The Maryland Centrifugal Experiment
and Velocity Shear Stabilization
of Ideal MHD Interchanges

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Outline

1. Brief Status of the Experiment

*Poster Session #2*

- *Ellis et al*: MCX - Status
- *Teodorescu et al*: H-mode
- *Huang et al*: Resistive stability
- *Ng et al*: $V'$ shear + FLR

2. What do we know about MHD Stability?
   
   *A first assessment*
Centrifugal Confinement

- initial vacuum $E.B$ => breakdown
- centrifugal forces => axial confinement
- rotation shear => stability to interchanges
- rotation shear => viscous heating
MCX – May 2004
Simple mirrors are unstable to flute interchanges
MCX - Mission

- Can the plasma be centrifugally confined along B?
- Can V’ shear stabilize flute modes?
NMCX - Centrifugal Confinement

Huang et al, PRL, 2001
Flute Interchange with Velocity shear
Artificially Suppressed
Recovery of discharge as Velocity Shear is Restored
Status of the Experiment
Circuit Model
I-V Traces

\[ B_{\text{mid}} = 2 \text{ KG} \]

\[ R_M = 9 \]

\[ V_B = 7 \text{ KV} \]
0-D Model

\[ \frac{1}{2} Q_p V_p = \frac{1}{2}(\text{Mass})u \hspace{1em}^2 \]

\text{[stored energy = kinetic energy]}

\[ u \approx \frac{V_p}{aB} \]

\text{[average speed inferred from } V_p] \Rightarrow u \approx 100 \text{ km/s}

\text{Assuming } H \text{ plasma} \Rightarrow n \approx \text{few } 10^{20}

MCX Spectroscopy Measurement Layout

- CII, CIII, and CIV lines measured
- Input slit imaged to vertical spot ~ 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 $V_{\text{rotation}} = 89 \pm 5 \text{ km/sec}$
Average $T_{\text{ion}} = 40 \text{ eV} \pm 10 \text{ eV}$

Average $V_{\text{rotation}} = 60 \pm 5 \text{ km/sec}$
Average $T_{\text{ion}} = 40 \text{ eV} \pm 10 \text{ eV}$

Intensity (a.u.)

Wavelength ($\lambda$) Å
Rotation is Supersonic, (Weak) Stability Criterion Reached

Stability Criterion for Ideal Interchanges

\[ u_j' > (\text{sonic growth rate}) \times (\text{logarithmic factor}) \]

\[ \Rightarrow M_s > (a/L)^{1/2} \times (\text{log factor}) \]

**Supersonic**

\[ M_s = \frac{u_j}{(T/M)^{1/2}} \sim 1 - 2 \]
Summary of measured and inferred plasma parameters on MCX

\[ B \sim 2 \text{kG} \quad \text{Mirror ratio} \sim 9 \]
\[ V_0 \sim 5-10 \text{kV} \]
\[ n \sim \text{few} \times 10^{20} \text{ m}^{-3} \quad T \sim 30-50 \text{ eV} \]
\[ u_\parallel \geq 100 \text{ km/s} \]
\[ M_s \sim 1-3 \quad M_A \sim \text{upto} 0.5 \]
H - mode!

Rotation speed \( H \geq 3 \)
Mach number \( H \sim 3 \)
Confinement time \( H \sim 3 \)

See Poster
Teodorescu et al
What do we know about MHD stability to date?
Voltage across plasma remains steady for 1000’s of MHD instability times

- MHD instability growth time $t_{\text{MHD}} \sim 2 - 20 \text{ ms}$
- Measured momentum confinement time $t_{\text{mom}} \sim 200 \text{ ms}$

- No “major disruptions” $\Rightarrow$ MHD Stable?
Carbon series suggests shear in rotation profile
Interchange instabilities lead to mixing, not catastrophic termination.

Huang et al, PoP, 2004
Radial Doppler Shifts smaller than azimuthal shifts

H - 1ms delay after crowbar
O - 2.5 ms delay

Intensity (a.u.)

Occurences

O mode
H mode

Ion drift velocity (km/s)
Interchange instabilities lead to collapse of density/pressure - i.e., poor confinement time

\[ \text{Reynolds \#} \]
\[ R = \frac{L}{\Delta_{\text{MHD}}} \sim 1000 \]

\[ L \sim a^2/\Delta \]

Rayleigh-Benard Theory =>

**turbulent confinement time**
\[ \sim \Delta_{\text{MHD}} R^{1/3} \]

“Flattening parameter”
\[ \frac{<(n'/n) - (n'/n)_{marginal}>_{\text{Laminar}}}{<(n'/n) - (n'/n)_{marginal}>_{\text{Turbulent}}} \sim 50 \]
$\tau_{mom}$ can be measured from stored energy or from “free-wheeling”

\[Q_p \Rightarrow C_p = \frac{Q_p}{V_p}\]
\[R_p \quad \frac{V_p}{I_p} \Rightarrow \tau_{mom} \quad \frac{R_p C_p}{I_p}\]

**Crowbar**

Disconnect $\Rightarrow \tau_{mom}$ measured directly

Crowbar $\tau_{mom} \sim 220 \mu s$

Freewheel $\tau_{mom} \sim 210 \mu s$
Is momentum loss classical or turbulent?

- $\square_{\text{mom}} \sim 200 \, \text{s}$

**Classical loss chc**

- $\square_{\text{on-ion}} \sim a^2/|q|^2$
- $\square_{|l|} > 100 \, \text{s}$
- $\square_{\text{CX}} \sim (N\square u)^{-1}$

**Turbulent loss:**

- $\square_{\text{turb}} \sim \square_{\text{MHD}} \, R^{1/3}$

$\Rightarrow R_{\text{class}} \sim 1000$

- Inconclusive, suggestive?
- MHD modes are ideal
Magnetic probes could yield info on wobbles at the edge

\[ p + B \frac{\partial B}{\partial \rho} = 0 \]

\[ \frac{\partial p}{\partial \rho} \sim p' \frac{\partial r}{\partial r} \]

\[ \frac{\partial r}{\partial a} \sim B \frac{\partial B}{\partial \rho} p \]

\[ \Rightarrow \frac{\partial r}{\partial a} < 1 \text{ cm} \]
Simulations suggest possibility of localized turbulence and transport barriers

- If flow profiles are parabolic, velocity shear not efficacious at the peak
- Localized instability and turbulence
- Transport barriers
Velocity Shear Stabilization of Z-Pinch: Numerical Experiment

Z-Pinch

=> spontaneously unstable to kinks and sausages

Now, force axial flow, with no slip walls

=> stabilization. Wobbles decrease with increasing Mach #
Z-pinch density profile approaches laminarity with increasing Mach #

(1) is the laminar profile (green).

(2) - (6) are turbulent states (blue) with respective (turbulent) Mach numbers 0.3, 1.4, 2.2, 3.7, 4.8.

DeSouza et al, PoP, 2000
V’ Stabilization: Aspect Ratio

- The system approaches laminar as R increases
- $R=4$

Huang et al, PoP, 2004
SUMMARY

- MCX routinely produces fully ionized, high density, supersonically rotating plasmas

- “H-mode” discovered; H-factors in speed, Mach number, confinement time

- Voltage trace across plasma is steady for up to ~1000 MHD instability times, no major disruptions. Suggestive of stable plasma but does not rule out turbulent convection

- Spectroscopy shows radial Doppler shifts x10 smaller than azimuthal
  => no long-lived large scale wobbles

- Confinement times > x10 larger than MHD times
  => MHD instability “ideal”
  => suggests not strongly turbulent from ideal MHD instability
Assessment of MHD stability and V’ shear - Future Plans

- Magnetic probe arrays
- Multi-chord spectrometer for u[r]
- 18 kV Bank to check stability vs applied voltage (M<sub>s</sub>?)
- Confinement time scalings
- Comparison with theory and numerical simulation