Spinning an Unmagnetized Plasma for Magnetorotational and Dynamo Experiments

Cami Collins
Cary Forest, Mike Clark, John Wallace, Carl Wahl, Blair Seidlitz, Chris Cooper, David Weisberg, Jason Milhone, Ken Flanagan, Ivan Khalzov, Fatima Ebrahimi

University of Wisconsin - Madison

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Where do magnetic fields come from?

Why does matter rapidly fall inward in accretion disks?

\[ \rho V^2 \gg B^2 / \mu_0 \]

\[ Rm = \mu_0 \sigma VL \gg 1 \]
Why Plasma? (instead of liquid metal)

- Explore large $Rm$ and destabilize at lower $B$

- Vary $Pm = \mu_0 \sigma v$ from the liquid metal/protoplanetary disk regime ($Pm << 1$) to black hole, neutron star disk ($Pm >> 1$)

- Study effects beyond ideal MHD (two fluid Hall effect, plasma-neutral interactions, compressibility)
Laboratory Studies of Flow-Driven MHD Instabilities

Plasma Couette Experiment

Madison Plasma Dynamo Experiment

• Challenge:
  - Need confinement for plasma to be hot ($\sigma$) and dense ($\rho$)
  - Difficult to drive flow in an unmagnetized plasma
• Confining and stirring an unmagnetized plasma in the Plasma Couette Experiment (PCX)

• Creating flow profiles to study the magnetorotational instability, a mechanism thought to be important in accretion disks

• Application of this new stirring technique for dynamo studies in MPDX
Keplerian flows of conducting fluids are hydrodynamically stable.

Can be destabilized by a magnetic field: the magnetorotational instability (MRI).

\[ V_\phi = \sqrt{\frac{GM}{r}} \]  
\[ V_\phi = Ar + \frac{B}{r} \]
The Concept: Create Plasma Rotation Using Biased Cathodes

- Toroidally localized electrodes are biased to create JxB torque
- Velocity couples inward through viscosity
- Rotation is axisymmetric
The Rotation Scheme Works!

He Velocity Profile
2 Outer Cathodes Biased 550 V
(measured with Mach probe)

$Pm \approx 10$  $Rm \approx 50$

$V_\phi$ couples inward through viscosity

Rotation Driven
At Magnetized Edge

$\mathbf{ECH}$

Current

Pressure

$kW$ or Amp

Pressure

Current

$Te$

$\rho$

$V_\phi$[km/s]

$N_{el}$/m$^3$

Time [s]

Radius [m]

$m^{-3}$
The Rotation Scheme Works!

He Velocity Profile
2 Outer Cathodes Biased 550 V
(measured with Mach probe)

Thursday, April 11, 2013
Ion Centrifugal Force is Balanced by Electron Pressure

\[ m n \left[ \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] = q n \mathbf{E} - \nabla p \]

Electron force balance:

\[ 0 = e n_e \frac{d \Phi}{d r} - T_e \frac{d n_e}{d r} \]

Ion force balance:

\[ M_i \frac{V_\phi(r)^2}{r} = e \frac{d \Phi}{d r} \]
Radial Electric Field Measurement in Spinning Plasma

Ar Floating Potential Profile

Volts

Radius [m]

Location of Anode

Tips to Measure Floating Potential

Mach Probe

2 cm
Electric Field and Velocity Measurements Agree

Ar Floating Potential Profile

$M_i \frac{V_\phi(r)^2}{r} = e \frac{d\Phi}{dr}$

5.5 V/m

2 km/s

Ar Velocity Profile

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Viscosity Competes with Neutral Drag as Velocity Spreads Inward

\[ mn \frac{dV_\phi}{dt} = (\mathbf{J} \times \mathbf{B})_\phi - \frac{mnV_\phi}{\tau_{i0}} + mn\nu \left[ \nabla^2 V \right]_\phi \]

- edge-applied torque
- drag term, from ion neutral \( \sigma \)
- viscosity couples momentum inward

\[ \tau_{i0} \approx (n_0\langle \sigma \sigma \rangle)^{-1} \]
\[ \nu = 0.96v_{ti}^2\tau_{ii} \]

Steady state velocity profiles can be calculated using measured plasma parameters \((n, T_e, \text{neutral pressure})\) and modified Bessel functions:

\[ v_\phi(r) = AI_1(r/L_v) + BK_1(r/L_v) \]

where the characteristic momentum diffusion length scale is:

\[ L_v = \sqrt{\tau_{i0}\nu} = 21 \text{ cm} \sqrt{\frac{f_{i1, T_{i1, eV}}}{\nu}} \]

(without neutral drag, the solution is Couette flow)

\[ V_\phi = Ar + \frac{B}{r} \]
Viscosity Can Be Estimated By Fitting Velocity Profiles

<table>
<thead>
<tr>
<th>Case</th>
<th>n x 10^{11} (cm^{-3})</th>
<th>f_{ion} (%)</th>
<th>Te (eV)</th>
<th>Ti_{fit} (eV)</th>
<th>V_{max} (km/s)</th>
<th>Rm</th>
<th>Re</th>
<th>Pm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>.77</td>
<td>27</td>
<td>7</td>
<td>0.6</td>
<td>2.2</td>
<td>11</td>
<td>8</td>
<td>1.3</td>
</tr>
</tbody>
</table>

\[ \nu_{um} \propto \frac{T_i^{5/2}}{n \sqrt{\mu}} \]

Future plans to measure Ti and confirm Braginskii viscosity
Braginskii Viscosity Depends on Magnetization

<table>
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<tr>
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<th>$f_{ion}$ (%)</th>
<th>$T_e$ (eV)</th>
<th>$T_{i_{fit}}$ (eV)</th>
<th>$V_{max}$ (km/s)</th>
<th>$R_m$</th>
<th>$R_e$</th>
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Braginskii, Sec. 4, (1965)
Helium is less viscous in the magnetized region.

Helium has much smaller ionization fraction.

Neutral Drag Modifies Profiles

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<td>11</td>
<td>8</td>
<td>1.3</td>
</tr>
<tr>
<td>He</td>
<td>.45</td>
<td>0.6</td>
<td>11</td>
<td>0.4</td>
<td>2.4</td>
<td>22</td>
<td>5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

$\nu_{um} \propto \frac{T_{i}^{5/2}}{n \sqrt{\mu}}$

$\nu_{m} \propto \frac{n \sqrt{\mu}}{B_{0}^{2} \sqrt{T_{i}}}$

[PRL 108, 115001 (2012)]

Thursday, April 11, 2013
Next Step: Rotate from the Inner Boundary

![Graph showing velocity curves for Keplerian, Solid Body, and Couette models.](Image)
Center Stack Assembly for Inner Boundary Rotation

Pulley for raising and lowering center stack into garage

Cathodes are heated tungsten filaments

Center Stack
Cathode Placement is Critical
Spinning from the Inner Boundary

Helium, 3 Inner Cathodes
500 V inner, 400 V outer
Spinning from the Inner Boundary

### 3 Inner Cathodes
- Voltage: 500 V inner, 400 V outer
- Velocity: $V_\phi$ [km/s]

### 5 Inner Cathodes
- Voltage: 575 V inner, 350 V outer
- Velocity: $V_\phi$ [km/s]

#### Parameters

<table>
<thead>
<tr>
<th></th>
<th>3 Inner Cathodes</th>
<th>5 Inner Cathodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_\phi$ [km/s]</td>
<td>500 V inner, 400 V outer</td>
<td>575 V inner, 350 V outer</td>
</tr>
</tbody>
</table>

| Name         | 0.11 eV | 0.216 eV | 0.25 eV | 0.32 eV | 5.9 eV | 5.3 eV | 6.5 eV | 7.5 eV | 1.7 | 1.8 | 2.4 | 2.3 | 0.35% | 0.37% | 0.74% | 0.65% | 0.2 | 0.88 | 1.3 | 2.9 | 19 | 25 | 46 | 64 | 5.1 | 10 | 11 | 17 |
|--------------|---------|----------|---------|---------|--------|--------|--------|--------|-----|-----|-----|-----|------|------|------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $Ti$         |         |          |         |         | 5.9    | 5.3    | 6.5    | 7.5    |     |     |     |     | 0.35%| 0.37%| 0.74%| 0.65%| 0.2 | 0.88 | 1.3 | 2.9 | 19 | 25 | 46 | 64 | 5.1 | 10 | 11 | 17 |
| $Te$         |         |          |         |         | 5.9    | 5.3    | 6.5    | 7.5    |     |     |     |     | 0.35%| 0.37%| 0.74%| 0.65%| 0.2 | 0.88 | 1.3 | 2.9 | 19 | 25 | 46 | 64 | 5.1 | 10 | 11 | 17 |
| $n \times 10^{16}$ cm$^{-3}$ | 1.7 | 1.8 | 2.4 | 2.3 | 0.35% | 0.37% | 0.74% | 0.65% | 0.2 | 0.88 | 1.3 | 2.9 | 19 | 25 | 46 | 64 | 5.1 | 10 | 11 | 17 |
| Ionization   | 0.35%   | 0.37%   | 0.74%   | 0.65%   |        |        |        |        | 0.2 | 0.88 | 1.3 | 2.9 | 19 | 25 | 46 | 64 | 5.1 | 10 | 11 | 17 |
| $Pm$         | 0.2     | 0.88    | 1.3     | 2.9     |        |        |        |        | 0.2 | 0.88 | 1.3 | 2.9 | 19 | 25 | 46 | 64 | 5.1 | 10 | 11 | 17 |
| $Rm$         | 19      | 25      | 46      | 64      |        |        |        |        | 0.2 | 0.88 | 1.3 | 2.9 | 19 | 25 | 46 | 64 | 5.1 | 10 | 11 | 17 |
| $Rm$ inner   | 5.1     | 10      | 11      | 17      |        |        |        |        | 0.2 | 0.88 | 1.3 | 2.9 | 19 | 25 | 46 | 64 | 5.1 | 10 | 11 | 17 |

*Thursday, April 11, 2013*
Profiles are Approaching MRI Unstable Regime

To observe MRI, we simply need a weak seed field and Keplerian-like rotation that satisfies:

\[
\frac{\partial \Omega}{\partial r} < 0 \quad \frac{\partial (r^2 \Omega)}{\partial r} > 0
\]

-Note: still need to turn on the Bz field (may change filament placement)
• MRI growth rates can be estimated by a local stability analysis of incompressible, dissipative MHD with Hall term.
• The Hall term becomes important when ions are decoupled from the B field (ex: collisions with neutrals or finite device size)
• Result: Large growth rate appears only when $B$ is antiparallel to $\Omega$

Helium
$V_o=6.5$ km/s,
$n=2 \times 10^{18}$ m$^{-3}$,
$T_e=8$ eV,
$T_i=1.5$ eV,
How Does Ion-Neutral Drag Affect MRI?

\[
\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla) \mathbf{V} = \frac{(\mathbf{B} \cdot \nabla)\mathbf{B}}{\mu_0 \rho} - \frac{1}{\rho} \nabla (p + \frac{B^2}{2\mu_0}) + \nu \nabla^2 \mathbf{V} - \frac{\mathbf{V}}{\tau_{in}}
\]

- Ion Neutral Drag term
- Hall term

Helium

- \( n = 3 \times 10^{10} \text{ cm}^{-3} \)
- \( P = 1 \times 10^{-4} \text{ Torr} \)
- \( T_e = 5.3 \text{ eV} \)
- \( T_i = 0.216 \text{ eV} \)
- \( V_{inner} = 4.25 \text{ km/s} \)
- \( V_{outer} = 5.5 \text{ km/s} \)
Velocity and Magnetic Field Structures Appear in the Saturated State, Which Depend on the Hall Term

$V_\varphi$ [km/s]

$B_\varphi$ [mT]

F. Ebrahimi, 2011
Hydrodynamic Stability of Viscous Couette Flow with Drag

\[
\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla) \mathbf{V} = -\frac{\nabla P}{\rho} - \frac{\mathbf{V}}{\tau_{i0}} + \nu \nabla^2 \mathbf{V}
\]

Consider perturbations of the form:

\[
\mathbf{V} + \mathbf{u} = [u_r, V_0 + u_\theta, u_z]
\]

where \( u_r = e^{\gamma t} u(r) \cos(kz) \), \( u_\theta = e^{\gamma t} v(r) \cos(kz) \), \( u_z = e^{\gamma t} w(r) \sin(kz) \), \( \bar{\omega} = e^{\gamma t} \bar{\omega}(r) \cos(kz) \), and \( \bar{\omega} = \frac{\delta P}{\rho} \).

Linearized momentum eq. + continuity eq. results in:

\[
\frac{d}{dr} \to D \\
\frac{d}{dr} + \frac{1}{r} \to D_*
\]

\[
\frac{\nu}{k^2} \left[ DD_* - \left( k^2 + \frac{1}{\tau_{i0} \nu} + \frac{\gamma}{\nu} \right) \right] (DD_* - k^2) u = \frac{2V_0}{r} u
\]

\[
\nu \left[ DD_* - \left( k^2 + \frac{1}{\tau_{i0} \nu} + \frac{\gamma}{\nu} \right) \right] v = (D_* V_0) u
\]

\[
V_0 = C_1 I_1(\alpha r) + C_2 K_1(\alpha r)
\]
When is Viscous Couette Flow with Drag Unstable?

Marginal stability analysis with neutral-damping

- Taylor vortices could occur at high \( V_{\text{inner}} \), low viscosity
- What are the boundary conditions?

\[ \text{Rayleigh line} \]

\[ \alpha = (\tau_{i0} \nu)^{-1/2} \]

\[ \text{Taylor (1923)} \]

\[ \Omega_{x} = \frac{R_{3}^{2}}{R_{1}^{2}} = 1.292 \]

\( \Omega_{y} \)

\( \Omega_{z} \)
Why Not Run Full Blast?

heating/arcing issues
Laser Induced Fluorescence In Progress

**PCX rotating argon plasma**

- Laser Excitation: 1047.00475 nm
- Laser Excitation: 4p $^2$D (5/2)
- Laser Excitation: 3d $^2$F (7/2)
- Laser Excitation: 4s $^2$P (3/2)
- Florescence: 488.0 nm
- Branching ratio = 0.26
- $A_{ki} = 8.23 \times 10^7$ 1/s

Movable optical table

Laser Induced Florescence in ARII

- Lens
- Aperture
- Lens
- 488 nm filter
- PMT
- Laser
Laser Induced Fluorescence In Progress

Ti = 0.058 eV ± 4.4%

Laser Induced Fluorescence in ARII

Laser Excitation
1047.00475 nm

3d^2F (7/2)

4p^2D (5/2)

Florescence 488.0 nm

Branching ratio = 0.26
A_{ki} = 8.23 \times 10^7 1/s

4s^2P (3/2)
The Madison Plasma Dynamo Experiment

• 3 m diameter sphere
• strong magnets = good confinement
• fully ionized (200 kW LaB$_6$ + ECH)
• Goal: $R_m \sim 2000$
Electrostatic Biasing Controls Edge Rotation

Arbitrary
\[ V_\phi (r = a, \theta) \]
MHD Computation Predicts Laminar Plasma Dynamo


Rm=300, Re=100

Te = 9 eV, \( n = 8 \times 10^{17} \text{ m}^{-3} \)

\( U_{\text{max}} = 5 \text{ km/s}, \) Helium
3000 4 kG SmCo Magnets Installed in MPDX
Current Setup

- North pole faces plasma
- South pole faces plasma
- LaB$_6$ cathode
- Molybdenum anode

Coaxial LaB6 Cathode

Thursday, April 11, 2013
Even without microwave heating, LaB$_6$ stirring cathodes create hot, dense plasmas.

- Discharge powers of up to 20 kW result in $n_e = 5 \times 10^{17}$ m$^{-3}$, $T_e = 5$ eV plasmas.

- LaB$_6$ cathodes draw up to 50A each during each 10 second plasma discharge.
Flow observed with cathodes withdrawn into magnetized region

- Plasma spins up on neutral pump-out timescale.

- Max velocity measured near anode location.

\[
mn \frac{du_\phi}{dt} = (J \times B)_\phi - \frac{mn u_\phi}{\tau_{i0}} + mn \nu_{ii} [\nabla^2 u]_\phi
\]
**Make Predictions With Power Balance Calculations**

![Energy Balance (He)](image)

**First Results**

<table>
<thead>
<tr>
<th>Loss Mechanism</th>
<th>Expression [Energy/Time]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion losses at cusps</td>
<td>$\Gamma A_{cusp}(e\Delta V + 3/2 T_i)$</td>
</tr>
<tr>
<td>Electron losses at cusps</td>
<td>$\Gamma A_{cusp}(3/2 T_e)$</td>
</tr>
<tr>
<td>Replacement ionization</td>
<td>$Q_{ioniz} \equiv \Gamma A_{cusp} E_{ioniz}$</td>
</tr>
<tr>
<td>Neutral radiation</td>
<td>$M(T_e)Q_{ioniz}$</td>
</tr>
<tr>
<td>Charge-exchange collisions</td>
<td>$\frac{3}{2} nn_0 \langle \sigma_{cx} v \rangle e(T_i - T_0)Vol$</td>
</tr>
<tr>
<td>Ion radiation</td>
<td>$n^2 R^i(T_e)Vol$</td>
</tr>
</tbody>
</table>

Table I. Power loss mechanisms in magnetic bucket.

With given density by Dennis Whyte using the KPRAD code [13].

The ion temperature is more difficult to model. Ion losses at cusps can now vary over a large range, $R_m \sim 10^{18}$, as opposed to being fixed at $10^{16}$. With extra power, the magnetic Reynolds number is expected to reach $10^{18}$, and the magnetic Reynolds number to be increased.

The implications of this power balance calculation for multicusp plasma experiments.

Fig. 4. Power balance calculation for helium and argon with different heating powers. Comparison results of Fig. 4. It is seen that power losses listed in Table I. We neglect ion radiation and charge exchange losses, and we also ignore the electron temperature. Instead, we may estimate the ion temperature from Fig. 4. This gained energy is much larger than the initial ion thermal energy. The expression for ion losses at cusps since it is small relative to the heating power couples to the plasma. For example, to account for the electron temperature.
Operational space set by power, density, and ion species

Electron Temperature
P=200 kW

argon
helium

Rm/V_{km/s}

Re/V_{km/s}

argon
helium

density (m\(^{-3}\))

10\(^{17}\) 10\(^{18}\) 10\(^{19}\)
Soon (May, 2013) … eventually (Fall, 2013)

North pole faces plasma
South pole faces plasma
LaB$_6$ cathode
Molybdenum anode

0°
45° N
90° N
90° S
45° S
Summary

• Controlled velocity profiles can be created in axisymmetric ring cusp geometry using biased cathodes in the magnetized edge to drive flows in the bulk, unmagnetized plasma

• Within a factor of $T_i$, the measured viscosity is consistent with Braginskii

• Rotation at the inner boundary has recently been achieved in PCX, which now allows us to explore hydrodynamic and magnetohydrodynamic stability

• MPDX is entering final phase of construction, expected to achieve $R_m \sim 1000$
Further Reading

**PCX**

**Stirring Unmagnetized Plasma**

**Magnetic Bucket for Rotating Unmagnetized Plasma**

**Global Hall-MHD Simulations of MRI in a Plasma Couette Flow Experiment**

**Numerical Simulation of Laminar Plasma Dynamos in a Cylindrical Von Kármán Flow**

**MPDX**

**A Spherical Plasma Dynamo Experiment**

**Resistive and Ferritic-Wall Plasma Dynamos in a Sphere**

**Optimized Boundary Driven Flows for Dynamos in a Sphere**
The Goal: Achieve MRI Unstable Parameters

Helium, $P=1 \times 10^{-4}$ Torr

- $P_m=2.1$, $\alpha=6$, $\nu=134$
  - $n=2.5 \times 10^{10}$ cm$^{-3}$, $T_e=7$ eV, $T_i=0.3$ eV

- $P_m=1.3$, $\alpha=8$, $\nu=90$
  - $n=2.4 \times 10^{10}$ cm$^{-3}$, $T_e=6.5$ eV, $T_i=0.25$ eV

- $P_m=0.6$, $\alpha=10$, $\nu=44$
  - $n=5 \times 10^{10}$ cm$^{-3}$, $T_e=6.3$ eV, $T_i=0.25$ eV

MRI Could Be Unstable At Feasible Parameters
How Close Are We To MRI Instability?

- Still need to turn on the Bz field (may change filament placement)
- MRI analysis is local
\[ \gamma^4 + C_3 \gamma^3 + C_2 \gamma^2 + C_1 \gamma + C_0 = 0 \]

\[
C_3 = 2k^2(\eta + \nu) + 2\tau_{i0}^{-1}
\]

\[
C_2 = \kappa^2 \frac{k_z^2}{k^2} + 2(k_z V_A)^2 + (\eta + \nu)^2 k^4 + 2\eta \nu k^4 + C_H \Omega \left( C_H \Omega \frac{k_z^2}{k^2} + \frac{d\Omega}{d\ln r} \right) + \tau_{i0}^{-2} (1 + 2\nu k^2 \tau_{i0} + 4\eta k^2 \tau_{i0})
\]

\[
C_1 = 2\eta \kappa^2 k_z^2 + 2(\eta + \nu)k^2(k_z V_A)^2 + 2\nu \eta k^2(\eta + \nu) + 2C_H \Omega \nu k^2 \left( C_H \Omega \frac{k_z^2}{k^2} + \frac{d\Omega}{d\ln r} \right)
\]

\[
+ 2\tau_{i0}^{-1} C_H \Omega \left( \frac{d\Omega}{d\ln r} + C_H \Omega \frac{k_z^2}{k^2} \right) + 2\tau_{i0}^{-1} (\eta k^4 (2\nu + \eta + (\tau_{i0} k^2)^{-1}) + (k_z V_A)^2)
\]

\[
C_0 = \eta^2 k_z^2 k^2 \kappa^2 + (k_z V_A)^4 + \frac{d\Omega^2}{d\ln r} \frac{k_z^2}{k^2} (k_z V_A)^2 + \nu \eta k^4 (\nu k^4 + 2(k_z V_A)^2)
\]

\[
+ C_H \left. \right( (k_z V_A)^2 \left( \frac{\kappa^2}{2} + 2\Omega^2 \right) + C_H \Omega^2 \kappa^2 + \frac{k_z^2}{2k^2} \kappa^2 \frac{d\Omega^2}{d\ln r} + \nu k^2 \left( \frac{1}{2} \frac{d\Omega^2}{d\ln r} + C_H \Omega^2 \frac{k_z^2}{k^2} \right) \right) + C_H \Omega \tau_{i0}^{-1} (2\nu k^2 + \tau_{i0}^{-1}) \left( C_H \Omega \frac{k_z^2}{k^2} + \frac{d\Omega}{d\ln r} \right) + 2\eta^2 \tau_{i0}^{-2} \left( k^4 \left( \nu k^2 \tau_{i0} + \frac{1}{2} \right) + \frac{\tau_{i0} k^2 (k_z V_A)^2}{\eta} \right)
\]

and the Hall parameter was defined as \( C_H = \frac{k_z^2 B_0}{\mu_0 ne \Omega} \).
Taylor Vortices Can Occur at High Vinner, Low Viscosity

- Marginal stability analysis is local
- What are the boundary conditions?
Preliminary LIF Temperature Measurements

\[ T_i = 0.058 \pm 0.0026 \text{ eV} \]

\[ \lambda_0 = 1047.00475 \]

\[ T_i = 0.5 \text{ eV} \]
\[ V_i = 5 \text{ km/s} \]
\[ \Delta \lambda = 0.009 \text{ nm} \]
\[ 0.0175 \text{ nm} \]
Center Stack Temperature Reduced By Silvering

Magnet Temperature (Front & Back)

Before

![Graph showing temperature before silvering](image)

After

![Graph showing temperature after silvering](image)

~3 cm from magnet

1700°C

Thursday, April 11, 2013
\[
\frac{dn}{dt} = \frac{1}{2} \frac{c_s n A_{loss}}{V_{plasma}}
\]

\[
V_{plasma} = 10 \text{ m}^3
\]

\[
A_{loss} = W_{cusp} \times L_{cusp}
\]

\[
W_{cusp} = 4\sqrt{\rho e \rho i} \sim 1 \text{ mm}
\]

\[
L_{cusp} = 220 \text{ m}
\]

Thursday, April 11, 2013