Flowing Magnetized Plasma Experiment: Progress and Plans

S. Hsu, Z. Wang, C. Barnes, P. Beinke, and G. Wurden

P-24 Plasma Physics Group, Physics Division
Funded by LANL LDRD Program

ICC Workshop
Madison, WI, May 25-28, 2004
The LANL Flowing Magnetized Plasma (FMP) experiment is a new facility for studying fundamental aspects of high $\beta$ flowing plasmas of relevance to ICC and astrophysical plasmas. Physics topics which can be addressed include: the magnetorotational instability (MRI), dynamo processes, and self-organization to non-Taylor relaxed states.
Physics of Self-Organized High $\beta$ Flowing Plasmas Is Relatively Unexplored

High $\beta$ flowing plasmas

$$\rho(U \cdot \nabla)U = j \times B - \nabla\rho + \rho v \nabla^2 U$$ (steady-state)

Generally, $j \times B \neq 0 \rightarrow$ could lead to interesting relaxed states (non-Taylor)

*in contrast with better understood*

Low $\beta$ plasmas with small or no flow

$j \times B \approx 0 \rightarrow \nabla \times B \approx \lambda B$

Leads to configurations (e.g., RFP, spheromak) well-approximated by force-free (including Taylor) states
An Astrophysical Application: Magnetorotational Instability (MRI)

- Destabilization of MHD slow-mode wave in weakly magnetized, differentially rotating system

- Incompressible fluid displacement in Keplerian disk leads to same equations as two orbiting masses connected by spring with spring constant \((k \cdot v_A)^2\)

- Due to tension, \(m_i\) loses ang. momentum to \(m_o\); \(m_i\) drops down in radius, \(m_o\) radius increases; tension stronger \(\rightarrow\) runaway process \(\rightarrow\) magnetic turbulence
Why Study MRI? Why in Plasma Experiment?

- Angular momentum transport not understood in accretion disks
  - Not from classical molecular or plasma viscosity due to high Reynolds numbers

- MRI postulated to excite magnetic turbulence → enhanced viscosity
  - MRI has not been identified in observations nor realized in laboratory experiments

- Plasma complements liquid metal experiments
  - scalable Prandtl number $P_m$
  - Couette flow profile achieved via $E_R \times B_z$ rotation
Experimentally difficult to keep $B_z < 30$ G →
places constraint on $\Omega_1$ and inner radius $R_1 > 15$ cm

$P_m=10, n=10^{14}$ cm$^{-3}, T_e=10$ eV
$R_1=15$ cm, $R_2=52$ cm

Courtesy of K. Noguchi
Plasma Source Requirements

- Time scale > few predicted growth times of MRI \( \rightarrow \sim 1 \text{ ms} \)
- Density \( \sim 10^{13} - 10^{14} \text{ cm}^{-3} \)
- Temperature \( \sim 10 \text{ eV} \)

Issues:
- End losses require average power input \( \sim 30 \text{ MW} \) to sustain required \( n \) and \( T \)
- Several ms duration requires \( \sim 100 \text{ kJ} \) total stored energy

*Pulsed coaxial gun discharge best candidate to satisfy all the above*
Plasma Rotation Requirements

- Need Couette flow profile \( U_\phi \sim 1/R \rightarrow E_R \sim 1/R \) if \( B_z(R) \) constant (for \( E \times B \) driven rotation)

- For \( U_\phi = U_{E \times B} = C_s \rightarrow E_R = C_s B_Z \approx 150 \text{ V/m} \) for \( B=50 \text{ G} \) and \( T_e=10 \text{ eV} \)

- For negative bias center electrode \( I_{\text{sat}} \approx (1/2) n e A C_s \approx 200 \text{ A} \) (5 cm diameter, 1 m long rod, \( T_e=10 \text{ eV} \)) \( \rightarrow 20 \text{ kW} \) required

Issues:
- Will \( U_\phi \) arise from \( E_R B_Z \)?
- Understand \( E_R(R) \) penetration into plasma
- How to get desired \( E_R(R) \) profile?
- Achieve desired biasing without drawing too much electrode current (worry about intolerably high \( B \)-field)
Old CTX Spheromak Facility Resurrected as FMP

c coaxial
gun
FMP Bank Constructed With Recycled Capacitors

0.72 F bank at 900 V → 300 kJ
More Experimental Details

- Base vacuum $1 \times 10^{-6}$ T
  - 3 turbo pumps (total 1500 l/s)
- Up to 500 G axial $B_{z0}$ via external magnets powered by 30 V, 1250 A DC supply

- Large control room
- LabView control and data acquisition, IDL analysis
- Dozens of CAMAC channels, 1-100 MHz, 8 & 10 bits
Sub-kV Breakdown Using Magnetic Trap Yields Long Duration Plasma w/Required $n_e T_e$

NdFeB rare-earth permanent magnets

5 kG

gun end-view

Los Alamos
Installed and Planned Diagnostics

- Mach probe
- Flux loops
- Edge magnetic probes
- Triple probe, magnetic probes
- Photodiode
- Phantom camera
- Coaxial gun
- Rogowski coil & voltage divider

Planned: Doppler spectroscopy, B-probe arrays
High $\beta$ Plasma Has Been Achieved

- Electron pressure from triple probe
- Magnetic energy from flux loop (assuming small $B_R$ and $B_Z \sim B_\phi$)
- Peak electron $\beta_e \approx 30\%$

See Wang poster regarding diamagnetism
Preliminary Measurements Suggest Radially Peaked Pressure Profile

Want to measure/establish radial force balance (in quasi steady-state):

\[ [\rho (\mathbf{U} \cdot \nabla) \mathbf{U} = \mathbf{j} \times \mathbf{B} - \nabla \rho + \rho \nu \nabla^2 \mathbf{U}]_R \]

need \( p(R) \), \( B(R) \), and \( U(R) \) measurements (to be finished in next experimental campaign)

Triple probe setup has just been upgraded to reach \( R=0 \). Data forthcoming.

\((n_e \text{ and } T_e \text{ averaged over } 1.5\text{–}2.5 \text{ ms})\)
Floating Potential Measurements Indicate Inward Radial Electric Field with Gradient

Triple probe setup has just been upgraded to reach $R=0$. Data forthcoming.

$V_f$ averaged over 1.5–2.5 ms

$E_R \approx -40$ V/m ($V_{ExB} \approx 2$ km/s)

$E_R \approx -250$ V/m ($V_{ExB} \approx 12.5$ km/s)

($C_s \sim 40$ km/s)
Edge Magnetic Probe Signals Consistent with Rotating $n=1$ Mode

phase velocity $\approx 34 \text{ km/s} \sim C_s \sim V_A/2$
$n=1$ Mode Frequency Increases with $B_{Z0}$

$$f \approx 32.2B_{Z0} \approx 0.02f_{ci}$$

$B_{Z0}$ scaling does not appear consistent with $E \times B$

mode frequency from dominant ($n=1$) Fourier component of magnetic probe signal
Addition of Floating End Electrode Improves Plasma Temperature and Density

Langmuir probe at $R=65$ cm (wall at 70 cm)
Flow Measurements Planned Using Mach Probe

\[ \frac{U}{C_s} = \alpha \ln\left( \frac{V_{up}}{V_{down}} \right) \]

where \( \alpha \approx 0.75 \) for unmagnetized Mach probe

Hutchinson, PoP (2002)

Built by E. Dies (NUF, 2003)
Need to Reduce Plasma Currents for MRI Studies: Try Different Bias Electrodes

1. Floating end electrode: leads to increased $n$, $T$ but still observe large currents and $n=1$ mode

2. End electrode electrically tied to inner gun electrode: expected to reduce $I_Z$ in plasma, might suppress $n=1$ mode

3. Center rod electrode tied to inner gun electrode: forces $\nabla \phi$ to be perpendicular to $B_Z$, probably best chance at sheared azimuthal flow profile if $E \times B$
Summary & Plans

• New Flowing Magnetized Plasma (FMP) experiment underway at LANL

• A unique experiment for studying fundamental plasma physics of high $\beta$ flowing plasmas and MRI

• Preliminary results indicate several ms duration high $\beta$ plasma with peaked pressure profiles and existence of rotating global mode

• Upcoming plans:
  - Diagnostic upgrade/additions, full profile measurements of $p$, $B$, $U$
  - Try different electrode biasing schemes to establish suitable rotational equilibrium for MRI excitation