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Sheared-Flow-Stabilized Z Pinch as a Compact Fusion Device

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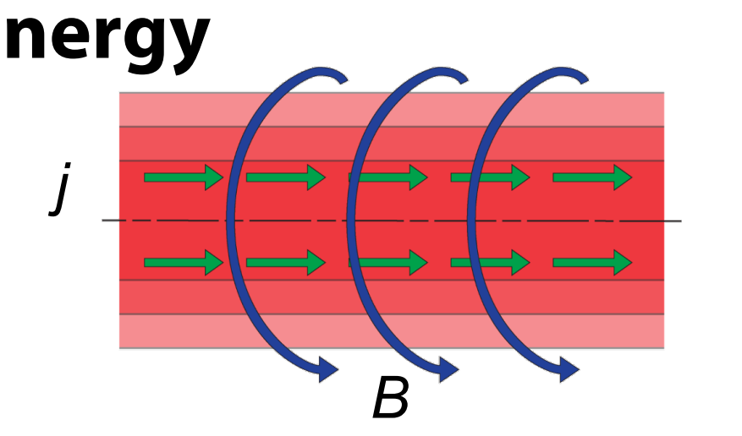
Abstract

The Z-pinch equilibrium radially confines plasma pressure with an axial current. High densities and temperatures should result from plasma compression from increasing the current. However, virulent pressure-driven instabilities quickly destroy the equilibrium and impede the path to a viable fusion device for the traditional Z pinch. Introducing a sheared axial flow to the plasma was theorized to stabilize the Z pinch[1]. Closely coupled with computational studies, a series of Z-pinch experiments (ZaP and ZaP-HD) at the University of Washington were used to test the theory of sheared-flow stabilization. Diagnostic measurements of the plasma equilibrium and stability confirmed that in the presence of a sufficiently large flow-shear, gross Z-pinch instabilities were mitigated, and radial force balance was achieved. Z-pinch plasmas of 50, 100, and 126-cm lengths were held stable for durations much longer than predicted for a static plasma, i.e. thousands of growth times. Experimental results were combined with adiabatic scaling relations and detailed single-fluid, multi-fluid, and kinetic computational studies to explore the limits of plasma properties that can be achieved in a sheared-flow-stabilized (SFS) Z pinch. The collaborative FuZE (Fusion Z-pinch Experiment) project between UW and LLNL scaled the SFS Z pinch to fusion conditions. Flow-shear stabilization was demonstrated to be effective even when a 50-cm long plasma column was compressed to small radii (3 mm), and improved understanding of stabilization provided a means of increasing plasma parameters, e.g. $n_e > 10^{17}$ /cc and $T_i > 1$ keV. Results have demonstrated that fusion reactions are sustained along a 50-cm long Z-pinch deuterium plasma. Steady neutron production[2] was observed for durations up to 8 microseconds during which the plasma was stable, and the current was sufficiently high to compress the plasma to fusion conditions. The neutron production was demonstrated to be consistent with a thermonuclear fusion process since it was not associated with MHD instabilities and beam-target effects were found to be negligible. Likewise, the neutron yield scaled with the square of the deuterium concentration and agreed with the thermonuclear yield calculated from the measured plasma parameters. Increasing the pinch current has demonstrated a corresponding increase in neutron yield. The dependence of yield on current will be presented and compared to theoretical scaling relations and numerical simulations. Experimental observations generally agree with theoretical and computational predictions, indicating that sheared flows can stabilize and sustain a Z-pinch equilibrium and offering a potential path to achieve even higher performing plasmas.

The Z pinch offers attractive scaling to fusion energy

The Z-pinch equilibrium (no applied axial fields) is described by

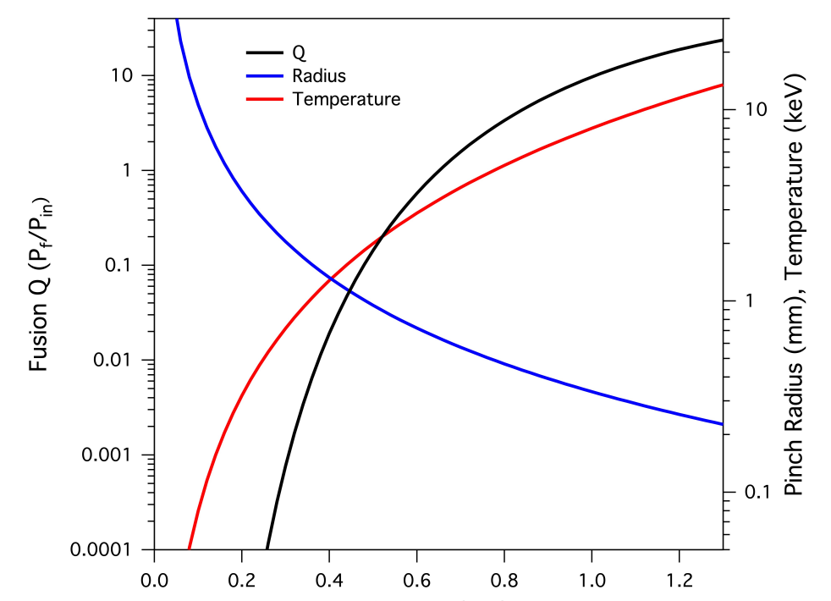
$$\frac{B_\theta}{\mu_o r}\frac{d}{dr}\left(rB_\theta\right)+\frac{d}{dr}\left(n\left(T_i+T_e\right)\right)=0$$



Increasing the current and the resulting azimuthal magnetic field compresses the plasma to fusion conditions in a compact device – no magnetic field coils.

Assuming adiabatic compression and radial force balance gives scaling relations for higher current.[3,4,5]

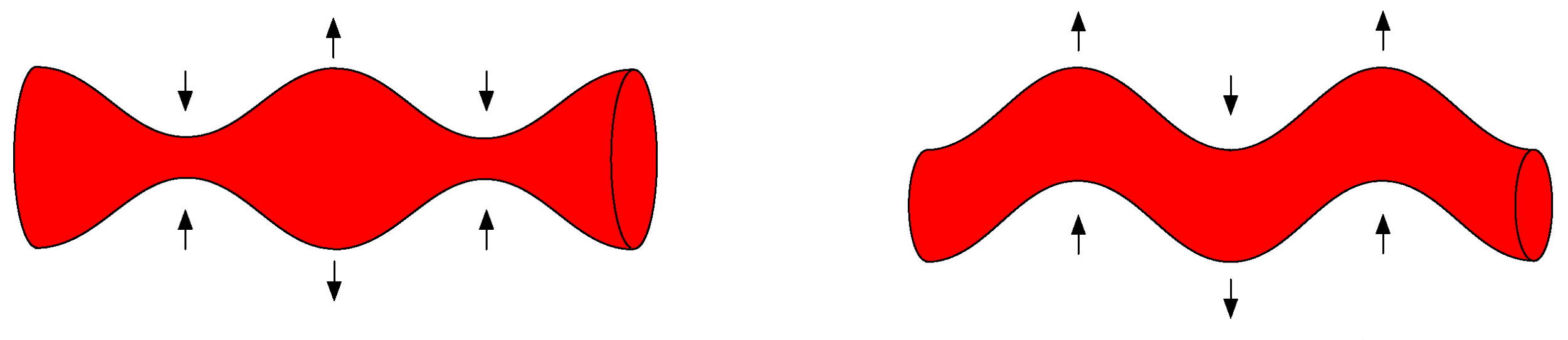
$$\frac{a_2}{a_1}=\sqrt{\frac{n_1}{n_2}\frac{N_2}{N_1}}=\left(\frac{I_1}{I_2}\right)^{\frac{1}{\gamma-1}}\left(\frac{N_2}{N_1}\right)^{\frac{\gamma}{2(\gamma-1)}} \qquad \frac{n_2}{n_1}=\left(\frac{T_2}{T_1}\right)^{\frac{1}{\gamma-1}}=\left(\frac{I_2}{I_1}\right)^{\frac{2}{\gamma-1}}\left(\frac{N_1}{N_2}\right)^{\frac{1}{\gamma-1}}$$



These results are predicated on having a stable plasma.

Stabilizing the Z pinch has proven challenging

While the equilibrium is attractive, the Z pinch is classically unstable to MHD modes: m=0 sausage and m=1 kink.



Stability can be provided by limiting the pressure gradient[6], introducing an axial magnetic field[7,8], or installing a close-fitting conducting wall[9]. These approaches are incompatible with magnetically confining a high-temperature, high-density plasma. Theory suggests the m=1 mode can be stabilized with a sheared axial flow[1],

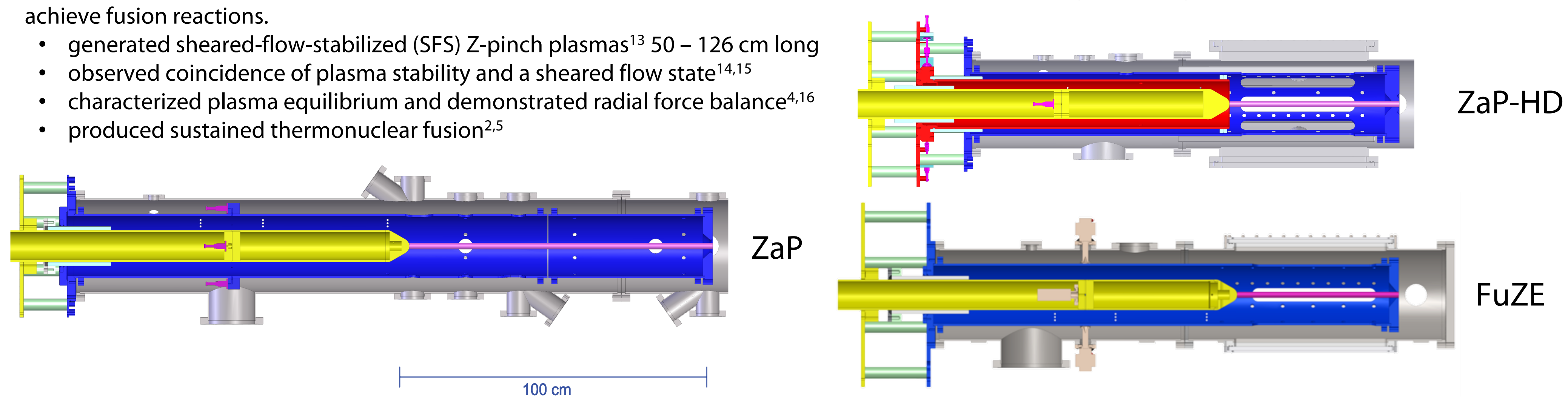
$$\frac{dv_z}{dr} \geq 0.1\,kV_A$$

though the value is sensitive to axis treatment[10,11]. Flow shear is observed to stabilize m=0 modes as well.[12]

Sheared-flow stabilization has been investigated through a series of experimental and computational projects

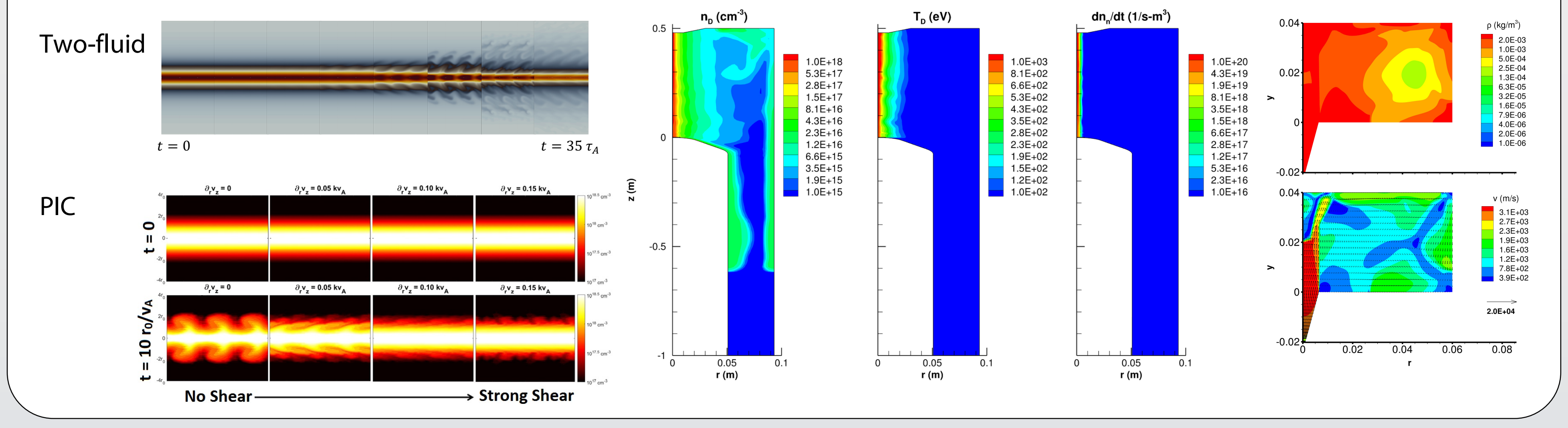
ZaP (1999 – 2009), ZaP-HD (2009 – 2015), and FuZE (2015 – present) are flow Z-pinch devices that investigated using sheared flows to stabilize an unstable plasma and magnetically confined the plasma and compressed it to high plasma parameters and eventually to achieve fusion reactions.

- generated sheared-flow-stabilized (SFS) Z-pinch plasmas[13] 50 – 126 cm long
- observed coincidence of plasma stability and a sheared flow state[14,15]
- characterized plasma equilibrium and demonstrated radial force balance[4,16]
- produced sustained thermonuclear fusion[2,5]



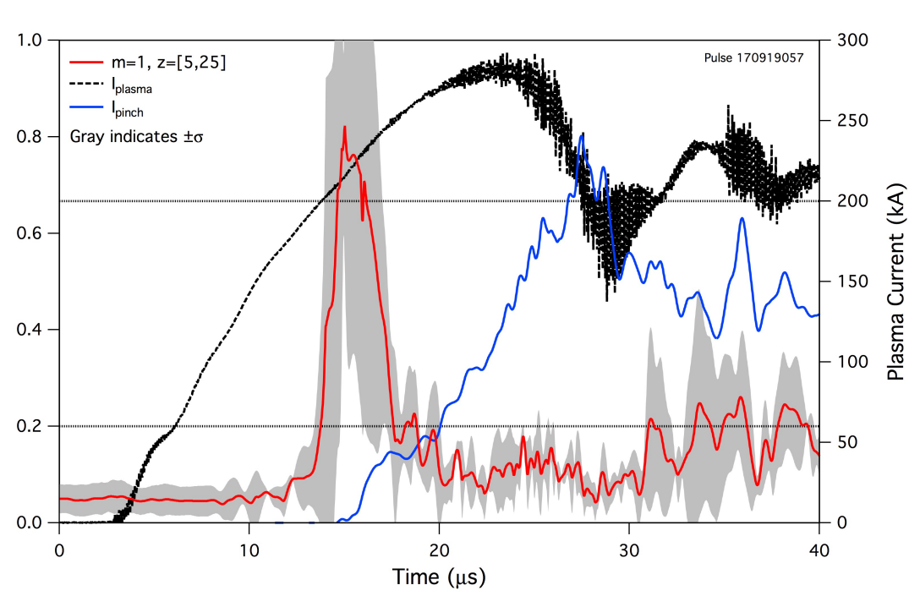
Detailed numerical simulations have been critical to improved understanding

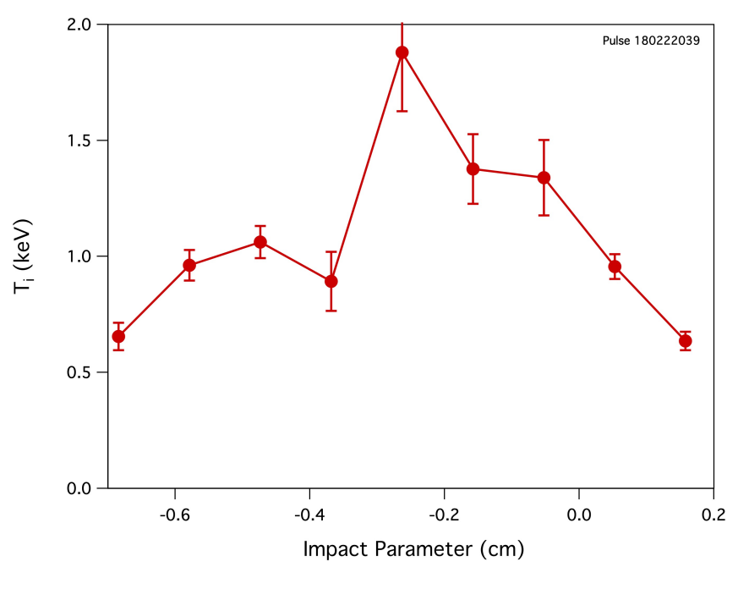
Nonlinear fluid[17] and kinetic[18] simulations using Mach2 (MHD), WARPXM (multi-fluid), and LSP (PIC) to: (a) study sheared flow stabilization, (b) design experimental details, (c) model whole device, (d) predict neutron yield



FuZE (Fusion Z-pinch Experiment) produces stable, high-performance plasmas

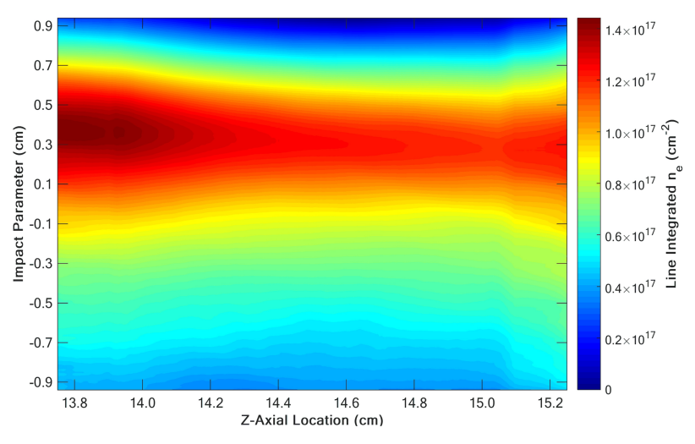
Stable behavior observed during quiescent period. Pinch current rises above 200 kA until it equals total plasma current.

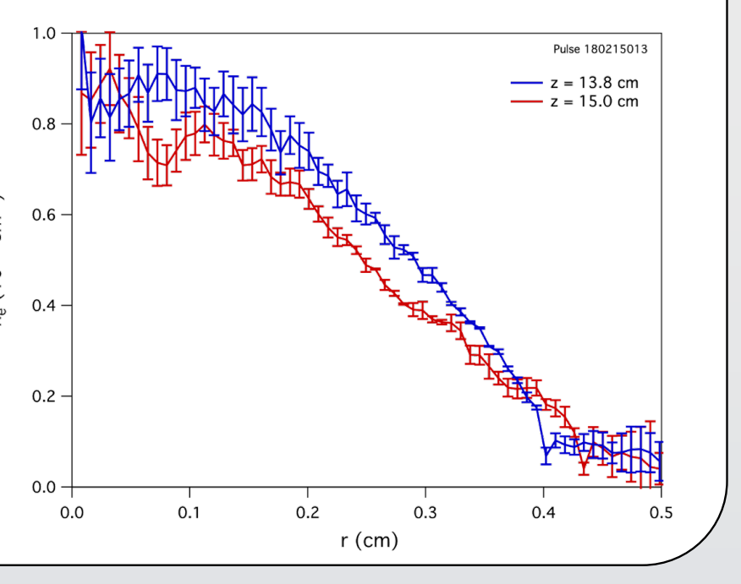




Digital holographic interferograms indicate pinched plasma density during quiescent period (t=25 μs):

- a≈3 mm
- B_θ≈10 T
- T_e+T_i≈1.8 keV

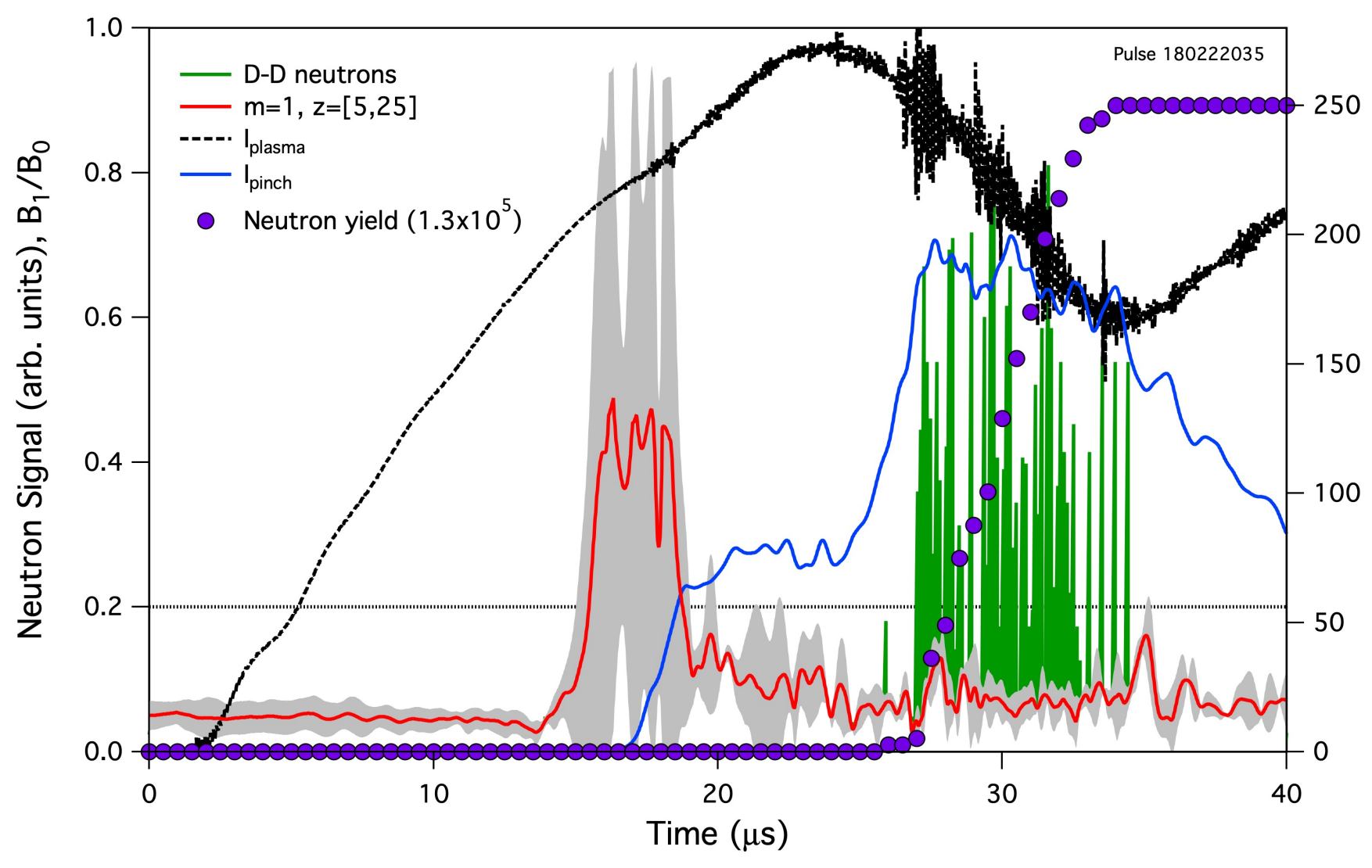


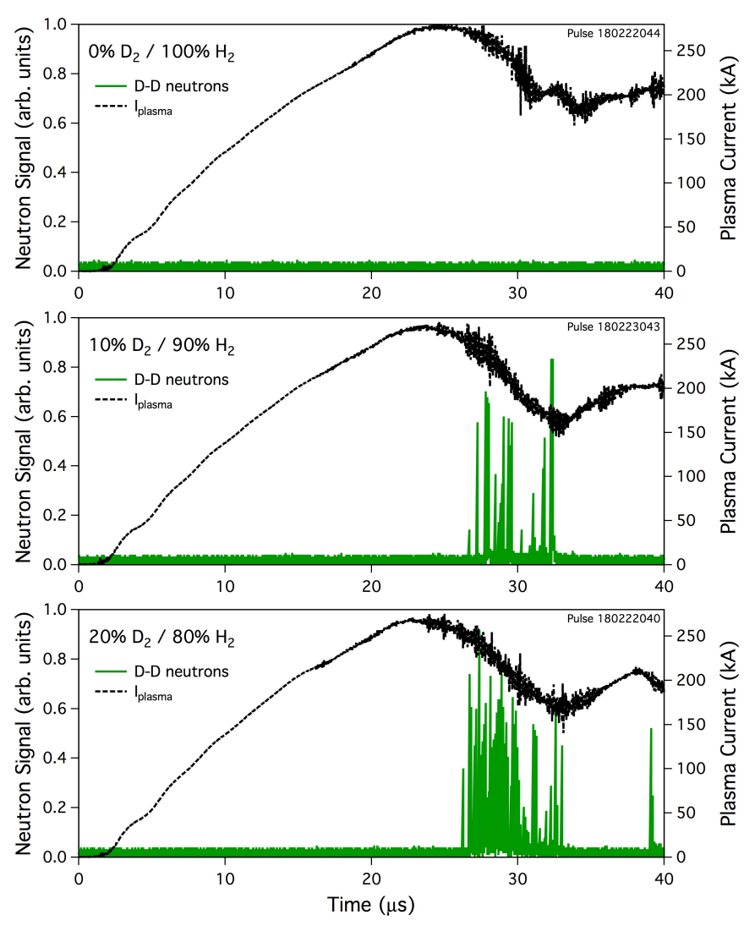


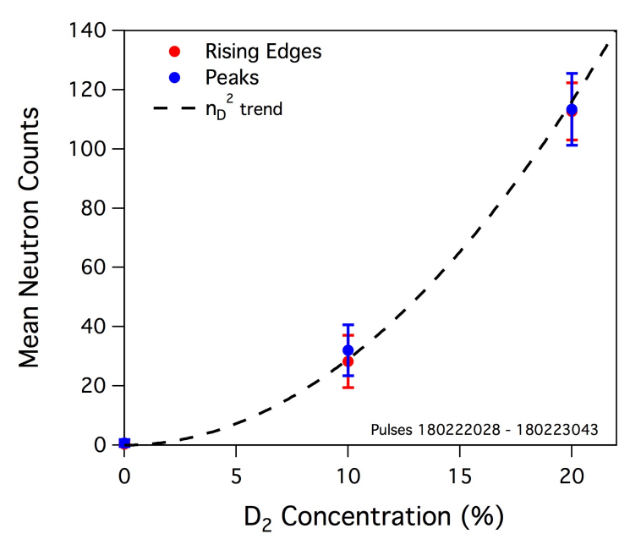
Doppler broadened spectra during quiescent period (t=25 μs) show T_i≈1.0–1.5 keV from He-like C V emission, presence suggests high T_e and well confined electrons.

Fusion neutrons are produced from FuZE deuterium plasmas with energy measurements indicating thermonuclear origin

When gas mixtures containing deuterium, $D_2 – H_2$, are used to make FuZE plasmas, sustained fusion neutron production[2] (≈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. Yield scales with the square of D_2 concentration.

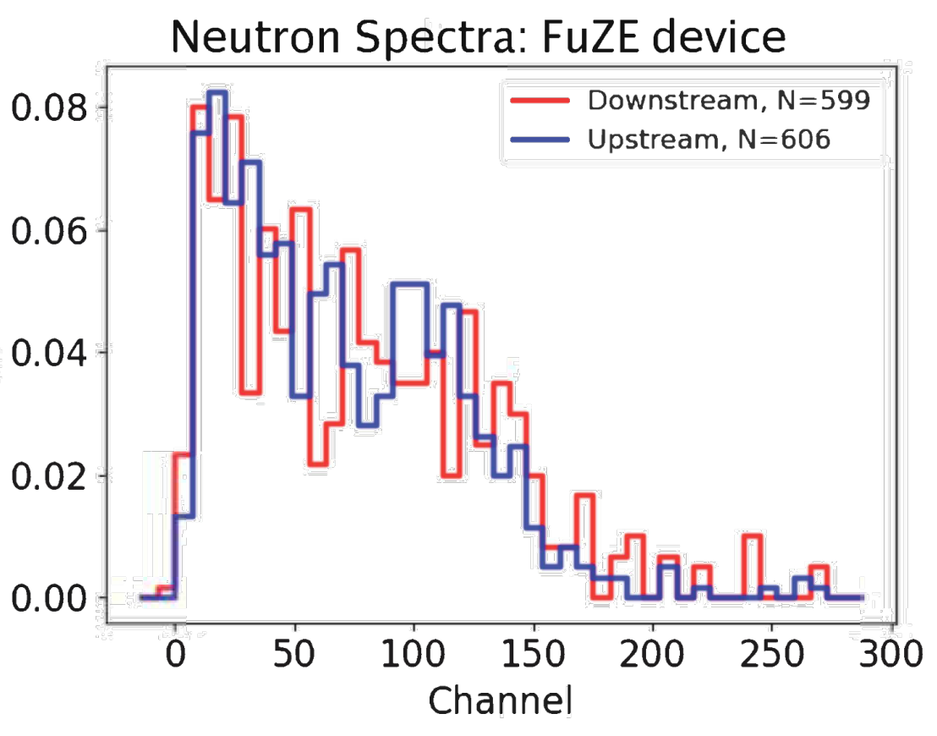


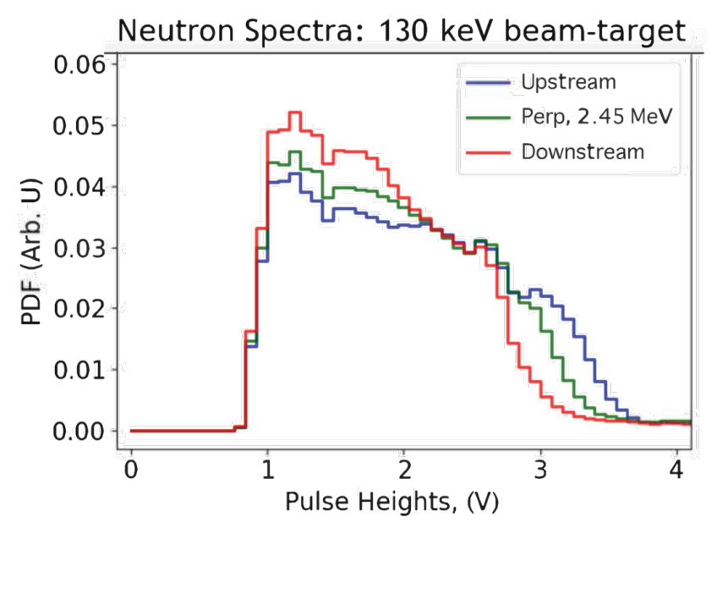




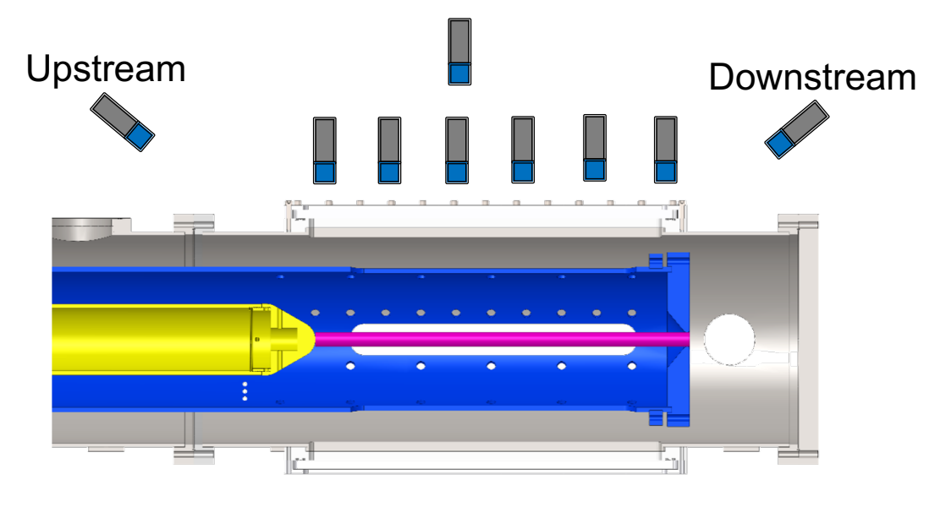
Neutron energy spectra are characterized from proton recoil signals of upstream and downstream plastic scintillator detectors. Maximum neutron energy is related to beam energy.

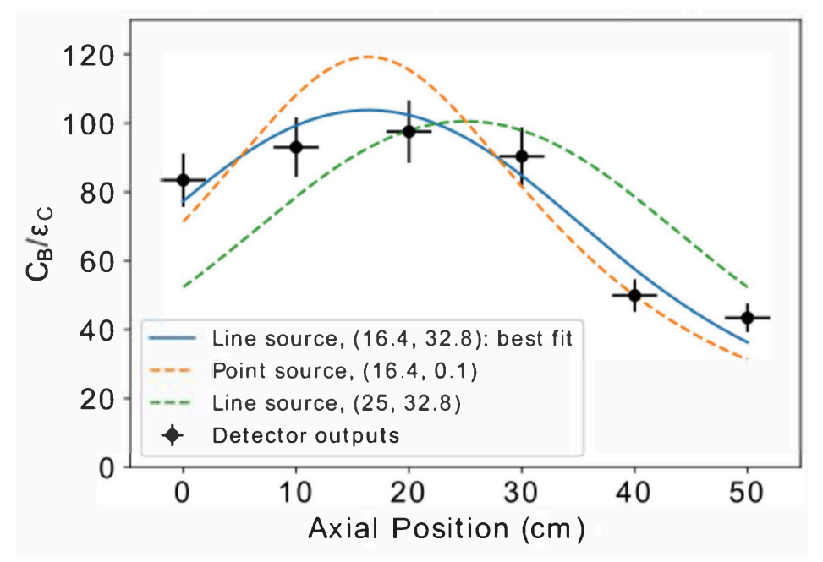
$$E_{n_{\max}}=\frac{1}{8}\left(\sqrt{E_b}+\sqrt{3(E_b+2E_f)}\right)^2$$





FuZE neutron energy spectra are statistically identical on both detectors. Measurement uncertainty of 140 keV limits the maximum deuteron beam energy to below 7.5 keV[19] indicating fusion from a thermonuclear process.

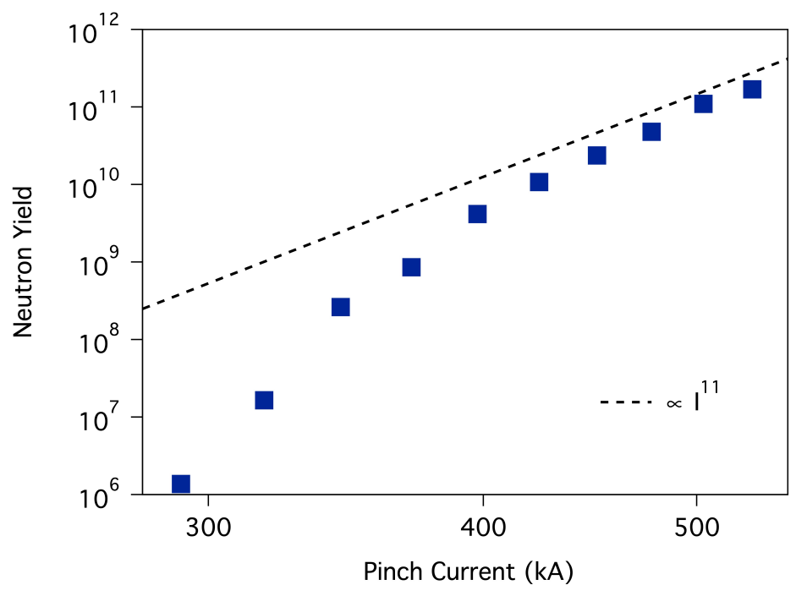




Fusion occurs uniformly along Z-pinch length, as a line source[20].

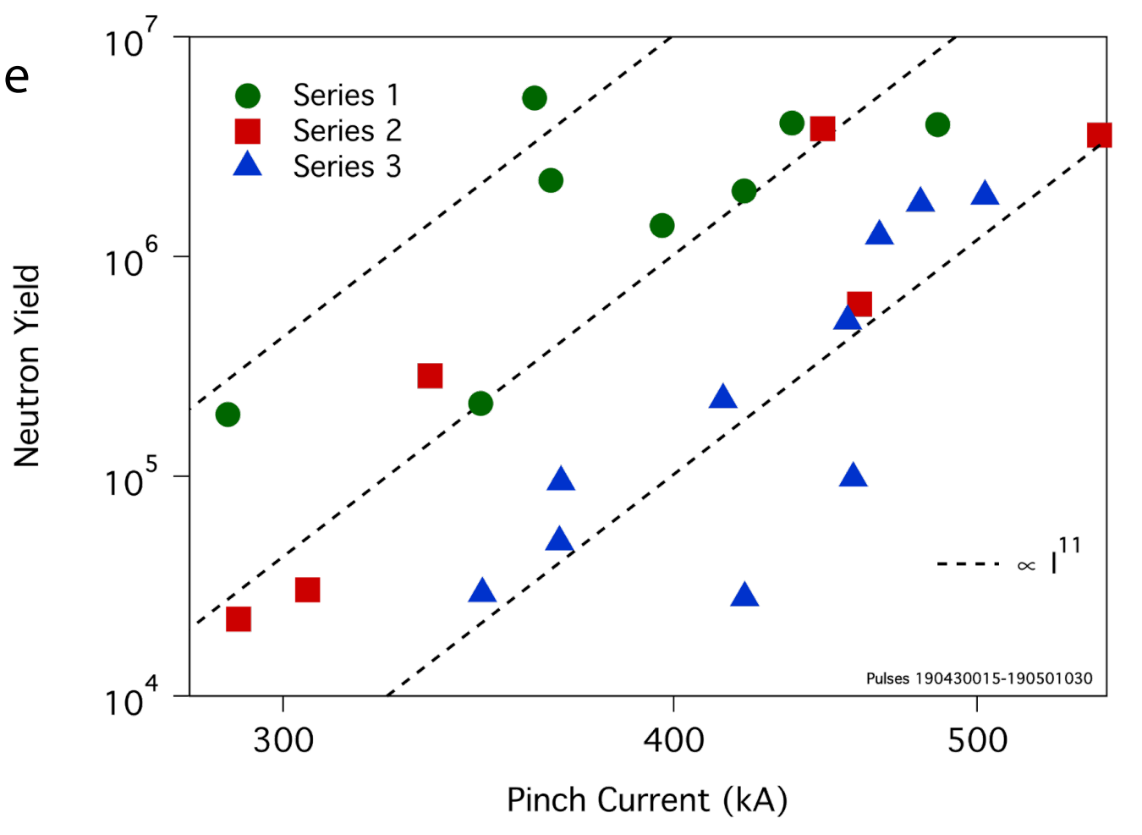
Neutron yield increases with pinch current

Adiabatic scaling relations[3,4] predict a neutron yield that strongly depends on Z-pinch current, $Y_n \propto I^{11}$.



Two-temperature MHD simulations of the FuZE SFS Z pinch support a similar scaling[5].

Experimental campaign on the FuZE SFS Z pinch current shows a yield that may be consistent with this expectation.



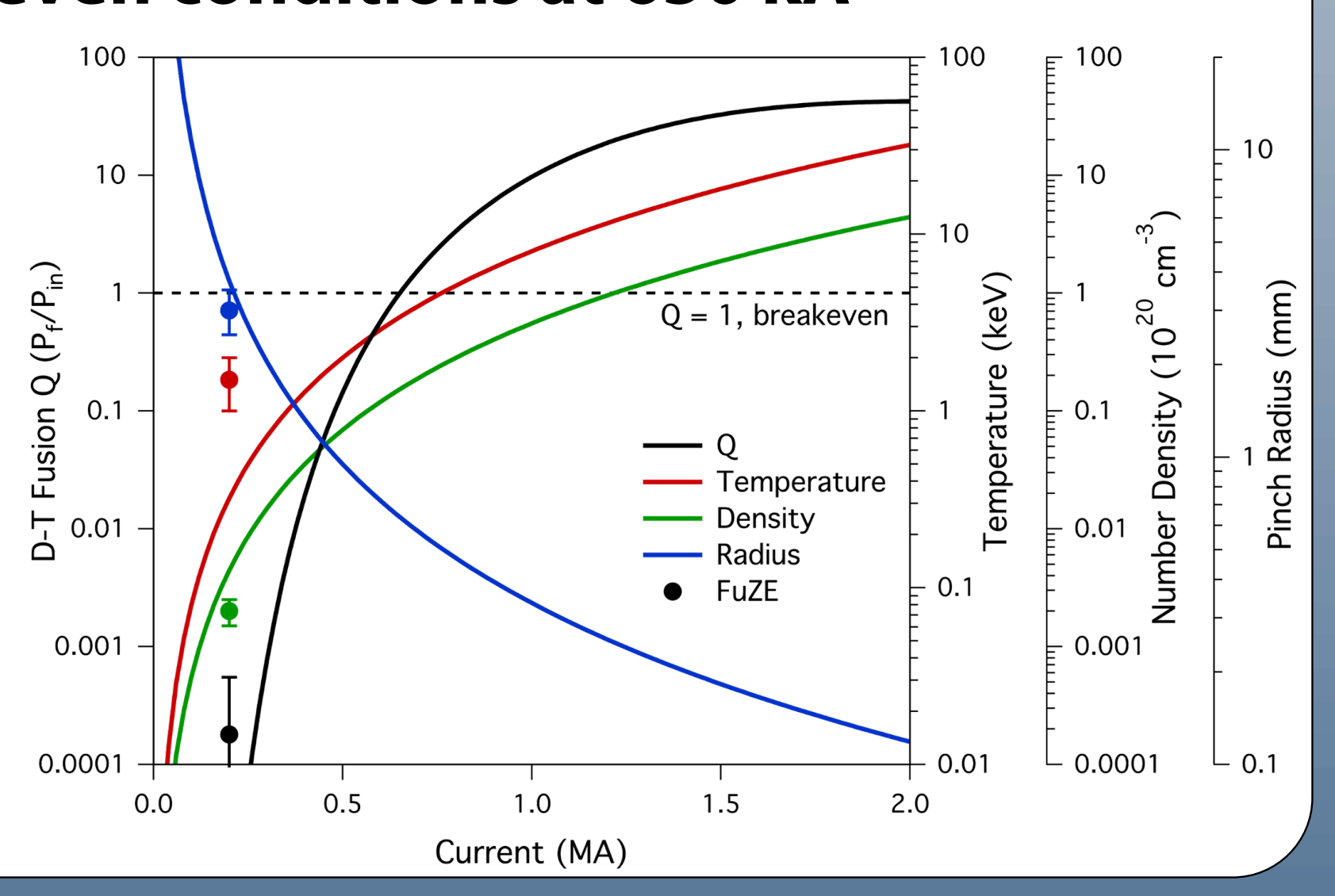
SFS Z pinch achieves fusion breakeven conditions at 650 kA

Starting with experimentally achieved plasma parameters at 50 kA, increasing the current with a fixed linear density rapidly reaches breakeven conditions. Fusion core remains compact[21] even at high Q. Large instantaneous power avails modest duty cycle operation. Adiabatic scaling results can be compared to experimental measurements obtained with higher currents, 200 kA:

- higher temperature
- lower density
- higher Q

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

Sample instantaneous conditions



Summary & Conclusions

- The sheared-flow-stabilized (SFS) Z pinch produces equilibrium plasmas that exhibit gross stability during an extended quiescent period.
- The quiescent period is coincident with a sheared plasma flow that is consistent with sheared flow stabilization theory.
- Combining fluid and kinetic numerical simulations with well-diagnosed experiments – ZaP, ZaP-HD, & FuZE – has demonstrated scaling of the SFS Z pinch to high energy density plasmas.
- Experimental measurements show an axially uniform, compressed plasma with high parameters:
  a≈3 mm, n_e≈10^{17} cm^{-3}, B_θ≈10 T, and T_e≈T_i≈1 keV.
- FuZE demonstrates sustained neutron production during the quiescent period through a thermonuclear fusion process.
- SFS Z pinch has no magnetic field coils resulting in a compact device for terrestrial fusion energy.

[1] Shumlak *et al.*, PRL (1995)
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[3] Shumlak *et al.*, FST (2012)
[4] Shumlak *et al.*, PoP (2017)
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[6] Kadomtsev, RPP (1966)
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