ent work, at least as far as the magnitude of ΔT is concerned. Unfortunately our experimental results do not permit accurate evaluation of R_s at the lowest temperatures as the anomaly becomes very small and not well defined.

An independent check of the present results and conjectures would clearly be desirable, at which point a detailed theory of initiation of turbulence in helium II at a solid interface will be needed. This is clearly outside of the scope of the present work.

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[11] Some of our data (for example, Fig. 3) also suggest the existence of a first transition at $\dot{Q}_0 < \dot{Q}_c$. This could correspond to a transition to superfluid turbulence, which gives further support to our association of $\dot{Q}_c$ with normal-fluid turbulence.

[12] J. T. Tough and C. E. Oberly [J. Low Temp. Phys. 6, 161 (1972)] have discovered a dimensionless parameter P which seems to characterize the transition to normal-fluid turbulence in the bulk liquid in the range 1–2 K. The parameter P does not seem to describe our data very well ($5 < P < 80$ as opposed to $P \sim 55$ for bulk helium). This is not surprising, as our results already suggest that a different theoretical treatment will be needed for the surface problem. Hence our use of a Reynolds number in the text.

[13] Arp, Ref. 9.

Neutral-Beam Heating in the Adiabatic Toroidal Compressor*

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Experiments have been conducted on an adiabatic toroidal compressor with tangential injection of two 14–15-keV, 3–4-A beams of H^0 or D^0. The ion-temperature rise for both H^+ and D^+ plasmas is 70–80 eV (i.e., 35–40%), consistent with theoretical expectations for charge-exchange–limited energy transport at neutral-atom densities $\approx 10^9$ cm^{-3}. The injected ions are found to decelerate in agreement with classical theory and produce an initial plasma ion heating rate of ~ 20 keV/sec.

In a toroidal fusion reactor, the plasma temperature will be maintained by the Coulomb collisions of the suprathermal α-particle population produced by DT reactions in the plasma. To attain fusion-reactor temperatures, a similar heating method can be used: namely, injection of a suprathermal ion population by means of neutral-atom beams. These ions need serve merely as a heat source; they need not serve to maintain or build up the plasma density.

For injection into the adiabatic-toroidal-compressor (ATC) precompression plasma, we have used neutral-beam sources developed and built at the Lawrence Berkeley Laboratory.[1] These sources are capable of operation up to 20 kV at 10 A per source; our present results are derived from operation at ~15 kV, with currents (through our rather restrictive aperture of 5×17 cm) of 3 to 4 A equivalent, of either H^0 or D^0.

The ATC target plasma into which the neutral beam is injected tangentially has the following parameters[2,3]: $R = 88$ cm, $a = 17$ cm, $\bar{n}_e \approx 1.5\times10^{13}$ cm^{-3}, $\bar{T}_e = 600$–700 eV, $\bar{T}_i \approx 200$ eV, $B_t = 15$ kG, and $I_p \sim 60$–70 kA. When injection takes place, the plasma current, loop voltage, position, and electron density remain unchanged. Very late in time, i.e., ~40 msec after injection begins, cold neutrals associated with injection cause a slight increase in hydrogen light, with an accompanying small shrinkage of the electron-temperature profile.

The two sources inject in opposing directions so as to minimize the net toroidal momentum imparted to the plasma. Some unbalance is to be expected as a result of more favorable orbital confinement properties of hot ions injected parallel to the current.[4] Even when using only a single source, however, we have not been able to detect any poloidal or toroidal rotational effects. The diagnostics were observation of frequency shifts of the $m = 2, 3$ oscillations, and Doppler measurements of hydrogen light. Both these diagnostics have a lower detection limit corresponding to a plasma rotational velocity $\sim10^6$ cm/sec; it should perhaps be borne in mind that they are most sensitive to outer regions of the plasma, whereas the injected fast-ion density peaks near the axis.[5]

A primary purpose of the experiment was to explore the ion heating that results from neutral-beam injection. Preliminary results obtained by heating with a single source have been reported earlier.[6] Using two sources, we have now improved the accuracy of measurement of the ion-temperature increase and have observed a number of interesting details of the heating process.

The ion-temperature rise from beam injection, as assessed by measurement of the thermal charge-exchange neutral flux, is shown in Fig. 1. We show ion temperature versus time, for (a) no beam injection, but with source valves open, admitting cold gas; (b) one beam; and (c) two beams. There is clear evidence of ion-temperature increase with beam injection; however, both cases (b) and (c) show a saturation in ΔT_i occuring just before beam turnoff, i.e., $\lesssim$10msec.

For ATC parameters, charge exchange is not a negligible energy-loss mechanism for the injected hot ions. The charge-exchange time τ_c is ≈ 7 msec, to be compared with a hot-ion slowing-down time τ_s of ≈ 5 msec. Computations have been made by Callen,[7] giving the fractional transfer of beam power to the plasma ions as a function of beam energy, with a quantity proportional to τ_s/τ_c as a parameter. (The time τ_s used in Ref. 7 is the Spitzer slowing-down time.) For ATC conditions, we arrive at $P_i \approx 0.35P_0$, where P_0 is the beam input power. The heating results of Fig. 1 thus correspond to a power input P_i, to the ions, of ≈ 10 kW per source. This is consistent with the observed rate of rise of T_i at beam-on time.

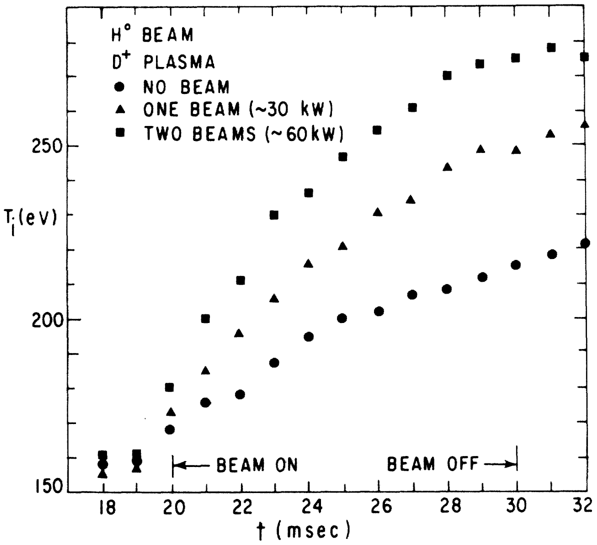

FIG. 1. Ion temperature versus time for no beam, but with source valves open, admitting cold gas (circles); one beam (average of the two cases) (triangles); and two beams (squares). The power transferred to plasma ions is about 35% of the indicated beam powers.

The ion energy distributions are inferred from measurement of the charge-exchange neutral flux emerging perpendicular to the magnetic surfaces. A few milliseconds suffice to degrade injected beam particles in energy and scatter them in angle so that they produce an observable contribution in the high-energy region of the measured distribution; for ATC conditions, the lowest energy to which this effect could extend is $E \geqslant 9kT_i$ or $E \geqslant 2$ keV. This is, in fact, just the region where the measured distribution departs from Maxwellian. The ion-temperature values in Fig. 1 are derived from the slope of the measured distribution below $9kT_i$.

The ion-temperature rise produced by neutral-beam heating, as indicated in Fig. 1, has been substantiated by plasma compression. A full

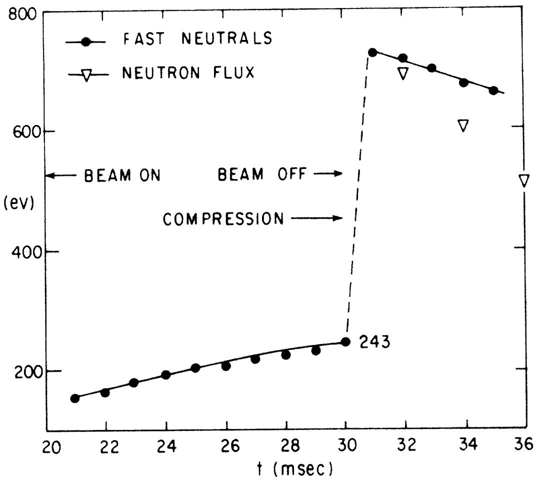

FIG. 2. Ion temperature versus time before and after compression of the H^0 beam-heated D^+ plasma. [Temperatures derived from (^2H, ^2H) neutron production are not corrected for density decay following compression.]

compression affords an ion-temperature rise of about a factor 3.[3] Therefore, heating D^+ plasmas by H^0 beams and then compressing gives one a substantial neutron count, which can be used to support the charge-exchange measurements of ion temperature (Fig.2) and the absence of any appreciable distortion in the thermal distribution. Charge-exchange measurements of T_i in the compressed state give, for beam-preheated plasma, the expected 150–200-eV temperature increment over that for no beam preheating. Ion temperatures inferred from the neutron yield are in good agreement, and show the same increment. The ion density is assumed, in the latter calculation, to follow the standard rules for compression[3]; actually there is some loss of particles following compression, giving the observed divergence of "neutron T_i" and "charge-exchange T_i" at late times in Fig. 2.

It would be very interesting to extract from the precompression ion-heating data some indication as to the relationship between the ion-energy confinement time τ_{Ei} and the ion temperature T_i. Unfortunately the relatively small temperature rises achieved experimentally so far render "agreement" with the model rather insensitive to the assumed relationship between τ_{Ei} and T_i. We can say, however, that the observed saturation of T_i with time is better accounted for by $\tau_{Ei} \propto T_i^{-1/4}$ (consistent with charge-exchange losses) than by a positive exponent of T_i.

TABLE I. Observed and calculated slowing-down rates for 15-keV ions parallel and antiparallel to the toroidal electric field. In terms of the difference between $(dE/dt)_{\uparrow\uparrow}$ and $(dE/dt)_{\uparrow\downarrow}$, $Z_{\text{eff}} \approx 3$ gives best agreement.

	dE(peak)$/dt$ (eV/msec) Expt.	Theory $Z_{\text{eff}}=2.8$
D^0, D^+ ↑↓	1450 ± 100	1200
D^0, D^+ ↑↑	900 ± 100	700
H^0, D^+ ↑↓	1700 ± 100	1650
H^0, D^+ ↑↑	1150 ± 100	1000

The ratio of energetic-ion pressure to plasma pressure is typically 0.1–0.2, and the corresponding poloidal-field β values are 0.03–0.06. These numbers are similar to those of a DT-reactor α-particle population. The present plasma ion heating rate of ~20 keV/sec would also be appropriate for neutral-beam heating to ignition or subsequent α-particle heating, in an appropriately larger device with $\tau_{Ei} \sim 1$ sec. It is most encouraging that in spite of the pronounced anisotropy of the injected population (i.e., $v_\parallel > v_\perp$), the behavior of the fast ions appears to be entirely classical.

Detailed studies have been made, for comparison with theory, of the slowing down of both injected H^+ and D^+ in deuterium plasmas, parallel and antiparallel to the toroidal electric field. For these measurements we inject a short beam pulse (≤1 msec) into the ATC plasma and follow the energy distribution with a tangentially viewing fast-neutral detector. We find that fast H^+ ions lose energy more rapidly than D^+ ions, as expected; moreover, both H^+ and D^+ lose energy much more rapidly when injected against the electric field than when injected parallel to it. This predicted effect[8] occurs only with a mixture of ion species and can be used to determine the effective ionic charge Z_{eff} due to impurity ions. The most important point of these data on fast-ion deceleration is that no evidence of anomalous energy losses has yet been observed. This result is of particular importance to the feasibility of the "two-component reactor" approach.[9] The results are summarized in Table I.

We reported earlier[3] the adiabatic behavior of the thermal-ion energy distribution following compression, namely, that the ion temperature scales as the compression factor ($C = R_0/R_c$) to

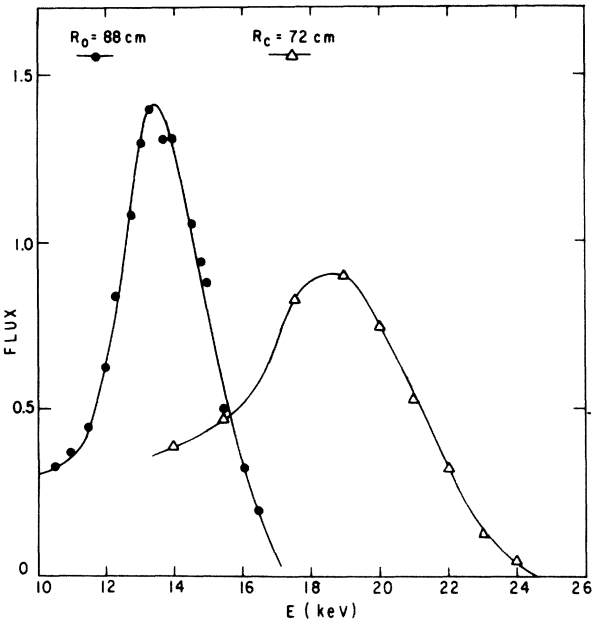

FIG. 3. Fast-ion energy distributions with and without a small compression, $R_0/R_c = 1.22$. The peak energy is found to scale as $(R_0/R_c)^2$.

the $\frac{4}{3}$ power. The rather anisotropic velocity distribution of the injected-ion population gives it a somewhat different energy multiplication following compression. For those injected ions whose velocity is still primarily parallel to B, compression results in an energy scaling that varies as the compression factor squared. We have examined, with our tangential-viewing neutral detector, the fast-ion energy distribution resulting from a small compression (such that the plasma remains within the field of view of the detector). The resulting ion energy distribution is shown in Fig. 3; the peak energy recorded, following a compression of $R_0/R_c = 1.22$, indeed scales as $(R_0/R_c)^2$.

The compression of an unthermalized injected-ion population could be of practical value in producing high densities of 100–200-keV ions, as required for the two-component reactor approach.[9] In the present experiments, neutron count rates due to injection of D^0 beams into a D^+ plasma are raised from $\sim 10^9$/sec before compression to $\sim 10^{11}$/sec in the compressed state.

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