

cise mechanism for the generation and maintenance of this minority population of superthermal electrons in the complex tokamak field geometry is not well understood. It is, in fact, the subject of some controversy.

At plasma densities around $5 \times 10^{12} \text{ cm}^{-3}$, the Versator II group found a sudden plasma current increase of 30 to 40% when their waveguides launched 800-MHz traveling waves along the magnetic-field lines in the same direction as the transformer-induced ohmic current—the direction of the slideaway tail. When the waves were launched in the opposite direction there was no appreciable current increase. Furthermore, when rf pulses were applied as the transformer-driven current was beginning to drop, the plasma current could be maintained at a constant value and the loop voltage around the plasma toroid was seen to drop through zero, indicating that the rf wave had taken over the current drive from the transformer emf.

Versator II is a small, student-built tokamak with a major radius of only 40 cm. For periods of 10 or 20 milliseconds, the MIT group was able to drive about 30 kiloamps of plasma current with only 30 kilowatts of rf power—considerably in excess of the efficiency predicted by the Fisch-Bers theory. "It's not clear that what we're seeing is in fact the Fisch-Bers current," Porkolab told us. The effect goes away when the plasma density is raised to 10^{13} cm^{-3} , just as it did in the JFT-2 tokamak. The density cutoff and the anomalously high efficiency appear to be related to the superthermal slideaway electrons, a population not considered in the Fisch-Bers theory. "We haven't arrived at the promised land," Porkolab summarized, "until we produce rf driven current at densities above the slideaway regime."

The Princeton Large Torus, with a major plasma radius of 130 cm, is by far the largest of the tokamaks that have demonstrated rf current drive. It is also the only one that has achieved current drive with the transformer induction entirely shut off—for periods up to a second. In recent months rf driven currents up to 400 kiloamps have been attained at the PLT, an order of magnitude higher than those driven in the smaller machines. "With a few hundred kilowatts of rf as our only power source, we're able to maintain the 1-keV electron temperature and even increase the current," Furth told us.

The rf current-drive experiment at Princeton is led by William Hooke. Like the MIT experiment, the PLT group has found current drive efficiencies much higher than those predicted by Fisch and Bers—up to two amps per watt of rf power. And, unhappily, it

suffers the same density cutoff; no current can be driven at densities above 10^{13} cm^{-3} . The PLT results are not yet published.

The PLT six-waveguide coupler array can deliver up to 500 kilowatts of rf power for periods of less than a second. The waveguide dimensions are such that the coupler can launch waves into the plasma with phase velocities from six to ten times the mean thermal velocities of the plasma electrons (roughly one-fourth to one-half the speed of light in vacuum). These wave velocities are somewhat higher than those considered in the Fisch-Bers theory. As with Versator II, rf current drive is seen only when waves are injected in the slideaway direction. Studying the soft-x-ray bremsstrahlung spectra of the plasma electrons, the Princeton, MIT and JFT-2 groups have recently verified that the rf input greatly enhances the population of the high-velocity tail.

Future. Porkolab, Jack Schuss and their MIT colleagues are just beginning an rf-current-drive experiment at the Alcator C, a high-field, high-current-density tokamak. Because the slideaway regime in the Alcator C extends almost to 10^{14} cm^{-3} , Porkolab expects to see current drive at much higher densities than have been reached to date. The Alcator group has, in fact, already found preliminary evidence for rf current enhancement at a density of $3 \times 10^{13} \text{ cm}^{-3}$.

"Even if we can't eventually get it to work at reactor densities," Furth told us, "rf drive will probably still be very useful." Fisch has suggested that one could bring the plasma current up from zero at low density in a tokamak reactor. After the current has reached its

operating level, Furth explained, one could raise the density by adding frozen fuel pellets to the plasma. "After that, you could maintain the current with a very weak transformer. With a hot-plasma conductivity thirty times that of copper, and a minor radius of about a meter, the transformer would have to supply only about 0.01 volts to keep the current going." Such a hybrid scheme, Furth argues, should offer almost all the engineering advantages of a steady-state tokamak.

David Ehst at Argonne has recently done a comparative analysis⁶ of the various schemes that have been proposed for steady-state tokamak current drive. He concludes that driving the plasma current with relativistic electron beams or low-phase-velocity electromagnetic waves would make for a more efficient reactor than would lower-hybrid-frequency drive. —BMS

References

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Electron cooling for light-ion beams

The nuclear physicists at the Indiana University Cyclotron Facility are proposing to enhance considerably the capabilities of this light-ion cyclotron by appending to it an electron-cooling storage ring. Electron cooling has been developed over the last decade at Novosibirsk, CERN and Fermilab primarily as a technique for "cooling" antiproton beams—reducing their spread in transverse and longitudinal momentum—for high-energy physics experiments (*PHYSICS TODAY*, August 1980, page 44). The IUFC would be the first attempt to exploit beam cooling for nuclear-physics ion beams.

Initial construction funds for the Indiana cooling-storage ring are included in the President's budget request for FY 1983. Robert Pollock, leader of the cooler project at Indiana, told us that the ring would probably be in operation

by 1987 if Congressional approval permits construction to begin in FY 1983. The cooling-ring proposal is accompanied by a companion "tripler" proposal to increase the beam energy of the Indiana cyclotron by about a factor of three. IUFC is operated as a national user facility for the nuclear-physics community.

Beam cooling for nuclear physics. The Indiana cyclotron is currently capable of accelerating light ions—protons to Li^7 —to kinetic energies of a few hundred MeV (215 MeV for protons, and 50 MeV per nucleon of ions heavier than He^3). Such beam energies have been available for about thirty years, but the earlier synchrocyclotron beams suffered much larger spread in energy and angle than the isochronous Indiana machine, completed in 1975. The emittance of the IUFC beams—their