Novel Source Concepts Working Group Report

B. Carlsten[1], F. Albert[2], S. Bajlekov[3], C. Barnes[1], K. Chouffani[4], E. Colby[5], E. Esarey[6], M. Fuchs[7], W. Graves[8], F. Hartemann[2], W. Leemans[6], R. Li[9], V. Litveneko[10], J. McVea[11], J. Mulroe[11], J. Osterhoff[6], D. Ratner[5], T. Raubenheimer[5], J. Rosenzweig[12], R. Ruth[5], W. Schlotter[5], M. Shverdin[1], G. Travish[12], F. Wang[5], V. Yakimenko[10], N. Yampolsky[1], Y. Yan[5].

[1] Los Alamos National Laboratory, bcarlsten@lanl.gov, [2] Lawrence Livermore National Laboratory, [3] Oxford University, [4] Idaho Accelerator Center, [5] Stanford Linear Accelerator Center, [6] Lawrence Berkeley National Laboratory, [7] Max-Planck Institut fuer Quantenoptik, [8] Massachusetts Institute of Technology, [9] Tsinghua University, [10] Brookhaven National Laboratory, [11] Thales Components Corporation, [12] University of California, Los Angeles

May 3, 2010

Performance Needs of Future Light Sources

Light sources are entering a new era, with the success of the Linac Coherent Light Source (LCLS) as the first Free-Electron Laser (FEL) operating in the hard X-ray regime [1]. LCLS represents a very significant achievement, demonstrating new levels of electron beam and wiggler control. LCLS is a major facility, with standard S-band travelling-wave cavities extending over 1 km, to accelerate an electron beam up to 14.5 GeV. Facility users will compete for time at the limited number of experimental stations. Because of the cost and size of this type of machine using conventional microwave accelerator technology, where the maximum accelerating gradient is limited to less than 100 MeV/m, it is hard to imagine that more than a few will be built, and the small number will create a severe bottleneck for enabling discovery science using coherent X-rays.

Lower energy FELs (~ 100 eV) are relatively simpler than hard X-ray sources. FLASH at DESY operates at 1 GeV, produces 180 eV with a 1-GeV electron beam [2]. The proposed JLAMP facility at JLAB would produce 10 to 100 eV photons with 600-MeV electron beam, at an estimated cost of below $100M (taking advantage of CEBAF's high-average current infrastructure [3]). There will be increasing difficulty to develop sources above the 100-eV level, and it will be likely that as the photon energy is increased, the repetition rate of the source will significantly decrease. For example, JLAMP may have a repetition rate of 4.68 MHz as compared to 120 Hz for LCLS. As an intermediate example, the proposed NGLS facility at LBNL [4] would produce photons up to 1 keV at a 100 kHz repetition rate, but at a cost significantly higher than JLAMP.

It is likely that advanced novel concepts will help reduce the cost and complexity of coherent X-ray sources. These concepts include both more efficient acceleration schemes and also photon generation schemes. In this working group report, we summarize the current status of several of these technologies and discuss how they may fit into future light sources as technology gaps are bridged through R&D over near term and long term horizons. To make these discussions more directly relevant and practical, each of these technologies are applied to a hypothetical 0.5-keV light source and a hypothetical 50-keV light source. Because of intrinsic differences in these technologies, they have different relative strengths and weaknesses in these different regimes.

These novel source concepts will require significant R&D investments before they are mature enough to be used as user light sources, with one exception (the use of an inverse Compton scattering source to generate non-coherent X-rays at a single laboratory level is mature enough that a system is already commercially available). The R&D needs are significant, probably in excess of tens of $M for most of these technologies to begin to replace second, third, and fourth generation light sources. However, if these investments are made, significant cost reductions may be realized in terms of photons/dollar, granularity of these sources, and accessibility to more users. Finally, it is important to point out that laser high-harmonic generation (HHG) will not be discussed in this report. HHG technology is very promising, and has demonstrated coherent X-ray generation up to about 300 eV (although at very low conversion efficiencies). However, the focus of this report is on electron-beam based technologies.

Overview of Novel Concepts

Remarkable new source and acceleration technologies are now emerging that will have significant impacts on the ability to provide new future light sources. Specifically, laser-driven plasmas and structures, as well as electron-beam driven plasmas and dielectric structures, have the promise to provide compact and cheap generation and acceleration of electron bunches that can provide a new paradigm of X-ray light sources in universities and small laboratories world-wide as well as significantly cheaper national-level high average flux hard X-ray sources.

These emerging acceleration technologies, along with alternative photon-generation techniques, are reviewed in this paper. A short summary of the physics behind laser-driven plasma wakefield acceleration, electron-beam driven plasma wakefield acceleration and laser-driven structure acceleration is provided. The technology challenges and overall technology readiness is also discussed for these beam generation and acceleration technologies. A comparison of them is made in the conclusion, considering five-year, ten-year, and greater than ten-year horizons.

As alternatives to X-ray generation through the FEL interaction, inverse Compton scattering (ICS) is also considered. Although betatron motion by electron beams injected into a plasma or formed in laser-driven plasma can be used as hard X-ray sources these concepts are not separately reviewed, but rather included in the discussions on laser-driven plasma and electron-beam driven plasma technologies. It is important to note that FELs produce coherent radiation while ICS and betatron emission do not. As compared to the other technologies, ICS is mature, and a commercial, laboratory-sized system can be purchased today. With advances in high-brightness average current injectors and accelerators (being currently pursued for high average power FEL systems), ICS systems will be able to rival second and third generation light sources in terms of average flux and serving multiple users, at greatly reduced costs.

As these emerging technologies mature, they each can fill a unique, and very useful, X-ray source niche. These niches vary from relatively inexpensive high-flux incoherent X-ray sources capable of servicing multiple users, to ultra-compact, low-average flux coherent university-scale sources, that significantly reduce the cost of X-ray FELs by replacing most of the RF accelerator by advanced accelerator technology.

Laser Plasma Accelerators (LPAs)

The technology of accelerators that power today's light sources was developed many decades ago, with presently only incremental improvements. As the LCLS becomes operational, it will provide scientists with unprecedented capabilities to answer key scientific questions. The LCLS and other machines under construction or existing will determine the performance requirements for the next generation of light sources, which will be enabled by advanced accelerator R&D. Technologies must be developed to make accelerators more compact and economical to address the future needs of users.

Laser-plasma accelerators (LPAs) [5, 6] have demonstrated accelerating gradients on the order of 10 to 100 GV/m, three orders of magnitude beyond conventional accelerators, and have produced high quality electron bunches at the 1 GeV level [5]. This makes LPAs promising candidates for the next generation of compact accelerators. In addition, the wavelength of the accelerating field (the plasma wavelength) in an LPA is ultrashort, on the order of 10-100 μm. Hence, LPAs are intrinsically sources of ultrashort (fs) particle bunches. If the high-brightness electron bunch from an LPA is used to drive a radiation source, such as an X-ray FEL, then this facility could deliver synchronized pulses of fs radiation, particles, and laser light, all from one compact machine.

In an LPA as shown in Fig. 1, an intense (>10^{18} W/cm^2), short (tens of fs) laser pulse is focused into a plasma to drive a large amplitude plasma wave [7]. Such laser-driven plasma waves can sustain electric fields in excess of, $E_0[\mathrm{V/m}]\cong 96(n_0[\mathrm{cm}^{-3}])^{1/2}$ with a wavelength $\lambda_0[\mu\mathrm{m}]\cong 3.3\times 10^{10}(n_0[\mathrm{cm}^{-3}])^{-1/2}$, where n_0 is the plasma density. For typical experimental densities $n_0=10^{17}$-10^{19} cm^{-3}, fields ranging from 30-300 GV/m are produced with a wavelength 10-100 μm.

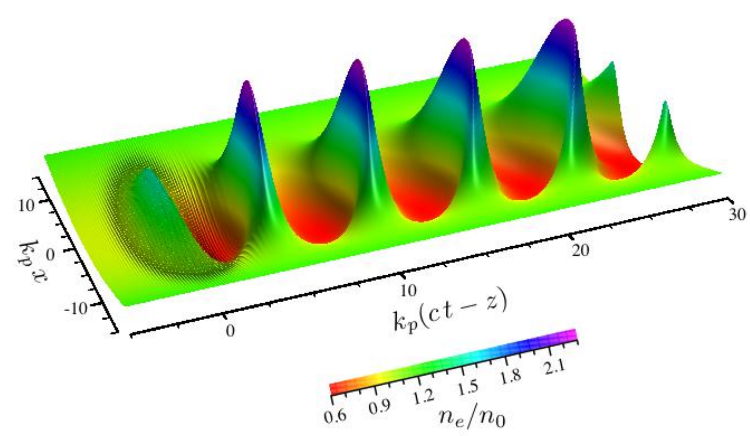

Figure 1. Numerical simulation of a large amplitude plasma wave (plasma electron density perturbation) generated by an intense laser pulse, with electrons trapped in the wave being accelerated.

In 2006, experiments at LBNL achieved a milestone with the production of high quality (few % energy spread, few mrad divergence, tens of pC) electron bunches at the 1 GeV level [8], using a 40 TW laser and a 3-cm long plasma with density near 10^{18} cm^{-3}. In these experiments, a plasma channel was used to guide the laser pulse (prevent diffraction) and extend the acceleration length by an order of magnitude (cm scale) compared to previous experiments [9] (mm scale), as well as lower the plasma density by an order of magnitude. The single-stage energy gain in an LPA scales inversely with plasma density. Hence, plasma channel technology is crucial to producing the long and relatively low density plasmas needed to obtain GeV energy gains and beyond.

LPA beams are well suited for radiation generation. Single-cycle THz radiation can be generated via coherent transition radiation using a foil or a plasma-vacuum transition. Incoherent, broadband hard X-rays can be generated by betatron (synchrotron) radiation in a plasma (as many as $10^8 – 10^9$ photons over 1 keV per shot with commercial 30 TW, 10 Hz lasers [10]). Directed beams of gamma-rays can be generated by Thomson scattering using a counter-propagating laser pulse. In addition, coherent VUV and soft X-ray radiation can be generated directly by the laser interacting with a gas and/or plasma (high harmonic generation (HHG)). In particular, the high brightness bunches from an LPA are ideally suited for producing high peak brightness coherent X-ray radiation via the FEL mechanism, provided the bunch quality is sufficiently high [11]. Since LPAs are sources of very high peak current beams (tens of kA), the FEL gain length can be greatly reduced, and, hence, LPA electron beams are not only generated from a compact accelerator, but can use a much reduced undulator length to achieve saturation. Further compactness (reduced saturation length) can be achieved by seeding the FEL using HHG radiation from the drive laser. For example, a 0.5 GeV LPA generated electron beam can be used to coherently amplify a HHG seed in a FEL, generating $>10^{13}$ photons/pulse at 30 nm in less than 3 m using a conventional undulator [11].

For driving light sources, key benefits of LPAs include compactness (i.e., a few to tens of cm plasma channel driven by a laser occupying a few m^2 area), relative low cost, intrinsic synchronization between the drive laser pulses, electron bunches and radiation pulses, and the ultrashort (fs) duration of the electron and radiation pulses. An LPA could be the basis for a hyperspectral source, spanning THz to gamma-ray regimes, that would be ideal for pump-probe experiments and enable new applications in many fields of science.

Technology Gaps to Bring LPA Technology to a User Facility

The laser intensity required to drive an LPA is on the order of 10^{18}-10^{19} W/cm^2, which is now routine with solid state lasers using the technique of chirped-pulse amplification, initial developed during the 1990s. The rep-rate of high peak power 0.1-1 PW laser systems is currently limited to about 1-10 Hz (an average power on the order of 10-100 W). Development of higher average power laser systems is crucial to many applications of LPAs.

Several groups around the world, including the Berkeley Lab Laser Accelerator (BELLA) Project at LBNL, have plans to explore LPA-physics issues using petawatt (PW) laser systems with up to 10 Hz repetition rates. Spurring on the worldwide LPA progress is the fact that commercial companies (most notably in France) have developed the know-how to build sophisticated multi-100 TW and even PW-class systems, a capability that used to be available at only a few select institutions in the world. These laser systems are compact, occupying only a few m^2 in area. With PW-class short-pulse systems in operation (e.g., BELLA), it is anticipated that 10 GeV-class beams will be generated in meter-scale LPAs. These high-brightness beams have the potential to be used to drive an FEL for coherent hard X-ray generation, with greatly reduced undulator length owing to the high peak currents (tens of kA) produced by LPAs, as further progress is made reducing the emittance and energy spread of these beams.

Within the next five years, LPA electron beams at 10 GeV should be demonstrated from a 10 cm plasma channel driven by a PW laser system (now commercially available at 1 Hz rep-rate) with the required beam quality to drive an FEL in the 1-10 nm range. Techniques for improving the bunch quality will be explored, such as tailoring the profiles of the laser pulses and the plasma channels, as well as laser-based injection techniques for initiating the electron bunches from the background plasma, such as the use of density down-ramps and colliding laser pulses. Techniques for producing long (10 cm or greater) plasma channels with adjustable density profiles will be developed. Time-resolved diagnostics need to be developed and implemented with the ability to measure such properties as the slice emittance with fs accuracy. Initial experiments on producing undulator radiation with an LPA electron beam are underway. Demonstration of an electron beam energy spread on the order of 0.1% (presently at the 1% level) is a necessary step in the development of an LPA-driven FEL and is likely to be achieved in the next 5-10 years. Initial experiments on the staging of two or more LPA modules are underway. This includes development of compact methods (e.g., plasma mirrors) of laser in-coupling to the plasma structure. The in-coupling methods must be compact, i.e., less than the length of plasma structure, so as not to significantly degrade the overall acceleration gradient. Radiation generation driven by LPAs would also benefit from research in short-period, compact undulator technology. Understanding the details of the LPA physics requires the continued development of analytical and numerical modeling, in particular, efficient methods for simulating LPAs on massively parallel computers. Laser technology needs to continue its rapid pace of development to allow higher average power systems with improved efficiency.

LPA Machine Concept

Incoherent X-ray radiation can be generated by passing an electron beam from an LPA through a magnetic undulator. Recent LPA experiments have demonstrated this process with the observation of undulator radiation at the fundamental and second harmonic (11 eV and 22 eV photons respectively). Since this is spontaneous radiation, it does not require extremely low energy spreads, as does an X-ray FEL. In the near term (next few years), 500 eV incoherent radiation (approximately 10^9 photons at 10 Hz) can be produced by passing a 100-pc, 550-MeV electron beam from an LPA through an undulator. In the mid-term (~ 10 years), it is likely that an LPA will produce electron beams of sufficiently high quality so as to drive an FEL that generates 500 eV radiation. A 600-pC electron bunch can produce 10^{12} photons at a 10 Hz repetition rate at a cost of roughly $20M. A 50-keV light source driven by an LPA is significantly more complex. In the far term (say ~ 20 years) we can envision a 2.8 GeV LPA beam radiating in an plasma undulator induced by a laser, producing about 10^{10} photons with a 1 nC electron bunch, also at a 10 Hz repetition rate and at a comparable cost. A higher energy beam from an LPA (~10 GeV) can generate 50-keV photons using a conventional magnetic undulator with a 1-cm period.

Plasma Wakefield Accelerators (PWFAs)

Demonstration of the PWFA concept was first achieved at ANL in the late 1980's with experiments that mapped the plasma wakefield produced by a drive electron beam by measuring the energy gain (<1 MeV) of a time-delayed witness electron beam [13]. Since that time, progress for beam-driven plasma accelerators has been remarkable with the maximum energy gained in the plasma exceeding 40 GeV in 2007 [14], enabled by the capability of the SLAC linac to deliver high intensity bunches.

As shown in Fig. 2, a high-amplitude oscillation can be set up in a plasma by the wakefield of a drive electron bunch. The oscillations are set up by the expulsion of the plasma electrons as the drive bunch traverses the plasma. The drive bunch needs to be shorter than the plasma wavelength and for symmetric bunches, the maximum accelerating field is twice the field decelerating the drive bunch. Plasma wakefield experiments have also demonstrated that high gradients, ~50 GeV/m, can be sustained over meter-scale distances [14]. This gradient is roughly 3,000 times that in standard S-band linacs. In addition, a variety of other effects has been demonstrated in the SLAC experiments, such as the generation of betatron X-rays from a few keV to tens of MeV energy, and the acceleration of electrons from the plasma itself with extremely high acceleration gradients.

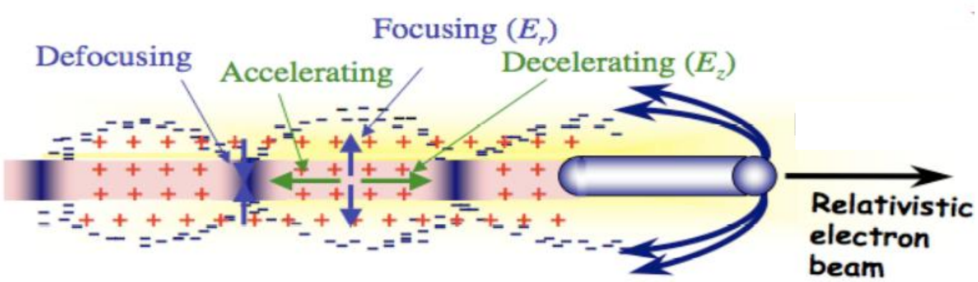

Figure 2. PWFA schematic, indicating plasma oscillations set up by drive electron bunch expelling plasma electrons from the path of the drive bunch.

In addition to reducing the size and cost of future high-energy physics machines, beam-driven plasma acceleration may also enable more compact accelerators to drive X-ray FELs. In perhaps the simplest 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 extend the wavelength reach of an accompanying FEL (e.g., a factor of four for an energy doubler).

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 energy bunches. This process can be characterized by the ratio of the peak accelerating field to the peak decelerating field in the plasma wake, called the transformer ratio [15]. 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 one and two. Recent analytic and numerical models have predicted that by optimizing the longitudinal profile, transformer ratios of five may be attained [16], e.g. a 1 GeV drive bunch with several nC of charge could boost the energy of a 1nC, 1GeV bunch to an energy of 5 GeV on the scale of a meter. In the example studied in [17], a 5-nC, 0.56-ps, 1-GeV drive bunch is able to accelerate a 0.35-nC, 23-fsec, 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 preserved emittance. If these calculations prove out, this technology has the potential 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 [18], with an overall foot print on the same order of magnitude as in a 10-GeV LPA. These types of preliminary experimental and numerical results, plus the high average-power capability of conventional RF accelerators, lead to the observation that, with sufficient R&D support, this technology may potentially drive light sources that match the anticipated high average flux of future X-ray FELs and ICS systems, more so than other novel accelerator technologies.

Plasma induced betatron radiation is also an attractive potential incoherent and broadband alternative to a traditional X-ray FEL. In an ion channel the incoming electron beam (or, alternatively, a laser pulse) expels the plasma electrons and an ion-focusing channel is formed. The betatron motion of the individual electrons in the channel leads to synchrotron radiation, and potentially, to self-amplified spontaneous emission in an ion channel laser [19] with wavelengths that are up to 100 times shorter than that from conventional undulators (depending on plasma density and beam energy). Plasmas provide stronger radial fields and shorter periods than conventional undulators, in principle enabling an ion channel to operate at a given wavelength with a comparatively short plasma and lower energy electron beam. Additionally, the high effective wiggler strength in a plasma leads to very high harmonic generation. In a first step, beam driven plasma experiments have measured spontaneous emission in the X-ray region (6.4kV) due to the betatron motion of 30 GeV electrons in a plasma of density ~ 2 x 10^{14} cm^{-3}. These results were later extended to Gamma-rays with multi-MeV energy produced in a plasma with density ~10^{17} cm^{-3}. Stimulated emission relies upon the coherent interaction between elections in the beam and the radiation field. Numerical simulations using a combination of PIC and modified FEL algorithms are needed to study these concepts and define an experimental program.

Recent experiments operating with field ionized plasmas and multi-GeV/m gradients have measured trapped plasma electrons with multi-GeV energy, mm-mrad emittance and multi-kilo-Ampere peak currents. The emittance of these trapped electrons scales inversely with the plasma density. Future experiments will continue to investigate the physics of the trapping process while optimizing the measured brightness.

Technology Gaps to Bring PWFA Technology to a User Facility

After the initial concept demonstrations of beam driven plasma acceleration, the challenge now is to develop these techniques into useful acceleration methods for light source and high-energy physics applications. Among the issues that need to be resolved are:

- Efficient high-gradient acceleration of mono-energetic beam bunches with a narrow energy spread
- Shaped single bunches and/or multiple bunches to increase the transformer ratio, and the energy gained per stage, including stability of the drive bunch train
- High demagnification focusing of electrons
- Study of emittance degradation due to matching, hosing, and ion motion for electrons

- Study of plasma stability and heating or damage effects with a multi-bunch or high repetition rate beam

The Facilities for Accelerator Science and Experimental Test Beams (FACET) at SLAC is being constructed to address these issues. Appropriate investment in these second generation facilities will allow the continued development of the plasma acceleration concepts that hold so much promise for future compact accelerators.

PWFA Machine Concepts
A lower photon energy light source based on a PWFA is probably not compelling. The advantage of a PWFA is that a PWFA is a transformer between the high average-current capability of a moderate energy RF accelerator to a very much higher energy, somewhat lower average-current beam used to drive a conventional FEL. At a final beam energy of 1 GeV or so, the drive beam would be only on the order of 100 MeV, which would lead to excessive head erosion and not a significant decrease in size considering the increase in complexity. As a counter example, consider the size of a modern X-band 1-GeV accelerator (such as the NLCTA), which would make a much better driver for a 500-eV FEL. However, a PWFA makes very good sense for a 50-keV FEL. Consider a 5-nC, 4-GeV drive beam accelerating a 0.35-nC, 10-GeV witness bunch with an energy conversion of 35% and with an energy spread less than 1%. This kind of architecture could produce 10^{12} photons easily at 120 Hz (based on SLAC technology at a couple $100M) or higher (up to 100 kHz based on NGLS technology for closer to a $1B).

Dielectric Wakefield Accelerators (DWA)

A dielectric wakefield accelerator (DWA) is very much like a PWFA, except the wakefield is established in a dielectric rather than a plasma [20], as shown below.

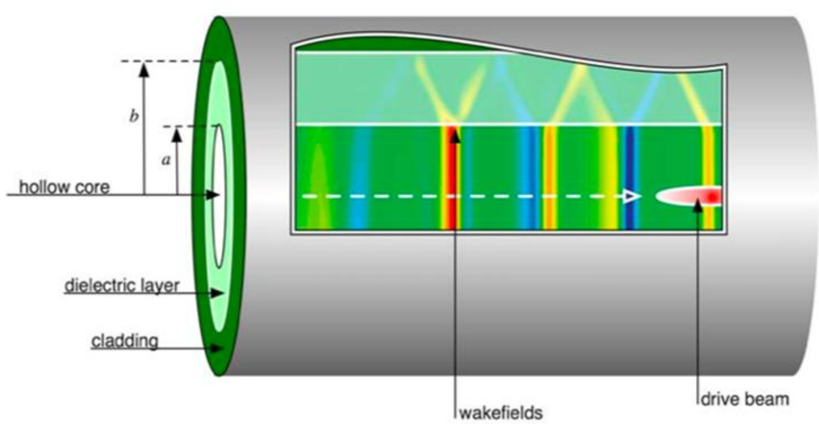

Figure 3. Wakefields set up by the interaction of a drive beam with a dielectric liner. The Cherenkov cone is seen in the dielectric.

There has been a significant amount of experimental investigation into DWA at ANL, but at moderate gradients (~ 50 MV/m because of the length of the drive beam) [21]. Recent numerical work has shown that transformer ratios > 10 are possible and the dielectric breakdown is over 10 GV/m [22], which makes this technology relatively equivalent to PWFA. Specific advantages of this technology are that there is no transverse field dependency, which leads to no head erosion and better emittance preservation of the witness bunch, the coupling mechanism is solid-state, leading to better stability of operation.

Technology Gaps to Bring DWA Technology to a User Facility

Although some areas of this technology are very mature, the key technology demonstrations that need to be performed are: demonstration of >GV/m gradients, demonstration of transformer ratios of 10 or higher, and verification of the preservation of high-brightness electron beam.

DWA Machine Concept

As with a PWFA, the DWA technology is not compelling for a lower photon energy light source (less than ~ 10 keV), and the DWA's advantages become more significant as they rely on the high average-current capabilities of modern RF accelerators. Compared to PWFA, this technology does not suffer from head erosion of the drive beam, will typically have much lower peak accelerating gradients, and will suffer from accumulating damage from the dielectric structure which will limit its lifetime. As with the PWFA, we can consider a NCLTA-type RF accelerator producing a 4-GeV, 5-nC drive bunch accelerating a 4-GeV, 0.5-nC high-brightness beam to 20 GeV over 10 m. The costs and performance of a DWA driving a 50-keV FEL should be comparable to that of a PWFA.

Direct Laser Acceleration (DLA) in Dielectric Structures

Laser-driven acceleration in dielectric structures is a direct, linear process with the beam phase space directly controlled by the laser properties and the properties of the dielectric structure. The result is that the accelerated beams can have attosecond duration, opening a new regime for experiments using ultrafast electron sources, or if used in an FEL, in producing ultrashort radiation pulses. Moderate laser powers are required for structure-based acceleration, permitting very high repetition rates (MHz). R&D to develop large-aperture dielectric structures (to enhance peak brightness), and experimental demonstration of acceleration gains of tens of MeV are required to make this technology interesting for photon science. The challenges for direct laser acceleration in dielectric structures include laser damage of the structure and the aperture size of the structure, limiting the beam charge.

"Direct" Laser Acceleration is taken here to mean the acceleration of charged particles with laser light confined by a waveguide structure. The coupling impedances of such structures can be very high, permitting high efficiency acceleration at high gradient (~ GeV/m) with very low laser power (typically ~μJ/pulse or less). Dielectrics exhibit considerably better damage resistance at optical wavelengths than metals, making them an interesting choice for high-gradient accelerator structures. Efficient, rack-mounted lasers are commercially available that, with added provisions for mode-locking and optical phase locking, are suitable for powering such structures. With the wealth of knowledge about making optical- and sub-optical-scale structures by semiconductor lithography, there is a route to make these structures with the same cost-effective techniques used to make computer chips today.

Broadly, there are three main types of DLA structures under active study: two-dimensional photonic band gap structures such as fibers; planar three-dimensional photonic band gap structures; and non-resonant grating-type structures.

Of the possible means of propagating slow-wave EM modes in dielectric guides, photonic band gap (PBG) structures offer an interesting combination of (1) shedding long-range higher-order modes by radiation, (2) confinement of only the fundamental accelerating mode, and (3) broadly controllable group and phase velocity properties. These properties, incidentally, are maintained for dielectric photonic band gap structures made in the microwave range. While photonic band gap fibers are available commercially to guide transverse-electric (TE) modes, the DLA community is exploring—for the first time—the use of PBGs for the confinement of transverse-magnetic (TM) type modes that are suitable for acceleration.

Slab-symmetric structures offer a more open geometry with attendant benefits in wakefields, higher charge (through flat beams), and vacuum conductance. Four schemes illustrate some of the approaches taken with this geometry: (1) the woodpile structure is a 3D PBG device [23, 24]; (2) the Micro Accelerator Platform (MAP) is a transversely coupled resonator that resembles an etalon [25]; (3) the non-resonant phase-mask or "grating" accelerator [26], and (4) photonic band gap fibers [27]. These concepts are illustrated in Fig. 4 below. While these devices differ significantly in their electromagnetic properties and beam dynamics, they share a number of common technical challenges (see next section).

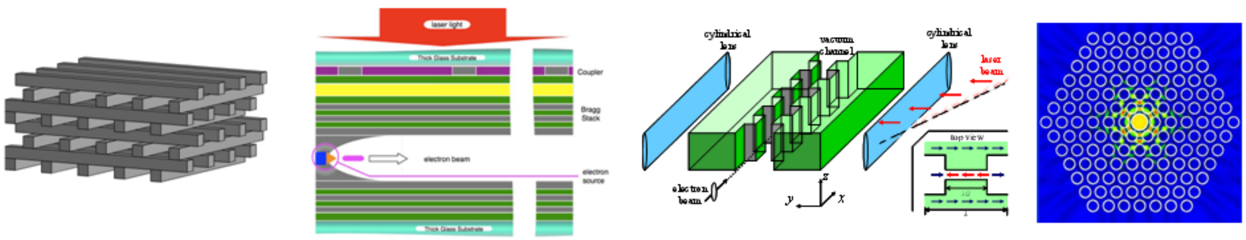

Figure 4. Left to right: examples of the woodpile, MAP, grating, and photonic band gap fiber accelerator structures.

Finally, the non-resonant grating-like structure offers the possibility of operating at still higher gradients (~10 GeV/m) due to its ability to operate with ultra-short (10 fs) laser pulses. The structure also affords simple fabrication; industry can already supply suitable geometries.

The advances in producing quantum well and hybrid silicon lasers by conventional semiconductor manufacturing processes raises the very interesting possibility of integrating the laser, waveguides, and accelerator structure on a single chip, dramatically reducing the cost and increasing the range of applications for the accelerator.

Technology Gaps to Bring DLA Technology to a User Facility

For laser-driven dielectric accelerators, the useful accelerating gradient must be experimentally established, wakefield effects on beam quality quantified, suitable sources of electrons and positrons devised, and methods of integrating large numbers of structures together to economically produce large voltage gain must be devised. The timescale for completing this research and development work puts light sources based on dielectric laser accelerator structures into the next decade.

Specific goals for DLA projects as applicable to light sources include:

- Show significant acceleration;
- Show practical injection or low-beta structure;
- Proof of optical undulator or alternate micro undulators;
- Lifetime: optical breakdown, radiation damage, etc.; and,

- Technology development: alignment, fabrication tolerance, focusing, low-charge diagnostics, tuning and feedback.

DLA Machine Concept

With the realization of optical-scale structures capable of sustaining high accelerating gradients, the development of optical-scale deflection structures suitable for use in producing radiation will be straightforward [28]. Advances in photo-assisted field emission from micron-scale metal tips have led to electron sources with currents and brightnesses in the right range [29, 30]. With the injection of optically bunched beams into laser-powered structures and undulators, there is the possibility of an all-optically powered ultra-compact attosecond electron and x-ray source. The low micropulse charge (~10^3-10^4 e/optical cycle) that can be efficiently accelerated in these structures requires that high repetition rates be used to develop fluxes of interest to experimenters.

The DLA technology niches are the same for a 500-eV and a 50-keV source – an ultra compact way to reach a modest amount (10^4 – 10^5) coherent photons per pulse at perhaps ~ $10M (in the far-term, say about 20 years). Although the number of photons per pulse is very small, high repetition rates possible with laser systems can produce fluences in the 10^{13} – 10^{14} photons per second range. No other technology considered has the potential to generate any amount of coherent photons for this kind of cost or size, which will enable smaller users (such as individual universities and industrial laboratories) to have their own coherent sources. Specifically for a 500-eV strawman design, one would accelerate a fC of charge to 250 MeV and interact with an optical undulator. For 50-keV, the fC of charge would be accelerated to 2.3 GeV.

Inverse Compton Scattering (ICS) Sources

Compared to the other technologies described in this report, inverse Compton sources are by far the most mature. These sources have been used for imaging samples (direct transmission of the X-ray flux and also using phase contrast imaging) for quite some time, and a commercial system is even now available. That said, it is important to note that Compton source technology is not yet advanced enough to provide large fluxes to multiple users, and the X-ray production has 100% bandwidth and is incoherent. So whereas ICS technology today is sufficient to provide small, very reasonably priced X-ray sources to small laboratories, significant advances in high-average current injectors and accelerators will need to be established to bring large ICS X-ray fluxes to multiple user stations. Much of the required technology is being developed through Office of Science and DoD free-electron laser programs (ampere-class SRF and NCRF injectors and SRF accelerating cavities), which may lead to performance comparable to third generation light sources with an order of magnitude lower cost.

The typical embodiment of a Compton scattering light source involves a bright electron source, an accelerator, a transport/focusing lattice, and an interaction laser. Experiments have been conducted with field-emission, thermionic, photo-emission, and plasma electron sources. Accelerators ranging from warm conventional rf to superconducting rf, laser wakefield, storage rings, and electrostatic machines, have been used. Both conventional and free-electron lasers have been employed to generate Compton scattering radiation, with scattered photon energies ranging from a few eV to above 50 MeV. The number of photons produced during the interaction spans a wide range: from a few photons, to some 10^8/pulse.

At least 3 different accelerator technologies offer good prospects for improved performance: high-gradient (100 MeV/m), X-band RF linacs; superconducting linacs; and laser wakefield accelerators. Roughly speaking, the X-band technology leads to narrow bandwidth, high energy, precision machines with high peak brightness and a relatively compact footprint; superconducting RF systems will provide very high average photon flux and brightness; finally, laser wakefield accelerators may lead to ultrashort pulse applications, with very compact systems. In terms of machine parameters, 2 different approaches have been considered here at some length: a high energy (5 MeV), high peak brightness (10^{23} photons/(s x mm^2 x mrad^2 x 0.1% bandwidth), X-band driven machine with a base repetition rate of 120 Hz, and 80 x multiplexing, resulting in an effective repetition rate of 10 kHz; a lower energy (50 keV), superconducting energy recovery machine, producing extremely high average brightness.

Both designs retain the key features of Compton scattering light sources: broad tunability, narrow-bandwidth (in a given solid angle), ultrashort pulse capability. While these machine produce incoherent radiation in a laser undulator, the electron beam requirements are stringent: the normalized emittance and the brightness of the beam directly map onto the x-ray and gamma-ray phase space density; coherent synchrotron radiation (CSR) and other radiation mechanisms can quickly lead to emittance dilution; pulse compression and other beam manipulations for transport, matching, and focusing are also potential source of performance degradation; finally, parasitic radiation processes, including Bremsstrahlung, can lead to low signal-to-noise ratios in detectors.

For each design, the electron source quality is of paramount importance: typically, the initial beam quality impacts each subsequent subsystem, and can lead to drastic source performance degradation. In particular, for head-on collisions, the source brightness is shown to scale inversely with the square of the geometric emittance; this favors high-energy interactions, and requires very bright electron beams. Moreover, at high energy, the efficiency of the system scales favorably: for example, a 250 MeV beam radiating 2.2 MeV photons has nearly 1% energy transfer efficiency; this number is quite high, even when compared to coherent sources. It can also be shown that a laser energy in the 5-10 J range can lead to quantum efficiencies approaching unity; in other words, each electron can radiate one photon, thus leading to potential electron/photon energy transfer efficiencies in the 0.1%-1% range.

The laser energy required, combined with pulse durations in the ps regime, and repetition rates in the 0.1-1 kHz range, is currently quite challenging, especially in view of additional requirements such as Fourier transform-limited spectrum, very low M^2 (near unity), and highly repeatable parameters, including energy, pointing and centering, and overall timing (sub-picosecond synchronization), all required for precision operation of the source.

In terms of electron sources, photo-emission is the current mechanism of choice, and high quantum efficiency photocathode materials, compatible with ultrahigh vacuum and high gradient operation are required in order to relax the photocathode illumination laser system requirements, which include advanced spatial and temporal shaping to achieve minimum emittance after compensation

Technology Gaps to Bring ICS Technology to a User Facility

Currently, both high-gradient (> 100 MeV/m) warm RF linac and superconducting linac technologies are moving toward maturity, while high-average current photoinjectors need more R&D to fully reach their potential. Specifically, ICS technology would be able to rival second and third generation light sources once low-emittance ampere-class photoinjector technology has been developed. The photoinjector can be either normal conducting (NC) RF (as the 100-mA, 700-MHz one currently being commissioned at LANL [38] or the mA-class photoinjector being designed at LBNL [39]), or SRF (as the 0.5-A photoinjector being developed at BNL [40]).

Advanced electron beam diagnostics are also needed in conjunction with these systems, including high-precision (sub-micron), non-destructive beam position monitoring; ultrafast temporal measurements (transverse deflection RF cavities, femtosecond streak cameras, THz radiation, optical transition radiation, coherent transition radiation, etc.); phase and synchronization measurements; advanced feedback loops for stabilization; Gs/s data acquisition systems.

X-band RF technology has made rapid advances, but appropriate high power RF sources are still lacking, requiring the use of complex and expensive pulse compression lines to properly drive high-gradient linac sections. In terms of superconducting RF, large LHe infrastructures are required, making the entry price quite high; on the other hand, the RF systems tend to be relatively less complex, and for energy recovery superconducting linacs, the overall system efficiency can be good, with the added bonus of operating an electron dump below neutron activation threshold.

In terms of laser technology, besides of chirped-pulse amplification (CPA), which is arguably one of the most important advances in the last 25 years, diode-pumping has revolutionized both the efficiency and reliability of laser systems. Compared to flashlamp-pumping, the energy efficiency is considerably improved by using light emitting diodes that are tuned to the maximum absorption of the lasing medium; this also lowers the thermal energy in the system, simplifies cooling, and guarantees much better shot-to-shot reproducibility. Dielectric gratings are also important for CPA, as they are much more efficient than metal-coated gratings, and less prone to thermal problems. The aforementioned laser stability afforded by diode-pumping is of particular importance for photocathode illumination systems, where emittance compensation can be fully implemented with highly stable RF guns, both in terms of photocathode laser and RF.

Advanced electron beam manipulation techniques, such as chicane compression, also play an important role in the development of modern Compton scattering light sources, allowing for optimal beam matching into the interaction region, and capture of the beam after the interaction. It is expected that this role will increase over time, especially if energy recovery superconducting machines are used to drive high average brightness light sources.

The photocathode laser system will be fiber-based and will produce a few uJ per micropulse to drive the 1 nC bunches, the overall 120 Hz repetition rate will be multiplexed to generate trains of 80 micro-pulses per macro-pulse. Either advanced spatial and temporal shaping will be used for optimal emittance, or the Luiten-Serafini scheme could be implemented, although it does not scale favorably for high frequency RF operation because the charge per bunch is severely limited.

Long-range and short-range wakes are currently under investigation for high-Q (few thousands) X-band RF guns, as beam breakup, and bunch-to-bunch disruptions may degrade the overall bunch train brightness; if those prove problematic, photonic bandgap structures may provide a path forward.

Specific R&D gaps include:

- High-brightness superconducting RF guns

- Multi-bunch RF guns with wakefield suppression
- High quantum efficiency photocathode materials compatible with ultrahigh vacuum, high gradient operation, and fabrication processes (brazing, diffusion bonding, etc.)
- 100-200 MW X-band klystrons (or other RF source); multi-beam klystrons with 200 MW output power and 100 kV operating voltage (simpler HV solid state modulator technology)
- Dark current mitigation/suppression
- kHz repetition rate, high-power RF sources
- Detector rates do not match machine pulse format
- MeV gamma-ray spectroscopy and imaging
- High-average power, short pulse lasers with improved wall plug efficiency and overall stability

ICS Machine Concept

ICS naturally scales to higher photon energy, and is not a compelling source technology for energies less than a few keV. ICS technology is very mature, and, today, users can buy a Lyncean 'Compact Light Source' for ~ \$10M that can produce $10^{11\text{-}12}$ photons per second tunable from 7 to 35 keV, shown in Fig. 5. These sources are not coherent and have a few mrad divergence of the X-ray beam as all low-energy ICS sources do; however, they are very compelling as a relatively inexpensive source of X-rays for universities and industrial laboratories.

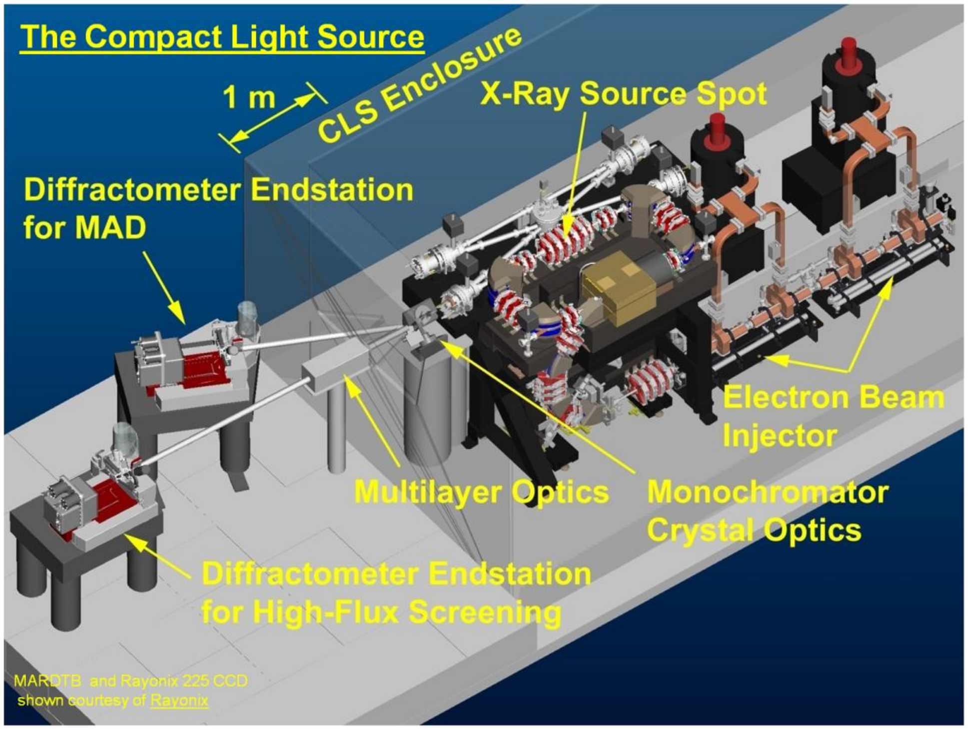

Figure 5. Drawing of the 20 to 45-MeV Lyncean Compact Light Source, available now.

With significant advances in high-average current accelerator technology development, an ICS source can provide average flux and brightness similar to a 2nd generation synchrotron beamline in a high-repetition rate configuration. MIT has proposed a high-repetition rate linac-based ICS source, also with a 25-MeV electron beam, capable of producing 3-12 keV photons, shown in Fig. 6. This device is intended to operate at 100 MHz, and would produce photon fluxes of 10^{14} photons/sec (full bandwidth), at a cost significantly under \$100M.

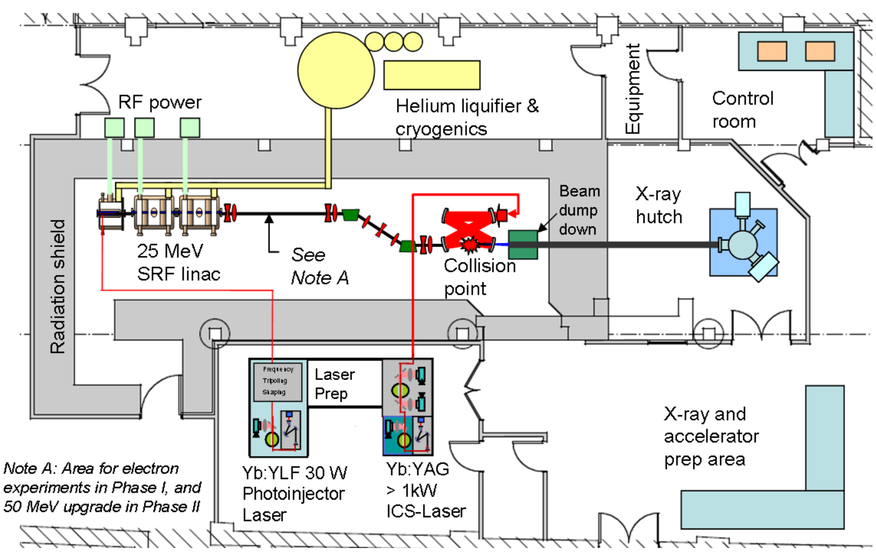

Figure 6. Proposed MIT ICS user facility.

The MIT ICS concept has been extended to an ERL-based ring geometry, with multiple ICS interaction locations serving multiple beamlines. In this configuration, the ICS source technology can be used to generate 3rd generation light source performance at a fraction of the cost in the near- to mid-term 5 to 10 years).

As a final example, we consider an approach to generate very high photon energies. LLNL is currently proposing using a 250-MeV electron beam (operating at 120 Hz) to produce 10^8 photons/shot up to energies of 2.2 MeV, shown in Fig. 7.

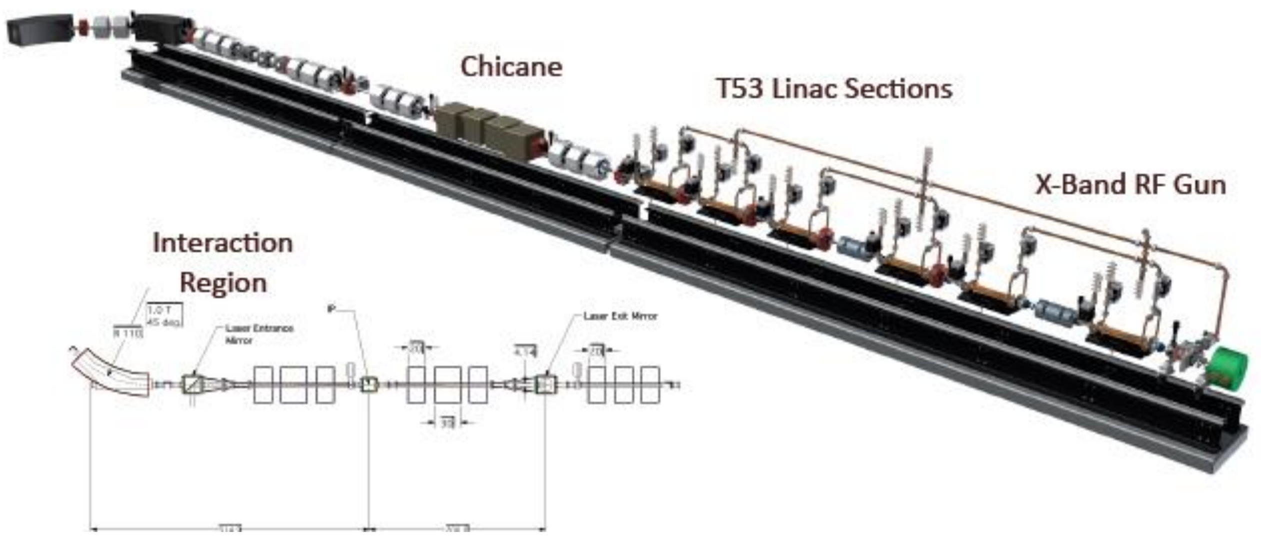

Figure 7. Schematic of the LLNL 2.2-MeV light source.

This architecture can be extended to produce 5-MeV photons with a 400-MeV electron beam. The basic machine parameters are as follows: the electron beam is a train of 80 1 nC, 1 ps, 1 mm-mrad, microbunches accelerated up to 0.4 GeV by a 100 MeV/m X-band linac operating at 120 Hz. The drive laser produces 10 J , 10 ps pulses at 120 Hz, which are trapped into a dichroic ring using a nonlinear conversion crystal; in the ring, 5 J pulse of 532 nm light are synchronized to interact with the electron microbunch train to generate up to 10^9 Compton scattered photons per interaction, with a peak energy of 5 MeV. The total average flux is estimated at 10^9 x 10 kHz = 10^{13} photons/s. In a 0.1% bandwidth, this translates into 10^{10} photons/s/0.1%bandwidth. For a normalized emittance of 1 mm-mrad, and a gamma of 780, the peak brightness is estimated at 10^9 x 0.1% x $(g/e_n)^2$ /ps ~ 10^{23} photons/(s x mm^2 x mrad^2 x 0.1% bandwidth).

Conclusion

The following table summarizes the results of the previous sections, directly comparing X-ray source capabilities of the novel source technologies. For the maturity levels, near term (NT) refers to technologies available in < 5 years, mid-term (MT) to those available in ~ 10 years, and far term (FT) to those available in ~20 years. Each $ in the cost column roughly corresponds to $5M to $10M.

Source Type	Photon energy (keV)	Charge /bunch (nC)	E (GeV)	Photons/ pulse	Rep Rate (Hz)	Cost ($M)	Maturity	Comments
LPA Undulator radiation	0.5	0.1	0.55	10^9	10	$-$$	NT	Incoherent undulator radiation, lower energy already demonstrated
LPA FEL	0.5	0.6	0.6	10^{12}	10	$$-$$$	MT	Coherent, 0.6 GeV at 10 Hz done now with 50 TW laser systems
LPA FEL	50	1.0	2.8	10^{10}	10	$$$	LT	Coherent plasma undulator
PWFA FEL	50	5/0.35	4/20	10^{12}	100-10^5	$$$ to x10^2$	MT	Takes advantage of high-power capability of RF acceleration
DWA FEL	50	5/0. 5	4/20	10^{12}	100-10^5	$$$ to x10^2$	MT	Some advantages and disadvantages compared to PWFA
DLA FEL	0.5	10^{-6}	0.25	10^5	100x10^6	$-$$	LT	Optical undulator
DLA FEL	50	10^{-6}	2.3	10^4	100x10^6	$-$$	LT	Optical undulator
ICS	7-35	1	0.02to0. 045	10^4	65x10^6	$	available now	Lyncean CLS, incoherent, (flux at 3% BW)
ICS	3-12	?	0.025	10^6	10^8	$$$$	MT	Proposed MIT user facility, incoherent
ICS	5000	80	0.4	10^{11}	120	x10^2$	MT	Extension of LLNL proposed facility, incoherent, 80 bunches

Each technology falls into a clear niche or set of niches. The LPA technology is very much suited for the lower X-ray energy, with a modest photon flux per pulse, as a low-repetition rate laboratory coherent source. The PWFA and DWA technologies are better suited for the higher photon energy (50-keV) and can exploit the high-average current capabilities of RF accelerator technology. Both offer the interesting possibility of being installed as “afterburner” accelerators at an existing facility to significantly raise the photon energy, at the expense of fluence. They represent a less expensive alternative than conventional RF for 10-20 GeV electron accelerator systems, and are best suited for regional-scale facilities. The DLA can be developed to be a very cheap CW source of coherent X-rays with competitive average fluences, and are well-suited for smaller laboratories. ICS is a very mature technology, and is very cost effective as a source of high energy incoherent x-rays. ICS is not compelling for photon energies less than a few keV, and is the only technology that can yield MeV class photons in the near-term. The drawbacks for ICS include lack of photon coherency and higher X-ray beam divergence. If these are characteristics are not important, ICS is most likely the source of choice above a few keV.

References

1. http://lcls.slac.stanford.edu/
2. http://flash.desy.de/
3. http://www.jlab.org/FEL/jlamp.html

4. http://www.lbl.gov/LBL-Programs/ngls/science/index.html
5. E. Esarey, C. B. Schroeder, W. P. Leemans, "Physics of laser-driven plasma-based electron accelerators," *Rev. Mod. Phys.* **81**, 1229-1285 (2009).
6. W. Leemans and E. Esarey, "Laser-driven plasma-wave electron accelerators," *Physics Today*, **63** (3), 44-49 (2009).
7. T. Tajima and J. M. Dawson, *Phys. Rev. Lett*. **43**, 267 (1979).
8. W. P. Leemans, B. Nagler, A. J. Gonsalves, C. Toth, K. Nakamura, C. G. R. Geddes, E. Esarey, C. B. Schroeder, S. M. Hooker, "GeV electron beams from a centimetre-scale accelerator," *Nature Phys*., **2**, 696 (2006).
9. C. G. R. Geddes, C. Toth, J. Van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, W. P. Leemans, "High quality electron beams from a plasma channel guided laser wakefield accelerator," *Nature* **431** (7008), 538 (2004).
10. F. Albert, R. Shah, K. T. Phuoc, R. Fitour, F. Burgy, J.-P. Rousseau, A. Tafzi, D. Douillet, T. Lefrou, and A. Rousse, "Betatron oscillations of electrons accelerated in laser wakefields characterized by spectral X-ray analysis," *Phys. E*, **77**, 056402 (2008).
11. C. B. Schroeder, W. M. Fawley, F. Gruner, M. Bakeman, K. Nakamura, K. E. Robinson, C. Toth, E. Esarey, W. P. Leemans, "Free-electron laser driven by the LBNL laser-plasma accelerator," in C. B. Schroeder, E. Esarey, W. Leemans (Eds.), Advanced Accelerator Concepts, Vol. 1086, AIP, New York, 2009, pp. 637-642.
12. Fuchs, M. *et al.* Nature Phys. doi:10.1038/NPHYS1404 (2009).
13. J. B. Rosenzweig, D. B. Cline, B. Cole, H. Figueroa, W. Gai, R. Konecny, J. Norem, P. Schoessow, and J. Simpson, "Experimental observation of plasma wake-field acceleration," *Phys. Rev. Lett*., **61**, 98 (1988).
14. I. Blumenfeld, C. E. Clayton, F. J. Decker, M. J. Hogan, C. Huang, R. Ischebeck, R. Iverson, C. Joshi, T. Katsouleas, N. Kirby, W. Lu, K. A. Marsh, W. B. Mori, P. Muggli, E. Oz, R. H. Siemann, D. Walz, and M. Zhou, "Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator," *Nature*, **445**, 741 (2006).
15. T. Katsouleas, "Physical mechanisms in the plasma wakefield accelerator," *Phys. Rev. A*, **33**, 2056 (1986).
16. C. Huang, et al, *Phys. Rev. Lett*., **99**, 255001 (2007).
17. C. Huang, et al, *Journ. Comp. Phys*., **217**, 658 (2006).
18. R. Ruth et al, "Test accelerator for the next linear collider," SLAC PUB-6293 (1993).
19. A.M. Sessler, D. H. Whittum, and L.-H. Yu, *Phys. Rev. Lett*. 68, 309 (1992).
20. C. T. M. Chang and J. W. Dawson, J. Appl. Phys. **41**, 4493 (1970).
21. W. Gai, P. Schoessow, B. Cole, R. Konecny, J. Norem, J. Rosenzweig, and J. Simpson, Phys. Rev. Lett. **61**, 2756 (1988).
22. M. C. Thompson et al, *Phys. Rev. Lett*., **100**, 214801 (2008).
23. B. Cowan, "Three-dimensional dielectric photonic crystal structures for laser-driven acceleration", *PRST-AB*, **11**, 011301, (2008).
24. C. McGuinness, *et al*, "Accelerating electrons with lasers and photonic crystals", *J. Modern Optics*, **56** (18&19), p.2142ff, (2009).
25. G. Travish, R. Yoder, J. Rosenzweig, patent application no. WO/2008/156896.
26. T. Plettner et al "Proposed few-optical cycle laser–driven particle accelerator structure", *Phys. Rev. ST AB* **9**, 111301 (2006).
27. X. Eddie Lin, "Photonic band gap fiber accelerator", Physical Review Special Topics – Accelerators and Beams, **4**, 051301 (2001).
28. T. Plettner, R.L. Byer, "Proposed dielectric-based microstructure laser-driven undulator," *Phys. ST Accel. Beam* **11**, 030704 (2008).
29. C. Boulware, *et al*, "Needle Cathodes for high-brightness beams", in "The Physics and Applications of High Brightness Electron beams", World Scientific, p. 95 (2007)30. Hommelhoff, *et al*, "Field emission tip as a nanometer source of free electron femtosecond pulses", *PRL*, **96**, 077401, (2006).