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ION HEATING IN A TURBULENT PLASMA

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The production of highly energetic ions (up to 10 keV) in, for example, large pinch discharges is well known, and has usually been attributed to acceleration of the ions by electric fields associated with the dynamics of the unstable plasma, i.e., by the fluctuating fields of the large-scale (hydromagnetic) turbulence[1]; the time scale for this kind of process is necessarily many ion Larmor periods. We wish to report evidence for the noncollisional heating of ions to energies up to 3 keV in a situation in which the heating must be due to fluctuation frequencies $\omega \gg \Omega_i$, the ion cyclotron frequency, and which we believe results from statistical accelerations in the microfields of the turbulent spectrum of longitudinal plasma waves.

The apparatus is shown schematically in Fig. 1. It consists of a silica torus, 65-cm major diam, 10-cm bore, in a quasistatic axial magnetic field $B_\varphi \approx 3$kG. A plasma with density ~10^{12} cm^{-3} and electron temperature a few eV is prepared by passing a 1-kA axial current through weakly preionized hydrogen gas at 2-mTorr pressure. A large electric field E_φ is then electromagnetically induced in this partially ionized plasma by discharging four 0.25-μF capacitors, each charged to 35-40 kV, in series into a primary winding closely fitting the torus. With plasma loading the circuit, $E_\varphi \sim 200$ V cm^{-1} at $t = 0$ and exhibits heavily damped oscillations at 1 Mc/sec. The maximum current is ~20 kA at $t \approx 0.1$ μsec, and the plasma resistance during the discharge is typically ~1 Ω. A magnetic probe shows that current fully penetrates the plasma during the first current pulse.

For the purposes of this note we are concerned only with the phenomena which occur during this time, when the electrical power input is greatest. For instance, a very rapidly rising pulse of soft x rays is observed from a graphite target in the plasma, which is accompanied by intense microwave emission, observed in the band $\lambda = 1$-2 cm ($\omega \gtrsim \omega_{pe}$). No hard x rays are observed, and the electron temperature is found from absorber measurements to be ~2-3 keV. A floating differential electrostatic probe also shows large high-frequency potential fluctuations in the plasma in the range 100-300 Mc/sec. Typical noise signals correspond to rms voltages ~50 V received between two fine wire electrodes 1 mm apart, measured in a band 90-110 Mc/sec, and occur at about the same time as the microwave noise and soft x rays, i.e., $t \sim 0.1$ μsec. Some of these observations are typical of those already reported[2] in experiments in which the electron drift velocity exceeds the electron random velocity, when strong turbulence initiated by two-stream instability is expected to occur.[3]

A neutral-particle detector is situated to receive those fast atoms which leave the plasma as a result of charge-exchanging collisions with ions which at the instant of impact have velocities within ~0.1° of a radial direction

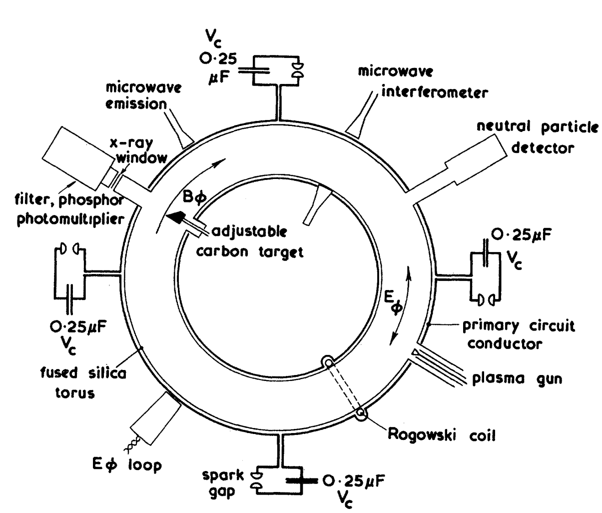

FIG. 1. Schematic arrangement of the apparatus.

(in the plane of the torus). A sample of these fast neutrals is ionized by passing through He gas at 5-mTorr pressure and the resultant ions are analyzed in energy by a 90° electrostatic deflection system and triple-grid energy analyzer.[4] The ions are finally detected at a total distance 210 cm from the plasma. Figure 2 shows the detector signal, averaged for nine consecutive shots, when the analyzer is adjusted to accept ions with energies ±100 eV around nominal values between 200 and 3000 eV. The data are not corrected for detector sensitivity, which is known only for 2-keV H^0 atoms, but it shows conclusively that the plasma contains ions moving perpendicular to B_φ with a continuous spread of energy between 200 eV (below which the detector is very insensitive) and ~3 keV; and that increasing the applied voltage by 14% significantly increases the relative proportion in the range 1-2 keV.

By time-of-flight analysis of neutral particles detected at various energies we find that (a) they are unambiguously hydrogen atoms and (b) they are first emitted between $t=0$ and $t=0.2$ μsec. A later signal occurs for all energy settings, which we identify as due to atomic nitrogen, presumably emitted by resonant charge exchange with nitrogen impurity ions accelerated in the same random fields as the protons.

The detected signal at 2 keV (±100 eV) corresponds to 10^{11} H^0 atoms entering per second within the solid angle of acceptance. If the flux is isotropic the ion density in this energy range would be ~10^{10} cm^{-3}. If these measurements are assumed to be representative of a general heating of all the ions ($n_{total} \sim 10^{12}$ cm^{-3}), resulting in a Maxwellian distribution, they are consistent with an ion temperature of about 700 eV.

Since the neutral atom density is ~10^{14} cm^{-3}, the mean free time for ions is determined by charge-exchange collisions and is $\tau_x = (N_0 \sigma_x v_i)^{-1} \approx 10^{-7}$ sec, which is about one-half an ion gyroperiod τ_i. After this time interval protons lose all their energy in a resonant collision with a hydrogen atom; but since many stochastic accelerating events are necessary to give a very wide energy distribution, the characteristic time for one such event must be $\ll \tau_x$ and hence $\ll \tau_{ci}$. This implies that the accelerating fields are those associated with high-frequency density fluctuations, $\omega \gg \Omega_i$, for which the magnetic field is relatively unimportant.

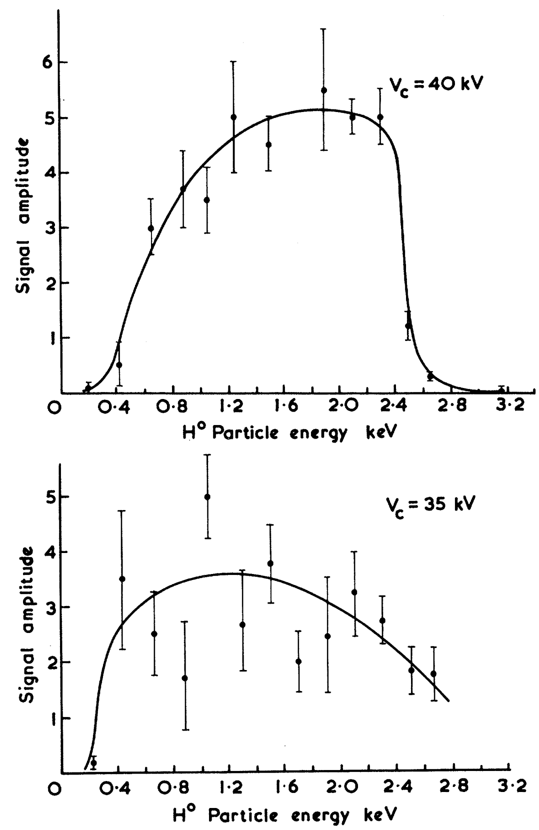

FIG. 2. Energy spectrum of neutral hydrogen atoms ejected from the plasma by charge exchange.

Equally, and especially since heavy ions seem to be accelerated to energies similar to the protons, we can discount interactions which depend on ion cyclotron resonance. We can make an order-of-magnitude estimate of the amplitude of the necessary electric fields $\tilde{E}$ since we must have $\epsilon_i = \frac{1}{2}Mv_i^2 \sim \frac{1}{2}\tilde{E}^2 e^2/M\omega^2$. For 3-keV protons this means $\tilde{E} \gg 10^3$ V cm^{-1}, such as we might associate with short-wavelength longitudinal electrostatic fluctuations. The development of the turbulent spectrum of plasma waves in the nonlinear phase after excitation by two-stream instability,[3] and the interaction of the waves with charged particles in the plasma, are extremely complex and so far have not succumbed to exact analysis. However, the collisionless heating of both ions and electrons is predicted in various nonlinear theoretical treatments,[5] and also shown to occur in computer experiments using simplified one-dimensional plasma models.[6] We believe our observations give general support to these concepts.

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OBSERVATION OF EXCITON FINE STRUCTURE IN THE INTERBAND MAGNETOABSORPTION OF InSb AND GERMANIUM

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Careful examination of individual absorption peaks in the low-temperature magnetoabsorption spectra of InSb and germanium reveal fine structure attributable to excitons. This confirms theoretical predictions concerning excitons in a high magnetic field and provides a means of experimentally determining the role of excitons in the analysis of the magnetoabsorption spectra for band parameters and for polaron effects.

We have observed and identified exciton fine structure in InSb and germanium with applied magnetic field. These results provide a means of experimentally evaluating the contribution of exciton effects to the position of the absorption lines. Now one can obtain more precise band parameters from the interband magnetoabsorption spectra of these materials than those obtained previously by neglecting exciton energy shifts[1,2] or by using theoretical estimates.[3] Excitons can be expected to add complications to the analysis of the polaron effects previously observed in the interband magnetoabsorption of InSb,[4,5] and a good knowledge of the role of excitons should contribute to the understanding of the polaron observations. The exciton problem in the interband magnetoabsorption of these materials is essentially that of a hydrogen atom in a high magnetic field, which is is a problem of long-standing theoretical interest.[6-11]

Absorption peaks associated with exciton formation have not yet been observed in InSb for $H=0$. A likely explanation for this situation is that the linewidths of the hypothetical absorption lines are too large relative to the spacings of the exciton energy levels and individual peaks cannot be resolved from the continuum absorption. One might say that the broadened discrete exciton states form a quasicontinuum. Elliott[12] has shown theoretically that the infrared absorption involving the exciton quasicontinuum is continuous, with the absorption involving the true continuum. If one compares the quadratic Zeeman effect on the exciton ground state with the behavior of the $n=0$ level, it becomes obvious that the exciton ionization energy should increase with magnetic field, and several workers have extended this consideration to high magnetic fields where the cyclotron energy is comparable with and much greater than the zero-field exciton binding energy.[6-11] One might expect that at sufficiently high magnetic fields one would begin to resolve discrete exciton lines from the continuous absorption. Indeed, experimentally it is found that the application of a small magnetic field (~2 kG) results in the appearance of peaks in the absorption. The difficulty, however, is that in the presence of a magnetic field, peaks occur in the density of states in the continuum and corresponding peaks might be expected in the absorption. There is then a question of experimentally distinguishing be-