Thermonuclear Fusion in an Equilibrium Z Pinch*

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ZAP ENERGY

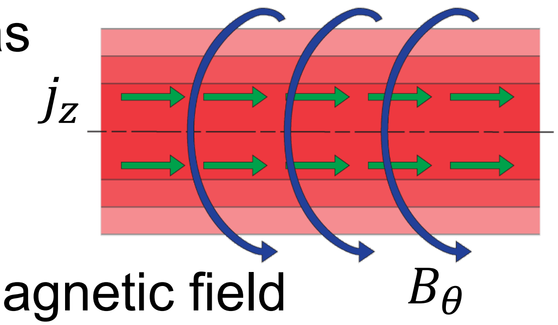
Presentation Outline

- Z-pinch equilibrium scales to plasma parameters reaching fusion conditions in a compact device
- Sheared-flow stabilization (SFS) applied to the Z pinch – theoretical findings and experimental investigation
- Experimental data from ZaP (Z Pinch) device indicating stable behavior coincident with sheared plasma flow
- Stabilizing effect works for higher performing plasmas, as demonstrated with the ZaP-HD device, supported by computational investigations
- FuZE (Fusion Z-pinch Experiment) explores the SFS Z pinch for fusion – extended experimental capability and numerical simulations
- Detailed experimental profile measurements → a tightly compressed plasma with high density, magnetic field, and temperature
- Sustained neutron production from thermonuclear fusion
- Looking forward: Scaling the SFS Z pinch to a compact core for fusion energy and to a fusion space thruster

Z-pinch offers attractive scaling to fusion energy

The Z-pinch equilibrium has no applied axial fields as described by

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

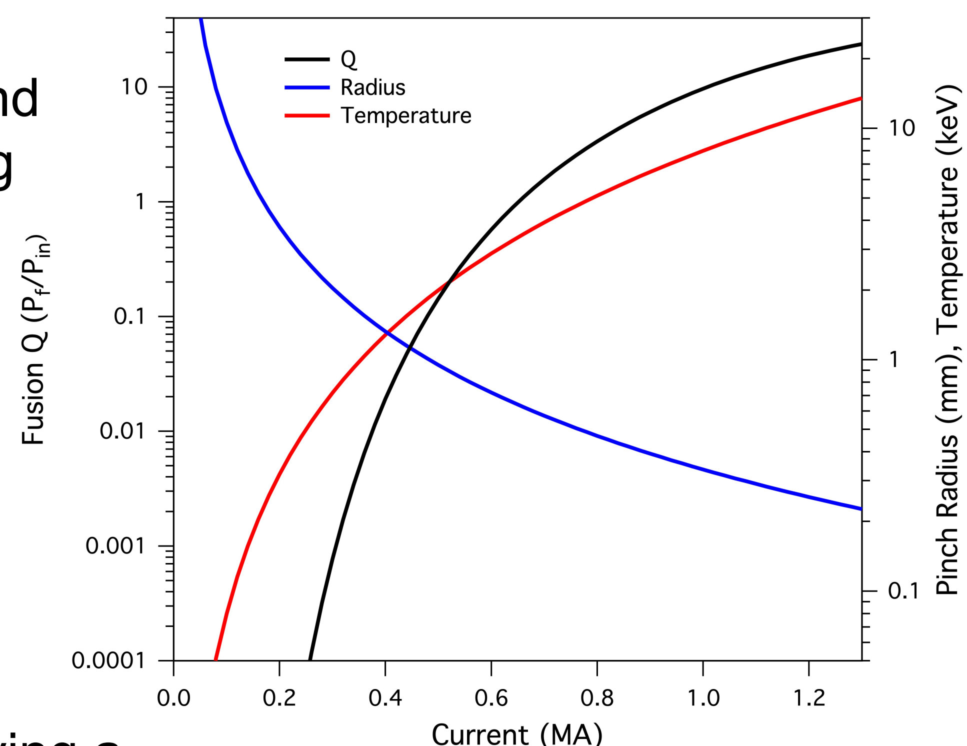


Increasing the current and the resulting azimuthal magnetic field compresses the plasma to fusion conditions in a compact device – no magnetic field coils.

Assuming adiabatic compression and radial force balance gives scaling relations for higher current.[1]

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

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



These results are predicated on having a stable plasma.

[1]Shumlak et al., FST (2012); Shumlak et al., PoP (2017); Shumlak, JAP (2020)

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]

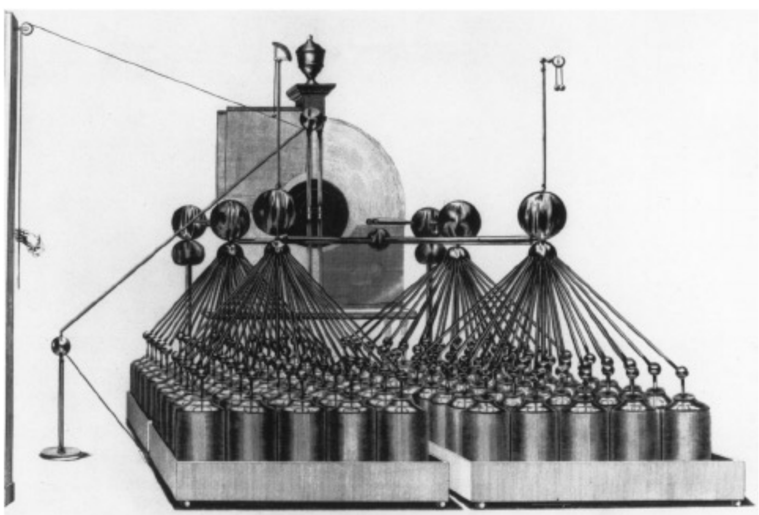
1907: “Pinch phenomenon” in liquid conductor by Northrup[3]

1934: Theoretical model of plasma Z pinch by Bennett[4]

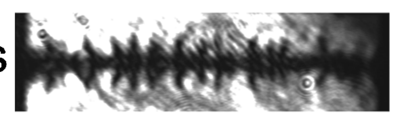
1950: Z pinch was Project Sherwood Jim Tuck’s preferred approach to achieve controlled fusion

1957: Theory and experiments demonstrated virulent instabilities, $m = 0{,}1$

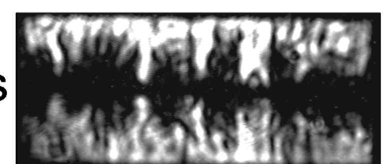
1998: Performance of Z pinches using frozen deuterium fibers was severely limited by these instabilities[5]



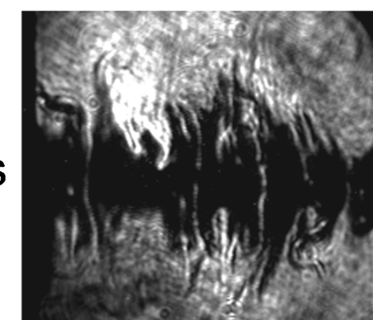
27 ns



55 ns



117 ns

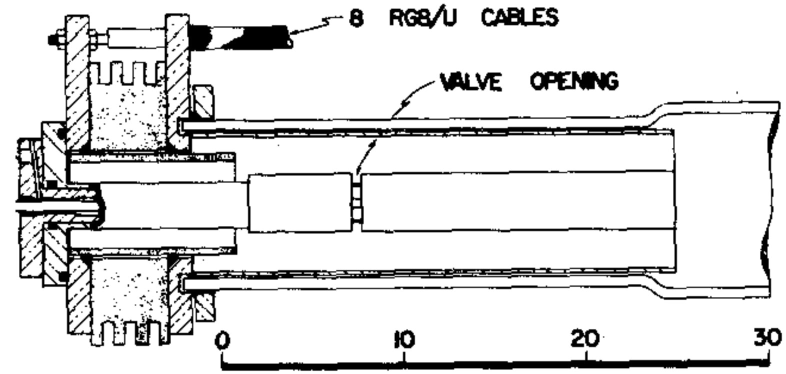


[1]Haines, PPCF (2011); [2]Pollock & Barraclough, PRS (1905); [3]Northrup, PR (1907); [4]Bennett, PR (1934); [5]Lebedev et al., PoP (1998)

Flow Z pinch observations and concept

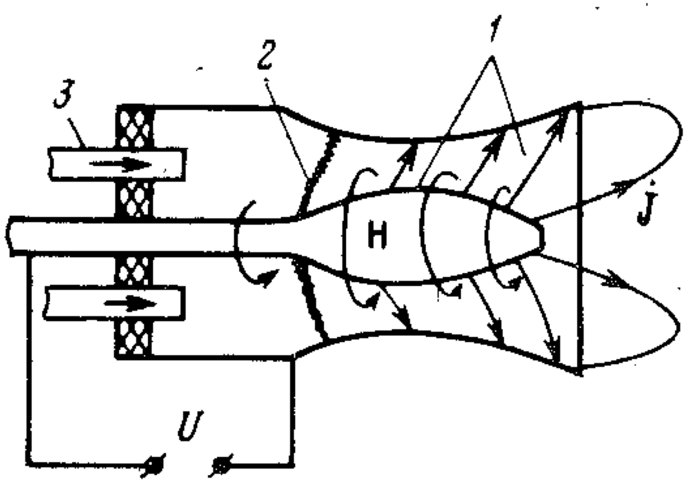
1969: Long-lived plasma column observed during coaxial plasma gun research[1] at LANL

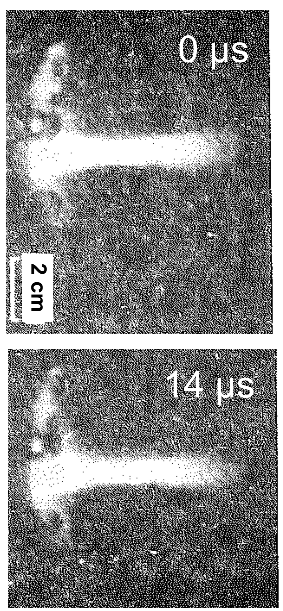
1973: High-density plasma beam formed with continuous-flow Z pinch[2] as a NASA project

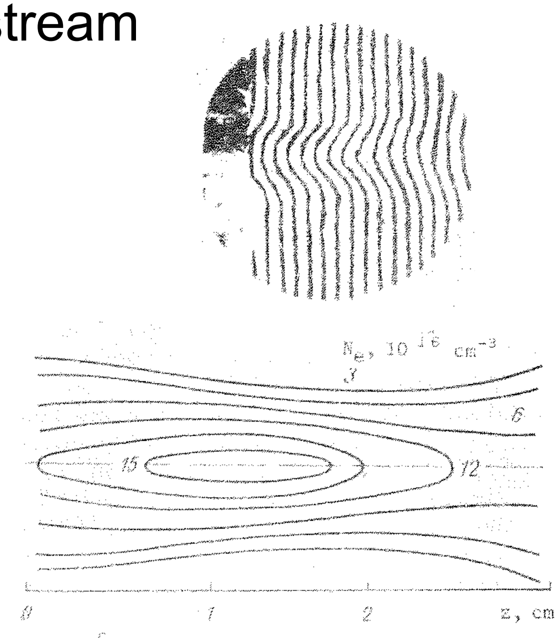


1977: Conceptual fusion reactor based on the flow Z pinch[3]

1990: Development of coaxial quasi-steady-state plasma accelerators[4] in the USSR produces 4 m long stable plasma stream



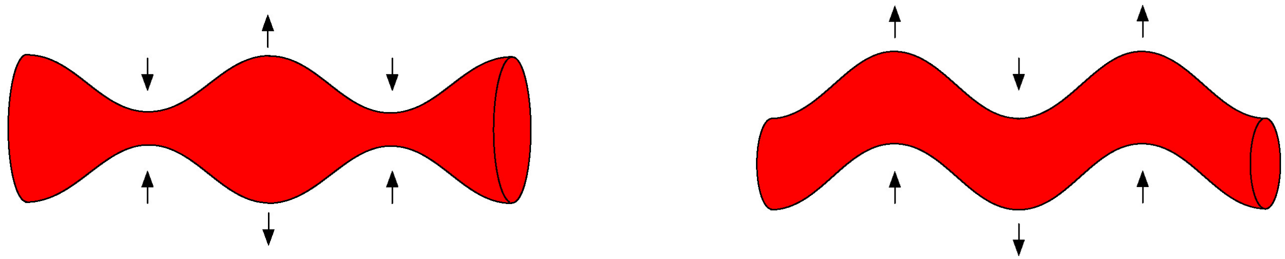




[1]Newton, Marshall, & Morse, IAEA (1969); [2]Cheng & Wang, NF (1973); [3]Hartman et al., NF (1977); [4]Ananin et al., SJPP (1990), Morozov, SJPP (1990)

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[1], introducing an axial magnetic field[2], or installing a close-fitting conducting wall[3].

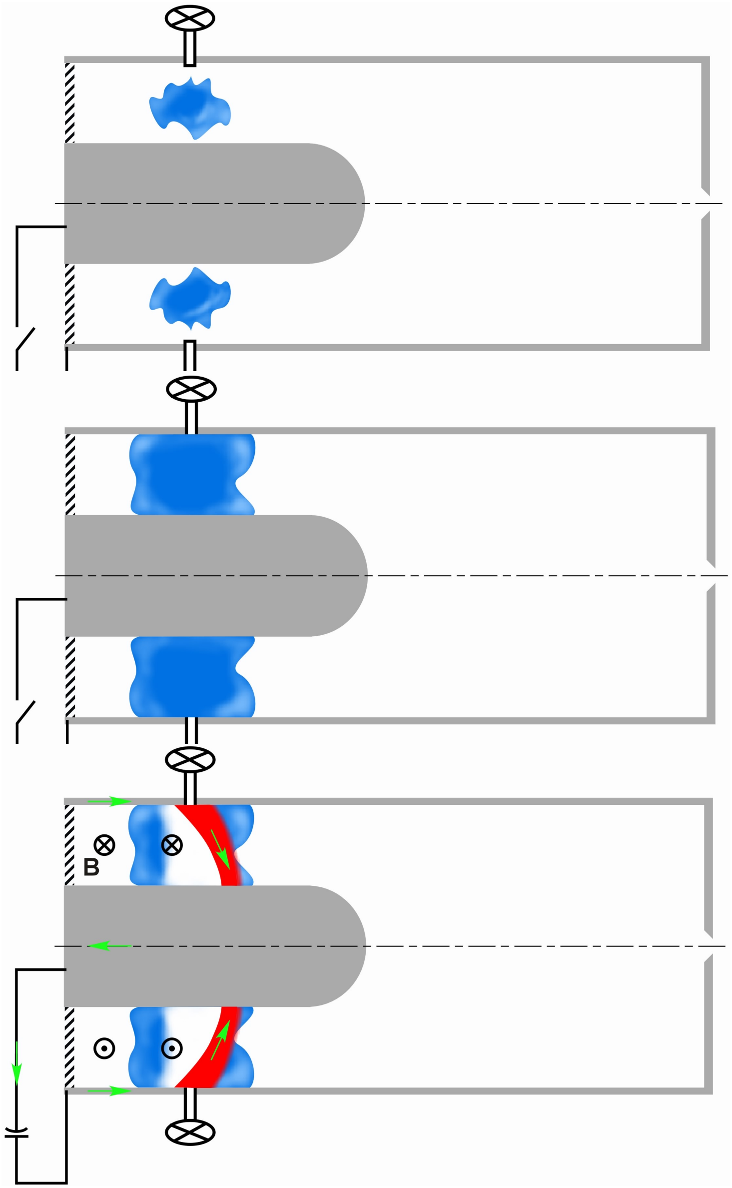
These approaches are incompatible with magnetically confining a high-temperature, high-density plasma. Work from a collaboration with Charles Hartman at LLNL suggests the $m = 1$ mode can be stabilized with a sheared axial flow[4],

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

though the value is sensitive to axis treatment[5]. Flow shear is observed to stabilize $m = 0$ modes as well[6].

[1]Kadomtsev, RPP (1966); [2]Kruskal et al., PRS (1954); Shafranov, SJAE (1956); [3]Knecht et al., IEEE TPS (2014); [4]Shumlak & Hartman, PRL (1995); [5]Arber et al., PoP (1996); Angus et al., PoP (2020); [6]Paraschiv et al., PoP (2010)

Schematic illustrates flow Z-pinch formation

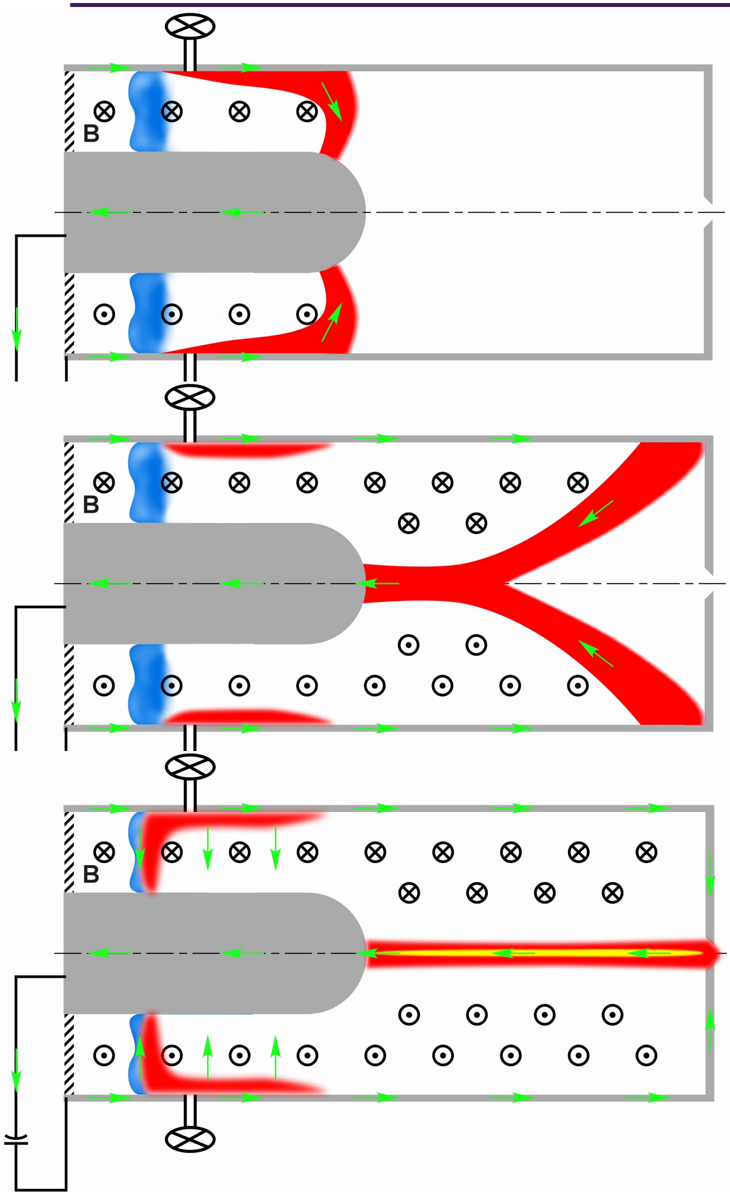


t_1 Neutral gas is injected through puff valves into the annulus of a coaxial plasma accelerator.

t_2 Neutral gas expands before a capacitor bank is discharged across the electrodes.

t_3 The plasma accelerates down the coaxial accelerator due to generated currents and magnetic fields.

Schematic illustrates flow Z-pinch formation



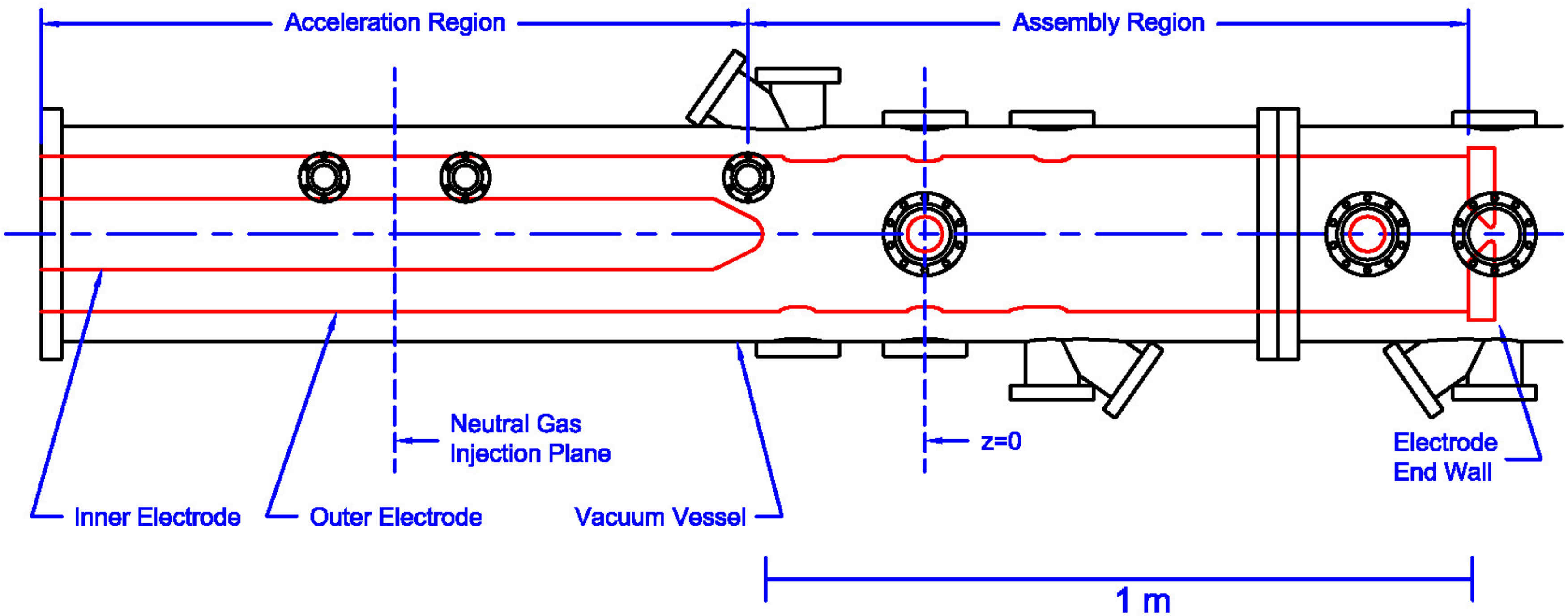
t_4 The plasma continues down the accelerator in a snow-plow manner.

t_5 At the end of the accelerator the plasma assembles into a Z-pinch configuration.

t_6 Inertia and gun currents maintain the plasma flow and supply until the accelerator plasma empties or the capacitor current vanishes.

ZaP Flow Z-Pinch Experiment

The ZaP Flow Z-Pinch project investigated the concept of using flows to stabilize an otherwise unstable plasma configuration.



Diagnostics measure plasma flow and stability

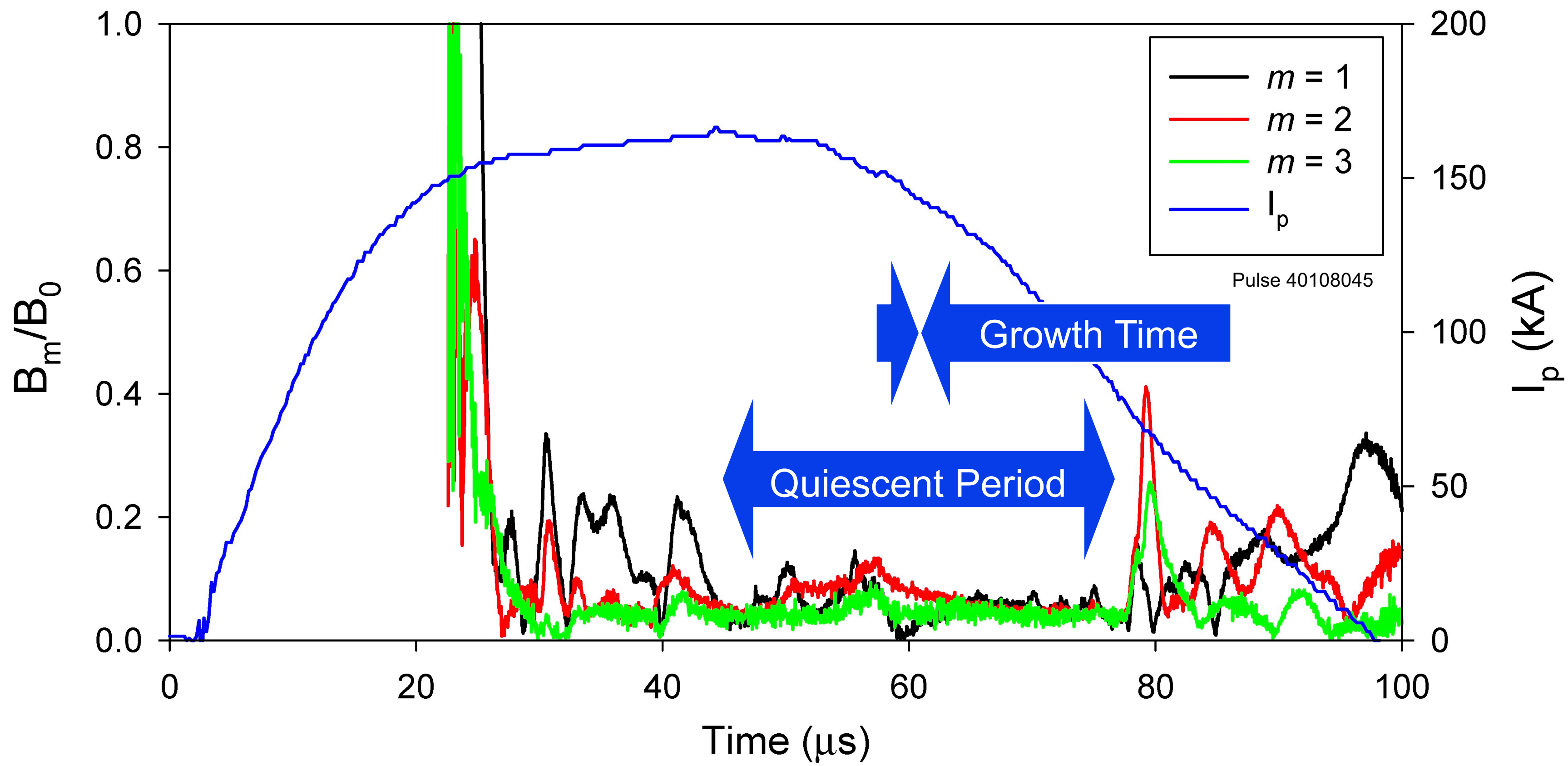
ZaP diagnostics measure equilibrium plasma parameters, plasma flow, and magnetic mode activity (stability).

- Surface-mounted magnetic field probes → Determine magnetic topology, magnetic fluctuations, and plasma stability[1]
- Fast framing camera with optical filters → Qualitative measure of plasma structure
- Four-chord HeNe interferometry → Measure plasma density profile[2]
- 0.5 m imaging spectroscopy with 20 input chords and an intensified CCD detector → Doppler shift for plasma flow profile[1], Doppler broadening for ion temperature[3], Zeeman splitting for magnetic fields[4], Stark broadening for density[5]
- Thomson scattering system using a ruby laser and a Hibshman spectrometer → Measure electron temperature
- Digital holographic interferometer → Measure two-dimensional plasma density structure[6]

[1]Shumlak et al., PRL (2001), Shumlak et al., PoP (2003), Golingo et al., PoP (2005); [2]Jackson et al., RSI (2006); [3]Forbes et al., RSI (2020); [4]Golingo et al., RSI (2010); [5]Vogman et al., RSI (2011); [6]Ross et al., RSI (2016)

Magnetic fluctuations diminish after pinch forms

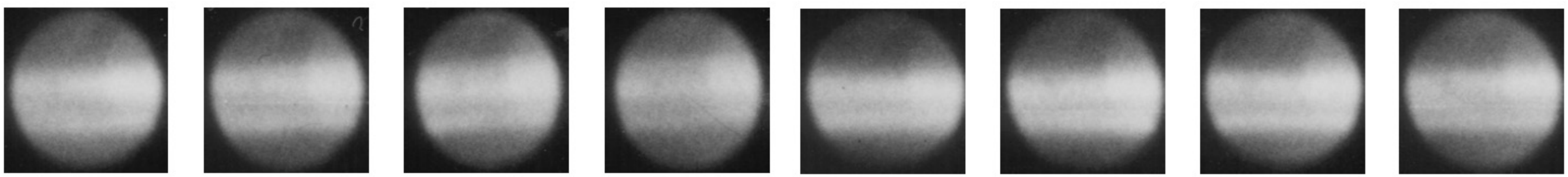
Fluctuations of the magnetic modes are significantly reduced for ≈ 37 μs after pinch forms. Mode activity increases again after this quiescent period. Experimental data suggests the quiescent length is limited by plasma supplied from the accelerator.



Optical images show a stationary plasma pinch

Visible emission images are obtained of the pinch, every 200 ns, through a 5 cm hole with an Imacon fast-framing camera.

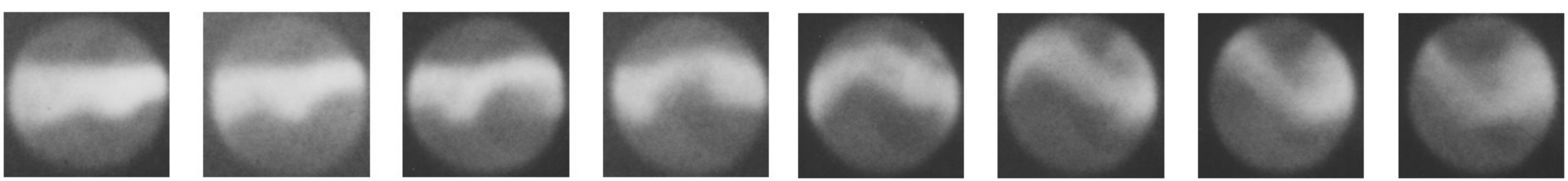
Images show a stationary plasma pinch during the quiescent period. Note hollow structure.



Pulse 40115035

Time

Gross kink & sausage instabilities appear at the end of the quiescent period.

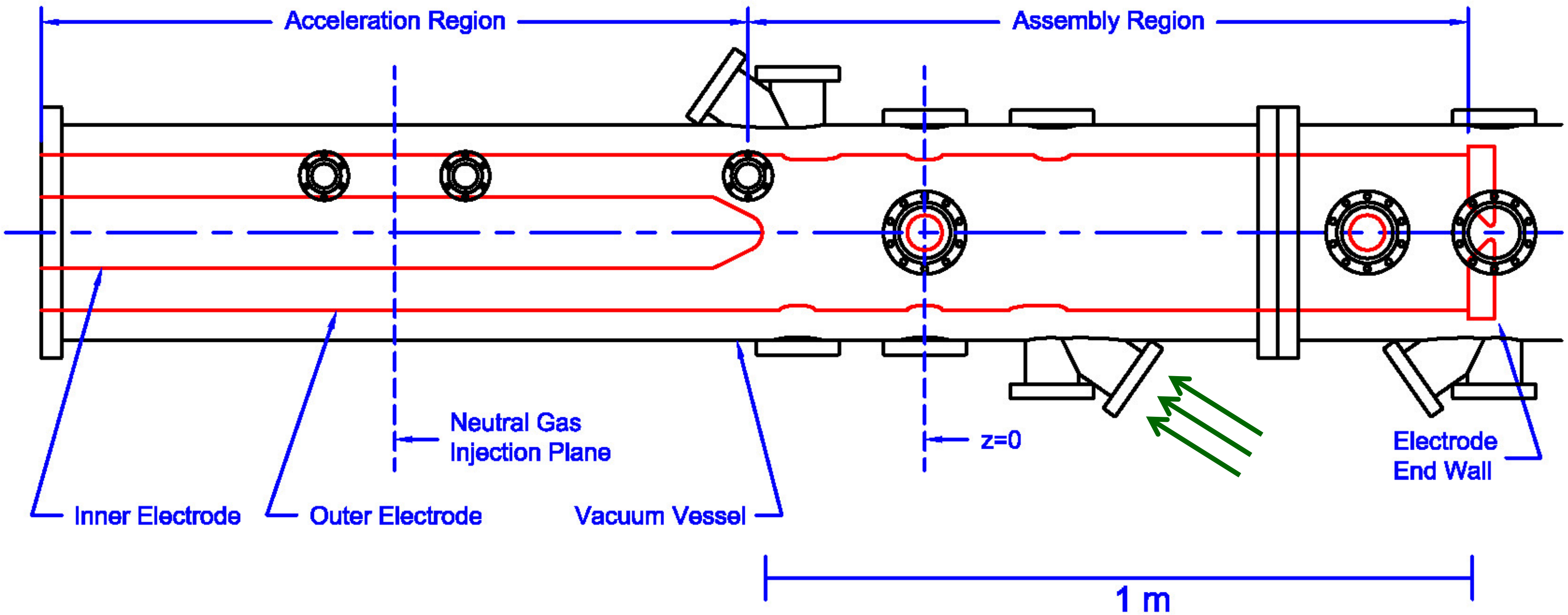


Pulse 40127041

Multichord spectrometer provides velocity profiles

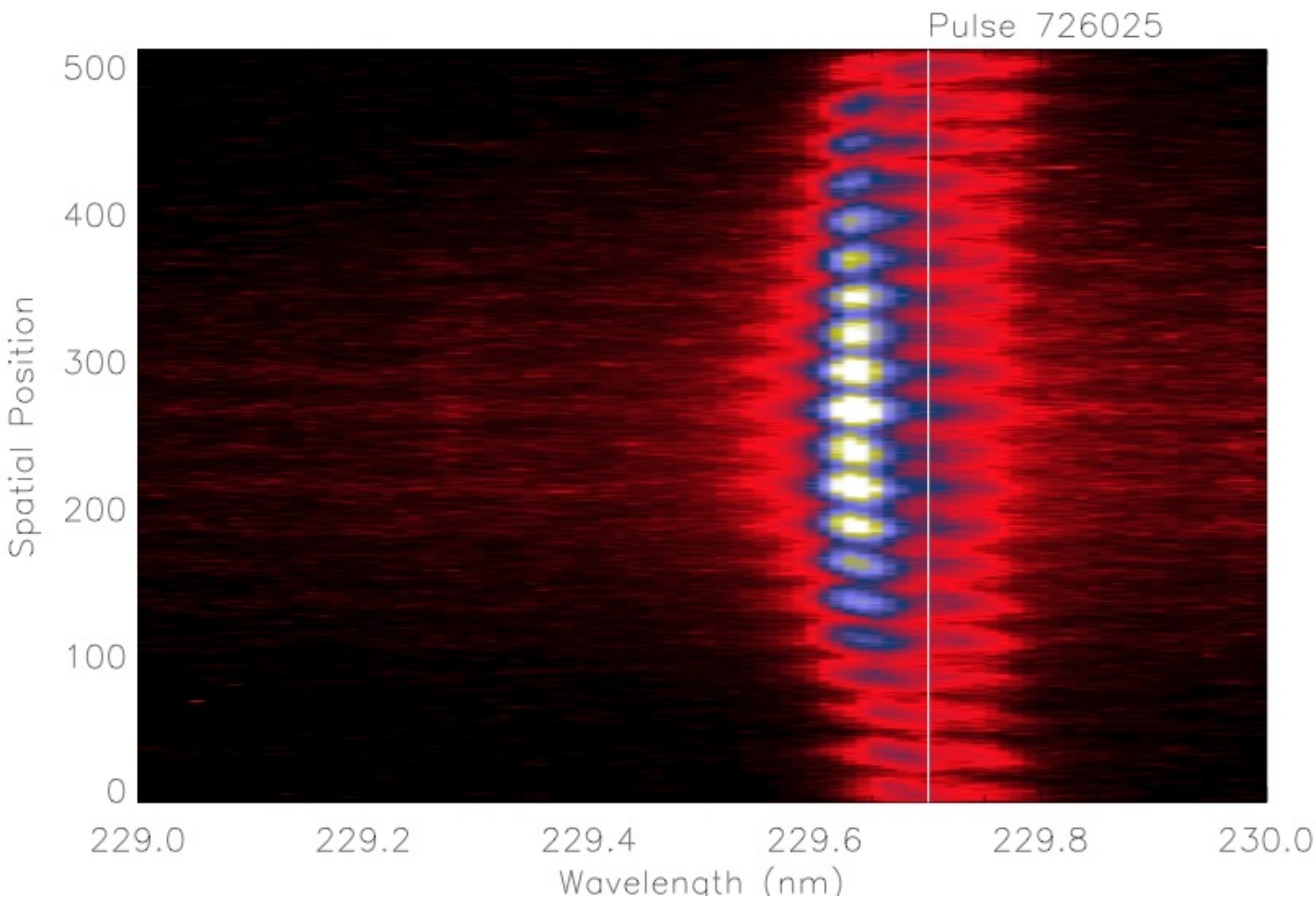
A 20-chord imaging spectrometer is connected to an intensified CCD detector to measure the Doppler shifts of impurity emission lines.

The chords are spaced out of plane in the drawing below.



Large flow velocity exists during the quiescent period[1]

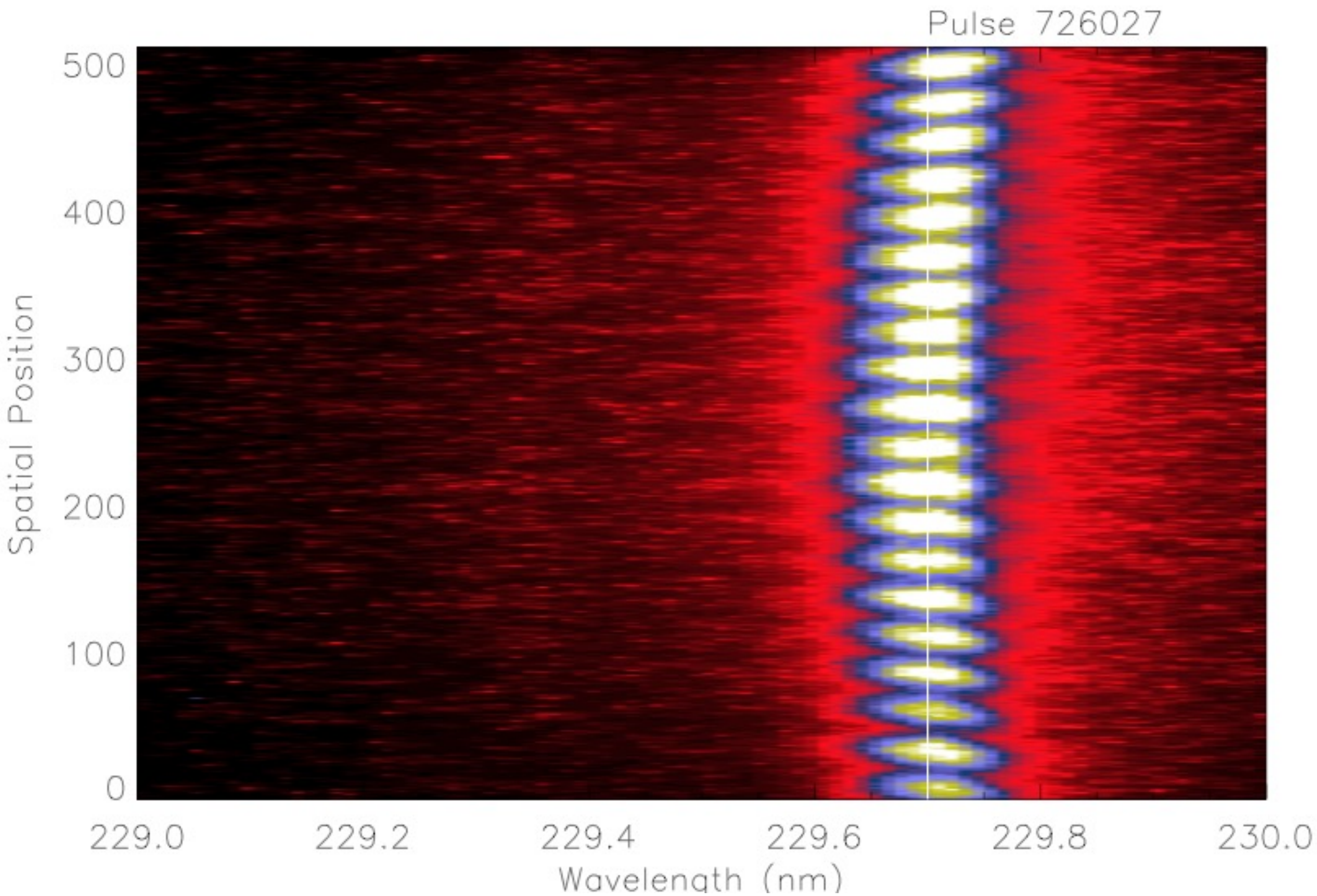
Large Doppler blue-shift of the C-III impurity line (229.7 nm) during the quiescent period.



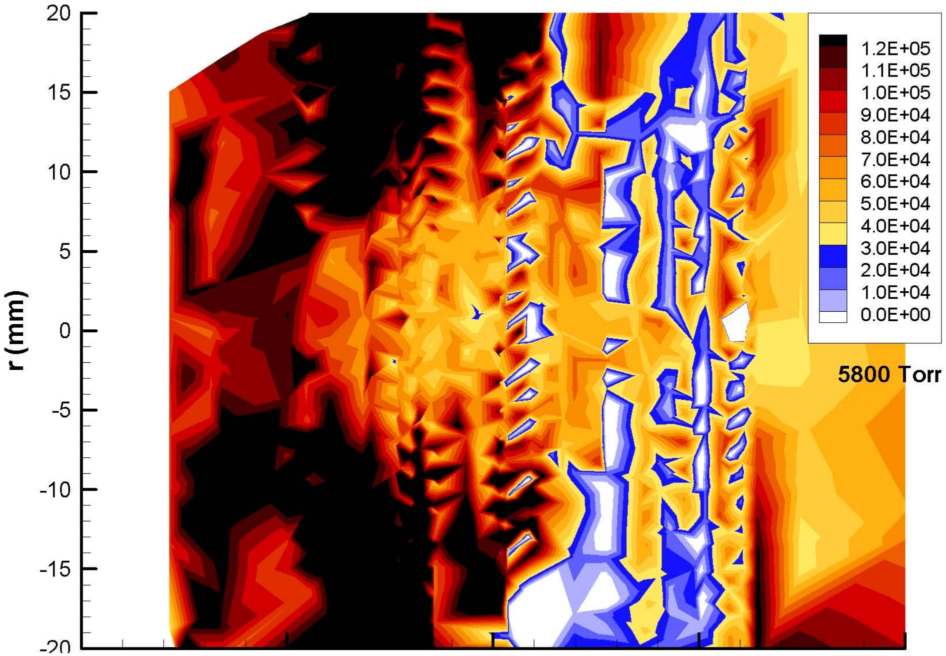
[1]Shumlak, Golingo, Nelson, & Den Hartog, PRL (2001)

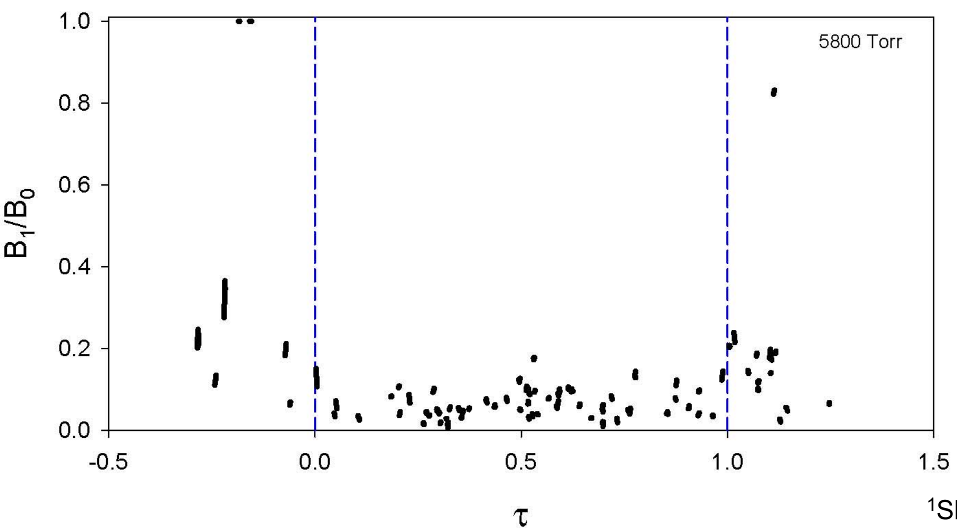
Flow velocity decreases at end of the quiescent period

Small Doppler shift of the C-III impurity line (229.7 nm) at the end of the quiescent period.



Flow profile is correlated to plasma stability[1]





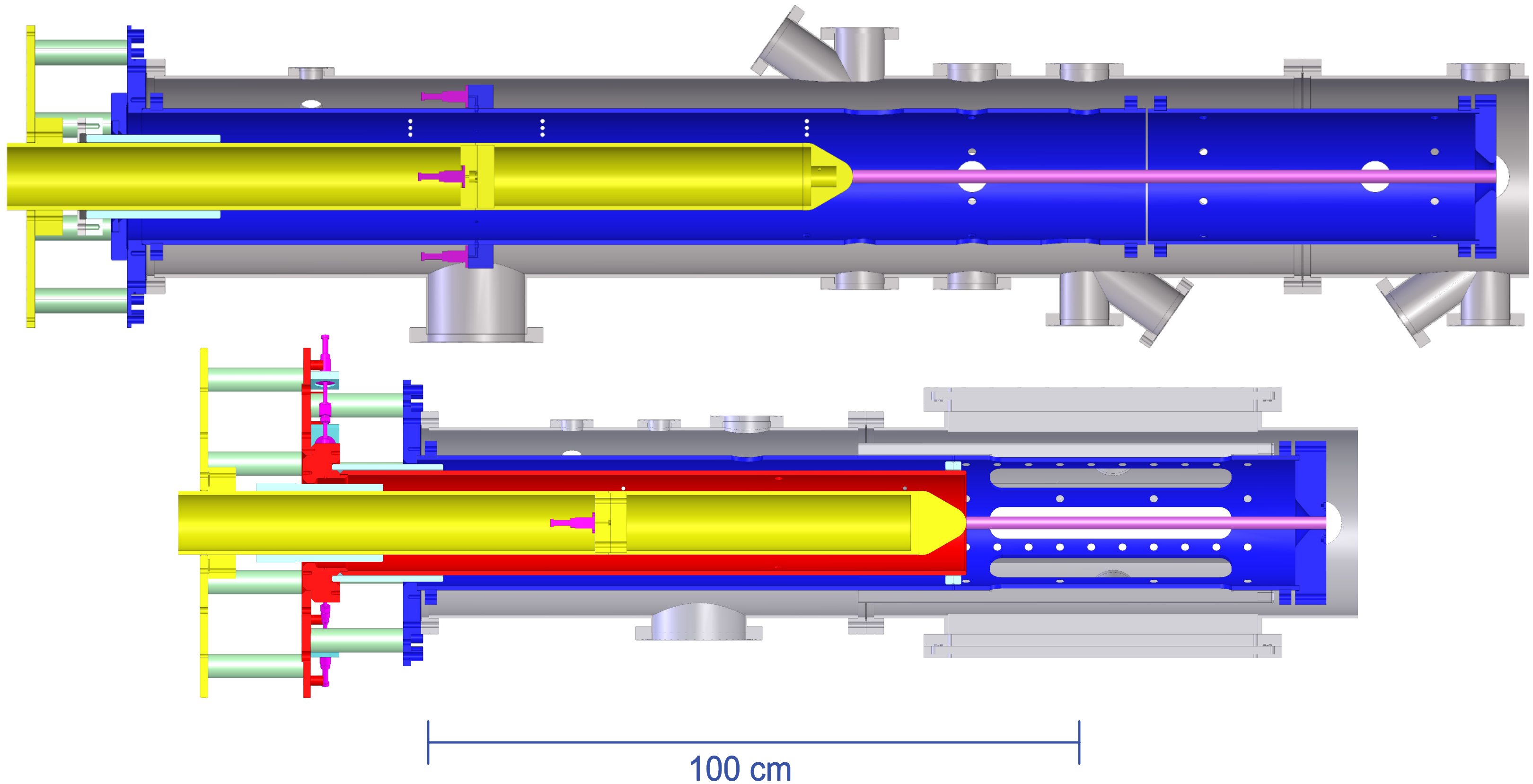
- Plasma assembly ($\tau < 0$), the axial plasma velocity is high and uniform. $\frac{dv_z}{dr} \approx 0 - 4{\times}10^6$ s^{-1}
- Start of quiescent period ($\tau = 0$), the velocity profile is high at the plasma edge and lower at the axis. $\frac{dv_z}{dr} \approx 7 - 12{\times}10^6$ s^{-1}
- End of quiescent period ($\tau = 1$), the plasma velocity profile is low and uniform. $\frac{dv_z}{dr} \approx 0 - 6{\times}10^6$ s^{-1}
- For these plasma parameters, the theoretical growth time ≈ 20 ns.
- Linear theory specifies a shear threshold of $\approx 5{\times}10^6$ s^{-1}.

[1]Shumlak et al., PoP (2003); Golingo et al., PoP (2005); Shumlak et al., NF (2009)

ZaP & ZaP-HD investigated sheared-flow stabilization

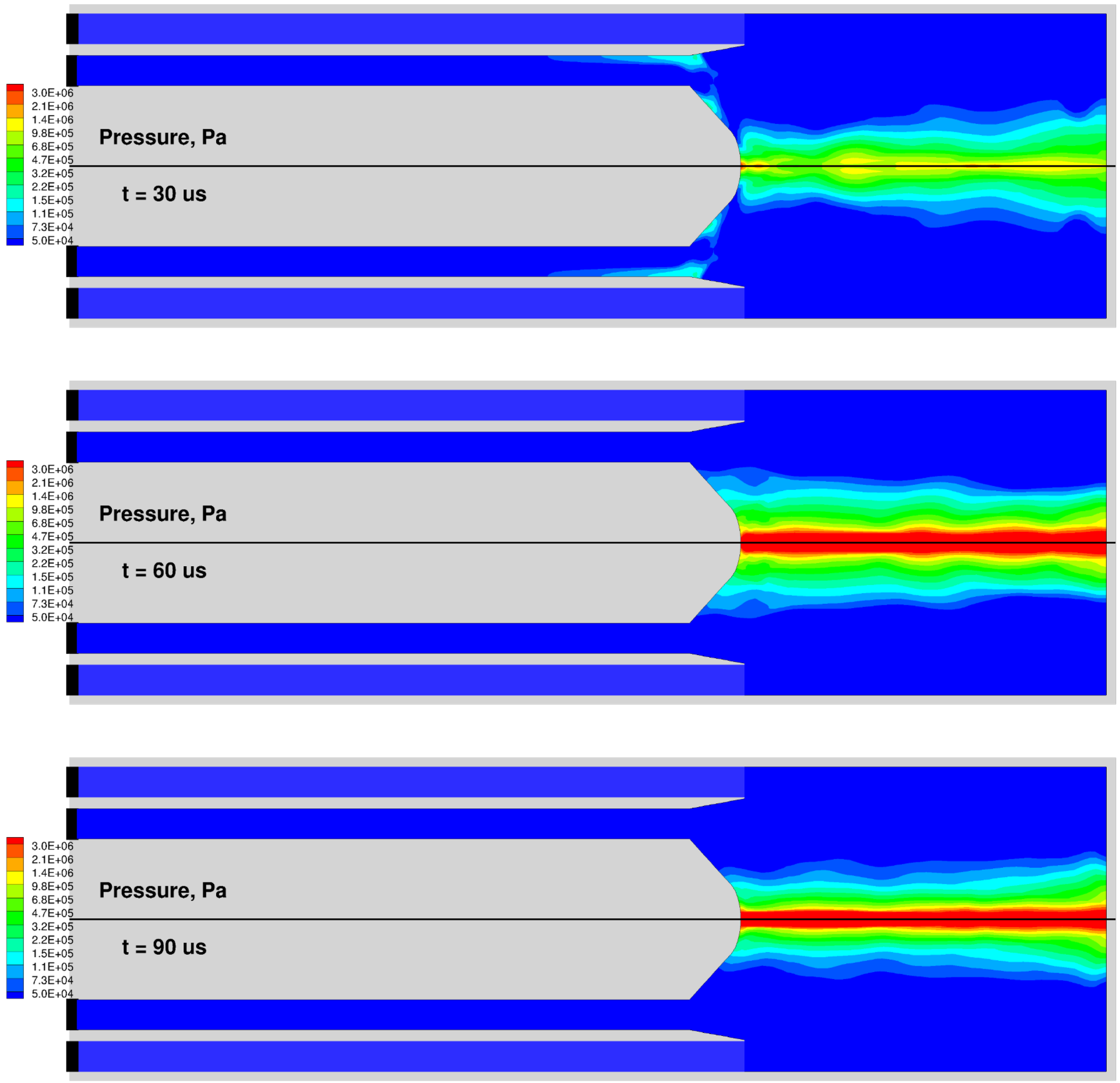
ZaP (1999 – 2009) / ZaP-HD (2009 – 2015) Flow Z-Pinch projects investigated using sheared flows to stabilize an unstable plasma.

- generated sheared-flow-stabilized (SFS) Z-pinch plasmas 50 – 126 cm long
- observed the coincidence of plasma stability and a sheared-flow state
- characterized the plasma equilibrium and demonstrated radial force balance



Simulations show formation of high-pressure plasma

- Time-dependent simulations of ZaP-HD indicate the formation of a high-pressure plasma that extends through the Z-pinch assembly region and has a high degree of axial uniformity.
- Whole-device simulations are performed with the Mach2 resistive MHD code using realistic circuit solvers from two capacitor banks.
- Multi-fluid plasma model using WARPX[1] are also applied to study the onset of drift instabilities and turbulence[2].

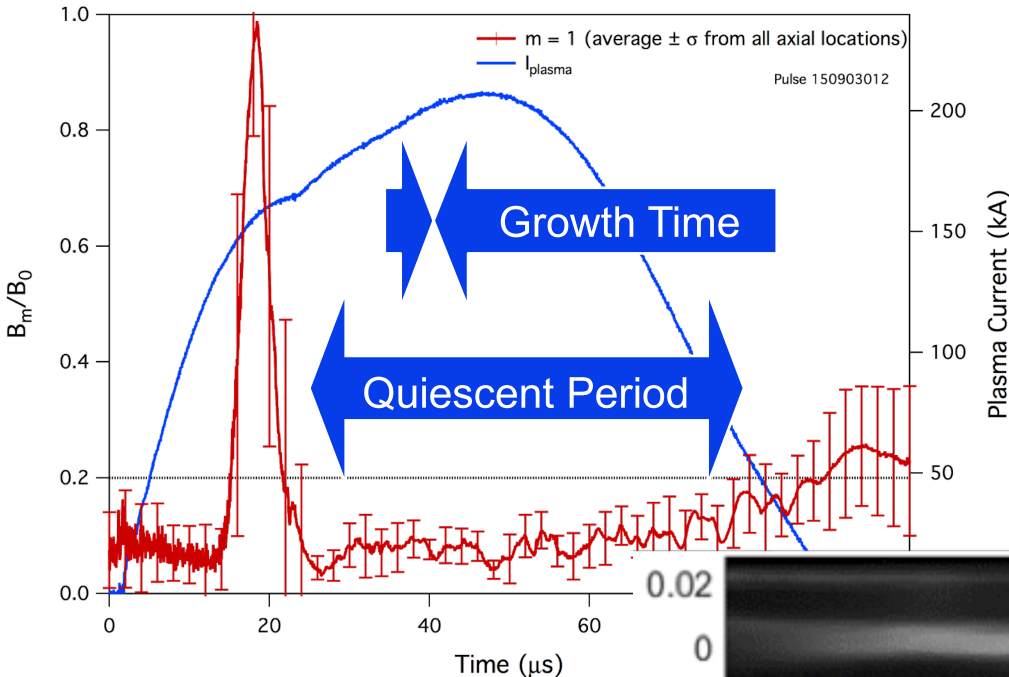


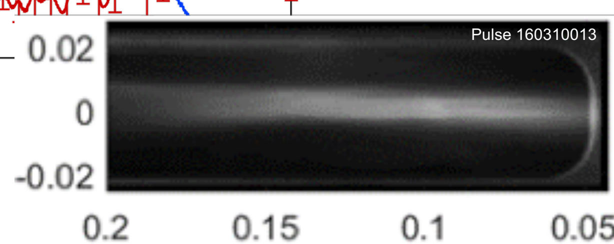
[1]Shumlak et al., JCP (2003), Shumlak et al., CPC (2011); [2]Loverich et al., PoP (2006)

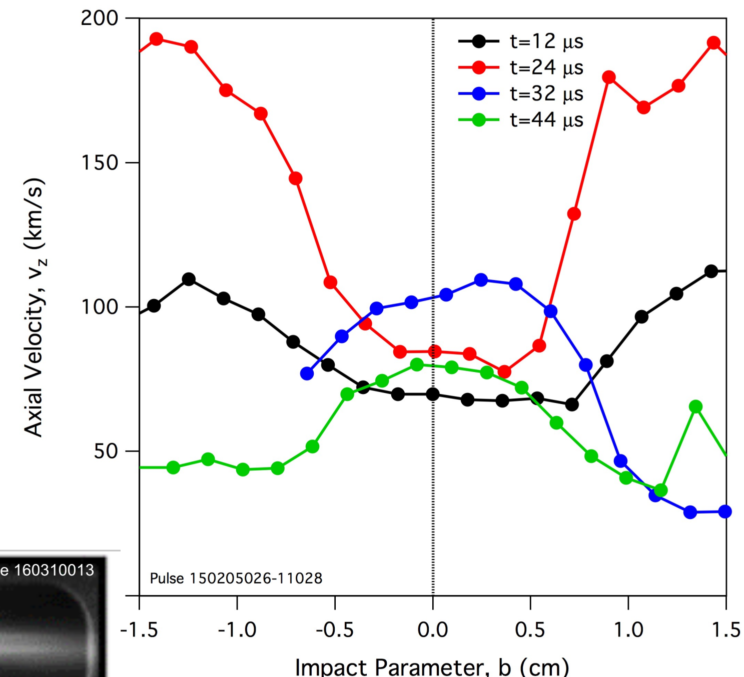
Magnetic fluctuations diminish after pinch forms

Fluctuations of the magnetic modes along the entire length of the Z-pinch plasma are significantly reduced for 40 – 80 μs after pinch forms. Mode activity increases again after this quiescent period.

The quiescent period is coincident with a sheared axial flow, $v_z' \neq 0$. The velocity profiles agree with calculations of Braginskii ion viscosity[1] for spatially dependent magnetization. Viscous damping time is consistent with the stable Z-pinch lengths observed[2].



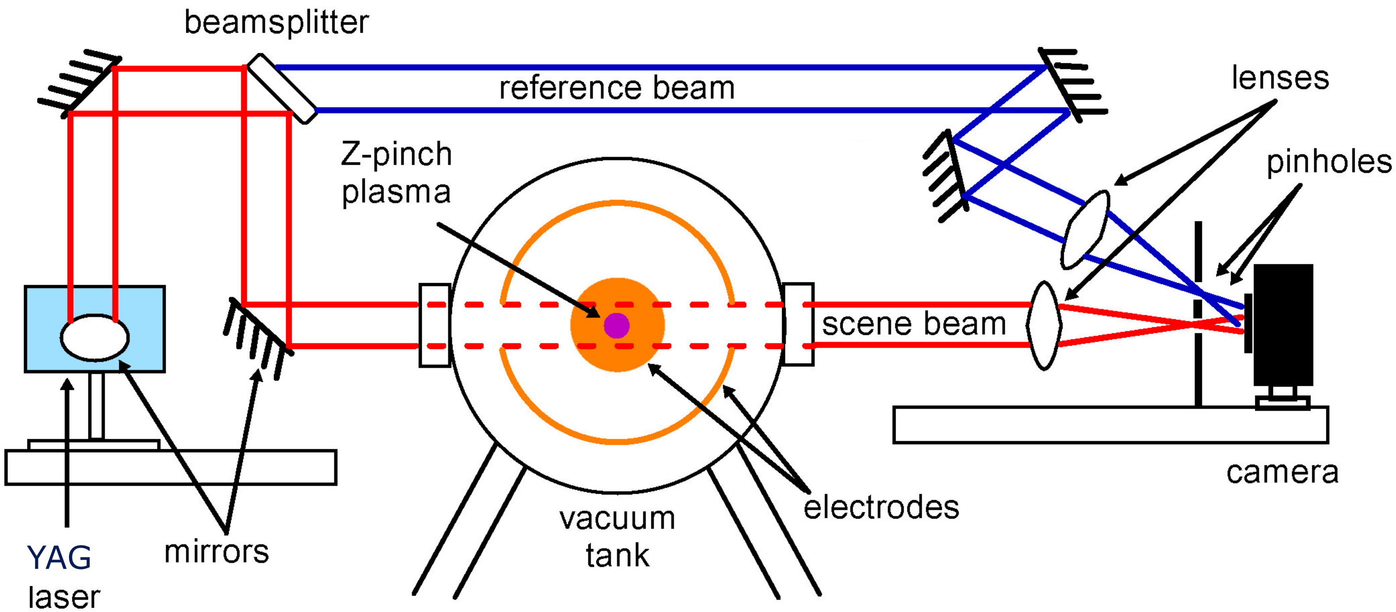




[1]Braginskii, RPP (1965); [2]Shumlak et al., PoP (2017)

Holographic interferometry measures density structure

Digital holographic interferometer[1] uses a Nd:YAG laser and digital SLR to provide high-resolution measurements of the plasma density structures, which can be used to characterize the equilibrium.



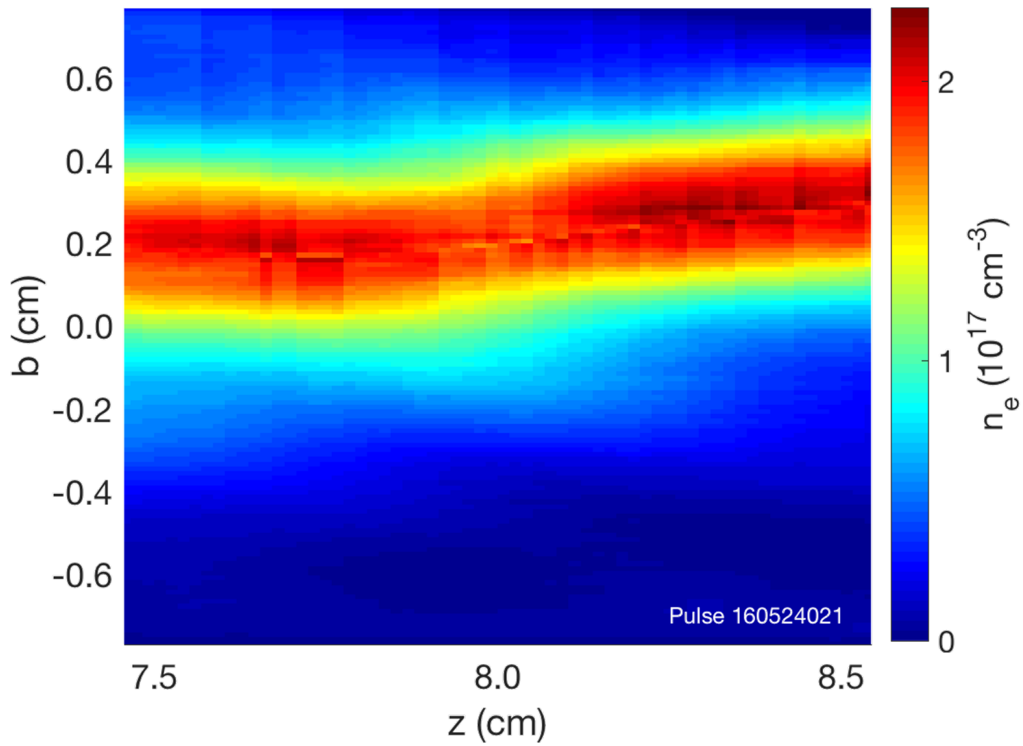
The phase change gives the line-integrated density

$$\Delta\phi = \frac{\lambda e^2}{4\pi c^2 \epsilon_0 m_e} \int n_e(x) dx.$$

[1]Ross et al., RSI (2016)

Holographic interferometry measures density structure

- The digital hologram is recorded on the camera and then numerically reconstructed to give the complex wave field, which yields the phase change. After unwrapping, a 2D map of phase change results.
- The line-integrated density is Abel inverted to yield electron number density profiles $n_e(r)$ along the axial extent of the hologram.



- The data plot retains the displacement of the pinch axis relative to the geometric axis.
- Notice a peak density of $\approx 2\times10^{17}$ cm^{-3} and a pinch radius of ≈ 3 mm along the axial extent of the image.

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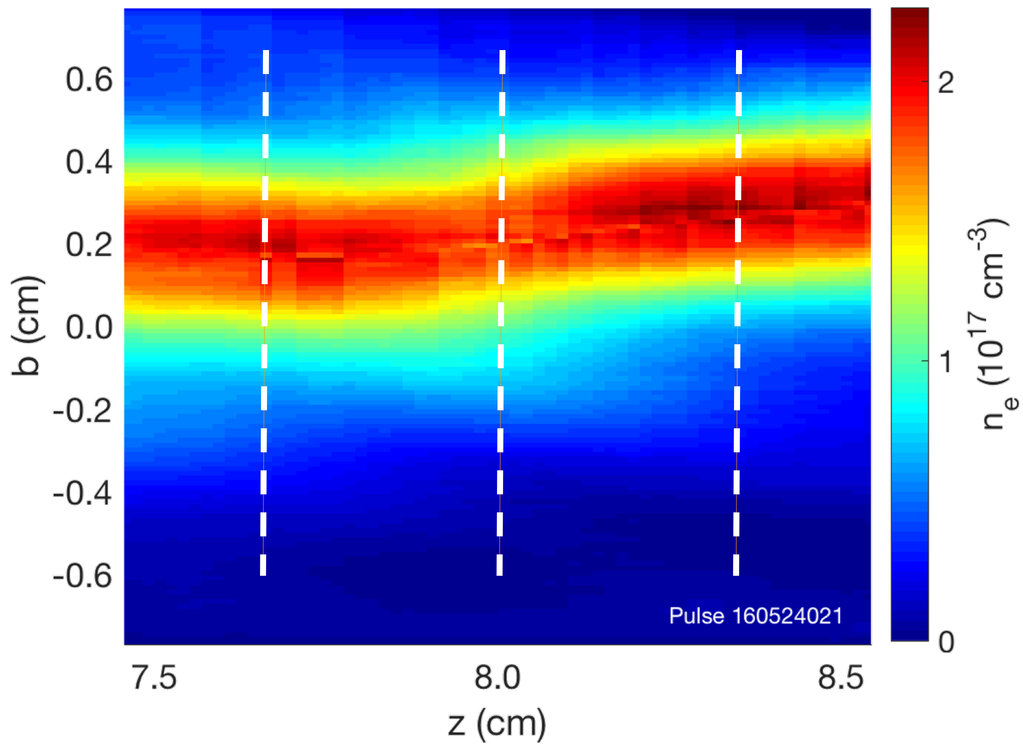

- The data plot retains the displacement of the pinch axis relative to the geometric axis.
- Profiles at 3 axial locations are extracted and analyzed.

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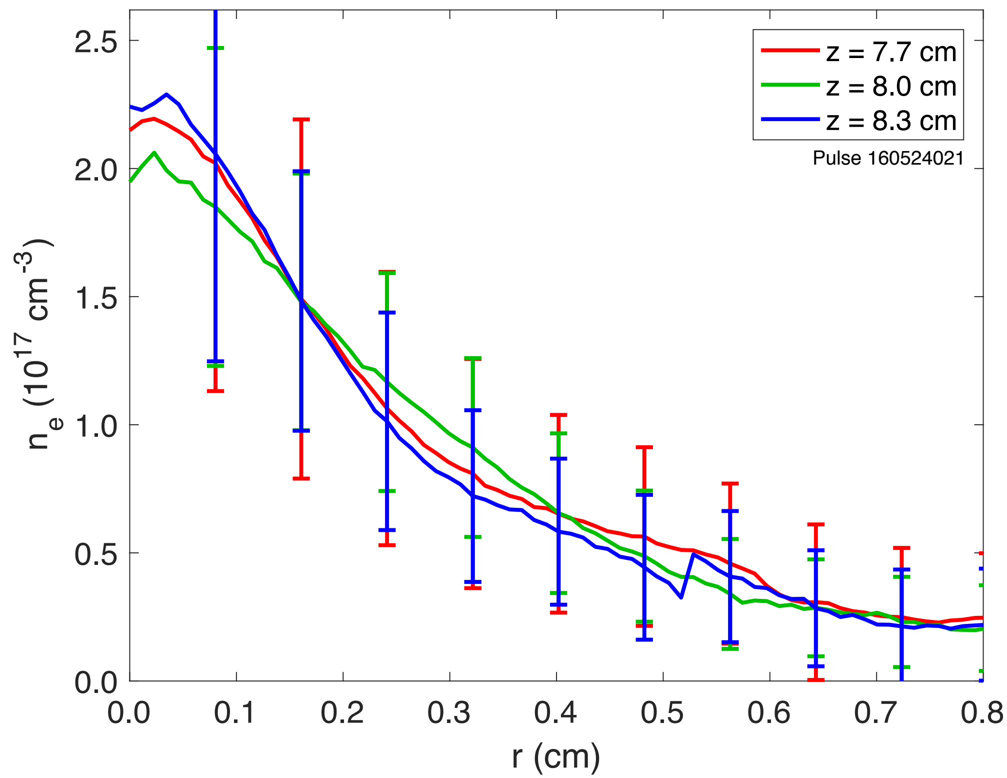


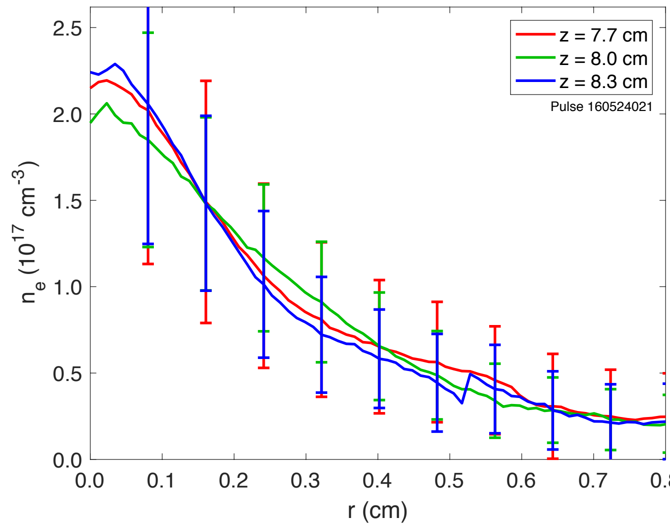
- The data plot retains the displacement of the pinch axis relative to the geometric axis.
- Profiles at 3 axial locations are extracted and analyzed.

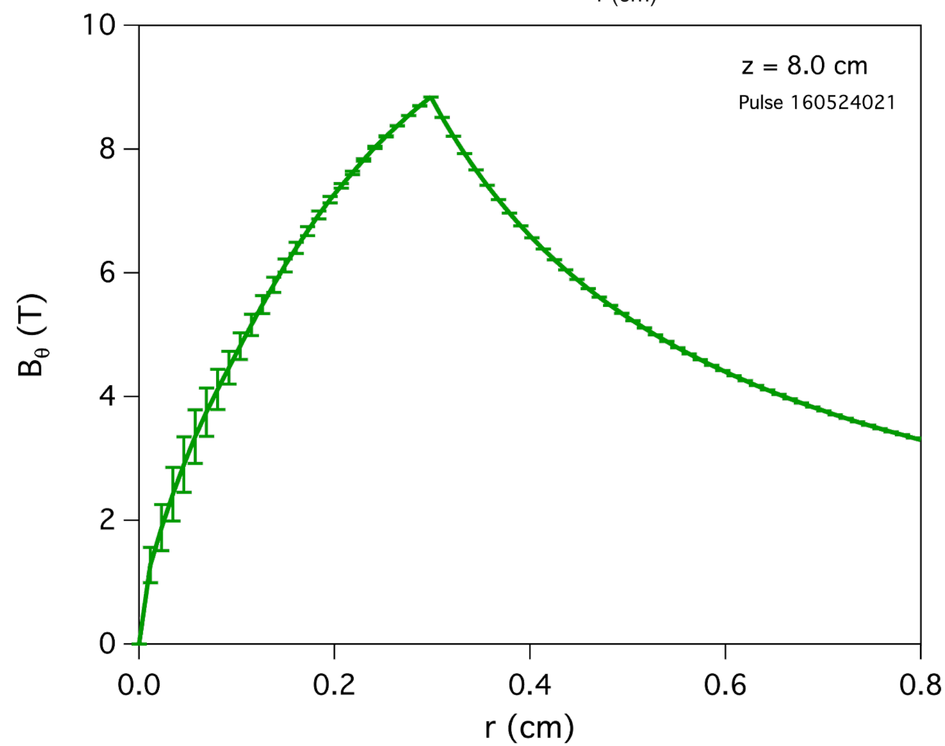
$B_\theta(r)$ and $T_e(r)$ are computed from the density profiles

Assuming a uniform drift speed, $v_d = v_i - v_e$, and matching the experimentally measured plasma current, magnetic field profiles $B_\theta(r)$ are computed as

$$B_\theta(r) = \frac{\mu_0 e v_d}{r} \int_0^r n_e r' dr'$$

Notice a peak magnetic field of 8.5 T.





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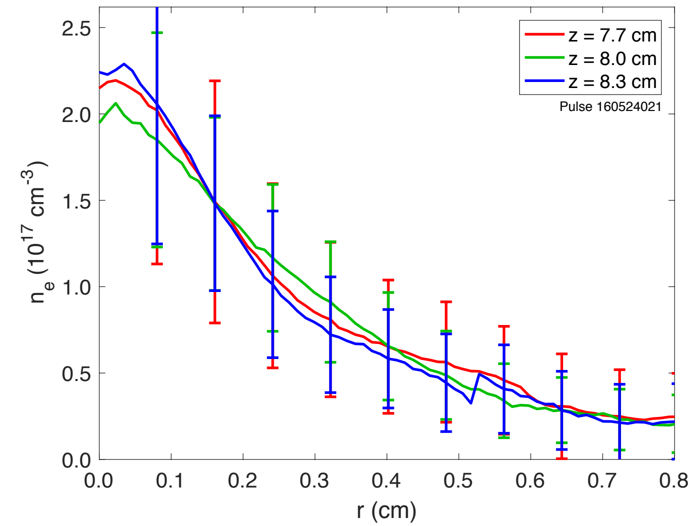
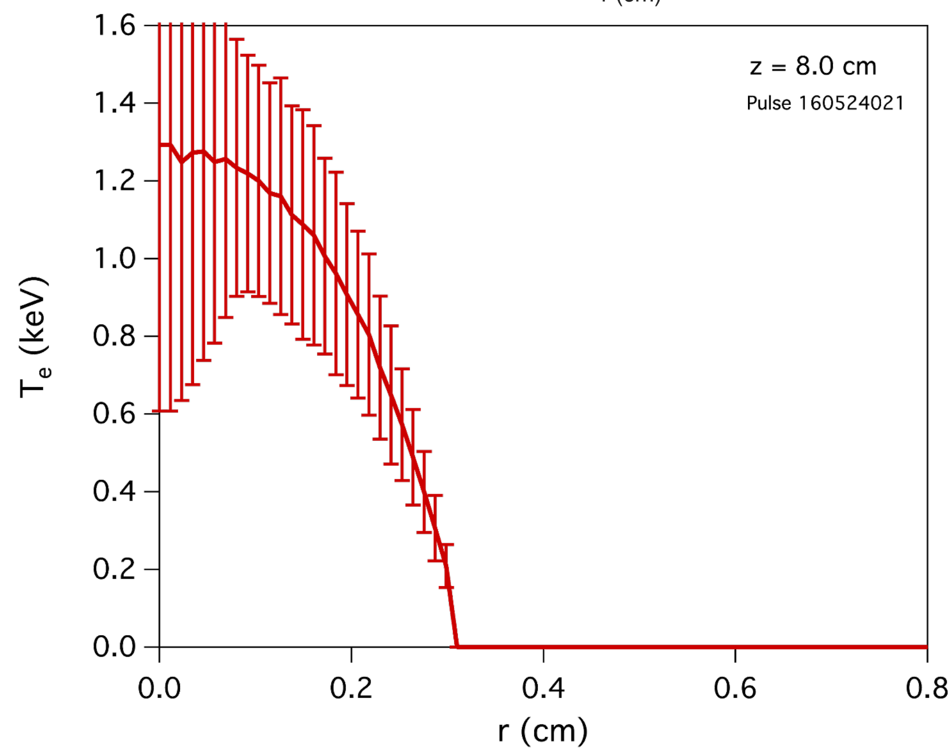


Integrating the radial force balance equation gives the electron temperature profile $T_e(r)$.

$$T_e(r) = \frac{1}{2\mu_0 n_e} \int_0^r \frac{B_\theta}{r'} \frac{d}{dr'}(r' B_\theta)\, dr'$$

assuming $T_e = T_i$, consistent with the expected collisionality.

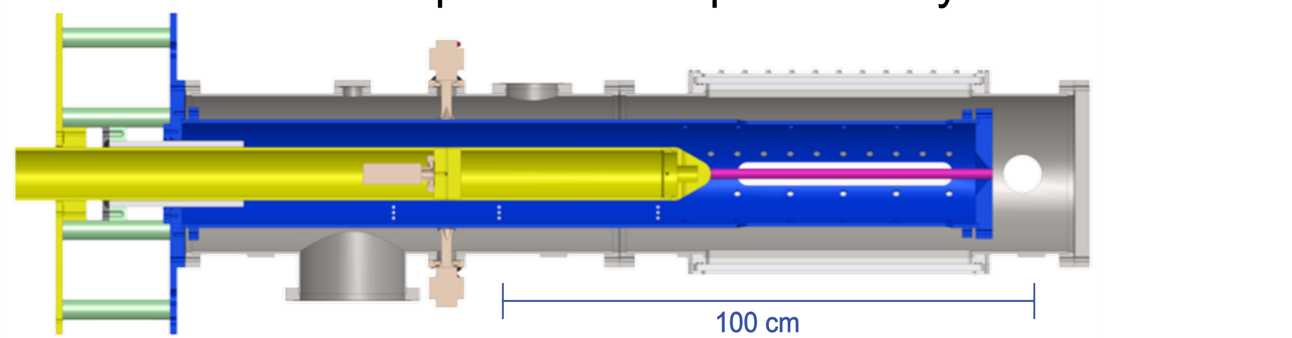


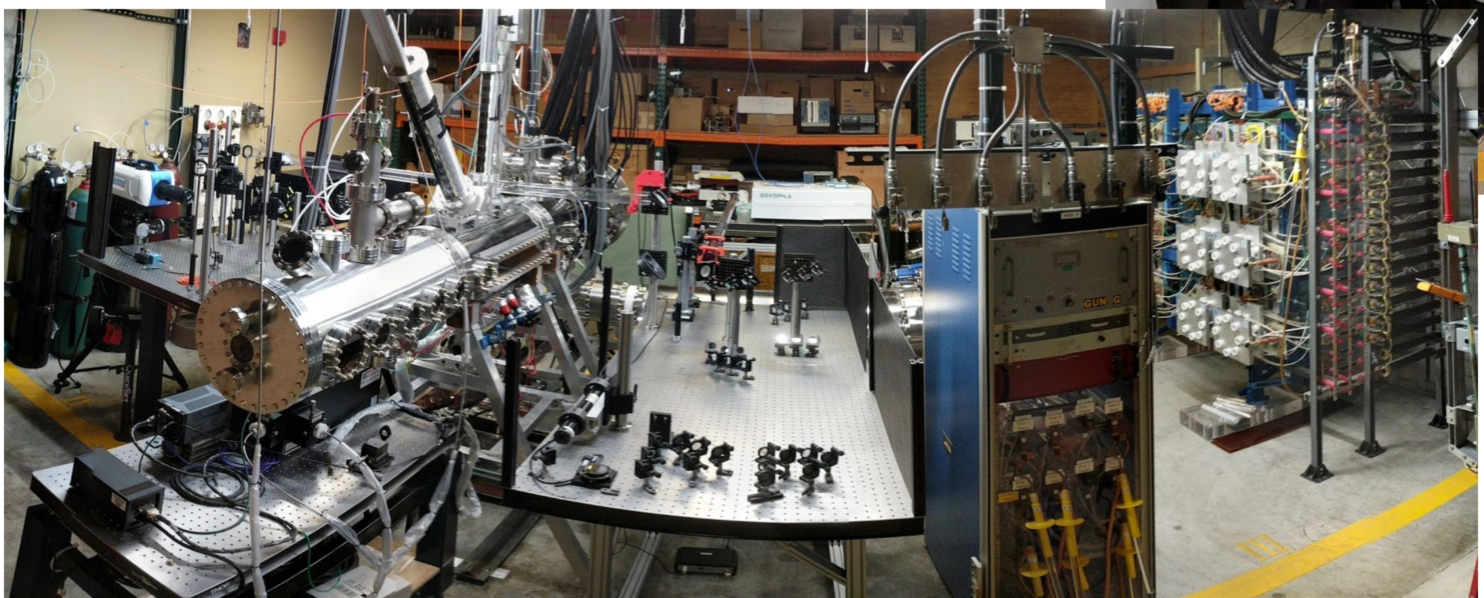
Notice a peak electron temperature of ≈ 1 keV. Independent spectroscopic measurements indicate $T_i \approx 800$ eV.

FuZE Project advances the SFS Z pinch for fusion

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 multi-fluid modeling
- additional personnel/capabilities by LLNL & UW



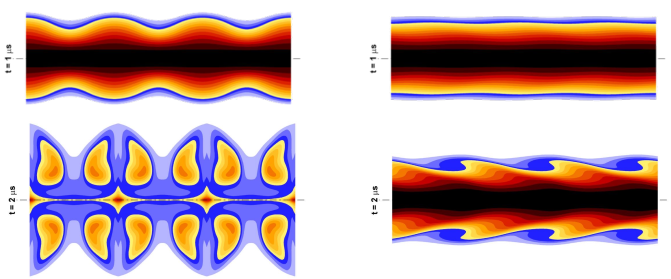


FuZE benefits from detailed numerical simulations

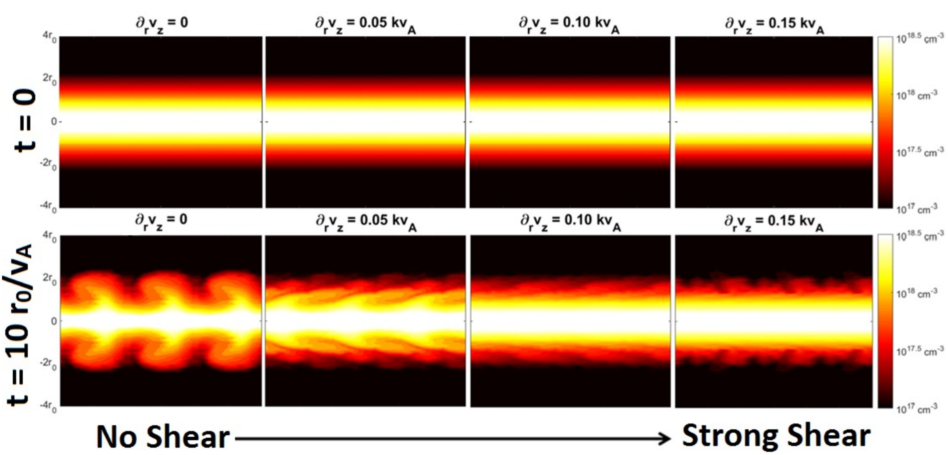
Nonlinear fluid & kinetic simulations using Mach2 (MHD), WARPXM (2-fluid), and LSP (PIC) to: (a) study sheared-flow stabilization, (b) design experimental details, (c) model whole device, (d) predict neutron yield

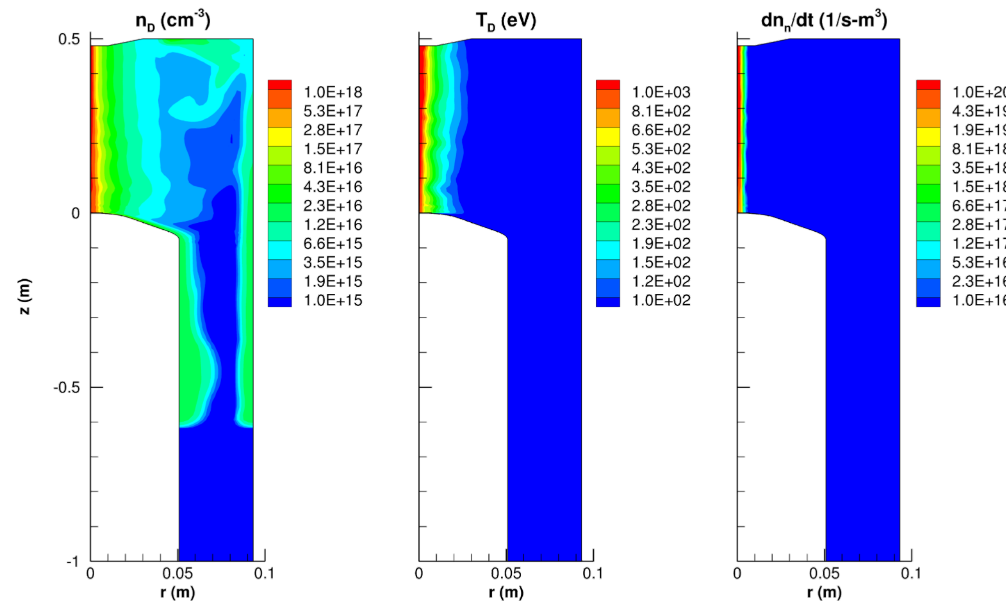
Results show plasma stabilization with sufficient flow shear.

MHD Fluid Results

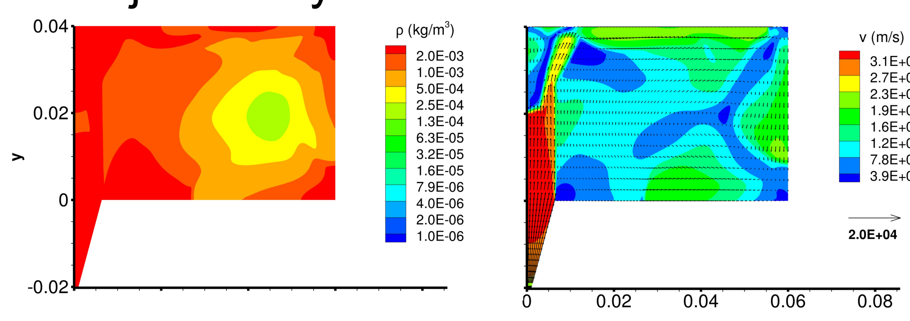


PIC Kinetic Results





Simulations provide insight to gas injection dynamics.



Multi-fluid models are solved in balance law form

Multi-fluid plasma models capture physical phenomena beyond single fluid models. The 5*N*-moment multi-fluid model is solved using the WARPXM code[1] using a high-order discontinuous-Galerkin finite-element method.

$$\frac{\partial \rho_s}{\partial t} + \nabla \cdot (\rho_s \boldsymbol{u}_s) = 0$$

$$\frac{\partial}{\partial t}(\rho_s \boldsymbol{u}_s) + \nabla \cdot (\rho_s \boldsymbol{u}_s \boldsymbol{u}_s + p_s \boldsymbol{I} + \Pi_s) = \frac{\rho_s q_s}{m_s}(\boldsymbol{E} + \boldsymbol{u}_s \times \boldsymbol{B}) - \sum_{s^*} \boldsymbol{R}_{s,s^*}$$

$$\frac{\partial \epsilon_s}{\partial t} + \nabla \cdot \Big(\big((\epsilon_s + p_s)\boldsymbol{I} + \Pi_s \big) \cdot \boldsymbol{u}_s + \boldsymbol{h}_s \Big) = \frac{\rho_s q_s}{m_s} \boldsymbol{u}_s \cdot \boldsymbol{E} + \sum_{s^*} Q_{s,s^*}$$

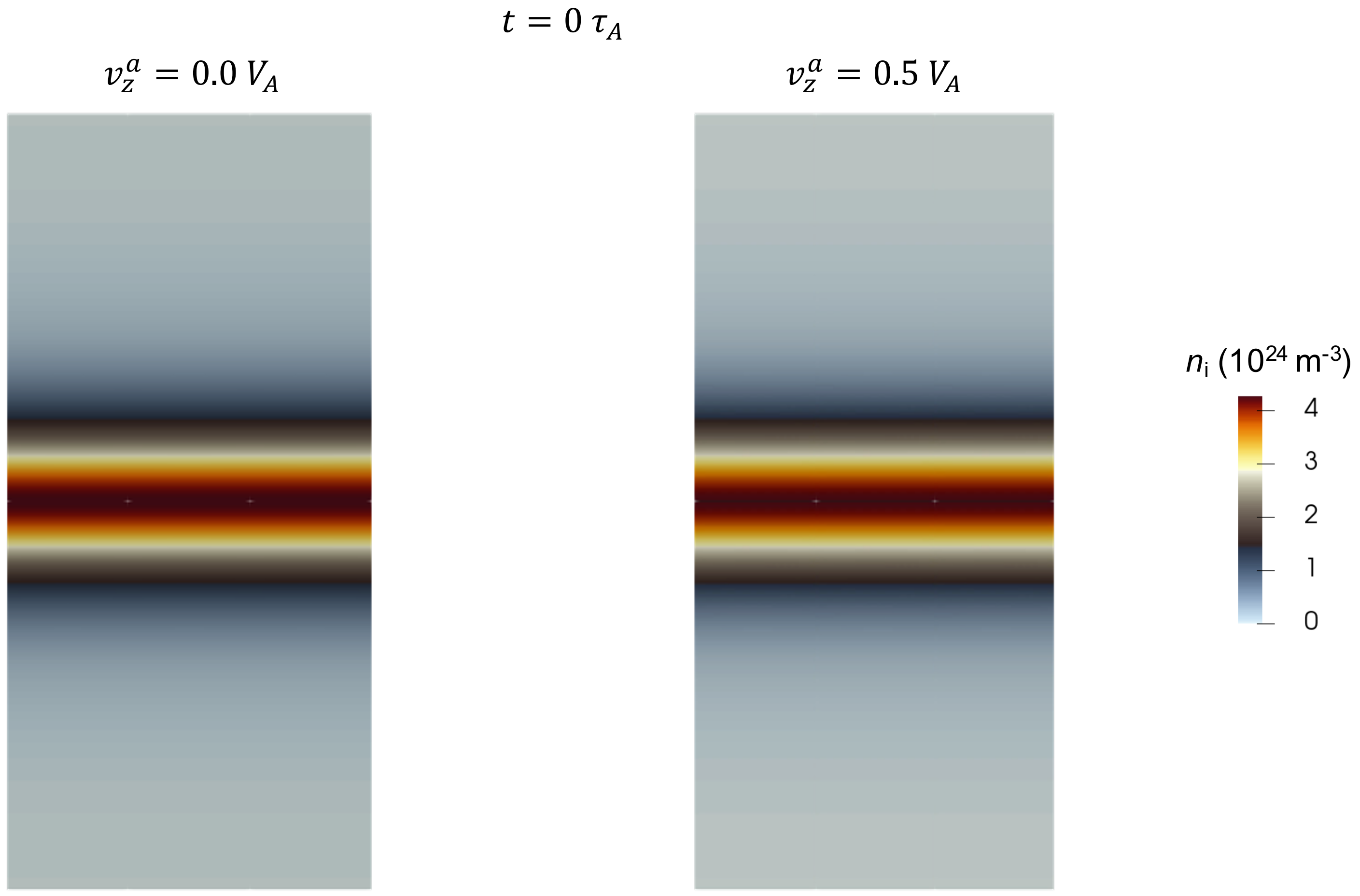
where the total energy is $\epsilon_s = \frac{1}{\gamma - 1} p_s + \frac{1}{2} \rho_s u_s^2$, for each species s.

The fluids are coupled to each other and to the electromagnetic fields through Maxwell's equations and collisional transport terms[2].

[1]Loverich et al., CPC (2005); Shumlak et al., CPC (2011); Miller et al., PoP (2016); [2]Braginskii, RPP (1965)

Multi-fluid models study sheared-flow stabilization

Multi-fluid (5*N*-moment) plasma model simulations using the WARPXM code suggests that sheared flows are effective in mitigating macro (fluid) instabilities.



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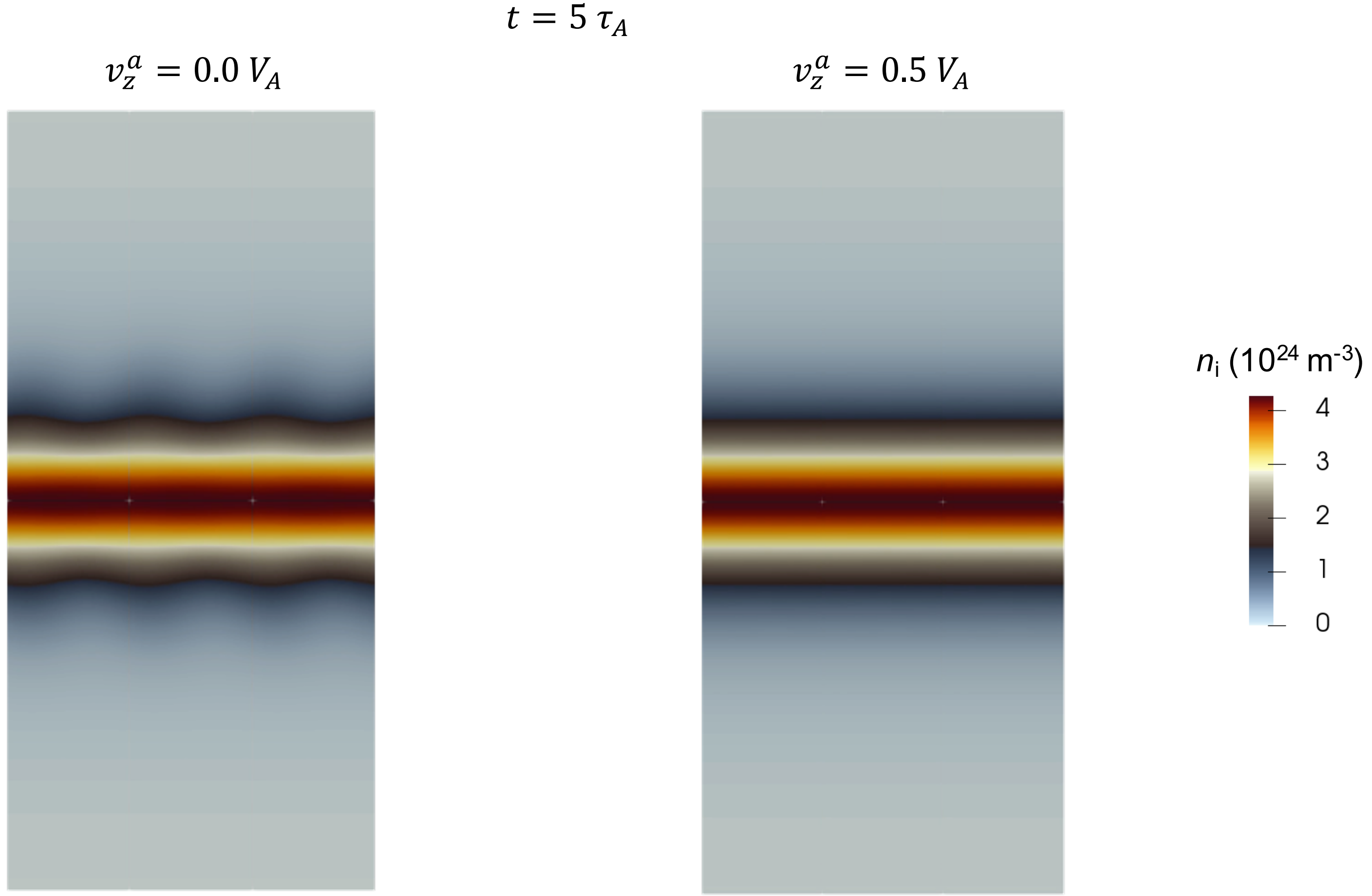

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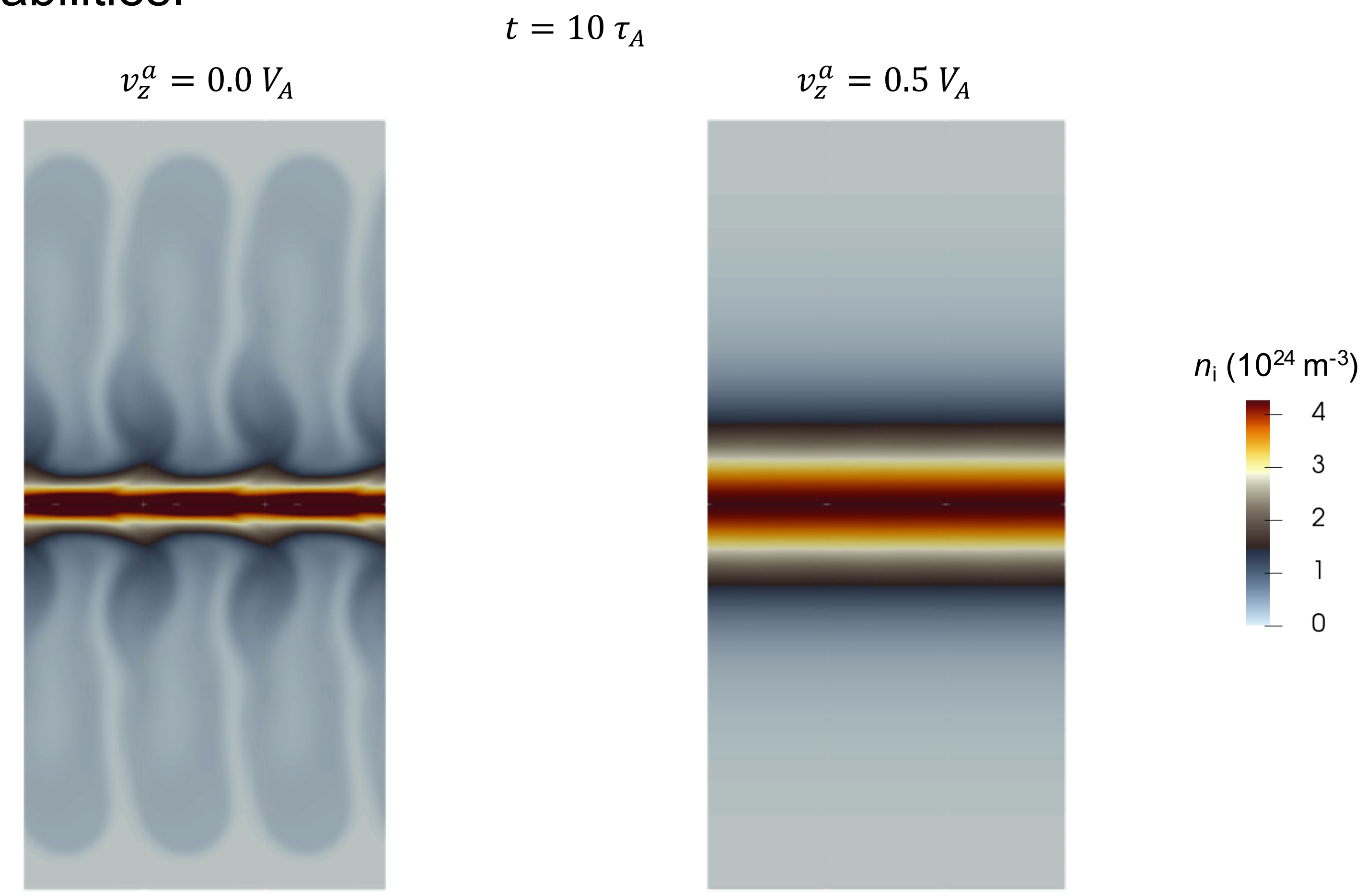
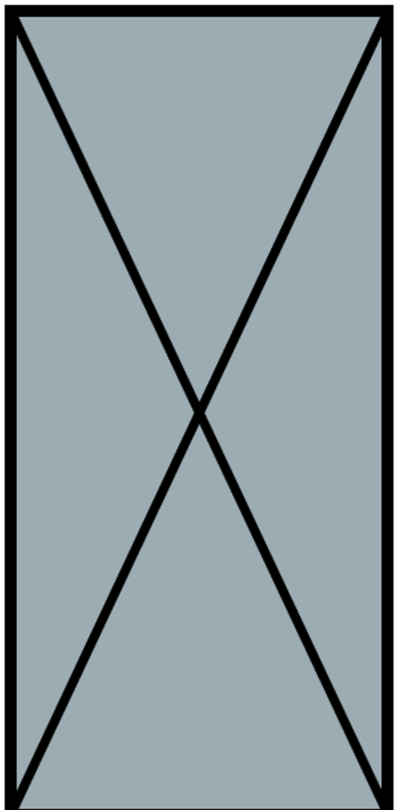


Multi-fluid models study sheared-flow stabilization

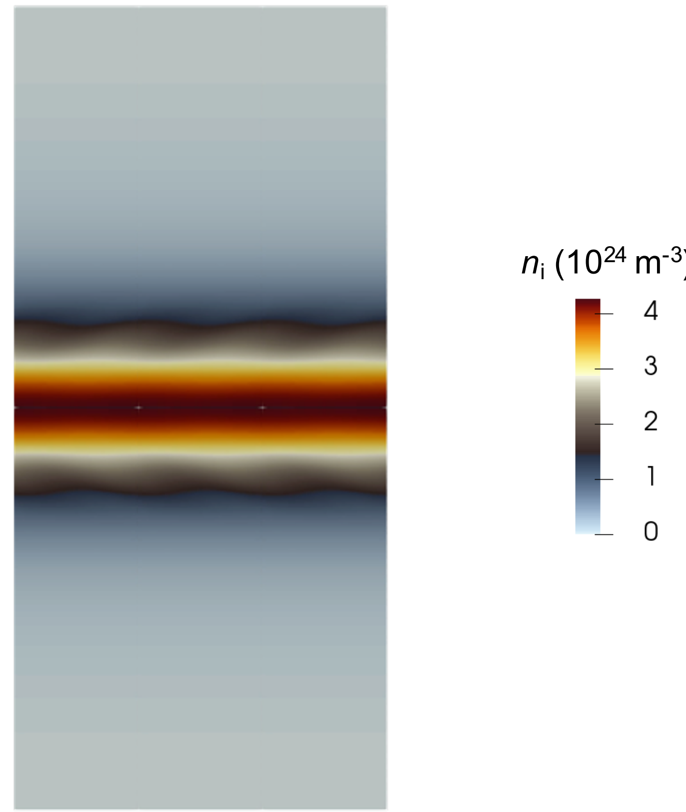
Multi-fluid (5*N*-moment) plasma model simulations using the WARPXM code suggests that sheared flows are effective in mitigating macro (fluid) instabilities.

$t = 15\ \tau_A$

$v_z^a = 0.0\ V_A$



$v_z^a = 0.5\ V_A$



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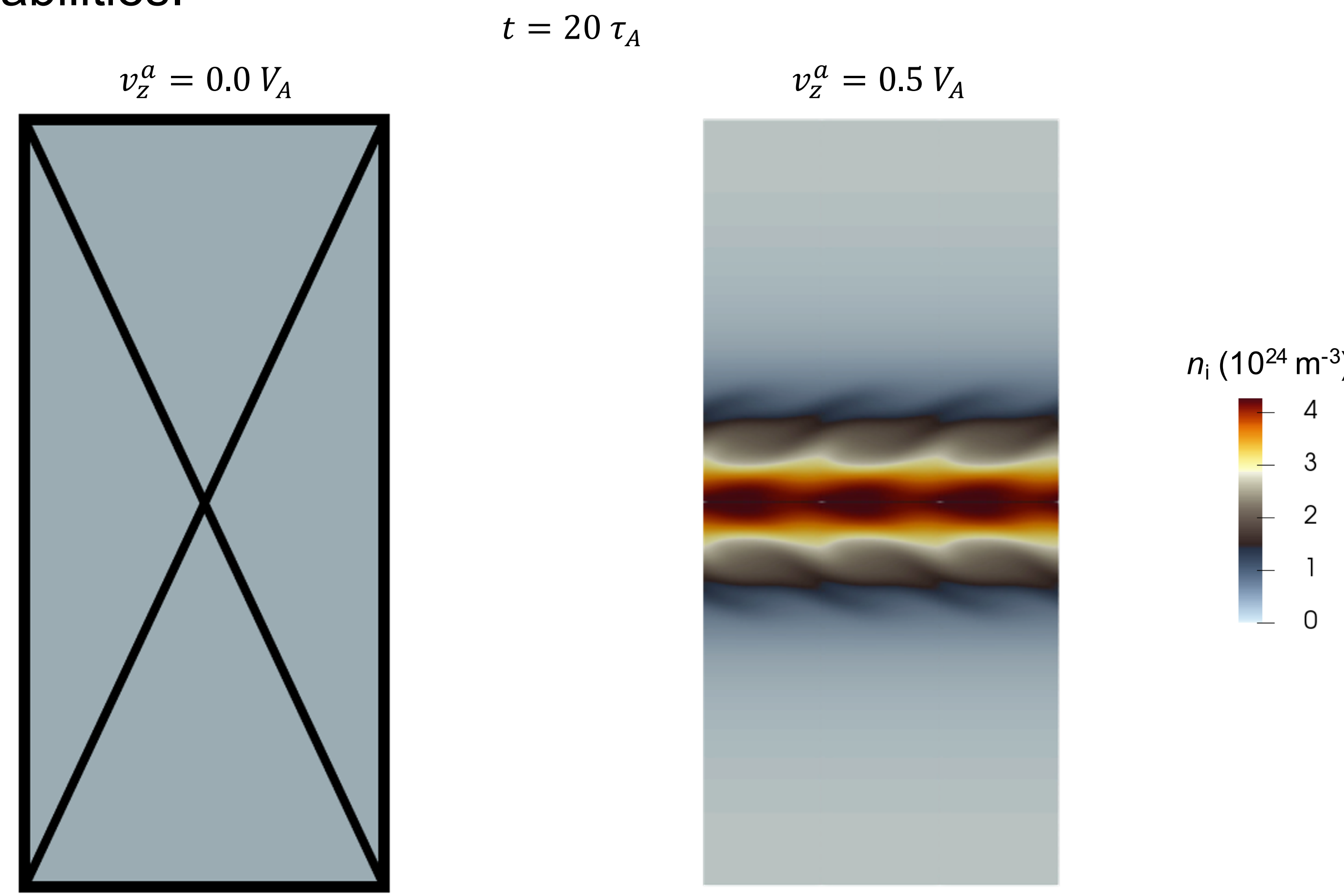
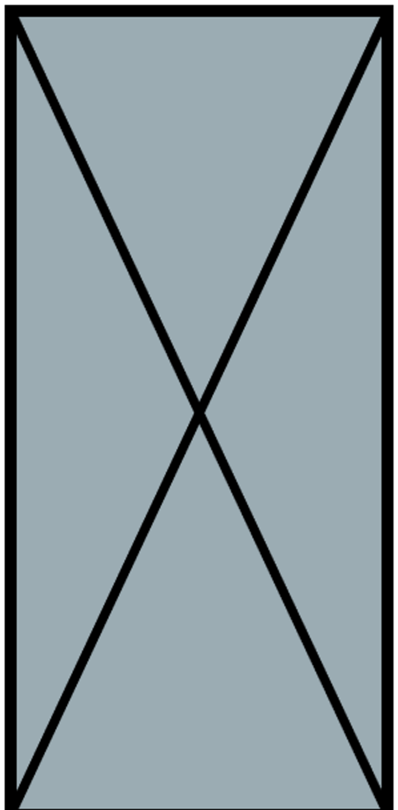


Multi-fluid models study sheared-flow stabilization

Multi-fluid (5*N*-moment) plasma model simulations using the WARPXM code suggests that sheared flows are effective in mitigating macro (fluid) instabilities.

$t = 25\ \tau_A$

$v_z^a = 0.0\ V_A$



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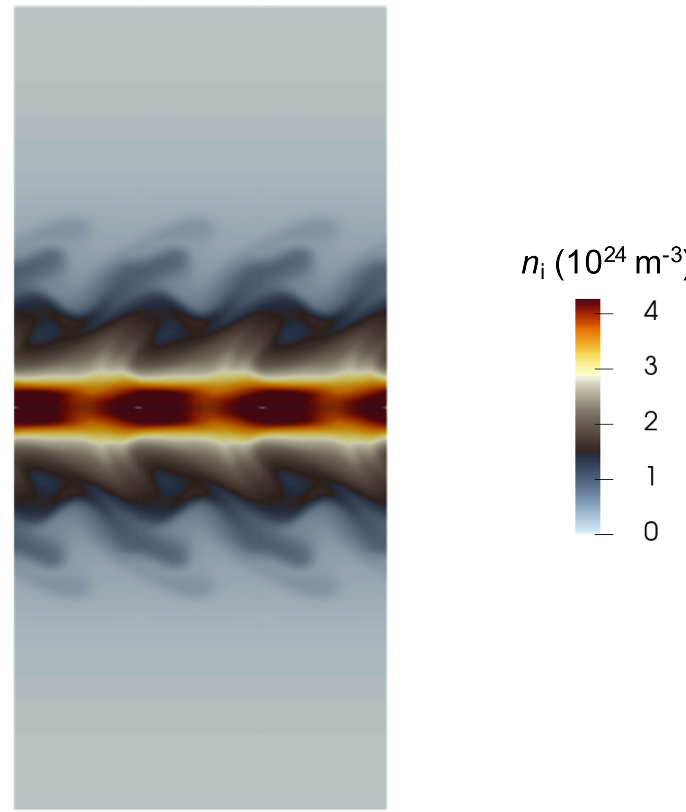

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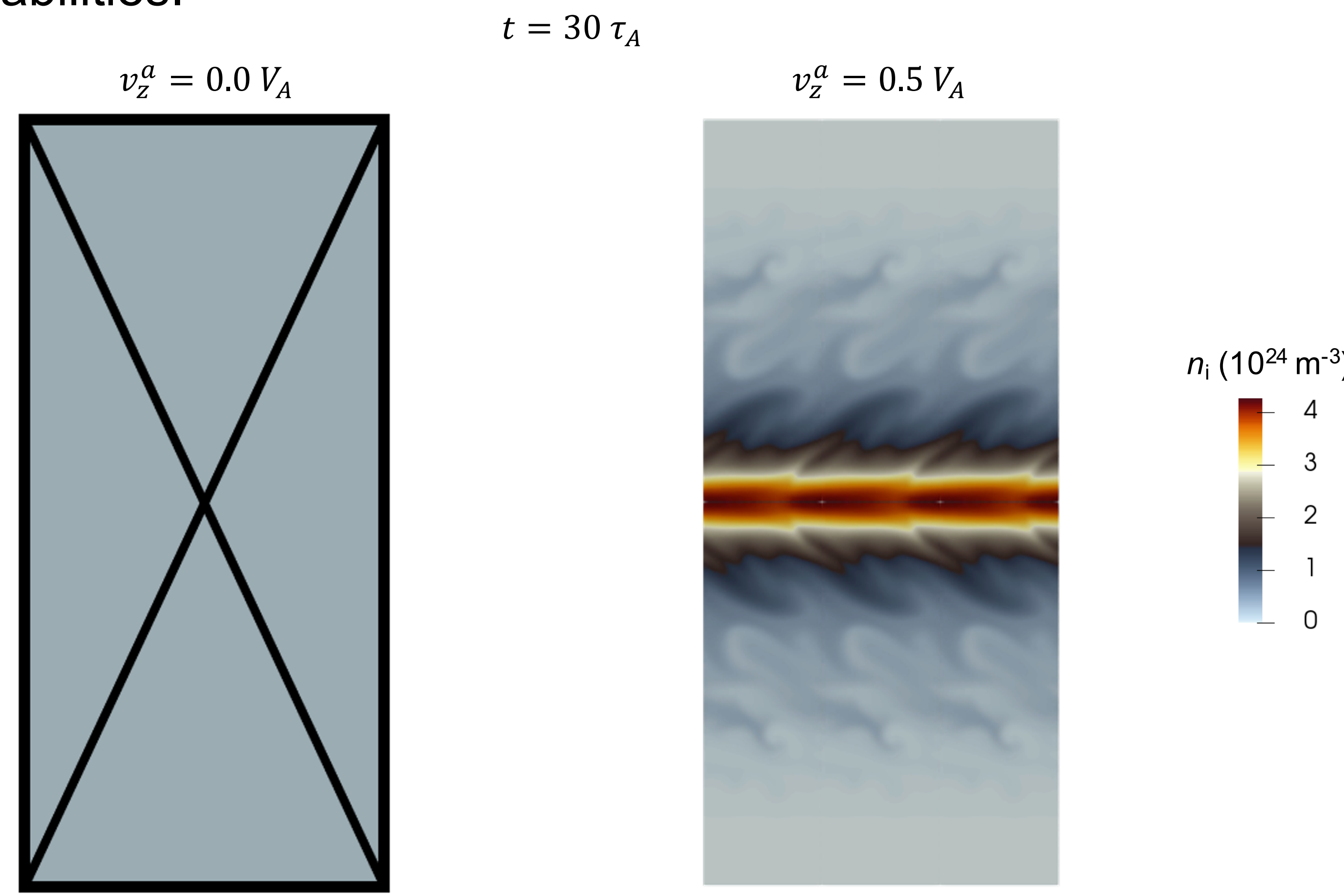
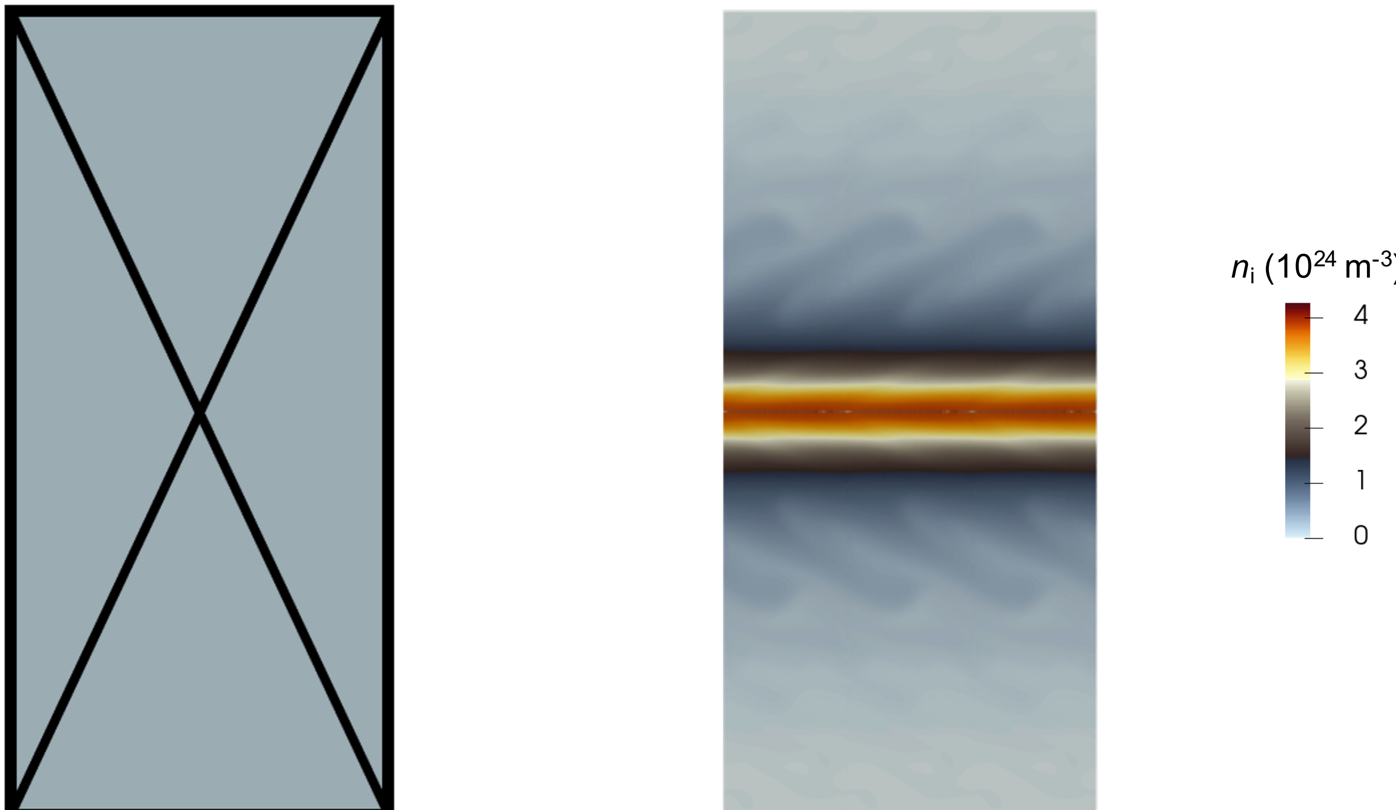


Multi-fluid models study sheared-flow stabilization

Multi-fluid (5*N*-moment) plasma model simulations using the WARPXM code suggests that sheared flows are effective in mitigating macro (fluid) instabilities.

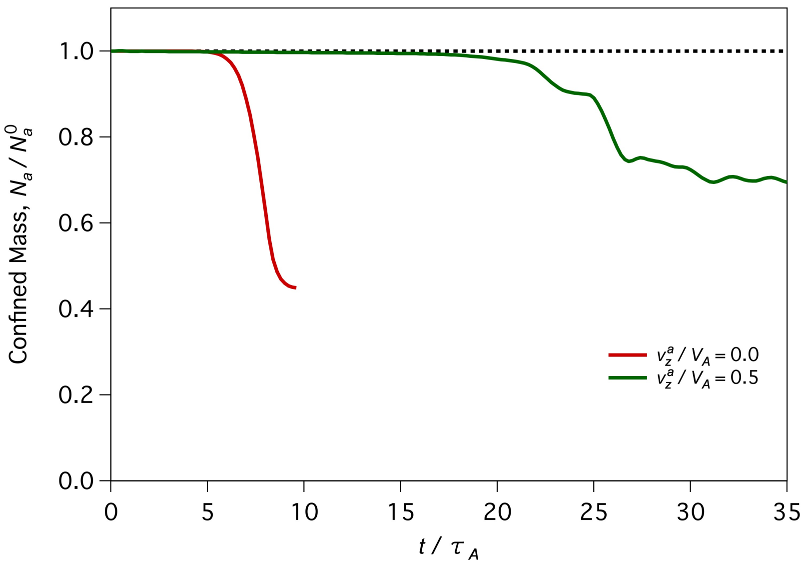
$t = 35\ \tau_A$

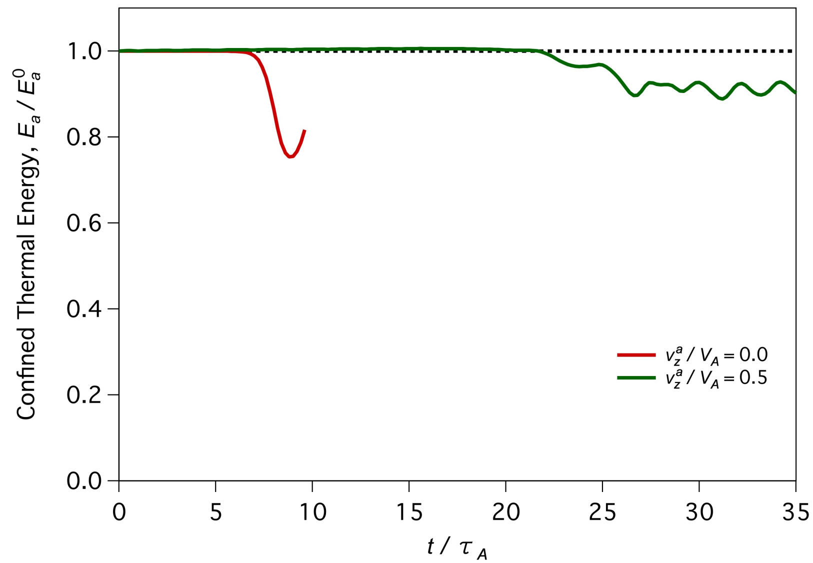
$v_z^a = 0.0\ V_A$ $v_z^a = 0.5\ V_A$



Multi-fluid models study sheared-flow stabilization

- Multi-fluid ($5N$-moment) plasma model simulations using the WARPXM code suggests that sheared flows are effective in mitigating macro (fluid) instabilities. Defining pinch mass and thermal energy as $\int_0^a n_i\, dx^3$ and $\int_0^a (p_i + p_e)\, dx^3$ provides a measure of confinement.



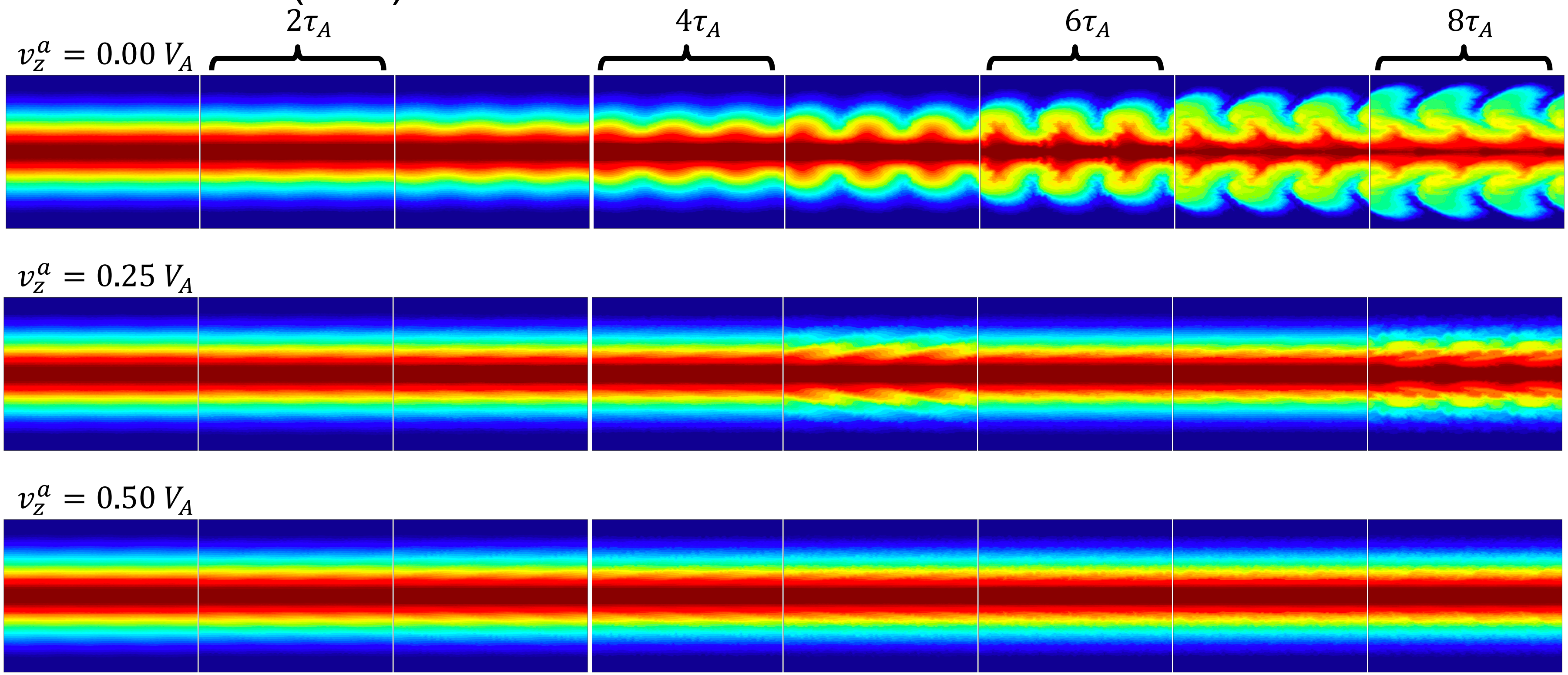


- Confinement rapidly degrades in the static Z pinch as a result of instabilities. Flow shear enhances confinement[1]. Even when instabilities appear in the sheared-flow Z pinch, confinement is better maintained.
- Flow direction matters, with increased stabilization for $\boldsymbol{\Omega} \cdot \boldsymbol{B} < 0$, similar to recent KHI studies[2].

[1]Meier et al., PoP (2021); [2]Vogman et al., PoP (2020)

Kinetic models also study sheared-flow stabilization

Fully kinetic simulations using the LSP PIC code suggests that sheared flows are effective in mitigating micro (kinetic) instabilities[1], in addition to macro (fluid) instabilities.



Gyrokinetic simulations[2] of the SFS Z pinch with COGENT show a stabilizing effect with increased flow shear, but not complete linear stabilization.

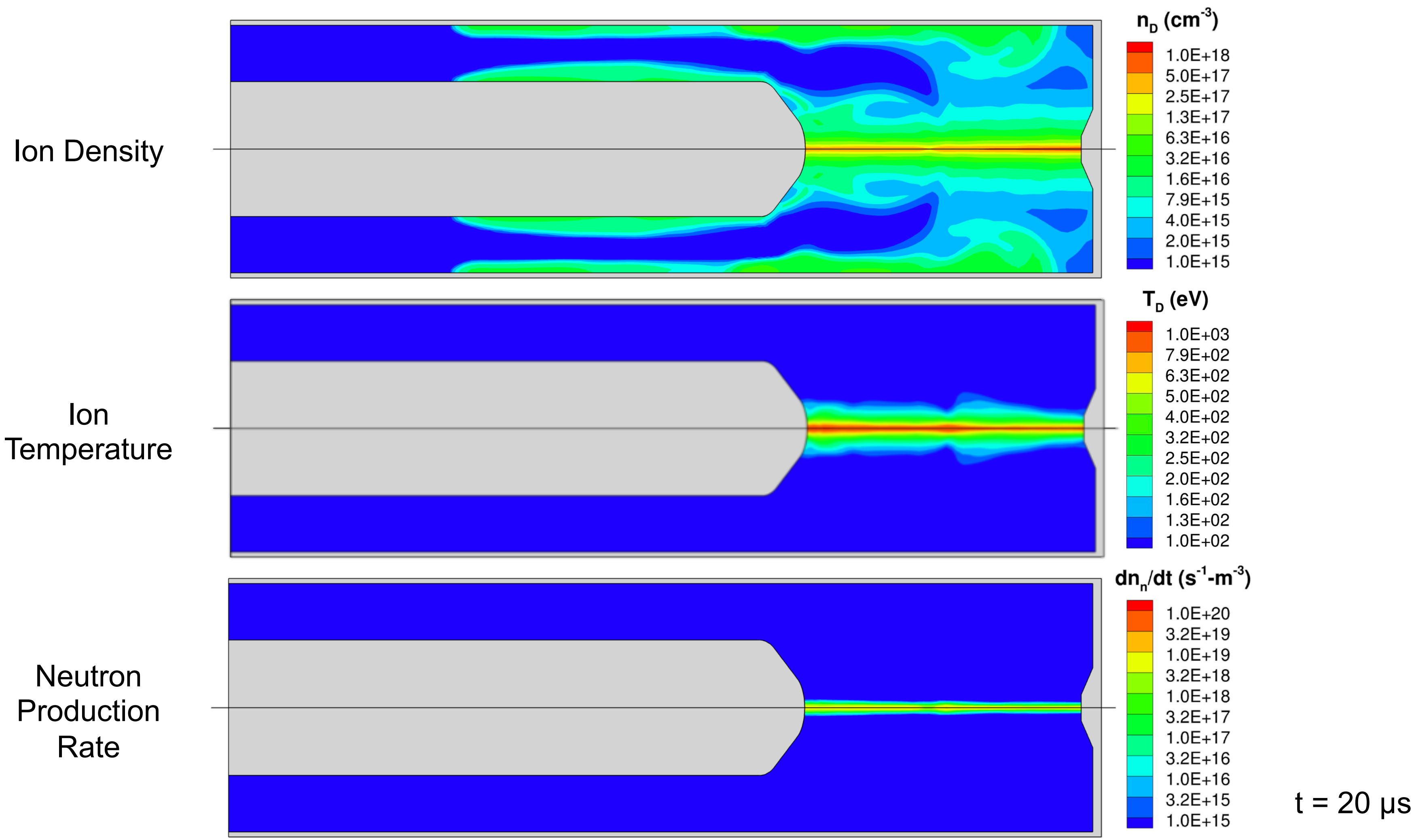
[1]Tummel et al., PoP (2019); [2]Geyko et al., PoP (2020), Geyko et al., PoP (2021)

UNIVERSITY of WASHINGTON

ZAP ENERGY

Whole-device modeling provides insight to experiment

Time-dependent simulations of the FuZE device indicates the dynamics of the Z-pinch plasma formation, heating, and fusion neutron production from an extended line source for approximately 10 μs.



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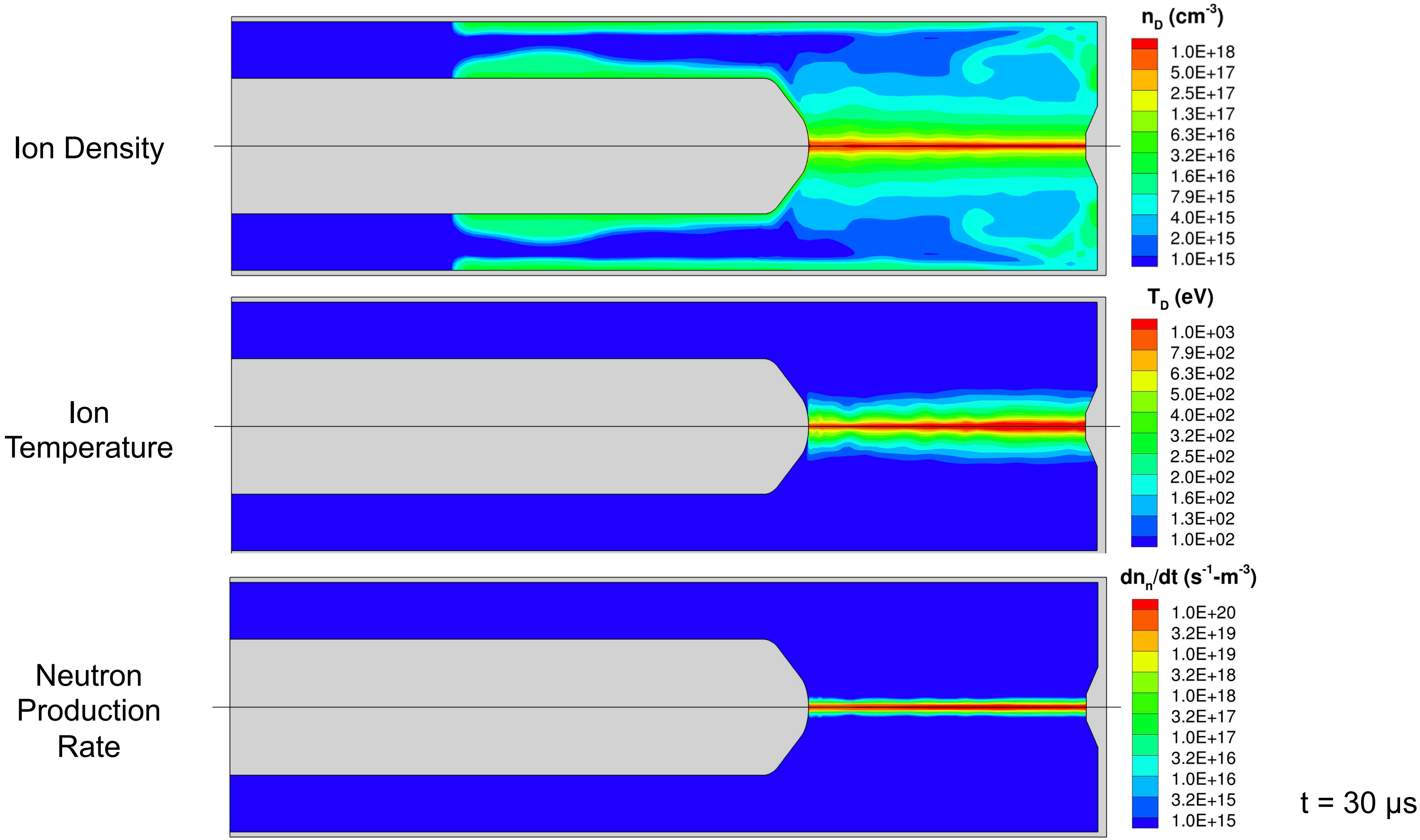

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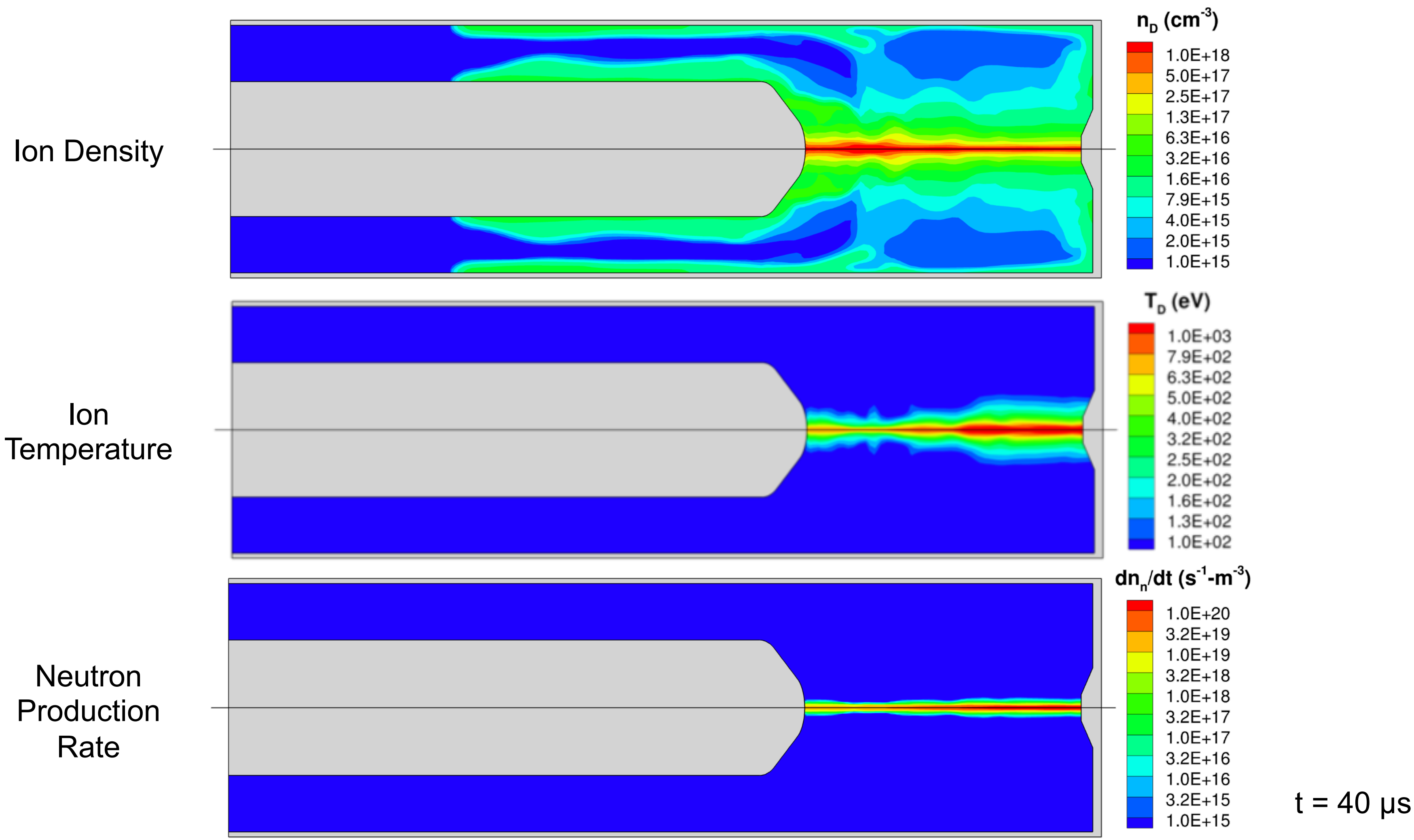
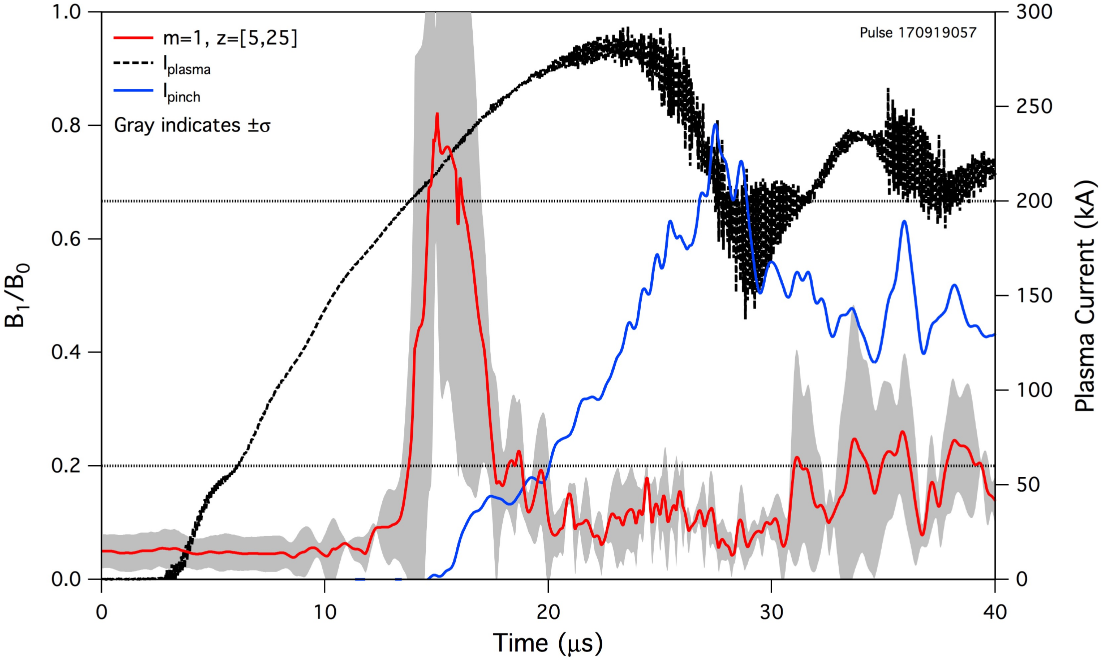
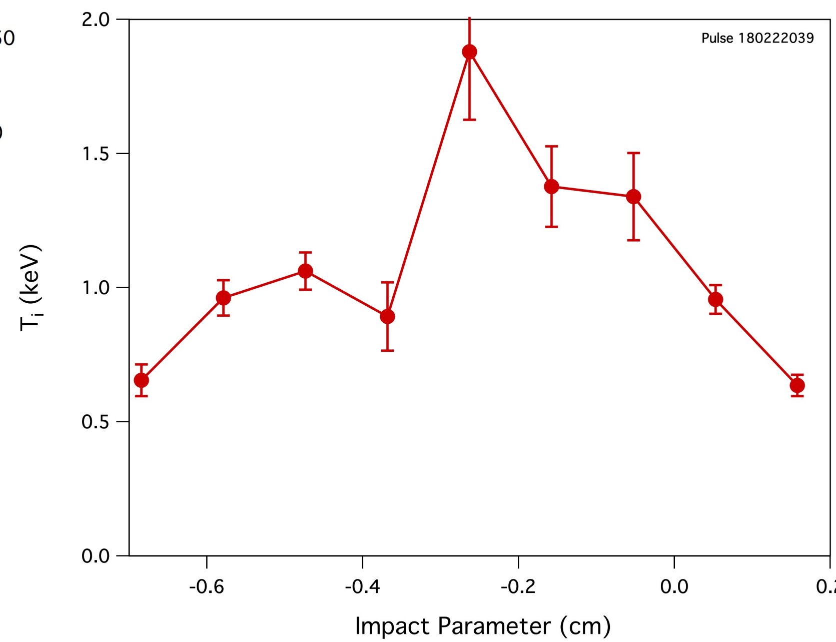


FuZE produces stable, high-performance plasmas

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



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



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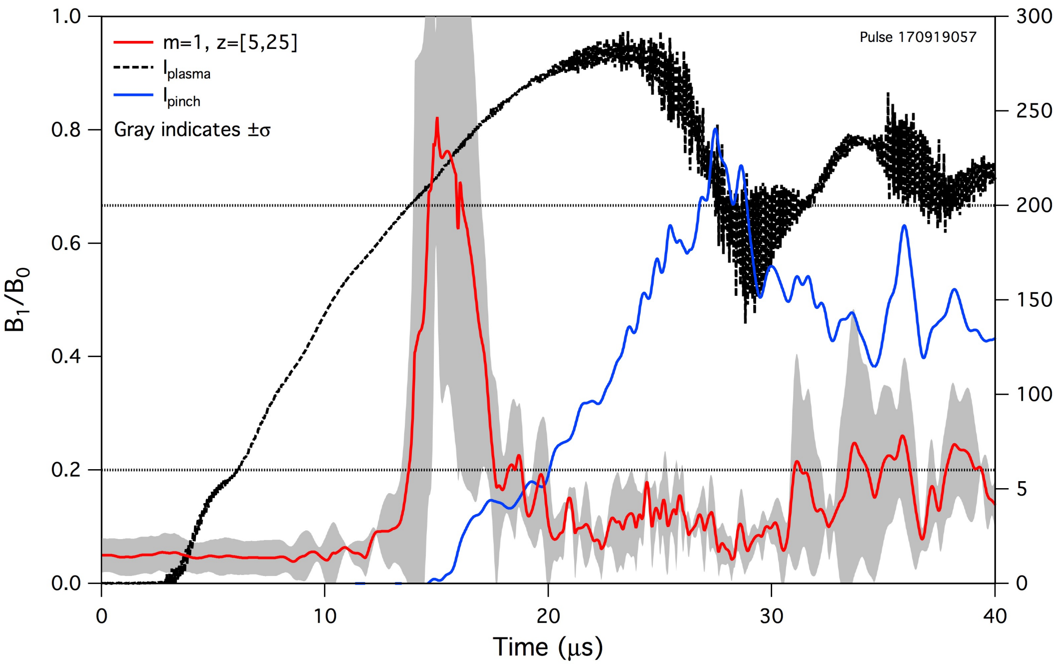
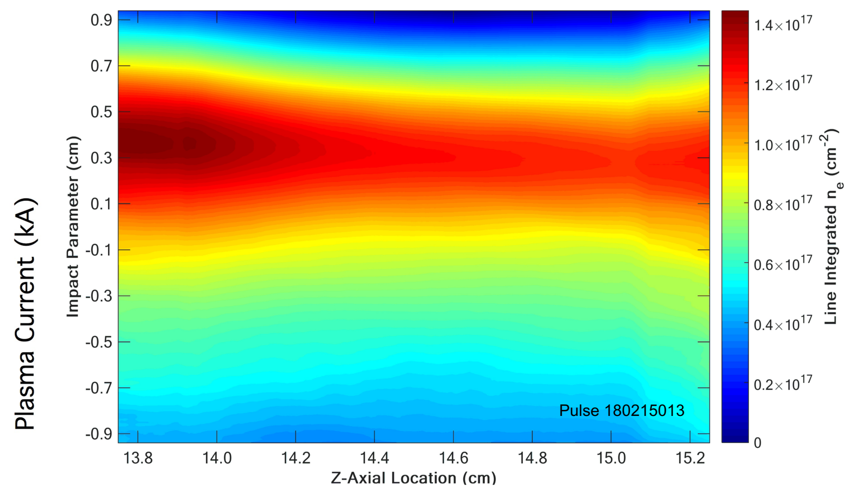


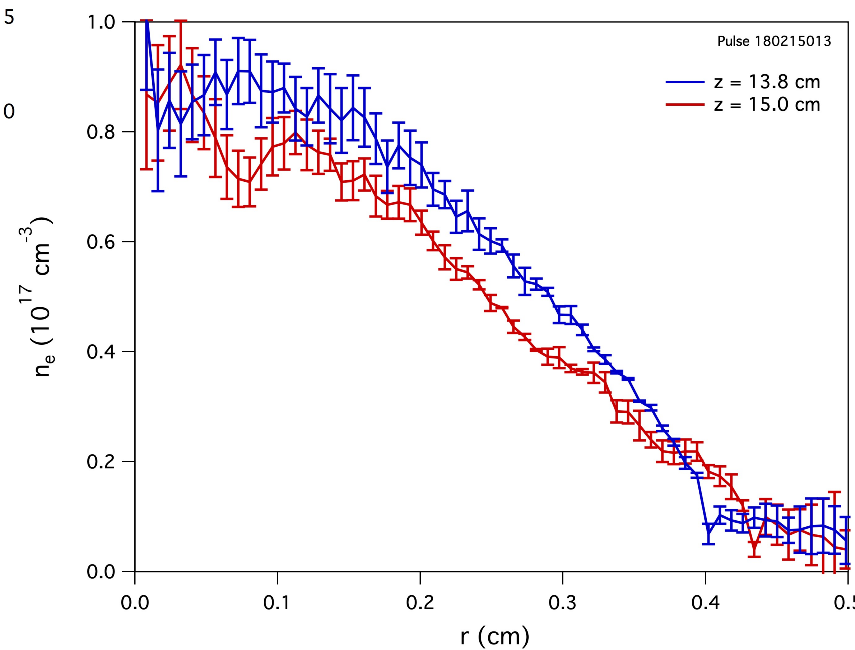


Digital holographic interferograms indicate pinched plasma density during quiescent period ($t = 25$ μs):

$$a \approx 3 \text{ mm}$$

$$B_\theta \approx 10 \text{ T}$$

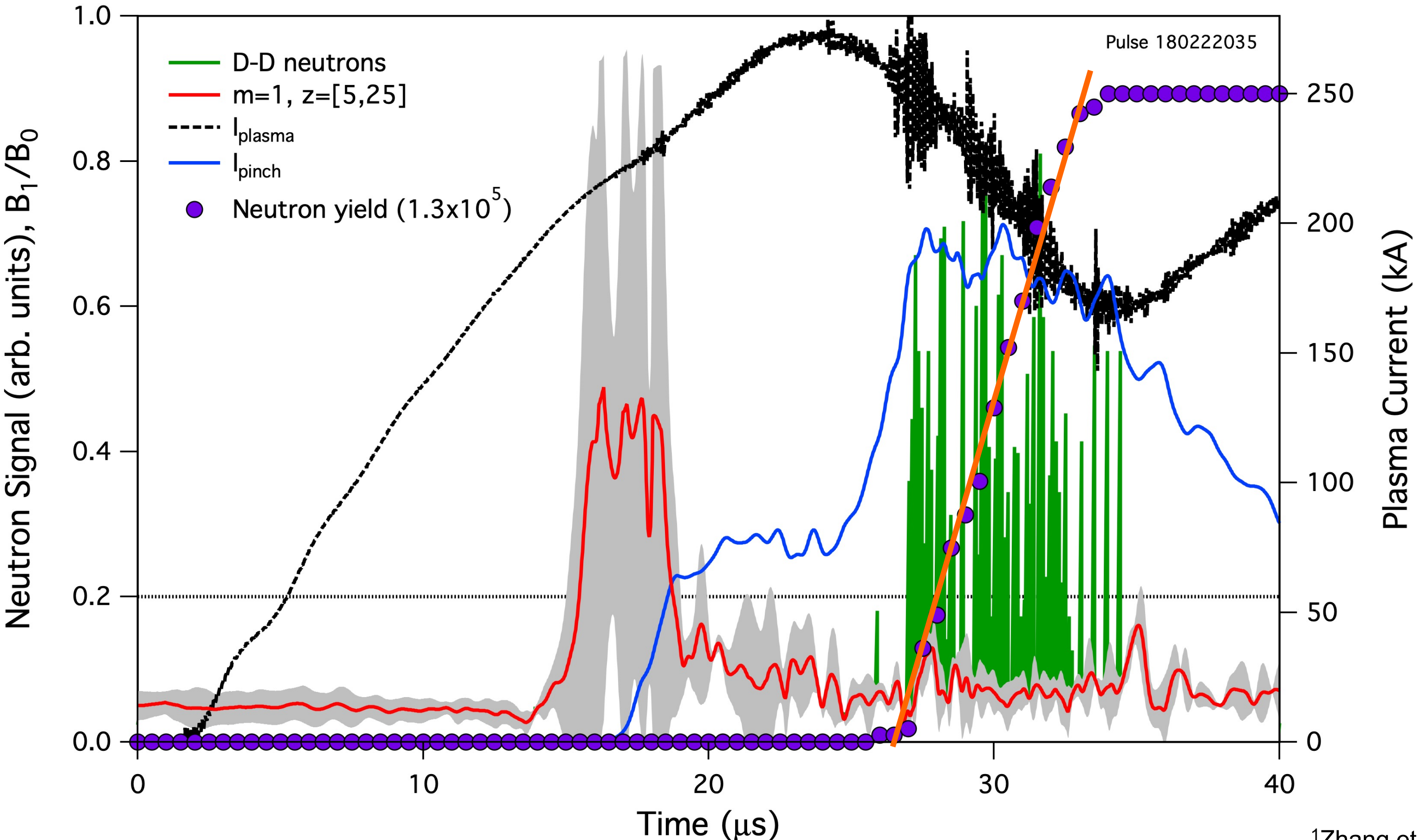
$$T_e + T_i \approx 1.8 \text{ keV}$$



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.

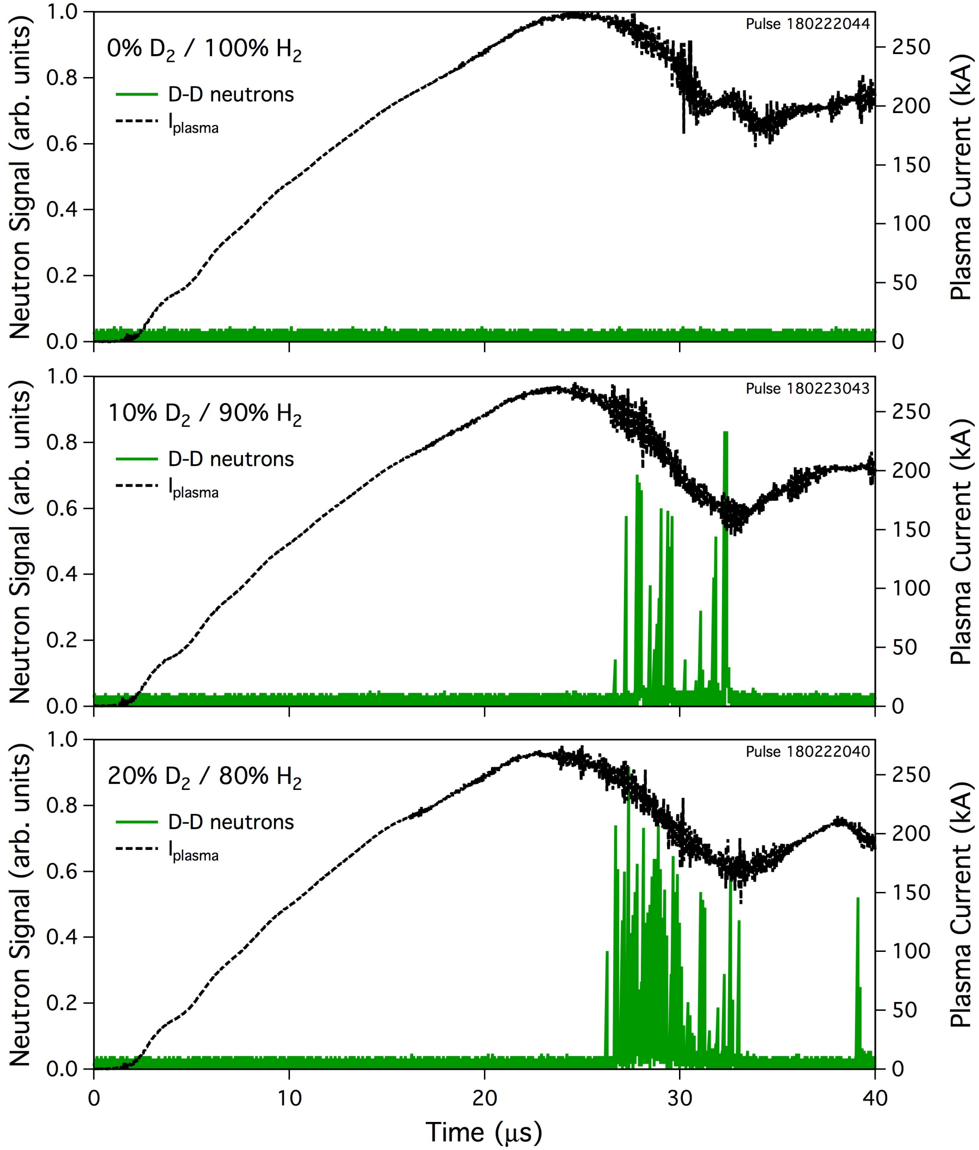
Measurements indicate a steady neutron emission to within statistical expectations consistent with a thermonuclear process.

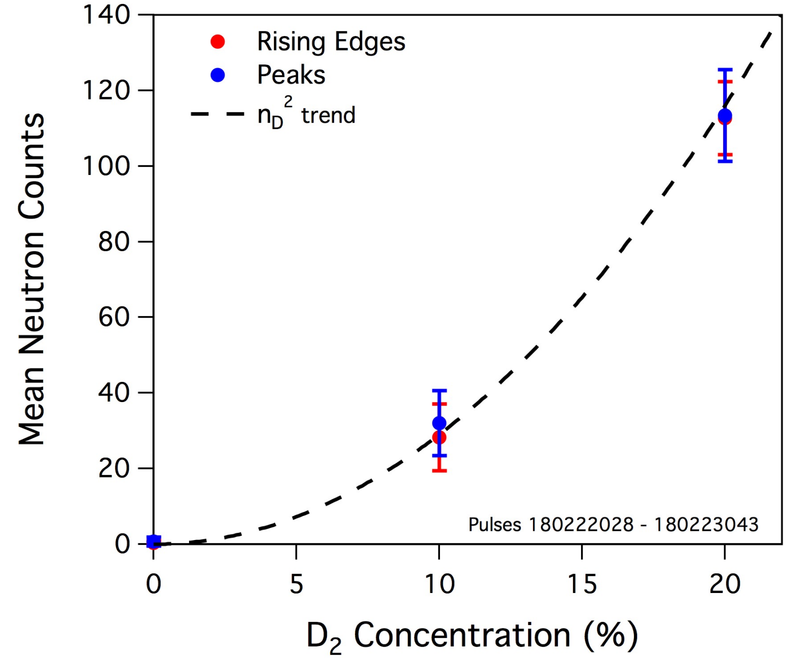


[1]Zhang et al., PRL (2019)

Fusion neutrons scale with deuterium concentration

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





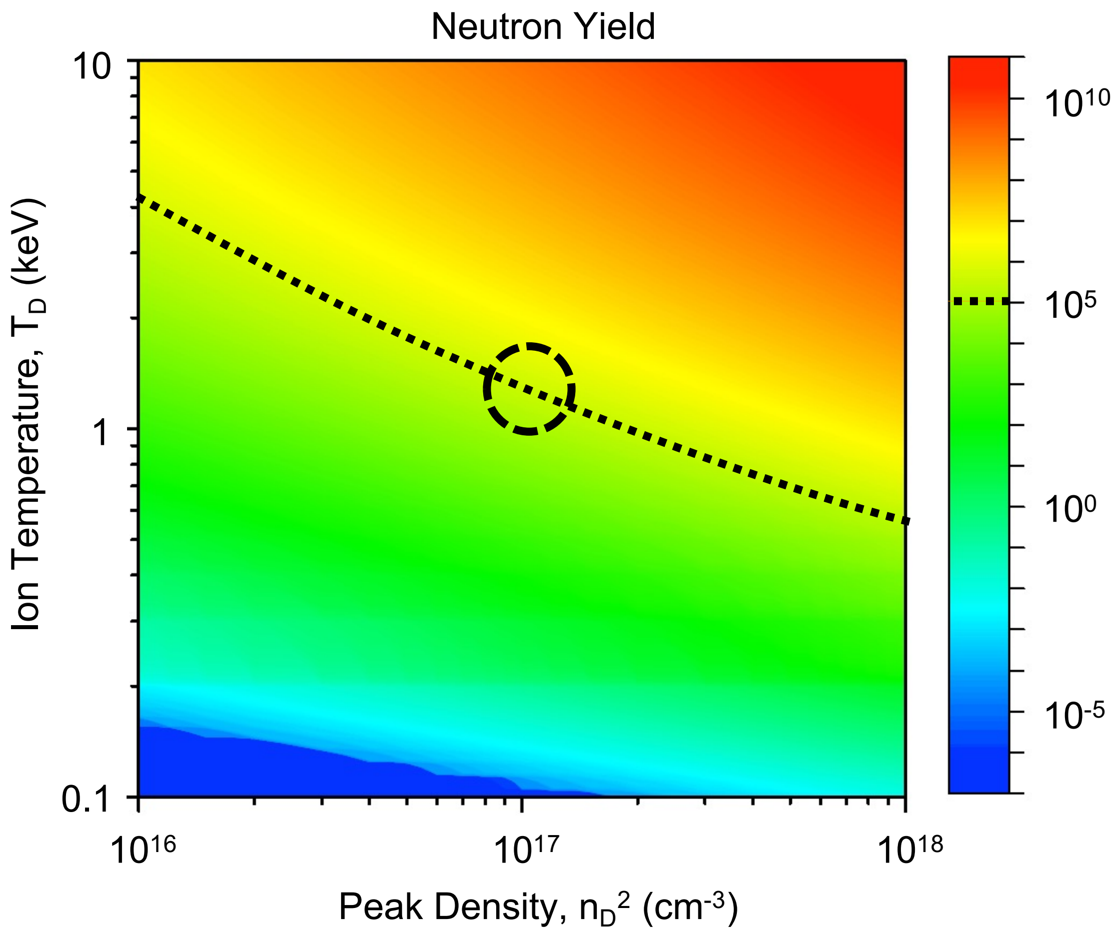
Neutron count dependence agrees with expected scaling with n_D^2.

Fusion neutron yield agrees with theoretical expectation

Expected neutron yield can be calculated from the experimental measurements.

- ion temperature (gives thermonuclear reaction rate parameter[1])
- radial profile of the ion density
- neutron emission time
- plasma volume

$$Y_n = \int \frac{1}{2} n_D^2 \langle \sigma v \rangle \tau d x^3$$



Measured neutron yield is 10^5, agrees[2] with theoretical thermonuclear process with $T_i \approx 1.2$ keV.

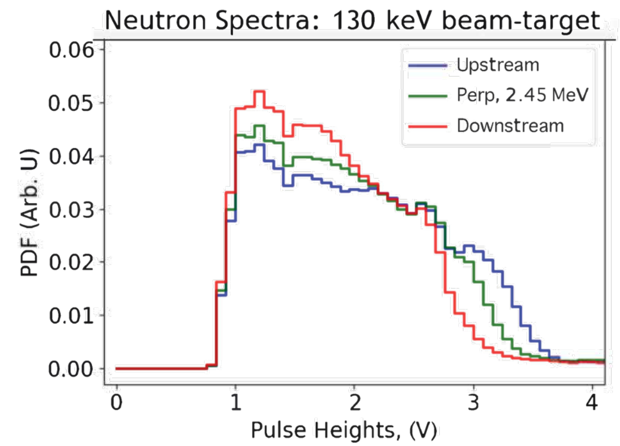
Spectroscopy indicated $T_i \approx 1.0 - 1.5$ keV.

[1]Bosch & Hale, NF (1992); [2]Zhang et al., PRL (2019)

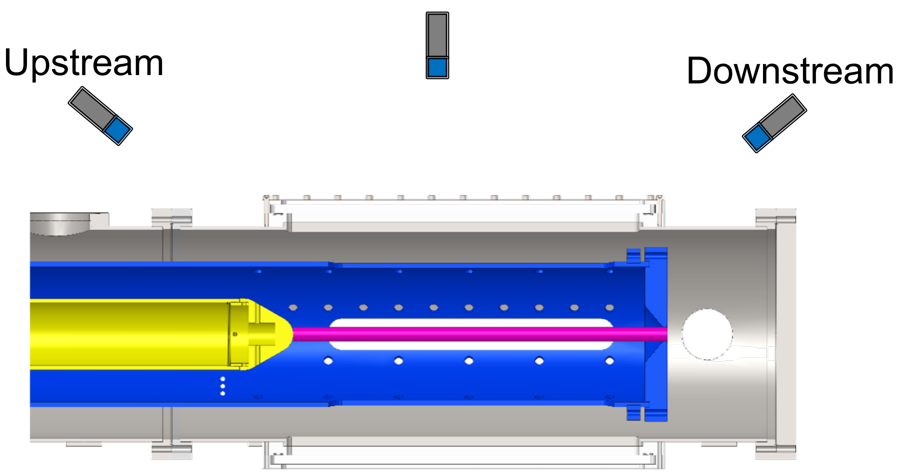
Neutron energy isotropy excludes D^+ beams >8 keV

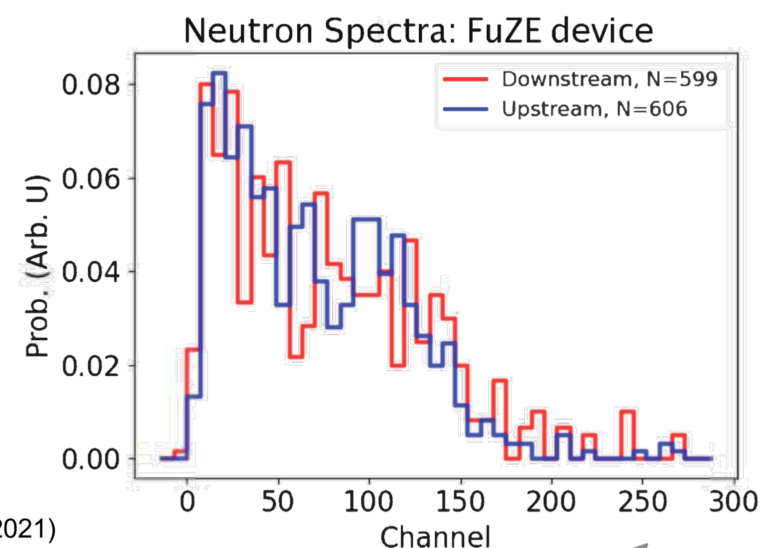
Neutron energy spectra are characterized from proton recoil signals of upstream and downstream plastic scintillator detectors. Maximum neutron energy is related to beam energy.

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



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[1] indicating fusion from a thermonuclear process.



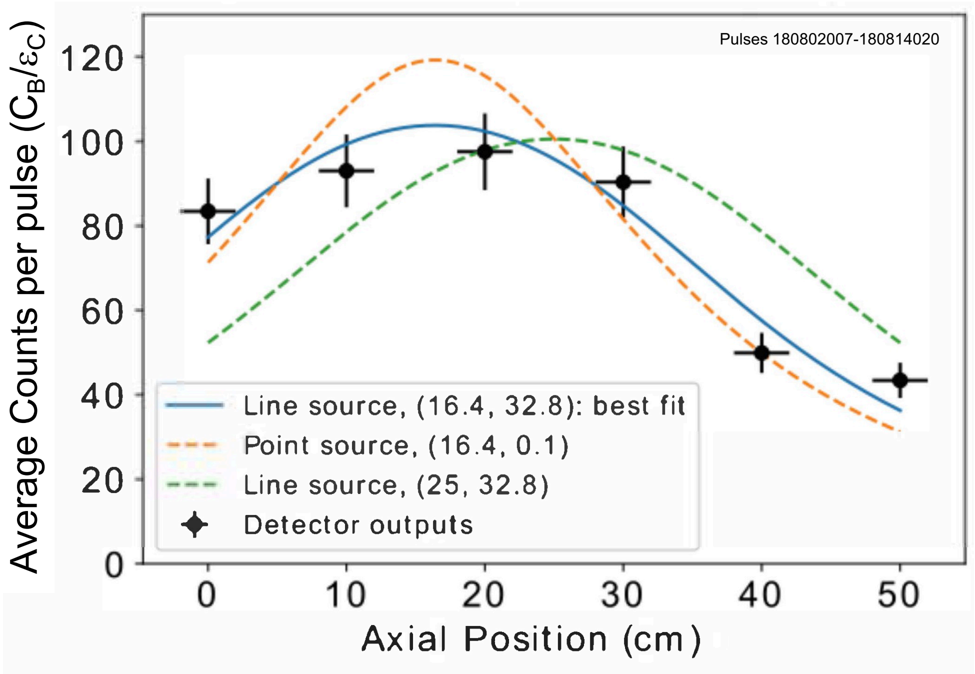


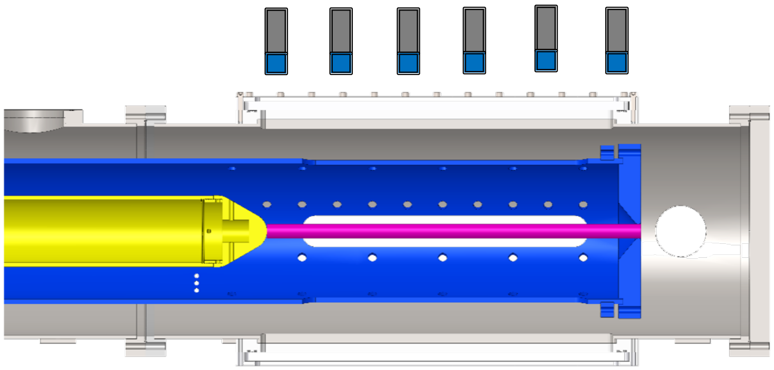
[1]Mitrani et al., PoP (2021)

Spatially-resolved measurements indicate line source

Determining the neutron emission volume[1] is accomplished by making measurements from multiple detectors at varying axial positions.

The data are fit to an analytical calculation for a uniform source of arbitrary length and center.





Least squares fit to the data gives a neutron emission geometry that is an extended line source:

32.8 cm length

16.4 cm centroid

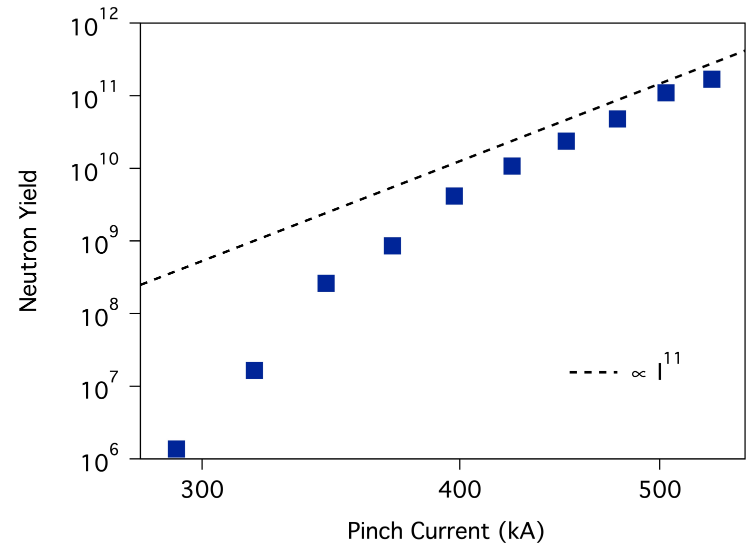
[1]Mitrani et al., NIMA (2019)

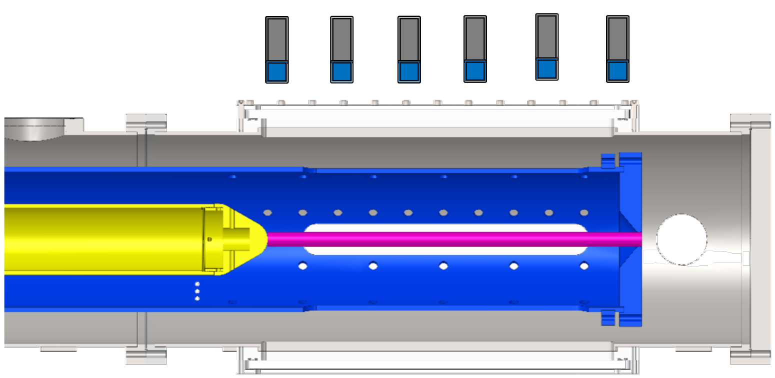
Neutron yield increases with pinch current

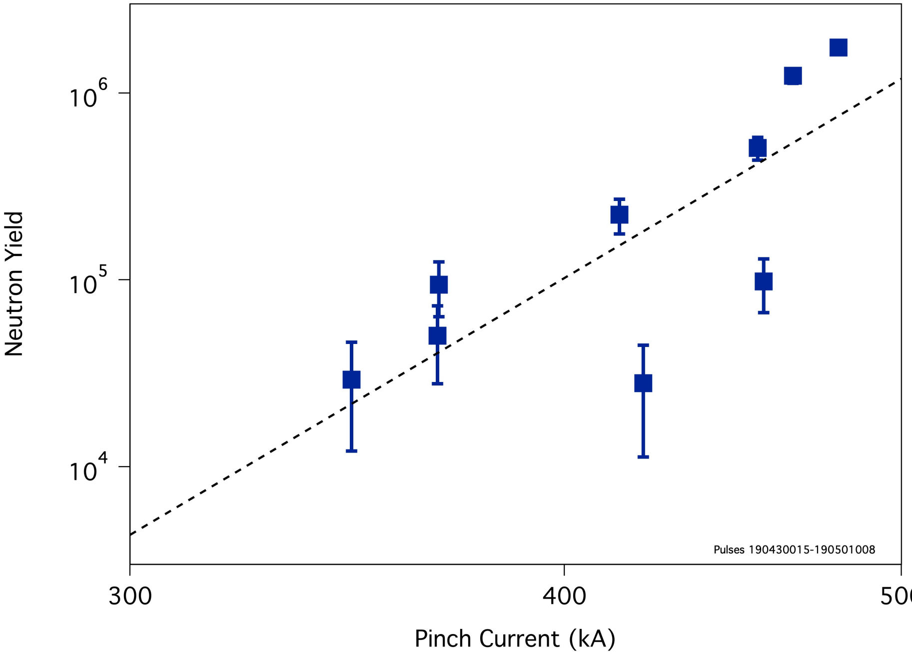
Adiabatic scaling relations[1] predict a neutron yield that strongly depends on Z-pinch current, $Y_n \propto I^{11}$.

Two-temperature MHD simulations of the SFS Z pinch support a similar scaling[2].

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







[1]Shumlak et al., FST (2012) , Shumlak et al., PoP (2017); [2]Shumlak, JAP (2020)

SFS Z pinch achieves fusion breakeven at 650 kA[1]

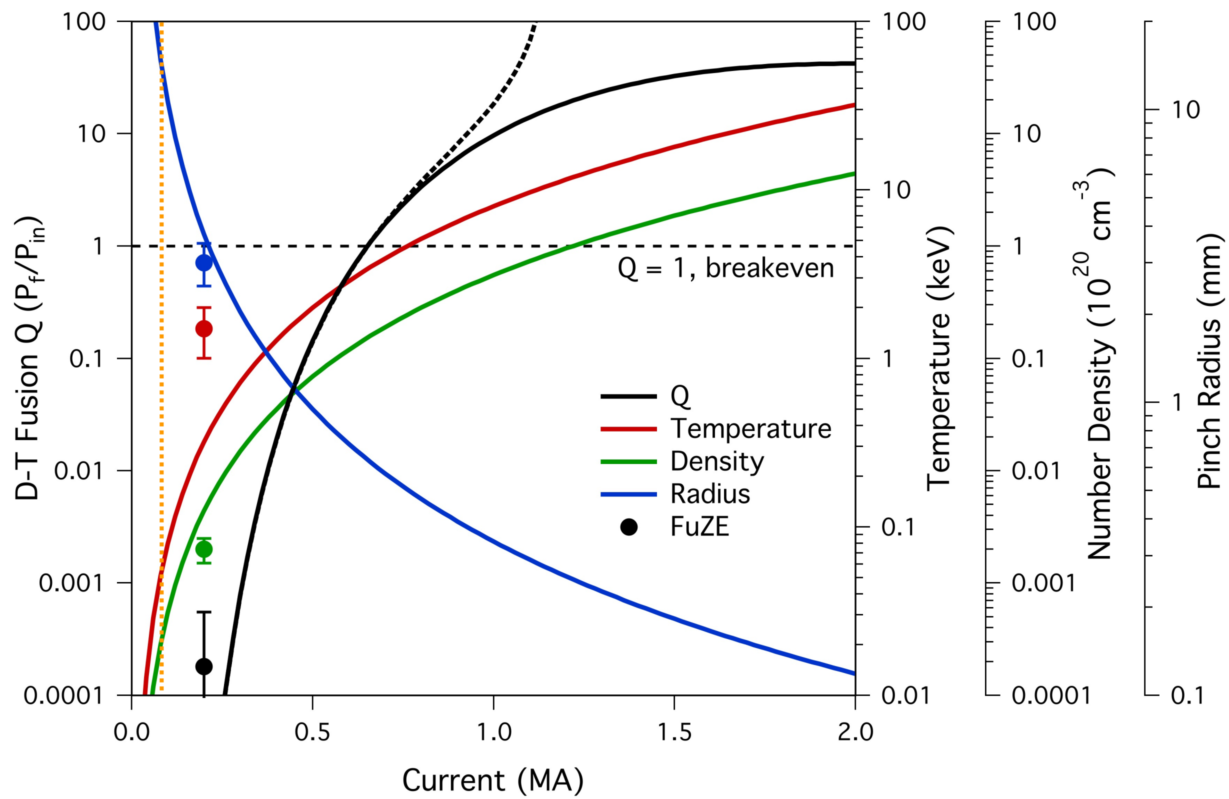
Starting with experimentally achieved plasma parameters at 50 kA, increasing the current with a fixed linear density rapidly reaches breakeven conditions. Fusion core remains compact[2] even at high Q. Large instantaneous power avails modest duty cycle operation.

Sample instantaneous conditions

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

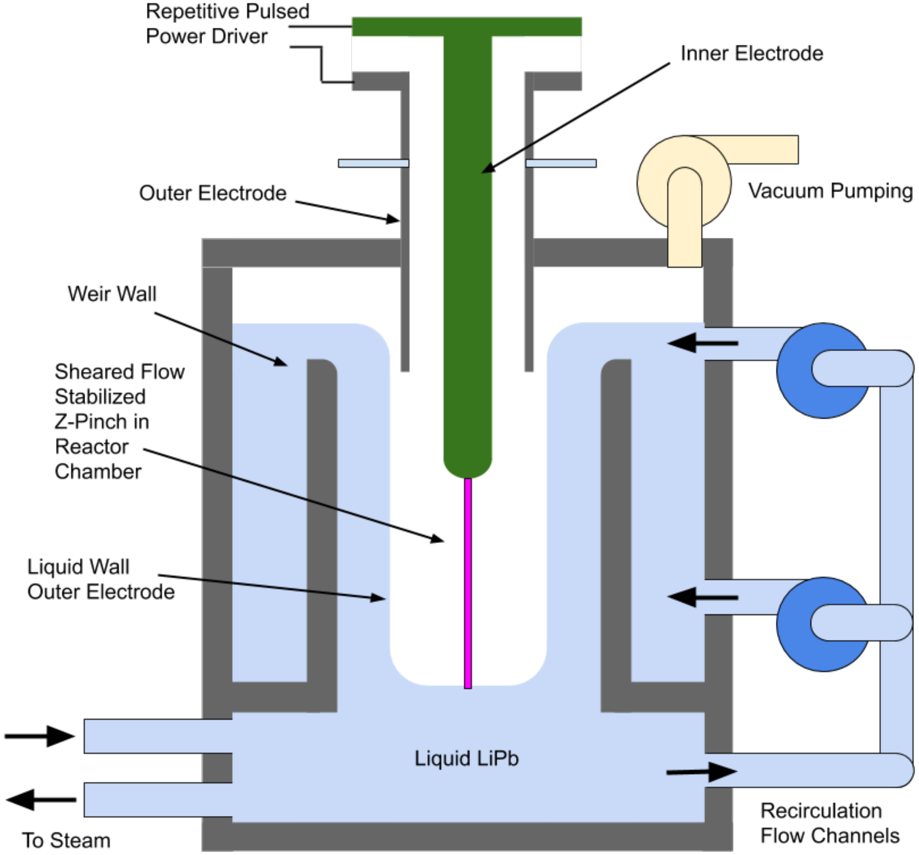
Adiabatic scaling results can be compared to experimental measurements obtained with higher currents, 200 kA:

- higher temperature
- lower density
- higher Q



[1]Shumlak et al., FST (2012) , Shumlak et al., PoP (2017), Shumlak, JAP (2020); [2]Forbes et al., FST (2019)

SFS Z-pinch reactor conceptual design is underway

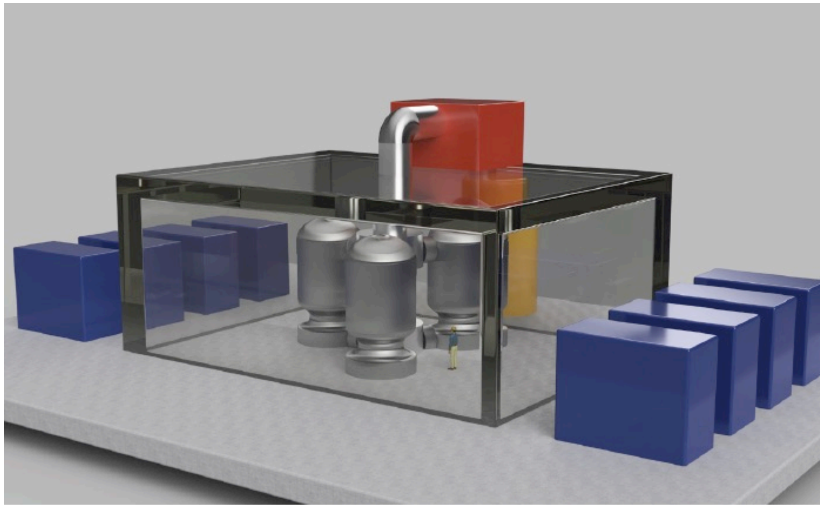


Individual SFS Z-Pinch Reactor Core (One of Several)

Liquid LiPb serves multiple functions:

- outer electrode
- heat transfer fluid
- biological shield
- tritium-breeding blanket

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



SFS Z-pinch reactor conceptual design

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

SFS Z pinch achieves D-^{3}He fusion Q=1 at 1.9 MA[1]

The D-^{3}He reaction results in ionized fusion products*, which are directed axially for thrust. Lower reactivity requires higher currents, but can still achieve high Q for a low-α (kg/kW) fusion space thruster[2] with high specific impulse $\approx 10^6$ s and high thrust $\approx 10^6$ N.

Sample instantaneous conditions

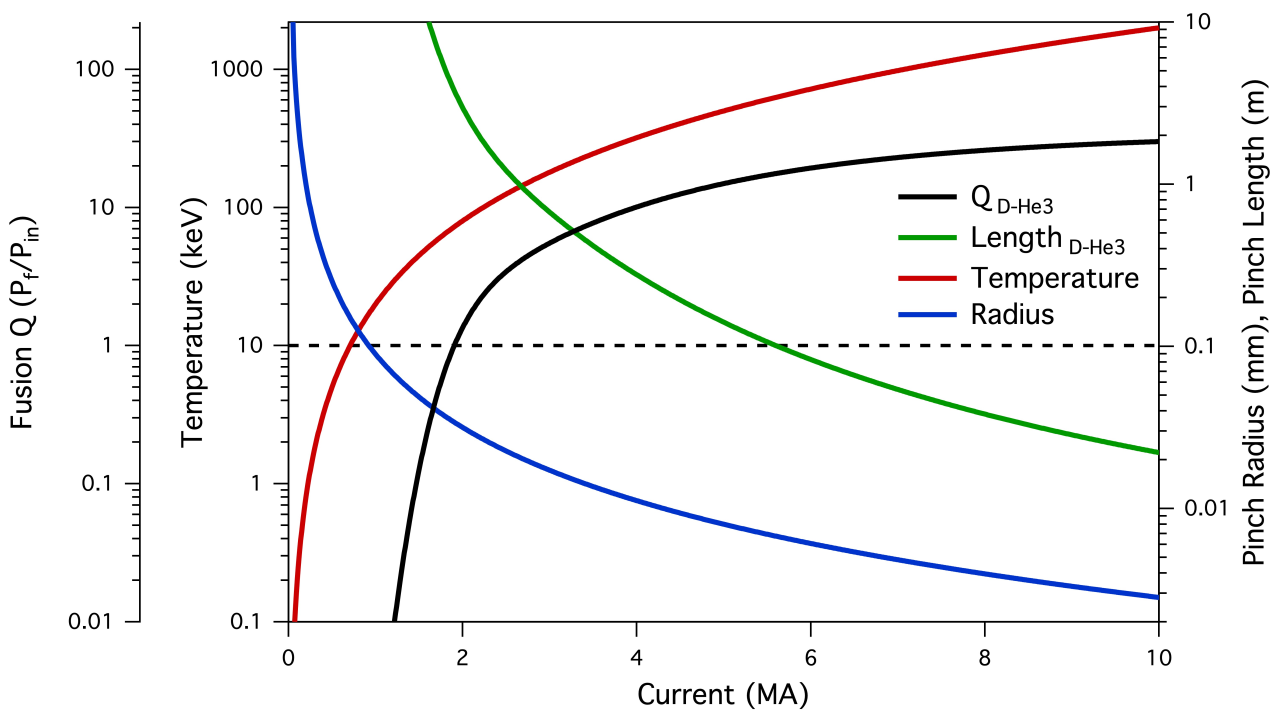
I_p = 4 MA	Q = 10
L = 30 cm	P_f = 13 TW

The SFS Z-pinch device leads naturally to a fusion space thruster by exhausting the highly energetic ionized fusion products as the propellant.

Fuel mixtures diluted with non-fusing gases provides throttle-ability.

The device would operate as a fusion-augmented MPD thruster.

*Note: D-D reactions will still produce neutrons.



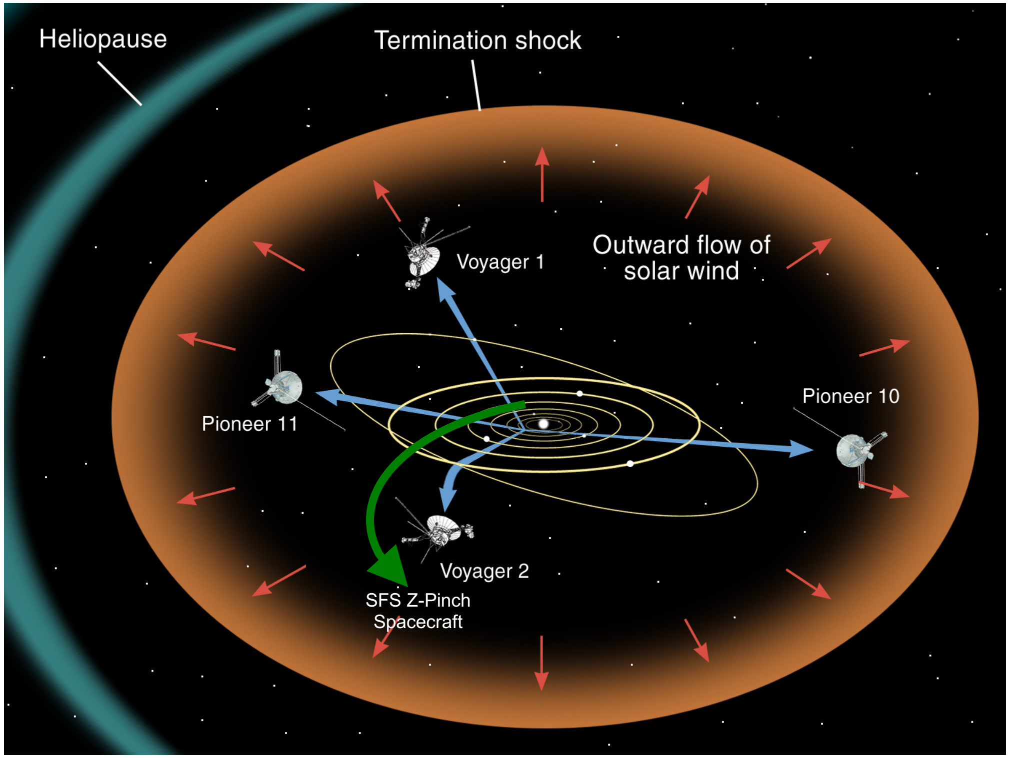
[1]Shumlak et al., FST (2012) , Shumlak et al., PoP (2017), Shumlak, JAP (2020); [2]Shumlak et al., AIAA 2006-4805

SFS Z-Pinch Fusion Space Propulsion System

Operating a 4 MA SFS Z-pinch fusion thruster at 1 Hz with a 0.001% duty cycle could deliver a 2,100 kg payload to a 125 AU orbit (interstellar space) in 9 years with a 70,000 kg spacecraft.

Advancing the SFS Z-pinch fusion space propulsion system requires:

- Maintaining plasma stability and control at higher pinch currents
- Developing electrode designs that withstand plasma contact
- Integrating the systems, which includes spacecraft modeling and mission architecture



Open Questions and Future Research

- Is compression in the sheared-flow-stabilized Z pinch an adiabatic process? Do shocks occur during the Z-pinch assembly process?
- Under what conditions will shear-flow stabilization breakdown?
- Will compressing the plasma to even smaller radii increase the drift speed faster than the thermal speed – potentially leading to drift or kinetic instabilities?
- What barriers may prevent the Z pinch from being scaled to even higher plasma parameters?
- Can flow shear replace or augment magnetic shear in other plasma confinement configurations? Is this already happening?
- Does flow shear play a role in astrophysical objects?

Summary & Conclusions

- The sheared-flow-stabilized 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 & 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: $a \approx 3$ mm, $n_e \approx 10^{17}$ cm^{-3}, $B_\theta \approx 10$ T, and $T_e \approx T_i \approx 1$ 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 and would translate to a low-α fusion space thruster.