that these Boolean circuits have to be really big for problems in NP and for problems farther up the polynomial hierarchy. So what Sipser and his colleagues did was to look at restricted versions of the network. Suppose that the networks can grow as wide as you want but that their depth is limited. Then, Sipser asked, Can you prove that there is a difference between classes in the polynomial hierarchy? The three investigators looked at the parity function, which simply computes whether there is an even or odd number of ones in a string of bits and showed that, if they limit the depth of the circuit, the width of it blows up so that it is bigger than any polynomial. At about the same time, Miklós Ajtai of Hungary, who is now at IBM in San Jose, proved a similar result.

But this finding, impressive as it was, was not enough to show that the polynomial hierarchy is distinct in this restricted circumstance. This result was finally obtained by Yao, who now has shown that the width of the Boolean circuit for the parity function increases even faster than Sipser, Furst, and Saxe and Ajtai found. It grows exponentially, which is incomparably faster than polynomial growth. And, as a consequence and extension of his result, he showed that there exists an oracle for which the polynomial hierarchy is distinct.

It is, says Yao, "a difficult proof." Sipser describes it as "very intricate and deep rather than just a clever trick." But Yao, Sipser, and others think the implications of the proof go far beyond the immediate discovery that the polynomial hierarchy is separable in the strange world of oracles. In fact, Yao remarks, his work is "a positive step" toward proving that the polynomial hierarchy may be distinct without oracles, although mathematicians find the oracle approach controversial. Some are enthusiastic whereas others say that the results have no obvious connection to the real world.

The true importance of Yao's proof, according to even the oracle skeptics, is that it shows that a combinatorial approach, using Boolean circuits, might be used to get at the polynomial hierarchy problem.

Graham explains, "To many people, Andy's result provides real evidence that there's a lot to be learned by looking at sophisticated combinatorial arguments. People could never really get their hands on circuits until now. I expect that this will give people renewed impetus to push this approach. There is a lot more hope now that the circuits will give you something."

If the circuits really are to solve the polynomial hierarchy problem, and without an oracle, then researchers will have to extend their results to unrestricted circuits, those that can grow to any depth necessary. How feasible is this? Sipser, for one, suspects that it can be done. "I have some ideas on how to go to unrestricted circuits," he says. "Let's just say that I am confident enough to invest my time on it."

And, finally, there is a small but not insignificant practical application of this highly abstract research. Certain kinds of circuits, called programmable logic arrays, are easy to put on chips and, Sipser points out, "they have intrinsic depth limits." Computer engineers had noticed that there are certain kinds of operations that simply could not be put on these circuits, a key one being the parity function and another being multiplication. "Everyone knew that you can't do parity or multiplication on a programmable logic array, but no one could prove it," Sipser remarks. "Now we know why these things are impossible."—GINA KOLATA

Synchrotron Radiation Takes Over at Orsay

Once a small, piggyback operation, the LURE laboratory now has exclusive use of all Orsay accelerators and is building a new one

Those used to a "small science" style of research now often have to travel to large centralized research facilities in order to do forefront experiments. This article is one of a series in which Science *looks at such centers in Europe.*

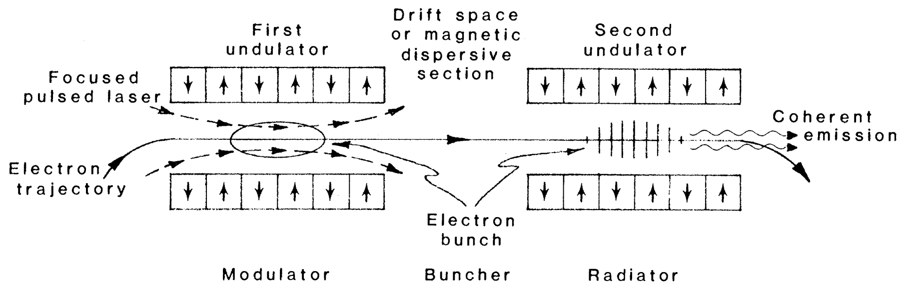
Orsay. The rags to riches tale of the clerk who rises to become president of the company applies at least in part to the Laboratory for the Use of Electromagnetic Radiation (LURE in French) here at the University of Paris-South. As of 1 January, LURE assumed full responsibility (hardware, personnel, and administration) for the accelerators formerly operated for high energy physicists by Orsay's Linear Accelerator Laboratory (LAL) and now dedicates them to the production of ultraviolet and x-ray synchrotron light.

Now renamed the Laboratory André Lagarigue (after its founder), LAL has by no means gone out of business. Its high energy physicists, as is the custom nowadays in Europe, carry out their elementary particle experiments at the large laboratories CERN near Geneva and DESY in Hamburg. At the same time, from its meager start in 1972 as a single research group siphoning off ultraviolet synchrotron light from the ACO electron-positron storage ring at LAL, LURE has grown into a major research center serving over 400 scientists.

In addition to 130 former LAL engineers, technicians, and support staff inherited as part of the restructuring, LURE is gaining a 2-billion-electron-volt (GeV) electron linear accelerator (the one from which LAL got its name) and a 1.85-GeV electron-positron storage ring named DCI, which serves as the x-ray source for 11 instruments. The laboratory already had taken control in 1975 of the smaller 547-million-electron-volt (MeV) ACO, which generates ultraviolet light for a dozen experimental stations.

At 20 years of age, ACO is ancient as storage rings go and, of course, was not designed with synchrotron radiation in mind anyway. LURE is nearing the end of the civil construction phase of a project to build Super ACO, an 800-MeV machine that should be ready for experimenters in a little under 2 years. Super ACO will compare favorably with dedicated ultraviolet synchrotron sources in Berlin and at Brookhaven National Laboratory (*Science*, 15 March, p. 1323), but it will also be quite innovative.

Most notably, Super ACO will be the first synchrotron facility to rely on a special kind of magnet called an undulator as the primary source of radiation, which will make for an extremely bright light. As frosting on the cake, it will also store a beam of positrons rather than electrons in order to enhance the stability and lifetime of the beam and thereby allow longer uninterrupted periods of bright light for researchers.



Optical klystron

Schematic diagram of the optical klystron showing the modulator, buncher, and radiator sections. The infrared laser light is focused in the modulator, while the coherent output light comes from the radiator. [*Source: J. M. Ortega, LURE*]

Super ACO is, in fact, the future of LURE. The European nations have been inching their way toward a decision on building jointly a 5-GeV storage ring (the European Synchrotron Radiation Source or ESRF), which will be a center for x-ray research (*Science*, 27 July 1984, p. 391 and 14 December 1984, p. 1294). Assuming the ESRF eventually does find a home, it is unlikely that any significant improvements in DCI itself or expansion of experimental facilities for x-rays would be made beyond those already planned, says Denis Raoux, the deputy director of LURE.

Storage rings are not perfectly circular. As described by Pierre Marin, who is in charge of the project, Super ACO will be more like an octagon with a circumference of 72 meters and eight straight sections 3 meters long. With a beam energy of 800 MeV, Super ACO will generate synchrotron light at wavelengths blanketing the entire ultraviolet and reaching into the soft (long wavelength) x-ray region. The light will come from two types of sources, bending magnets and undulators.

Bending magnets are the dipoles that confine the electron (or positron) beam in its roughly circular orbit and are the traditional sources of synchrotron radiation. Undulators are special magnets that sit in the long straight sections and wiggle the beam through a sinusoidal (or sometimes helical) trajectory. Light from bending magnets smoothly covers a broad spectrum with an exceptionally high brightness, as compared to that from ordinary sources. However, the light from undulators is compressed into a few narrow bands and therefore may be, in the optimum cases, 10,000 times brighter still. Researchers can select the undulator wavelength bands by adjusting the strength of its magnetic field.

Because of the superior brightness of undulator light, all proposals for new synchrotron sources emphasize their use, and LURE plans no exception for Super ACO. Of the eight straight sections, two are taken by the radio-frequency cavity that feeds energy into the circulating beam and by the magnets that guide positrons from the linear accelerator, where they are generated and accelerated, into the storage ring. LURE plans undulators for the remaining six, says Marin. And eight beamlines, the evacuated pipes that channel light from the storage ring to the experimental stations, from bending magnets are presently under consideration.

As for DCI, three new beamlines are in the offing. One will take light in the conventional way from a bending magnet, while a second will make use of a device similar to an undulator that is called a wiggler. A wiggler provides a smooth spectrum like that from a bending magnet, but the light is much more intense and extends to shorter wavelengths. DCI's wiggler will use high-field superconducting magnets in order to reach down to 0.2-angstrom wavelengths, three times smaller than is now generated. These beamlines are just being commissioned. The third is still under discussion, although an undulator is a possibility. Improvements to DCI that would allow it to make maximum use of undulators (a low-emittance lattice, in the jargon) are unlikely, given the ESRF.

Reliance on undulators will give Super ACO a considerably enhanced brightness as compared to the Berlin and Brookhaven sources, which were not designed to make optimum use of undulators, although the brightness of the bending magnet light of all three will be similar. The use of positrons will help in quite a different way.

Positrons come into play because even the best vacuum in a storage ring contains a considerable number of residual gas particles, such as contaminants dislodged from the surface of the beam pipe. These become ionized and subsequently, in the case of an electron beam, are attracted by the electrons with the result that the beam intensity decays rapidly because of collisions or other effects. When the intensity is too low, experiments cease while the ring is refilled. Positrons repel the positive ions, leading to an improved beam lifetime.

Until this year, LURE has had exclusive use of the x-ray ring DCI about 25 percent of the available running time. Since the machine uses both electrons and positrons for high energy physics, LURE researchers could choose one type of beam or the other. The investigators chose positrons and have been getting beam lifetimes of 35 to 45 hours (depending on beam energy and current), quite a bit more than the 10 hours typical of electron storage rings. The ESRF and a comparable American x-ray source that is being planned (*Science*, 25 January, p. 396) may also use positrons for the same reason.

The surge in the value of the dollar relative to the French franc makes Super ACO seem a bit of a bargain at the moment. The total of 131 million French francs (1983 values) is split three ways, with 55 percent coming from the National Center for Scientific Research (CNRS), 25 percent from the Atomic Energy Commission (CEA), and 20 percent from the Ministry of Education. Included in this amount are funds for the machine itself, a 3200-square-meter building to house it, upgrading of the linear accelerator, beamline development, and a three-story laboratory and office building. The goal, according to Raoux, is to begin commissioning Super ACO by the middle of next year, so that the facility will be ready for the first users by early 1987.

How many users will there be? With six undulator and eight bending magnet beamlines, the level of activity could be similar to that of the busy basic research area of the BESSY facility in Berlin. In principle, there could be more bending magnet beamlines, up to three for each of the right dipoles. The number of instruments getting light from Super ACO will most likely be limited by the funding available. Beamlines and experimental stations for ultraviolet synchrotron radiation run about $1 million in the United States.

In the past, funding has been a problem for LURE, leading to a style of operation that differs considerably from the typical European user-oriented way of running centralized facilities. The well-heeled Institut Laue-Langevin, a neutron-scattering center in Grenoble, is the prototype. Staff researchers there have as their first duties developing instrumentation and helping outside investigators who come from universities and other institutions to use them.

LURE has had to rely quite heavily on a core of staff scientists hired by the university as synchrotron radiation researchers. This group of about 40 together with an additional 60 or so from other Paris-area universities, who spend about half their time using synchrotron light, have developed most of the instrumentation. But they have been generous in allowing visitors to use their equipment.

With the advent of Super ACO, LURE is looking to expand this approach, which bears some resemblance to what are known in the United States as participating research teams or PRT's. In exchange for funding and building a beamline and instrument, the PRT receives a significant fraction of the available beam time outside of the competitive proposal process by which experiments in centralized user facilities are selected. According to Raoux, LURE would like to see PRT-like arrangements with consortia comprising universities or research institutes outside of the Paris area. One consisting of investigators from Grenoble and neighboring areas has already formed and has begun building a beamline.

In any case, LURE has managed its share of successes. Under the leadership of founder Yves Farge, who is now in private industry, researchers put one of the first undulators into operation in any storage ring. In the process, they thereby demonstrated not only that the previously only theoretical principles worked in practice but that the undulator did not disrupt the electron beam in the storage ring, an obviously important piece of information.

Since then, in a project begun under Farge and brought to fruition under the present LURE director Yves Petroff, the group collaborated with Stanford University scientists in the use of a variation of the undulator called an optical klystron to make the first free electron laser that operates in the visible wavelength region of the spectrum (*Science*, 2 September 1983, p. 937).

Most recently, the LURE investigators pushed toward the generation of laser-like ultraviolet light by using the optical klystron to generate higher order harmonics of the radiation from an infrared laser (*1*). In brief, when the laser and electron beams travel together through the optical klystron, the electrons lose a small part of their energy, which goes into the production of light at the laser wavelength and at odd harmonics. In this case, the researchers observed the third harmonic of the 1.06-micrometer radiation from a solid-state (Nd:YAG) laser; that is, 355 nanometers.

As explained by Jean-Michel Ortega, a member of the group, the optical klystron conceptually resembles the conventional klystron. It consists of two undulators in series with a third element in between (see drawing). The third element may be a drift space, as in the drawing, but for relativistic electron beams, as at LURE, it is an undulator-like magnetic dispersive section.

The undulators consist of linear arrays of dipole magnets of alternating polarity, which cause the electron beam to follow a sinusoidal trajectory. The magnetic dispersive section has a stronger field and longer period than the undulators on either end.

Light from an infrared laser is focused into the first undulator, where the interaction between the light wave and the oscillating electrons cause some electrons to lose and some to gain energy, hence the name modulator for this section. In the dispersive section or buncher, the energy modulation is converted into a spatial modulation; that is, the electrons congregate in tiny microbunches with a periodicity equal to that of the infrared laser light. Finally, in the second undulator or radiator, the electrons emit spontaneous synchrotron radiation at a wavelength determined by the beam energy, the undulator period and the magnetic field strength.

An energy dispersive EXAFS instrument built at LURE can record complete spectra in 10 to 100 milliseconds.

These parameters are adjusted so that the wavelengths emitted are that of the infrared laser and its odd harmonics. Because the microbunches have the correct periodicity, the light from each bunch is in phase. Hence, the overall light output is coherent or laser-like.

Ortega says that it should be possible to generate pulses of 50-nanometer coherent radiation with peak powers of about 1 kilowatt by this means with Super ACO. This is enough for studies of the type usually needing lasers, such as the absorption of more than one photon simultaneously (multiphoton excitation) by an atom or molecule and other nonlinear processes. Synchrotron radiation is not intense enough in this wavelength region for these kinds of investigations.

LURE scientists have also been active in the more traditional areas of synchrotron radiation research. In common with most synchrotron light facilities, extended x-ray absorption fine structure (EXAFS) has become a workhorse technique because of its ability to quickly and accurately determine local atomic structures. About half of all proposals for research at LURE are for EXAFS experiments.

Energy dispersive EXAFS is a fast method of collecting data that illustrates the importance of instrumentation. As in most spectroscopic techniques, EXAFS data traditionally are collected by scanning through the wavelength region of interest, so that only a small part of the light irradiates the sample and is used at a given time. In the energy dispersive mode, all wavelengths are analyzed at once, thereby vastly reducing the time to collect a spectrum. Among the benefits is the possibility of studies of the kinetics of dynamic processes. For example, one experiment being planned, according to LURE researcher Alain Fontaine, is to look at the kinetics of processes within hemoglobin after the rupture of the bond between iron and carbon dioxide by absorption of laser light.

Fontaine describes an energy dispersive EXAFS instrument built at LURE that can record complete spectra in 10 to 100 milliseconds, as compared to 10 minutes in the scanning mode. The idea is to focus the incident x-ray beam on the sample with a curved crystal monochromator so that the photons of different wavelengths diverge from the sample at different angles. A linear array of solid-state detectors records the transmitted photons, with each element of the array receiving only photons in a narrow wavelength range dictated by the geometry. High-speed analog-to-digital electronics and digital memory complete the process of recording data.

All in all, sums up Raoux, despite some early apprehension, the transition of LURE from a small to a major organization has gone quite smoothly. While the staff is still wrestling with the problem of keeping everything under control during the 9-month (March through November) operating year, one advantage of being proprietor of all the accelerators is already apparent. The ability to make detailed machine improvements as needed is translating into a higher quality light source. Given Super ACO, the future prospects are quite bright.

—Arthur L. Robinson

References

1. B. Girard *et al.*, *Phys. Rev. Lett.* **53**, 2405 (1984).