Intermediate-Energy Light

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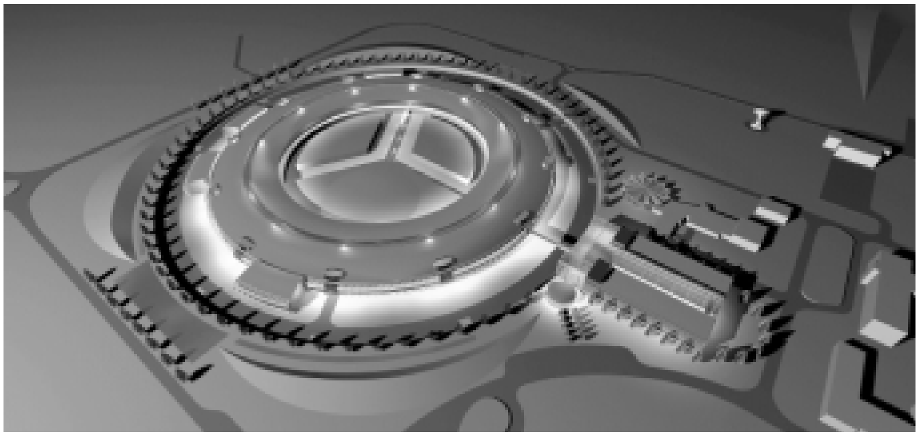
The high performance and relatively moderate cost of these 2.5–4 GeV machines make them the popular choice, with six now in construction and more proposed.

INCREASINGLY, ATOMIC SCALE information underlies scientific and technological progress in disciplines ranging from pharmaceutical development to materials synthesis to environmental remediation. While a variety of research tools are used to provide atomic scale information, synchrotron radiation has proved invaluable in this quest. The rapid growth of soft- and hard X-ray synchrotron light sources stands as stark testimony to the importance and utility of synchrotron radiation. Starting from just a handful of synchrotron light sources in the early 1970s, this burgeoning field now includes over 70 proposed, in-construction, or operating facilities in 23 countries on five continents. Along the way, synchrotron light facilities have evolved from small laboratories extracting light parasitically from storage rings designed for high-energy physics research to large, dedicated sources using the latest technology to produce extraordinarily bright photon beams.

The basic layout of a multi-GeV storage ring light source employs periodic bending magnets to guide a charged particle beam around the storage ring. As the charged beam is accelerated in an arc, it produces a sweeping fan of synchrotron radiation that extends from the infrared part of the electromagnetic spectrum (<1 eV) to hard X rays (>20 keV). Quadrupole magnets keep the electrons tightly focused, and a radio-frequency acceleration system replenishes beam energy lost to radiation emission. To optimize the output radiation, a premium is placed on high current electron beams with small cross section and extreme position stability. Magnetic insertion devices are used to further enhance

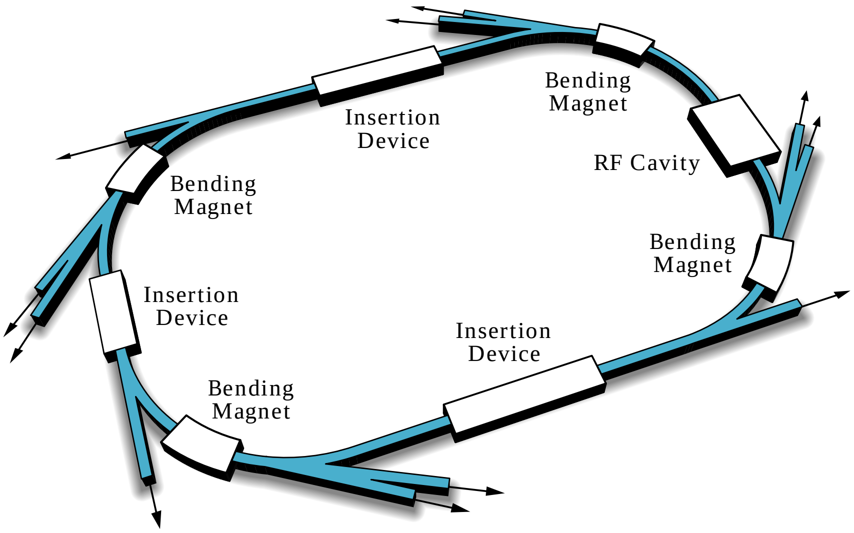
Sources



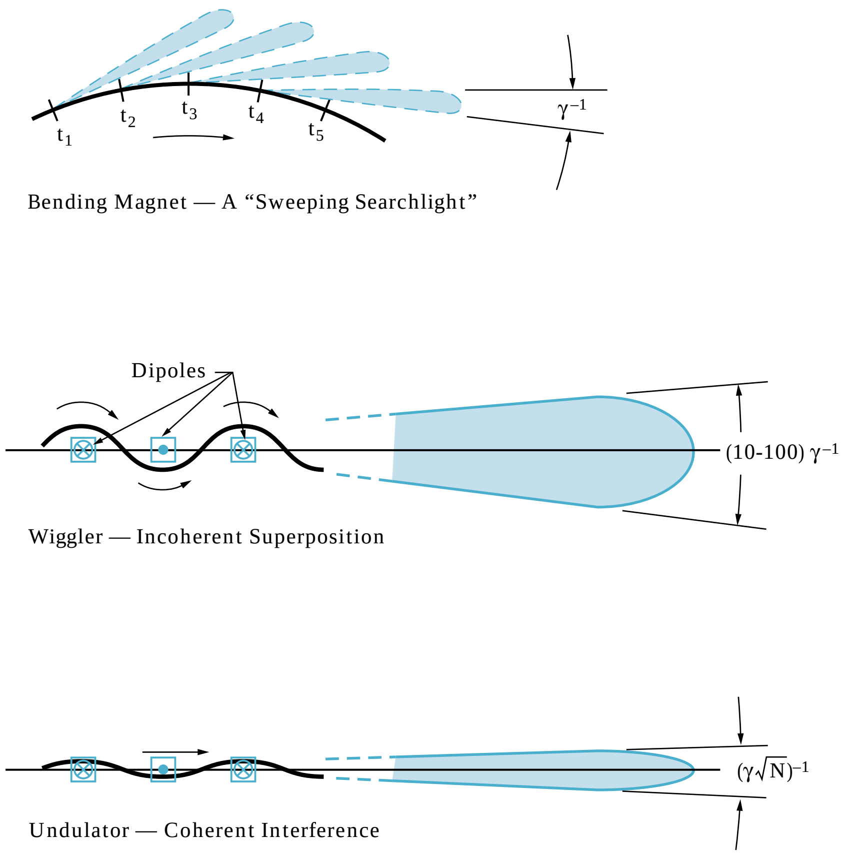
Artist's rendition of the DIAMOND light source under construction in the UK.

radiation output by a factor of 10 or more over bend magnet sources. The storage ring vacuum chamber includes exit ports to allow portions of the radiation fan to propagate down photon beam transport lines to optical systems and experimental stations. A typical storage ring features 10 or more such radiation ports. The photon beam from each port can be subdivided into several separate beams, each of which can serve an independent experimental station. All told, 50 or more scientific teams can simultaneously and independently conduct research using intense photon beams from a single intermediate-energy synchrotron radiation facility.

As suggested above, today's synchrotron light sources are the product of several generations of light source technology. The first-generation of hard X-ray light sources utilized storage rings



Basic components of a storage ring light source.
Not shown is the injection system.



Bend magnet sources produce a sweeping beacon of light. Insertion devices consist of an array of magnet poles each of which acts as an individual bend magnet source. The characteristic photon emission angle γ^{-1} is related to the electron beam energy by $\gamma = 1957E$ (GeV). [$\gamma = E/mc^2$]

designed for high-energy physics research. Despite the difficulties of working parasitically to research programs with different objectives and operational requirements, the unique properties of synchrotron light (energy tunability, brightness, time structure and polarization characteristics) rendered these early research programs extremely successful. These early successes, coupled with the scarcity of available beam time, spawned demand for facilities dedicated to the production of synchrotron light. The resulting second-generation machines were optimized to produce VUV and X-ray light from bend magnets and featured many beam extraction ports for cost effective operation.

Starting in the late 1980s, second-generation light sources gave way to third-generation light sources featuring the workhorse of modern synchrotron light production—the insertion device (ID). As shown in the figure at left, the first IDs consisted of a sequence of short back-to-back dipole magnets arranged to enhance radiation output from the electron beam. In this configuration, the radiation intensity is amplified by the strength and number of dipoles N contained in the ID. These so-called *wiggler* magnets soon evolved into more sophisticated *undulator* devices to further enhance photon beam brightness. Radiation from each of the undulator poles constructively interferes with radiation from each of the other poles to produce a highly forward-directed and quasi-monochromatic photon beam. Viewed along the undulator axis, the output intensity can scale as N^2 rather than as N in a wiggler.* The energy of the photon beam depends on the energy of the electron beam and the strength and spacing of the poles. The photon beam energy from an undulator can be tuned by adjusting the magnetic field strength.

** In the extreme case, undulators can cause the electron beam to “lase” into a coherent fourth-generation photon beam (see Pellegrini and Stöhr, this issue), but the more common application is to utilize the less-coherent spontaneous radiation.*

The pioneering third-generation machines fell into two distinct groups: smaller low energy rings (< 2 GeV) optimized for ultraviolet and soft X-ray production from undulators, and larger high-energy rings (6–8 GeV) optimized for hard X-ray science. While recent innovations in superconducting magnet technology have been used to boost radiation output of the low-energy machines into the 10 keV range, undulators on third generation, high-energy machines remain the pre-eminent sources for high brightness, hard X-ray science.

More recently, a new class of third-generation light source is rapidly gaining popularity. This new class of machines, the intermediate energy light source (ILS), occupies the ~3 GeV middle ground between low-energy and high-energy storage rings.

The concept of an intermediate energy light source is hardly new as a number of first- and second-generation machines have operated in this energy range since the 1970s. What distinguishes third-generation ILS machines is the combination of high operating current, low beam emittance, and advanced insertion device technology. At present eight such machines are proposed or under construction in Armenia, Australia, Canada, China, France, Spain, the United Kingdom, and the US. Although the smaller ILS machines cannot provide the ultimate hard X-ray brightness nor the total number of beam lines of the larger 6–8 GeV machines, these ILS class sources fulfill regional needs for highly capable multiport X-ray sources that can be constructed and operated at moderate cost. The ILS

A Prototypical Intermediate Energy Light Source

TO ILLUSTRATE THE PROPERTIES of a third-generation light source in the intermediate energy range, we simulated the performance of a relatively conventional 3.3 GeV storage ring with 307 meter circumference and 500 mA stored current. Similar to many storage rings now in operation, this ILS ring utilizes vertical focusing in the dipole magnets and low dispersion in the straight sections to reduce horizontal emittance (ε_x = 9.9 nm-rad). Presented in the illustrations on pages 12 and 13 are the calculated emission spectra from bend magnet, wiggler (W70) and small gap undulator (U20) sources on this ring. The characteristics of these sources are listed in the table below. While the wiggler is a conventional out-of-vacuum geometry, the undulator model assumes the addition of extra vertical focusing magnets to reduce the vertical source size (*for example*, β_y = 2 meters) permitting use of small pole gap, in-vacuum magnet technology.

To place the ILS performance into context, the ILS sources are benchmarked by sources on a representative third generation, high-energy light source, the HLS. The HLS features twice the energy of the ILS, half the emittance of the ILS, similar magnetic lattice functions as the ILS, and 200 mA stored current. A description of the HLS source parameters is listed in the table. Examination of this table reveals that the HLS is a high performance composite of the current operating characteristics of the three existing high-energy, third generation light sources. While the overwhelming majority of insertion devices installed on these high-energy rings are undulators, the performance comparison includes both wiggler (W70) and typical hybrid undulator (U32) sources for completeness. Note, however, that the technical challenges associated with the power radiated by high flux wigglers on high energy machines are significant. These challenges, coupled with the brightness advantages of undulators, have rendered undulators the insertion device of choice on high energy rings except in specialized applications such as those requiring very high photon energies.

ILS and HLS Source Characteristics

Parameter	*ILS/HLS Bend*	*ILS/HLS W70*	*ILS U20/HLS U32*
energy (GeV)	3.3/6.6	3.3/6.6	3.3/6.6
current (mA)	500/200	500/200	500/200
emittance x(nm-rad)	9.9/5.0	9.9/5.0	9.9/5.0
coupling (%)	1.0/1.0	1.0/1.0	1.0/1.0
energy spread (%)	0.1/0.1	0.1/0.1	0.1/0.1
sigma x(mm)	0.127/0.109	0.302/0.216	0.302/0.216
sigma x′ (mrad)	0.163/0.147	0.033/0.024	0.033/0.024
sigma y (mm)	0.041/0.029	0.022/0.016	0.014/0.016
sigma y′ (mrad)	0.008/0.0057	0.0045/0.0032	0.007/0.0032
magnet gap (mm)	na	16.0/16.0	5.0/10.0
B_{peak} (T)	1.12/0.7	1.05/1.05	0.95/0.78
period (mm)	na	70.0/70.0	20.0/32.0
number periods	na	50/50	100/109

class machine can provide competitive performance for all but the most demanding high brightness, hard X-ray applications. In addition, the specific design goals of ILS machines can be tailored to regional interests and machine technology can be matched to local industrial strengths.

One of the fathers of modern insertion device technologies, Klaus Halbach (shown above with grandson) of Lawrence Berkeley National Laboratory worked on early wiggler magnets and envisioned the permanent magnet undulator configuration that has become an industry standard for insertion device design.

SOME OF THE MOST significant technical advances stimulating the growth of ILS class storage rings have been in the field of insertion device design. The first important breakthrough originated at the high-energy light source laboratories where scientists using small pieces of magnetic foil and/or tuning stubs developed techniques to adjust the magnetic field quality of undulators to achieve near-ideal field quality. Properly tuned the undulators can achieve bright X-ray beams at higher photon beam energies than thought feasible a decade ago. Technologies were then developed to place the undulator magnets directly into the storage ring vacuum chamber. Coupled with focusing techniques to squeeze the dimensions of the charged particle beam, this permits use of undulators with very small magnet gaps and shorter magnetic periods for photon production at higher X-ray energies. Together these improvements permit undulators in an ILS machine to operate with high brightness in the 10–15 keV photon energy range.

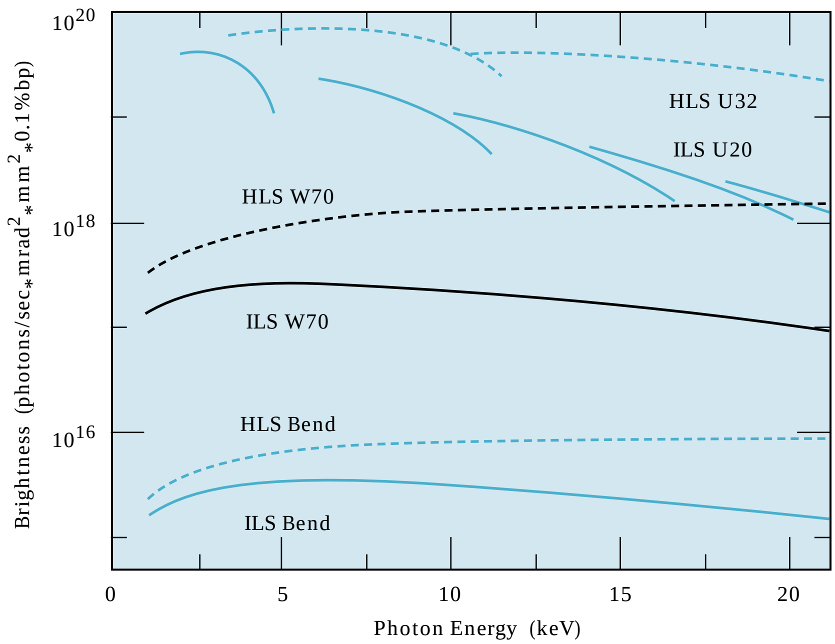
The trend toward construction of mid-size storage rings is also made possible by recent developments in accelerator and beam line technology. In particular, modern light sources benefit from magnet and vacuum chamber fabrication experience from their predecessors and from advances in feedback control and radio-frequency acceleration developed at third-generation light source facilities working with the high-energy physics community. Photon beam lines have seen advances in high heat-load materials, high precision mirrors, and the development of liquid nitrogen cooled monochromators. Computer technology has also allowed accelerator scientists to predict light source behavior under increasingly demanding conditions and to understand complex electron beam dynamics. Photon beam line designers and synchrotron radiation scientists also use sophisticated computer programs to analyze thermal stress problems and photon beam optics.

The rapid growth of synchrotron radiation light sources stands as a stark testimony to the importance and utility of synchrotron radiation.

AN IMPORTANT aspect of intermediate energy light source performance is the match between the radiation source characteristics and requirements of the experimental sample irradiated by the beam. Perhaps the source characteristic of greatest importance is the source phase space, with a small source phase space implying a highly collimated laser-like beam. More technically, source phase space is the product of the transverse cross section of the radiation at the source and the angular spread of photon emission, where the angular spread includes both charged particle beam parameters and photon emission effects.

At the sample, one is interested in the photon beam acceptance or the product of the cross-sectional area of the sample and the angular spread of the photon beam that can be usefully coupled into the sample. A sample with a small acceptance phase space demands a high brightness beam at the source and brightness-preserving optics to conduct the X-ray beam to the sample. Combining the concepts of source phase space and sample acceptance phase space we arrive at the notion of mapping the radiation source phase-space into the sample acceptance phase space in order to determine the capabilities of a given light source for a particular measurement. The widely quoted figures-of-merit flux and brightness represent two extremes of source performance. They are typically employed when the sample acceptance is significantly larger or smaller than the source phase space, respectively. Unfortunately, these merit-functions often fail to represent accurately the requirements of many experiments that do not fall neatly into the category of flux- or brightness-limited measurements. Specifically, large classes of experiments require a photon beam with modest angular collimation and spot size. For such experiments, the best figure-of-merit explicitly maps the source phase space into the sample acceptance phase space. With appropriate optics to transform from source to sample, this approach provides a means to relate the demands of a given experiment to the light source properties.

In macromolecular crystallography, for instance, a typical sample with ~0.1 mm transverse dimensions and ~2 mrad angular acceptance has approximately 0.2 mm-mrad sample acceptance phase space in each transverse direction. Since the sample acceptance significantly exceeds the source phase space of typical third generation hard X-ray undulators, the flux from the entire central cone of the undulator radiation can be imaged onto the sample. In contrast to undulators, a typical wiggler on a low emittance ring overfills the horizontal phase- space acceptance while under filling the vertical acceptance. The accepted wiggler flux on the sample is often comparable with the accepted undulator flux despite several orders of magnitude difference in source brightness. This surprising result underscores the importance of selecting



Calculated X-ray beam brightness from bend magnets, wigglers (W70), and undulators (U20 and U32) on ILS and HLS class storage rings. The HLS U32 spectrum includes only the fundamental and third harmonic tuning curves, while the ILS U20 spectra includes the tuning curves for the fundamental and odd harmonics through ninth order.

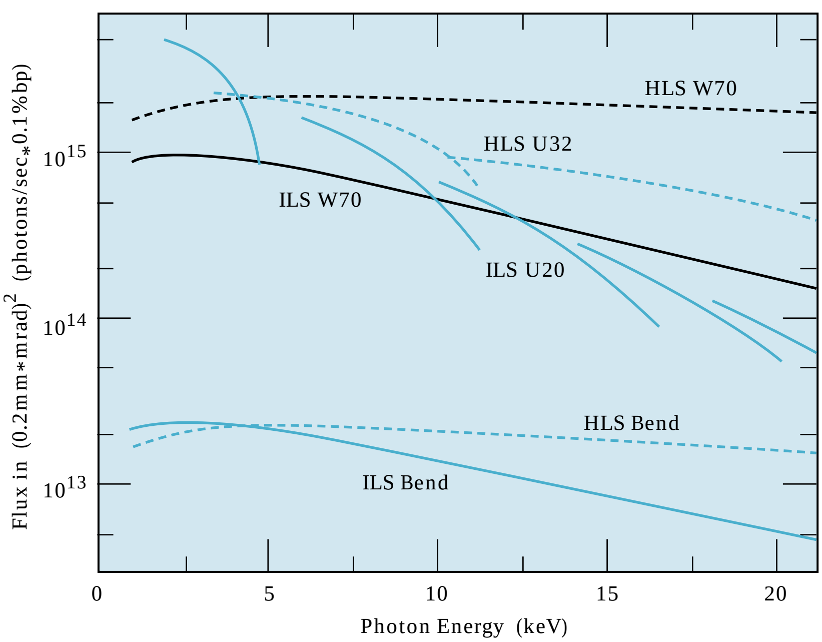
the appropriate figure-of-merit for the science in question.

Relating the photon beam requirements to the design of a storage ring, we find specifications for flux, brightness, and particularly phase space matching from a high current ILS class machine readily meet or exceed the needs of the synchrotron radiation user community for a wide range of applications. To illustrate this point, consider the comparison between a prototypical 3.3 GeV, 500 mA intermediate energy light source and a 6.6 GeV, 200 mA high energy light source (HLS) (see sidebar on page 9).

The X-ray emission spectra from representative bend magnets and insertion devices on these two rings illustrate the relative performance of these classes of synchrotron radiation sources. The X-ray brightness for bend magnet, wiggler (W70), and undulator (U20 and U32) sources demonstrate that for brightness-limited measurements, undulators on either ring outperform either wiggler or bend magnet sources (see figure above). While the ILS U20 in-vacuum undulator provides high brightness below approximately 15 keV, the HLS U32 provides higher brightness at these energies and sustains high brightness to much higher energies. Nonetheless, many high brightness applications do not require high energies and as such are well served by a small gap undulator on an ILS class machine.

Next consider the relative source performance for the (0.2 mm-mrad)^2 phase-space acceptance of a typical macromolecular sample as described. Despite the differences in storage ring characteristics, the figure below demonstrates that the undulator performance is roughly equivalent in the 7–15 keV energy range owing to the relatively small gap of the U20 undulator. Given the small sample acceptance phase space, what is more surprising is the efficacy of the W70 wiggler. These examples demonstrate that experiments which do not fully exploit the extraordinary brightness of an undulator are well served by a wiggler in a high current, intermediate energy storage ring.

THE EXPANDING worldwide investment in synchrotron light facilities is testimony to the social and scientific impact of synchrotron radiation research in the physical, biological, and environmental disciplines. To meet growing user demand, many laboratories are turning to high current, third generation, intermediate energy storage rings. These ILS machines are relatively low risk construction projects that rely upon proven technology developed throughout the evolution of many storage rings. Through the construction of mid-size, moderate cost, high performance X-ray machines, regional governments can cultivate local synchrotron radiation communities and promote private, industrial, and government-sponsored research and development efforts while stimulating local economic activity.



Calculated X-ray flux accepted by the (0.2 mm-mrad)^2 phase-space of a typical macromolecular sample.