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Measurement of Escaping Fast Ions in CHS

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Abstract

Measurements of escaping 40 keV neutral beam ions have been carried out on the Compact Helical System (CHS). The diagnostic producing these measurements is a vertically-movable scintillator-based probe, like those used in TFTR, and it gives time-resolved energy and pitch angle distributions. Initial results from quiescent plasmas are reported.

Keywords:
helical device, fast ion loss, neutral beam ion

1. Introduction

Good confinement of fast ions is required in a fusion reactor plasma so that the plasma is self-heated and the wall heat load is minimized. Thus, it is important to measure and understand fast ion loss processes in present-day magnetic confinement devices, so that losses in future devices may be accurately predicted. The primary purpose of this work is to make measurements of fast ion losses in a helical system in order to understand the loss mechanisms that might affect alpha particles and other fast ions in a reactor plasma of helical geometry. The secondary purpose of this work is to gain experience in loss measurement diagnostics for helical geometry in order to design such a diagnostic for the Large Helical Device (LHD)[1].

2. Hardware Description

A single scintillator-based fast ion loss probe, of a construction similar to those used in TFTR[2,3], has been installed on CHS[4] and is depicted in Fig. 1. The total assembly has a length of ~103 cm, and is mounted on a port above the plasma at a major radius of 120 cm. The ion grad-B drift direction is upwards in CHS for the usual magnetic field configuration, which is counterclockwise as seen from the top. The probe is mounted on a linear translation stage that allows it to be moved vertically, and it can be withdrawn behind a gate valve. The typical range of probe tip positions for which a measurable signal can be found is between $z=14.1$ and 11.1 cm.

The detection end is essentially a metal box, ~3 cm on a side, with an inorganic scintillator on the bottom of the box. Two apertures, one behind the other, are on one side, and restrict the orbits of fast ions that can enter the probe. The first aperture is 0.8 mm high × 2 mm wide, the second is 0.8 mm high × 11.5 mm wide, and they are separated by 10 mm. A line passing through the center of the two apertures makes an angle of 35.2° from the major radial direction, as shown in Fig. 1.

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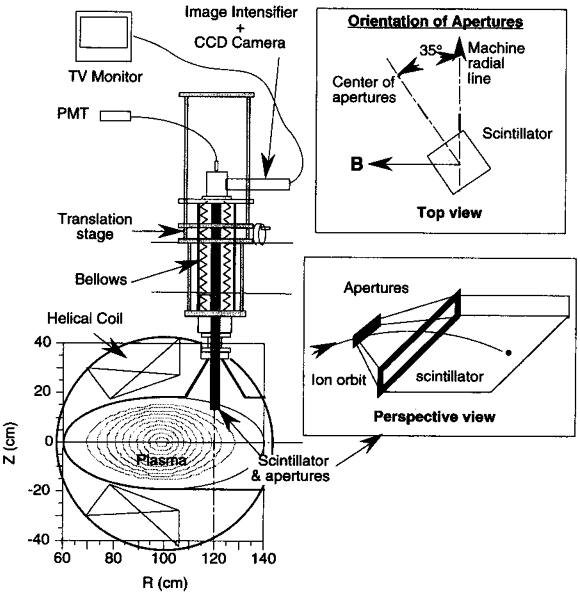

Fig. 1 Schematic diagram of the CHS fast ion loss probe, showing its principal components and its position relative to the flux surfaces of a plasma at R_{ax} = 97.4 cm. The inset shows the orientation of the apertures relative to the machine radial line and ordinary orientation of the toroidal field (counterclockwise as seen from above).

The device functions as a magnetic spectrometer: ions with larger gyroradii strike the scintillator farther from the apertures than those with smaller gyroradii, and their strike points are dispersed across the orthogonal dimension of the scintillator according to their pitch angles. The amount of light produced by an ion is approximately linearly proportional to its energy. At present, a ZnS(Ag) scintillator (EIA designation P11) of ~ 10 microns thick is in use. The requisite thickness can be determined from the stopping range of energetic ions of interest and their angle of incidence upon the scintillator. For typical energetic ions in magnetic confinement fusion experiments, thicknesses of a few tenths of microns to ~ 30 microns are adequate.

The light produced by the ions striking the scintillator is focused by a lens to an image plane outside the machine vacuum. A beamsplitter placed just before the image plane divides the light between two detection paths. In the first path, the light from the scintillator is carried by a fiber optic bundle to a photomultiplier (PMT). This gives the total fast ion loss rate to the probe as a function of time with response up to ~ 10 kHz. The response is limited by both the time constant of the scintillator material and the response of the PMT (Hamamatsu model H5784 with integral preamplifier). The PMT signal is digitized and recorded by the CHS data acquisition system.

On the other optical path, there is a microchannel plate image intensifier (Hamamatsu model V2697HX) at the focal plane. This enhances the relatively dim image of the light emission pattern on the scintillator so that a following monochrome CCD videocamera (Hitachi Denshi, Ltd., model KP-M 1, NTSC format) can record the 2-D pattern. The video signal is transmitted via fiber optic cable to the CHS control room, where it is viewed and recorded on video tape with a Victor HR-X7 video cassette recorder. The images from the camera are digitized after the experiment using a Macintosh computer equipped with a Hamamatsu IQ-V50 video frame grabber board. The frame grabber captures only frames, which are 33.3 ms in duration. Because a typical CHS discharge has no more than 100 ms of neutral beam injection, at most three frames per pulse will have useful data. The camera can be triggered from the CHS trigger system to synchronize the frames with respect to the time during the pulse.

3. Initial Results

Figure 2 displays the total loss to the probe, as measured by the PMT, for two comparable pulses. For

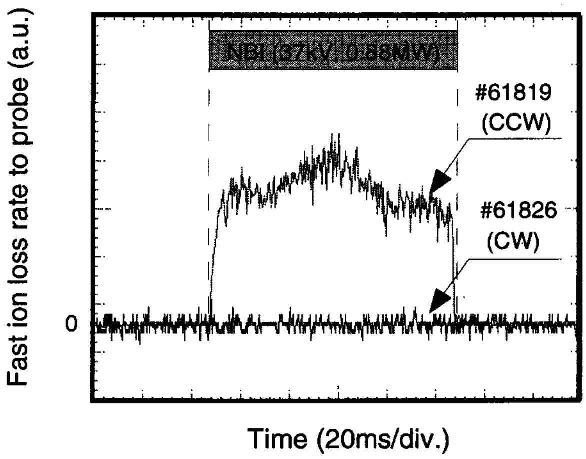

Fig. 2 A comparison of the total loss rate signal of the probe, measured by the PMT, for two discharges. The discharge shown in the solid line has the toroidal field oriented counterclockwise as seen from above, such that the ion grad-B drift is upwards, toward the probe. In this case, a signal is seen. For the discharge shown in the broken line, all the magnetic fields have been reversed, so that the ion grad-B drift is away from the probe. For this orientation of the fields, no loss is seen.

the pulse shown as a solid line, the toroidal field was counterclockwise as seen from above (the standard condition), for which the ion grad-B drift is upward. The PMT trace shows that light is detected in this case coincident with the "coinjecting" (*i.e.* particles traveling clockwise as seen from above) neutral beam. The broken line shows the results of a pulse whose toroidal field was clockwise. For this condition, the ion grad-B drift is downward, and no beam ion loss should be seen at the probe. Indeed, no signal is seen. These properties of the signal indicate that it is not due to visible light leakage into the probe or X-ray-induced light in the scintillator, for these should be equally strong for either direction of the magnetic field. Only the ion loss to the probe should be altered by changing the direction of the toroidal field.

Figure 3 depicts a typical frame of data taken by the CCD camera, shown as contours of constant intensity. Overlaid on the image is a grid showing where the centroids of the particle strike points for certain gyroradii and pitch angles lie. The grid is computed by a numerical simulation which contains the geometry of the apertures and scintillator, plus knowledge of the direction of the local magnetic field. This is the same numerical simulation used to generate grids for the fast ion loss detectors on TFTR.[2] It generates trajectories of a specified pitch angle and gyroradius, uniformly distributed over the first aperture, and determines their strike points on the scintillator. The centroid of the resulting strike point distribution is plotted. Note that in this grid, "gyroradius" is not the particle's actual radius of gyration, which varies with pitch angle, but is instead $\rho=\sqrt{2mE}/qB$ (MKS units). Put another way, the grid lines of constant gyroradius in Fig. 3 are lines of constant ion energy.

As seen in Fig. 3, the distribution of lost beam ions has a pronounced feature centered around a pitch angle of 51° and a gyroradius of ~5.1 to 5.5 cm. There is a flaw in the image intensifier used for this diagnostic, which results in a diagonal dark line that overlies the region of light emission in the scintillator image and makes it hard to determine with accuracy the true

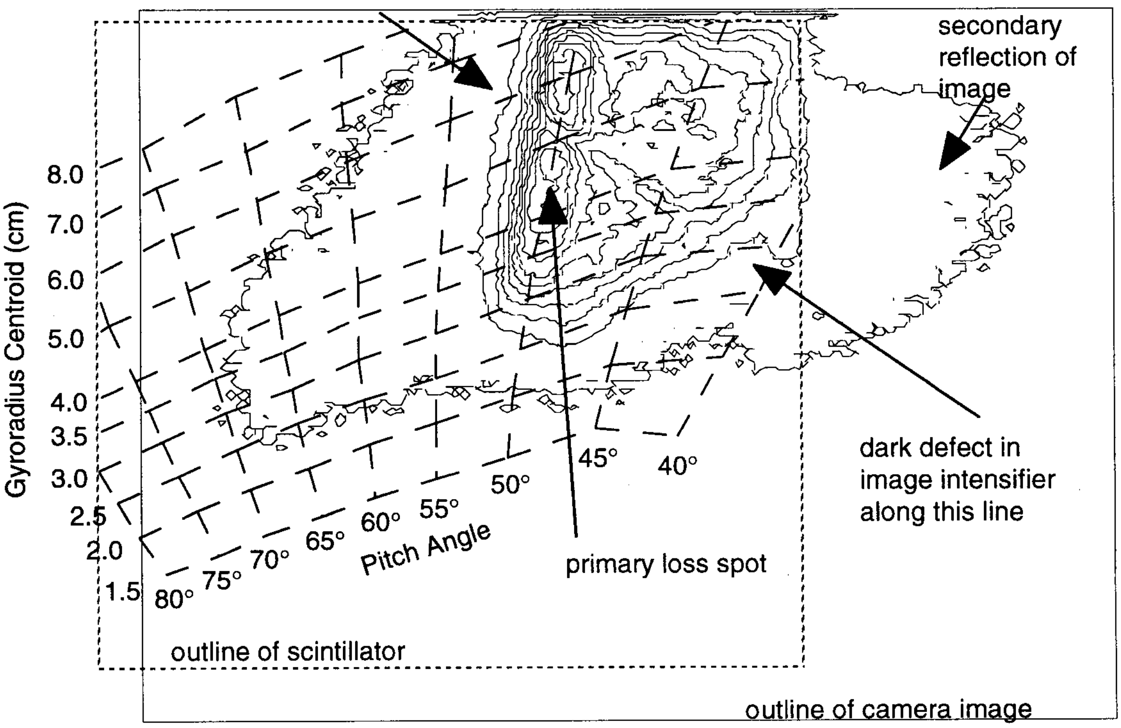

Fig. 3 Contours of constant intensity in the scintillator image captured by the CCD camera. This is first frame captured during pulse 66521. The signal is typical of other shots seen in CHS, and comprises a strong loss spot centered at a gyroradius of 5.1 cm and a pitch angle of 50°, plus a more diffuse, less intense loss extending from about 49° to 44° in pitch angle. The image intensifier used in this diagnostic has a dark line diagonally across the field of view, shown by the arrows, which affects the signal level over part of the spot illuminated by beam ions. Two boxes delineate the outline of the scintillator and the field of view of the CCD camera. Some luminosity is recorded outside the outline of the scintillator, and it arises from a reflection from the second surface of the beamsplitter in the optical system.

gyroradius centroid of this feature. There is a dimmer adjoining feature at lower pitch angles, extending from about 49° to 44°. Both features, unfortunately, appear to be cut off by the edge of the scintillator on their high gyroradius side (and possibly on the low pitch angle side for the dimmer feature).

For the discharge in which this data was taken, the magnetic axis was at a position of $R=94.9$ cm, and the magnetic field at the probe was 0.57 T. At this field, a 40 keV H beam ion has a gyroradius of 5.1 cm, which agrees, within the error bars, with the measurement above. When the detector simulation code mentioned above is run with particles at a single gyroradius and pitch angle, namely 5.1 cm and 50.5°, the resulting distribution of ion strike points on the scintillator looks very similar in size and extent to the principal spot shown in Fig. 3. The FWHM of the computed strike point distribution, in the pitch angle coordinate, is 2.0°, which appears comparable to the FWHM in the data in Fig. 3. The loss must arise at a single pitch angle in order to produce such a narrow response on the scintillator.

The beam ion loss distribution shown in Fig. 3 is typical of those seen in CHS plasmas. In the initial study of these losses, several effects have been seen to alter the total measured loss. In particular, increases in the beam ion loss rate have been associated with electron cyclotron heating (ECH), radiative thermal collapses, and MHD modes. While these effects are not understood, it is conjectured that ECH changes the plasma density profile, thus changing the deposition profile of the neutral beam ions, altering the fraction lost. One series of recent discharges showed a fast ion loss rate increasing approximately linearly with the plasma density, indicating that density does play an important role in beam ion loss. During tokamak disruptions, large fast ion losses arise from the destruction of magnetic surfaces as the rotational transform vanishes[5]. However, the magnetic structure of the CHS discharge during thermal collapses should remain unchanged, meaning that magnetic perturbations cannot explain the losses. It may be that a changing density profile plays a role in these losses also. During fishbone-like instabilities [6], short bursts of beam ion losses are seen coincident with the bursts on the Mirnov coils. This behavior is probably very much like that seen during fishbones or toroidicity-induced Alfvén eigenmode activity in tokamaks[7-9].

4. Summary

A probe to measure neutral beam ion losses has been fabricated and installed on CHS. The probe provides a measure of the total loss rate, as well as several measurements per discharge of the pitch angle and gyroradius distribution of the losses. Evidence showing that the probe is detecting neutral beam ion loss has been presented in the fact that the losses have the correct dependence on the direction of the toroidal field, and that the observed gyroradius matches that of the injected beam ions. Losses correlated with ECH, radiative collapses, and MHD modes have also been briefly described.

In the future, we plan to use the probe to perform a systematic study of the dependence of the loss parameters on density, plasma position, and beam injection angle. We also hope to understand, in greater detail, the losses related to the three effects noted above.

Acknowledgments

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