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PBX EXPERIMENTAL RESULTS IN 1984

By

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PBX EXPERIMENTAL RESULTS IN 1984

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Abstract

Experimental activities of the PBX project during its first seven months of operation are summarized.

Introduction

The Princeton Beta Experiment (PBX) is a project with the broad goal of producing plasmas with β values well beyond those attained in conventional tokamaks. β is a measure of the heat content of the plasma relative to the confining magnetic field strength, and is one of the important parameters that determine the economic feasibility of fusion reactors. Several ideal MHD instabilities that limit plasma heating must be overcome in order to produce high β plasmas. This is necessary even when the plasma becomes so hot and electrically conducting that the resistive instabilities common to present tokamaks all vanish.

The Ballooning instability is a short wavelength mode, mostly internal to the plasma, that is driven unstable by the plasma thermal pressure. This instability is theoretically expected to limit β : the maximum attainable β is the upper limit of the so-called first region of stability. All tokamaks have

* Deceased

so far operated in this region. A conventional approach to increasing β in the first region has been to make the plasma major radius small in relation to the minor radius.

The PBX tokamak will instead attempt to overcome the ballooning instability by unconventional cross-sectional shaping: the plasma cross section is indented on its inboard side so that its shape is like that of a kidney bean. As the degree of indentation increases beyond a certain critical value, the β limit set by the ballooning instability becomes very large, or disappears altogether. It is a specific goal of the PBX project ultimately to reach this so-called second region of stability. All other instabilities that may set a limit lower than that of the ballooning mode must also be overcome to reach this second stability region.

The fishbone instability is another pressure-driven mode internal to the plasma but with a long wavelength. It has a strong tendency to expel hot heating ions from the plasma and thus limit the efficacy of neutral-beam injection (NBI) heating. This instability was found to limit plasma heating in the PDX tokamak. Fortunately, the theory predicts that bean shaping will help suppress this instability by strengthening the MHD stability properties of internal flux surfaces where the instability originates.

The external kink instability is a long wavelength mode driven primarily by the plasma current. A conducting shell tightly surrounding the plasma would help stabilize this instability, but it would also severely limit the operational flexibility. The PBX, in its initial configuration, has opted to preserve the flexibility in order to establish the ability to form and maintain a bean-shaped plasma.

One instability which arises as a consequence of the plasma cross-sectional shaping is the vertical instability. The very force that produces

the indentation and elongation by pulling and pushing various parts of the plasma also causes it to be vertically unstable. This positional instability must also be brought under control for the PBX tokamak to succeed.

In addition to helping suppress the various instabilities, cross-sectional shaping has the added benefit of enhancing the current-carrying capacity of the plasma and reaping any advantages that may be associated with a large plasma current. For example, higher current increases the β limit in the first region of stability for plasmas of any shape. Since the energy confinement time of NBI heated plasmas in most tokamaks is proportional to the plasma current, the higher current-carrying capacity leads to a better confinement time.

In order to test these theoretical expectations within a relatively short time and at a modest cost, the PBX device was created by reconfiguring its predecessor device, the PDX tokamak. The reconfiguration primarily involved rearrangement of internal coils and reorientation of two of the four neutral beamlines from near perpendicular to a tangential direction. The other two beamlines remained in the near perpendicular direction. The first six months of FY84 were spent completing the conversion of PDX to PBX, which had begun in the previous fiscal year. A poloidal cross section of the device is shown schematically in Fig. 1 and a photographic view of the interior in Fig. 2.

On April 6th the first plasma was produced, and on May 8th NBI heating experiments were commenced. On September 14th PBX achieved a volume-averaged toroidal β value $\langle\beta_t\rangle$ of 5.3%--a record to date for major tokamaks. At the end of October PBX was shut down for two months for internal hardware repair and new diagnostics installation. Activities during the month of October are included in this report for the sake of continuity. Over this seven-month period PBX operated on 56 days including 28 days with NBI heating.

The experimental program during this period first focused on learning to produce and sustain a bean-shaped plasma in a controlled manner. The effort then shifted toward producing plasmas with high $\langle \beta_t \rangle$. Studies of how bean shaping influenced the greatest achievable current density, $\langle \beta_t \rangle$ and the fishbone instability followed. The H-mode--a regime of high energy confinement time--and fueling by pellet injection were also investigated briefly.

Interim results have been reported at the 10th International Conference on Controlled Thermonuclear Fusion Research (London).¹ Many introductory materials on the topics covered in this article can be found in earlier Princeton Plasma Physics Laboratory Annual Reports.² Materials on the PBX device can be found in the PBX section of the 1983 Annual Report and in the theory section of the 1982 report. The fishbone instability is covered in the PDX and theory sections of the 1982 report and the H-mode is discussed in the PDX section of the 1983 report. Theoretical and engineering aspects of PBX are also described in detail in the project proposal.³

PLASMA CROSS-SECTIONAL SHAPING

The PBX is the first tokamak designed to produce a plasma with the unconventional bean-shaped cross section. The initial experimental program therefore addressed the issues of whether a bean-shaped plasma with a desired degree of indentation can be produced and maintained, and what parameters are important in determining the degree of indentation.

The PBX operates routinely with the magnetic decay index (n-index) around -2.0, and the plasma is subject to a strong vertical (axisymmetric) instability. Passive stabilizers and a modest active feedback amplifier act to stabilize this vertical instability. This stabilization proved adequate

both in the plasma start-up phase and during the main discharge phase under moderate conditions. Photographs of a stable bean-shaped plasma as seen through TV are shown in Fig. 3. Under more severe conditions, e.g., at very high indentation or during high-power NBI heating, loss of the plasma through the vertical instability has been observed. In some cases the instability appeared to be the cause of the loss, while in other cases the instability appeared to be the terminal phase of the plasma which had disrupted and whose current channel had shrunken.

For the geometrical arrangement of shaping coils in PBX, the radial plasma position and the strength of the indentation field (or "pusher coil") current (I_{IP}) in relation to the plasma current (I_p) are important elements that determine the degree of indentation. It is possible to maintain a well-indented plasma in steady-state for over 400 ms, nearly one-half the entire discharge length, by controlling these quantities with feedback systems. However, fine control of the precise shape and location of the separatrix surfaces is not possible with the present PBX configuration because all of the shaping coils are powered by a single generator, and their currents are not individually adjustable.

Further improvement in the indentation comes from the plasma current profile: a broad current profile results in a more bean-shaped plasma. In such a plasma both the plasma outer boundary and the inner flux surfaces are well elongated and indented. In this sense, good MHD properties of such shaped surfaces are strengthened in a plasma with a broad current profile.

The desired broad current profile is realized in PBX partly by operating at low q values at the plasma edge (high I_p at low toroidal magnetic field, B_t). The dependence of indentation on edge q value (q_{edge}) is shown in Fig. 4. The q_{edge} , evaluated on surface enclosing 95% of poloidal flux, was

varied here by changing B_t while holding all other parameters the same. The data were taken in the steady-state phase of the discharges. A clear trend toward higher indentation is seen in this figure as q_{edge} becomes smaller and the current profile becomes broader.

The broad current profile is obtained also by ramping up I_p rapidly (high dI_p/dt) to take advantage of the skin-current effect, i.e., the time delay associated with the diffusion of the current from the plasma edge to the center. The resultant current profile is broader than one expected from the classical resistivity based upon the electron temperature profile. A comparison between the toroidal current profile produced in PBX using the skin-current effect and a typical profile in PDX, both as functions of major radius, is shown in Fig. 5(a). The same comparison as a function of the normalized flux, $\tilde{\psi} \equiv (\psi - \psi_0)/(\psi_{\text{edge}} - \psi_0)$, where ψ_0 and ψ_{edge} are, respectively, values of the poloidal magnetic flux function, ψ , at the magnetic axis and plasma edge, is shown in Fig. 5(b) along with the profile used in the PBX project proposal.³ The profiles obtained to date in PBX are much broader than those of PDX but are not quite as broad as anticipated.

MODE OF OPERATION

The present PBX design accommodates a wide range of operating modes in order to evaluate their relative advantages. For example, nearly circular and D-shaped plasmas, which may be needed as transitional states before reaching the final bean shape, can also be produced. This means, however, lack of optimization under some circumstances. For example, a tightly fitting conducting shell on the plasma outboard side is theoretically expected to help suppress the external kink mode, but has not been employed to allow for a wider range of plasma shape and location.

Two different methods to form an indented plasma are used: the first method is initially to form a fully developed circular plasma and then slowly indent it by increasing I_{IP} , and the second method is to elongate and indent the plasma during the start-up phase. The latter process is subject to greater vertical instability because the passive stabilizers are less effective for the small current channel of start-up plasmas. The PBX experiments have, nevertheless, demonstrated successfully both methods of forming indented plasmas.

Either a material surface or magnetic separatrix can define the plasma outline in the PBX tokamak. In the limiter plasma operation, graphite limiters on the inboard or outboard midplane, or graphite limiters on the top and bottom passive stabilizers define the plasma boundary. In the separatrix operation, the absence of any material limiting surfaces allows the so-called H-mode--a regime of improved energy confinement time.

Table I summarizes the range of parameters of PBX operation to date. Many parameters are close to their design values. The plasma current, for example, reached 560 kA in comparison with the design value of 600 kA. The indentation reached 0.22 in both ohmically and NBI heated plasmas, somewhat below the design value of 0.30. The difference has most likely arisen because the plasma current profile was not quite as broad as originally hoped. On the other hand, the elongation reached routinely its maximum value of 1.8, a high value for tokamaks. The indentation and strong elongation of PBX plasmas facilitate an increased current-carrying capacity. This, in turn, leads to an increased β limit and higher energy confinement within the first region of stability.

An alternative way of expressing the enhanced current-carrying capacity is in terms of the equivalent cylindrical q value, defined as $q_{cyl} \equiv 2\pi \langle \alpha \rangle^2$

$B_t(0)/(\mu_0 R_p I_p)$, where R_p is the plasma major radius, $B_t(0)$ is the toroidal field at the geometrical axis and $\langle a \rangle$ is the radius of a circular plasma that would have the same cross-sectional area as the indented plasma. For PBX q_{cyl} reached as low as 1.04, whereas q_{edge} remained equal to or above 3.0. While indentation and elongation, and their effect on the lowest achievable q_{cyl} , are closely coupled for PBX, no other major tokamak has attained this low value of q_{cyl} , even at elongations comparable to those of PBX.

The operating range in terms of the dimensionless parameters, β_p and $\langle \beta_t \rangle$, is shown in Fig. 6. The β_p is the β value based upon the poloidal component of the magnetic field. The data points fall roughly within a triangular region. The data points around the lower right-hand side of the triangle are near the low- q (high- I_p , low- B_t) disruption limit. The points around the upper left-hand side are near the low- I_p heating limit: as I_p is reduced, hot heating ions will increasingly be lost through large unconfined orbits. The data around the remaining upper right-hand side are near the boundary of the first region of stability. Discharges with the normalized β_n (see below) greater than 2.0 are indicated by the solid dots in the figure. Not all of these boundaries have been seriously tested yet because of the relatively limited period that PBX has been in operation. The region of operable parameter space is likely to be extended in the future. In particular, the ultimate goal of the PBX--to enter the second region of stability--means breaking through the upper right-hand side of the triangle.

B SCALING

As fusion research enters into a more technologically oriented phase, the issue of attaining higher β values has become increasingly more important. The volume-averaged toroidal $\langle \beta_t \rangle$ is a dimensionless ratio of the plasma

pressure to the confining toroidal magnetic field pressure. The generation of toroidal field is a costly element of the reactor, and the magnitude of $\langle \beta_t \rangle$ has a direct impact on the economic feasibility of the fusion power generation.

Much experimental data go into the determination of $\langle \beta_t \rangle$ they are poloidal flux (measured by flux loops), displaced toroidal flux (by diamagnetic loop), coil and plasma currents (by Rogowski coils and shunts), central ion temperature (by charge-exchange recombination spectroscopy), impurity levels (by spectroscopy), and electron temperature and density profiles (by TVTS Thomson scattering). The $\langle \beta_t \rangle$ is calculated using some or all of the above data by several different methods. A fast between-shot moments code called SURFAS (see below) calculates $\langle \beta_t \rangle$ for the majority of discharges. A full MHD equilibrium code (Grad-Shafranov equation solver) is also used for selected shots. In computing $\langle \beta_t \rangle$ both the plasma and magnetic pressures were averaged over the plasma volume rather than choosing the magnetic pressure at a reference point as has been sometimes done.

One example of a $\langle \beta_t \rangle$ determination is summarized in Fig. 7. The central graph (a) shows the time evolution of $\langle \beta_t \rangle$, β_p , and $\Lambda \equiv l_i/2 + \beta_p$ computed by the SURFAS code, where l_i is the dimensionless internal inductance. The inset (b) shows the electron temperature and density profiles measured at one time point two-thirds of the way into the M/I phase of the discharge. Based upon these profiles, the diamagnetic measurement, and other kinetic data, the full MHD code also determined $\langle \beta_t \rangle$. The two calculated values at this time point agree well with each other as indicated in the graph. The full MHD calculation was repeated at a later time point near the disruptive end of the discharge. The profiles were not measured at this point and were assumed unchanged from the previous time point. The inset (c) shows the central ion

temperature variation, and the inset (d) compares the toroidal flux measured by the diamagnetic diagnostic with that computed by SURFAS.

The peak volume-averaged toroidal β for the discharge shown in Fig. 7 achieved a value of $\langle \beta_t \rangle = 5.3\%$ according to the SURFAS calculations. The on-axis $\beta_t(0)$ was 16.2% and β_p was 0.77. The indentation was 0.19 and total heating power (NBI plus ohmic) was 4.5 MW.

Concerted efforts to raise $\langle \beta_t \rangle$ by many tokamak installations around the world produced a striking result⁴: the highest achievable $\langle \beta_t \rangle$ is bounded by a critical value determined by some combination of plasma parameters. Theorists have proposed that this so-called β scaling reflects a limitation on $\langle \beta_t \rangle$ caused by ideal MHD instabilities. The limit is the boundary of the first region of stability when the underlying instability is the ballooning mode. The limit set by the external kink mode may be lower or higher depending upon the proximity of the plasma to a conducting shell.

Many researchers conducted numerical experiments to determine the parametric dependence of the critical β . One formula obtained by Troyon and Gruber⁶ for the external kink instability has a particular appeal in its simplicity. It states that the maximum achievable $\langle \beta_t \rangle$ depends upon the plasma current (I_p), toroidal field (B_t), and the plasma size (a) in accordance with the formula:

$$\langle \beta_t \rangle \leq C u_0 I_p / (a B_t),$$

where $\langle \beta_t \rangle$ is in percent and C is a numerical constant. Troyon and Gruber chose a to be the half-width along the midplane (a_{mid}) and B_t to be the toroidal field at the geometrical axis [$B_t(0)$], and they determined C to be between 2.0 and 2.5.

In order to examine the β scaling for the PBX tokamak, $\langle\beta_t\rangle$ is plotted in Fig. 8 against $\beta_c \equiv \mu_0 I_p / a_{\text{mid}} \langle B_t \rangle$. Here, the volume-averaged toroidal field, $\langle\beta_t\rangle$, was used in order to be consistent with the definition of $\langle\beta_t\rangle$. This choice results in a slight underestimate of β_c for bean-shaped plasmas. The figure also shows the data from the predecessor PDX tokamak for comparison. Both groups of data essentially fall below the line, $\langle\beta_t\rangle = 2.5\beta_c$, i.e., $C = 2.5$. The $\langle\beta_t\rangle$ near this line was usually limited by the disruptive termination of the discharge. The ballooning mode limit is believed to lie higher than this line (i.e., $C > 2.5$). Neither the ballooning mode nor the external kink mode, however, has been positively identified to date. Determining the underlying physical mechanism of the disruptive β limit in PBX will be the central research subject in the coming months.

The right-hand edge of the PBX data group in Fig. 8 at $\beta_c \approx 2.4$ is greatly extended from that of PDX at $\beta_c \approx 1.2$. The nearly twofold increase in maximum attainable β_c reflects the enhanced current-carrying capability of PBX plasmas. The PBX tokamak has thus not yet demonstrated access to the second region of stability, but has significantly extended the operating range in terms of β_c .

Discharges in PBX with high β_c were mostly highly indented plasmas and all had a high rate of rise of the plasma current to take advantage of the skin current in generating a broad current profile. Some high $\langle\beta_t\rangle$ plasmas also had pellet injection to further influence the plasma profiles. This promising alternative, which has been studied very briefly during this reporting period, will be one of the major topics in the coming year.

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FISHBONE INSTABILITY

The fishbone instability is an MHD activity that alternates between rapid growth and quenching in repetitive bursts of a few millisecond duration. Loss of fast ions and a drop in neutron production occur coincident with each burst. The instability was first discovered in the PDX tokamak. The fast ion loss due to the instability was believed to be the cause of reduced heating efficiency in PDX as the NBI power was increased. The current theoretical understanding is that the fishbone instability is the pressure-driven ideal internal kink mode and that the triangularity of inner magnetic surfaces in a bean-shaped plasma helps suppress the instability.

Observation to date indicates that the fishbone instability is generally much less pronounced in PBX than in PDX and in fact is nearly absent in some cases. The Mirnov coil signal, which measures fluctuations in the poloidal magnetic field, is shown in Fig. 9 (top) for a PBX discharge with the fishbone instability. Many bursts of oscillations, mostly due to the fishbone instability but also partly due to the sawtooth relaxation, can be seen in the figure. A drop in neutron emission associated with each of the fishbone bursts and sawtooth relaxation is shown in Fig. 9 (bottom). This is an example of bean-shaped plasmas with a relatively narrow current profile, a modest indentation ($i = 0.12$), medium $\langle \beta_t \rangle \leq 3.7\%$, and a moderate plasma current rise rate ($dI_p/dt = 0.9$ MA/sec). It represents a class of discharges with fishbone activity which is large for PBX standards. The Mirnov coil and neutron emission signals shown, respectively, in Fig. 10 (top) and 10 (bottom) are for a PBX discharge with a broad current profile, a strong indentation ($i = 0.19$), high $\langle \beta_t \rangle \leq 5.3\%$, and a large plasma current rise rate ($dI_p/dt = 1.5$ MA/sec). The discharge is nearly free of the fishbone instability in spite of higher $\langle \beta_t \rangle$. Both discharges were heated with two perpendicular beams and one tangential beam at a comparable power level.

The fast ion loss is much less important in PBX than in PDX, reflecting in part the lower level of the fishbone instability. A slowing-down spectrum of fast ions measured by the electrostatic charge-exchange analyzer of the Fast Ion Diagnostic Experiment (FIDE) is shown in Fig. 11(a) for a high $\langle\beta_t\rangle$ PBX plasma. Three deuterium beams (two perpendicular and one tangential) with the total power of 4.0 MW were injected into a hydrogen plasma with $I_p = 516$ kA and $B_t(0) = 0.86$ T. The slowing-down spectrum is smooth and there is no evidence of beam ion loss due to fishbone activity. A PDX slowing-down spectrum with a spiky structure is shown in Fig. 11(b). Three deuterium beams (all perpendicular) were injected into a hydrogen plasma with $I_p = 400$ kA and $B_t(0) = 1.2$ T. The slowing-down spectra were obtained by varying the analyzer detection energy in time so that the fast ion loss appears as a spike in the charge-exchange signal at each fishbone burst.

The severity of the fishbone instability can be characterized in a semiquantitative manner by noting how frequently the bursts occur and how great the drop in neutron emission associated with them: the neutron loss rate may be defined in terms of quantities defined in Fig. 9 (bottom) as $\nu_{\text{loss}} \equiv (\Delta I/I)/T$. The reciprocal of ν_{loss} is a qualitative estimate of the fast ion confinement time. The ν_{loss} in PBX and PDX is plotted in Fig. 12 against the normalized $\beta_n \equiv \langle\beta_t\rangle/\beta_c$. The reduction in neutron loss in PBX relative to PDX, as seen in the figure, is due in part to the fact that two of the PBX neutral beams inject in the tangential direction. In PDX all four beams injected in the near-perpendicular direction. According to the theory, it is the perpendicularly injected particles which are affected most by the fishbone instability: therefore, some reduction of fast ion loss is expected merely from the reorientation of two of the four PBX beamlines. However, more detailed comparisons between PBX and PDX with just the two perpendicular beams

appear to indicate that bean-shaping is also responsible for reducing fast ion loss associated with fishbone instability.

H-MODE OPERATION

The separatrix-defined plasma in PBX can undergo transition into the H-mode when the neutral-beam power (P_D) is above a threshold value, as observed in many other tokamaks. The H-mode plasma is of interest to the PBX project in three ways. First, its higher confinement time may help to raise $\langle \beta_t \rangle$ for a given NBI power. Secondly, rapid density build-up associated with the H-mode serves as an efficient fueling mechanism and also may help to raise the $\langle \beta_t \rangle$. Thirdly, high electron temperature at the plasma edge can lead to a broader current profile needed for high indentation. Studies of the H-mode discharges in the PBX are, however, still preliminary.

The H-mode transition manifests itself in many different diagnostics. One of the more striking examples is the appearance of the plasma seen through the plasma TV. The central part of the plasma suddenly becomes more transparent and the outer edge becomes much more sharply defined as the plasma goes through the transition. The photograph in Fig. 3(a) shows a plasma before the H-mode transition (so-called L-mode) with diffuse outline, especially on the outboard side. The photograph in Fig. 3(b) is the same plasma after the H-mode transition. The plasma outline is now sharply defined, possibly reflecting steep density and temperature gradients at the plasma edge.

The time variation of the H_α emission signal from the upper separatrix region is shown in Fig. 13(a) and the signal from the midplane region in Fig. 13(b). Both signals show a characteristic drop at the transition, but the separatrix signal appears to indicate repeated transitions back and forth

between the L- and H-modes. Close tolerance between the separatrix and the rail limiters and lack of fine control of the separatrix position may be responsible for this behavior.

An initial jump in the energy confinement up to 70% of the pretransition value can occur at the H-mode transition in PBX. However, it falls gradually back to the pretransition value in a few hundred milliseconds. (See the top right graph in Fig. 14). The errant separatrix location may in part be responsible for this degradation, and finer control of the separatrix is an important agenda item in future experiments.

DIAGNOSTIC DEVELOPMENT

Some new diagnostic techniques have been developed during this reporting period. They include a plasma TV system that enables visual observation of the plasma shape and a new ion temperature diagnostic.⁷ The most important development from both the machine operational and plasma analysis standpoints is the SURFAS code. Plasma parameters, such as the plasma major and minor radii, q_{edge} and I_i , are readily obtainable for circular plasmas from geometrical and magnetic data. The β_p and $\langle \beta_t \rangle$ can also be easily calculated for circular plasmas from diamagnetic measurements. For bean-shaped plasmas all of these quantities are more intricately related to the plasma shape and are not as apparent as for circular plasmas.

The SURFAS code was developed to provide a quick between-shot analysis of these parameters. The code determines the shape of the plasma surface using measured magnetic data as boundary conditions, computes the magnetic field components on the surface and relates them to useful MHD and kinetic properties of the plasma. The reliability of this shorthand analysis was checked for selected discharges against the full MHD equilibrium code using

the same set of boundary conditions and additional magnetic and kinetic data. The SURFAS analysis proved to be an indispensable tool for guiding the machine operation as well as for building a data base for a large number of discharges.

A sample page of this multipage SURFAS output is shown in Fig. 14 for the same discharge whose H_α signals are given in Fig. 13. Sharp breaks in curves at 300 ms and 400 ms were caused by initiation of inward radial motion of the plasma and onset of NBI heating, respectively. The discharge had an H-mode transition at about 445 ms and was terminated disruptively at about 625 ms.

A new technique to measure the ion temperature and plasma rotation speed was also implemented during this reporting period. The technique relies on charge-exchange recombination of impurity ions with neutral particles of the heating beams, and is capable of measuring the radial profiles of these parameters. An example of the time variation of the central ion temperature is shown in Fig. 7(c).

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References

- ¹M. Okabayashi et al., "Studies of Bean-Shaped Tokamaks and Beta Limits for Reactor Design" in Plasma Physics and Controlled Nuclear Fusion Research 1984 Vol I, (IAEA, Vienna, 1985) 229.
- ²Annual Report (October 1, 1981 to September 30, 1982), PPPL-Q-40, Princeton Plasma Physics Laboratory;
Annual Report (October 1, 1982 to September 30, 1983), PPPL-Q-41, Princeton Plasma Physics Laboratory.
- ³K. Bol et al., "PEX: The Princeton Beta Experiment," Princeton Plasma Physics Laboratory Report PPPL-2032, September 1983.
- ⁴K.M. McGuire, "Observation of Finite- β MHD Phenomena in Tokamaks," Proceedings of the Invited Papers of the International Conference on Plasma Physics, Lausanne, Switzerland, June, 1984, M.Q. Tran and O.J. Verbeek, eds. (Commission of the European Communities, Directorate General XII-Fusion Program, Brussels, 1984) pp. 123-154.
- ⁵R.D. Stambaugh et al., "Tests of Beta Limits as a Function of Plasma Shape in the Doublet III Device," IAEA-CN-44/A-IV-2-1;
M. Keilhacker et al., "Confinement and β -limit Studies in ASDEX H-mode Discharges," IAEA-CN-44/A-II-1;
D.C. Robinson et al., "Limiting β Investigations at Low Collisionality," IAEA-CN-44/A-IV-1;
All in Plasma Physics and Controlled Nuclear Fusion Research 1984 (IAEA, Vienna, 1985).

⁶F. Troyon and R. Gruber, "A Semi-empirical Scaling Law for the β -limit in Tokamak," Report LRP 239/84, Centre de Recherches en Physique des Plasmas, Association Euratom-Confédération Suisse, Ecole Polytechnique Fédérale de Lausanne, 21, av. des Bains, CH-1007 Lausanne, Switzerland;

F. Troyon et al., "MHD Limits to Plasma Confinement," Plasma Physics and Controlled Fusion 26, 209 (1984).

⁷K.P. Jaehnig et al., "Charge Exchange Recombination Spectroscopy Measurements of Ion Temperature and Plasma Rotation in PBX," Princeton Plasma Physics Laboratory Report PPPL-2172, November 1984;

R.J. Fonck, "Charge Exchange Recombination Spectroscopy as a Plasma Diagnostic Tool," Princeton Plasma Physics Laboratory PPPL-2181, December 1984.

TABLE I

Definition and Range of Parameters Covered to Date by the PBX Tokamak

$B_t(0)$	0.7 - 1.4 T	toroidal magnetic field at geometrical center
$\langle B_t \rangle$	0.73 - 1.46 T	volume-averaged toroidal magnetic field
I_p	≤ 560 kA	plasma current
di_p/dt	≤ 1.5 MA/sec	rate of rise of plasma current
R_p	1.43-1.55 m	major radius
a_{mid}	0.30-0.45 m	midplane half-width
P_b	≤ 5.5 MW	injected neutral beam power
q_{edge}	≥ 3.0	edge q value (on 95% flux surface)
q_{cyl}	≥ 1.04	equivalent cylindrical q value
n-index	≥ -2.5	magnetic field decay index
i	≤ 0.22	indentation
κ	≤ 1.8	elongation
δ	≤ 0.3	triangularity
$\langle \beta_t \rangle$	$\leq 5.3\%$	volume-averaged toroidal β
$\beta_t(0)$	$\leq 16.2\%$	on-axis toroidal β
β_c	≤ 2.4	critical β [$= \mu_0 I_p / a_{mid} \langle B_t \rangle$]
β_n	≤ 2.5	normalized β ($= \langle \beta_t \rangle / \beta_c$)
β_p	≥ 1.5	poloidal β

Figure Captions

- Fig. 1. Schematic diagram of a poloidal cross section of the PBX identifying several major components. The tokamak center is to the left of the figure. Compare this figure with a photographic view in Fig. 2. [85X0604]
- Fig. 2. Photograph of the interior of the PBX in a tangential view. Semicircular graphite armor (at left center) protects the pusher coil from direct contact with the plasma. The upper and lower stabilizer plates are protected by four graphite rail limiters each. One is visible on the upper stabilizer plates. The cylindrical stabilizers on the inboard side are visible at left. The upper and lower active feedback coils are visible between the inner and outer passive stabilizer plates. Compare this photograph with the schematic in Fig. 1. [84E0601]
- Fig. 3. TV picture of a stable bean-shaped plasma in a tangential view. The light kidney-bean-shaped area is the image of the plasma. The inner passive stabilizer cylinders and the pusher coil are visible at left. (a) picture of the plasma before the H-mode transition with fuzzy outline, especially on the outboard side (at right), and (b) picture after the H-mode transition with sharply defined outlines, reflecting steeper gradients of plasma parameters near the edge. [84X2160 for (a) and 84X2161 for (b)]

Fig. 4. Variation of indentation as a function of the q value at the plasma edge (q_{edge}). The q_{edge} was varied by changing B_t while holding all other parameters the same. As the q_{edge} becomes smaller and the plasma current profile broadens, the indentation becomes deeper. [85X0592]

Fig. 5. Plasma current profile comparisons. (a) Current profiles of PBX and PDX as a function of the major radius. (b) Same comparison as a function of the normalized poloidal flux function together with the profile anticipated in the PBX project proposal. The magnetic axis is at left end and the plasma edge at right end in this graph. The PBX skin-effect current profile shown here is much broader than a typical PDX profile, but not quite as broad as the PBX proposal. [85X0587]

Fig. 6. Operating range of PBX in terms of dimensionless parameters, β_p and $\langle\beta_t\rangle$. The data points fall roughly within an area of triangular shape. The data around the lower right-hand side of the triangle are near the low- q (high- I_p , low- B_t) disruption limit. The data around the upper left-hand side are near the low- I_p heating limit. The data around the upper right-hand side are near the boundary of the first region of stability. The data points with $\beta_n \geq 2.0$ are identified by a different symbol (solid) and they all lie in the vicinity of the upper right-hand limit. [85X0586]

Fig. 7. Summary of the data and analysis of the highest $\langle \beta_t \rangle$ discharge.

(a) Time variations of $\langle \beta_t \rangle$, β_p , and $\Lambda \equiv 1_i/2 + \beta_p$ computed by the SURFAS code. The $\langle \beta_t \rangle$ values computed by the full MHD equilibrium code are also shown. (b) The TVTS Thomson scattering profiles of the electron temperature $[T_e(R)]$ and density $[n_e(R)]$ at one time point. (c) The central ion temperature variation with time. (d) Time variation of the displaced toroidal flux measured by the diamagnetic diagnostics and computed by the SURFAS code. The highest $\langle \beta_t \rangle$ reached in this discharge is 5.3%--a record for major tokamaks. The on-axis $\beta_t(0)$ reached 16.2%. [85X0621]

Fig. 8. Plot of $\langle \beta_t \rangle$ vs $\beta_c \equiv \mu_0 I_p / a_{mid} \langle B_t \rangle$ for the PBX and PDX tokamaks. The data for both groups are essentially bounded by the Troyon limit, $\langle \beta_t \rangle \leq 2.5\beta_c$, and are in the first region of stability. However, the operating range within this region has been more than doubled in PBX in relation to PDX. [85X0580]

Fig. 9. Fishbone instability and its effects on the neutron emission in a discharge with narrow current profile in PBX. (a) Fluctuations in the poloidal magnetic field measured by a Mirnov coil showing bursts associated with fishbone instability and sawtooth relaxation. (b) Neutron emission rate showing a drop at each of fishbone bursts as well as sawtooth relaxation. [85X0773]

Fig. 10. Fishbone instability and its effects on the neutron emission in a discharge with broad current profile in PBX. (a) Fluctuations in the poloidal magnetic field measured by a Mirnov coil showing bursts associated mostly with sawtooth relaxation. Only one fishbone burst is recognizable in this discharge. (b) Neutron emission rate showing a drop at sawtooth relaxation. [85X0772]

Fig. 11. Fast ion slowing-down spectra measured by charge-exchange diagnostics. (a) Smooth classical slowing-down spectrum for a PBX discharge. (b) PDX spectrum with spikes corresponding to fast ion loss at the time of each fishbone burst. [85X0589 for (a) and 85X0637 for (b)]

Fig. 12. Neutron loss rate ν_{loss} as a function of the normalized β_n for PBX and PDX. The reciprocal of ν_{loss} is a qualitative estimate of the fast ion confinement time. The PDX data are plotted against slightly different abscissa, $\beta_n (q_{\text{shaf}}/q_{\text{cyl}})$, where q_{shaf} is the true MHD q value at the plasma edge. However, the ratio, $q_{\text{shaf}}/q_{\text{cyl}}$, is not far from unity for all PDX data for the purpose of this comparison. [85X0585]

Fig. 13. Time variation of the H_α signals during the L- and H-mode from (a) the upper separatrix region and (b) the midplane region. The separatrix signal appears to indicate repeated transitions back and forth between the two modes. [85X0912]

Fig. 14. A sample page of the multipage output of the SURFAS code for the same discharge shown in Fig. 13. Sharp breaks in curves at 300 ms and 400 ms were caused by initiation of inward radial motion of the plasma and onset of NBI heating, respectively. The discharge had an H-mode transition at about 445 ms and was terminated disruptively at about 625 ms. This example also shows a jump in the energy confinement time (τ_E) at the H-mode transition (top right graph). [85X0638]

#85X0604

Fig. 1

Fig. 2

Fig. 3a

Fig. 3b

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

PBX: Bean Shaped $i=0.19$
 (2.7 MW (I) from 385 ms & 1.4 MW (II) from 485 ms)

Fig. 10

Fig. 11a

Fig. 11b

Fig. 12

Fig. 13

Fig. 14

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