of systematic errors to obtain the necessary precision.

The Mark II experimenters used a new trigger chamber built by Perl for improving the on-line triggering of the detector. Feldman and Trilling realized that the trigger chamber would help measure the tau lifetime because it is relatively close to the interaction point and has reasonably good spatial precision.

Positrons and electrons with 29 GeV center-of-mass energy were allowed to collide, tau particles were produced, and they decayed in a variety of ways. Examining tracks exiting perpendicular to the beam pipe, the experimenters selected four- and six-pronged events. The four-pronged events had a jet of three tracks moving in the forward direction and one track in the backward direction. The six-pronged events had a jet of three tracks in the forward direction and a jet of three tracks in the opposite direction.

To eliminate the only important background, they rejected events in which any pair of particles is an electron–positron pair. The remaining events in the sample are almost all tau pair production, that is, $e^+ + e^- \rightarrow \tau^+ + \tau^-$. The single prong comes from the tau decaying into an electron and two neutrinos, a muon and two neutrinos, a pion and a neutrino, a charged pion, neutral pion and a neutrino, or a kaon and a neutrino. The triplet of prongs comes from the tau decaying into three pions and a neutrino or three charged pions, a neutral pion and a neutrino.

Surrounding the beam pipe and coaxial to it are first the trigger chamber and then the main chamber. To determine the location in the beam pipe where the tau decayed, the group determined the distance, l, between the position where $e^+ + e^- \rightarrow \tau^+ + \tau^-$ and the reconstructed vertex where the τ decayed into a triplet. Because the tau is known to have 14.5 GeV energy, its velocity is known and the time, t, it lived can be determined. In principle, from the distribution of t's, one can determine the lifetime. In practice, however, the group looks at the distribution of l's and fits it with a calculated l distribution, which depends on the lifetime of the tau.

If conventional weak-interaction theory holds, then the coupling constant for the tau decaying to ν_τ and W, $g_{\tau\nu_\tau}$, is the same as g for an electron decaying to ν_e and W and a muon decaying to ν_μ and W, and the theoretical value for τ_τ is 2.8×10^{-13}. If $g_{\tau\nu_\tau} \neq g$, then

$$\frac{\tau_\tau(\text{theor.})}{\tau_\tau(\text{meas.})} = \frac{g^2_{\tau\nu_\tau}}{g^2} \qquad (1)$$

Plugging in the Mark II value for τ_τ

$$0.66 < g_{\tau\nu_\tau}/g < 1.02$$

for one-standard-deviation limits. So, Perl told us, within the errors of their measurement they found the tau vertices have the same strength as the electron vertices and the muon vertices.

Is there a tau neutrino? If there were no tau neutrino, but only the electron and muon neutrinos, the tau decay would have to occur through a $\tau\nu_e$ coupling with coupling constant $g_{\tau\nu_e}$ and/or through a $\tau\nu_\mu$ coupling with $g_{\tau\nu_\mu}$. Then equation 1 would be replaced by

$$\frac{\tau_\tau(\text{theor.})}{\tau_\tau(\text{meas.})} = \frac{g^2_{\tau\nu_e}}{g^2} + \frac{g^2_{\tau\nu_\mu}}{g^2}. \qquad (2)$$

The 90% confidence level (2.3σ) lower limit on this ratio is 0.40 from the Mark II data. So the right-hand side of equation 2 is greater than 0.40. The present limits on $g_{\tau\nu_e}$ and $g_{\tau\nu_\mu}$ are so small that this inequality could not be satisfied were $g_{\tau\nu_\tau} = 0$.

A number of particle-physics experiments have searched for tau production by either muon neutrinos or electron neutrinos, thus also measuring $g_{\tau\nu_\mu}$ and $g_{\tau\nu_e}$. (Such production could either signal the presence of neutrino oscillations or an admixture of different neutrinos in the original neutrino beam.) In 1978 a Columbia–Brookhaven group, using the 15-foot bubble chamber at Fermilab, set[2] an upper limit of $g^2_{\tau\nu_e}/g^2 < 0.025$ (90% confidence level). A recent emulsion experiment by N. Ushida and his collaborators, working at Fermilab, reduced[3] this limit to 0.0063 (90% confidence level). Upper limits (at the 90% confidence level) on $g^2_{\tau\nu_e}/g^2$ of 0.35 and 0.30 have been obtained in neutrino bubble-chamber experiments using BEBC at CERN[4] and the 15-foot chamber at Fermilab[5] respectively. These electron neutrino searches for tau production combined with the muon neutrino search by Ushida and his collaborators set upper limits on the right side of equation 2 of 0.36 and 0.31. But these limits disagree with the lower limit of 0.40 set by the tau lifetime measurement, thus indicating, Perl says, that an additional neutrino exists and couples to the tau. "This we call the tau neutrino. Of course, this result is still statistically weak. We need a more precise measurement of the tau lifetime and on the upper limit on $g^2_{\tau\nu_e}$ to get a stronger result."

Charles Baltay (Columbia) told us that he and his collaborators are now designing an experiment to look directly for the tau neutrino. The experiment has been approved to run at the Fermilab Tevatron about three years from now. To produce the tau neutrino beam, the experimenters would use the decay of F mesons produced by 1000-GeV protons. The F is a charmed particle with 2-GeV mass already observed in some Fermilab emulsion experiments; it is expected to have a 3% branching ratio into τ and ν_τ. At 1000 GeV the upgraded Fermilab accelerator is expected to produce ten times as many F particles as at 500 GeV. In addition, the experimenters plan to put their target 200 meters from the 15-foot bubble chamber instead of 1400 meters away, gaining an additional factor of more than ten. The signature of the tau neutrino would be an interaction of a penetrating neutral particle producing a tau but no muon or electron.—GBL

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RF drives tokamak plasma currents

A steady-state scheme for plasma-current drive would greatly enhance the attractiveness of the tokamak as a fusion reactor. The fact that a conventional tokamak reactor would have to operate in a pulsed mode presents serious engineering difficulties. Even though the length of such pulses could be as long as an hour (followed by a recovery time of less than a minute), pulsed operation raises the problem of thermal fatigue.

The "ohmic" plasma current that twists the confining magnetic field and heats the plasma in a conventional tokamak is induced by the transformer action of external induction coils. Plasma current is induced only so long as the external current is increasing. Thus the duration of a tokamak pulse is limited by the current capacity of the induction coils.

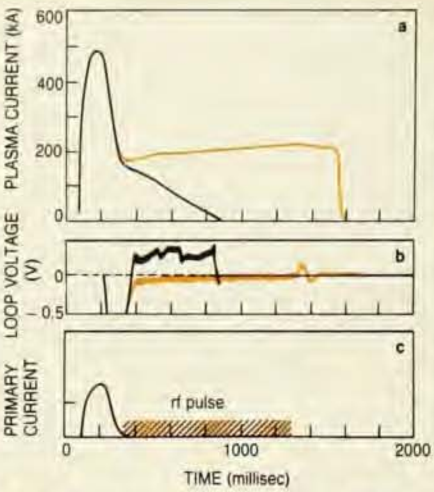
This high-voltage induction poses another problem, even more serious than thermal fatigue. To avoid unwanted currents in the walls of the vacuum vessel, one must interrupt this metallic torus with sections of resistive bellows. These voltage breaks, however, permit undesirable pulsed currents and stresses to be induced in the external coils when all-too-frequent plasma disruptions occur. If one could devise a steady-state mode of tokamak operation that does not rely on transformer action, one could avoid these stresses and thus build a smaller, cheaper and more efficient tokamak structure with a continuous vacuum vessel.

To this end, a group at the Princeton Large Torus has recently succeeded in driving the plasma current of the PLT tokamak for periods up to a second entirely by radio-frequency current drive—with the transformer induction shut off. The first rf-driven tokamak current had been reported two years ago[1] in a smaller machine, the JFT-2, at the Japan Atomic Energy Reseach Institute in Tokai. In this earlier work, as in similar experiments recently carried out at the small MIT Versator II and Kyoto University WT-2 tokamaks, rf plasma-current drive was demonstrated[2,3] for periods on the order of 10 milliseconds, but without shutting off the transformer induction.

In all of these experiments, the rf current drive could not be maintained for plasma particle densities above about 10^{13}cm^{-3}. This is well below the density at which these tokamaks operate in their conventional mode—not to speak of the densities a tokamak reactor would require. Before one can be optimistic, therefore, that rf current drive will yield the much-sought-after goal of a steady-state tokamak reactor, one must learn to generate rf-driven currents at much higher plasma densities, or one must devise some sort of transformer–rf hybrid scheme.

RF current drive. It has been known since the theoretical work of Lev Landau in the 1940s that one could drive a current by transferring momentum from an electromagnetic wave injected into a plasma to electrons whose velocities roughly match the phase velocity of the wave. But this "Landau damping" mechanism was until recently thought to be far too inefficient to be of any practical use. Even in a hot plasma, it was argued, the fraction of electrons with sufficiently high velocity to couple to a traveling wave was too small to yield reasonable current per unit power input.

A 1978 theoretical prediction by Nathaniel Fisch and Abraham Bers[4,5] (both then at MIT) changed this preconception. Calculating the diffusion of electron velocities parallel to the magnetic field of a tokamak plasma into which a traveling rf wave has been injected with a phase velocity three or four times the mean thermal electron velocity, they predicted that the high-velocity tail of the electron Maxwell distribution would be greatly enhanced. This, they argued, would yield rf-driven currents with surprisingly high efficiency. Traveling rf waves in the "lower hybrid frequency" region around a gigahertz, injected parallel to the tokamak magnetic field, they calculated, would generate plasma currents of several tenths of an ampere per watt of rf power.



Radio-frequency plasma current drive at the Princeton PLT. When the primary transformer current (**c**) that normally induces a tokamak plasma current is shut off, the plasma current (black curve in **a**) rapidly falls to zero. But when 90 kilowatts of 800-MHz rf power are injected (shaded time interval in **c**), the plasma current can be maintained at 200 kA for up to a second (colored curve in **a**). The vanishing of the loop voltage (integrated around the plasma torus) when the rf power is on (colored curve in **b**), indicates that the rf has taken over the plasma current drive from the transformer-induced emf.

Such an efficiency level begins to be plausible for a tokamak reactor. In a reactor one would need a plasma current of 5 to 10 megamps. By the Fisch–Bers estimate this would require no more than 50 megawatts of rf power. This would represent only 5% of the electrical output of a typical gigawatt fusion reactor. "One could certainly spare that fraction of the output for the rf current drive," we were told by Harold Furth, director of the Princeton Plasma Physics Lab. "A significantly less efficient current drive would be painful."

When Fisch's paper appeared, the MIT and Japanese groups were already using rf injection in the lower-hybrid region to study rf auxiliary heating (as distinguished from current drive) for tokamaks. It has been clear for some time that ohmic heating by the plasma current alone would be insufficient to achieve ignition temperature in a tokamak; thus rf heating is one of a number of auxiliary heating schemes under active investigation.

The lower hybrid frequency is a resonant frequency near the ion plasma frequency, the natural oscillation frequency for ion displacements in a plasma. Its precise value depends on both the plasma density and the magnetic field, but for the normal operating parameters of all the tokamaks under discussion here (except for the high-field Alcator C experiment recently begun at MIT) it lies near 800 MHz. The lower-hybrid region is thought to be particularly efficient for rf heating, and electromagnetic waves near this frequency are expected to penetrate a plasma with relative ease.

The first experiments. To inject lower-hybrid waves for their heating experiments, the Japanese, MIT and Princeton groups had coupled their rf sources to the tokamak plasmas by phased arrays of contiguous waveguides mounted at right angles to the vacuum vessel. By adjusting the phase relation of consecutive waveguides, one can govern the angle at which the rf wave enters the plasma and the relative amplitudes of waves traveling parallel and antiparallel to its magnetic field. For the lower-hybrid heating experiments, adjacent waveguides were set to be 180° out of phase; so standing waves would be generated along the magnetic-field lines.

When the provocative prediction of Fisch and Bers became known, the MIT Versator II group, led by Miklos Porkolab and Stanley Luckhardt, set out to look for rf current drive. They built a new 6-waveguide array whose dimensions would avoid ion heating and optimize coupling to electrons. Adjacent modules were set to be 90° out of phase so that waves would be launched into the plasma traveling in a single direction along the magnetic flux lines—to the left or right, depending on the sense of the phase difference between adjacent waveguides.

Looking for current drive at the Versator's normal plasma density of about 2×10^{13} cm^{-3}, the MIT group found nothing. Not until the Tokai group, led by T. Yamamoto, reported observing rf current drive at a density of 3×10^{12} cm^{-3} did the MIT group look at lower densities. They had been avoiding densities below 10^{13} cm^{-3}, Porkolab told us, because that would take them into the "slideaway regime," rendering a test of the Fisch–Bers theory more ambiguous.

Slideaway is a phenomenon that occurs in tokamak plasmas at sufficiently low density. Because collision cross sections decrease with increasing energy, some of the plasma electrons are driven to very high, "superthermal" velocities by the tokamak's transformer induction field. The Maxwell distribution of electron velocities takes on an enhanced high-velocity nonthermal tail. (Note that, even though one is looking for rf current drive, all the experiments discussed here *begin* with the conventional transformer induction that generates slideaway at densities below about 10^{13} cm^{-3}.) The precise 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 5×10^{12} 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 bremmstrahlung 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 3×10^{13} 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 analysis[6] 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

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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 IUCF 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. IUCF 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 IUCF beams—their