Bright Synchrotron Sources Evolve

While funding is not yet assured for all the third-generation synchrotron sources, accelerator scientists are struggling to design a machine that can provide ultrahigh-brightness light

ACCELERATOR designers are stretching machine technology to the limit as they struggle to come up with an electron storage ring that can deliver the tightly focused electron beam needed to power the upcoming third-generation synchrotron light sources. Four of several proposed projects around the world are awaiting final funding decisions and a spurt of construction could begin starting this fall.

Officially speaking, construction has already started on one third-generation light source, the "1- to 2-GeV Synchrotron Radiation Source" at the Lawrence Berkeley Laboratory, which is getting $1.5 million during the current fiscal year for architecture and engineering studies, the first phase of a construction project. President Reagan's proposed fiscal 1988 budget contains $18 million for the project, allowing the first ground-breaking this fall if Congress makes no changes. Total cost over the 5-year construction period is $98.7 million, according to project director Klaus Berkner.

A very similar machine to be built together with a new laboratory near Trieste has already been approved by the Italian government along with half of the roughly $100-million construction cost. The remaining half is to be released after review of a report recently submitted to the government by a machine design group headed by Sergio Tazzari at the Frascati National Laboratory near Rome. The laboratory will be built by a private corporation established specifically for this purpose, a unique undertaking in Italian research.

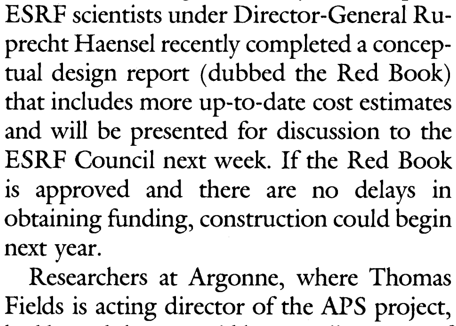
A slightly less ambitious project is also under way in Taiwan, where ground-breaking for the Synchrotron Radiation Research Center took place last fall at a site near the National Tsing Hua University. Construction of what might be a 2.5-generation light source is being headed by Edward Yen.

The Berkeley and Trieste facilities will provide vacuum-ultraviolet and long-wavelength (soft) x-ray radiation. The other two synchrotron sources nearing hoped-for construction starts will generate shorter wavelength (hard) x-rays, which requires a much higher energy storage ring. As a result, the costs of the European Synchrotron Radiation Facility (ESRF) to be operated by a five-nation consortium on a site adjacent to the Institut Laue-Langevin in Grenoble, France, and the Advanced Photon Source (APS) proposed by Argonne National Laboratory are higher in preliminary estimates at from $325 to $375 million.

Currently operating on funding of $4.6 million provided by France, West Germany, the United Kingdom, Italy, and Spain, ESRF scientists under Director-General Ruprecht Haensel recently completed a conceptual design report (dubbed the Red Book) that includes more up-to-date cost estimates and will be presented for discussion to the ESRF Council next week. If the Red Book is approved and there are no delays in obtaining funding, construction could begin next year.

Researchers at Argonne, where Thomas Fields is acting director of the APS project, had hoped there would be a small amount of money for at least a nominal construction start in the fiscal 1988 budget, but the President proposed $5.5 million to cover another year of R&D instead. This year Argonne is receiving $3 million from the Department of Energy (DOE) and is spending about $2.5 million in internal discretionary funds on R&D for the APS.

The core of a synchrotron light source is the electron (or positron) storage ring through which a densely packed beam of electrons circulates for periods of 10 hours or more before recharging. Most of the light from the third-generation synchrotron sources is designed to come when the electrons pass through so-called insertion devices, which are linear arrays a few meters in length of closely spaced dipole magnets of alternating orientation that force the electron beam into an oscillatory trajectory. Roughly speaking, the more tightly squeezed the electron beam is, the brighter the synchrotron radiation it emits during its pass through an insertion device.



Low-emittance *lattices showing dipole bending magnets (rectangles) and quadrupole focusing magnets (lenses) between two straight sections to be filled by insertion devices. The position of the beam in the insertion devices must be independent of the spread of energies in the beam (zero dispersion). The Chasman-Green lattice (top) is the simplest one that achieves this condition. The triple-bend achromat (bottom) replaces the central quadrupole above with a third dipole flanked by two quadrupoles. [Courtesy A. Jackson, Lawrence Berkeley Laboratory]*

In the third-generation sources, the electron beam will be only a few tenths of a millimeter in width and height when passing through an insertion device. At any instant, however, the trajectory of an electron in a storage ring has horizontal and vertical (transverse) components relative to its ideal path. For optimum brightness, it is necessary not only to minimize the beam size but also these transverse motions, since they give rise to a divergence in the emitted light and hence a lower brightness. The technical name for the electron beam parameter that is to be minimized and that reflects both beam size and divergence is emittance.

In attempting to store the lowest emittance electron beams ever, accelerator scientists are pushing into new territory because storage rings for high energy physics are not designed to have low emittances. In general terms, as the emittance decreases, the storage ring becomes less flexible and less tolerant of errors. Scientists at Argonne, for example, consider it a substantial victory to have recently found a design that requires the magnets that guide and focus the beam to be aligned with a root-mean-square (rms) error of 0.1 millimeter, which is just within the limits of today's technology. Earlier designs had required a 0.01-millimeter rms alignment error, well beyond the state of the art.

The magnets comes in three general categories. Dipole magnets bend the electron beam into a curved trajectory; they have also been the primary source of synchrotron radiation in previous generations of synchrotron light facilities. Quadrupole magnets act like lenses and focus the beam. However, unlike optical lenses, which focus both horizontally and vertically, quadrupole magnets focus horizontally and defocus vertically or vice versa, so that they are used in combinations to obtain focusing in both directions. Finally, since the electrons in a beam have a small spread of energies and the focusing properties of quadrupoles depend on the energy, sextupole magnets are needed to correct the resulting focusing errors. The sextupoles also correct for errors in the positions and inhomogeneities in the fields of the quadrupoles.

In a storage ring, the specific arrangement of these magnets, which occur in periodic groupings, is called the lattice. Overall, the storage ring comprises an alternating series of straight sections, which will be the sites of the insertion devices in the new light sources, and curved sections made up of the three types of magnets. The prototype low-emittance lattice is the double-focusing achromat, more commonly known as the Chasman-Green lattice, after the late Renate Chasman and G. Kenneth Green of Brookhaven National Laboratory, whose concept is the basis for the 0.8- and 2.5-GeV storage rings at the National Synchrotron Light Source (NSLS).

Although the Chasman-Green lattice works superbly in the NSLS storage rings, it is not a simple matter to scale this design to a still lower emittance or to a higher energy. Obtaining a low emittance requires strongly focusing quadrupole magnets. The energy dependence of the focusing (chromaticity) means that strong sextupole correction magnets are also needed.

A particularly sensitive parameter is the dynamic aperture of the lattice. As they circulate in the storage ring, the electrons make gentle transverse oscillations (betatron oscillations), but usually remain in stable orbits. If the amplitude of the oscillations is too large, the electrons may be lost from the beam because the nonlinear effect on the electron orbits of the sextupole correcting magnets makes large-amplitude oscillations unstable. The dynamic aperture is the largest excursion an electron may make without being lost.

For storage rings with high emittances, the dynamic aperture is usually larger than the beam pipe and is not a problem. For those with low emittances and consequently the nonlinearities associated with strong sextupole correcting magnets, it shrinks and can pose some difficulties. The small aperture is especially a problem when a new beam is injected, because the amplitude of the betatron oscillations is largest during injection before the electrons are cooled down, as it were, by emitting synchrotron radiation.

It is quite possible to design an ultralow-emittance Chasman-Green lattice with an adequate dynamic aperture. In fact, Berkeley's 1- to 2-GeV synchrotron source, when first proposed in 1983 as the Advanced Light Source, incorporated a straightforward modification of the NSLS 2.5-GeV lattice with an improved emittance and twelve long straight sections for insertion devices. When the project was delayed for political reasons, Berkeley researchers had plenty of time to explore their design in greater detail, particularly after a 1985 workshop on storage rings called attention to the possibility that other lattices may have better properties.

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An important advance that helped in this process relates to the detailed dynamics of the orbiting electrons that are so complicated that complex computer codes are needed to simulate the performance of candidate machine lattices. In the last few years, partly because of the immense effort going into designing the $4-billion Superconducting Super Collider for high energy physics, these codes have become markedly more realistic in that they include such nonideal characteristics as misaligned magnets and inhomogeneous magnetic fields.

In any case, Berkeley researchers began an in-depth study of a version of the triple-bend achromat lattice that had been proposed by Gaetano Vignola of Brookhaven as a candidate for the hard x-ray source. In January 1986, Berkeley convened a panel consisting of Samuel Krinsky of Brookhaven, Tazzari, Vignola, and Helmut Wiedemann of the Stanford Synchrotron Radiation Laboratory to evaluate this and several options, including the original Chasman-Green lattice, a so-called expanded Chasman-Green lattice, and two lattices related to the traditional FODO lattice (for focus-defocus) of high energy physics.

One outcome of the panel's brief study was a recommendation against the Chasman-Green lattice. While the addition of sufficient sextupole correction magnets could end any doubts about too small a dynamic aperture, overall the lattice was too inflexible, and the panel considered flexibility to be of paramount importance. A flexible lattice, wrote the panel, can be "tailored to the diverse requirements of the users while maintaining a satisfactory overall performance. Such lattices also seem to be more forgiving in the presence of magnetic field and misalignment errors." One example of flexibility is the ability to choose or change the kind of insertion device in a given straight section after the machine is built. The ideal electron beam for each insertion device is different in character and requires different magnet settings.

The basic means of incorporating flexibility is the addition of more dipole and quadrupole magnets. The FODO lattice is the most densely packed with magnets, which simultaneously makes it flexible and forgiving but also costly and inconvenient to work with because of the lack of space. In the end, Berkeley decided to adopt the triple-bend achromat lattice. The design group working on the Trieste machine has been looking in detail at the expanded Chasman-Green lattice but has made no final choice, while the Taiwan group has been looking into a FODO lattice.

For hard x-rays it is necessary to go much higher in energy than the nominal 1.5 GeV of Berkeley's source, which is 197 meters in circumference. Argonne scientists are studying a 7-Gev machine with 40 straight sections and a circumference of 1000 meters. Accelerator scientists generally agree that achieving an ultralow emittance and adequate dynamic aperture on the higher energy storage ring is more difficult than on the lower energy ring.

As recently as last fall, computer simulations at Argonne seemed to be bearing out this grim scenario. The simulations were indicating that the dynamic aperture would be too small unless the quadrupole focusing magnets could be extremely accurately placed to 0.01 millimeter in position and 0.01 milliradian in orientation. According to Yanglai Cho of Argonne, new simulations and analytical studies are dispelling this pessimism. In brief, by optimizing the number, positions, and strengths of the magnets, it is possible to find a configuration that is less sensitive to errors.

The general sentiment among accelerator researchers now seems to be that "With enough effort, any of several lattices will work equally well." Both Argonne and ESRF scientists are leaning toward an expanded Chasman-Green lattice over the triple-bend achromat, mainly for matters of convenience. One last sticky point, however, is mentioned by Robert Siemann of Cornell University. Although there is little danger that the new storage rings will fail completely, there is a chance that they will not achieve the designed high brightness, if the computer simulation codes by which these conclusions are being reached are deficient in some respect. There has been little opportunity so far to test the validity of the codes against the performance of existing machines. ■

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