NEUTRAL PROBE BEAM Q-PROFILE MEASUREMENTS IN PDX AND PBX-M

By

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JUNE 1988

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PPPL--2526

DE88 012717

Abstract

Using the Fast Ion Diagnostic Experiment (FIDE) technique, a Neutral Probe Beam (NPB) can be aimed to inject tangentially to a magnetic surface. The resultant ion orbit shifts, due to conservation of canonical toroidal angular momentum, can be measured with a multi-sightline charge-exchange analyzer to yield direct measurements of radial magnetic flux profiles, current density profiles, the radial position of the magnetic axis, flux surface inner and outer edges, q-profiles, and central-q time dependencies. An extensive error analysis was performed on previous PDX q-measurements in circular plasmas and the resulting estimated contributions of various systematic effects are discussed. Preliminary results of fast ion orbit shift measurements at early times in indented PBX-M plasmas are given. Methods for increasing the absolute experimental precision of similar measurements in progress on PBX-M are discussed.

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1. Introduction.

A fundamental need of present tokamak physics research, and in particular the PBX-M high-beta experimental program, is for precise and detailed radial measurements of plasma current profiles. Closely related parameters include the poloidal magnetic flux, poloidal magnetic field, plasma current density, magnetic rotational transform ($2\pi/q$), and magnetic safety factor (q). Although almost 20 years of extensive experimental and theoretical studies have implied that the detailed behavior of these quantities is important for understanding tokamak stability limits and accessing new regimes of operation, there is little direct experimental data on the radial and time characteristics of these quantities for various plasma conditions.

Recently, several complementary experimental methods have been initiated or proposed for measuring these parameters. Some of these methods are complex, exhibit an unfavorable signal-to-noise ratio (S/N), cannot be applied conveniently to non-circular plasmas, or involve relatively large uncertainties from deconvoluting the plasma line-density.

The Fast Ion Diagnostic Experiment (FIDE) technique, as demonstrated on two previous tokamak experiments [1-3], avoids most of these difficulties. This previous work has shown that radial profiles of these parameters can be measured directly by detecting the orbital displacement of injected circulating fast ions from magnetic surfaces (Figure 1). A tightly collimated Neutral Probe Beam (NPB) can be aimed to inject tangentially to a magnetic surface at a chosen plasma minor radius on the midplane (R_{inj}), and the resultant ion orbit shifts (R_{obs}), due to conservation of canonical toroidal angular momentum, can be determined with a multi-sightline charge-exchange analyzer. The most convenient location for measuring these shifted ion orbits is at a point in the poloidal plane 180° opposite the injection point (Figure 1). If $\Psi(R)$ is the magnetic flux at major radius R , and the injection velocity is effectively the tangential velocity V , then conservation of canonical toroidal angular momentum gives

$$mVR_{inj} - e\Psi(R_{inj}) = mVR_{obs} - e\Psi(R_{obs}) \quad (1)$$

and the change in the radial magnetic flux profile,

$$\Psi(R_{obs}) - \Psi(R_{inj}) = \frac{mV}{e} (R_{obs} - R_{inj}) \quad (2)$$

Measurements at different beam energies can be used to locate the magnetic axis (R_0) and the flux surface midplane locations R_{opp} and R_{inj} shown in Figure 1. Using Eq. (2), the radial poloidal magnetic field (B_p) is

$$B_p(R_{obs}) = \frac{1}{R} \frac{\partial \Psi}{\partial R} = \frac{mV (R_{obs} - R_{inj})}{e R_{obs} (R_{opp} - R_{obs})} \quad (3)$$

and the radial current density profile is

$$J(R) = \frac{1}{\mu_0} \frac{dB_p}{dR} = \frac{1}{\mu_0} \frac{d}{dR} \left(\frac{1}{R} \frac{\partial \Psi}{\partial R} \right) \quad (4)$$

In the case of a circular plasma q (q -circular) is given by

$$q(R_{obs}) = \frac{\Omega t}{2V} (R_{opp} - R_{obs}) \quad (5)$$

For a flux surface with a small elliptical elongation ($\epsilon \approx b/a$), q (q -elliptical) can be approximated in terms of a small correction to q -circular as

$$q\text{-elliptical} = \frac{(\epsilon^2 + 1)}{2\epsilon} q\text{-circular} \quad (6)$$

In addition, since the NPB has three energy components (E_1 , E_2 , E_3), each injection major radius can yield three independent measurements of the change in magnetic flux relative to the injection point and can be used to eliminate the need to know the location of the magnetic axis. Using these three NPB energy components, the measured fast ion orbital shifts yield a direct measurement of radial magnetic flux profiles, current density profiles, the radial position of the magnetic axis, flux surface inner and outer edges, and q -profiles for circular and near-circular flux surfaces.

In the case of highly non-circular plasmas, the generalized definition of $q(R)$ must be employed, *i.e.*,

$$q(R_{\text{obs}}) = \int \frac{dl B_t}{2\pi R |B_p|} \quad (7)$$

Since this involves a line-integral of the ratio of the toroidal and poloidal fields taken over the applicable flux surface, both local and line-averaged q -measurement methods require a detailed knowledge of the shape of the flux surface in order to derive q from their measured signals. However, for non-circular plasmas, the relative simplicity, directness, and precision of the FIDE method should allow it to be used in conjunction with magnetic diagnostic loop data to yield a measurement of radial q -profiles, or relative changes in central- q , for highly indented, highly lobed, or rapidly changing plasmas, and can place rigorous constraints on the analysis of plasma conditions presently derived solely from plasma-edge magnetic measurements.

2. Analysis of PDX Results.

Measurements using this technique were performed for circular plasmas in the ATC [1] and PDX tokamaks [2,3]. Preliminary radial measurements of q in PDX were obtained with a 30 keV NPB, and values of central- $q < 1$ were obtained during ohmic conditions and low power neutral-beam-heated discharges [3]. In addition, the time evolution of central- q profiles during start-up were studied, and changes in central- q were measured during MHD activity. The fundamental experimental limitation in these previous experiments [3] was the 30 keV upper energy limit of the NPB. In the case of neutral-beam-heated plasmas, the "tail" of the Maxwellian bulk plasma distribution and the population of fast heating beam ions contributed sufficiently to the neutral flux above 10 keV to eliminate the usefulness of all but the highest energy NPB component. These ion backgrounds reduced the measurements derivable from a given NPB pulse from three to one, decreased the S/N ratio, and eliminated the convenience of not having to know the location of the magnetic axis. In addition, for high density plasmas, the beam

attenuation of the lowest beam energy components (10 and 15 keV) was particularly severe, thus further reducing the signal. This is similar to the difficulty encountered with the plasma penetration of the PDX vertical 15 keV doping beam for the mass-resolving charge exchange (MACE) analyzer array [4].

Recently, an extensive reanalysis of the experimental conditions and uncertainties in these PDX measurements has been in progress with a view toward upgrading this technique for application to PBX-M plasmas. Fokker-Planck simulations of the observed NPB fast ion spectra for a 70 keV injection energy were performed and used to simulate the expected NPB signals for dense ($n_0(0) = 1.0 \times 10^{14} \text{ cm}^{-3}$) PBX-M plasmas heated with 6 MW of 50 keV D⁰. The results showed that for these PBX-M plasma conditions, the expected S/N ratio, using the previous methodology, was about 4:1 at 23 keV (comparable to the S/N ratio at 30 keV in the PDX q measurements), and 11:1 at 35 keV. There was no observable background predicted at 70 keV. These results supported empirical conclusions from the PDX experiments regarding the need for higher NPB injection energies in order to avoid the limitations described above.

In addition to these Fokker-Planck calculations, a guiding center drift orbit code was used to investigate the accuracy of the present approximations, the relative contributions of higher order terms, and various data analysis procedures across the full range of expected PBX-M plasma configurations (from circular to highly indented and elongated). The preliminary results indicate that the present theory of the measurement is accurate to sufficient order, and that while the flux gradients for highly indented plasmas tend to be larger than for circular plasmas, the expected ion orbit shifts for very highly indented, highly elongated and lobed PBX-M plasmas are relatively large and observable (e.g., $\sim 4 \text{ cm}$ for $q \sim 1$), and can be used for both absolute q-measurements and monitoring small relative changes in central-q.

Various experimental uncertainties encountered in the previous work have been analyzed and include systematic effects involving background corrections, energy band width, stray fields, finite spatial resolution, and toroidal field uncertainty. This work and the analyses described above have suggested methods for reducing the relative

and absolute experimental uncertainties in similar measurements to be performed on PBX-M. For example, the use of an 80 keV NPB will allow the study of highly indented, neutral-beam-heated, high temperature plasmas by providing injected probe ions with energies well above those of the fast ions from the bulk Maxwellian distribution and the heating beams. This will permit the detection, during high power neutral beam heating, of much stronger signals with only a few amps of injected beam current, and yield larger ion orbit shifts due to the increased beam momentum. Additional improvements in experimental precision should accrue from improvements in alignment, spatial resolution, background correction, and magnetic shielding. For example, improved magnetic shielding of stray fields can reduce the correction for an apparent shift in the observed major radius from 1 cm for a 100 g stray field to 0.2 cm for a 20 g stray field.

3. Initial PBX-M results.

A 28.5 keV, 10 msec, D^0 beam pulse was counter-injected during the nominal 1 MA/sec, early current-rise phase of an ohmic, 300 kA, H^+ , indented, PBX-M plasma. The injection point, at a major radius of 175 cm, was tangent to the outer side of a near-circular central flux surface having a nominal magnetic axis at 165 cm. The beam was modulated at a frequency of 10 KHz to allow discrete background measurements during the pulse. Figures 2a and 2b show the signals from the full energy component obtained by viewing the modulated circulating fast ion beam on the midplane at a point poloidally 180° opposite the injection point (Figure 1). In general, from the start of injection at 136 msec, the signals have very different characteristics at the two spatial locations. The more central region at 151.8 cm (Figure 2a), except for small discontinuities at 142 msec and 145 msec, exhibited a time decay similar to that observed in PDX plasmas as the central magnetic flux increased during the current-rise phase [3]. However, the signal from 147.5 cm (Figure 2b) exhibited a significant increase at 142 msec and 145 msec. Such effects were also observed during the start-up phase of PDX discharges [3].

Figure 3 shows the signals at 200 msec from the 30 available detector

channels, as summed into 10 groups over the 10 msec beam pulse duration, *versus* detection radius (cm), and it exhibits the shape and position of the detected circulating fast ion beam. As discussed above, similar measurements with at least two energy components of the neutral probe beam can yield a q -measurement that is independent of a knowledge of the magnetic axis location. Preliminary measurements, at 200 msec during first attempts at PBX-M, ohmic, 300 kA, H^+ indented plasmas, yielded a value of $q = 1 \pm 0.3$ at minor radius $r = a/3$, assuming near-circular central flux surfaces.

Although the perturbations evident in Figure 2 were sufficient to significantly affect 28.5 keV fast ion orbits, the correlation of these effects with variations in the PBX-M magnetic behavior is still in progress, because the diagnostic signals were relatively weak at this early time in the discharge. However, these observations support the sensitivity and usefulness of tangentially injected fast ion beams for studying magnetic fluctuations during the early current-rise phase and other times of tokamak discharges that have MHD activity [3].

4. Conclusion.

In general, the results of this work indicate that with higher NPB energies, an experimental precision of $\sim 20\%$ should be achievable for measurements of $q \sim 1$ in very dense high power neutral-beam-heated plasmas, and that with the improvements discussed above, experimental precisions of $\sim 10\%$ may be possible. Higher precision may be obtained in plasmas with smaller fast ion populations. In addition, actual operating experience with an improved NPB system may suggest additional ways to further reduce residual experimental uncertainties. Work is in progress on an 80 keV, 2.7 A NPB, and on upgrading the detection and data analysis techniques so these measurements can be pursued in PBX-M plasmas.

Acknowledgments

We wish to acknowledge technical contributions from F. Polom Sr., R. Yager, and the PBX-M technical staff. This work was supported by the U. S. Department of Energy Contract No. DE-ACO2-76-CHO-3073.

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Figure Captions

Figure 1. Orbits for fast ions with $V(\text{tangent})/V(\text{total}) = 1$ born inside the magnetic axis in major radius.

Figure 2. Flux of circulating fast ion beam injected into PBX-M at 136-146 msec and measured at major radius (a) $R = 151.8$ cm, (b) $R = 145.4$ cm.

Figure 3. Measured shape of the circulating fast ion beam injected into PBX-M at 200 msec.

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Fig. 1

#88X0416

Fig. 2

Fig. 3

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