Scaling of the Sheared-Flow Stabilized Z-Pinch: The Fusion Z-Pinch Experiment "FuZE"

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Sheared Flow Can Stabilize a Z-Pinch

- The ZaP experiment used sheared-flow stabilization to produce long-lived Z-pinches
  - Quiescent plasmas last thousands of instability growth times and several flow-through times

- Low MHD mode activity is correlated with sheared plasma flow

- Quiescent plasmas can be maintained as long as the plasma source and current persists

- The new Fusion Z-pinch Experiment “FuZE” will study sheared-flow stabilization scaling to higher densities
ZaP and FuZE Personnel

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- Masayoshi Nagata (U Hyogo)
Sufficient Sheared-flow Stabilizes a Z-Pinch

- Linear stability applied to marginally-stable Kadomtsev equilibrium

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

- In the no-wall limit, \( r_w > 4a \), stability seen for

\[ \frac{d V_z}{dr} \equiv V_z' \geq 0.1 kV_A \]

- Destructive interference and phase mixing from sheared flow

Shumlak and Hartman, *PRL* 1995
Non-radially-uniform Acceleration Process Produces Sheared Flow Z-pinch

Gas is injected and capacitor is discharged.

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

Inertia and gun currents maintain the flowing plasma state until the accelerator plasma empties or current diminishes.
ZaP Experiment and Diagnostics

ZaP Z-pin with sheared-flow stabilization

- 1 m acceleration & 1-m assembly regions
- Axial and azimuthal surface probe arrays
- Heterodyne-quadrature HeNe interferometry (4 chords)

- Plasma current and voltage measurements
- 20-chord ion Doppler spectroscopy
- Digital holographic interferometry
- Fast-framing camera
## ZaP Operating Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor bank energy</td>
<td>$E_{\text{cap}}$</td>
<td>144 kJ (max)</td>
</tr>
<tr>
<td>Charge voltage</td>
<td>$V_c$</td>
<td>10 kV (max)</td>
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<tr>
<td>Plasma current</td>
<td>$I_p$</td>
<td>480 kA (max)</td>
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<tr>
<td>Pinch radius</td>
<td>$a$</td>
<td>0.5–1 cm</td>
</tr>
<tr>
<td>Pinch length</td>
<td>$\ell_p$</td>
<td>50–126 cm</td>
</tr>
<tr>
<td>Electron density</td>
<td>$n_e$</td>
<td>$10^{16}–10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Plasma temperature</td>
<td>$T_e + T_i$</td>
<td>150 – 250 eV</td>
</tr>
<tr>
<td>Plasma lifetime</td>
<td>$\tau_p$</td>
<td>20 – 100 $\mu$s</td>
</tr>
</tbody>
</table>

Working gas is hydrogen (sometimes with CH$_4$ as a dopant)
“Quiescent period” defined for normalized azimuthal mode data $B_1/B_0 \leq 0.2$ (displacement of a plasma radius).

$\approx 37 \mu$s quiescent period
(Instability growth time $\approx 20$ ns; flow through time $\approx 10 \mu$s)
Flow Profile is Correlated to Plasma Stability

- $\tau < 0$, plasma assembly, axial plasma velocity is high and uniform, $v'_z \simeq 0 - 4 \times 10^6$ s$^{-1}$
- $0 \leq \tau \leq 1$, quiescent period, the velocity profile is high at the plasma edge and lower at the axis, $v'_z \simeq 7 - 12 \times 10^6$ s$^{-1}$
- At a point during the quiescent period, the edge velocity slows so the velocity is higher at the axis than the edge.
- $\tau > 1$, end of quiescent period, the plasma velocity profile is low & uniform, $v'_z \simeq 0 - 6 \times 10^6$ s$^{-1}$

Theoretical growth time is $\simeq 20$ ns

Shear threshold is $\simeq 5 \times 10^6$ s$^{-1}$
Experimental Modifications Confirm the No-wall Limit

Close-fitting conducting walls can stabilize, providing 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.
ZaP Shows Evidence for Long-length Pinches

Magnetic data up to 86 cm from inner electrode show quiescent pinch of nearly constant field

Interferometer data 57 cm from inner electrode show density peaked on axis

End of inner electrode is at $z=-17$ cm
Axial $B_\theta$ Profile Shows Long-length Z-pinch

\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \Rightarrow \frac{\partial B_\theta}{\partial Z} = -\mu_0 J_R \]

Long-length axial current structures ($\frac{\partial B_\theta}{\partial Z} \simeq 0$) observed throughout the assembly region during the quiescent period.
Viscosity Shear Damping Time Allows Long Pinches

Viscous damping time:

\[ \tau_\mu \simeq \rho L_v^2 / \mu \]

Unmagnetized \( \mu \) (Spitzer Eq. (5-54) in SI–eV units):

\[ \mu = 1.52 \times 10^{-25} T^{5/2} A_i^{1/2} / Z^4 \ln \Lambda \]

Magnetized \( \mu_\perp \) (Eq. (5-55)):

\[ \mu_\perp = 2.89 \times 10^{-4} A_i^{3/2} Z^2 n_i^2 \ln \Lambda / T_i^{1/2} B^2 \]

\( \mu_\perp \) and \( \tau_\mu \) adiabatic scalings are independent of \( I_p \) (Hughes et al., APS 2015) \( \Rightarrow \) Viscous damping time \( \sim 1 \) m flow-through time
ZaP demonstrates evidence of flow-shear stabilization of a Z-pinch:

- MHD stability correlated with sheared velocity

- Stability lasts as long as there is flow shear, plasma in the acceleration region, and the power supply current persists

- Stability period increased with increasing pinch length

- Removal of a large section of the outer wall did not affect stability

- Viscous damping time greater than flow-through time
  - Adiabatic scaling of $\mu_\perp$ and $\tau_\mu$ independent of $I_p$
Adiabatic pinch scaling for a Bennett equilibrium:

\[
\frac{\partial}{\partial t} \left( \frac{p}{n^\gamma} \right) = \frac{\partial}{\partial t} \left( \frac{(1 + Z) kT}{n^{\gamma-1}} \right) = 0; \quad (1 + Z) NkT = \frac{\mu_0 I^2}{8\pi}
\]

FuZE is designed as an intermediate step towards a sheared-flow-stabilized Z-pinch fusion reactor.
FuZE Program Goals
Funded Through the ARPA-E ALPHA Program

100-cm-long acceleration & 50-cm-long assembly region

- Extend ZaP sheared-flow stabilized Z-pinch results to higher currents, densities, and temperatures
  - Improved gas puff fueling (SSPX valves)
  - Improved pumping capacity (additional surge tank)
  - More flexible power supply capability (SSPX power supplies)
- Operation with $H_2$ and $D_2$ gas mixtures
  - Increase fraction of $D_2$ to study neutron production
- Detailed kinetic calculations, including neutronics
  - LSP PIC code to include kinetic particles (Schmidt and Tummel)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>ZaP Value (Nominal)</th>
<th>FuZE Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor bank energy</td>
<td>$E_{\text{cap}}$</td>
<td>70-110 kJ</td>
<td>90(+) kJ</td>
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<td>Charge voltage</td>
<td>$V_c$</td>
<td>7–9 kV</td>
<td>20(+) kV</td>
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<tr>
<td>Plasma current</td>
<td>$I_p$</td>
<td>100–200 kA</td>
<td>300–500(+) kA</td>
</tr>
<tr>
<td>Pinch current</td>
<td>$I_{\text{pinch}}$</td>
<td>50–100 kA</td>
<td>150–300 kA</td>
</tr>
<tr>
<td>Pinch radius</td>
<td>$a$</td>
<td>0.5–1 cm</td>
<td>&lt; 1 mm</td>
</tr>
<tr>
<td>Pinch length</td>
<td>$\ell_p$</td>
<td>50–126 cm</td>
<td>50 cm</td>
</tr>
<tr>
<td>Electron density</td>
<td>$n_e$</td>
<td>$10^{16}$–$10^{17}$ cm$^{-3}$ *</td>
<td>$10^{19}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Plasma temperature</td>
<td>$T_e + T_i$</td>
<td>100 eV</td>
<td>800–1000 eV</td>
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<td>Plasma lifetime</td>
<td>$\tau_p$</td>
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<td>TBD</td>
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<tr>
<td>Working gas</td>
<td></td>
<td>H$_2$</td>
<td>H$_2$ &amp; D$_2$ mix</td>
</tr>
</tbody>
</table>

* $n_e = 10^{18}$ cm$^{-3}$ and $a=0.3$ cm already achieved in ZaP-HD

Nelson et al. ZaP Scaling and FuZE EPR 2016 17 / 20
FuZE On Track for First Plasma in Spring 2016

More flexible LLNL power supply and gas-fueling valves

50-cm-long Rectangular Viewports

LLNL Puff Valves

LLNL Cap Bank:
- $24 \times 18.5 \ \mu F$ at 20 kV
- $12 \times $D$-size ignitrons
- Diode crowbar and isolation between ignitrons

Pumping System and Surge Tank
FuZE LSP Code Kinetic Simulations are Underway
Evolution of a Bennett profile (Kurt Tummel and Andréa Schmidt of LLNL)
Summary:

- ZaP shows long-length (1 m) Z-pinches, stable for thousands of instability growth times and several flow-through times

- Stability correlated with presence of sheared-flow, a source of accelerated plasma, and power supply current

- Stability shown to not be affected by conducting wall

Future Work:

- Fusion Z-pinch experiment, “FuZE”, will study scaling of flow-shear stabilized Z-pinches to higher densities and temperatures

- First plasma Spring 2016