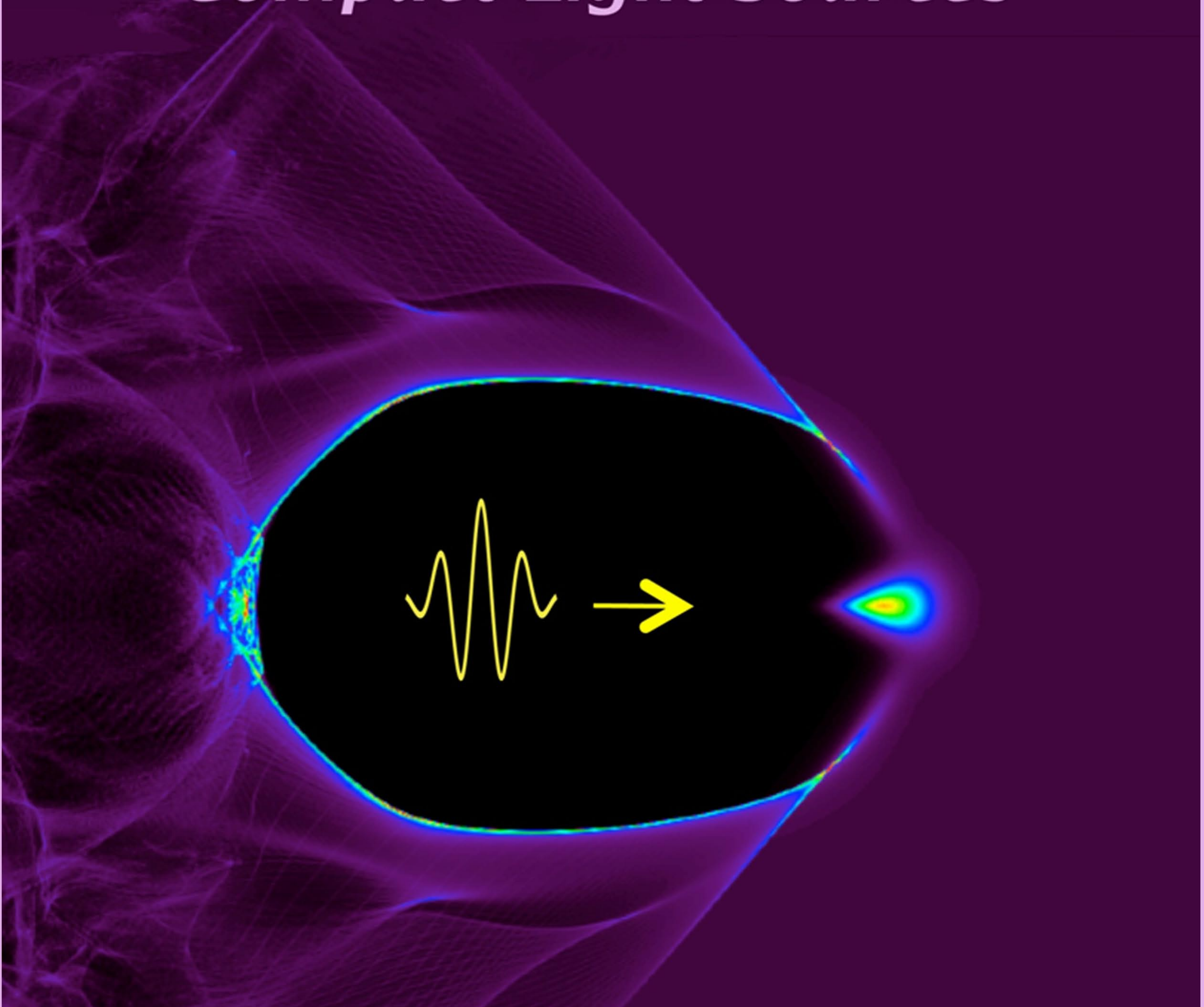
Report of the

Basic Energy Sciences Workshop on *Compact Light Sources*



May 11–12, 2010

On the Cover

The cover figure depicts simulation results from a method for producing coherent x-rays via high-harmonic generation (HHG) using ultra-intense lasers interacting with highly stripped ions in plasmas. An ultrashort pulse laser (represented schematically in yellow) propagating in the plasma cavity generates laser harmonics. This method enables harmonic generation to be extended to the sub-Å regime.

Coherent soft x-ray and vacuum ultraviolet light sources are of interest for many applications, and HHG is a compact method for producing ultrafast, coherent light in this spectral region. In HHG, an ultrashort intense laser is focused into a gas, generating multiharmonics of the laser frequency.

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Inverse Compton Sources

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Plasma-Based Accelerator Sources

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May 11-12, 2010 – Rockville Hilton, Rockville, MD

Executive Summary

The BES-sponsored Workshop on Compact Light Sources examined the state of the technology for compact light sources and their expected progress. The workshop evaluated the cost efficiency, user access, availability, and reliability of such sources. Working groups evaluated the advantages and disadvantages of CLS approaches, and compared their performance to the third-generation storage rings and free-electron lasers (FELs). The primary aspects of comparison were 1) cost effectiveness, 2) technical availability v. time frame, and 3) machine reliability and availability for user access. Five categories of potential sources were analyzed: 1) inverse Compton scattering (ICS) sources, 2) mini storage rings, 3) plasma sources, 4) sources using plasma-based accelerators, and 5) laser high harmonic generation (HHG) sources.

Overarching Conclusions

Compact light sources are not a substitute for large synchrotron and FEL light sources that typically also incorporate extensive user support facilities. Rather they offer attractive, *complementary capabilities* at a small fraction of the cost and size of large national user facilities. In the far term they may offer the potential for a new paradigm of future national user facility. In the course of the workshop, we identified overarching R&D topics over the next five years that would enhance the performance potential of both compact and large-scale sources:

- Development of infrared (IR) laser systems delivering kW-class average power with femtosecond pulses at kHz repetition rates. These have application to ICS sources, plasma sources, and HHG sources.
- Development of laser storage cavities for storage of 10-mJ picosecond and femtosecond pulses focused to micron beam sizes.
- Development of high-brightness, high-repetition-rate electron sources.
- Development of continuous wave (cw) superconducting rf linacs operating at 4 K, while not essential, would reduce capital and operating cost.

Inverse Compton Sources

This concept is based on inverse Compton scattering (ICS), which is the back-scattering of light from free electrons. If electrons having relativistic factor γ scatter photons having wavelength λ, the scattered photons have wavelength $\lambda/4\gamma^2$. For example, 0.1-nm x-rays result from scattering an IR laser from a 25-MeV electron beam. To produce significant flux, both beams must be tightly focused at the interaction point, giving a strongly divergent x-ray beam that is ideal for some imaging applications. Uniquely among compact hard x-ray sources, the photon wavelength may be varied over a broad range by varying the electron beam energy. In addition, such a source is compact and relatively low cost, with estimates of 10~15 M$ for commercial systems supporting a single beamline.

The average flux and brightness, while significant, cannot compete with third-generation storage rings. Femtosecond x-ray pulses are feasible, but cannot compete with FELs in peak flux or brightness. (The current state of the art for ICS sources is such that only incoherent radiation is available, although there are concepts for making use of coherent emission to significantly enhance performance.) In addition, existing sources support a single operating beamline at a time, although multi-beamline concepts exist.

Several ICS sources are already in existence for both cw and pulsed applications. For cw applications, the commercially available source from Lyncean Technologies, Inc. (LTI), a source based on the JLab IR FEL, and a bunch-train-based source at KEK have demonstrated ICS at bunch repetition rates of 65~165 MHz. LTI has achieved an average flux of 10^{11} ph/s/0.1%BW and average brightness of 10^{12} ph/s/mm^2/mrad^2/0.1%BW, and has used their source for crystallography and phase-contrast imaging. For pulsed applications, a source at BNL's Accelerator Test Facility has demonstrated peak brightness in excess of 10^{20} with 5×10^8 photons/pulse at 10 Hz in a 50% bandwidth. The MIT concept would significantly improve the peak brightness, giving 10^{23} with 10^8 photons per pulse.

Considerable effort is proceeding in Japan, China, and Europe to develop such x-ray sources. KEK has an ongoing effort that is expected to culminate in an ERL-driven source in 2014. Thales/CEA are developing a ring-based source similar to the LTI effort. Significant R&D, particularly into lasers, laser storage cavities, high-brightness guns, photocathodes, and superconducting technology, is required in order to realize the full potential of these sources. Much of this R&D work is common to ICS sources and other advanced light source concepts.

Cost of these devices, whether based on a storage ring or a superconducting linac, is $10-15 M per system, exclusive of R&D. Storage-ring-based systems exist already and are commercially available (Lyncean Technologies) or under development (Thales/CEA). Superconducting-linac-based systems are now under development (KEK) or proposed (MIT). The estimated cost for the first article is $30 M. These devices will serve a single beamline. They are comparable in cost to a complex, state-of-the-art undulator beamline at a major synchrotron light source facility with the advantage of great flexibility in where they can be located.

High-Harmonic Generation Sources

High-harmonic generation (HHG) in gases driven by femtosecond lasers offers a standalone, tabletop-scale, tunable EUV/XUV source with full spatial and temporal coherence and ultrafast pulse duration. Moreover, since the laser pulse energy required to generate harmonics is < 5 mJ, the repetition rate of HHG sources can scale to 100s of kHz or higher. HHG can be understood in a semi-classical picture, in which an atom is tunnel ionized by the intense electromagnetic field of an ultrashort pulse laser. The emitted electron accelerates in the laser field, gaining energy that can subsequently be released as harmonics of the fundamental laser if the electron recombines with the ion. Bright harmonic beams are emitted if the emission from many atoms in a medium are combined together coherently (phase matched). Conversion efficiencies from laser to harmonic flux in the range of 10^{-7} – 10^{-5} per harmonic per pulse can be achieved when the frequency conversion process is phase matched (corresponding to ≈ μJ per harmonic per pulse). The high-harmonic spectrum and pulse duration can be controlled by manipulating the macroscopic phase matching conditions and the electron recollision process. This allows the pulse duration to be adjusted from tens of femtoseconds to < 100 attoseconds—the shortest pulse durations of any light source to date, and significantly shorter than a single optical cycle of the fundamental driving laser. One great advantage of HHG sources is that the emission is perfectly synchronized to the driving laser. To date, bright high harmonics at photon energies of ~ 0.5 keV has been achieved, and bright beams at energies exceeding 1 keV are foreseen within the next few years using mid-infrared driving lasers.

Many applications of HHG sources have already been demonstrated in ultrafast molecular and materials science and nanoimaging using EUV photon energies < 150 eV. Efforts are underway throughout the world to extend these applications into the soft x-ray region, and to develop HHG sources as seeds of soft x-ray FELs. The cost of current HHG systems that deliver beams in the EUV spectral region is relatively low (< $1 M) and use commercially available Ti:sapphire driving lasers with up to 50 W average power (e.g., systems that deliver 10 kHz, 3 mJ; 10 Hz, 300 mJ; 50 kHz, 1 mJ and pulse durations ≈ 25 fs can be readily purchased). Future HHG sources that can extend into the soft x-ray regions to ≈ 1 keV will be slightly higher initially (~ $2-4 M), with the pace of progress governed by future developments of mid-IR lasers. Such research is being pursued worldwide.

The principal technical challenges with future HHG sources are associated with the mid-IR laser development needed to generate bright harmonics in the soft x-ray region (0.2–1 keV and higher), the need for very high average flux (approaching MHz levels for some experiments), and the need for very high energy-per-pulse HHG generation for applications in x-ray nonlinear optics. To the extent possible, these advances should be done though collaborations between leading groups in universities and national labs with commercial partners, with U.S. industry prominently represented. Such partnerships would ensure a rapid pace of progress, strengthen U.S. science and industry, and ensure that advances in this area will become broadly available to maximize the range of science and technology that would benefit from advances in HHG sources—particularly the smaller-scale high-average-power x-ray sources that have potential for industrial application.

Advances in the technology of these compact light sources will require investment in a moderate number of “mid-scale” facilities that implement a coordinated program in both technology development and in applying these compact light sources to a range of applications in materials science, AMO science, nanoscience, and chemical sciences. To extend bright, high-average-power harmonics to the keV region and beyond, initial investments of $2–4 M are needed. Once the facility is developed, it would contain more than one HHG source, where two research teams could access a beamline for extended periods. An operating cost in the range of $1M/yr is expected, including salaries for research and maintenance. For high-energy lasers at low repetition rates used to generate mJ harmonic pulses, somewhat higher operating costs are anticipated.

Laser-Driven Plasma Sources

Laser-driven plasma x-ray (LPX) sources emit ultrashort, hard x-ray pulses and rely on the interaction of ultrashort laser pulses with solid density materials, such as metal surfaces. The subsequently generated x-rays in the angstrom wavelength regime are emitted into 4π synchrotron radiation and consist of line radiation, which has been used for ultrafast x-ray diffraction, and continuum radiation, which has been used for ultrafast x-ray absorption spectroscopy. The radiation has also been applied to x-ray phase-contrast imaging, which works well with polychromatic emission and benefits from the large x-ray emission angle achieving a large field of view. The LPX source and its driving laser fit onto a 10′ × 5′ optical table.

The x-ray pulse length can be shorter than 100 fs. Depending on the target material and the properties of the laser driver, x-radiation with photon energies of tens of keV can be generated. The x-ray wavelength is not tunable but can be selected by choosing different target materials.

The x-ray flux delivered onto a sample can be as high as 6×10^6 ph/pulse 0.1% BW. Systems with repetition rates of up to 5 kHz are currently in use.

LPX sources are based upon a mature understanding of the underlying physics and upon robust technology. Development from the current technology readiness level of 6–8 (depending on source design details) to a level of 8–9 requires primarily system engineering and can be accomplished in 3 to 4 years at a cost of $500 K/year.

The total system cost (driver laser plus x-ray source) is estimated to be $1.5 M with an operation budget of $20/hour and the cost of one laser/beamline scientist.

LPX sources, synchrotron x-ray sources, and x-ray lasers form a symbiotic community. Each source type addresses specific needs of the scientific community, such as average and peak x-ray flux, x-ray pulse lengths, available beam time, and cost effectiveness. LPX sources are best used for applications that are x-ray flux limited but not brightness limited, such as x-ray phase-sensitive imaging, and ultrafast x-ray diffraction and absorption of molecular structural dynamics. Furthermore, LPX sources can serve as training environments for ultrafast experiments at third-generation sources and x-ray FELs.

Sources Based on Plasma-Based Accelerators

In the five- to ten-year time frame, plasma-driven accelerators may form the basis for user facilities that would produce coherent, high peak brightness, ultrafast pulses for time-resolved experiments. Such facilities might be built around the concept of a compact, coherent seeded free-electron laser based x-ray source, driven by a laser-plasma accelerator (LPA) or plasma wakefield accelerator (PWFA). This possibility is based on rapid advancements in high-power laser technology and the demonstration of accelerating gradients well in excess of 10 GeV/m using both LPAs and PWFAs. In addition, a PWFA might be used to extend the reach of an existing x-ray FEL facility by increasing the energy of the accelerator driver. Both types of plasma-based accelerator yield ultra-short (fs), multi-kiloampere electron bunches that may be suitable for driving an x-ray FEL if the requisite low emittance and energy spread can be demonstrated in research to be performed over the next five years. An LPA-based facility could deliver synchronized pulses of fs radiation, particles, and laser light, all from one compact machine. In addition to being hyperspectral, such a source would also allow the direction of the x-ray light to be changed by changing the accelerator direction via rerouting of the laser beams. Plasma-based accelerators may also allow, in a single facility, the possibility of providing many small, GeV-class linacs, each of which would be tailored in energy to drive an FEL of different wavelengths from the EUV to hard x-rays.

The range of photon energies available from plasma-based accelerators could be extended to multi-MeV gamma rays by using inverse Compton scattering or radiation due to the betatron motion of particles in the electron bunch as it passes through a dense plasma channel. Unlike the radiation from the FELs, the radiation in these latter cases would be incoherent.

At present a disadvantage of plasma-based accelerators is that the repetition range is presently limited to ~100 Hz for LPAs and a few hundred Hz for PWFAs. The cost and performance limits of LPA facilities will depend on the further development of high average power, multi-TW lasers. For driving hard x-ray FELs, facilities based either on a LPA or PWFA are likely to be in the range of $20-40 M$.

Compact Storage Rings

Storage rings have a long history of success as flexible, multi-user synchrotron radiation sources from the IR to x-rays. However, major storage ring facilities are complex and expensive and, in spite of each being able to serve numerous simultaneous users, have insufficient capacity, especially on the highest-performance beamlines, to meet demand. Because of this, third-generation storage-ring-based light sources continue to be built around the world. Among the characteristics of third-generation light sources is optimization of the emittance and emphasis on high-performance insertion devices. These choices allow delivery of very high brightness and flux, but drive up the complexity and cost of the facility, while at the same time reducing the number of available beamlines for a given circumference.

Recognizing that many potential users of synchrotron radiation do not require the highest possible performance, an alternative concept is to step back from a fully optimized third-generation design, emphasizing instead low cost and high capacity. In this concept, one can eliminate the use of insertion devices, thereby making it possible to obtain reasonably low emittance (e.g., 10 nm) in a compact ring (e.g., 60- to 80-m circumference) at moderate energy (e.g., 1.5-2 GeV). Storing high current (e.g., 500 mA) and using a combination of normal- and superconducting dipole magnets (5 T) would allow delivering a significant flux of hard x-rays over a broad spectrum. Such a facility could support up to 40 bending magnet beamlines, perhaps half of which would be on superconducting dipoles, providing a flux of about 4×10^{13} photons/second/mrad/0.1%BW at 8 keV. This is the same as provided by productive superbend beamlines at ALS). Flux above 4×10^{12} would be available from about 8 eV to 80 keV.

The estimated cost (excluding beamlines) is about $50 M if built by industry. This estimate is based on recent community experience building or purchasing relatively small, third-generation facilities and their booster synchrotrons. Beamlines would cost perhaps 2.5 M$ each. Assuming 40 beamlines, the total cost is 150 M$.

The advantages of this approach include high flux, moderate brightness, many beamlines, low overall cost per beamline, relative ease of operation, and high stability. In addition, no significant R&D is required in order to create such sources. One might build several such facilities to conveniently serve specialized user communities throughout the U.S. For example specialized sources could service significant biohazard facilities or could conduct classified research. Disadvantages of this approach are that, while small, it is not a “tabletop” source. There is also very little potential for short pulses.

Section 1: Inverse Compton Sources

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A. Physical Basis

Inverse Compton scattering (ICS) is the scattering of electrons on photons. From a classical point of view, the process is referred to as "Thomson scattering" [1-1] and can be visualized as a plane wave of frequency ω_0 impinging on an electron. In the approximation where laser energy is much lower than rest electron energy (i.e., in the rest electron frame), the scattered electromagnetic wave frequency is conserved. In the laboratory frame, as electrons are relativistic, the incident electromagnetic wave undergoes two frame changes, and its frequency is increased by a $4\gamma^2$ factor due to the relativistic Doppler effect. In quantum electrodynamics, ICS is visualized as a succession of absorption and emission of a photon by an electron. In this approach we refer to "Compton scattering," which lets us consider electron recoil and particle polarization. The process is described as the collision between photons and electrons. This collision is elastic, so the interaction parameters can be calculated according to energy and momentum conservation. The scattered photon energy is a function of electron energy, laser wavelength, collision, and scattering angles:

$$E_x = \frac{E_p\left(1-\beta\cos\theta_1\right)}{\left(1-\beta\cos\theta_2\right)+\dfrac{E_p\left(1-\cos\left(\theta_2-\theta_1\right)\right)}{E_e}}\,, \tag{1}$$

where E_X is the energy of the scattered photon, E_p is the energy of the laser photon, E_e is the energy of the electron, γ is the relativistic factor, θ_1 is the collision angle, and θ_2 is the scattering angle (see Figure 1-1).

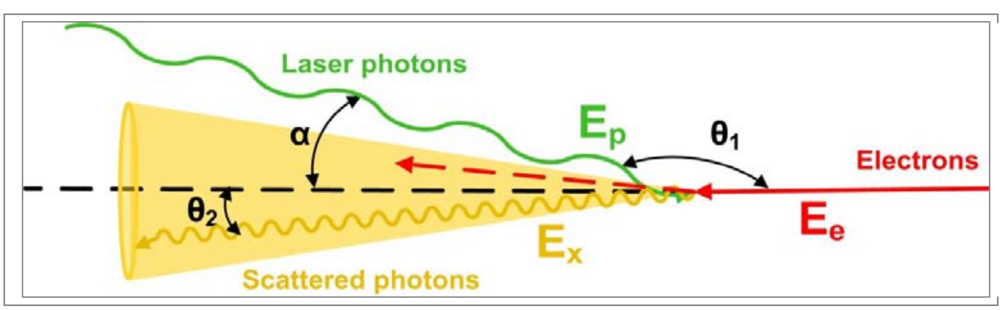

Figure 1-1: *Schematic view of the photon-electron interaction.*

For a given angle θ_1 between laser beam and electron beam directions, the scattered photon energy is maximal in the direction of the electron beam ($\theta_2 = 0$). If we consider a head-on collision ($\theta_1=\pi$), the scattered photon energy E_X becomes

$$E_x = 4\gamma^2 E_p \, . \tag{2}$$

Head-on scattering of an IR laser with a wavelength of 1 micron from a 25-MeV electron beam produces 0.1-nm (or 12-keV) x-rays. Examination of these equations shows that ICS has several interesting characteristics:

1. The scattered photon energy depends on the collision angle, incident photon energy, and incident electron energy, which gives several options for creating a continuously tunable source. For example, an accelerator delivering energies between 20 and 40 MeV could cover the photon spectrum between 8 and 30 keV, assuming an IR laser.
2. The strong dependence on γ of the scattered photon energy allows having high-energy x- or γ-rays with a moderate-energy electron beam. This reduces the cost of the source.
3. Since the photon energy depends on the scattered angle θ_2, an aperture can be used to monochromatize the flux.
4. The emission cone is due to relativistic boost and is in the electron beam direction. The half angle of the cone is on the order of $1/\gamma$. Thus a high-energy electron beam can insure a narrow emission cone and so a higher photon beam brilliance.

Because of the modest electron beam energy, ICS sources are compact. Hence, they could be distributed to many countries and laboratories around the world, and put x-ray capability in locations where unique science can be done—in university nano-centers or pharmaceutical companies. A major increase in x-ray accessibility would be to make phase-contrast imaging available in hospital settings. Some of the most interesting and important applications involve work that cannot otherwise be undertaken, since the experiments are impossible at centralized facilities. Examples include combining x-ray and neutron beams in the same sample, studying membrane proteins that are too fragile to be transported, studying precious museum art objects that cannot be transported, studying highly pathogenic proteins for which there is inadequate biohazard containment at the central facilities, and studying materials in the ultrahigh magnetic fields available only at specialized centers. In this sense such distributed compact sources will be more available and user friendly than the large machines.

The photon scattering cross section is approximately given by the Thomson cross section: $\sigma_{TH} = 6.65 \times 10^{-29}$ m². This is quite a low value and implies challenges in obtaining high x-ray flux. The number of emitted photons is given by the product of the luminosity of the interaction by the cross section:

$$N_X = \frac{N_e N_p \sigma_{Compton} f_{rep}}{4\pi s^2}, \qquad (3)$$

where N_e is the number of electrons, N_p is the number of photons, f_{rep} is the repetition rate, and s is the rms beam size at the collision point. As this interaction has a low cross section, to increase the flux, we need:

- High electron bunch charge
- High laser pulse energy
- High repetition rate
- Small beam sizes at the interaction point. However, the beam size must be comparable to the bunch length to avoid reduced flux due to the hourglass effect.

Any workable technical approach to creating an ICS source must address these issues.

B. Technical Approaches

Workable technical approaches to a high-flux ICS facility have been developed based on either a small storage ring (as shown in Figure 1-2) or a high-repetition-rate linac [1-1–1-4]. In addition, use of a laser storage cavity is essential in order to obtain sufficient laser pulse power and repetition rate. We will address these two topics in turn, as well as some alternative approaches.

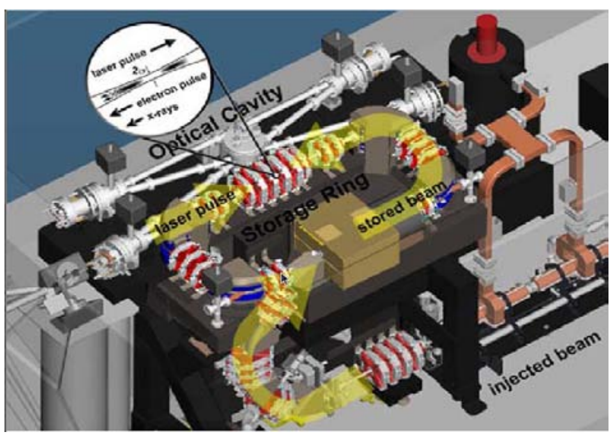

Figure 1-2: *CAD drawing of the Compact Light Source illustrating the laser-electron pulse interaction. Major components are the injector (electron gun not shown), the electron storage ring, and the optical cavity. Electron-photon scattering at the interaction point produces naturally collimated, narrow bandwidth x-rays that exit a window at the left of the figure. The storage ring is a rectangle of approximately 1 m × 2 m.*

Accelerator Options

Early efforts to create an ICS source made use of conventional room-temperature pulsed linacs, which have repetition rates limited to several hundred Hz, which significantly limits the flux. Three concepts have been suggested to improve flux: use of a small storage ring, use of a pulsed linac with bunch trains, and use of a cw superconducting linac.

Use of a small storage ring to recirculate the electron bunch can provide repetition rates of many tens of MHz. Because of the relatively low energy and small emittance, the beam emittance and energy spread gradually grow due to intrabeam scattering. Hence, the beam must be replaced periodically, at a rate (e.g., 30 Hz) that is easily managed with a pulsed room-temperature linac. This concept is the basis of the ICS available from Lyncean Technologies, Inc., shown in Figure 1-2, as well as the design proposed by Thales/CEA (see Figure 1-3). Photon energies between 8 and 90 keV are envisioned from such sources.

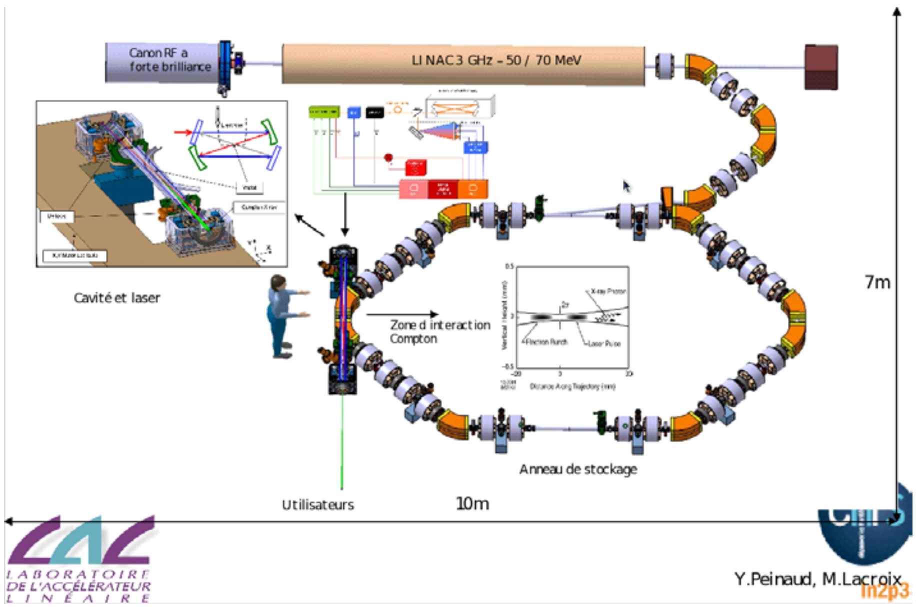

Figure 1-3: *Detailed layout of the THomX concept (Thales/CEA).*

A common feature of storage-ring-based sources is that the electron bunch length is quite long, e.g., many picoseconds. This is necessary in order to reduce the intrabeam scattering rate and reduce rf voltage requirements. Hence, like the large storage-ring-based x-ray sources, ring-based ICS sources are not suitable for experiments probing sub-picosecond phenomena.

This limitation of ring-based sources is addressed by linac-based concepts, since linacs are capable of delivering high-brightness beams with sub-picosecond bunch durations. As mentioned above, early ICS source concepts were based on pulsed linacs and suffered from lack of flux due to low repetition rates. One approach to resolving this, being pursued in the LUCX project at KEK [1-5] is use of a bunch train. The bunch rate within the train is matched to the laser cavity round-trip time, so that each linac bunch produces x-rays. This approach has been applied to an existing room-temperature linac as a demonstration and development platform, and will soon be applied to a pulsed superconducting linac. The disadvantage of this approach is that the bunches in each train are very closely spaced, which reduces the usefulness of the source for timing experiments.

Another linac-based approach is proposed by MIT [1-2], using a cw superconducting linac that supports high repetition rates without such closely spaced bunches. This is illustrated in Figure 1-4. As in any linac, the average electron beam current is limited by considerations of power consumption and the challenge of safely dumping the used beam. This can be mitigated by using an energy recovery linac (ERL). A test of this approach is planned as part of KEK's Compact ERL project.

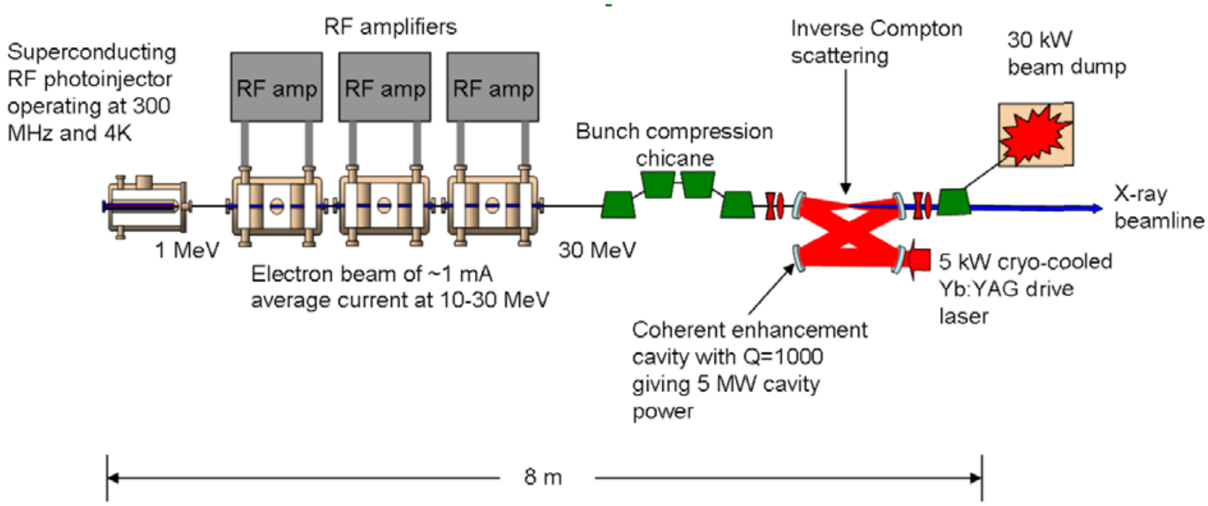

Figure 1-4: *Layout of MIT inverse Compton scattering x-ray source in its most compact configuration. Additional space is required for cryogenic equipment and radiation shielding.*

In both storage-ring- and linac-based sources, the highest flux is nominally obtained when the electron and photon pulses are focused to the smallest spot size. However, if the spot size is much smaller than the length of the pulses, the flux will be reduced because of the hourglass effect. Hence, making the spot size smaller than the pulse duration is not useful. Since linacs can deliver much shorter electron pulses, they can allow one to capitalize on smaller spot sizes. Thus, when other parameters (e.g., bunch charge, laser energy, repetition rate, emittance) are equal, a linac should provide higher flux and photons per pulse than a storage ring. In addition, compared to a storage ring, a single-pass linac-based source is better able to achieve both small electron beam emittance and small focus at the interaction point since, unlike a storage ring, it does not suffer appreciably from intrabeam scattering and does not have the optics constraints imposed by the need to maintain stored beam.

Laser and Laser Storage Cavity

Because the cross section is so low, the fraction of photons that are scattered from the laser pulse is extremely small. Hence, it is extremely inefficient to discard the laser pulse after a single collision. A better approach is to use a laser storage cavity to recirculate the laser pulse for repeated use. This greatly reduces the required laser power. Further, it allows one to accumulate energy in the pulse, which further improves flux. All the projects and proposals mentioned above make use of this technique, with various geometries. For example, the LTI source uses a bow-tie cavity bracketing two dipole magnets, providing head-on collisions, while the KEK source uses a compact cavity that requires a slight deviation from head-on geometry.

In addition to standard, incoherent ICS, where all electrons scatter radiation in an independent, uncorrelated fashion, the MIT proposal advances the possibility of coherent ICS. The concept becomes clearer if we invoke the analogy between the laser and an undulator magnet. In an undulator magnet, if the electron beam is bunched at the wavelength of the emitted radiation, then emission is coherent, and intensity is enhanced by a term proportional to N_e^2. If significant technical challenges can be overcome, this has the potential to dramatically increase the flux from linac-driven ICS sources. In addition, the radiation would be transversely coherent.

Other Concepts

There are several other concepts that make use of Compton scattering for radiation production. One of these [1-6] has been demonstrated and makes use of the JLab free-electron laser, which operates in the IR. An optical cavity around the FEL wiggler is used to build up IR pulses. With proper choice of the electron bunch interval and optical cavity length, the IR pulse can be made to collide with every other electron bunch. Hence, the electron beam creates both the IR laser (via the FEL principle) and the x-ray beam (via Compton scattering). The x-rays thus produced are inherently synchronized with the IR pulse, as well as THz radiation produced by the JLab system.

A second alternative concept is the Relativistic Electron Mirror [1-7], which relies on very intense (ultrafast) optical laser with extremely high contrast hitting a very thin solid target. By ponderomotive force, this laser pulse can drive the electrons out of the solid as a bunch or sheet of electrons at near solid density with narrow energy spread. These electrons can act as a “relativistic mirror” for a counter-propagating optical laser pulse via inverse Compton scattering. Because the electrons have been accelerated in phase, free-electron-laser-like micro-bunching is observed in simulations, and the resulting x-ray emission is transversely coherent. Because the sheet of electrons is only a few laser cycles thick, the burst of x-rays is extremely short (<< femtoseconds). The solid density of the mirror provides complete reflection of the backscattered light.

Characteristics of Radiation

As described in the introduction, the radiation emitted from inverse Compton scattering is directed in a narrow cone in the direction of the electron beam. The spot size of the x-ray beam is determined by the combination of the focused spot sizes of the laser beam and the electron beam, while the divergence of the x-ray beam, typically several milliradians, is largely determined by the divergence of the electron beam at the interaction point. The electron beam divergence and energy spread determine the natural energy bandwidth of the x-rays of about 3–4%.

C. Present and Projected Performance

At present the highest performance of any ICS source is achieved by the LTI machine. It's present and projected performance are summarized in Table 1-1. The flux and brightness are presently about 12 orders of magnitude below that delivered by third-generation storage ring light sources. However, planned improvements should increase the flux and brightness by about three orders of magnitude. Also, for experiments that can take advantage of a larger energy bandwidth, flux is improved by 2 to 4 orders of magnitude.

Table 1-1: Present and projected performance of the LTI source.
Average brightness is given in standard units of ph/s/mm^2/mrad^2/0.1%BW.

Parameter	Present	Planned	Notes
Total flux	~10^{11} ph/s	~ 3×10^{13} ph/s	Full bandwidth
Total flux (output BW)	~10^{9} ph/s	~5×10^{11} ph/s	3–4% bandwidth
Flux in 0.1%	~10^{7} ph/s	~5×10^{10} ph/s	
Source spot size	50 μm rms	30 μm rms	Also image size for 1:1 optics
Source divergence	~2.5 mrad	~2.0 mrad	e beam
Average brightness	~10^{7}	~5×10^{11}	Increases with photon energy
X-ray energy range	10–20 keV	7–35 keV	Tunable
Energy conversion		1.7%	Avg. x-ray power/Avg. e-beam power

At present, there is no operating ICS-based linac source that provides significant flux or brightness. However, the MIT proposal provides an idea of what kind of performance should be possible in the near and long term. This performance is summarized in Table 1-2. In the incoherent mode, which assumes use of an ERL, projected flux is similar to the planned values for the LTI source. Average brightness is improved by 7 orders of magnitude, though it is still well below the 10^{19} to 10^{20} levels offered at third-generation storage rings. Peak brightness is about 4 orders of magnitude below what is provided by the APS in hybrid fill mode or what is projected for the short pulse x-ray scheme using deflecting cavities. The beam repetition rate is 100 MHz, which is too high to be of interest for the majority of timing experiments. The system can also operate in a lower-flux mode with a smaller repetition rate, delivering similar peak brightness.

Considerable gains are projected in the case of coherent ICS. In this mode, the average brightness is within an order of magnitude of present third-generation sources. The photon energy range is similar to that covered by NSLS-II. However, the average brightness is about two orders of magnitude lower. Peak brightness is considerably improved, but it is at the bottom of the range that can be covered by SASE FELs. For example, LCLS is 5 or more orders of magnitude brighter.

Table 1-2: Projected performance of the MIT ICS proposal in the incoherent and coherent cases. Brightness is given in standard units. The incoherent case assumes the use of an ERL due to the high average current required.

Parameter	**Incoherent**	**Coherent**
Tunable monochromatic photon energy [keV]	3 – 30	3 – 12
Pulse length [ps]	0.3	0.01
Flux per shot [photons]	10^6	10^7
Repetition rate [Hz]	10^8	10^8
Average flux [photons/s]	10^{14}	10^{15}
FWHM bandwidth [%]	25	0.01
On-axis bandwidth [%]	1	0.01
Source rms divergence [mrad]	1	0.2
Source rms size [mm]	0.002	0.002
Peak brightness	2×10^{19}	10^{26}
Average brightness	6×10^{14}	10^{19}

Operational Considerations

Experience with modern synchrotron light sources shows that reliability and availability can be very high. For example, 98% availability with 100 hour mean-time-between-faults is common. ICS sources are in the early stages of development. However, many of the components are similar to those used at the large facilities and can be expected to offer comparable reliability.

The LTI machine gives a good indication of the level of operational resources needed to run a storage-ring-based ICS facility. One model to reduce operational costs is to make use of remote operation, which allows multiple facilities to be operated in part by remote, centralized contractors. Estimated power requirements are modest at 100 kW. Each source would serve about three x-ray end stations. Experience shows that excellent reliability can be expected, with about one day down per month for maintenance.

Once in production, the proposed MIT source is projected to require \$0.5 M per year to operate, including two full-time staff members.

D. R&D Needs

Because the x-ray flux is proportional to the laser pulse energy, continued R&D into high average power laser systems will benefit ICS facilities based on both storage rings and linacs. At the same time, there must be development of stable laser storage cavities capable of delivering pulses approaching 10 mJ. In the case of linac-based systems, these cavities should ideally provide the ability to make few-micron laser spot sizes at the collision point. Use of non-Gaussian cavity modes, which allow use of mirrors with on-axis apertures for the electron beam, has the potential to improve the performance of both types of ICS sources.

Both flux and brightness will benefit from brighter electron beams. This is particularly important for linac sources for which, unlike ring sources, there is no dilution of the emittance by recirculation for millions of turns. However, a multi-collision linac-based ICS system would require careful optical design to preserve beam quality. To achieve flux that is comparable to that projected for storage-ring ICS systems, linac-based systems must include energy recovery and a high-brightness cw gun, which requires development of gun and cathode technology. Continuous wave superconducting (SC) rf linac cavities operating at 4K are essential in order to reduce operating costs.

Once a detailed machine design is in hand, optimized x-ray beamlines must be designed to match the unique characteristics of ICS radiation.

E. References

[1-1] J. Urakawa, *Nucl. Instrum. Methods A* (2010); doi:10.1016/j.nima.2010.02.019.

[1-2] W.S.Graves et al., *Nucl. Instrum. Methods A* **608**, S103 (2009).

[1-3] E. Bulyak et al., *Nucl. Instrum. Methods A* **487**, 241-248 (2002).

[1-4] R. Lowen, SLAC-Report-632, June 2003.

[1-5] K. Sakaue et al., *Rev. Sci. Instrum.* **80**, 123304 (2009).

[1-6] J. Boyce et al., Proc. 2003 PAC, 938-940 (2003).

[1-7] V. Kulagin et al, *Phys. Rev.Lett.* **99**, 124801 (2007).

Section 2: Coherent, Ultrafast Soft X-rays on a Tabletop from High-Harmonic Generation

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A. Introduction

Advances in x-ray science and technology have resulted in breakthrough discoveries ranging from unraveling the structure of DNA and proteins, to visualizing molecules and materials at the nanoscale. Ultrafast x-ray beams, by virtue of their short wavelength, are ideal probes of the nanoworld. x-rays can penatrate and image small objects and, by using elemental absorption edges, allow for element and chemical species-specific imaging.

The past twenty years has seen an explosion in x-ray science with the development of second- and third-generation synchrotron sources. These sources delivered unprecedented average x-ray flux and revolutionized many areas of investigation. One of the salient features of these machines is that, because of their geometry, they are well suited to servicing many beamlines simultaneously, enabling many kinds of experiments at different wavelengths to be performed at the same time, with the same machine.

Advances in the 21st century have opened up a new frontier in ultrafast (femtosecond and attosecond) x-ray science - driven by the development of revolutionary new free electron laser sources [2-1] as well as by new tabletop light sources as discussed here. However, the new x-ray FELS (FLASH in Germany, LCLS at SLAC, and within a few years XFEL at DESY) differ from third generation light sources because, as currently configured, they service a small number of experiments at one time—constrained by their linear geometry and because they operate at a defined wavelength if the electron beam from the accelerator is sent to only one undulator at any given time. The combination of new capabilities but limited numbers of experiments means that, not surprisingly, these XFEL facilities are oversubscribed.

In parallel with the development of these large-scale FEL sources, the capability to generate ultrashort-pulse, femtosecond-to-attosecond, coherent high harmonic (HHG) beams in the extreme ultraviolet (EUV) and now soft x-ray regions of the spectrum has also developed rapidly. In high harmonic generation, few-millijoule pulses from a femtosecond laser are focused into a gas. The nonlinear interaction between the laser and the electrons in the atoms results in a coherent laser-like beam of EUV and soft x-ray high harmonics that is perfectly synchronized to the laser, even on the sub-optical cycle, attosecond timescale. Since the discovery of the HHG process just over two decades ago [2-2], through advances in our understanding of the atomic physics and nonlinear optics of the process [2-3], and through advances in ultrafast laser technology [2-4], the flux obtainable from these sources has increased by many orders of magnitude, and the accessible wavelength range has expanded from the VUV into the EUV and soft x-ray regions of the spectrum. These sources have also provided the first direct access to attosecond time-scale physics, through studies of the process itself [2-5, 2-6] and by using attosecond pulses generated using HHG .[2-7, 2-8] As a result, tabletop high-harmonic sources provide us with a new light source with characteristics uniquely complementary to XFELs, but at a much lower cost per instrument, enabling broader access.

Make no mistake—HHG light sources are not a substitute for XFEL technology, in that a tabletop source is unlikely to ever provide the very high single-pulse energies of a km-scale machine. However, many experimental techniques can be very effectively implemented with small-scale HHG sources, while their complementary characteristics and small-scale accessibility make it possible to accelerate the pace of scientific and technological progress in this area. Furthermore, HHG sources provide a route for applications of coherent x-rays to diffuse into analytical techniques with impact on industry and the broader economy, and they also provide excellent training for students in laser and x-ray science and applications.

The areas of complementarity with large sources also extend to common laser requirements as well as the potential to seed XFELs using HHG sources (to enhance their spatial and temporal coherence). HHG sources also distinguish themselves as being quite complementary to synchrotron light sources, allowing for easy and rapid development of time-resolved pump-probe studies that have proven challenging at synchrotron sources. As a result, a vigorous development of small-scale HHG light sources by DOE will serve to cultivate a broad x-ray science community, ensuring that the *best* possible science, suited to the unique characteristics of the XFELs, is done using these sources.

Furthermore, rapid progress in the understanding of the HHG light sources provides the potential for exciting and revolutionary new capabilities. Until recently, high harmonic sources were bright enough to be useful only in the XUV and EUV region of the spectrum, for photon energies < 150 eV [2-9]. HHG sources in the EUV have already been used to capture the fastest electron dynamics in atoms, molecules, and materials and to capture function in nanostructures relevant to magnetic storage, nanoscience and nanotechnology, energy transport and harvesting, thermal management, nanoscale imaging, and more [2-10–2-19]. However, the useful parameter range for high-order harmonic sources promises to expand considerably in the next few years. A very recent breakthrough promises to make possible bright high harmonic beams with wavelengths that extend into the soft x-ray region of the spectrum, to 0.5 keV [2-20–2-22]. The physics of this scaling was recently demonstrated by driving the HHG process using mid-infrared (mid-IR) lasers at wavelengths of 2 μm. Furthermore, *for driving laser wavelengths of 3μm and higher, bright harmonic emission is predicted to span into the 1-keV region and higher, making compact, fully coherent ultrafast sources at keV photon energies and higher a feasible prospect.* Because of the many important technological and scientific opportunities that can be addressed by ultrafast high harmonic sources in the keV region, and the potential to proliferate them into many labs and industry because of their small footprint and cost, it is critical to make strategic investments in this compact light source technology. Current ultrafast x-ray studies using HHG light have been extremely successful in addressing new science, even given a scale of funding that is dwarfed by recent investments in large-scale light sources. Furthermore, given the complimentary nature of these light sources and the large parameter range that remains to be exploited, it is an easy argument that the U.S., and DOE in particular, given its stewardship in x-ray science, has been under-investing in this area. Finally, it is important to note that significant efforts in high harmonic sources are funded elsewhere in the world, with increasing penetration into applications in materials and nanoscience, and nanotechnology.

B. Current and Future Impact of HHG Sources on Science and Technology

HHG sources are distinguished by their accessibility and relatively low cost. An HHG light source can be driven by a tabletop, 2-mJ-level laser system, and the light naturally emerges as a broadband burst of coherent light with pulse durations in the femtosecond-to-attosecond regime. This combination of accesibility and unique characteristics easily makes possible high risk research, often leading to unexpected breakthroughs. Moreover, the small size allows for rapid advance in source technologies, with impact on a wide range of science and technology. Students trained on these sysems graduate with a broad range of versatile capabilities in optical and x-ray science. Moreover, many advances that emerged from small-scale sources are now in use at the large XFEL facilities, including femtosecond lasers, attosecond pulses and measurement techniques, and synchronizations techniques. Finally, the small footprint of HHG sources increases the potential for technological and commercial applications.

Sample applications of HHG sources light are described briefly below. These examples show that HHG is an ideal source for experiments that require averaging (coincidence measurements, photoemission), very short pulse durations (electron dynamics), and coherence and broad bandwidth (spectromicroscopy). All of these applications will benefit from the broader wavelength and increased flux that would be made possible by the R&D proposed in section F below.

Angle-Resolved Photoelectron Spectroscopies

Angle-resolved photoemission spectroscopy (ARPES) has emerged as a leading experimental technique for studying the electronic structure of solids. The simultaneous detection of the kinetic energy and angle of the emitted photoelectrons offers the possibility of obtaining a two-dimensional energy-momentum map along a given direction in *k*-space, thus providing accurate information about the dispersion of filled electronic bands. High harmonics are an ideal probe because the dynamics of the transient electrons is typically in the femto- to picosecond time scales, mainly due to electron-electron and/or electron-phonon interactions, and precludes the use of conventional sources of radiation typically employed for ARPES (gas-discharge lamps or synchrotron sources). Moreover, to avoid space charge issues, very high (multi-kHz) repetition rates are required, which is ideal for HHG sources. The scientific impact of fs-ARPES as currently envisioned allows one to understand dynamic coupling processes between the electronic, lattice, and spin degrees of freedom that appear in future functional materials such as correlated electron materials or quantum confined (reduced dimensionality) nanostructures. The first example of such a measurement is shown in Figure 2-1.

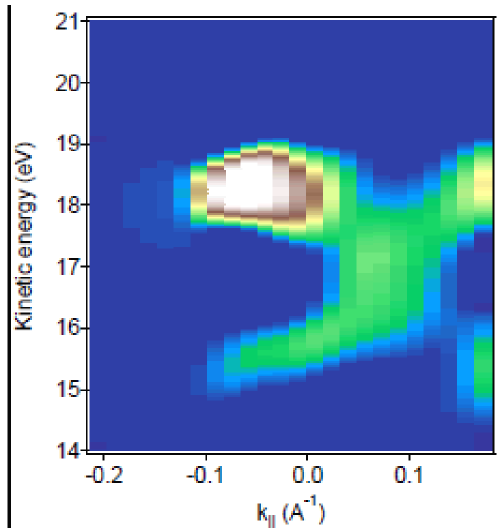

Figure 2-1: *The enigmatic hidden-order phase in URu_2Si_2 is of great interest in the solid-state community. At least three different energy scales coexist in this compound at very low temperatures. The largest scale is the hybridization gap, already well-developed below 50 K. The hidden-order gap, with yet unknown order parameter, forms below 18 K. Finally, the superconducting gap forms at 1.5 K. This measurement of the electronic structure of URu_2Si_2 is the first example of a momentum-resolved dispersive band structure measured in a 5-f electron system with an HHG source.*

Ultrafast X-Ray Nanomagnetics

Studies of magnetism, magnetic materials, and the dynamics of magnetic materials are topics that are both of fundamental interest to our understanding of correlated systems and spintronics, and are directly relevant to technology for information storage. New approaches to efficient data storage will require novel technologies with critical dimensions of ~15 nm. As a result, novel tools to understand and probe complex magnetic nanostructures are needed. High harmonic sources are well suited to such studies, because of their ability to capture element-specific dynamics and images of nanostructures on the fastest timescales.

In recent work, HHG sources were used to measure element-specific demagnetization dynamics with a resolution of 50 fs, which is the fastest magnetics measurement performed to date using any x-ray source [2-10]. The magnetization state and the speed at which it randomizes when the material is heated with an ultrafast laser pulse were measured at the M absorption edges of Fe and Ni, around 50-70 eV, as shown in Figure 2-2. Because image contrast, resolution, and transparency of materials are all greatly improved at soft x-ray L-edge energies, as the energy range of HHG sources is extended to the keV region over the next few years, imaging of buried magnetic structures, domain interactions, strongly coupled nanolayers, and spin dynamics will all become accessible with femtosecond and even sub-femtosecond time resolution.

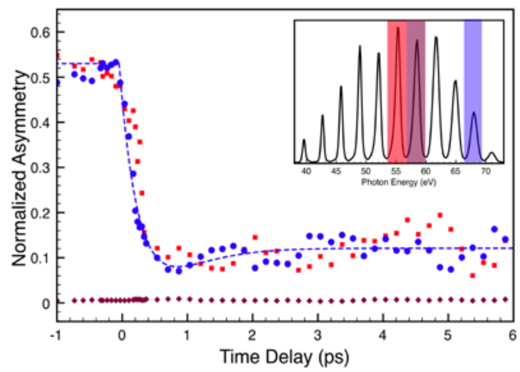

Figure 2-2: *First time-resolved, element-specific, measurements of demagnetization in a compound (Permalloy) material. High-harmonic photons around the Ni (blue circle) and Fe (red square) M-edges were used to probe the demagnetization time in the heated material, which was 400 fs (with 50-fs resolution). This is the fastest x-ray measurement of magnetic dynamics to date. Purple diamonds show the off-resonant signal.*

Energy Transport at the Nanoscale

Thermal transport in nanostructures is significantly different from that at the macroscale due to classical and quantum size effects of energy carriers. Moreover, thermal management in nanoelectronics and other nanosystems has become a bottleneck for continued Moore's law scaling in electronics. In recent work, ultrafast HHG beams were used to directly measure the ballistic contribution to heat flow from a 70-nm-scale hot spot into its surroundings and was able to deduce how to correct Fourier heat flow at the nanoscale [2-11]. In the future, shorter wavelength harmonics could be used to study how heat dissipates in nanosystems with dimensions ≈ 50-5 nm.

Element Specific Imaging at the Nanoscale

x-ray microscopy is a critical tool for nanoscience, capable of imaging small objects, penetrating thick samples, with an elemental and chemical specificity without the need to label or stain a sample. The high spatial coherence of harmonics makes them ideal for lensless coherent imaging techniques, which have been demonstrated to the 50-nm level using HHG [2-13, 2-16, 2-23]. Extending this work to higher photon energies up to the keV region would also enable magnetic, thermal, biological, and plasma imaging with high (sub-10-nm) spatial and fs time resolution.

Ultrafast Femtosecond-to-Attosecond Atomic and Molecular Dynamics

The time resolution of high harmonics, in the femtosecond-to-attosecond regime, can capture the fastest electronic dynamics in molecules and materials [2-24, 2-25]. Moreover, high harmonics are perfectly synchronized to the driving laser pulse, enabling time-resolved experiments on the fastest timescales to date. Traditional x-ray spectroscopies such as photoelectron diffraction, transient absorption, and photoemission can be implemented using HHG, as well as a host of new electron imaging techniques. It is possible to follow, in real time, fast electron charge transfer dynamics in molecules and clusters, to understand how chemical reactions might be controlled using light, and to obtain a complete image (at the level of electrons) of ultrafast chemical reactions using time- and position-sensitive reaction microscopes [2-12, 2-18]. Such dynamics can be captured using either isolated attosecond pulses or pulsetrains of attosecond pulses. The availability of attosecond pulses will 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. In addition, fundamental questions in AMO science such as the timescale and nature of how atoms and molecules ionize can be addressed. Finally, fundamentally new spectroscopic techniques based on interferometry and attosecond continua, can be developed [2-26, 2-27].

C.1 Status of High Harmonic Compact Light Sources

In high-harmonic generation, short wavelength harmonics are emitted as an electron ionizes from an atom driven by a strong femtosecond laser field. A broad comb of odd harmonics of the fundamental laser are generated while the atom is ionizing, up to some maximum (cutoff) energy given by: $h\nu_{max} = I_p + 3.2\ U_p$, where I_p is the ionization potential of the atom, and $U_p \approx I_L\ \lambda^2$ is the ponderomotive potential corresponding to a laser field with intensity I_L and wavelength λ. This very favorable scaling means that weak harmonics from single atoms can be generated at very high photon energies, above 1 keV. The pulse duration of the emitted harmonics can range from 10-100 attoseconds to >30 femtoseconds, depending on the generation conditions.

Wavelength Scaling of Bright HHG

Until recently, the conversion efficiency of laser light into soft x-rays above 150 eV has been vanishingly small. This is because in order to generate bright coherent soft x-ray harmonics for applications, harmonics from many atoms in a medium must add together coherently (phase matching). To achieve this, the driving laser must propagate at the same velocity as the generated harmonics, where the index of refraction of the neutral gas (n>1) balances the index of the generated plasma (n<1) and any geometrical contributions to phase matching. This phase-matching condition can easily be satisfied at photon energies < 150eV using 0.8-μm Ti:sapphire driving lasers. Several groups have demonstrated conversion efficiencies of laser light to single harmonics of $>10^{-5}$ around 50 eV, and 10^{-6}-10^{-7} around 100 eV, in a phase-matched geometry [2-9, 2-28–2-30]. However, at the high laser intensities required to generate harmonics photon energies > 150 eV, the nonlinear gas medium is significantly ionized [2-28, 2-31]. At some critical level where the phase velocity of the laser exceeds that of the harmonics, phase matching is impossible. This prevents coherent buildup of a bright harmonic output beam. Overcoming the phase matching limit was thus a grand challenge in nonlinear optics.

Fortunately, in recent work [2-20–2-22], phase matching of high harmonic generation was extended to 0.5 keV by increasing the wavelength of the driving laser (Figs. 2-3 and 2-4). Using few-millijoule laser pulses at 1.3 μm and 2 μm (derived from an optical parametric amplifier), full phase matching spanned the soft x-ray "water window" region of the spectrum up to ~0.5 keV for the first time, at flux levels 1000× brighter than possible to date. Very high gas pressures close to 10 atm are needed for this scheme, which together with the increased gas transparency, compensates for the low single-atom response at long wavelengths [2-20, 2-31]. The HHG brightness is roughly constant between 200 and 500 eV, with an initial flux of $\approx 10^6$ photons/s or 10^5 photons/shot in a fractional bandwidth of $\lambda/\Delta\lambda \approx$ 100. Increases in the flux of > 100 are expected using simple improvements such as increasing the interaction length and beam quality, corresponding to conversion efficiencies of 10^{-7}.

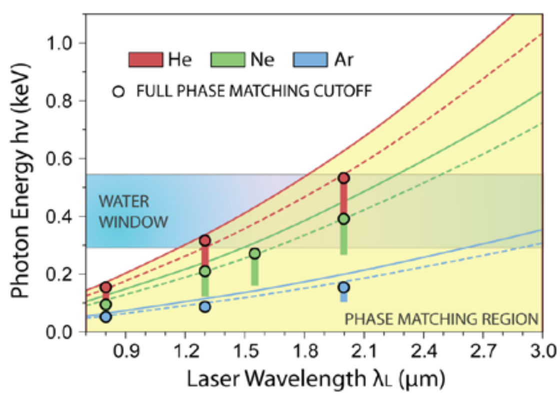

Figure 2-3: *Solid (dashed) color lines plot the predicted phase-matched cutoff energies as a function of the driving laser wavelength for a pulse duration of 3 (8) optical cycles. Solid circles show the* <u>*experimentally observed*</u> *phase matching cutoffs for 0.8-μm, 1.3-μm, 1.55-μm and 2-μm driving lasers. Vertical stripes show the experimentally observed bandwidths. Theory and experiment agree well.*

This work also extends the generation of bright attosecond pulses into the soft x-ray region. Since the phase of the carrier wave of the 2-μm laser field is intrinsically stabilized with respect to the pulse envelope, different portions of the 300-eV bright soft x-ray supercontinuum are perfectly synchronized with respect to one another, on attosecond timescales. Although most application experiments would not require transform-limited attosecond pulses, if the attosecond chirp were compensated, it is likely that stable ~10 attosecond pulses (10^{-17} s) could be generated through gated phase matching [2-32]. Theory also suggests that HHG has the potential to become a useful source even in the hard x-ray region of the spectrum, at photon energies > 10keV.

Another area of rapid progress in high-order harmonic generation physics is in the development of quasi-phase-matching (QPM) techniques. The attosecond quantum physics of the HHG process is particularly amenable to the application of quantum control techniques [2-5, 2-33], and this quantum control has recently been shown to allow for "adaptive" quasi phase matching [2-34, 2-35], where a weak "control" pulse intersects with the harmonic generation pulse, perturbing the phase of HHG emission. This technique can be used to further extend the photon energy range of HHG [2-36] to maintain higher conversion efficiency, and perhaps most importantly to provide detailed control of the spectral characteristics of HHG, for example making a quasi-monochromatic source.

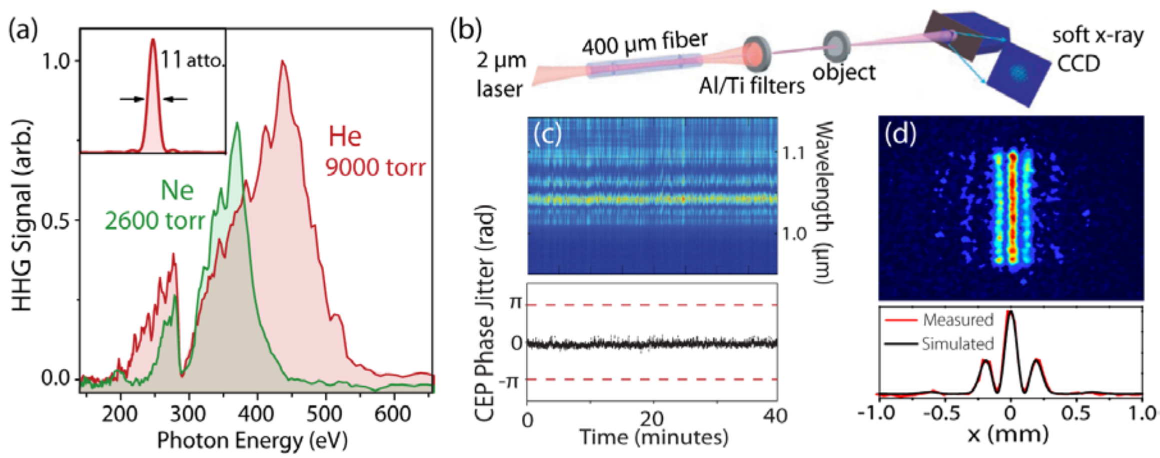

Figure 2-4: *(a) Spectra for phase-matched HHG emission from He and Ne driven by 2-µm light. Inset: HHG from He can support an 11-attosecond pulse. (b) Setup to measure spatial coherence. (c) An f-2f carrier-envelope phase (CEP) measurement shows 2-µm light that is CEP stable to 210 mrad over 40 min. (d) Measured double-slit interference using HHG from Ne at 330 eV, showing a comparison with simulation for a 300-eV beam with 60-eV FWHM bandwidth. The broad bandwidth limits the visible number of fringes.*

Efficiency of HHG

The conversion efficiency of laser energy into a single harmonic, when the frequency conversion process is phase matched, is approximately 10^{-4} to 10^{-7}, with the high numbers corresponding to the VUV region of the spectrum and the lower numbers characteristic of the soft x-ray region. Several groups have reported these flux levels, and HHG sources are unique in terms of the wide range of applications that have already been demonstrated.

C.2 Specifications of Current and Future HHG Sources

Because high harmonics can be generated either by high average power or high peak power femtosecond lasers, in Tables 2-1 and 2-2 we considered two cases: 1) HHG generated by low laser pulse energies at high laser repetition rates; and 2) HHG generated by high-energy lasers at low repetition rates. A variety of lasers with specifications in between those considered here can be used to drive HHG, provided that the minimum laser intensity given by the cutoff rule is used to generate a given harmonic. To scale the HHG pulse energy, the laser pulse energy and spot size can be increased. To scale the HHG flux, the laser repetition rate is increased.

Table 2-1: Comparison between Current HHG Sources and XFEL Sources

Parameter	LCLS	FLASH	High Average Power (10-W driving lasers, e.g., 2 mJ, 5 kHz)	High Peak Power HHG (1-W driving lasers, 100 mJ, 10 Hz)
Photon energy	800 eV – 8 keV	10 eV – 200 eV	20 – 100eV	20 – 500 eV
Energy per pulse	2 mJ @ 150 fs 50 µJ @ 5 fs	10 – 100 µJ	20 nJ @ 30 eV 1 nJ @ 100 eV	1 µJ @ 50 eV
Repetition rate	30 – 60 Hz	10 Hz, with microbunches	1 – 10 kHz	10 Hz
Pulse duration	5 – 150 fs	10 fs	10 attosec – 30 fs	10 attosec – 30 fs
Focused intensity	5×10^{16} W/cm^2	~ 10^{15} W/cm^2	~10^{14} W/cm^2	~10^{15} W/cm^2
Average power	100 mW @ 150 fs 2.5 mW@ 5 fs	0.1 – 1 mW	0.5 µW @ 50 eV	10 µW
Coherence	Full spatial, limited temporal	Full spatial, limited temporal	Full spatial and temporal coherence	Full spatial and temporal coherence
Polarization	Linear	Linear	Linear	Linear

Table 2-2: Future HHG Sources Specifications

Parameter	High Average Power HHG 100-W Lasers (2 mJ, 50 kHz) (2 years)	High Average Power HHG 200-W Lasers (5 yrs)	High Peak Power HHG – Petawatt Laser (2-5 yrs)
Photon energy	20 eV – 1 keV	20 eV – 10 keV	20 – 100eV
Energy/harmonic /pulse in 1% BW	2 - 20 nJ	> 20 nJ	1 mJ
Repetition rate	≈ 10 - 50 kHz	> 100 kHz	1 – 10 Hz
Pulse duration	10 attosec – 30 fs	1 attosec – 30 fs	10 – 30 fs
Average powers	~ 1 mW	> 2 - 10 mW	~10 mW
Peak powers	$\sim10^{14}$ W/cm^2	> $\sim10^{14}$ W/cm^2	$\sim10^{16}$ W/cm^2
Coherence	Full spatial and temporal coherence	Full spatial and temporal	Full spatial and temporal coherence
Polarization	Linear	Linear	Linear

C.3. Principal Technical Challenges

The principal technical challenges are associated with the laser development and the need for advanced HHG conversion cells for either high average flux or high peak flux HHG generation. To the extent possible, these advances should be done though collaboration among leading groups in universities and national labs with commercial partners, with U.S. industry prominently represented. Such partnerships would ensure a rapid pace of progress, strengthen U.S. science and industry, and ensure that advances in this area will become broadly available to maximize the range of science and technology that would benefit from advances in HHG sources—particularly the smaller-scale high average power x-ray sources that have potential for industrial application.

D. Size of Investment Needed and Operability Considerations

Advances in the technology of these compact light sources will require investment in a moderate number of “mid-scale” facilities that implement a coordinated program in both technology development and in applying these compact light sources to one or more specific scientific problems. To extend bright high average power harmonics to the keV region and beyond, initial investments of $2 - 4 M are needed. Once the facility is developed, which would likely contain more than one HHG source, two research teams could access a beamline for extended periods. An operating cost in the range of $1 M/yr is expected, including salaries for research and maintenance personnel. To generate millijoule energy HHG using high energy lasers at low repetition rates, higher costs are anticipated, as tabulated in Table 2-3.

Table 2-3: Investment and Operational Considerations for HHG Driven by High-Average-Power vs High-Peak-Power Lasers

Status and outlook for HHG	driven by high average power lasers
Present status	Ti:sapphire based pump lasers ~μW average power
2 year goal	Sub-100 W average power Yb/OPA systems at 1.5 μm and 3 μm > 400 W 1μm Yb-doped femtosecond lasers > 100W lasers or recirculating cavities for HHG up to 100 eV
5 year goal	Sub-M$, 0.1-1 mW coherent soft x-ray sources Fully coherent hard x-rays

Investments required	
Initial R&D (2 yr)	$2M - $4M
Facility construction	Fits in existing labs

Operations Considerations	
Staffing levels required	1 FTE
Annual operations cost	$1 M (including science program)
User access	2 teams at one time, access every other week

Status and outlook	HHG driven by high peak power lasers
Present status	TW class drivers demonstrated: ≤ 50 μJ per pulse @ 30 eV; 10 Hz; focused intensity ~10^{13} W/cm^2
2 year goal	Demonstrate 1 mJ @ 30 eV; single shot Perform R&D on rep. rated 100 J amp
5 year goal	Construct PW-HHG facility with 2-4 beamlines

Investments required	
Initial R&D (2 yr)	$2M - $4M
Facility construction	$10M - $15M per facility

Operations Considerations	
Staffing levels required	6 – 10 FTEs
Annual operations cost	$2M
User access	~ 2-4 users at one time
Scheduled availability	~4 day/week

E. Reliability of the Compact Light Sources

Significant advances in the reliability and engineering of femtosecond lasers will benefit HHG compact x-ray sources. State-of-the-art commercial lasers now approach 50 W and higher, and their development over the past three years is now beginning to allow for HHG sources that can run without intervention for extended periods. Experiments that require $\approx$ 1 week of run time, for example to study molecular dynamics for low-probability events, are now feasible [2-18]. Continued development will, in time, allow for reliability comparable to large-scale synchrotron light sources, which have benefitted from 75 years of accelerator technology development.

F. Suggested R&D to Improve Performance

The highest impact R&D that will allow improved HHG performance would focus on four thrusts. The first is to develop new laser architectures that would allow the range of harmonic photon energies to be extended to keV photon energies and beyond. This would significantly increase the range of applications for HHG. The second is to develop robust high average power lasers that would increase the harmonic flux at current and future HHG photon energies. Third is to implement HHG using high peak-power petawatt-scale lasers to demonstrate millijoule-energy high harmonic pulses. And finally, novel schemes must be explored to significantly enhance the HHG conversion efficiency.

R&D Program to Increase the Photon Energy Range of HHG

By developing mid-IR femtosecond driving lasers, bright multi-keV harmonics with $\approx$ 50 µW average powers could be generated. The required femtosecond laser performance in order to generate HHG flux sufficient for application experiments would be (see Fig. 2-3):

- > 2-mJ output
- 1- to 5-µm wavelength
- 10- to 100-kHz rep rates
- efficient diode-pumped and cryogenically cooled laser technologies

R&D Program to Increase the Flux of Current HHG Sources

Research and development programs that would scale the driving laser average power in the range of 100 kHz – 1 MHz would scale the HHG flux for application experiments that demand very high repetition rates. Current Ti:sapphire laser systems can be scaled to higher average powers. Improvements in the stability, thermal management, reliability, pointing, rep rate, optics and gratings at all pump/driving laser wavelengths, when appropriate in collaboration with industry, would also greatly benefit HHG sources.

Dispersion-free femtosecond cavities may be able to scale the 100-eV HHG flux, if laser losses can be reduced.

R&D Program to Increase the Energy of Current HHG Sources

Novel multi-TW and PW laser architectures are needed to scale the HHG pulse energies to millijoule pulse energies at 100 eV. High-repetition-rate glass slab amplifiers with 10-cm apertures that are flashlamp pumped at 1 Hz, but that could be diode pumped at 10 Hz, would be required. Significant effort would also be needed to develop large (~1 cm) gas targets for generating harmonics with very high laser pulse energies.

Novel HHG Schemes

There is a great possibility for revolutionary advances in high harmonic sources by pursuing a range of approaches that could increase the HHG conversion efficiency beyond the current 10^{-5} levels. Many of these schemes have very promising results to date. These include:

- High-harmonic generation using mid-infrared driving lasers, that has reached 0.5 keV
- Quasi-phase-matching techniques using visible lasers that have high single-atom brightness
- X-ray parametric amplification schemes
- Buildup cavities

G. Comparison with FELs

Please see Tables 2-1 and 2-2.

H. References

[2-1] V. Ayvazyan, N. Baboi, J. Bahr et al., “First operation of a free-electron laser generating GW power radiation at 32 nm wavelength,” *Eur. Phys. J. D*, vol. **37**, 297-303 (2006).

[2-2] A. McPherson, G. Gibson, H. Jara et al., “Studies of multiphoton production of vacuum-ultraviolet radiation in the rare gasses,” *J. Opt. Soc. Am. B* **4**, 595-601 (1987).

[2-3] H. C. Kapteyn, M. M. Murnane, I. P. Christov, “Extreme Nonlinear Optics: Coherent X Rays from Lasers,” *Phys. Today* **58**, 9-44 (2005).

[2-4] D. Müller, S. Backus, K. Read et al., “VERY HIGH-PEAK-POWER LASERS: Cryogenic cooling multiplies output of Ti:sapphire laser,” *Laser Focus World*, October 2005.

[2-5] R. Bartels, S. Backus, E. Zeek et al., “Shaped-pulse optimization of coherent emission of high-harmonic soft x-rays,” *Nature* **406**, pp. 164-166 (2000).

[2-6] Z. Chang, A. Rundquist, H. Wang et al., “Temporal Phase Control of Soft-X-Ray Harmonic Emission,” *Phys. Rev. A* **58**, R30-R33 (1998).

[2-7] P. M. Paul, E. S. Toma, P. Breger et al., "Observation of a train of attosecond pulses from high harmonic generation," *Science* **292**, 1689-1692 (2001).

[2-8] M. Hentschel, R. Kienberger, C. Spielmann et al., "Attosecond metrology," *Nature* **414**, 509-513 (2001).

[2-9] A. Rundquist, C. G. Durfee III, S. Backus et al., "Phase-matched Generation of Coherent Soft x-rays," *Science* **280**, 1412-1415 (1998).

[2-10] C. La-O-Vorakiat, M. Siemens, M. M. Murnane et al., "Ultrafast Demagnetization Dynamics at the M Edges of Magnetic Elements Observed Using a Tabletop High-Harmonic Soft X-Ray Source," *Phys. Rev. Lett.* **103**, 257402/1-4 (2009).

[2-11] M. E. Siemens, Q. Li, R. G. Yang et al., "Quasi-ballistic thermal transport from nanoscale interfaces observed using ultrafast coherent soft x-ray beams," *Nat. Mater*. **9**, 26-30 (2010).

[2-12] A. S. Sandhu, E. Gagnon, R. Santra et al., "Observing the Creation of Electronic Feshbach Resonances in Soft x-ray-Induced O-2 Dissociation," *Science* **322**, 1081-1085 (2008).

[2-13] R. L. Sandberg, C. Y. Song, P. W. Wachulak et al., "High numerical aperture tabletop soft x-ray diffraction microscopy with 70-nm resolution," *P. Natl. Acad. Sci. USA* **105**, 24-27 (2008).

[2-14] L. Miaja-Avila, G. Saathoff, S. Mathias et al., "Direct measurement of core-level relaxation dynamics on a surface-adsorbate system," *Phys. Rev. Lett.* **101**, 046101 (2008).

[2-15] W. Li, X. B. Zhou, R. Lock et al., "Time-Resolved Dynamics in N_2O_4 Probed Using High Harmonic Generation," *Science* **322**, 1207-1211 (2008).

[2-16] R. L. Sandberg, A. Paul, D. A. Raymondson et al., "Lensless diffractive imaging using tabletop coherent high-harmonic soft-x-ray beams," *Phys. Rev. Lett.* **99**, 098103 (2007).

[2-17] H. Kapteyn, O. Cohen, I. Christov et al., "Harnessing attosecond science in the quest for coherent x-rays," *Science* **317**, 775-778 (2007).

[2-18] E. Gagnon, P. Ranitovic, A. Paul et al., "Soft x-ray driven femtosecond molecular dynamics," *Science* **317**, 1374-1378 (2007).

[2-19] N. L. Wagner, A. Wuest, I. P. Christov et al., "Monitoring molecular dynamics using coherent electrons from high harmonic generation," *P. Natl. Acad. Sci. USA* **103**, 13279-13285 (2006).

[2-20] T. Popmintchev, M. C. Chen, A. Bahabad et al., "Phase matching of high harmonic generation in the soft and hard x-ray regions of the spectrum," *P. Natl. Acad. Sci. USA* **106**, 10516-10521 (2009).

[2-21] T. Popmintchev, M. C. Chen, O. Cohen et al., “Extended phase matching of high harmonics driven by mid-infrared light,” *Opt. Lett.* **33**, 2128-2130 (2008).

[2-22] M.-C. Chen, P. Arpin, T. Popmintchev et al., “Full Phase Matching of Ultrafast Coherent High Harmonic X-Rays at 0.5 keV,” *Conference on Lasers and Electro-optics/ Quantum Electronics and Laser Science (CLEO/QELS)* San Jose, CA: Optical Society of America, 2010, p. JThI3.

[2-23] R. L. Sandberg, D. A. Raymondson, C. La-o-Vorakiat et al., “Tabletop soft-x-ray Fourier transform holography with 50 nm resolution,” *Opt. Lett.* **34**, 1618-1620 (2009).

[2-24] S. Baker, J. S. Robinson, C. A. Haworth et al., “Probing Proton Dynamics in Molecules on an Attosecond Time Scale,” *Science* **312**, 424-427 (2006); doi 10.1126/science.1123904.

[2-25] S. A. Aseyev, Y. Ni, L. J. Frasinski et al., “Attosecond angle-resolved photoelectron spectroscopy,” *Phys. Rev. Lett.* **91**(22), 223902 (2003).

[2-26] T. Kanai, S. Minemoto, and H. Sakai, “Quantum interference during high-order harmonic generation from aligned molecules,” *Nature* **435**, 470-474 (2005).

[2-27] X. Zhou, R. Lock, W. Li et al., “Molecular Recollision Interferometry in High Harmonic Generation,” *Phys. Rev. Lett.* **100**, 073902 (2008).

[2-28] C. G. Durfee, A. R. Rundquist, S. Backus et al., “Phase matching of high-order harmonics in hollow waveguides,” *Phys. Rev. Lett.* **83**, 2187-2190 (1999).

[2-29] E. Takahashi, Y. Nabekawa, T. Otsuka et al., “Generation of highly coherent submicrojoule soft x rays by high-order harmonics,” *Phys. Rev. A* **66**, 021802 (2002).

[2-30] Y. Tamaki, J. Itatani, M. Obara et al., “Optimization of conversion efficiency and spatial quality of high-order harmonic generation,” *Phys. Rev. A* **62**(6), 063802 (2000).

[2-31] A. Gordon and F. X. Kärtner, “Scaling of KeV HHG efficiency with drive wavelength,” *Opt. Express* **13**, 2941 (2005).

[2-32] I. Thomann, A. Bahabad, X. Liu et al., “Characterizing isolated attosecond pulses from hollow-core waveguides using multi-cycle driving pulses,” *Opt. Express* **17**, 4611-4633 (2009).

[2-33] I. P. Christov, R. Bartels, H. C. Kapteyn et al., “Attosecond time-scale intra-atomic phase matching of high harmonic generation,” *Phys. Rev. Lett.* 86**,** 5458-5461 (2001).

[2-34] X. H. Zhang, A. L. Lytle, T. Popmintchev et al., “Quasi-phase-matching and quantum-path control of high-harmonic generation using counterpropagating light,” *Nat. Physics* **3**, 270-275 (2007).

[2-35] X. Zhang, A. L. Lytle, O. Cohen et al., "Quantum-path control in high-order harmonic generation at high photon energies," *New J. Phys.* **10**, 025021 (2008).

[2-36] O. Cohen, X. Zhang, A. L. Lytle et al., "Grating-assisted phase matching in extreme nonlinear optics " *Phys. Rev. Lett.* **99**, 053902 (2007).

Section 3: Plasma Sources

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This section addresses compact plasma sources for the generation of intense coherent and incoherent soft x-rays and x-ray light. Bright plasma-based soft x-ray lasers are discussed in Section 3.A, Section 3.B. addresses the generation of incoherent x-ray radiation from laser-driven plasmas, and Section 3.C. discusses a technique that compresses the light output of sources from the visible to the soft x-ray.

Section 3.A. Plasma-Based Tabletop Soft X-ray Lasers

A. Introduction

Plasma-based soft x-ray lasers are compact, bright, tabletop-size devices with unique characteristics that make them complementary to free-electron lasers and high harmonic sources. They presently produce the highest pulse energy and average power available from a tabletop coherent soft x-ray source. These compact lasers currently operate in the 10- to 50-nm wavelength region, and can be expected to also operate at significantly shorter wavelengths in the near future. Injection-seeded techniques, illustrated in Figure 3-1, allow the generation of beams with full spatial and temporal coherence. Their compact size makes them ideal for installation in university and industrial laboratory settings.

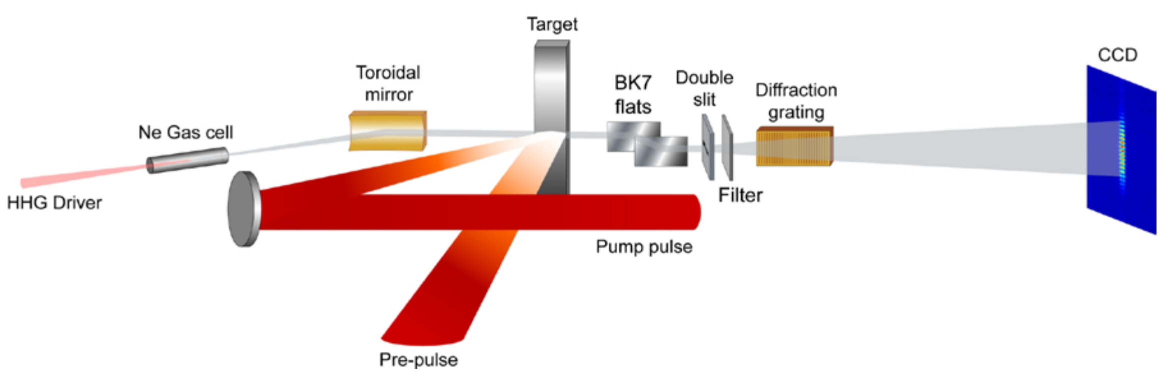

Figure 3-1: *Schematic diagram of injection-seeded soft x-ray laser amplifier that produces a high-brightness phase-coherent soft x-ray laser beam by seeding a dense laser-created plasma amplifier with high-harmonic pulses.*

Physical Basis

High-brightness tabletop soft x-ray laser beams with a large number of photons per pulse and high average power are generated in dense plasmas heated by irradiating targets of selected materials with intense tabletop optical lasers. Since their first demonstration in the mid 1980s [3-

1, 3-2] their size has been dramatically reduced, and their repetition rate and average power have greatly increased [3-3, 3-4]. Rapid collisional electron impact excitation of transitions of highly ionized ions in hot, dense plasmas [3-5, 3-6] produces bright, soft x-ray laser beams at a broad range of wavelengths [3-3–3-9] that are currently enabling numerous tabletop experiments. Other atomic excitation mechanisms for soft x-ray laser amplification at shorter wavelengths such as electron-ion recombination producing gain in transitions to the ground state are also under investigation [3-10]. Fully phase-coherent soft x-ray beams have been demonstrated by injection-seeding the laser-pumped collisional plasma amplifiers with high harmonic pulses generated using the same pump laser that excites the plasma amplifier [3-11–3-13]. Operation at longer wavelengths (e.g., 46.9 nm) can be also achieved by exciting the plasma with a fast electrical discharge [3-14].

Technical Components

These soft x-ray laser systems consist of an advanced high-energy, high-repetition-rate ultrashort pulse optical laser to excite the plasma [3-4, 3-15], focusing optics, and a renewable target of a selected material [3-16]. Injection seeding, which allows for full spatial and temporal coherence [3-13], requires the addition of a high-harmonic seed generation set-up and optics to relay-image the seed pulse into the plasma amplifier.

B. **Properties and Potential Impact**

Plasma-based soft x-ray lasers are bright tabletop-size devices presently operating in the spectral region from 10.9 nm to 50 nm with pulse energies ranging from 1 μJ to several hundred μJ. Gain-saturated operation has been demonstrated at wavelengths as short as 10.9 nm, with future work expected to extend saturated lasing to significantly shorter wavelengths. Two modes of operation are possible for the laser-pumped soft x-ray lasers: amplified spontaneous emission (ASE), and injection seeding. In the ASE regime these lasers presently produce partially coherent picosecond-duration laser pulses with up to 10 μJ energy. Future work can be expected to increase pulse energy to > 0.1 mJ. Current systems operate at repetition rates up to 10 Hz, with work towards achieving 100-Hz repetition rate already underway using diode-pumped laser drivers. Operation in the injection-seeded regime produces fully phase-coherent light with defined polarization and 1-ps pulse duration [3-14]. Future work has the potential to result in generation of 50- to 100-fs soft x-ray laser pulses with extremely high peak-spectral brightness, approaching that of the present FELs in the 13- to 30-nm spectral region. At longer wavelengths (e.g.. 46.9 nm), extremely compact capillary discharge lasers already produce laser pulse energies of several hundred μJ and average powers in excess of 1 mW.

These compact lasers have already impacted a broad range of applications that include nanoscale microscopy [3-17–3-19], imaging of dynamic processes in the nanoscale [3-20], single-photon ionization mass spectrometry of clusters and molecules [3-20–3-22], industrial metrology at the nanoscale [3-23], nanopatterning [3-24], nanoscale ablation for the development of analytic nanoprobes [3-25], study of dynamic phenomena on surfaces [3-26, 3-27], and dense plasma diagnostics [3-28–3-30]. With the increased capabilities that are expected to result from their further development, compact soft x-ray lasers will enable an even broader range of studies of materials in all phases of matter ranging from solids to plasmas, and will enable unique probes and processing tools for nanotechnology. With their compact footprint, they can be installed in relatively small laboratories and industrial sites, and provide ready access for the training of numerous students and young scientists.

***Pros*:**

- High energy per pulse: Produces the highest pulse energy presently available from tabletop soft x-ray coherent source (e.g., > 6×10^{11} photons per pulse at hν ~ 100 eV from laser-pumped soft x-ray lasers in the 13- to 33-nm wavelength region. (Extremely compact capillary discharge lasers presently produce > 1×10^{14} photons per pulse at hν = 26.5 eV.)
- High average flux: (e.g., 20 μW already demonstrated at hν ~ 100 eV) Multi-mW average power potentially resulting from further development using high repetition rate laser drivers. The capillary discharge lasers already emit mW average power at λ= 46.9 nm.
- Full phase coherence in injection-seeded mode: Plasma-based lasers are presently the only soft x-ray lasers with full temporal and spatial coherence.
- Narrow linewidth: Operated in the picosecond regime, the linewidth is $\Delta\lambda/\lambda < 1 \times 10^{-4}$.
- Compact: (1-3 optical tables) The capillary discharge-pumped lasers are as small as desktop size.
- Short pulse: (duration 1-5 ps) Potential for 50-100 fs with further development.
- Low time: Jitter between soft x-ray pulse and optical laser pulse.

***Cons*:**

- Numerous laser wavelengths accessible but not continuously tunable.

C. Status of the Approach

Plasma-based tabletop soft x-ray lasers have been demonstrated to operate in the gain-saturated regime at numerous wavelengths ranging from 10.9 nm to 50 nm at repetition rates ranging from 1-10 Hz [3-3, 3-4, 3-31]. In the ASE regime (unseeded regime of operation) pulse energies up to 10 μJ and average power up to 20 μW have been generated in the 13 nm wavelength region [3-4]. At present the peak spectral brightness of these lasers exceeds by about 5 orders of magnitude that of third-generation synchrotrons. These lasers have already enabled tabletop experiments such as very-high-resolution microscopy (e.g., sub-38-nm spatial resolution [3-18]) in transmission and reflection, and the first demonstration of at-wavelength inspection of lithographic masks done outside a synchrotron. The injection-seeding of plasma-based soft x-ray lasers have been demonstrated to produce pulses with full temporal and spatial coherence at wavelengths down to 13 nm [3-12]. In this case the time structure of the pulses consists of a single transform-limited light pulse of about 1 ps duration, with pulse energies that at present approach 0.1 μJ.

D. Size of Investment and Size of Facility

Plasma-based soft x-ray lasers are compact devices that fit into a small-sized laboratory. Depending on the performance parameters, the size of the laser can range from a single standard optical table to three optical tables. Capital cost for a tabletop laser plasma-based soft x-ray laser beamline is estimated to range from $2-4 M depending on desired characteristics. The cost of a larger (but still compact) facility designed to generate fully coherent, high-energy laser pulses with brightness approaching current 0.6-30-nm FELs would be higher. The cost of a discharge-pumped 46.9-nm laser is $0.3-0.4 M. The cost of a 5-year research program designed to improve performance is estimated to be on the order of $1-1.5 M per year.

E. Operability Considerations

Plasma-based soft-ray lasers are compact tabletop devices that are very cost efficient and require limited staff for their operation. Typically one staff person (occasionally two) and a user can typically operate the light source for most experiments. Operating costs also include consumables such as targets, and the occasional replacement of optical components subjected to high laser fluences. Such facility can have very broad user access and can allow for a wide range of experiments. For example, during the past two years the soft x-ray laser facility at Colorado State University has accommodated experiments with researchers from several other U.S. universities and France, as well as experiments done in collaboration with industry.

F. Suggested R&D to Improve Performance

Results from research and development in three areas can lead to greatly improved performance:

a) research in injection-seeding of plasma amplifiers can result in femtosecond soft x-ray laser pulses with greatly increased peak spectral brightness potentially approaching that of current FELs in the 100-eV photon energy region;

b) development of high-repetition-rate diode-pumped amplifiers that can result in greatly increased average brightness;

c) investigation of pumping schemes to extend saturated laser operation of high-repetition-rate plasma soft x-ray lasers to shorter wavelengths.

G. Comparison with Present State of the Art Synchrotron Light Sources and Prospects

Presently the peak spectral brightness of plasma soft x-ray lasers in the 13-nm spectral region exceeds by nearly 5 orders of magnitude that of third-generation synchrotrons and is about four orders of magnitude below that of FELs. (See Table 3-1 for a comparison to FELs). Research during the next five years can be expected to lead to peak spectral brightness that approaches that of current FELs in the 13- to 30-nm spectral region. Plasma-based lasers are presently the only soft x-ray lasers with full temporal and spatial coherence (FELs will also achieve full temporal coherence in the future when seeded). Future prospects of tabletop soft x-ray lasers include mW average power with repetition rate > 100 Hz, pulse energies > 0.1 mJ in sub-picosecond pulses, and sub-10-nm wavelengths, as summarized in Table 3-2.

Table 3-1: Comparison between Current Tabletop Soft X-ray Lasers and the FLASH FEL

Parameter	FLASH	Tabletop Soft X-ray Lasers Unseeded	Tabletop Soft X-ray Lasers Seeded	Tabletop Capillary Discharge Laser
Photon energy	10 – 200 eV	25 – 114 eV	25 – 94 eV	26.5 eV
Energy per pulse	10 – 100 µJ	1 – 10 µJ	0.01 – 0.1 µJ	0.1 – 0.5 mJ
Repetition rate	10 Hz with microbunches	2.5 – 10 Hz	1 – 10 Hz	3 – 10 Hz
Pulse duration	10 fs	1 – 5 ps	1 ps	1 ns
Focused intensity	~ 10^{15} W/cm^2	~ 10^{14} W/cm^2	~ 10^{14} W/cm^2	~ 4×10^{13} W/cm^2
Average power	0.1 – 1 mW	2 – 20 µW	0.1 – 0.5 µW	0.1 – 2 mW
Coherence	Full spatial Limited temporal	Partial spatial and temporal	Full spatial Full temporal	Full spatial
Polarization	Linear	Unpolarized	Linear	Unpolarized

Table 3-2: Future Tabletop Soft X-ray Lasers

Parameter	Soft x-ray Lasers Unseeded	Soft x-ray Lasers Seeded
Photon Energy	25 – 400 eV	25 – 100 eV
Energy per pulse in 1% bandwidth	0.1 – 1 mJ	0.01 – 0.5 mJ
Repetition Rate	1 – 100 Hz	1 – 100 Hz
Pulse Duration	1 – 5 ps	50 – 500 fs
Average Power	1 – 10 mW	0.1 – 1 mW
Coherence	Full spatial Limited temporal	Full spatial Full temporal
Polarization	Unpolarized	Linear

H. References

[3-1] D. L. Matthews, P. L. Hagelstein, M. D. Rosen et al., "Demonstration of a soft-x-ray amplifier," *Phys. Rev. Lett.* **54**, 110 (1985).

[3-2] S. Suckewer, C.H. Skinner, H. Milchberg et al., "Amplification of stimulated soft x-ray emission in a confined plasma column," *Phys. Rev. Lett.* **55**, 1753 (1985).

[3-3] Y. Wang, M.A. Larotonda, B.M. Luther et al., "Demonstration of high-repetition-rate tabletop soft-x-ray lasers with saturated output at wavelengths down to 13.9 nm and gain down to 10.9 nm," *Phys. Rev. A* **72**, 053807 (2005).

[3-4] D. Martz, D. Alessi, B.M. Luther et al., "High Energy 13.9 nm Table-top Soft x-ray Laser at 2.5 Hz Repetition Rate Excited by a Slab-pumped Ti:sapphire Laser," *Opt. Lett.* **35**, 1632 (2010).

[3-5] P. V. Nickles, V. N. Shlyaptsev, M. Kalachnikov et al., "Short pulse x-ray laser 32.6 nm based on transient gain in Ne-like titanium," *Phys. Rev. Lett.* **78**, 2748 (1997).

[3-6] J. Dunn, Y. Li, A. L. Osterheld et al., "Gain saturation regime for laser-driven tabletop, transient Ni-like ion x-ray lasers," *Phys. Rev. Lett.* **84**, 4834 (2000).

[3-7] D. Alessi, D.H. Martz, Y. Wang et al., "1 Hz Operation of a Gain-Saturated 10.9 nm Table-Top Laser in Nickel-like Te," *Opt. Lett.* **35**, 414 (2010).

[3-8] D. Alessi, B.M. Luther, Y. Wang et al., "High repetition rate operation of saturated table-top soft x-ray lasers in transitions of neon-like ions near 30 nm," *Opt. Express* **13**, 2093 (2005).

[3-9] S. Sebban, R. Haroutunian, P. Balcou et al., "Saturated amplification of a collisionally pumped optical-field-ionization soft x-ray laser at 41.8 nm," *Phys. Rev. Lett.* **86**, 3004 (2001).

[3-10] S. Suckewer, J. Ren, S. Li et al., "Towards ultraintense RBS pump for recombination 3.4 nm laser via optical filed ionization," Proc. 11th International Conference on X-ray Lasers, Belfast, Eds. C.L.S. Lewis and D. Riley (2008).

[3-11 Ph. Zeitoun, G. Faivre, S. Sebban et al., "A high-intensity highly coherent soft x-ray femtosecond laser seeded by a high harmonic beam," *Nature* **431**, 426 (2004).

[3-12] Y. Wang, E. Granados, M.A. Larotonda et al., "High-Brightness Injection-Seeded Soft-x-ray-Laser Amplifier Using a Solid Target," *Phys. Rev. Lett.* **97**, 123901 (2006).

[3-13] Y. Wang, E. Granados, F. Pedaci et al., "Phase-coherent, injection-seeded, table-top soft-x-ray lasers at 18.9 nm and 13.9 nm," *Nature Photonics* **2**, 94 (2008).

[3-14] B.R. Benware, C.D. Macchietto, C.H. Moreno et al., "Demonstration of a High Average Power Tabletop Soft x-ray Laser," *Phys. Rev. Lett.* **81**, 5804 (1998).

[3-15] F. Furch, B. Reagan, B. Luther et al., “Demonstration of an all-diode-pumped soft x-ray laser,” *Opt. Lett.* **34**, 3352 (2009).

[3-16] A. Weith, M.A. Larotonda, Y. Wang et al., “Continuous high repetition rate operation of collisional soft x-ray lasers using solid targets,” *Opt. Lett.* **31**, 1994 (2006).

[3-17] G. Vaschenko, C. Brewer, F. Brizuela et al., “Sub-38 nm resolution tabletop microscopy with 13 nm wavelength laser light,” *Opt. Lett.* **31**, 1214 (2006).

[3-18] C.A. Brewer, F. Brizuela, P. Wachulak et al., “Single shot extreme ultraviolet laser imaging of nanostructures with wavelength resolution,” *Opt. Lett.* **33**, 518 (2008).

[3-19] C.S. Menoni, F. Brizuela, S. Carbajo et al., “Reflection microscope for actinic mask inspection and other progress in soft x-ray laser nano-imaging,” Proc. 12th International Conference on X-ray Lasers, Gwangju, Korea, May 30 – June 4, (2010).

[3-20] S. Heinbuch, F. Dong, J.J. Rocca et al., “Single photon ionization of hydrogen bonded clusters with a soft x-ray laser: $(HCOOH)_x$ and $(HCOOH)_y(H_2O)_z$,” *J. Chem. Phys.* **126**, 244301 (2007).

[3-21] F. Dong, S. Heinbuch, J.J. Rocca et al., “Single photon ionization of van del Waals clusters with a soft x-ray laser: $(SO_2)_n$ and $(SO_2)_n(H_2O)_m$,” *J. Chem. Phys.* **125**, 154317 (2006).

[3-22] S. Heinbuch, F. Dong, J.J. Rocca et al., “Gas phase study of the reactivity of optical coating materials with hydrocarbons bye use of a desk-top size extreme ultra-violet laser,” *J. Opt. Soc. Am. B* **25**, B85 (2008).

[3-23] F. Brizuela, Y. Wang, C.A. Brewer et al., “Microscopy of extreme ultraviolet lithography masks with 13.2 nm tabletop laser illumination,” *Opt. Lett.* **34**, 271 (2009).

[3-24] A. Isoyan, F. Jiang, Y.C. Cheng et al., “Talbot Lithography: Self-Imaging of Complex Structures,” *J. Vac. Sci. Technol. B* **37**, 2931 (2009).

[3-25] G. Vaschenko, A.G. Etxarri, C.S. Menoni et al., “Nanometer scale ablation with a table-top soft x-ray laser,” *Opt. Lett.* **31**, 3615 (2006).

[3-26] R.Z. Tai, K. Namikawa, M. Kishimoto etal., “Picosecond snapshot of the speckles from ferroelectric BaTiO3 by means of x-ray lasers,” *Phys. Rev. Lett.* **89**, 257602 (2002).

[3-27] A.J. Nelson, J. Dunn, J. Hunter et al., “Time-resolved x-ray laser induced photoelectron spectroscopy of isochoric heated copper,” *Appl. Phys. Lett.* **87**(15), 154102 (2005).

[3-28] J. Filevich, K. Kanizay, M.C. Marconi et al., “Dense plasma diagnostics with an amplitude-division soft-x-ray laser interferometer based on diffraction gratings,” *Opt. Lett.* **25**, 356 (2000).

[3-29] R.F. Smith, J. Dunn, J. Nilsen et al., “Picosecond x-ray Laser Interferometry of Dense

Plasmas," *Phys. Rev. Lett.* **89**, 065004 (2002).

[3-30] M.A. Purvis, J. Grava, J. Filevich et al., "Collimation of dense plasma jets created by low energy laser pulses and studied with soft x-ray interferometry," *Phys. Rev. E* **81**, 036408 (2010).

[3-31] Y. Wang, M. Berrill, F. Pedaci et al., "Measurement of 1 Picosecond Soft x-ray Laser Pulses from an Injection-Seeded Plasma Amplifier," *Phys. Rev. A* **79**, 023810 (2009).

Section 3.B. Incoherent X-ray Plasma Sources

A. Introduction

Brief Description of Physical Basis

Laser driven plasma x-ray (LPX) sources emitting ultrashort x-ray pulses rely on the interaction of ultrashort laser pulses with solid density material surfaces, such as metal surfaces. Owing to the high light intensity, a dense metal plasma is generated that strongly heats plasma electrons that penetrate the solid target material. The subsequently generated x-rays in the angstrom wavelength regime are emitted into 4π steradians and consist of line radiation, typically used for ultrafast x-ray diffraction, and continuum radiation, which can be used for ultrafast x-ray absorption spectroscopy. The radiation can be used for time-resolved, phase-contrast imaging, which has been demonstrated to work well with polychromatic emission and benefits from a large x-ray emission angle achieving a large field of view. A sub-100-fs x-ray pulse width is critically dependent upon rapid electron heating and cooling below an electron temperature insufficient to generate significant amounts of radiation. The time scale of heating and cooling can be controlled through the laser pulse length, irradiance, contrast, polarization, and incidence angle on the material's surface, as well as the specifics of the surface's structure.

LPX sources are based on a mature understanding of the underlying physics and robust technology. Further development to a technology readiness level (TRL) of 8–9 primarily requires system engineering and can be accomplished in about fpur years at the performance level defined below. LPX sources serve applications that are typically x-ray flux-limited but not brightness-limited such as x-ray phase-sensitive imaging, and ultrafast x-ray diffraction and absorption of molecular structural dynamics.

Brief Description of Technical Components

A driving laser and focusing optics is needed that can generate light intensities in the range of 10^{15} to 10^{19} W/cm^2 depending on the Kα x-radiation energy that one tries to generate with maximum efficiency[1]. A target chamber that presents the target to laser light needs to be evacuated or filled with low-density gas (He) to avoid laser light self-defocusing in front of the

[1] Soft x-rays, for instance in the water window, can be generated from a gas target with laser pulses of ten to hundreds of picoseconds. These pulses can be conveniently generated by mode-locked YAG lasers. Such systems emit on the order of 10^{13} ph / s 4π for a few Watts laser power.

target. Typically the target needs to be replaced after every laser shot, which necessitates a moving metal-wire, metal-foil, or liquid-metal target. The focusing optics needs to be protected from the target debris. A deformable mirror in front of the focusing optics is desirable to optimize the laser light intensity on the target.

B. Properties / Goals / Potential Impact

Laser-driven plasma x-ray sources form a symbiotic community with synchrotron x-ray sources and x-ray lasers. Each source type addresses specific needs of the scientific community, such as average and peak x-ray flux, x-ray pulse lengths, or available beam time. The time-averaged x-ray brightness and x-ray flux of synchrotrons will always be larger than that of laser-driven x-ray sources. The x-ray pulse length of LPX sources is, however, a factor of 1000 shorter than that of synchrotrons. Consequently, LPX sources provide substantial performance for time-resolved structural dynamics measurements. Furthermore, while these laser-driven sources are valuable in their own right, they also serve as training environments for ultrafast experiments at third-generation sources and FELs.

What Science is Best Done with LPX Sources?

- Large field-of-view x-ray imaging (ultrafast microscopic structural dynamics, such as material melting or turbulent flow imaging, but also biomedical imaging)
- Ultrafast experiments using broad x-ray bandwidth (ultrafast EXAFS)
- Ultrafast experiments using hazardous materials

Advantages of LPX Sources:

- LPX sources are highly cost effective
- LPX sources are part of a symbiotic community with synchrotron x-ray sources and x-ray lasers
- Hard x-ray pulse length as short as tens of femtoseconds
- x-ray flux per pulse ($>5 \times 10^6$ ph / pulse 0.1%BW @ 8 keV) can approach that of monochromatic third-generation synchrotron sources on sample
- Current Technology Readiness Level: 6 – 8, (depending on source design details)
- X-ray photon energy selectable (K and L lines from 1.5 keV (Al Kα) to about 90 keV (Bi Kα)[2])
- Very compact system envelope (diode-pumped) at kHz repetition rates possible
- Repetition rate perfectly matched to the available pump laser rep. rate[3] → x-ray photons

[2] This energy has not been demonstrated yet. The generation will be most efficient at a laser intensity of about 5×10^{19} W/cm^2. Targets could be liquid Pb/Bi alloys.

[3] This is a trivial consequence of the fact that laser sample-pump and x-ray probe pulses are derived from the same

produced per pulse are optimally matched to the experiment

- Transversal coherence suitable for x-ray holography; phase contrast imaging
- Maintenance free x-ray source designs possible (like an x-ray tube)
- No timing jitter between pump and x-ray probe (because both are derived from the same laser system)

Disadvantages of LPX Sources:

- X-ray emission into 4π (an advantage for imaging and dispersive XAFS beamlines)
- Polychromatic emission (an advantage for dispersive XAFS beamlines; irrelevant for many X-ray phase-sensitive imaging applications)
- X-ray photon energy not continuously tunable but selectable
- X-ray photon energy bandwidth determined by the emission line width (1.5 eV for Al Kα to 70 eV for Bi Kα)

C. Status of this Approach

What is the Present Level of Technical Achievement? Where is the Technology?

- Sources: Technology Readiness Levels 6 and 8 for liquid-metal and metal-foil target systems, respectively.
- Beamlines: TRL 5 for XAFS, TRL 6 for diffraction and imaging.

What Could be Done Now? In Five Years?

Current performance of typical LPX source is less then 1% of the performance numbers listed below. Relatively little research, but laser and source development will impact the performance on a few-year time scale. The projected performance data rely on a combination of currently available laser systems. Since more advanced systems might be available in five years, the future source performance might be higher than that listed in the following section.

Specify in Terms of Both Time Average and Peak Brightness[4]

- Brightness:

  5-kHz rep. rate, Cu Kα emission, 10-µm source diameter, 100-fs pulse length:[5]

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laser system.

[4] The following numbers for the LPX sources consider line emission but ignore the continuum background emission that is superimposed on the line spectrum. Thus, 0.1% BW does not imply that the beam is monochromatic. For line radiation this monochromatization can be accomplished with little loss. For arbitrary x-ray energies, the monochromator crystal rocking curve width may cause a reduction of the reported numbers by 2 orders of magnitude. However, higher throughput condenser optics designs are likely possible.

[5] These projections are an extrapolation from current LPX source performances (~10^8 ph / s mrad^2 mm^2 0.1% BW) using a laser system with 10 W, 40 fs, 5 kHz to a 100-W laser system using experimentally known scaling laws.

10^{11} ph /s mrad^2 mm^2 0.1% BW (time average)

3×10^{20} ph / s mrad^2 mm^2 0.1% BW (peak, i.e., during the x-ray pulse)[6]

100-Hz rep. rate, Cu Kα emission, 50-μm source diameter, 100-fs pulse length: [7]

10^{10} ph / s mrad^2 mm^2 0.1% BW (time average)

10^{21} ph / s mrad^2 mm^2 0.1% BW (peak, i.e., during the x-ray pulse)

- Average flux generated:

  10^{14} ph / s 4π 0.1% BW (time average)

- Flux on sample:

  3×10^9 ph/s 0.1% BW (time average)

  (For ref.: APS (top-up) 7 ID-C: ~5×10^{12} ph/s @ 8 keV, 1 eV BW)

  3×10^{14} ph/s 0.1% BW (peak) [8]

  (For ref.: APS (top-up) 7 ID-C: ~ 10^{16} ph/s @ 8 keV, 1 eV BW)

- Flux on sample per pulse:

  kHz: 6×10^5 ph / pulse 0.1% BW (For ref.: APS (top-up) 7 ID-C: ~7×10^5 ph / pulse @ 8 keV, 1 eV BW)

  100 Hz: 6×10^6 ph / pulse 0.1% BW

- Estimated total white-beam flux on sample per pulse:

  kHz: 2×10^6 ph / (pulse 20 keV BW)

  100 Hz: 2×10^7 - 10^8 ph/(pulse 20 keV BW)

Characterize Stability of Output, Time Structure, Polarization, etc.

Short-to-shot stability: 10%, sub-100-fs pulse length, unpolarized, Hz-kHz repetition rates possible

Principle Technical Challenges

- High-average-power laser system development (this favors kHz laser rep rates)
- Improvement of the shot-to-shot stability of x-ray source
- Source engineering to handle the laser heat and target debris

What is the Size of Investment Needed?

Table 3-3 provides a summary of the projected capital costs. This does not include general beamline cost such as x-ray CCD, goniometers, etc.

[6] Calculated by dividing the average brightness by the repetition rate and the x-ray pulse length.

[7] These projections are an extrapolation from current LPX source performances (2×10^8 ph / s mrad^2 mm^2 0.1% BW) using a laser system with 2 W, 200 fs, 100 Hz to a 100-W laser system by scaling the brightness linearly with laser power.

[8] Calculated by dividing the flux per pulse by the x-ray pulse length.

Table 3-3: Projected Capital Costs

Current Systems		Future Systems, performance as defined above	
Laser (20 W, 40 fs, 5-10 kHz):	750 k$	Laser (100 W, 40 fs, 5-10 kHz):	1300 k$
X-ray chamber:	100 k$	X-ray chamber:	150 k$
Deformable optics (optional):	50 k$	Deformable optics (optional):	50 k$
Total:	900 k$	Total:	1500 k$

Size of Facility

Laser system, x-ray source, and experiment: Laser-table top 10′ × 5′
Typical beamline lengths (source to detector) for x-ray imaging, diffraction, XAFS: 1 – 2 meters

D. Operability Considerations

Kilohertz repetition rate is best for high average power. Such laser system systems are also relatively easy to operate. Lower rep. rate operation is better for high pulse flux.

Operating Cost and Cost Efficiency, Staffing Levels

One operator, who can be an experimenter him/herself (about 100 k$ /year). If laser system is diode pumped: electrical and cooling power cost, laser diode replacements cost about $20/hour.

User Access / Availability

Systems exist currently in individual laboratories, mostly in Europe and Japan, three in the U.S. Systems can have 90% availability. This does require additional development to make the sources truly maintenance free. Such compact light sources are expected to have a high degree of reliability.

E. Suggested R&D to Improve Performance

Little research, but much development is needed, especially in heat and debris management in the target area.

Construction of high-average-power, kHz rep rate, ultrafast laser systems that are diode pumped would be of great benefit.

F. Comparison with the Present State-of-the-Art Synchrotron Light Sources (Third-Generation Storage Rings and FELs)

- Low rep rate plasma sources could generate up to 10^{12} ph/pulse (e.g., for a laser system with 1-J pulse energy). Their x-ray flux per pulse on sample (6×10^6 ph/pulse @ 8 keV and 0.1% BW) can be comparable to that of monochromatic third-generation synchrotron beams. For example, the flux per pulse at the APS, ID-7-C is 10^6 ph/pulse @ 8 keV and 1 eV BW. In hybrid mode the pulse flux at the APS is about 4 times higher. Furthermore, the APS beam is truly monochromatic, while the LPX radiation is polychromatic as discussed in footnote 5 above.

- Owing to their excellent beam collimation and high repetition rate, synchrotrons produce a much higher average x-ray flux on sample than LPX sources but their x-ray pulse length is about 1000 times longer.
- Compared to LPX sources FELs deliver far superior beam quality, flux on sample, and x-ray intensity on sample, but LPX sources are highly cost effective for many experiments that do not need such high pulse performance but require comparable x-ray pulse length.

Section 3.C. Compact Resonant Raman Compression for Light Sources

A. Introduction

Resonant Raman compression is a technique that compresses the light output of sources from the visible to the soft x-ray. It can be used as a means of improving the output of the compact sources discussed at the workshop, such as from compact FELs in, say, the UV regime. It also may provide the means to generate very intense optical laser pulses of ultra-short time duration to drive plasma-based soft x-ray and x-ray sources.

The compression relies on transferring the energy from a long pump laser to a short duration counter-propagating seed beam. In doing so, the laser light is not only compressed but processed in several other important ways as well. First, the seed, being at low intensity, may be more easily focused than the pump - and an unfocusable pump can transfer its energy to the focusable seed. Second, any incoherence in the long laser beam is cleaned up in the transfer, so as long as the seed is coherent, the extra entropy is taken up by the plasma wave.

The regime in which this technique is indispensable is when the intensities are too large to be handled by material gratings, or when those gratings are too difficult to fabricate in the first place.

Experiments to date have shown good, compact, and fairly efficient (effectively around 10%) pulse compression at one-micron wavelengths, compressing ps pulses to 100 fs or less. This is done in a University scale experiment. The next steps would be to demonstrate higher efficiency and shorter wavelengths. The technology for a shorter wavelength is significantly different, since the plasma density scales inversely with the square of the wavelength.

Brief Description of Physical Basis

Figure 3-2 shows how a plasma slab accomplishes at high intensity what material gratings cannot. At high intensities the short pulse shortens as it grows, because as the front of the pulse grows, it shades the trailing part [3-32].

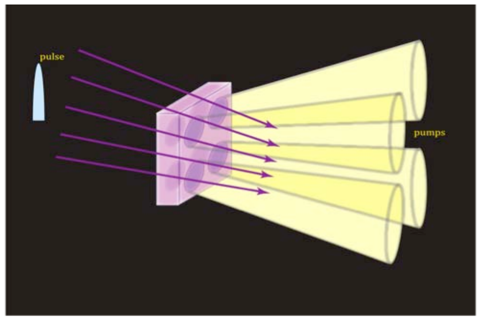

Figure 3-2: *Raman compression effect.*

B. Properties / Goals / Potential Impact

The advantage of this compact approach is that material optical components are avoided. The tolerable fluence in optical gratings in the sub ps range of pulse lengths and at 1 micron is on the order of J/cm^2; at shorter wavelengths, optical gratings are even more intolerant to high fluence and are difficult to fabricate. However, ps pulses at J/cm^2 give intensities of only $TW/\ cm^2$. At these intensities, and even moreso at shorter wavelengths, the resonant Raman backscattering can proceed relatively unimpeded by competing higher-order effects. The disadvantage is that it is more complicated.

C. Status of this Approach

What is Present Level of Technical Achievement? Where is the Technology?

The compression effect has now been observed in plasma at micron wavelengths in tabletop terawatt experiments, with many of the underlying physical mechanisms demonstrated with output intensities about 100 times the input intensities at several per cent efficiencies [3-33]. Although the technological means of implementation may be very different, the compression effect has been predicted to occur also in the UV and soft x-ray regime [3-34].

What Could be Done Now? In Five Years?

The next important technological step will be to extend this compression effect to higher pump energies and further into the submicron range of pump frequencies. It will also be important to show it at larger cross sections (higher power).

Principle Technical Challenges

It remains to be shown that the short pulse stays focusable under compression, the efficiency can reach closer to theoretical limits, and that the compression itself can be fast enough to overcome modulational instabilities.

D. Size of Investment Needed

a. Projected capital costs. The next steps can proceed at several hundred K$/year.

b. Size of facility, including all components is university-scale.

E. Operability Considerations

This is still in the research and development stage of the source itself. As such, it is at a single- to several-PI level, with graduate students or postdoctoral fellows involved, at one or more institutions, but with no user facility for the next few years.

F. References

[3-32] V.M. Malkin et al., "Fast Compression of Laser Beams toHighly Overcritical Powers," *Phys. Rev. Lett.* **82**, 4448 (1999).

[3-33] J. Ren et al., "A Compact double-pass Raman Backscattering amplifier/compressor," *Phys. Plasmas* **15**, 056702 (2008).

[3-34] V. M. Malkin et al., "Compression of powerful x-ray pulses to attosecond durations by stimulated Raman backscattering in plasmas," *Phys. Rev. E* **75**, 026404 (2007).

Section 4. Plasma-Based Accelerator Sources

Working Group: Carl Schroeder, Mark Hogan, Wim Leemans, Victor Malka, Warren Mori

A. General Considerations

Compact x-rays beams can be produced using intense lasers, plasmas and/or magnetic devices in several different schemes: emission from betatron motion, laser wigglers to produce nonlinear Thomson (or Compton) scattering, undulators, etc. Mechanisms that can produce x-ray radiation are all based on the same fundamental principle: the radiation from the acceleration of relativistic electrons. Even if the details of the electron orbits are different for each source, the main features can be obtained using onlyfive parameters: the relativistic factor γ of electrons, the number of electrons N_e, the field strength parameter K, the period λ_u, and the number of periods N of the undulator/wiggler. In addition, the incoherent radiation provided by these sources can eventually be enhanced to coherent radiation via the FEL mechanism for high enough electron beams quality; the use of conventional undulators represents the most promising route toward such a goal.

In the XUV domain, conventional undulator coupled with a laser-plasma accelerator (LPA) yields the monochromatic radiation, if the electron bunch is monoenergetic. Up to 10^9 photons collimated within a few mrad could be produced in a single shot using 10^9 electrons (160 pC) at an energy in the 100's of MeV range and an undulator of strength parameter K = 1 with 100 periods. By varying the electron energy, the radiation wavelength can be tuned. Because the acceleration and the wiggling are independent, a stable and/or tunable regime of acceleration can be used, resulting in a stable and/or tunable radiation source. With GeV electron beams, this scheme will produce radiation in the keV range. However, this source is more complex to realize because the electron bunch must be transported into the undulator. The transport can degrade the electron bunch duration (and so the x-ray pulse duration) and the transverse emittance, which leads to a broader bandwidth in the radiation spectrum and a smaller brightness. This scheme deserves to be developed as it is on the path towards a free electron laser based on laser-plasma accelerators.

In the range of a few keV, the emission due to the betatron motion of the electrons in the self-field of the beam as it traverses a plasma has been demonstrated to be an efficient and simple method to produce x-ray pulses. This source can produce up to 10^9 photons per shot, collimated within less than 50 mrad (FWHM). On the one hand, controlling the electron orbits within the cavity in order to ensure a better energy transfer from the electron to the radiation could allow us to extend the spectral range to the 10's of keV range, while keeping a 50-TW-class laser. On the other hand, petawatt-class lasers and/or capillaries would be suitable to create larger ion cavities with lower plasma density and accelerate electrons to the GeV range. This approach should allow the production of x-ray beams whose divergence is in the mrad range and photon energies in the 10's and 100's of keV range, with a higher number of photons.

Above 10 keV and up to a few MeV, an attractive mechanism is Thomson backscattering. Here, high-energy radiation is produced thanks to the short period of the electron motion. This scheme is very similar to the case of a laser-plasma accelerator coupled with a conventional undulator, except that it benefits from the short period of the electron motion resulting in emitted photons of high energies and it does not need transport. By tuning the electron energy, the photon energy can be chosen. Although only one experimental demonstration of this scheme has been accomplished with the use of laser-plasma accelerators, it may be the most promising one for generating tunable incoherent hard x-ray and γ -ray radiation. While x-rays allow performing diffraction experiments on the femtosecond time scale, tunable γ-rays allow nuclear spectroscopy experiments. Increasing the number of electrons and the counterpropagating laser energy and reducing the electron beam emittance will help to produce a brighter x-ray or γ -ray sources.

As free-electron lasers (FELs) are the natural evolution of synchrotrons, FELs based on laser-plasma interaction could be the next step in the development of laser and plasma based x-ray sources. In the free-electron laser process, the emitted radiation is amplified and becomes coherent with a number of photons increased by orders of magnitude. The most promising scenario uses a conventional undulator coupled to a laser-plasma accelerator. Because very stringent conditions apply to the electron beam parameters such as energy spread and transverse emittance, challenging developments are required in the laser-plasma accelerator domain, including ultra compact transport system. Thanks to the high brightness of FEL radiation, many experiments can be performed in single shot or with small data accumulation such that the low repetition rate of laser facilities becomes a more benign disadvantage than for incoherent sources.

Table 4-1 gives the typical parameters and features of the different radiation mechanisms as well as scaling laws[9]. For the features of the sources produced, interaction parameters accessible with currently available 10's of TW-class lasers have been chosen. The spectra of each mechanism show that an energy range from eV to MeV can be covered. The main difference between these sources discussed resides in their photon energy. Depending on the spectral range required for a desired application, Table 3-4 helps to select the most suitable type of source.

The first sub-table gives typical features for the different sources achievable with a 50-TW-class laser. The values represent the orders of magnitude of the parameters. The second sub-table provides the scaling of the radiation features with the relevant parameters K, λ_u, and γ. The last sub-table presents the scaling of the relevant parameters with the practical parameters for each scheme.

[9] S. Corde *et al*., submitted to Rev. Mod. Phys.

Table 4-1: Typical Parameters, Features, and Scaling Laws of Various Radiation Mechanisms

Typical features	γ	λ_u	K	N	N_{e^-}	E_X / E_{Xc}	θ_r	N_X
Betatron:	200	150 µm	10	1	10^9	5 keV	50 mrad	~ 10^8
Conventional Undulator:	400	1 cm	1	100	10^8	25 eV	2.5 mrad	~ 10^8
Thomson Backscattering:	400	0.4 µm	1	10	10^8	650 keV	2.5 mrad	~ 10^7

Scalings of the radiation features	
Fundamental radiation energy E_x for undulators ($K < 1$):	$2\gamma^2 \times 2\pi\hbar c / \lambda_u /(1+K^2/2)$
Critical radiation energy E_{Xc} for wigglers ($K > 1$):	$K \times \frac{3}{2}\gamma^2 \times 2\pi\hbar c / \lambda_u$
Radiation half divergence θ_r for undulators ($K < 1$):	$1/\gamma$
Radiation half divergence θ_r for wigglers ($K > 1$):	K/γ
Number of emitted photons per electron and per period $N_{X/e^-/period}$:	
for undulators ($K < 1$):	$1.5\times10^{-2} K^2$
for wigglers ($K > 1$):	$3.3\times10^{-2} K^2$

Scalings of the relevant parameters	K	λ_u
Betatron (n_e, r_β and γ):	$\sqrt{\gamma/2}\, k_p r_\beta$	$\sqrt{2\gamma}\,\lambda_p$
Conventional Undulator (B_0, λ_u and γ):	$eB_0\lambda_u/(2\pi mc)$	λ_u
Thomson Backscattering (a_0, λ_L and γ):	a_0	$\lambda_L / 2$

B. Plasma WakeField Accelerator (PWFA)-Driven Sources

The electron-beam-driven plasma accelerator was first proposed by Chen et al. in 1985. In the last decade, the capability of the SLAC linac to deliver high intensity bunches has led to remarkable progress for beam-driven plasma accelerators with the maximum energy gained in the plasma increasing to over 40 GeV in less than 1 meter in 2007.

As shown in Figure 4-1, a high-amplitude oscillation can be set up in a plasma by the passage of a relativistic electron bunch in the highly nonlinear yet highly stable blowout regime. The oscillations are set up by the expulsion of the plasma electrons as the drive bunch traverses the plasma and have a wavelength related to the electron plasma frequency. The drive bunch needs to be shorter than the plasma wavelength and smaller than the dimensions of the plasma wake in the radial dimension. The fields increase with the square root of the plasma density. For a typical density of 10^{17} e^-/cm^{-3}, the plasma wavelength is ~ 100 µm, the accelerating fields is ~ 10 GeV/m and the focusing gradients are ~ MT/m. Experiments have shown that plasmas can accelerate and focus high-energy electron beams. Plasma wakefield experiments have also demonstrated that gradients of ~50 GeV/m, roughly 3,000 times that in standard S-band linacs, can be sustained over meter-scale distances.

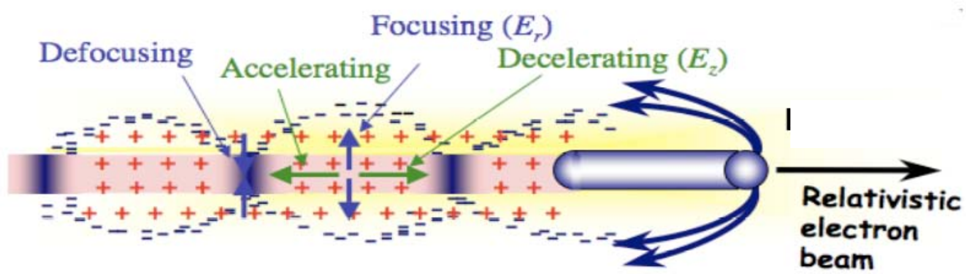

Figure 4-1: *PWFA schematic, indicating plasma oscillations set up by drive electron bunch expelling plasma electrons from the path of the drive bunch.*

The PWFA is an attractive technology because existing microwave accelerators can efficiently produce high-current bunches well suited for driving plasma wakes with fields over 10 GeV/m. The PWFA then acts as a transformer, converting one or more high-current, low-energy bunches into one or more relatively low-current, high-nergy bunches. This process can be characterized by the ratio of the peak accelerating field to the peak de-accelerating field in the plasma wake, called the transformer ratio. The transformer ratio can be manipulated by tailoring the longitudinal profile of the beams driving and sampling the plasma wake. Experiments to date with Gaussian-shaped bunches have operated with transformer ratios between 1 and 2. Recent analytic and numerical models have predicted that by optimizing the longitudinal profile and/or the plasma density, transformer ratios of 5 may be attained, e.g., a 1-GeV drive bunch with several nC of charge could boost the energy of a 1-nC, 1-GeV bunch to an energy of 5 GeV on the scale of a meter. In the example studied, a 5-nC, 0.56-ps, 1-GeV drive bunch is able to accelerate a 0.35-nC, 23-fs, 1-GeV trailing bunch to 5 GeV with an energy spread of less than 1%, with an energy conversion efficiency of 35% from drive to accelerated electrons and with emittance preservation at or below 1 mm-mr. This technology could be used to reduce the length of LCLS by a factor of five with the same basic microwave accelerator technology, or even more significantly, lead to a vastly more compact system if the GeV drive beam is generated in a modern X-band accelerator, like the Next Linear Collider Test Accelerator (NLCTA) at SLAC, with an overall footprint on the same order of magnitude as in a 10-GeV LPA. Considering the high-average-power capabilities of rf accelerators, this technology can match the high average flux of conventional x-ray FELs and ICS systems with the cost and size of the linac reduced by a factor of 5.

In a shorter term application, when added to an existing linac, a short plasma afterburner could boost (e.g., double for a Gaussian drive bunch) the energy of the beam on the scale of a few meters and dramatically extend the tunable wavelength reach of an accompanying FEL. A few-cm plasma stage can boost the energy by a factor of 2-5, increasing the accessible wavelength range to 4-25 times shorter wavelengths. For example, an afterburner case has been studied based for the Italian soft x-ray FEL FERMI@ELLETRA. Calculations were performed assuming the charge out of the injector can be increased to 2 nC, with a resulting projected normalized emittance of 1.5 mm-mrad. By adding a third stage of bunch compression/collimation system, a pair of bunches can be crafted from the initial 2 nC with 0.75 nC/0.25 nC in the drive/witness pair respectively. The high-current bunch pair is then injected into a ~1-cm plasma source in the 10^{18} e^-/cm^3 resulting in a single, 0.25-nC bunch boosted from 1.2 to 2.4 GeV. Without modifications to the undulators, this new bunch would radiate at 10 nm, with 2.6% bandwidth and producing 5×10^{13} photons per bunch and saturate in only 14 m.

PWFA Performance Challenges and Overall Readiness

Plasmas have demonstrated the ability to deliver the large gradients required to make GeV energy changes in a few cm of plasma. Following the initial concept demonstrations of beam-driven plasma acceleration, the challenge now is to develop these techniques into useful methods for generating useful beams for light sources and high-energy accelerators. A proposed research and development program that addresses the needs for light sources includes:

- investigating the basic science of 6D phase-space manipulation in nonlinear wakefields, including pulse shaping, self and external injection,
- Providing efficient high-gradient acceleration of mono-energetic beam bunches while maintaining a small energy spread,
- demonstrating higher transformer ratios using higher plasma density and/or shaped bunches while mitigating hosing, and
- studying emittance degradation due to matching, CSR, and hose instability.

The emittance and energy spread of conventional sources is sufficient for light source applications in the keV range. Research over the next five years will aim to demonstrate the high-gradient acceleration of electron bunches while preserving the incoming emittance and producing a final energy spread sufficient for light source applications. Specifically, the beam emittance needs to be maintained at the level of the corresponding photon emittance ($\lambda_{rad}/4\pi$). The energy spread must be small enough that the electrons are radiating within the gain bandwidth of the FEL ($1/N_u$). These constraints need to be satisfied for a slice of the beam as long as the cooperation length ($\lambda_{rad}*L_g/\lambda_u$).

The Facilities for Accelerator Science and Experimental Test Beams (FACET) at SLAC is being constructed to study the physics of PWFA over the next five years. We envisage an R&D program centered around experiments by a broad community at this facility including a strong simulation and theory effort. The goal would be to lay the science foundation for a compact XFEL facility based on PWFA. Such a program would require $2 M/year for research for 10 years. The cost of a new compact XFEL user facility would be $50 M.

C. Laser-Plasma Accelerator (LPA)-Driven Free-Electron Lasers

A user facility that would produce coherent, high-peak-brightness, ultrafast pulses for time-resolved experiments could be build around the concept of a compact, coherent seeded free-electron-laser-based x-ray source driven by a laser-plasma accelerator (LPA) [4-1], owing to rapid advancements in compact, high-power laser technology as well as in compact LPAs that have produced high quality electron bunches at the 1-GeV level using a 40-TW laser pulse interacting with a 3-cm-long plasma [4-2]. This progress has also relied heavily on advances in theory and simulation. Due to the intrinsic ultrashort (fs) duration of the electron bunches, these high-brightness electron bunches are suitable for driving an x-ray FEL. Such a facility could deliver synchronized pulses of fs radiation, particles, and laser light, all from one compact machine. In addition to being hyperspectral, such as source would also allow the direction of the x-ray light to change by modifying the accelerator direction via rerouting of the laser beams.

In contrast to conventional electron accelerator based facilities, many small GeV-class linacs could be built, each of which would be tailored in energy and drive undulator-based FELs of different colors. Recent LPA experimental results [4-2, 4-3] open the possibility of a new class of compact, high-peak flux, FELs in which the conventional accelerator is replaced by a 1-10 GeV LPA (1 m in length), in principle greatly reducing the size and cost of such light sources. LPAs are of great interest because of their ability to sustain extremely large acceleration gradients (10-100 GV/m), enabling compact accelerating structures. In addition to extremely large accelerating gradients, plasma-based accelerators can produce extremely short (femtosecond) electron bunches. With such short durations, peak currents >10 kA are generated. The ultra-short laser-plasma accelerated beams are well-suited to drive an FEL, and the ultra-high currents allow for greatly reduced undulator lengths [4-4–4-7].

Experiments at LBNL, Rutherford Appleton Laboratory, and LOA in France in 2004 have demonstrated generation of low-energy-spread, high-quality ~100-MeV beams containing tens of pC of charge using laser-plasma-based acceleration [4-8]. Experiments at LBNL in 2006 have demonstrated generation of low-energy-spread, high-quality 1-GeV beams [4-2, 4-3] from a cm-scale plasma channel. Among future experiments planned in the next few years is the BErkeley Lab Laser Accelerator (BELLA) to produce 10-GeV electron beams in one meter plasma. Such beams could then be used to drive a compact FEL for coherent hard x-ray generation.

Several key steps remain to be demonstrated and require express R&D support:

- *Demonstration of a SASE-based FEL*: The simplest mode of FEL operation is to rely on self-amplified spontaneous emission (SASE) in the undulator. SASE operation allows for straightforward wavelength tuning via the beam energy or undulator gap. The key challenge is production of e-beam with sufficiently small energy spread and emittance. Techniques are being developed to reliably produce < 0.25% rms energy spread and normalized emittances less than 1 mm-mrad.

- *Demonstration of a seeded FEL*: Owing to the intrinsic synchronization between the laser and the electron beam, external seeding can be done by a high-harmonic generation (HHG) source at the FEL fundamental wavelength for radiation in the VUV and soft-x-ray regime [4-9]. HHG seeding has significant advantages over the simpler SASE mode of operation as it provides improved temporal coherence, reduced fluctuations, and a much reduced power saturation length.

Figure 4-2 shows a timeline of anticipated R&D developments that could enable a user facility based on LPA-driven FELs. Experiments are currently underway at LBNL that aim at demonstrating a proof-of-principle LPA-driven FEL producing 40-eV photons (10^{13} photons/pulse) coupled to a HHG seed (produced from the same drive laser). The overall length of this source (accelerator and undulator) is a few meters. In addition, experiments at LLNL and UCLA are aimed at studying acceleration to GeV energies using self-guiding and novel self-injection concepts are also currently underway. Upon successful BELLA commissioning in 2012, experiments will proceed to produce 10 GeV electron beams in a ~1 m plasma. Using existing ALS undulators at LBNL an LPA-driven FEL producing 1 nm radiation will be demonstrated. It is envisioned that a compact user facility could be available in 2015 delivering coherent soft x-rays. Following demonstration of sufficient beam quality the 10 GeV beam could be coupled to a short-period undulator and used to drive a compact FEL generating hard x-rays.

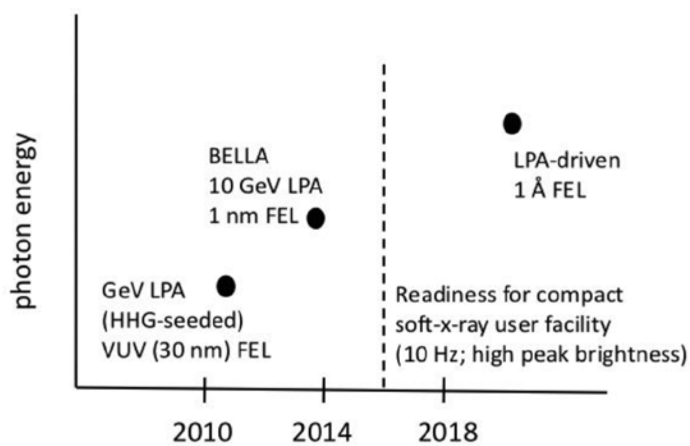

Figure 4-2: *Timeline for LPA-driven FEL R&D milestones (solid circles) and readiness for user facility based on LPA-driven FELs (dashed line).*

Figure 4-3 shows a conceptual schematic of an LPA-driven FEL farm with multiple beamlines providing light for users. LPA-driven sources are capable of providing ultra-short pulses of light, from THz to optical to x-rays, and particles (e.g., electrons, positions, and protons) all synchronized to the drive laser, enabling a wide variety of ultrafast pump-probe science applications.

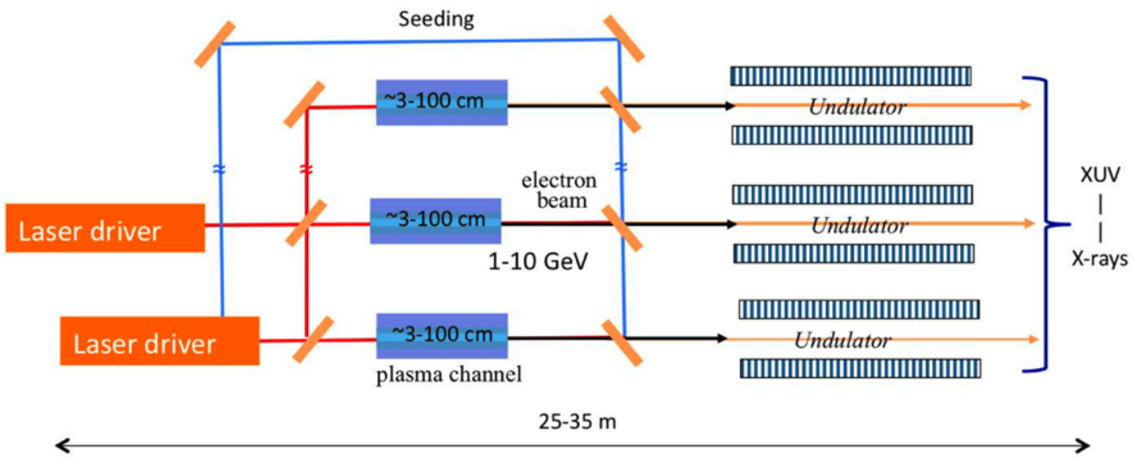

Figure 4-3: *Strawman sketch of user facility based on multiple LPAs and FELs.*

Investment in multiple programs at a level of $5 M/yr could deliver novel approaches to injection, acceleration, and manipulation of 6-dimensional phase space of the electron beam on a timescale commensurate with the construction of a compact user facility operating at the 1 nm wavelength in 5-10 years. The technology and know-how to build reliable compact high peak brightness coherent soft x-ray user facilities could be available beginning in 2015.

D. References

[4-1] E. Esarey, C.B. Schroeder, W.P. Leemans, *Rev. Mod. Phys.* **81**, 1229 (2009).

[4-2] W.P. Leemans, B. Nagler, A.J. Gonsalves et al., *Nature Phys.* **2**, 696 (2006).

[4-3] K. Nakamura, B. Nagler, C. T´oth et al., *Phys. Plasmas* **14**, 056708 (2007).

[4-4] C.B. Schroeder, W.M. Fawley, E. Esarey et al., Proc. FEL 2006, 455-458 (2006); www.JACoW.org.

[4-5] F. Grüner, S. Becker, U. Schramm et al., *Appl. Phys. B* **86**, 431 (2007).

[4-6] H.-P. Schlenvoigt, K. Haupt, A. Debus et al., *Nature Phys.* **4**, 130 (2008).

[4-7] M. Fuchs, R. Weingartner, A. Popp, *Nature Phys.* **5**, 826 (2009).

[4-8] S.P.D. Mangles et al., *Nature* **431**, 535 (2004); C.G.R. Geddes et al., *ibid*. **431**, 538 (2004); J. Faure et al., *ibid*. **431**, 531 (2004).

[4-9] G. Lambert, T. Hara, D. Garzella et al., *Nature Phys.* **4**, 296 (2008).

Section 5: Compact Storage Ring Group Report

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A. Introduction

This discussion groups storage rings into four categories:

1. third-generation light sources, which are large storage rings optimized for high-average-brightness hard and soft x-rays with a large number of users,
2. smaller storage rings with only dipole magnet sources (i.e., no insertion devices—IDs) that can produce hard x-rays at high flux,
3. very small and low-energy ring with two superconducting dipoles producing EUV for, e.g., lithography, and
4. very small rings used for short-term storage in inverse Compton scattering sources.

The first type was discussed in our group as a reference to the second type, which was more relevant for this workshop, and which was discussed the most in our group. We talked briefly of the third type, which can't produce hard x-rays in sufficient quantity. The fourth type was covered by the ICS working group; hence we discussed this type only briefly.

Third- and Fourth-Generation Rings

Large storage rings have many desirable features and are expensive, but the expense is shared by many beamlines. The range in cost is $100 to $1000 M in today's dollars. The annual operating cost is $30 to $120 M, roughly one-tenth of the initial cost. Because of the circular nature of the source, there can be many beamlines, typically 20-60. This amounts to a cost per beamline of $5-20 M for construction and $1-2 M for annual operations. With a range of 1000 to 5000 users per light source, the cost per experiment is $20-30 K.

The beam parameters, cost effectiveness, and reliability of large storage rings are well documented. The following is a list of features, not necessarily unique to these sources:

- High average brightness (2×10^{20} for 12-keV photons for APS, ESRF) and flux
- High repetition rate (5 MHz to 500 MHz)
- Ability to simultaneously serve a large number of users with multiple requirements
- Stability in position, angle, beam size, current and energy
- Wide photon spectrum from IR to hard x-rays, with easy and rapid tuneability, and polarization control

As the circumference is made larger, the optimized emittance is smaller, which allows higher x-ray beam brightness. This optics property can be exploited for designing an "ultimate" large-circumference storage ring light source. However the goal of this workshop is to find a low cost storage ring solution that produces the types of x-ray beams that other proposed compact light sources are producing. Reducing the circumference will reduce the cost and almost certainly reduce the brightness of the ring, but the flux may be preserved.

Smaller Third-Generation Rings

In the past smaller rings with dipole-magnet-only sources were called second-generation light sources (before insertion devices were used). With today's technology (e.g., superconducting dipole magnet of 5 T such as the ALS Superbend), one could make a smaller ring (say, 60 m circumference) with substantial brightness for dipole magnet beams. Without IDs, these optimized source could be called third-generation sources.

Such rings don't exist yet, but can be conceived as a thought experiment for comparison with the other types of compact light sources. The primary inspiration is the ALS Superbend technology, and the secondary inspiration is the commercial production of booster synchrotrons of present 3rd generation light sources. The superbend of ALS is a 10-degree superconducting 5-T dipole that supports four beamlines, which indicates that a high density of beamlines can be crowded around a ring. Note that the dipole beam is fan-shaped in contrast to a cone for an ICS source. The preference of a fan or a cone is application dependent.

The parameters of the ring source would be:

- 60- to 80-m circumference
- 1.5 to 2 GeV
- Several 5-T dipole sources
- 10 nm or lower emittance
- 500 mA or more stored current
- At least 10 dipole magnet beamlines (half on superconducting magnets)
- Flux: 4×10^{13} photons/s/0.1% BW at 1 Angstrom or 4×10^{15} photons/s/10% BW

The number of beamlines is variable and depends on funding. One could plan to have up to 80 beamlines (this is actually realistic because each beamline takes up a few milliradians of arc and the radius of the ring is small) but only build ten beamlines initially or simply build ten and no more after that. If one has many beamlines, then the overall facility cost will be determined by the number of beamlines. The flux would duplicate that of the present ALS Superbend source (see Figure 5-1).

The impedance of such rings is expected to be smaller than that of a third-generation light source because there are no IDs and no vacuum chamber transitions. Thus we expect much smaller impedance than in third-generation light sources. This may give some flexibility in bunch filling patterns. It is assumed that state-of-the art feedback systems used in present storage rings permit the high total stored current specified above.

This ring would be too large to fit in a university setting. Perhaps rings such as this one could be built regionally, close to a group of universities. A single university would be allocated its own block of beamlines that they manage, making the cost per university reasonable. The use of commercial cryo-coolers, such as those in hospital MRI machines would alleviate the complexity of operating a superconducting device such as the Superbend in a university-like setting. Small ring installations, such as CAMD, operate superconducting wigglers/wavelength shifters.

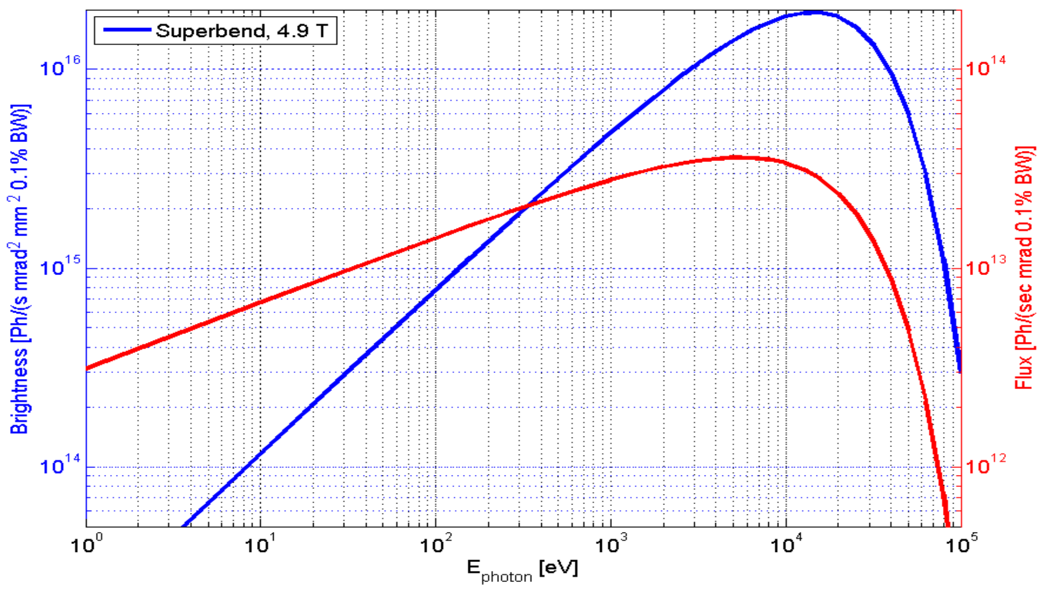

Figure 5-1: *Brightness and flux for the ALS superbend source and for a possible small third-generation storage ring.*

Costs of Mini-Storage Rings

The following cost estimates are based on scaling from engineering cost estimates of real projects and existing installations that were built within a national lab framework, which probably increases the cost a bit. Based on the NSLS-II injector cost estimate, a ring with injector alone might be $30 M, built commercially. This assumes that the booster can be placed in the same tunnel as the storage ring, which is a low-cost configuration. The cost of each beamline generally depends on beam power. A regular dipole magnet beamline would be $2 M. A high-power beamline like that of the ALS Superbend crystallography beamlines would cost $2.5 M. Thus, five beamlines of each type plus the ring and injector would make the total $53 M.

The operating cost of the ring alone may be $5 M/year, following the 10% rule-of-thumb seen in many light sources. This figure agrees with the operating cost of the CAMD light source. The operating cost for each beamline would be one full-time beamline scientist plus incidentals; approximately $0.3 M per year. The total would be $8 M/year.

Compact Storage Rings

The physical basis of compact storage ring sources is to use the photons that are produced by synchrotron radiation in high-field dipole magnets. There are no insertion devices. The ring itself would be a conventional one with no straight section, except for injection and rf cavities. The periodic cells would be theoretical-minimum-emittance-type cells, which is a well-known optics.

The storage ring Helios 2 by Oxford Instruments is used at the Singapore Light Source. It has two 4.5-T dipoles, an energy of 700 MeV, and an emittance of 1.3 mm-mrad. The photon spectrum is limited to EUV. Though the ring is small enough to fit in a University basement, it does not produce the photon energy sought by other types of compact sources.

Mini-storage rings could also be used for short-term beam storage for ICS sources. As laser cavities with high finesse and small spot size are further developed, it would be desirable to develop small ß* storage ring lattices as well.

B. Properties / Goals / Potential Impact

1. *Advantages*: High flux, moderate brightness, many beamlines, reasonable cost per beamline, high stability, option for (partial) circular polarization out of plane, if desired could provide round beams (with lower brightness). Alignment of electron beam is easy since there is no collision involved.
2. *Disadvantages*: Facility is smaller but not tabletop, moderate total cost, very limited potential for short pulses, must be located in a region of multiple research institutions for sharing costs.

C. Status of this Approach

The concept uses proven technology that is operating at third-generation light sources. A practical configuration of the lattice optics could be developed with optimized dipole source points to yield a time average flux from the dipole source of 4×10^{13} photons/s/0.1% BW at 1 Angstrom or 4×10^{15} photons/s/10% BW. The peak brightness figure would depend on the bunch pattern stored. The position and angle stability can be made 10% of the beam size and divergence. Bunch pattern can be arbitrary, though rms bunch time length would be of the order of 20-50 ps. There are no technical challenges foreseen until an explicit design is made. Perhaps a fast kicker for clean injection with accumulation might be necessary. Perhaps special on-axis injection might be adopted if optics design for low emittance is aggressive; in which case injectors would be required to produce 500 mA in 180 ns (60 m).

Such a source would have a projected capital cost of ~$53 M, roughly scaled from existing third-generation ring sources. The size of the facility would include initially 10 beamlines and be expandable to 50 around a ring circumference of 60 m.

D. Operability Considerations

Operating cost and cost efficiency, staffing levels: $8 M/year. Staffing level will depend on the number of beamlines; say a total of 30 for a 10-beamline ring source, with 1 staff per additional beamline. The ring would allow user access/availability of ~5000 hours/year or more. Compact light sources based on mini storage rings would have 97% availability—the same as existing sources.

E. Suggested R&D to Improve Performance

An aggressive optics design could lower the emittance or lower the cost. In addition, the integrated magnet and girder designs of MAX-III and MAX-IV could lower the cost further. One would also have to integrate the ALS superconducting dipoles in these types of lattices. The flux and brightness would be the same as a third-generation light source dipole source.

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