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The effects of rf fields on the energy of ions hitting the surface of an ion cyclotron range of frequencies (ICFR) antenna exposed to a plasma must be investigated to provide an understanding of the impurity generation from the antenna. A resonant loop antenna with a two-tier Faraday shield, installed on the Radio Frequency Test Facility at Oak Ridge National Laboratory, was used to study these effects. Samples of silicon were placed below the antenna and on the Faraday shield surface, facing the plasma, to measure incident ion energy. The samples were exposed to electron cyclotron heated plasmas without rf power and with 22 kW of rf power at antenna currents of up to 400 A. The fluence of $\sim 5 \times 10^{17}$ D/cm^2 from deuterium plasmas was near the saturation level of the samples. The energy of the incident ions was estimated by measuring the amount of deuterium trapped in the samples with D(^{3}He,p)^{4}He nuclear reaction analysis. The results obtained from the trapped deuterium measurements are compared with ion energies measured directly with a gridded energy analyzer located near the antenna. They show that the rf-enhanced ion energy distribution measured in the plasma is proportional to the impact energies on the surface of the Faraday shield and increases with antenna current.

I. INTRODUCTION

The generation of impurities during ion cyclotron resonance heating (ICRH) of plasmas in magnetic confinement devices has been observed in several experiments,[1-10] and the Faraday shield of the ion cyclotron range of frequencies (ICRF) antenna has been identified as a local impurity source.[11-14] The increase in the impurity level caused by the interaction of the plasma with the antenna may limit the usefulness of ICRH as a method for auxiliary heating of fusion plasmas. The processes occurring near the antenna that cause the impurity production must be identified in order to understand and ameliorate this problem. Specifically, the interaction of the rf fields from the antenna with the local plasma and the effects of these fields on the energy of the ions that hit the antenna need to be determined.

Experiments have been conducted on the Radio Frequency Test Facility[15] (RFTF) at Oak Ridge National Laboratory to measure the energy of ions that hit the Faraday shield of an ICRF antenna. A single-strap resonant loop antenna with a grounded two-tier Faraday shield,[16] shown in Fig. 1, was used for these experiments. It was operated at 42 MHz, with the rf power varied up to 60 kW and the antenna current varied up to 400 A. The RFTF plasma was initiated and sustained by electron cyclotron heating (ECH) using a 10.6-GHz klystron with an output power of ~ 17 kW. Typically, the plasma discharge was pulsed for 200 ms, and for discharges with rf power the antenna was pulsed for 150 ms during the plasma pulse. Hydrogen or deuterium was used as the operating gas, at pressures ranging from $(1\text{ to }4) \times 10^{-4}$ Torr. Langmuir probe measurements indicated that the electron temperature T_e at the antenna without power from the antenna was 5–10 eV, and the electron density was $\sim 5 \times 10^{10}$ cm^{-3}. The magnetic field in RFTF was in a mirror configuration and is shown in Fig. 2, along with the relative position of the antenna. The magnetic field at the antenna was ~ 2 kG.

II. EXPERIMENT

Silicon-surface collector probes were placed on and near the Faraday shield to estimate the energy of the ions accelerated through the plasma sheath that formed on the surfaces exposed to plasma. The amount of deuterium retained in the silicon after exposure to saturation levels of a deuterium ion fluence is related to the energy of the incident ions,[17] and D(^{3}He,p)^{4}He nuclear reaction analysis can be used to measure this amount, yielding an estimate of the incident ion energy.

The silicon samples were 7.6×6.4 mm and about 1.6 mm thick. Some of the samples were placed on a sample holder located ~ 4 cm below the antenna, as shown in Fig. 3, and others were placed on the surface of the Faraday shield at a location ~ 16 cm from the shorted end of the antenna. The sample holder was placed so that the front face of the sample was in the same vertical plane as the front of the Faraday shield.

After exposure to RFTF plasmas, the samples were removed from RFTF and placed in the Triple Ion Beam Test Facility.[18] They were bombarded with a 600-keV ^{3}He beam from a 2.5-MeV van de Graaff accelerator, which hit the surface at an angle of 60° from the surface normal. The energy spectrum of the ^{4}He (alpha) reaction product was measured with a silicon-surface barrier detector (70 μm depth), placed 55° from the incident beam path. The detector had an

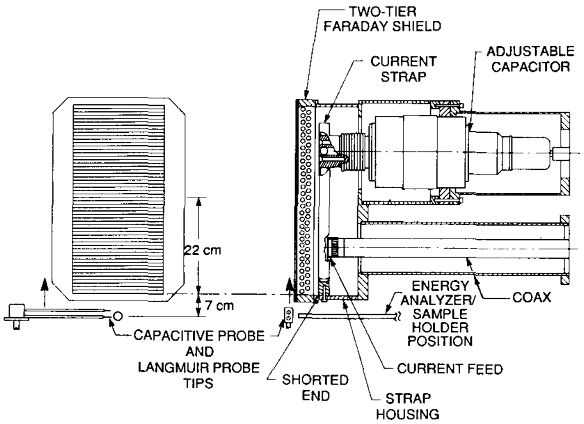

FIG. 1. Front view and cross section of the antenna, showing the position of the energy analyzer/sample holder and the location of the Langmuir probe and capacitive probe.

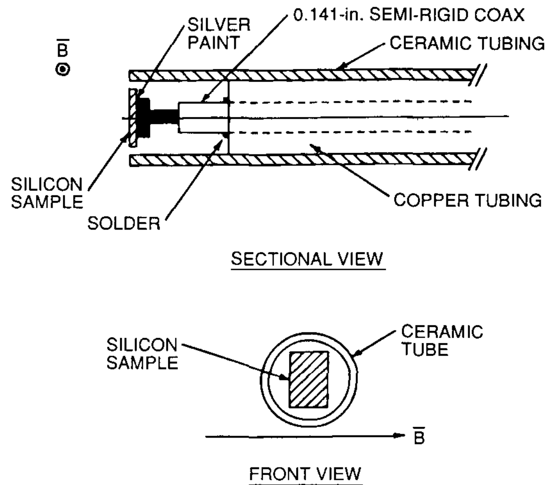

FIG. 3. Front view and cross section of the sample holder used for the silicon-surface collector probes. The silicon samples were held on the center pin by silver paint.

acceptance solid angle of 8 mb/sr; a 6-μm Mylar foil was placed in front of it to prevent detection of the scattered ^{3}He beam. The total number of ^{3}He ions hitting the sample was measured by integrating the ^{3}He current on the sample, which had a bias voltage of 40 V to suppress secondary electrons. The total fluence of deuterium atoms trapped in the sample was calculated from the alpha spectrum by a deconvolution method described in Ref. 19.

As a calibration experiment for the method, some silicon samples were biased negatively with a dc power supply and exposed to an ECH plasma in RFTF with no rf power from the antenna. Biases of -50, -150, and -250 V were used. The negative bias gave the incident ions an equivalent energy of the absolute value of the bias potential plus the local plasma potential. The floating potential for these experiments was typically about 0 V, the plasma potential was about 20 V, and the electron temperature was ~ 8 eV.

The negatively biased samples were placed in the sample holder below the antenna (see Fig. 3). they were attached to a cylindrical connector with silver paint, which in turn was

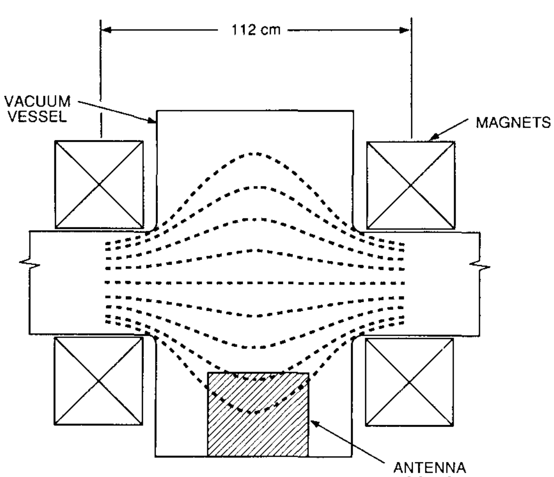

FIG. 2. Top view schematic of the RFTF, showing the magnetic field pattern and the relative position of the antenna.

attached to the center conductor of a coaxial line and to a dc power supply. A 1.27-cm-o.d., 1.07-cm-i.d. ceramic cylinder was placed around the connector so that plasma ions would be incident only on the front face of the silicon sample.

The incident ion fluences were estimated by measuring the current to the sample during the exposure to the plasma. Fluence is related to the current by

$$\text{fluence} = tI/eA_s, \qquad (1)$$

where t is the total exposure time, I is the average ion current per plasma pulse, e is the ion charge, and A_s is the effective ion collection area of the sample, that is, the area exposed to the plasma.

The uncertainty in the measured incident fluence was due to uncertainties in A_s and in the effect of ion-induced secondary electron emission on the collected current. The effective ion collection area of the samples was probably larger than their geometric area. The correct area can be estimated by considering that some plasma may have hit the samples from the side instead of the front. A conservative estimate of A_s is the cross-sectional area of the ceramic cylinder that surrounded the sample, which is ~ 1.85 times the geometric area (calculated from the inner diameter of the cylinder). This estimate provides an upper bound for A_s; the lower bound is simply the geometric area.

The ion fluence may also be affected by deuterium ion-induced secondary electron emission from the silicon. Since the exact distribution of ion energies hitting the surface was not known for all the experiments, and estimate of 0.1 was used for the secondary electron emission coefficient of deuterium incident on silicon.[20]

Ion energies perpendicular to the RFTF magnetic field were measured with a small gridded energy analyzer located ~ 4 cm directly below the antenna, with the front of the analyzer in the same vertical plane as the front of the Faraday shield (Fig. 1). The perpendicular energy distribution was measured instead of the parallel energy distribution because the Faraday shield surface is nearly parallel to the magnetic field lines, and the plasma sheath that develops will have an electric field that is into the surface, perpendicular to the static magnetic field. To collect the ions for analysis, the total thickness of the analyzer had to be smaller than the ion gyroradius.

The construction of the analyzer is shown schematically in Fig. 4. It consisted of three parallel grids and a collector plate that were contained in a boron nitride cup, which was inside a 0.625-in.-o.d. stainless-steel tube. The outermost grid was 400-mesh (400 lines/in.) nickel spread over a 3-mm-diam entrance hole. The second and third grids were 400-mesh copper disks, with a diameter of 3.05 mm, and the collector plate was a 3-mm-diam solid copper disk. The grids were separated by 0.20-mm-thick mica washers with a 4.76-mm o.d. and a 2.38-mm hole. The entire assembly was ~1 mm thick. This analyzer was similar to a design used on the Phaedrus mirror device[21] and to a Katsunami probe.[22,23] The outer (nickel) grid was grounded, and the first copper grid was biased at a low potential to shield out the electrons. The second copper grid was swept in voltage to selectively screen the ions; the ion current was collected by the collection disk and measured across a 10-kΩ resistor. The ion energy distribution was calculated by taking the derivative of the collected ion current.[24] Since the RFTF magnetic field was parallel to the grid and collector surfaces, any secondary electrons emitted from the collector were probably turned back into the collector because of their small gyroradius, thus having no net effect on the collected current.

Other plasma parameters were measured with a capacitively coupled probe and a Langmuir probe, described in Ref. 25. The capacitively coupled probe was used to measure the time-varying floating potential, and the Langmuir probe was used to measure the time-average floating potential, the electron temperature, and the electron density. The Langmuir probe was terminated on a small dc and rf load and thus measured the time-averaged current as a function of applied bias voltage. The electron temperature was taken from the lower portion of the I_e versus V curve to avoid problems associated with response of a Langmuir probe to an rf plasma.[26] The electron density was calculated by measuring the probe current well into ion saturation and then corrected with the LaFramboise method.[27] The time-averaged floating potential was taken from the time-averaged current measurement and then corrected for self-bias due to rf effects.[28]

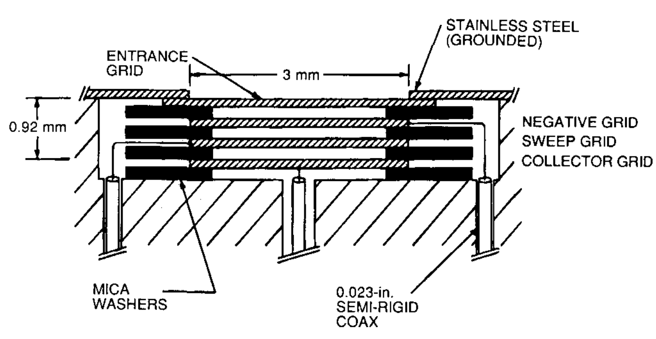

FIG. 4. Schematic view of the energy analyzer. The total thickness of the analyzer had to be less than the ion gyroradius to allow measurement of the perpendicular energy distribution.

The time-averaged plasma potential was estimated by adding 2.5 T_e to the time-averaged floating potential.[29]

III. RESULTS

Experiments on samples with the −150-V bias were run for average incident fluences of $\sim 1.3\times10^{16}$, $\sim 3.1\times10^{17}$, and $\sim 9.2\times10^{17}$ D/cm^2. These fluences were chosen for comparison with monoenergetic results [17] for one nonsaturation fluence level ($\sim 1.3\times10^{16}$ D/cm^2) and two saturation fluence levels (~ 3.1 and $\sim 9.2\times10^{17}$ D/cm^2). Nuclear reaction analysis results for these samples are shown by the solid circles in Fig. 5. The two samples with the highest incident fluence had about the same amount of trapped deuterium, indicating that a saturation fluence was reached. The average trapped fluence was at an energy level slightly greater than that for the 150-eV monoenergetic results, indicated by the dotted line in the figure. As expected, the sample with the lowest incident fluence had much less trapped deuterium than the samples with the higher incident fluences. The value does not come as close to the 150-eV monoenergetic curve as those of the other samples, but the uncertainty in the measurement was much greater for this sample because the number of plasma pulses needed to reach the incident fluence level was much lower than for the other samples (by more than a factor of 10), and the number of counts from the nuclear reaction analysis was much lower.

The −50-V bias sample was exposed to a fluence of $\sim 3.1\times10^{17}$ D/cm^2, and the −250-V bias sample was exposed to a fluence of $\sim 6.1\times10^{17}$ D/cm^2. Nuclear reaction analysis results for these samples are also shown in Fig. 5. As in the −150-V case, the amount of trapped deuterium in the samples was close to the monoenergetic curves of comparable energy. This is not surprising, because the negative bias voltages on the samples were much greater than the energy of the ions, thus giving the ions a directed energy into the silicon samples that was slightly greater than the absolute value of the bias voltage.

Two nonbiased samples were exposed to ECH plasmas in which rf power was injected from the antenna. One sample was placed in the sample holder below the antenna, and the

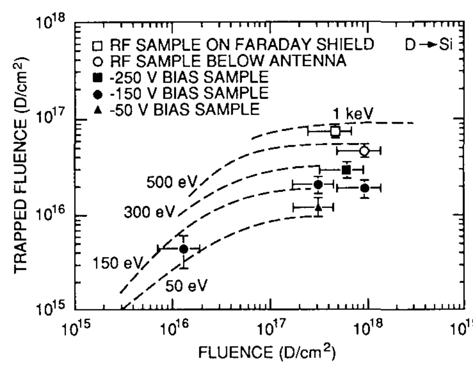

FIG. 5. Results of nuclear reaction analysis of the surface collector probes. The dashed lines are results for monoenergetic deuterium incident on silicon (see Ref. 17). Both of the samples exposed to ECH plasmas with rf power from the antenna (open data points) showed more trapped deuterium than the dc-biased samples (closed data points).

other was placed on the surface of the Faraday shield. The Faraday shield sample was placed in the center of the shield and was ~16 cm above the shorted end of the antenna. For this experiment, the antenna was operated with ~22 kW launched into the plasma at an antenna current of 270 A and a peak antenna voltage at the capacitor of ~12 kV. The flux to the sample below the antenna was monitored by measuring the voltage drop across a 50-Ω resistor. The ion current to the sample on the Faraday shield could not be measured directly, so the incident ion fluence was estimated to be half that on the sample below the antenna, because the plasma density in front of the antenna was about half that below the antenna. From Langmuir probe and capacitive probe measurements in the same area, the electron temperature was estimated to be ~60 eV and the time-averaged plasma potential was estimated to have a lower bound of ~190 V below the antenna and to be slightly higher in front of the antenna. The time-varying component of the plasma potential was ~50 V.

Nuclear reaction analysis results for these samples are shown by the open data points in Fig. 5. Both of the samples exposed to plasmas with rf power from the antenna had significantly more trapped deuterium than the dc-biased samples, indicating that the ions incident on the samples had an energy at least comparable to the local plasma potential. The amount of trapped deuterium in the sample placed in front of the antenna was ~150% more than that in the −250-V bias sample and is between the monoenergetic curves for 500-eV and 1-keV ions. The amount trapped in the sample placed below the antenna (in the same area as the energy analyzer) was 60% more than that in the −250-V bias ample and is between the monoenergetic curves for 300- and 500-eV ions.

The increase in the ion energy due to rf effects was also observed with the energy analyzer. The perpendicular ion energy distribution measured with the energy analyzer is shown in Fig. 6 for three sets of plasma and antenna conditions. These ion energy distributions are not representative of the ion energies in the bulk plasma but are a measurement of the energy of the ions accelerated through the sheath that formed between the plasma and the grounded outer surface of the energy analyzer. The operating gas for these experiments was hydrogen. The fine structure of the distributions is not meaningful because of the uncertainty involved in the measurement. The distributions were normalized so that the integral over the energy range was one.

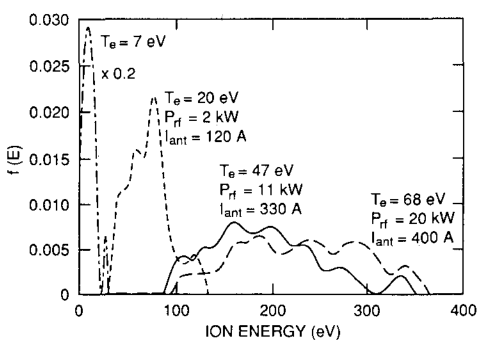

FIG. 6. Ion energy distributions measured with the energy analyzer for the indicated values of T_e, antenna power, and antenna current. The distributions have been normalized to unity over their energy range.

The ion energy distributions were generally peaked near the time-average plasma potential for all of the experiments. Energy distributions were peaked at 5–10 eV for the experiments without rf power and increased with increasing rf power. Ions with energies above 300 eV were measured for experiments with rf power of ~20 kW, an antenna current of ~400 A, and an antenna voltage of ~16 kV. The distributions were clearly shifted to higher energies for plasmas with higher rf power and antenna current. The electron temperature also increased with increasing rf power and antenna current, as shown by measurements of the electron temperature and the plasma potential with the Langmuir probe and the capacitive probe. The electron temperatures are listed in Fig. 6. The magnitude of the energy shift follows roughly the same scaling as the electron temperature increase, indicating that the electrons caused an increase in the sheath potential, thereby increasing the energy of the ions that hit the surface. The ion energies did not appear to depend on the local plasma density or on the fractional ionization near the antenna.

IV. DISCUSSION

The fact that there was more trapped deuterium in the surface probes for the rf samples than in the samples from the experiment with the −250-V applied voltage does not mean that all the ions had an energy greater than 270 eV (the bias voltage plus the 20-V plasma potential). The ion energy distribution and the ion impact angle with the surface [30] affect how much ion fluence is retained in the sample. Higher-energy ions from the distribution can cause the trapped amounts to increase.[17] Since the exact distribution is not known, these results should be interpreted as indicating that, for these experimental conditions, a large number of the ions hitting the Faraday shield had an energy above 270 eV.

The sample on the Faraday shield surface retained more deuterium than the sample below the antenna, indicating that the ions reaching the shield surface had higher energies. This is consistent with the Langmuir probe and capacitive probe measurements, which showed that the plasma potential and the electron temperature were higher in front of the antenna than just below it. It also indicates that the sheath potential was higher in front of the antenna than below it.

The sheath potential through which the ions were accelerated is equal to the difference between the plasma potential and the potential of the surface that the ions hit. For the energy analyzer, the sheath potential was equal to the plasma potential, since the outer surface of the analyzer was grounded. However, for the Faraday shield, the surface potential was not known (although it could be estimated from the ion energy).

Theoretical studies have shown that the rf fields from the antenna current strap can induce time-varying currents and voltages on the Faraday shield surface.[31,32] If these potentials were comparable to the plasma potentials, then the sheath potential would be small, as long as the plasma potential variation was in phase with the surface potential variation. However, these experiments showed that the ions hit the Faraday shield surface with a substantial energy, which is consistent with a large sheath potential. The results do not indicate the magnitude or form of the potential variation, but they do indicate that a large sheath potential existed on the shield surface, as shown by the large amount of trapped deuterium in the surface probes. It is not clear that the increase in the sheath potential was caused solely by the increase in the electron temperature and in the time-varying plasma potential. An rf sheath rectification effect, as suggested as a possible explanation for impurity generation by ICRF antennas,[33,34] may have contributed in some way to the increase in the sheath potential.

The energy analyzer measurements clearly show that the energy of the ions that hit a grounded surface increases with increasing antenna current. A higher antenna current increases the magnitude of the electromagnetic and electrostatic fields near the antenna. These measurements indicate that the fields interacted with the electrons and increased their energy. This is consistent with predictions of increases in electron temperature due to interactions between electrons and rf plasma sheaths at the Faraday shield.[33–35] The increase in the electron energy increased the local plasma potential near the antenna. The larger sheath potential caused by this increase in plasma potential was evident in the shift of the ion energy distribution to higher energies.

The ion energy distributions were consistently peaked near the time-average plasma potential. However, it is not clear that the spread in the distributions indicates an actual broadening in the ion energies. The spread might have been caused by ions streaming along magnetic field lines in front of the analyzer. If an ion entered the sheath along a field line that intersected the sheath near the center of the sheath, it would be accelerated onto the surface with an energy below the total sheath potential. Thus, ions with a perpendicular energy less than the total sheath potential could reach the analyzer and be measured. Because of the uncertainty in the magnitude of this effect, the results of the energy analyzer measurement should be interpreted as indicating only that the ion energy distribution shifts to higher energies with increased antenna current and is generally peaked near the local average plasma potential.

This study has shown that large plasma potentials exist in front of the Faraday shield of an ICRF antenna. The silicon-surface collector probes showed evidence for large sheath potentials at the surface of the Faraday shield. Energy analyzer measurements of the energy distribution of ions accelerated through an rf-plasma sheath clearly showed a shift of the distribution to higher energies with increased antenna current. The scaling of the ion energy increase was consistent with increases in the local plasma potential and the electron temperature, indicating that the increase in the sheath potential was caused by the increase in the electron temperature, along with a possible contribution due to rf sheath rectification effects on the Faraday shield surface.

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