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PLASMA MEASUREMENTS WITH SURFACE BARRIER DETECTORS

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Plasma Measurements with Surface Barrier Detectors*

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ABSTRACT

A surface barrier detector system for measuring the loss rate of protons from a hydrogen plasma and their energy spectrum is described. A full width at half maximum (FWHM) resolution of 1.4 keV for 15-keV hydrogen atoms was obtained using a selected detector having a sensitive area of 3 mm^2 and a depletion depth of 700 microns.

Silicon surface barrier detectors are small in area, insensitive to magnetic fields, and may be operated at liquid nitrogen temperatures. These are desirable characteristics for a detector in many plasma physics experiments. Recent improvements in charge-sensitive preamplifiers have made possible the use of these detectors at low energies ($\approx 10 \text{ keV}$) to measure the energy spectrum of protons and energetic hydrogen atoms.^{1,2} In addition to the energy spectrum, the plasma density, the background gas density and some time-dependent knowledge of the energy spectrum may be obtained from the same detector.

The inherent low noise of field-effect transistors in the input stages of high-resolution preamplifiers has reduced the electronic contribution to the resolution of a surface barrier detector system to approximately 300 eV. With present detectors, the resolution of the system for heavily ionizing particles is determined by spectral broadening effects originating in the detector. These effects include statistical broadening due to fluctuations in the number of electron-hole pairs formed in the active layer of the detector. This contribution to the spectral broadening depends on the relative fractions of the particle energy transferred to the medium by elastic and inelastic collisions.³ Other broadening effects originating in the detector include the dispersion due to energy loss in the gold layer which forms the window through which the particle must pass to reach the sensitive region. For an energy of 15 keV, a proton will lose approximately 1 keV in passing through a 100 Å gold layer.

Recently, it has been shown that an additional dead layer exists between the gold and the sensitive region of a surface barrier detector.⁴ This additional dead layer was explained by taking into account the role of oxygen in the formation of the rectifying contact. The diffusion of oxygen into the silicon crystal where it acts as an acceptor and enhances significantly the recombination of the electron-hole pairs was shown to best describe the experimental data. Dead layers as large as 1000 Å, depending on the resistivity and bias voltage applied to the detector, were observed. A 15-keV proton would lose approximately 5 keV in passing through a silicon layer of this thickness. The spectral broadening resulting from an inactive silicon layer appears to dominate the resolution obtainable with many detectors.

The present paper describes a surface barrier detector system for measuring the count rate and energy spectrum of energetic neutral atoms escaping from a plasma by charge-exchange collision of the trapped protons with the background gas. The plasma was formed by the injection and trapping of energetic hydrogen atoms. Since the energy dependence of the charge-exchange cross section is known, the energy distribution of the trapped protons may be calculated from the measured neutral atom spectrum. A similar detector along the magnetic field lines measures the loss of energetic particles by instability scattering into the loss cone.

Figure 1 shows a schematic diagram of the experiment and the location of the two surface barrier detectors. Detector A measured the charge-exchange neutral flux and detector B the energetic ions scattered into the mirror. The charge-exchange neutral flux to detector A was collimated by 0.15 mm in diameter to reduce the count rate to less than 10,000 counts per second.

A collimating hole 0.5 mm in diameter limited the number of ions incident on detector B. This collimator was shaped to fit the detector so that the collimating hole could be positioned approximately 0.5 mm from the front surface of the detector. It was necessary to position the collimating hole close to the front surface of the detector to insure that the spiraling ions would strike the sensitive area after passing through the collimator. In addition, the detector was moved back along a pipe both to reduce the count rate to detector B and to decrease the angle of the ions with respect to the field lines. The count rate at detector B was approximately 15,000 counts/sec. A negative bias could be applied to the detector to

prevent electrons from contributing a signal and a bias could be applied to a grid approximately 2.5 cm in front of the detector to prevent the detection of slow ions.

Detectors A and B were silicon surface barrier detectors having sensitive areas of 3 mm² and depletion depths of approximately 700 microns. The detectors were ring-mounted in ceramic with an evaporated front surface of 100-Å-thick gold.

The charge-sensitive preamplifier was designed for this application. The first two input stages of the preamplifier were placed next to the detector in the high-vacuum chamber. This enabled the field effect transistors to be cooled simultaneously with the detector to achieve a better signal-to-noise ratio. The present detector system was operated at a temperature of approximately 170°K. A circuit diagram of the preamplifier is shown in Fig. 2.

A measurement of the electronic noise for one of the preamplifiers yielded a zero-input-capacitance noise of 330 eV (Si). The full width at half maximum (FWHM) resolution for 15-keV hydrogen atoms⁵ was measured for three different detectors of the same type as previously described. The measured resolutions obtained were 1.4, 2.3 and 6 keV. In all three cases, the electronic noise contribution to the broadening was approximately the same and resulted in a negligible contribution to the resolution. The position of the peak in the proton energy spectrum was shifted to lower pulse heights for detectors with poorer resolution, suggesting the existence of an inactive silicon dead layer as demonstrated by Forcinal et al.⁴

The electronic instrumentation as well as the measurements obtained from the detector monitoring the charge-exchange neutral flux are shown in Fig. 3. The signal from the preamplifier is fed into a linear amplifier having pulse-shaping integrating and differentiating time constants of $1.6 \mu\text{sec}$. The output of the linear amplifier passes into a base line restorer unit to prevent broadening of the spectrum at moderate count rates. The signal from the base line restorer unit is then fed into two discriminators, a single-channel analyzer, and a pulse-height analyzer.

The two discriminator levels were adjusted to permit monitoring of both the total neutral flux and that fraction of the neutral flux which has been increased in energy by an amount ΔE above the injected energy. The window on the single-channel analyzer was adjusted to monitor that fraction of the neutral flux with an energy ΔE below the injected energy. The lower level of the single-channel analyzer was used to discriminate against electronic noise. The pulse-height analyzer measured the energy spectrum of the charge-exchange neutral flux. By integrating the pulses from the two discriminators and the single-channel analyzer, low-frequency time-dependent signals proportional to the density in different parts of the spectrum were obtained. These analog signals were stored on magnetic tape and read out in graphical form at a later time. The scaler monitoring the total neutral flux was gated on at beam turn-off to integrate the energetic neutral flux during the plasma decay. This technique provides a measurement proportional to the trapped proton density at the time of beam turn-off which is independent of the background gas density.⁶ With a knowledge of the proton density, the background gas density may then be calculated from the measured charge-exchange count rate.

The spectrum produced by the energetic neutral atom flux from a 15-keV hydrogen plasma in the absence of instability is shown in spectrum (a) of Figure 4. The FWHM resolution obtained at low count rates by this detector was 1.4 keV. All measurements of the charge-exchange flux discussed in this paper were made with this detector since the resolution obtained was superior to that of other detectors tested.

In plasmas formed by energetic particle injection, the trapped ion distribution is usually monoenergetic and highly anisotropic. Velocity-space instabilities are observed to occur in plasmas of this type. To study the effect of broadening the ion energy distribution on the threshold density for the instability, an energy modulation of about 25% was applied to the proton beam before neutralization. Spectrum (b) of Fig. 4 shows the measured distribution obtained. This broadening was observed to raise the instability threshold density by about 25%. Spectrum (c) shows the distribution obtained under conditions of strong instability. Extreme broadening of the spectrum is apparent.

The time-dependent effects of the instability on the energy spectrum of the energetic neutral atoms are shown in Fig. 5. Curve (a) is an electrostatic signal which was calibrated to measure the plasma potential excursions. The positive spikes on this detector indicate the presence of an instability. Curve (c) shows the total charge-exchange flux as a function of time. Curve (b) shows that component of the neutral spectrum which has been spread in energy by at least 3 keV, and it can be seen that this component increases in amplitude following the instability, as contrasted with the total spectrum which decreases. These measurements indicate spreading of the proton energy spectrum during the instability.

Time-dependent correlations of the integrated count-rate signal from detector B are shown in Fig. 6. Strong correlations of this signal with the plasma potential are observed to occur, as measured by two electrostatic probes. Also seen are correlations with oscillations at the ion gyrofrequency or one of its harmonics. Since the instability was weakly driven in this case, no significant change in the total plasma density as measured by the fast-atom detector was observed.

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FIGURE CAPTIONS

- Fig. 1. Schematic diagram of the experiment showing the location of the two surface barrier detectors.
- Fig. 2. Circuit diagram of the charge-sensitive preamplifier.
- Fig. 3. Block diagram of the electronic instrumentation.
- Fig. 4. Energy spectra of hydrogen atoms emitted from the plasma by charge-exchange.
- Fig. 5. Time dependence of: (a) the plasma potential, (b) that component of the ion density which has an energy less than 12 keV or greater than 18 keV, and (c) the total ion density.
- Fig. 6. Time-dependent correlations of the integrated count rate signal from detector B with measurements of other plasma signals.

Futch - Fig. 1

Futch - Fig. 2

Futch - Fig. 3

Futch - Fig. 4

Futch - Fig. 5

Futch - Fig. 6