

PRINCETON TOKAMAK BEGINS EXPERIMENTS WITH TRITIUM-DEUTERIUM PLASMAS

Tokamak research entered a new and important phase last month. Shortly before midnight on 9 December, the 11-year-old Tokamak Fusion Test Reactor at the Princeton Plasma Physics Laboratory was fired for the first time with a 50:50 mixture of deuterium and tritium. That's the mixture of hydrogen isotopes envisioned for the first generation of fusion reactors, because DT fusion can be harnessed at much lower temperatures than DD or D³He fusion, and the cross section for the proton-proton reaction that powers the Sun is hopelessly small. But until now most tokamak research has been done, for practical reasons, with pure deuterium plasmas.

Two years ago the Joint European Torus in England, a larger machine of TFTR's generation, did perform two shots with a 10% admixture of tritium. JET's tritium experiment was purposely limited so as to minimize radioactivation of the machine. Not only is tritium a radioactive beta emitter; it also generates 14-MeV neutrons when it fuses with deuterium. The accumulating neutron flux from an extended series of 50:50 DT shots gradually activates a tokamak's superstructure.

That's less of a problem for the TFTR, because it is scheduled for retirement this fall, after a series of about a thousand DT shots, to free up funds for the proposed construction of PPPL's next major undertaking: the Tokamak Physics Experiment. The \$600 million TPX would be this country's first fully superconducting tokamak. (See PHYSICS TODAY, November, page 79.) One of the principal purposes of this new national facility would be to study techniques for running tokamak reactors in a continuous, as distinguished from pulsed, mode. If the TPX is not eventually funded, the useful life of the TFTR could be extended by the installation of remote handling equipment.

The reaction that is to power the first generation of tokamak fusion reactors is ${}^2\text{H} + {}^3\text{H} \rightarrow \text{n} (14 \text{ MeV}) +$

${}^4\text{He} (3.5 \text{ MeV})$. Pure deuterium plasmas are very useful surrogates for the requisite DT mixture when it comes to the investigation of magnetohydrodynamic stability and energy transport. But they don't generate the energetic alpha particles (helium nuclei) that are essential for maintaining the temperature of an ignited plasma. (The even more energetic neutrons deposit almost none of their energy in the plasma. Their function is to carry useful energy out to the external world.)

So the crucial physics of alpha heating has remained a *terra incognita*. Are the alphas adequately confined in the plasma, and how efficiently do they heat it? Do they contribute to magnetohydrodynamic stability, or instability? Veteran theorist Marshall Rosenbluth told us that "we've all been speculating for decades about what MHD effects might be induced by the large gyroradii of the energetic alphas. Now we'll finally see." Then there's the question of isotope effects: What are the consequences, if any, of the greater atomic mass of the triton (irrespective of its fusion proclivity) on the macroscopic MHD stability and microscopic transport properties of a tokamak plasma?

The first shot

On the night of 9 December, with Rosenbluth and former PPPL Directors Harold Furth and Melvin Gottlieb in festive attendance, the very first 50:50 DT shot generated a peak power of 3 megawatts of fusion energy. (Each of these experimental shots lasts for only a few seconds.) That was, admittedly, only 12% of the 24-MW input heating power from the beams of energetic deuterons and tritons fired into the plasma. But it was, far and away, a world record.

By the following night the peak power had risen to 6.2 MW. The total fusion output energy integrated over the duration of that shot came to 3.5 megajoules. In 1976 Furth had

set "1 to 10 megajoules" as a target for the culminating tritium phase of the proposed TFTR. The more ambitious goal of demonstrating "scientific break-even" would require that the output fusion power match the input heating power. The experimenters at JET plan a brave assault on that goal with tritium in 1996. But break-even, or even its simulation in a pure deuterium plasma, is probably beyond the capabilities of the TFTR, whose plasma volume is five times smaller. The smaller the surface-to-volume ratio, the easier it becomes to confine a plasma's heat.

The TFTR experimenters gradually raised the output power during this first series of shots by increasing the tritium fraction beyond 50%. Of course one wants equal numbers of deuterons and tritons in the plasma. But years of pure deuterium running have saturated the graphite inner walls of the TFTR with adsorbed deuterium. (See the cover of this issue.) The result is that one has to inject more tritium than deuterium to get an effective 50:50 fusion plasma.

The first week of DT shots at Princeton has already provided some tantalizing glimpses into the new territory of the tritons and their alpha progeny. To see if anything new was happening, the experimenters compared every DT shot with the results of a pure deuterium shot done under otherwise identical conditions. "We saw right away that the ion temperature rose from 27 keV [in the deuterium shots] to 35 keV with tritium," says PPPL Deputy Director Dale Meade. That's much more of a temperature rise than one can simply attribute to alpha heating, Meade explained, because the lion's share of the alpha heating goes to the electrons in the plasma rather than to the ions. "So we seem to be seeing some sort of subtle enhancement of energy confinement by the tritium."

An important figure of merit is the energy confinement time τ , which characterizes the rate at which heat leaks

out of the plasma. It was not known *a priori*, whether introducing tritium would have any effect, beneficial or deleterious, on τ . "Our very first tritium shot showed a τ of 190 milliseconds, where the corresponding τ in pure deuterium had been 160," Meade told us. "And it's been 20 to 30% τ enhancement

ever since. Our next job is to sort out whether the improved confinement is due to the alphas or directly to the tritons." The detailed study of confinement and alpha heating in DT plasmas will take up much of the TFTR's remaining months.

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NEW SYNCHROTRON LIGHT SOURCES TURN ON AROUND THE WORLD

"First light" shone forth this fall from three new synchrotron radiation facilities around the world: the Advanced Light Source, at the Lawrence Berkeley Laboratory in California; Elettra, at the Sincrotrone Trieste in Italy; and the Synchrotron Radiation Research Center, in Hsinchu, Taiwan. With electron energies ranging from 1 to 2 GeV, they are designed to produce high-brightness beams ranging from the ultraviolet to soft x rays, corresponding to photon energies from 10 eV to several keV. Hard x rays, with energies between 1 and 250 keV, have been produced since the summer of 1992 by the 6-GeV European Synchrotron Radiation Facility in Grenoble, France. The first of three synchrotron facilities designed to supply hard x rays from undulators, the ESRF is preparing to welcome external users to its site adjacent to the Laue-Langevin Institute in September 1994.

All these machines are third-generation synchrotron radiation facilities, specifically designed to produce low-emittance beams so that they can provide high-intensity radiation that is strongly concentrated both spatially and spectrally. (See PHYSICS TODAY, April 1991, page 17.)

These facilities bring to their respective regions a valuable tool for a variety of uses, such as x ray microscopy, the characterization of materials, the determination of protein structure and the study of chemical reactions in real time.

All synchrotron radiation facilities use linacs, synchrotrons or both to accelerate a beam of electrons or positrons, which are then circulated in a storage ring. Collimated radiation streams naturally from the sites of bending magnets, and this radiation can be channeled into beams for experiments. Beams from the first two generations of synchrotron radiation facilities consisted mostly of bending-magnet radiation. Machines of the third generation incorporate straight sections between the bending mag-

nets long enough for the insertion of wigglers or undulators. These insertion devices create magnetic regions whose polarities alternate rapidly, causing the electron beam to snake back and forth, emitting radiation as it does so. Undulators produce light in a narrow wavelength region, in contrast with the wide spectrum that emanates from a bending magnet. Third-generation machines should produce radiation of greater brightness than was available with earlier machines. (Brightness is a measure of the number of photons per second per unit source area per unit solid angle, expressed as a function of some percentage of the bandwidth $\Delta\lambda/\lambda$.)

Soft-x-ray machines

Last April the builders of the Advanced Light Source stored a current of 460 mA through the 1.5-GeV storage ring. (Its design current is 400 mA.) By early October they sent the first synchrotron light from a bending magnet to an experimental station. Funded by the Department of Energy and built at a cost of \$150 million, the ALS has room for ten insertion devices and 36 bending-magnet ports. The ALS staff expects about half of the straight sections to be occupied within two years. Brian Kincaid has been the director of the ALS since August 1992.

Elettra, whose design characteristics are similar to those of the ALS, produced its first light not long after its California rival. The first electrons circulated through Elettra in October, and ultraviolet radiation was channeled into one of its beam lines a few weeks thereafter. The electron-beam energy was 1.2 GeV, but the operators aim eventually to hit 2.0 GeV. Elettra has now reached a current of 410 mA, just over the design current of 400 mA. Nine beam lines are under construction, including one to explore the use of this radiation for mammography.

The Sincrotrone Trieste, which built and operates the \$200 million

facility, is a publicly held company whose biggest investors are Italian government agencies. Its president is Carlo Rubbia, whose term as director general of CERN ended last month. Renzo R osei is in charge of the scientific programs, and Albin Wrulich directs the accelerator development. Sadly, Wrulich's predecessor, Mario Puglisi, died just four months before the storage rings were completed.

At the Synchrotron Radiation Research Center in Taiwan operators have stored a 1.3-GeV electron beam with a current of 303 mA. Those numbers are to be compared with nominal design values of 1.3 GeV and 200 mA. Yuen-Chung Liu has been the center's director since last June, when the former director, Edward Yen, returned to his teaching post at Hsinghua University in Hsinchu. Yen reports that researchers have been conducting some synchrotron radiation experiments on three vacuum-ultraviolet beam lines since October 1993. On the four straight sections of the synchrotron, the center plans to install one wiggler by mid-1994 and three undulators in the next five years. SRRC is one of the national laboratories under the aegis of the National Science Council of Taiwan, and it was funded by the council at a cost of about \$100 million.

Hard-x-ray machines

The European Synchrotron Radiation Facility has been in the commissioning phase since the first beam circulated in the 850-m-circumference ring in August 1992. At that time the beam reached its design energy of 6 GeV and its design current of 100 mA. By now, reports its director, Yves Petroff, the ESRF ring has stored currents as high as 160 mA. With a current of 100 mA, the beam had a lifetime of 30 hours and its position was stable to within 2 microns.

One problem that faced the builders early on was the failure of the concrete floor in the experimental hall to meet tight specifications for vibration and stability. That problem is now solved, reports Petroff. In September 1994 the facility will have eight beam lines for outside users and four more built by participating research teams. ESRF is funded by a 12-nation collaboration.

The other two third-generation synchrotron radiation facilities meant to operate in the hard-x-ray region are the 7-GeV Advanced Photon Source, being built at Argonne National Laboratory, and SPring-8, an 8-GeV ring under construction in Harima Science Garden City, Japan.

—BARBARA GOSS LEVI ■