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By

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HIGH BETA PLASMAS IN THE PBX TOKAMAK

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ABSTRACT

Bean-shaped configurations favorable for high β discharges have been investigated in the Princeton Beta Experiment (PBX) tokamak. Strongly indented bean-shaped plasmas have been successfully formed, and beta values of over 5% have been obtained with 5 MW of injected neutral beam power. These high beta discharges still lie in the first stability regime for ballooning modes, and MHD stability analysis implicates the external kink as responsible for the present β limit.

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Theory has long predicted that indentation of the poloidal cross section on the small major radius side of axially symmetric toroidal plasmas should enhance MHD stability against localized pressure-driven flutelike modes.[1-4] More recent numerical work has shown that such indentation, or "bean" shaping, also enhances the stability of the plasma to the short wavelength ballooning mode as well as the long wavelength internal kink: indeed, with sufficient indentation it appears that the second stability region for both types of modes is directly accessible.[5,6] Moderate aspect ratio equilibria have been found stable to both modes up to $\beta \approx 10$-20%, a very attractive reactor regime.

The advantages of bean shaping are partly offset by two potential problems: producing and maintaining such shapes, and their possible vulnerability to other ideal/resistive instabilities. In order to explore these issues as well as to deepen our understanding of the MHD properties of toroidal plasmas, the Poloidal Divertor Experiment (PDX)[7] was modified to the Princeton Beta Experiment (PBX) tokamak. The present paper covers the major initial objectives of the experiment: the production of bean-shaped plasmas and the study of the β limit.

Noncircular plasmas require nonuniform external fields. The external field needed for PBX was obtained by reassignment and some relocation of the PDX divertor coils. The new poloidal coil arrangement is shown in Fig. 1. Basically, coils 1-4 provide the shaping and coils 5-7 the radial equilibrium. Since the indentation field and resulting plasma elongation make the plasma vertically unstable, three pairs of conducting plates (p_1-p_3) were installed around the lobe area. The residual vertical drift due to the finite resistivity of these passive stabilizers is feedback controlled with a small radial field produced by coil 8. The 8-MW PDX neutral beam heating system remains the same except that two of the four neutral beam lines were reoriented from near-perpendicular to co-tangential in order to ensure the reduction of fast ion loss should a strong fishbone instability[8] still persist in PBX.

The formation of bean-shaped plasmas is easiest when the plasma current profile is broad and when high plasma pressure (i.e., high β_p) shifts the magnetic axis outward. The more peaked the current profile, the steeper the gradients of the required shaping field, and the less stable the vertical plasma position. Furthermore, shaping the inner flux surfaces becomes effectively impossible. In PBX, flat current profiles are obtained transiently with a fast plasma current ramp (~ 2 MA/sec), a technique also useful for obtaining discharges with a low safety factor q.

The high β experiment is performed at low toroidal field strength (B_t = 0.8 - 1.1 Tesla) in order to maximize β with given heating capability. The current ramp is begun just before neutral beam injection in order to pass without disruption through the 5,4 integer resonances of q_ψ, where q_ψ is the value of the safety factor at the plasma edge. Quite remarkably, a high rate of current ramp during neutral beam injection, especially with proper gas fueling, can produce a unique discharge with no MHD activity, not even sawteeth, for several energy confinement times. Using a fast current ramp to achieve high beta has the double advantage of longer confinement time due to the resultant high plasma current and of avoiding the loss of central stored energy by MHD activity.

A high β discharge with a current ramp of 2.0 MA/sec is illustrated in Fig. 2. The plasma parameters at 580 msec are listed in Table 1. The value of β increases from 0.5% in the ohmic phase to >5% during neutral beam heating. Here β is defined as $2\mu_0\langle p\rangle/\langle B_t^2\rangle$, where p and B_t denote total plasma pressure and vacuum toroidal field, respectively, and the brackets indicate a volume average. If β is defined using the local value of B_t at the magnetic axis instead of the average value, the β values are 10% higher. The plasma current reaches 590 kA with $q_\psi = 3$ just before the plasma disrupts, at which time the indentation relative to the plasma width projected on the midplane is 0.2.

A simple measure of current density is the "equivalent cylindrical q": $q_{cyl} \equiv \langle a \rangle B_t / R_{mag} B_p(a)$, where $\langle a \rangle$ is the volume-average minor radius, and $B_p(a) \equiv \mu_o / 2\pi \; I_p / \langle a \rangle$. Typically in PBX, $q_{cyl} \approx 1$ while $q_\psi \approx 3$. The success of the bean configuration to date is basically due to the current-carrying capacity implied by these numbers. The achievement of $q_{cyl} = 1.0$ is, to our best knowledge, the lowest value which has been achieved in large tokamak experiments without further deterioration of energy confinement properties below L-mode. The internal inductance l_i shown in Fig. 2b decreases continuously from 1.0 to 0.5 between 370 msec and 460 msec, indicating that the current profile flattens. Here the internal inductance is determined from formulas given by Shafranov,[9] using as inputs the observed flux values, the diamagnetic flux signal, and plasma current. This low value is confirmed by the full MHD equilibrium analysis discussed below. (Note that for an elongated plasma l_i for a given current profile is generally lower than for a circular plasma.)

The MHD behavior during the beam injection phase is shown by soft X-ray and Mirnov probe signals (Fig. 2c, d). After the last sawtooth occurs at 470 msec, the MHD activity detected by the Mirnov coils becomes very small and only shows a mild resurgence as β increases above 3%. Even then there is no hint of either sawteeth or fishbones.

The time variation of the plasma density and temperature profiles shown in Fig. 3 is constructed from time slices of several reproducible discharges at a β of about 4.5%, measured by the multipoint Thomson scattering system. $T_e(0)$ increases with time from 1.0 keV and reaches 2.0 keV just before the disruption. The $T_e(x)$ profile becomes broader with higher current. The density profile, initially rather peaked, becomes extremely flat with an outward asymmetry developing, behavior similar to that in the high density mode in PDX.[7] The average density reaches 5-6 x 10^{13} cm^{-3}. The central ion temperature, measured from the Doppler broadening of charge exchange recombination light of fully stripped impurity ions, shows $T_i(0)$ increasing to 4-5 keV and then saturating; this is due to the buildup of plasma density. From the kinetic data and estimates of ion dilution based on Z_{eff}, the contribution of electrons and ions to the total β is about 30% each, with the balance coming from the fast ion component.

High beta discharges frequently terminate in a so-called "high beta disruption" at values given by Troyon et al.[10] as typical for ideal kink modes. To determine the MHD stability limit more accurately for actual PBX discharge parameters, detailed numerical studies have been carried out. Self-consistent equilibria are constructed that satisfy the Grad-Shafranov equation using the experimental constraints: poloidal fluxes, diamagnetic flux, and external fields generated by both measured coil currents and calculated eddy currents. The profile of total plasma pressure is scaled from the electron pressure profile as determined from Thomson scattering. The current profile is adjusted to match the total plasma current and the approximate location of the $q = 1$ surface. However, within this parametrization the choice is tightly constrained by the data; e.g., $q(0)$ cannot be varied more than ten percent without violating the experimental error bars on the input data.

The MHD stability of the high β equilibrium of Fig. 1 was investigated with the PEST code,[11] and found to be unstable to the $n = 1$ external kink (conducting wall at infinity) but stable to the n = 1 internal kink (conducting wall bounding the plasma) and to ballooning modes. Since [1-q(0)] can be a sensitive parameter for these instabilities, q(0) was varied in the stability calculation by scaling the toroidal field. As Fig. 4 illustrates, a variation of q(0) within the range of 0.8 - 0.9 has only a slight effect, whereas the presence of a conducting wall one plasma radius away would raise the critical beta to the observed value. It also suggests -- as subsequent calculations have indeed shown -- that a closer wall could raise the kink limit above the ballooning limit.

The MHD oscillation observed at the time of disruption is characterized by n = 1 and m $\geq$ 3, with a growth time of 100 - 150 μsec. A detailed study of this mode, which will be published elsewhere, shows quite reasonable agreement between signals measured by an array of magnetic pickup coils and those calculated from PEST.

In conclusion, bean-shaped configurations have been successfully formed and investigated for their suitability in reaching high beta. The ability of such shaped discharges to accommodate high mean current densities ($q_{cyl} \approx 1$) has made betas of 5% and over accessible within the usual first stability β limit. The mode which limits beta has a long toroidal wavelength (n = 1) and fits the theoretical model for a free boundary kink with a conducting wall at approximately one plasma radius removed from the plasma boundary. This interpretation indicates that a more tightly fitting shell would raise the kink beta limit above the ballooning limit and allow a test of the bean shape as a means for achieving access to the second stable region for ballooning modes.

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Table 1

β_t (%)	5.3
B_t(t)	0.9
I_p (kA)	590
R_{mag} (m)	1.43
q_ψ	3.1
q_{cyl}	1.0
$P_{neutral\ beam}$ (MW)	4.7
Stored energy (kJ)	140

Figure Captions

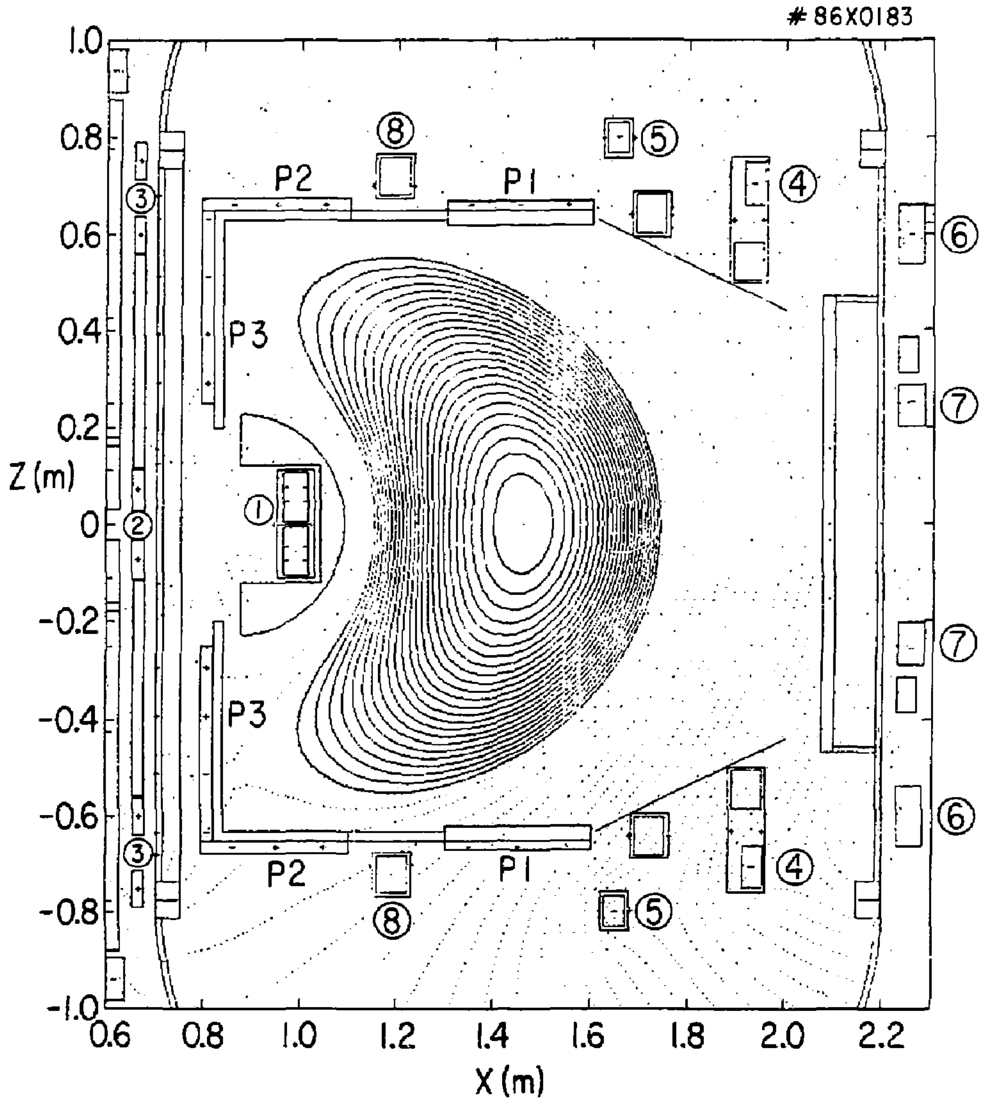
Fig. 1. Layout of PBX with magnetic field configuration for β = 5%.

Fig. 2. Time behavior of plasma parameters for high β: (a) Plasma current I_p, injected power P_{inj}, absorbed power P_{abs}, and plasma beta β; (b) Internal inductance l_i; (c) X-ray signal on the horizontal plane; and (d) Mirnov signal $\dot{B}_\theta$. Note that (c) and (d) are expanded between t = 400 msec and 600 msec.

Fig. 3. Electron temperature and plasma density profiles vs time; composite picture based on many shots. Note that the last sawtooth crashed at t = 490 msec.

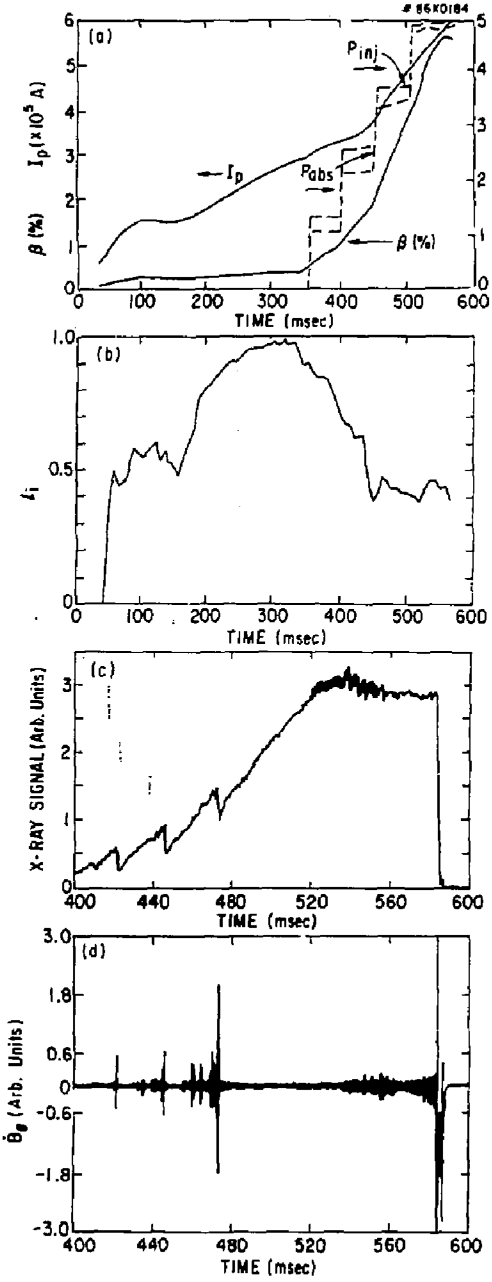
Fig. 4. Critical β vs q(0) from ideal MHD analysis. a_{edge} is the plasma width on the midplane and b_w is the wall location measured from the geometrical center on the midplane. The first stability limit for a ballooning mode of 8.5% is indicated by the shaded area. The achieved maximum β in PBX is 5.0 ~ 5.5%.

Table 1. Plasma parameters at $\beta \gtrsim$ 5%.



86X0183
1.0
0.8
0.6
0.4
0.2
Z (m)
0
-0.2
-0.4
-0.6
-0.8
-1.0
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
X (m)
P1
P2
P3
1
2
3
4
5
6
7
8

Fig. 1



86K0184
(a)
P_{inj}
I_p
P_{abs}
β (%)
$I_p (\times 10^5 A)$
β (%)
P_{abs} (MW)
P_{inj} (MW)
TIME (msec)
(b)
ℓ_i
TIME (msec)
(c)
X-RAY SIGNAL (Arb. Units)
TIME (msec)
(d)
$\dot{B}_\theta$ (Arb. Units)
TIME (msec)

Fig. 2

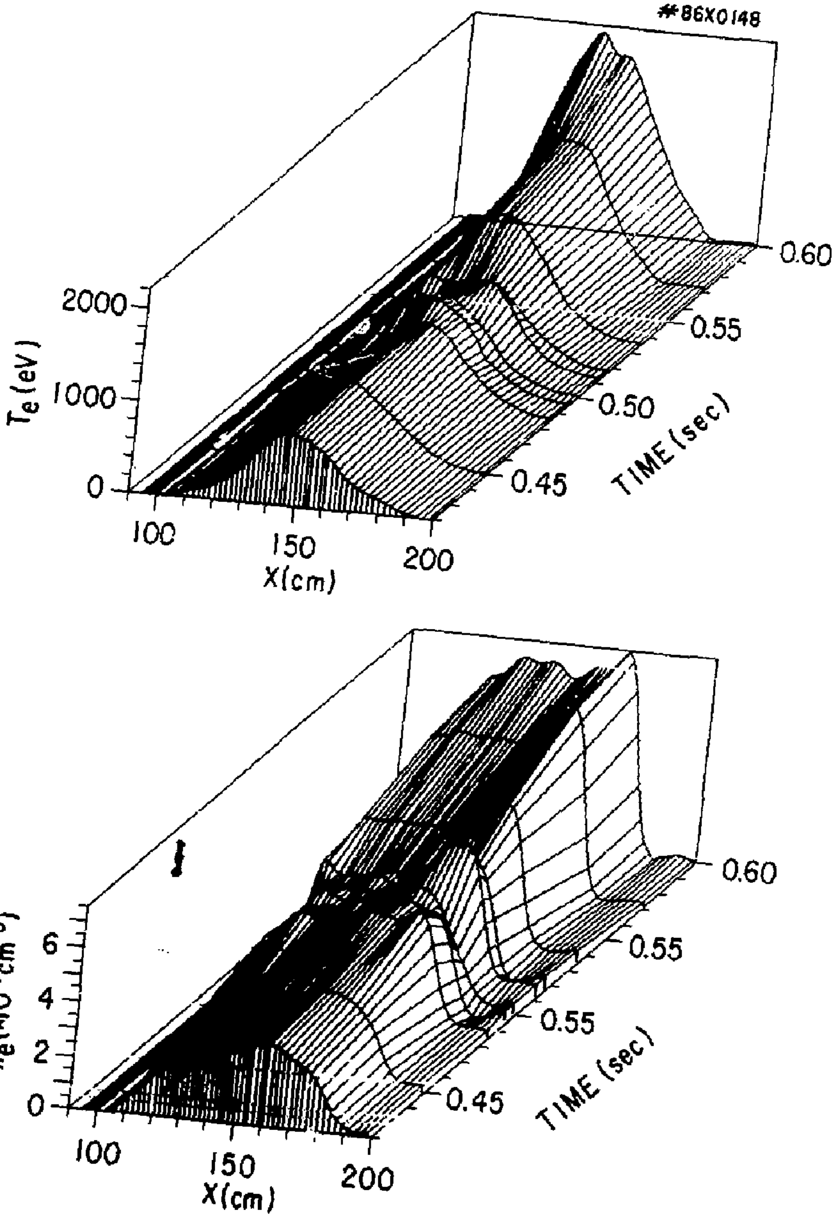

#86X0148
T_e (eV)
2000
1000
0
100
150
200
X(cm)
0.45
0.50
0.55
0.60
TIME (sec)
n_e ($\times 10^{13}$ cm^{-3})
6
4
2
0
100
150
200
X(cm)
0.45
0.55
0.55
0.60
TIME (sec)

Fig. 3

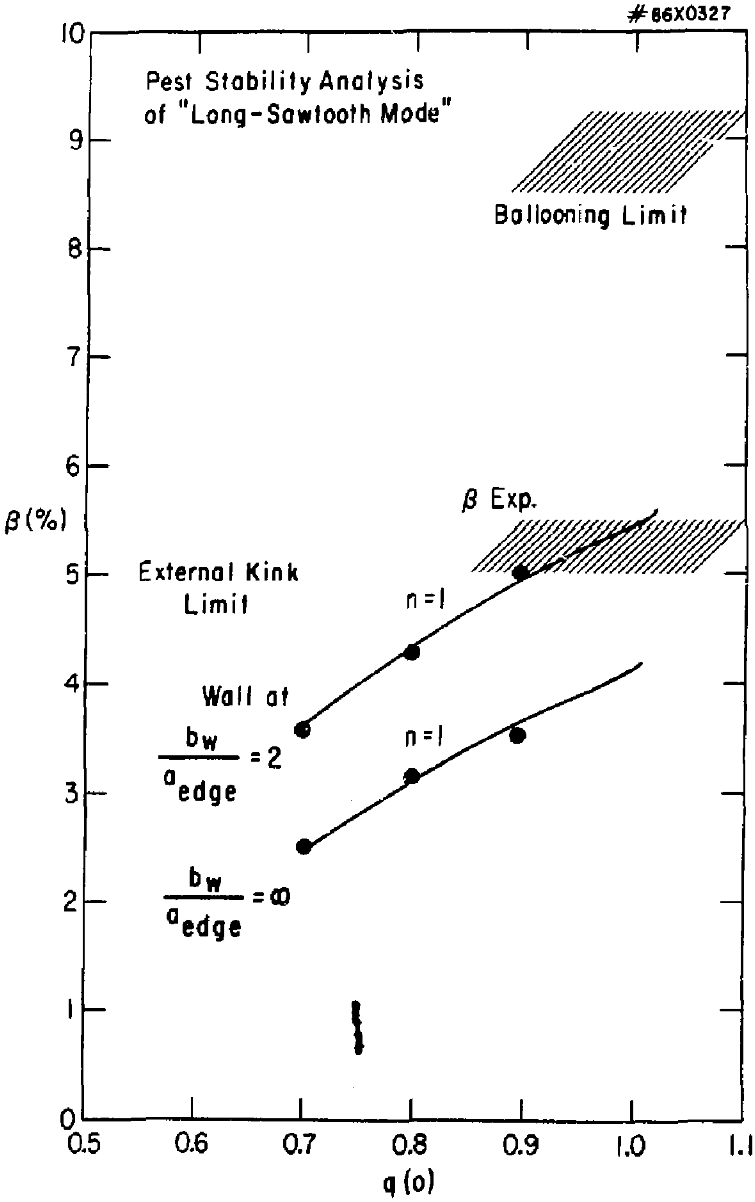

#86X0327
Pest Stability Analysis
of "Long-Sawtooth Mode"
Ballooning Limit
β Exp.
β (%)
External Kink
Limit
n = 1
Wall at
$\frac{b_w}{a_{edge}} = 2$
n = 1
$\frac{b_w}{a_{edge}} = \infty$
q (o)
10
9
8
7
6
5
4
3
2
1
0
0.5
0.6
0.7
0.8
0.9
1.0
1.1

Fig. 4

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