The Ultimate Hard X-Ray Storage-Ring-Based Light Source

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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.

OVER THE PAST thirty years, the storage-ring-based synchrotron light source has proven to be an outstanding success, both as a scientific tool and a major accomplishment of accelerator technology. In the 1960s storage rings were designed as electron-positron colliders for particle physics research. The scientific potential of synchrotron radiation was very quickly recognized, and in the 1970s parasitic programs started in many laboratories. With the growing demand for such radiation coming from many fields of science, new higher performance storage rings were designed and optimized exclusively for the production of such radiation. Today, more than 60 dedicated synchrotron radiation facilities are in operation throughout the world.*

Their increasing performance has resulted in a number of totally new applications in scientific disciplines such as physics, chemistry, biology, and medicine and also in industrial areas such as microelectronics, pharmaceutics, metallurgy, and plastic materials. This success is due largely to the properties of the radiation: the flexible polarization and the high intensity and concentration in a narrow forward cone similar to, or even narrower than, laser beams. In the VUV and X-ray range of the electromagnetic spectrum these sources can produce photon fluxes on the small samples

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** A database of web addresses of synchrotron radiation facilities is kept at the following web address: http://srs.dl.ac.uk/SRWORLD/index.html or http://www-ssrl.slac.stanford.edu/sr_sources.html.*

under study which are 10^6 to 10^{10} higher than those available from low cost tubes, such as those extensively used for medical radiography. Also important is the fact that this high radiation flux is available over a broad spectral range, enabling an experimenter to select the precise wavelength of interest or to scan over a range of wavelengths. This tunability is indeed critical to many experiments. Other properties of synchrotron radiation include the ability to conduct many simultaneous experiments, the high stability of the X-ray beams, and the extreme reliability of the sources.

With the immense growth in the user community and the number of applications that have been made possible by the increasing performance of synchrotron light sources, one can ask whether even higher performance is possible in future storage rings. This article presents a description, and the associated engineering and physics challenges, of what could be an ultimate storage ring source optimized to produce hard X-ray radiation. It is based on a study made at the European Synchrotron Radiation Facility (ESRF).*

TO ADDRESS THE DESIGN issue of such a source, one must first review how the radiation is produced. In the past the most important sources of radiation were the bending magnets of the storage ring. The choice of the electron energy was related to the critical energy of the radiation,

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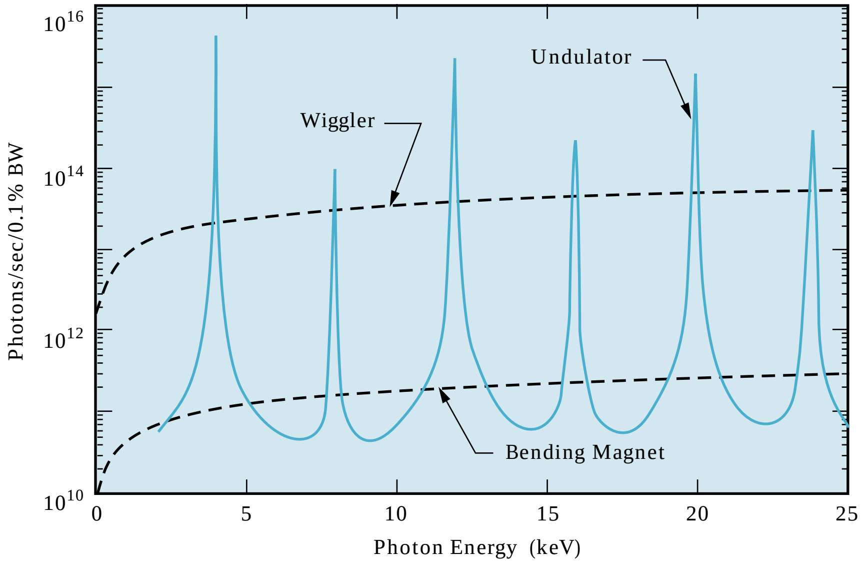
* A. Ropert, J.M. Filhol, P. Elleaume, L. Farvacque, L. Hardy, J. Jacob, U. Weinrich, *"Towards the Ultimate Storage Ring Based Light Source,"* EPAC 2000. Available at http://accelconf.web.cern.ch/accelconf/e00/PAPERS/TUZF101.pdf

which is related to the electron energy E and the magnetic field B of the magnet according to

$$\varepsilon_c[\text{keV}] = 0.665\, B[T]E^2[\text{GeV}].$$

The intense and therefore useful flux extends from the infrared up to about four times this critical energy and then falls off rapidly. Assuming that a 1.5 T magnetic field is used (close to economical optimum for a conventional magnet), an electron energy of 1 GeV (7 GeV) is necessary to reach a critical energy of 1 keV (50 keV).

Until the mid 1980s this was the basis of the selection of the electron energy in relation to the energy spectrum to be covered. In the early 1980s, it was recognized that one could accumulate the radiation from a number of such bending magnets with alternating field polarity which result in an approximately sinusoidal trajectory of the electron beam. The flux from those devices, called wigglers, which could be located in the straight sections between the bending magnets, is proportional to the number of bends. As the number of periods of oscillation is increased, there is an increasing interference in the radiation produced by an electron in each period with the radiation emitted at the other periods. This interference results in the enhancement of the



Comparison of spectra produced by an undulator, a wiggler, and a bending magnet type of source installed on the UHXS. The collection aperture is located at a distance of 50 m from the source. The flux is collected over an aperture of 0.5×0.5 mm^2. The bending magnet and wiggler type sources present continuous spectra while the undulator presents a series of intense peaks. The peaks are harmonically related starting from the fundamental around 4 keV. The photon energy of each peak can be tuned by changing the undulator field. The collection of high flux through such a narrow aperture reduces the power to a few hundred watts.

spectral flux at some particular photon energies ε_n. To distinguish them from wigglers, these devices are called undulators.

Contrary to bending magnet radiation, which is broadband, undulator radiation is made of a series of narrow peaks of emission (see figure on facing page). The energy ε_n of the peaks is a multiple of a fundamental energy ε_1 ($\varepsilon_n = n\varepsilon_1$) which depends on the electron energy E and the undulator period λ_0 according to

$$\varepsilon_1[\mathrm{keV}] = \frac{0.95E^2[\mathrm{GeV}]}{\lambda_0\,[\mathrm{cm}](1 + K^2/2)}$$

where K is a dimensionless factor proportional to the product of the peak undulator field and the period. The precise location of these interference peaks can be tuned by varying K which can be accomplished by varying the magnetic field. As a result of this interference, the peak spectral flux grows more rapidly than linearly with the number of periods, and it is concentrated in very narrow emission cones.

However, one must consider that electron beams in storage rings are made of a collection of electrons with slightly different directions of propagation and a range of energies. The angular spread increases the cone angle of emission. Similarly, the electron energy spread increases the spectral width of the peak. Both effects reduce the peak spectral flux that can be collected through some narrow aperture and made to strike a small sample. In other words, to fully benefit from the properties of an undulator, a highly collimated electron beam with a small energy spread is required.

The quantity used to characterize the degree of collimation of the electron beam is the emittance. It is approximately expressed as the product of the angular divergence and the transverse size at the source. The lower the emittance, the brighter the electron beam and the brighter the radiation that it can produce.

The recent third generation sources, which started operation in the 1990s, are designed to accommodate many undulators and to optimize their performance using low emittance electron beams. As an example, the ESRF operates with an electron emittance in the horizontal (vertical) plane of 4 nm (0.03 nm) corresponding to a horizontal (vertical) rms beam size and divergence of 400 μm and 10 μrad (10 μm and 3 μrad). For comparison, this is 10 (1000) times smaller than the emittance of the light produced by a helium neon laser. The classical figure of merit used to characterize the undulator emission is the brilliance (also called brightness). It is equal to the total spectral flux produced by the undulator normalized to the product of the horizontal and vertical emittance of the light. Undulator emission is typically 10^3–10^4 more brilliant than the radiation from bending magnets and, indeed, it has opened new fields of scientific experimentation.

SYNCHROTRON radiation light sources are expensive devices, costing typically several hundred million dollars. The cost is essentially dictated by the size of the infrastructure required (ring, injector, beam lines, technical facilities). The size of the ring is the direct consequence of the electron energy and therefore of the range of photon energy over which the source is optimized. A 6–8 GeV, 1 km perimeter hard X-ray source can be 10 times more expensive than a 1 GeV, 100 meter perimeter source, but the spectrum and therefore the scientific applications are different. One should also keep in mind that the simultaneous and transparent operation of a number of experimental stations or beam lines (50–100 on a 6–8 GeV ring) reduces the cost per experiment.

The present trend in the development of new synchrotron radiation facilities is towards 2.5–3.5 GeV, 200–400 meter perimeter type sources. There are a number of facilities under construction and a number of others are being envisaged. They are described in the previous article. The medium energy makes them suitable to cover a large spectral range from the VUV to the hard X ray. These facilities will perform less well above about 10 keV than the present 6–8 GeV hard X-ray sources (APS, ESRF, SPring8), but they are less expensive and can therefore be financed at a national or regional level. Several of them intend to compensate for the expected short lifetime of the stored beam by using continuous injection and to extend the photon energy range of the undulator radiation by placing the ID magnet arrays in the vacuum chamber to allow a magnetic gap as small as 3–5 mm instead of the 10–15 mm achieved in most present facilities in operation. The reduction of the magnetic gap in the undulators allows a reduction of the

Optimizing Dynamic Aperture

IN STORAGE RINGS, electrons make transverse horizontal and vertical oscillations around a reference orbit. However, electrons executing a large oscillation may not follow stable trajectories and are ultimately lost on a wall of the vacuum chamber. To avoid such losses, the number of oscillations per circumference (called the tune number) must be carefully selected. In addition, the spread of tune from one electron to the other must be controlled within narrow limits. The quadrupoles used between the bending magnets have a focusing strength inversely proportional to the electron energy. As a result, they induce a so-called chromatic aberration with a tune varying from one electron to the next, depending on its energy. Note the similarity with chromatic aberration induced by the focal length varying with wavelength in visible optics. For the beam to be stable, the chromatic aberration must be compensated.

Special types of magnets called sextupoles provide this compensation. Roughly speaking, sextupoles can be regarded as focusing elements with a focal strength varying linearly with the transverse position of the electron. However, sextupoles also produce additional aberrations which make large transverse oscillations unstable. In other words, electrons travelling far away from the sextupole's axis will not execute stable oscillations. By analogy with the physical aperture set by the transverse dimension of the vacuum chamber, the stability limit imposed by the sextupoles is called dynamic aperture. The design and location of the sextupoles must be carefully selected in order to correct the chromatic aberration while keeping a large dynamic aperture. This optimization is particularly delicate for such a small emittance lattice.

The small emittance and high current results in a high density of the electron beam. As a result of the high density, a large number of collisions take place every second between electrons within a single bunch. The colliding electrons may lose or gain energy to the point that their associated trajectory in the ring becomes unstable. The stored electron beam lifetime is therefore reduced by this intra-beam scattering (also called Touschek scattering). Contrary to modern hard X-ray sources operating with a lifetime in the 50–100 hours, the UHXS will have a shorter lifetime around 5–10 hours. As mentioned earlier, the remedy might simply be to re-inject a small current every 5 to 10 minutes using a continuously running injector system. It is likely that such a source will require a number of slow and fast active stabilization feedback systems to prevent the onset of transverse and longitudinal instabilities and to maintain a stability of the centre of gravity of the beam to a fraction of the beam size. Such feedback systems have already been implemented on a number of rings and the associated technology is considered to be mature. Other challenges in the design of such a source include tight mechanical tolerances in the machining of magnets, precise alignment, sensitivity to ground vibrations. Even though such tolerances have not yet been worked out in detail for the UHXS, the very successful experience with third generation sources makes us optimistic. The full exploitation of such a facility with more than 40 undulator beam lines would normally require the construction of a large experimental hall around the accelerator tunnel. Alternatively, one may consider recycling an existing large sized tunnel such as those in use for PEP or PETRA to house this new facility.

period, thereby shifting the spectrum to higher energies. Optimizing an undulator with magnets in-vacuum and a magnetic gap of 5 mm instead of 10 mm allows a reduction (and therefore a saving) of the electron energy by 16 percent. However, both the gap and the electron energy reduction result in a shorter lifetime and an increased sensitivity to beam instabilities.

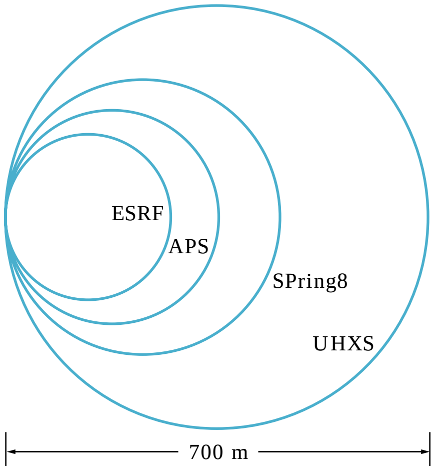
The ultimate hard X-ray source (UHXS) is a large capacity source (40–50 beam lines) covering the 0.5–500 keV range with emphasis on very high brilliance in the 10–20 keV range, which is increasingly in demand for applications in structural molecular biology and many other applications. This is obtained by simultaneously running a high electron current of 500 mA and achieving a very small emittance of the electron beam, around 0.2 nm in the horizontal plane and smaller than 0.01 nm in the vertical plane. Such circulating current and emittances are respectively 2.5–5 times larger and 40–80 times smaller than what is achieved in present synchrotron radiation facilities of similar energy. The brightness of the radiation varies linearly with the stored current and inversely with the emittance, or in some cases with the square of the emittance.

The operation of a 500 mA current requires a power of 7 MW of radio-frequency to be sent to the beam through a series of radio-frequency cavities. These cavities must produce a total accelerating voltage of 14 MV

Flux and Brilliance

Comparison of flux and brilliance between the ESRF and some proposed sources including the UHXS storage ring source, the Cornell Energy Recovery Linac, and X-ray FEL sources based on Self-Amplified Spontaneous Emission (SASE). Part of the data in this table has been taken from the report "ERL_CHESS_memo_01_002.pdf" available from http//erl.chess.cornell.edu/Papers/Papers.htm

Source *Type*	*ESRF* *Storage Ring*	*UHXS* *Storage Ring*	*Cornell* *ERL*	*LCLS* *SASE FEL*	*TESLA* *SASE FEL*
Electron Energy [GeV]	6	7	5.3	15	25
Average Current [mA]	200	500	100	7.20E-5	0.063
Hor. Emittance [nm]	4	0.2	0.15	0.05	0.02
Vert. Emittance [nm]	0.01	0.005	0.15	0.05	0.02
FWHM Bunch Length [ps]	35	13	0.3	0.23	0.09
Undulator Length [m]	5	7	25	100	200
Fundamental [keV]	8	12	8	10	12.4
Average Flux [Ph/s/.1%]	1.3E+15	2.0E+16	1.5E+16	2.4E+14	4.0E+17
Average Brilliance [Ph/s/.1%/mm^2/mrad^2]	3.1E+20	3.5E+22	1.3E+22	4.2E+22	8.0E+25
Peak Brilliance [Ph/s/.1%/mm^2/mrad^2]	3.3E+22	1.0E+25	3.0E+25	1.2E+33	7.0E+33



Size of the UHXS compared to the presently operated hard X-ray synchrotron source ESRF (Europe), APS (US), SPring8 (Japan). The larger size of the UHXS is imposed by the requirement of an ultra-small emittance.

over the circumference. This voltage and power is necessary to compensate for the energy and power loss by the electrons due to synchrotron radiation emission in the bending magnets and undulators. At this high current, some instabilities can occur through the interaction of the beam with the higher order resonant mode of the radio-frequency cavities (HOM). Recent development in the engineering of radiofrequency cavities makes stable operation possible at such a high current by either using super-conducting technology or by using conventional room temperature copper cavities equipped with heavy dampers for the HOMs.

An electron energy of 7 GeV has been selected for the UHXS, which is a compromise between lifetime, beam stability, and cost. The beam lines where the X-ray beams are processed are equipped with mirrors to refocus the beam on the samples and monochromators to select a narrow slice in the spectrum.

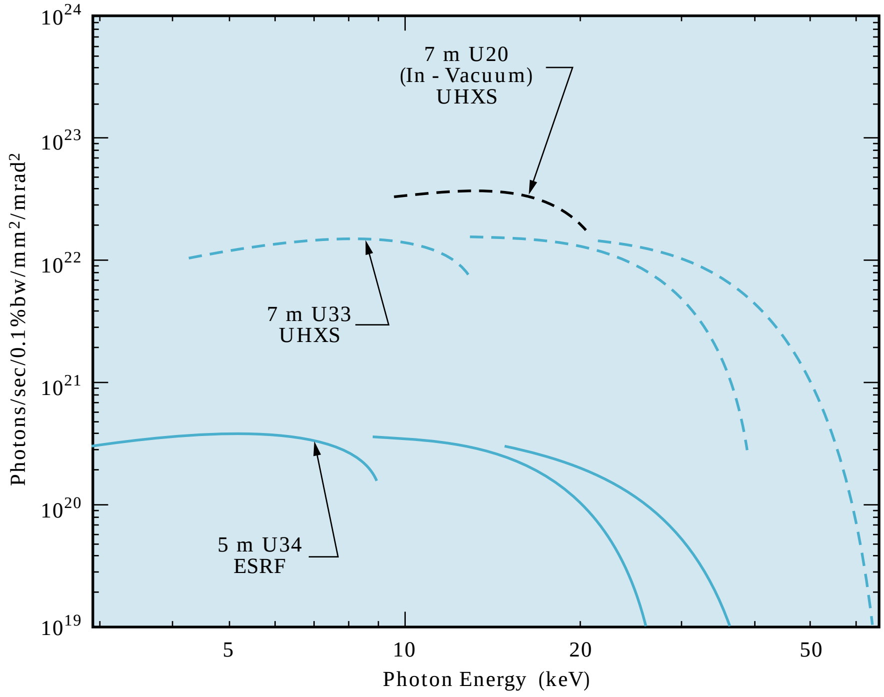
One of the major difficulties with the use of radiation in such a facility is the extreme heat load imposed by the X-ray beam on the mirrors and monochromators. A typical undulator beam of the UHXS type produces a continuous-wave X-ray power of 50 kW and a power density close to 1 kW/mm^2 at a distance of 40 meters from the undulator. To maintain a narrow energy resolution, the monochromators are normally made of silicon crystals cooled by liquid nitrogen. Diamond crystals may also be used. A narrow slit (typically 0.5×0.5 mm) is placed in front of the crystal. This reduces the power to 250 W while transmitting most of the flux available on the peak of the undulator spectrum. Most of this power is dissipated in the monochromator's crystal.

The selection of a small electron beam emittance is therefore essential since it reduces the cone of emission of the undulator emission and allows the collection of the useful undulator radiation over a small aperture. In other words, the reduction of the emittance of the electron beam results in an important reduction of the power transmitted through the slit without sacrificing any flux at the photon energy of interest. Another benefit of small emittance is the high transverse coherence of the X-ray beam. The high coherence opens the door to a number of new experiments making use of this spatial coherence (Speckle, Holography). The achievement of the small emittance is therefore essential and is a major challenge.

While a 7 GeV ring could be built with a circumference of 500 meters but with a rather large emittance, around 20 nm, the achievement of a 0.2 nm emittance requires a perimeter of about 2200 meters. This is because the electron beam emittance in a storage ring is determined largely by the emission of synchrotron radiation in the bending magnets, which perturb the electron orbits by exciting oscillations, the so-called betatron oscillations. These excitation effects are mitigated by segmenting the bending magnets into a large number of short units with rather low magnetic field, separated by quadrupole magnets which refocus the electron beam from one bending magnet to the other. The extra space required by these quadrupoles and the large number of low-field bending magnets are the reasons for the increase in the circumference. As a result of these factors the electron beam emittance in a storage ring scales approximately inversely as the third power of the circumference.

The figure at left presents the size of the UHXS compared to the present hard X-ray synchrotron sources in operation in Europe (ESRF), United States (APS), and Japan (SPring8). Such a ring would contain 160 bending magnets and 720 quadrupole magnets to be compared to 64 and 320 at the ESRF. Indeed, the size of the circumference is the price to pay for the low emittance. The figure below presents the expected brilliance from a conventional fully tunable 7 meters long undulator. Apart from the heat load and magnet lattice design, there are several other challenges (see box on page 18).

It is interesting to compare the performance of such a ring with the alternative types of sources presently envisaged for the future such as the energy recovery linac (ERL) (see article by Sol Gruner and Donald Bilderback in this issue) and self amplified spontaneous emission free electron laser (SASE) (see article by Claudio Pellegrini and Joachim Stöhr in this issue). The table on page 19 presents a comparison of the flux, average brilliance, and peak brilliance of different projects compared to those presently achieved at the ESRF. The electron beam is made of a series of short bunches spaced in time periodically at the radiofrequency period of the accelerating cavities. The peak brilliance is defined as the average brilliance multiplied by the duty factor, defined as the ratio of the peak current to the average current. Note that the flux and average brilliance of this source compares very favorably with those expected in the Cornell ERL and LCLS SASE projects; however, the electron bunch length of the UHXS is expected to be 50 times longer.



Predicted brilliance versus photon energy for the ultimate hard X-ray source (UHXS) compared with those presently achieved at the ESRF. A gain of brilliance close to two orders of magnitude is reached.