The Sheared Flow Stabilized Z-Pinch

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Abstract

The stabilizing effect of a sheared axial flow is investigated in a Z-pinch in the ZaP Flow Z-pinch experiment at the University of Washington. Long-lived, Z-pinch plasmas are generated that are 100 cm long with a 1 cm radius and exhibit gross stability for many Alfvén transit times. Stability of the Z-pinch plasma is diagnosed with an azimuthal array of eight magnetic probes that measures the plasma's magnetic structure. Data from these probes are Fourier analyzed to determine the time-dependent evolution of the low order azimuthal modes (m = 1, 2, 3). Large magnetic fluctuations occur during pinch assembly, after which the amplitude and frequency of the magnetic fluctuations diminish. This stable behavior continues for an extended quiescent period. At the end of the quiescent period, the fluctuation levels again change character, increase in magnitude and frequency, and remain until the end of the plasma pulse. Plasma flow profiles are determined by measuring the Doppler shift of plasma impurity lines using an imaging spectrometer with an intensified CCD camera operated with a short gate. The spectrometer images 20 spatial chords through the plasma pinch at an oblique angle to the plasma axis to give the instantaneous, axial-velocity profile. Varying the trigger time between pulses provides a measure of the time-dependent evolution of the plasma flow profile throughout the plasma pulse. Experimental measurements show a sheared flow profile that is coincident with the low magnetic fluctuations during the quiescent period. The experimental flow shear exceeds the theoretical threshold during the quiescent period and the flow shear is lower than the theoretical threshold at other times. The observed plasma behavior and correlation between the sheared plasma flow and stability persists as injected neutral gas (and resulting plasma parameters) is varied over a wide range. The quiescent period is seen to increase with the amount of injected neutral gas. Computer simulations have been performed using experimentally observed plasma profiles and show a consistent sheared flow stabilization effect. A fusion reactor based on the sheared flow stabilized Z-pinch concept provides a compact linear system that can be operated as a continuously flowing system.

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Z-Pinch Equilibrium & Conventional Stabilization

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

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

is classically unstable to $m = 0$ sausage and $m = 1$ kink modes.

Conventional techniques to provide stability have drawbacks.

- <u>Profile Control</u> ➜ Stabilizes the sausage mode, but not the kink.

- <u>Close-Fitting Wall</u> ➜ Must be very close, $r_{wall}/a<1.2$.

- <u>Axial Magnetic Field</u> ➜ Limits the plasma current (and pressure) according to Kruskal-Shafranov limit and opens field lines.

Theoretical analysis suggests that a sheared flow can stabilize the modes in a pure Z-pinch provided $v_z' > 0.1\,kV_A$.*
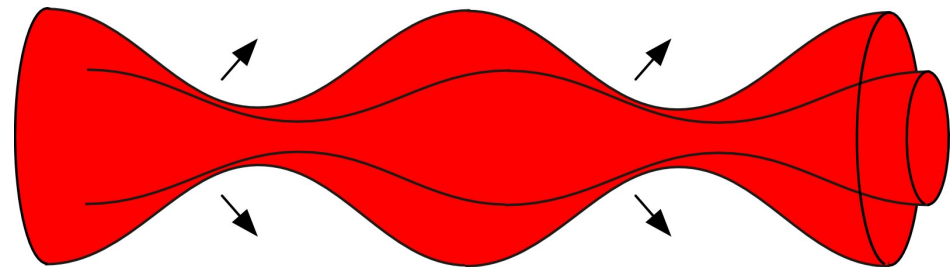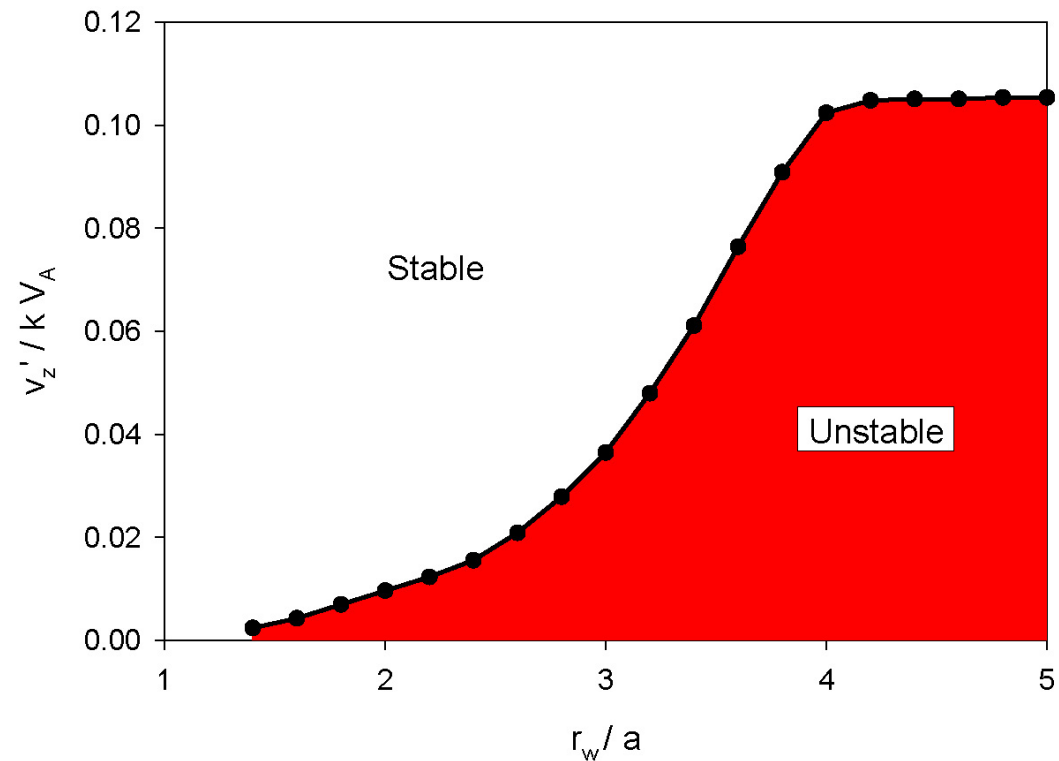
Stabilizing the Z-Pinch with Sheared Flow

Linear stability analysis is applied to a marginally stable Kadomtsev equilibrium,

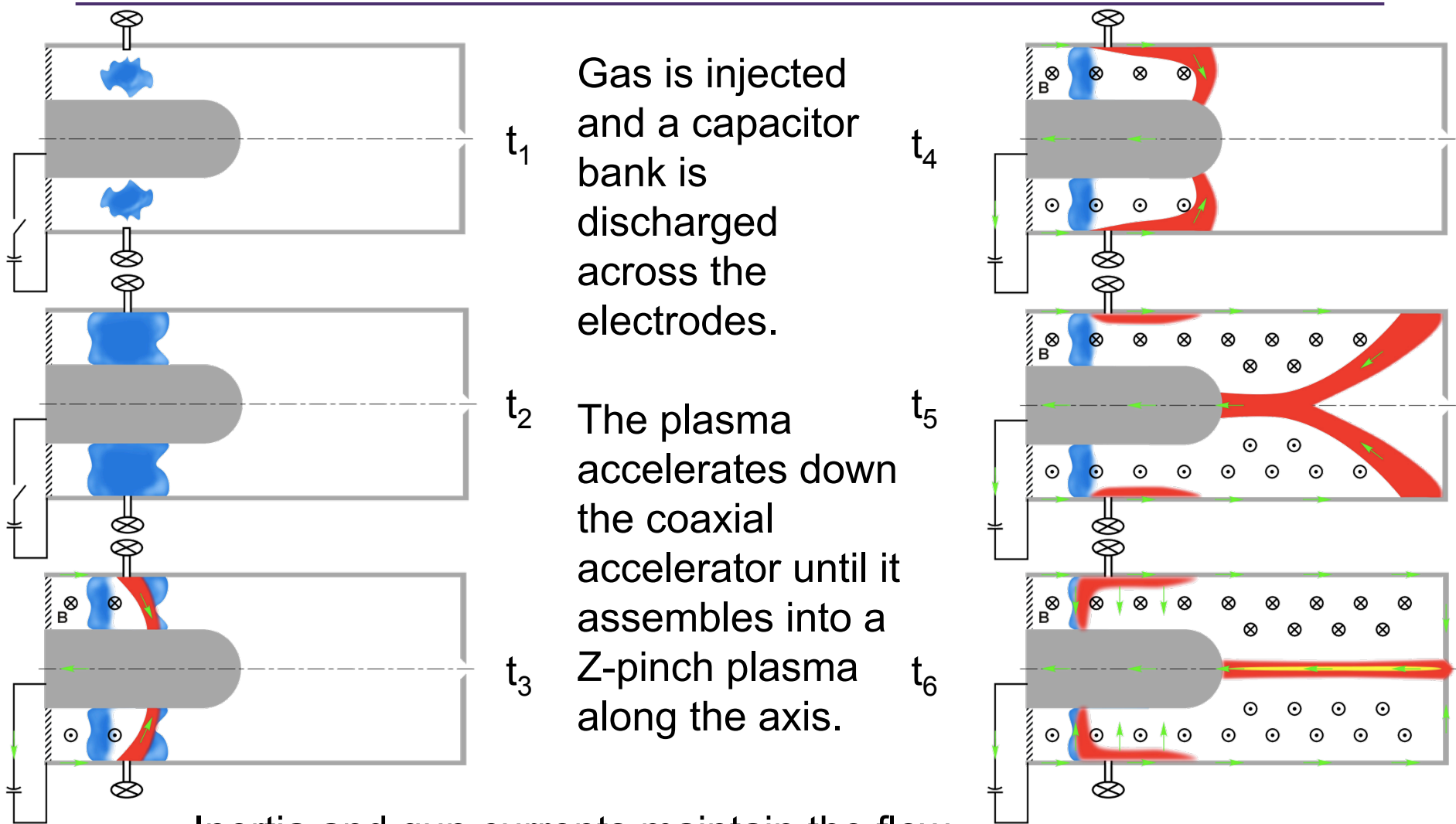$$-\frac{d \ln p}{d \ln r} = \frac{4\gamma}{2 + \gamma\beta}$$

In the no-wall limit, the Z-pinch is stabilized with a sheared flow,

$$\frac{d\mathsf{v}_z}{dr} \equiv \mathsf{v}'_z \geq 0.1\, kV_A.$$

The effect is a phase mixing at different radii in the pinch.

The ZaP Flow Z-Pinch Concept

t_1

t_2

t_3

t_4

t_5

t_6

Gas is injected and a capacitor bank is discharged across the electrodes.

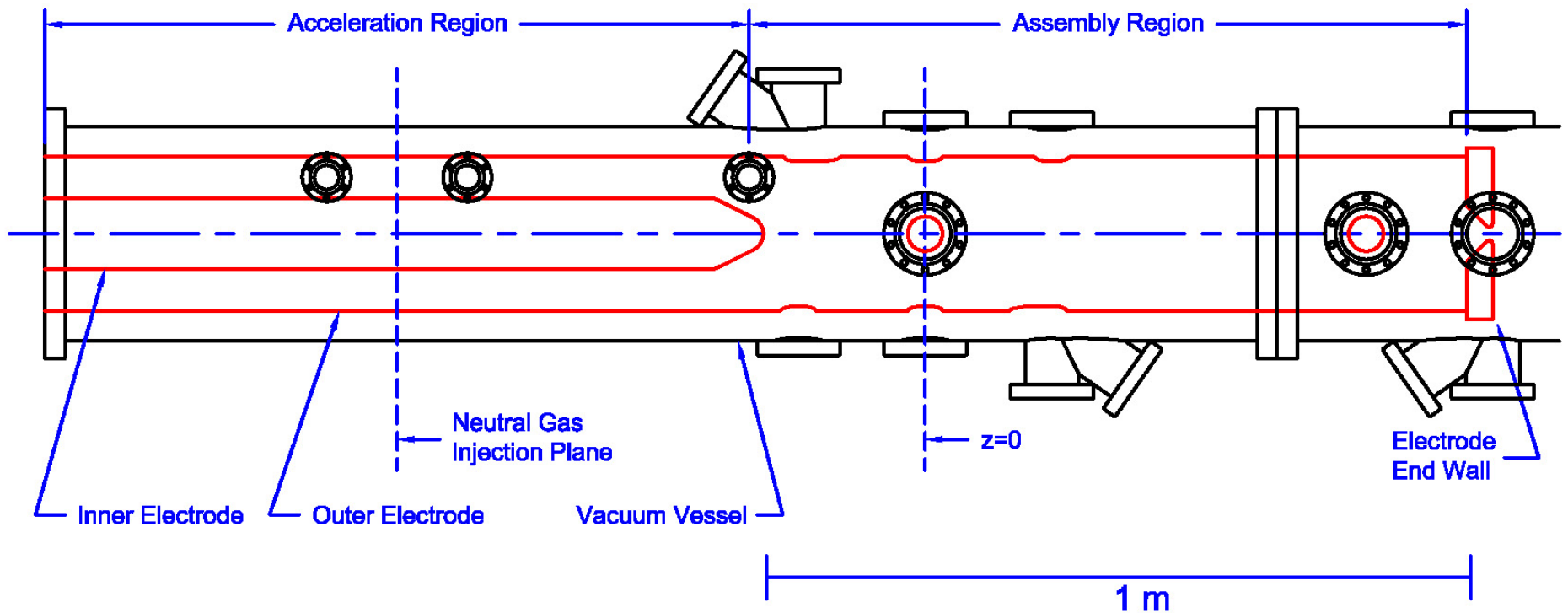The plasma accelerates down the coaxial accelerator until it assembles into a Z-pinch plasma along the axis.
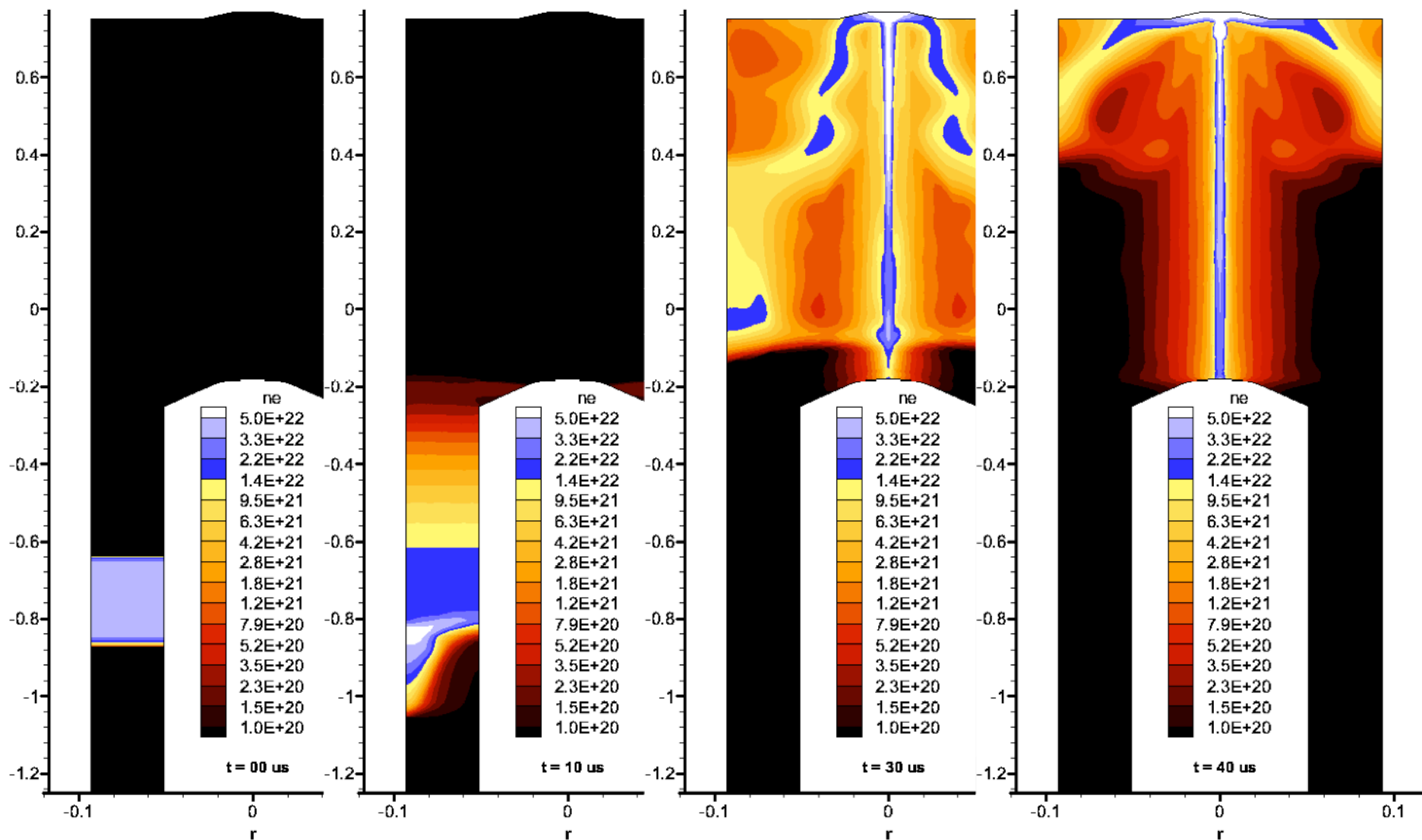
Inertia and gun currents maintain the flow until the accelerator plasma empties.

The ZaP Flow Z-Pinch Experiment

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

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Simulations show formation of a high density plasma.

Simulations with the MACH2 resistive, MHD code.

Operating Parameters

The ZaP operating parameters produce a high-temperature, high-density, long-lived pinch plasma.

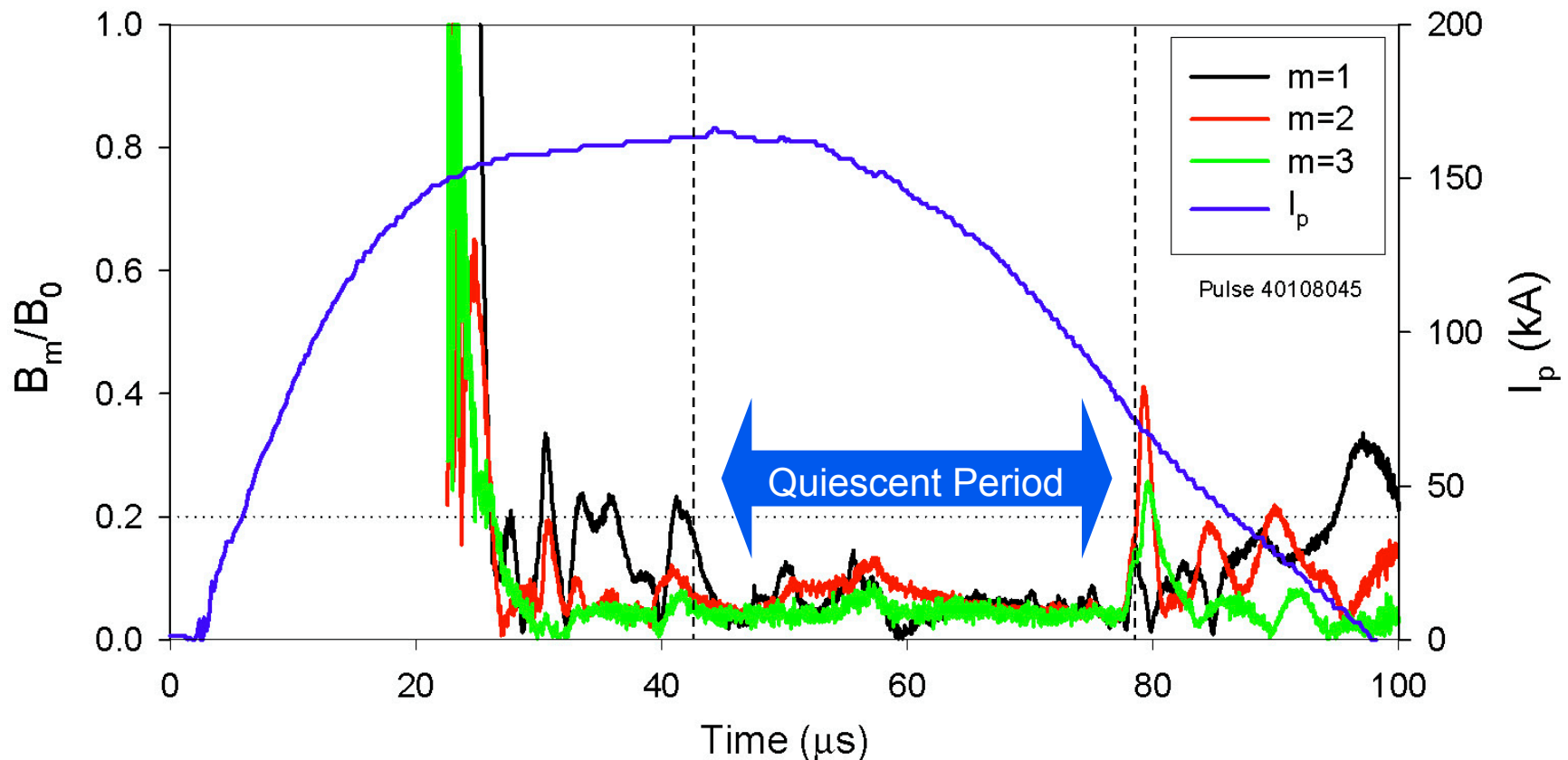| Entity	Value
Capacitor Bank Energy	144 kJ (max)
Charge Voltage	10 kV (max)
Peak Current	480 kA (max)
Plasma Pinch Radius	0.5 – 1 cm
Plasma Pinch Length	100 cm
Density	$10^{16} - 10^{17}$ cm^{-3}
Plasma Temperature ($T_e + T_i$)	150 – 250 eV
Plasma Lifetime	20 – 100 µs

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Diagnostics measure plasma flow & stability.

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

- Surface-mounted magnetic field probes ➔ Analyze magnetic fields, magnetic fluctuations, and plasma stability

- Fast framing camera with optical filters ➔ Qualitative measure of plasma structure

- Four-chord, visible He-Ne interferometer ➔ Measure plasma density profile

- 0.5 m imaging spectrometer with 20 input chords and an intensified CCD detector ➔ Measure plasma flow profile, Doppler broadening for ion temperature, Zeeman splitting for magnetic fields

- Thomson scattering system using ruby laser & Hibshman spectrometer ➔ Measure electron temperature

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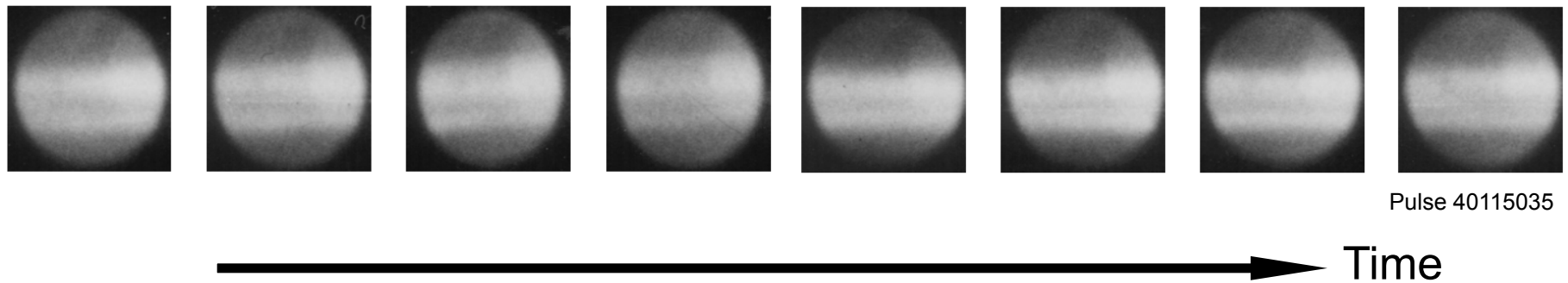WASHINGTON

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. (Flow time, $\tau_n \approx 20$ μs.)
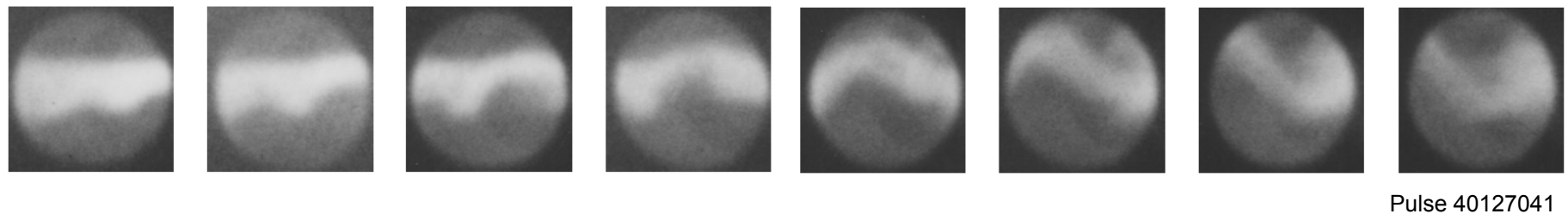

Pulse 40108045

Quiescent Period

*Shumlak et al., Phys. Rev. Lett. (2001)

Optical images show a stationary plasma pinch.*

Visible emission images are obtained at z = 0, every 200 ns, through a 2" hole with an Imacon fast-framing camera.

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

Pulse 40115035

Time

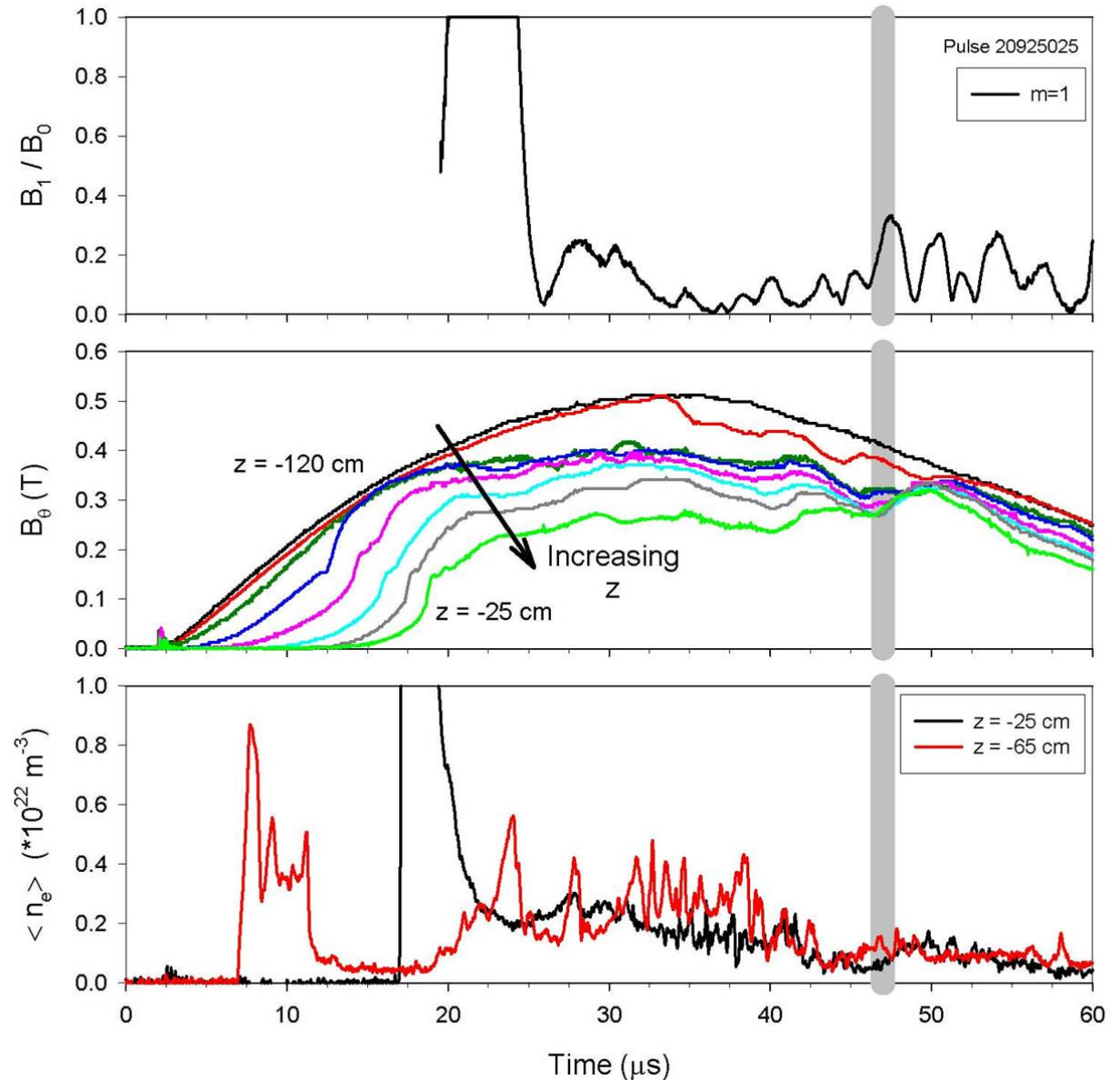Gross kink & sausage instabilities appear at the end of the quiescent period.

Pulse 40127041

*Shumlak et al., Nuc. Fusion (2009)
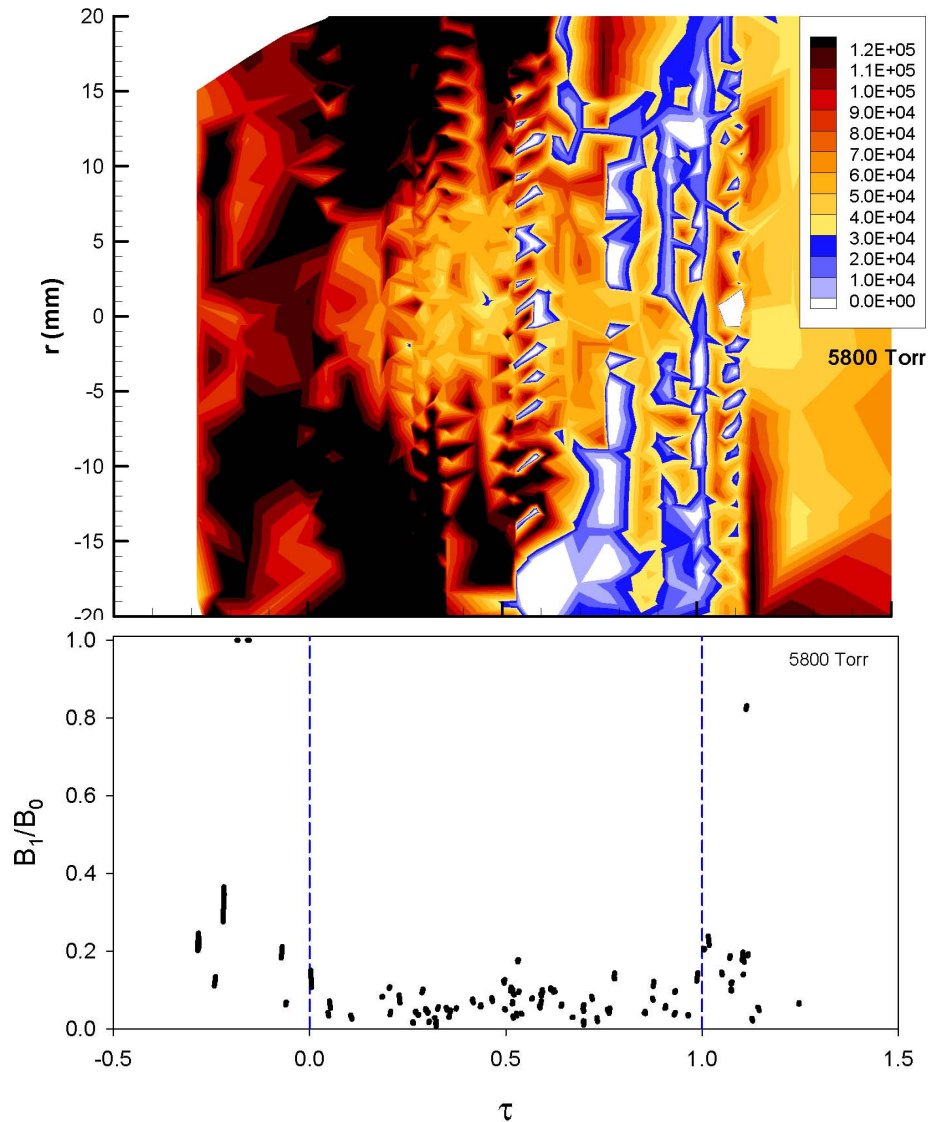
Plasma supply limits quiescent period length.

The end of the quiescent period is associated with a drop in the current and density in the acceleration region.

This suggests the plasma source has been exhausted.

It also suggests a means for extending the plasma lifetime.

Flow profile is correlated to plasma stability.*

$\tau < 0$, plasma assembly, the axial plasma velocity is high and uniform, $v_z' \approx 0\text{-}4 \times 10^6 \text{ s}^{-1}$.

$0 \leq \tau \leq 1$, quiescent period, the velocity profile is high at the plasma edge and lower at the axis, $v_z' \approx 7 - 12 \times 10^6 \text{ s}^{-1}$.

At a point during the quiescent period, the edge velocity slows so the velocity is higher at the axis than the edge.

$\tau > 1$, end of quiescent period, the plasma velocity profile is low & uniform, $v_z' \approx 0 - 6 \times 10^6 \text{ s}^{-1}$.

Theoretical growth time is ≈ 20 ns.

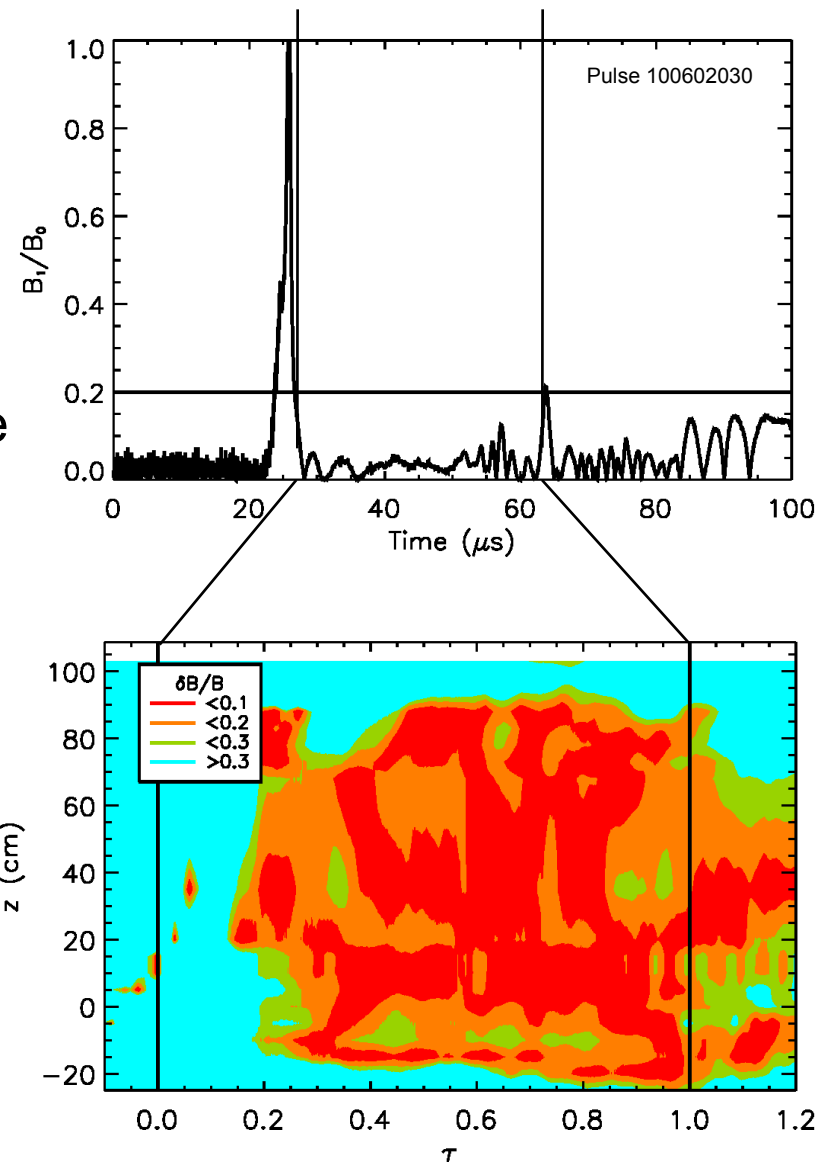Shear threshold is $\approx 5 \times 10^6 \text{ s}^{-1}$.

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Magnetic structure shows an axially uniform plasma.

During the quiescent period, the plasma exhibits a more axially uniform magnetic structure.

The axial array of magnetic field probes are used to determine the magnetic structure by looking at the time evolution of the field at 25 axial locations along the Z-pinch plasma. Regions of z < -15 cm and z > 90 cm show significant variation conjectured to be caused by the end effects. However, the region between -15 – 90 cm shows a largely uniform and axially coherent structure.

This evidence supports the existence of a long-lived, stable Z-pinch plasma with a long axial extent, 90 – 110 cm.

Pulse 100602030

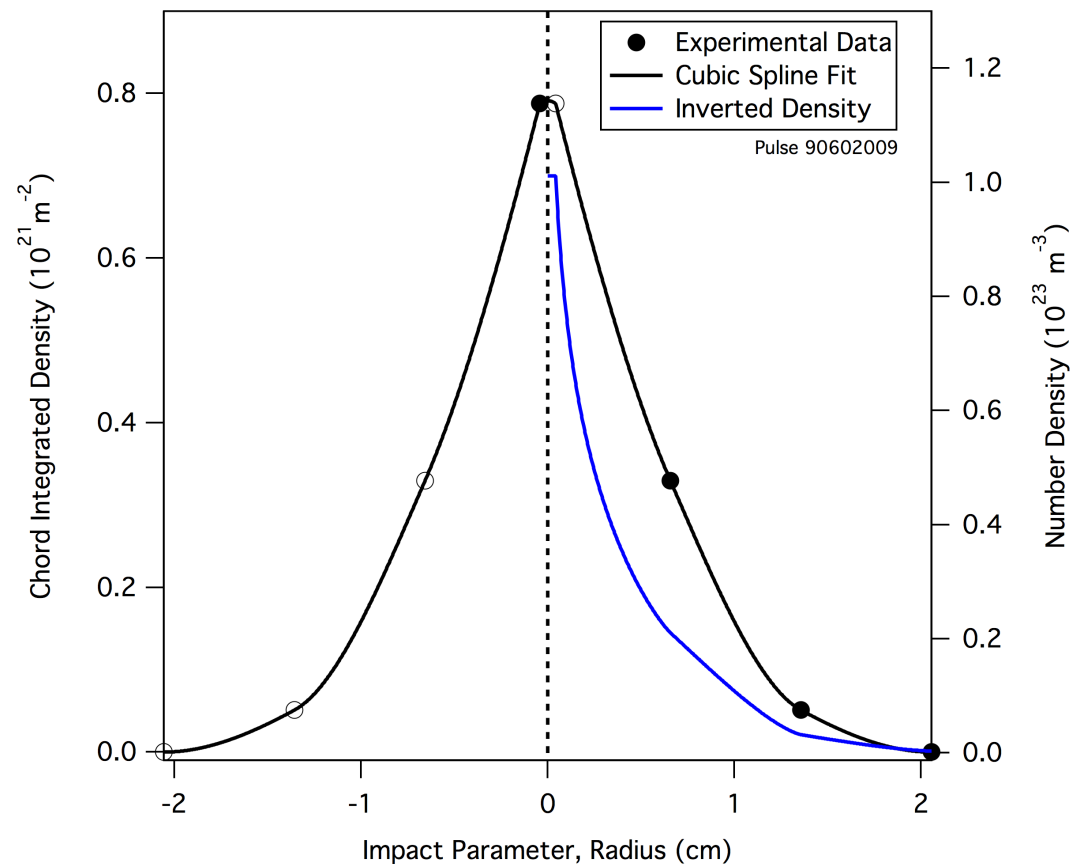# Density measurements show a strongly pinched plasma.

A four-chord interferometer provides chord-integrated density along parallel chords spaced through the plasma column. The data are interpolated assuming axisymmetry and inverted to provide the density profile.

Profiles show a peaked density with a low surrounding background.

Plasma radius, a, and core density, n_e, are determined.

Shown are a $\approx$ 1 cm, $n_e \approx 10^{23}$ m^{-3}.

Density data is used with radial force balance to confirm temperature and magnetic field measurements.

Pulse 90602009

Legend:
- ● Experimental Data
- — Cubic Spline Fit
- — Inverted Density

X-axis: Impact Parameter, Radius (cm)
Left Y-axis: Chord Integrated Density (10^{21} m^{-2})
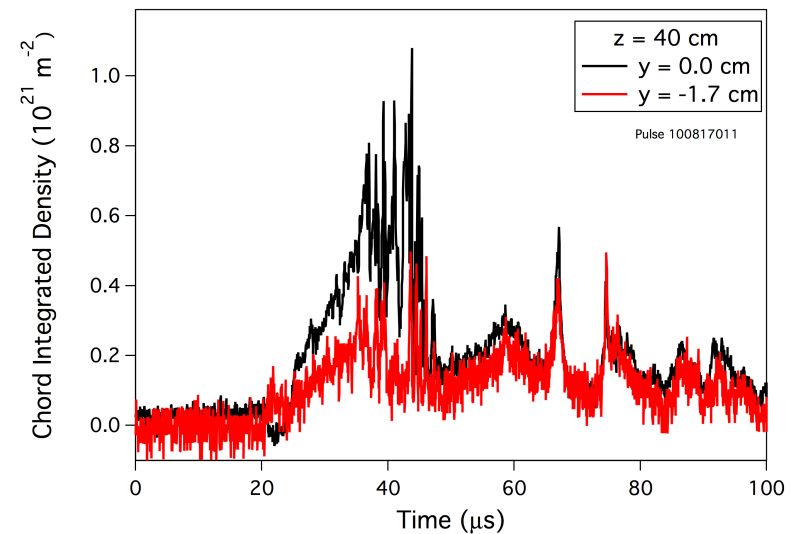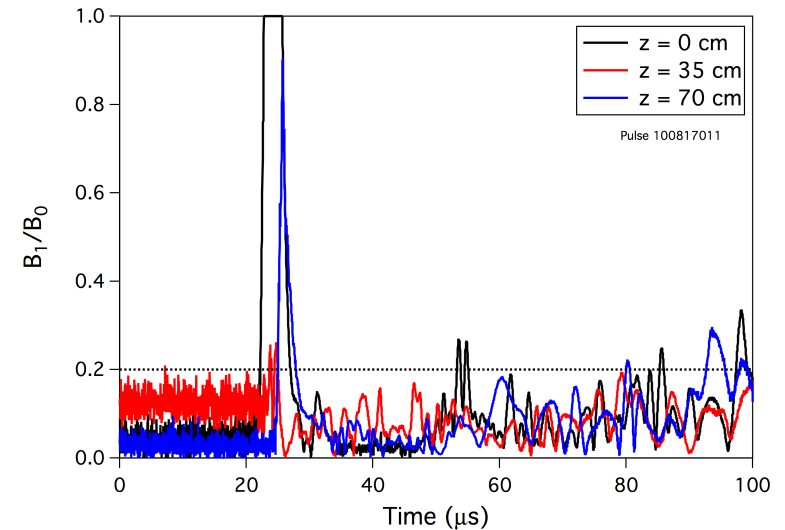Right Y-axis: Number Density (10^{23} m^{-3})

Pinched density is also measured 40 cm downstream.

Periods of low magnetic mode fluctuations exist for an extended duration at three axial locations along the pinch.

The quiescent periods are coincident for a significant portion of time. The plasma remains quiescent for many Alfvén and flow time scales.

Placing two of the four interferometer chords 40 cm downstream shows a peaked plasma density that is coincident with the quiescent period of the magnetic mode fluctuations.
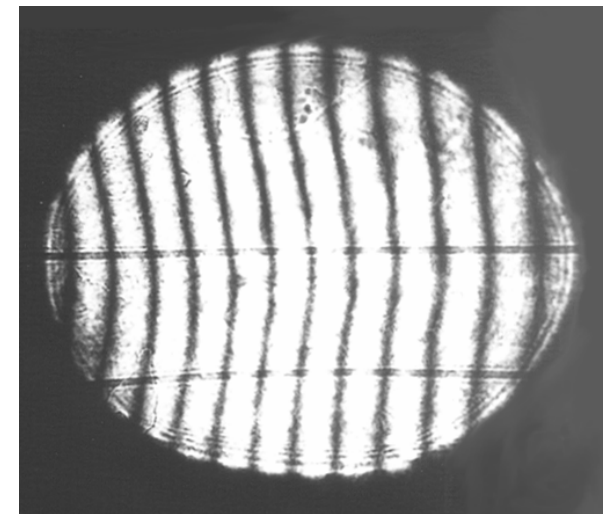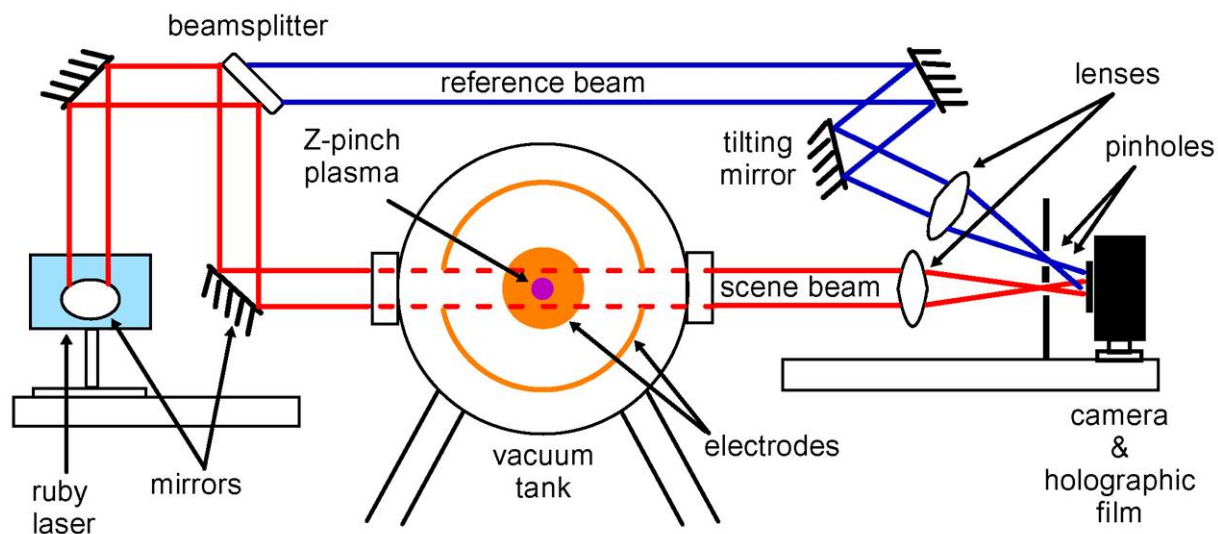
This evidence supports the existence of an axially extended Z-pinch plasma that is long-lived and stable.

Holographic interferometer provides density profiles.*

A holographic interferometer has been installed to measure chord-integrated density profiles. The system uses a pulsed ruby laser in a double-pass or single-pass configuration.

The holograms are reconstructed using a He-Ne laser. The chord-integrated data are deconvolved to determine the density profile.

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Holography measures a discrete plasma pinch.

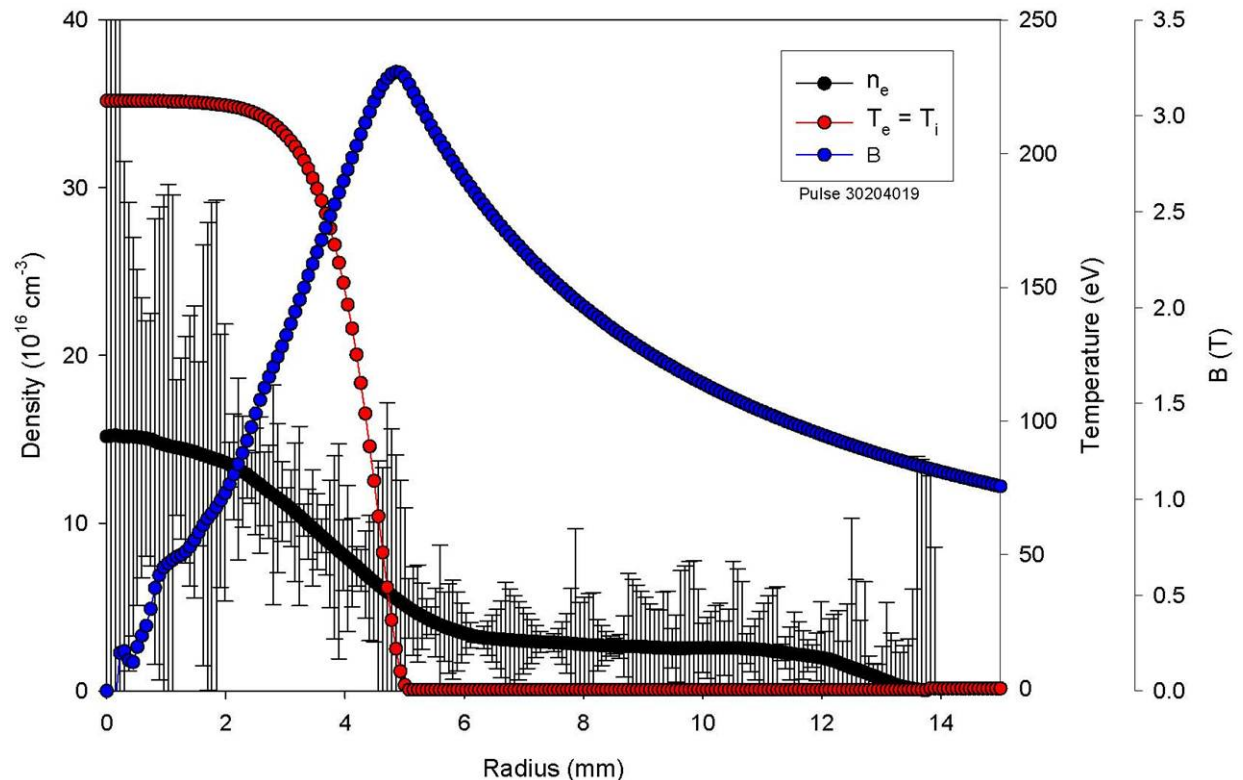During the quiescent period, the density profile shows a discrete plasma pinch.

Radius ≈ 6 mm.

Peak density ≈ 1.5×10^{17} cm^{-3}.

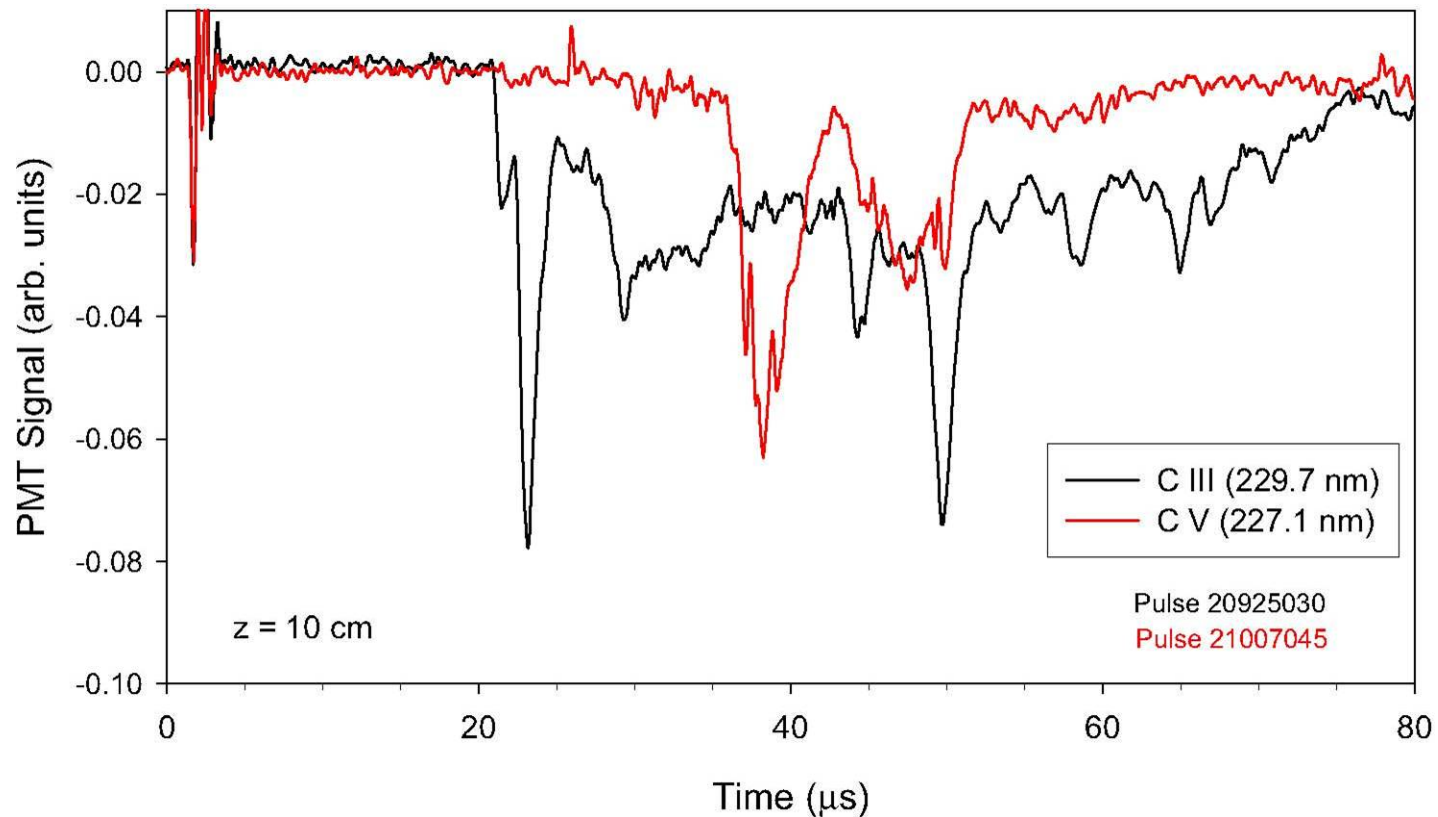As the quiescent period evolves, the profile looks similar but the magnitude decreases.

Temperature and magnetic field profiles are computed from the magnetic field measured at the wall and a power balance assuming thermal conduction and equilibrium force balance.

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Impurity line emission indicates heating.

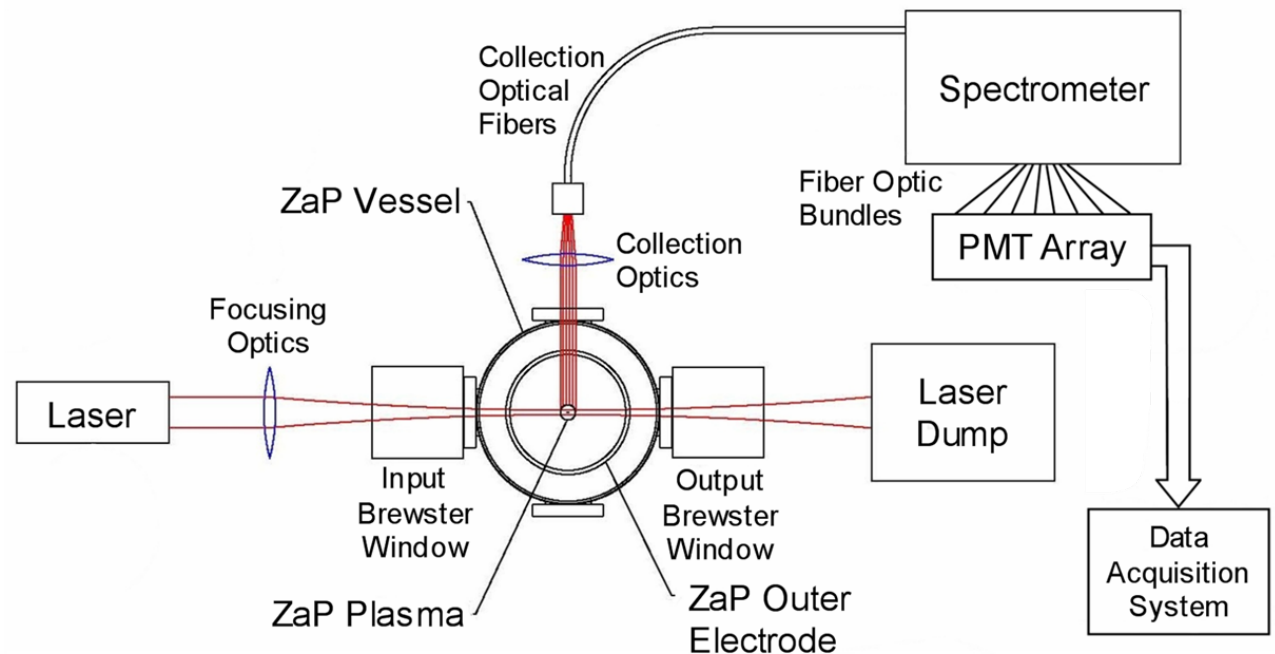Evolution of impurity line emission from C III at 229.7 nm and C V at 227.1 nm are recorded at z = 10 cm.

The appearance of the C V emission later in the quiescent period indicates a progressive heating of the plasma.

Thomson scattering system measures local T_e.

The experimental evidence from impurity ionization states, Doppler temperature broadening, and interferometry indicates a confined plasma pinch that progressively heats.
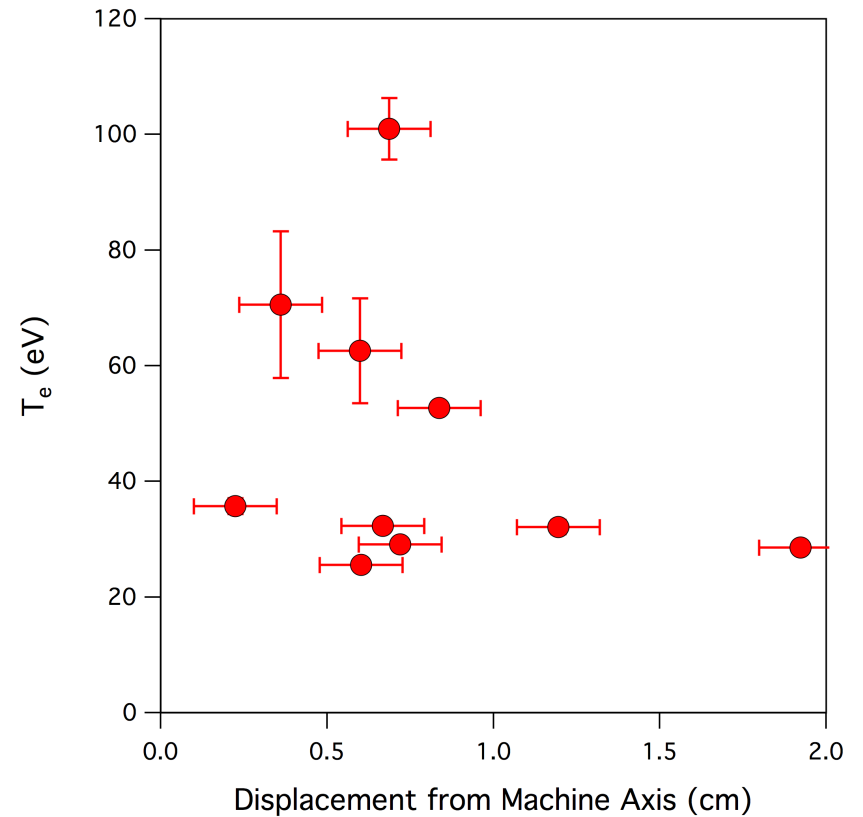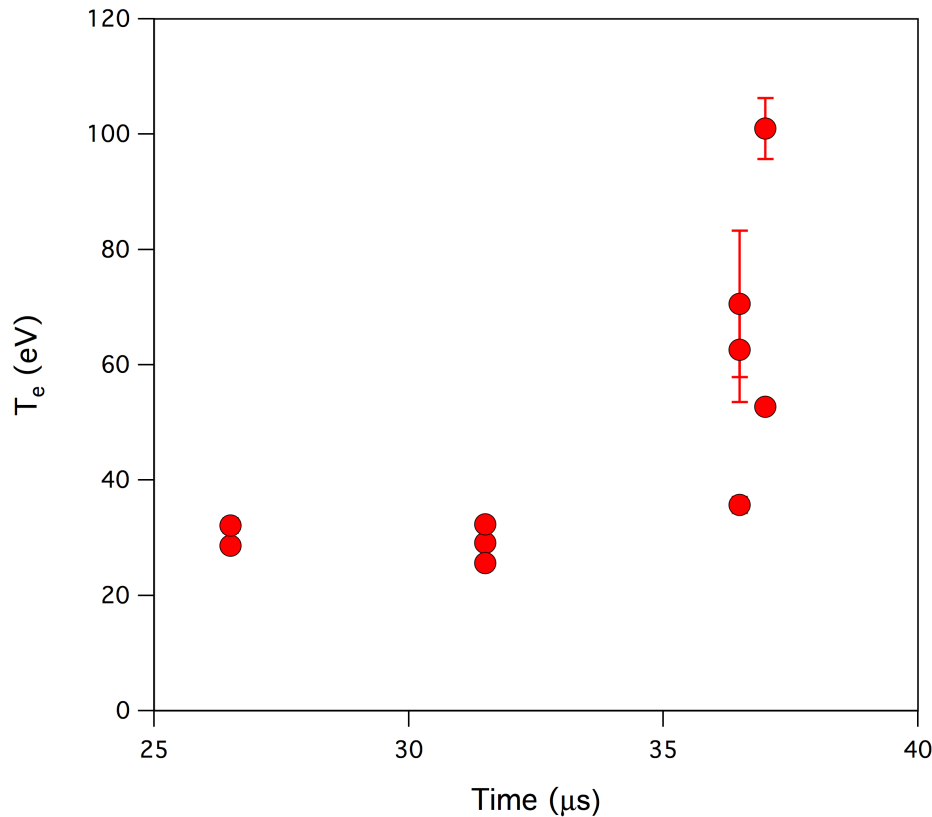
For more accurate, local temperature measurements a multipoint Thomson scattering system is designed, which uses a 1970 Korad ruby laser, the ZT-40 spectrometer, and an array of PMT detectors.

(Schematic is shown.)

Plasma temperature increases throughout pulse.

T_e evolution is found by adjusting ruby laser trigger time between pulses.

Data show a variation between 30 – 100 eV at the pinch axis.

Even during the quiescent period, the plasma can be displaced 0.5 cm away from the machine axis.

Z-pinch scales to HEDP and to fusion reactor plasmas.

Flow-stabilization theory of a Z-pinch shows no additional limitations as the plasma is scaled to different parameters. If the experimental results also hold, then the Z-pinch can be scaled from ZaP conditions to higher performance conditions by assuming adiabatic compression

$$\frac{d}{dt}\left(\frac{p}{n^\gamma}\right) = \frac{d}{dt}\left(\frac{(1+Z)kT}{n^{\gamma-1}}\right) = 0$$

and using the linear density is given by the Bennett relation:

$$(1+Z)NkT = \frac{\mu_0 I^2}{8\pi}, \quad \text{where} \quad N = \int_0^a n(r)2\pi r\,dr.$$

The resulting scaling relations are

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

$$\frac{p_2}{p_1} = \frac{n_2}{n_1}\frac{T_2}{T_1} = \left(\frac{I_2}{I_1}\right)^{\frac{2\gamma}{\gamma-1}}\left(\frac{N_1}{N_2}\right)^{\frac{\gamma}{\gamma-1}}$$

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

Flow Z-pinch can generate fusion reactor plasmas.

Analysis of the flow Z-pinch using the scaling laws, leads to a solution with reasonable size (length L and radius a) and high power.

Fusion power is given as

$$P_f = n_D n_T \langle \sigma v \rangle_{DT} E_{DT} \pi a^2 L = \frac{n^2}{4} \langle \sigma v \rangle_{DT} E_{DT} \pi a^2 L$$

Input power must be supplied to heat and compress the plasma, drive the flow, and replace radiative losses.

$$P_{th} = \frac{3}{2} \sum_\alpha \dot{n}_\alpha k T_\alpha \pi a^2 L \quad \text{for } \alpha = D, T, e, e$$

$$= 3\dot{n}kT\pi a^2 L = 3nkTv_z \pi a^2$$

$$P_{flow} = \frac{1}{2}\dot{m}v_z^2 = \frac{M_D + M_T}{4}\dot{n}v_z^2 \pi a^2 L = \frac{M_D + M_T}{4} n v_z^3 \pi a^2$$

$$P_{rad} = C n_e T_e^{\frac{1}{2}} \sum_i Z^2 n_i = 3.4 \times 10^{-38} n^2_{m^{-3}} T^{\frac{1}{2}}_{eV}$$

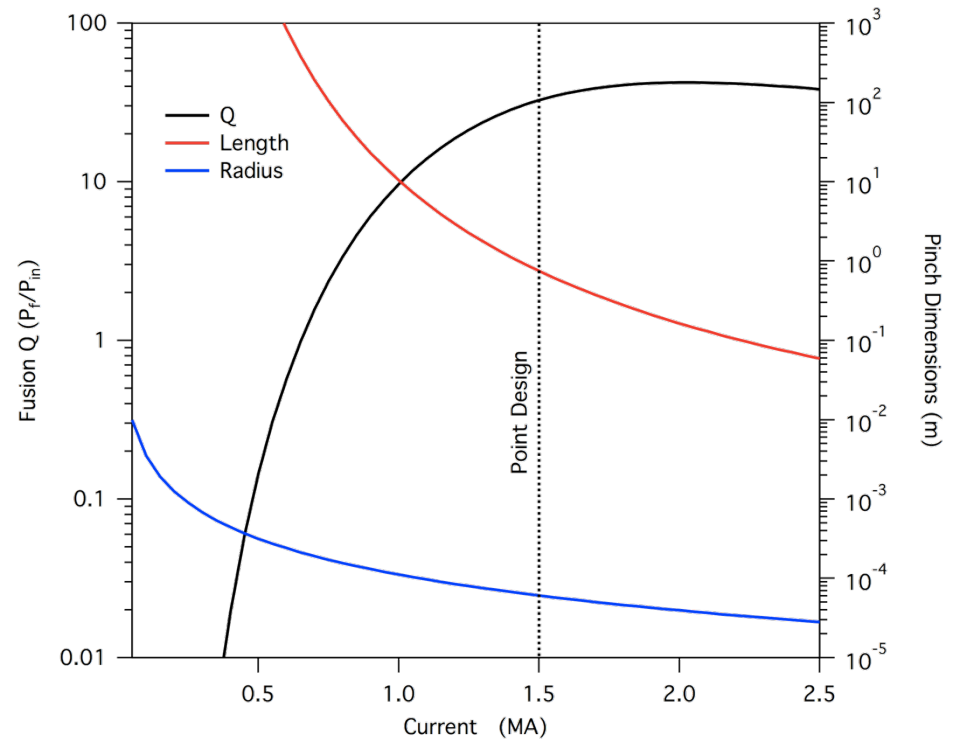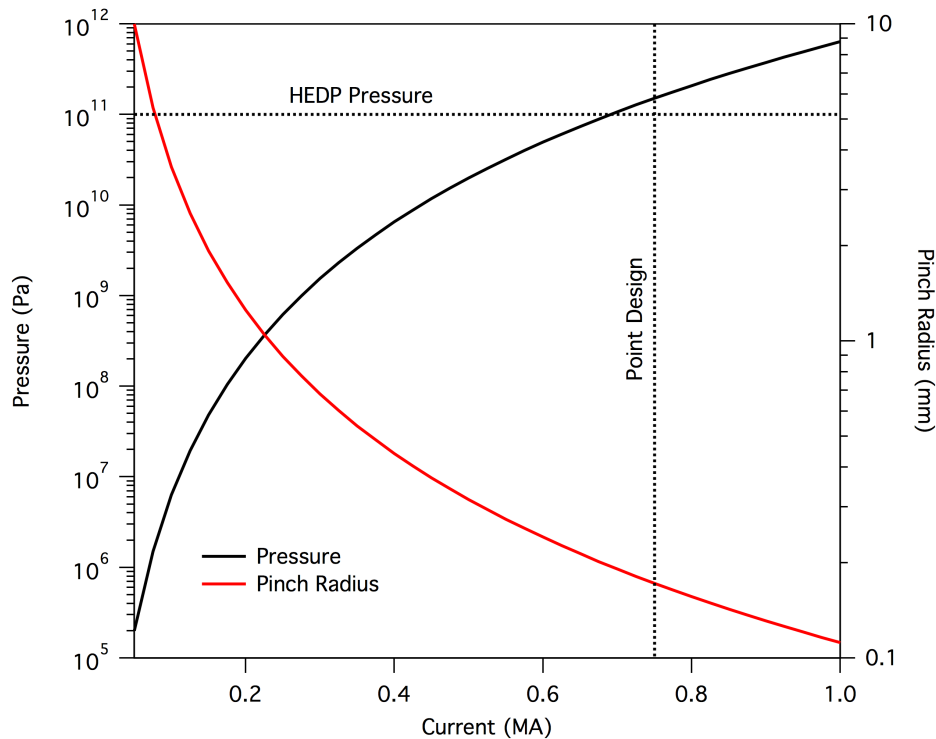# Z-Pinch scales to HEDP and to fusion reactor plasmas.

Starting with ZaP plasma parameters, the plasma can be scaled by increasing the current with a fixed linear density. Fusion gain Q now includes flow power.

$$Q \equiv \frac{P_f}{P_{th} + P_{flow} + P_{rad}}$$

I_p = 750 kA	T = 4.5 keV
p = 0.3 TPa	a = 170 μm

I_p = 1.5 MA	T = 22.5 keV
L = 75 cm	a = 61 μm
Q = 33	P_f = 4.6 TW

Summary & Conclusions

- The ZaP project is producing Z-pinch plasmas that exhibit gross stability during an extended quiescent period.

- The quiescent period is coincident with a sheared plasma flow.

- Thomson scattering measurements indicate a high-temperature Z-pinch plasma.

- Quiescent period is observed at several axial locations simultaneously.

- A peak density profile is measured at axial locations separated by 40 cm.

- Magnetic structure is axially uniform during the quiescent period.

- Experimental evidence supports the existence of axially extended Z-pinch plasma that is long-lived and stable.

- Scaling relations demonstrate that the flow-stabilized Z-pinch can be scaled to HEDP parameters and to fusion reactor conditions with reasonable parameters.

For reprints of ZaP posters, visit www.aa.washington.edu/research/ZaP/publications.html

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