Wiggler Magnet Shakes Light from Electrons

Successful test at Stanford shows that new device enhances synchrotron radiation from orbiting electrons in storage rings

The story begins with Maxwell and his famous equations. Loosely put, shake an electron and light falls out. Moreover, the faster the electron is moving and the more violently it is shaken, the more intense is the radiation emitted and the shorter its wavelength. Thus, the oscillating electrons in a television transmitter give off microwave radiation, whereas the energetic electrons scattered by the atoms of a solid target in an x-ray tube emit bremsstrahlung.

Late in February, researchers at the Stanford Synchrotron Radiation Laboratory (SSRL) demonstrated experimentally that this principle could be used to enhance the synchrotron radiation from the electrons orbiting in the SPEAR storage ring at Stanford by the insertion of a special magnet called a wiggler. Although not the first wiggler ever operated in a storage ring, it was the first inserted specifically to produce more radiation and that is exactly what it did. In one quick and dirty experiment, SSRL researchers were able to record in only 2 minutes an x-ray absorption spectrum that would have taken 10 days without the wiggler.

Although several storage rings are under construction solely for the purpose of providing useful synchrotron radiation, most of those now existing were built by high-energy physicists to study elementary particles. For several reasons, synchrotron radiation is a nuisance to the particle people, who would just as soon not have to bother with it. It is therefore more than a little ironic that the wiggler added to the SPEAR storage ring has also proved beneficial to the physicists of the Stanford Linear Acceleration Center (SLAC), who run the SPEAR storage ring, by substantially increasing the rate at which data can be taken. Says the deputy director of SSRL, Herman Winick, "For the first time we can describe our relationship with SLAC not as parasitic but as symbiotic." SLAC physicists are already taking a hard look at what it would take to install up to four wigglers in SPEAR and are planning two by the summer of 1980. And the new, much more energetic storage ring (PEP), which is scheduled to begin operation at Stanford this fall, will have three wigglers in place from the start although this was contemplated well before the recent wiggler success.

The future may hold even more exciting developments. A modified form of wiggler has been intensively studied theoretically (and some early experiments done in the U.S.S.R.) that could convert the broad synchrotron radiation spectrum (which extends from the infrared to the x-ray regions of the electromagnetic spectrum) into a well-defined narrow band of wavelengths, which would then become even more intense. These devices which are called undulators, can also be used to make extremely bright lasers that can be tuned to any wavelength desired, from the infrared to the ultraviolet. Some observers feel that the likelihood of developing powerful, efficient visible or ultraviolet lasers by conventional approaches is rapidly diminishing and that, therefore, undulator or free electron lasers are the best hope for such devices, which are necessary for industrial laser-induced chemistry processes to be practical. Although more speculative, using a free electron laser for laser fusion has also been discussed.

Wigglers are hardly a new idea; a primitive form of an undulator was even demonstrated in the 1951 experiments of Hans Motz (now at the University of Oxford), who used a linear electron accelerator (there were no storage rings in those days). The origin of the SSRL wiggler, however, lies in the fact (unfortunate for synchrotron radiation users) that the most interesting high-energy physics at SPEAR occurs when the electrons in the ring each have an energy from 1.5 to 2.2 billion electron volts (GeV), whereas the maximum possible energy is almost 4 GeV. The synchrotron radiation spectrum has its maximum intensity and short wavelength cutoff fixed by the electron beam energy, and to obtain adequate fluxes of x-rays, which is the radiation most in demand at SSRL, the beam energy should exceed 2.5 GeV. A wiggler provides the solution because, for the same beam energy, it can shake more radiation at all wavelengths from electrons and it can reduce the short wavelength cutoff, or so it was widely believed. An extra bonus is that nearly all the radiation produced by the wiggler can be used, since it is emitted in a small area, whereas ordinary synchrotron radiation is emitted almost everywhere around the storage ring.

To test the effect of a wiggler on storage ring performance, a joint SSRL-SLAC team headed by James Spencer began a low-budget project to design, construct, install, and operate a wiggler in SPEAR. The team built a conventional electromagnet (iron core and copper windings) that could create a magnetic field up to 2 teslas, weighed about 1100 kilograms, and was about 1.2 meters in length. Although the magnet itself cost just under \$20,000, the total cost of all equipment needed reached to over ten times that amount. By last November, the wiggler was in place in the storage ring in a space "grudgingly" given up by the high-energy physicists. A month later, these same scientists were using the wiggler in their own elementary particle experiments. But it took until February to use the enhanced synchrotron radiation because it was also necessary to install a new beam line (an evacuated pipe through which the radiation emitted by the orbiting electrons passes on its way from the storage ring to whatever x-ray optical equipment is needed for a given experiment). Quipped Spencer, "By the end of February we could see the light at the end of the tunnel."

Although only preliminary studies have been done so far, the results meet or surpass all expectations. As a general rule, the intensity of the synchrotron radiation is increased by a factor of 6. The effect on the short wavelength cutoff depends on the electron beam energy, but at a typical operating energy at SPEAR (1.5 GeV), the minimum wavelength is reduced by a factor of 4. (Since the flux of radiation at wavelengths shorter than the cutoff is effectively zero, the increase in intensity in the wavelength region between the old and new cutoffs is much, much greater than a factor of 6.)

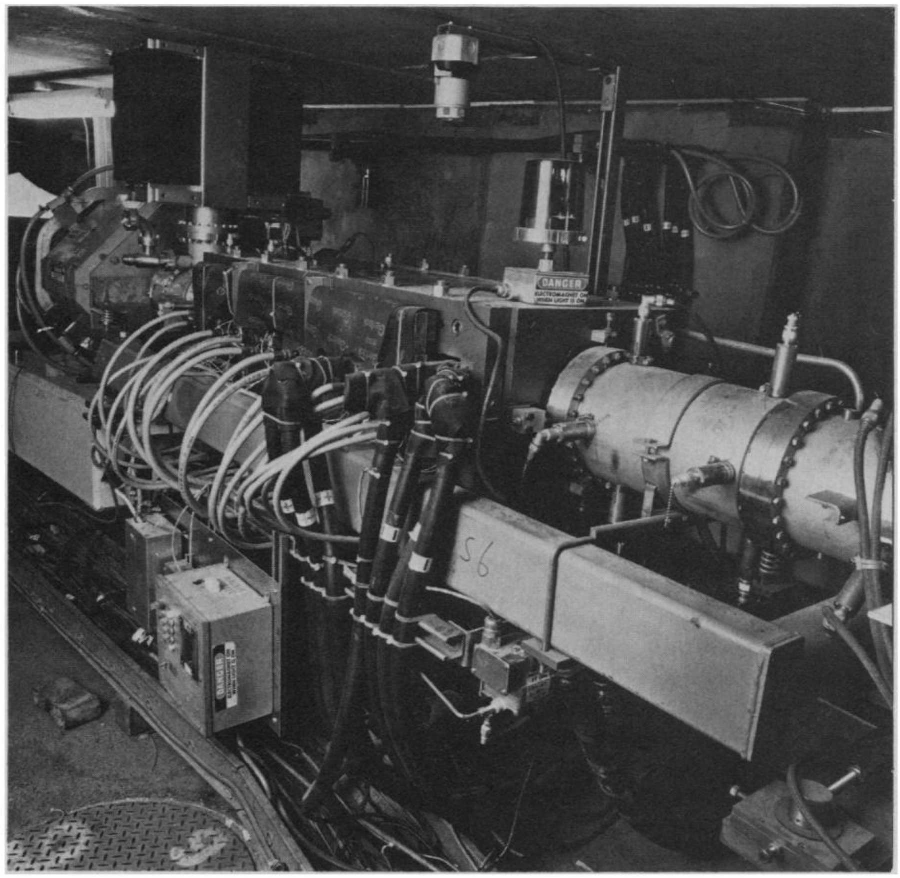
Successful operation of the wiggler is causing more than just elation among the SSRL staff. A number of new beam lines have been under construction, mainly to serve the vast waiting line of researchers who want access to x-rays. The SLAC proposals to add additional wigglers to SPEAR have set off a flurry of activity aimed at revamping the plans for the expanded SSRL facilities to take advantage of the wigglers. Revamping is necessary because wigglers are placed at locations in the ring where synchrotron radiation normally is not produced.

At other synchrotron radiation centers around the world, wigglers are also planned, but these plans all predate the successful SSRL demonstration. Brookhaven National Laboratory's new National Synchrotron Light Source that is expected to begin operation in October 1981 will have a wiggler made from a superconducting magnet and is designed to produce a very high flux of short-wavelength x-rays sometime during the first year, according to Samuel Krinsky of Brookhaven. The University of Wisconsin's Synchrotron Radiation Center in Stoughton has a storage ring now that is dedicated to the production of synchrotron radiation and has a larger ring under construction (scheduled for completion by the summer of 1980). But, says Walter Trzeciak of Wisconsin, there are no plans for wigglers in the short term, although eventually special wigglers to produce circularly polarized radiation may be added. Ordinary synchrotron radiation is plane polarized.

Overseas, a wiggler is ready to be installed in the ADONE storage ring at Frascati, near Rome, which will allow that 1.5-GeV machine to produce x-rays. Elsewhere, wigglers at centers in Europe, the Soviet Union, and Japan are in various stages of study or construction.

How do wigglers cause their wondrous effects? To begin with, synchrotron radiation is itself a prime example of shaking light out of electrons. In this case, the shaking is to the laboratory observer more like a nudge, but it seems to do the job. Electrons confined to a circular path by a magnetic field, as in a synchrotron or in a storage ring, experience a constant radial acceleration. And Maxwell's equations say that accelerated electrons radiate electromagnetic waves. The more sharply curved their path, the more intense is the electrons' radiation.

A magnet with a single north and a single south pole is a dipole magnet. A wiggler (at least in its simplest form, the transverse wiggler) consists of a linear array of alternating dipoles—that is, the polarities of the neighboring dipoles are reversed. Thus, on passing through a wiggler, an electron is alternately pushed toward and away from the center of its circular orbit in the storage ring; its path wiggles a little rather than being smooth. And the radius of its trajectory, while wiggling, is smaller than the radius of its circular orbit so that the intensity of the synchrotron radiation is increased and the short wavelength cutoff is reduced.



Stanford Synchrotron Radiation Laboratory wiggler magnet installed in the SPEAR storage ring at the Stanford Linear Accelerator Center.

Wigglers' effects on high-energy physics experiments are considerably more subtle. For elementary particle studies, it is necessary to smash a beam of particles (usually either electrons, protons, pions, neutrinos, or photons) into a target. In storage rings, the target is replaced by a second beam of particles circulating in the ring in the opposite direction. It is the collisions between particles in the two counterrotating beams that provide the high-energy physicists their data. In SPEAR, the second beam consists of positrons (anti-electrons). When electrons and positrons collide, they annihilate, and the energy created is used to make other elementary particles by way of Einstein's $E = mc^2$. Electrons and positrons, being pointlike, do not collide often, and physicists want to make the respective beams as densely packed as possible in order to collect a useful amount of data in a short time.

The problem is that, even when they do not collide, electrons and positrons passing by one another can perturb the other's trajectory. If too many electrons and positrons are in the beams, each beam will tend to destroy the other and experiments are over until the ring is refilled with particles. (In storage rings dedicated to the production of synchrotron radiation, there is only a single electron beam, so beam-beam interactions are not a problem.)

At first glance, the wiggler would seem to make the collision rate even lower because the increased emission of synchrotron radiation tends to increase the cross sectional area of the beam, thus decreasing the probability of a collision. (Synchrotron radiation consists of a random emission of photons, and these give an electron a little kick each time one is given off.) But, as it happens, it is also possible to store more electrons and positrons in the beams than previously before they are destroyed; and it works out that the overall effect is to increase the collision rate. In one set of experiments, according to SLAC's Roy Schwitters, the time needed to collect data was reduced by 20 to 30 percent.

Keeping a colliding beam storage ring operating at the highest possible collision rate seems to require a tightrope act. Another complication is that the diameter of the beam and hence the maximum number of electrons (or positrons) that can be stored in it decrease rapidly as the beam energy drops toward the lower end of a storage ring's operating range. The new PEP ring and its already operating cousin PETRA at the Deutsches Elecktronen Synchrotron laboratory in Hamburg will span fairly wide energy ranges, from about 4 to 19 GeV. For effective operation at the lower end of this range, it is imperative to increase the collision rate. For this reason, PEP will use wigglers. PETRA engineers are now experimenting with another approach but, in the end, they may have to go to wigglers. At a third new storage ring called CESR and just now coming into operation at Cornell University, plans for wigglers have been temporarily dropped in favor of the German method, according to Maury Tigner of Cornell.

Wigglers have still another use in storage rings. The electrons do not maintain a uniform orbit in the ring but tend to oscillate, back and forth, with the theoretical orbit as a kind of average trajectory. Ordinary synchrotron radiation can make these oscillations decrease or increase, depending on the design of the machine. The now dismantled Cambridge Electron Accelerator (CEA), for example, which started life as an electron synchrotron, was an example of the latter. In a synchrotron, gradually growing oscillations are not a problem because the electron beam is shot forth to bombard a target as soon as it reaches a designated energy. A storage ring, however, holds beams for hours, and a gradually growing oscillation would soon destroy the beam. Thus, Kenneth Robinson (recently deceased) and his colleagues at CEA hit upon the idea of using two wigglers to convert the machine from one in which oscillations grew to one in which they did not. This trick in the late 1960's was the first use of a wiggler in a large storage ring (the CEA had a maximum energy of 3.5 GeV). In view of the present frantic pace of building new storage rings to produce synchrotron radiation, it is interesting to recall that many years ago there was already in place a machine that could have served well, and it even had wigglers.

Undulators differ from wigglers in two respects, and it is these differences that cause the radiation from undulators to be confined to a narrow band of wavelengths. The first difference is that the number of dipoles making up an undulator is usually larger than the number in a wiggler. The SPEAR wiggler consists of seven dipoles, for example, and the PEP wigglers under construction consist of three. Undulators may have 20 or more dipoles. A device built by John Madey and his colleagues at Stanford University for free electron laser experiments has the equivalent of 320 dipoles. (Madey's magnet consists of helical windings that extend over the entire length of the magnet, and therefore it is not, strictly speaking, a linear array of dipoles.) The second difference is that the magnetic field generated in an undulator is much lower than in a wiggler. The field in Madey's magnet was 0.24 tesla, for example, and lower fields than this are not unusual in theoretical models of undulators.

The center wavelength in the band of light emitted by undulators is determined primarily by the spacing between the dipoles (or the wavelength of the periodicity of the windings in a helical magnet) and by the energy of the electron beam, and secondarily by the magnetic field. In general, the wavelength is considerably longer than the short wavelength cutoff of the synchrotron radiation from the storage ring without a wiggler. Thus, a ring such as SPEAR, which can generate copious quantities of x-rays as synchrotron radiation, could not generate x-rays from an undulator, although "soft x-ray" wavelengths as short as 5 angstroms are a possibility. The main advantage of an undulator lies in the promise of exceedingly intense radiation in a narrow band of wavelengths. Theorists calculate that the intensity of light from an undulator could be as high as 10,000 times that of synchrotron radiation of the same wavelength in the same storage ring. This enhancement is possible because the energy used in producing the broad range of wavelengths in the synchrotron radiation spectrum is devoted only to the production of the narrow band of undulator wavelengths.

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So far, undulators have been installed in circular machines only in the Soviet Union, where experiments have been done at the electron synchrotrons at the P. N. Lebedev Physical Institute near Moscow and at the S. M. Kirov Polytechnic Institute in Tomsk. According to Winick, these are strictly test devices designed to verify the predictions of theory, and are not practical light sources. The first useful light from an undulator may come from a group headed by Yves Farges at the ACO storage ring of the Laboratory for the Utilization of Electromagnetic Radiation in Orsay, near Paris. Construction of a superconducting magnet with 24 dipoles is under way, and it may be operational by early 1980.

Free electron lasers are by far the most speculative application of wiggler-like devices in storage rings. To transform an undulator into a free electron laser, it is necessary to create an optical cavity by the use of two mirrors between which the light reflects back and forth. The buildup of a highly intense, monochromatic, and coherent light beam then proceeds as with any laser. Free electron lasers have been built (by Madey's group at Stanford in 1977 and by a collaboration between researchers at Columbia University and the Naval Research Laboratory last year), but these low-efficiency devices were built around linear accelerators of two quite different types.

A simple view would be that a storage ring could considerably enhance the efficiency (the fraction of the energy used to run the electron accelerator that is converted into photons coming out as a laser beam) because the electrons could be used repeatedly as they circulate around the ring. But Madey has estimated that only from 1 to 10 percent of the synchrotron radiation could be transformed into laser light. Moreover, when the free electron laser was operating, the dozens of research groups that now simultaneously use the synchrotron radiation from a storage ring would no longer be getting the intense light they are used to. Nonetheless, for a storage ring such as SPEAR, a laser with an output power of up to 10 kilowatts and with a wavelength that could be tuned from the infrared to the ultraviolet simply by adjusting the electron beam energy would be possible. The existence of such a facility would surely send physicists, chemists, and biologists scrambling to use it.

To reach even higher levels of output power, either special purpose storage rings or even another type of accelerator altogether may be necessary. Numerous alternatives are under study, according to Claudio Pellegrini of Brookhaven, who gave a review of free electron lasers at a conference on accelerators this March.

—ARTHUR L. ROBINSON