

FUTURE SYNCHROTRON RADIATION SOURCES

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Sources of synchrotron radiation (also called synchrotron light) and their associated research facilities have experienced a spectacular growth in number, performance, and breadth of application in the past two to three decades.

In 1978 there were eleven electron storage rings used as light sources. Three of these were small rings, all below 500 mega-electron volts (MeV), dedicated to this purpose; the others, with energy up to 5 giga-electron volts (GeV), were used parasitically during the operation of the ring for high energy physics research. In addition, at that time synchrotron radiation from nine cyclic electron synchrotrons, with energy up to 5 GeV, was also used parasitically.

At present no cyclic synchrotrons are used, while about 50 electron storage rings are in operation around the world as fully dedicated light sources for basic and applied research in a wide variety of fields. Among these fields are structural molecular biology, molecular environmental science, materials, analytic chemistry, microfabrication, archaeometry and medical diagnostics. These rings span electron energies from a few hundred MeV to 8 GeV. Several facilities serve 2000 or more users on 30-60 simultaneously operational experimental stations. The largest rings are more than 1 km in circumference, cost about US\$1B to build and have annual budgets of about US\$100M.

This growth is due to the remarkable properties of synchrotron radiation, including its high intensity, brightness and stability; wide spectral range extending from the infra-red to hard x-rays; variable polarization; pulsed time structure; and high vacuum environment.

The ever-expanding user community and the increasing number of applications are fuelling a continued growth in the number of facilities around the world. At present this includes nine storage rings in construction and about fifteen in various stages of design and planning. For a list of synchrotron radiation sources currently in operation, construction, and design see http://www-ssrl.slac.stanford.edu/sr_sources.html. This web page has links to the web sites of each facility. Most of the facilities mentioned in this article can be accessed in this way.

In the past few years new types of light sources have been proposed based on linear accelerators. Linac-based sources now being pursued include the free-electron laser (FEL) and energy recovery linac (ERL). In some respects (e.g., coherence, peak brightness, sub-picosecond pulse duration) these sources will far exceed the performance of storage-ring-based sources. As a consequence, they will open entirely new experimental opportunities. In particular, scientific interest is growing in the short pulse lengths that linacs can provide, making it possible to study chemical reactions and biological processes on the femtosecond time scale. The high peak brightness and peak power of the FEL also makes it possible to create and probe novel states of matter such as warm dense matter. It may also make it possible to determine the structure of proteins using single molecules as targets rather than crystal arrays. Depending on the linac

energy, these sources can reach photon energies of 10 keV or higher. The reasons that linacs can deliver higher performance than rings, particularly high peak brightness and short pulse length, are given below.

Short pulses can also be obtained in other ways. At the Advanced Light Source at LBNL a femtosecond laser has been used to slice out part of the longer electron bunch to provide short pulses of x-rays. Such a facility could operate at high repetition rate with natural synchronization with the laser, facilitating pump-probe experiments. Also, a project called the Sub-Picosecond Photon Source (SPPS) is in construction at SLAC using a magnetic compressor in the linac to produce an 80 femtosecond electron beam which, when passed through an undulator at the end of the linac, will generate 80 femtosecond x-ray pulses. The figure (expanded from a figure on the Cornell ERL web site; <http://erl.chess.cornell.edu/>) shows how these sources compare in peak brightness and pulse length with conventional storage ring beams, ERLs and FELs.

We can thus discern some broad trends for new sources. One is making more synchrotron radiation available, including regions in which there are no present facilities. Another is the focus on high performance intermediate energy facilities. A third is the use of linac-based sources to achieve shorter pulses and higher brightness and peak power than storage rings can provide.

STORAGE RING-BASED SOURCES

Most of the new sources under construction and in design are based on storage rings. This technology is now well-developed so that there is a high degree of confidence that they will work as planned. Furthermore, storage rings are very cost-effective since they provide many beams from bending magnets and insertion devices. Even the simplest storage ring provides radiation that is many orders of magnitude more intense than other sources, leading to the spreading of their use around the world.

Future storage rings now under construction range from rather small (~100 meters in circumference) devices with electron energy around 1 GeV, to intermediate energy rings (200-400 meters in circumference) with electron energy in the 2.5-4 GeV range. Because of the large growth in applications and in the user community requiring hard x-rays (5-20 keV and higher), the low energy rings use superconducting wigglers with magnetic fields of 7-8 tesla to access this photon energy range.

Low Energy Rings

There are three current projects in the low energy range based on upgrading older storage rings. A 1 GeV ring (the decommissioned SORTEC facility) was given as a gift by Japan to Thailand where it has been upgraded and is now operating (the Siam facility). Holland has given the MEA-AmPS facility to Russia where it is being upgraded in Dubna to a 1.4 GeV ring called DELSY. Germany has offered the 0.8 GeV BESSY I ring to the Middle East. It will be upgraded to a 1-2 GeV ring (SESAME) in Jordan as a UNESCO-sponsored international project with 14 member countries from the Middle East region (see related article in *IUMRS Facets*, vol.

1, No. 1, pg. 7). All of these projects include an injection system as part of the gift. The SIAM and SESAME facilities will bring synchrotron radiation to regions that now have no such facilities.

Intermediate Energy Rings

The high performance and relatively moderate cost of 2.5-4 GeV machines make them the popular choice, with seven now in construction (Australia, Canada, England, France, India, Spain, and the US) and more proposed (Armenia, China). This popularity arises largely from the high performance of these machines, made possible by recent technological developments. These include shimming of undulator magnets to near perfection, which increases high harmonic content, and the use of in-vacuum, small gap, short period undulators. These developments allow these relatively low energy rings to deliver hard x-ray (5-20 keV) undulator beams with brightness that is closer to that of the larger 6-8 GeV rings than was previously thought possible. Beams from bending magnets and wigglers provide high flux density on small samples extending to 50 keV. When operational, these new rings 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

Possible 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. Although none are now under construction, there is a plan to use the 2.2 km Petra facility in Hamburg, Germany, in this way. Perhaps one of these will eventually be built in the existing large tunnels now being used for B-Factories at KEK (Tsukuba, Japan) and the Stanford Linear Accelerator Center (SLAC) in California, USA. With the proliferation of intermediate energy rings and the increasing interest in linac-based sources, it now seems unlikely that a new, large circumference 6-8 GeV ring will be constructed in the near future.

To achieve higher performance, particularly higher brightness, storage rings require ever-larger circumference. This is because quantum emission of radiation from the bending magnets reacts on the electron beam to produce energy spread and growth in beam size (in all three dimensions) and transverse emittance (the product of beam size and divergence). 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 quadrupoles to refocus the beam after its dispersion in each bending magnet. This leads to geometries with many magnetic elements and large circumference. It also provides many straight sections for insertion devices.

LINAC-BASED SOURCES

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.* In the absence of bending magnets there is no excitation of oscillations by emission of synchrotron radiation and the beam properties are determined by the electron source. Rather than increasing

with electron energy, emittance in a linac decreases linearly with electron energy. However, the precision with which bright linac beams must be made, accelerated and used in undulators poses severe challenges. Several relatively recent developments have given confidence that these challenges can be met, opening a path to the use of high energy linacs to provide higher performance than any storage ring. One of these developments is the high brightness electron source, particularly the laser-driven radio-frequency gun initially developed at Los Alamos National Laboratory (New Mexico, USA). Another is the improved capability to accelerate, compress, and transport such bright electron beams, as demonstrated in the Stanford Linear Collider (SLC) beams at SLAC. A third is the precision undulator, as developed in many light source facilities. In combination, these developments have opened two main directions for future linac-based light sources; the energy recovery linac and the x-ray free-electron laser. Both offer extremely short duration pulses, more than 100 times shorter than storage rings. It is interesting to note that reaching higher light source performance requires using linacs rather than storage rings, much like electron-positron colliding-beam storage rings are now giving way to linear colliders.

The Energy Recovery Linac (ERL) as a Synchrotron Light Source

The ERL exploits the ability of linacs to generate shorter bunches and brighter (lower emittance) electron beams than storage rings. In most linacs the electron beam is dumped after acceleration and a fresh beam is accelerated on each cycle. This results in high electrical power consumption and high operating cost. In the ERL operating costs are brought down significantly by decelerating the electrons in a second "out of phase" pass through the linac, recovering the energy from the electrons after they have been used to produce radiation, and dumping the electron beam at low energy. In addition to the benefits of high duty cycle with reasonable power costs, residual radioactivity in the beam dump is significantly less due to the low electron energy after deceleration. The principle has been tested at low energy at the Thomas Jefferson National Accelerator Facility (Newport News, Virginia, USA) where a recirculating linac is used to drive an infrared free-electron laser. By using a superconducting linac, the ERL can produce high average current, resulting in high average photon beam brightness as well as high peak photon beam brightness. Several laboratories are developing designs for an ERL. In collaboration with the Jefferson Laboratory, Cornell University proposes to build a 100 MeV ERL which will provide a test bed along the way to a higher energy x-ray ERL facility.

X-ray Free-Electron Lasers

The dream of a fully coherent x-ray laser seems now to be in reach. With bright 10-20 GeV electron beams and 100-meter-long undulators, it is possible to produce sub-picosecond hard x-ray pulses with 9 orders of magnitude higher peak brightness than the best present third generation storage rings. The Linac Coherent Light Source (LCLS) (<http://www-ssrl.slac.stanford.edu/lcls/>) project at SLAC is on a path to operate the first such machine in 2008, making use of the last kilometer of the 3 kilometer SLAC linac. A similar project is planned in Hamburg, Germany, at the Deutsches Elektronen-Synchrotron (DESY), where an x-ray laser is included in the proposed TESLA superconducting linear collider project (<http://www-hasyllab.desy.de/>).

The x-ray FEL operates on the principle of Self-Amplified Spontaneous Emission (SASE), a process by which a bright electron beam passing through a long undulator interacts with its own spontaneously produced radiation to produce a microbunching of the electron beam on the Ångström scale. As the microbunching progresses, the radiation intensity increases, since the emitted radiation grows with the square of the number of electrons within an optical wavelength. The radiated power increases exponentially until the electron beam is fully bunched at which point the process saturates, with an increase of 5-6 orders of magnitude in photon beam brightness. The SASE process has been demonstrated at several laboratories at wavelengths down to about 100 nanometers using electrons with energies up to several hundred MeV. With brighter electron beams at higher energy (10-20 GeV), x-ray laser light can be produced at Ångström wavelengths.

Figure Caption

Different performance metrics are appropriate for different classes of experiments. Source flux, flux density on a sample, and average source spectral brightness are among the commonly used performance metrics and plots of these can be found on many synchrotron radiation facility web sites. With the increasing interest in Peak Brightness and Pulse Duration, we offer this plot showing where several existing and future sources sit in a graph correlating these parameters. See text for details on these sources.

