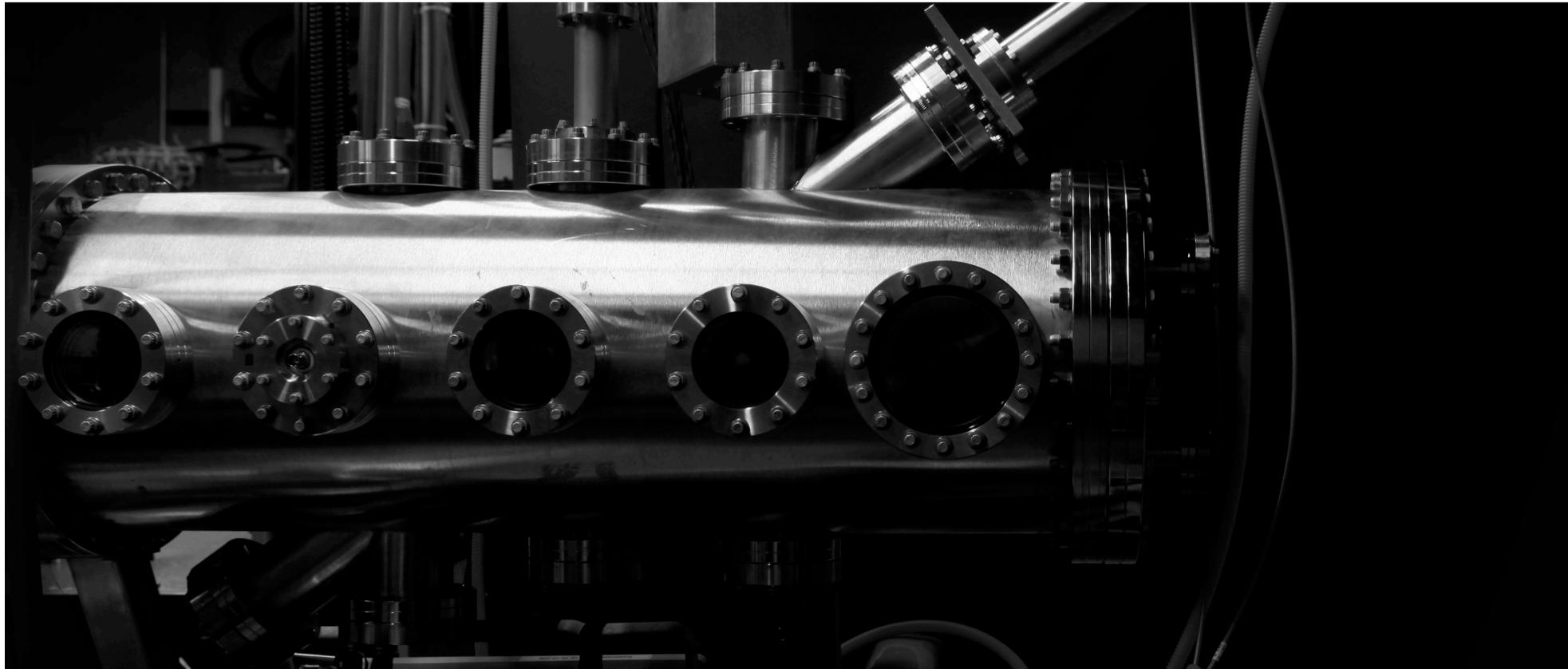


ZAP ENERGY



STATUS: THE SHEARED-FLOW STABILIZED (SFS) Z-PINCH REACTOR

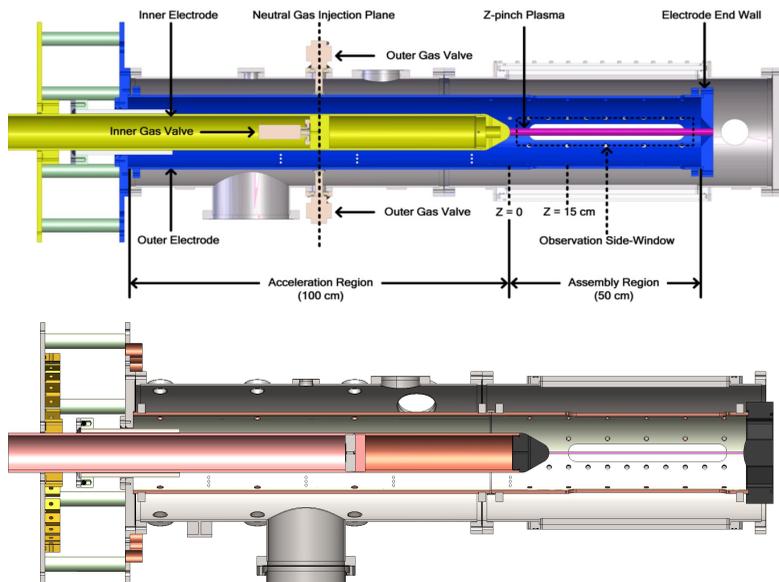


FPA ANNUAL MEETING – 16 DECEMBER 2021
BEN LEVITT, Director R&D, Zap Energy



Zap Energy Then and Now

	2020	2021
personnel	7	+40
location(s)	(1) UW	(3) UW / Everett Lab / Mukilteo Lab
platforms	FuZE	FuZE FuZE-Q



FuZE

- 2 electrode
- Advanced diagnostics

FuZE-Q

- 3 electrode capable
- Advanced gas puff
- Advanced materials
- Breakeven power supply
- Advanced diagnostics



EverLab

Research & Development

- Z Pinch experimental program
- Performance scaling to $Q=1$, single pulse
- Prototypes
 - FuZE 2 electrode
 - FuZE-Q 3 electrode capable

MukLab

Systems & Engineering

- Reactor relevant technologies:
 - Repetitive Pulsed Power
 - Durable electrodes / Advanced Materials
 - Liquid Metal Wall

ZapLab

Fundamental & PMI

- Three electrode performance studies
- Plasma Material interaction
- Talent pipeline!

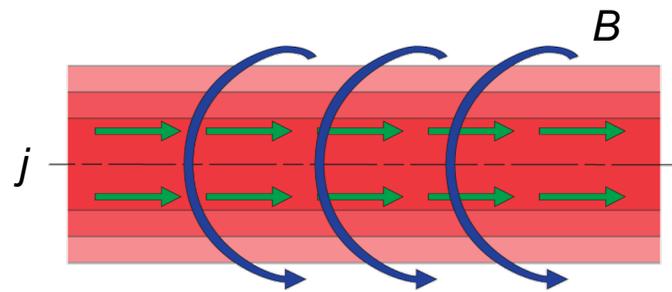


Z pinch Stabilization *via* Sheared Flow

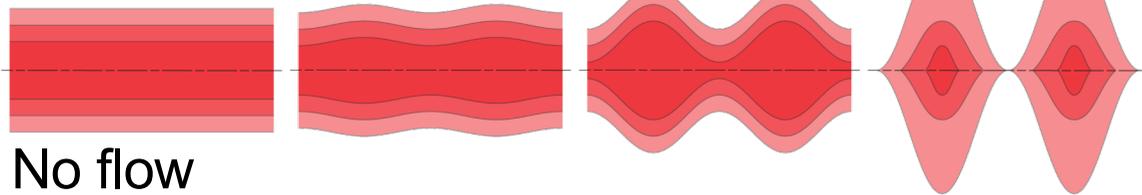
Z pinch:

- Axial current (“z” direction)
- Azimuthal magnetic field
- Field compresses plasma

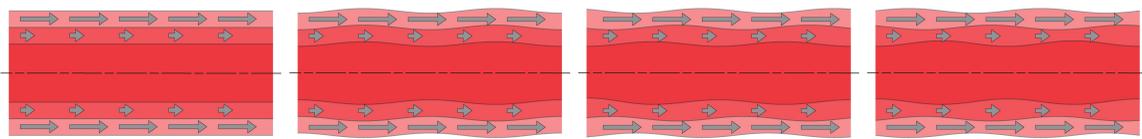
SFS: Radial shear in axial flow stabilizes the Z pinch



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



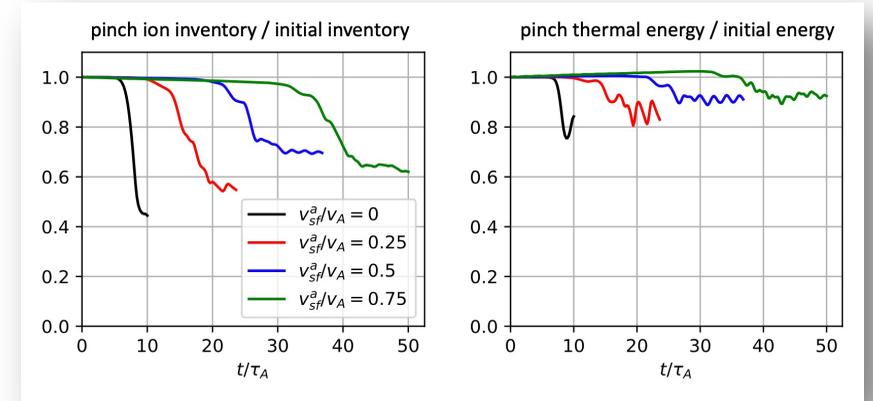
No flow



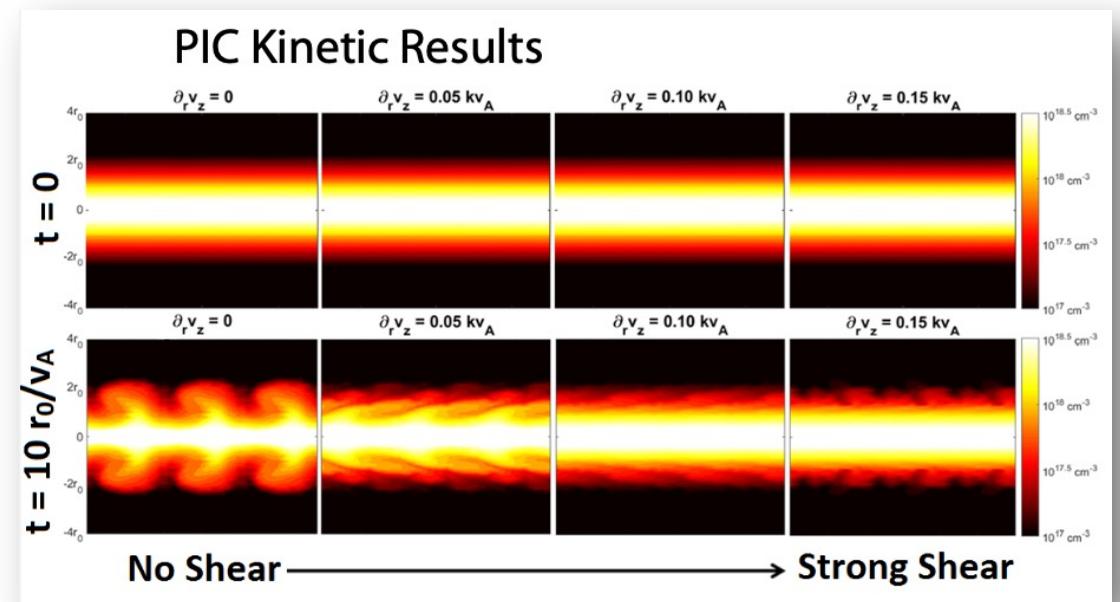
Sheared flow

SFS Mechanism borne in out in WARPXM multi fluid simulation¹:

$$\frac{dv_z}{dr} \cong 0.5 V_A/a$$

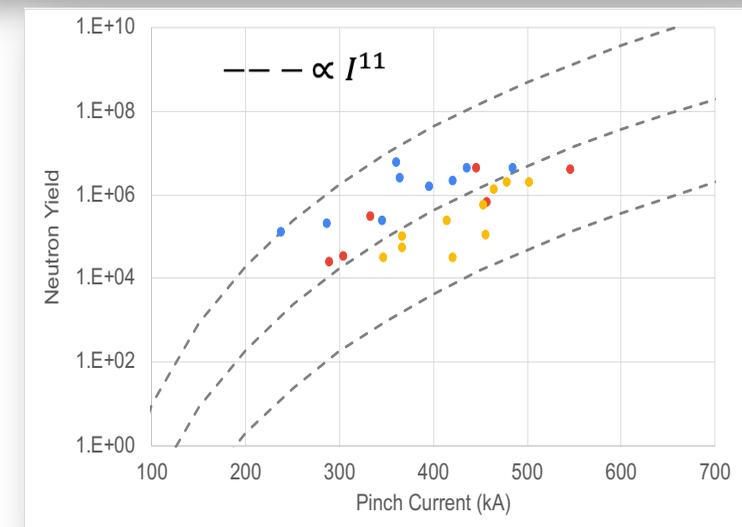
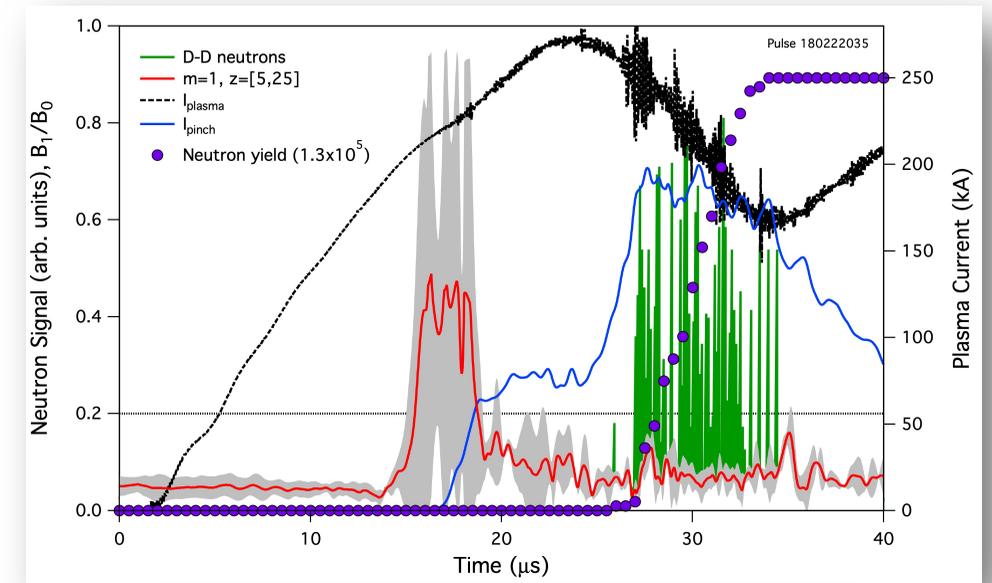
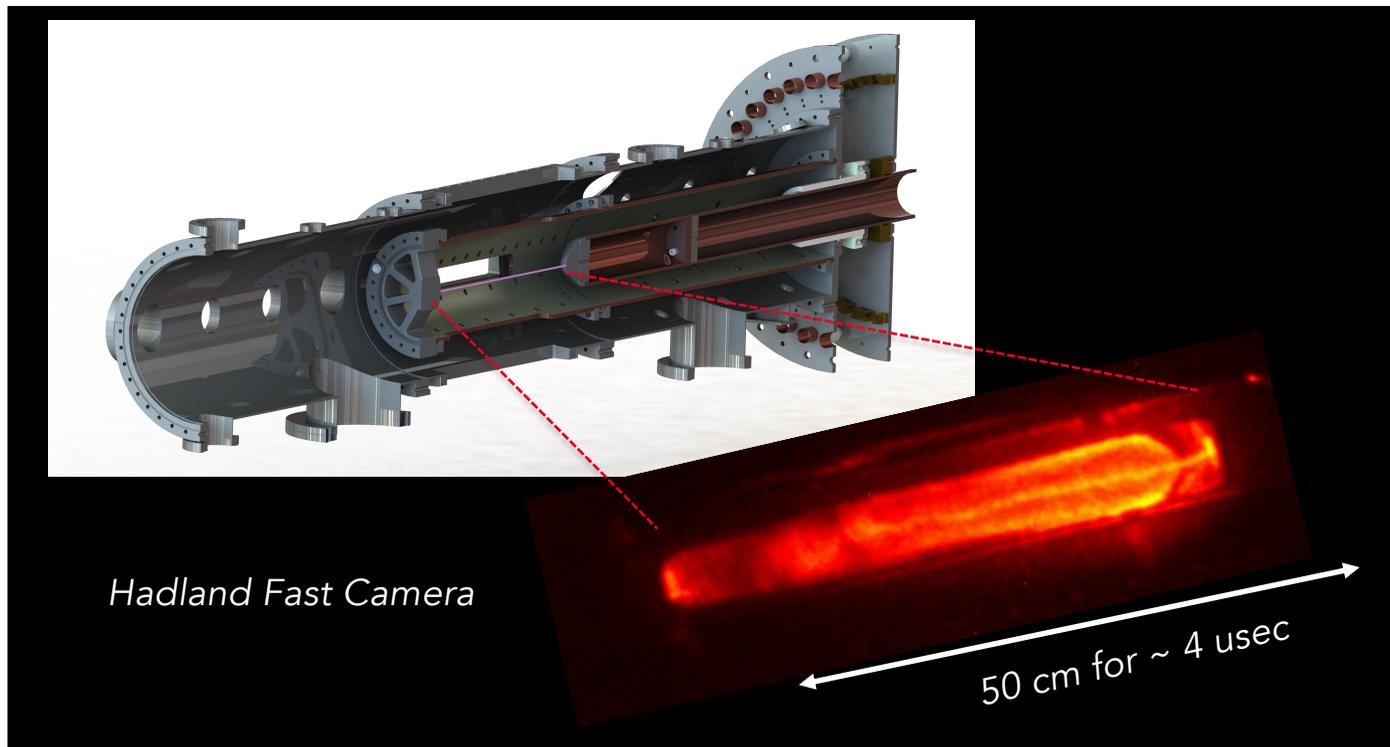


¹Meier, POP, (2021)



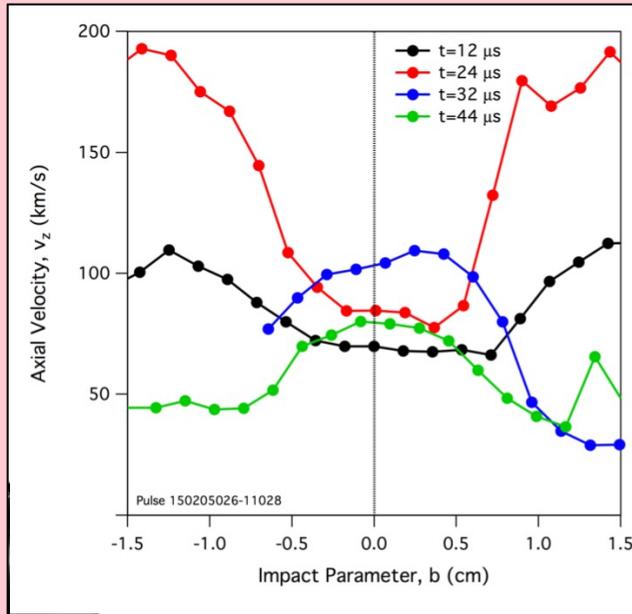
Fusion Performance in FuZE SFS Pinch Plasmas

- Neutron production for ~ 10 μs , thousands of MHD growth times¹
- Neutron spectra consistent with thermonuclear production²
- Neutron yield consistent with $Y_n \propto I^{11}$ (0-D scaling, experimental and computational results)
- Recent campaign neutron yields $\sim 10^8$



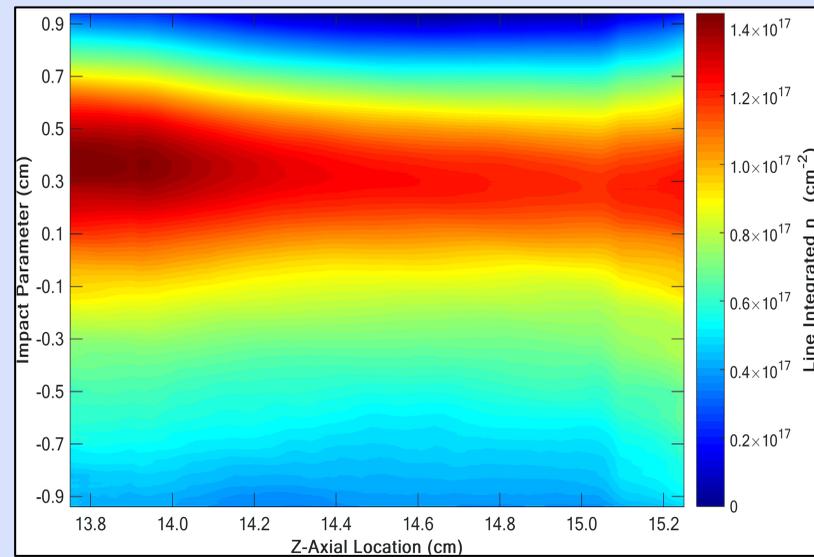
¹Zhang *et al.*, PRL (2019), ²Mitrani *et al.*, POP (2021)

SFS Z Pinch Confirmed by Advanced Diagnostics



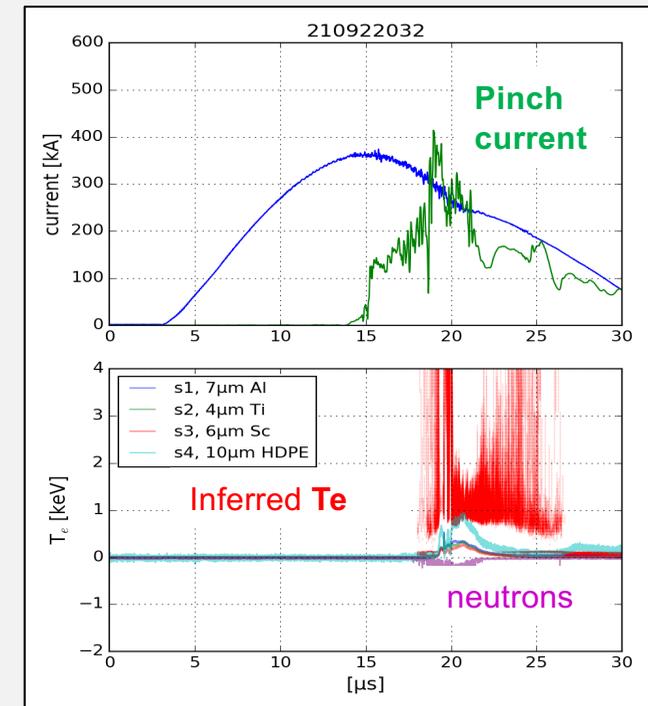
Ion Doppler Spectroscopy¹

Confirms sheared flow profile
 $T_i \approx 2$ keV



Digital Holographic Interferometry²

Confirms pinch radius $a \approx 3$ mm



LANL Soft XUV Diodes³

$T_e > 1$ keV.

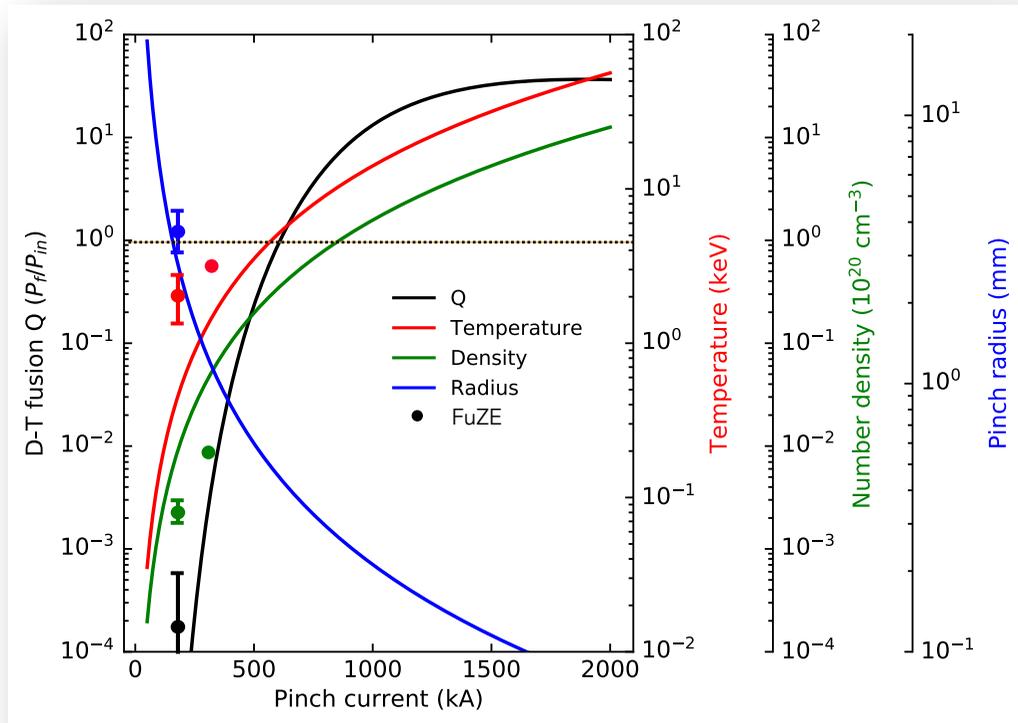
Inferred $n_e \approx 3 \times 10^{23} \text{ m}^{-3}$.

$n_i \tau_E T_i \approx 8 \times 10^{17} \text{ m}^{-3} \text{ keV s}$

$T_e + T_i \approx 3\text{-}4$ keV

¹Shumlak *et al.*, Pop (2017), ²Forbes *et al.*, F&ST (2019), ³Levitt *et al.*, *in prep.* (2022)

Performance Scaling to a SFS Z pinch fusion core



Increases in plasma current mark the key steps along the development path for the SFS Z-pinch fusion core. Adiabatic scaling shows potential path to breakeven.

Q	1	10-15
T_i [keV]	7	15-30
L [cm]	50	50
I_p [MA]	0.65	1.2-1.5
a [mm]	2	0.150
n_e [m^{-3}]	$5e25$	$1e26$

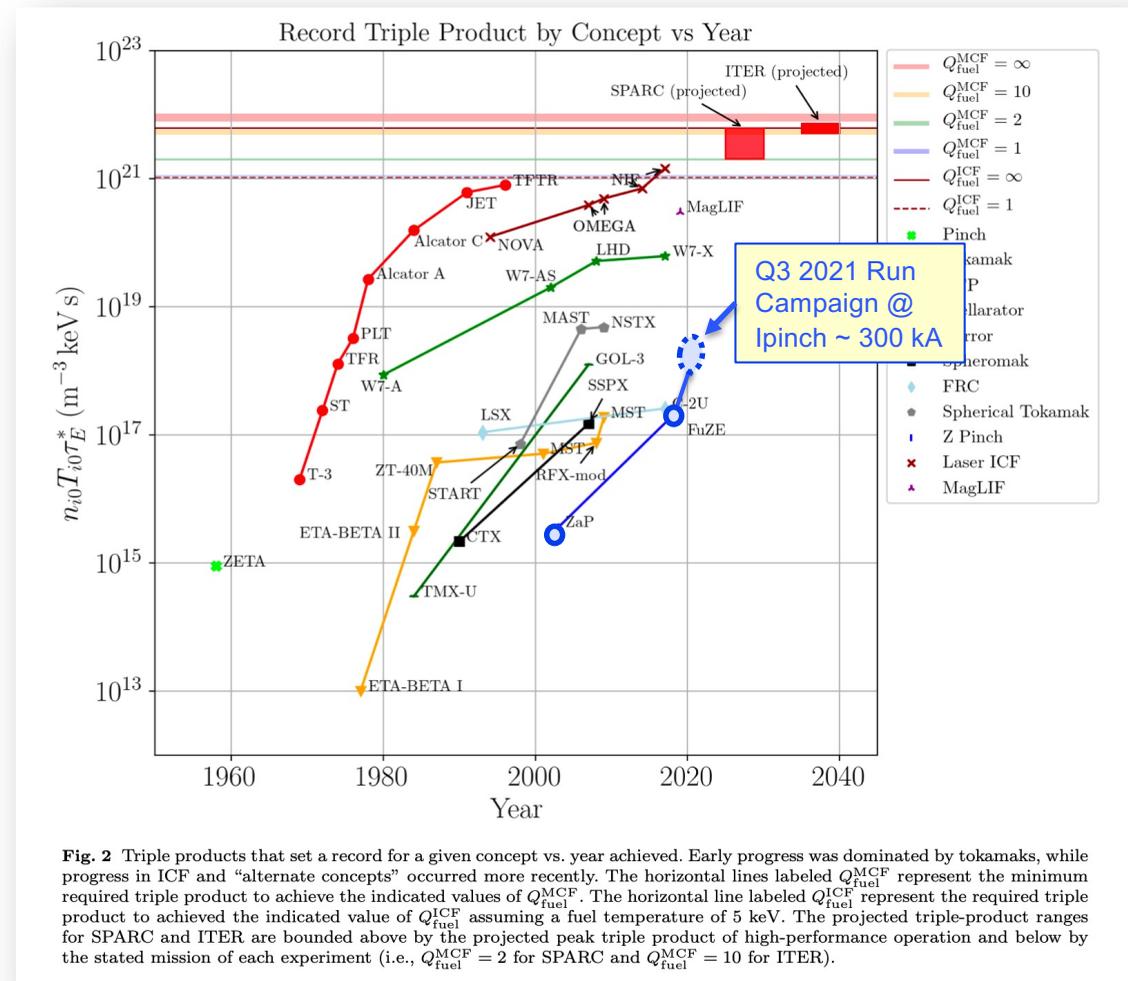


Fig. 2 Triple products that set a record for a given concept vs. year achieved. Early progress was dominated by tokamaks, while progress in ICF and “alternate concepts” occurred more recently. The horizontal lines labeled Q_{fuel}^{MCF} represent the minimum required triple product to achieve the indicated values of Q_{fuel}^{MCF} . The horizontal line labeled Q_{fuel}^{ICF} represent the required triple product to achieved the indicated value of Q_{fuel}^{ICF} assuming a fuel temperature of 5 keV. The projected triple-product ranges for SPARC and ITER are bounded above by the projected peak triple product of high-performance operation and below by the stated mission of each experiment (i.e., $Q_{fuel}^{MCF} = 2$ for SPARC and $Q_{fuel}^{MCF} = 10$ for ITER).

Zap Energy Continuing High-profile Publications & Presentations

- Publications:

- FS&T (2019), Forbes *et al.*
- PoP (2019) Tummel *et al.*
- PRL (2019) Zhang *et al.*
- NIMA (2019), Mitrani *et al.*
- JoAP (2020), Shumlak (Invited “Perspective”)
- RSI (2020), Forbes *et al.*
- PoP (2020), Claveau *et al.*
- PoP (2020), Stepanov *et al.*
- **PoP (2021), Meier & Shumlak**
- **PoP (2021), Mitrani *et al.***

- Invited Talks:

- Tummel, APS DPP 2018
- Stepanov, APS DPP 2019
- Shumlak, USZnet 2020
- Mitrani, APS DPP 2020

- Plenary Talk:

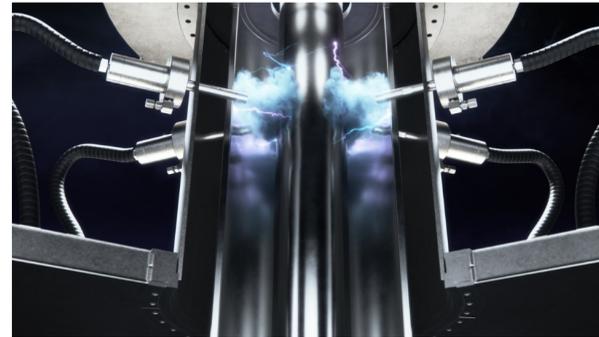
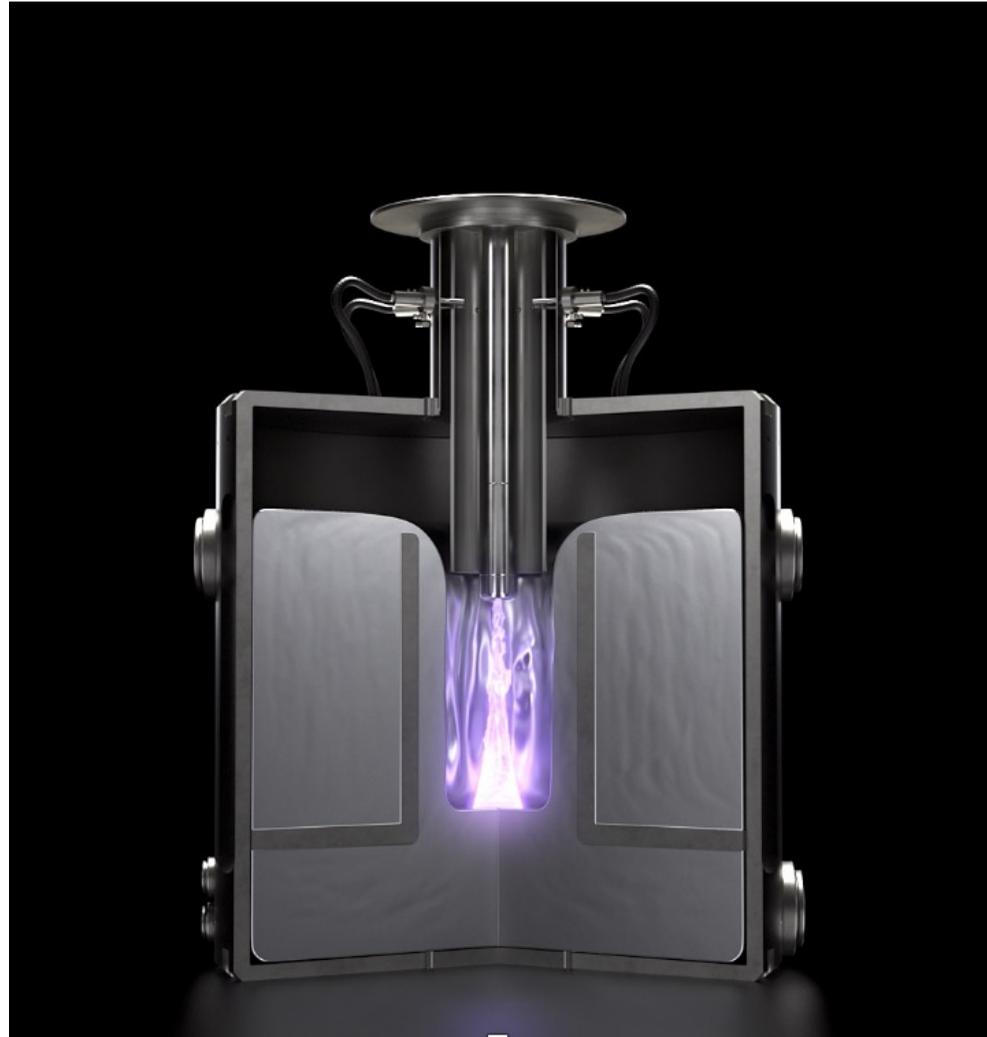
- Shumlak, IEEE PPS 2019
- Shumlak, JPP 2021

- IAEA 2021 Poster

- APS 2021

The image displays a collage of scientific publications and article pages. The top row shows the cover of 'Journal of Applied Physics' with the article 'Z-pinch fusion'. Below it is the cover of 'Physics of Plasmas' with the article 'Kinetic simulations of sheared flow stabilization in high-temperature Z-pinch plasmas'. The middle row features the cover of 'Physical Review Letters' with the article 'Sustained Neutron Production from a Sheared-Flow Stabilized Z Pinch'. The bottom row shows the cover of 'Physics of Plasmas' with the article 'Plasma exhaust in a sheared-flow-stabilized Z pinch'. To the right, there are several article pages from 'Physics of Plasmas' and 'Journal of Applied Physics', including 'Flow Z-pinch plasma production on the FuZE experiment' and 'Thermonuclear neutron emission from a sheared-flow stabilized Z-pinch'. The pages include author names, titles, and publication details.

Zap Energy Fusion Core Concept



1. DT Gas Injected and Ionized



2. Plasma Acceleration

Flowing Liquid LiPb Outer Wall:

- Outer Electrode
- Heat Transfer Fluid
- Tritium-Breeding Blanket
- Biological Shield

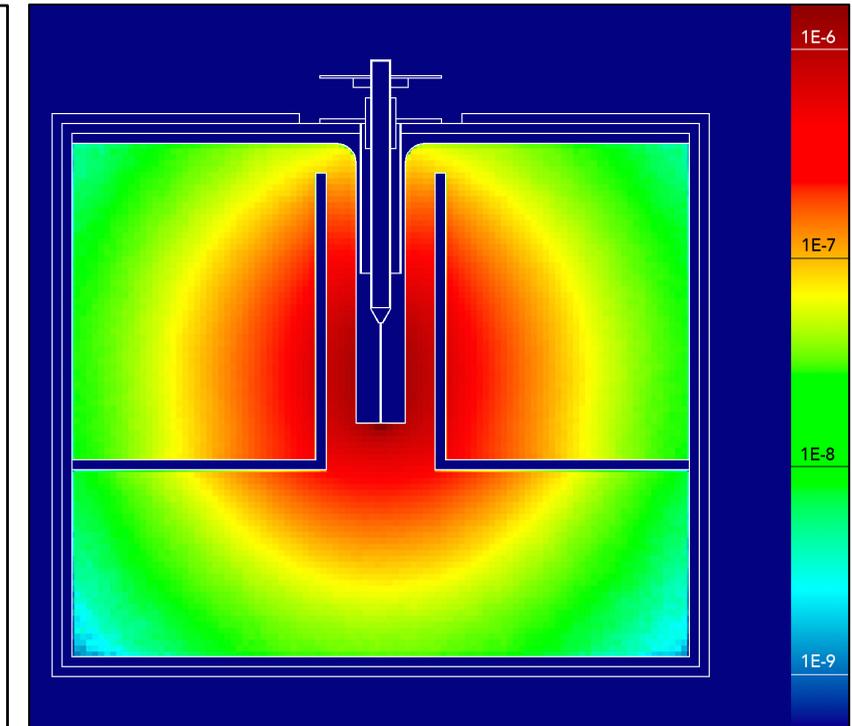
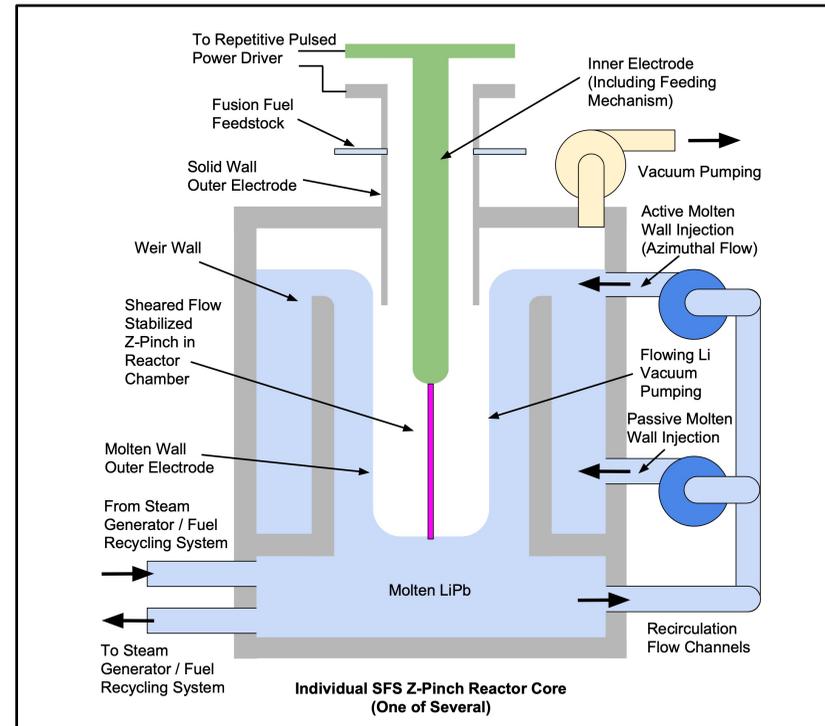
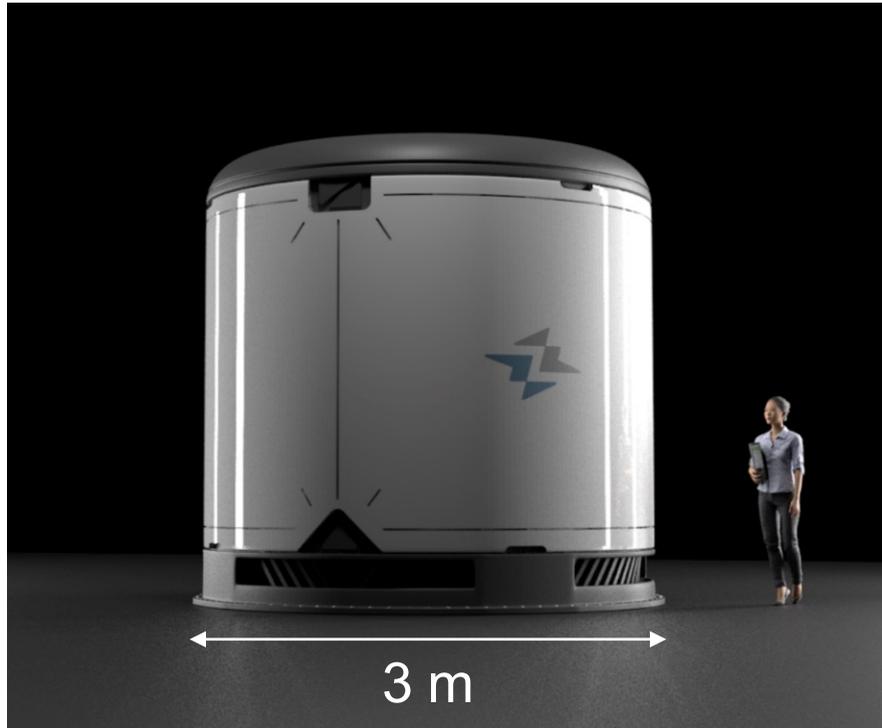


3. Z-Pinch Plasma Formation & Compression



4. Fusion Products Captured In Liquid LiPb Blanket

Zap Energy Reactor Anatomy



~200 MWth per core

- 10 Hz pulsed operation
- Multiple fusion cores / plant
- Common tritium-handling facility
- Firm, flexible power

Liquid LiPb outer wall

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

Tritium Breeding

- TBR ~ 1.1 w/eutectic LiPb & natural 6-Li enrichment
- Bootstrap from D-D to 50-50 D-T in about 1 month

Summary

Zap Energy rapidly growing; 3 labs, >40+ team

- R&D team scaling to breakeven
- Systems Engineering team developing plant relevant technologies

Demonstrated SFS Z-pinch fusion operation:

- lifetimes 10,000x MHD growth time
- D-D neutron production $Y_n \propto I^{11}$ & consistent w/thermonuclear production
- $n \text{ kT } \tau \sim 10^{18} \text{ keV s m}^{-3}$
- $T_e \sim T_i \approx 1\text{-}2 \text{ keV}$

Compact reactor concept

- Modular 3 m, 200-MWth cores
- LiPb walls
- TBR ~ 1.1 ; D-D to 50-50 D-T bootstrap in ~ 1 month

