The ZaP Flow Z-Pinch Project:
Investigations of Flow Shear on MHD Stability

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Abstract

The ZaP Flow Z-Pinch observes gross stability of a Z-pinch while a sheared axial flow is present.* The Z-pinch is maintained more than 700 times the predicted kink instability growth time of a static pinch. The stable time is correlated with measurements of a sheared axial flow, and instability of the pinch is correlated with measurements of lower velocities with little or no shear. The sheared-flow Z-pinch is created by coaxial electrodes accelerating an annular plasma into a Z-pinch assembly region. Diagnostics include axial and azimuthal surface magnetic probe arrays, internal magnetic field probes, an azimuthal Rogowski array, a gridded energy analyzer, a bolometer, fast framing photography and diode arrays using spectral filters, ruby laser holographic interferometry, a CCD survey spectrometer, and a high-resolution gateable 20-channel ICCD spectrometer system. Recent modifications include a solid “bullet-nose” inner electrode, an opening in the outer electrode end wall, and the replacement of two outer electrode gas puff valves by eight faster valves.

Introduction

Virtually all plasmas, man-made or naturally occurring, have a finite fluid (mass) flow. The magnitude of the flow can be a large fraction of the Alfvén velocity.

Many MHD stabilizing effects have been attributed to either plasma flow or sheared plasma flow.

The \textit{ZaP} experiment studies the effect of flow on stability in a simple Z-Pinch geometry. \textit{ZaP} allows re-examination of the Z-pinch for propulsion, neutron production, and fusion applications.
## ZaP Experiment Personnel

### Faculty
- Uri Shumlak (PI)
- Brian A. Nelson (Co-PI)

### Staff
- Edward A. Crawford
- Daniel E. Lotz
- Dennis Peterson
- John A. Rogers
- Dzhung Tran

### Graduate Students
- Raymond Golingo (A&A)
- Stuart Jackson (A&A)
- Justin Bright (A&A)

### Undergraduates
- Daniel Jackson
- John Kim
- Tuan Le
- Peter Norgaard
- Theodore Shreve
- Kristopher Yirak
- Matthew O’Brien

### Consulting Scientific Staff
- Daniel J. Den Hartog (UW–Madison)
- Charles W. Hartman (LLNL/UCB)
- Eric Forbes
Marshall and Newton Observed Stability in a “Continuous Flow Pinch” Configuration

- Coaxial electrode ejecting into a large vacuum region
- Gross stability for more than 20 flow-through times
- $n \tau T$ of Marshall-Newton was similar to ’68 tokamaks
- Conclusion:
  - “appears that the pinch could be maintained indefinitely”
Z-Pinch Equilibrium Set by Radial Force Balance

Radial pressure balance involves plasma pressure, magnetic pressure, and field line tension:

\[
\frac{d}{dr} \left( p + \frac{B_\theta^2}{2\mu_0} \right) + \frac{B_\theta^2}{\mu_0 r} = 0
\]

The presence of an axial flow does not affect the equilibrium.
Z-Pinch Stability Limits Operating Range

- Unstable to $m = 0$ (sausage) and $m = 1$ (kink).
- $m = 0$ can be stabilized by tailored density profile or wall.
- $m = 1$ can be stabilized by axial field or wall.

This leads to an axial current limit (Kruskal-Shafranov) decreasing the operating density (due to compression of the axial field).
Numerical Results Show Shear in the Axial Velocity can Stabilize the $m = 1$ Mode

- Shumlak and Hartman* showed the $m = 1$ mode to be stable for $v_z'/kV_A^0 \sim 0.1$

- Conducting walls greater that 4 times the plasma radius no longer contribute to stability

- This stabilization can be understood as the sheared velocity precluding the setup and growth of a coherent $m = 1$ distortion

*Phys Rev Lett 75(18) 1995, p 3285
Nonlinear Simulations Support Sheared-Flow Theory

With no flow, the $m=0$ sausage mode quickly develops.

With $\frac{dV_Z/dR}{kV_A} = 0.2$, most of pinch still has good confinement.
The *ZaP* Experiment

- Acceleration region
- Assembly region
- Inner Electrode
- Outer Electrode
- Neutral Gas Injection Plane
- Pinch Midplane
- Vacuum Vessel
- Electrode End Wall
- 1 meter
### ZaP Experimental Parameters

<table>
<thead>
<tr>
<th>Entity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector length</td>
<td>100 cm</td>
</tr>
<tr>
<td>(gas puff at $z = -75$ cm)</td>
<td></td>
</tr>
<tr>
<td>Inner electrode O.D.</td>
<td>6.3 cm</td>
</tr>
<tr>
<td>Outer electrode I.D.</td>
<td>19.2 cm</td>
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<tr>
<td>Assembly region length</td>
<td>50 cm</td>
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<tr>
<td>Peak current</td>
<td>500 kA (design)</td>
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<tr>
<td>(280 kA with 1/2 cap bank, 72 kJ)</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>$10^{16} - 10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Plasma diameter</td>
<td>2 cm</td>
</tr>
<tr>
<td>Pulse length</td>
<td>0.1 ms</td>
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<tr>
<td>$T_e + T_i$</td>
<td>150 – 200 eV</td>
</tr>
<tr>
<td>Bakeability</td>
<td>$&gt; 200^\circ$ C</td>
</tr>
<tr>
<td>Wall material</td>
<td>W-sprayed Cu</td>
</tr>
<tr>
<td>Wall conditioning</td>
<td>He glow</td>
</tr>
</tbody>
</table>
Sheared Flow Generation via Coaxial Startup
MACH2 Shows $ZaP$ Pinch and Upstream $n$

Density contours for MACH2 simulation of $ZaP$ (aspect ratio not 1-to-1).

A high density pinch assembles on axis, with residual density (and radial current) in the acceleration region.
ZaP Diagnostics Measure Flow and Stability
Side View
- Surface mounted magnetic field probes (axial/azimuthal)
- Fast framing camera (Imacon) with optical filters
- Two chord, visible HeNe interferometer
- 0.5 m imaging spectrometer with 20 input chords and ICCD
- CCD-based 0.5 m SPRED and PMT
- Holographic interferometer (pulsed ruby laser)
- Gridded end loss analyzer, Rogowski, and calorimeter
- Diode-based bolometer, filtered light, and axial array
**ZaP Waveforms: Acceleration and Pinch Formation**

- **Pulse:** 21014009
- **Plasma Current** ($I_p$) (kA)
- **B$_{n=1}$/$\langle B_{Z=0} \rangle$**
- **Gap Voltage** ($V_{gap}$) (kV)
- **Avg Density** ($\langle n_e \rangle$) ($10^{21}$ m$^{-3}$)
- **Wall B Field** ($B_{wall}$) (T)

![Graphs showing various waveforms and data points](image-url)
Axial Probes Show Current Sheet Acceleration
Midplane $m = 1$ Mode Analysis Shows "Quiescent" Period Followed by Mode Activity
Framing Camera Shows Stability then Mode Activity
Filament Model Shows Small then Large Motion

Non-linear fitting of a current filament model to $Z=0$ azimuthal fields shows small plasma excursions followed by larger excursions.

Plasma location is approximately $R_{\text{wall}}B_{m=1}/\langle B_0 \rangle$ (J. Bright, UW MS Thesis)
Quiescent Time Correlated with Accelerated Plasma

Plasma is continuously accelerated from the coaxial region (axial spread in $B_\theta$ in middle trace, and presence of upstream density in lower trace).
Soon after this plasma supply is exhausted, the quiescent period (upper trace) ends (vertical gray band).
Holography Shows Peaked then Hollow Profiles

For more details, please see Poster KP1.110, Jackson et al.
Gated Intensified CCD Camera
Measures Impurity Flow

- Impurity ions (C, O, etc.), emit distinguishable line radiation
- 20 chords through either a 35° port (sees axial Doppler shift) or a 90° port (sees no axial Doppler shift)
- Chords span approximately 2.5 cm
- Single gated snapshot, down to 50 ns window (1 μs typical)
- 0.078 Å wavelength resolution
ICCD Data Show Large Flow and Shear in C-III During Quiescent Time
ICCD Data Show Low Flow and Shear in C-III After Quiescent Time
Flow/Shear Correlated with Quiescent Period

- **Normalized $m=1$ mode**
- **High mode activity:** Little flow, little shear

**Formation:** Flow, little shear

**Quiescent Period:** Large flow and shear
Plasma Shell Model Used for Velocity Deconvolution

For more details, please see Poster KP1.109, Golingo et al.
ZaP Results Agree with Stabilization Theory

ZaP data: $a \approx 1 \text{ cm}$, $B_{\text{wall}} = 0.18 \text{ T}$, and $n_e = 9 \times 10^{22} \text{ m}^{-3}$. For $I_p = 0$ for $R > a$: $B_a = 1.8 \text{ T}$, yielding $V_A = 1.3 \times 10^5 \text{ m/s}$. For mode wavelengths equal to the diameter ($ka = \pi$) the static Z-pinch growth time is:

$$\tau_{\text{growth}} = (kV_A)^{-1} = 24 \text{ ns}$$

Sheared flow stabilization theory requires:

$$\frac{dV_Z}{dR} \geq 0.1kV_A = 4.2 \times 10^6 \text{ s}^{-1}$$

ZaP shows stable times of 17 $\mu$s or 700 $\tau_{\text{growth}}$, and a measured flow shear of $1.9 \times 10^7 \text{ s}^{-1}$

$\Rightarrow$ Consistent with sheared flow stabilization theory
Summary

- Magnetics and imaging show quiescent period followed by mode activity

- $Z_a P$ quiescent period shows stability for 700 times longer than the static MHD growth time

- Quiescent period correlated with continued presence of accelerated plasma

- $Z_a P$ parameters and flow measurements are consistent with sheared-flow stabilization theory
Future Hardware Plans

- Increase assembly region from 0.5 m to 1 m (then 2 m)
- Perform frequency compensation on surface probes
- Add internal probes in the acceleration region
- Increase bank capacitance by factor of two in a pulse-forming network (100 µs flat-top at up to 500 kA)
Future Operational Plans

- Continue optimization of inner and outer electrode gas puff
- Higher current operation
- Measure internal magnetic fields by Zeeman line splitting (with ICCD and optical filters)
- Commission axial photodiode array to investigate $k_Z$
Other *ZaP* APS DPP02 Presentations

- U. Shumlak, “Sheared Flow Stabilization Experiments in the ZaP Flow Z-Pinch”, *Invited Talk, Friday am, UI2.006*

- R. P. Golingo, “Formation and Sustainment of a Sheared Flow in a Z-pinch”, *Poster this session, KP1.109*

- S. L. Jackson, “Holographic Interferometry on the ZaP Flow Z-Pinch Experiment”, *Poster this session, KP1.110*