

With these two changes, the plan was to run PLT with low-density plasma to see what would happen in the collisionless regime (high ratio of mean free path to device length). To produce a hot, collisionless plasma, it is helpful to have fewer particles to heat. In theory, the collisionless regime was expected to produce instabilities such as trapped-particle modes (driven by particles that are trapped in mirror-like regions, causing plasma to leak out of the device).

Harold Furth, head of the Princeton Plasma Physics Laboratory research program, explained that no reactor need be more collisionless than the PLT experiment, because reactor plasmas have to be denser as well as hotter. That is, the PLT experiment was intended to test the "worst case." The "best case" of high collisionality was previously tested with the Alcator experiment at MIT.

The first runs were done with two neutral beams delivering 1.1 MW into the plasma. This year two additional beams were added, producing a total of 2.1 MW. With the graphite limiter and titanium gettering, electron heating occurred reliably and no enhanced line radiation was observed from the plasma core. The occurrence of an electron temperature rise is an essential precondition for the achievement of high ion temperature because the electron and ion components of the plasma tend to equilibrate thermally by means of collisions.

They started with a high-density plasma, then lowered the density in 200–300 milliseconds to produce a suitable target (with low collisionality) for the neutral beams. With a bolometer, the group measures ultraviolet radiation from the plasma, along many chords, and then calculates the power per unit volume radiated at each plasma radius. When a tungsten or steel limiter was used, the radiation peaked in the center, suggesting that metallic impurities were holding down the electron temperature. But with the carbon limiter, the total radiation was halved and was found to be coming only from the plasma edge. They found that with 2.1-MW neutral-beam power, the electron temperature increased by 50%. At the lowest densities, 4.5×10^{13} particles per cm^3 , the electron temperature rose to 3.5 keV, the ion temperature reached 5.5 keV and confinement times of 20 msec were measured.

There are some special problems in measuring the ion temperature in this new regime, Goldston told us. To increase the reliability of the measurement, the Princeton group used three independent methods: Doppler broadening on radiation from impurity ions, energy analysis of charge-exchange neutral atoms, and neutron yield.

The ion temperatures deduced from these independent measurements agreed well, Goldston said, and the resulting overall uncertainty in the central ion

temperature measurement is ± 10 –15%.

Goldston told us that, according to theory, the beams should be providing only rather modest heating of the electrons in the plasma core. Nevertheless, the central temperature of the electrons was found to rise substantially, as if the thermal conductivity decreased—a favorable result that surprised everyone.

Comparison with theory. Not all the plasma parameters have been measured yet. For example, the group needs more accurate data on the neutral atom density and the impurity ion concentrations inside the plasma. Details of the profiles are also important for the behavior of collective modes. Such measurements will allow the group to compare their results more precisely with competing theories of heat transport. In the neoclassical theory, introduced by Roald Sagdeev and Alex Galeev (then both at Novosibirsk) about ten years ago and developed by Marshall Rosenbluth (Institute for Advanced Study), Frederick Hinton and Richard Hazeltine (University of Texas) and others subsequently, particles collide with each other, diffusing across magnetic-field lines and transporting energy. The effects of such collisions on the orbits of particles confined by tokamak fields should provide a lower bound to the energy and particle losses to be expected. Scaling these calculations to reactor size indicated that ignition temperatures could be achieved in very small sizes.

On the other hand, using the trapped-particle theories pioneered in the early 1970's by theorists such as Boris Kadomtsev (Kurchatov Institute), the scaling calculations suggest that ignition temperatures could be reached only with much larger tokamaks, because instabilities would interfere with confinement and heating. Such theoretical predictions are only tentative, Rosenbluth told us, because of the difficulties in estimating the nonlinear behavior of these collective modes.

To the extent the Princeton group is able (estimating some of the parameters), they have compared their experimental results with neoclassical predictions and they agree reasonably well. Now comparisons with trapped-particle theoretical predictions are under way. Furth noted that although enhanced energy losses from trapped-particle instabilities have not been observed, the Princeton group has actually seen some high-frequency (about 100 kHz) density fluctuations at the highest power levels (when the ion temperature was above 4 keV). Such fluctuations, he said, might be related to trapped-particle modes, but the losses observed are less than most trapped-particle theories would have predicted.

To produce the most economical tokamak fusion reactor, it is generally believed desirable to keep the magnetic field low and the value of β high. The parameter

β , which is the ratio of plasma pressure to toroidal magnetic field energy density, measures the efficiency with which the system uses the field produced by the coils. In a tokamak reactor, β -values of 5% or more will be appropriate. With ohmic heating, β has only reached 1%, Furth noted. More powerful neutral-beam heating experiments are needed to push the β -value up and provide the critical test of high- β magnetohydrodynamic stability theory. Experiments designed to reach β values of 6%, with neutral injection, will be done this Fall on the ISX-B device at Oak Ridge.

The PLT experiment gave a maximum fusion yield of 10^{13} neutrons per shot in deuterium plasmas heated with deuterium beams. The fusion events were due mainly to the injected ions, which build up the high-energy tail of the ion distribution. (The average PLT ion energy at the plasma center actually reaches about 12 keV, counting the injected ions.) If deuterium and tritium had been used, the fusion yield would have increased several hundredfold, giving a ratio Q of fusion output power to plasma heating power of about 1%. This "equivalent D-T Q -value" represents a record for fusion research to date, Furth said.

When the Tokamak Fusion Test Reactor starts running at Princeton in 1981, Furth hopes that it will reach break-even in an actual D-T plasma. He feels "We've got it boxed now. All we need is higher heating power." The Tokamak Fusion Test Reactor will have 30 MW of neutral beam, and he expects to reach electron and ion temperatures of 10 keV and an $n\tau_E$ of at least a few times $10^{13}\text{cm}^{-3}\text{sec}$, all in one machine. In a beam-heated plasma, this is theoretically more than sufficient for a break-even demonstration. —GBL

in brief

A group of geophysicists headed by Fred K. Duennebieber of the University of Hawaii at Manoa plans to place a seismic sensor into a hole drilled under 4000 feet of water at the mouth of the Gulf of California. Placing the sensors into the drill hole rather than on the ocean bottom, as has been done in the past, is expected to give much less complex signals and much better signal-to-noise ratios.

A group from MIT's Lincoln Laboratory headed by John V. Evans has built a new ionospheric research radar in Westford, Mass. The system was assembled from a surplus Air Force 150-ft antenna and an existing transmitter/receiver with peak power of about $2\frac{1}{2}$ MW. It will be used to study the atmosphere between 100 and 1000 km in high northern latitudes. □