Roadmap to a Compact Fusion Device based on the Sheared Flow Stabilized Z-Pinch*

Uri Shumlak for the FuZE Team

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Presentation Outline

• The simplicity and many other advantages of the Z-pinch
• Current status of the sheared flow stabilized (SFS) Z-pinch
• Historical scientific developments of the Z-pinch leading to sheared flow stabilization approach
• Theoretical work indicating sheared flows may stabilize the Z-pinch
• DOE-funded basic science investigation of sheared flow stabilization in the Z-pinch
• ARPA-E-funded FuZE, Fusion Z-pinch Experiment, project and progress towards a compact low-cost fusion device based on the SFS Z-pinch
• Comments on the progress for the SFS Z-pinch concept and possible parallels for other concepts
The Z-pinch has the simplest geometry of any magnetic confinement configuration:

- cylindrical plasma column
- directly driven axial current
- self-generated magnetic field compresses the plasma

- perfect utilization of the magnetic field for compression, $\beta=100\%$
- no magnetic field coils: greatly reducing cost, size, and complexity
- increasing the current generates higher plasma parameters, increased fusion production, and smaller plasma radius

\[
\frac{dp}{dr} = -\frac{B}{\mu_0 r} \frac{d(rB)}{dr}
\]
Today: Demonstrated sustained fusion from FuZE

Today, the sheared flow stabilized Z-pinch regularly produces steady fusion reactions over an extended period of time\(^1\) from a compact device.

- stable plasma: 50 cm long, 0.3 cm radius
- fusion reactions along 34 cm length, likely thermonuclear process
- extensive computational modeling
- \(T_i \approx T_e \approx 1.0 \text{ keV}\)
- \(n_e \approx 10^{17} \text{ cm}^{-3}\)
- \(B_a \approx 10 \text{ T}\)
- continue to scale up current & yield

\(^1\text{Zhang et al., PRL (2019)}\)
Z-pinches research predates nuclear fusion understanding

1790: Earliest “Z-pinches” research by Martinus van Marum
1905: Observation of crushed lightning rod by Pollock & Barraclough
1907: “Pinch phenomenon” in liquid conductor by Northrup
1934: Theoretical model of plasma Z-pinches by Bennett
1950: Z-pinches was Project Sherwood Jim Tuck’s preferred approach to achieve controlled fusion
1957: Theory and experiments demonstrated virulent instabilities, \( m = 0, 1 \)
1998: Performance of Z-pinches using frozen deuterium fibers was severely limited by these instabilities

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\(^1\) Haines, PPCF (2011); \(^2\) Pollock & Barraclough, PRS (1905); \(^3\) Northrup, PR (1907); \(^4\) Lebedev et al., PoP (1998)
Key Innovation: sheared flows can stabilize the Z-pinch

Prior theoretical and experimental research focused on static Z-pinch plasmas, and demonstrated that $m = 0$ and $m = 1$ instabilities persist.

1995: Theoretically demonstrated that a Z-pinch could be stabilized with low-speed axial flows* → sheared flow stabilization (SFS).

No flow

Sheared flow

\[
\frac{dv_z}{dr} \neq 0
\]

* NAS Postdoc Fellowship
Scientific advancement of sheared flow stabilization

1998 – 2014: DOE-funded* experimental project at the University of Washington to conduct a scientific investigation of sheared flow stabilization in the Z-pinch ➔ ZaP & ZaP-HD projects

- produced long-lived, stable Z-pinch plasmas
- performed detailed measurements\(^1-6\): \(n_e(r,t), n_e(r,z), B(\theta,z,t), B(r), T_i(r), T_e, v_z(r,t)\)
- coupled computational investigations\(^7-12\)
- demonstrated robustness of sheared flow stabilization: stable for 1000’s times longer than static pinch
- investigated limits of stability
- developed understanding of plasma behavior and how to control it
- achieved pinch currents of 50 kA

*Innovative Confinement Concepts and Joint DOE-NNSA HEDLP Programs

\(^1\)Golingo & S, RSI (2003); \(^2\)Jackson & S, RSI (2006); \(^3\)Golingo et al., RSI (2010)
\(^4\)Vogman & S, RSI (2011); \(^5\)Knecht et al., IEEE TPS (2014); \(^6\)Ross & S, RSI (2016)
\(^7\)S & Roderick, PoP (1998); \(^8\)S et al., PRL (2001); \(^9\)S et al., PoP (2003)
\(^10\)Loverich & S, PoP (2006); \(^11\)S et al., NF (2009); \(^12\)S et al., PoP (2017)
FuZE Project to investigate the SFS Z-pinch for fusion

ARPA-E-funded Fusion Z-pinch Experiment, FuZE, expands on the success of ZaP and ZaP-HD.
- more robust device that achieves fusion
- concerted effort on kinetic and fluid modeling
- highly effectual UW & LLNL collaboration
- modest funding level to push towards breakeven
- **Objective:** scientific investigation to explore the potential of the SFS Z-pinch as a compact fusion device
FuZE benefits from detailed numerical simulations

Nonlinear fluid & kinetic simulations using Mach2 (MHD), WARPX (2-fluid), and LSP (PIC) to: (a) study sheared flow stabilization, (b) design experimental details, (c) model whole device, (d) predict neutron yield.

Results show plasma stabilization with sufficient flow shear.

Simulations provide insight to gas injection dynamics.

1Tummel et al., PoP (2019)
When gas mixtures containing deuterium, $\text{D}_2 - \text{H}_2$, are used to make FuZE plasmas, sustained fusion neutron production\(^1\) ($\approx 8 \mu\text{s}$) is detected coincident with quiescent period and large pinch current. Measurements indicate a steady neutron emission to within statistical expectations consistent with a thermonuclear process.

\(^1\)Zhang et al., PRL (2019)
Fusion neutrons scale with deuterium concentration

Neutron counts disappear for plasmas with no deuterium, 100% H₂.

Dependence agrees with expected thermonuclear scaling with $n_D^2$.

Neutron yield of $10^5$ agrees with theoretical thermonuclear process with $T_i \approx 1.2$ keV.

$$N_{neutrons} = \int \frac{1}{2} n_D^2 \langle \sigma v \rangle \tau dV$$
Neutron isotropy measurements exclude beams >9 keV

Difference in neutron energy inferred by measuring proton recoil from two extreme angles.

Maximum measured energy difference is 110 keV.

For 2.45 MeV neutrons, this difference corresponds to a deuteron beam energy of 9 keV.

\[ E_{n_{\text{max}}} = \frac{1}{8} \left( \sqrt{E_b} + \sqrt{3(E_b + 2E_f)} \right)^2 \]

Backward

Forward

Cathode

Anode

Plasma, 50cm
Spatially-resolved measurements indicate line source

Neutron emission volume can be calculated from measurements of multiple detectors at varying locations.

Least squares fit to the data gives emission volume:
- 33.6 cm length, \( L_C \)
- 16.8 cm centroid, \( Z_C \)

1 Mitrani et al., “Using plastic scintillator detectors for diagnosing neutron production on a sheared-flow stabilized (SFS) Z-pinch”, NIMA
Adiabatic scaling yields scientific breakeven at 650 kA$^1$

Starting with experimentally achieved plasma parameters, increasing the current with a fixed linear density rapidly reaches Q>1 conditions. Fusion core$^2$ remains compact even at high Q, resulting in a low-α fusion space thruster$^3$ with high specific impulse ≈10$^6$ s & high thrust ≈10$^5$ N.

Sample instantaneous conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$I_p$</td>
<td>2 MA</td>
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<tr>
<td>$T$</td>
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</tr>
<tr>
<td>$L$</td>
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</tr>
<tr>
<td>$a$</td>
<td>120 μm</td>
</tr>
<tr>
<td>$Q$</td>
<td>29</td>
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<tr>
<td>$P_f$</td>
<td>3.1 TW</td>
</tr>
</tbody>
</table>

$^1$S et al., FST (2012), S et al., PoP (2017); $^2$Forbes et al., FST (2019); $^3$S et al., AIAA 2006-4805
SFS Z-Pinch reactor conceptual design is underway

Liquid LiPb serves multiple functions:
- outer electrode
- heat transfer fluid
- biological shield
- tritium-breeding blanket

Future technology developments:
- liquid LiPb
- solid electrode design
- repetitive pulsed power

Bechtel, WSI, and Dec. Sys.
SFS Z-Pinch Study w/3 Cores

SFS Z-pincher reactor conceptual design
- several cores share tritium-handling facility
- pulsed at 10 Hz, 190 MWth each core
Accelerated progress on the SFS Z-pinch fusion concept

Critical factors converged to facilitate progress:

1. **ARPA-E funding** has enabled us to push the SFS Z-pinch concept much further than previously possible, e.g. 8x current increase.

2. Keys include deliberate scientific approach and the excellent people of the FuZE team: UW & LLNL scientists, postdocs, graduate students, undergraduate students

3. Computational power and simulation tools allow detailed modeling of sheared flow stabilization that complement the experimental effort.

4. **Inherently compact low-cost fusion device** means that the embodiment of a power-producing fusion reactor also remains compact.

Other innovative confinement concepts have potential for significant progress as fusion devices: spheromak, FRC, levitated dipole, MagLIF, MIF, mirrors, …
Zap Energy is driving technology forward

- Continued funding by ARPA-E Open award and strategic investor base
- Increasing current and corresponding plasma parameters towards higher $Q$
- Building next generation device to replace FuZE next year
- Moving into new facility in the Seattle area
- Continuity of strong existing team and adding new personnel
- Ongoing partnerships with UW and LLNL