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CHANGING WHAT'S POSSIBLE

Sheared Flow Stabilized Z Pinch Performance Scaling

Fusion Review Meeting
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Brian A. Nelson & Ben Levitt
Zap Energy

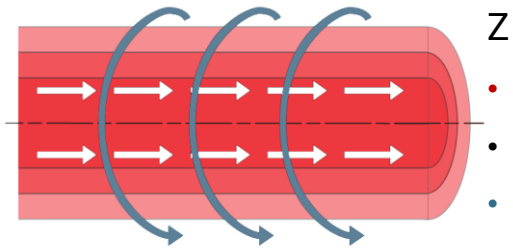
ZAP ENERGY™

Team members and roles

- Brian Nelson, PI, CTO
- Ben Levitt, Director of R&D
- Scientific Operations Team
  - Anton Stepanov, Andrew Taylor, Aria Johansen, Lucas Morton, Pi-En Tsai, Chelsea Liekhus-Schmaltz
- FuZE-Q Leads
  - Morgan Quinley, Z-pinch systems
  - Dan Jackson, HV power supplies
- Computational Team
  - Uri Shumak (CSO)
  - Eric Meier, Lead
  - Iman Datta, Peter Stoltz, Noah Redell
- ARPA-E Capability Teams
  - LANL/UN-Reno: X-ray & Neutronics
    - Glen Wurden, Bruno Bauer, Aidan Klemmer
  - LLNL/Berkeley: Neutronics
    - Drew Higginsen, Amanda Youmans, James Mitrani, Bethany Goldblum
  - LLNL/UCSD: Thomson Scattering
    - Clement Goyon, Simon Bott-Suzuki, Jacob Banasek

Radially-sheared axial flow stabilizes the Z Pinch

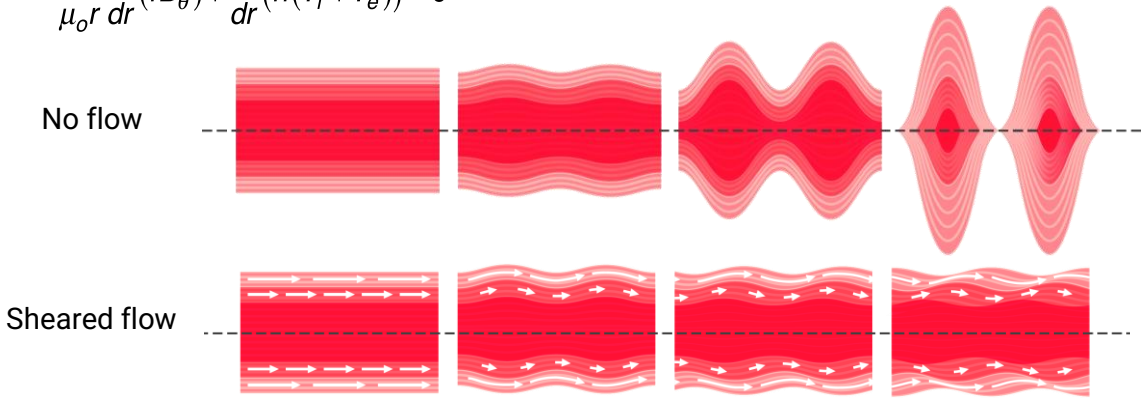
- The sheared flow stabilized (SFS) Z pinch is a very simple geometry



Z pinch plasma confinement concept

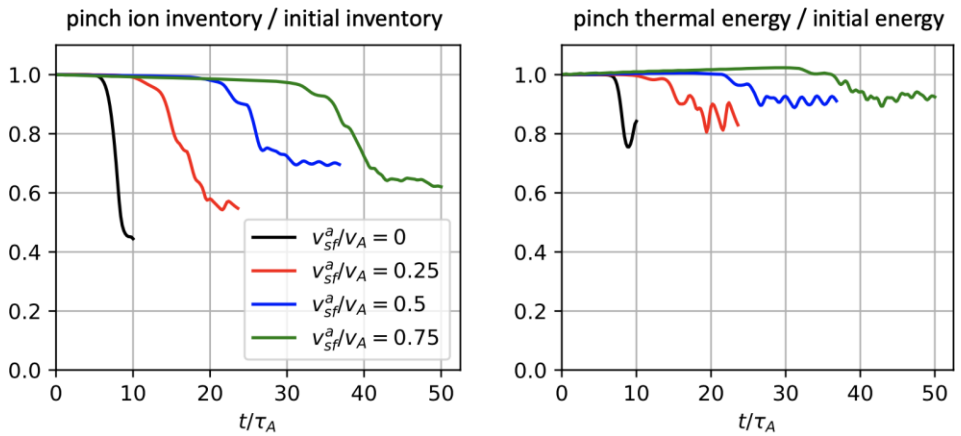
- Cylindrical plasma column
- Current in Z direction
- Self-generated azimuthal magnetic field compresses plasma

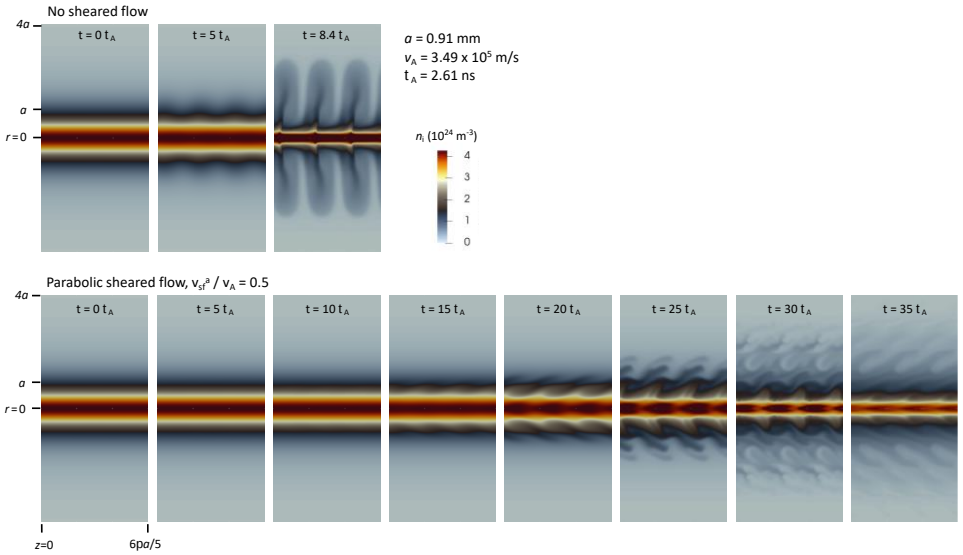
$$\frac{B_\theta}{\mu_o r}\frac{d}{dr}(rB_\theta)+\frac{d}{dr}(n(T_i+T_e))=0$$



- Layers of flow at higher velocity moving out from the center of the column
- Sheard flows limit formation of instabilities

High-fidelity simulations show nonlinear saturation

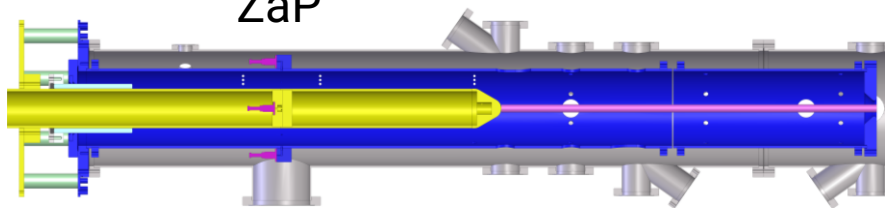




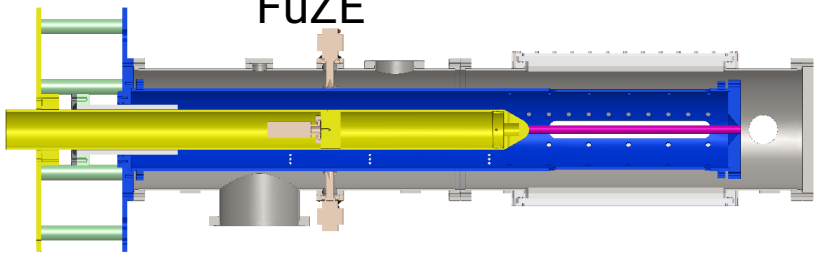
Meier and Shumlak, Phys. Plasmas (2021)

FuZE-Q is scaling current to scientific equivalent breakeven

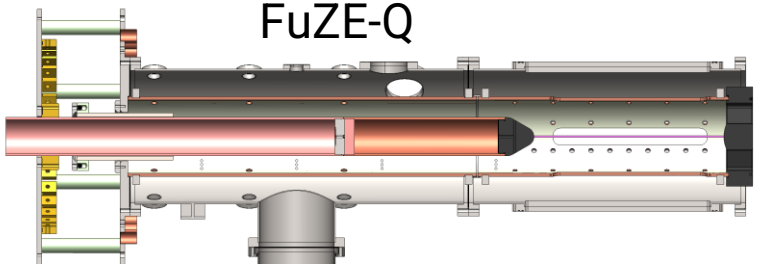
ZaP



FuZE

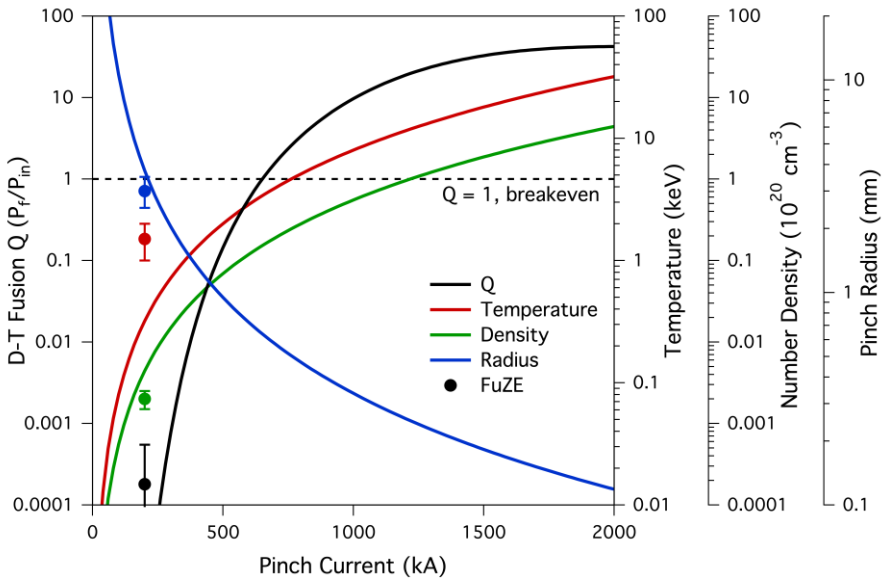


FuZE-Q

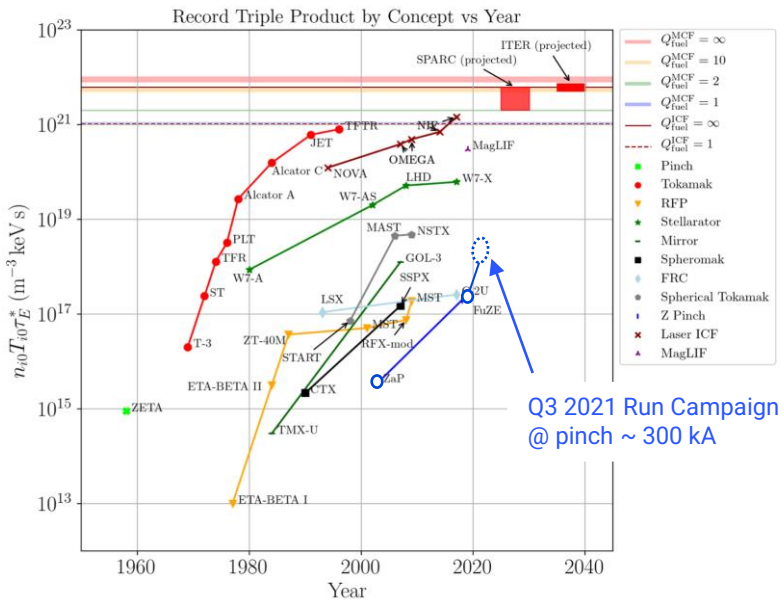


Parameter		ZaP	FuZE	FuZE-Q
Year built		1998	2015-2022	2022
Cap Bank Energy	E_{cap}	70 – 110 kJ	500 kJ	1 – 2 MJ
Charge voltage	V_c	7 – 9 kV	8 - 25 kV	15 kV
Plasma current	I_p	100 – 200 kA	300 – 700 kA	800 – 1000 kA
Pinch current	I_{pinch}	50 – 100 kA	150 – 500 kA	600 – 800 kA
Pinch radius	a	0.5 – 1 cm	1 – 3 mm	<1 mm
Pinch length	l_p	50 – 125 cm	50 cm	50 cm
Electron density	n_e	10^{16} cm^{-3}	2 x 10^{17} cm^{-3}	>10^{18} cm^{-3}
Plasma temperature	T_i	100 eV	> 1000 eV	>7 keV
Plasma lifetime	τ_p	10 – 50 μs	10 μs	TBD
Working gas		H_2	H_2, D_2, or mix	H_2, D_2, or mix

Pinch current is key to scaling the SFS Z pinch



Current vs. Q: Increases in plasma current mark the key steps along the development path for the SFS Z-pinch fusion core.



S. Wurzel, 2021, Journal of Fusion Energy

Triple product yields show rapid progress.

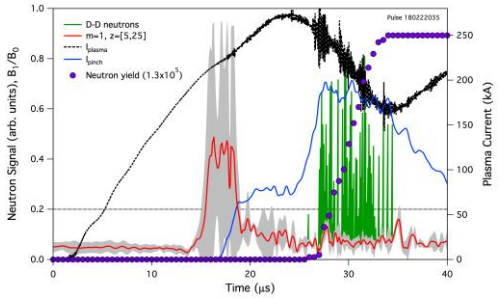
Parameter		Scientific Breakeven	Engr Breakeven	Reactor (Each Core)
Pinch current	I_{pinch}	600 – 700 kA	1 MA	1.2 – 1.5 MA
Pinch radius	a	0.25 mm	0.2 mm	0.15 mm
Electron density	n_e	5×10^{25} m^{-3}	10^{26} m^{-3}	1.5×10^{26} m^{-3}
Plasma temperature	T_e	7 keV	10 – 15 keV	15 – 30 keV
Plasma lifetime	T_p	100 μs	150 μs	200 μs

FuZE Science Accelerated by ARPA-E Capability Teams

- Advanced suite of measurements support progress towards breakeven

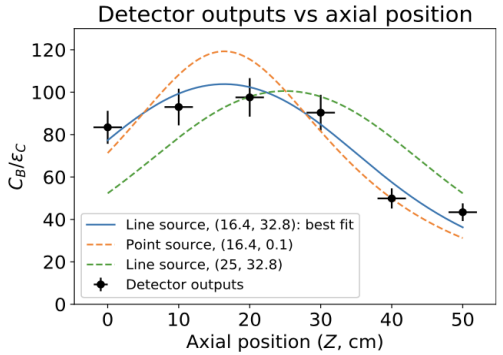
Neutron production (green) ~10 us, 1000x MHD growth times during plasma quiescence[1]

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

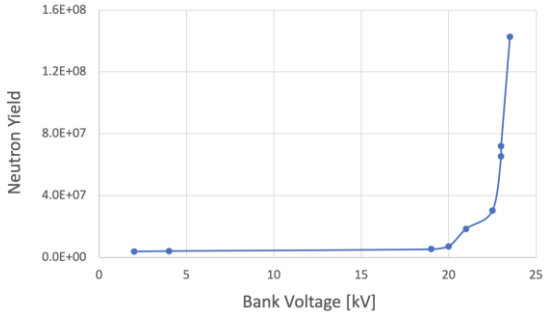


Neutron spectra consistent with ~30 cm axially extended[2] thermonuclear production[3] (LLNL)

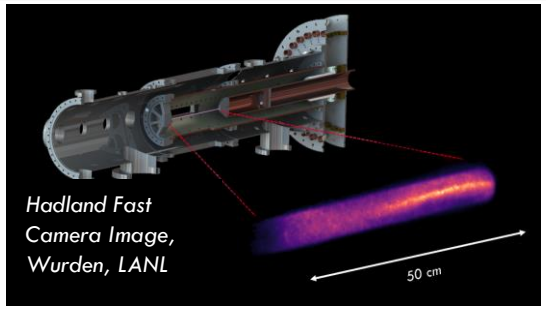
[2] Mitrani *et al.*, NIMA (2019),
[3] Mitrani *et al.*, POP (2021)



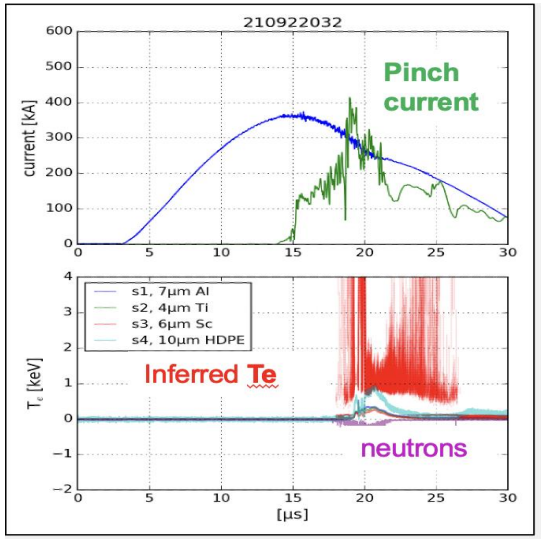
$Y_n > 10^8$ neutrons / 2 usec, strong scaling w pinch current (LANL, LLNL)



Visible fast camera & X-ray pinhole imaging (LANL)

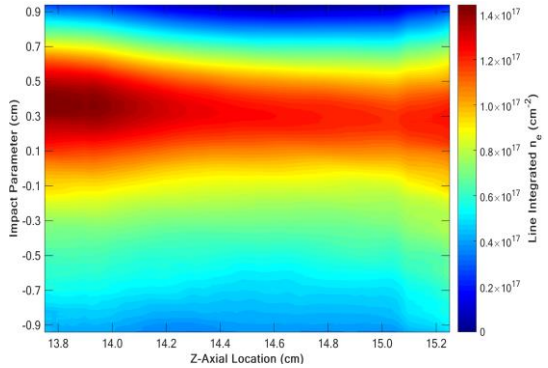


T_e ~ 1-2 keV (LANL soft XUV, Wurden)



Pinch radius, a ~ 3mm[4]

[4] Forbes *et al.*, F&ST (2019)



SFS Z pinch concept leads to compact power plant core

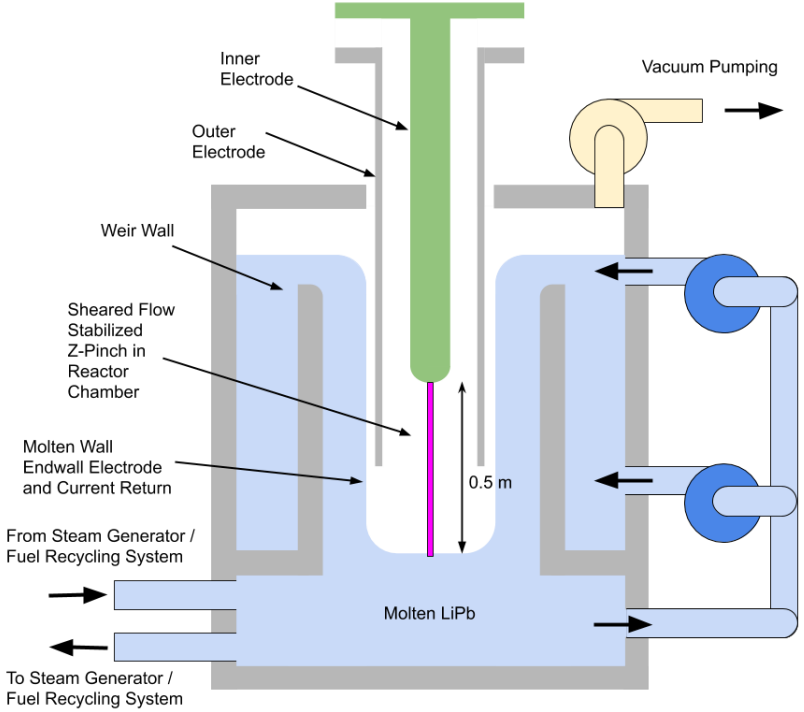
No magnetic field coils or auxiliary heating

Liquid lithium-lead outer wall

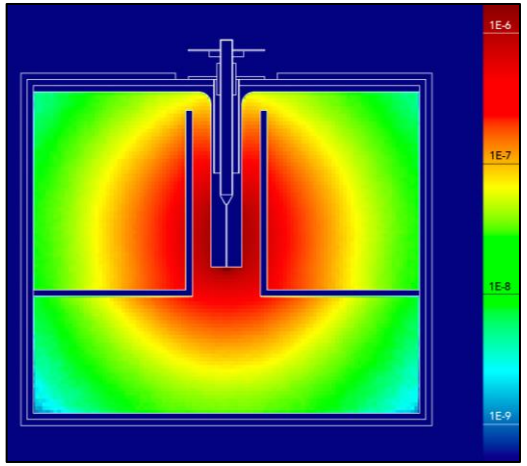
- Return electrode
- Heat-transfer fluid
- Tritium breeding
- Biological shield

Modular design with multiple fusion cores per plant

- 10 Hz pulsed operation
- ~200 MWth per core
- Shared tritium-handling facility



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



Tritium breeding ratio ~ 1.1 w/eutectic LiPb & natural 6-Li enrichment

Zap Energy Systems Engineering Teams developing prototypes of electrodes, liquid wall, repetitive pulsed power, and integrated power plant design.

Path to Market

- The heart of a Zap Energy fusion system does *not* require magnet coils nor auxiliary heating.
  - Very compact and low-cost power plant module.
  - Modules built in a factory and shipped to the plant site
  - Each module is ~50 MWe allowing scaling from small plants to GWe
    - Multiple modules have advantages of maintainability & balance-of-plant economies of scale
- Systems Engineering Division actively de-risking engineering needs for power plant, leading to design of the next step integrated platform
  - Simplicity => rapid iteration process
- Power plant module ~3-m height and diameter

Summary

- Sheared flow stabilized Z pinch leads to a compact fusion power plant

- FuZE (ARPA-E ALPHA) has achieved:
  - 500 kA pinches
  - 10^8 neutrons per pulse
  - Measured T_i > 2.5 keV; T_e > 1.5 keV
  - Demonstrated successful collaborations with ARPA-E Capability Teams

- FuZE-Q (ARPA-E OPEN 2018 & BETHE) beginning operations this summer
  - Push to scientific equivalent breakeven (650 – 700 kA)

- Zap Energy Systems Engineering Teams prototyping power plant components