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Stable Supersonic Rotation in the Maryland Centrifugal Experiment.

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The MCX Device The Maryland Centrifugal Experiment[1] tests the concepts of centrifugal plasma confinement[2,3] and the stabilization of MHD instabilities by velocity shear[4-6] , employing supersonic rotation about a strong confining magnetic field. The magnetic configuration of MCX (Fig 1) is a long solenoid with axisymmetric mirror end fields up to 2T and independent midplane field up to 0.3T. A rod runs down the axis of the device and acts as the high voltage electrode. Biasing of the rod relative to the outer wall drives **E**×**B** azimuthal rotation.

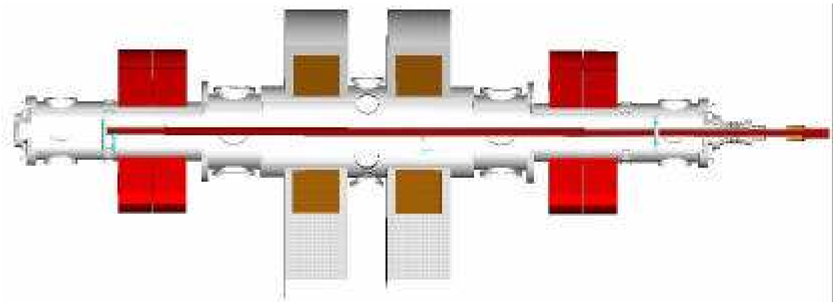

Fig 1. Cutaway of the MCX device. For scale the mirror end coils are 1m in diameter.

The high voltage is provided by a 10 kV ignitron switched crowbarred capacitor bank, shown schematically in Fig 2, along with the associated plasma model. The *plasma crowbar* allows us to terminate the discharge at any time by short-circuiting both the capacitor bank and plasma to ground. The *freewheeling crowbar* is not discussed .

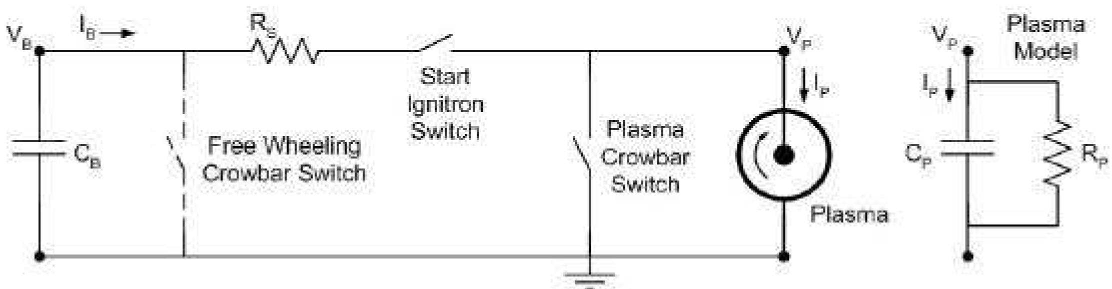

Fig 2. MCX capacitor bank. V_B = 5-11kV, C_B = 1.3-7 mF, R_S = 0.5-3 Ω

Typical Discharge Figure 3 displays the plasma voltage V_P and current I_P for a typical MCX discharge type referred to as *O mode* (a new high rotation mode, *HR mode,* is briefly discussed below but is not the subject of this paper). After a holdoff and formation time of ~1 ms the plasma voltage settles at about 2kV and holds steady, while the current slowly decreases to about 1kA. At t ≈ 5ms the discharge is terminated by the plasma crowbar, which is followed by a strong reversal pulse in the plasma current, representing the stored energy in the rotating plasma. Time integration of the reversal current yields the equivalent charge Q_P stored in the rotating plasma. We note that I_P can be held more constant by increasing the bank capacitance.

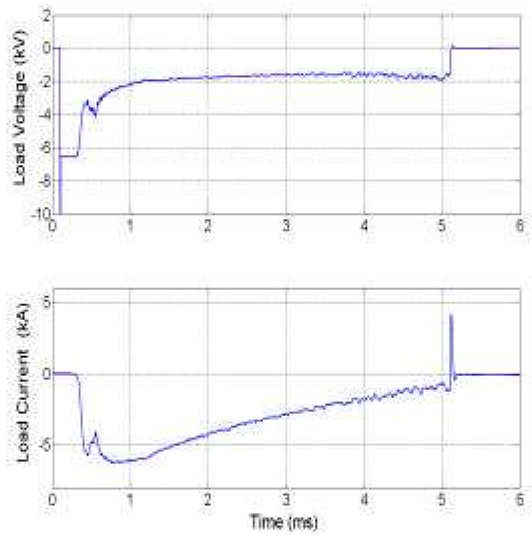

Fig 3. Typical O mode discharge, C_B = 3.5 mf, V_B = 6.5 kV, B_{mid} = 0.2T, R_M=9, R_S= 0.5Ω

0-D Plasma Model The plasma is modeled as a capacitor, C_p, which stores rotational plasma energy and a parallel resistance R_p which represents the losses of rotational angular momentum due to any frictional forces. In 0-D the model equations are :
$(1/2)C_PV_P^2 = (1/2)\rho u_\varphi^2 * VOL$; $C_P = Q_P/V_P$, $R_P = V_P/I_P$; $u_\varphi = V_P/a_PB$; $\tau_M = R_P C_P$. Here u_φ is the azimuthal velocity, ρ is the plasma mass density, VOL is the plasma volume, a_P the plasma radial extent at midplane ~ 0.2m, L_P(used below) is the plasma length ~ 3m. I_P, V_P, Q_P are independently measured and u_φ is measured by Doppler spectroscopy for many discharges.

Doppler spectroscopy Visible spectroscopy is employed to directly measure rotation velocity (Doppler shift) and ion temperature (Doppler broadening) for H_α and impurity lines (CII-CIV, N,Si) in the plasma[7]. CIV ion velocity and temperature are most representative of the plasma center due to the greater penetration depth of higher ionization states.

Results For a wide range of parameters the data and 0-D model, and Doppler spectroscopy, show that MCX plasmas are high density($n > 10^{20} m^{-3}$), rotating supersonically with u_φ exceeding 100 km/s ; ion temperatures are typically 20-40 eV. Doppler measurements of u_φ for chords viewing above, below, and directly at the center rod, and with reversed B field direction, all confirm **ExB** rotation. Sonic Mach numbers ($M_S = u_\varphi/(T/M_p)^{1/2}$) are in the range

1-2 , with Alfven Mach numbers ($M_A = u_\varphi/v_A$) typically ~ 0.4, and peak thermal betas of ~20%. The plasmas are essentially fully ionized.

Fig 4 shows histograms of the distribution of measured sonic and alfven Mach numbers for a large number of O mode discharges. Azimuthal velocities are peak values for an assumed radial parabolic profile, to agree with Doppler measurements.

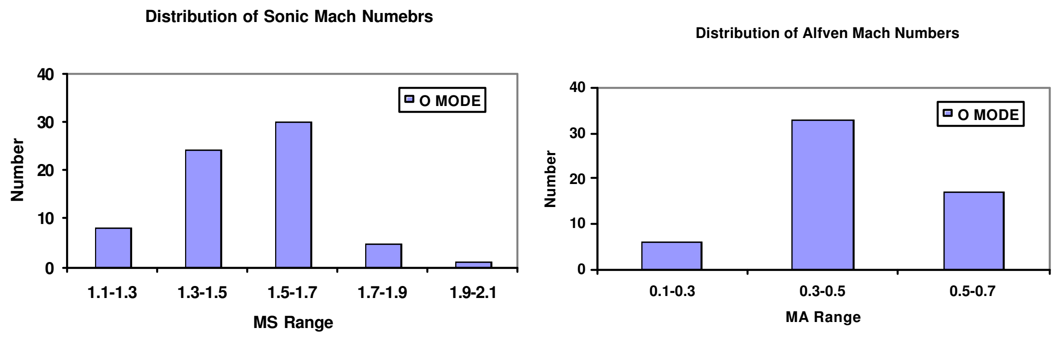

Fig 4. Distribution of measured sonic and Alfven Mach numbers for a variety of O mode discharges

Time scales and stability The relatively quiescent and "steady state" current and voltage traces of Fig 3 show steady rotation over long periods. Characteristic plasma times for MCX parameters are shown in the table below. If MCX were unstable to MHD interchanges, the time scale could be as short as a rotation period and not longer than an interchange growth time, both of the order of 10 μs, whereas the MCX I-V traces hold steady up to 8ms, being limited only by the crowbar or by the finite charge in the external capacitor bank. In addition, if there were large unstable flute turbulence in the discharge, momentum and heat would be lost from the discharge on time scales of order the flute rotation period but the observed damping time of the rotation, R_pC_p, is measured to be 100-200μs.

Axial Alfven time ~ L_P/v_A	5μs
Period of rotation ~ $(2\pi R/u_\phi)$	10μs
Interchange growth time ~ $[(a_P L_P)/(T/M_p)]^{1/2}$	10μs
Axial electron heat conduction time ~ $(L_P/\lambda)^2\ \tau_e$	10μs
Axial sonic time ~ $L_P/(T/M_p)^{1/2}$	30μs
Electron-ion heat exchange time ~ $(M_p/m_e)\tau_e$	50μs
Classical viscous damping time ~ $(a_P/\rho)^2\ \tau_{ii}$	2000μs

Note the classical damping time of the rotation from ion-ion collisions is approximately 2000μs - there is a clear separation of ideal MHD instability times and dissipative time scales. The plasma sustenance over long time scales and the clear separation of dissipative and ideal time scales is a strong indication that the plasma is MHD stable. At present there is no direct evidence that stability results from rotational velocity shear but both O and HR modes satisfy the simplest condition for shear stabilization, that the radial shear exceed the instability growth rate ($du_\varphi /dr >$?$_{MHD}$).

Magnetic Fluctuations Magnetic probes near midplane and near mirror maximum (located on approximately the same B line, at the plasma edge) measure magnetic fluctuations. The magnetic fluctuations in O mode have $\delta B/B$ of about 0.1 % and the frequency spectrum has significant activity at the edge rotation frequency and does not exclude Alfven eigenmodes with parallel wavelengths comparable to the machine length.

HR Mode In varying operating parameters on MCX a new mode of operation was discovered which we called High Rotation or HR mode. HR mode appears when discharge current is limited, by increasing the resistor R_s 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 is characterized by higher rotation velocities (200-300 km/sec), longer momentum confinement times (200-400µs) , higher resistance, and larger magnetic fluctuations. All HR modes are transient, appearing just after formation and transitioning to O mode after some milliseconds or less. However, quasi-steady HR discharges for durations of 3-4 ms are common.

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REFERENCES

1. R.F.Ellis, et al, PHYS PLASMAS 8 (5), 2057 (2000)
2 B.Lehnert, NUCL FUSION 11, 485 (1971).
3. G.F.Abdrashitov, et al., NUCL FUSION 31, 1275 (1991).
4. Y.M.Huang and A.B.Hassam, PHYS REV LETT 87 (23), 235002(2001)
5. U.Shumlak , et al., PHYS REV LETT 87 (20), 205005 (2001)
6. Y.M.Huang and A B.Hassam , PHYS PLASMAS 10 (1) , 204 (2003)
7. J.Ghosh, et al , PHYS PLASMAS (to appear July 2004)