LONG, STABLE PLASMA GENERATION IN THE ZAP FLOW Z-PINCH


Aerospace & Energetics Research Program
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The ZaP Flow Z-pinch\(^1\) at the University of Washington investigates the effect of sheared flows on MHD stability. Axially flowing Z-pinch plasmas are produced that are 100 cm long with a 1 cm radius. The plasma is quiescent for many radial Alfvén times and axial flow times. The quiescent periods are characterized by low magnetic mode activity measured at several locations along the plasma column and by stationary visible plasma emission. Profiles of the plasma’s axial flow are measured with a multi-chord ion Doppler spectrometer. A sheared flow profile is observed to be coincident with the quiescent period. The flow profile is well understood and consistent with classical plasma viscosity. Plasma lifetime appears to only be limited by plasma supply and current waveform. Equilibrium is determined by the following diagnostic measurements: interferometry for density; spectroscopy for ion temperature, plasma flow, and density\(^2\); Thomson scattering for electron temperature; Zeeman splitting for internal magnetic field measurements\(^3\); and fast framing photography for global structure. A radial heat conduction analysis is performed to calculate equilibrium profiles from the experimental data by assuming Braginskii thermal conductivities and radial force balance. The profiles are corroborated by additional experimental measurements. To confirm the importance of shear flow stabilization, the effect of wall stabilization is investigated by removing large portions of the surrounding conducting wall. The configuration is also computationally modeled to demonstrate no wall effects contributing to observed stability of the Z-pinch plasma.
Abstract II/II

These studies have led to the design of the newly-funded "ZaP-HD" project, which investigates high energy density plasmas generated using the flow Z-pinch concept. ZaP-HD uses three electrodes to provide individual control of the acceleration and compression of the plasma. This innovation allows compression to much higher densities than previously achieved on ZaP (a factor of three to ten times larger, $1-3 \times 10^{18}$ cm$^{-3}$) by reducing the linear density and increasing the pinch current. ZaP-HD has several large viewports allowing optical access to the entire assembly for the existing diagnostics, as well as a new digital holography system, presently under development.


Work supported by a grant from the U.S. DoE
Z-pinches offer a simple means to achieve HEDP

The pure Z-pinch equilibrium (no applied axial fields) is described by

\[
\frac{B_\theta}{\mu_0 r} \frac{d}{dr} \left( rB_\theta \right) + \frac{dp}{dr} = 0.
\]

Increasing the current and the resulting azimuthal magnetic field scales to HEDP conditions \((10^{11} \text{ J/m}^3)\). However, the equilibrium is classically unstable to \(m = 0\) sausage and \(m = 1\) kink modes.

ZaP Flow Z-Pinch investigates using sheared flows to stabilize these classical instabilities without requiring close-fitting walls or axial magnetic fields. (See adjacent posters by M. Hughes & M. Ross.)

Theoretical analysis suggests that a sheared flow can stabilize the modes in a pure Z-pinch provided \(v_z' \geq 0.1kV_A\).*

Schematic illustrates flow Z-pinch formation used by ZaP

Gas is injected and a capacitor bank is discharged across the electrodes.

The plasma accelerates down the coaxial accelerator until it assembles into a Z-pinch plasma along the axis.

Inertia and gun currents maintain the flow until the accelerator plasma empties.
The ZaP Flow Z-Pinch experiment investigates the concept of using flows to stabilize an otherwise unstable plasma configuration.
Simulations show formation of a high-density plasma

Simulations with the MACH2 resistive MHD code.
The ZaP operating parameters produce a high-temperature, high-density, long-lived pinch plasma.

<table>
<thead>
<tr>
<th>Entity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor Bank Energy</td>
<td>144 kJ (max)</td>
</tr>
<tr>
<td>Charge Voltage</td>
<td>10 kV (max)</td>
</tr>
<tr>
<td>Peak Current</td>
<td>480 kA (max)</td>
</tr>
<tr>
<td>Plasma Pinch Radius</td>
<td>0.5 – 1 cm</td>
</tr>
<tr>
<td>Plasma Pinch Length</td>
<td>100 cm</td>
</tr>
<tr>
<td>Density</td>
<td>$10^{16}$ – $10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Plasma Temperature ($T_e + T_i$)</td>
<td>150 – 250 eV</td>
</tr>
<tr>
<td>Plasma Lifetime</td>
<td>20 – 100 µs</td>
</tr>
</tbody>
</table>
Diagnostics measure plasma flow & stability

The ZaP diagnostics measure equilibrium plasma parameters, plasma flow, and magnetic mode activity (stability).

- **Surface-mounted magnetic field probes**
  - Analyze magnetic fields, magnetic fluctuations, and plasma stability

- **Fast framing camera with optical filters**
  - Qualitative measure of plasma structure

- **Four-chord, visible HeNe interferometer**
  - Measure plasma density profile

- **0.5 m imaging spectrometer with 20 input chords and an intensified CCD detector**
  - Doppler shift for plasma flow profile, Doppler broadening for ion temperature, Zeeman splitting for magnetic fields, Stark broadening for density

- **Thomson scattering system using ruby laser & Hibshman spectrometer**
  - Measure electron temperature
Magnetic fluctuations diminish after pinch forms*

Fluctuations of the magnetic modes are significantly reduced for $\approx 37 \, \mu s$ after pinch forms. Mode activity increases again after this quiescent period. Experimental data suggests the quiescent length is limited by plasma supplied from the accelerator. (Flow time, $\tau_v \approx 10 \, \mu s$.)

Optical images show a stationary plasma pinch*

Visible emission images are obtained at $z = 0$, every 200 ns, through a 2” hole with an Imacon fast-framing camera.

Images show a stationary plasma pinch during the quiescent period. Note hollow structure.

Gross kink & sausage instabilities appear at the end of quiescent period.

*Shumlak et al., Nuc. Fusion (2009)
Flow profile is correlated to plasma stability*

\[ \tau < 0, \text{ plasma assembly, the axial plasma velocity is high and uniform, } v_z' \approx 0 - 4 \times 10^6 \text{ s}^{-1}. \]

\[ 0 \leq \tau \leq 1, \text{ quiescent period, the velocity profile is high at the plasma edge and lower at the axis, } v_z' \approx 7 - 12 \times 10^6 \text{ s}^{-1}. \]

At a point during the quiescent period, the edge velocity slows so the velocity is higher at the axis than the edge.

\[ \tau > 1, \text{ end of quiescent period, the plasma velocity profile is low & uniform, } v_z' \approx 0 - 6 \times 10^6 \text{ s}^{-1}. \]

Theoretical growth time is \( \approx 20 \text{ ns}. \)
Shear threshold is \( \approx 5 \times 10^6 \text{ s}^{-1}. \)

Experimental modifications examine the no-wall limit

Close-fitting conducting walls can provide a stabilizing effect, which could provide an alternative explanation to the observed stability. To test the no-wall limit, a section of the outer electrode is inserted which contains large perforations.

Experimental results show no effect of the perforated section.
Numerical calculations verify no-wall behavior

The effect of the perforated conducting wall is also examined numerically using the HiFi code*. The computational domain is extended through the perforations. Case with a solid wall provides a reference. Numerical results show the perforated section affects stability only when the pinch size is close to the perforation size and the plasma is displaced close to the wall radius.

*Glasser & Tang, CPC 164 (2004)
Z-pinch scales to HEDP and to fusion reactor plasmas

Flow-stabilization theory of a Z-pinch shows no additional limitations as the plasma is scaled to different parameters. If the experimental results also hold, then the Z-pinch can be scaled from ZaP conditions to higher performance conditions by assuming adiabatic compression

\[
\frac{d}{dt} \left( \frac{p}{n^\gamma} \right) = \frac{d}{dt} \left( \frac{(1+Z)kT}{n^{\gamma-1}} \right) = 0
\]

and using the linear density is given by the Bennett relation:

\[
(1+Z)NkT = \frac{\mu_0 I^2}{8\pi}, \quad \text{where} \quad N = \int_0^a n_i(r)2\pi rdr.
\]

The resulting scaling relations are

\[
\frac{a_2}{a_1} = \sqrt{\frac{n_1 N_2}{n_2 N_1}} = \left( \frac{I_1}{I_2} \right)^{\frac{1}{\gamma-1}} \left( \frac{N_2}{N_1} \right)^{\frac{\gamma}{2(\gamma-1)}}
\]

\[
\frac{p_2}{p_1} = \frac{n_2 T_2}{n_1 T_1} = \left( \frac{I_2}{I_1} \right)^{\frac{2\gamma}{\gamma-1}} \left( \frac{N_1}{N_2} \right)^{\frac{\gamma}{\gamma-1}}
\]

\[
\frac{n_2}{n_1} = \left( \frac{T_2}{T_1} \right)^{\frac{1}{\gamma-1}} = \left( \frac{I_2}{I_1} \right)^{\frac{2}{\gamma-1}} \left( \frac{N_1}{N_2} \right)^{\frac{1}{\gamma-1}}
\]
Flow Z-pinches can generate fusion reactor plasmas

Analysis of the flow Z-pinches using the scaling laws leads to a solution with reasonable size (length $L$ and radius $a$) and high power.

Fusion power is given as

$$P_f = n_D n_T \langle \sigma v \rangle_{DT} E_{DT} \pi a^2 L = \frac{n^2}{4} \langle \sigma v \rangle_{DT} E_{DT} \pi a^2 L$$

Input power must be supplied to heat and compress the plasma, to drive the flow, and to replace radiative losses.

$$P_{th} = \frac{3}{2} \sum_\alpha \hat{n}_\alpha k T_\alpha \pi a^2 L \quad \text{for } \alpha = D, T, e, e$$

$$= 3 \hat{n} k T \pi a^2 L = 3 n k T v_z \pi a^2$$

$$P_{flow} = \frac{1}{2} \hat{m} v_z^2 = \frac{M_D + M_T}{4} \hat{m} v_z^2 \pi a^2 L = \frac{M_D + M_T}{4} n v_z^3 \pi a^2$$

$$P_{rad} = C n_e \sqrt{T_e} \sum_i Z_i^2 n_i = 3.4 \times 10^{-38} n^2 \text{ m}^{-3} \sqrt{T_e}$$
Z-Pinch scales to HEDP and to fusion reactor plasmas

Starting with ZaP plasma parameters, the plasma can be scaled by increasing the current with a fixed linear density. Fusion gain $Q$ now includes flow power.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_p$</td>
<td>750 kA</td>
</tr>
<tr>
<td>$T$</td>
<td>4.5 keV</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.3 TPa</td>
</tr>
<tr>
<td>$a$</td>
<td>170 µm</td>
</tr>
</tbody>
</table>

Fusion gain $Q$:

$$Q \equiv \frac{P_f}{P_{th} + P_{flow} + P_{rad}}$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_p$</td>
<td>1.5 MA</td>
</tr>
<tr>
<td>$T$</td>
<td>22.5 keV</td>
</tr>
<tr>
<td>$L$</td>
<td>75 cm</td>
</tr>
<tr>
<td>$a$</td>
<td>61 µm</td>
</tr>
<tr>
<td>$Q$</td>
<td>33</td>
</tr>
<tr>
<td>$P_f$</td>
<td>4.6 TW</td>
</tr>
</tbody>
</table>

*Shumlak et al., Fusion Sci. & Tech. 61 (2012)*
New ZaP-HD project investigates HEDP in flow Z-pinch

ZaP-HD experiment uses two separate power supplies: one to form a flow Z-pinch and one to provide a high current to compress the plasma.

Comparison of ZaP and estimated ZaP-HD plasma parameters are

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ZaP</th>
<th>ZaP-HD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinch Current ($I_p$)</td>
<td>50 – 100 kA</td>
<td>150 – 300 kA</td>
</tr>
<tr>
<td>Density ($n_e$)</td>
<td>$\approx 5 \times 10^{22}$ m$^{-3}$</td>
<td>$10^{24}$ m$^{-3}$</td>
</tr>
<tr>
<td>Pressure ($p_e$ + $p_i$)</td>
<td>$\approx 2 \times 10^6$ Pa</td>
<td>$5 \times 10^8$ Pa</td>
</tr>
</tbody>
</table>
Summary & Conclusions

- The ZaP project is producing Z-pinch plasmas that exhibit gross stability during an extended quiescent period.
- The quiescent period is coincident with a sheared plasma flow.
- A well-formed, high-temperature Z-pinch is measured during the quiescent period by several diagnostics.
- Investigations of wall stabilization indicate the conducting wall has negligible effect. The wall can be placed arbitrarily far from the plasma.
- Scaling relations demonstrate that the flow-stabilized Z-pinch can be scaled to HEDP parameters and to fusion reactor conditions with reasonable parameters.

For reprints of ZaP posters, visit www.aa.washington.edu/research/ZaP/publications.html
Backup Slides
Plasma supply limits quiescent period length.

The end of the quiescent period is associated with a drop in the current and density in the acceleration region. This suggests the plasma source has been exhausted. It also suggests a means for extending the plasma lifetime.
Zeeman splitting measurements have been made to determine the internal magnetic field of the plasma pinch.

Impurity emission of the C IV doublet at 580.1 & 581.2 nm is collected perpendicular to the plasma.

Circularly polarized light is collected along 10 parallel chords through the pinch.

Operated with reduced capacitor bank energy of 35 kJ.

Zeeman splitting measures internal magnetic field

Deconvolved magnetic field values are compiled for many pulses to provide an average magnetic field profile. The magnetic field peaks at the pinch radius and then decays as inverse radius to the value measured at the outer electrode.
Interferometry provides plasma density and radius

The Z-pinch equilibrium has no applied magnetic fields and is described by

$$\frac{B_\theta}{\mu_0 r} \frac{d}{dr} \left( rB_\theta \right) + \frac{d}{dr} \left( n(T_i + T_e) \right) = 0$$

The four-chord interferometer provides chord-integrated density along parallel chords spaced 10 mm apart. Density data obtained at the same time as spectroscopy can be fit with a constant density plasma core with a surrounding background.

Plasma radius, $a$, and core density, $n_e$, are determined.

Shown are $a = 13$ mm, $n_e = 1.5 \times 10^{22}$ m$^{-3}$.
Holographic interferometer provides density profiles.*

A holographic interferometer has been installed to measure chord-integrated density profiles. The system uses a pulsed ruby laser in a double-pass or single-pass configuration.

The holograms are reconstructed using a He-Ne laser. The chord-integrated data are deconvolved to determine the density profile.

Holography measures a discrete plasma pinch.

During the quiescent period, the density profile shows a discrete plasma pinch.
Radius $\approx 6$ mm.
Peak density $\approx 1.5 \times 10^{17} \text{ cm}^{-3}$.

As the quiescent period evolves, the profile looks similar but the magnitude decreases.

Temperature and magnetic field profiles are computed from the magnetic field measured at the wall and a power balance assuming thermal conduction and equilibrium force balance.
Ion temperature is measured from spectroscopy

Viewing the plasma radially with the ICCD spectrometer, the Doppler broadening of impurity lines are measured.

A 100 ns gate is used and triggered at $\tau = 0.2$ to collect C III emission (229.7 nm).

The chord-integrated data is fit to determine ion temperature.

Shown is $T_i = 71$ eV.
Impurity line emission indicates heating.

Evolution of impurity line emission from C III at 229.7 nm and C V at 227.1 nm are recorded at $z = 10$ cm.

The appearance of the C V emission later in the quiescent period indicates a progressive heating of the plasma.
Thomson scattering system measures local $T_e$.

The experimental evidence from impurity ionization states, Doppler temperature broadening, and interferometry indicates a confined plasma pinch that progressively heats.

For more accurate, local temperature measurements a multipoint Thomson scattering system is designed, which uses a 1970 Korad ruby laser, the ZT-40 spectrometer, and an array of PMT detectors. (Schematic is shown.)
Plasma temperature increases throughout pulse.

$T_e$ evolution is found by adjusting ruby laser trigger time between pulses. Data show a variation between 30 – 100 eV at the pinch axis. Even during the quiescent period, the plasma can be displaced 0.5 cm away from the machine axis.
Thomson scattering measures hot plasma core

A single-point Thomson scattering system has been developed and installed on ZaP. The diagnostic uses a 10 J Korad ruby laser, a Hibshman spectrometer, and an array of PMTs for 8 wavelength bins.

The system views a cylindrical scattering volume $2.5 \text{ mm} \times \Phi 3 \text{ mm}$ at the machine axis. The laser pulse and scatter pulse waveforms are recorded, as well as background light.

Results show an electron temperature of $T_e = 64 \pm 11 \text{ eV}$. 

![Graph showing scattered light signal vs. wavelength with a peak at $660 \text{ nm}$ and $T_e = 64 \text{ eV}$]
Radial forces balance demonstrating equilibrium

The experimental values can now be used to determine consistency with equilibrium force balance. Using the data presented:

\[ a = 13 \text{ mm}, \quad n_e = 1.5 \times 10^{22} \text{ m}^{-3}, \quad B_{\text{wall}} = 0.13 \text{ T}, \] (assuming no current outside of pinch \( B_a = 1 \text{ T} \)).

Assuming a uniform pressure inside the plasma core, gives a total temperature

\[ T_i + T_e = 160 \text{ eV}. \]

This value can be compared with the independently measured ion and electron temperatures.

\[ T_i + T_e = 71 \text{ eV} + 64 \text{ eV} = 135 \text{ eV} \]
The pure Z-pinch (no applied axial fields) is described by

\[ \frac{B_\theta}{\mu_0 r} \frac{d(rB_\theta)}{dr} + \frac{dp}{dr} = 0 \]

is classically unstable to \( m = 0 \) sausage and \( m = 1 \) kink modes.

Conventional techniques to provide stability have drawbacks.

- **Profile Control** ➔ Stabilizes the sausage mode, but not the kink.
- **Close-Fitting Wall** ➔ Must be very close, \( r_{wall}/a < 1.2 \).
- **Axial Magnetic Field** ➔ Limits the plasma current (and pressure) according to Kruskal-Shafranov limit and opens field lines.

Theoretical analysis suggests that a sheared flow can stabilize the modes in a pure Z-pinch provided \( v'_z \geq 0.1kV_A \).*

Stabilizing the Z-Pinch with Sheared Flow

Linear stability analysis is applied to a marginally stable Kadomtsev equilibrium,

\[ \frac{d \ln p}{d \ln r} = \frac{4 \gamma}{2 + \gamma \beta} \]

In the no-wall limit, the Z-pinch is stabilized with a sheared flow,

\[ \frac{dv_z}{dr} \equiv v'_z \geq 0.1 kV_A. \]

The effect is a phase mixing at different radii in the pinch.