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Prospects for an X-Ray FEL Light Source and some Possible Scientific Applications

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Abstract. Free electron lasers are now being designed which will operate at wavelengths down to about 1 Å. Due to the physics of the high-gain, single pass FEL process that these sources will exploit, the radiation produced will have unique properties. In particular:

- The FEL peak intensity and peak brightness will be many orders of magnitude higher than can be produced by any other source.
- The pulse length will be less than 1 picosecond, orders of magnitude shorter than can be achieved with any other bright source such as a synchrotron.
- The FEL radiation will have full transverse coherence and a degeneracy parameter (photons/coherence volume) equal to 10^9 or more. No other source can produce hard x-radiation with a degeneracy parameter significantly greater than 1.

These properties offer the chance to study chemical, biological, and condensed matter dynamical processes with sub-picosecond time resolution and angstrom spatial resolution. The high peak power of the FEL radiation (greater than 10^{14} W/cm^2) could be used to create precisely-controlled chemical and structural modifications inside samples. There is also the possibility that nonlinear x-ray interactions could be used to give increased resolution for spectroscopic studies, to greatly expand the parameter space for atomic physics studies, and to permit new fundamental tests of quantum mechanics. The exploration of these new x-ray techniques will require considerable development, not only in technical areas such as optics and detectors, but also in understanding the basic physics of the interaction of very intense x-radiation with matter. A large collaboration of US institutions is now conducting preliminary research and development in these areas, with the intention of creating an FEL operating at 1.5 Å in about the year 2006. Germany also has a strong short-wavelength FEL research program, with a soft x-ray FEL under construction and a proposal for a future large facility which would produce a variety of hard and soft x-ray laser beams.

INTRODUCTION

There have been tremendous changes over the last 30 years in all areas of science which depend on radiation with wavelength shorter than about 10 Å (throughout this paper the x-rays being discussed are those in this short-wavelength region of the spectrum). These scientific areas have benefited tremendously from the development of x-ray sources based on high-energy electron accelerators. The most advanced of these, the so-called third generation synchrotron light sources, are about 11 orders of magnitude brighter than the x-ray sources of the 1960's. Many of the papers included in this volume present results which depend on the capabilities of modern synchrotron sources.

The continued increase in synchrotron brightness cannot continue indefinitely, however. Though improvements to existing sources will probably yield a few orders of magnitude more, it is most likely that the next large jump in x-ray source capability will come from a different type of high-energy electron machine, the linear-accelerator-based free-electron laser (FEL). This new technology offers an increase in brightness over today's synchrotron source comparable to the synchrotron's increase over the lab sources of 30 years ago.

As bright as they are, synchrotron light sources are not lasers. The radiation that is produced comes from a spontaneous emission process, and is not amplified. The coherence properties of the radiation reflect the incoherence of the source. Because the wavelength is much smaller than the source size, the coherent fraction of the radiation is quite small. Also, the number of x-ray photons emitted in a single pulse is relatively small, so that nearly all time-resolved studies must be done in a stroboscopic way, requiring samples with repeatable behavior.

On the other hand, the coherence characteristics of FEL radiation derive from the phase matching criteria for the amplification process, which leads to a diffraction-limited, highly degenerate pulse of photons. In addition, the pulse length is orders of magnitude shorter than that produced by a synchrotron source, and the number of x-ray photons per pulse is high enough to do complete measurements in single flash mode. The characteristics of the radiation are in fact so unusual that, rather than replacing other x-ray sources such as synchrotrons, FELs will most likely be used to address completely new scientific questions, using completely new experimental methods.

This paper consists of a brief review of physics and technology issues related to the development of an x-ray FEL, and a more detailed discussion of the important aspects of FEL radiation. This is followed by a speculative look at possible applications in various scientific areas. Finally, the US and German plans for developing x-ray FELs are discussed.

THE FEL PROCESS

A free-electron laser relies on the interaction between a high-energy electron beam and a co-propagating electromagnetic field to produce coherent amplification of the field [1]. This interaction requires the presence of a periodic magnetic field (such as in an undulator insertion device), which causes the electron beam to follow an oscillatory path, and produce synchrotron radiation. A strong electromagnetic field moving with the electron beam slightly deflects the oscillatory motion of the electrons. With proper phase matching (a condition satisfied at the odd harmonics of the undulator fundamental emission frequency), this deflection leads the electrons to become longitudinally bunched, with the period of the bunching matching the wavelength of the electromagnetic field. The bunched electrons then tend to produce synchrotron radiation which is coherently phased with the electromagnetic field. Thus the field produces some bunching which produces a stronger field, which in turn leads to more bunching, and so on. Eventually the process saturates when enough energy is removed from the electron beam to cause it to lose phase matching with the electromagnetic field.

Since the 1970's more than 50 FELs have been constructed, with operating wavelengths ranging from the infrared to the near ultraviolet. About 40 are still in operation [2]. All of these devices include resonant optical cavities to contain the electromagnetic field, surrounding an undulator insertion device. They require multiple passes of electron pulses through the undulator/optical cavity before the FEL radiation field reaches full intensity. Some of these machines are operated as user facilities, for experiments needing very intense, short pulses of infrared radiation.

AN X-RAY FEL BASED ON SELF-AMPLIFIED SPONTANEOUS EMISSION

In order to extend the FEL concept into the x-ray region of the spectrum, it will be necessary to do without a resonant optical cavity. A scheme to achieve strong FEL action in a single pass of a high-energy electron pulse through a long undulator is known as self-amplified spontaneous emission (SASE) [3]. This scheme relies on spontaneous undulator radiation to form the electromagnetic field that initiates electron bunching. It also requires the FEL gain to be large enough to lead to an exponentially-growing radiation intensity along the length of the undulator. To achieve the high-gain FEL regime (also called the FEL instability), four conditions must be met:

1. The electron beam transverse emittance must not be much larger than the wavelength of the FEL radiation. In other words, the phase space of the electron beam must be matched to that of the radiation field.

2. The electron beam energy spread must be small, to give a sufficiently narrow line width to the spontaneous undulator radiation peaks.

3. The FEL power gain length must be short enough so that the increase in radiation intensity along the undulator is not lost due to diffraction spreading.

4. The electron pulse length must be longer than the FEL radiation wavetrain that is produced from it.

Of these conditions, the most difficult to achieve for an x-ray FEL is the first. Even the "low emittance" storage rings used in third-generation synchrotron sources have emittance values that are measured in tens of angstroms, much too large to support an angstrom-wavelength SASE FEL. The emittance limits for these machines are ultimately due to recoil effects on the circulating electrons from the spontaneous emission of synchrotron radiation.

The most promising way to achieve the required beam emittance is by using a linear electron accelerator. Linacs do not produce synchrotron radiation, and in principle the emittance can be reduced without limit, scaling inversely with the energy of the electrons.

In practice, it is still not easy to achieve an electron emittance of an angstrom and create an FEL operating in the angstrom range. However, three recent technical advances give confidence that such an FEL will soon be built.

RF Photocathode Gun. In a perfect linac the output emittance is simply proportional to the source emittance divided by the output energy, so a smaller source emittance yields a smaller output emittance. A new type of electron source has recently been developed, using a photocathode built into an RF-accelerator section. A laser pulse synchronized to the accelerator radio-frequency wave creates photoelectrons which are nearly instantly accelerated to relativistic energy. This suppresses the photoelectrons' tendency to disperse due to electrostatic repulsion, providing a very bright electron source which can be easily coupled to a linac.

Control of Emittance in the Linac. To achieve angstrom emittance, the electron pulse from even an RF photocathode gun must be accelerated to more than 10 GeV. To achieve this acceleration without having the emittance spoiled requires a detailed understanding of the interactions between the electron pulse and the accelerator. This level of sophistication in accelerator physics has come from recent studies related to future high-energy electron-positron colliders based on linear accelerators.

Undulators. A SASE x-ray FEL will require an electron beam to be guided through tens of meters of undulator, while maintaining alignment with the radiation field that it is creating. The ability to assemble and adjust thousands of blocks of permanent magnet material so as to create an undulator of the required precision is a product of research associated with the third-generation synchrotron sources.

A TYPICAL SASE X-RAY FEL

Meeting the conditions for SASE FEL operation in the angstrom wavelength region will require some advancement of the state of the art in all three areas mentioned above: electron gun technology, emittance preservation in the linac, and

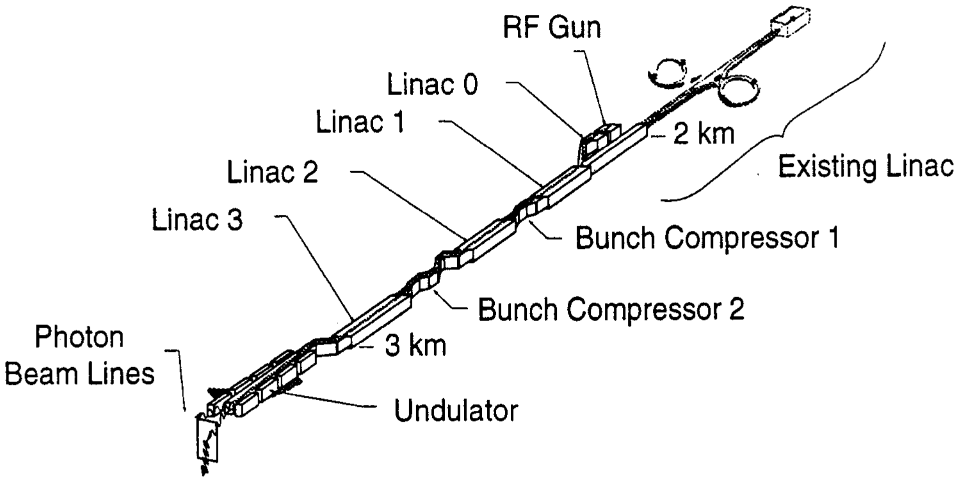

FIGURE 1. The Linac Coherent Light Source (LCLS), a proposed SASE FEL that would utilize one third of the 3-km linac at the Stanford Linear Accelerator Center. An RF photocathode electron gun would be added, along with electron bunch compressors and a 100 m undulator. The design FEL radiation wavelength is 1.5 Å.

electron beam control in a long undulator. Two groups have recently prepared conservative designs minimizing innovation in all three areas [4,5], and their proposals are quite similar. These proposals give a good picture of what an x-ray FEL is likely to look like. Figure 1 shows a schematic of the design prepared by the SLAC group.

The x-ray FEL will begin with an RF-photocathode gun producing an electron pulse with a normalized transverse emittance of about 3 μm. This pulse will be accelerated to 15–20 GeV in a linear accelerator. At one or more points during the acceleration process, the pulse will be routed through dispersive magnets in order to compress it longitudinally (increasing the instantaneous electron current). At the end of the linac about 10^9 electrons will be contained in a pulse lasting about 100 fs. This high-energy pulse will be directed through an undulator similar in design to those used at synchrotron sources, but roughly 100 m long. At the end of the undulator, the electron pulse will be deflected away from the radiation pulse.

A SEEDED X-RAY FEL

A SASE FEL operates as an oscillator, amplifying particular spectral components of the spontaneous fluctuations in the density of the electron pulse in order to produce coherent emission of radiation. This approach is straightforward, although as described above the constraints on the beam parameters are stringent. However, the startup from noise gives a few undesirable characteristics to the FEL radiation. The random variations in noise amplitude at the FEL frequency lead to large pulse-to-pulse variations in FEL radiation intensity. Also, the temporal coherence length of the radiation is much shorter than the length of the pulse.

A more controlled output pulse could be achieved by using the FEL process to amplify a well-controlled x-ray seed pulse. This would require a seed with coherent power of 200 kW or more, sufficient to dominate the power in the spontaneous undulator radiation. It would be possible to use a SASE FEL as a source of intense radiation, which could be filtered through a monochromator to produce a strong seed. A more attractive idea is to use as a seed an x-ray pulse obtained from a less expensive source. Perhaps within a few years x-ray sources based on intense optical lasers will be able to produce seed pulses of sufficient power.

A seeded FEL could in principle produce a completely coherent pulse of radiation, with a pulse length adjustable from sub-fs to several fs, based on the bandwidth of the seed. This would make the FEL even more attractive for very fast time-resolved studies. While it is most likely that the very first x-ray FELs will rely on SASE, in the long run FEL light sources are more likely to involve seeded FELs.

PROPERTIES OF THE RADIATION

The radiation from a SASE x-ray FEL will have properties never seen before in this spectral region. Coming from a laser which amplifies only a single spatial mode, the radiation will have complete transverse coherence, with a beam diameter of about 100 μm. This beam will be diffraction limited, with a divergence of about 1 μrad. In the direction of propagation, the roughly 1000 undulator periods comprising the final few gain lengths of the amplifier will yield a coherence length of about 0.1 μm. The coherence volume will contain about 10^{10} photons (degeneracy parameter = 10^{10}). This number is remarkable in that no previous x-ray source has produced a degeneracy parameter significantly greater than 1. The peak brightness of the FEL radiation will be about 10 orders of magnitude greater than then next brightest x-ray sources, which are the third-generation synchrotron sources (see Fig. 2).

Current designs for SASE FELs envision an electron pulse about two hundred times longer than the FEL longitudinal coherence length, producing an output that consists of two hundred independent, sequential micropulses in a macropulse lasting roughly 100 fs. Note that this macropulse length is at least two orders of magnitude shorter than the x-ray pulses created by other bright sources such as synchrotrons. The amplitudes of the micropulses will vary greatly, representing amplified stochastic variations in the electron density. A seeded FEL could provide a totally coherent output pulse, of length determined by the bandwidth of the seed.

The linac repetition rate would determine the firing rate for the FEL system. A superconducting linac could provide several thousand nanosecond-spaced pulses in a train separated by milliseconds from other pulse trains. Though this pulse spacing is much more sparse than that produced by a synchrotron source, nevertheless the average brightness of the FEL will still be several orders of magnitude higher than today's third-generation synchrotron sources.

Table 1 lists a number of calculated properties for the radiation to be produced

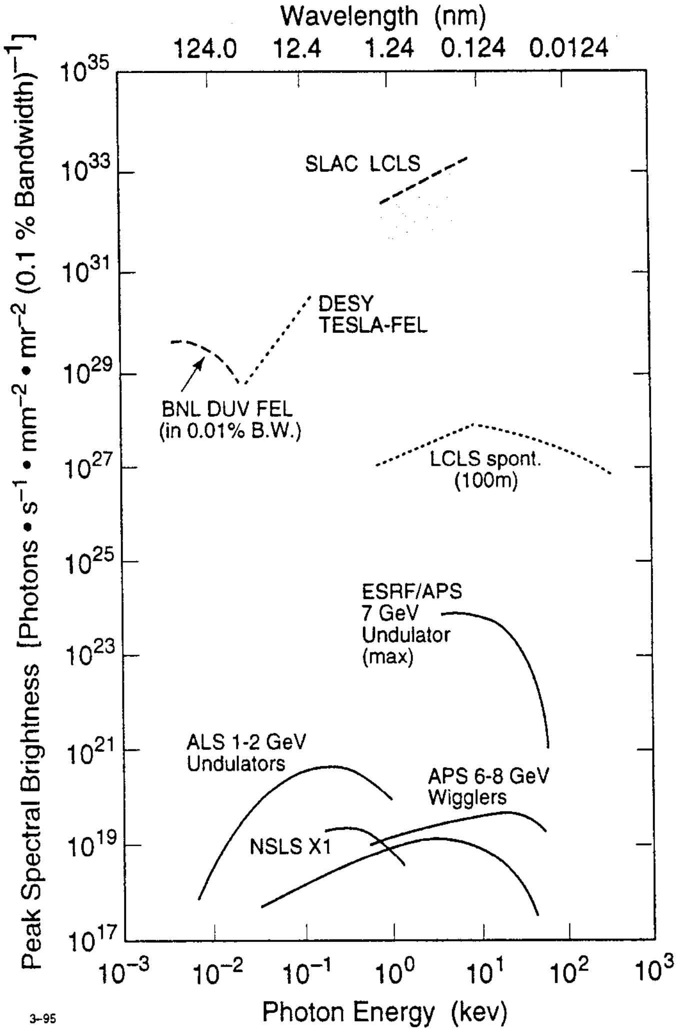

FIGURE 2. A comparison of the peak spectral brightness (photon density in phase space) of several hard and soft x-ray sources. The top curves all apply to FEL sources that are either proposed or under construction. These curves represent calculated values (the shading around the LCLS curve indicates an estimated range of uncertainty, allowing for possible errors in the electron optics). The curves at the bottom apply to existing synchrotron sources, but they are also calculated values incorporating expected future improvements in brightness. One curve in the middle shows the expected peak brightness of the spontaneous (non-FEL) radiation from an x-ray FEL source.

TABLE 1. Calculated characteristics of the LCLS radiation.

Parameter	Value	Unit
FEL wavelength	1.5	Å
FEL bandwidth ($\delta E/E$)	0.002	
Pulse duration (FWHM)	233	fs
Pulse length (FWHM)	67	μm
Peak coherent power	9	GW
Peak coherent power density	1.5×10^{12}	W/mm^2
FEL energy/pulse	2.6	mJ
Peak brightness	1.2×10^{33}	photons/(s mm^2 mrad^2 0.1% bandwidth)
FEL photons/pulse	$2. \times 10^{12}$	
FEL photons/second	2.4×10^{14}	
Degeneracy parameter	3.3×10^{9}	
Peak EM field (unfocused)	3.4×10^{10}	V/m
Average FEL power	0.31	W
Average FEL brightness	4.2×10^{22}	photons/(s mm^2 mrad^2 0.1% bandwidth)
Transverse size of FEL beam (FWHM)	78	μm
Divergence of FEL beam (FWHM)	1	μrad
Peak power of spontaneous radiation	81	GW

by the LCLS, a SASE FEL proposed by the Stanford Linear Accelerator Center. The properties of most interest to an experimenter are:

- The FWHM of the radiation pulse is 280 fs.
- Each pulse contains about 10^{12} photons in the FEL fundamental peak.
- The degeneracy parameter (photons per coherence volume) for these photons is about 10^{10}. The beam is circular in cross-section (diameter 80 μm), and has complete transverse coherence. The longitudinal coherence length is about 0.1 μm.

In addition to the FEL laser radiation, the SASE device will produce an intense, broadband pulse of spontaneous undulator radiation (see Fig. 3). Though without the coherence properties of the FEL radiation, the spontaneous radiation will be scientifically useful because of its broad spectrum and sub-picosecond pulse length. The spontaneous radiation spectrum will extend to several MeV; above about 100 keV its brightness will exceed that of any other radiation source.

SCIENTIFIC APPLICATIONS

The exceptional characteristics of FEL radiation lead one to envision applications requiring very good time resolution or very high coherence. To assess the possibilities in these areas, it is useful to carefully compare the capabilities of an x-ray FEL with those of other short-pulse or highly-coherent x-ray sources.

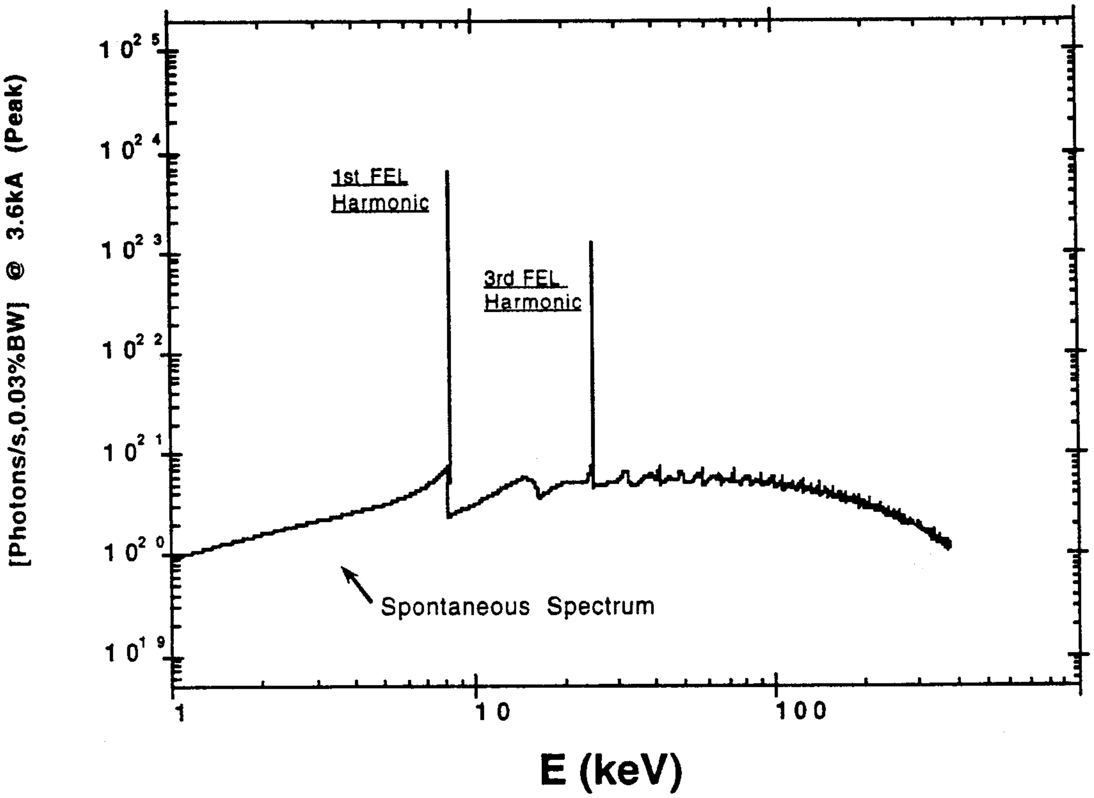

FIGURE 3. Calculated spectrum for the LCLS, a SASE FEL source. The FEL fundamental wavelength is 1.5 Å. FEL amplification is also possible at the third harmonic wavelength, though the gain is much less than for the fundamental, and may be suppressed by errors in the electron beam alignment.

Short-pulse x-ray sources

The brightest x-ray sources today, the third-generation synchrotron sources, produce pulses whose duration is about 100 ps. The x-rays are highly collimated, with 10–100 μrad divergence, and the pulses are repeated at a rate measured in MHz. The time-averaged monochromatic flux (in a bandwidth of about 10^{-4}) is about 10^{14} s^{-1}. In order to use such a source for sub-ps time-resolved experiments, schemes have been developed which utilize a sub-ps optical laser to serve as a sort of gate [6], subdividing the longer synchrotron x-ray pulse. These approaches, and any time-resolved techniques that make use of pulsed optical lasers, suffer from the incommensurability between the synchrotron pulse rate and that of the laser (which is typically in the kHz range). Thus, for an experiment requiring 100 fs time resolution, the synchrotron flux is effectively reduced by at least 6 orders of magnitude due to the need to subdivide the synchrotron pulse and to match the repetition rate of an optical laser. The net useful flux is around 10^6–10^8 s^{-1}.

Other sources have been developed to produce sub-ps pulses of x-rays, including pulsed plasma sources [7], and inverse Compton effect sources [8]. These sources can be fast (100 fs), but are not very bright. The flux that they can send into an experiment with mrad divergence requirements is typically 10^4–10^6 s^{-1}. There have also been extensions of traditional atomic lasers toward shorter wavelengths, utilizing inner-shell transitions or non-linear generation of very high harmonics of optical lasers. These sources can be quite fast (10 fs) and intense, but are so far confined to the very soft x-ray region, with their performance deteriorating rapidly at wavelengths shorter than 100 Å.

These fast sources produce enough useful x-ray flux to perform sub-ps time resolved experiments in which the signal intensity is a fair fraction of the incident beam intensity, such as studies of Bragg reflections of good-quality crystals. The x-ray FEL, on the other hand, can produce enough flux to study much weaker effects with sub-ps resolution. The FEL is highly collimated, and its pulse repetition rate is compatible with that of a pulsed optical laser, so that essentially all of its average flux of 10^{14}–10^{16} s^{-1} can be effectively used for fast time-resolved experiments. And because of the very high flux delivered by a single pulse (10^{12}), the FEL allows the possibility of completing an experiment with a single pulse.

Coherent x-ray sources

Coherent x-ray experiments typically require spatial coherence lengths of about 10 μm [9]. A synchrotron source can provide an average flux of about 10^9 s^{-1} with this level of coherence. Other existing x-ray sources cannot approach this level of coherent flux in a collimated, monochromatic beam.

An x-ray FEL, with complete transverse coherence, can provide a spatially coherent flux of 10^{14}–10^{16} s^{-1}. In addition, the FEL radiation exhibits coherence beyond the single-photon level. The degeneracy of the photon wavefunction produced by the FEL (the number of identical, coherent photons in a coherence volume) is greater than 10^9. No other x-ray source produces radiation with a degeneracy significantly greater than 1. This means that multi-photon coherence experiments should be practical with an FEL, whereas they are impractical with any other x-ray source.

Since the FEL is a fast pulsed source as well as a coherent one, it offers the possibility of conducting coherent experiments with sub-ps time resolution, or of conducting single-shot coherence experiments.

With such a leap in capability over existing sources, it is nearly impossible to correctly identify the most scientifically fruitful applications that will emerge. Nevertheless, several international workshops have been convened during the past five years to explore ideas for applications of an x-ray FEL [10–15]. Below is a summary of the ideas presented at these workshops.

Fundamental Quantum Mechanics

Nonlinear scattering of the high-brightness FEL beam could be used to produce large numbers of entangled multi-photon states, which could be used to study correlation effects such as the Bell inequality. It would be advantageous to use x-rays for experiments of this type, rather than optical photons, because the high quantum efficiency of x-ray detectors would make it easier to keep track of every photon.

The ability to create intense, short-wavelength electric field patterns using an x-ray FEL would be useful for atom-interferometry experiments. FEL standing wave interference patterns could be used as beam splitters and mirrors for the atom beams. This is achieved today with visible lasers; using the FEL would allow these optics to be created with shorter periods, allowing larger scattering angles for the atom beams, and thereby giving the interferometry experiments much higher sensitivity.

If the full peak power of the x-ray FEL were focused into a submicron spot, the peak electric field could approach 10^{15} V/m. This value is high enough to be interesting for tests of quantum electrodynamics.

Atomic, Molecular, and Plasma Physics

The extremely high peak brightness of a focused FEL x-ray beam offers the chance to extend the study of photon interactions with core atomic electrons well into the nonlinear regime. The new experimental capability would provide tests of theoretical analysis that goes beyond the dipole approximation. For example, it would allow tests of nonlinear processes such as core-resonant ionization in helium, and adiabatic stabilization [16], in which under certain conditions transition rates are predicted to decrease with increasing intensity.

In the area of molecular physics, the high brightness and short pulses of the FEL source would allow one to better understand ionization and dissociation processes by controlling them coherently. One could also study chemical reactions in the time domain with pump/probe techniques.

The plasma physics community could use an FEL x-ray source to greatly extend their studies of the interactions between matter and extremely high-power-density electromagnetic fields. This would allow new tests of the scaling properties of nano-plasma multiple ionization, and inner-shell excitations.

Chemical Physics

The x-ray FEL has the potential to become a powerful monitor of surface chemical reactions, using x-ray fluorescence or XPS as the system probe. This application has the ability to fully characterize the kinetics (reactants, products and rates) of surface reactions.

By using the x-ray pulse as a probe beam, a fast-pulse optical laser could be used to set up femtosecond-resolution structural dynamics studies. Local structure would be obtained by EXAFS and global structure would be obtained via diffraction measurements. The intensity of the FEL would allow both dilute and complex systems to be analyzed.

Eventually, one can expect that x-ray FEL sources will be developed which have sub-femtosecond time resolution, which would allow probing the next level of temporal dynamics in atomic systems.

Condensed Matter Physics and Materials Science

The characteristic distances important for studies of condensed materials typically range from micrometers down to angstroms, and the typical interaction energy runs from about 1 eV down to 1 μeV (corresponding to interaction times in the femtosecond to nanosecond range). These values match very well with the characteristic length and time scales of an x-ray FEL pulse: Angstrom wavelength with coherence length of many micrometers, and pulse duration measured in femtoseconds.

In addition, the brightness is much higher than that produced by any other x-ray source. This feature will allow a large number of standard x-ray techniques to be applied to smaller samples, and to record the relevant signal in less time. Examples include surface scattering studies of very small samples, diffraction from samples in very high pulsed magnetic fields, time-resolved studies of crack propagation, diffraction from materials undergoing shock wave distortion, diffraction from single grains in complex polycrystalline materials, studies of critical phenomena, and scattering studies of laser pulse-induced charge modulations in materials [5]. One large class of experiments that can take advantage of the x-ray FEL are those involving x-ray photon correlation spectroscopy (XPCS) [9]. This technique today is limited by source brightness to studying length scales larger than 100 nm and time scales longer than 1 ms. Both the length and time limits could be reduced by orders of magnitude with an x-ray FEL. In particular, time scales shorter than 1 ps could be probed, allowing the XPCS technique to complement energy-resolved inelastic x-ray scattering techniques. Initial FEL designs, such as the LCLS, are particularly suited for XPCS measurements in the ps-ns time range. This range is complementary to that covered by the neutron spin echo technique, which is now being used to study the dynamics of the glass transition. The vastly higher brightness of the FEL source would allow experiments to be performed in much less time and with much smaller samples.

In addition to these extensions of existing techniques, the x-ray FEL should allow the development of some completely new ways to study condensed matter. Some of these new techniques will most likely involve the high degeneracy of the FEL photon state. By analogy with visible laser science, one can envision gaining higher spectroscopic resolution through multi-photon excitations, or nonlinear interactions between the FEL x-rays and synchronized visible laser pulses [17]. If suitable resonances can be identified, x-ray photon echo experiments could provide a new sensitive probe of internal fields in materials.

The very high peak power of the x-ray FEL could also be used to induce desired permanent changes in materials. For example, a spatial interference pattern created from the FEL radiation could have enough intensity to carve a high-quality Fresnel optic into a smooth block of material. The focused FEL beam could also be used to create small holes (microexplosions) deep inside a sample.

Biology

Structural biologists wish to determine the atomic structures and to observe the dynamical interactions between large molecules (mass between 5 kDa and 5×10^6 kDa). The dynamical time scales of interest are typically microseconds or longer, but for some extremely interesting systems (*e.g.*, photosynthetic reaction centers, light-harvesting complexes, photosystem II, and light sensors such as photoactive yellow protein and bacteriorhodopsin) the interesting time scale can be as short as a few femtoseconds.

The high brightness of the x-ray FEL would allow structures to be determined using very small samples. It should be possible to study two-dimensionally ordered crystals (*e.g.*, membrane proteins), which are notoriously hard to crystallize in three dimensions and which are both numerous and of keen biological interest. In addition to conventional crystallographic techniques, it might be possible to exploit the spatial coherence of the FEL radiation to get structural information holographically.

The short time structure of the FEL pulse could be used to probe sample dynamics on a femtosecond to nanosecond time scale. There is interest in both time correlation studies of thermal fluctuations, and pump-probe relaxation studies (using as a pump either an external synchronized laser or the FEL x-ray pulse itself).

X-RAY FEL DEVELOPMENT PLANS

Since the realization in the early 1990's that it is probably technically feasible to construct a SASE FEL operating at angstrom wavelengths, the x-ray community has come to embrace the idea of an FEL machine as the "fourth generation" in the progression of large x-ray facilities based on high-energy electron accelerators. At the ICFA Workshop on 4th Generation Light Sources in 1996 in Grenoble, France [11], the working group on hard x-ray applications of future x-ray sources concluded that "[The] hard x-ray group [is] unanimously excited about the FEL project as [the] 4th generation". This sentiment was echoed in the report of a Dept. of Energy (DOE) working group considering the state of synchrotron radiation in the US in 1997 [18], which stated that "We have also considered 'fourth generation' x-ray sources which will in all likelihood be based on the free electron laser concept... It is our strong view that exploratory research on fourth generation x-ray sources must be carried out and we give this item very high priority". More recently, a DOE panel charged with setting priorities in the area of novel coherent light source development [19] decided that "The Panel found that the most exciting potential advance in the area of innovative science is most likely in the hard X-ray region in the range of 8–20 keV, and even higher. This is especially the case if a light source can be built with a high degree of coherence, temporal brevity, and high pulsed energy".

In response to this rising enthusiasm, the DOE has established a plan for development of FEL light sources. The ultimate goal of this plan is to build a working SASE x-ray source in the 1–10 Å range. This will be accomplished through R&D efforts toward satisfying the technical requirements of such a machine, and through studying SASE FEL physics at a sequence of FEL projects with progressively shorter wavelength. A number of DOE National Laboratories are collaborating in this effort, along with several university labs. If adequate funding is provided, an x-ray FEL based on the SLAC linear accelerator (the only existing linac capable of reaching the necessary 15 GeV electron energy) will begin producing 1.5 Å radiation in about 2006.

In parallel with the US FEL program, Germany is also building short-wavelength SASE FELs. The TESLA project at DESY in Hamburg is building an FEL facility based on a new superconducting linac. Proceeding in stages, this project is expected to become an FEL scientific user facility within a few years, with radiation wavelengths as short as 60 Å. DESY has also developed an ambitious plan for a large x-ray FEL user facility, with 50 experimental stations operating simultaneously, based on a huge superconducting linac which would also supply electrons for high-energy physics experiments [5]. This plan is not funded yet, but enjoys political support.

Though many technical and political hurdles remain, it now seems quite likely that one or more fourth-generation x-ray source, based on FELs, will be built within the next ten years. It will provide a basis for a fantastic new generation of x-ray science.

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