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US TOKAMAK RESEARCH

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BY

H. P. FURTH

PLASMA PHYSICS
LABORATORY

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Presented at the 9th European Conference on Controlled Fusion and Plasma Physics, Oxford, England, 17-21 September 1979.

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ABSTRACT

Current experiments on ISX-B, Alcator C, PDX, and PLT respectively address the four areas of principal concern in the development of a tokamak reactor: optimization of MHD-stability at high β-values; achievement of high $n\tau_E$; preservation of plasma purity; and development of effective techniques for achieving high plasma temperatures. The neutral-beam-heated ISX-B is the first tokamak device to have reached a β^*-level of approximately 3%, thus exploring — or even challenging — the theoretical MHD beta limit. Pellet fueling has also been demonstrated successfully. Alcator C, in its initial half-field operation, has obtained τ_E values exceeding 20 msec and has found a modified empirical scaling pattern. The Poloidal Divertor Experiment (PDX) has entered initial "round-plasma" operation at currents up to 500 kA. Low-power ion-cyclotron heating on PLT has given bulk-ion-temperature rises up to 600 eV and energetic efficiencies exceeding those of neutral-beam heating. Interactive energization of beam-injected ions has also been demonstrated. Some further information on the phenomena accompanying unidirectional tangential neutral-beam injection has been obtained. The Doublet III results are reported at this conference in a separate paper [1].

I. THE ISX-B DEVICE

A schematic of the ISX-B device at the Oak Ridge National Laboratory (ORNL) is shown in Fig. 1. A more detailed discussion of recent experimental results is being presented at this conference in Ref. 2. The nominal machine parameters are $R = 93$ cm, $a_{Lim} = 27$ cm, $b_{Lim} = 50$ cm, $B_T \leq 18$ kG, $I_p \leq 200$ kA. Thus far, operation has concentrated on roundish plasmas ($b/a \sim 1.1$) at limiter q-values in the range 2.8 - 3.2. Neutral-beam heating is applied through coinjection at 40 keV, and has risen in the course of the past year to about 1 MW of hydrogen (two beamlines). The ohmic-heating power drops from about 200 kW before injection to as little as 60 kW during injection. The discharge duration is of order 300 msec, with beam heating applied for 100 msec.

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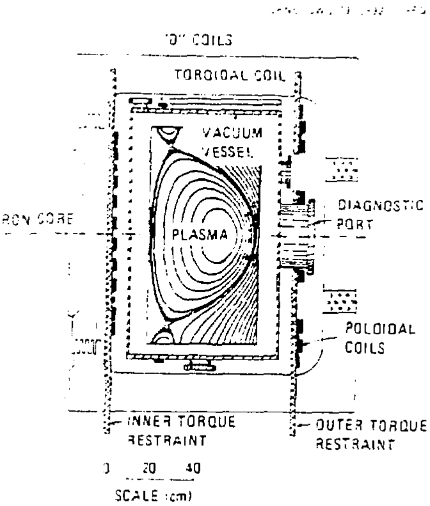

Figure 1. Schematic of the ISX-B device at ORNL.

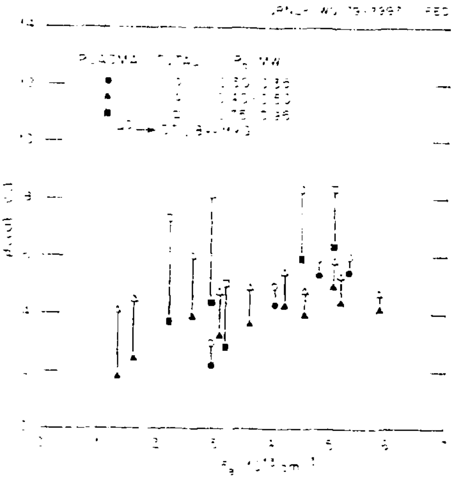

Figure 2. Central β-values obtained by neutral-beam heating in ISX-B. The contributions due to the plasma pressure and the beam-ion pressure are distinguished.

The central β-values achieved at various beam-power levels and plasma densities are shown in Fig. 2. In the lower-density cases, an appreciable fraction of the central β-value is seen to be contributed by the energetic injected ions, rather than by the bulk plasma. At higher plasma densities and for space-averaged β-values, the pressure contribution of the energetic particles is minor.

The dependence of the quantity $\beta^* = 8\pi(\langle p^2\rangle)^{1/2}/B_T^2$ on beam power and density is shown in Fig. 3. There is no evidence of saturation at the highest power levels used thus far. Correspondingly, no deterioration of τ_E has been observed at the highest β-values. The pattern of MHD activity undergoes some rather marked changes during neutral-beam heating, but these phenomena could well be caused by the injection process itself, rather than by the β-level. In particular, since injection is unidirectional, one would expect plasma rotation (cf. Section IV) to shift the MHD mode frequencies, and quite probably to drive new kinds of MHD modes. As one contemplates the possibilities, it becomes clear that the onset of the true ballooning mode β-limit may be rather difficult to identify uniquely, unless some variation can be introduced in the plasma heating method.

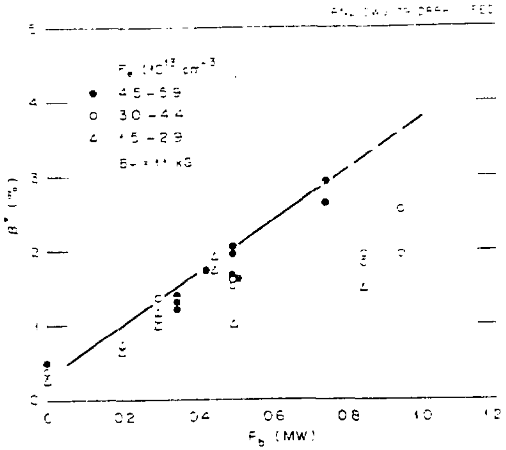

Figure 3. Average beta, $\beta^* = 8\pi(\langle p^2 \rangle)^{1/2}/B_T^2$, in ISX-B versus beam power.

To demonstrate experimentally that the β-value can rise above the theoretical limit is considerably more straightforward. On the basis of the ideal-MHD analysis of Ref. 3, the β-values of Fig. 3 are already somewhat excessive; in the case of a round plasma with an aspect ratio of 4.5 the critical β* should be around 2%. In the near future, when the injection power is raised above 1.5 MW, a decisive demonstration of the discrepancy — if it is real — will be forthcoming.

In the event that the experimental tokamak β-limit in ISX-B is found to exceed the predictions of the ideal MHD theory, some interesting questions will arise: Are finite-gyroradius effects significant? Do the beam-ions play a helpful role (possibly by helping to shape the poloidal field)? Is a finite level of ballooning-mode activity compatible with adequate energy confinement? Perhaps the most interesting question of all is whether an upward revision of the theoretical β-limit would apply across the board, as a multiplicative factor, or would simply tend to bring the critical betas of round plasmas closer to those of specially shaped plasmas. This question will be addressed in ISX-B — and later in PDX — when their capabilities for noncircular plasma shaping are utilized.

A second new ISX-B result of major reactor significance has been the demonstration of plasma fueling by pellet injection (cf. Fig. 4). Hydrogen pellets of millimeter diameter, with velocities in the 10^5 cm/sec range have been injected successfully. In ohmic-heated plasmas [$T_e(0) \leq 0.7$ keV] the pellets traverse most of the plasma and even reemerge. In neutral-beam heated plasmas, the penetration is much shallower. In these experiments, the plasma density has been multiplied severalfold (up to $\Delta n/n \sim 4$) without disturbing the discharge appreciably or causing a substantial instantaneous loss of plasma energy. Many interesting details of the pellet ablation process are being obtained by means of holographic interferometry and shadowgraphy.

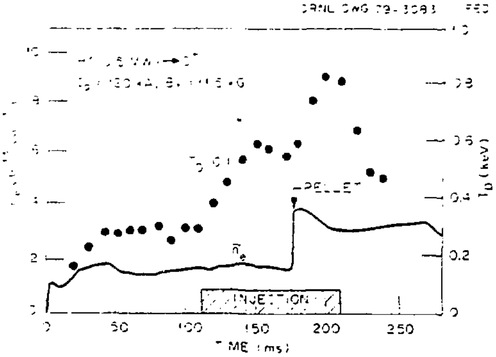

Figure 4. Hydrogen pellet injection into a neutral-beam-heated ISX-B plasma.

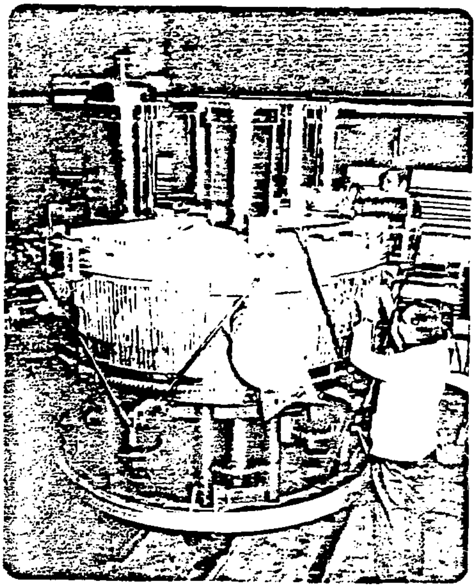

Figure 5. The Alcator C device during assembly.

II. ALCATOR C

The remarkable accomplishments of the Alcator A device [4] at the Massachusetts Institute of Technology (MIT) have now begun to be extended by the Alcator C (Fig. 5), a larger device of the same type (R = 64 cm, a = 17 cm) with a capability for $B_T \approx 120$ kG and $I_p = 1.0$ MA. Thus far, experimental operation has been limited by the power supply to $B_T \leq 60$ kG and $I_p \leq 500$ kA, but extension of operations to approximately 100 kG is expected to take place during the next few months.

The initial experimental results of Alcator C will be reported in Ref. 5. A preliminary view of the plasma behavior is given in Fig. 6 for a set of discharges at the 400-kA level. The confinement time of about 20 msec at $\bar{n}_e = 2.2 \cdot 10^{14}\text{cm}^{-3}$ represents a simple scale up, according to the a^2-law, relative to Alcator A. The electron and ion temperatures are somewhat higher than in Alcator A. A surprising feature of the new results is that τ_E does not appear to rise with increasing density.

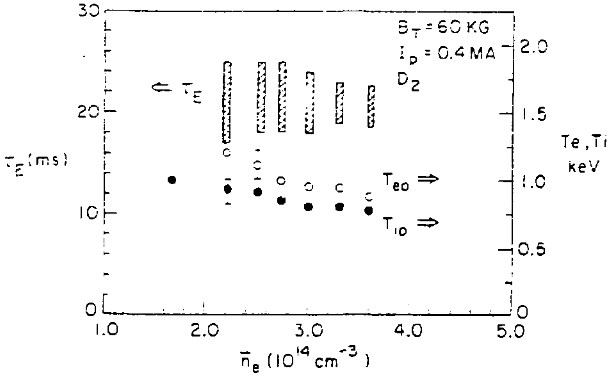

Figure 6. Temperature and energy confinement for half-field operation in Alcator C.

While a saturation of τ_E with rising density has been observed in many previous tokamak experiments, notably in ISX, and has been interpreted in terms of neoclassical ion heat transport, the present Alcator numbers would seem to stretch this hypothesis. The Alcator group regards the saturation phenomenon as perhaps arising from heavy-ion radiation or from a lack of optimization of the discharge conditions. Extensive new experimental information from Alcator C will soon be forthcoming, with the introduction of bolometric scans and higher-current operation. Meanwhile, the reformulation of tokamak transport theory would clearly be premature.

III. THE PDX DEVICE

The Poloidal Divertor Experiment [6] at Princeton (Fig. 7) has been operated initially as a tokamak with ordinary limiters — made of titanium, like the rest of the plasma environment in PDX. The PDX device has been tested up to its full ratings (B_T = 25 kG, I = 500 kA). Typical operating parameters have been: R = 142 cm, a = 40 cm, B_T = 20 kG, I = 360 kA. At $\bar{n}_e = 2 \cdot 10^{13}$ cm^{-3}, PDX has obtained $T_e(0)$ = 1.4 keV, $T_i(0)$ = 0.6 keV, and τ_E ~ 30 msec (cf. Fig. 8).

The effective resistivity Z_η is seen to be quite close to unity. Spectroscopic and x-ray data are in fairly good agreement with the resistivity results. The main contributors to the Z-enhancement appear to be oxygen and titanium. Bolometric measurements show that, for low-density regimes ($\bar{n}_e \sim 2 \cdot 10^{13}$ cm^{-3}), about half the input power of 450 kW is radiated by impurities; the most important radiator is titanium.

Operation with the full PDX divertor system is scheduled to begin during the next month. Neutral-beam heating at 6 MW (a joint project of PPPL and ORNL) will begin in early 1980, and will put the efficacy of the poloidal divertor concept to its critical test.

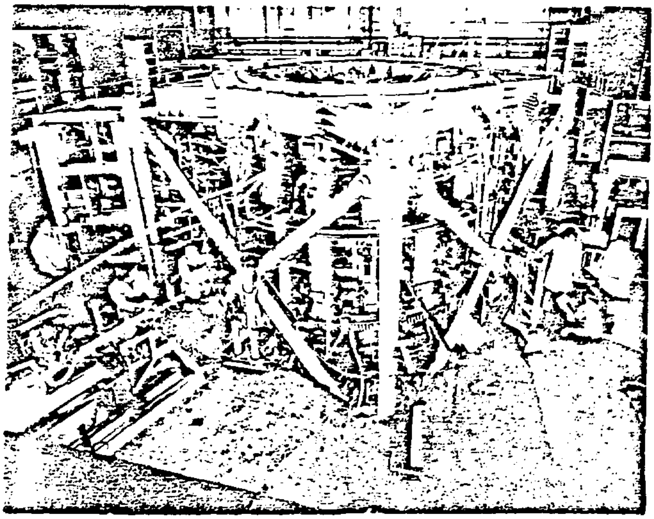

Figure 7. The PDX device in experimental operation. (PPL 794163)

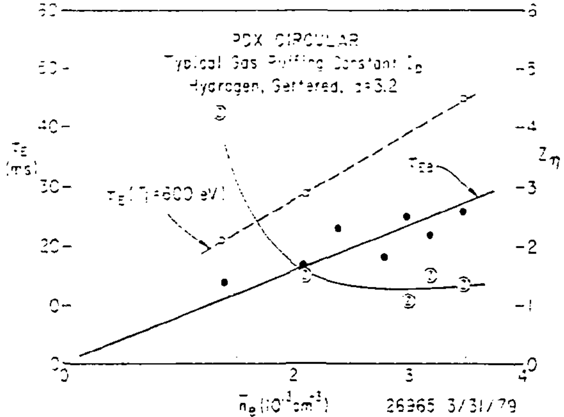

Figure 8. Energy confinement and effective Z in PDX, for a divertorless ohmic-heating operation.

IV. PLT HEATING EXPERIMENTS

A number of PLT technical papers are being reported at this conference [7-10]. The present review addresses itself to some recent results in ICRF and neutral-beam heating that have practical implications for next-generation tokamak heating.

Initial ICRF experiments on PLT [9,11] have used a single half-turn loop antenna to couple up to 350 kW of 25-MHz power into plasma waves. The most interesting results have been obtained by utilizing minority-ion damping, with the applied frequency adjusted to the fundamental cyclotron frequencies of small admixtures of H^+ or $^3He^{++}$ ions in deuterium bulk plasmas.

In the hydrogen minority experiments, the admixtures were typically 5-10% and the deuterium plasma parameters were: B_T = 17 kG, I_p = 300 kA, $T_e(0)$ = 1.4 keV, $T_i(0)$ = 0.6 keV (before heating), τ_{Ee} ≈ 20 msec, τ_{Ei} ≈ [illegible] msec and Z_{eff} = 3 - 5; the density was adjusted to reach $\bar{n}_e$ ≈ [illegible] cm^{-3} at the end of the rf pulse. As illustrated in Fig. 9, the bulk ion temperature rises appreciably during the heating process, as determined from the usual charge-exchange, spectroscopic, and neutron diagnostics.

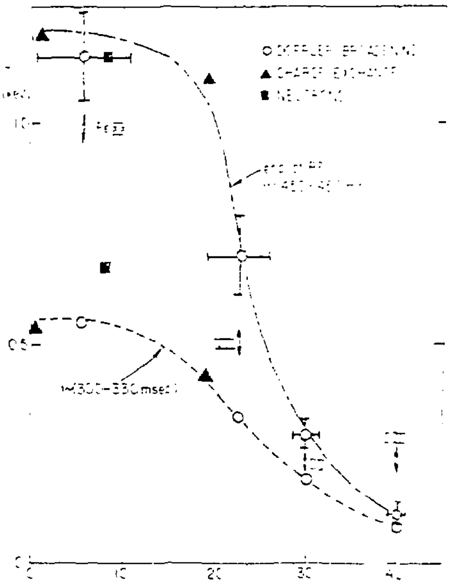

Figure 9. Radial ion temperature profile evolution in PLT for an ICRF heating pulse of 350 kW power and 100 msec duration. (PPL 796013)

In this process the hydrogen minority ions are typically raised to energies of order 10 keV, and have been measured up to 80 keV. The poor orbital confinement of such energetic protons at the relatively low plasma currents that have been used thus far presumably gives rise to wall bombardment and may contribute to the marked density rise (typically from $\bar{n}_e$ ≈ [illegible] cm^{-3} to [illegible] cm^{-3}) during the rf heating; alternatively, the typically observed transition of the discharge into a strong sawtooth regime during the rf pulse may be responsible for the density rise.

A promising feature of the ICRF experiments is their energetic efficiency (cf. Fig. 10). Plotting ΔT_i against $P/\bar{n}_e$ for the hydrogen minority heating case, one finds a straight line with a slope very similar to that obtained previously for neutral-beam heating on PLT. The favorable impression is strengthened by experiments using a $^3He^{++}$ minority of 5-10%, together with a resonant field of 25 kG and currents up to 500 kA (cf. Fig. 10). The heating efficiency is then found to be improved by a factor of two.

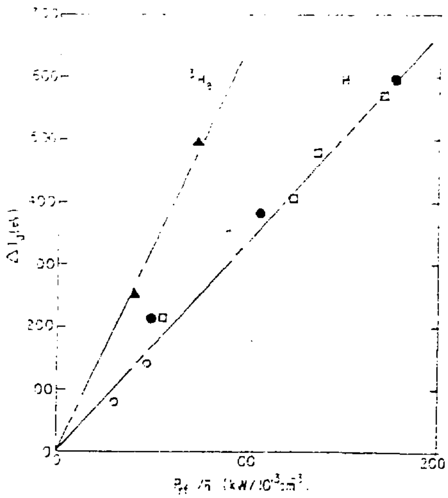

Figure 10. Empirical scaling of the deuterium ion temperature increase in PLT versus ICRF power, normalized by density. Minority heating through H^+ and $^3He^+$ ions has been studied. (PPL 796021)

Recently, two coupled half-turn coils have been put into operation on PLT, an arrangement that offers some control over the parallel wavelengths of the excited plasma modes and may permit the heating power to be deposited more centrally. This modification would be desirable, since the ion temperature profile for single-coil heating is rather broad (Fig. 9) and may be responsible for the observed enhancement of impurity influx during rf-heating — somewhat comparable to that associated with neutral-beam counter-injection. The use of two coupled coils will also allow the input power to be raised; 25-MHz-power levels in the 1-MW range are expected to be reached during the coming months.

The PLT device contains two additional coupling loops, which will begin to be used, this fall, with 42-MHz rf power, thus allowing the study of fundamental hydrogen minority heating in a 30-kG field, or second-harmonic heating at correspondingly lower fields. The ultimate PLT capability is for 4-coil, 42-MHz (or 55-MHz) heating in the multimegawatt range.

Minority heating by ICRF waves can be viewed as a kind of "internal" beam heating, which bears a fairly close resemblance to beam-injection heating. The initial PLT results are helping to establish the ICRF approach as a realistic alternate contender for the achievement of ignition in large next-generation tokamak devices, but the relative attractiveness of ICRF heating equipment will depend on practical details that are still far from clear. Some issues of special importance will be the relative ability of ICRF power to achieve good penetration in large, dense plasmas, and the feasibility of ICRF coupling structures that are suited to the reactor environment. In the latter context, the demonstration of efficient higher-harmonic (i.e., higher-frequency) heating will be particularly important.

A number of experiments have been carried out on PLT to study the phenomena associated with simultaneous ICRF and neutral-beam heating [8] at comparable input powers (approximately 250 kW each). Generally speaking, the ion temperature increments due to these two types of input power are linearly additive, but regimes that are associated with substantial impurity evolution give rise to unfavorable nonlinear effects. An interactive phenomenon that may have useful applications is the secondary energization of neutral-beam-injected minority ions by the ICRF waves. In the illustrative case of Fig. 11, the normal injected-ion spread of 1.3 keV about the 30 keV injection energy is raised to 4.3 keV by the rf pulse. This phenomenon is of potential interest for "ion-energy clamping" in a TCT reactor, but energy diffusion, rather than net energy input, may turn out to be the principal feature of the rf-beam interaction.

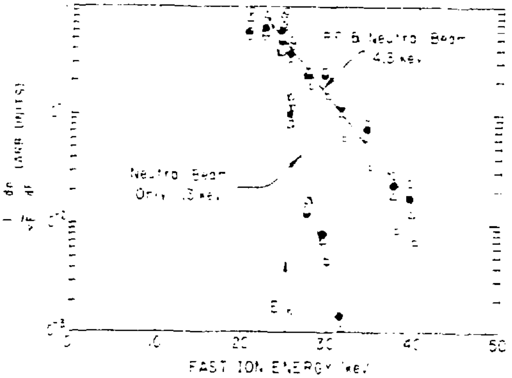

Figure 11. Interactive effect of simultaneous ICRF and neutral beam power in PLT: The beam ions are "heated" above the injection energy. (PPL 793766)

High-powered neutral-beam heating on PLT, first reported in Ref. 12 for the 1.1-MW level, was extended to 2.4 MW in Ref. 13, with resultant ion temperatures ranging up to 6.5 keV. During the past half-year, the power of the injection system has been raised to 3.0 MW. Recent high-temperature heating experiments on PLT have been handicapped, however, by the imposition of an upper limit of 25 kG on the toroidal field. This limit — which was imposed as a cautionary measure following minor TF coil damage — is about to be restored to the 30-kG level of the previous experiments.

While the confinement results obtained in the high-temperature experiments of Refs. 12 and 13 were generally very encouraging, the central mysteries of tokamak transport remain unresolved. The apparent ion heat conductivity is compatible with neoclassical theory, but since the ion heat conduction channel is a relatively minor feature of the energy balance, one cannot exclude an anomalous enhancement up to a factor of approximately 5 in the highest-temperature cases. The effect of trapped-particle modes in PLT is clearly less severe than had been anticipated on the basis of some simplified quasi-linear transport models, but the onset of important anomalous-diffusion losses at collisionalities somewhat below those of the PLT regime cannot be ruled out — and is even rather probable. Fortunately the degree of collisionlessness required in a conventional tokamak ignition reactor need not go beyond that already achieved in PLT, but "hot-ion ignition" schemes, for example, will enter an entirely new regime.

As regards the electron thermal conductivity, further studies on PLT have confirmed the original impression [12] that confinement in the central high-temperature plasma region actually improves during neutral-beam driven electron-temperature excursions. From these observations, one could draw the simpleminded conclusion that τ_{E_e} scales up proportionately with T_e, but a number of other interpretations are equally reasonable. For example,

τ_{Ei} may be affected favorably by the beam-driven increase in T_i/T_e, or by the secondary effect associated with the presence of the beam-injected ion population, so that the rise in T_e is not a cause of the rise in τ_{Ee}, but only an accompanying phenomenon.

While a great deal of effort has been devoted in recent years to the study of plasma energy and particle transport in the tokamak, the investigation of ion momentum transport (i.e., viscosity) has been undertaken only recently [14]. That these three forms of plasma transport are all related and provide essential clues to one central physical transport phenomenon, seems rather likely. The expectation that something important may be learned from rotating-plasma studies is being heightened by the recent PLT data, which continue to confound attempts at simple explanations.

The toroidal velocity profile shown in Fig. 12 was obtained by means of 1.5 MW of tangential deuterium coinjection into a hydrogen plasma of $T_i(0) \sim 2$ keV, with $n_e(0)$ rising from 3 to $5 \cdot 10^{13}$ cm^{-3} during injection. The characteristic viscous-damping times calculated for this profile were of order 10-20 msec — roughly comparable to the electron and ion energy confinement times, but very short compared with classical expectations (2.5 sec), and somewhat short compared with the conceivable damping due to charge-exchange (40-300 msec).

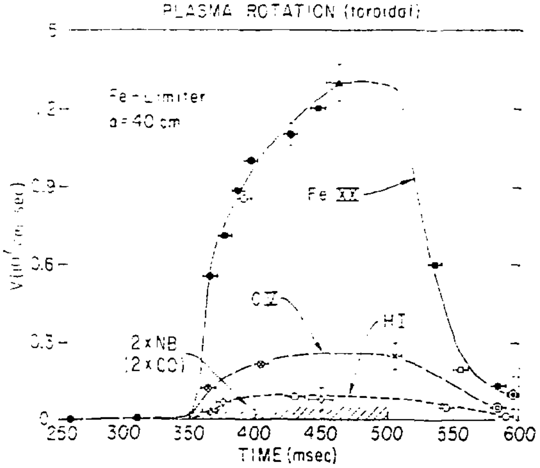

Figure 12. Toroidal velocity profile in PLT during unbalanced tangential injection of 1.5 MW from two coinjectors. (PPL 786284)

The neutral-damping hypothesis could be laid to rest entirely by measuring the dependence of the rotation velocity on plasma density. Recently, the authors of Ref. 14 have carried out this experiment, and find that the rotation velocity shows a moderate inverse dependence on density, with the viscous-damping time increasing only mildly at the higher densities (up to $\bar{n}_e = 5 \cdot 10^{13}$ cm^{-3}) where charge-exchange becomes negligible. At this point, we are left without any known mechanisms that could explain the main damping effect.

Another source of information about the plasma rotation phenomenon is the variation of the relative mass of injected and plasma ions. For example, one might expect a D-beam injected into an H-plasma to give substantially higher rotational velocities than the converse arrangement. Surprisingly, this mass effect has turned out to be quite weak; the literal interpretation would be that the hydrogen plasma has higher viscosity.

Aside from challenging our intuitions about toroidal transport, the uni-directional neutral-beam injection experiments have important practical consequences for next-generation tokamak facilities. It is well known by now that counterinjected neutral beams give rise to far more impurity evolution (at a given power) than coinjected beams. This effect is not surprising, since counterinjected ions are more likely to strike the walls and cause sputtering. In addition, recent PLT experiments with argon admixtures have provided some indication that counterinjection may actually promote the ingestion of edge impurities into the plasma. A critical question for the future is whether unbalanced coinjection into next-generation tokamak plasmas should be utilized to minimize the impurity problem, or must be avoided meticulously in order to prevent rotation-driven instabilities. In present-day tokamak devices, such as ISX-B and PLT, unbalanced coinjection is clearly advantageous, but in the absence of knowledge concerning the nature and scaling of the tokamak plasma viscosity, one worries that long-pulse injection into large, hot tokamak plasmas may result in dangerous rotation velocities. On the basis of the classical transport theory, the velocities predicted for TFTR could clearly become enormous, even when the unbalanced injection is of the near-perpendicular, rather than tangential kind. On the other hand, if the rotation damping time continues to be of the order of the gross energy confinement time, as in PLT, then even tangential coinjection might well present an attractive risk.

ACKNOWLEDGMENTS

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