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PBX: THE PRINCETON BETA EXPERIMENT

By

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ABSTRACT

A rearrangement of the divertor coils in PDX will enable a test in 1984 of the MHD stability properties of deeply indented "bean-shaped" plasmas. The goal is a beta of 10%. Indentation is expected to counter the deterioration of MHD stability against pressure driven modes that is occasioned by the larger aspect ratios typical of anticipated reactor oriented devices. Indeed, as shown by M. Chance et al., indentation may offer direct access to the second region of stability for ballooning modes, and numerical analyses with PEST show the internal kink to be stabilized completely with even relatively modest indentation. The internal kink is implicated in the loss of beam ions in PDX. In this report the theoretical basis for the forthcoming experiment, and the design considerations underlying the modification from PDX to PBX, are described in detail. Additional theoretical material, including an analysis of particle orbits in an indented tokamak plasma, is appended.

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Proposal authorship is usually left wrapped in anonymity, but the computational and theoretical effort that has gone into the PBX proposal is so extensive - and intensive - that acknowledgments are in order.

The original inspiration for converting PDX into PBX came from M. Okabayashi, who, with the help of H. Fishman and M. Reusch, also carried the full burden of the design work.

The theoretical work which justifies PBX was motivated by the work of M. Chance, who showed that indenting the plasma cross section could provide stable access to the second region of stability to ballooning modes.

Those most deeply involved in the subsequent computational analysis were R. Grimm, S. Jardin, and J. Manickam. Important contributions were also made by A. Boozer, L. Chen, R. Dewar, R. Goldston, D. Jassby, D. Monticello, F. Perkins, G. Rewoldt, J. Schmidt, W. Stodiek, W. Tang, A. Todd, and R. White. Numerical calculations were supported by A. Miller and Y. Sun.

The engineering staff who have been, and will continue to be, responsible for detailed design and fabrication are identified in Table 4.1.1. Particularly extensive efforts came from J. Chrzanowski, S. Hand, P. Heitzenroeder, H. Kugel, and M. Pelovitz.

P. Rutherford has provided constant support and, indeed, set the project in motion earlier this year.

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K. Bol

PDX Project Head

DISCLAIMER

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1. EXECUTIVE SUMMARY

Plasma beta values of 3% have been achieved in circular plasmas in ISX and PDX, and above 4% in shaped plasmas in DIII.^{1.1-1.3} However, a demonstration of significantly higher values would undoubtedly increase still further the lead that the tokamak presently holds with respect to other approaches to a fusion device. The Princeton Beta Experiment (PBX) is intended to provide such a demonstration, and to do so in a very short time, and at a very low cost, by making use of the PDX facility. The basic modification consists of relocating and reconnecting the existing divertor coils to achieve the desired plasma shape, as well as reorienting two neutral beams from co-perpendicular to co-tangential. Preliminary results on the confinement and stability properties of bean shaped plasmas would be obtained in FY84; the cost of the machine modification (much of it in FY83) is about \$1.2M, including 20% contingency.

Recent theoretical studies and numerical calculations have shown that a sufficiently indented, kidney-bean-shaped plasma provides strong stabilization against the internal kink mode and against ballooning modes, and may provide direct access to the second stability regime for such modes.^{1.4-1.5} Bean shaping, or strong indentation, can be seen as reinforcing the MHD stabilizing properties of minimum B and shear, which are weakened by the larger aspect ratios characteristic of reactor designs. It is worth noting that strong shaping is greatly aided by the flat current profiles which the success of low-q operation has made possible.

A configuration with indentation can be viewed as an optimized limit of strong triangular shaping, which has been considered theoretically as the best approach to stabilizing local flute modes.^{1.6-1.10} Ways of utilizing the strong MHD stability properties of triangularity have been studied before, and

several concepts have in fact been proposed. The first conceptual design of PDX (1973), for example, was based on a kidney-bean-shaped cross section, and the more recent heliac proposal embodies the same concept in stellarator geometry. Following the development of the theory of ballooning modes, these advantages have been re-examined^{1,11} and confirmed quantitatively^{1,12-1,13} as part of extensive numerical optimization of small aspect ratio tokamak configurations.

To obtain kidney-bean-shaped plasmas in PDX requires a relatively small modification of the divertor coil arrangement inside the vacuum vessel. One of the two innermost 16 turn coils would be shifted to the midplane to serve as the pusher coil which creates the basic bean shape. The second coil is parked out of the way. The other coils are shifted away from the midplane to provide more space for a bigger plasma, and are used for the active feedback system to control axisymmetric instabilities. The pusher coil is armored with graphite against neutral beam and plasma impingement. Extended conductors must be installed to provide passive stabilization of $n=0$ modes. By varying the relative strengths of the equilibrium field (EF) and the shaping field (SF), the indentation of the poloidal flux surfaces can be varied from 0.1 to 0.3. For some shapes the plasma is bounded by a magnetic separatrix, but for others the separatrix intersects a passive stabilizer surface. In any case, no specific divertor chamber is planned.

The specific focus of the PDX experimental program would be to derive evidence for the accessibility of a second stability regime from a mapping of the critical beta versus the depth of indentation of the poloidal flux surfaces. A rapid increase in the β limit at a critical indentation would be a very strong indication of the existence of such a regime. With 7 MW of neutral beam heating power and an estimated 40 ms energy confinement time (D^+ ,

600 kA), the boundary could be followed to a β of 10-15% (at $B_T=0.8$ T). In the course of this work we would, of course, address the issues of the formation and $n=0$ stabilization of a bean-shaped plasma, and the behavior of $n=1$ modes (sawteeth, fishbones, resistive tearing modes, and possibly surface modes) in a plasma with strong MHD stability properties.

To form the plasma we would deform an initially circular one by raising the pusher coil current. The relative rates of current buildup in the plasma and the pusher coil are likely to affect the final plasma parameters and would need to be optimized experimentally. Achieving a stable vertical position of the plasma on the midplane requires both active and passive feedback. The PDX bipolar 1 kA amplifier would be used for the active feedback as it has been routinely heretofore; the size and location of the coils necessary to provide adequate passive feedback have been determined from stability calculations.

An indented plasma shape will be a possibility for the Doublet Big Dee in 1986. The Princeton experiment is on a much smaller scale, but complements the forthcoming GA experiment in two important ways: the aspect ratio is about 50% higher, and the relative indentation - and hence the triangularity of the center flux surfaces - is much more pronounced. Thus while the GA test also offers the possibility of high beta, the stability would come primarily from the low aspect ratio; the role of indentation in stabilizing a higher aspect ratio plasma would not be tested, nor could the experiment explore the access to the second stability regime. It is just these two points which are the goal of PBX.

The detailed stability properties of bean shaped plasmas are still being explored numerically and theoretically. The triangularity of the center flux surfaces readily stabilizes the ideal $1/1$ mode, and so one might expect at least a slower growth rate for the resistive $1/1$ mode. However, given the

present level of understanding, the actual behavior of sawteeth and fishbones is best regarded as an experimental issue. A plasma which is stable for $1/1$ modes would obviously be an extremely interesting object.

Resistive tearing modes would have to be dealt with in the same way they are today: by careful control of gas feed and rate of plasma current buildup. No close conducting boundary is planned to suppress free boundary kink modes, except insofar as the passive stabilization coils for vertical motion will have some effect. Since the very occurrence of such modes in a tokamak with a sufficiently diffuse boundary is not established, this topic is also best dealt with on the experimental level.

The reorientation of two neutral beams to co-tangential would have the dual purpose of better beam ion trapping at low and medium densities (the plasma waist is ~ 50 cm thick in a fully indented bean), and of ensuring against beam losses from the fishbone instability. This somewhat weakens the test of the ruggedness of a bean with respect to withstanding this beam-associated instability; however, we gain a check of the present theory for this problem by injecting various combinations of perpendicular and tangential beams into a somewhat smaller circular plasma.

Finally, the decision not to include a divertor in the proposal has the following basis. First, the passive stabilizers would have to be located farther from the plasma, thus compromising the all important $n=0$ stability of the configuration. Second, a divertor would represent a significant complication: one would have to build new liners and more flux shaping coils. Third, according to present scaling laws for beam heated plasmas in PDX, values of beta greater than 10% can be reached without H-mode confinement. Furthermore, the present evidence is that H-mode confinement may be very difficult to obtain at our maximum beam power. Nevertheless, the

separatrix never lies far outside the stabilizers, and in many cases it is the bounding surface (unless a limiter is intentionally run in). Whether such a q profile is advantageous from a stability standpoint is an experimental issue that theory has not yet successfully addressed.

Experimental goals and related physics in the proposed experiment are listed in Table 1.1. These are goals for FY84; at the end of that period the program will be evaluated, and it will then be decided whether or not it should be continued into FY85, and if so, with what further modification.

TABLE 1.1

EXPERIMENTAL GOALS

<u>Experimental Tasks</u>	<u>Comments</u>
Achieve stable bean-shaped plasmas with indentations to 0.3 at $\beta \ll \beta_c$	Document passive stabilization of n=0 mode; demonstrate active control
Obtain β dependence on indentation to $\beta_c > 10\%$	Identify unstable modes; document accessibility to second stable region
Maximize β critical	Transient plasma states to obtain highest β_c

Achieving these goals will create an additional strain on PPPL physicists. The impact will be lessened, however, by the formation of a joint PLT/SSX/PBX operating and diagnostic team, and an even heavier reliance on visiting physicists than this year. (The two machines share power supplies and cannot operate simultaneously in any case.) Consequently, the main burden of PBX will fall, not on TFTR, but on PLT/SSX.

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2. THEORETICAL ADVANTAGES OF STRONG BEAN SHAPING

2.1 INTRODUCTION

The principal motivation of the proposed PBX experiment is to exceed the β values expected for conventional configurations while enhancing our understanding of high- β tokamak plasmas. The results of theoretical research reported in this section show that these objectives may be achieved by indenting the inboard side of the minor cross section, thereby deforming a circular or Dee-shaped plasma into a bean shape (Fig. 2.1). This indentation substantially enhances the stabilizing forces which inhibit ballooning modes, and it introduces favorable cross-sectional shaping near the $q=1$ surface leading to stabilization of the ideal MHD internal $n=1$ kink mode. Since these instabilities play a central role in selecting the criteria for reasonable β values, the experimental demonstration of these stabilizing effects could significantly alter the design of future devices.

Our present understanding of β limiting processes in tokamaks is based primarily on ideal single fluid MHD equilibrium and linear stability analyses in axisymmetric toroidal configurations. While additional kinetic and resistive effects need to be seriously considered (e.g., see Appendices 2 and 3), and the simple MHD model has the virtue of being understood well both qualitatively and quantitatively, it is generally accepted that only configurations which have favorable properties in this model are likely to be viable candidates for serious consideration. It thus provides the foundation for more elaborate and extensive models. Because of the complexity of the equations involved, detailed analysis can only be carried out numerically. Ideal MHD equilibrium and stability calculations have been carried out in support of the design of all present day tokamaks (ISX, PLT, PDX, Doublet, TFTR, and JET) and for future reactor designs (INTOR and FED).

The usual way of carrying out an MHD analysis requires the calculation of a suitable equilibrium solution of the Grad-Shafranov equation in which the plasma is modeled as an infinitely conducting fluid surrounded by a vacuum region and supported by an external field. This is usually called a free boundary equilibrium. For a practical application it is necessary to specify the external field in considerable detail in order to determine the shape of the plasma surface. This aspect of the FBX experiment is described in the next section. Alternatively, one can prescribe a reasonable shape of the plasma surface, solve the equilibrium problem with an infinitely conducting shell on this surface and determine the necessary external equilibrium field as a separate calculation (fixed boundary equilibrium). This is the approach most convenient for theoretical parameter studies and is the one followed for the calculations presented in this section.

To specify an equilibrium, two surface functions must be chosen. The pressure profile is usually chosen to be consistent with experimentally measured profiles, but within the limits of experimental measurements and without too much controversy, some optimization is usually made in the direction of improving the stability properties. The second surface function can be specified either as the poloidal current distribution or as the safety factor profile. In either case it, together with the pressure profile, specifies the toroidal plasma current which is determined only after the equilibrium calculation has been carried out. In general, specifying $q(\psi)$, which is the approach followed in this section, is most convenient for carrying out a stability analysis, but it provides little practical control over the current profile, which must be systematically reviewed for consistency with experiment. We will return later to this issue.

The stability of the MHD equilibrium is usually studied from the MHD energy principle. For localized perturbations Mercier's criterion is computed on each magnetic surface. For small wavelength (large n) modes, the ballooning equation is solved to determine the stability to internal ballooning modes, and a WKB solution is constructed to determine a critical- n value above which instability occurs. For long-wavelength ($n \approx 1-3$) modes, various versions of the PEST code are run to determine the stability to both internal (fixed boundary) and external (free boundary) instabilities.

While these techniques are standard and have been used in a number of previous studies, constant improvement in numerical techniques and in our understanding of the equilibrium and stability properties of high- β configurations has enabled the difficult calculations (especially at high- β with large indentation) incorporated in this study to be carried out with greater accuracy and confidence.

Ideal MHD theory predicts a variety of different instabilities depending on the specific parameters chosen for β , the pressure and safety factor profiles, and the various geometrical shaping factors. Modes are generally categorized as internal, where the plasma displacement vanishes at the plasma surface, or external, where the perturbed magnetic field can extend into the vacuum region. In typical high- β tokamaks instabilities can be driven by both pressure and current forces, and the plasma displacement can be large over most of the plasma region. In carrying out stability analyses over the large space of equilibrium parameters, however, it is convenient to attempt to minimize these driving forces separately so both types of calculations are performed. For internal modes stability is usually studied by solving the infinite n -ballooning equations. Although one can argue with the validity of the MHD model in this limit, it is reasonably well-established

that stability in this limit will ensure the stability of longer wavelength modes. This approach is pessimistic in the spirit of SW. At low- β values this approach omits the internal $n=1$ kink mode which is primarily current driven, and full 2D calculations for this instability should be carried out. For external modes it is usual to consider only low- n modes ($n=1,2$) since shorter wavelength modes become very localized near the plasma surface where the MHD model is difficult to justify and resistive effects (tearing) are important.

Various parameter studies^{2.1} have been performed to establish the scaling of β set by MHD instabilities. These have shown that at low β stability to ballooning modes is improved by small aspect ratio, elongation and triangularity, broad pressure profiles and low q -edge values. The safety factor on axis has usually been taken slightly greater than 1 to avoid internal kinks and Mercier interchanges. For present day tokamaks this ballooning limit is $\leq 5\%$, but at very small aspect ratio ($R/a \sim 2 - 2.5$) β values around 10% have been achieved theoretically.^{2.2} In this last study where β ballooning was optimized allowing the shape of the plasma cross section to vary, the higher β , stable values were obtained with a small indentation supporting the conjecture that bean shaping should be favorable.^{2.3} However, a detailed study of indentation was not carried out.

While the majority of design studies have been performed at low β , it has also been known that at very large β , stability to ballooning modes could be obtained because of the magnetic well effects produced by the large outward Shafranov shift.^{2.4-2.6} This effect was called the "second region" of stability and many attempts were made to discover operating scenarios which would make this region accessible from the low- β regime. Detailed numerical calculations^{2.7} demonstrated that in near circular plasma cross sections the

second stable region occurred only for large aspect ratio configurations and accessibility was not possible. The results of the next section show that while moderate indentation can improve the stability window at low β , sufficient indentation can result in complete stability to ballooning modes and hence provide an operating path into the "second" stability regime.

Most tokamaks operate in practice with $q(0) \leq 1$. The dynamics of such tokamak discharges are determined by resistive relaxation inside the $q=1$ surface which tends to flatten the q profile near the magnetic axis. This interpretation motivated taking $q(0) \geq 1$ in previous parameter and reactor design studies. Recent experimental results in PDX strongly suggest that the onset of the internal $n=1$ kink is associated with the degradation of confinement and β limitations seen with fishbone phenomena. If this is the case, this mode could be the first finite pressure ideal MHD effect observed in tokamak experiments. Stabilization of this mode not only offers the possibility of avoiding fishbones, but also opens up the possibility of tokamak operating procedures at low q , which are economically attractive in the reactor regime. In Sec. 2.3 it is shown that indentation can stabilize this mode at all β values. Of course, higher n ($\sim 2,3$) internal ballooning modes may still occur depending on the parameters.

Present understanding of external modes is not really satisfactory. In the models used for most design studies the low $n=1$ external modes set β limits below the internal ballooning results^{2,8} and also placed constraints on the current profiles near the plasma boundary, which may be unreasonable. Such modes have not been definitively observed in tokamak experiments, although there is mounting evidence that the H_α spikes observed during H-mode operation in PDX may be due to free surface kinks. It may be therefore reasonable to expect that efficient divertor action may sufficiently improve

the purity of the edge region so that the ideal model may be taken seriously. If this is the case, stability is most readily achieved by enclosing the vacuum region in a conducting shell. The calculations of Sec. 2.4 show that the external modes in strongly indented plasmas can be stabilized with the wall at a modest distance from the plasma surface. These results are comparable to what one would expect in more conventional tokamak configurations.

2.2 BALLOONING STABILITY

2.2.1 Ballooning Modes and Local Shear

An important feature of conventionally shaped tokamak plasmas with circular or nearly circular cross sections is the beneficial averaged magnetic well which is formed as the result of the equilibrium shift of the magnetic axis at finite pressure. Provided that the safety factor q is roughly unity or above, this feature tends to stabilize interchange modes which are constrained to be localized within a surface and constant along a field line. If this last constraint is relaxed, the plasma may be susceptible to ballooning where the perturbation can adjust itself to be large where the well is weak or nonexistent and to be small elsewhere. If the stabilizing effect of the magnetic field tension can be overcome by such a perturbation, then the plasma becomes unstable. These effects are contained in the ballooning equation^{2.9}

$$\frac{B}{2} \nabla \left(\frac{|\nabla \alpha|^2}{B^2} \right) \cdot \nabla \phi + 4\pi p' \kappa_{\omega} \phi + \rho \omega^2 \frac{|\nabla \alpha|^2}{B^2} \phi = 0 \quad (2.1)$$

where

$$\underline{B} = \nabla\phi \times \nabla\psi + Rg\nabla\phi = \nabla\alpha \times \nabla\psi$$

$$\kappa_{\omega} = \frac{1}{2\pi} \frac{\underline{\kappa} \cdot \underline{B} \times \nabla\alpha}{B^2}$$

$$\underline{\kappa} = \frac{\underline{B}}{B} \cdot \nabla \frac{B}{B}.$$

The first term represents the field tension, the second the potentially destabilizing combination of pressure curvature, and the third term is due to the inertia. A detailed study of this mode shows that the connection length and the local shear play important roles.^{2,6} The local shear^{2,10} can be written as

$$S = - \underline{F} \cdot \nabla \times \underline{F} \text{ where } \underline{F} \equiv \frac{\underline{B} \times \nabla\psi}{|\nabla\psi|^2} \text{ or}$$

$$S = - \underline{B} \cdot \nabla \left(\frac{\nabla\alpha \cdot \nabla\psi}{|\nabla\psi|^2} \right) \equiv \underline{B} \cdot \nabla I$$

$$= \frac{R}{J} \left[\left(\frac{Jg}{x^2} \right)' + \frac{\partial}{\partial\theta} \left(\frac{\nabla\psi \cdot \nabla\theta}{|\nabla\psi|^2} \frac{Jg}{x^2} \right) \right]$$

where

$$J \equiv (\nabla\psi \times \nabla\theta \cdot \nabla\phi)^{-1}.$$

Since $q(\psi) = (R/2\pi) \oint (gJ/x^2) d\theta$,

$$\frac{1}{2\pi} \oint S J d\theta = q'(\psi)$$

so that S is composed of the averaged global shear and a residual oscillating part.

Using the fact that in Eq. (2.1)

$$|\nabla\alpha|^2 = \frac{B^2}{|\nabla\psi|^2} + |\nabla\psi|^2 I^2$$

and

$$\kappa_\omega = \frac{1}{2\pi B^2} \left[\frac{B^2}{|\nabla\psi|^2} \kappa_n - I \kappa_s \right],$$

where

$$\kappa_n \equiv \underline{\kappa} \cdot \underline{\nabla\psi},$$

$$\kappa_s \equiv \underline{\kappa} \cdot \underline{B} \times \underline{\nabla\psi},$$

we can display the dependence of the ballooning equation on S (seen explicitly through I), as

$$\begin{aligned} \underline{B} \cdot \nabla \left[\left(\frac{1}{|\nabla\psi|^2} + \frac{|\nabla\psi|^2}{B^2} I^2 \right) \underline{B} \cdot \nabla\phi \right] + 2 \frac{P'}{B^2} \left(\frac{B^2}{|\nabla\psi|^2} \kappa_n - I \kappa_s \right) \phi \\ + \rho \omega^2 \frac{|\nabla\alpha|^2}{B^2} \phi = 0. \end{aligned}$$

The solution of this equation is discussed in Ref. (2.9).

In a conventional tokamak the residual part of the local shear S can be negative on the outer side of the major radius where the poloidal field is

usually the strongest; it can, in fact, be so negative that S can vanish there (Fig. 2.2a). This promotes ballooning instabilities because the vanishing of S is the condition that surfaces containing both $\underline{B}$ and $\nabla\psi$ exist and, thus, the local interchange of magnetic field lines can be most easily realized there. This phenomenon is difficult to prevent in the conventional tokamak. However, a strong outward shift of the magnetic axis can further strengthen the poloidal magnetic field on the outside and cause the vanishing points of S to move away from the destabilizing region. This shift may be realized by increasing the pressure, but the onset of the instability usually occurs before the stabilization due to local shear and/or shortened connection length takes place. Another way, emphasized here, is to indent the plasma at the inner major radius so that the effective shift of the axis is present even at low β . Further increase of the pressure enhances the shift even more, then renders the plasma immune to the instability. The enhanced stability features of such a configuration have been observed previously by Mercier,^{2,3} and Miller and Moore.^{2,2}

Contours of $S=0$ are shown in Fig. 2.2a for a moderately indented low- β plasma. There the local shear is zero or weak in the outer region of the plasma. Increasing the pressure at this indentation causes instability at about $\beta \sim 2.6\%$. A stronger indentation as shown in Fig. 2.2b causes the $S=0$ contour to move further out. In this case, even though the shear is still weak at low β , an increase in pressure strengthens the local shear (Fig. 2.2c). This preserves the stability by the self-healing process.

The stabilization due to the shortened connection length of an indented plasma is also effective here. The strong poloidal field at the outside of the torus due to the indentation and finite pressure causes the magnetic field lines to move rapidly through the bad curvature region, spending longer at the

tips of the bean where the curvature is favorable. As shown in Fig. 2.2d, there is a reduction of the dangerous region where the normal curvature is negative.

2.2.2 Indentation and Accessibility to Very High- β

A numerical study of the effect of bean shaping has been carried out by examining the stability of a class of equilibria whose plasma surface in the poloidal cross section is described by the formula

$$x(\theta) = \tilde{x} + \rho \cos \theta ,$$

$$z(\theta) = E \rho \sin \theta ,$$

where $\rho = A + B \cos \theta$, $t = C \sin \theta$, and $0 < \theta < 2\pi$. An example is given in Fig. 2.1 with $A=1$, $B=0.6$, $C=97^\circ$, and $E=0.895$. The fixed boundary solutions of the Grad-Shafranov equation are computed from a flux-coordinate code operating in the mode in which we fix the safety factor and pressure profile. These are taken to be

$$q(y) = \sum_{i=0}^3 q_i y^i$$

and

$$p(y) = p_0 (1-y^2)^2, \text{ where}$$

$y = \psi/\Delta\psi$, $\Delta\psi$ being the poloidal flux within the plasma. The coefficients q_i are specified such that

$$q(0) = 1.03$$

$$q(1) = 4.2$$

$$q'(0) = 0.84$$

$$q'(1) = 9.0.$$

These profiles are shown in Fig. 2.3.

Sequences of flux conserving equilibria at fixed values of indentation, C , are generated by varying the parameter p_0 . Each of these equilibria is examined for ballooning stability by solving Eq. (2.1) on every third one of the 97 flux surfaces spanning the cross section. The equilibrium is considered ballooning stable if it is stable on each of these magnetic surfaces. Figure 2.4 shows the advantage of bean shaping in the stabilization process for a PBX-like tokamak with an aspect ratio of 4. As shown in the figure, at low indentation an increase of β causes the plasma to become unstable, but further increasing the pressure places the plasma in the so-called second stability regime. However, if the indentation is large enough, the plasma can bypass completely the unstable region as the pressure is increased. Bean shaping thus provides an accessible path to the second region of stability for ballooning modes.

2.2.3 Aspect Ratio Scaling

The effect of aspect ratio is shown in Fig. 2.5 for a plasma with indentation fixed at $d/2a=0.304$ ($C=97^\circ$) and for the same p and q profiles as in Sec. 2.2.2. There we see that higher stable β values in the first region

are obtained with low aspect ratio. However, in that region the second regime becomes increasingly remote. At $R/a \sim 2$ equilibria up to $\beta_{av} \sim 80\%$ are still unstable. As the aspect ratio is increased, the region of instability decreases making it appear more likely that operation above the ballooning limit should be possible. For this case the instability region does not vanish, as in Fig. 2.4, at least out to $R/a \sim 20$, which is as far as present calculations have been performed.

2.2.4 Safety Factor Scaling

Several preliminary calculations have been carried out to determine the effect of q on Fig. 2.4. This is important since varying the q profile within this model can strongly affect the resulting plasma current profile.

In Fig. 2.6 we have repeated the calculations of Fig. 2.4 with a flatter q profile [$q(1)=3.2$, $\Delta q'(1)/q(1)=2.14$]. While at small indentation this has the disappointing effect of apparently removing the second stable region to infinite n -ballooning modes, the calculations still demonstrate the absence of any pressure driven modes for large indentations. In fact, compared with Fig. 2.4, this completely stable region occurs for slightly less indentation. Moreover, at smaller indentations, WKB ballooning calculations show that the critical n value above which instability occurs is very large ($n \gg 30$) in the region where we would hope to find the second stable region. Since kinetic effects appear to stabilize short wavelength modes (see Appendix 2), it is quite reasonable to suspect that operation at high β below the critical indentation would still be possible. Future calculations for finite n ($n=3-5$) will be carried out to produce a harder stability boundary.

A second set of calculations to determine the sensitivity of the results of Fig. 2.4 to $q(0)$ is obtained by taking each of the equilibria used

A second set of calculations to determine the sensitivity of the results of Fig. 2.4 to $q(0)$ is obtained by taking each of the equilibria used in generating that figure and scaling the toroidal field. Unfortunately, at finite β , this does not separate the effects of q and q' , but the results show that the favorable effects of indentation with respect to stabilizing ballooning modes can still be achieved. Figure 2.7 illustrates the results of this procedure. Note that these results are plotted in terms of β_p . We see that increasing q on axis reduces the instability region making accessibility easier. When $q(0)$ is reduced below 1, it becomes increasingly difficult to stabilize the modes.

2.2.5 Current Profiles

To date all the theoretical calculations illustrating the accessibility to the second stable region have been carried out by generating sequences of MHD equilibria with a specified q profile. As remarked earlier, in such a procedure the current profiles cannot then be separately adjusted. In Fig. 2.8 we illustrate different current profiles; Figs. 2.8a and 2.8b indicate the variation with indentation at fixed β , and Fig. 2.8c illustrates the effect of varying β at similar indentation. While these are only model MHD equilibria, they are not necessarily inconsistent with what one would expect experimentally. At very high β the current profiles do indeed become very peaked near the plasma edge, and additional understanding of plasma evolution is required before one can judge whether they are achievable without auxiliary (non-ohmic) current drive schemes.

In alternate approaches (see Chapter 3 and Appendix 1) to generating equilibria for stability studies, it is possible to constrain the plasma current profiles. While such configurations illustrate improved β values in

the first stability regime as indentation is increased, an identification of the second region or complete stabilization has not been obtained in the calculations performed to date. Additional work is clearly required to understand the effect of current profile.

One can, however, examine how closely the current profiles in the calculations used in this section compare with idealized ohmic profiles by computing the surface quantity $\langle J \cdot B / \langle B \cdot \nabla \phi \rangle$, which for steady-state operation should be approximately proportional to $T_e^{3/2}$ (Appendix 1). Figure 2.9 plots this quantity versus poloidal flux, and we see that according to this criterion the profiles are not too unrealistic.

2.3 STABILITY TO THE INTERNAL KINK

2.3.1 Background

Instabilities in tokamak plasmas associated with the existence of a $q=1$ surface in the plasma region have been the subject of considerable interest, both theoretically and experimentally. Experimentally this mode shows up primarily as a resistive mode in present low- β devices, and its evolution is associated with the sawtooth phenomenon. At low β the ideal version of this $n=1$ mode is stabilized by toroidicity^{2.11} and destabilized by plasma elongation. At larger β values toroidicity is not sufficient to stabilize the mode and its character changes from being primarily current driven to pressure driven. At higher β values, even with $q_0 < 1$, the mode can take on a distinct ballooning character and its growth rate can exceed that of the resistive internal kink. At very high β values it can be stabilized by the well introduced by a large Shafranov shift^{2.12} in a manner similar to the stabilization of higher n -ballooning modes.

Recently, this mode has been interpreted as being associated with the

onset of fishbone MHD oscillations, resulting in poor fast ion confinement. Since to date this is the only clearly identifiable detrimental experimental effect associated with increasing β , it is obviously of considerable interest to attempt to find configurations which are stable to this mode. In this section we review recent theoretical calculations which demonstrate that indentation can have this effect.

2.3.2 Calculations at Large Aspect Ratio

In this first series of calculations we compare the marginal stability contours for $R/a=10$ plasmas with circular, elliptical, dee-shaped, and indented cross sections. The results are shown in Fig. 2.10.

To produce Fig. 2.10 sequences of fixed boundary equilibria were generated with identical p and q profiles as previously described in Sec. 2.2.2. The boundary shape was

$$X(\theta) = R - B + (a + B \cos\theta)\cos(\theta + \delta \sin\theta)$$

$$Z(\theta) = E a \sin\theta,$$

and Fig. 2.11 shows the cross sections of the four different shapes studied in Fig. 2.10. The calculations used $p(y) = p_0 (1-y)^{2.5}$, $q(y) = q_0 + q_\beta y^2$, with $y \equiv \psi/\Delta$, as before. q_0 and q_β were chosen such that $q_{\text{edge}}/q_{\text{axis}} \sim 2.5$. Each member of the sequences so generated was then scaled to lower q values at fixed β poloidal, as described in Sec. 2.2.4. This procedure generates a mesh of equilibria so that one can map out a region in the parameter space defined by $q(0)$ and $\epsilon\beta_{\text{pol}}$, as shown in Fig. 2.10. Each member of this mesh of equilibria was then analyzed with the PEST code for stability to internal

modes with $n=1$.

The results of Fig. 2.10 demonstrate that shaping the plasma surface has a strong effect on the $n=1$ internal kink. For circular and elliptical plasmas, the $n=1$ mode can be unstable without a $q=1$ surface inside the plasma. This is a pressure driven large wavelength ballooning mode. When $q(0) < 1$, the mode becomes an internal kink. It is stabilized at sufficiently high β . We note that ellipticity is destabilizing. The region of instability is seen to shrink considerably with the introduction of triangularity for the D-shaped plasma and the bean.

2.3.3 Calculations for PBX Parameters

Using sequences of equilibria generated as in Sec. 2.2.2 with aspect ratio of 4, the procedure described in the last section was followed to determine the explicit stabilizing effect of indentation as envisioned in the PBX experiment. The results are shown in Fig. 2.12, which shows regions of instability on the $q_0 - \epsilon \beta_{pol}$ plane for several values of indentation. For comparison with Fig. 2.4, we note that the indentations chosen are all less than the first sequence of ballooning results at $d/2a=0.1$. The most unstable shape corresponds to a D-shaped plasma with essentially vertical inboard plasma surface. It is seen that even small indentations are quite stabilizing. The inset on Fig. 2.12 shows the variation of the height and width of the unstable region as a function of indentation. The critical indentation for complete stability to this mode is shown to be $1/2a \sim 0.1$. Consistent with this, all equilibria shown explicitly on Fig. 2.4 are stable to the internal $n=1$ kink mode, even with $q(0)$ as low as $1/2$.

The results of Fig. 2.12 were obtained with the flat pressure profile given in Sec. 2.2.2, which has $p'(0) = 0$. While the internal kink stability

boundary can be sensitive to the variation of plasma profiles, we do not believe that this choice is responsible for the stabilization, since the favorable effect of bean shaping was already seen in the calculations presented in the previous section which had finite $p'(0)$. To be more specific with respect to PBX, we tested this on the most unstable shape of Fig. 2.12 (the Dee) by varying the pressure profile to $p(y)=p_0(1-y)^2$, i.e., approximately quadratic near the magnetic axis. The results are shown in Fig. 2.13. As expected, this peaked profile is more unstable, especially when the $q=1$ surface is near the magnetic axis. Thus, while flattening the pressure profile certainly reduces the region of instability, indenting the cross section is the principal stabilizing ingredient.

2.4 EXTERNAL KINK MODES

As described earlier, theoretical understanding of the importance of ideal MHD external kink modes is not entirely satisfactory. There is considerable evidence that detailed results are strongly model dependent and very sensitive to the shape of the current profile near the plasma boundary. In stability calculations using the plasma vacuum model, obtaining favorable results is a strong function of where an enclosing, infinitely conducting boundary is placed. Without one at all, it is usually very difficult to find stable configurations at finite β and with some arbitrarily given q profile. Because of this, it is quite usual to present results as a function of the distance from the plasma surface to the conducting shell. Alternatively, one can imagine the plasma surrounded by a cold pressureless plasma which carries no equilibrium current. If this region extends out to the vacuum vessel, complete stability to external ideal kinks would be achieved. Line tying, resistive modes, and other nonideal effects could clearly play a role. It is

undoubtedly an aspect of tokamak research where detailed experimental results could shed important information.

As part of the ideal MHD stability analysis of bean-shaped tokamaks, we have followed the conventional approach and studied the external $n=1$ kink mode as a function of wall radius. To do this we have examined each of the equilibria in the β indentation plane of Fig. 2.4 as a function of a_w/a (see Fig. 2.1). The results are shown in Fig. 2.14, where contours of marginal stability are shown for various wall positions.

At low β these external modes are mostly localized near to the plasma surface and can be described as surface kinks. Indentation is destabilizing in the sense that the wall must be closer to achieve stability as indentation is increased.

At modest values of this indentation, $d/2a \leq 0.2$, the modes take on a strong ballooning character as β is increased. Eventually, as the second stable region is approached the advantages associated with more favorable local shear appear and, with the wall at a finite distance, the configuration eventually becomes stable. At strong indentations, finite β effects are seen to stabilize the kink modes, presumably through a variation of the current profile at fixed q , but additional work is needed to understand in detail which factors are important.

When the results shown in this diagram are considered simultaneously with those of Fig. 2.4, they indicate that with a stabilizing wall at 1.3 plasma radii, accessibility to the second stable region without encountering current driven kinks should be achievable, even ignoring the nonideal stabilizing effects which must be present in current experiments.

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FIGURE CAPTIONS

- FIG. 2.1 (a) Parameters used to describe the basic bean shapes used in the stability analysis.
- (b) For external kink mode calculations results are given in terms of the wall position a_w/a .
- FIG. 2.2 (a-c) Contour plots of the local shear showing the effect of increasing indentation and β . Both effects move the region where S vanishes away from the region with unfavorable normal curvature (Fig. 2.2d).
- FIG. 2.3 Typical profiles used in the stability calculations.
- FIG. 2.4 Stability boundary to infinite n-ballooning modes as a function of indentation and β , showing complete stability beyond $d/2a \sim 0.3$ and accessibility to the second stability region at lower indentations.
- FIG. 2.5 Stability boundary to infinite n-ballooning modes at fixed indentation ($d/2a=0.3$) as a function of aspect ratio.
- FIG. 2.6 Stability boundaries similar to Fig. 2.4 but with lower $q(1)=3.2$. Also shown are contours of marginal stability when including the stabilizing finite Larmor radius effects.

FIG. 2.7 Ballooning mode stability boundaries showing the variation with respect to q on axis.

FIG. 2.8 Midplane profiles of J_ϕ . Cases (a) and (b) are at low $\beta = 0.1\%$. Case (c) is at $\beta_a = 10\%$.

FIG. 2.9 $J_{OH} = \langle J \cdot B \rangle / \langle B \cdot \nabla \phi \rangle$ plotted versus minor radius, for the case shown in Fig. 2.8(c).

FIG. 2.10 Stability boundaries to the internal $m=1$, $n=1$ kink mode, for a variety of plasma cross sections at $R/a=10$.

FIG. 2.11 Cross-sectional shapes used in Fig. 2.10.

FIG. 2.12 Stability boundary for the internal kink in PBX configurations, showing the stabilization with increasing indentation. The critical indentation is determined in the inset by plotting the height $[\epsilon \beta_p]$ and width $[q(o)]$ as functions of $d/2a$.

FIG. 2.13 Stability boundary to the internal $n=1$ kink mode for a D-shaped plasma with two different pressure profiles. Flattening the profile near the magnetic axis is stabilizing.

FIG. 2.14 Stability boundaries to the external $n=1$ kink mode for different wall positions (a_w/a) for the same configurations shown in Fig. 2.4.

(a)

83T0209

$$R/a = 4.0$$

$$b/a = 1.386$$

$$d/2a = 0.304$$

Conducting Shell

Vacuum Region

(b)

Fig. 2.1

Fig. 2.2

Profiles
 $\beta_{AV}=8.75\%$
 $\frac{d}{2a}=0.304$

83T0208

Fig. 2.3

Fig. 2.4

Fig. 2.5

Fig. 2.6

Fig. 2.7

Fig. 2.8

#83T0185

Fig. 2.9

Fig. 2-10

#83T0202

Fig. 2.11

Fig. 2.12

#83T0203

Fig. 2.13

Fig. 2.14

3. PLAN OF THE EXPERIMENT

3.1 INTRODUCTION

Theoretical studies, as discussed in Sec. 2, have shown that indentation of the plasma shape can drastically improve MHD stability. The internal kink, now viewed as a strong candidate for the cause of fishbone instability in PDX, is completely stabilized even with modest indentation ($d/2a=0.1$). With larger indentation ($d/2a = 0.25 - 0.3$), the plasma may be able to bypass completely the unstable regime of ballooning modes as the plasma pressure is increased. Also, it is clearly advantageous to enhance the MHD stability properties of plasmas with the geometry of the external field - i.e., curvature characteristics and average/local shear - rather than with $p(\psi)$ and/or $q(\psi)$, which are dependent on various anomalous transport processes.

For the modification of PDX discussed below, the first priority was to ensure the experimental documentation of the β limit with configurations up to 0.3 indentation in order to carry out a test of the essence of the theoretical predictions. Special attention has also been given to stabilizing the potentially dangerous $n=0$ mode, known as the vertical instability in elongated plasmas and observed experimentally in PDX and DIII (Secs. 3 and 4).

The theoretical stability studies described in Sec. 2 were carried out with fixed boundary equilibria derived from solutions of the Grad-Shafranov equation. For the purpose of machine design, the plasma shapes used in the theoretical analysis were recalculated as free boundary equilibria, for various configurations by using those coils which are available and/or relocatable without major modification in the present PDX. The major calculations for the design study were carried out with 65×65 or 129×129 rectangular mesh coordinates. A free boundary code using flux coordinates has just begun to be available.

The pressure profiles used here are mainly of the form $p(y) = \sum_{i=0,1} p_i y^{\alpha_i}$, where $y = \psi/\Delta\psi$ is the normalized poloidal flux. Typical values of the profile parameters were $\alpha_0 = 1.3 - 1.5$, $\alpha_1 = 1.05 - 1.1$, and $p_1/p_0 \approx 0.25$. These values were found to be appropriate in the analysis of PDX high- β /low- q experiments and they are consistent with all experimentally available results such as $n_e(\psi)$, $T_e(\psi)$, $T_i(0)$, and measured magnetic fluxes.^{3,1} Some calculations were carried out with $p(y) = p_0 [(1 - \alpha/(\alpha + 1) y)y^\alpha]$, with $\alpha=1.5-2$, a form which is in better agreement with the experimental results during the OH phase of a discharge sequence. The $q(\psi)$ profile was specified in a manner similar to what was done for the PDX analysis by giving $q(0)$ and the total toroidal current I_p . This requirement on $q(\psi)$ is accommodated by a poloidal current distribution function $G(\psi)$ in the Grad-Shafranov equation $\Delta^*\psi = -4\pi^2(x^2 p' + GG')$. The function $G(\psi)$ is taken to be of the form $GG' = \gamma_1 F_1(y) + \gamma_2 F_2(y)$ where $F_1(y) = y^{\gamma_3}$ and $F_2(y) = -4y(1-y)$. The value γ_1 is determined from $q(0)$, γ_2 from the total current I_p , and γ_3 adjusts the width of the $q=1$ surface to the experimentally known $q=1$ radius.

The relatively flat current profiles characteristic of low- q operation, combined with large indentations, result in a separatrix that is close to the specified plasma surface. When in the free boundary equilibrium calculation, the separatrix is very near the plasma edge. The plasma edge is redefined to be the surface enclosing 95% of the poloidal flux at the separatrix in order to avoid the ambiguity in q_ψ , the q value at the edge, which is otherwise created. The q_ψ treatment is similar to that in the PDX divertor analysis. The foregoing scheme for choosing MHD equilibria represents a snap shot type analysis, rather than a flux conserving sequence as described in the theoretical study of Sec. 2. The actual process by which the plasma is

brought to a high- β equilibrium is necessarily an experimental question, but an attempt has been made to simulate the time sequence of MHD equilibria with a time-dependent, resistive MHD evaluation code (Ref. 3.3), which is discussed in Sec. 3.5.

A value of $q_\psi=3$ was chosen as standard for the purpose of the design. The existence of a separatrix close to the plasma surface, however, weakens the significance of the value of q_ψ because of its sensitivity to the precise location of the plasma surface with respect to the separatrix. This same difficulty exists in the application of theoretical stability results dependent on q_ψ and q_ψ' to the actual experimental setup. Since a parameter range exists for which the separatrix is well inside all fixed boundaries, an experimental evaluation of the effect of a separatrix on stability is a feasible goal.

The implication for the machine design of the theoretical results on the external kink instability is somewhat unclear. In the past, theoretical predictions of the β limit due to the external kink in tokamaks have been more pessimistic than the actual results achieved. This apparent discrepancy does not seem unnatural because little experimental information is available on the current density and plasma parameters at the edge. Furthermore, toroidal and poloidal asymmetries in the edge parameters complicate the analysis. Therefore, in the initial stage of PBX operation no specific arrangement is planned to stabilize the surface mode, except for the secondary effect of the passive stabilizing plates around the two lobes of the bean. Should the surface mode become a serious problem, the operation time sequence could be modified to attempt to bypass the unstable regime as shown in Fig. 2.14 (Sec. 2.4), or the installation of additional nearby conductors could be considered.

The maximum available neutral beam power of 7 MW into the vacuum vessel, the present empirical confinement scaling law for beam-heated plasmas, the PDX machine parameters, and the desired β range of 10-15% determine the operating values of toroidal field and plasma current. Suitable values are $I_p=600$ kA and $B_T=0.8$ T at $R=1.4$ m, a value of B_T at which we have run successfully in the past. If, with more experience, operation at lower fields becomes practical, then this would be reflected in higher achievable β values.

A plasma current of 600 kA, although even now attainable, is above the normal PDX operating range of $I_p < 500$ kA. It can become routine in FFX (Table 3.3.3) because of the additional volt-seconds gained from the shaping field coils and from disconnecting the EF back winding (i.e., EF solenoid).

3.2 PLASMA PARAMETERS

An example of a high- β equilibrium ($\beta=10\%$) obtained with the procedures discussed in Sec. 3.1 is shown in Fig. 3.1. The geometrical parameters of $d/2a=0.26$, $b/a=1.44$, and $R/a=3.7$ are similar to the typical parameters used in the theoretical studies. A full list of parameters is given in Table 3.2.1. The J_ϕ current profile on the horizontal plane (Fig. 3.2) has an inflection point at the magnetic axis; however, the $J_{OH}=\langle J \cdot B \rangle / \langle B \cdot \nabla \phi \rangle$ profile is still a monotonic function peaked at the magnetic axis, but with a broadened profile (Fig. 3.3). The $p(\psi)$ and $q(\psi)$ profiles of the present configuration are shown in Fig. 3.4.

The MHD stability analysis with PEST indicates that the above configuration is stable against the internal kink instability, even at $\beta=20\%$ (the maximum β in the present study) and for high n -ballooning modes up to

TABLE 3.2.1

TYPICAL PARAMETERS

$R_{geo}(m)$	1.425
$R_{mag}(m)$	1.425
$\langle \beta \rangle (\%)$	10
β_p	0.97
$\langle a \rangle (m)$	0.44
$a_{edge}(m)$	0.32
R/a^*	3.7
R_{geo}/a_{edge}	4.52
$d/2a$	0.26
b/a	1.44
q_0	0.8
q_ψ	3.0
$I_p(kA)$	600
$I_{SP}(kA)$	15
$I_{EP}(kA)$	8.2
$\int p dV (kJ)$	150
$B_T(T)$	0.8
n_{mag}	-1.5

* a is defined in Fig. 2.1.1

$\beta_c \approx 9\%$. A narrow region near the origin becomes unstable against the Mercier criterion, but this can be remedied by some flattening of $p(\psi)$ on the axis. This high predicted critical β at an aspect ratio ~ 3.5 is in remarkable contrast with $\beta_c = 2.7\%$ (ballooning) and $\beta_c = 1.4\%$ (internal kink) in the PDX circular high β /low q discharge (Ref. 3.1) at a somewhat lower aspect ratio.

The flux pattern of the required field is shown in Fig. 3.5. As might be expected, a strong field gradient exists in front of the pusher coil, and even the direction of the vertical field is reversed there. This strong non-uniformity drives the $n=0$ global mode. Configuration indentations in the range 0.1-0.3 can be produced by changing the geometrical center of the plasma. The plasma parameters are listed in Table 3.2.2 for $d/2a = 0.17$ and 0.10. A configuration with an indentation of 0.1 (corresponding to the case of $R=1.6$ m in Table 3.2.2) is shown in Fig. 3.6. Another example of the various possible configurations is given in Fig. 3.7. In this case the separatrix around the plasma is located inside the limiter and this configuration is adequate to examine the effect of the existence of a separatrix on MHD stability as well as on transport properties.

TABLE 3.2.2

EFFECT OF MAGNETIC AXIS LOCATION ON CONFIGURATION

$d/2a^*$	0.172	0.105
b/a^*	1.37	1.20
$R_{geo}(m)$	1.50	1.6
$R_{mag}(m)$	1.50	1.67
$\langle \beta \rangle (\%)$	11.5	13.9
β_p	1.13	1.34
$P_0 (J/m^3)$	8×10^4	8×10^4

* $d/2a$ and b/a are defined in Fig. 2.1

3.3 POLOIDAL COIL SYSTEM

The new arrangement for the poloidal field coil system is given in Table 3.3.1 and the inductance matrix in Table 3.3.2. Identification of coils and new roles are shown in Figs. 3.8 and 3.9. The pattern produced by each set of coils is shown separately: the equilibrium field (EF) is shown in Fig. 3.10, and the shaping field (SF) is shown in Fig. 3.11. The shaping field coils (SF) are a combination of DF/CF/NF coils so chosen as to provide the desired field and to retain the zero mutual inductance with the OH coils that characterizes the present PDX divertor. The negative current in the center pushing coil (DF 2/4 coil lowered to the horizontal midplane) essentially determines the inner plasma edge. The strength of the indentation is controlled by the combination of the pusher coil, the vertical equilibrium field (EF), and the positive current in CP9, which pulls the plasma edge towards the major axis. Positive currents in NF11 and DF7 control the location of the stagnation points in front of the bean lobes. Divertor coils which are not part of the shaping circuit are used for the active feedback system which stabilizes the $n=0$ mode. These are coils DF 3, 5, and 6; all are interior to the vacuum vessel.

The EF system is the same as that in the present arrangement except that the inner solenoid is disconnected. Especially at high β , the large positive current in the solenoid would distort the magnetic surfaces, particularly near the separatrix. The elimination of the inner solenoid reduces the vertical field by $\sim 10\%$, but increases the voltseconds available for inducing plasma current. The detailed poloidal flux balance is listed in Table 3.3.3.

Because of the increased mutual inductance between the EF and OH systems, an extra 2 kV will appear at the EF power supply at startup and up

TABLE 3.3.1

PDX AND PBX POLOIDAL COIL LOCATIONS

	R(m)	Z(m) _{PDX}	Z(m) _{PBX}	# Turns	Label	Change
Equilibrium Field (RF)	1.65	± 0.8	± 0.8	- 7	EF 20	None
	2.255	± 0.6	± 0.6	- 13	EF 21	None
	2.255	± 0.254	± 0.254	- 8	EF 22	None
	0.667			0	solenoid	disconnected
Shaping Field (SF)	0.99	± 0.570	+ 0.065	- 8	DF 2	Down to Midplane
	0.99	± 0.700	- 0.065	- 8	DF 4	
	1.932	± 0.705	± 0.705	- 3	CF 8	None
	0.667	± 0.600	± 0.600	+ 3	DF 7	None
	0.667	+ 0.750	± 0.705	+ 3	NF 11	None
	0.665	± 0.071	± 0.071	+ 5	CF 9	None
Feedback (FB)	1.190	+ 0.562	± 0.700	± 8	DF 3 0.138 m	up/down
	1.720	± 0.562	± 0.642	± 8	DF 5 0.08 m	up/down
	1.920	± 0.545	± 0.545	± 8	DF 6	None
OH	No Change					

TABLE 3.3.2

INDUCTANCE MATRIX

	(H)			
	Plasma	OH	EF	SF
plasma	4.2841E-06	7.5389E-05	9.7076E-05	-2.5622E-05
OH	7.5389E-05	1.3657E-02	4.3157E-03	-1.5082E-05
EF	9.7076E-05	4.3157E-03	1.4332E-02	-1.3651E-03
SF	-2.5622E-05	-1.5082E-05	-1.3651E-03	1.1401E-03
resistance (Ω)		2.5974E-02	5.0706E-02	1.1483E-02

TABLE 3.3.3

POLOIDAL FLUX BALANCE

I_p (kA)	600
L_{EXT} (H)	2.3×10^{-6}
L_{INT} (H)	0.45×10^{-6}
ψ_p (Wb)	1.65
ψ_{ext} (Wb)	1.17
ψ_{EF} (Wb)	0.79
ψ_{SF} (Wb)	0.38
I_{EF} (kA)	8.1
I_{SF} (kA)	15
ψ_{OH} (Wb)	
(Swing + 10 kA + - 20 kA)	2.62
Flux Swing Total (Wb)	3.72

to 1 kV may be additionally induced on the OH power supply when the EF current is reduced abruptly following a plasma disruption. The present power supplies have no difficulty in accommodating those voltages.

3.4 STABILIZATION OF $n=0$ MODE

The price of the unique advantages of bean shaping for MHD stability is the potential problem of the $n=0$ global instability due to the negative field decay index. This instability can be stabilized by appropriately located conducting walls, if assisted by a relatively slow and low power active feedback system. The applicability of this approach has been demonstrated in DIII and PDX (Refs. 3.2, 3.3, and 3.4). In this scheme the conducting walls stabilize fast MHD plasma displacements, and then flux loss due to the finite conductivity of the wall is compensated actively to maintain the plasma shape. The required location of the conducting wall was found from a series of computer runs with different codes: standard PEST, modified PEST, and a resistive MHD code. The results were also tested with a simple rigid displacement model.

Figures 3.12 and 3.13 show the effectiveness of a D-shaped conducting wall (Fig. 3.14) surrounding a strongly bean-shaped configuration ($d/2a=0.3$, $\beta=3\%$, for which the negative decay index reaches a maximum). B is the location of the conducting wall normalized to the plasma radius on the midplane. Without a conducting wall the plasma displacement is a nearly rigid vertical shift, even near the pusher coil where the direction of vertical field is reversed. The effective magnetic decay index corresponding to the growth rate without the conducting wall is $n_{eff}=-1.4$. As the wall is moved in closer, the simple vertical motion becomes a sliding motion toward the nose area with a reduced growth rate. In the present experiment the conducting

wall can be located only around the nose areas; the backside (at large major radius) must be kept free to accommodate the planned range of indented configurations. Such a partial wall was simulated in PEST by modifying the wall location as shown in Fig. 3.15, and then studied in two steps. Firstly, the angle subtended by the close-in section of wall was varied; secondly, the distance from the plasma was varied. Figure 3.16 shows the normalized growth rate vs. the wall distance normalized to half of the plasma diameter on the horizontal plane. In spite of the existence of higher harmonic components in the wall geometry, the growth rate as a function of the highest Fourier component in the analysis, $l_{\max} = 10$ and $l_{\max} = 15$, gave a converged value of $B=0.27$. This indicates the wall separation of this configuration should be 9-10 cm around the nose areas.

The same subject was further studied with a time-dependent resistive MHD code^{3.5} for a configuration with stronger shaping ($I_{SP}=20$ kA, $I_p=600$ kA, and $R=1.425$ m). In this case the partial conducting wall consisted of surfaces of constant R and Z around the nose areas. When the plates are located further from the plasma, a plasma initially in equilibrium on the horizontal plane starts to slip with small change in shape as if the plasma is pulled by the separatrix. It was found that surfaces at $Z=\pm 0.68$ m and $R=0.83$ m or $Z=\pm 0.75$ m and $R=0.9$ m would stabilize the plasma motion. However, when the wall was moved to $Z=\pm 0.75$ m, $R=0.83$ m, the plasma became unstable as illustrated in Fig. 3.17. The mode behavior, as well as the conductor locations, are in good agreement with those predicted from the PEST analysis.

Preliminary analysis of the active feedback system has been carried out with a rigid vertical plasma displacement. The required voltage to stabilize a sudden shift of $Z=1$ cm is 10 V initially, and down to 5 V with $I_{\text{active}}=200$ A when quasi-equilibrium is reached in a few resistive decay times (0.2 sec or

less). This indicates that the present 100 V, 1 kA active system can handle up to 5 cm vertical shift. A detailed study of vertical and radial plasma position control has recently begun with a time-dependent resistive MHD code.

3.5 DISCHARGE SEQUENCE

The main considerations for the discharge sequence in noncircular tokamaks are (1) easy startup and (2) shaping stability. These goals are met by starting with a circular plasma and then deforming it while the current is raised. Further adjustments are made while the neutral beams increase β . It is interesting to note that at high- β the outward shift of the magnetic axis makes shaping easier.

The proposed time sequence is shown in Fig. 3.18. The plasma starts in a circular shape with $R=1.55$ m and $I_{SF}=0$, in contact with the inner limiter (pusher coil armor). After the plasma current reaches about 150 kA, I_{SF} is increased monotonically to 10 kA, while I_p reaches 400 kA. The ratio of $I_{SF}/I_p=10$ kA/400 kA is then kept fixed up to the maximum plasma current of 600 kA.

After β starts to increase with neutral beam injection, the plasma major radius is shifted to $R=1.425$ m to produce a configuration with indentation 0.3. The indentation reaches a maximum near $\beta=3\%$ and then decreases somewhat because the increase in the ratio of the uniform equilibrium field to the nonuniform shaping field weakens the vertical field gradient on the midplane.

In Fig. 3.19 we illustrate the current buildup and bean-shaping stage of the discharge as computed by the time-dependent resistive MHD evolution code.^{3,5} Figures 3.19a through 3.19d illustrate the evolution of the magnetic flux surfaces when perfectly conducting plates are present (nonshaded

boxes). The top-bottom plates are connected in anti-series so that they do not couple to the OH or EF systems, but do provide stabilization of the $n=0$ instability.

The plasma current I_p , equilibrium field current I_{PF} , and shaping field current I_{SF} take on the following values:

<u>Figure 3.19</u>	<u>Plasma Current</u>	<u>Equilibrium Field Current</u>	<u>Shaping Field Current</u>	<u>$\langle \beta \rangle$</u>
(a)	100 kA	1.08 kA	0	0.5
(b)	150 kA	3.42 kA	6 kA	0.5
(c)	400 kA	5.6 kA	16 kA	1.7
(d)	600 kA	8.1 kA	20 kA	3.0

The plasma size is limited by either contact with the midplane limiter at $R=1.1$ m or by the magnetic x-point. In the case of the x-point limiter, we require that the actual plasma/vacuum boundary will be the surface containing 95% of the flux between the axis and the x-point.

We see from examining Figs. 3.19a through 3.19d that the plasma evolves smoothly from a circular cross section into a strong bean shape without exhibiting any tendency to bifurcate or to lose equilibrium. These calculations used enhanced classical transport in the plasma with additional enhanced resistivity inside the $q=1$ surface to flatten the current density. Other calculations performed with other transport models or without the additional enhanced resistivity give qualitatively similar results, but predict different current distributions.

To illustrate the necessity of the conducting plates, we show in Figs. 3.19e through 3.19h the same calculation, but have included a high resistivity in the stabilizing plates. We see that the plasma becomes unstable to an $n=0$ mode and moves downward into the bottom plate. The actual time constant of this plate is ~ 100 ms, and presently an active feedback system is being designed to stabilize the system on this slower resistive time scale.

Figure 3.20 shows the achievable β for parameters given in Sec. 3.2: $b/a = 1.4$, $\langle a \rangle = 0.44$ m, $a_{\text{edge}} = 0.30$ m, plasma volume = 5.6 m^3 , $q_{\psi} = 3.0$, $I_p = 600$ kA, and $P_{\text{absorbed}} = 6$ MW. Confinement time is assumed to be proportional to plasma current and to $\sqrt{\kappa}$ where κ is the elongation. The reciprocal c of the proportionality constant varies from a minimum of ~ 7 for the H mode in ASDEX, and the best PDX results, to a maximum of 20 for low mode confinement in hydrogen discharges in PDX. For low mode deuterium discharges in PDX, DIII, and ASDEX the appropriate value is about 15. The dotted line shows B_T as a function of q_{ψ} for fixed $I_p = 600$ kA. Evidently β values above 10% can be obtained even with a quite conservative application of the scaling laws.

3.6 DIAGNOSTICS

To turn FBX on initially, we will need measurements of plasma density and poloidal flux and field. Subsequently, at least a few soft X-ray channels will become essential to check MHD behavior; and when neutral beam heating begins, T_e and T_i measurements will become highly desirable. Even during the beam heating phase, however, shot-to-shot monitoring of the discharge will continue to depend heavily on beta values derived from magnetic measurements, as it does in present operation. Measurements of impurity radiation and Z_{eff} need to be available, but do not need constant monitoring. For the final

stage of the experiment, when the beta limit has been established as a function of indentation, one would want to operate the full soft X ray and Mirnov coil arrays we now have on PDX in order to identify the loss mechanism. The CO₂ and microwave scattering systems could be available to aid the diagnosis, but would require some machine accommodation. The FIDE detectors and diagnostic beam would require no change. The list of diagnostics required for the total experiment and the modifications necessitated by the bean geometry are given in Table 3.6.1.

TABLE 3.6.1

DIAGNOSTICS IN FBX

<u>Diagnostic</u>	<u>Modification</u>
1. Magnetics	
diamagnetic measurement	no change
flux loops	add new ones
B loops	add new ones
Rogowski coils	no change
2. Density	
horizontal heterodyne	relocate inner wall horn to
channel	pusher coil
infrared interferometer	5 cm x 5 cm hole in center of
	pusher coil
3. Fluctuations	
soft X rays	
horizontal array	no change
vertical array	raise to clear plasma
Mirnov coils	relocate
CO ₂ scattering	no change
microwave scattering	horn relocation optional
FIDE	no change
4. T _e	
PHA (vertical profile)	no change
TVTS (horizontal profile)	lower lens, reposition fiber optics
5. T _i	
CX	no change
neutrons	no change
Doppler broadening	no change
6. Impurity Radiation	
Bolometer	
array	no change
four vertical channels	new (electronics available)
SPRED	no change
Z-meter	no change
7. TV Camera	ensure viewing port

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- 3.3 H. Takahashi et al., Nucl. Fusion 22 (1982) 1597.
- 3.4 H. Yokomizo et al., in Plasma Physics and Control Nuclear Fusion Research (Proc. Ninth Int. Conf. Baltimore, 1982) IAEA, Vienna (to be published) R-1.
- 3.5 S. Jardin and W. Park, Phys. Fluids, 24 (1981) 679.

FIGURE CAPTIONS

- FIG. 3.1 Typical configuration with an indentation of $d/2a=0.26$. A full list of parameters is given in Table 3.2.1.
- FIG. 3.2 J_ϕ current profile on the horizontal midplane. High beta shifts the peak of the J_ϕ profile toward larger major radius.
- FIG. 3.3 J_{OH} profile. In spite of the distortion of the J_ϕ contours from the magnetic surfaces, the J_{OH} profile is still a monotonical function peaked at the magnetic axis with a broadened profile.
- FIG. 3.4 $p(\psi)$ and $q(\psi)$ profiles.
- FIG. 3.5 External field pattern for the configuration shown in Fig. 3.2.1.
- FIG. 3.6 Configuration with indentation $d/2a=0.1$. The parameters are listed in Table 3.2.2.
- FIG. 3.7 Example of configuration with separatrix inside the limiter.
- FIG. 3.8 Identification of PDX coils.
- FIG. 3.9 Identification of PBX coils and passive conducting plate. Passive conducting plates are shown by shaded areas. FB indicates the coils for the active feedback system.

- FIG. 3.10 Field produced by equilibrium field coils (EF).
- FIG. 3.11 Field produced by shaping field coils (SF).
- FIG. 3.12 $n=0$ mode growth rate without a conducting wall. Growth rate is normalized to the poloidal Alfvén transit time.
- FIG. 3.13 $n=0$ mode pattern with a conducting wall located at $B=0.65$.
- FIG. 3.14 Conducting wall used in the calculation.
- FIG. 3.15 Conducting wall used to simulate a partial conducting wall around two lobes.
- FIG. 3.16 Growth rate vs. location of the partial conducting wall. The configuration corresponding to small indentation $a/2a=0.17$ ($R=1.6$ m cf. Table 3.2.2) is stable with remotely located wall $B=0.65$.
- FIG. 3.17 The $n=0$ mode stability condition for various wall locations with resistive time-dependent MHD code.
- FIG. 3.18 Schematic discharge time sequence.
- FIG. 3.19 Sequence of plasma configuration calculated with resistive time-dependent MHD code.

FIG. 3.20 Power and confinement limited values of β vs. q_ψ for the typical configuration with $P_{\text{absorbed}} = 6$ MW.

83P0097

Figure 3.1

Figure 3.2

Figure 3.3

Figure 3.4

VACUUM FLUX CONTOURS

Figure 3.5

#83P0085

Figure 3.6

83P0091

Figure 3.7

Figure 3.8

#83P0094

Figure 3.9

#83P0098

Figure 3.10

#83P0084

Figure 3.11

83P0078

Figure 3.12

#83P0077

Figure 3.13

Figure 3.14

83P0079

Figure 3.15

83P0073

Figure 3.16

#83T0154

Figure 3.17

Figure 3.18

Figure 3.19

Figure 3.20

4. TECHNICAL IMPLEMENTATION

Table 4.1.1 summarizes the tasks to be performed in converting PDX to PBX, the work breakdown structure, and the responsible individuals. In general, the modifications do not result in mechanical or thermal stresses that are higher than in the unmodified machine: the plasma current and the vertical equilibrium field current (EF) will be 20% higher than in PDX, but the toroidal field will typically be operated at less than half of the PDX design value (2.4 T). Nevertheless, coil lead stems and buswork will all be mechanically supported to withstand full field forces. Joule heating of coils and buswork is also within PDX design values, which were based on somewhat longer pulses than are typically run. Consequences of the changes in inductive coupling between the electrical circuits have received some attention, but will be examined in greater detail. The sections below are keyed to Table 4.1.1.

4.1 POWER SYSTEMS

4.1.1 OH and EF Rectifiers

Until now the OH and EF rectifier power supplies have been electrically coupled only through the plasma current. In PBX the EF backwinding, which in PDX reduces the direct EF-OH coupling to a negligible value, is taken out of the EF circuit. The open circuit EF voltage is more than twice the back emf induced by the OH, and so no trouble is anticipated. However, before PDX is finally shut down, a quick experiment will be performed with the EF in the new configuration to verify that the control circuits need not be modified. If problems do arise, there will be ample time to correct them before PBX begins operation.

Table 4.1.1

From the electro-technical standpoint, it is the EF which will limit the highest beta at which the plasma can be held in equilibrium. With no modification of the EF supply, this limit is presently $\beta=10\%$ at $B_t=0.8$ T, corresponding to an EF current of 8.3 kA. The operating limit for the supply is not a hard number. The original system design was for 7.2 kA, but the bridge itself - the weakest link - was subsequently rebuilt to carry 15 kA. The next current limitation is thought to be the transformer. A 15 kA replacement is on hand and its installation cost is included in the basic proposal (\$120K). What the consequent operating limit will be awaits a detailed assessment of the other chief components in the power train: the harmonic filter and the circuit breaker, the latter now supplying both OH and EF bridges. To complete the system upgrade to 15 kA, however, it is considered necessary to add a new circuit breaker and possibly to rebuild the harmonic filter. This phase of the system upgrade is not included in the present proposal. Its cost is estimated to be an additional \$200-250K.

4.1.2 Shaping and Toroidal Field Supplies (SF and TF)

The existing MG sets will be used for the SF and TF systems. Presently, 8-10 generators (4-5 pairs in series) are used for the TF and 1 parallel pair for the divertor, which has top and bottom coils connected in parallel. While fewer sets will be needed for the TF in PBX, this has no consequence other than a reduced energy cost. For the SF, one parallel pair of coils is connected in series with the remainders of the coils. To obtain a sufficiently high forcing voltage, two generators in series can be chosen to drive the SF. The coupling between SF and OH is nominally zero (no net turns. The reaction back to the generators through SF-EF coupling has been evaluated for a worst case and appears to be well within safe limits (half the open circuit output voltage of the generators).

4.1.3 Feedback Amplifier for Vertical Position Control

A 100 V, 1 kA bipolar transistorized wideband audio amplifier has been routinely used in PDX to control the plasma vertical position, and will also be used in PBX. The interaction of the active and passive feedback loops with the plasma position is being modeled with a resistive MHD code and the results should be available when this proposal is formally reviewed. The results obtained with an ideal MHD code are discussed in Sec. 3.

4.2 COIL SYSTEMS

4.2.1 DF Coil Repositioning

The tasks in this area have been examined in detail. The most difficult and time consuming job is the repositioning of DF 2/4 on the midplane to act as the pusher coil. Figure 4.1 is a detail of the required modification to the lead stem of this coil. A fixture has been made and tested on a model of the detail to verify that bending the leads to the necessary radius is without problems. A new stem will be brazed to the old one and then must be encased to regain vacuum integrity. The other old divertor coils can all be vertically shifted without changing the lead stems. New vacuum feedthroughs will be identical to the present ones.

4.2.2 Bus and Bus Supports

This work, which is all exterior to the vacuum vessel, is straightforward and presents no difficulties.

4.2.3 Passive Coils

The "coils" are in fact aluminum plates held in place by stainless steel supports. No difficulties are foreseen.

4.3 NEUTRAL BEAMS

4.3.1 Neutral Beam Realignment

PDX was built with the intent of injecting the neutral beams tangentially, and vacuum vessel flanges, toroidal field coils, and coil casings were all designed accordingly. The necessary ceramic breaks and bellows sections are on hand now, and only the gate valves, a stock item, need to be bought. Since the realignment requires only a rotation, the impact on beam utilities and plasma diagnostics is small.

4.3.2 Armor for Pusher Coil

Armor composed of graphite sections (schematically shown in Figs. 3.1 and 4.1) will protect the pusher coil from neutral beam shine-through and plasma impingement. The graphite will be water-cooled to ensure that its temperature stays below the point where damage to the pusher coil insulation might occur. Uncoated ATJ graphite will be used.

4.4 FIELD DESIGN

The physics aspects are discussed at length in Sec. 3. The study of electromagnetic forces on the passive stabilizers and on the pusher coil is not yet complete. On the other coils the forces are no greater than at present.

4.5 MECHANICAL SYSTEMS

Detailed designs for the pusher coil supports remain to be done. A pair of movable graphite limiters will use the existing limiter drives, and will present an area to the plasma comparable to that which has been successful in PDx.

4.6 DIAGNOSTICS

The Thomson scattering image forming system and the vertical X-ray array in PDx are too close to the midplane for PBx, and the midplane pusher coil obstructs several diagnostics. The Thomson scattering system will be rebuilt by the PPPL laser group. Details of the solutions for the other interferences created by the new geometry remain to be worked out.

FIGURE CAPTION

FIG. 4.1. Schematic diagram of the lead stem of DP2/4 coil.

Fig. 4.1

FIGURE CAPTION

FIG. 4.1. Schematic diagram of the lead stem of DF2/4 coil.

5. PBX FABRICATION PLAN

5.1 MANAGEMENT ORGANIZATION

To ensure both accurate cost estimates and schedule control for the PDX conversion to PBX, it was decided to set up an engineering management plan in accordance with usual PPPL practice (see Table 4.1.1). We are fortunate that at the supervisory level we have been able to staff the most critical areas - Coil Systems, Neutral Beams, Mechanical Systems, and Diagnostics - with individuals who have been intimately associated with PDX since its inception, and who are thoroughly familiar with the areas to be modified. We can also count on a similarly experienced cadre of support personnel. The collective experience with PDX that is being brought to bear on the conversion is good assurance for the accuracy of the cost and schedule estimates.

5.2 COST AND SCHEDULE

The estimated costs of the conversion of PDX to PBX are given in Table 5.2.1*; work by PDX technicians on the conversion has been folded into the labor costs. The 20% contingency is intended specifically to cover remaining uncertainties with respect to the interaction between the poloidal field power supplies and the stabilization of the axisymmetric mode. All overhead charges are fully covered.

Table 5.2.2* presents schedule information. The critical path is the work inside the vacuum vessel, which is labor intensive but does not permit a large parallel effort. Two shifts per day are assumed to be available inside the vacuum vessel throughout the conversion; the necessary personnel have been identified and will be available.

*Tables 5.2.1 and 5.2.2 have been deleted for this PPPL Report.

6. PBX OPERATION

6.1 MANPOWER

Given the strain on PPPL physicists that the commissioning of TFTR will in time bring about, it is clearly necessary to plan for the operation of PBX. The basic plan is to form a joint PLT/SSX/PBX team of physicists and technicians; however, both machines will continue to have core groups wholly devoted to their respective devices with the PLT/SSX being the larger group.

The two machines will continue to share facilities and will not run simultaneously. Occasional help with some of the diagnostics can no doubt be anticipated from former PDX staff who will have transferred to TFTR, especially during the TFTR opening for neutral beam installation early in CY 84. We can also anticipate at least a continuation and more likely an expansion of visitor programs. Thus, considering the high degree of automation of the diagnostics now on PDX, and their sufficiency for the planned program, it should be quite possible to carry out this program so that the impact on other PPPL efforts is tolerable.

Another critical question is support for neutral beam operation. It is the position of the head of the group that (a) the fully automatic control of the PDX neutral beams minimizes the need for operating technicians; and (b) that the PBX project is of sufficient importance to merit some additional effort on the part of the neutral beam group, an effort which in any case will be small relative to TFTR needs.

6.2 OPERATING BUDGET

Budget and manpower assumptions are given in Table 6.2.1*, which is taken from the Field Task Proposals submitted April 1, 1983. Data

*Table 6.2.1 has been deleted for this PPPL Report.

acquisition, motor generator operation, and energy costs are not included since the costs are fully supported in the PLT baseline budget. If PBX is undertaken, the PLT operating schedule will necessarily be reduced so that there is no incremental cost in those areas.

6.3 MILESTONES

1. Begin generation of indented plasmas	December 1983
2. Begin determination of beta limits as
function of indentation	March 1984
3. Optimize beta for chosen configuration	July 1984
4. Review and evaluate effectiveness of
indentation for plasma stabilization;
determine appropriate next step	September 1984

APPENDIX 1

STABILITY STUDIES WITH "OHMIC" EQUILIBRIUM CURRENT PROFILES

As discussed in Sec. 2.2.5, ideal MHD stability calculations, based on model equilibria in which the pressure and safety factor profiles are prescribed, may involve current profiles which are not readily obtainable in present day tokamak experiments. While future heating or current drive techniques may be capable of achieving these states, it is prudent to attempt to compare the model equilibria used with those obtained from other plasma models. While doing this, however, it should be appreciated that the detailed prediction of tokamak current profiles is a very difficult task theoretically because it depends on an accurate knowledge of plasma transport coefficients, impurities, edge physics, etc., none of which are known or modeled sufficiently well to enable a definitive critical appraisal of an ideal current profile. Even the appeal to experimental data is somewhat unreliable, since current profiles are not directly measurable (but inferred from other measurements after making "reasonable" assumptions about plasma transport coefficients, etc.). Nevertheless, it is helpful in evaluating ideal MHD models to make what comparisons we can, and this appendix presents preliminary results of an ongoing study to better understand the conditions under which the second region of stability may be accessible experimentally.

One way of measuring the experimental relevance of the current profiles used in the theoretical studies of Chapter 2 is to examine their relationship to the steady-state solutions of the magnetic field resistive evolution equations. In the steady-state, flat top portion of the discharge, Maxwell's equation together with Ohm's law imply that the surface quantity $J_{OH} \equiv \langle \vec{J} \cdot \vec{B} \rangle / \langle \vec{B} \cdot \nabla \phi \rangle$ should be proportional to the plasma conductivity, which classically is proportional to $T_e^{3/2}$. In Fig. A.1.1 we plot J_{OH} for several

different β values corresponding to the indentation $d/2a=0.3$ on Fig. 2.4. These profiles, while not being too unrealistic, imply that the temperature profile is very broad, that it has a plateau near the outer edge, and that it does not go smoothly to zero but to a pedestal value $T_{e\text{-edge}} \sim 1/2 T_{e\text{-center}}$. Similarly, the midplane toroidal current density J_ϕ plotted in Fig. A.1.2 is seen to have a small rise at the inner edge and to approach a pedestal value at low β .

An alternative method for parameterizing equilibrium is, instead of specifying the safety factor profile, to fix the temperature profile and then to use the Ohmic equilibrium condition

$$\frac{\langle \vec{J} \cdot \vec{B} \rangle}{\langle \vec{B} \cdot \nabla \phi \rangle} = K T_e^{3/2}$$

to prescribe the current distribution. The free parameter, K , is used to determine either the total plasma current or the safety factor on the magnetic axis. The safety factor profile, and in particular q_{edge} , will vary in sequences constrained in this way.

We have performed a parameter study assuming the particular temperature and pressure profiles

$$T_e(\psi) = T_0 [1 - (\psi/\Delta\psi)^4],$$

$$p(\psi) = p_0 [1 - (\psi/\Delta\psi)^2]^2,$$

the latter being the same as in the flux conserving sequence described previously in Sec. 2.2.2. The exponents in the T_e profile were chosen to avoid excessive current peaking and the corresponding large shear or lack of

equilibrium. Typical current profiles from this sequence with $d/2a=0.3$ and $q_0 \sim 1$ are shown in Fig. A.1.3.

The ballooning stability results from this study are summarized in Fig. A.1.4, where we plot contours of λ , the infinite- n eigenvalue on the most unstable surface, for a continuous range of q_0 and $\langle \beta \rangle$. We see that, while these configurations exhibit improved β values in the first stability regime, the second regime of complete stabilization has not been obtained in the calculations performed to date. It appears likely that the second regime may lie in the upper right corner of this diagram, but a competing tendency for q_{edge} to increase as both q_0 and $\langle \beta \rangle$ increase make obtaining equilibrium difficult in this region. It is quite plausible that slightly different temperature profiles will exhibit the second stable regime, and additional work in this area is clearly required.

FIGURE CAPTIONS

FIG. A.1.1 Averaged parallel current for 3 points with indentation $d/2a$ on flux conserving sequence diagram (Fig. 2.4).

FIG. A.1.2 Toroidal current on midplane for the three cases Fig. A.1.1.

FIG. A.1.3 Toroidal current on midplane for three equilibria of the ohmic sequence.

FIG. A.1.4 Contours of λ , the infinite n eigenvalue on the most unstable surface for a continuous range of central q values, q_0 , and average β .

Fig. A.1.1

Fig. A.1.2

Fig. A.1.3

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Fig. A.1.4

APPENDIX 2

KINETIC EFFECTS

As noted in Sec. 2.1, ideal MHD estimates of beta limits in tokamaks indicate that short wavelength (large n) ballooning mode stability requirements can often impose the most severe constraints. However, it has also been established that for such large values of n , kinetic modifications to the MHD analysis can be very important. In particular, the stabilizing finite gyroradius contribution from the ion diamagnetic drifts acts directly against the interchange driving mechanism and becomes significant when $k_{\perp}^2 \rho_i^2$ is comparable to L_p/L_K . Here, ρ_i is the ion gyroradius and L_p and L_K are the respective scale lengths for the pressure gradient and field-line curvature. Since the worst ideal MHD cases exist for the smallest value of L_p , substantial modifications can result even for small values of $k_{\perp} \rho_i$. Previous calculations have shown that when both the radially nonlocal (finite n) corrections and the finite gyroradius effects just described are simultaneously included, the resultant estimates of beta criteria can be significantly more optimistic for specific equilibria.^{A.2.1} Hence, an analysis of this type for bean-shaped tokamak equilibria is of considerable interest.

The lowest order (radially local) ballooning mode equation, including the ion diamagnetic drifts, can be expressed in the notation of Sec. 2.2 as

$$\underline{B} \cdot \nabla \left(\frac{|\nabla \alpha|^2}{B^2} \underline{B} \cdot \nabla \phi \right) + |\nabla \alpha|^2 \left[2 \frac{\omega_K \omega_p}{b} + \frac{\rho}{B^2} \lambda(q, \theta_K) \right] \phi = 0 \quad (\text{A.2.1})$$

where

$$\lambda(q, \theta_k) = \hat{\omega}^2 - \frac{n^2 \omega_{*p1}^2}{4}$$

$$\hat{\omega} \equiv \omega - \frac{n \omega_{*p1}}{2},$$

$$\omega_{*p} \equiv \frac{cT}{eB} \underline{k}_\perp \cdot (\hat{n} \times \nabla p),$$

$$\omega_k \equiv \frac{cT}{eB} \underline{k}_\perp \cdot (\hat{n} \times \underline{k}),$$

v_A is the Alfvén speed, $\hat{n} \equiv B/B$, $b = |k_\perp|^2 / \rho_1^2$, $\theta_k = k_q / k_\alpha$ is the ratio of perpendicular wave number components, and other quantities are defined in Sec. 2.2.1. The ψ -dependence of ω_{*p1} is assumed to be negligible and the perturbations are taken to have the eikonal form,

$$\xi = \phi(\theta, \psi, \alpha, \epsilon) \exp(-i\omega t - iS(\alpha, \psi)/\epsilon) \quad (A.2.2)$$

where $\alpha \equiv \zeta - q\theta$, ζ is the toroidal angle, and $\epsilon = 1/n$ is the finite- n expansion parameter. The eikonal S has the form

$$S(\alpha, \psi) = \omega_\alpha \alpha + \int d\alpha(\psi) k_q(\psi) \quad (A.2.3)$$

where $k_\alpha \equiv en$ is a constant of order unity, and k_q/ϵ is the radial wave-number in α - q coordinates. Hence,

$$\underline{k}_\perp = k_\alpha [\nabla \zeta - q \nabla \theta - (\epsilon - \theta_k) \nabla q] \quad (A.2.4)$$

The ideal MHD form of Eq. (A.2.1) [i.e., Eq. (2.1)] is recovered in the limit $\omega_{pi} \rightarrow 0$. Equation (A.2.1) is solved numerically as an eigenvalue equation leading to a dispersion relation of the form, $\omega^2 = \lambda(q, \theta_k)$. Contours of constant λ (as a function of q and θ_k) can be readily computed, and the WKB quantization condition leads to the result

$$n = \frac{\pi}{q \frac{d\theta_k}{dq}} \quad . \quad (A.2.5)$$

The denominator here is just the area enclosed by a λ constant contour in the q - θ_k plane. For the ideal MHD limit, $\lambda = \omega^2 = 0$ corresponds to marginal stability. However, for the kinetic case the marginal point occurs for $\hat{\omega} = 0$ or at

$$\lambda = -n^2 \left(\frac{cp'}{2\omega_{pi}(1+\tau)} \right)^2 \quad (A.2.6)$$

with $\tau = T_e/T_i$ and ω_{pi} being the ion plasma frequency. Hence, the kinetically modified values of n_c (critical n) are obtained from the intersections between the curve of $n(\lambda)$ plotted as a function of $(-\lambda)^{1/2}$ and the line generated by the square root of Eq. (A.2.6).

When the procedure just described is applied to representative bean-shaped tokamak equilibria, it is found that the kinetic effects lead to significantly more optimistic β -criteria. This is illustrated on Fig. 2.6 where the kinetically modified stability boundaries are shown by solid curves. For typical parameters, the actual values of $k_{\perp} \rho_i$ in these calculations remain well below unity.

In the preceding analysis attention was focused on kinetic modifications due to the ion diamagnetic drift term, since this factor alone

directly influences the interchange driving mechanism of ideal MHD ballooning modes. However, other kinetic effects, such as wave particle resonances and trapped particle dynamics, can also be important. In particular, collisional and collisionless dissipative processes can destabilize both the drift and shear Alfvén waves leading to residual growth rates on the drift wave time scale. Here again the dominant kinetic modes or microinstabilities are strongly influenced by curvature effects. Since bean-shaped tokamak equilibria generally exhibit more favorable curvature properties, it is likely that microinstabilities will also be favorably influenced. These effects will be investigated in future studies of bean-shaped configurations.

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APPENDIX 3

EFFECT OF INDENTATION ON RESISTIVE MODES

In the body of this report the major emphasis on the favorable aspects of bean shaping has been associated with the enhanced stability to ideal MHD modes. It is useful to consider the effect on resistive MHD modes, and we report here on a very preliminary study of the $m=2$ tearing mode made with the resistive PEST code. A.3.1

We consider a set of pressureless MHD equilibria with varying indentation as described in Sec. 2.2.2. We use similar q profiles with $q(0)=1.1$ and $q(1)=2.9$, so that for the $n=1$ mode there is only one rational surface at $q=2$, and stability to tearing modes can be determined by examining the sign of Δ' . The results of this study are shown in Fig. A.3.1. At this value of the aspect ratio ($R/a=4$) these profiles are all stable to the $m=2$ tearing mode. This is consistent with recent calculations which show that toroidicity can be quite stabilizing. A.3.2

Figure A.3.1 illustrates the variation in Δ' as indentation is increased (open circles) with a conducting wall on the plasma surface and the effect of moving the wall away (solid circles) at fixed indentation. Indentation alone is stabilizing and can be understood in terms of a flattening of the equilibrium current profile around the $q=2$ surface as the indentation is increased. The resultant steepening of the current gradients near the plasma surface may destabilize higher n tearing modes, although these are rarely observed in tokamak devices. Such modes would lead to small islands near the edge of the plasma and possibly bad confinement. Additional work is needed to understand this effect in detail.

As the wall is moved from the plasma surface, the results for indentation $\delta/2a \approx 0.1$ show little variation until the wall is moved out close to the marginal point for the $m=3, n=1$ ideal MHD external kink mode, at which point the tearing mode is strongly destabilized. Additional work is needed to understand the effect of plasma current shape on these modes.

It is possible that strong indentation and reasonable profile control may provide for some stability against the nonlinear tearing phenomena which are believed to be responsible for plasma disruptions. Fully MHD 3D nonlinear codes are being modified to study this. Linear resistive stability work will be undertaken to study finite β resistive modes, including the $n=1$ internal resistive kink.

REFERENCES

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- A-3.2 Izzo, R., Monticello, D. A., Park, W., Manickam, J., Strauss, H. R., Grimm, R. C., and McGuire, K., PPPL-1982, March 1983.

FIGURE CAPTION

Fig. A.3.1 The required wall location to stabilize the resistive tearing ($m=2$) mode in a bean-shaped configuration.

APPENDIX 4

ORBIT CALCULATIONS

Two separate computer codes have been developed at PPPL to study orbits in bean-shaped tokamaks. The first is a generalization of the Hamiltonian orbit code which was used to study fishbone phenomena in PDX. This code has now been linked to PEST, so that it can pick up directly 2-D finite beta equilibria. Thus the background plasma can be made as realistic as possible (Fig. A.4.1). In addition, this code will be able to take the perturbed field calculations from PEST and calculate particle orbits in these fields. Similarly, it should be possible to take perturbed fields from HIB and calculate orbits. It will then no longer be necessary to approximate either the background equilibrium or the perturbations (Fig. A.4.2).

In addition to this, the bean orbit code in TRANSP (our TRANSPORT analysis code) has been generalized to operate in MHD "moments" geometry, with any number of independent moments in the radial and vertical directions. When this code is linked to a fast MHD equilibrium solver, it will be particularly well-suited to treating highly time dependent axisymmetric problems, such as major radius compression in TFTR or a time evolving bean. We find that the inclusion of about six independent radial and vertical moments in an equal arc choice of poloidal variable gives an excellent representation of bean plasmas (Fig. A.4.3).

These codes have been used to make some preliminary investigations of particle orbits in bean-shaped geometries. We have found two major topics of interest in these studies. The first is orbit topology and confinement of energetic particles. Here we have found interesting and favorable results.

The second topic is toroidal precession in bean geometry. Here we have found some remarkable results arising from the negative local shear in the outer regions of the plasma. These may prove to be very favorable for suppressing the fishbone phenomenon.

ORBIT TOPOLOGY AND ENERGETIC ION CONFINEMENT

The outstanding feature of the bean geometry is that the magnetic field on the outer flux surfaces has two local minima, one at large major radius and the other at small major radius. In Fig. A.4.3 the circles represent the points of maximum total B field in a 10% beta PBX plasma. Note that the points of maximum B do not necessarily lie at the precise minimum R; this is because the poloidal field strength is playing a significant role. Orbits which travel on the inner flux surfaces and have a very broad single maximum in B on the inside in major radius produce strong, distorted World's Fattest Bananas (WFB). Particles traveling on the outer flux surfaces, which have two minima in B, have topologically different WFB's. In this case, as one goes from a passing to a trapped orbit by varying the pitch angle, the orbit breaks up into two separate branches, an "outer" banana as usual (Fig. A.4.4), and also what we choose to call an "inner" banana, trapped in the minimum in B on the inboard side in major radius (Fig. A.4.5). Because of the concave nature of the inboard flux surfaces, these "inner" bananas have some unusual features. One striking example is the fact that initially co-moving orbits travel inward in minor radius when they execute an "inner" banana. In more familiar geometries such as circles or Dee's, co-moving ions which are born near the inner edge (in major radius) of the plasma move outward along their orbits, and can be lost from the plasma. This difference between bean and conventional geometries could be exploited to obtain near 100% initial orbit

confinement in an extreme bean with near-perpendicular injection. In the contemplated PBX geometry, however, we do not inject directly onto any "inner" banana orbits.

We have studied perpendicular and parallel injection into the PBX geometry at a plasma current of 500 kA. We found that the initial orbit confinement is excellent. While we have not yet performed full Monte-Carlo orbit studies (including collisional effects), we anticipate that the orbit loss with co-perpendicular injection should be quite comparable to the present PDX geometry, where 10% loss at high current is typical. The co-tangential geometry should be similar to PLT where losses are less than 5%, except at very high electron temperature and Z_{eff} .

The creation of a new class of trapped particles could have some significant effect on the formalism required within neoclassical theory to calculate ion thermal transport. However, we find that the orbit widths are small, and the fraction of phase space which corresponds to "inner" bananas is also small. While the effective collision frequency for these particles will be high, we anticipate little net effect on neoclassical transport.

TOROIDAL PRECESSION

The fishbone phenomenon in PDX has been found to be connected to a resonance between the toroidally precessing beam ions and an MHD internal kink mode. This effect was compounded by the fact that at low q the banana-trapped beam ions at all radii tend to precess at nearly equal toroidal speeds. In addition, the initially injected passing ions in the very center of the plasma travel around the torus at a similar speed (Fig. A.4.7). In a high beta bean this situation is greatly altered. In the outer region in major radius, the local shear in the field lines is reversed. This comes from the increased

poloidal field strength at increasing minor radius. The rising poloidal field strength is both due to the gradient in the Shafranov shift and to the rapidly increasing plasma circumference. The final result is that the beam ions tend to see a negative shear in the vicinity of their orbits. This causes the shear driven component of their precession to reverse sign. Furthermore, at high poloidal beta the diamagnetic effect reduces the cross-field gradient of magnetic field in the horizontal midplane. This reduces the component of the co-toroidal precession due to cross-field drifts within the flux surface. In 10% beta PBX plasmas the final result is to cause the banana-trapped beam ions to precess in the counter direction, while the passing orbits circulate the torus in the co-direction (Fig. A.4.6).

The full implications of these results for fishbone oscillations are difficult to predict. First of all, the accidental result in low-q circular plasmas of near constant toroidal precession across the minor radius will be eliminated. The gradient in the precession speed will be such as to make it difficult for a single mode to resonate with many particles. Furthermore, since the precession speed plays an important role in the kinetic interaction of particles with both MHD modes and with micro-turbulence, one might anticipate some significant favorable effects on plasma stability. The precession direction of the banana-trapped particles corresponds to what would be observed in a minimum B geometry.

FIGURE CAPTIONS

- FIG. A.4.1 PEST-calculated flux surfaces plotted out by following low energy parallel moving particles in the Hamiltonian orbit code.
- FIG. A.4.2 Poincaré plot of perturbed flux surfaces transferred from PEST to the Hamiltonian orbit code.
- FIG. A.4.3 Magnetic moments geometry fit to a 10% beta PBX plasma. The use of 6 independent radial and vertical moments with an equal-arc choice of poloidal variable allows a fit to within 1-2 cm at all locations. The circles indicate the location of the maximum value of B on each flux surface.
- FIG. A.4.4 A WFB in PBX on a magnetic surface with two local minima in B. As the pitch angle is varied, starting with a passing orbit, the contour of constant canonical angular momentum breaks up into two separate pieces, an "outer" banana as usual, and what we choose to call an "inner" banana.
- FIG. A.4.5 The WFB "inner" banana associated with the WFB "outer" banana shown in Fig. A.4.4.
- FIG. A.4.6 Toroidal circulation frequency vs. initial ionization point for perpendicularly injected ions in PBX. In cm the horizontal axis prerepresents the "average" minor radius. Values greater than zero indicate ionization in the horizontal midplane outboard of

the magnetic axis. Values less than zero indicate ionization inboard of the axis.

FIG. A.4.7 Toroidal circulation frequency vs. initial ionization point for co-injection in the present PDX.

Fig. A.4.1

Fig. A.4.2

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Fig. A.4.3

Fig. A.4.4

Fig. A.4.5

Fig. A.4.6

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Fig. A.4.7