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HIGH TIME RESOLUTION ION TEMPERATURE
PROFILE MEASUREMENTS ON PBX

By

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PROFILE MEASUREMENTS ON PBX

MASTER

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ABSTRACT

Ion temperature profiles with a time resolution of 2-5 ms have been measured on PBX by charge-exchange-recombination spectroscopy (CXRS) and a neutral-particle charge-exchange analyzer (NPA). The sightlines of both diagnostics crossed the trajectory of a near-perpendicular heating beam, which enhanced the local neutral density ($\propto$ signal strength) and provided spatial resolution. The time resolution of these two independent techniques is sufficient to see sawtooth oscillations and other MHD activity. Effects of these phenomena on the toroidal rotation velocity profile, $v_\phi(r)$, are clearly observed by CXRS. For example, a sharp drop in the central v_ϕ occurs at the sawtooth crash, followed by a linear rise during the quiescent phase. The NPA results are compared with those from CXRS.

I. INTRODUCTION

The ability to measure changes in plasma ion temperatures on the relatively short time scale of a few msec is of special interest in studies of low- q high- β plasmas, such as those produced in the Princeton Beta Experiment (PBX)¹ tokamak. At low- q , sawtooth amplitudes can become large, and the affected plasma region extends over most of the radial profile, while rapidly changing MHD behavior and plasma rotation are often characteristics of high- β discharges. In both cases, the determination of ion temperature profiles requires high time resolution in order to study ion thermal transport.

To that end, two complementary techniques to measure ion temperature profiles with high time resolution, one based on charge-exchange-recombination spectroscopy (CXRS) and the other on charge-exchange neutral-particle analysis, have been refined and compared. CXRS has been described in detail elsewhere,² but the present work also includes profile results. The second technique utilizes the neutral particle analyzer of the Fast Ion Diagnostic Experiment (FIDE).³ Brief descriptions of the two techniques follow.

In CXRS, fully ionized impurity ions undergo charge exchange with fast neutrals (H^0 or D^0) injected by the heating beams. One of the near-perpendicularly injected heating beams was used for the results obtained in PBX. The fully ionized impurity becomes a hydrogenlike impurity in an excited state, which consequently emits spectral lines anywhere from the extreme ultraviolet to the visible as it radiatively decays. Radiation from intrinsic impurities, such as the O^{7+} transition at $2976 \text{ \AA}$ ($n = 8-7$), can be used conveniently. Ion temperatures are deduced from the line width, and toroidal rotation velocity from the

line shift. Radial profiles for temperature and toroidal rotation velocity are generated on a shot-by-shot basis by changing the spectrometer sightline. The radial points are those corresponding to the intersection of the various sightlines with the heating beam trajectory.

The optical system for CXRS on PBX consists of an $f/10$ 1-m Ebert spectrometer which is quartz lens coupled to view the plasma through a quartz window. An optical multichannel analyzer, consisting of a proximity-focused microchannel plate image intensifier fiber optically coupled to a 1024 element photodiode array, is used as the detector.² The readout and control electronics are similar to those described by Fonck, Ramsay, and Yelle.⁴ Using the maximum available entrance slit width of ~ 200 μm , and grouping the pixel readout in groups of 4 pixels each, allowed sufficient signal and readout time to provide accurate line profiles every 2 msec. This was found to be adequate to resolve sawtooth activity in the central ion temperature and toroidal rotation velocity.

The FIDE analyzer detects thermal charge-exchange neutrals, and can thus be used to determine ion temperatures. With the analyzer in its most tangential position, three of its five sightlines span the plasma from near its center to its outside edge. Neutral particles entering the analyzer pass through a helium gas cell, and a fraction of them are re-ionized. That fraction passes through a pair of deflection plates and are detected by a microchannel plate array. Their energy is determined by the deflection plate voltage, which is swept as a function of time. To study thermal neutrals, the plate voltage is swept over a range of 0 to 1-2 kV, which corresponds to ion energies between

0 and 10-20 keV. The signal is integrated over 50 μ s intervals to accumulate sufficient statistics, and with this integration time a flux vs. energy plot can be obtained for sweep periods as fast as 2.5 ms (i.e., 50 points/sweep). The temporal resolution of the ion temperature measurement is thus determined by the sweep time, and is similar to CXRS.

An advantage of this analyzer is that temperatures can be measured simultaneously along as many as five sightlines. This allowed the evolution of radial profiles to be followed during a single shot with high temporal resolution, and three sightlines were instrumented to obtain the measurements presented in this paper. The principal disadvantage is that the measured temperature is artificially high due to contamination from the slowing-down beam ions. However, the time evolution and the profile shapes of the two techniques are qualitatively similar. It should be noted that the FIDE signals are strongly enhanced (by a factor of 10 to 30) when viewing across the heating beam. As in CXRS, this is because the beam neutrals increase the local charge-exchange rate, and the measurements are then effectively localized to the intersections of the FIDE sightlines and the heating beam trajectory.

II. DATA AND ANALYSIS

Figures 1.a. and 1.b. show the time evolution of the central toroidal rotation velocity, v_ϕ ($r=0$), and the central ion temperature, T_i ($r=0$), measured by CXRS with a temporal resolution of 4 ms, for a discharge with strong sawtooth activity. Figures 1.c. and 1.d. show sample Gaussian fits to the data at two particular times, before and after the crash. The characteristic sawtooth activity is clearly seen on both T_i ($r=0$) and v_ϕ ($r=0$).

Figure 2.a. shows raw flux vs. time from FIDE just before and just after a sawtooth crash, digitized every 50 μ s. Also shown is the energy corresponding to the deflection plate voltage. Figure 2.b. shows the flux vs. energy plots that are constructed from the data in Fig. 2.a. and corrected for ionization efficiency of the gas cell and energy bandwidth of the analyzer. On a log scale, the plot should be linear for Maxwellian distributions, and the inverse slope gives the temperature.⁵ Figure 2 shows that the temperature and the energy corresponding to peak flux both decrease after the sawtooth crash.

The time dependence of the temperature from CXRS and the three FIDE sightlines are compared in detail around the time of a sawtooth crash in Fig. 3. The toroidal rotation velocity (at $r = 1$ cm) as a function of time appears similar to Fig. 3.a., dropping from 1.3×10^7 cm/sec before the crash to 1.0×10^7 cm/sec after, and then gradually increasing again. Radial temperature profiles are shown in Fig. 3.c. for times before and after the sawtooth crash.

The FIDE ion temperatures are generally higher than the CXRS ion temperatures, especially in the plasma core region. This is presumably due to contamination from the slowing-down heating beam particles, as illustrated in Fig. 4. FIDE data from the three sightlines are shown in Fig. 4.a., and results of a Fokker-Planck simulation of the FIDE spectrum using the plasma parameters for the same shot are shown in Fig. 4.b. Both the simulation and the data show curvature in the $\ln(F)$ plots over the same energy range. In the simulation, this curvature is due to the beam ion contribution. The curvature becomes less severe in the simulation and the data for sightlines closer to the plasma edge. Indeed, the quantitative agreement between CXRS and FIDE is best in this region.

III. SUMMARY

Ion temperatures have been determined in PBX with high time resolution (2-5 ms) using two independent methods. The evolution of the temperature profiles can be measured by the FIDE analyzer on the same time scale, and the results are in qualitative agreement with CXRS profiles accumulated on a shot-by-shot basis. Ion temperature and plasma rotation measurements show sawtooth oscillations similar to those seen in the electron temperature. Contamination of the FIDE analyzer energy spectrum from slowing-down heating beam particles is the primary cause of the quantitative discrepancy between the two techniques.

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FIGURE CAPTIONS

1. CXRS central toroidal rotation velocity (a) and central ion temperature (b) vs. time during sawteeth. Also shown are plots of the raw data with their corresponding Gaussian line fits for two particular times, just before (c) and after (d) a sawtooth crash. The spectrometer was tuned to the O^{7+} line at 2976 Angstroms.
2. a. Flux and analyzer viewing energy vs. time for FIDE, before sawtooth crash (A) and after crash (B).
b. FIDE flux vs. energy, corresponding to Fig. 2.a. corrected for analyzer efficiency and bandwidth, before crash (3.5 keV) and after crash (2.6 keV). Sightline is near center.
3. a. CXRS $T_i(t)$. The CXRS line width decreased 15% after the crash, and the line center shifted $\sim 0.3 \text{ \AA}$.
b. $T_i(t)$ along the three instrumented FIDE sightlines for the same shot.
c. CXRS T_i profiles before (●) and after (■) the sawtooth crash, generated by changing the spectrometer sightline over a series of shots. Also shown are the three FIDE sightlines before (O) and after (X) the crash for one of the shots in the series.
4. Upper figure shows flux vs. energy for the three FIDE sightlines. The sightlines move progressively from the center (uppermost curve) to the edge (lowest curve) of the plasma. Lower figure shows results of a Fokker-Planck model for the same three sightlines. The heavy lines are the results with the heating beams on, and the light lines are for no heating beams. The lowest curve, for the sightline just grazing the edge of the plasma, is not affected by the heating beams. The data and the calculation with heating beams show curvature in the energy spectrum, due to slowing-down heating beam particles, over the same energy range.

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Fig. 1

Fig. 2

Fig. 3(a,b)

Fig. 1(c)

Fig. 4

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