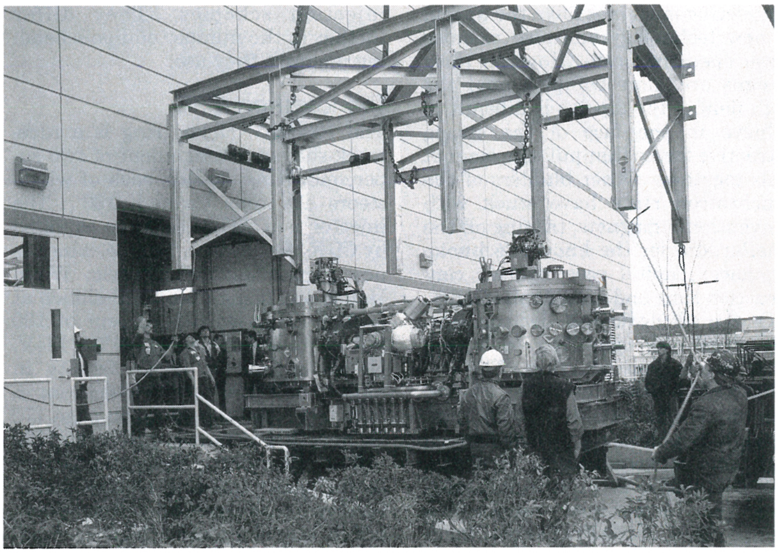
INDUSTRY GAMBLES ON ELECTRON SYNCHROTRONS FOR X-RAY LITHOGRAPHY

Ultralarge-scale integrated circuits are patterned by optical lithography, which can now imprint linewidths narrower than 0.8 micron in commercial production. With some promising innovations, optical lithography may be able to push its limiting linewidths below 0.25 microns, narrow enough to produce the next two generations of circuits—16-Mbit and 64-Mbit dynamic random-access memory chips. To cram still more electronic features onto a given area, as is envisioned for the manufacture of chips with 256 Mbits or more, will probably require wavelengths typical of soft x rays rather than visible or ultraviolet light. Thus for nearly 20 years researchers have been developing the sources, masks, aligners, resists and other components of x-ray lithographic systems.



Helios compact synchrotron being guided into IBM's Advanced Lithography Facility after being shipped from the supplier, Oxford Instruments in England. This superconducting storage ring features two 180° bending magnets, seen at either end, that steer the electrons in a racetrack-shaped trajectory. The company is exploring the machine's potential as a commercial source of x rays for lithography.

The leading contender among x-ray sources is the synchrotron radiation from electron storage rings, largely because it is the only x-ray source that clearly promises the high flux needed to match the throughputs of roughly thirty to fifty 6-inch wafers per hour per station that optical lithography can support. Expensive though they are, synchrotrons are seen as the necessary ante to stay in this high-stakes competition for chips. Industrial and governmental organizations in Japan and Germany put their money into the pot several years ago, and compact synchrotrons specifically dedicated to x-ray lithography have been built in those countries. The US and England are now entering the game: Oxford Instruments of England has built a small electron storage ring that IBM began commissioning this summer at its Advanced Lithography Facility in East Fishkill, New York. DARPA is funding the construction of a similar machine at Brookhaven National Laboratory, with participation by two US corporations. And Louisiana State University, with funding from DOE, has bought a new ring made for it by the Brobeck Division of Maxwell Laboratories in Richmond, California.

Does the world really need more synchrotron facilities? There is an ever increasing number of synchrotron radiation facilities around the world (see PHYSICS TODAY, April, page 17), and many of these have in fact been used to study the potential of x rays for lithography. In the US, for example, extensive research is being done by the Center for X-Ray Lithography of the University of Wisconsin, using five beam lines at Wisconsin's Aladdin storage ring, and by IBM, using two beam lines at Brookhaven's National Synchrotron Light Source. In Japan, NTT, Hitachi, NEC and Fujitsu have beam lines devoted to lithography research at the KEK photon factory. But if the x rays are to be used for commercial manufacturing, their sources will have to fit into industrial settings, where floor space is at a premium. Thus the storage rings must be very compact, on the order of a few meters across. The injectors must also be small, and so the rings will have to accept injected electrons with the lowest energy possible. Finally, the facilities should be reliable, long lived and easy to operate. The goal of the compact synchrotron projects is to gain experience in building and operating synchrotrons specifically dedicated to lithographic work. (See PHYSICS TODAY, January 1988, page 49.)

Warm or cold magnets?

Synchrotron radiation is produced as electrons in a storage ring are bent in curved trajectories by the dipole magnets. Roughly half of the rings dedicated to x-ray lithography incorporate superconducting magnets, which allow fields higher than the 1.4 teslas at which iron saturates; these higher fields can bend electrons in tighter circles. Compact superconducting storage rings have circumferences on the order of 10 m or less. Those based on room-temperature magnets are far larger, with girths of 30 m or more. (See the table on this page.) Superconducting machines have the appeal of new technology and also promise lower operating costs. However their designs are more complex, and the high field of the dipoles is difficult to achieve in the face of the strong attractive forces that pull the magnet coils together. Other builders of the synchrotron rings have stuck with conventional magnets, trading off the smaller size for the known technology, lower capital cost, shorter construction time and greater simplicity.

Of the six dedicated electron storage rings now operating in Japan, three are superconducting. The Oxford Instruments machine, Helios, and the Superconducting X-Ray Lithography Synchrotron at Brookhaven rely on superconducting magnets. The LSU ring uses conventional magnets. The German entry—a machine named COSY at the Fraunhofer Institute for Microstructure Technology in Berlin—is a superconducting ring. It has recently stopped running after struggling since 1988 with dipoles whose poor field quality prevented operation with full current at the design energy of 590 MeV.

The optimal critical wavelength for synchrotrons dedicated to lithography is felt to be about 10 angstroms. That wavelength calls for energies of about 600 or 700 MeV in superconducting machines and over 1 GeV in rings with warm magnets. The requirement of injecting electrons at a relatively low energy (typically 200 MeV or less) poses a big challenge for the designers. When the injection energy is low the electron takes time to settle into its proper orbit, and many electrons are lost in the process. The machines built to date have adopted various injection schemes. They differ further in the number of dipole bending magnets they use.

The latest entrants

The 700-MeV Helios ring is a racetrack-shaped arrangement of two superconducting dipoles, each of which steers electrons through 180°. The injector is a 200-MeV linac supplied by CGR MeV of Buc, France, which is now part of General Electric. When Helios was being precommissioned at Oxford it ran with a current of 100 mA at its design energy of 700 MeV. Helios arrived at IBM's facility in March, and IBM got its first beam in mid-July. (See the photo on page 17.) By now IBM is storing currents of 250 mA at full energy. Helios is adjacent to the main building of IBM's new facility for lithography development, which boasts an ultraclean environment and vibration controls. IBM estimates that it spent about one hundred million dollars to build the x-ray lithography facility. IBM is the only US firm to make this kind of investment in x-ray lithography. To learn about x-ray lithography, Motorola has joined in a partnership with IBM.

IBM will use the new facility not only to explore the synchrotron as a prototype machine for lithographic work but also to continue its research on the other components of a complete lithography system. The firm has conducted such research using two beam lines at Brookhaven's National Synchrotron Light Source for the past ten years. In July 1989 IBM exercised the full capabilities of that system by etching a simple, fully functional semiconductor circuit having features 0.5 microns wide. All ten lithographic exposures to create the pattern were done with soft x rays from NSLS.

Like Helios, the Superconducting X-Ray Lithography Synchrotron being built at Brookhaven is based on two superconducting 180° dipole magnets. This machine is being constructed in two phases. The first step is to build a storage ring according to the final design specifications, except with low-field iron dipoles rather than superconducting magnets. The second phase is to replace the room temperature magnets with superconducting ones, assemble all the parts in a new building and install a different injector. The objective of this plan is to understand as much as possible about the acceleration and injection processes before moving on to the superconducting coils. Richard Heese, director of the SXLS, told us that the phase-I machine was completed last winter, and that it had recently stored currents of over 1 A at 200 MeV. The superconducting machine will operate at about 700

Electron storage rings for x-ray lithography*

Machine	Circumference (m)	Energy (MeV)	Critical wavelength (A)	Injection energy (MeV)	Location
Superconducting rings					
Aurora	3.14	650	10.0	150	Sumitomo Heavy Industries
SXLS	8.50	700	10.0	< 200	Brookhaven
COSY	9.60	590	12.0	50	Fraunhofer Institute
Helios	9.60	700	8.5	< 200	IBM
NIJI III	16.0	620	11.7	< 200	ETL & Sumitomo Electric
Super-ALIS	16.8	600	17.3	15/600	NTT
Warm rings					
NIJI II	17.0	600	37.0	200	ETL & Sumitomo Electric
Luna	23.5	800	22.0	45	Ishikawajima–Harima Heavy Industries
SORTEC	46.0	1000	15.5	1 000	Tsukuba
NAR	52.0	800	20.0	15	NTT
CAMD	52.8	1200	9.5	150	Louisiana State University

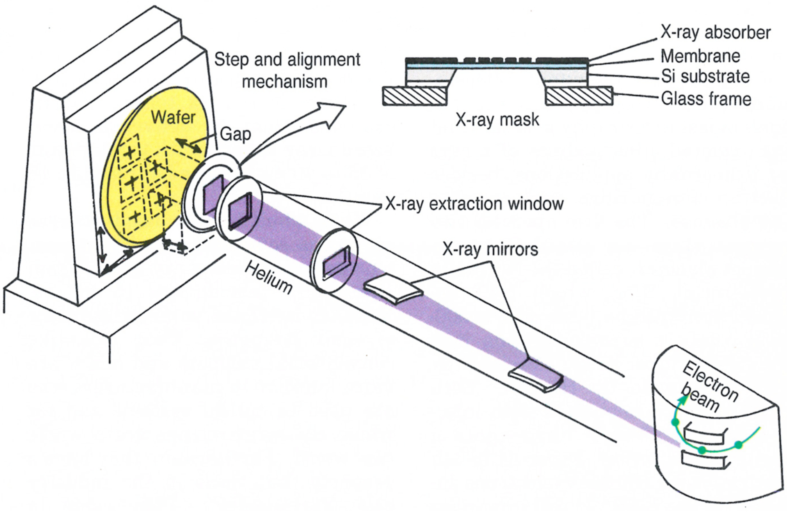
*J. P. Murphy, *Proc. SPIE* **1263**, 116 (1990).

MeV. It is expected to come on line in early 1994.

The Defense Department, through DARPA, is spending $32.5 million on the Brookhaven project in hopes that the US will have a domestic supplier of superconducting x-ray lithography sources. As part of the program, Brookhaven is working to transfer the technology to Grumman Aerospace Corporation and General Dynamics. Grumman is learning to build synchrotrons, while General Dynamics is supplying the superconducting magnets.

The only company in the US that is attempting to build a commercial electron storage ring is the Brobeck Division of Maxwell Laboratories, which is supplying LSU with a machine that has eight room-temperature magnets arranged roughly at the corners of an octagon. Volker Saile, director of the J. Bennett Johnston Sr Center for Advanced Microstructures and Devices at LSU, told us that his commissioning team hopes to store a beam in the ring by end of the year. The Department of Energy has given LSU a grant of $20 million for the ring and $5 million for the CAMD building that houses it.

Unlike the rings at IBM and Brookhaven, the LSU facility is not strictly dedicated to x-ray lithography but rather is regarded as a general research facility. There is room along the straight sections between the bending magnets for the addition of superconducting wigglers or other insertion devices. LSU will operate one beam line for lithography and another for basic science, and the university expects research teams from other institutions to work at CAMD. LSU has not had a strong group in lithography but Saile feels that the new facility is attracting researchers in this area: He reports that the CAMD staff has grown from 7 to 14 in the past six months, and that LSU has hired several faculty to do research at the new facility.



X-ray lithography system at NTT is typical of many x-ray proximity printing schemes. The pattern to be printed is outlined on a mask (shown enlarged in inset) in a material that absorbs x rays. Synchrotron radiation from an electron storage ring (at right) forms an x-ray beam, mirrors along the beam sweep it over the mask, and the x rays pass through onto the wafer. A stepper moves the wafer to position each new chip, and an aligner assures that the positioning is exact.

Japanese rings

The Japanese have invested heavily in x-ray lithography. The status of their programs was reviewed recently by a group of US experts convened by the Japanese Technical Evaluation Center at Loyola College in Maryland. (The study was funded by the Office of Naval Research; all previous JTEC reviews have been funded through NSF grants.) The JTEC group, which had toured Japanese facilities last October, will issue its report soon. The group notes that in Japan, unlike in the US, "all major industrial semiconductor manufacturers work in almost all phases of synchrotron-based x-ray lithography." Most of the funding is from the individual companies, with some seed money coming from the government.

In 1986 the Ministry of International Trade and Industry encouraged the creation of a consortium of 13 companies, named SORTEC. The consortium's ten-year plan focuses on development of sources, beamlines and steppers, all for synchrotron-based lithography. According to JTEC, SORTEC has a $100 million budget, of which $70 million comes from the government.

SORTEC decided to build a room temperature ring with a very conservative design. The finished ring can store 200 mA at 1 GeV with a 13-hour lifetime. Mitsubishi built the 40 MeV-linac injector and the final storage ring, while Toshiba supplied the 1-GeV booster synchrotron. Perhaps the greatest benefit of this collaboration is the training of the SORTEC staff, virtually all of whom are on loan from the Japanese chip makers.

The Japanese government also sponsors R&D on x-ray lithography through its support of the Electrotechnical Laboratory. Since 1981 ETL has operated a synchrotron called TERAS, where companies can conduct lithographic experiments. ETL researchers began collaborating in 1984 with Sumitomo Electric to build a series of compact rings known as NIJI-1, -2 and -3. The first of these rings demonstrated the possibility of low-energy injection. The next two are like the two phases of Brookhaven's SXLS, with NIJI-2, using normally conducting dipoles, serving as a prototype for the superconducting NIJI-3. NIJI-3 is now operational and will soon be transferred to Sumitomo Electric.

Sumitomo Heavy Industries in Japan operates the only single-dipole storage ring, and it is superconducting. The machine, called Aurora, is necessarily a weak-focusing ring, because there is no room to incorporate focusing quadrupoles. The ring has no troublesome fringing field regions, and the massive iron magnet (120 tons) provides its own shielding. The JTEC panel felt that SHI was the Japanese company closest to producing a marketable compact synchrotron. The machine is designed to accept electrons at 150 MeV and accelerate them to 650 MeV, with currents of 300 mA. At the time of the JTEC visit Aurora had just come on line and was running with 90 mA current. In the design of Aurora SHI used a novel injection scheme that has proved quite successful. The injection system uses the racetrack microtron that was designed by Ednor Rowe and his colleagues at the Synchrotron Radiation Center of the University of Wisconsin as the injector for Aladdin.

NTT, Japan's dominant telecommunications company, has the nation's oldest lithography program and has explored other sources of x rays for lithography applications, besides electron storage rings, such as tubes and plasmas. The firm operates two compact rings—an 800-MeV warm-magnet machine, called the Normally Accelerating Ring, which NTT designed and Toshiba built, and a 600-MeV compact superconducting ring known as Super-ALIS, designed by NTT and made by Hitachi. Both rings are built to operate with injection from a 15-MeV linac—quite a challenge. However, Super-ALIS can also run with 600-MeV electrons injected by the NAR. It can now store 150 mA for 4 hours, or 100 mA for 5 hours. NTT has a large semiconductor facility adjacent to the two rings, and the new beam lines will support further lithography development there.

A fourth superconducting ring is being built by Mitsubishi Electric, which acquired experience with linacs and synchrotrons by building a room temperature electron storage ring for the SORTEC collaboration. Begun in 1988, the 800-MeV machine is nearing completion. Its design incorporates four dipole magnets.

Ishikawajima–Harima Heavy Industries is building a warm-magnet prototype known as Luna, and it hopes to market such a machine by the mid-1990s. This 800-MeV storage ring has four, 90° bending magnets, and is designed to accept electrons from a 45-MeV linac and to hold a current of 50 mA.

The Japanese firms reported to the JTEC team that the current cost of the synchrotrons is in the range from \$20 to \$25 million.

Alternatives to synchrotrons

Although synchrotrons are attracting the most attention, some researchers remain seriously interested in lithographic systems based on plasma sources of x rays. Radiation emanates from the plasma that is formed when a high-power pulsed laser is focused onto a metal target. The x rays diverge strongly from the point source, so that it is desirable to have a collimator to collect a fraction of the radiation and generate a beam of parallel rays. Collimators satisfactory for x-ray lithography have not yet been successfully demonstrated. And the flux from existing plasma sources is at least a factor of 10 below what commercial lithography requires. One of the US manufacturers of plasma sources is, however, quite optimistic about the future: Robert Frenkel of Hampshire Instruments in Rochester, New York, told us that his company plans to deliver a laser-based x-ray stepper with throughputs of 35 to 40 wafers per hour within 18 months.

While admitting the disadvantages of plasma sources, Larry Thompson, who uses a plasma x-ray source from Hampshire Instruments in his research at Bell Labs, summarized some of their strengths: They look like conventional steppers and hence are more familiar to manufacturers who are used to optical systems and for whom the synchrotrons are a whole new world. Furthermore they have a property that those in the industry call "granularity": They come in small increments, whereas synchrotrons only come in chunks of 20 lithographic beam lines, each with its own stepper. A manufacturer that wanted to add a single lithography exposure station could order a plasma source. It would not pay to buy a synchrotron for a small volume application.

Some researchers have looked at alternatives to the proximity printing techniques usually envisioned for x-ray lithography. In proximity printing the radiation shines through a mask onto a wafer only a few tens of microns away. (See the figure on page 19.) The pattern transferred is the same size as the mask. The method is essentially shadow printing. Although experimental masks with features smaller than 0.1 micron have been demonstrated, it will be a challenge to make a commercial mask with features that narrow. (Current masks are made of very thin membranes.) An alternative is to develop projection lithography, in which light reflects off a mask onto a wafer, with reductions in the pattern by a factor of 5 or so. This method would obviate the need for masks with incredibly fine lines but it will require reflective masks rather than the standard transmission masks. Reflective masks could rest on a rugged, stable backing but it would be difficult to make these multi-layer surfaces with the required uniformity of reflectivity.

Many technical difficulties impede the development of x-ray projection systems. One challenge is the construction of the reflective masks and the mirrors that would form the optical systems to reduce the images. Mirrors for x-ray imaging are made by depositing multiple layers of thin reflective coatings onto a substrate. High reflectivity is obtained by coherently summing the very weak individual reflections from the many interfaces in the multilayer coating. Today the best reflectivity (about 65%) is obtained for wavelengths around 130 Å. Therefore development of x-ray projection systems centers around these wavelengths. John Bjorkholm of Bell Labs explained to us that the extreme precision required of the mirror surfaces—about one-tenth of a wavelength—is well beyond the current state of the art, even with this longer-wavelength radiation. Bjorkholm and his colleagues at Bell recently demonstrated nearly diffraction-limited imaging over a small area (only 50 microns on a side) with a projection system fed by x rays from the NSLS. A group at Sandia has performed a similar experiment using a laser-plasma source it developed. The Bell group recognizes that commercial realization of this technology is far from certain: Many of the steps needed to produce a complete x-ray projection system are beyond today's technology.

How far can optical means go?

When research on synchrotron-based lithography first began, it was anticipated that optical lithography would reach its useful limits at linewidths of about 1 micron. However, innovations have pushed that lower limit to shorter and shorter widths. In part the innovations are driven by the desire of manufacturers to cling to the investment they have in this technology: They are resistant to the radical shift in equipment and techniques that something like synchrotron-based lithography represents.

One evolutionary change that helped keep optical lithography alive was the move toward shorter-wavelength sources. Both mercury light sources and krypton-fluoride lasers reduced the wavelength of light into the deep ultraviolet region. Lenses and mirrors were developed to handle these shorter wavelengths. But these wavelengths still run up against a diffraction limit at linewidths of about 0.4 micron. There has thus been recent interest in a technique, known as phase-shifted masks, that received little attention when it was proposed in 1980 by Marc Levenson and colleagues at IBM's San Jose Research Lab (now the IBM Almaden Lab). The concept is to compensate for the diffraction that occurs as light "bends" around the edges of the features on the mask. In places where constructive interference of light might occur outside the geometric shadow of the mask, a phase shift might be introduced into some portion of the wavefront to cancel the constructive interference with destructive interference. This might be done by varying the thickness of the mask. But the variation of mask thickness would have to be specific to the particular pattern on the mask, and the technique may not work on all types of patterns.

Researchers have now turned their minds to proving the practicality of the method in commercial production. This year two Japanese firms—Oki and Hitachi—announced production of very simple devices with features of 0.17-0.18 micron using phase-shifted masks. In the US, Advanced Microstructure Devices in Santa Clara, California, Du Pont and IBM now have programs in phase-shift masks. Levenson feels that the technique has the potential to extend optical lithography to linewidths below 0.20 micron.

The balance of the system

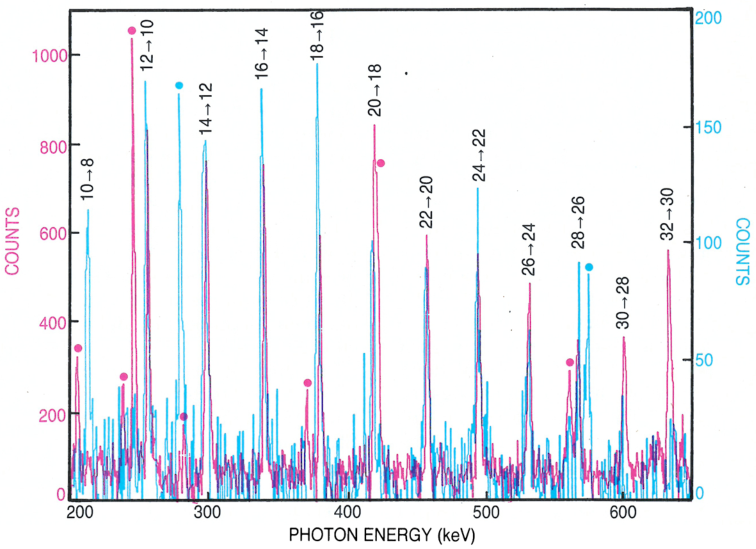
X-ray sources are of course only one part of the entire system that needs to be developed and integrated to make x-ray lithography a practical commercial tool. For example, Franco Cerrina, director of the Center for X-Ray Lithography at the University of Wisconsin, told us that the US has fallen a bit behind in the development of aligners that can position the image correctly to within 50 nm over areas about 3 cm wide, while progress is being made in process development. Henry Smith of MIT advocates a stronger emphasis on improving mask patterning, mask inspection and repair, and alignment systems. Smith would also like to see more work on granular x-ray sources and on collimators for them. Work on some of these components, as well as on integrated systems, is being done at many active centers around the world.

—Barbara Goss Levi

A NEW GENERATION OF GAMMA DETECTORS FOR NUCLEAR PHYSICS

The construction of Gammasphere, an important new photon detector for nuclear physics, began last month at the Lawrence Berkeley Laboratory. The principal purpose of this $20 million spherical array of germanium and bismuth germanate crystals will be to measure simultaneously the energies of as many as half a dozen gammas from the step-by-step deexcitation of a single excited nucleus.

Such multifold coincidence measurements are particularly important for unearthing extensive spectral patterns that would be hopelessly lost in background noise if one could measure only one or two gammas at a time. Patterns of this kind, laboriously uncovered by the present generation of smaller gamma detectors in spectra from the angular deceleration of high-spin nuclei, have in recent years taunted experimenters and theorists with some spectacular surprises.



Almost identical gamma spectra from the angular deceleration of two superdeformed nuclei—mercury-192 (red) and lead-194 (blue)—measured by the HERA detector array with different ion beams at Berkeley's 88-inch cyclotron. Each of the angular-deceleration peaks gives the energy of a quadrupole-radiation gamma that carries away $2\hbar$ of spin from the blimp-shaped nucleus. These peaks are labeled by the initial and final spin of the transition, in units of $\hbar$. The superdeformed ^{194}Pb spectrum only goes up to the $32\hbar$ peak shown here, but the ^{192}Hg spectrum continues all the way up to $42\hbar$. Other peaks in the figure, marked with dots whose colors indicate which nucleus they belong to, are known lines from gammas emitted *after* the nuclei have spun down below $10\hbar$ and are no longer superdeformed.

Gammasphere is to be a national user facility. Its siting at Berkeley's 88-inch cyclotron is not permanent. The expectation is that after an initial period of about two years at LBL, the detector will sojourn at other heavy-ion accelerators around the country. The Holifield tandem Van de Graaff at Oak Ridge and the Atlas linac at Argonne, for example, were avid competitors of the LBL 88-inch cyclotron for the initial siting of Gammasphere.

Across the Atlantic a similar gamma-detector facility, named Eurogam, is nearing completion at the embattled Daresbury Laboratory near Liverpool. Although Gammasphere was proposed before this British–French joint venture, Eurogam has benefited from more expeditious funding. Its first phase will be ready for experiments next spring. Gammasphere is scheduled for completion in 1994, but it should go into partial operation early in 1993.

Eurogam will also be an itinerant facility. After a year of first-phase operation at Daresbury's tandem Van de Graaff, it will move across the Channel to the new Vivitron Van de Graaff at Strasbourg. Brushing aside vehement protests from the nuclear physics community worldwide, Britain's Science and Engineering Research Council has recently decided