The Maryland Centrifugal Experiment

MCX

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Centrifugal Confinement

- initial vacuum $\mathbf{E} \cdot \mathbf{B}$ => breakdown
- centrifugal forces => axial confinement
- rotation shear => stability to interchanges
- rotation shear => viscous heating
MCX Highpoints

- Supersonic rotation for times up to 8ms (sonic Mach numbers 1 to 3)
- Steady for up to ~1000 MHD flute instability times, no major disruptions.
- Plasma densities exceed $10^{20}$ m$^{-3}$; ionized fraction > 99%
- Momentum confinement times up to ~200µs
- Alfven Mach number as high as 0.5; $\beta$ as high as 40%.

New HR Mode

- New **high rotation** mode (HR) discovered. Rotation speeds are up to 2.5 x higher than O mode, as are Mach numbers, stored energy and momentum confinement times.
Recent MCX Hardware Upgrades

- Increased capacity of discharge bank by a factor of 5, leading to steady 8 ms long discharges. Implemented limited freewheeling.
- Developed new fiber/ICCD camera based Doppler spectrometer.
- Implemented diamagnetic loops, improved magnetic probes.
- Tested Swarthmore HeNe interferometer.
Summary of plasma parameters on MCX

\[ B_{\text{midplane}} < 0.33 \text{T}, \quad B_{\text{mirr}} < 2 \text{T} \]

Mirror ratio \( \sim 1\text{-}20 \) (9 standard)

\[ V_{\text{bank}} \sim 7 \text{kV} \]

\( n \sim \text{few } 10^{20}\text{ m}^{-3} \) (\( > 99\% \text{ ionized} \))

\( T \sim 20\text{-}50 \text{ eV} \)

\( u_\phi \geq 100 \text{ km/s} \)

\( M_s \sim 1\text{-}3, \quad M_A \sim \text{up to } 0.8 \)
MCX Capacitor Bank and Associated Plasma Model

\( V_B = 5\text{-}11\text{kV} \), \( C_B = 1.3\text{-}7 \text{ mF} \), \( R_S = 0.5\text{-}3 \text{ \( \Omega \)} \)
I-V Traces

\[ B_{\text{mid}} = 2 \, \text{KG} \]
\[ R_M = 9 \]
\[ V_B = 7 \, \text{KV} \]
Model rotating plasma as capacitor $C_p$, in parallel with a plasma “leakage” resistance $R_p$. Energy stored in $C_p$ as rotational kinetic energy. Data from machine diagnostics and spectroscopy employed.

\[(1/2)C_p V_p^2 = (1/2)\rho u_\varphi^2*VOL\]  
[energy stored in capacitor = rotational kinetic energy]

\[C_p = Q_p/V_p\]  
[defines $C_p$]

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

\[\tau_M = R_p C_p\]  
[plasma rotation damping given by the RC time constant]

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

$u_\varphi$ is azimuthal velocity, $\rho$ the plasma mass density, VOL the plasma volume. Plasma radial extent at midplane, $a_p$, is estimated from “last good flux surfaces” (LGFS) from the vacuum B field.
MCX Spectroscopy Measurement Layout

- CII, CIII, and CIV lines measured
- Input slit imaged to vertical spot $\sim 2.5$ cm high
- Gated CCD intensified one D diode array
CIV spectroscopy shows supersonic rotation in red and blue shifts

**CIV line at 5801.33**
Measured at 550 μsec into the discharge
Integration time = 100 μsec

Average $V_{\text{rotation}} = 89 \pm 5$ km/sec
Average $T_{\text{ion}} = 40 \text{ eV} \pm 10 \text{ eV}

Average $V_{\text{rotation}} = 60 \pm 5$ km/sec
Average $T_{\text{ion}} = 40 \text{ eV} \pm 10 \text{ eV}
Spectroscopic $u_\phi$ lies between average and max speed from $V/(aB)$

Ion Velocity Scan  
(a=20 cm, $R_m=9$)
Doppler shifts for various ionization states demonstrates shear in rotation profile.
radial doppler shifts show little rotation
Distribution of Sonic and Alfvén Mach Numbers for Many Discharges
(O and HR mode)
Typical Discharge with Transition from High Mode to Ordinary Mode

\( C_{\text{bank}} = 3.5 \text{ mF}, \; B_{\text{mid}} = 2 \text{ kG}, \; R_s = 1.1 \text{ ohm} \)
Parameters bracketing H to O mode transition. Averages for 3 discharges each mode.

<table>
<thead>
<tr>
<th>Discharge Mode</th>
<th>Plasma Capacitance (µF)</th>
<th>Stored energy (kJ)</th>
<th>Momentum confinement time (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR (t = 1.6 ms)</td>
<td>137</td>
<td>1.08</td>
<td>260</td>
</tr>
<tr>
<td>O (t = 2.0 ms)</td>
<td>94</td>
<td>0.31</td>
<td>80</td>
</tr>
</tbody>
</table>
Doppler shifts are larger in HR mode

- **HR mode:**
  \[ v_\phi = 238 \pm 10 \text{ km/s} \]
  \[ T_i = 50 \pm 10 \text{ eV} \]
  \[ M_s \sim 3.1 \]
  \[ V = 4.5 \text{ kV}, \ B = 3 \text{ kG} \]
  \[ (V/aB) = v_\phi \text{ if } a \sim 10 \text{ cm} \]

- **O mode**
  \[ v_\phi = 46 \pm 10 \text{ km/s} \]
  \[ T_i = 28 \pm 10 \text{ eV} \]
  \[ M_s \sim 0.9 \]
  \[ V = 2.3 \text{ kV}, \ B = 3 \text{kG} \]
  \[ (V/aB) = v_\phi \text{ if } a \sim 20 \text{ cm} \]
Crowbar during HR Mode phase shows huge current reversal

( Bmid = 2kG, Rs = 1.1Ω)
Bdot Probe signals show significant changes in activity between HR and O mode.
Major Planned Device Upgrades

- **Capacitor Bank**  Increase voltage to 20 kV using available capacitors. Use new bank as a second or “boost” bank to drive the plasma to higher rotation speeds after formation using the 10 kV bank.

- **Increased Magnetic Field**  **Short run**: increase $B_{\text{mid}}$ to 0.5 T driving the solenoid coils in parallel. **Longer term**: Add red coil to each mirror $>> B_{\text{mirr}} \sim 2.6$ T. New electrolytic capacitor bank to drive the solenoid coils $>> B_{\text{mid}} \sim 1.0$ T.

- **Surface Conditioning**  **Baking**: activate MCX heating blankets(150°C) to remove the bulk of water vapor. **Discharge cleaning**: Implement standard glow discharge cleaning, experiment with pulsed discharged cleaning.

- **Contingencies**  Advanced end insulators. ECH pre-ionization to aid in density control( we have acquired the use of two high power microwave sources). Toroidal (azimuthal) magnetic field.
Major Planned Diagnostic Upgrades

• **Multichord Doppler Spectroscopy** Completion of multichord system, allowing a determination of the rotational velocity profile.

• **Magnetic probes** Design and construction of extensive array (theta and z) to measure MHD activity.

• **Laser interferometer** Development of a two color system to allow precise measurements of density at two axial locations. HeNe visible for vibration compensation, IR( CO2 or HeNe) for plasma.

• **Loops, Analyzers** Improvement of diamagnetic loop capability and development of end loss analyzers to assess centrifugal confinement.
New Spectroscopy measurement layout

- Spectra acquired with gated 2D ICCD camera.
- Typically mounted at the chamber midplane.
- Input slit imaged to vertical spot ~ 0.5 cm high.
Current and Planned Bdot diagnostics

Currently 4 x,y,z triple Bdot probes:
- $z = +81$ cm (near HV end) 1 probe
- $z = 0$ cm (midplane) 1 probe
- $z = -81$ cm: 2 probes separated by 7.5 degrees in theta

Planned:
- 7 probe Bz array mounted on 8 inch port at midplane (hardware 50% complete)
- 16-24 probe array surrounding the plasma at $z = 62$ cm (in planning stage)
Research Roadmap

• Complete new diagnostics to study stability and relation to velocity shear (multichord spectrometer, magnetic probe arrays, two color interferometer system).

• Study MHD activity and correlation with velocity profiles. Identification of mode numbers, correlation functions, etc. Measure corresponding ion velocity and temperature profiles. Correlate fluctuation activity with confinement times. Compare results with theory and simulation models of MHD stability.

• Complete development, testing, and implementation of new diagnostics to allow study of centrifugal confinement (interferometer chord at mirror throat, diamagnetic loop at the mirror throat, endless analyzers at disk insulators).

• Studies of centrifugal confinement effect for established regimes of operation. Done in concert with the fluctuation studies.

• Expand parameter space with the goal of increasing Mach number and confinement time and producing cleaner, hotter, high Mach number plasmas. Seek to optimize centrifugal confinement (higher voltage 20 kV capacitor bank, increased magnetic field, surface conditioning, pre-ionization, gas puffing).
Dummy Load:
τ from RC, plasma crowbar, and freewheeling
Plasma Load:
Compare $\tau$ from plasma crowbar and freewheeling

Shot Information for MCX040429 - 11
$\tau$ (freewheel) = 222 us
$C = 75$ uF
$Q = 279$ mC

Shot Information for MCX040429 - 12
$Q$ (crowbar) = 285 mC
$C = 77$ uF
$\tau$ = 212 us
Comparison of Plasma and Dummy Load Reversals

Rs = 1 Ohm
Rp = 0.85 Ohms
C = 178 uF

Rs = 1.5 Ohms
Rp = 1 Ohm
C = 176 uF
Dual stage (prebank+boost bank) 10kV capacitor bank shows promising results
(Bmid=3 kG)