

Synchrotrons round the bend to make cheaper, better x rays

After a slow start, a technique that promises deep sample penetration and improved spatial resolution is catching on fast.

Sweden's new national synchrotron light source, the MAX IV in Lund, is blazing the trail to produce the brightest x rays yet from a storage ring. The record brightness, achieved by shrinking the emittance—the product of beam size and angular divergence—of the source electrons, is thanks largely to multibend achromats (MBAs).

Today's synchrotrons use groups of magnets, typically two or three dipole bending magnets plus focusing and correction magnets, to send electrons around a circular storage ring. The trick with MBAs is to use more bending magnets per group, or achromat. More focusing magnets can then be interspersed between bending magnets, which makes it easier to return wayward electrons to the fold. The resulting x-ray beam is smaller, brighter, and more coherent.

"It's mind-boggling that in electron storage rings, which have been mature for a couple of decades, there is still a factor of 50 improvement lurking, and if we are smart enough, we can figure out how to grab it," says Stuart Henderson, director of the upgrade project at the Advanced Photon Source (APS) at Argonne National Laboratory, near Chicago.

The first generation of light sources, in the 1970s, was parasitic to machines built for particle-physics experiments. (See the article by Giorgio Margaritondo, *PHYSICS TODAY*, May 2008, page 37.) The second generation was optimized for flux. "In the third generation, we deployed undulators to produce bright beams, which were accompanied by reduced emittance," says Henderson. (See *PHYSICS TODAY*, January 1994, page 18.) The jump in performance promised by MBAs, in parallel with other technical advances, has people calling the MAX IV and other MBA-adopting facilities fourth-generation synchrotrons.

"Coherence is the game changer for these fourth-generation storage rings," Henderson says. "It gives you incredible resolution, particularly in [imaging] nonperiodic systems, which after all are what most of life is made of." The improved coherence, the increased brightness—which "takes what you can



The large storage ring at the MAX IV light source in Lund, Sweden, has 20 seven-bend magnets; the lower half of one is shown here. The upper half will be added as the final installation step. Carving the magnets into iron blocks cuts costs and simplifies the alignment process.

do today and puts it on steroids"—and the larger field of view hold the promise of applications across many areas of science. For example, says Henderson, "with coherent flux at high x-ray energy, you could penetrate a fully functioning battery and, with resolution approaching atomic scale, look at the electrochemistry." Other examples include studying the early stages of crack formation in structural materials and looking at a beating heart or a breathing lung *in vivo*.

Picking up the ball

Initially, the MBA approach was widely dismissed. But now, says Hamed

Tarawneh, who is in charge of insertion devices at MAX IV, "many labs are copying the idea. Lund is the Mecca." (See the interview with Tarawneh in the Singularities department of *PHYSICS TODAY*'s online Daily Edition.)

The idea of MBAs for synchrotron sources goes back to a 1995 paper by Dieter Einfeld, who was a machine physicist at the Elettra light source in Trieste, Italy. But, says Einfeld, now a consultant for the upgrade to the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, "my colleagues didn't look at this option in detail." Until, he says, Mikael Eriksson of Sweden's MAX IV "picked up the ball" in 2003.

Eriksson, who heads the machine group at MAX IV, says the attraction of MBAs was their relatively low cost. "In Sweden, a small country, there was no use asking for money for a large machine," he says. "So we went the other way and looked at how to build small technology, small magnets." The MAX IV, with a circumference half the size of some existing third-generation light sources, will produce brighter beams.

Meanwhile, several technical advances have smoothed the way to realizing MBAs. For example, the magnet requirements drive down the size of the vacuum tubes in which the electrons circulate, from the conventional diameter of 50 mm to only 22 mm. Evacuating such narrow tubes is possible with a nonevaporable getter, a distributed pumping system that uses an alloy coating to passively absorb molecules.

Emitance decreases as the third power of the number of bending magnets in the storage ring. The vertical emitance is already small in third-generation storage rings, typically 5–10 picometer radians; it's the horizontal emitance that is mainly affected as the electrons fly around the ring and radiate x rays. In the synchrotron business, there is a strong push toward the diffraction limit, for which the emitance is small enough that the brightness of the x-ray beams depends only on wavelength. "That is the holy grail," says Eriksson. "MAX IV is a factor of 20 from that." At MAX IV, the horizontal emitance will start at about 300 pm-rad, and go down to 150 pm-rad as undulators are added.

Integrated magnets

MAX IV will have two storage rings: a 528-m-circumference, 3-GeV ring for hard x rays, and a 96-m, 1.5-GeV ring for soft x rays, which is a traditional research strength in Sweden. Both rings will be fed by a 1.5-GeV injector that could later be lengthened for use as a free-electron laser.

An innovative feature of MAX IV is that the MBAs are being machined into solid iron blocks (see photo on page 21). Each block is about 2.8 m long and houses a dipole bending magnet plus focusing and correcting quadrupole, sextupole, and octupole magnets. The 3-GeV ring will have 20 "seven-bend" MBAs, each made up of seven blocks. The 1.5-GeV ring will have 12 double-bend achromats. "The revolutionary thing is to have several magnets in one block," says MAX IV laboratory director Christoph Quitmann. "Instead of in-

stalling 1000 magnets and aligning them carefully," says Eriksson, "we only have to install 140 blocks. This is simpler. Everything is prealigned."

The computerized precision machining "makes it possible to build a huge number of magnets, mechanically stable, all for affordable cost," says Quitmann. And, he adds, "because the magnets are smaller, the magnets in the new facility will use 10 times less power per meter of circumference than Sweden's present third-generation machine. We will have five times more circumference but use half the electrical power. We are much more environmentally friendly, which gives a political benefit, and we save money." The total cost of MAX IV is \$500 million, including the site, buildings, three accelerators, and the first 8 of as many as 26 beamlines. Startup for users is scheduled for June 2016.

"Everybody got excited"

Two other new synchrotrons are being built from scratch with MBAs: Sirius, a 3-GeV facility in Campinas, Brazil, and Solaris, a replica of MAX IV's low-energy ring, in Krakow, Poland (see the story on page 23). The ESRF is the only upgrade to MBAs yet funded, but considerations are under way at many facilities, including Soleil in France, Diamond in the UK, SPring-8 in Japan, and the APS and Advanced Light Source in the US.

The \$430 million Sirius will use five-bend MBAs. "We achieve the same emitance as Lund with fewer bends because our optics is more aggressive," says Sirius accelerator physicist Liu Lin. "It's a tradeoff. In principle, we have more room for insertion devices." At Sirius, the magnets will be mounted separately, partly because the precise machining capability for the integrated magnet blocks is not locally available. Sirius is slated to turn on for debugging in 2018.

ESRF director Francesco Sette says that the idea of an upgrade using MBAs was abandoned in 2008 because at the time switching would have meant an injection efficiency of less than 1% "or an unsustainable upgrade cost." Then, he says, in 2012 Pantaleo Raimondi, who heads the facility's accelerator and source division, found a solution: a hybrid seven-bend achromat, in which the dipoles are not all identical. "By adapting the bending," explains Sette, "the energy and momentum of the electrons from the injector can be matched to the storage ring. Everybody got excited."

The approval and funding process for an ESRF upgrade moved quickly. "We will rip out everything in the storage ring except the straight sections," says Sette. The horizontal emitance will shrink to 60–100 pm-rad from its current 4 nm-rad, he says. The €340 million (\$380 million) upgrade began in January and is scheduled to be finished by 2022. Now, says Sette, "the biggest challenge is to deliver with minimal disruption of the user program."

At around the same time the ESRF upgrade got the green light, the US Department of Energy's Basic Energy Sciences Advisory Committee looked at the US position in the international landscape of light sources. "The consensus was that the US has to get its act together in terms of light sources. The US has to have a plan to ensure competitiveness," says Henderson.

The APS upgrade team is looking at a hybrid MBA design similar to ESRF's. The emitance drops rapidly with the number of bends, but there are trade-offs to having more bends, Henderson says. "It requires gymnastics in the correction magnets. There seems to be a sweet spot around seven bends [for the APS]. Five is not aggressive enough, and nine looks too complicated."

Along with the switch to MBAs, the APS would decrease the energy of its storage ring from 7 GeV to 6 GeV. That's advantageous because emitance scales as the square of the energy, explains Henderson. Combined, he says, the two changes will reduce the emitance by a factor of 50. The horizontal emitance will be about 67 pm-rad. "We can make up for the beam energy by using superconducting undulators. Replacing permanent magnets with superconducting undulator magnets gives you a boost in flux, particularly with hard x rays."

Fourth-generation upgrades for APS and the Advanced Light Source are not yet priced out or funded. But to stay competitive, says Henderson, they have to be in operation by the mid 2020s. "Pretty much everyone is looking to upgrade with MBA." And, says Eriksson, "Others are now pushing their magnet lattices harder than we dared to do."

Japan intends to upgrade its light source, SPring-8, on a similar time scale. The plan there is to use five-bend hybrid achromats and to reduce the storage ring energy from 8 GeV to 6 GeV; the ultimate target emitance is around 10 pm-rad, says director Tetsuya Ishikawa. The project, not yet funded, will cost an estimated ¥40 billion (\$340 million).

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