ANL/OTD-APS/CP-98889

Toward a Fourth-Generation Light Source

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Historically, x-ray research has been propelled by the existence of urgent and compelling scientific questions and the push of powerful and exquisite source technology. These two factors have gone hand in hand since Röntgen discovered x-rays. Here we review the progress being made with existing third-generation synchrotron-radiation light sources and the prospects for a fourth-generation light source with dramatically improved laser-like beam characteristics.

The central technology for high-brilliance x-ray beams is the x-ray undulator, a series of alternating-pole magnets situated above and below the particle beam. When the particle beam is oscillated by the alternating magnetic fields, a set of interacting and interfering wave fronts is produced, which leads to an x-ray beam with extraordinary properties. Third-generation sources of light in the hard x-ray range have been constructed at three principal facilities: the European Synchrotron Radiation Facility (ESRF) in France; the Super Photon Ring 8-GeV (or Spring-8) in Japan; and the Advanced Photon Source (APS) in the United States. Undulator technology is also used on a number of low-energy machines for radiation in the ultraviolet and soft x-ray regimes.

At the APS, these devices exceed all of our original expectations for beam brilliance, tunability, spectral range, and operational flexibility. Shown in Fig. 1 are the tuning curves of the first few harmonics, showing x-ray production from a few kV to better than 40 keV. High-brilliance radiation extends to over 100 keV.

The new science coming from the APS depends on its unique beam characteristics. A very high degree of collimation makes it possible to monochromate 20-keV x-ray beams to ~1 meV. These beams can be used for triple-axis inelastic scattering studies of lattice dynamics that had previously been the sole province of neutron scattering. But the most important aspect of x-ray inelastic scattering will be in charge excitations rather than in lattice dynamical excitations. Beautiful work in that respect is ongoing at the ESRF and beginning at the APS.

Although the x-ray beams from undulators are not substantially coherent, their extreme brilliance allows one to extract a small coherent fraction, which contains a significant

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number of photons. Recently, x-ray photon correlation spectroscopy methods have been developed to exploit this coherence for measuring the dynamics of fluid systems.

The unique characteristics of undulator radiation have recently been applied to macromolecular crystallography. The results have been spectacular. It is now possible, with a good crystal, to get a data set for a structure determination in well under one hour. In some cases, 15 or 20 minutes is adequate to collect all of the data necessary for structure determination. The x-ray step in a structure determination is no longer the rate-limiting step. The current ability to do structures at synchrotron x-ray sources would seem to be an ideal solution to determining the better than 100,000 structures whose codes are contained in the human genome. Such a "structural genomics" enterprise has generated considerable excitement.

But structural biologists will be able to go beyond static structures. X-ray beams from the APS undulators are so intense, one can acquire a high-quality diffraction pattern in a single pulse. These pulses are on the order of 100 ps long and each of them contains enough photons to get a reasonable diffraction pattern from a good biological crystal. That opens the possibility of studying the time evolution of a molecular structure, for example by using a laser to initiate a chemical reaction.

Very simple developments in instrumentation can have a profound scientific impact. Because the beam from APS undulators exhibits a high degree of brilliance and collimation, Fresnel zone plate lenses work extremely well to provide very-high-quality focal characteristics. With our most successful Fresnel lenses, we are able to achieve focal spots down to 100 nm and to preserve very high optical efficiency in the 10% to 30% range. That small focal spot can be used for studying how the properties of materials vary on the submicron length scale. In another application, we propose to mount a number of Fresnel lenses on a chip. We would use these lenses to simultaneously probe a number of micro-samples deposited on a second chip that have gradients in their chemical composition or in their preparation parameters, and thus obtain data in a highly parallel fashion.

The sample chips could be used for x-ray diffraction experiments or x-ray microscopy experiments. Those same samples could be put into other instruments which would measure their physical properties, such as specific heat or conductivity. Thus, one can develop methodologies for accumulating very large databases, which will be very useful for studying complex materials problems, such as high-T_C superconductors.

Concurrent with developing new applications for third-generation light sources, the community is thinking about the fourth generation of light sources (Fig. 2) based on x-ray free-electron lasers (FELs). The most compelling parameter associated with this technology will be peak brilliance. It now appears possible to obtain a beam with a peak brilliance ten orders of magnitude higher than we have in APS today. That beam will also have a time-average brilliance higher by 6 orders of magnitude and a time-average flux higher by 2 orders of magnitude. Any new facility must serve a broad clientele, so R&D is underway to develop superconducting linacs, which should be capable of serving multiple (~100) beamlines simultaneously. It also appears possible to design a source that could serve the entire spectral range, from the infrared to the hard x-ray regime, in order to eliminate the need for different energy machines for different regions of the electromagnetic spectrum.

The technology for this next-generation light source is based on undulators just like those at the APS, but with significant interaction between the high-density particle beam generated in the linac and the electromagnetic fiel it generates. It is this interaction which produces the lasing action. There are different ways to achieve that lasing action in an FEL. But in the x-ray range, we will rely on self-amplified spontaneous emission. If the electron density is high enough, then the field that it produces causes an interaction which creates a lasing action. The undulator has to be long in order for that interaction to build up. At the APS, our undulators are typically a few meters long and produce beams which, 20 m away from the source, are on the order of ~1 mm in size. The new facility will have undulators that are ~100 m long and its beam will be on the order of 1/10 mm in size at 100 m.

Of the many scientific opportunities associated with this new facility, a few are extremely compelling. One is the large quantitative improvement in coherence. We expect significant advances in imaging structures using x-ray holographic methods, which could revolutionize structural chemistry and biology. And since this fully coherent beam will be only 100 fs long rather than the 100 ps at the APS, there will be opportunity for significant improvement in time-resolved measurements in what is clearly a very important time regime. But the advance that can potentially change the paradigm for x-ray research in the next century will be a 10^{10}-10^{12} increase in photon degeneracy. It will enable the multi-photon methods that are not possible with third-generation sources, permit the study of x-ray nonlinear processes in matter, and perhaps open some new regimes of fundamental high-field physics, a very recent idea.

To have this major fourth-generation user facility ready by the year 2010, an aggressive research-and-development program must begin now. Fourth-generation light-source technology development represents a bigger step than did third-generation light source technology. But existing linear accelerators, including those at Argonne National Laboratory, Brookhaven National Laboratory, and the Stanford Synchrotron Radiation Laboratory offer a cost-effective way to reduce technical risk and begin to explore the extraordinary scientific possibilities that lie ahead.

Fig. 1. Tuning curves for the on-axis brilliance, first three odd harmonics of APS undulators.

Brilliance of APS undulator A
(2.5% coupling)

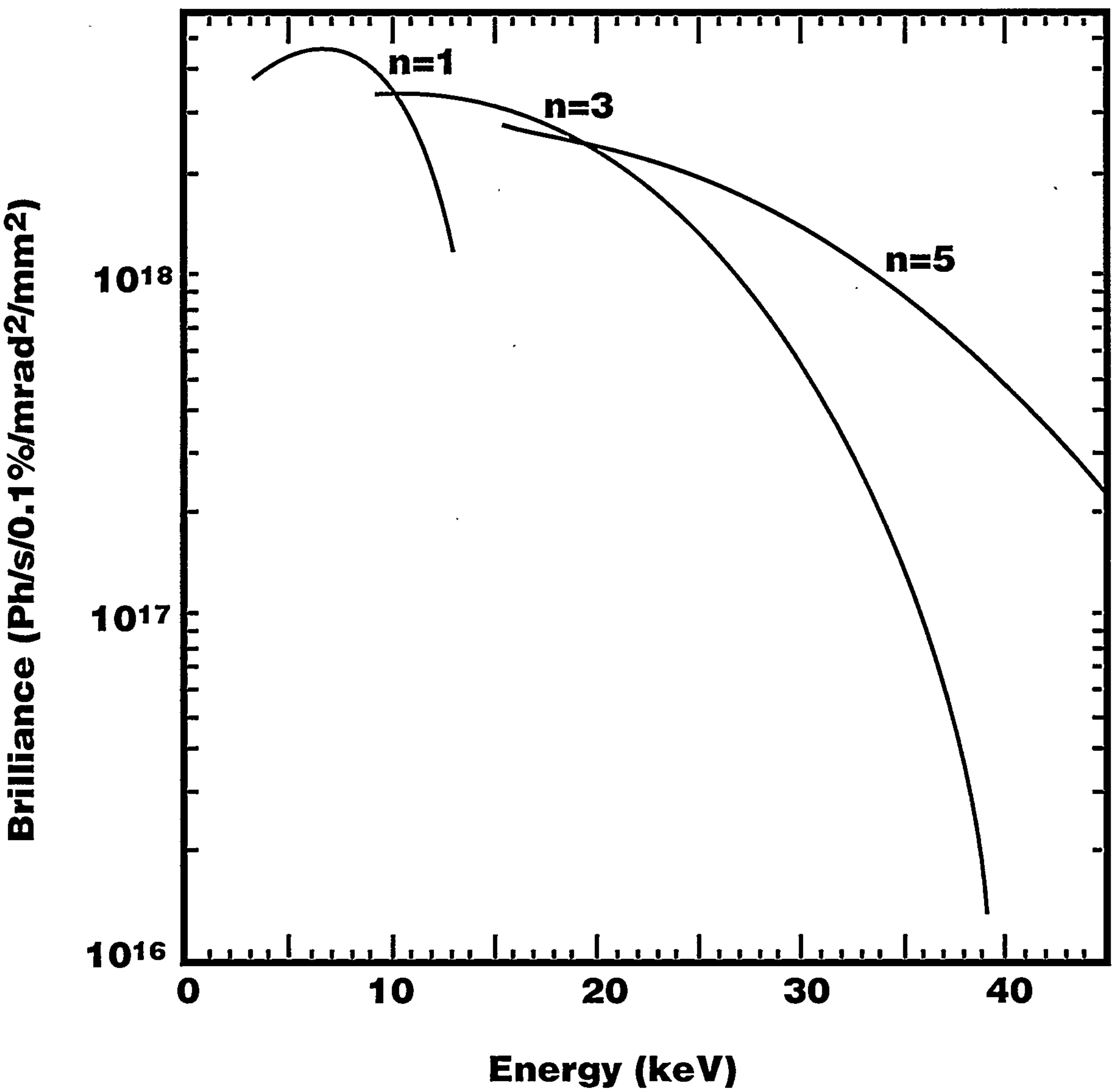
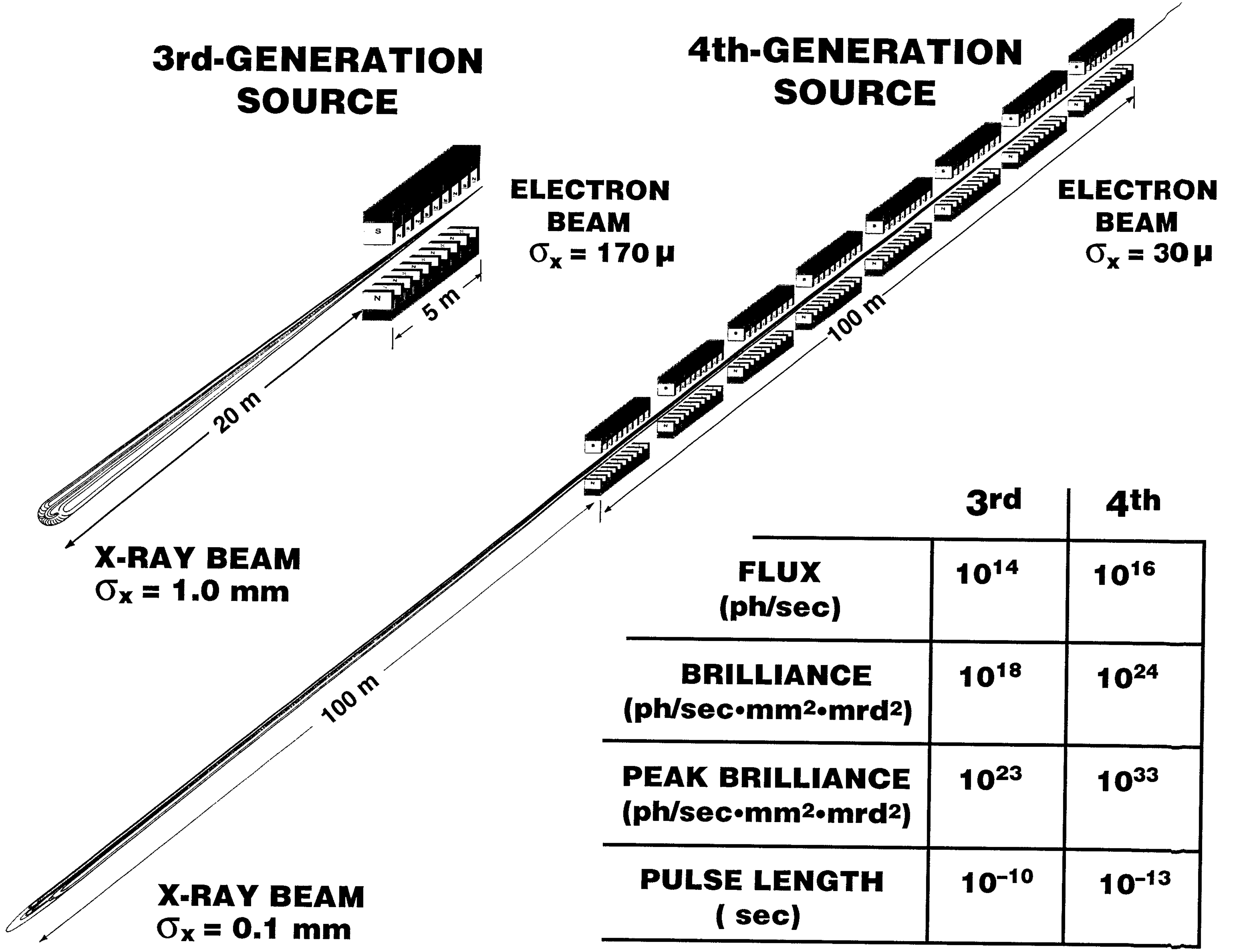


Fig. 2. Comparison of technical parameters for third- and fourth-generation x-ray sources.



	3rd	4th
FLUX (ph/sec)	10^{14}	10^{16}
BRILLIANCE (ph/sec•mm²•mrd²)	10^{18}	10^{24}
PEAK BRILLIANCE (ph/sec•mm²•mrd²)	10^{23}	10^{33}
PULSE LENGTH (sec)	10^{-10}	10^{-13}