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

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The LANL Flowing Magnetized Plasma (FMP) experiment is a new facility for studying fundamental aspects of high β 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.

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Physics of Self-Organized High β Flowing Plasmas Is Relatively Unexplored

High β flowing plasmas

$\rho(\mathbf{U}\cdot\nabla)\mathbf{U} = \mathbf{j} \times \mathbf{B} - \nabla p + \rho\nu\nabla^2\mathbf{U}$ (steady-state)

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

in contrast with better understood

Low β plasmas with small or no flow

$\mathbf{j} \times \mathbf{B} \approx 0 \rightarrow \nabla \times \mathbf{B} \approx \lambda\mathbf{B}$

Leads to configurations (*e.g.*, RFP, spheromak) well-approximated by force-free (including Taylor) states

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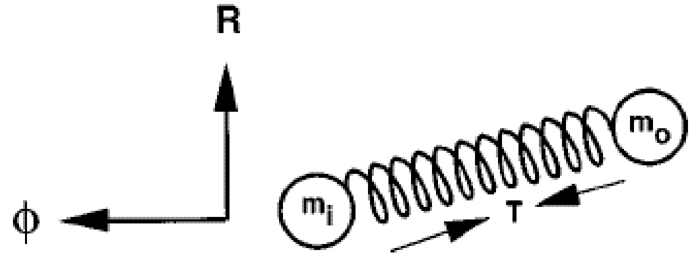
An Astrophysical Application: Magnetorotational Instability (MRI)

- 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 $(\mathbf{k}\cdot\mathbf{v}_A)^2$



- Due to tension, m_i loses ang. momentum to m_o; m_i drops down in radius, m_o radius increases; tension stronger → runaway process → magnetic turbulence

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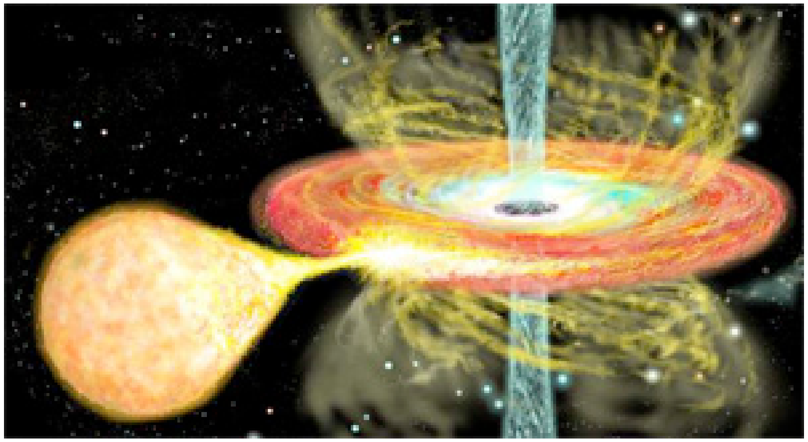
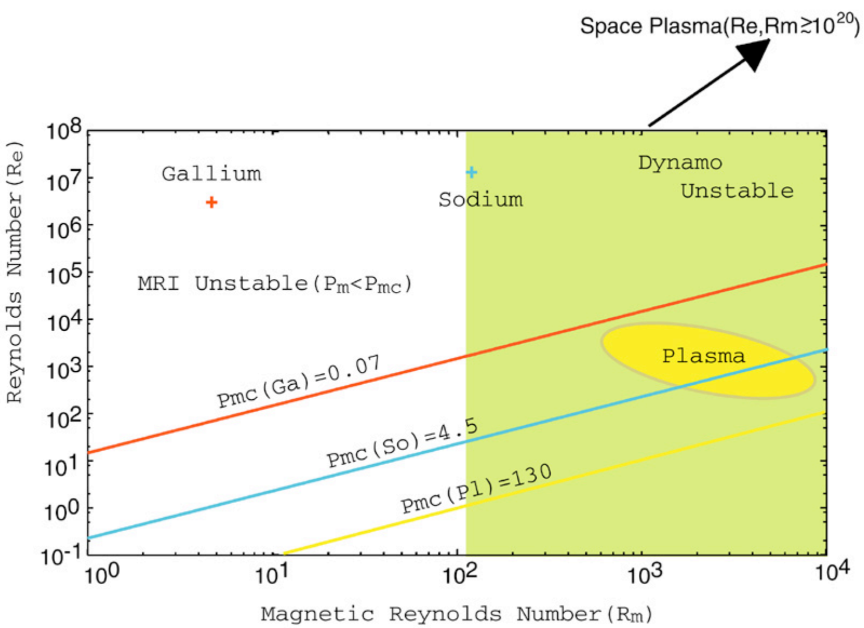
Why Study MRI? Why in Plasma Experiment?



Drawing of binary star system with accretion disk and jets.



- 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

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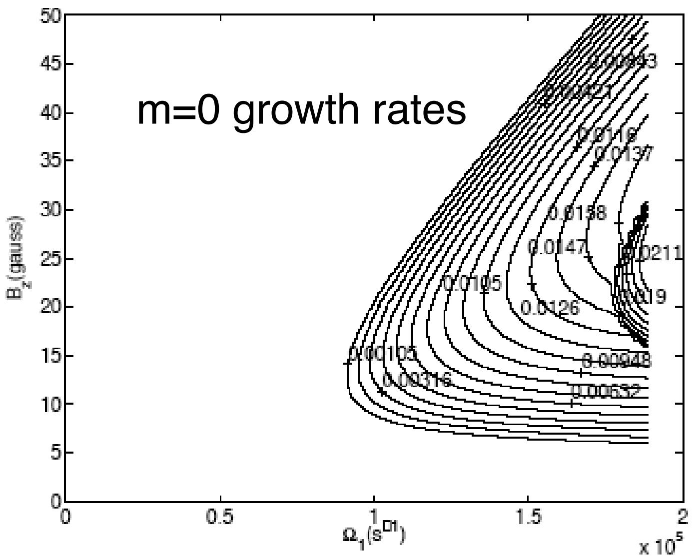
MRI Linear Stability Analysis

$$[(\gamma+\nu k^2)(\gamma+\eta k^2)+\omega_A^2]^2+\frac{\partial\Omega^2}{\partial\ln r}\frac{k_z^2}{k^2}\omega_A^2=0.$$

Instability Condition

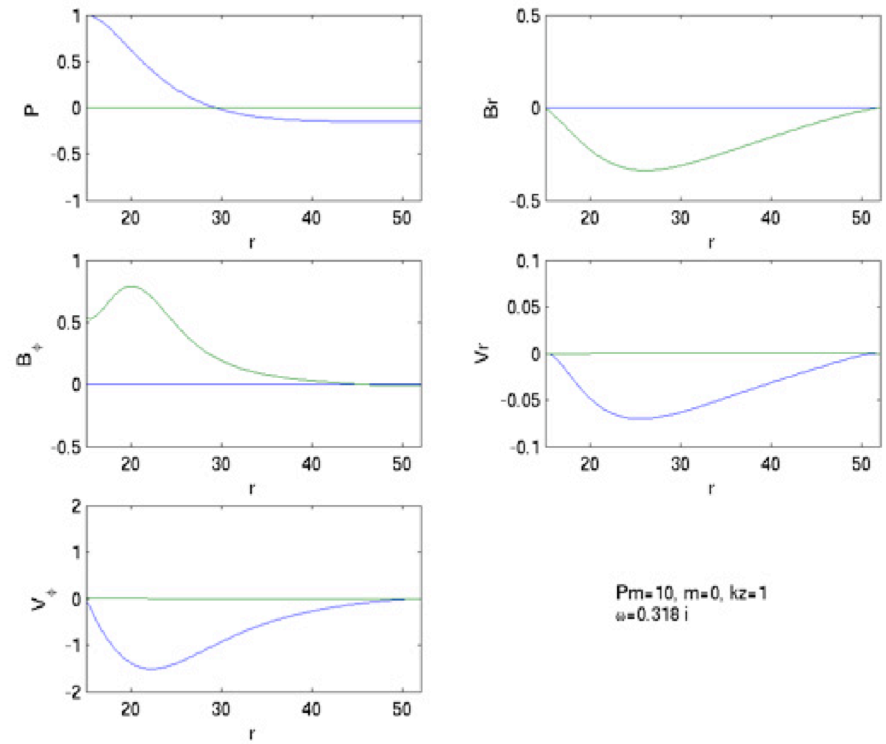
$$\omega_\nu\omega_\eta+\omega_A^2<\sqrt{2r\Omega\Omega'}\frac{k_z}{k}\omega_A$$

shear Ω´ destabilizing; ν,η stabilizing



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

m=0 perturbed eigenfunctions



Experimentally difficult to keep $B_Z < 30$ G →
places constraint on Ω_1 and inner radius $R_1 > 15$ cm

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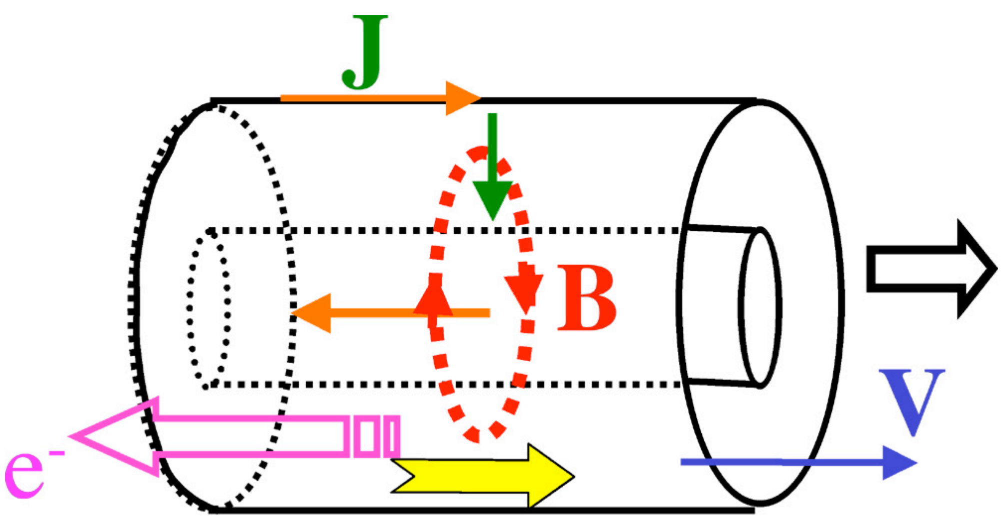
Courtesy of K. Noguchi

Plasma Source Requirements

- Time scale > few predicted growth times of MRI → ~1 ms
- Density ~ $10^{13} – 10^{14}$ cm^{-3}
- Temperature ~ 10 eV

Issues:

- End losses require average power input ~30 MW to sustain required *n* and *T*
- Several ms duration requires ~100 kJ total stored energy



Pulsed coaxial gun discharge best candidate to satisfy all the above

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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)

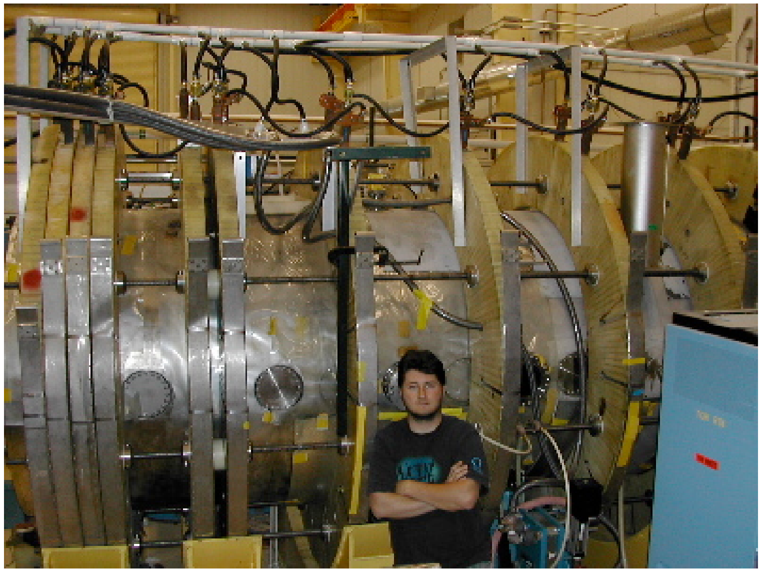
- For $U_\phi = U_{E\times B} = C_s \rightarrow E_R = C_s B_Z \approx$ 150 V/m for B=50 G and T_e=10 eV

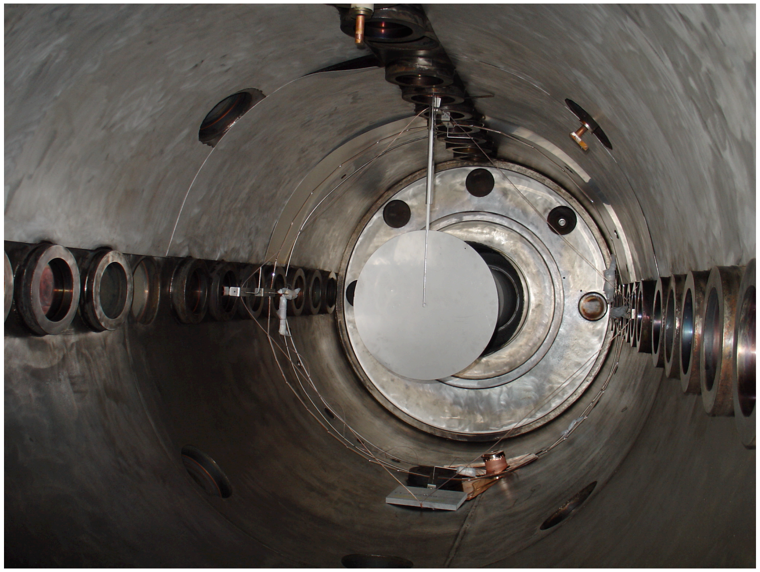
- For negative bias center electrode $I_{sat} \approx (1/2) neAC_s \approx 200$ A (5 cm diameter, 1 m long rod, T_e=10 eV) $\rightarrow$ 20 kW required

Issues:

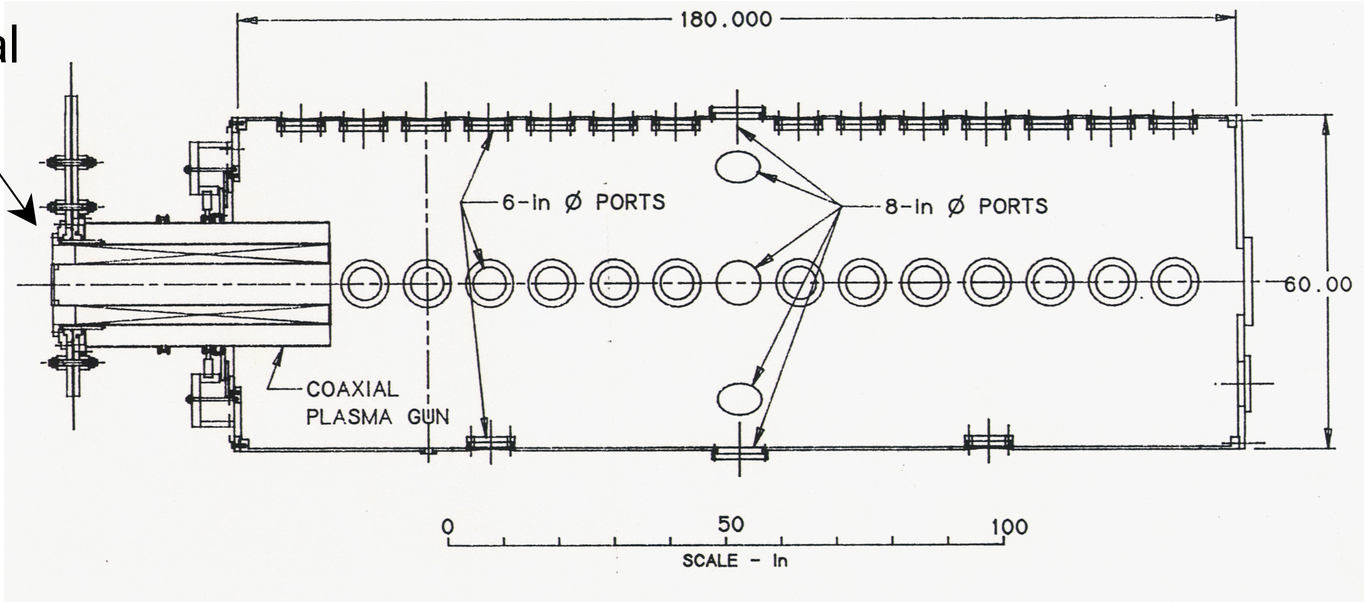
- Will U_ϕ arise from $E_R B_Z$?
- Understand $E_R(R)$ penetration into plasma
- How to get desired $E_R(R)$ profile?
- Achieve desired biasing without drawing too much electrode current (worry about intolerably high B-field)

Old CTX Spheromak Facility Resurrected as FMP

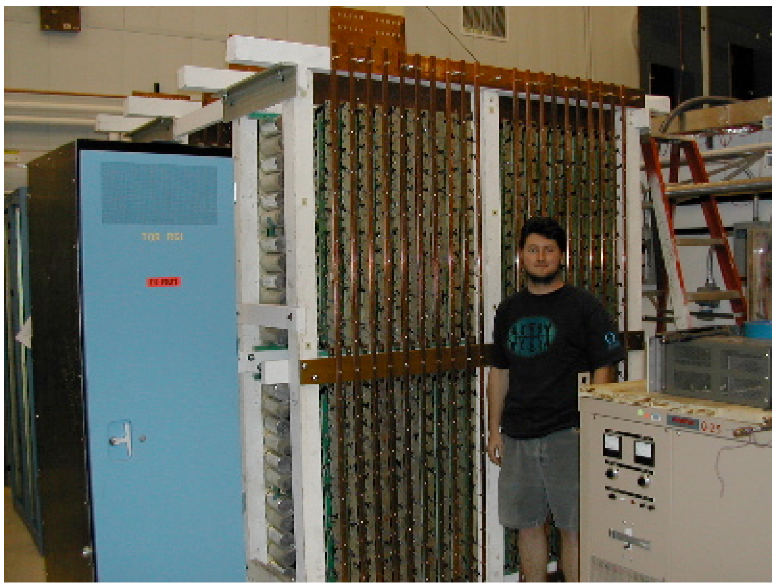


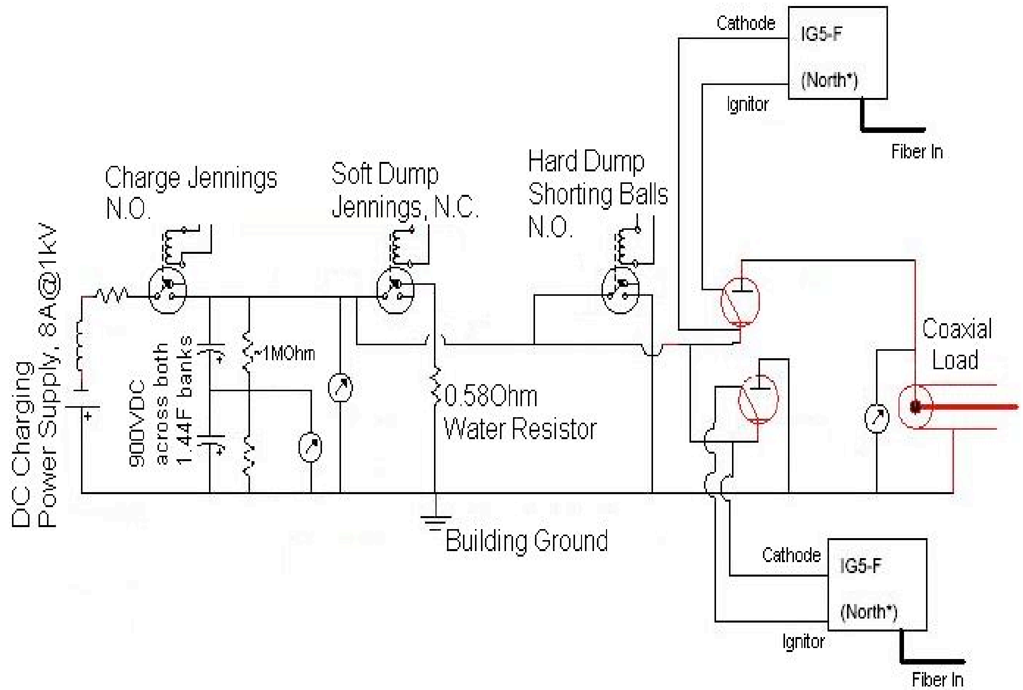


coaxial gun



FMP Bank Constructed With Recycled Capacitors

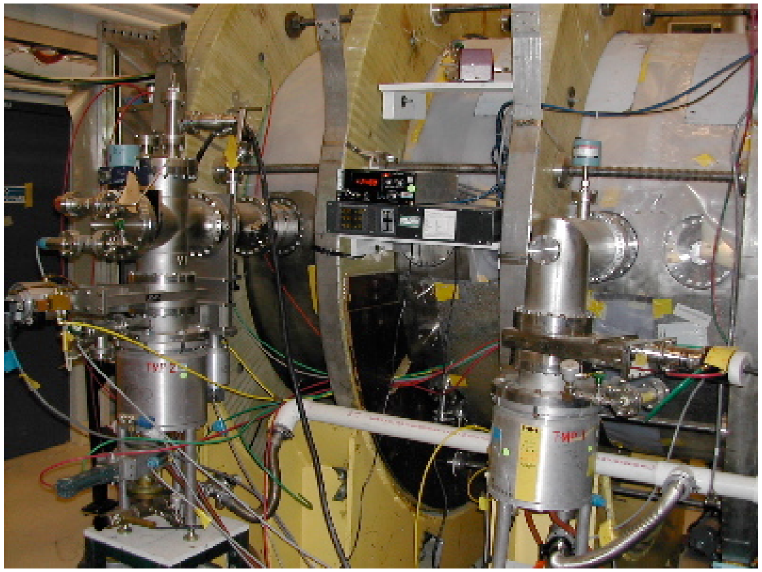




0.72 F bank at 900 V → 300 kJ

More Experimental Details

- Base vacuum 1×10^{-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

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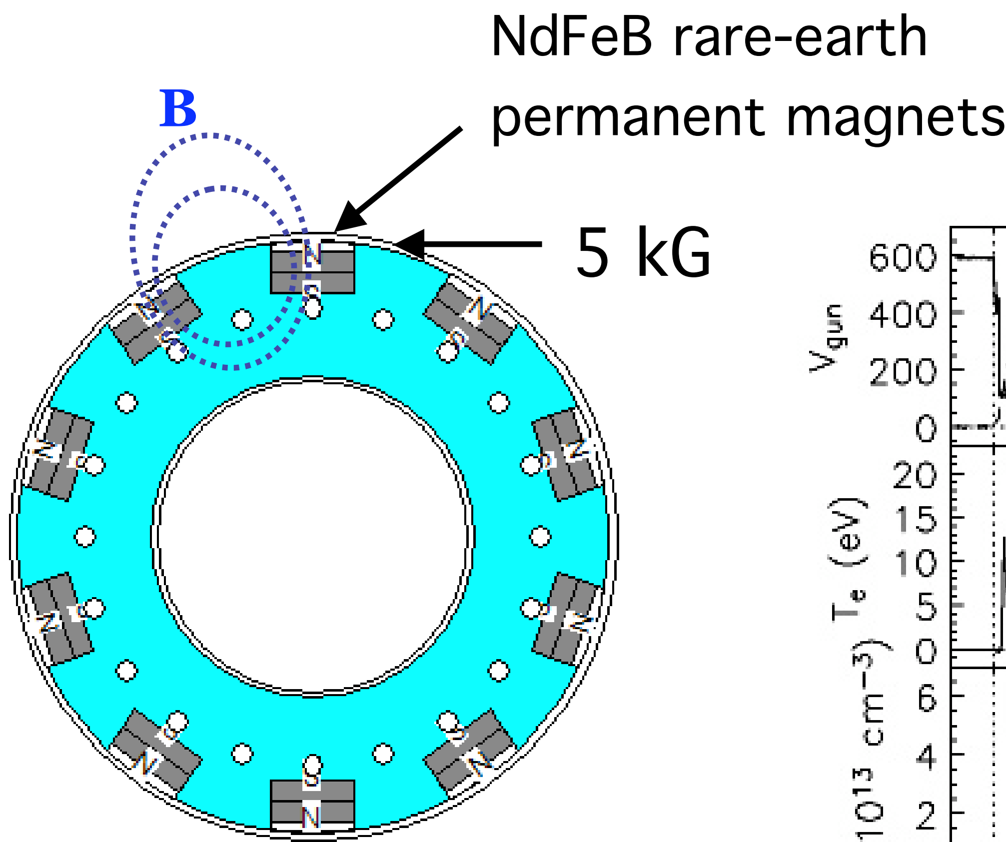
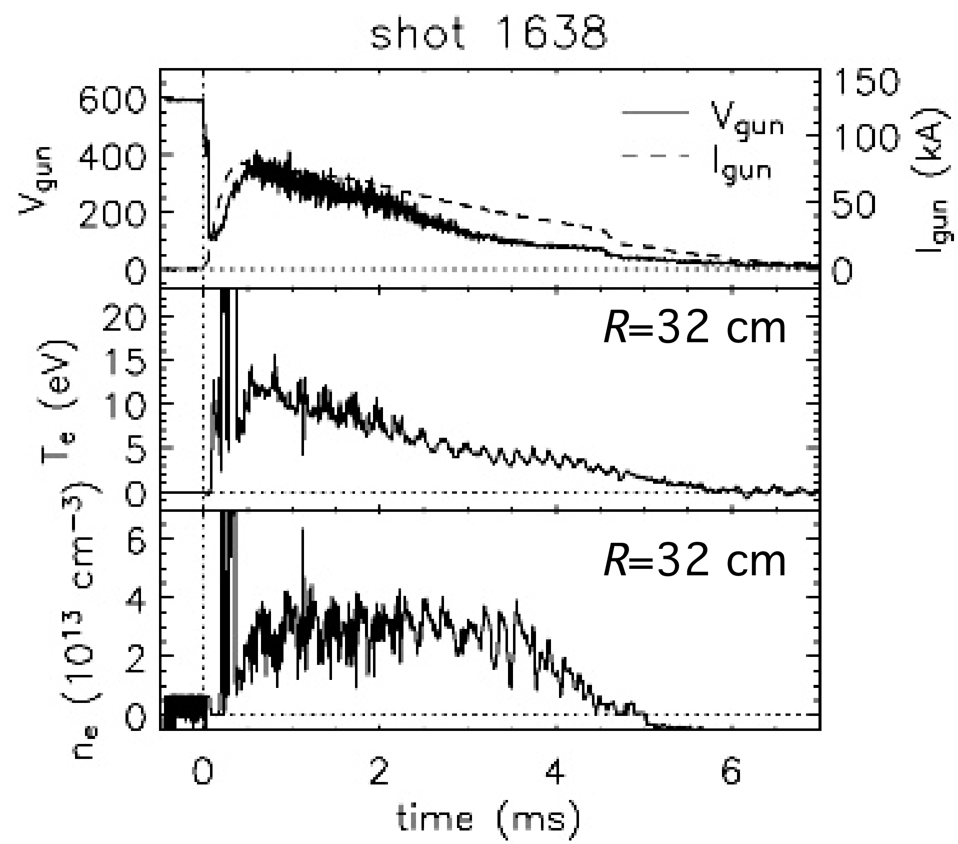
Sub-kV Breakdown Using Magnetic Trap Yields Long Duration Plasma w/Required $n_e T_e$



gun end-view



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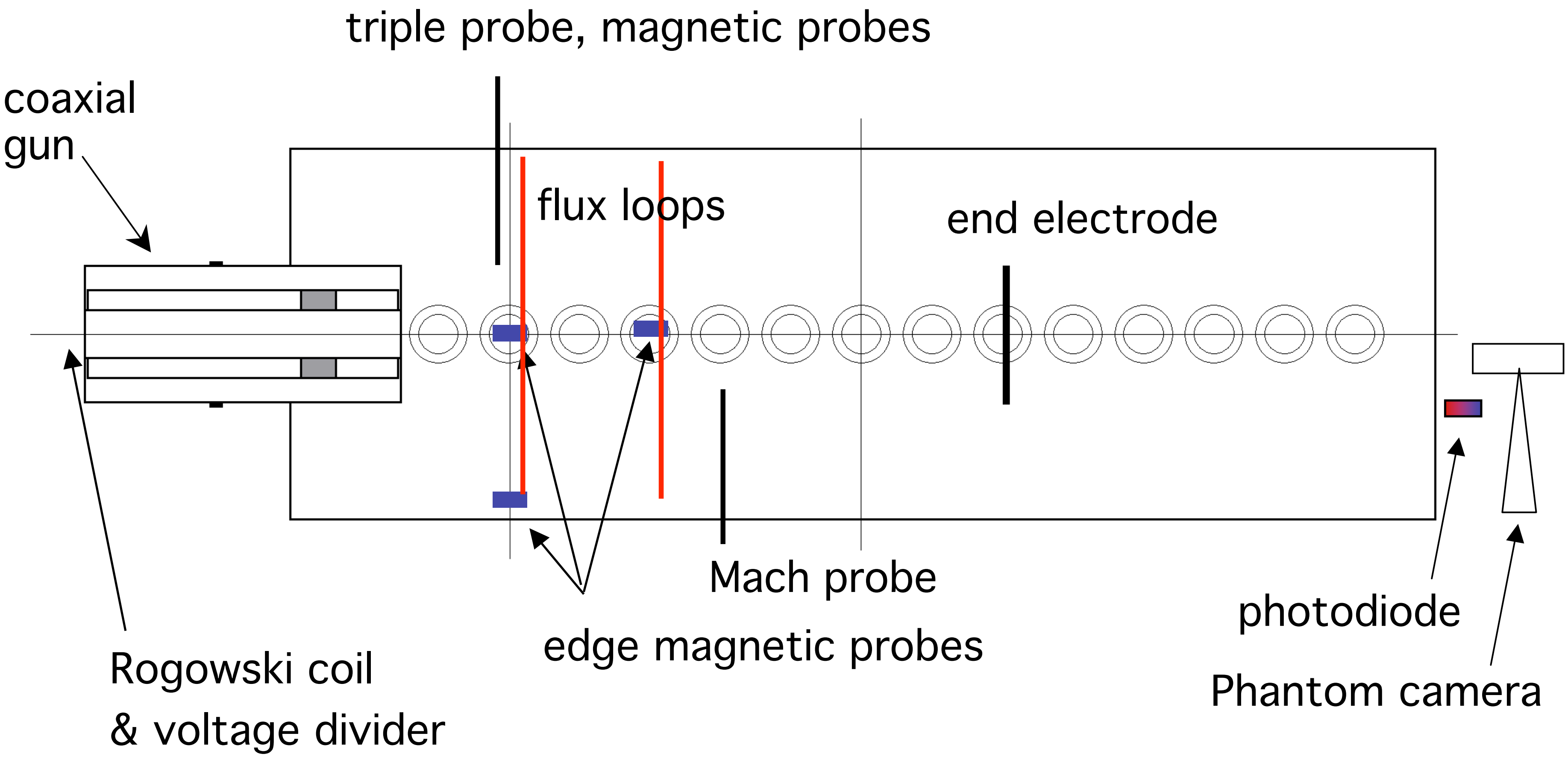
Installed and Planned Diagnostics



Planned: Doppler spectroscopy, B-probe arrays

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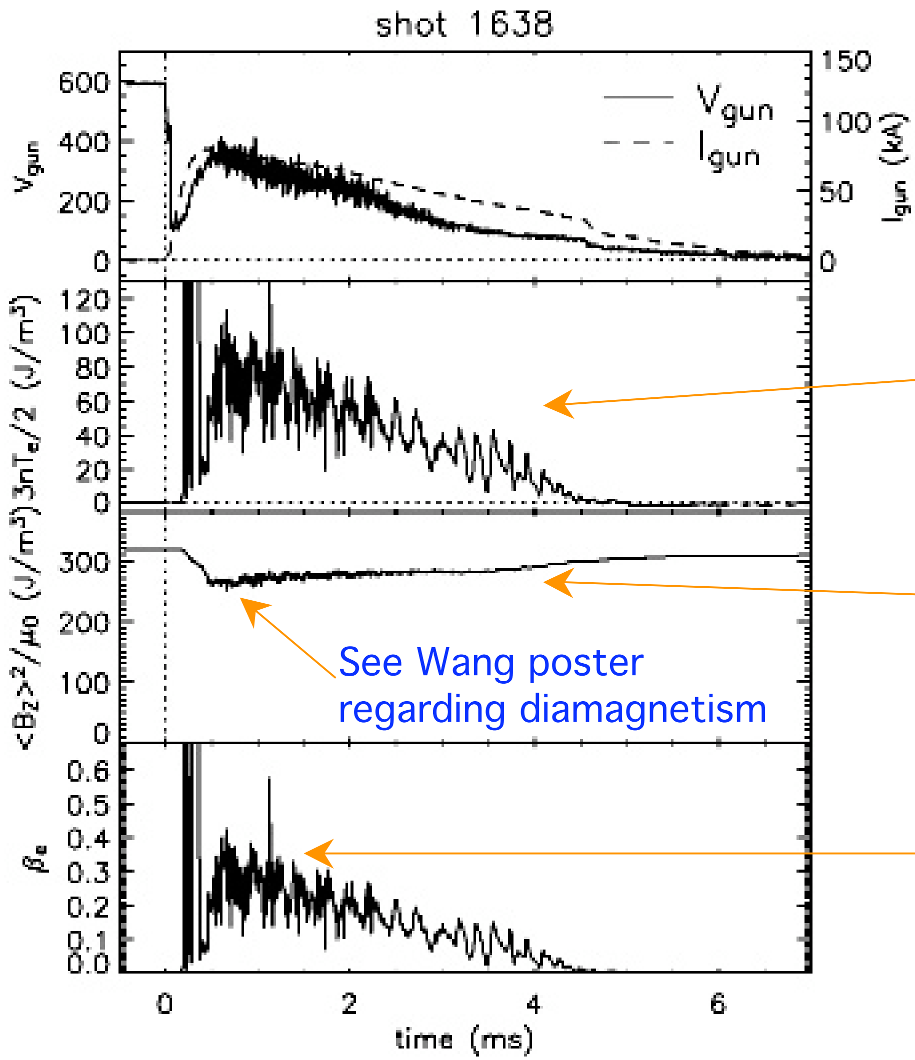
High β Plasma Has Been Achieved



electron pressure from triple probe

magnetic energy from flux loop (assuming small B_R and $B_Z \sim B_\phi$)

peak electron $\beta_e \approx 30\%$

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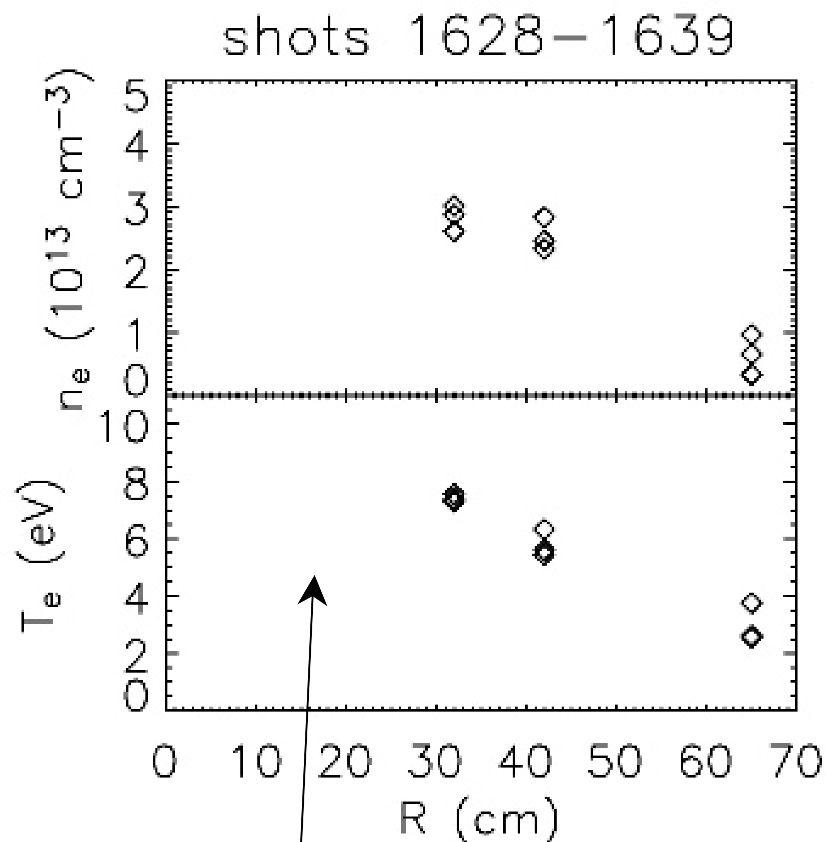
Preliminary Measurements Suggest Radially Peaked Pressure Profile



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

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

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 and T_e averaged over 1.5–2.5 ms)

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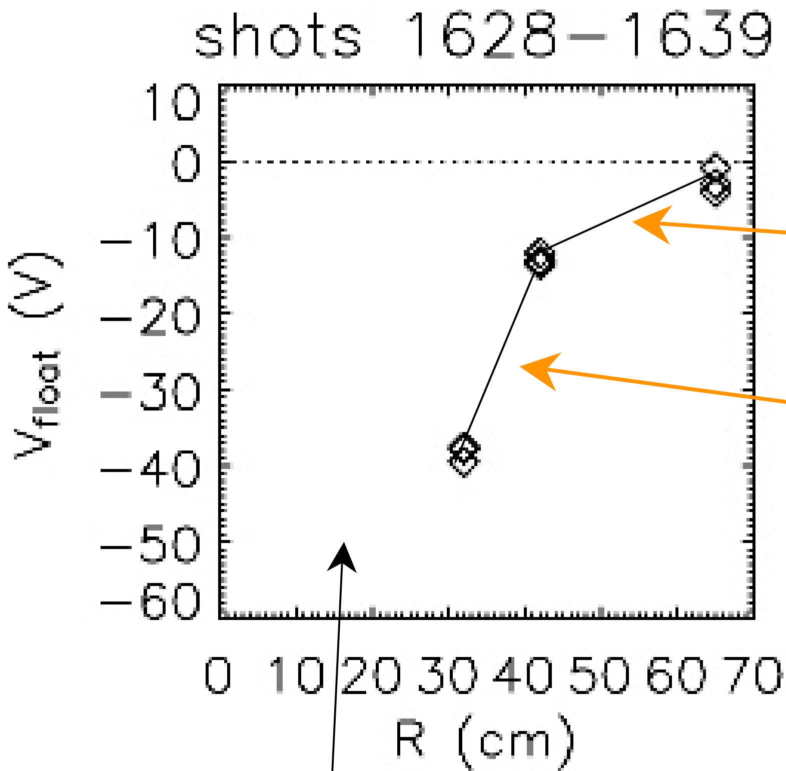
Floating Potential Measurements Indicate Inward Radial Electric Field with Gradient



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

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

($C_s \sim$ 40 km/s)

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

(V_f averaged over 1.5–2.5 ms)

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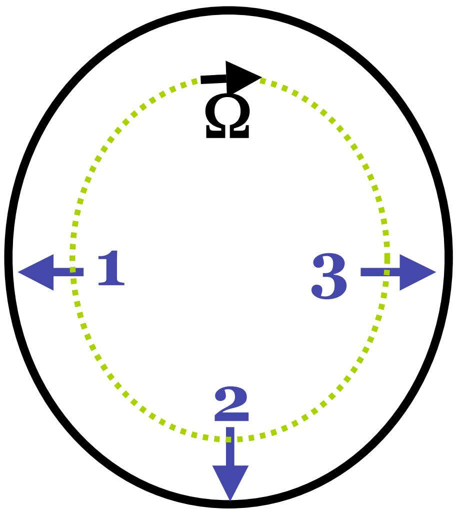
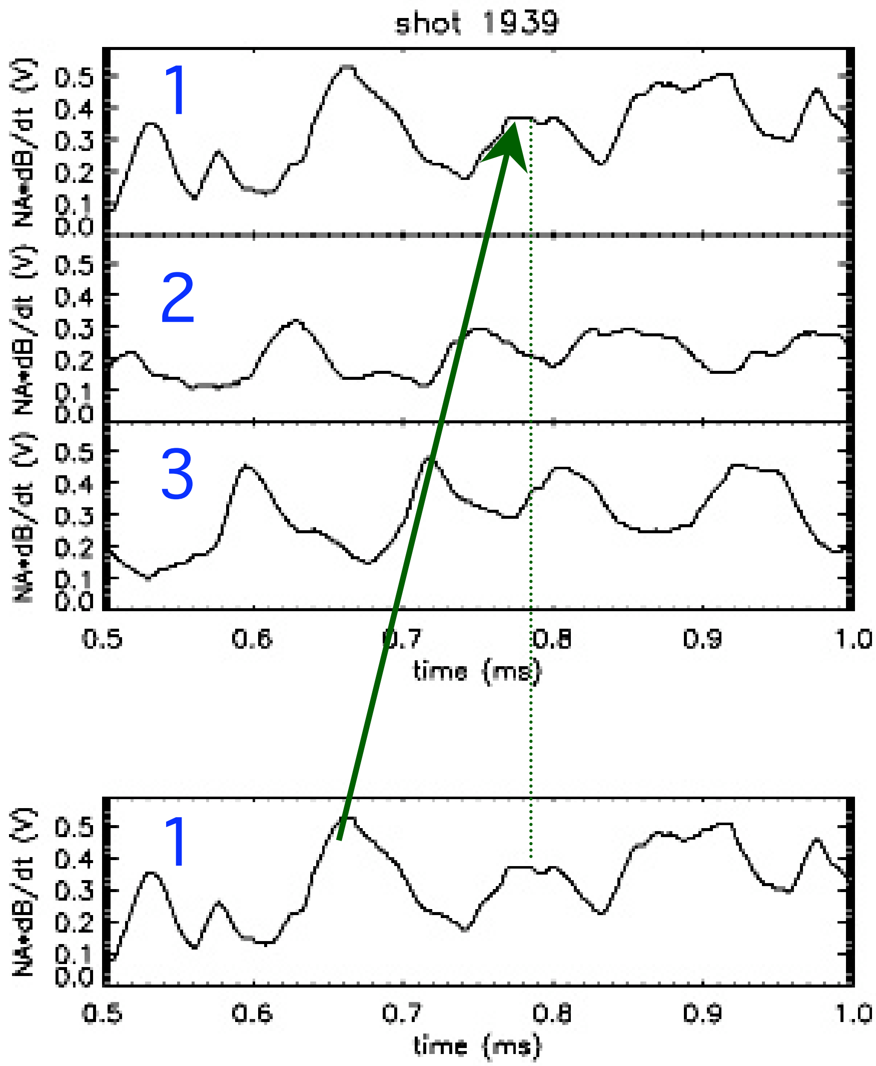
Edge Magnetic Probe Signals Consistent with Rotating *n*=1 Mode





phase velocity ≈ 34 km/s ~ $C_s \sim V_A/2$

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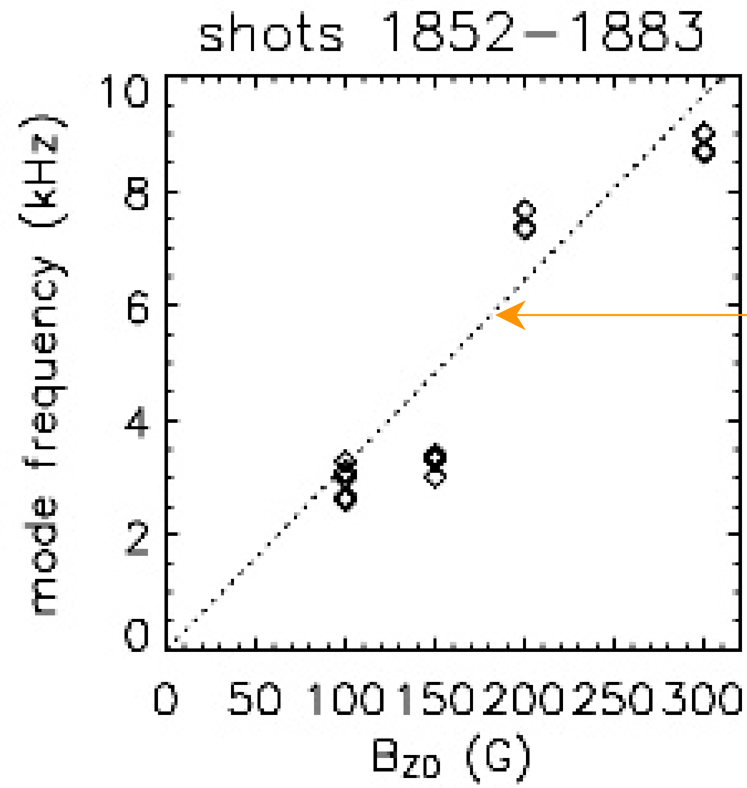
n=1 Mode Frequency Increases with B_{Z0}



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

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

mode frequency from dominant (n=1) Fourier component of magnetic probe signal

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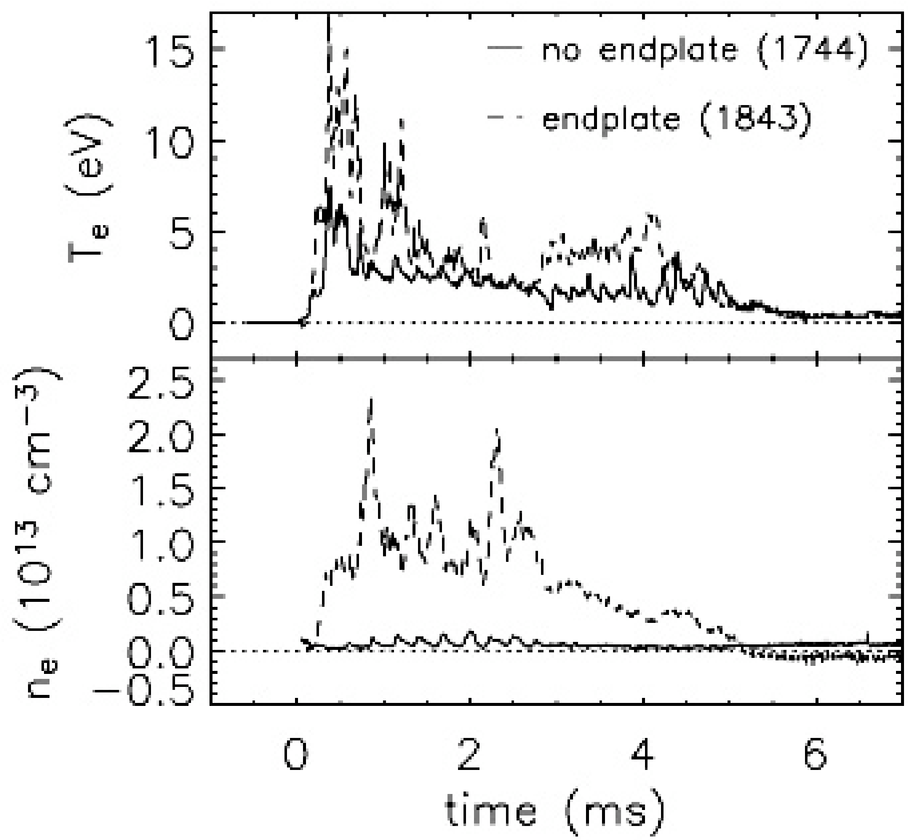
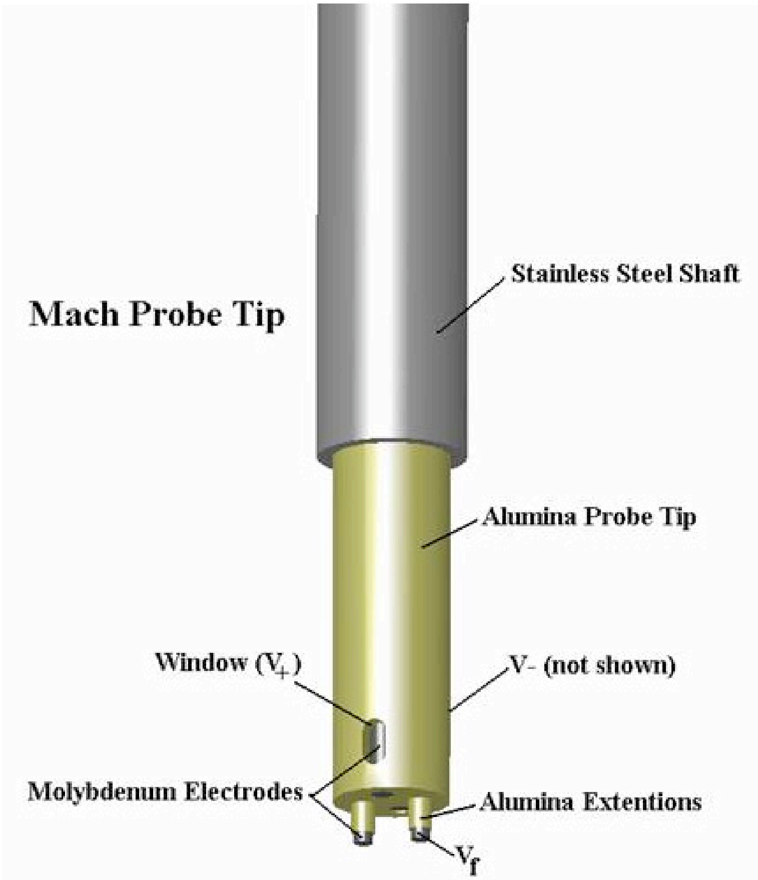
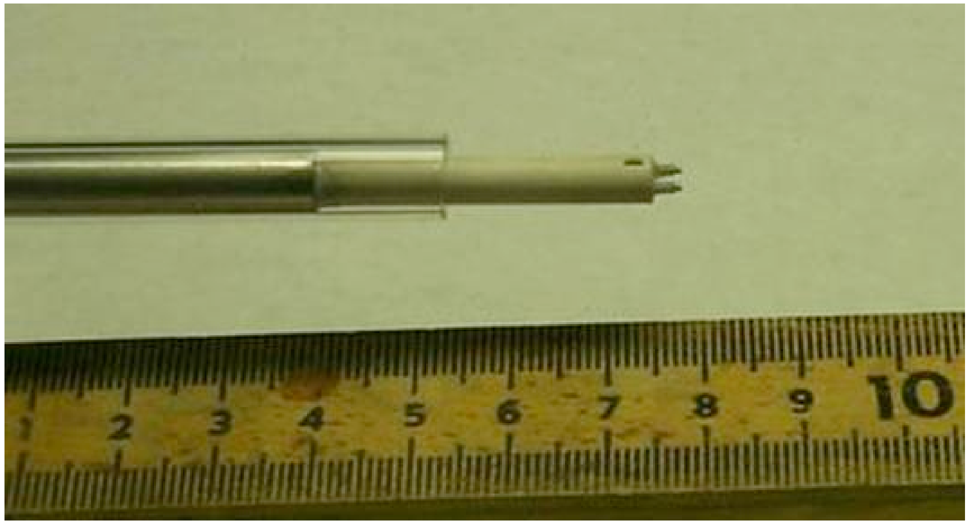
Addition of Floating End Electrode Improves Plasma Temperature and Density



Langmuir probe at *R*=65 cm (wall at 70 cm)

Flow Measurements Planned Using Mach Probe





$$U/C_s = \alpha \ln(V_{up}/V_{down})$$

where $\alpha \approx 0.75$ for unmagnetized Mach probe

Hutchinson, PoP (2002)

Built by E. Dies (NUF, 2003)

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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 β flowing plasmas and MRI
- Preliminary results indicate several ms duration high β 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

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