Ion Heating Due to Rotation and Collision in Magnetized Plasma

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The $\mathbf{E}\times\mathbf{B}$ rotation and associated collisional ion heating of noble-gas magnetized plasmas are investigated with high resolution by means of laser-induced fluorescence and electrical probes. Plasma rotation results from a radial potential gradient which can be controlled by biasing of the discharge electrodes. The time and space evolution of the potential, the rotation velocity v_θ, and the ion perpendicular temperature indicate that heating is due to the randomization of v_θ by ion-neutral collisions, and leads to temperature increases as high as a factor fo 50 over initial values.

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Even though collisions constitute an energy loss, in the presence of a source of free energy they can maintain plasmas in states of high temperature. We demonstrate this concept in a study of the rotational acceleration and deceleration of a magnetized gas discharge in the presence of neutrals. Laser-induced fluorescence (LIF) and probe measurements allow us to measure all the relevant parameters (rotation velocity, ion temperature, electric field) of the phenomenon with high spatial and temporal resolution. We find that collisions with neutrals scatter rotating ions, which then acquire random kinetic energy (effective temperature) comparable to their directed rotational energy, up to 50 times larger than in the absence of rotation. This process can be important in plasmas where collisionality is significant, such as gas discharges, centrifuge schemes,[1] and fusion,[2] in which it provides an additional channel for energy input, and in the recently discovered "rotational" cross-field particle transport.[3]

The experiments were performed in a grounded stainless-steel vacuum vessel (diameter 40 cm, length 9.18 m),[4] with a magnetic field homogeneous over 20 cm diameter and 475 cm length to better than $\Delta B/B = 0.3\%$ (Fig. 1). A pulsed or continuous dc gas discharge is established between a 5-cm-diam hot cathode, an annular anode, and a biased end plate. At $B = 3$ kG, typical plasma parameters are discharge current = 0.5–50 A, $n_e = 10^{10}$–10^{12} cm^3, ionization degree = 2%–20%, $T_e \sim 7$ eV, and initial $T_{i0} < 0.4$ eV. Typical ion-neutral collision frequencies are $\nu_{i0}/\omega_{ci} \sim 0.02$ at 1×10^{-4} Torr in neon,[5] and dominate over ion-ion and electron-ion collision frequencies by more than a factor of 10.

Ion rotational and thermal velocities are obtained from the ion distribution function, which is measured by LIF.[6] A pulsed dye laser (10 nsec), tuned to resonance with the ions [Ne II, $\lambda = 333.4836$ nm, for the transitions $3s^4P_{5/2}$ (metastable) to $3p^4D_{7/2}$; Ar II, $\lambda = 611.492$ nm, for $3d^2G_{9/2}$ (metastable) to $4p^2F_{7/2}$] is scanned across the radius. The fluorescence light (Ne II, $\lambda = 333.4836$ nm; Ar II, $\lambda = 460.957$ nm) from the decay $4p^2F_{7/2}$ to $4s^2D_{5/2}$ is viewed at right angles with a telescope. The diagnosed volume, at the intersection of laser and optical axes, is about 50 mm^3.

To induce rotation, a metallic end plate across the column is negatively biased or floated electrically. In this condition part or all of the cathode current flows across the magnetic field to the annular anode because of electron-neutral collisions and ionization. Strong modifications of the plasma are observed: (a) A radial electric potential well as deep as 65 V is formed [Fig. 2(a)]. (b) The ion velocity distribution function is shifted and broadened, indicating respectively a simultaneous rotation and heating of the plasma ions. The inferred rotation velocity v_θ is equal in magnitude but opposite in direction at diametrically opposed radial positions, and increases linearly with radius, implying "rigid body" rotation [Fig. 2(b)]. Rotation and heating both increase monotonically and saturate when the end-plate negative voltage approaches 80% of the plasma floating potential. The cathode emission current and plasma density change only slightly. The electron temperature increases, typically, from 7 to 14 eV. It is found that E_r increases as B^2, and v_θ as B (as in Fig. 2).

Figure 2(a) shows typical radial profiles of the plas-

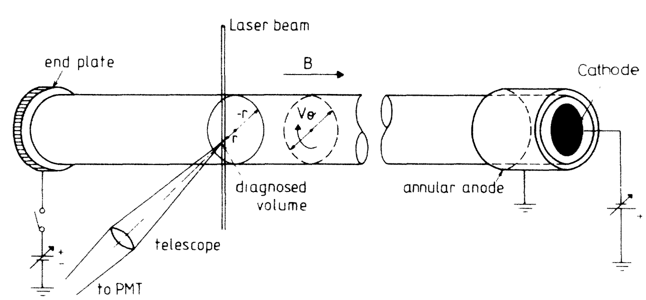

FIG. 1. Schematic of the experimental setup.

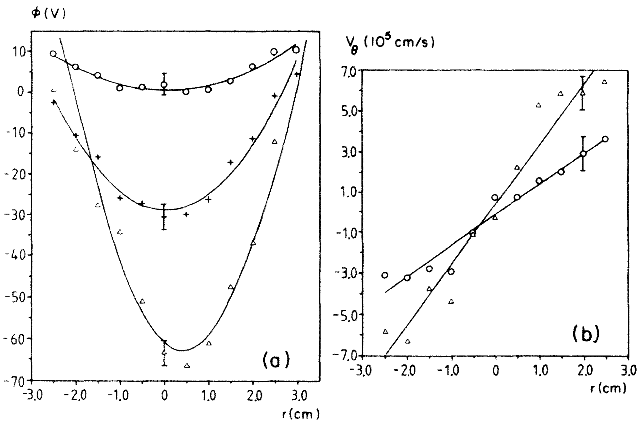

FIG. 2. (a) Radial profile of the plasma potential Φ. Measured points are fitted by parabolic curves. Circles, end plate grounded, $p=2.5\times10^{-4}$ Torr (neon); triangles, end plate grounded, $p=1.5\times10^{-4}$ Torr; crosses, end plate floated, $p=1.0\times10^{-3}$ Torr. All data at $B=3$ kG. (b) Radial profile of the rotation velocities v_θ; $p=2.5\times10^{-4}$ Torr (neon). Triangles, $B=3$ kG; circles, $B=1.5$ kG.

ma potential ϕ with the end plate grounded (top trace), and at two different pressures with the end plate floating (lower traces). The profiles are nearly parabolic, which implies a uniform excess of electrons (typically $\Delta n_e/n_i\sim10^{-5}$). The potential increases when the magnetic field is increased or the neutral pressure reduced. In neon the maximum observed v_θ is 1.2×10^6 cm sec^{-1} at a radius of 2.5 cm, 3 kG, and 1.5×10^{-4} Torr. This corresponds to a kinetic energy of 14 eV and to a rotation frequency $\omega_{\rm rot}/\omega_{\rm ci}=0.43$. The measured values of v_θ, E_r, dn/dr, and $T_{i\perp}$ satisfy radial force balance for rotating plasmas. The highest observed value of the ion temperature $T_{i\perp}$, 14 eV, is more than 35 times higher than the initial temperature $T_{i0}<0.4$ eV in the absence of rotation. The radial temperature profile is nearly flat except at pressures below 1.5×10^{-4} Torr. Rotation and heating are also observed in argon plasmas. A maximum rotation frequency of 0.52 with the corresponding $T_{i\perp}=19$ eV were found. These elevated temperatures are in sharp contrast with normal gas-discharge properties, in which ion temperature is not strongly sensitive to potential or pressure. LIF measurements performed on the neutral Ne I and Ar I showed no rotation or heating.

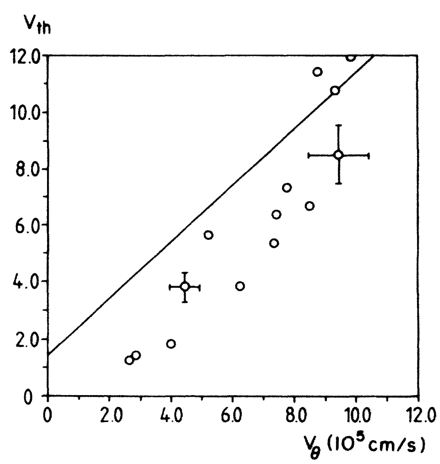

FIG. 3. Thermal velocities as a function of rotation velocities. Measurements performed at radius $R=2$ cm. The line represents $v_{\rm th}=v_\theta+v_{\rm th}(v_\theta=0)$ (neon).

The essential feature in our findings is the very large increase in $T_{i\perp}$ (up to a factor of 50) over its initial value. A clue to the understanding of this effect is provided by the very strong correlation between the thermal velocity $v_{\rm th}=(T_{i\perp}/m_i)^{1/2}$ and v at saturation (steady state) pressures and magnetic fields (Fig. 3). The proportionality is close to 1. The monotonically increasing relationship and its pressure dependence (below) suggest that the enhanced thermal velocity results from the local scattering of the directed rotational velocity by ion-neutral collisions.[7]

To identify unambiguously the role of ion-neutral collisions in the heating process, we carry out time- and space-resolved simultaneous measurements of ϕ,

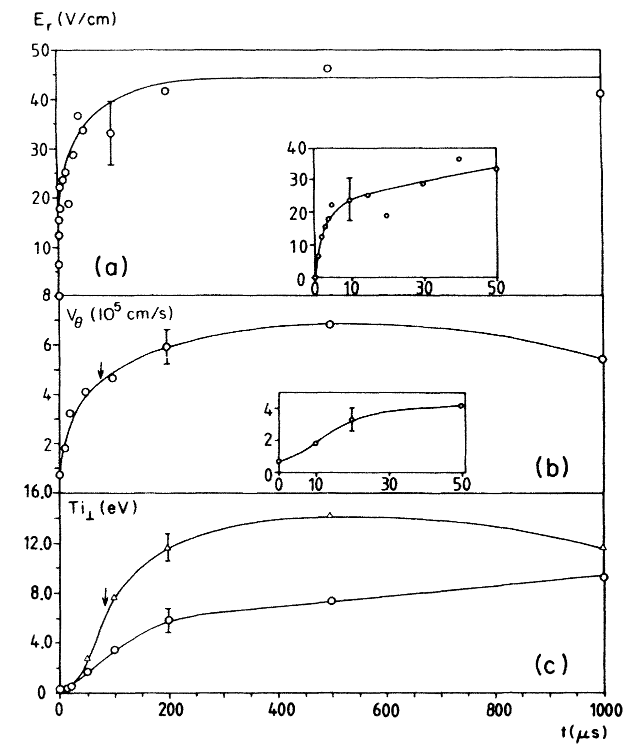

FIG. 4. Time evolution of (a) the radial electric field, (b) the rotation velocity, and (c) the ion temperature. Field and velocity measurements performed at radius $R=2$ cm, $B=2.35$ kG, $p=1.5\times10^{-4}$ Torr (neon). The ion temperature is measured in the center (circles) as well as at $R=2$ cm (triangles).

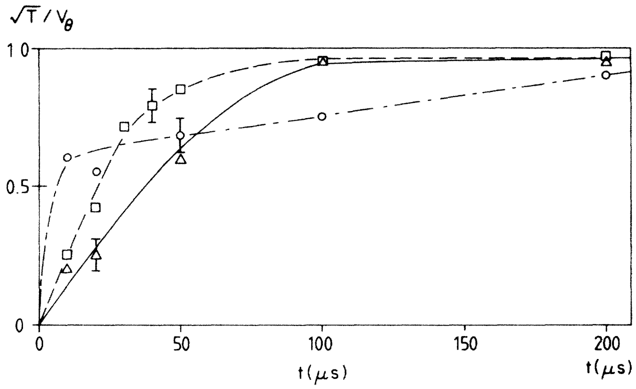

FIG. 5. Time evolution of $T_{i\perp}^{1/2}$ normalized to v_θ for various pressures (neon). All measurements at radius $R=2$ cm.

$T_{i\perp}$, and v_θ, which yield the heating rate, as a function of collisionality. In these tests, the end-plate bias is switched from ground to floating potential in less than 100 nsec, much less than a collision period.

Four time scales are observed, as illustrated in Fig. 4. (i) The radial electric field [Fig. 4(a)] is established after 5 μs. This represents the time necessary to establish the necessary electron excess (typically $\Delta n_e/n_i \sim 10^{-5}$). (ii) Rotation begins within a cyclotron period (~ 5 μs) after the potential formation and continues to evolve on a longer time scale [Fig. 4(b)]. (iii) Plasma temperature [Fig. 4(c)] evolves much more slowly and initially rises to a higher value at the edge than at the center ($R=0$). Since v_θ is also larger at the edge [Fig. 2(b)], this behavior is in agreement with the proposed heating mechanism. Because the subsequent evolution ($t > 10$ μs) of v_θ depends on the collisionality, it is necessary to normalize $T_{i\perp}^{1/2}$ to v_θ at each instant (Fig. 5) to be able to sort out the dependence of the temperature rise time on neutral pressure. The higher the pressure, the shorter the time it takes to convert directed into thermal energy. Quantitatively, we find that the e-folding time of the ratio $T_{i\perp}^{1/2}/v_\theta$ is proportional to the pressure p, and within the accuracy of the experiment is close[5] to the corresponding ion-neutral collision time ν_{i0}^{-1}, as shown in Table I. On this time scale, the ratio of $v_{\rm th}$ to v_θ becomes constant for radii larger than 1 cm and for all pressures. These two facts, i.e., that heating in regions of finite v_θ occurs on a time scale ν_{i0}^{-1}, and that it is more intense at the edge than at the center at early time, confirm that collisions randomize the rotation velocity into thermal velocity.

Finally, (iv) in a transport time τ of up to 1 ms, the temperature across the whole discharge becomes roughly constant. As shown in Fig. 4(c) the ion temperature at the center, $R=0$, increases in time when rotation is switched on, even though the rotation speed v_θ vanishes at that position. The asymptotic

TABLE I. Comparison between measured heating rate and collision times (data of Fig. 5).

p (Torr) (neon)	Measured e-folding time of $T_{i\perp}^{1/2}/v_\theta$ (μsec)	Ion-neutral collision time (μsec)[a]
6×10^{-5}	40	50
1×10^{-4}	20	30
2×10^{-4}	10	15

[a]Reference 5.

value of the temperature at the center becomes close to that at the edge of the plasma, $R=2$ cm. However, the temperature-rise rate at this radius is much slower than at $R=2$ cm. We interpret the temperature increase at small radii, with the longest characteristic time τ, to be due to transport of hot ions from the surrounding rotating plasma layers.

Since the process we have identified is a momentum transfer in the presence of an electric field,[7] it is important to assess whether the measured broadening of the distribution function corresponds to a thermodynamic temperature. As a test we have launched electrostatic ion Bernstein waves in the frequency range ω_{ci}–$3\omega_{ci}$ and measured their dispersion relation.[8] With T_e determined from the ion-sound speed and by Langmuir probes, a best fit by theory shows that in a typical nonrotating Ne plasma $T_{i0}=0.2$ eV, while in the presence of rotation, $T_{i\perp}=10\pm2.5$ eV at $B=3$ kG and $p=2.5\times10^{-4}$ Torr, in agreement with LIF measurement. It can be concluded that this process leads to a thermalization of the ions.

Deceleration of the plasma rotation and cooling were also investigated by switching the end plate from floating to ground potential. Plasma potential decays on the τ scale. It is therefore not surprising that $T_{i\perp}(r)$ and $v_\theta(r)$ also decrease with the same time scale τ, consistent with transport of particles. The process of cooling is not reciprocal to heating and does not reveal any other time scale.

Density fluctuations show a sharp rise in low-frequency noise ($\omega/\omega_{ci} < 0.3$) when the plasma is rotating ($\delta n/n \sim 5\%$). There are discrete peaks in the spectrum which, from correlation measurements, correspond to azimuthal mode numbers $m=1,2,3$. The rise time for these fluctuations is only slightly slower than the rise time of $T_{i\perp}$. However, the wave energy content is very small ($\Delta\phi/kT_e < 10\%$) compared to the kinetic energy of the particles. The drift frequency agrees with an estimate of ω^* using the parameters of the rotating plasma, indicating that wave instability may be the result of plasma heating.

There are nearly 3 orders of magnitude more neutrals than ions in the test chamber, in thermal contact with the cooled walls. Hence, they remain cool and constitute a large energy sink. Note that collisions with neutrals scatter (randomize) the directed rotational ion momentum, increasing $T_{i\perp}$, while also extracting energy from the plasma, i.e., cooling it. Both processes have rates proportional to the neutral pressure, but energy-loss collisions tend to decrease the temperature-rise rate, while momentum scattering tends to increase it. When rotation is switched on, the initial rate of temperature rise normalized to the rotational energy (Fig. 5 and Table I) is found to be nearly proportional to the neutral pressure and quantitatively close to the momentum scattering collision frequency. This dependence indicates that field-induced collisional heating[7] is the dominant process.

In summary, using space- and time-resolved measurements of the distribution function, we have shown that the kinetic energy of an $\mathbf{E}\times\mathbf{B}$ rotating plasma can be thermalized via ion-neutral collisions. Thus collisional conversion is an important mechanism for feeding energy to these types of plasmas. From an instrumental point of view, our experiment demonstrates that gas-discharge ion temperatures can be controlled over a large range by a simple technique. Changes in $T_{i\perp}$ and their time-dependent gradients can affect phenomena such as diffusion and transport as well. The concept described here may be extended to charged-particle collisions in plasmas with differential rotation or motion between electrons and ions. This process may occur in centrifuge schemes, and geophysical and fusion plasmas; it could also be responsible for anomalously high ion temperatures encountered in some experiments,[9] as well as in heating experiments, where the plasma potential is influenced by the heating process.

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