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Measuring the escaping beam ions from a tokamak plasma

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A new technique using a silicon surface barrier (SSB) diode has been developed for measuring the escaping fast ion flux from a tokamak plasma. Calibration of the detector with an ion beam showed that at a fixed energy the diode's output current varied linearly with the incident deuteron flux. The diode was mounted inside the PDX vacuum vessel with collimating apertures designed to admit the spiraling orbits of 50-keV deuterons expelled from the plasma by MHD instabilities. Results from PDX indicated that relative measurements of the escaping fast ion flux due to several plasma instabilities could be made.

INTRODUCTION

Recent evidence from charge-exchange and neutron emission has indicated that a loss of fast ions was associated with the fishbone instability in the PDX tokamak,¹⁻³ although no direct measurement of the escaping ions had been made. The fast ions are produced by high-power neutral beam injection (NBI) and are used primarily to heat the plasma. The bursts in the charge-exchange signal and sudden drops in the neutron production rate could also have been explained by a redistribution of the fast-ion population to regions of lower plasma density (and higher neutral density) rather than a loss from the plasma. To confirm this expulsion of beam ions from the plasma, we have developed and tested a prototype D^+ detector. The design of the detector was adapted from detectors used to measure charged fusion products^{4,5} and relies upon a silicon surface barrier (SSB) diode to measure the ≈ 50 -keV deuterons. Silicon surface barrier diodes have ample time response to detect modulation of the ion flux at frequencies characteristic of MHD instabilities in the plasma and are compact enough to be located close to the plasma.

The remainder of this paper is divided into three sections: Section I deals with energy deposition in SSB detectors, the D^+ detector mechanical design, and the results of test stand calibrations. Section II examines typical data obtained with the detector in PDX along with tests used to determine the noise level during flux measurements. Finally, Sec. III is a discussion of future applications of the techniques developed and a summary.

I. DETECTOR DESIGN AND CALIBRATION

The response of SSB diodes to heavy particle fluxes is well understood in terms of electron-hole production in the sensitive area of the diode.⁶ The small energy required for electron-hole production (average of 3.62 eV in silicon) is responsible for the inherent high gain in detecting ≈ 10 -keV ions (here and below, gain refers to the amount of current produced by the diode when irradiated with D^+ ions). There are two effects, however, which can reduce this large gain: energy losses in the front contact and damage to the silicon lattice due to large fluences. Variations in gain due to magnetic fields can also occur, but they have been shown to

be negligible for fields as high as 15 kG.⁷

Energy losses in the front contact of the diode can become large for incident deuteron energies below 1 MeV. The energy lost in the window is found by integrating the stopping power (dE/dx) along the distance traveled by the projectile

$$E_{\text{loss}} = \int \frac{dE}{dx} dx. \quad (1)$$

The stopping power depends upon the window material and the velocity and charge of the incident particle. At energies near 50 keV, the slowing down of the deuterons is still primarily due to collisions with free electrons, the contribution from shielded nuclei amounting to only about 5% of the total stopping power. Estimates of E_{loss} are complicated, however, by nuclear collisions which cause deviations of the particle trajectory from a straight line. The difference between the total path length and the projected range of an ion is quite large and has been modeled both numerically⁸ and analytically.⁹ Using fits to published experimental data,¹⁰ dE/dx is about the same for 50-keV deuterons incident on gold or aluminum, however, thinner gold windows are available and hence preferable at low flux levels. The energy loss for 10-keV protons (20-keV deuteron equivalent) incident upon 210-Å gold windows has been measured to be 2.59 keV.⁷

If sufficiently large fluxes of low-energy deuterons impinge upon the detector, damage can occur by the creation of trapping sites (lattice defects) which remove charge carriers before collection. The effects of large fluences of protons on silicon through thin gold windows were measured by Coleman *et al.* and found to decrease the gain of the diode and increase the reverse current (I_{rev}) flowing through the diode, and hence also increase the detector-preamp system noise level.¹¹ As the fluence level was increased, the performance of the diode eventually became impaired. For proton fluences of 4×10^{14} protons/cm² on a SSB diode with ≈ 200 -Å gold window, the reverse current increased from 0.2 to 80 μ A. Since the reverse current increases roughly linearly with fluence while the deterioration in gain increases less rapidly, the current is a useful monitor of the degradation in gain of the diode. For the detector used in PDX, a significant increase in the reverse current was measured during the six

months of operation inside the tokamak. This deterioration theoretically affects the overall gain of the detector and the pulse shape of individual pulses, thus relative measurements taken over a much shorter time interval remained reliable.

The diode used in PDX was chosen to handle the highest flux loads possible while retaining some sensitivity to the expected D^+ signal. The prototype D^+ detector used a ruggedized type (1850-Å aluminum window) SSB diode supplied by EG & G Ortec. The thicker aluminum window provided for less susceptibility to contact damage and a longer fluence lifetime. Although this diode had a maximum depletion depth of 200 μm at 110-V bias, the device was used primarily at 100 μm to minimize the false signal created by hard x rays stopping within the depletion region. In addition, no filter was used in front of the diode due to its relatively thick window. The spiraling entrance apertures successfully prevented any visible damage from occurring to the diode. About 5% of the active surface area ($3 \times 25 \text{ mm}^2$) of the diode was exposed to the incident flux.

During routine operation on PDX, the flux of deuterons to the detector was too large to allow the charge pulses from single deuterons to be observed. Operating in current mode, therefore, the diode was connected to a current-to-voltage preamp with a low-capacitance cable (15 pF/ft) to keep the total input capacitance (detector plus cable) below 165 pF. This produced a negligible rise time for charge to be collected from the diode. The bandwidth of the system was measured to be 100 kHz using the SSB diode response to light emitted from an infrared LED while the output impedance was 50 k Ω . The bias on the diode was remotely controlled to allow the sensitivity of the signal to this voltage to be estimated.

A. Aperture design

The D^+ detector shown in Fig. 1 was composed of the surface barrier diode, its mounting assembly, and a radiation shield with collimating apertures. With this configuration of

Fig. 1. Internal schematic of the D^+ detector showing the collimating apertures, shielding, and SSB diode. During operation in the tokamak, the top of the detector faced towards the plasma.

baffles, the three holes which were used to provide pitch angle and energy resolution of the spiraling D^+ orbits defined the solid space observed by the diode (i.e., scattering off the walls and tunneling through the edges could be neglected⁴). In addition, this collimation accepted slightly positive pitch angles ($v_{\parallel}/v_{\perp} \gtrsim 0$) when the toroidal field was energized in the usual direction (here $v_{\parallel}$ refers to the guiding center velocity along the magnetic field while $v_{\perp}$ refers to the magnitude of the perpendicular energy). This direction for the toroidal magnetic field will be referred to as co- B_{ϕ} operation since the neutral beam is injected in the direction along the toroidal magnetic field. During counter- B_{ϕ} operation (NBI antiparallel to the toroidal magnetic field), however, fast ions had the wrong sense of gyration to enter the detector. This ability to reject fast ions during counter- B_{ϕ} operation was used as the primary method of evaluating the contribution of noise to the signal observed under various conditions. The shielding dimensions were 1.4 mm perpendicular to the toroidal magnetic field and 2.0 mm toward the plasma, and the entire assembly used a reentrant mount in order to avoid the need for vacuum cabling.

The location for the D^+ detector inside PDX (Fig. 2) was on the opposite side of the machine from the outer limiter¹² to reduce the hard x-ray signal produced by runaway electrons. To minimize the heat loading from plasma disruptions, the detector was mounted on the top of the plasma about 20 cm outside the separatrix. This location, shown in Fig. 2, is in a region where the poloidal field caused by the plasma current is comparable to fields produced by divertor field coils. This effect complicated the calculation of fast ion orbits entering the detector.

To interpret the flux of ions detected by the D^+ detector, it is necessary to construct a model for the emission of fast ions from the plasma. Methods for calculating the emission of charged fusion products⁴ cannot be used due to uncertainties in the orbits of the fast ions during MHD phenomena. For example, during fishbones the fast ion orbits are suspected to be significantly altered on the time scale of their bounce motion.¹³ An alternative approach to this formalism is to relate the count rate entering the detector to the local velocity space distribution of guiding centers. This technique only requires knowledge of the orbit for a time on the order of a gyroperiod and thus can be used during the fishbone events. If classical drifts and the bounce motion dominate the particle's motion, the flux of ions entering the detector can be shown to be [see Eq. (A2) in the Appendix]

$$\frac{dD^+}{dt} = 2\pi [f_{gc}(E_d, \kappa_d) dE d\kappa] \left(\int v_{gc} dA \right). \quad (2)$$

Here f_{gc} is the density of guiding centers with energy E_d and pitch angle κ_d and the integration is over a differential area intercepting the guiding center orbits whose fast ions would enter the detector. For Eq. (2) to be valid, the apertures must be small enough that f_{gc} can be considered constant over the velocity space intercepted by the detector. In practice, this requires fairly small apertures since the gyroradius depends rather weakly on the energy of the ion.

The large diameter of the apertures ($\approx 2 \text{ mm}$) used for the prototype detector allowed deuterons with energies

Fig. 2. Poloidal cross-section view showing the divertor field coils and the D^+ detector and its support. The coil groupings are up-down symmetric.

above a certain threshold to enter the detector. For the data presented here, the lower-energy bound was about 25 keV and the pitch angle was centered on $v_\phi/v \approx 0.25$ (here ϕ refers to the toroidal direction). This amount of velocity space was too large to allow estimations of f_{gc} , but did provide information about the high-energy part of the distribution due to the high-energy weight of the SSB diode response to fast D^+ ions (see Sec. I B). In this case, the integral over the ion energy, pitch angle, and gyrophase must be performed, and the detector signal becomes [see Eq. (A1) in the Appendix]

$$\frac{dD^+}{dt} = \int f_{gc} v_{gc} dA dE dk d\phi. \quad (3)$$

For the prototype detector, the major contribution to this integral comes from 40–50 keV ions with small positive pitch angles.

This method for interpreting the fast-ion count rate depends critically on a good estimation of the orbits for the fast ions. The method used was the same as that in Ref. 4, and a typical orbit observed by the D^+ detector is shown in Fig. 3(a). The path of the ion traverses the poloidal cross section from bottom to top and represents the inner leg of an extremely large banana orbit. Although this orbit was calculated for a 45-keV deuteron, other fast ions behave similarly. Also shown are the locations of the divertor coils, the equilibrium field coils, and the plasma current which were modeled as toroidal ring currents in the calculation. Other models of the plasma current distribution were used and gave similar results. Figure 3(b) shows an expansion of the orbit near the D^+ detector. For this magnetic field, the detector is very close to the location of the upper turning point of the banana.

B. Diode calibration

The response of the SSB diode used in the D^+ detector was measured both before and after irradiation in the PDX tokamak. A charge-exchange calibration beam capable of producing nanoamp currents of fast deuterons was used to determine both the flux and energy sensitivity of the PDX diode and several other diodes which were not used in the tokamak. The calibration shown in Fig. 4 illustrates that, despite a previous irradiation with the beam, the increase in current (dN_e/dt) with incident D^+ flux for a typical diode remained nearly linear in the range shown. This range of D^+ fluxes was the same as that observed with the diode used in the D^+ detector on PDX. The linear behavior was also observed for the detector diode both before and after use in PDX, and the slow deterioration of the detector's response was noted during its operation on the machine. As a result, only relative flux measurements made on a given day could be used in the physics studies.

Although the passage of a deuteron with energy E results in a proportional number of electron-hole pairs created in the active area of the detector, the diode's response to deuterons of varying energies is nonlinear due to the tendency for faster ions to penetrate further into the active region. Figure 5 shows the resultant dependence of the diode gain on incident energy. The cutoff energy at ≈ 15 keV is in rough agreement with a theoretical estimation of 14.4 keV obtained when nuclear collisions are included in the projected range of deuterons in the aluminum window.¹⁰ The gain observed for all diodes tested was well below the value predicted from purely electron stopping. For detectors which had not been irradiated, this discrepancy was about a factor of 2 and was

Fig. 3. Poloidal cross-section view showing the divertor field coils, equilibrium field coils, plasma current, and the orbit of a 45-keV beam ion entering the D^+ detector. $B_\phi = 11.3$ kG, $I_p = 265$ kA, $DF = 12.5$ kA, and $EF = -3.4$ kA. The coil groupings are up-down symmetric.

presumably due to additional energy lost in the window caused by nuclear range straggling.

II. TESTING AND OPERATION IN PDX

During the six months of operation of the D^+ detector in PDX, beam ion losses were routinely observed to be correlated with fishbone events.¹⁴ Figure 6 shows the time dependence of the D^+ flux and $\delta B_\theta/B_\theta$ amplitude during a low toroidal field shot with high-power neutral beam injection [$\delta B_\theta/B_\theta$ is the poloidal field fluctuation at $r = 60$ cm as measured by a Mirnov coil (M13) on the bottom of the machine]. Although the 100-kHz sampling frequency is not fast enough to observe minor details of the 20-kHz modulation of the fast-ion flux, the peaks in the D^+ signal do tend to increase with increasing beam power (and increasing fishbone amplitude). The increase in the background D^+ signal during the neutral beam injection shown in Fig. 6 was typical, but was not caused by fast ions entering the detector. Data taken during counter- B_ϕ operation indicated that it was probably caused by noise associated with the neutral beams.

Checks on the noise level from hard x rays and other sources were made for conditions similar to those in Fig. 6

by reversing the toroidal field and, on another occasion, by injecting hydrogen instead of deuterium in the neutral beams. Figure 7 shows the D^+ flux and the poloidal field fluctuation during a shorter time window during the fishbone activity with a 500-kHz sampling rate. The observed D^+ signal in the co- B_ϕ case (a) should be compared with the amplitude measured in the otherwise identical counter- B_ϕ case in (b) (please note the change of scale from 10^{12} counts per second for co- B_ϕ to 10^{11} counts per second for counter- B_ϕ). Here co and counter refer to the direction of the toroidal field relative to the neutral beam injection which was fixed during these experiments. Since the D^+ detector was collimated with a positive helix, flux striking the detector during the counter- B_ϕ case should be rejected and, therefore, Fig. 7(b) is a measure of the hard x-ray and magnetic-pickup rejection of the detector-electronics combination. Despite the uncertainty in the absolute gain of the detector, the number of fast deuterons entering the detector is far too large to be explained by collisional sources or other high-energy fusion products. Another check using co-injection of hydrogen neutral beams at the same energy was made. The smaller gyroradius of the hydrogen prevented its orbit from entering the detector and no signal was observed on the D^+

Fig. 4. Current output of a SSB diode (dN_q/dt) plotted vs a 40-keV incident D^+ flux (dD^+/dt). The diode bias was 30 V (100- μ m depletion depth), and had previously been irradiated with a moderate flux of 40-keV deuterons.

Fig. 5. Gain of an irradiated surface barrier diode as a function of incident deuteron energy. The gain is defined as the ratio of the current output (dN_q/dt) to the D^+ -flux input (dD^+/dt) and represents the charge multiplication provided by the SSB diode. This data was obtained with a 30-V bias applied to the diode.

Fig. 6. D^+ detector current (dN_g/dt) and M13 signal observed during a low toroidal field discharge with high-power neutral beam injection. $B_\phi = 11.2$ kG, $a/R_0 = 40$ cm/140 cm, $q \approx 3.0$, $\beta_T \approx 1.6$, and $E_{inj} = 45$ keV.

detector. Bursts of fast deuterons were also measured at high-frequency (≈ 100 kHz) MHD instabilities and the toroidal field check used above indicated no significant noise contamination. Both charge exchange¹⁵ and neutron³ measurements have suggested that these events, like fishbones, were also associated with a loss of fast ions.

In contrast to the results during fishbones and high-frequency events, reversal of the toroidal field showed that during major disruptions and edge relaxation phenomena¹⁶ the detector signal was contaminated by noise. Measurements with neutron scintillators³ indicated that bursts of hard x rays at these instabilities were responsible for the noise.

III. DISCUSSION

The measurements made with the prototype detector indicate that quantitative information about the major loss of fast ions could be made with D^+ probe located on the tokamak midplane. Here the signal recorded by the detector could be unfolded to give the velocity space distribution function of fast ions in the vacuum region just beyond the plasma surface, a region of phase space which is highly populated by the neutral beam injection. If the velocity of the fast ions across flux surfaces is small compared with the guiding center motion along the the field lines and the curvature drifts, then the velocity space integral over the orbits entering the detector can be reduced to obtain the guiding center distribution function. This determination of f_{gc} would require smaller and more accurately positioned apertures along with some reorientation of the detector head to accept

Fig. 7. D^+ detector current and M13 signal during fishbone activity for (a) co- B_ϕ and (b) counter- B_ϕ operation. D^+ flux should be rejected in the counter- B_ϕ case. Please notice the difference in scales from 10^{12} counts/s in (a) to 10^{11} counts/s in (b). $B_\phi = 11.3$ kG, $a/R_0 = 40$ cm/140 cm, $q \approx 3.3$, $\beta_T \approx 1.0$, and $E_{inj} = 45$ keV.

the higher $v_{||}$ of trapped orbits at the midplane. To determine an outward flux of guiding centers, however, a separate determination of the outward velocity of the banana centers would be required since the count rate is determined mainly by the density at the detector location.

One of the main difficulties in computing the velocity space observed by the detector is the ability to accurately determine the orientation of the collimating apertures. This would be greatly improved by using a method involving baffles oriented parallel to one another. The relative spacing of a set of plates can be controlled carefully with a mechanical grating, while the size and position of holes drilled perpendicular to the plates can be made with much better accuracy than holes drilled at angles. This would also decrease the flux of ions entering the diode by reducing the solid angle observed, thus increasing the lifetime of the detector. Another possibility for improving the accuracy in the determination of the observed velocity space is through calibration of the apertures in a magnetic field with high-energy β particles from a radioactive source. Other attractive features for a collimation scheme would include (1) combining several sets of apertures and slides to allow various pitch angles or energies to be viewed without repositioning the detector head and (2) the addition of another SSB diode inside the

assembly to continuously monitor the activity of hard x rays inside the machine.

The use of a SSB diode with a gold contact would have the benefit of less energy loss in the dead layer (< 3 keV), but would increase the rate of deterioration of the detector. The improved energy sensitivity could possibly be exploited to allow pulse heights to be measured, but due to the rather large fluxes present near the plasma edge, the collimation would have to be reduced even further.

In summary, a flux of escaping fast ions has been detected during fishbone and other MHD activity in PDX using a prototype D^+ detector. The detector's response to deuterons was measured with an ion beam and found to depend linearly with ion flux, but increased rapidly with ion energy in the range above 20 keV. Results from tests of the detector in PDX indicated that the gain of the SSB diode degraded over a six-month interval, possibly due to the magnitude of the integrated flux during that time. Noise levels during MHD instabilities were estimated and found to be small when evidence of hard x rays was lacking; thus relative measurements run over several days could be used in physics studies.

The operational results from the detector also indicated that absolute flux levels for various energies and pitch angles could be made using a thinner window without serious degradation of the diode performance, but such measurements would require careful monitoring of the reverse current flowing through the detector. Measurements with a movable probe on the outside midplane would be useful for studying anomalous outboard losses and comparing details of the mode-particle pumping theory of fishbone-induced fast-ion losses.¹³

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APPENDIX: GUIDING CENTER THEORY

Consider a collection of guiding centers to describe the beam ion distribution in the vacuum region:

$$f_{gc} = f_{gc}(x, E, \kappa, \phi, t),$$

where E is the energy of the beam ion, κ is the pitch angle, and ϕ is the gyrophase angle. In the vicinity of the detector (i.e., outside the plasma), the motion of one of the guiding centers in the distribution can be well approximated by the usual guiding center drifts¹⁷ neglecting any effects to do with fishbones ($\dot{B}$) as long as we look on a time scale short compared with the bounce period. This is because significant changes in the guiding center motion due to the oscillating fields observed in PDX require about a bounce time to appear.¹³ In PDX the classical orbits are banana shaped due to the perpendicular orientation of the neutral beams and the

orbits entering the detector are not usually populated with beam ions except for those ions which can pitch angle scatter onto them from inside the plasma. During a fishbone event, however, the magnetic field structure is sufficiently perturbed to allow significant numbers of ions to migrate onto these orbits. This motion can be calculated as an outward banana center drift which is slow compared to the classical drifts and is responsible for the increased density of these ions at the detector.

Consider a small five-dimensional volume of phase space normal to the orbit of a guiding center,

$$\hat{n} dA dE d\kappa d\phi,$$

where $\hat{n}$ is the normal vector in the direction of the orbit of the guiding center and dA is the differential area perpendicular to the orbit. The D^+ detector acts as a sink for particles entering certain volumes of phase space such as this one. If we sum them up, multiplying by the velocity of the guiding center and the distribution function, we find the count rate of the detector

$$\frac{dD^+}{dt} = \int f_{gc} v_{gc} dA dE d\kappa d\phi, \quad (A1)$$

where dD^+/dt is the count rate at the detector and f_{gc} is the distribution of guiding centers (f_{gc} is assumed to be independent of ϕ). The integral extends only over those orbits which can enter the detector. If the apertures are chosen sufficiently narrow such that f_{gc} can be considered uniform over the five-dimensional space observed by the detector, then we can pull f_{gc} outside the integral. The integral can then be evaluated on a computer by following the guiding center orbits backwards in time from the detector for a few gyroperiods. Further restriction of the apertures could be used to simplify this integral by collimating to a tube with only one pitch angle, one energy, and one gyrophase angle. This would result in

$$\frac{dD^+}{dt} = 2\pi [f_{gc}(E_d, \kappa_d) dE d\kappa] \left(\int v_{gc} dA \right), \quad (A2)$$

where the subscript d denotes the detector energy and pitch angle. The accuracy of this determination of f_{gc} relies on three factors: (1) precise knowledge of the toroidal and poloidal field in the vicinity of the detector, (2) precise knowledge of the relative location and orientation of each aperture, and (3) use of a small enough phase space such that f_{gc} can be considered constant.

If the apertures are opened to allow more of velocity space to be observed, say more pitch angles, then interpretation of the signal becomes complicated. This is because $v_{gc} dA$ is a strong function of κ , so that the integral cannot be reduced to find

$$n_E dE \equiv \left(\int f_{gc} d\kappa d\phi \right) dE.$$

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