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Supersonic Rotation Exceeding the Alfven Ionization Limit in the Maryland Centrifugal Experiment

R. Ellis, S. Messer, A. Case, R. Elton, J. Ghosh, H. Griem, A. Hassam, R. Lunsford, C. Teodorescu

University of Maryland, College Park, MD, USA

There has long been a debate over the existence of a limit to the directed velocity with which a neutral gas cloud can move through a magnetized plasma. It was postulated[1] that the relative velocity between the ions and the neutrals cannot exceed $v_c = (2e\Phi_i/m_n)^{1/2}$, where Φ_i is the ionization potential and m_n is the neutral mass, known as the critical ionization velocity (CIV). This limit may have been observed in a variety of experiments [2, 3] and may be operating in astrophysical and geophysical situations [4]. In laboratory experiments it is thought that the interaction produces rapid ionization in the boundary layers near the insulating surfaces, which occur primarily at the ends of the devices. In particular, rotating plasma devices, such as MCX, where an electric field perpendicular to B produces rapid **ExB** motion, may be subject to this limit. The CIV phenomenon may be related to the Alfven Mach number $M_A = v_\varphi/v_A$ where v_φ is the velocity of rotation and v_A is the Alfven velocity in the vicinity of the insulator, with higher M_A correlating with higher velocities [4].

The Maryland Centrifugal Experiment (MCX) [5,6] was designed to assess centrifugal confinement [7] and has achieved supersonic rotation. MCX has two modes of operation, an "ordinary" or O mode and an enhanced mode with higher rotation velocities, HR mode. Data is presented here which shows that O mode has a rotation velocity at the end insulators which is near or below the CIV limit (51 km/s for hydrogen) while the HR mode velocities exceed this limit by more than a factor of two. The rotation velocity of the bulk of the plasma at midplane exceeds the CIV limit for both modes.

The MCX Device MCX has a magnetic mirror configuration with end fields to 2T and independent midplane field, B_m, to 0.33T. A rod runs down the axis of the device and is the high voltage electrode; biasing of the rod at high voltage relative to the outer wall drives the **E**×**B** rotation. The plasma is terminated axially by Pyrex disc insulators which prevent short circuiting of the radial electric field; these are the insulators at which the CIV limit, if operable, should apply. Figure 1 is a schematic showing representative magnetic field lines for a mirror ratio of 9 as well as outlines of the coils, the vacuum vessel, the rod, and the disc insulator.

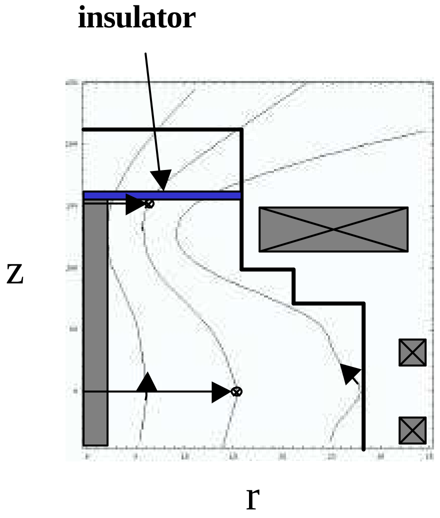

Fig 1. Schematic of magnetic field line geometry. Not to scale.

MCX operates in a pulsed discharge mode with high voltage provided by a 10 kV ignitron switched, crowbarred , capacitor bank. Typical pulse lengths are 2-10 ms. Crowbarring allows us to terminate the discharge at any time by short-circuiting the plasma to ground and allows us to measure the resultant reversal current pulse and determine the stored energy in the rotating plasma [2]. A OD circuit model [5] is used to infer the average plasma density and the average rotation velocity $v_\varphi = V_P/a_P B_m$, where a_P is the plasma radial extent at midplane and V_P is the measured plasma voltage. Visible spectroscopy is employed to measure rotation velocity (Doppler shift) and ion temperature (Doppler broadening) for H_α and impurity lines in the plasma for selected discharges [8]. Comparison of the spectroscopic velocities with those from the circuit model confirm the value of v_φ obtained from the model and the appropriate value of a_P . Line averaged plasma density was measured at midplane with a HeNe interferometer for a selection of discharges and these results were in excellent agreement with the circuit model and reconfirmed the determination of a_P [9]. MCX plasmas are high density ($n > 10^{20} m^{-3}$), rotating supersonically with v_φ >~ 100 km/s and ion temperatures 20-40 eV. Sonic Mach numbers ($M_S = v_\varphi/(T/M_p)^{1/2}$) are in the range 1-4 , with Alfven Mach numbers $M_A = v_\varphi/v_A$ of 0.2 –1; the plasmas are fully ionized except at the boundaries. Assuming isorotation of the plasma along B lines[2] the azimuthal velocity at the disc insulators, v_i is $(r_i/r_m)^{1/2}$ times the midplane value v_φ, where r_m is the mean radial position of the field line at midplane and r_i is the mean radial position of the same line at the insulator (Fig. 1). HR modes are transient, appearing just after formation and transitioning to O mode after a few milliseconds or less. Discharges with an HR mode phase mode appear when the discharge current is limited, by increasing the resistor in series with the plasma (typically 0.5-4 O) and/or increasing the strength of the magnetic field, both causing an increase in effective plasma resistance. HR mode has a much higher rotation velocity (200-300 km/sec) and longer momentum confinement time (200-400µs) though a somewhat lower plasma density. When the conditions for HR mode are not met MCX operates in the O mode and we present O mode data for discharges with and without an HR mode phase.

Results Measurements of rotational velocity and Alfven mach number were made for a wide range of parameters with the majority at $B_m = 0.2$ T and mirror ratio 9. In Fig 2 are shown v_i/v_c and the corresponding Alfven mach numbers for a large set of discharges, where all values are those at the disc insulators; the values at midplane are higher by the square root of the radius ratio. The rotational velocities are peak values for a parabolic velocity profile at a time during a steady state phase of each mode. We see that O mode discharges have $v_i / v_c < 1$ while HR plasmas have values comparable to and exceeding 2. HR mode plasmas also show an Alfven mach number significantly greater than O mode. In fact, at midplane the Alfven mach number for HR mode is approximately one. In Fig 3 the parameters are plotted against the magnetic field at the disc insulator, B_i. For HR mode the range in B_i is too narrow to establish scaling but for O mode they show no dependence.

Edge magnetic probes near midplane and mirror maximum measure magnetic fluctuations which at midplane in O mode have $\delta B/B$ of about 0.1 % and in HR mode a factor of 2-3 higher. However, in O mode the amplitude of the fluctuations near the mirror maximum are about the same as that at midplane, while in HR mode the amplitude is much lower at the ends.

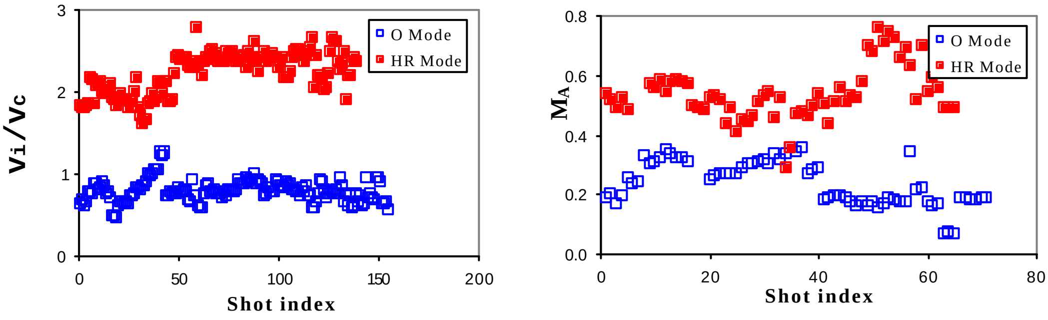

Fig 2. Normalized rotational velocities and Alfven Mach Numbers

Discussion The data show that O mode may be limited by the CIV phenomenon at the disc insulators but HR mode velocities exceed this limit. This might occur if HR plasmas are detached from the disc insulators so that the boundary layer CIV interaction is not operable. This is what one would expect if centrifugal confinement were pulling the plasma axially away from the insulators as predicted for high rotation velocities. The magnetic probe data support this conclusion.

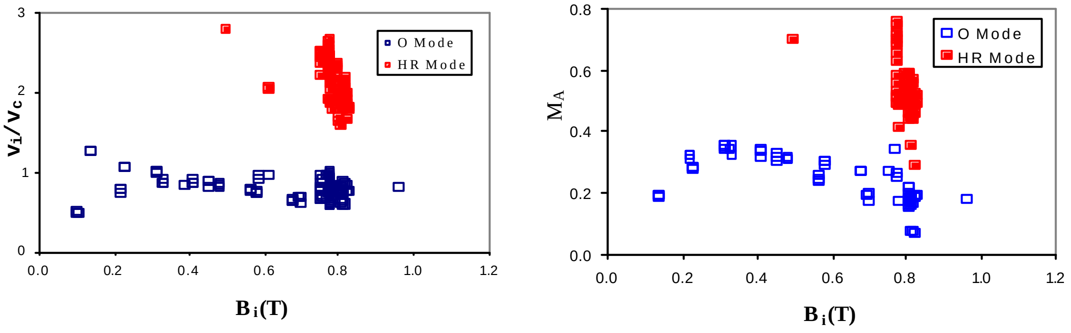

Fig 3. Normalized rotational velocities and Alfven Mach numbers vs B

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