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HIGH BETA STUDIES ON ISX-B WITH NEUTRAL BEAM INJECTION*

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NEUTRAL BEAM INJECTION EXPERIMENTS IN THE ISX-B TOKAMAK

ABSTRACT

Injection of H^0 into D^+ plasmas with beam power P_b of up to 1.7 MW has produced rms betas of $\sim 4\%$, volume-averaged betas of $\sim 3\%$, and central betas of $\sim 10\%$ in the ISX-B tokamak. Although theoretical calculations indicate that the observed equilibria may be unstable to ballooning modes, no catastrophic loss of confinement has been observed, and beta continues to increase with injection power. In these beam-dominated high-beta discharges the electron and ion energy confinement times are still similar to those obtained with ohmic heating: ion energy confinement is neoclassical within a factor of ~ 2 , and electron energy confinement follows the usual Alcator scaling. In high-power injection discharges the character of the magnetohydrodynamic (MHD) behavior changes, the particle confinement time decreases, and the inward impurity transport appears to be inhibited. These effects, however, may not be linked directly to beta.

1. INTRODUCTION

The main objective of neutral beam injection experiments in the Impurity Study Experiment (ISX-B) tokamak is to study high-beta plasmas. This study aims at reaching the highest possible beta, identifying any beta limit on MHD stability and confinement, and exploring the dependence of the beta limit on the plasma cross section. For this purpose the ISX-A tokamak was modified to accept two tangential neutral beam injectors and a poloidal coil system capable of producing a circular, elliptical, or D-shaped plasma with an elongation ϵ of up to 1.8 in a rectangular-shaped vacuum vessel (major radius $R_0 = 93$ cm, horizontal limiter radius $a_2 = 27$ cm, and vertical limiter radius $b_2 = 50$ cm). The device and the results of initial neutral beam injection experiments were discussed elsewhere [1,2]. Results of other experimental programs are presented in the companion paper [3]. In the present experiments the tokamak has been operated at toroidal field B_T values of 0.9-1.5 T, plasma currents I_p of 75-190 kA, and flat-top current pulse durations of up to 250 ms with nearly circular ($\epsilon \leq 1.1$) plasmas. The limiters defining the horizontal plasma radius were made of either stainless steel or TiC-coated graphite [3]. The discharge chamber was conditioned by hydrogen-discharge cleaning. In experiments conducted in 1979 H^0 beam power of up to 1 MW at 40 kV was

delivered to the plasma by two 22-cm-diam ion sources. Recently the neutral beam system was upgraded to accommodate two 30-cm-diam sources, delivering up to 1.7-MW neutral power at ~ 32 kV (with a design capability of 3 MW at 40 kV). We report here preliminary results from the recent experiments as well as results from experiments last year. Thus far only co-injection has been employed, and essentially all ($>95\%$) of the injected power is absorbed. The neutral beam systems were developed at ORNL [22,23].

2. TYPICAL DISCHARGE CHARACTERISTICS

Figure 1 illustrates the behavior of several parameters for a discharge with high-power injection. The discharge is sustained for 200 ms with the plasma current ramped from 110 kA to a flat-top value of 190 kA (yielding a safety factor of 2.7 at 1.3 T) with feedback control of both plasma current and position. The line-averaged electron density (as measured by a far-infrared laser interferometer) is raised to $7 \times 10^{13} \text{ cm}^{-3}$ at 180 ms with intense gas puffing during injection. Beam pulses from the two injectors are staggered so that the injection power increases from 0.7 MW to 1.6 MW. The beam heating of electrons drops the loop voltage from ≈ 2 V before injection to ≈ 0.4 V during the full-power injection. Therefore, at this time the ohmic heating power is only 1/20 of the beam heating power, almost eliminating the role of the discharge current in plasma heating. Figure 1 shows the rise of the central ion temperature $T_i(0)$, measured from charge exchange analysis.

Figure 2 shows the electron temperature and density profiles obtained by Thomson scattering measurements at 150 ms into the discharge. The outward shifts of the profiles are characteristic of high-beta, beam-heated discharges. The case shown in figures 1 and 2 has been computed using the ORNL PROCTR 1-D transport code. "Alcator scaling," using an average value for density, was used for electron density and particle transport. For the ions, 1.5 times neoclassical scaling was used. The transport coefficients were enhanced inside the $q = 1$ surface. The experimental gas puff rate was used along with a complete model for wall recycling [16]. Both the temporal and the spatial evolution of the plasma are a good match to the experimental results. This agreement supports the belief that there is no substantial degradation of confinement as beta is increased in this range. The difference in density profiles near the plasma edge is presumably due to a loss rate higher than "Alcator" in this region.

3. HIGH-BETA EQUILIBRIUM AND STABILITY

Strong heating due to high-power injection with favorable confinement at low toroidal field has resulted in relatively high beta values. Figures 3 and 4 show the peak toroidal beta $\beta(0)$ and the volume-averaged beta $\langle\beta\rangle$ as a function of plasma density for a variety of beam powers. The solid points indicate the thermal plasma contribution to beta, and the open points show both thermal and fast-ion contributions. The plasma contribution to the total beta is calculated from $n_e(r)$, $T_e(r)$, and an assumed $T_i(r)$ profile derived from the measured central value with the same radial profile as the electron density. The fast-ion component (from slowing-down beam ions) to the total beta is computed using a Fokker-Planck code [4] that calculates beam deposition and slowing-down. The same results, within a few percent, are obtained using a Monte Carlo code developed at the Princeton Plasma Physics Laboratory (PPPL) [5] that allows for diffusion of the fast ions in both velocity and real space. Average beta values of about 3% have been obtained, with peak beta values of up to ~10%. The fast-ion contribution is a significant fraction of the total pressure (and beta) at low density and high beam power, but it amounts to <25% of the total at high density. As shown, both $\beta(0)$ and $\langle\beta\rangle$ increase with density at low values of $\bar{n}_e$ but tend to reach a plateau at high values of $\bar{n}_e$. A more relevant beta value than $\langle\beta\rangle$ for a fusion reactor design is the rms beta $\beta^* = 2 \mu_0 \sqrt{\langle p^2 \rangle} / B_T^2$, because fusion power production is approximately proportional to $\langle p^2 \rangle$. Figure 5 shows β^* versus beam power for densities above $4 \times 10^{13} \text{ cm}^{-3}$. Values of β^* increase linearly with beam power up to ~4% with no indication of saturation.

Magnetic measurements yield values of total volume-averaged β_p that can be compared with those calculated in the same manner as $\langle\beta\rangle$ (i.e., from the energy measurement). The points in Fig. 6 show energy-derived β_p versus B_z/I_p , where B_z is the average vertical field calculated from the poloidal coil currents incorporated with an iron core model. The Shafranov formula [6] (neglecting a small correction for the anisotropic fast-ion pressure) estimates β_p values from B_z/I_p and gives the dashed line for a constant value of the plasma internal inductance of 1.0. Although the energy-derived values are in reasonable agreement with those from the Shafranov formula for $\beta_p < 2$, they clearly depart from the line for $\beta_p > 2$. Some departure at high β_p is expected because the Shafranov formula

is valid for $\beta_p \ll A = R_0/a$ and $A \gg 1$. Indeed, the range of agreement can be extended with the solid line obtained from free-boundary magnetic equilibrium calculations (which are not limited by the above restrictions) using pressure profiles similar to those deduced from the experiment and current density profiles yielding $q(0) \approx 1$. However, even this curve does not give values as high as those from the energy measurements. The discrepancy appears to be beyond the uncertainties ($\pm 20\%$) in the energy measurement. Two possibilities for error in the magnetic measurements are being considered: (1) the effects of the iron core on high- β_p equilibria are not correctly included; (2) current density profiles at high β_p are flatter than those based on $q(0) \approx 1$, as might be concluded from the absence of definitive sawtooth oscillations in soft x-ray signals at high beta (as discussed below). Both these effects tend to increase β_p values obtained from the magnetic measurement, which may therefore be regarded as providing the lower limits. In this regard the β_p value obtained in the equilibrium measurement for the case shown in Fig. 1 is 1.7; the one based on the energy measurement is 2.4.

A critical question regarding beta limits is whether the measured plasma states are theoretically stable or unstable to ideal or resistive MHD modes. The ISX-B values exceed the typical critical beta values calculated for both low- n (toroidal mode number) ballooning interchange modes and high- n localized ballooning modes. For example, the results of the PEST code [7] predict the low- n stability limit for β^* to be typically $\approx 2\%$; the values are even lower for typically observed peaked pressure profiles. Furthermore, high- n stability limits are found to be similar to low- n limits.

Stability analyses based on plasma parameters more closely simulating the experimental values also indicate that the ISX-B plasma should be unstable for both low- n and high- n modes. Plasma equilibria that model experimental data are calculated by a free-boundary equilibrium code that includes the effects of the ISX-B iron core and the poloidal coil system, but not the fast-ion anisotropy. Figure 7(a) shows two pressure profiles thus calculated, together with the measured plasma thermal pressure profile and the total (including the fast-ion contribution) pressure profile for a discharge with $P_b \approx 1$ MW.

The two theoretical equilibria (A and B) that bound all of our experimental uncertainties form the basis of these stability studies. The range for $\langle \beta \rangle$ is 1.5-2.3%.

Figure 7(b) shows the results for high- n modes for this 1-MW case; the calculated regions of instability are shown

based on numerical calculations using the General Atomic (GA) ballooning code BLOON [8] and the analytical expression of Pogutse and Yurchenko [9]. Both results indicate that there should be unstable regions in the plasma interior for both equilibria in which the gradient of beta exceeds the critical value for ballooning stability. Inclusion of the anisotropic pressure (due to fast ions) with a modification by Cooper of Bateman's initial-value ballooning code leads to the same conclusion [10].

Low-n stability has been tested with the Oak Ridge National Laboratory (ORNL) version of ERATO [11] and with the PPPL PEST-II code [7]. A complicating factor arises: the boundary condition in the ERATO calculations assumes an ideally conducting shell close to the plasma. With $r_w/a = 1.2$ (where r_w is wall radius), ERATO calculates equilibrium A to be unstable and equilibrium B to be stable. PEST calculations, on the other hand, indicate that both A and B are unstable as the perfectly conducting shell is taken away. The assumption of a perfect conductor at $r_w/a = 1.2$ probably overestimates the stabilizing effect of the ISX-B poloidal coil conductors. Although stabilities of the discharges with $P_b \approx 1.7$ MW have not been analyzed, the equilibria are expected to be more unstable against both low- and high-n modes.

Even though the measured beta values are above the stability limits predicted by ideal MHD stability theory, neither serious loss of confinement nor catastrophic MHD perturbations directly related to high beta have been observed. Certainly no phenomena analogous to disruptive instabilities have been associated with high beta. The energy confinement times for both electrons and ions have not deteriorated significantly at high beta, giving no evidence of saturation of β^* at the highest injection power levels.

The character of MHD activities, as detected by soft x-ray emission and Mirnov probe signals, undergoes gradual changes (as opposed to the sudden ones that might be expected at the ballooning instability threshold) as the beam power is increased. Low injected powers enhance the period and amplitude of the sawtooth behavior that is characteristic of the base discharges. However, even slight enhancement leads to larger Mirnov signals that are then frequency coupled to the concomitant large soft x-ray oscillations (at 10-20 kHz) and exhibit a dominant $m = 2$, $n = 1$ symmetry. The apparent poloidal propagation of this B_θ perturbation is reversed from the usual electron-diamagnetic direction, implying that these modes are Doppler shifted due to beam-driven (toroidal) plasma rotation. These

features of the coupled Mirnov signals are retained at higher injected powers. As illustrated in Fig. 8, high powers produce a relaxation behavior characterized by a much shorter period (1-2 ms) and intense oscillations lasting only a few cycles. Primitive features of the classical sawtooth are still observed: inside-outside behavior for $m = 0$, and odd- m symmetry for the oscillation signals from the 0- and 8-cm-x-ray detectors, which straddle the displaced magnetic axis. Intermediate powers can result in continuous levels of oscillation in x ray and B_θ ,

without the sawtooth but with odd- m symmetry still indicated by the interior detectors. Whether these instabilities are the usual modes only modified by injection effects or are new instabilities is not known. The answer awaits more detailed documentation with improved diagnostic capabilities.

4. ENERGY CONFINEMENT WITH INJECTION

The ISX-B experiment has emphasized both high-power neutral beam heating and operation at relatively low toroidal field. High input power from beams and favorable energy confinement at low B_T are important ingredients for achieving high-beta values in ISX-B, and the major question here is whether energy confinement deteriorates at high beta. In addition, this mode of operation is of interest from other points of view because:

(1) operation at low B_T and high $\bar{n}_e$ exaggerates neoclassical heat conduction loss in the ion power balance, and (2) the heating role of the plasma current is completely negligible in the electron power balance.

The measured central ion temperature and its scaling with plasma density agree with neoclassical calculations for ion energy transport, as shown in Fig. 9. The central ion temperature is obtained from charge exchange measurements by assuming a parabolic ion temperature profile. The line shown in the figure corresponds to a heating rate of 3.5×10^{13} keV cm⁻³/MW, which is about equal to that obtained in the Princeton Large Torus beam heating experiments [12]. The theoretical central ion temperature is calculated from a 1-D ion power balance using measured electron parameters, classical beam-ion and electron-ion energy transfer rates, and an ion thermal conductivity 1.5 times the neoclassical values [13]. The neutral density, which significantly affects charge exchange losses of slowing-down fast ions and of thermal ions, is estimated from a cylindrical neutral transport code [14] in which the integrated neutral flux to the plasma edge is taken to be 2.5 times the gas feed rate in order to account for recycling of the wall (as

discussed below). Effects of halo neutrals (resulting from charge exchange between beam neutrals and plasma ions) are small in the present operational regime and are not included in the calculation. The calculated $T_i(0)$ values agree well with the measured values, as shown in the figure. Based on the calculated ion temperature profile, the ion energy confinement time τ_{Ei} scales roughly with $I_p/\bar{n}_e$. However, the values of τ_{Ei} are nearly equal to those of ohmically heated discharges with similar conditions, contrary to expectations that τ_{Ei} would improve due to reduction of the thermal conductivity resulting from increased ion temperature. Apparently the improvements are offset by increased losses due to charge exchange and convection at higher neutral density resulting from large gas puffing.

Electron energy confinement times for beam-dominated discharges (P_{inj}/P_{OH} values of up to 30) are also similar to those for ohmically heated discharges. Figure 10 shows the dependence of the electron energy confinement time τ_{Ee} (within half the plasma radius) on the line-averaged density $\bar{n}_e$ for different levels of injection power; τ_{Ee} continues to increase linearly with density. The slope shown corresponds to the usual Alcator scaling: $\tau_{Ee} = 5 \times 10^{-19} \bar{n}_e a^2$ (s, cm⁻³, cm). To within experimental uncertainties ($\pm 20\%$), there is no significant deterioration of τ_{Ee} for high-beta data, i.e., at high P_b and high $\bar{n}_e$. However, there is some decrease in the slope of τ_{Ee} versus $\bar{n}_e$ at low $\bar{n}_e$ and high P_b . This may be due either to some underestimation of fast-ion charge exchange losses or to increased convection losses with increasing injection power (due to the apparent deterioration of particle confinement discussed below). The electron energy confinement time appears to be roughly independent of the plasma current and the toroidal field (the latter independence is especially important in attaining higher β_T values).

Gross energy confinement time is a combination of electron and ion energy confinement times through $\tau_E = (1 - P_i/P_T)\tau_{Ee} + (P_i/P_T)\tau_{Ei}$, where $P_T = P_{be} + P_{bi} + P_{OH}$ and $P_i = P_{bi} + P_{ei}$. In ohmically heated discharges, τ_E clearly shows the transition from electron-dominated to ion-dominated confinement as $\bar{n}_e$ increases, as in ISX-A [15]. With injection the transition is

not as evident, because a smaller fraction of the injected beam power goes to ions (compared with that to electrons) and because P_{ei} decreases as the difference between T_e and T_i decreases. Nevertheless, τ_E tends to reach plateau values at high density, as indicated by the behavior of the plasma components (black points) of $\langle \beta \rangle$ for a given injection power in Fig. 4.

5. PHENOMENA RELATED TO HIGH-POWER INJECTION

In addition to being a source of heat, neutral beam injection is a source of momentum and particles, and these may alter various transport and stability properties significantly enough to lead to a limit on heating. The ISX-B operational regime (high-power co-injection at modest toroidal field and plasma current) provides a good opportunity to explore any limits and to test various theoretical predictions related to beam heating. So far we have observed two new phenomena involving particle confinement. Explanations for them are not yet in hand, but they do not seem to be specifically beta dependent.

The first of the new phenomena observed is the apparent deterioration of plasma particle confinement. Neutral injection into discharges with linearly rising $\bar{n}_e$ (fed by a constant gas puff) results in a "clamp" of $\bar{n}_e$ shortly (≈ 20 ms) after the beams are turned on, as shown in Fig. 11. Also shown are results of a transport simulation that takes into account the reduction of the recycling rate due to the hardening of the energy spectra of particles impinging on the plasma boundary surfaces during injection [16], indicating that the change in wall recycling is not enough to explain the density behavior. The major part, therefore, is considered to be the result of deterioration of particle confinement. Indeed, intense (2 to 4 times normal) constant gas puffing can restore the slope of $\bar{n}_e(t)$ to its original value before neutral beam injection, and this puffing has been used for the high density operation such as that in the high-beta case shown earlier. The deterioration of particle confinement is correlated neither with the onset of significant MHD oscillations nor with the toroidal field (and thus high beta). However, increasing the plasma current reduces the extent of the density clamp substantially. In addition, an intense short gas puff or a mild disruption just before the start of beam injection can often improve the density behavior (possibly due to the resultant change in current profile for both cases).

The deterioration of plasma particle confinement with injection may be related to the second phenomenon, which

involves impurity transport observed in VUV spectroscopic measurements. The emission from the 15^+ state of argon injected during beam heating does not increase as strongly as it does in ohmically heated discharges, possibly indicating that inward transport is inhibited in the interior of the plasma, as discussed in the companion paper [3]. Observations of high ionization states of naturally occurring iron impurities substantiate the above interpretation. Furthermore, profiles of radiative power density from an array of pyroelectric detectors tend to be broader (and even hollow) than those with ohmic heating. These observations may be due to the theoretically predicted effects of beam-induced plasma rotation [17,18,19].

The typical ISX-B operational regime (e.g., 40-kV H^0 injection into $\bar{n}_e > 3 \times 10^{13} \text{ cm}^{-3}$ at 1.1 T) has achieved beam-ion velocities higher than the Alfvén velocity at which the beam-ion instability is theoretically predicted [20]. The absence of significantly harmful effects is encouraging in relation to alpha particle heating in D-T plasmas.

6. SUMMARY AND PROJECTION

The beta values ($\beta^* \leq 4\%$ and $\langle \beta_T \rangle \leq 3\%$) achieved with injection power of up to 1.7 MW in circular ISX-B plasmas are apparently above the theoretical thresholds for ballooning instabilities. Yet there have been no indications of beta limits; i.e., no significant deterioration of confinement has been observed. Since the present beam sources should give P_b values up to 3 MW, a more decisive demonstration of the discrepancy is forthcoming. The high-beta studies will, then, be addressing questions of accessibility to reactor-relevant beta values and dependences of beta limits, if any, on plasma cross section.

Confinement scalings indicate that high beta values can be achieved with high P_b , lower B_T , higher $\bar{n}_e$, and higher I_p , and these are the directions that the ISX-B high-beta studies will follow. In addition to increased beam power, operation at low B_T is strongly preferred. Practical lower limits of B_T depend on the requirement of acceptably high plasma current (or low q value) and high density. In this regard recent results of low- q experiments with ohmic heating alone are encouraging. Values of $q_a = 1.9$ (or 2.4 including toroidal and noncircular correction) have been obtained at $B_T = 0.83 \text{ T}$ and $I_p = 150 \text{ kA}$ but at low density. The low- q discharge has a broader $T_e(r)$

profile, as expected, and a broader density profile, which should give a smaller ratio of $\beta(0)/\langle\beta\rangle$ and theoretically a higher stability limit for β^* . In addition, operation at higher plasma currents should improve neoclassical ion confinement, reduce the tendency toward density clamping (or equivalently increase particle confinement time), and decrease β_p (which should become significant for $\beta_p \sim A$). In addition to intense gas puffing, hydrogen pellet injection can be used to achieve higher plasma density, as demonstrated on ISX-B [21]. The high-beta studies will also be extended to noncircular plasmas to determine the effect of plasma elongation and triangularity on any beta limits. Toward that end, preliminary studies have been made of a D-shaped plasma with an elongation of ≈ 1.5 , which was created and held stably throughout the discharge duration.

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FIGURE CAPTIONS

Fig. 1. Discharge time behavior for high-density, high-power injection case.

Fig. 2. (a) Electron temperature profile from Thomson scattering for the discharge shown in Fig. 1, and (b) corresponding electron density profiles. The PROCTR code prediction is superimposed.

Fig. 3. Dependence of peak toroidal beta on line-averaged plasma density.

Fig. 4. Dependence of volume-averaged toroidal beta on line-averaged plasma density.

Fig. 5. rms beta as a function of injection power for $B_T = 11^{-13}$ kG and $\bar{n}_e \geq 4 \times 10^{13} \text{ cm}^{-3}$.

Fig. 6. Comparison of β_i determined from energy measurements and magnetic measurements.

Fig. 7. Equilibrium and stability results: (a) experimental pressure profiles and equilibrium results of free-boundary MHD equilibrium calculations bracketing the experimental data; and (b) instability regions for the equilibria shown in (a) using the BLOON code and the Pogutse-Yurchenko theory.

Fig. 8. Responses of Mirnov coil and soft x-ray diagnostics to high-power injection. The x-ray detectors view from above and their tangent radii lie approximately along the (outgoing) major radius: 170 kA, 12 kG, $\bar{n}_e \approx 5.5 \times 10^{13} \text{ cm}^{-3}$, $\beta^* \approx 4.4\%$.

Fig. 9. Central ion temperature (determined from charge exchange analysis) as a function of ratio of beam power to line-averaged density. The experimental temperature values are compared with neoclassical theory predictions.

Fig. 10. Electron energy confinement time τ_{Ee} within radius $a/2$ as a function of $\bar{n}_e$ for different values of beam power.

Fig. 11. Experimental and calculated line-averaged density $\bar{n}_e$ with and without neutral beam injection with the same gas puffing. The decrease of $\bar{n}_e$ at 130 ms is due to a disruptive instability.

Fig. 1

Fig. 2(a)

Fig. 2(b)

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 8

Fig. 7

Fig. 9

Fig. 10

Fig. 11