the interference of the wake fields becomes significant beyond $(\omega/\omega_p)^2 \sim 40$. To extend the simulations to really high energy, one needs much longer system size for the simulation; however, since the scaling agrees with Eq. (8) we can use it with some confidence there.

The present mechanism of electron acceleration seems feasible within present-day technology. Although the pulse lengths of $(2n+1)\pi c/\omega_p$ are also allowed, techniques of making short pulses have to be perfected (e.g., pulse chopping by backscattering). Having two laser beams with $\Delta\omega = \omega_p$ as mentioned above is an alternative.

We may speculate that the present acceleration process may play a role in such an environment as a pulsar atmosphere, where the dipole radiation fields can be so large that $eE/m\omega \gg c$. In the early life of a pulsar when the blowoff plasma, still not far from the pulsar, faces these intense fields, the pulsar plasma can be a strong cosmic-ray source through this mechanism.

We thank D. Vitkoff, J. N. Leboeuf, M. Ashour-Abdalla, and C. F. Kennel for discussions. This work was supported by the U. S. National Science Foundation Grant No. PHY 79-01319.

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Neutral-Beam–Heating Results from the Princeton Large Torus

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Experimental results from high-power neutral-beam–injection experiments on the Princeton Large Torus tokamak are reported. At the highest beam powers (2.4 MW) and lowest plasma densities [$n_e(0) = 5\times10^{13}$ cm^{-3}], ion temperatures of 6.5 keV are achieved. The ion collisionality $\nu_i{}^*$ drops below 0.1 over much of the radial profile. Electron heating of $\Delta T_e/T_e \approx 50\%$ has also been observed, consistent with the gross energy-confinement time of the Ohmically heated plasma, but indicative of enhanced electron-energy confinement in the core of the plasma.

The purpose of the Princeton Large Torus (PLT) tokamak neutral-beam–injection experiments is to produce collisionless high-temperature tokamak plasmas in which to study ion and electron thermal transport. In this paper we present data from recent neutral-beam–heating experiments on the PLT tokamak, extending the results of previous injection-heating experiments,[1-6] to the better confinement conditions associated with large tokamaks, and also extending our previous results[7] to injection power levels of up to 2.4 MW and ion temperatures of 6.5 keV. The PLT beam-injection system consists of four tangentially aimed beam lines and 40-keV ion sources.[8] Two sources inject parallel to the plasma current and two inject antiparallel.

Ion heating.—The techniques for measuring ion temperature on PLT fall into three categories: mass and energy analysis of the fast neutrals generated by charge exchange, measurements of the Doppler broadening of impurity line radiation in the x-ray and ultraviolet, and thermonuclear-neutron–emission measurements for H^0 injection into D^+ plasmas. The nature of the respective uncertainties and the extent to which the proper correction can be applied to each specific measurement technique has been discussed previously.[7] Generally the ion-temperature assessments agree to within ~ 10%.

With 2.4 MW of D^0 injection into an H^+ plasma, we have achieved ion temperatures up to 6.6 keV recorded by an analysis of charge-exchange neutrals as shown in Fig. 1. A supportive diagnostic for this ion-temperature measurement is Doppler broadening of Fe XXIV. At this power level, ion temperature and central density [$n_e(0) = 5\times 10^{13}$ cm^{-3}], Fe XXIV is strongly heated by the beam ions and can be raised to temperatures well above the thermal H^+ plasma. We calculate, for this case, that the temperature of Fe XXIV should exceed that of the thermal protons by 1700 eV. The Fe XXIV temperature shown in Fig. 1, which reaches 8 keV, is thus in good agreement with the charge-exchange data.

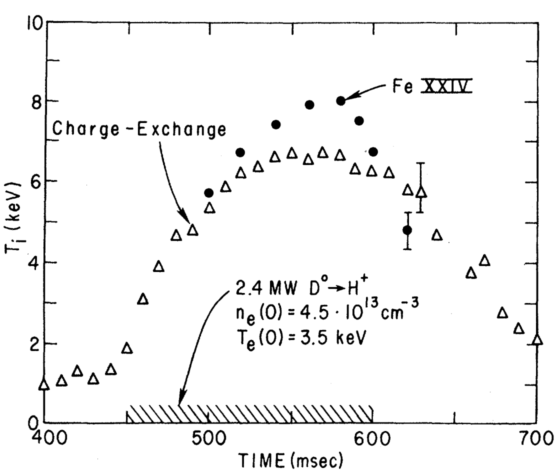

FIG. 1. Ion temperature (H^+) vs time as measured by analysis of charge-exchange neutrals and Doppler broadening of Fe XXIV for 2.4-MW D^0 injection into a H^+ plasma. Calculations indicate that the maximum temperature of Fe XXIV should exceed that of H^+ by 1700 eV.

While the achievement of an ion temperature in excess of that required for ignition in an ideal D-T fusion reactor (~ 4 keV) is noteworthy, the true significance of the data lies in the linear relationship of ion temperature to beam power as the temperature moves into the collisionless regime, where trapped-particle modes were predicted to produce enhanced energy transport. (See Fig. 2.) At $T_i = 6.5$ keV, $Z_{\text{eff}} \approx 3.5$, and $n_e(0) = 5\times10^{13}$ cm^{-3}, the ion collisionality parameter ν^* reaches a minimum of 2×10^{-2} and is below unity out to $r = 30$ cm (limiter radius = 40 cm). This represents an ion thermal component as deep within the banana regime as required for many tokamak reactor designs. As we proceed into the collisionless regime by increasing the ion temperature, there is a strong enhancement in the level of density fluctuations as measured by microwave scattering. So far, however, no observable effect on the ion energy balance nor on the circulating fast beam particles has been seen. The scattering volume is wave-number dependent but encompasses about one-half of the minor radius and is centered at $r/a \cong \frac{1}{2}$. The spatial profile of the fluctuations is not known, the rather rapid buildup of the fluctuation intensity occurs at $T_i \gtrsim 4$ keV for these low-density discharges. Although the observed frequency spectrum is characteristic of drift waves, neither the nature of the fluctuation nor the driving source is known at this time.

Injection of 2.2 MW of ~ 40-keV D^0 into D^+ plasmas, has produced a flux of $1.6\times 10^{14} n$/sec or 2

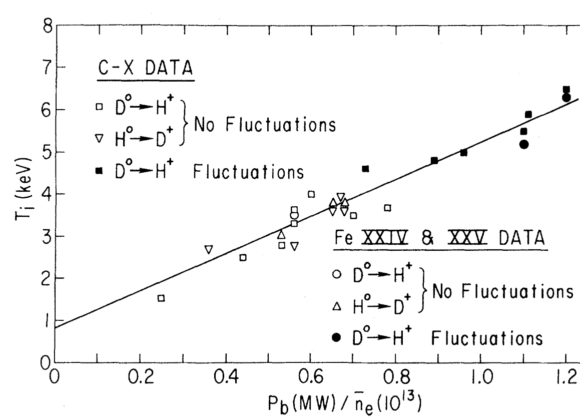

FIG. 2. Ion-temperature increase vs beam power per unit line-average plasma density, illustrating linearity despite the onset of strong density fluctuations.

$\times 10^{13} n$/pulse in good agreement with calculations (Fig. 3). We calculate that these neutrons arise about equally from beam-plasma and beam-beam interactions with less than 10% contribution from the thermal particles by themselves.

Electron heating.—The electron heating obtained in PLT with neutral injection is very sensitive to the choice of limiter material and to the conditions of the vacuum-vessel wall. In early experiments with tungsten limiters and even in more recent experiments with steel limiters, counterinjection into low-density plasmas has consistently resulted in metallic line radiation from the plasma core of ~ 1 W cm^{-3} (greater than the input beam power), quenching any significant electron-temperature rise. At low densities only with carbon limiters have we been able to routinely maintain a discharge relatively free of metallic impurities, with central radiation $\lesssim 200$ mW cm^{-3} and obtain strong electron heating with beam injection. With titanium gettering onto the vacuum-vessel wall, we have also been able to limit the density increase to $\Delta n_e(0) = 2.5 \times 10^{13}$ cm^{-3} with four-beam injection into a plasma which starts at $n_e(0) = 2.5 \times 10^{13}$ cm^{-3}. At higher densities [$n_e(0) > 5 \times 10^{13}$ cm^{-3}] metallic radiation drops to negligible levels and we are also able to hold the density nearly constant during injection through feedback control of the pulse-valve gas feed. In addition, gettering results in a decreased $Z_{\rm eff}$ and a wider operating range in density.[9] Ion heating has been obtained for all of the limiter materials employed in PLT, namely C, Fe, and W. The efficiency is, of course, affected by the ion-electron coupling and thus the electron temperature. The best ion-heating results have therefore been obtained with carbon limiters.

Figure 4 shows the electron-temperature increase which we obtain with 2.4 MW of D^0 beams into a low-density H^+ plasma as determined by electron-cyclotron emission measurements at the first harmonic. These results are consistent with Thomson scattering measurements of T_e. While the overall radiation level increases with injection, $Z_{\rm eff}$ remains nearly constant. The overshoot in T_e at the end of the injection pulse which is due to ending the cold-electron influx associated with the neutral beam, is reproduced by transport-code calculations.[10]

Ion and electron power balance.—Numerical calculations of the ion and electron radial power flows have been made for a number of discharges both with and without neutral injection and will be discussed in detail elsewhere. Here we summarize only the important results.

For the ions, we calculate $T_i(r)$ on the basis of a Monte Carlo simulation of the beam-heating process, and numerical calculation of energy

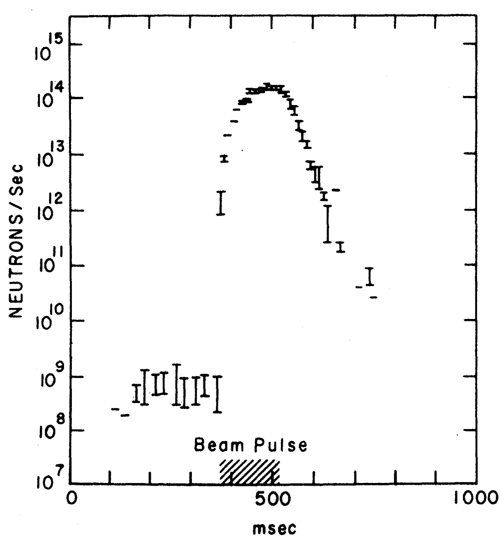

FIG. 3. Neutron emission vs time for 2.2-MW D^0 injection into a D^+ plasma. Peak fusion output is 170 W. D-T equivalent power is 50 kW or $Q = 2\%$. Before injection, $T_i(0) = 1$ keV and $\langle W_i \rangle = 1.5$ keV. During injection, beam ions have $\langle W_i \rangle = 20$ keV and comprise 30% of $n_i(0)$. Bulk ions have $T_i(0) = 6.6$ keV and $\langle W_i \rangle = 10$ keV and are 70% of $n_i(0)$. Thus $\langle W_i \rangle = 13$ keV.

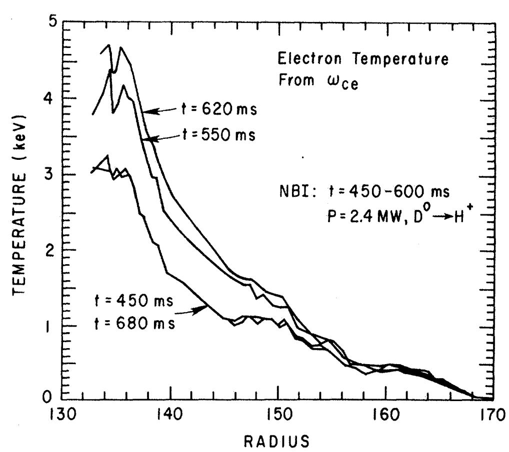

FIG. 4. Electron-temperature profiles during beam heating. $T_e(r)$ has nearly saturated at 550 ms. The short increase following beam turnoff, exemplified by $T_e(r)$ at 620 ms, is due to ending the cold-electron influx associated with the neutral beam, while beam ions circulating inside the plasma continue to heat the electrons.

loss by neoclassical thermal conduction, ion-electron coupling, empirical thermal convection, and charge-exchange, as in Stott.[11] Because of the uncertainties in $Z_{\rm eff}(r)$, $q(r)$, and $n_0(r)$, we find, for a case of 2.1-MW D^0 injection into a low-density $[n_e(0)=4.5\times10^{13}\ {\rm cm}^{-3}]$ H^+ plasma, a range of predictions for $T_i(0)$ extending from 4 to 7.5 keV, to be compared to the measured value of 5.5 keV. The volume-integrated net ion-energy confinement time τ_{Ei} is 25 msec for this case or about half the value of Ohmic heating alone for the same discharge. In the numerical simulation this difference in τ_{Ei} is primarily due to the enhanced role of charge-exchange and empirical convective losses at the high ion temperatures and steep temperature gradients which occur with beam heating. As neoclassical thermal conduction is only a small fraction of the total ion-energy flow, we cannot rule out, on the basis of the measured temperature, as much as a fivefold enhancement of the thermal conduction over the neoclassical value, which is itself uncertain by almost as large a factor.

In cases of neutral injection into higher-density plasmas, charge-exchange and convective losses are reduced and ion-electron coupling becomes the dominant term in the ion-energy flow. Neoclassical thermal conduction remains a small term in the total ion–power-balance picture, in part because of the reduction of $Z_{\rm eff}$ at higher densities. The neoclassical prediction for ion temperature with injection of 2.0 MW of D^0 into a H^+ plasma of $n_e(0)=7.5\times10^{13}\ {\rm cm}^{-3}$, is $T_i(0)=3.1\pm0.5$ keV, rather closely bracketing the measured value of 3.2 keV. The net ion-energy confinement time calculated for this case was 95 msec, close to the Ohmic-heating-only value of ≤ 120 msec. Even in this case, however, the possible enhancement of ion thermal conduction over the neoclassical value remains as much as a factor of 3–4. We, therefore, cannot rule out appreciable anomalous ion thermal conduction under these beam-heated conditions.

On the basis of the ion–power-flow calculations, we proceed to examine the electron power balance. From the Monte Carlo beam-orbit code, we get the radial profile of P_{be}, the power flowing directly from the beam ions to the electrons; and from the experimental measurements of $T_e(0)$, coupled with the neoclassical ion-temperature profile calculations, we find $P_{ie}(r)$, the power flowing from the bulk ions to the electrons. In addition, the beam-orbit code evaluates $P_{he}(r)$, the power required to thermalize the cold electrons entering the plasma from the neutral beam. The Ohmic input power is calculated from the experimental $T_e(r)$ profile, assuming $Z_{\rm eff}(r)=$ const and $\sigma\propto T_e^{3/2}$. Finally, we subtract the bolometrically measured radiated power, and find the radial power flow due to electron thermal transport which is required to complete the power balance. Dividing the result by $n_e dT_e/dr$, we arrive at an experimentally determined anomalous electron thermal transport coefficient $\chi_e(r)$.

The intriguing result of applying this analysis to our beam-heating measurements is that, although the volume-integrated net electron-energy confinement time is approximately unchanged during injection, χ_e in the core of the plasma appears to fall roughly as $(n_e T_e)^{-1}$ when the temperature and density are increased with neutral injection. This effect is reflected in a 50% rise in T_e on axis, in moderate density cases, equal to the fractional increase at $r/a=\frac{1}{2}$, even though P_{be} and P_{ie} are relatively much smaller in the hot central core. It seems unlikely, however, that the evident reduction in thermal transport in the central plasma region is due to a simple scaling of χ_e with T_e, since χ_e was not reduced in the outer regions of the plasma, which are also heated.

The results of high-power neutral-beam–heating experiments on the PLT tokamak are very encouraging. We have observed that the thermal-ion component in a tokamak plasma can be driven deep into the collisionless regime without a large enhancement of thermal transport. In addition, we have observed the surprisingly optimistic effect that the anomalous electron transport always observed in tokamak plasmas appears to be reduced in the hot core region of the plasma when T_e is increased by neutral injection. These two results together generate very encouraging predictions for the Tokamak Fusion Test Reactor under construction at Princeton Plasma Physics Laboratory, and for future tokamak fusion devices.

The continuing support of Dr. M. B. Gottlieb, Dr. E. A. Frieman, and Dr. H. P. Furth is gratefully acknowledged. The authors express their appreciation to Dr. D. Post, Dr. J. Ogden, Dr. D. Jassby, and Dr. H. Towner for contributing modeling calculations and to Dr. T. Stix for his significant contributions to the early design work and expected performance evaluations. This work was supported by the U. S. Department of Energy Contracts No. EY-76-C-02-3073 and No. W 7405-ENG-26.

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Lower-Hybrid-Wave Heating in the Alcator-*A* Tokamak

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(Received 13 April 1979)

We report the results of injecting 90 kW of microwave power near the lower hybrid frequency into the Alcator-*A* tokamak through a two-waveguide array. The observed plasma heating is in disagreement with that expected from linear waveguide-plasma coupling theory. From these results and auxiliary rf probe measurements we infer the nonlinear formation of a high-$k_{\parallel}$ wave power spectrum at the plasma edge.

There is currently extensive interest in raising plasma temperatures in tokamaks through auxiliary heating methods. Microwave heating of tokamaks near the lower hybrid frequency has been tried on ATC,[1-2] Wega,[3] Petaul,[4] Doublet IIA,[5] and recently on JFT2.[6] In these experiments ion heating was obtained when the wave frequency was in the vicinity of the central lower-hybrid frequency, and some electron heating was also observed at lower densities. This ion heating was accompanied by a density rise and some impurity influx. No contradiction with the Brambilla waveguide-plasma coupling theory[7] was reported in these experiments.

Here we report the results of injecting 90 kW of microwave power at 2.45 GHz into the Alcator-*A* tokamak through a split waveguide array. Ion heating occurs at well-defined values of central plasma density; below these densities electron heating occurs. No density changes or impurity influx take place during the rf pulse. Contrary to previous experiments, the waveguide phasing has no effect on plasma heating. In addition, the densities at which heating occurs are significantly reduced from those expected from waveguide-plasma coupling theory.[7] These results and the frequency spectra obtained from an rf probe suggest that the wave power spectrum formed near the plasma edge is shifted to higher $k_{\parallel} = \vec{k} \cdot \vec{B}/|\vec{B}|$ than predicted by linear theory.[7]

The waveguide array employed here consists of two adjacent independently driven waveguides mounted flush with the vacuum vessel walls; each has inner dimensions of 1.275 cm by 8.13 cm and are separated by a 0.09-cm-wide septum. Toroidally, the array is located 180° away from the limiter, which extends out 2.5 cm from the wall and defines a plasma minor radius of 10.0 cm