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ORIGIN OF HOT IONS OBSERVED IN A MODIFIED PENNING DISCHARGE

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ABSTRACT

Ions with a Maxwellian energy distribution and kinetic temperatures ranging from below 100 eV to several keV have been observed in a steady-state modified Penning discharge. Observations in the plasma, with capacitive probes at several azimuthal locations, are consistent with the existence of two distinct spokes rotating with different velocities in the sheath between the plasma and the anode ring. The faster (0.5-10 MHz) spoke consists of electrons rotating with the E/B drift velocity. The slow (0.1-1.0 MHz) spoke consists of ions, the measured thermal velocity of which is directly proportional to the spoke velocity. The interaction of the two spokes is apparently responsible for the observed electrostatic "turbulence" and ion thermalization. The anode sheath thickness is smaller than the ion gyrodiameter in this plasma. Thus the ions are in the electric field of the sheath for only a fraction of their orbit, and their E/B drift (spoke) velocity is smaller than that of the electrons.

INTRODUCTION

There have been many reports of hot ion and even neutron production from Penning discharges. Hot ions and neutron production were first reported from a Penning-discharge-like configuration by K. A. George in 1961.[1] Another early paper reporting hot ion production was that of

Angerth et al.[2] in 1965. A significant body of subsequent work has confirmed the production of hot ions with energies up to several kilovolts in Penning discharges.[3-7] Although the existence of hot ions in Penning discharges may be regarded as well established, the physical processes responsible for the ion heating are not understood. An entirely separate body of literature on the Penning discharge have reported a rotating electron drift in the anode sheath,[8-15] but these observations have not been related to the ion heating process.

In addition to Penning discharges, there have been reports of hot ion production in ion magnetrons and other similar devices based on crossed electric and magnetic fields.[16-22] The ion heating process in such devices has been variously attributed to cyclotron resonance of ions with an ion acoustic wave,[5] beam-plasma interaction,[18-19] or to various instabilities in the vicinity of the ion plasma frequency.[20-22] No convincing experimental evidence has been put forward in support of these theories, however, and the ion heating mechanism in these devices must be regarded as an open question.

Observation of Hot Ions in a Penning Discharge

In Fig. 1 is shown a schematic drawing of the modified Penning discharge in which the present experiment was performed. The experimental apparatus and operating characteristics of the discharge have been described elsewhere.[3,6,23] The magnetic mirror geometry has a mirror ratio of 2.5:1, and is usually operated with 10 kG maximum at the mirror throat. The anode ring at the midplane is maintained at a positive dc potential of up to several tens of kilovolts with respect to the grounded vacuum tank walls, which serve as the cathodes.

A principal diagnostic used on this device is the retarding potential energy analyzer illustrated in Fig. 1.[6] By putting a positive retarding potential on the intermediate grid, the collector current can be made to sweep out an integrated ion energy distribution function. Some raw data from this retarding potential energy analyzer is shown on Fig. 2A, and on top of it is drawn the best-fitting integrated Maxwellian distribution. The ordinate is the fraction of ions whose energy is greater than the value shown on the abscissa. There are two very interesting features of this data. The first is that the ion kinetic temperature is quite high, about 1900 electron volts in the case shown. The second interesting feature is that the ion energy is approximately Maxwellian along a radius in velocity space, even in tail of the distribution. This is a desirable feature of any ion heating process, because the Maxwellian distribution implies one less reservoir of free energy available to drive plasma instabilities.

The general trend of the ion energy data from this modified Penning discharge is indicated on Fig. 2B. The ion kinetic temperature is plotted as a function of the anode voltage for four different background pressures of deuterium gas. The ion kinetic temperature is directly proportional to the anode voltage at a fixed neutral gas pressure. No limiting values of the ion kinetic temperature were found within the 40 kV limit of the power supply used.

The best simultaneously measured set of Lawson parameters for this plasma are an ion kinetic temperature of 5 keV, ion density of $2\times10^{10}/cm^3$, and an ion confinement time of 27 microseconds, obtained from the plasma decay after crowbarring the anode ring to ground. Under these conditions, the electron energy was no more than 200 eV, indicating that the energy input was preferentially heating the ions.[7] The relatively unimpressive densities and containment times are due at least in part to rapid ion losses into the escape cone of this open-ended magnetic mirror geometry.

The Ion Heating Process

The data that have just been presented indicate that there are hot thermalized ions in this modified Penning discharge. It is of interest to determine the physical process responsible for this ion heating and thermalization. On Fig. 1 is a schematic of the diagnostics used to observe oscillatory phenomena in this plasma. The capacitive probes used are inserted at opposite ends of a diameter, midway between the mirror throat and the midplane. The capacitive probes measure the waveform of the electrostatic potential fluctuations in the plasma.

On Fig. 3 is shown typical waveforms from these capacitive probes, at three time scales, but for the same set of plasma operating conditions. At the top of Fig. 3 is the signal from the two probes on a fast time scale. The signal is 180° out of phase at opposite ends of the diameter. A possible explanation is that there exists a concentration of charge, or "spoke" rotating about the plasma axis. It was verified by observing the phase of signals from probes at other azimuthal positions that this was an $m = 1$ azimuthal disturbance. The sign convention for potential in this photograph is such that a negative deflection is upward, so the rotating spoke must consist of electrons. As the spoke approached the probe, the potential became more negative, and as the spoke passed by the probe, a cusp-like peak on the waveform is evident. This rotating disturbance has a frequency of about 3 MHz, and the anode ring was 15.2 cm in inside diameter, indicating that the energy of rotation of the electrons is of the order of the ionization potential of the gas.

On a slower time scale, one observed the data in the middle photograph of Fig. 3. There is a modulation of the probe amplitude at a frequency of about 330 kHz, with the signals 180° out of phase at opposite ends of the diameter. It was verified with probes at other azimuthal locations that this slower rotating concentration of charge was a single "spoke" in the case shown, although $m = 2$ and $m = 4$ spokes were observed under other operating conditions. Under conditions not shown on Fig. 3, cusps were occasionally observed on the ion waveform, and these indicated a spoke of positive ions approaching the probe. The direction of the ion and electron spoke rotation was the same, in the $\underline{E} \times \underline{B}/B^2$ drift direction. Typically the rotational frequencies of the ion spoke are a factor of 5 or 10 below the rotational frequencies of the electron spoke. It was verified by placing probes at various axial stations that the spokes are in phase along the axis of the discharge.

At the bottom of Fig. 3 is shown the potential waveform on an even slower time scale. Here one can see a third frequency at about 70 kHz modulating the data, and the oscillations are in phase throughout the plasma volume. This is the continuity equation oscillation, which has been reported on elsewhere.[24,25]

The physical picture that emerges from this interpretation of the data on Fig. 3 is indicated schematically on Fig. 4. The outer circle corresponds to the anode ring, the interior is occupied by the bulk of the plasma, and a sheath exists between the plasma and anode ring. The plasma in this apparatus is within a few hundred volts of ground potential, so the voltage drop across the sheath is typically tens of kilovolts. The electrons are highly magnetized in this plasma, since they are in magnetic fields of at least several kilogauss. The anode sheath thickness is assumed herein to be approximately equal to the ion Debye length,[26] rather than the electron Debye length, because the ions are the more mobile species.

The ion Debye length is on the order of a centimeter in this discharge, a thickness consistent with the visible sheath thickness. The electrons have gyrodiameters much smaller than this sheath thickness, and continuously experience a large electric field. The large resulting E/B drift velocity then gives rise to the faster electron spoke, which rotates with megahertz frequencies. The operating conditions for this discharge are such that the ion gyrodiameter is so large that ions are in the sheath for only a part of their orbit. The ion spoke therefore moves with a slower drift velocity than the electrons.

This slower ion drift velocity in this apparatus cannot be due entirely to centrifugal effects, as was suggested by Alexeff, et al.,[20,21] since the radius of the plasma (7.6 cm) is too large to account for an ion drift velocity as much as 10 times smaller than the electron drift velocity. However, this centrifugal effect might be important in the "bootstrsp" process when the discharge is first turned on.

There is an intimate relation between the velocity of this rotating spoke and the high observed ion energies. The experimental data were reduced on the assumption that the strong electrostatic turbulence reported in reference 7 resulted in equipartition of energy between the parallel, perpendicular gyrorotary, and guiding center (spoke) velocities, such that the total energy is given by

$$W_i = \frac{1}{2} m_i v_i^2 = \frac{1}{2} m_i \left(v_{\parallel}^2 + v_{\perp i}^2 + v_s^2\right) = 2\ m_i v_s^2 \tag{1}$$

Since the ion energy was acquired from the ion spoke rotational velocity, it also appeared plausible that the total velocity v_i given above is the velocity which corresponds to the most probable energy,

$$\frac{1}{2} m_i v_i^2 = \frac{1}{2} eV_i \tag{2}$$

If the guiding centers of the ions are assumed to be at the inner radius, R, of the anode ring, the expected ion spoke rotation frequency for ions with kinetic temperature $V_i eV$ is given by

$$\nu_1 = \frac{1}{4\pi R} \sqrt{\frac{eV_i}{m_i}} \tag{3}$$

Figure 5 shows plotted on the ordinate the drift frequency of the ion spoke, $\nu_{i,obs}$. Plotted on the abscissa is ν_1 from equation (3), the ion drift frequency calculated from the ion energy V_i which was measured by the retarding potential energy analyzer. If there were a one-to-one correspondence between the observed ion drift frequency and the ion drift frequency calculated from V_i, then one would expect the data to lie on the straight line of slope 45° designated $m = 1$. The frequency ν_i was calculated on the assumption that the guiding centers were on the inner surface of the anode ring. The data lie somewhat above this straight line, as a result of the fact that, because of a finite gyroradius, the centers of gyration are at an effective spoke radius of about 0.85 R. It is clear that the data have a slope of 45 degrees, and this implies that the E/B drift velocity of the ions is directly proportional to the ion thermal velocity. This rotating spoke is the fundamental physical mechanism by which the ions are raised to high energy.

Only one datum from each experimental run is plotted in Fig. 5. Harmonics of the fundamental frequency, sidebands, and peaks due to RF interference were omitted. Some of the data in Fig. 5 best fit the hypothesis that two ($m = 2$) or four ($m = 4$) spokes, equally spaced in azimuth, were simultaneously present. These data lie adjacent to the lines designated $m = 2$ and $m = 4$ in Fig. 5. A few of the $m = 2$ and $m = 4$ data may be explained as harmonics of $m = 1$ spokes whose fundamental frequency was buried in the background turbulent spectrum. However, this explanation cannot hold for the majority of $m = 2$ and $m = 4$ data shown in Fig. 5.

Thermalization of Ion Energy

The Maxwellianization of the ion energy can be understood as a result of the interaction of the ion and electron spokes. The ion spoke rotates with frequencies that are typically between 100 kHz and 1 MHz. The electron spokes typically have frequencies from 0.5 to 10 MHz. On the average, the electron spoke will pass through the ion spoke several times each microsecond. One would expect two spokes consisting of charge concentrations of opposite sign to interact very strongly, and to give rise to very violent electrostatic turbulence. Such violent electrostatic turbulence is observed, and has been reported previously.[7] In Fig. 6 is shown the spectrum of electrostatic potential fluctuations from 100 kHz to 1 MHz. The spectrum is plotted on log-log axes, and the peak is at the ion spoke rotation frequency of about 320 kHz.

In Fig. 6, one can observe that the energy is injected into the spectrum at the peak frequency, corresponding to the ion spoke rotation frequency. Then the energy cascades upward in frequency and downward in scale size, as one can see from the enhancement of the spectrum above the energy input frequency. It is characteristic of this strong electrostatic turbulence that, when plotted on log-log axes, the spectrum follows a straight-line, power law relationship. Below the energy input frequency the spectrum in a straight line, and above the input frequency it is also a straight line with the same slope, but there is a considerable enhancement of the spectrum. This enhancement results from the energy cascading upward in frequency and downward in scale size as the ion energy is degraded into random thermal motions. This randomization of the ion energy is also implied by the Maxwellian distributions illustrated in Fig. 2A.

Discussion

The ion spoke velocities and ion energies observed in the present series of experiments are substantially higher than the empirically determined limit of Fahleson[27] and Lehnert.[28] On the basis of pulsed experiments at neutral gas pressures higher than those employed in the present experiment (above 10^{-3} torr), these authors suggest a fundamental limitation on the ion energy obtainable with devices employing $\underline{E} \times \underline{B}/B^2$ drifts. They find that the limiting ion energy is of the order of the ionization potential V^*, of the gas used. This would imply an ion spoke rotation frequency given by

$$\nu = \frac{1}{4\pi R}\sqrt{\frac{eV^*}{m_i}} \tag{4}$$

where $V^* = 15.6$ eV for the present case, and $R = 7.62$ cm. Were their limiting velocity applicable to the present experiment, the spoke rotation frequency calculated from equation (4) would be 9 kHz. The ion velocities in Fig. 5 are from one to two orders of magnitude higher than this limit. Thus the phenomenological limit of Fahleson[26] and Lehnert[27] does not appear to be applicable to the conditions of the present experiment.

Datlov[29] and Bannenberg and Brakenhoff[15] have pointed out that, if the electrons rotate with a velocity corresponding in energy to the ionization potential of the gas, and if the ions are dragged behind the electron spoke with the same velocity, the ions would then possess very high energies, given by

$$V_i = \frac{m_i}{m_e} V^* = 57.4 \text{ kV} \tag{5}$$

Equation (5) would imply rotation frequencies for the ion spoke given by

$$\nu = \frac{1}{4\pi R} \sqrt{\frac{eV^*}{m_e}} \tag{6}$$

This limiting rotational frequency would be 1.7 MHz for the present experimental conditions. As inspection of Fig. 5 shows, the ion rotational frequencies fall below 1.0 MHz in this experiment. This lower ion spoke velocity can be understood as a result of the ion passing through the electric field of the sheath for only a part of their orbit. It is probable that the ion spoke velocity cannot be equal to the electron drift velocity, since the magnetic fields are seldom strong enough, or the densities low enough, to make the ion gyrodiameter smaller than the sheath thickness.

The ion heating process in a modified Penning discharge is a very simple means for converting high voltage dc electrical power to ion energies that are limited only by the applied anode voltage. The rotating spoke of ions drifting with the $\underline{E} \times \underline{B}/B^2$ velocity in the anode sheath is the basic ion heating mechanism. Since the electron and ion drift velocities are generally within an order of magnitude of one another, their large mass ratio assures that the input energy will not be wasted in heating the electrons.

Another very significant advantage of the modified Penning discharge is that the presence of the anode ring at the magnetic field midplane produces a radially inward electric field which may tend to stabilize the plasma. In addition, the radially inward electric field provides an electrostatic potential well which tends to drive the positive ions radially inward across the sheath, and into the bulk of the plasma. Heating and confinement schemes empolying the modified Penning discharge can then provide a mechanism for infusing ions into the plasma, rather than promoting classical or anomalous radial diffusion of the ions.

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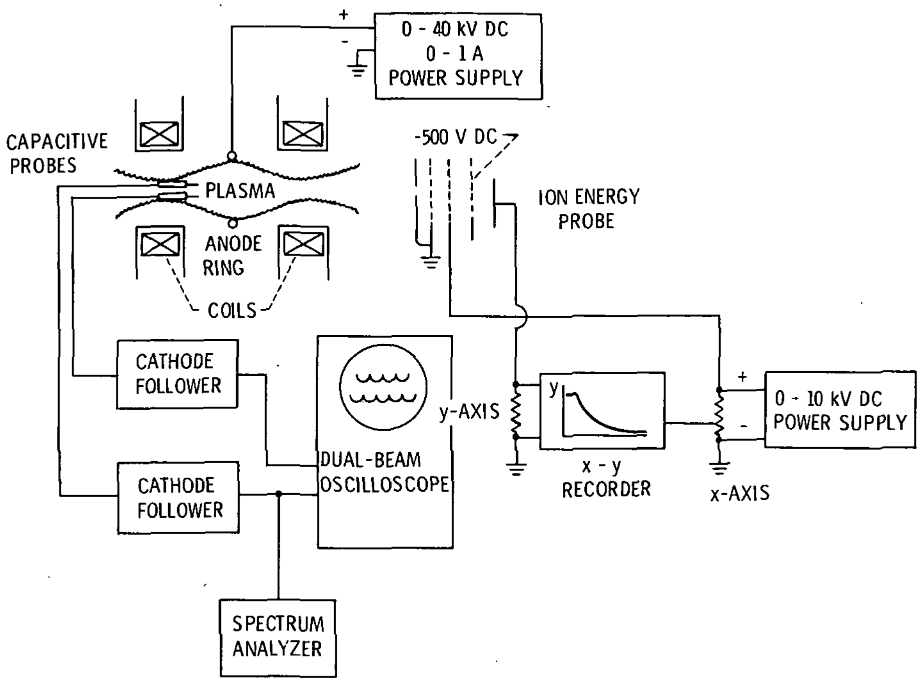
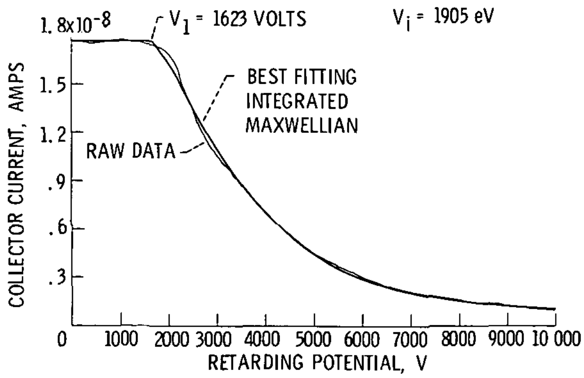


Figure 1. - Schematic diagram of diagnostic equipment. The retarding potential energy analyzer is located 10 cm from the magnetic axis, about 20 cm outside the magnetic mirror throat. The capacitive probes and the energy analyzer are located on field lines that pass approximately 1.0 cm from the inner surface of the anode ring at the magnetic field midplane.



(A) TYPICAL RETARDING POTENTIAL CURVE FOR DEUTERIUM GAS, AND BEST-FITTING INTEGRATED MAXWELLIAN DISTRIBUTION WITH KINETIC TEMPERATURE OF 1905 eV. ANODE VOLTAGE WAS 17.5 kV, BACKGROUND PRESSURE 4×10^{-6} TORR.

Figure 2

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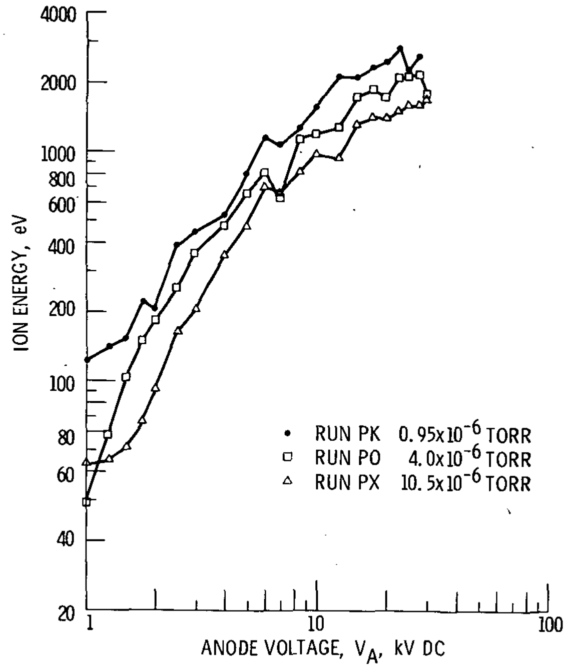

(B) ION KINETIC TEMPERATURE AS A FUNCTION OF ANODE VOLTAGE FOR THREE BACKGROUND PRESSURES OF DEUTERIUM GAS. MAXIMUM MAGNETIC FIELD STRENGTH WAS 1.0 T, ANODE RING RADIUS R = 7.62 CM.

Figure 2. - Concluded.

(A) ELECTRON SPOKE ROTATION AT A FREQUENCY OF 3 MHz AROUND THE INNER CIRCUMFERENCE OF A 15.2 CM I.D. ANODE RING.

(B) THE ION SPOKE ROTATION AT A FREQUENCY OF 300 kHz.

(C) THE IN-PHASE CONTINUITY-EQUATION OSCILLATION AT A FREQUENCY OF ABOUT 70 kHz.

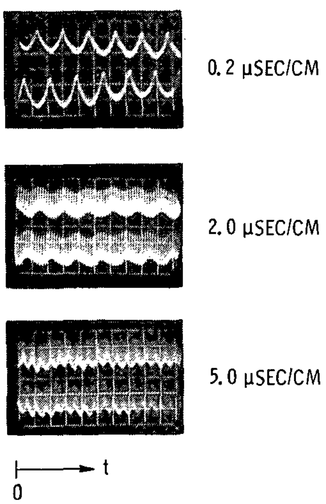

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Figure 3. - Waveform of electrostatic potential as measured by capacitive probes at opposite ends of a diameter. An upward deflection implies an increasingly negative potential.

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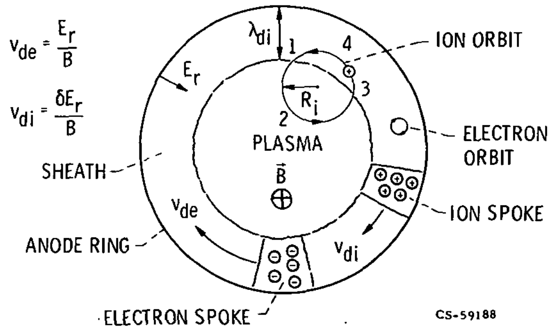

Figure 4. - Schematic drawing of processes in the sheath between the anode ring and the plasma of a modified Penning discharge. Note that the sheath thickness is determined by the ion Debye length, and the ion gyrodiameter is larger than the ion Debye length.

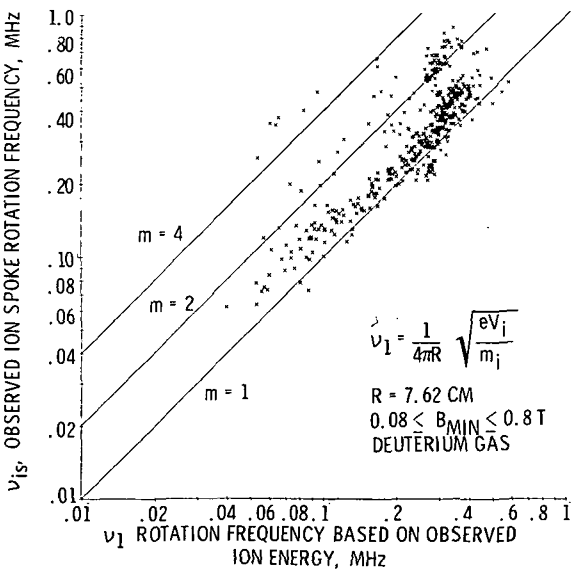

Figure 5. - The observed ion spoke rotation frequency as a function of the rotational frequency based on eq. (3). The mode numbers indicated are the number of radial spokes equally spaced in azimuth. The m = 1 line is the rotational frequency expected for a single spoke of ions of the observed energies, if their gyro centers were at the inner radius of the anode ring.

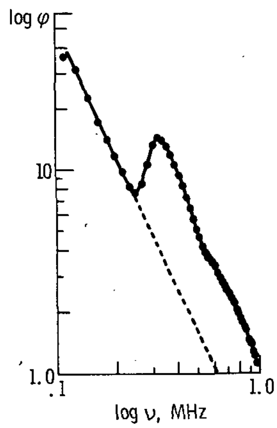

Figure 6. - Spectrum of electrostatic potential fluctuations from 100 kHz to 1.0 MHz under conditions for which the ion spoke rotation frequency was 330 kHz. Note the enhancement of the spectrum above the energy input frequency.

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