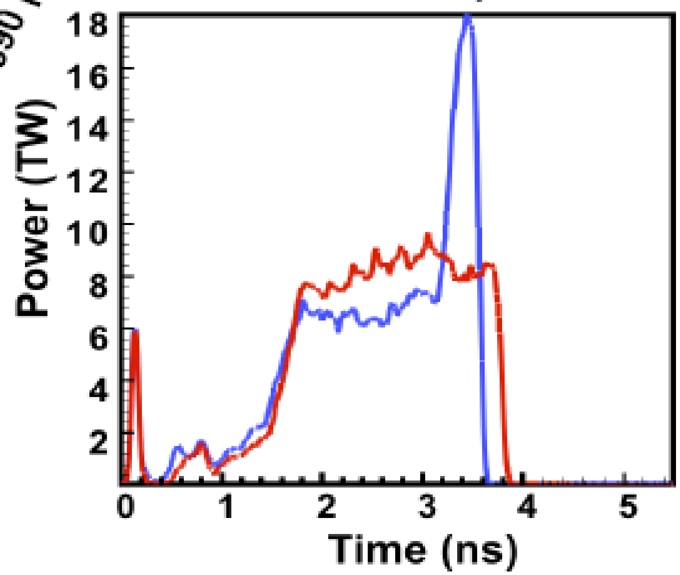
Target

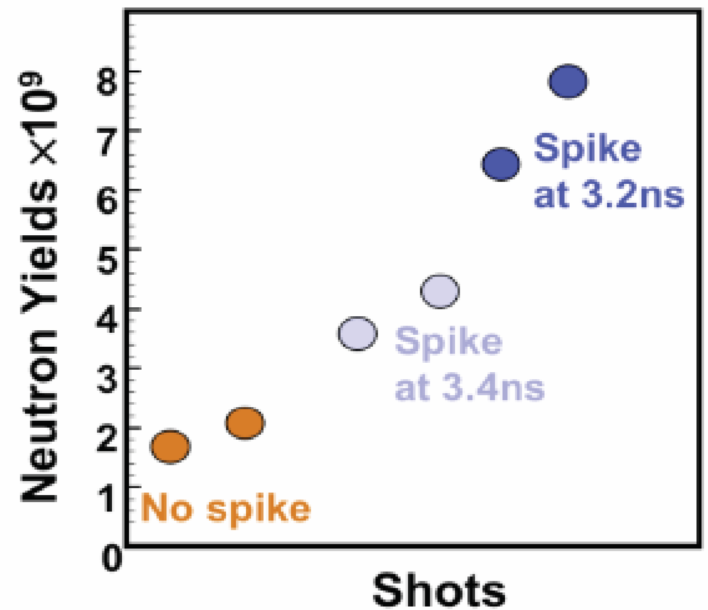


W. Theobald,
R. Betti,
C. Zhou,
C. Stoeckl
(UR-LLE)

E_L=17-18kJ
α≈1.3

Pulse shape with and without shock spike





The neutron yield increases considerably when a shock is launched at the end of the pulse

More experiments with CH targets in '07-'08, cryo-targets in '09

R. Betti, FO 1.3, "Shock Ignition of Thermonuclear Fuel with High Areal Density"

Magneto-Inertial Fusion (MIF)
An Emerging Concept in IFES and Dense Plasma in Ultrahigh Magnetic Fields

An aggressive approach to lower the implosion velocity and to address the challenge of attractive targets and drivers for IFE

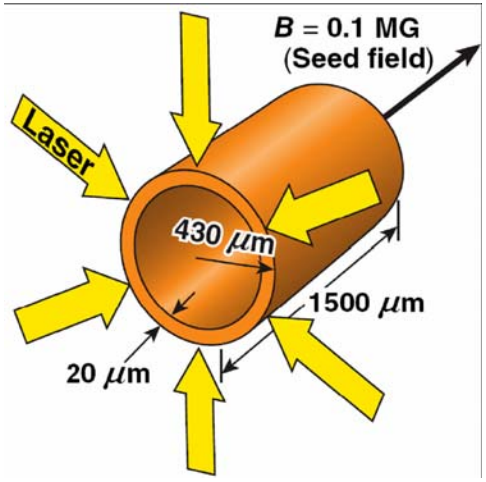
- High-Gain MIF
- Low-to-Medium Gain MIF
- Both make use of a strong magnetic fields (MGs) to suppress thermal conduction from the hot spot or target plasma to the imploding shell
- Different strategies in addressing the target and driver challenge for IFE

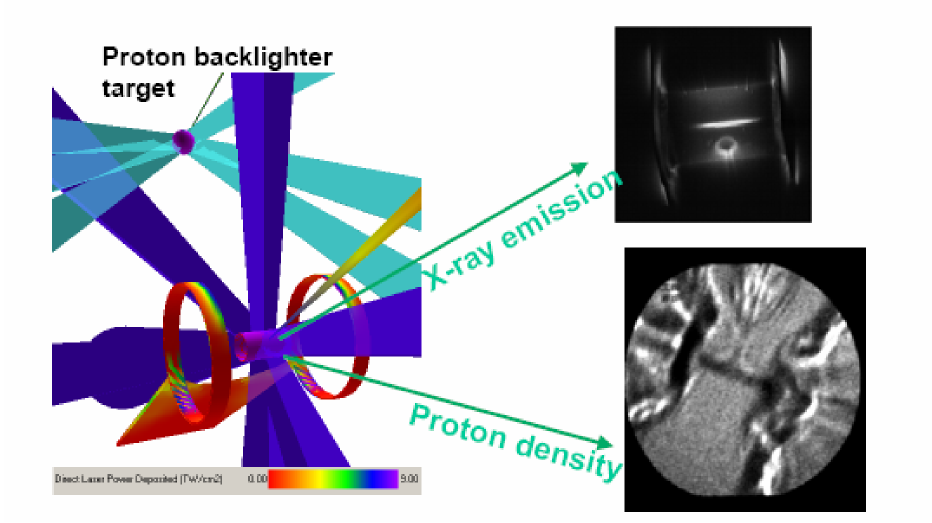
High-Gain MIF is conventional ICF with an ultrahigh magnetic field in the hot spot

- Seed the target prior to implosion with a B-field of ~ 0.1 MG
- After a central part of the target acquires a temperature of ~ 100 eV from the initial shocks, the magnetic flux is frozen with the plasma – the plasma becomes the "hot spot"
- As the hot spot implodes, the magnetic flux is compressed with it.
- $B \sim 1/r^2$: The magnetic field at peak compression 10 MG – 100 MG.
- For the NIF point design, $\rho_{hs} \sim 30$ g/cc, $T_{hs} \sim 7$ keV, $r_{hs} \sim 50$ μm, at ~100 MG, two good things happen:
  - According to Braginskii, the cross field thermal conductivity is reduced by ~ 100
  - The gyro-radius of the alpha particles ~ 27 μm. Alpha deposition in the hot spot is greatly enhanced.
- This should provide plenty of room in the parameter space to design an optimized trajectory for ignition and burn with significantly reduced implosion velocity

At OMEGA, Rochester, flux compression experiments for High-Gain MIF is underway …..

- A magnetized cylindrical target is imploded to compress a seed magnetic flux
- A ~0.1 MG seed magnetic field is generated with a double coil driven by a portable capacitive discharge system
- Mono-energetic 14.7 MeV proton beam deflectometry is used for measuring the compressed magnetic fields
- The 14.7 MeV protons are produced by D + ^{3}He fusion reactions from imploding a D^{3}He filled glass micro-balloon by 20 beams of the OMEGA lasers
- Experiments are in progress

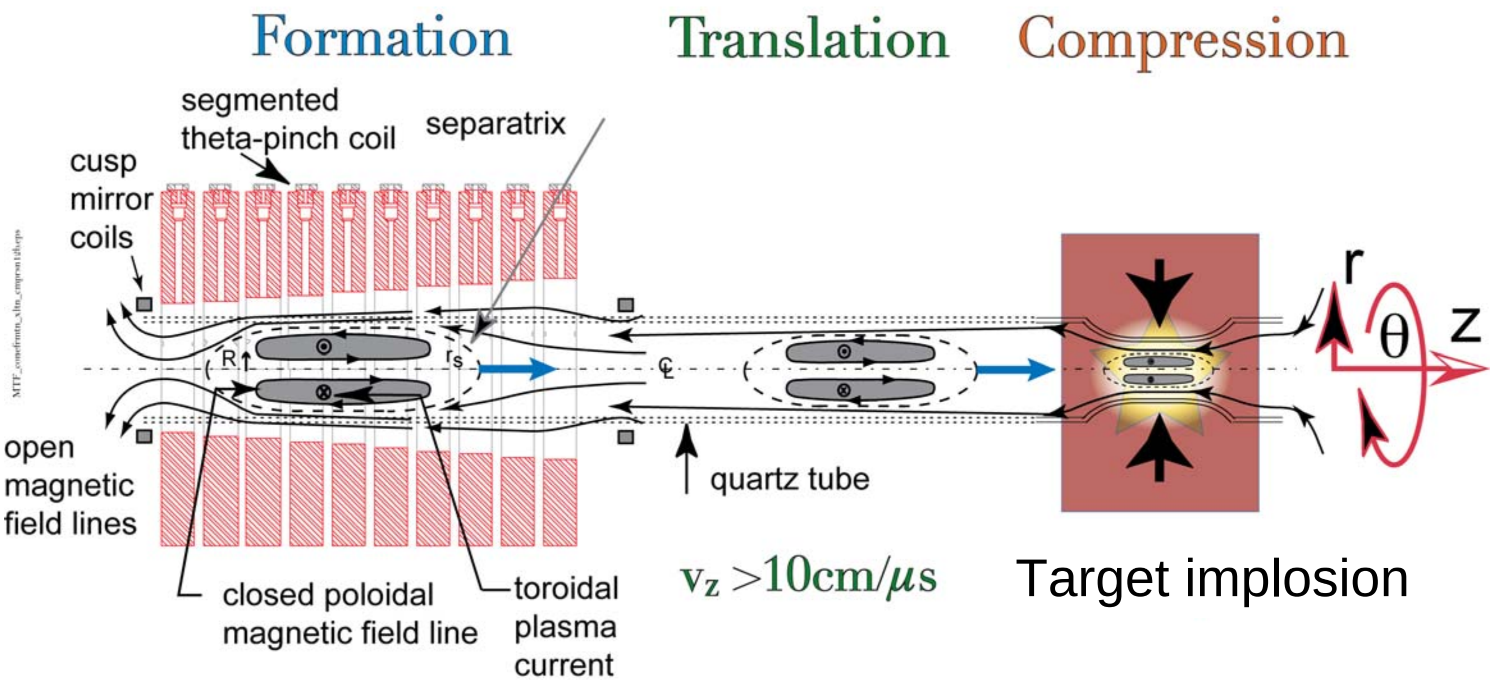




Low-to-Intermediate Gain MIF trades fusion gain in favor of non-cryogenic gaseous targets and high-efficiency low-cost drivers …..

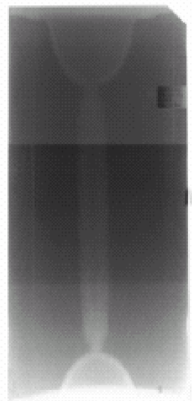
- Electromagnetic (EM) pulsed power has ***higher wall-plug efficiency*** and ***lower cost***
- By using (1) a magnetic field and (2) a low-density target plasma, the required compression and heating power density is reduced to such an extent as to allow direct compression of the target by EM pulsed power.
- ***With considerably higher wall-plug efficiency, target fusion gain needed for economic power generation can be much lower than conventional ICF.***
  - e.g. $\eta_D \sim 30\%$, $G \sim 30$ would be sufficient
- **Lower fusion gain G required → lower target density for burn required**
- Lower implosion velocity allows larger inertial for confining the fusion burn → longer confinement time → lower target density for burn
- ***The idea is to lower the target density to the extent that gaseous initial targets could be used instead of cryogenic solid targets***
- ***Candidate materials for imploding shell: Solid, liquid, plasma***
- **Goal: By 2012, demonstrate multi-keV, multi-MG, multi-megabars plasmas**

Solid-Liner Driven MIF



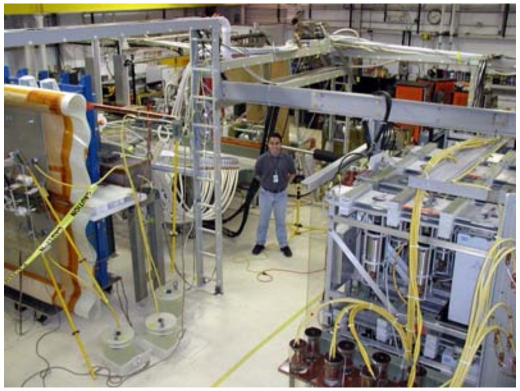
- A variety of target configurations, topologies, sizes are possible:
  - Field reversed configuration (FRC), spheromaks, z-pinch, diffuse z-pinch, etc.
- Initial target density: 10^{16} – 10^{19} per cc
- Initial target temperature: 100 eV – 300 eV
- Radial convergence ratio: ~ 10

Multi-MJ pulsed power experimental facilities for solid-liner MIF research with potential for creating multi-keV, multi-MG, dense plasmas for fusion research



Current experiment point design
- Target : FRC 30 cm long x 10 cm dia
- Solid liner: Al, 30 cm long, 10 cm dia, 1 mm thick
- By 2012, (1) develop predictive understanding of the dominant physical processes governing MIF, (2) create multi-keV, multi-MG, HED plasmas

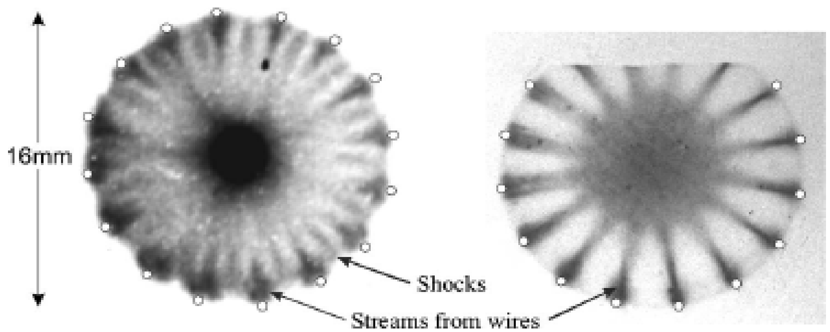
- **Air Force Reseach Lab Shiva Star pulsed power facility:** Up to 9 MJ, 3 μs rise time
- Demonstrated imploded a 30-cm long, 10 cm diameter, 1.1 mm thick Al liner in 24 μs reaching 0.5 cm/μs
  - x16 radial convergence
  - 1.5 MJ liner kinetic energy from 4.4 MJ stored energy of cap bank
  - No observable Rayleigh-Taylor
- ***Integrated MIF implosion experiment begins in 2008.***

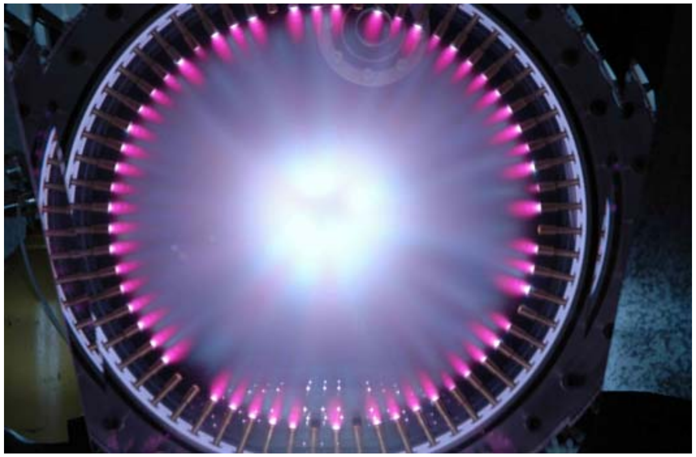


Los Alamos National Laboratory FRX-L pulsed power facility
Demonstrated FRC ~ 5 x 10^{16} cm^3, 300 eV, ~ 10 μs

Plasma-liner driven MIF

- Converging array of plasma jets can be merged to form plasma shells (liners) for imploding a magnetized plasma





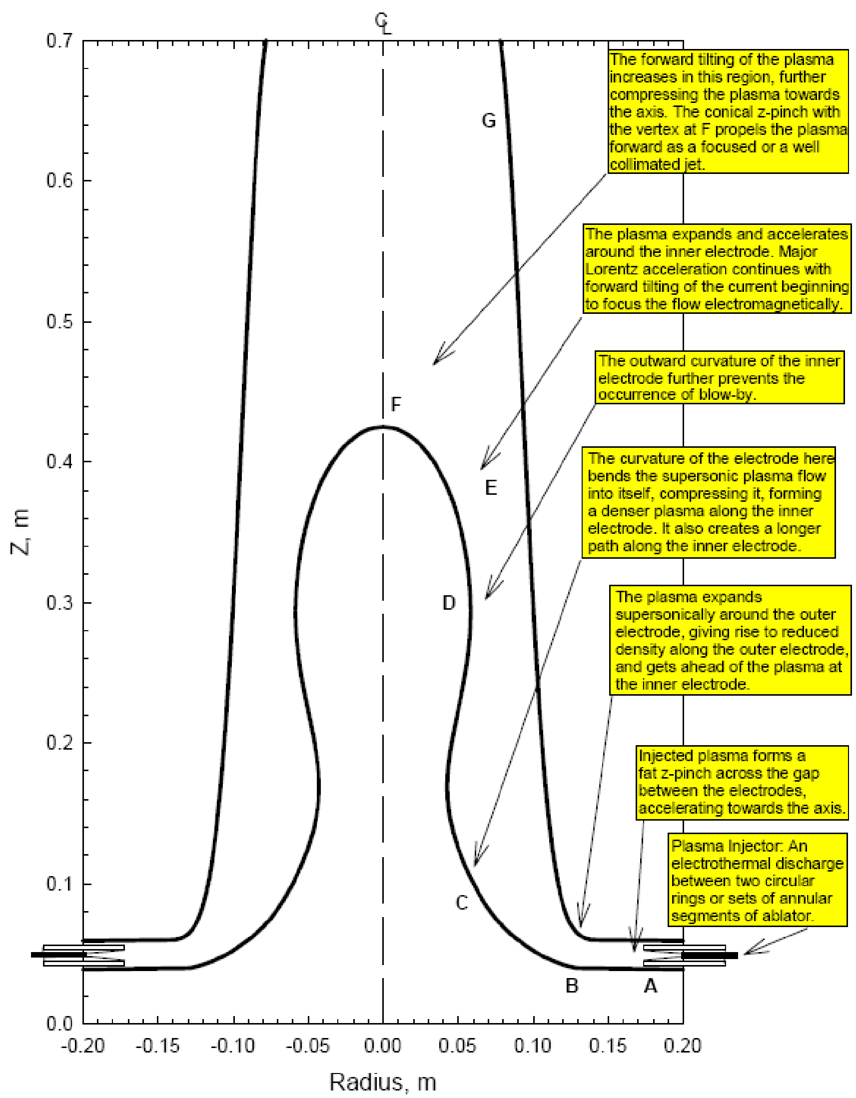
Plasma jets from capillary discharges merge to form a plasma liner (Witherspoon, 2007)

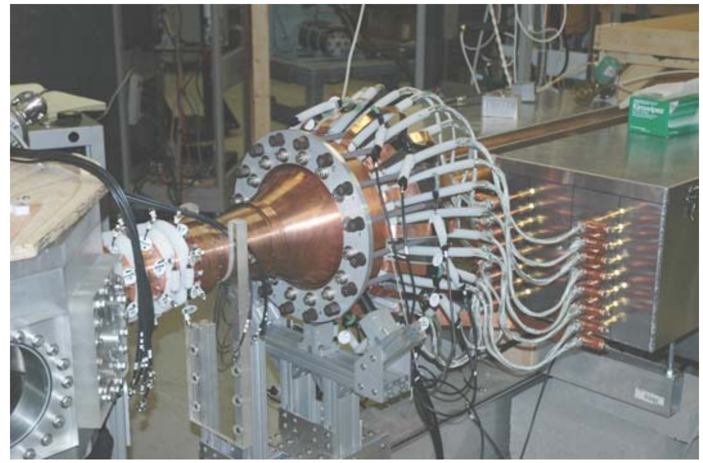
- Very high Mach-number plasma flows have been seen in wire-array Z-pinch
- Radial plasma flows stagnate on axis forming dense HED plasmas

(Bott, et. al. Phys Rev E, 74, 2006)

- Address 3 major issues for low-to-intermediate gain MIF
    - Standoff delivery of liner
    - Repetitive operation
    - Liner fabrication and cost
- Plasma jets with Mach number > 20, 10^{17} per cm^3, 200 km/s, are required in order to produce implosion with radial convergence > 10, and pressures > 1 Mbar

Advanced coaxial plasma gun to accelerate plasma slab without the blow-by instability is under development

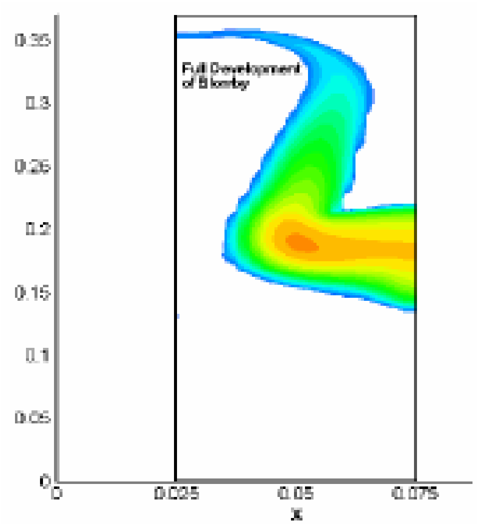


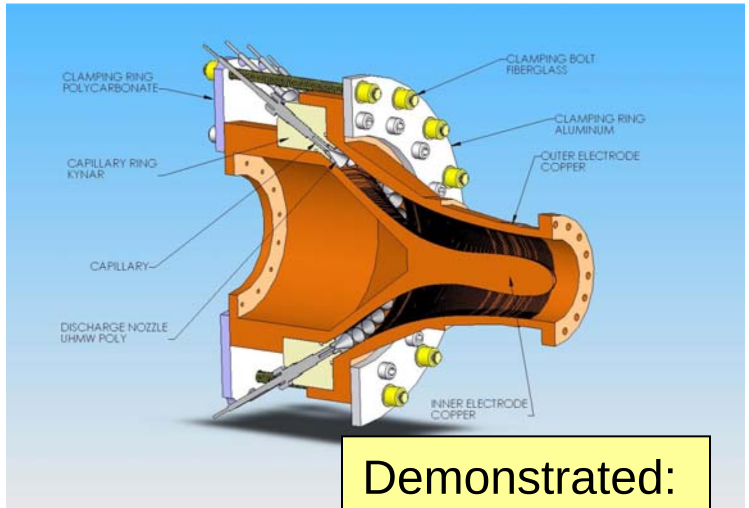


Pulsed power facility to develop advanced plasma guns at HyperV Technologies Corporation, Virginia, USA

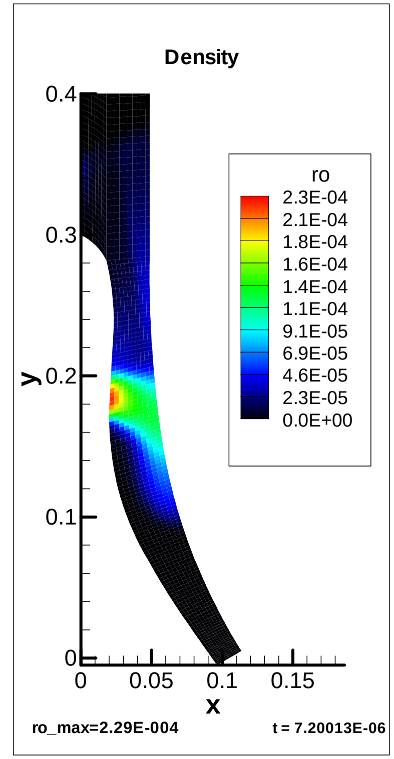
- By 2010, demonstrate Mach > 10, 10^{16} per cc, 200 km/s
- If successful, (1) demo jets merging to form imploding liner, (2) demo Mach > 20, 10^{17} per cc, 200 km/s by 2012.

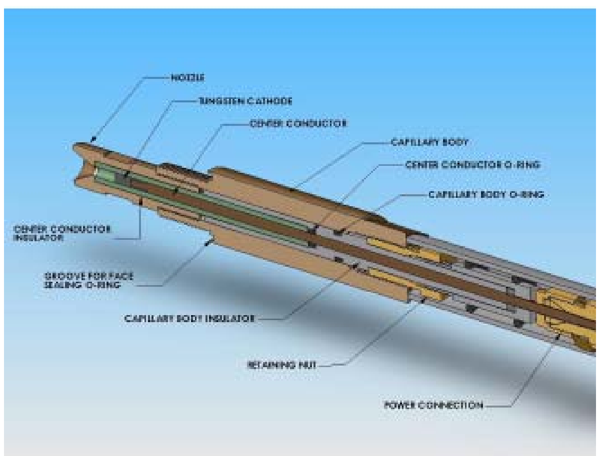
Development of High Mach Number Plasma Jets

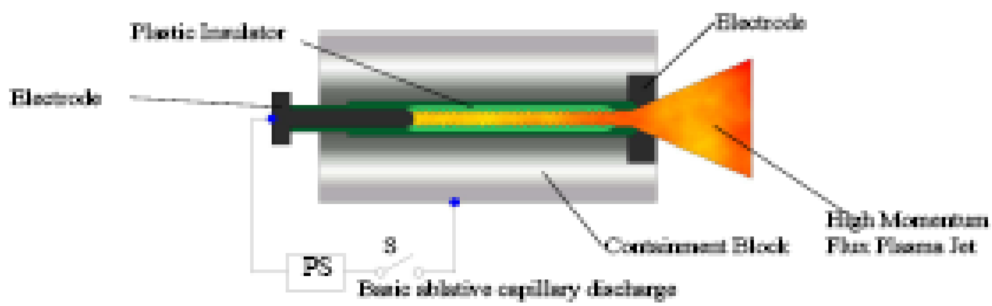




Demonstrated:
157μg, 70km/s

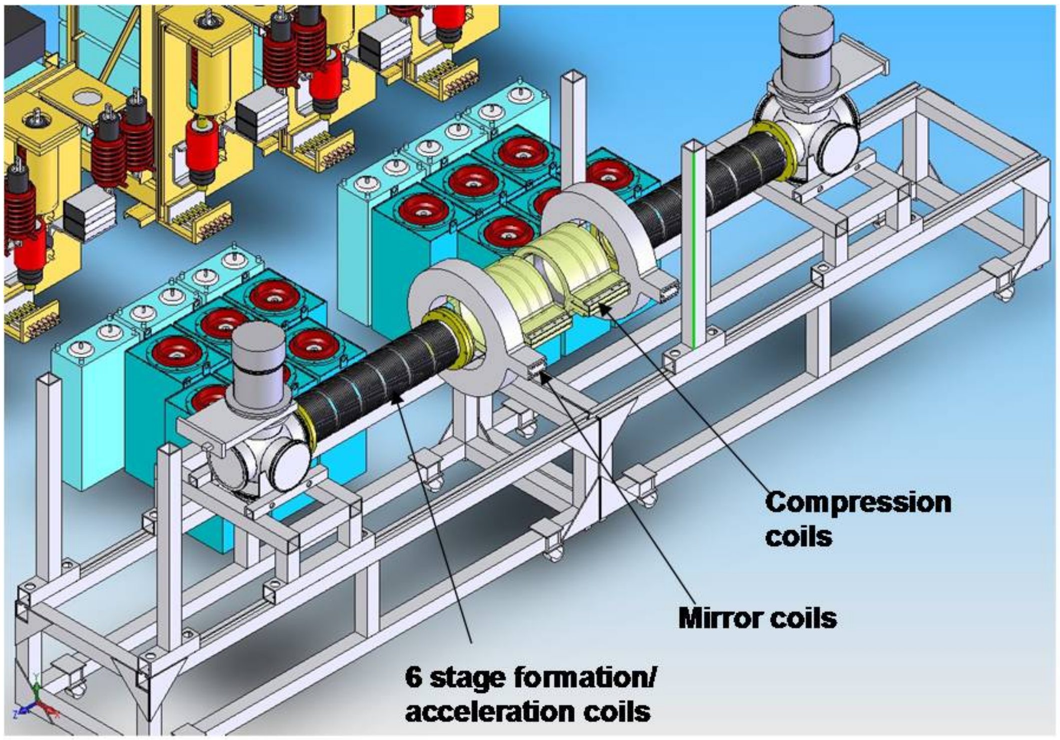






Experiment to study the behavior of the magnetized target plasma imploded by a plasma liner

- θ-pinch is a convenient way of generating cylindrical plasma shell for imploding a magnetized plasma.



Experimental facility under development at the U. Washington – Seatle

• Two inductive plasma accelerators (IPA) have been developed, each accelerate an FRC to ~ 200 km/s

• The two FRC collide forming a hot FRC of ~ 500 eV

• Cylindrical plasma liners will be generated by a θ-pinch to implode the FRC

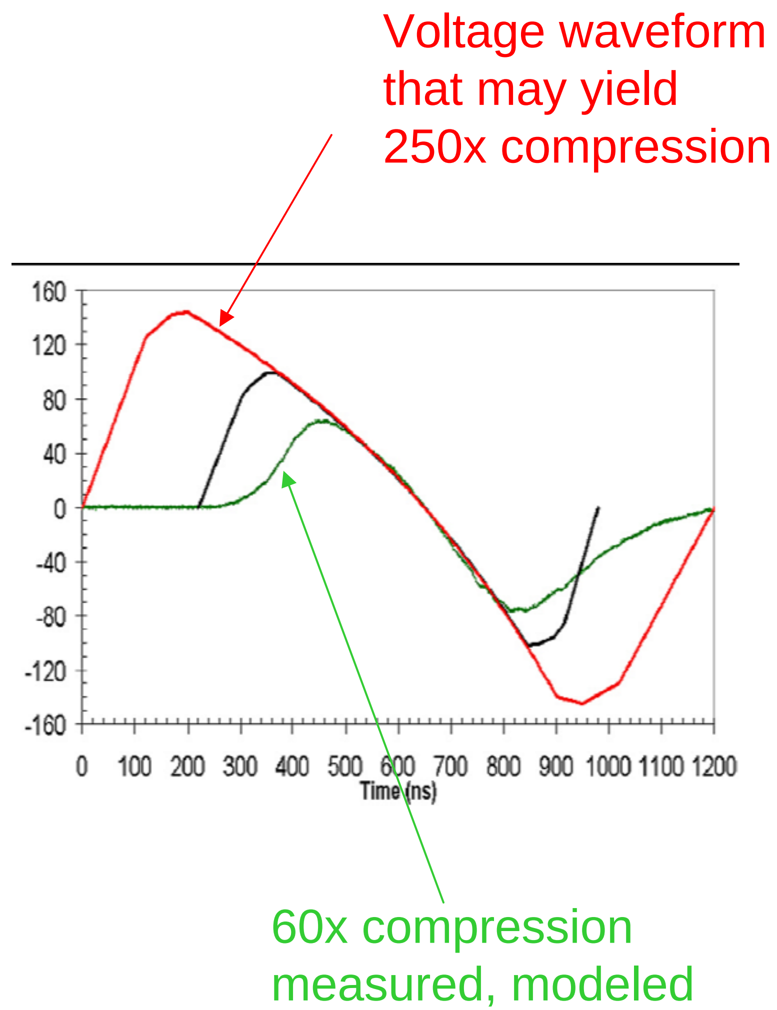
• Create high density (> 10^{19} per cm^3) and multi-keV magnetized plasmas over the next five years

In summary, for magneto-inertial fusion, the research over the next five years will address the questions …

- *How can strong magnetic fields be created in the hot spot of conventional ICF and what limits the intensity of the field that can be created?*
- *What limits the temperature, density, and dwell time of a magnetized plasma imploded by a solid liner or a plasma liner?*
  - *How do nearby boundaries (walls) driven by intense magnetic and radiation fields turn into plasmas? Will the impurities transport across the magnetic field?*
  - *What are the stability and the transport properties of the magnetized plasma during the implosion?*
- *How can plasma be formed, accelerated and focused to form dense, high Mach number, high velocity plasma jets and plasma liner suitable for compressing a magnetized plasma to thermonuclear temperatures and for magnetized HEDLP research?*

We are conducting research in heavy ion fusion science

- At the Lawrence Berkeley National Laboratory, with collaboration from Lawrence Livermore and Princeton Plasma Physics Laboratory, we are developing a heavy ion beam facility for research in:
  - Warm dense matter and strongly coupled plasmas
  - HED physics of inertial fusion energy sciences (IFES)
  - Non-neutral plasma physics
- Develop longitudinal neutralized drift compression (NDC)
  - Velocity ramp
  - Plasma neutralizes the space-charge electric field

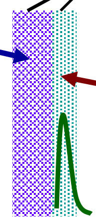


Double-pulse planar target interaction experiments should reveal unique *heavy-ion direct-drive coupling physics*

Solid D_2 "payload"

Payload and ablator D_2 layers are doped with different impurities to diagnose optical depth modulations

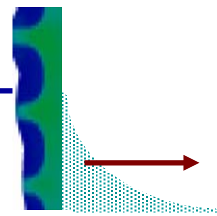
Time just before first pulse



Ablator D_2 layer ~ > than initial ion range

First ns ion beam pulse dE/dx (beam enters from the right)

Time ~ 10 ns later before second pulse arrives

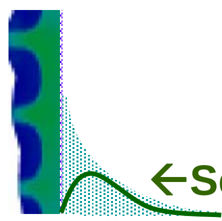


RT "bubbles & spikes" grow measurable amplitudes.

(1) Can upstream beam GHz RF modulation reduce RT?

(2) Do RT non-uniformities in ablation plasma smooth out with time and distance (any "ablative stabilization")?

2nd higher energy ion pulse arrives, and stops ***partly within ablation blow-off*** (in 1-D)

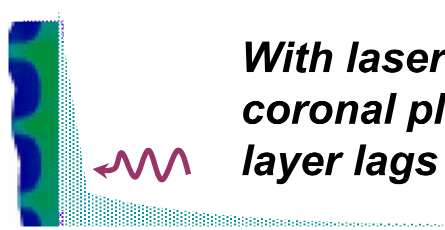


(1) "Rocket science": what ion range/ablator thickness maximizes hydro implosion efficiency with later ion pulses interacting with ablation layer mass?

←Second ns ion beam pulse dE/dx

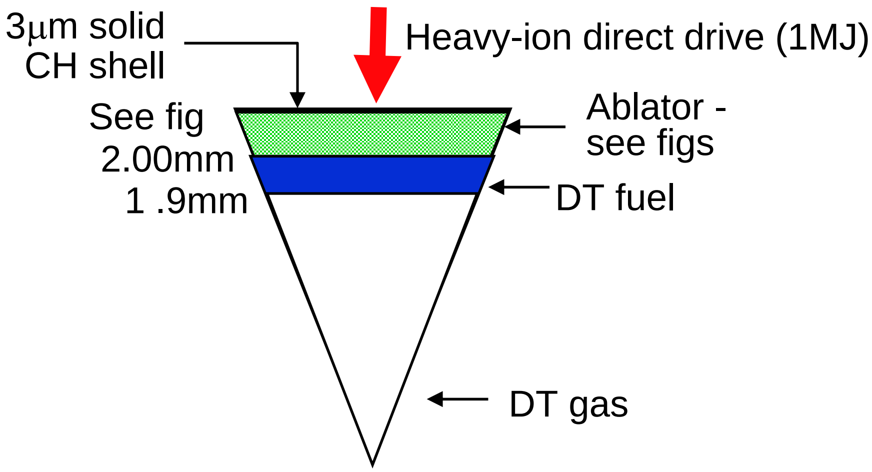
(2) How is RT growth affected (any "cloudy day" effect?)

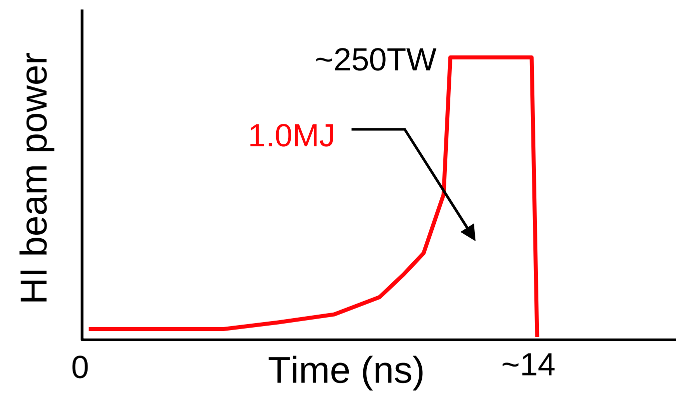
With laser direct drive, later pulse ablates at fresh critical density layer further left

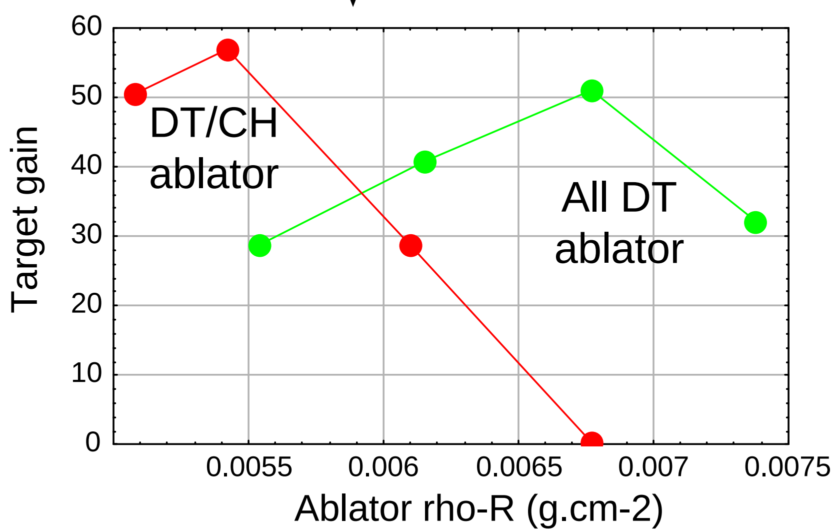


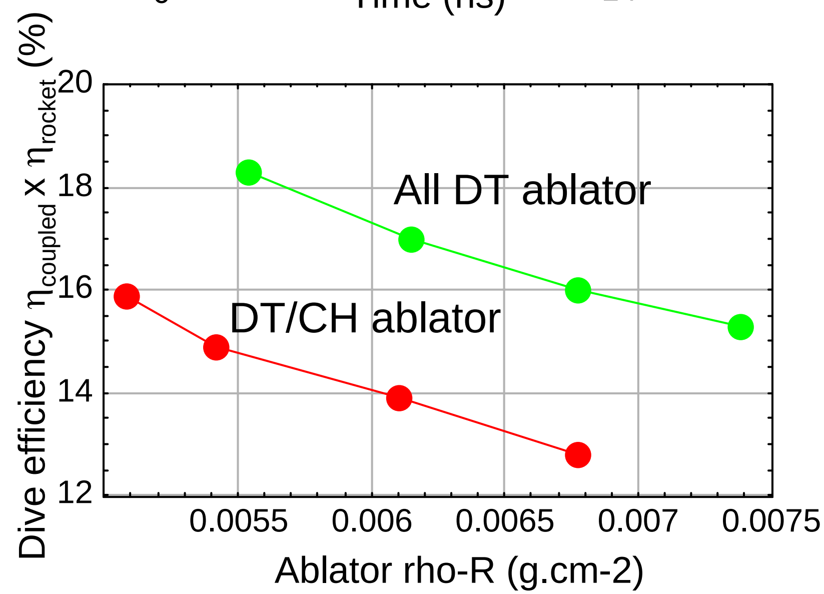
With laser direct drive, light transmits through most coronal plasma → Absorption in inverse bremsstrahlung layer lags behind dense shell trajectory

First heavy-ion direct drive LASNEX runs by John Perkins (LLNL) suggests gains ≥ 50 at 1MJ with high drive coupling efficiencies > 15% beam to ignition fuel energy





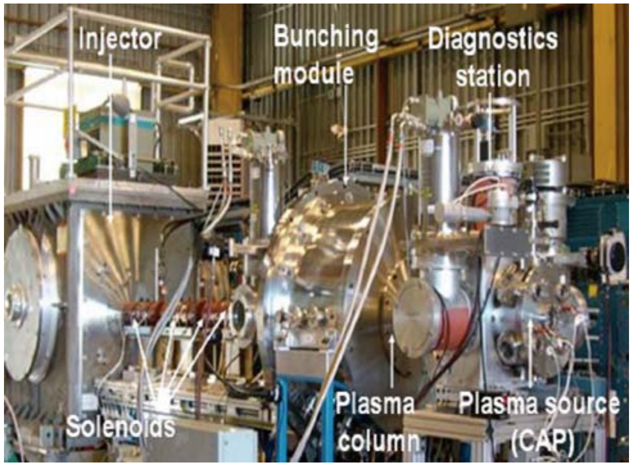


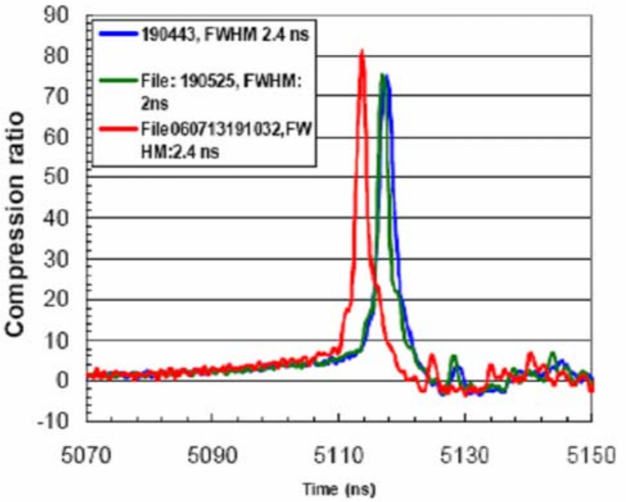


Higher drive efficiencies (≥20%) may be possible by ramping the ion kinetic energy during the drive, 50 → 200MeV, as the capsule implodes

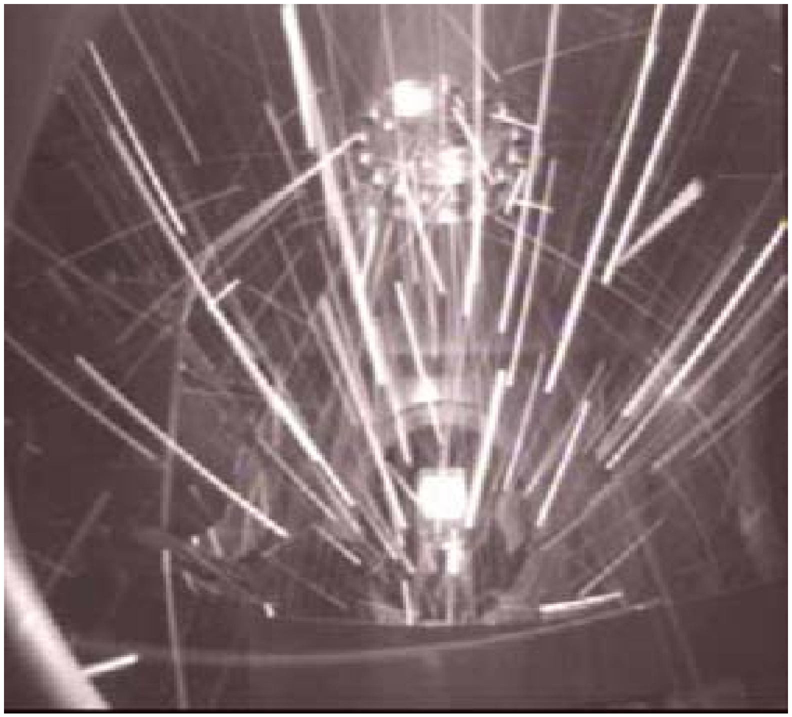
Current Activities in Heavy Ion Fusion Science

- NDCX-1 has compressed ion beams from 200 ns to 2 ns
  - 60x in beam intensity with ~0.2 MeV ions
- Begun heavy-ion driven isochoric target heating experiments to 1 eV in joint experiments with GSI, Germany,
- Measurements of electron cloud effects on intense heavy-ion beam transport in both quadrupole and solenoid magnets.
- Computer simulation models matching experiments in both neutralized beam compression and e-cloud studies.
- Running HYDRA code to explore new heavy ion fusion direct drive target concept





Joint experiments with GSI in isochoric heating & expansion

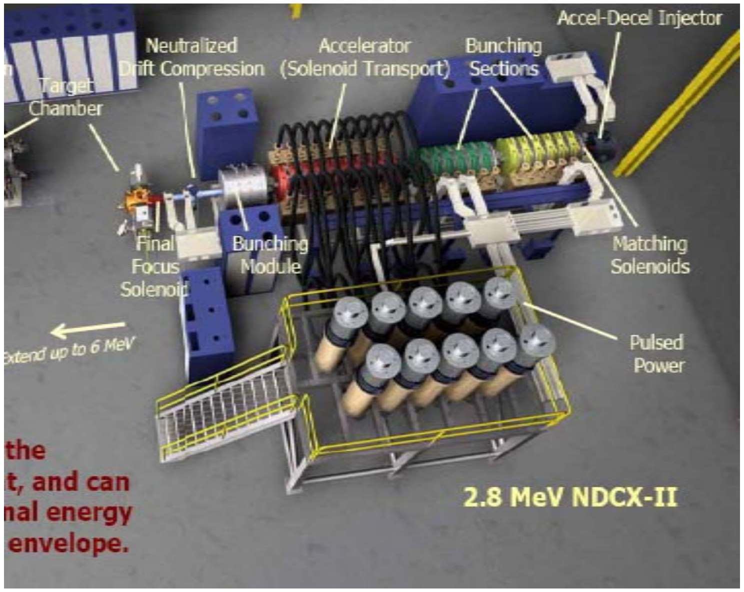


Visible ms camera frame showing hot target debris droplets flying from a VNL gold target (~ few mg mass) isochorically heated by a 100 ns, 10 J heavy ion beam to 1 eV in joint experiments at GSI, Germany (see ThO7.2-Tahir)

- **Measuring two-phase WDM EOS and expansion of target materials @ 1 eV can benchmark and improve models relevant to isochoric neutron heating effects in NIF high yield shots (see poster MPo72 by Eder).**

Program Plan for Heavy Ion Fusion Science

- NDCX-I (by 2008)
  - Develop longitudinal neutralized drift compression of ion beam
  - Integrate neutralized drift compression with transverse (ballistic and magnetic) focusing
  - Demonstrate intensity amplification of ~ 1000X
  - Conduct first beam-on-target WDM experiments in 2008 (~ 0.5 eV and solid density; transient darkening experiment)



- Develop NDCX-II (2011)
  - 2.8 MeV, high-intensity beam
- WDM studies at ~ 1 eV
- HED physics for IFES
  - **Hydrodynamics experiments for stability and ion ablative direct drive target physics**
  - **Explore heavy ion fusion in two-sided polar direct drive**

Summary

- The US Office of Fusion Energy Sciences is conducting a program of research in high energy density laboratory plasmas (HEDLP), motivated by the science in
  - Achieving the grand challenge of fusion energy enabled by high energy density plasmas
  - Creating, probing and controlling new states of HED plasmas
- The present program involves 5 government laboratories (4 DOE national lab and 1 DOD lab), 13 universities, 5 private companies, 57 full-time-equivalent researchers, and 35 graduate students.
- It highly leverages the facilities and resources of the National Nuclear Security Administration
- Plans are being considered for expanding the program in breadth and scope