# Steady Supersonic Rotation in the Maryland Centrifugal Experiment

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**Abstract.**The Maryland Centrifugal Experiment(MCX) studies enhanced confinement and stability produced by sheared supersonic rotation about a linear confining magnetic field. MCX has a mirror geometry of 2.5 m length, mirror ratio 2-20,maximum mirror field 1.9T, maximum midplane field 0.33T. Biasing of an inner electrode relative to the outer wall produces a radial electric field which drives azimuthal rotation. MCX has achieved high density ($n>10^{20}$ $m^{-3}$) fully ionized plasmas rotating supersonically with velocities of ~100 km/sec for times exceeding 8 ms under a wide range of conditions. Ion temperatures are 30 eV and confinement times ~100 microseconds. Sonic Mach numbers are 1-2 and Alfven Mach numbers somewhat less than 0.5 for standard discharges. Plasmas remain grossly stable, or steady, for many milliseconds, much longer than MHD instability timescales for MCX, though significant magnetic fluctuations are clearly seen on magnetic probes. Recently MCX has demonstrated an enhanced mode of operation with sonic Mach numbers greater than 3, confinement times of several hundred microseconds and Alfven Mach numbers near one.

## 1. Introduction

Toroidal magnetic fields can contain the plasma pressures required for thermonuclear fusion but for plasma equilibrium and stability the fields need to incorporate magnetic shear, which usually translates to complex or interlocking coil configurations. An alternative approach is to set the plasma in rapid rotation and utilize centrifugal forces to augment magnetic confinement resulting in simpler coil configurations; this approach was pursued in earlier experiments [1-3]. Moreover, recent observations of the suppression of plasma turbulence by flow shear [4,5] have caused a revived interest in centrifugal confinement. Since rapid plasma rotation inevitably involves velocity shear, rotation could confine the plasma and stabilize it. Flow shear can be large enough to stabilize both large-scale MHD interchange modes (leading to simple coils) as well as small scale turbulence (leading to superior plasma transport). In addition, viscous heating alone might bring the plasma to fusion temperatures, obviating auxiliary heating systems.

The configuration is shown in Fig.1. The B field is a simple mirror geometry with central solenoidal region. A coaxial metallic core is biased with respect to the outer vessel. The radial electric field ionizes and forms the plasma and sets it into **E x B** *azimuthal* rotation. Radially outward centrifugal forces have a component parallel to **B** that contain the plasma to the solenoid region (the mirror loss cone is obviated if the rotation is supersonic). Plasma on field lines that end on conducting boundaries cannot rotate. Thus, only the field lines within the two shown as solid lines rotate and plasma viscosity and drag adjust the electric field profile and the flow profile to result in sheared rotation. The simple magnetic mirror of Fig 1 should be flute interchange unstable, on a time scale of the order of a rotation turnover time if the rotation is rigid. For sheared rotation, however, the flute is expected to be stable if the flow is supersonic [6]. The MCX experiment [7] is designed to access supersonic rotation and investigate centrifugal confinement and velocity shear stabilization of MHD instabilities.

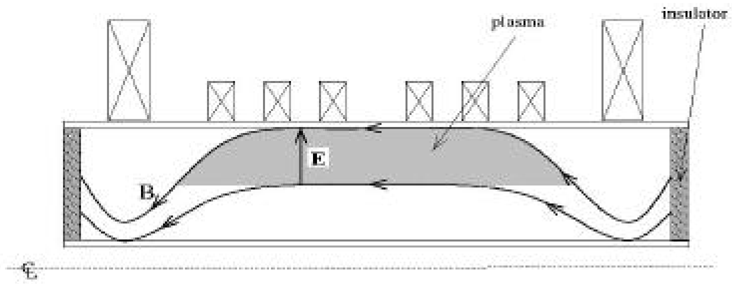


*Fig. 1 Schematic of the Centrifugal Confinement Scheme*

## 2. Experimental Setup

### 2.1 The MCX Device

The Maryland Centrifugal Experiment(MCX), Fig. 2, has the magnetic configuration of a long solenoid with axisymmetric mirror end fields. The length from mirror maximum to mirror maximum is 2.5 m with maximum field of 1.9 T; the independently controlled midplane field has a maximum of 0.33T and the resulting variable mirror ratio, $R_M$, is 2-20 . The midplane plasma diameter is 0.54 m. A 4.8 cm diameter rod runs down the axis of the device and acts as the high voltage electrode. Pyrex insulating discs terminate the plasma region axially 0.37 m beyond the mirror maxima. Biasing of the rod relative to the outer wall drives **E**´ **B** azimuthal rotation in the plasma region.

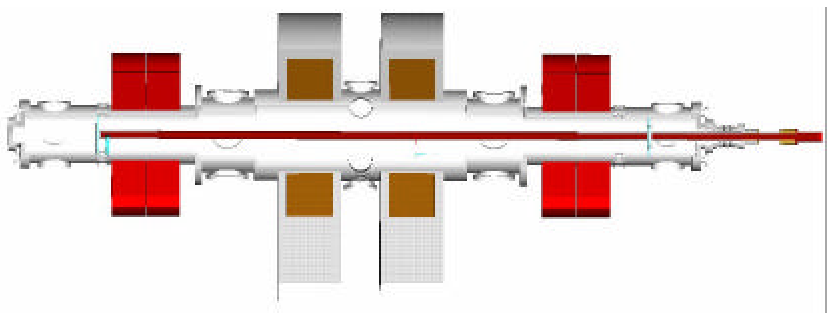

*Fig. 2. Cutaway of the MCX device. For scale the mirror end coils are 1m in*

The high voltage is provided by a 10 kV ignitron switched crowbarred capacitor bank, shown schematically in Fig. 3, 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 .

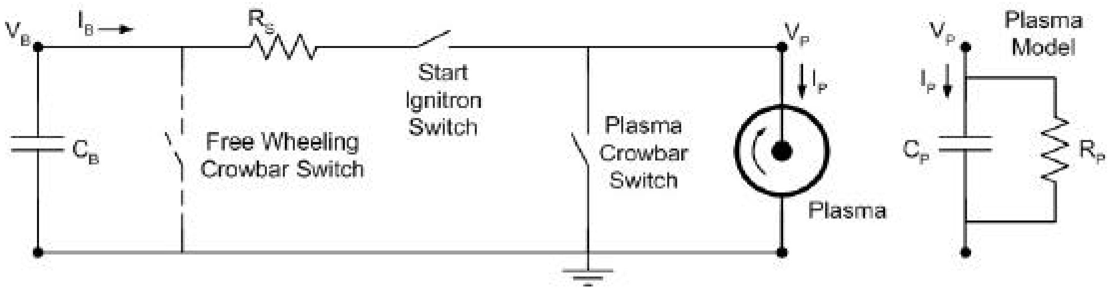


*Fig. 3 MCX capacitor bank. $V_B$ = 5-11kV, $C_B$ = 1.3-7 mF, $R_S$ = 0.5-3 W*

### 2.2 Circuit Measurements and Model

The basic analysis of the plasma employs data from the machine diagnostics ($I_P$ and $V_P$ versus time) and a 0-D equivalent circuit model [2]. We model the rotating plasma as a capacitor $C_P$, in parallel with a plasma "leakage" resistance $R_P$ (Fig. 3). Energy is stored in the dielectric medium as the rotational kinetic energy. The resistor, $R_P$, represents net plasma momentum losses from viscous or friction forces ; if the plasma capacitor were disconnected from the external voltage, the plasma rotational momentum would decay with a rate constant of $\tau_M = R_P C_P$. Based on these ideas, which are consistent with magnetized plasma dielectric theory and dissipative MHD, a set of model equations in 0-D can be written down to describe the basic discharge. These are:

$(1/2)C_P V_P^2 = (1/2)\rho u_\varphi^2 * VOL$ *[energy in plasma capacitor = rotational kinetic energy]*

$C_P = Q_P/V_P$ , $R_P = V_P/I_P$ *[defines $C_p$, $R_P$]*

$E_r = V_P/a_P$ , $u_\varphi = E_r/B$ *[$V_p$ and $a_p$ define average E field across capacitor => inferred average ExB azimuthal speed, $u_j$]*

$\tau_M = R_P C_P$ *[plasma rotation damping given by the RC time constant of the leaky plasma capacitor]*

$1/\tau_{cx} = n_0 \sigma_{cx} u_\varphi$ *[definition of $t_{CX}$ ; assumes supersonic flow]*

The charge stored in the plasma capacitor, $Q_P$, is directly measured by integrating the current reversal when the plasma is crowbarred (see below). If the momentum decay is primarily due to resonance charge exchange of $H^+$ and H, represented by the cross section $\sigma_{cx}$ , we can estimate $n_0$, the average neutral hydrogen density in the plasma by equating $\tau_{cx}$ with $\tau_M$ . Here $u_\varphi$ is the azimuthal velocity, $\rho$ is the plasma mass density, and VOL is the plasma volume. The plasma radial extent at midplane, $a_P$, is estimated by identifying the "last good flux surfaces" from the vacuum B field line mapping. The parameters in the model are meant to represent the highly ionized plasma annulus. For MCX $I_P$, $V_P$, $Q_P$ are independently measured and $u_\varphi$ is measured by Doppler spectroscopy for many discharges.

We note that the basic model behavior of the actual MCX circuit was tested by firing into a variety of dummy loads with parameters similar to the $R_P$ and $C_P$ of the MCX plasma. In all cases the circuit behavior was consistent with our analysis, in particular, in verifying that the charge in the current reversal pulse is an accurate measurement of the stored charge in the capacitor at crowbar and could be used to calculate the stored energy. In the next section we discuss the fact that the circuit model also can be used to accurately measure the volume averaged plasma density.

### 2.3 Diagnostics

Visible spectroscopy is employed to directly measure rotation velocity (Doppler shift) and ion temperature (Doppler broadening) for $H_\alpha$ and impurity lines (CII-CIV, N,Si) in the plasma [8]. The CIV ion velocity and temperature are most representative of the plasma center due to the greater penetration depth of higher ionization states and only those results are shown in this paper.

Magnetic probes located near midplane and near mirror maximum (located on approximately the same B line, at the plasma edge) are used to measure magnetic fluctuations. The probes can independently measure three orthogonal components of the fluctuating B fields.

A visible HeNe interferometer was borrowed from the SSX experiment at Swarthmore College and electron density was measured for a range of discharge parameters. For all cases these were in excellent agreement with the volume averaged plasma density calculated from the circuit model described in Sect. 2.2.

## 3. Experimental Results

### 3.1 Standard MCX Discharge (*O Mode*)

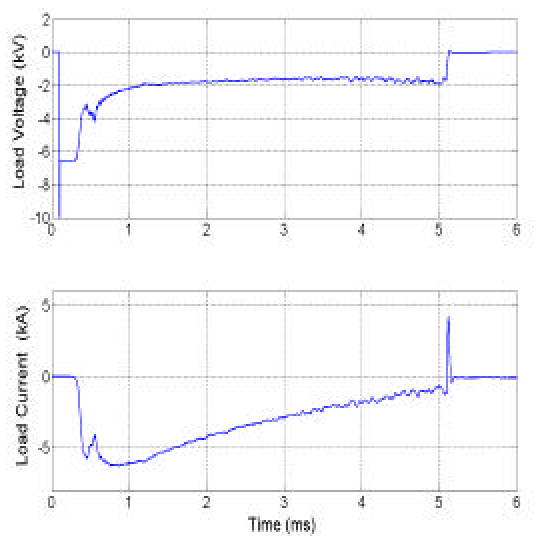


*Fig. 4 Typical O mode discharge, $C_B$ = 3.5 mf,*
*$V_B$ = 6.5 kV, midplane B = 0.2T, $R_M$=9, $R_S$= 0.5W*

Fig. 4 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 discussed below). 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 and from our experiments we conclude that the MCX O Mode discharge will remain in a steady state for as long as the plasma voltage and current can be maintained steady.

For a wide range of parameters the data and the 0-D model, in combination with Doppler spectroscopy and supported by limited HeNe interferometer density measurements, show that

MCX O mode plasmas are high density($n > 10^{20} m^{-3}$), rotating supersonically with $u_\varphi$ exceeding 100 km/s ; ion temperatures are typically 20-40 eV. Doppler measurements of $u_\varphi$ 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. *HR mode* is further described below.
Fig. 5 shows histograms of the distribution of measured sonic and alfven Mach numbers for a large number of O mode and HR mode discharges. Azimuthal velocities are peak values for an assumed radial parabolic profile, to agree with Doppler measurements.

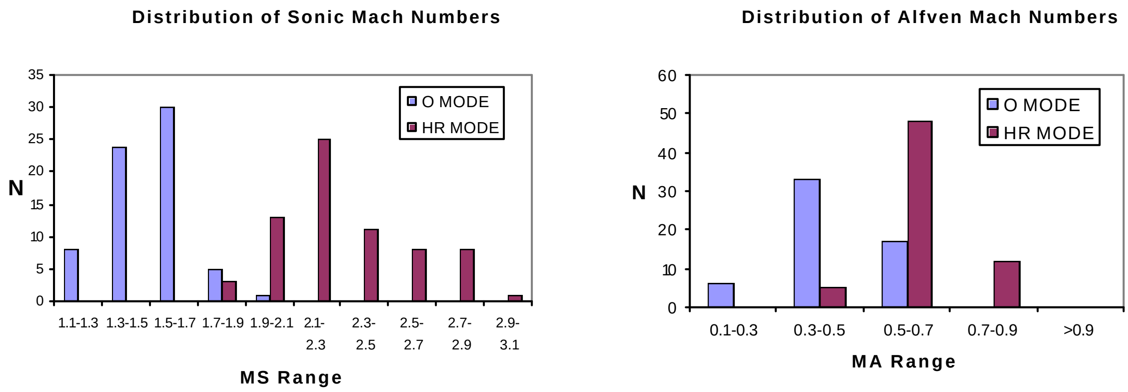


*Fig. 5 Distribution of Mach numbers for a set of O and HR mode discharges.*

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.

### 3.2 Higher Rotation MCX Discharge (*HR Mode)*

In varying operating parameters on MCX a new mode of operation was discovered which we called Higher 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.

Fig. 6 shows a typical discharge exhibiting HR mode. This discharge was run at our standard high B but with a series resistor of 1.5 ohms, which limits the plasma current. Note for times up to about 2 ms the voltage across the plasma is almost 4 kV but the current is less than 2 kA, indicating a plasma resistance exceeding 2 ohms. At t ~ 2 ms the mode transitions to the usual O mode described earlier. A cursory look at HR mode shows it is characterized by higher rotation velocities (higher $V_P$) and higher resistance(higher $V_P$ and lower $I_P$).

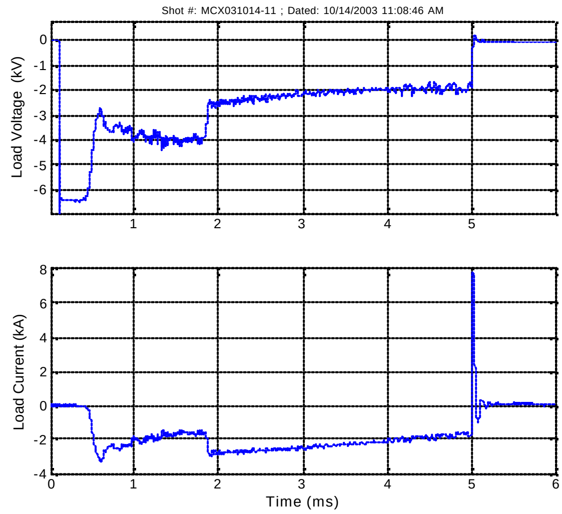


*Fig. 6 Discharge with HR and O mode*
*(midplane B = 0.2T, $R_M$ = 9, $R_S$ = 1.5O)*

In general, HR mode appears when discharge current is limited, by increasing the resistor Rs in series with the plasma (typically 0.5-4ohms) and/or increasing the strength of the magnetic field, both causing an increase in effective plasma resistance. In general HR mode occurs for midplane B of 0.2 T or greater and $R_S$ from about 1-3 ohms. Increasing $R_S$ beyond about 3 ohms leads to a weak discharge of little interest. The maximum possible midplane B is presently 0.33 T. All the data we have taken supports the hypothesis that limiting discharge current is the key to HR mode.

HR discharges show a factor of order 2-3 increase in rotation velocity, stored energy, and confinement time compared to O mode. This is confirmed by firing the plasma crowbar just before transition(HR mode) in one discharge and just after transition(O mode) in another identical discharge and calculating the plasma capacitance $C_P$, the energy stored in the equivalent plasma capacitor $0.5Q_PV_P$, and the momentum decay time $R_PC_P$. The results are shown in Table I for six such discharges; note that these results do not employ any profile information. The improved performance in HR mode is striking

TABLE I: PARAMETERS BRACKETING HR TO O MODE TRANSITION

| Discharge Mode | $C_P$ (µF) | Stored Energy (kJ) | Momentum Conf. Time (µs) |
|---|---|---|---|
| HR ( t = 1.6 ms) | 137 | 1.08 | 260 |
| O ( t = 2.0 ms) | 94 | 0.31 | 80 |

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Referring back to Fig. 5, we note it shows the distribution of Mach numbers for a large number of HR mode discharges along with the O mode results. We see again a clear separation of the two modes and note importantly that HR mode achieves sonic Mach numbers exceeding 2 and Alfven Mach numbers greater than 0.5. Confirmation of the high rotation velocity in HR mode was obtained with measurement of the Doppler shifted CIV emission for the HR and O portions of a discharge. A typical velocity from the Doppler shift gives 200-300 km/sec in HR mode. $T_i$ was measured from Doppler broadening. Finally both O and HR plasmas are high density(> $10^{20}$ $m^{-3}$) and can be characterized as very highly ionized

Also of importance, magnetic probe activity shows edge magnetic fluctuations in HR mode which are more than 3 times larger than O mode with a frequency spectrum shifted to higher frequencies consistent with the higher rotation velocities. This could be related to the higher alfven Mach number which brings MCX closer to an MHD stability boundary.

**4. Time scales and stability**

The relatively quiescent and "steady state" current and voltage traces of Fig. 4 and the O mode portion of Fig. 6 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 100μs for O mode. For HR mode the momentum damping time is greater than 200μs and the difference is even larger.

TABLE II: CHARACTRISTIC TIMESCALES

| | |
|---|---|
| Axial Alfven time ~ $L_P/v_A$ | 5μs |
| Period of rotation ~ $(2\pi R/u_\phi)$ | 10μs |
| Interchange growth time ~ $[(a_PL_P)/(T/M_p)]^{1/2}$ | 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 ($du_\varphi /dr > ?_{MHD}$) if we take $d/dr \sim 1/a$. The variation of rotation velocity with ionization state, as measured by Doppler spectroscopy, supports the proposition that such a radial variation exists. A multichord spectrometer is being developed to measure velocity profiles. We also note that if instability induced turbulence losses are small then the observed momentum confinement time might be mostly attributable the ion-neutral charge exchange collisions and as noted in Sect. 2.2 we can estimate an upper bound on the neutral hydrogen density in the main body of the rotating plasma. This calculation results in an ionized fraction greater than 99.9%.

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