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

Uri Shumlak for the FuZE Team

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ARPA-E Fusion Workshop

13-14 August 2019
San Francisco, California

*supported by a cooperative agreement from ARPA-E

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Presentation Outline

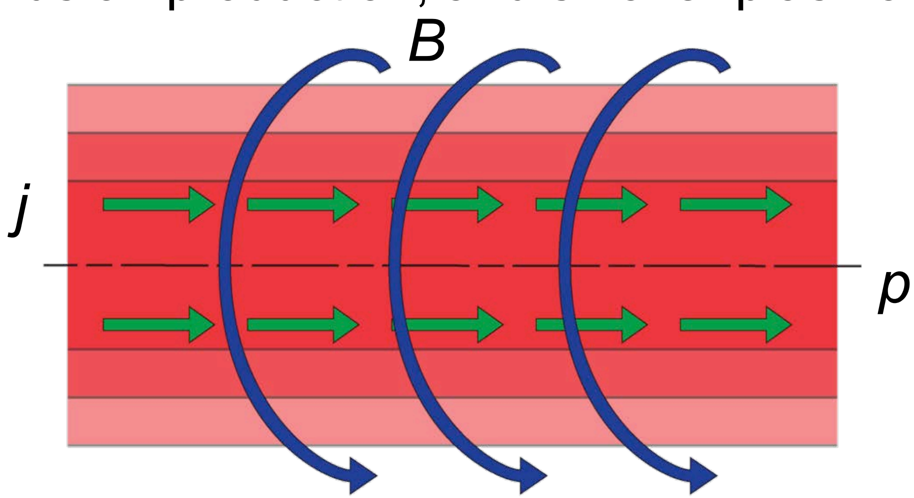
- The simplicity and many other advantages of the Z-pinch
- Current status of the sheared flow stabilized (SFS) Z-pinch
- Historical scientific developments of the Z-pinch leading to sheared flow stabilization approach
- Theoretical work indicating sheared flows may stabilize the Z-pinch
- DOE-funded 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

Z-pinch configuration has many appealing features

The Z-pinch has the simplest geometry of any magnetic confinement configuration:

$$\frac{dp}{dr} = -\frac{B}{\mu_o r}\frac{d(rB)}{dr}$$

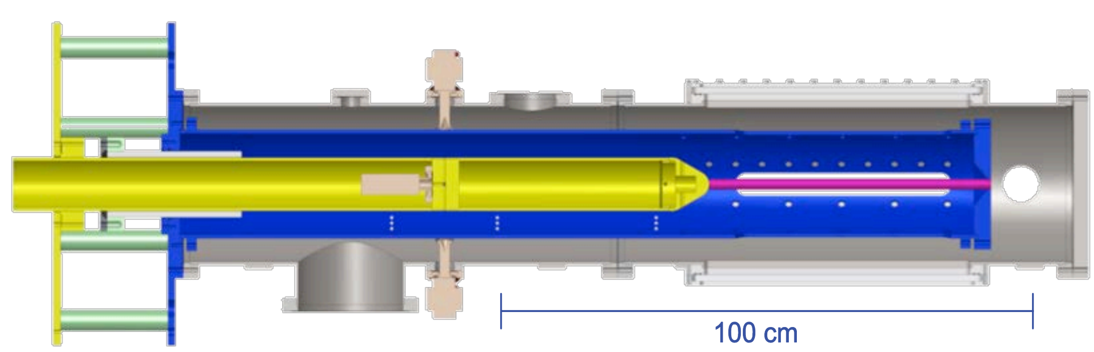
- cylindrical plasma column
- directly driven axial current
- self-generated magnetic field compresses the plasma
- ➢ perfect utilization of the magnetic field for compression, β=100%
- ➢ no magnetic field coils: greatly reducing cost, size, and complexity
- ➢ increasing the current generates higher plasma parameters, increased fusion production, and smaller plasma radius

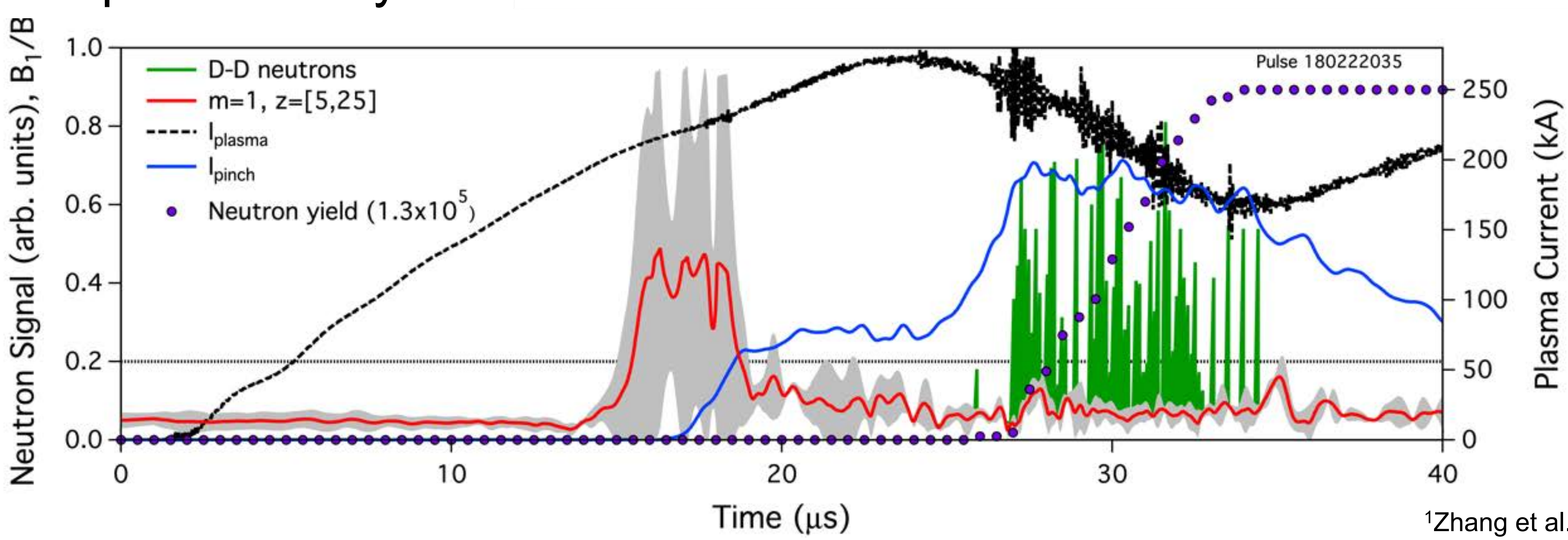


Today: Demonstrated sustained fusion from FuZE

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
- $T_i \approx T_e \approx 1.0$ keV
- $n_e \approx 10^{17}$ cm^{-3}
- $B_a \approx 10$ T
- ➢ continue to scale up current & yield





[1]Zhang et al., PRL (2019)

Z-pinch research predates nuclear fusion understanding

1790: Earliest “Z-pinch” research by Martinus van Marum[1]

1905: Observation of crushed lightning rod by Pollock & Barraclough[2]

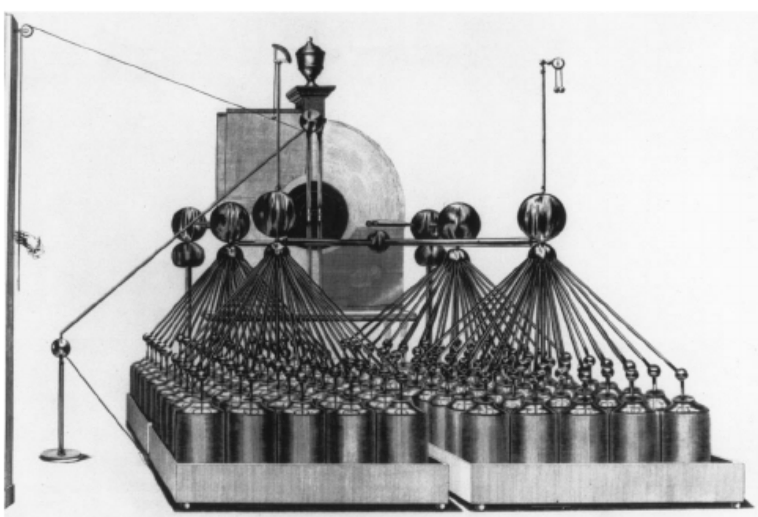
1907: “Pinch phenomenon” in liquid conductor by Northrup[3]

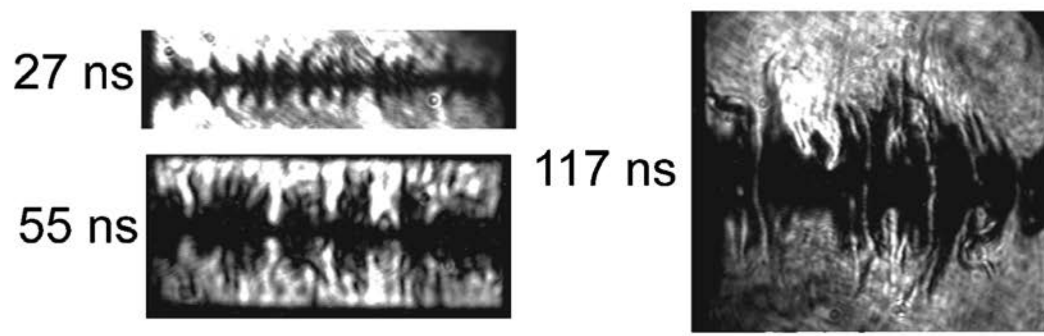
1934: Theoretical model of plasma Z-pinch by Bennett

1950: Z-pinch 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[4]





[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

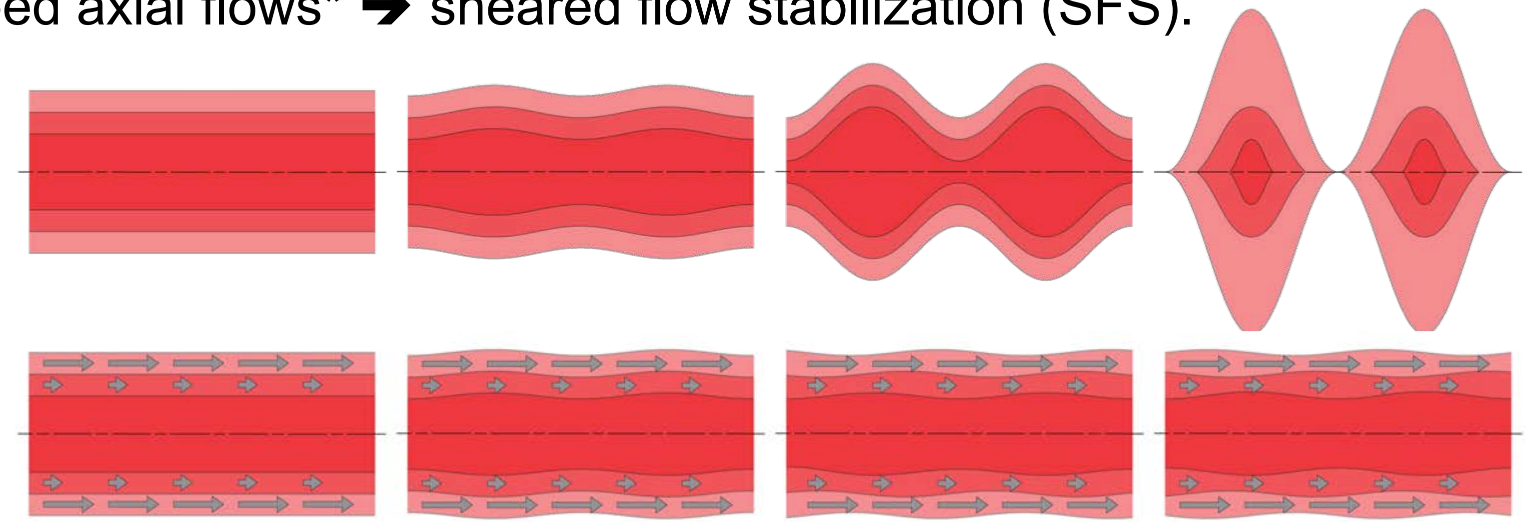
Prior theoretical and experimental research focused on static Z-pinch plasmas, and demonstrated that $m = 0$ and $m = 1$ instabilities persist.

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

No flow

Sheared flow

$$\frac{dv_z}{dr} \neq 0$$



VOLUME 75, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 1995

Sheared Flow Stabilization of the $m = 1$ Kink Mode in Z Pinches

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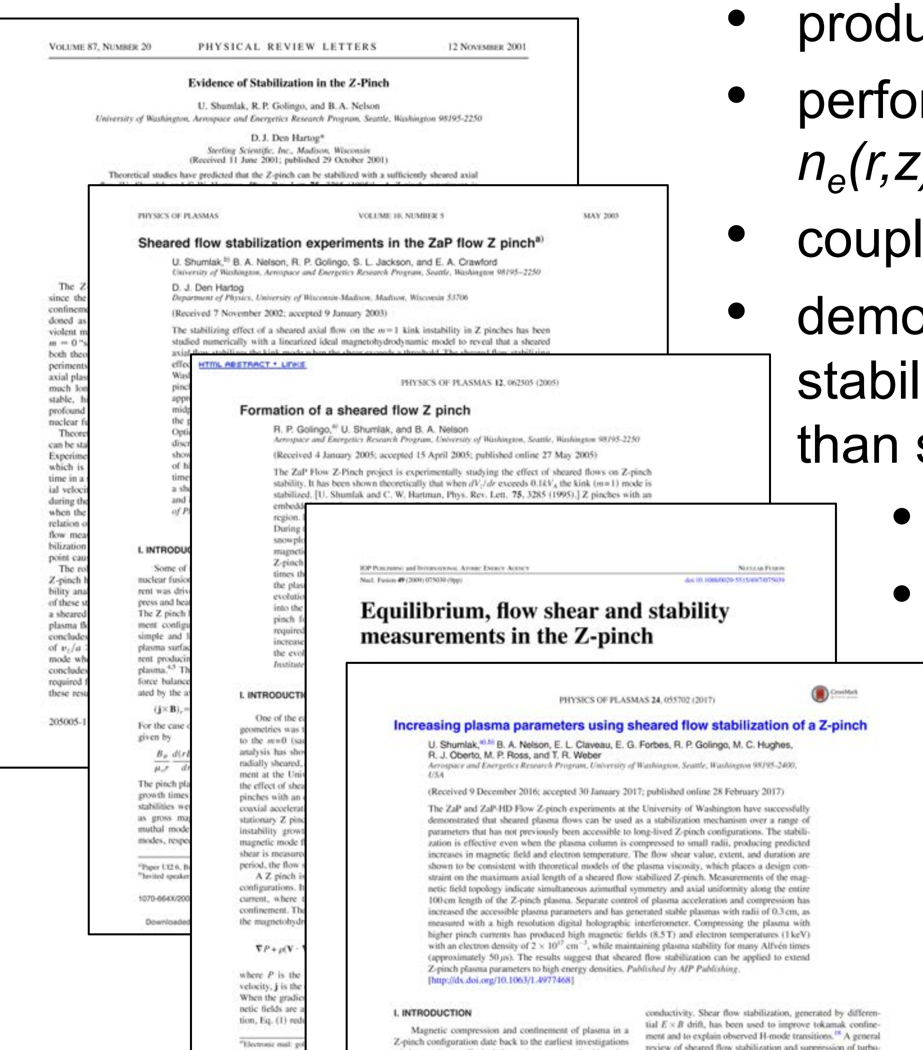
The effect of a sheared axial flow on the $m = 1$ kink instability in Z pinches is studied numerically by reducing the linearized magnetohydrodynamic equations to a one-dimensional displacement equation. An equilibrium is used that is made marginally stable against the $m = 0$ sausage mode by tailoring its pressure profile. The principal result reveals that a sheared axial flow stabilizes the kink mode when the shear exceeds a threshold that is dependent on the location of the conducting wall. For the equilibria studied here the maximum threshold shear (v_z'/kV_A^0) was about 0.1.

* 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.

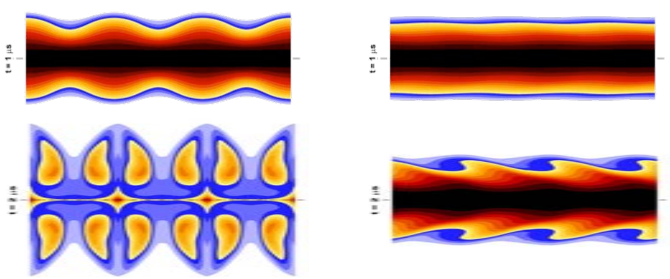
- more robust device that achieves fusion
- concerted effort on kinetic and fluid modeling
- highly effectual UW & LLNL collaboration
- modest funding level to push towards breakeven
- <u>Objective: scientific investigation to explore the potential of the SFS Z-pinch as a compact fusion device</u>

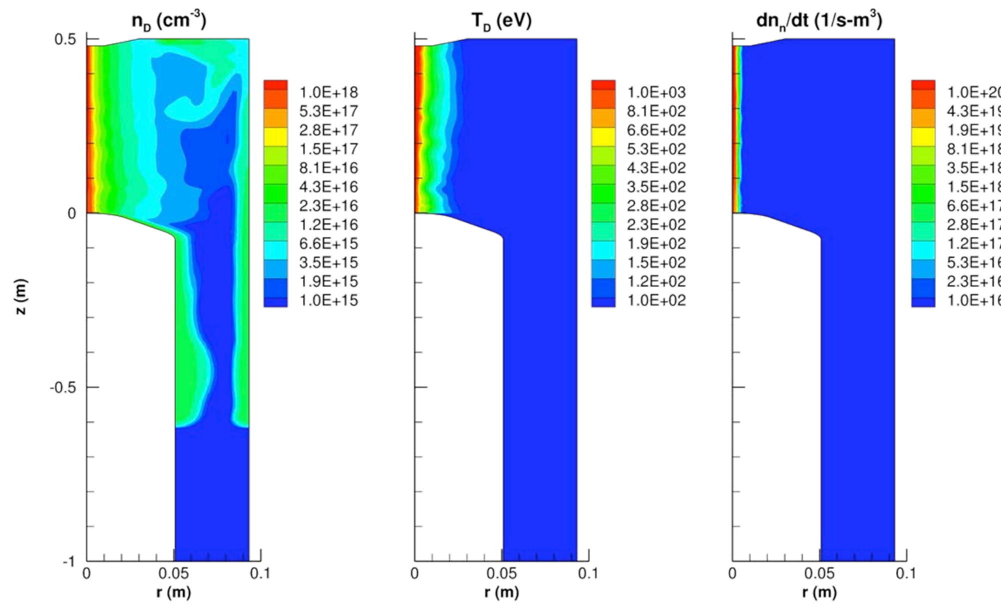
FuZE benefits from detailed numerical simulations

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

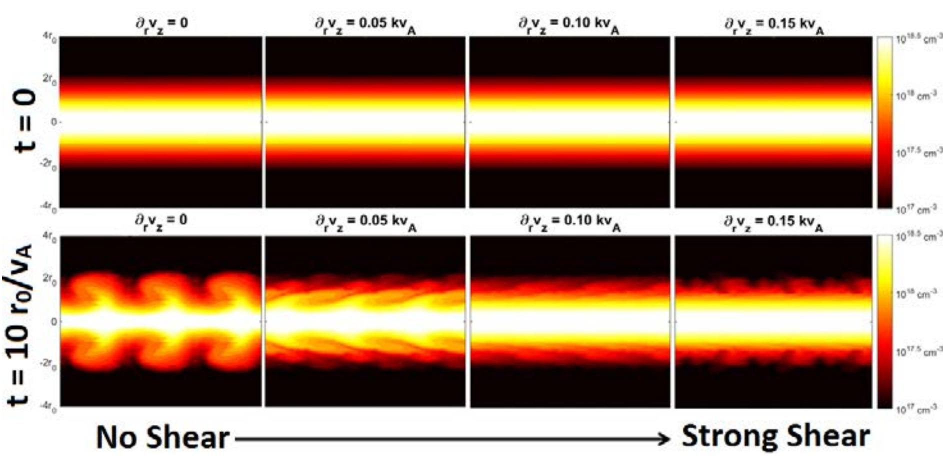
Results show plasma stabilization with sufficient flow shear.

MHD Fluid Results

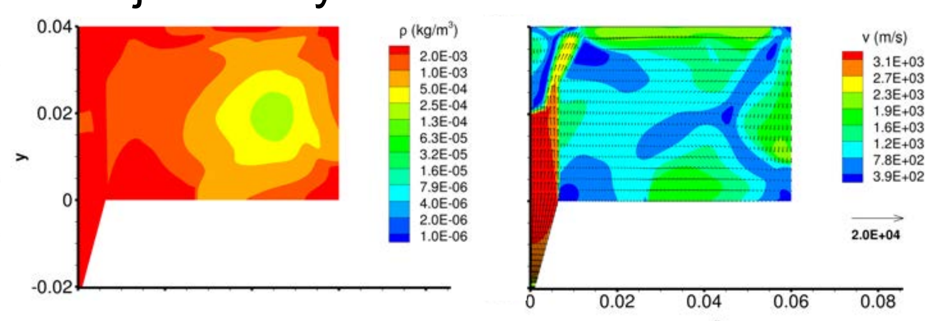




PIC Kinetic Results[1]



Simulations provide insight to gas injection dynamics.

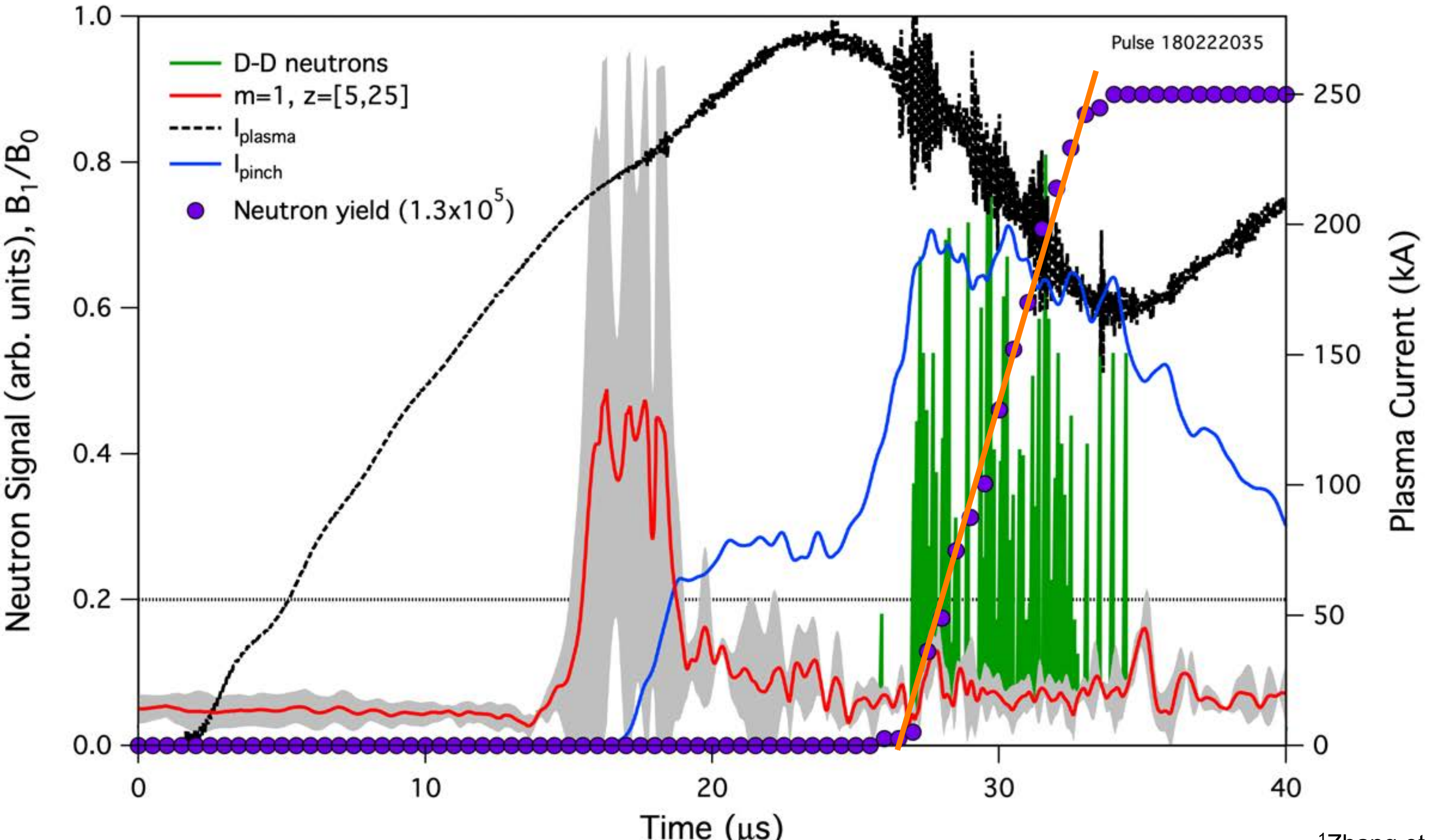


[1]Tummel et al., PoP (2019)

Fusion neutrons from FuZE deuterium plasmas

When gas mixtures containing deuterium, $D_2 - H_2$, are used to make FuZE plasmas, sustained fusion neutron production[1] (≈ 8 μs) is detected coincident with quiescent period and large pinch current.

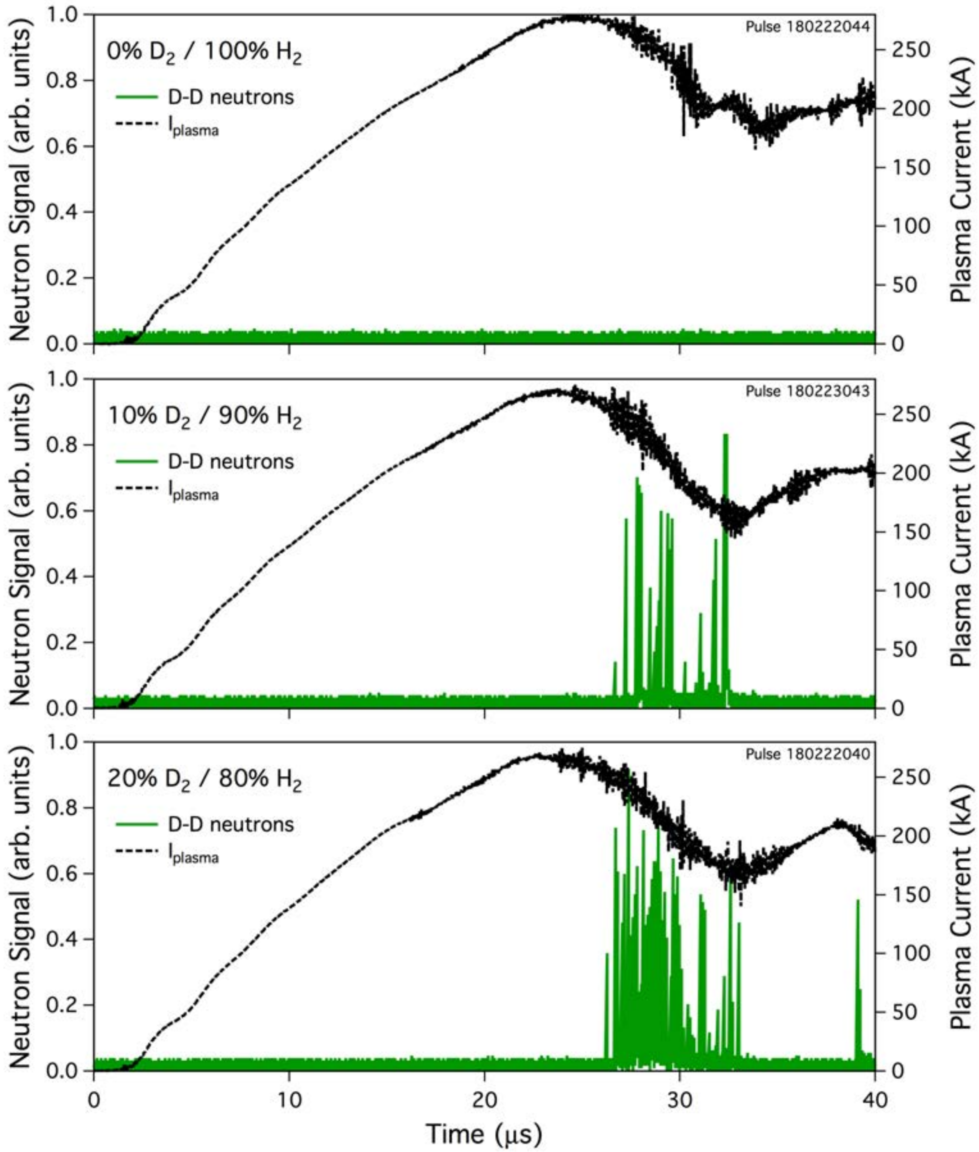
Measurements indicate a steady neutron emission to within statistical expectations consistent with a thermonuclear process.



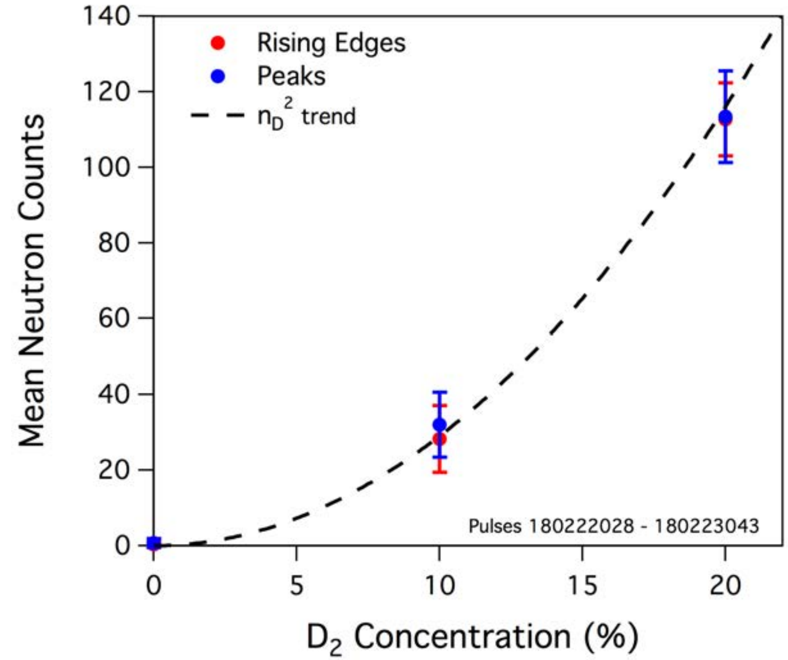
[1]Zhang et al., PRL (2019)

Fusion neutrons scale with deuterium concentration

Neutron counts disappear for plasmas with no deuterium, 100% H_2.



Dependence agrees with expected thermonuclear scaling with n_D^2.

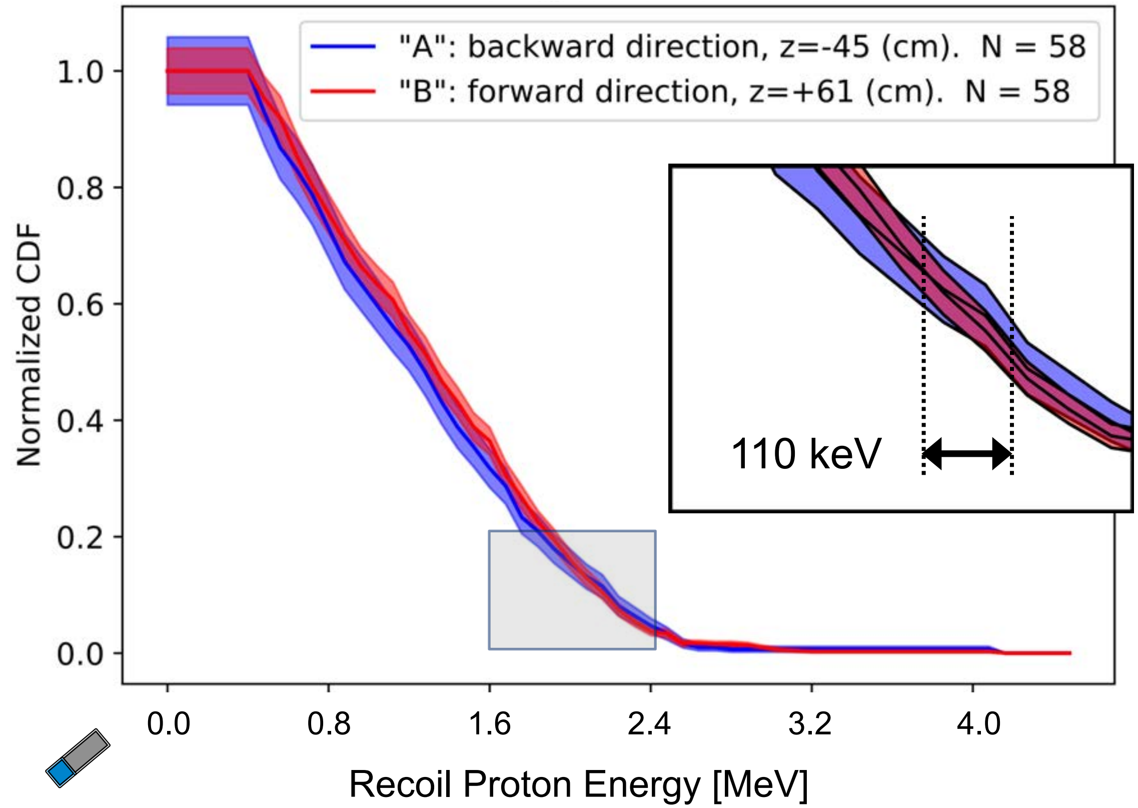


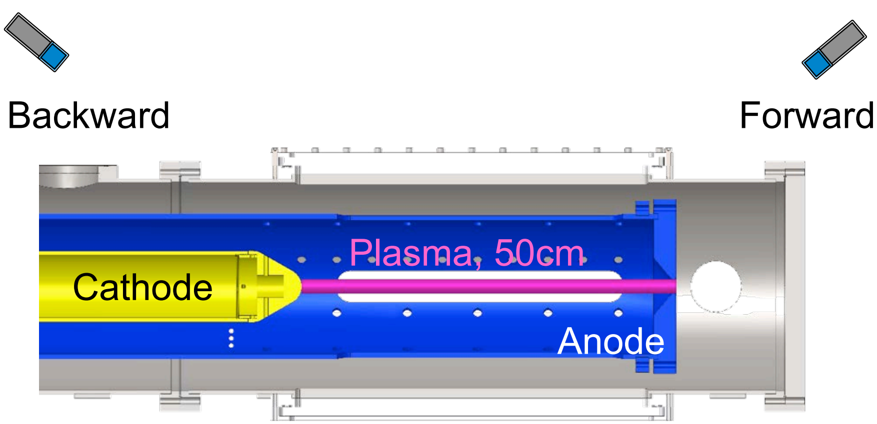
Neutron yield of 10^5 agrees with theoretical thermonuclear process with $T_i \approx 1.2$ keV.

$$N_{neutrons} = \int \frac{1}{2} n_D^2 \langle \sigma v \rangle \tau dV$$

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.



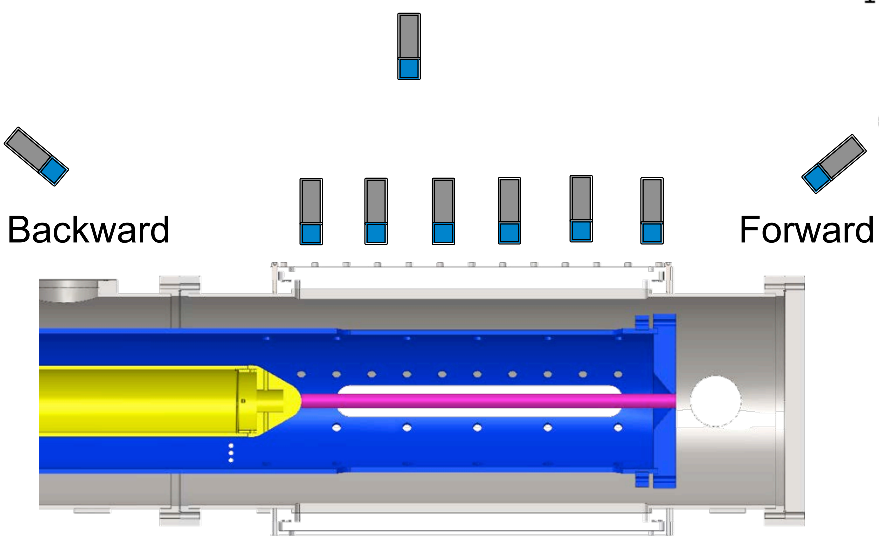


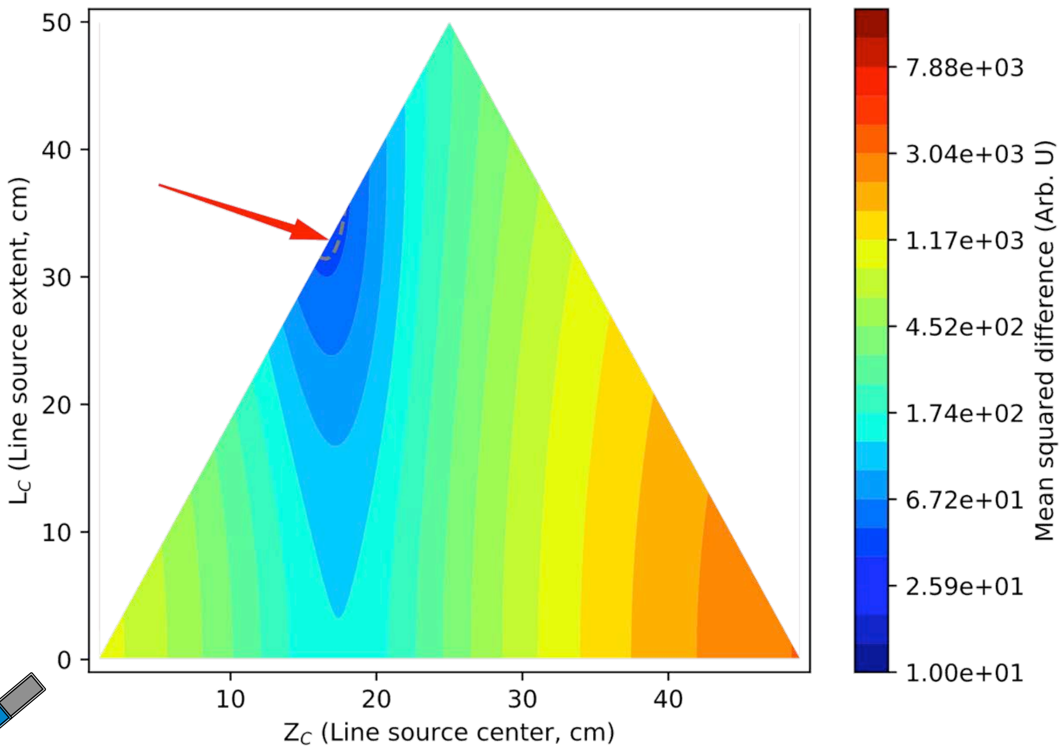
$$E_{n_{\max}} = \frac{1}{8}\left(\sqrt{E_b} + \sqrt{3\left(E_b + 2E_f\right)}\right)^2$$

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





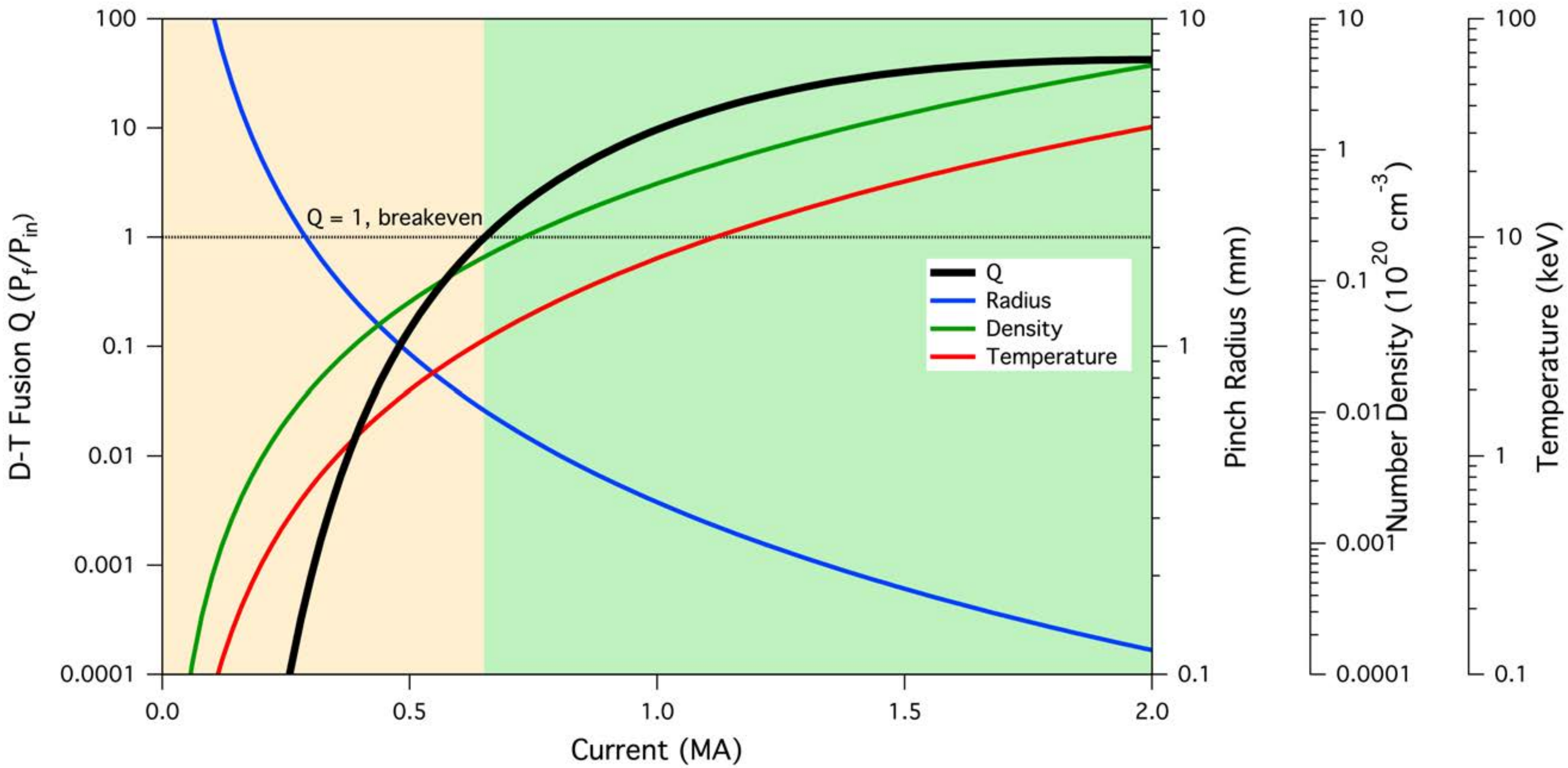
[1] Mitrani et al., “Using plastic scintillator detectors for diagnosing neutron production on a sheared-flow stabilized (SFS) Z-pinch”, NIMA

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.

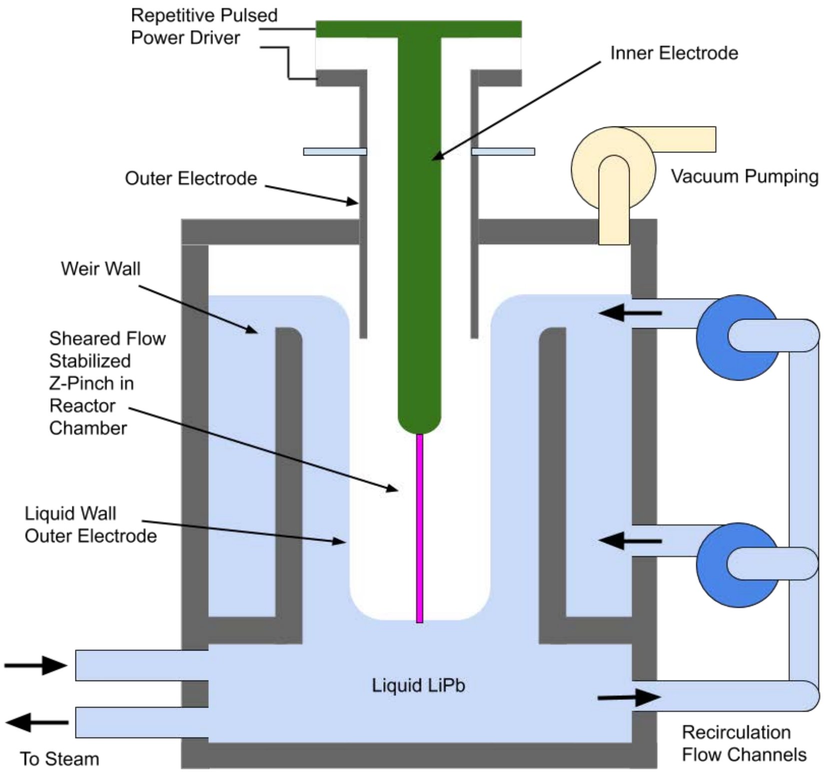
Sample instantaneous conditions

I_p = 2 MA	T = 32 keV
L = 75 cm	a = 120 μm
Q = 29	P_f = 3.1 TW



[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



Individual SFS Z-Pinch Reactor Core (One of Several)

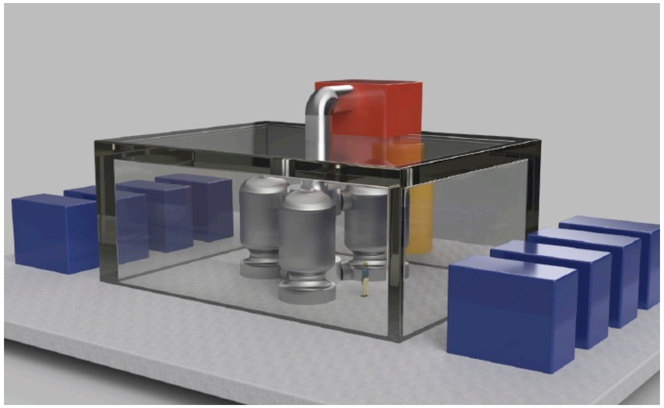
Liquid LiPb serves multiple functions:

- 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-pinch reactor conceptual design

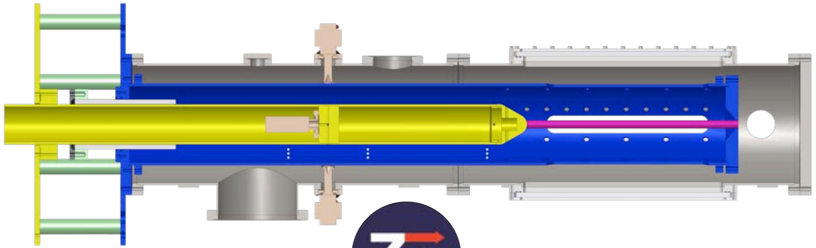
- several cores share tritium-handling facility
- pulsed at 10 Hz, 190 MWth each core

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