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Synchrotron Radiation Sources – Present Capabilities and Future Directions†

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Many of the more than 40 operational light sources around the world have achieved performance levels that exceed initial design goals. These accomplishments are reviewed, along with concepts and proposals for sources with performance levels exceeding those of present sources. These include storage rings with lower electron-beam emittance than present third-generation rings and free-electron lasers (FELs). It now appears that the highest performance sources will be based on linacs rather than storage rings. This is because emittance originates differently and scales differently with electron energy for rings and linacs, so that the lowest electron-beam emittance can be achieved in high-energy linacs equipped with high-brightness electron sources. Such electron beams can be used to provide X-ray beams with very high brightness and coherence in sub-picosecond pulses in a single pass through a small-gap short-period undulator by spontaneous emission, and with even higher beam brightness and coherence by stimulated coherent emission in an FEL. Designs for such FEL sources, and associated research and development, are underway at several laboratories.

Keywords: fourth-generation sources; linacs; free-electron lasers; high brightness; low emittance.

1. Introduction

Since the first indirect observation of synchrotron radiation in 1945 (Blewett, 1946) there has been a rapid growth in the scientific use of this remarkable light source. Starting in the 1950's, cyclic electron synchrotrons were the sources used, yielding to the superior properties of electron storage rings starting in 1968. Storage-ring sources have evolved through three generations. First-generation rings are those originally built for high-energy physics research. Second-generation rings are those built from the outset as light sources. Third-generation rings, coming on-line since 1992, have many straight sections for insertion devices and lower electron-beam emittance. Undulators on third-generation rings provide $\sim 10^4$ times higher brightness than bending-magnet sources of earlier rings. There are now more than 40 operational rings of all generations used as synchrotron radiation sources in 14 countries; 10 of these rings are third-generation sources.

Almost all existing sources have achieved very high performance levels, in many cases exceeding their design goals. Herein, the challenges that must be met to reach even higher performance levels in fourth-generation rings and the reasons why linac-based sources appear very attractive as fourth-generation sources are discussed. In particular, the potential of linac-based sources to drive short-wavelength FELs, providing extremely high photon-beam brightness and coherence as well as sub-picosecond pulses, is discussed. Because of recent technological developments, it now appears possible to extend the wavelength at which FELs operate down to the ångström range, using ultra-low-emittance high-energy electron beams from linacs equipped with high-brightness r.f. photoinjectors and bunch-length compressors.

In the absence of mirrors to form optical cavities, short wavelengths are reached in FEL systems in which a high-peak-current low-emittance electron bunch becomes density modulated at the optical wavelength (resulting in radiation power emitted at that wavelength proportional to the square of the number of electrons rather than the linear dependence of spontaneous emission) in a single pass through a long undulator by self-amplified spontaneous emission (SASE); *i.e.* startup from noise. A SASE-FEL that will reach ~50 Å is under construction at DESY. Detailed designs are being developed for proposals to use 15–30 GeV electrons from the SLAC linac and the proposed linear collider at DESY to drive FELs down to 1–2 Å by SASE in 100 m-long undulators. In addition to extremely high brightness and full transverse coherence, these sources provide very short (a few hundred femtoseconds) pulses and broadband high-brightness spontaneous undulator radiation extending to hundreds of kilovolts.

2. Performance of present sources

One of the notable features of light source development has been the success of accelerator physicists and engi-

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neers in designing and commissioning increasingly sophisticated and complex storage rings and pushing their performance well beyond initial design goals. Examples of this were recently reviewed (Jackson, 1997). Many first- and second-generation rings have had their energy, stored current, lifetime and stability greatly improved over the past few years with the addition of feedback systems and improvements to critical components such as beam-position monitors, r.f. systems, control systems and magnet power supplies. Worthy of particular mention are the lattice modifications implemented in first- and second-generation rings to reduce electron-beam emittance and thereby increase source brightness. Such modifications have been successfully carried out at the Daresbury SRS, the Photon Factory, SSRL and other facilities, bringing emittances down from the 500 to the 100 nm rad level. Modifications to reduce further emittance to levels below ~50 nm rad are now underway at the Photon Factory and are planned at NSLS and SSRL. Another type of lattice modification, a bypass to a long straight section originally used for colliding-beam detectors, was implemented on the DORIS ring at HASYLAB to accommodate seven additional insertion devices. Such lattice improvements, coupled with major improvement in source stability and reproducibility, have enabled these older sources to keep pace with the increasing user requirements.

Equally impressive has been the performance of third-generation sources, many of which have also exceeded their design goals. Outstanding in this regard is the performance of the ESRF, which has exceeded its original brightness design goal by a factor of about 100. Details of these various improvements can be found in the activity reports of these laboratories as well as in the proceedings of the European Particle Accelerator Conferences (EPAC) and similar conferences in Japan and the US, as well as regional conferences such as those held periodically between China and Japan.

In addition to the performance improvement of storage rings there has been a steady increase in the performance of insertion devices (IDs) and the development of new ID concepts. This includes the many variations of permanent-magnet IDs, such as hybrid designs that use high-permeability steel to concentrate the flux from permanent-magnet blocks, IDs that provide variable polarization, and in-vacuum IDs that allow the smallest gaps and hence the shortest periods to reach short wavelength.

One may ask how such impressive performance levels have been achieved, particularly when one recalls the trepidation with which the original goals were set for third-generation sources. At the time of the planning of these facilities there were doubts about the ability to meet the ambitious design goals. For example, there were concerns that the stored-beam lifetime would not be long enough due to an inadequate dynamic aperture. Simulations indicated that dynamic aperture could be significantly reduced due to factors such as ring-component construction tolerances, alignment errors, and the effects of nonlinearities and imperfections of insertion devices. In retrospect we can say that the success of present sources in reaching and exceeding their design goals is due to major advances and improvements in capability in the following technical areas: (*a*) improved theoretical understanding and the development of increasingly sophisticated computer codes, such as particle tracking codes, for predicting beam dynamics behavior; (*b*) engineering design of technical components; (*c*) precision fabrication of these components; (*d*) survey and alignment; (*e*) electron- and photon-beam diagnostics; (*f*) beam-based modeling and control; and (*g*) feedback systems.

3. High brightness and low emittance

The concentration of the radiation is called the brightness, measured in photons s^{-1} mm^{-2} $mrad^{-2}$ (0.1% bandwidth)$^{-1}$. The increase in X-ray source brightness over the past 100 years, starting from the days of Röntgen, is illustrated in Fig. 1, showing the dramatic increase provided by synchrotron radiation from bending magnets, wigglers and undulators in increasingly powerful storage rings, and the projected brightness anticipated from short-wavelength X-ray FELs. The brightness of radiation produced by an electron beam depends on the beam transverse size and divergence, the product of which is called the emittance. Horizontal emittance ($\varepsilon_x = \sigma_x \sigma_{x'}$) is determined by the electron energy and the ring design. The vertical emittance ($\varepsilon_y = \sigma_y \sigma_{y'}$) depends primarily on coupling to the horizontal and can be as small as ~0.5% of the horizontal emittance, significantly less than the 10%

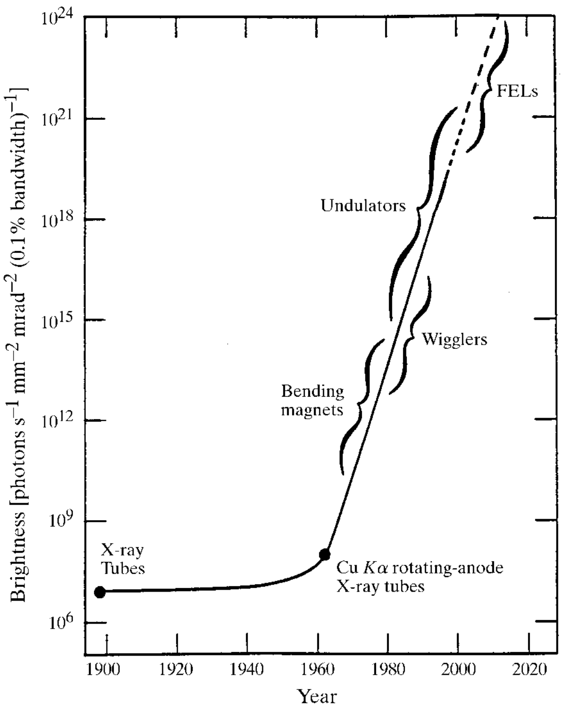

Figure 1
X-ray source brightness as a function of time since the discovery of X-rays in 1895.

coupling anticipated in the initial designs. Second-generation sources were originally designed with horizontal emittances of one hundred to several hundred nm rad, resulting in undulator beam brightnesses of up to $\sim 10^{16}$.

Since further reduction of electron-beam emittance would result in even higher brightness, in the mid-1980's efforts began at several laboratories to design and construct a new round of storage rings – the third-generation sources. These have many straight sections for insertion devices and electron-beam emittances of about 5–20 nm rad. These rings, which began operation in the early 1990's, have now reached undulator brightnesses as high as 10^{20}, about 10^{12} times higher than that provided by rotating-anode X-ray tubes. Although spectacular, this brightness is far from fundamental limits. Further reduction of electron-beam emittance would result in increased photon-beam brightness and coherence, particularly at X-ray wavelengths.

Diffraction sets an ultimate limit on the geometric properties of photon beams. Because of diffraction the lower limit on the photon-beam emittance is given approximately by the wavelength, λ. Using standard deviation values for Gaussian distributions, this diffraction-limited photon-beam emittance is given by $\lambda/(4\pi)$. For light produced by electron beams, photon-beam brightness increases as electron-beam emittance decreases, until the electron-beam emittance reaches a value of $\sim\lambda/(4\pi)$. Thus third-generation rings with a horizontal emittance of 5 nm rad can produce diffraction-limited light at wavelengths longer than ~60 nm (photon energies below ~20 eV). An emittance three orders of magnitude lower, 5 pm rad, would be needed to reach the diffraction limit at 0.06 nm (20 keV). As discussed below, producing an electron beam with such a low horizontal emittance is possible using a linac, but it would be extremely difficult in a storage ring. For this reason, the highest performance future sources are likely to be based on linacs.

3.1. *Emittance in storage rings*

The emittance of the electron beam in a storage ring is determined by an equilibrium between the consequences of the emission of synchrotron radiation. On the one hand, the quantum nature of the emission of radiation in ring bending magnets drives betatron oscillations which enlarge the emittance. On the other hand, the r.f. cavities in a storage ring restore the energy lost to synchrotron radiation by adding momentum only in the longitudinal direction, resulting in a damping of transverse oscillations and a reduction of emittance. Thus, the equilibrium electron-beam emittance in a storage ring depends only on the beam dynamics in the ring and is independent of the properties of the injector. This is different for linacs, as discussed in the next section.

Ring horizontal emittance can be reduced by lowering the amplitude of the quantum-induced oscillations. This amplitude is determined by the amount of radiation emitted and by the properties of the magnetic lattice of the ring, particularly the detailed values around the ring of the so-called dispersion function, which determines the separation of the orbits of electrons with different energy.

Consider an electron with slightly higher energy than the average. It tends to orbit at a larger average radius in a bending magnet in which it also emits radiation. When it emits a quantum its energy suddenly decreases and, although the electron does not change its position, its proper, or 'equilibrium', orbit (*i.e.* the orbit in which the electron would like to be) is instantaneously shifted inwards. The focusing properties of the ring magnet lattice cause this electron to begin to execute oscillations, called betatron oscillations, about this displaced orbit, resulting in an increase in source size and divergence, and hence an increase in emittance. We can reduce the amplitude of these oscillations by reducing the separation of orbits for different electron energies; *i.e.* by reducing the value of the dispersion function at locations at which quanta are emitted. Since this separation grows with bending angle, we can reduce it by reducing the magnetic field and/or length of the bending magnet.

In summary, low emittance is achieved in a storage ring by making the bending magnets short and weak (to reduce the angle of bend in each magnet and increase the bend radius) and by operating the ring at low energy (to reduce the emitted radiation and hence reduce the quantum excitation of betatron oscillations). In fact the horizontal emittance in a storage ring varies as the square of the electron energy and the third power of the angle of bend in each bending magnet.

3.2. *Emittance in linacs*

The limit of an accelerator with large bending radius is a linac. The almost complete absence of bends in a linac means that the emittance is no longer determined primarily by quantum effects in radiation emission. Thus, unlike a storage ring, in a linac the emittance starts at a value determined by its injector, the electron gun, then decreases linearly as the electron energy increases, unless wakefields or other effects counteract this decrease.

The normalized emittance, given by the geometric emittance times $\gamma = E/mc^2$, is therefore used for linac beams. Photocathode r.f. guns now produce beams with a normalized emittance, ε_n, of about 2 mm mrad. If such a beam was accelerated to 5 GeV ($\gamma = 10^4$) the emittance could be as low as 0.2 nm rad, the diffraction limit for 2.4 nm (500 eV) X-rays. Guns with $\varepsilon_n = 1$ mm mrad are now in development. A 20 GeV linac equipped with such a gun could reach the diffraction-limited emittance for 0.3 nm (4 keV) X-rays.

4. Fourth-generation sources

As remarkable as the performance of present sources has been, even higher brightness and laser-like coherence appear achievable and are needed scientifically, particularly at soft and hard X-ray wavelengths. Reaching higher performance levels is the goal of fourth-generation sources, which we may define as sources that exceed the performance of previous sources by one or more orders of magnitude in an important parameter such as brightness, coherence, or shortness of pulse duration. Directions for fourth-generation sources in the wavelength range from the VUV to hard X-rays include storage rings with even lower emittance than third-generation rings, and short-wavelength free-electron lasers (FELs), which offer sub-picosecond pulses with full transverse coherence.

4.1. *Lower emittance storage rings*

The relative ease with which third-generation light sources have reached, and indeed exceeded, design goals indicates that fourth-generation storage rings can reach even lower electron-beam emittance, producing higher photon-beam brightness and diffraction-limited light at shorter wavelengths. The challenges that must be met to accomplish this have been considered at workshops on fourth-generation light sources (Cornacchia & Winick, 1992; Laclare, 1996).

4.1.1. *Lattice design and dynamic aperture.* A formidable challenge in the design of fourth-generation storage-ring sources is to reach long lifetime in a very low emittance magnet lattice. This requires sufficient dynamic aperture to accommodate stable orbits with large-amplitude oscillations resulting from, for example, Coulomb scattering of electrons on the residual gas and off-axis injection. The former results in the continuous population of a halo much larger than the core. As the particles in this halo are damped, they coalesce with the core of the beam. If the aperture (dynamic or physical) is too small, particles in the halo are lost before being damped, resulting in reduced lifetime. It is difficult to maintain a large dynamic aperture in a low-emittance lattice because of the chromatic effects of the strong quadrupoles. This chromaticity, the energy dependence of the betatron tune, is corrected by sextupole magnets, whose non-linear fields reduce the dynamic aperture.

A possible countermeasure is the 'modified sextupole' (Cornacchia & Halbach, 1990), which provides a magnetic field with a quadratic dependence over the core of the beam, but which then levels off or rises much less rapidly with distance from the axis, thereby lowering the fields experienced by particles with large-amplitude oscillations. Dynamic aperture might also be enlarged by alternately rotating the lattice cells by $\pm 45^\circ$, so that sextupoles can be placed at locations of maximum dispersion in each plane for efficient chromaticity correction (Hofmann, 1997). The large dynamic aperture needed for injection in present rings is due to the fact that stored beam is accumulated with off-axis injection of many low intensity 'shots', each of which executes large-amplitude betatron oscillations until they coalesce with the already stored beam due to radiation damping. The aperture requirement can be reduced with single-shot on-axis injection from another ring, in which a high intensity beam has been accumulated with multi-shot off-axis injection. Injection into synchrotron phase space is another possibility.

As described in §3.1, the horizontal emittance in an electron storage ring scales as the square of the electron energy and the third power of the deflection angle in each bending magnet. Thus, lower emittance fourth-generation rings would have many short bending magnets separated by quadrupoles, leading naturally to the possibility for many straight sections for insertion devices. However, these factors also lead to a larger circumference at a given energy than third-generation rings. For example, the lattice working group at the Grenoble Workshop (Laclare, 1996) presented a 'straw-man' design for a 2–3 GeV fourth-generation ring with ~0.3 nm rad emittance and a circumference the same as the 6 GeV ESRF machine, ~850 m. LBNL is studying a 2 GeV ring (Jackson *et al.*, 1997), also with ~0.5 nm rad emittance and a circumference of about 350 m. Such rings might achieve a brightness at soft X-ray wavelengths of about 5×10^{23}, more than three orders of magnitude greater than third-generation VUV sources. Note that 0.3 nm rad is the diffraction limit for light at 3.6 nm, or 0.34 keV.

Fourth-generation rings for hard X-rays (below ~2 Å) would require higher electron energy and much larger circumference. They would cost much more than the lower energy rings discussed above, even to reach an emittance of about 0.3 nm rad, which is much larger than the diffraction limit for hard X-rays. Limited use has been made of undulators in the large-circumference colliding-beam rings PEP (2.2 km) (Bienenstock *et al.*, 1989) and TRISTAN (3 km) (Yagi *et al.*, 1996) operating as third-generation sources. However, both are now being converted to B-Factories for high-energy physics research. Although the PETRA (2.3 km) collider at DESY is now part of the HERA injection system, an undulator has been installed in PETRA for use between HERA injections. Operating at 12 GeV, this undulator will provide third-generation brightness extending to very high photon energy. In the future, fourth-generation hard X-ray rings may be installed in these tunnels.

4.1.2. *Beam lifetime – Touschek effect.* Very low emittance fourth-generation rings will have very high bunch charge density, leading to short lifetime due to the Touschek effect; *i.e.* the Coulomb scattering of an electron pair in the bunch resulting in the exchange of transverse to longitudinal momentum. If the resultant longitudinal momentum of one of the electrons exceeds the momentum acceptance of the ring, that particle is lost. This is particularly severe at low energy and is already a problem in third-generation 1–2 GeV rings. To achieve a lifetime of the order of 10 h, the bunch density must be reduced in several third-generation rings. This is usually performed by increasing the vertical emittance and/or the bunch length above their minimum values, trading brightness for lifetime. The problem is exacerbated by the success of third-generation rings in achieving very low vertical emittance, only ~1% of the horizontal rather than ~10% as assumed in their design reports. Multiple Touschek scattering also enlarges emittance and increases the energy spread of the electron beam, both of which result in reduced photon-beam brightness.

If all beam dimensions and the charge per bunch are kept constant, the Touschek lifetime increases quadratically with electron energy and with the third power of the momentum acceptance of the ring. Thus, lower emittance VUV/soft X-ray rings are designed with higher electron energy [the Swiss Light Source (2.1 GeV), Soleil in France (2.5 GeV) and the Shanghai Synchrotron Radiation Facility (2.2–2.5 GeV)] and large momentum acceptance. Momentum acceptance is determined by the ring magnetic lattice and r.f. system. Simulation studies of increasingly sophisticated lattice designs at the Swiss Light Source and the Soleil project show that it should be possible to increase the momentum acceptance of the lattice to values as high as $\pm$4–8% compared with about half that or less for most existing rings. The r.f. acceptance can be increased by providing a total voltage in excess of that required to achieve long lifetime due to quantum fluctuations, which is already greater than the minimum required to make up the energy loss due to the emission of synchrotron radiation. The Swiss Light Source plans to use a high-Q superconducting passive r.f. cavity, tuned several bandwidths away from the main r.f. system for this purpose (*SLS Design Handbook*, 1996; Marchand & Rivkin, 1991). Short lifetime can also be compensated with frequent, or 'top-up', injection. The nearly constant stored current also keeps a constant heat load on beamline optical elements and compensates for lifetime reduction if small-gap short-period undulators, which extend the spectral range, are used. 'Top-up' injection is planned for the 7 GeV APS facility at Argonne National Laboratory (Decker, 1997), and is being considered at other laboratories.

4.1.3. *Other considerations*. Reducing the energy at which a given ring is operated can be used to reduce the emittance, taking advantage of the quadratic dependence of emittance on electron energy, as has been done at PEP (Bienenstock *et al.*, 1989) and TRISTAN (Yagi *et al.*, 1996). However, damping-time constants increase and instability-threshold currents decrease as energy is reduced, limiting the effectiveness of this approach. To some extent this can be compensated by making more radiation with damping wigglers (Wiedemann, 1988), which also serve as high-flux sources and result in reduced emittance because they produce more radiation damping than quantum excitation of betatron oscillations.

Improving undulator field quality by shimming (Quimby *et al.*, 1989; Chavanne & Elleaume, 1995) also extends their spectral range beyond the 5th harmonic, previously the highest that could be used in practice. It also opens the possibility of designing future rings with smaller circumference and lower electron energy than those of the 6–8 GeV third-generation hard X-ray sources and yet producing hard X-ray brightness approaching that achieved in 6–8 GeV rings. For example, high harmonics of undulators in a 3.5–4 GeV ring with a circumference of about 300–400 m and an emittance of $\sim$10 nm rad could produce a brightness of $\sim 10^{18}$ or greater at photon energies up to $\sim$15 keV. Brightness of high harmonics is determined by emittance, undulator errors and electron energy spread. A comprehensive code taking all these into account has been developed at APS (Dejus & Sanchez del Rio, 1996; Sanchez del Rio & Dejus, 1997). As emittance is reduced and undulators are made more perfect, the electron-beam energy spread ultimately determines high harmonic brightness.

Reducing the pulse duration of the light from a storage ring from the 20–100 ps range of present sources to $\sim$1 ps would open up new possibilities for timing experiments. This is one of the goals of the 1–1.5 GeV New Subaru ring now under construction at the Spring-8 site in Nishi-Harima, Japan. It is also one of the design objectives of the 1 GeV UVSOR II proposal at Okazaki, Japan. In both cases the lattice is designed with flexible control over the momentum-compaction factor. As this parameter approaches zero the bunch duration becomes very small and may reach the 1 ps range, albeit with moderate levels of electron-beam current, lifetime and emittance.

4.2. *FELs based on storage rings*

FELs produce extremely bright, transversely coherent radiation by inducing a bunch-density modulation of an electron beam at the optical wavelength. This is achieved by the interaction of a bright (close to diffraction-limited emittance) electron beam with an intense optical field in the spatially periodic magnetic field of an undulator. When electrons are bunched within an optical wavelength, the power radiated at that wavelength varies as the number of electrons squared, rather than linearly as for an unbunched beam. FELs have operated at wavelengths from the IR to the UV for many years, using storage rings such as ACO, TERAS, UVSOR, VEPP-3, Super ACO, among others. Several storage rings have been designed with long straight sections to accommodate long FEL undulators. These include NIJI-IV in Japan and the new rings at Duke and Dortmund Universities. Long straight sections are also included in several proposed rings, such as the Swiss Light Source, the Shanghai Synchrotron Radiation Facility, Soleil (France) and Diamond (UK).

Storage-ring-based FELs provide light with very high brightness and coherence and may already be considered to be fourth-generation sources in the wavelength range in which they now operate. Reviews of operating storage-ring-based FELs and the prospects for future development, particularly the prospects for extending their operation to shorter wavelength, have been given (Couprie, 1997; also M. Poole's summary in Hofmann, 1997). Present storage-ring FELs operate in the oscillator mode, using optical cavities to build up the radiation from many passes of the electron beam until the optical field is strong enough to induce a density modulation of the electron bunch at the optical wavelength, resulting in coherent, stimulated emission of radiation at that wavelength. The shortest wavelength that has been reached to date is 240 nm, using the VEPP-3 ring at Novosibirsk and the UVSOR ring at Okazaki. It is difficult to make optical cavities at wavelengths below ~200 nm due to the lack of good reflectors. To overcome this, grazing-incidence reflection, with higher reflectivity at shorter wavelength, might be used in a multiple-mirror ring-cavity configuration. Also, harmonics have been used to reach shorter wavelength. Using these approaches some groups are aiming for the 20–50 nm range.

An alternative approach is to eliminate the cavity and to achieve lasing in a *single pass* of a very bright electron beam through a long undulator, either by amplifying an input signal or with no input, in a process called self-amplified spontaneous emission (SASE) (Bonifacio *et al.*, 1985; Murphy & Pellegrini, 1985; Kim, 1986; Pellegrini, 1988). A design for such a single-pass high-gain FEL amplifier operating down to 40 nm in a bypass of a 750 MeV storage ring was proposed at LBNL (Kim *et al.*, 1985) and was considered for PEP (Nuhn *et al.*, 1992).

4.3. *FELs based on linacs*

FELs using low-energy linacs have operated for several years, providing coherent infra-red radiation at several user facilities. These use bunch trains and optical cavities in oscillator configurations, as do the storage-ring-based FELs. Recent developments open the possibility to construct much shorter wavelength FELs, using bright electron beams from higher energy linacs and long undulators in single-pass high-gain amplifier configurations to achieve lasing by the SASE process. With no optical cavity the lack of good short-wavelength reflectors is no longer a limitation on the wavelength. However, the demands on the electron beam and undulator quality are severe, particularly to reach ångström wavelengths. The single-pass characteristic of linac-based FEL sources, compared with the multi-pass nature of storage-ring sources, has two important consequences:

(i) Very high bunch density can be achieved since there is no need to have a long Touschek lifetime.

(ii) The dynamic and physical aperture in the undulator can be much smaller than in a storage ring, again because long lifetime is not a factor. Thus, undulator gaps of only a few millimeters can be used.

The developments opening the path to single-pass SASE-FELs operating at such short wavelengths are:

(*a*) Photocathode r.f. electron guns (Sheffield, 1992; Palmer *et al.*, 1995), which provide bright intense electron beams in short (5–10 ps) pulses with a charge of ~1 nC and with normalized emittance (geometric emittance times γ) approaching 1 mm mrad.

(*b*) Control over emittance degradation during acceleration and compression, as demonstrated in the SLAC SLC project. Based on this and subsequent studies (Raubenheimer, 1995) it appears possible to accelerate and compress the beam from the gun to produce multi-GeV kiloampere beams with emittance approaching the diffraction limit at wavelengths down to a few ångströms.

(*c*) Precision undulators as have been built at many synchrotron radiation sources. These must be extended to 50–100 m lengths, while including focusing and maintaining tight tolerances on magnetic properties and alignment. They can have fixed gaps since the photon energy can be readily tuned by varying the electron energy.

Designs are being developed for single-pass FELs operating from the VUV to ångström range, using photocathode r.f. guns and bunch-length compressors to achieve high peak current in sub-picosecond pulses with emittance close to the diffraction limit, as required for FEL operation. BNL proposes the use of an existing 230 MeV linac to reach ~75 nm in a deep UV FEL by harmonic generation and single-pass amplification (Ben-Zvi *et al.*, 1997). At DESY the TESLA Test Facility (TTF) superconducting linac now under construction will be used to drive a single-pass FEL (Rossbach, 1997) for SASE tests at ~25 nm with 300–400 MeV electrons. The linac will then be extended to ~1 GeV for an FEL user facility operating down to ~6 nm. The DESY group also proposes (Brinkman *et al.*, 1997) to include several SASE-based FELs, operating down to about 1 Å, as an integral part of a proposed 250 GeV-per-beam linear collider using electron energies up to about 30 GeV. Two approaches are being considered at DESY: a 1.3 GHz superconducting linac operating for the FEL at 5 Hz with 11 300 microbunches in each macropulse and a 3 GHz linac operating at 50 Hz with 125 microbunches per macropulse. The goal is an average brightness of 10^{24}–10^{26} and a peak brightness of 10^{33}–10^{34}.

The SLAC group (Cornacchia, 1997; Winick, 1995) proposes to use the last third of the 3 km linac (the first 2 km will be used for injection to the B-Factory now under construction) to generate a 5–15 GeV electron beam for a 1.5–15 Å SASE FEL with an average brightness up to $\sim 10^{23}$ and a peak brightness up to $\sim 10^{34}$. A design report for the project, called the Linac Coherent Light Source (LCLS), is in preparation. With an available 15 GeV linac, SLAC provides an early opportunity to study the SASE process at very short wavelengths, to gain experience with the X-ray optics for handling very high peak power levels, and to start using the remarkable brightness, coherence and short pulse duration of an X-ray FEL for experiments. Initially, a single S-band microbunch per macropulse will be used.

The calculated LCLS beam properties at 1.5 Å are: bandwidth = 0.1%, pulse duration (FWHM) = 280 fs, peak coherent power = 10 GW, coherent photons/pulse = 2×10^{12}, coherent photons/s = 2×10^{14} (120 Hz), average coherent power = 0.3 W, transverse beam size (FWHM) = 70 µm, divergence (FWHM) = 10^{-6} rad. In addition, use will be made of the broad spectrum of spontaneous undulator radiation with the same pulse duration, several times higher peak power and a larger opening angle. [Note that the first suggestion that the short-pulse low-emittance electron beams from high-energy linacs such as SLAC could produce high peak brightness at X-ray wavelengths by spontaneous radiation in a single pass through a long undulator was made by Fuoss (1988).]

The characteristics of a short-wavelength linac-based FEL as a light source are different from those of a storage ring in several important respects. For example, because of the pulsed nature of linacs and also because the SASE-FEL process starts from fluctuations in spontaneous emission, the output light is more chaotic than that produced by storage rings. For the LCLS it is estimated that this will result in pulse-to-pulse intensity fluctuations of several percent. Also, the way in which many users could be served is different for a linac-based source and a storage ring. In the latter the electron beam traverses all the insertion devices and bending magnets simultaneously, whereas in the former the pulse train would be switched among an array of undulators located at the end of the linac, thus diluting the average power available on each source. Also, tandem undulators, one of which might be optimized for spontaneous radiation, could share a single linac pulse. In this way it may be possible for a linac-based source to serve several tens of users, particularly if a high-duty-cycle superconducting linac is used.

Many laboratories (ANL, BNL, DESY, LANL, SLAC, TJNAF, UCLA) are pursuing single-pass FEL research and development. A particular focus of recent work has been on studies of the SASE process to extend work performed at millimeter wavelengths many years ago (Orzechowski *et al.*, 1985) to micrometer wavelengths (Bocek *et al.*, 1996; Sheffield *et al.*, 1997; Prazeres *et al.*, 1997; Hogan *et al.*, 1997; Ben-Zvi, 1997) and below. The object is to gain a detailed understanding of startup from spontaneous radiation, exponential gain, saturation and fluctuations in the output radiation so that comparison can be made with theory and simulation codes. Although still in an early state, these recent experimental results have so far been very encouraging. Continued progress in this work should lead to confidence in extrapolation to the ångström wavelength range. Research and development work is also underway on the effects of space charge and coherent synchrotron radiation in bunch-length compressors, undulator design and alignment, photocathode r.f. gun design and characterization, electron and photon diagnostics, and X-ray optics capable of handling the very high peak power loads.

The projected characteristics of linac-based short-wavelength FELs, particularly their short pulse duration, peak brightness and coherence, are extraordinary. Fig. 2 shows the peak and average source brightness as a function of photon energy for SASE-FELs in comparison with storage-ring sources. The peak brightness of the X-ray FELs proposed at SLAC and DESY is $\sim 10^{10}$ times higher than that of third-generation storage-ring sources, with $\sim$100 times shorter pulses. These properties are likely to open entirely new opportunities in imaging, non-linear physics and pump-probe experiments (Spicer *et al.*, 1992; Arthur *et al.*, 1994). There is increasing confidence in the accelerator community that linac-based short-wavelength FELs can be built. There is also increasing realization that their properties will open new science in the 21st century.

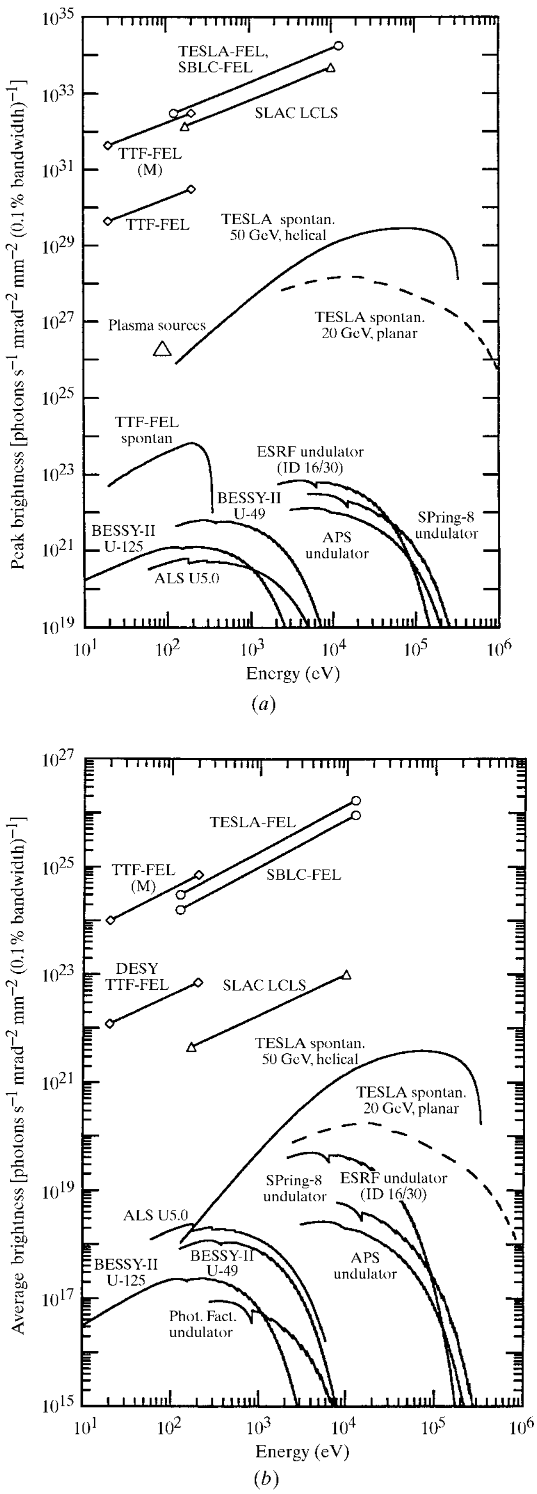

Figure 2
(*a*) Peak and (*b*) average source brightness as a function of photon energy for short-wavelength FELs in comparison with synchrotron radiation sources and conventional X-ray generators.

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