SLAC-PUB-10007
July 2003

INTRODUCTION TO SPECIAL SECTION ON FUTURE LIGHT SOURCES

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This special section of NIM is devoted to an overview of progress in the development of powerful new sources of X-radiation for use in advanced studies in the physical, chemical, and biological sciences. Included here are four articles on future light sources that were originally published in 2002 in the SLAC Beam Line quarterly magazine[1]. We are grateful to SLAC and the authors of these articles for their agreement to reprint[2] them in volume 500 of NIM. As is common for the Beam Line, these articles contain no references to reports in the literature and do not attempt to be comprehensive overviews of the field. Therefore, we offer this expanded overview and introduction in which we attempt to briefly cover recent developments and topics not covered in the four articles.

Synchrotron light sources[3] as user facilities have had a rapid and spectacular evolution from their humble beginnings about 30 years ago with parasitic operations exploiting the radiation from bending magnets of colliding-beam storage rings - the first generation. (Even earlier occasional work with synchrotron radiation was done in the 1950's and 1960's on cyclic electron synchrotrons whose primary program was high energy and nuclear physics. These might be called the "zeroth" generation.) In the early 1970's Renate Chasman and G. Kenneth Green first accounted for the intrinsic connection between electron beam emittance and brightness of the synchrotron radiation through their invention of the "double focusing achromat"[4] to minimize emittance. This optical design now called the "Chasman-Green lattice" was major advance in storage ring design. In the 1980's dedicated synchrotron radiation research facilities - the second generation - were constructed in China, France, Germany, Japan, the UK, and the US. The 1990's saw the construction of additional light sources in these and even more countries (e.g., Brazil, India, Italy, Korea, Russia, Switzerland, Taiwan and Thailand). Several of these facilities were more advanced rings[5] optimized both to maximize the brightness of the electron beams and to provide many straight sections between bending magnets for insertion devices (periodic magnetic structures called wigglers and undulators) to make even brighter X-rays - the third generation.

This technological evolution has been driven by and has facilitated a veritable scientific revolution brought about by the use of synchrotron radiation in several fields of basic and applied research conducted by a growing user community, now numbering about 20,000 scientists around the world. The reason for this transformation is the capability of synchrotron radiation, over a broad spectral range extending from the infrared to ultraviolet and X-rays, as an experimental tool. It provides information, often unavailable by any other means, relevant to the structure of matter (i.e., the arrangements of atoms in complex materials) and the electronic and magnetic properties of matter.

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The impact has been strong in fields such as:

- Structural molecular biology, including the determination of the structure of viruses and proteins and facilitating drug design,.
- Molecular environmental science via determining the chemical form of contaminants in soil and water - knowledge that is critical to developing strategies for separation, remediation, and storage of contaminants,
- Materials science via understanding the structural and electronic properties of a wide range of materials including catalysts, polymers and semiconductor materials.
- Medical diagnostics and therapy through utilizing X-ray beams of well-defined energy and direction to minimize risk and damage to healthy tissue.

Compared to conventional X-ray tubes, synchrotron radiation sources offer extremely high brightness, tunable, pulsed, polarized radiation. The most advanced sources now operating provide thirteen orders of magnitude higher brightness (photons/mm^2/mrad^2/0.1%BW) than the best rotating anode X-ray tubes. Around the world about 50 storage ring sources are now in operation, about 10 more are in construction, and about 15 more are in various stages of design awaiting construction approval. The most powerful facilities are the 6-8 GeV, hard X-ray (5-50 keV) rings in Europe, Japan, and the US with circumferences of 850 m to 1450 m. The most developed of these facilities conduct 30-60 simultaneous experiments and serve 2000 or more users annually. Equally significant is the spread[6] of these potent tools for scientific discovery into the developing nations.

Every year the user community continues to grow leading to the construction of new rings and the development of ideas for future sources with even higher performance in one or more important beam characteristics. The articles in this section of NIM describe some of the most important directions for these future sources. The first two articles describe storage rings.

INTERMEDIATE ENERGY LIGHT SOURCES

The high performance and relatively moderate cost of these 2.5-4 GeV machines make them the popular choice, with six now in construction and more proposed. This popularity is largely due to the high performance of these machines, due to recent technological developments as described in the article by Jeff Corbett and Tom Rabedeau. These advances include

- shimming of undulator magnets to near perfection to increase high harmonic content,
- higher harmonic rf-cavities to extend beam lifetime,
- bunch-by-bunch feedback systems[7] to control instabilities at high beam current[8] ,
- beam orbit control[9,,10]at the ~ 1 μm level to meet user expectations for X-ray beam stability and reproducibility,
- in-vacuum, small gap, short period undulators[11,,12] to generate copious hard X-rays at relatively low electron beam energy
- superconducting bend magnets[13] to shift the x-ray spectrum to higher energy,
- continual full energy top-off to extend the effective beam lifetime and eliminate thermal cycling of storage ring and X-ray beamline components.

These developments allow relatively low energy rings to deliver hard X-ray (5-50 keV) performance that is closer to that of the larger rings than was previously thought possible. When operational, these new rings, including a replacement of the venerable SPEAR ring[14], will go a long way in meeting the continued rapid growth in user demand around the world.

THE ULTIMATE HARD X-RAY STORAGE RING-BASED LIGHT SOURCE

In the future 6-8 GeV rings with circumference of about 2 km or more could provide X-ray brightness that significantly exceeds that of any present facility, opening new research opportunities. Plans are being made to use the PETRA[15] electron ring at DESY for this purpose and perhaps such a light source will eventually be built in the existing large tunnels now being used for B-Factories at SLAC and KEK. The challenges to be faced in realizing such an ultimate machine are described in the article by Pascal Elleaume.

LIMITS TO STORAGE RING SOURCES

The intrinsic properties of the synchrotron radiation process limit the ultimate performance of storage ring light sources, especially with respect to the brightness of the X-ray beams and the duration of the X-ray pulses. The brightness is determined by the current in the electron beam and the emittance (the product of beam size and divergence) of the electron beam. In storage rings, the quantum nature of the emission of radiation from the bending magnets reacts on the electron beam to produce energy spread and growth in beam size and emittance. Electron beam emittance in a ring increases quadratically with electron energy and with the third power of the angle of bend in each bending magnet. To minimize these effects the highest performance rings use short bending magnets with low magnetic field (to reduce radiation emission by bending the beam gently in an arc with a large radius of curvature) separated by many quadrupoles to refocus the beam after its dispersion in the bending magnets. This approach leads to geometries with many magnetic elements and large circumference as described by Pascal Elleaume.

Raising the current in the storage ring to obtain even brighter beams is limited both by beam-driven, collective instabilities in the accelerator and by operating costs (the total radiated power from the bending magnets, much of which is not used for experiments, is proportional to average beam current). This latter consideration parallels that in which colliding-beam, electron-positron storage rings will be supplanted by linear colliders at high energy. At some point a more practical means of achieving ever higher time averaged brightness or flux (photons/s/mm^2) is to recirculate the energy carried by the electron beam rather than the beam itself or to increase the conversion efficiency of the radiation process using free electron laser amplifiers.

The duration of the synchrotron radiation pulse is proportional to the duration of the electron bunches in the ring. In storage rings the quantum nature of the radiation process spreads the energy of the bunch making transport of high bunches with duration < 10 ps extremely difficult and unreliable . Even if this difficulty could be overcome, lower limits on pulse duration set in when radiation with a wavelength roughly equal to the bunch length from the back of electron pulse can pass within the vacuum chamber , overtake and interact strongly with the front of the pulse as the beam traverses a bend. This phenomenon, coherent synchrotron radiation (CSR) [16,17,18,19 ,20] becomes especially severe as the duration of electron bunch becomes less than 1 ps. CSR can rapidly drain energy from the electron beam, spread the energy of the particles in the beam and increase beam emittance. In this way CSR limits the performance of any electron beam based source with bend magnets especially as the beam energy exceeds 1 GeV.

Just as the first generation of light sources transformed the "troublesome" by-product incoherent synchrotron radiation into a potent scientific tool, accelerator physicists are now looking to "tame"[21] coherent synchrotron radiation in storage rings and transform it into IR-sources of unprecedented performance. Recent successes in controlling coherent emission at BESSY has led the Advanced Light Source at LBNL to propose a small, low energy storage ring[22] dedicated to producing infra-red radiation via CSR.

LINAC-BASED MACHINES

These fundamental limits on electron beam brightness and pulse length in storage rings can be overcome in linac-based light sources. The ultimate in large bending radius is a linac. With no bending magnets the beam properties are primarily determined by the electron source as long as effects[23,24,25] due to misalignments and wakefields are minimized. Rather than increasing with electron energy, emittance in a linac decreases linearly with electron energy. This "adiabatic damping" of emittance is due to the fact that the transverse momentum of the electron beam is essentially constant and equal to that at the source, whereas the longitudinal momentum increases linearly with energy. Thus the angular divergence of the electron beam, and hence the emittance, decreases linearly with electron energy.

However, the precision and reliability with which bright linac beams must be generated, accelerated and then used in long undulators poses severe challenges. Several relatively recent developments have essentially answered these challenges, opening a path to the use of high-energy linacs to provide higher peak performance than any storage ring. One of these developments is the high brightness electron source[26,27], particularly the laser-driven rf gun[28] initially developed at Los Alamos National Laboratory. Another is the improved capability to accelerate, compress, and transport such bright electron beams, as demonstrated[29] in the SLAC Linear Collider (SLC) beams. A third is the precision undulator, as developed in many light source facilities. A fourth is the availability of high quality computational modeling tools to understand beam transport through the accelerator and energy extraction[30, 31] via the free electron laser process In combination these developments have opened two main directions for future linac-based light sources as described in the article on the energy recovery linac by Sol Gruner and Don Bilderback and the article on the X-ray free-electron laser by Claudio Pellegrini and Joachim Stöhr.

ENERGY RECOVERY LINACS AS SYNCHROTRON LIGHT SOURCES

To bring operating costs of a high average power linac to a reasonable level the beam energy is recovered from the electrons after they are used - an approach[32] first proposed 38 years ago and now attracting much interest for radiation sources. The principle has been tested successfully at low energy at the Jefferson Lab where a recirculating linac is used to drive an infrared free-electron laser[33] oscillator. Sol Gruner and Don Bilderback describe the challenges and opportunities provided by a higher energy ERL, delivering X-rays with higher brightness and shorter pulses than any storage ring. In the ERL the electron beam brightness (and therefore the X-ray brightness) can be substantially higher than in a storage ring. In the US two significant proposed projects[34] seek to exploit this feature of the ERL in average current machines. In Brookhaven's PERL[35] and Cornell's ERL[36], an extremely bright, high average current electron beam is produced in a rf-photoinjector. The high current beam is accelerated to a high energy in a full energy, superconducting linear accelerator. This beam is taken through insertion devices to produce spontaneous (i.e., incoherent) synchrotron radiation and then returned to the linac where it is decelerated and its energy recovered, allowing very high efficiency operation. An added benefit of the ERL is that the electron beam is decelerated to a low enough energy (~ 10 MeV) such that essentially residual radiation is created in the beam dump.

The use of superconducting linacs offers many design options for the ERL. One way to lower cost of the ERL is to use multi-pass recirculation through the linac to reach the full beam energy. This geometry has the potential advantage of feeding amplified radiation from early bends (but after the beam is ~ 1 GeV) across the recirculation arcs to trigger the femtosecond lasers used in pump-probe experiments in synchronism with the X-ray pulses . The penalties for this choice are limiting the X-ray pulse repetition frequency and possibly electron beam emittance if one wishes also to use the ERL beam to a free electron laser at wavelengths <1nm. The lower limits to X-ray pulse duration in ERLs due to coherent synchrotron radiation may be circumvented if one can compress the X-ray pulses themselves. One such technique[37] has been suggested (originally for use in storage rings) using rf-orbit deflection to correlate the angle of X-ray emission with the time of emission. Subsequent compression of the radiation in an asymmetrically cut crystals may extend the pulse duration accessible with ERLs down to~50 fs. LBL is designing a light-source, LUX,[38] based on this technique.

X-RAY FREE-ELECTRON LASERS

For scientific studies requiring more than $\sim 10^8$ X-ray photons in sub-picosecond pulses it is not sufficient to rely on spontaneous incoherent emission of synchrotron radiation (from an electron bunch with charge ~ 1 nC) due to limitations on the radiation process imposed by quantum electrodynamics. Some amplification is required; the dream of a spatially coherent X-ray source seems now to be in reach using the free electron laser mechanism[39] operating in the Self Amplification of Spontaneous Emission (SASE) mode. With bright 15 GeV electron beams and 100 meter long undulators it appears possible to produce sub-picosecond X-ray pulses at 8 - 12 keV with 9 orders of magnitude higher peak brightness than the best present third generation storage rings. The Linac Coherent Light Source project[40] (LCLS) at SLAC is on a path to operate such a machine in 2008 initially as an exploratory facility. A similar project[41], with a fully developed set of user beamlines, was proposed at DESY to construct an X-ray laser in association with the proposed TESLA superconducting linear collider project. The TELSA FEL is now a stand-alone project. Claudio Pellegrini and Joachim Stöhr describe these projects, the challenges to be met, the extraordinary properties of the radiation, and the new science that is envisioned.

For producing EUV, XUV and soft X-ray radiation (20 eV to 1 keV), beams of much lower energies (1- 3 GeV) can drive a SASE free electron laser based on undulators 15 – 40 m long. Two projects in this wavelength range are presently well along in construction, the SPring-8 Compact SASE Source (SCSS) [42] in Japan and the TESLA Test Facility Upgrade[43] in Germany. Both employ full energy linacs based on high gradient accelerator technologies developed for linear colliders, C-band room temperature linacs in Japan and superconducting rf-linacs at DESY. The TTF upgrade will be a soft X-ray user facility testing SASE operation at ~200 eV; it will be a very important step on the way to realizing hard X-ray FELs. An unusual feature of the SCSS project is the use of a thermionic CeB6 cathode of proven reliability instead of a photocathode gun.

The Fourth Generation Light Source (4GLS)[44] project at Daresbury proposes the use of a superconducting linac to combine a low energy ERL with a suite of instruments providing radiation from the soft x-ray to the far infrared by using undulator sources, two cavity FELs and one SASE FEL. The SPARX[45] project in Rome proposes to deliver XUV and soft X-ray radiation from a full energy room temperature linac. A more modest proposal[46] at MAX-lab is to use the new injector system to drive an IR-FEL and a cavity FEL in the VUV spectral region.

A more ambitious project in the pre-approval stage is the BESSY FEL facility[47] based on a full energy 2.2 GeV superconducting linac. Noteworthy in the BESSY approach is the exploration of a variety of schemes to produce 1 keV pulses of duration <100 fs using femtosecond “optical slicing”[48] and multiple stages of high-gain, harmonic generation (HGHG)[49,50,51]. In HGHG free electron lasers the electron beam is bunched in an FEL tuned to a relatively long wavelength after which passes through a dispersive section and then a radiator tuned to a higher harmonic (2nd to 5th). HGHG has strong potential for use in XUV sources[52] where the FEL can be operated in a Master Oscillator Power Amplifier (MOPA) configuration[53] or in the SASE mode. The limits of using HGHG at wavelengths shorter than 10 nm in SASE systems are controversial[54] and are under serious study by several groups.

Since SASE FELs amplify the inherently noisy spontaneous radiation[55,56] from the electron beam, such sources may have limited utility for experiments that require a high degree of pulse-to-pulse reproducibility or a high degree of temporal coherence. In that case the master oscillator-driven, HGHG FEL offers an attractive alternative source of soft X-rays because the temporal coherence is determined by the properties of the master oscillator. Sincrotrone Trieste has adopted this approach implemented with its existing full energy, room temperature linac in its proposed FERMI project.[57] A more complex variant[58] allowing more stages of HGHG and aimed at much shorter (50 – 100 fs) X-ray pulses is found in Berkeley’s LUX design that includes two sets of MOPA HGHG chains along with the undulator beamlines driven by a superconducting recirculating linac.

SOURCES BASED ON PLASMA ACCELERATORS

For studying physical process at time scales <10 fs and at energies >> 10 keV, even conventional linac-based sources face formidable difficulties. One challenge is generating such short electron bunches.. Another problem is overcoming the ever stronger, emittance dilution effects of wakefields as electron bunches become extremely short due to subtle effects such as surface roughness of accelerator components[59],[60] A promising class[61] of alternatives is the use of all-optical, plasma-based accelerators. One way to convert the electron beam to a short burst of very hard X-rays is via Thompson scattering[62]. Such a "tabletop" source could be used directly for experiments.

The X-rays from optimized Thompson sources might be sufficient to serve as the master oscillator in a MOPA configuration of an LCLS or TELSA FEL beamline. In that case, the master oscillator would "slice" a portion of a longer electron pulse that would be amplified to generate X-ray pulses <10 fs. An even more radical approach would exploit the potential to use the pondermotive forces[63] from tightly focused sub-petawatt lasers to generate sub-femtosecond pulses of electrons with an emittance 100 to 1000 times smaller than photocathode sources. Once accelerated to a few hundred MeV via plasma wakefields, the beam could drive an "all optical SASE FEL"[64] with a wiggler consisting of electromagnetic radiation. A noteworthy feature of this possibility is that the number of electron in the beam is $\sim 10^6$; therefore the behavior of each electron in such a system can be completely simulated from plasma source to beam dump.

EARLY OPPORTUNITIES FOR SUB-PICOSECOND X-RAY SCIENCE

Much of the new science possible with the next generation light sources exploits the sub-picosecond pulses of the X-ray FEL and ERL. Interest in this new time domain for X-ray studies has stimulated other approaches to achieving short pulses, although with lower intensity that ERLs or FELs. The technique[65] of "optical slicing" for extracting radiation from a sub-100 femtosecond slice of a stored electron beam is being pursued on a user beamline at the Advanced Light Source at Lawrence Berkeley National Laboratory and elsewhere. . The Sub-Picosecond Photon Source (SPPS) project[66], now in construction at SLAC, will produce a similarly short pulse of X-rays by compressing the electron beam in the SLAC linac and using spontaneous radiation from an undulator at the end of the linac. These sources will enable researchers to begin to get experience with X-ray pulses at the 100-femtosecond level well before an X-ray ERL or FEL is available.

PERSPECTIVES

In the past it has been common to characterize the performance of synchrotron radiation sources by graphs presenting the time-averaged flux (photons/s/mrad/0.1%BW) and brightness (photons/mm^2/mrad^2/0.1%BW) available for experiments as a function of X-ray energy. More recently other metrics have been proposed such as flux density on a small sample. Another metric is useful flux within the phase space acceptance of a small sample such as a 50-100 micron protein crystal with a mosaicity of several milliradians (see the article on Intermediate Energy Light Sources for more on this). With the increasing scientific interest in short pulses, the peak (or instantaneous) values of these metrics during the pulse also become important. Some experiments require as many as 10^{12} X-ray photons in a single ultra-fast pulse; others cannot tolerate pulse intensities exceeding 10^8 photons and prefer smaller pulses space by the relaxation time of the process under investigation. Some experiments demand lasers synchronized[67] to within ~20 fs of the X-ray pulse; some require a high degree (~1 %) of pulse-to-pulse reproducibility and stability; some require no synchronization signal. Some experiment need tunable polarization of the radiation; others require multiple color X-rays on the sample.

In Fig. 1[68] and Table 1. we compare the performance of several types of X-ray sources from the point of view of peak brightness and pulse duration. We believe that these performance metrics will increasingly be used, to complement the flux and brightness spectral curves that are already in general use, to assess source performance for experiments that depend on the peak or instantaneous values.

The prospects for the blossoming of a new field of ultra-fast X-ray science in physics, chemistry and biology are indeed exciting. Nonetheless, such research is likely to remain a small minority of the experiments that rely on synchrotron radiation sources. Storage rings are and are likely to remain the workhorses of synchrotron radiation science for many years to come. By providing X-ray beams with high flux and brightness and outstanding stability, reproducibility and reliability, they will continue to serve the needs of a vast scientific community even as linac-based sources open up new scientific frontiers with their sub-picosecond pulse duration and extremely high peak brightness and coherence.

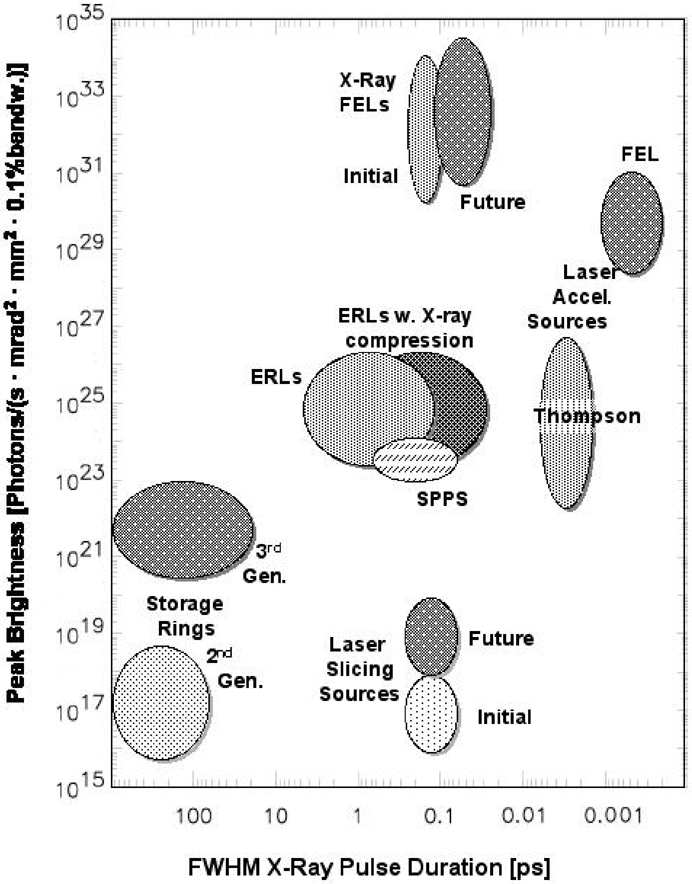

Figure 1. Brightness and pulse duration ranges of next generation light sources. The time average brightness is the peak brightness times the duty factor.

Table 1. Additional characteristics of X-ray sources

	Maximum Duty Factor	Laser synchronization	Pulse repetition rate
Storage rings	$\sim 10^{-3}$	No	10 – 100 MHz
Slicing Sources	$\sim 10^{-9}$	Limited	1 – 10 kHz
ERLs	$\sim 10^{-3}$	No	10 – 100 MHz
ERLs w. XRC	$\sim 10^{-8}$	Yes	10 kHz
SPPS	$\sim 10^{-11}$	No	100 Hz
X-ray FELs	$\sim 10^{-10}$	Some	100 – 1000 Hz
Laser Accel. Sources	$\sim 10^{-12}$	Yes	1 – 10 kHz

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