Evidence for Flow-Shear Stabilization of MHD Modes in a Z-pinch

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Background & Overview

— Newton, Marshall, and Henins (1968) saw gross stability of a plasma column, produced by an *un*-magnetized Marshall gun
— Shumlak and Hartman (1995) calculated that sheared-flow can stabilize the kink mode in a Z-pinch
— The ZaP flow Z-Pinch experiment began in 1998:

- ZaP shows global stability for *thousands* of MHD growth times
  - Stability is correlated with sheared flow
  - Loss of stability is correlated with loss of the flowing plasma source
- This stability behavior is observed over a large range of experimental conditions and configurations

Outline

1. Introduction
   - Z-Pinch Equilibrium and Stability
   - Flow Z-Pinch Concept
2. ZaP Experiment
   - Experimental Results: 5 cm radius inner electrode
   - Experimental Results: 7.5 cm radius inner electrode
   - Flow-shear Stabilization Simulations
3. Summary
   - Summary of Results
   - Future Plans

Conventional Z-Pinch Stabilization Techniques Limit Performance

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

$$\frac{B_\theta}{\mu_0 r}\frac{d\left(rB_\theta\right)}{dr}+\frac{dp}{dr}=0$$

$\Rightarrow$ Classically unstable to m=0 sausage and m=1 kink modes

Conventional techniques to provide stability have drawbacks:

- Profile Control: $\rightarrow$ Stabilizes sausage, not kink
- Close-fitting Wall: $r_{\text{wall}}/a < 1.2 \rightarrow$ Plasma-wall interactions
- Axial Magnetic Field: $\rightarrow$ Kruskal-Shafranov criterion limits plasma current (and pressure) *and* opens field lines

Linear Stability Analysis Shows Sheared-Flow Stabilization of the *m*=1 Kink

Shumlak and Hartman, *Phys. Rev. Lett.* 75, 3285 (1995)

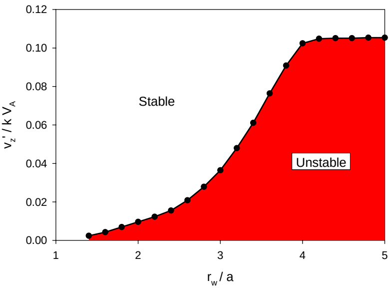
Linear stability analysis is applied to a marginally stable m=0 Kadomtsev equilibrium,

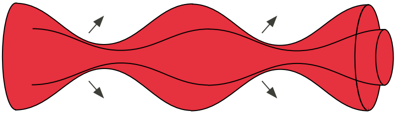
$$-\frac{d \ln p}{d \ln r} = \frac{4\gamma}{2+\gamma\beta}$$

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

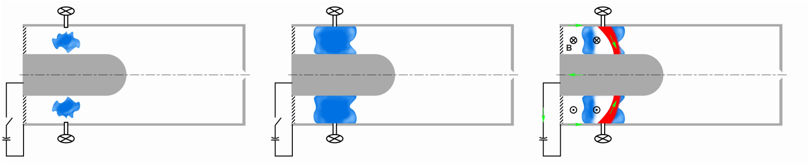
$$\frac{dv_z}{dr} \equiv v_z' \geq 0.1 k V_A$$

⇒ Phase mixing at different radii



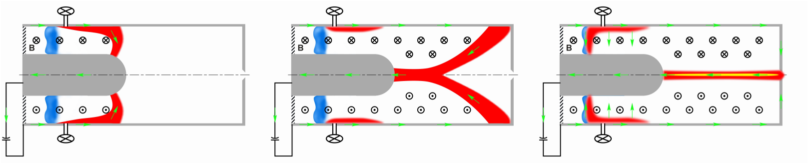


The ZaP Flow Z-Pinch Concept



- Gas is injected and allowed to expand in the coaxial accelerator region
- A capacitor bank is discharged between the electrodes, forming and accelerating a plasma annulus

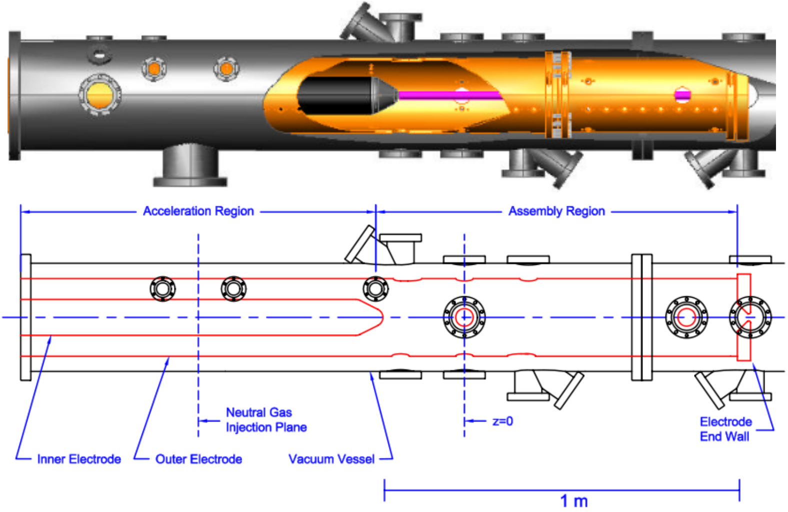
The ZaP Flow Z-Pinch Concept (cont.)



- Plasma accelerates down the coaxial accelerator, assembling into a Z-pinch plasma
- Inertia and gun currents maintain the flow until the accelerator plasma empties

A Z-Pinch with an Embedded Sheared Axial Flow

ZaP couples a coaxial accelerator with a pinch assembly region



Operating Parameters

ZaP produces a high-temperature, high-density, long-lived Z-pinch plasma

Parameter	Symbol	Value	
Inner Electrode Radius	R_{inner}	5 or 7.5	cm
Outer Electrode Radius	R_{outer}	10	cm
Assembly Region Length	Z_{assembly}	100	cm
Charge Voltage	V_{bank}	5 – 10	kV
Capacitor Bank Energy	W_{bank}	18 – 72	kJ
Peak Plasma Current	I_p	250 – 400	kA
Gap Voltage (sustainment)	V_{gap}	1 – 2	kV
Pinch Radius	a	0.5 – 1	cm
Average Density	$\langle n_e \rangle$	10^{16}–10^{17}	cm^{-3}
Total Temperature	$T_e + T_i$	150 – 250	eV
Quiescent Period	τ_Q	20 – 80	μs

Working gas is hydrogen (or with CH_4 dopant)

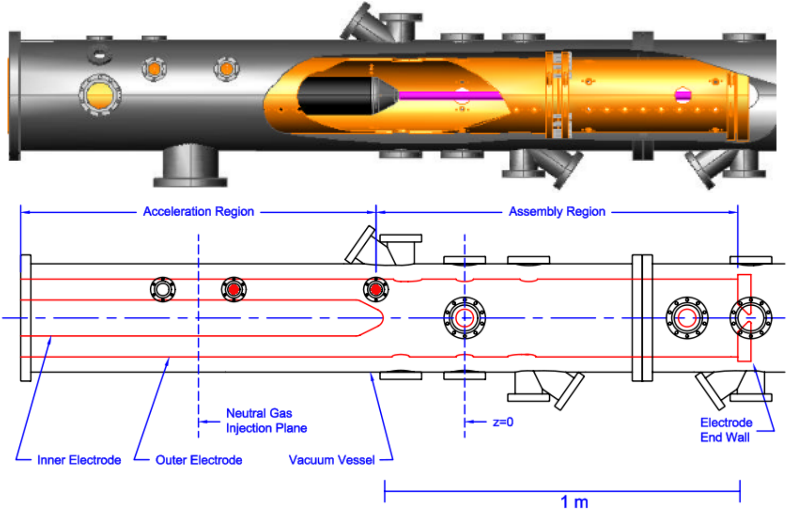
Overview of ZaP Diagnostics

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

- Surface-mounted magnetic field probes
  - Analyze B_θ, $\tilde{B}$, mode structure, and plasma stability
- Fast-framing Imacon camera with optical filters
- Four-chord, visible HeNe interferometer
  - Measure $n_e(r)$ and/or $n_e(z)$ as a function of time
- 0.5-m imaging spectrometer with 20 input chords and an intensified CCD detector
  - Measure single-time Doppler $v_z(r)$ and $T_i(r)$
- Thomson scattering system using ruby laser and Hibshman spectrometer
  - Measure single-point, single-time T_e and n_e

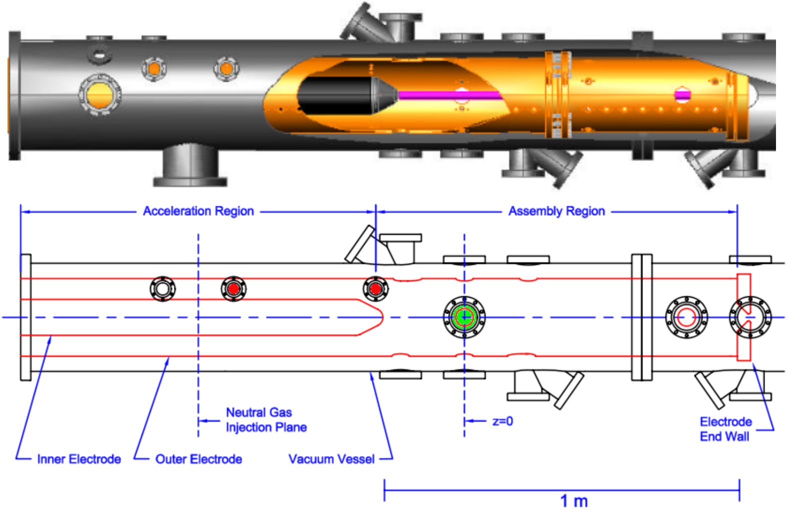
A Z-Pinch with an Embedded Sheared Axial Flow

Accelerator interferometer locations



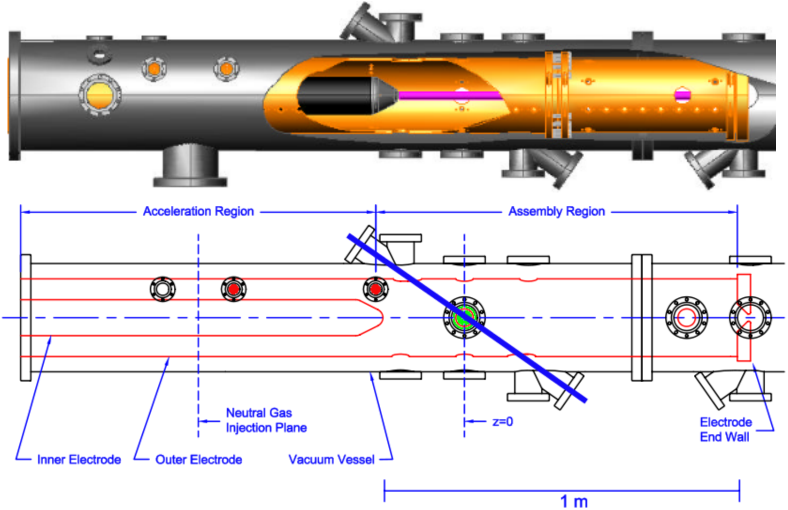
A Z-Pinch with an Embedded Sheared Axial Flow

Accelerator and Z=0 interferometer locations

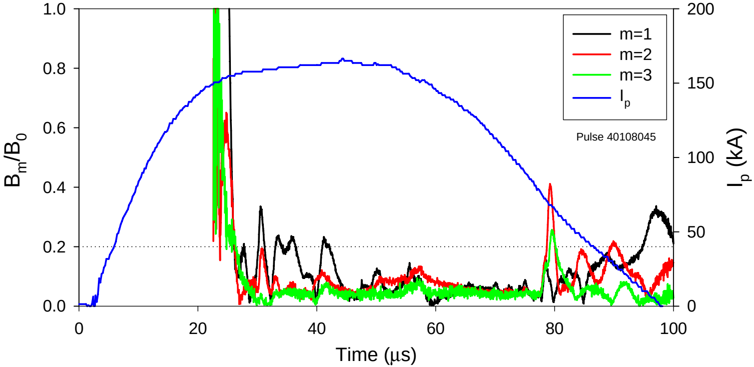


A Z-Pinch with an Embedded Sheared Axial Flow

Accelerator and Z=0 interferometer locations, and ICCD path



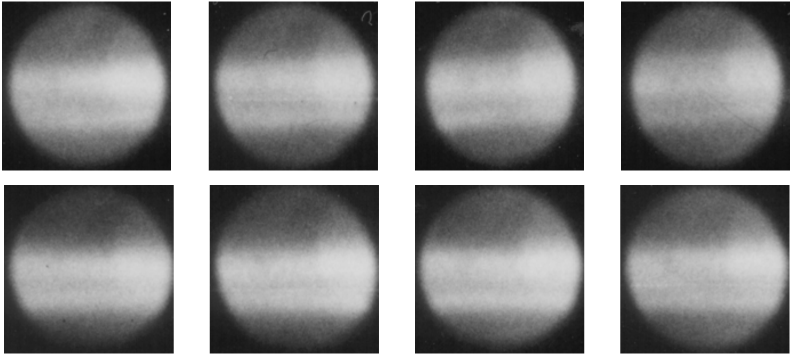
Stable Z-Pinch for *Thousands* of Growth Times



Quiescent period, $B_1/B_0 \leq 0.2$, lasts about 37 μs ($\gamma_{\mathrm{MHD}} \sim 20$ ns)
(flow-through time, $\sim 10 - 20$ μs, also $\gg \gamma_{\mathrm{MHD}}$)

Optical Images Show a Stationary Plasma Pinch

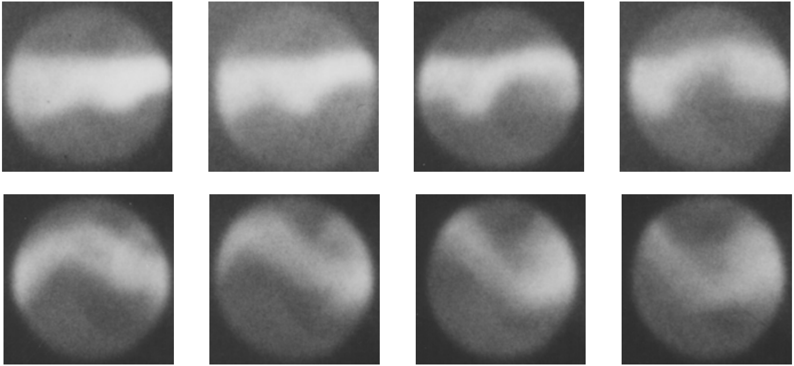
Stationary plasma pinch during the quiescent period



Images obtained through a 5 cm hole at z=0, every 200 ns, left-to-right, top-to-bottom
Pulse 40115035

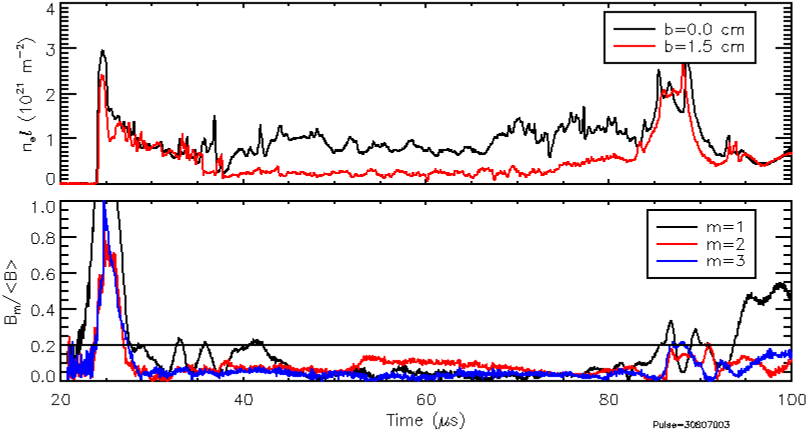
Optical Images Show an Unstable Plasma Pinch

Gross kink and sausage instabilities appear at the end of the quiescent period



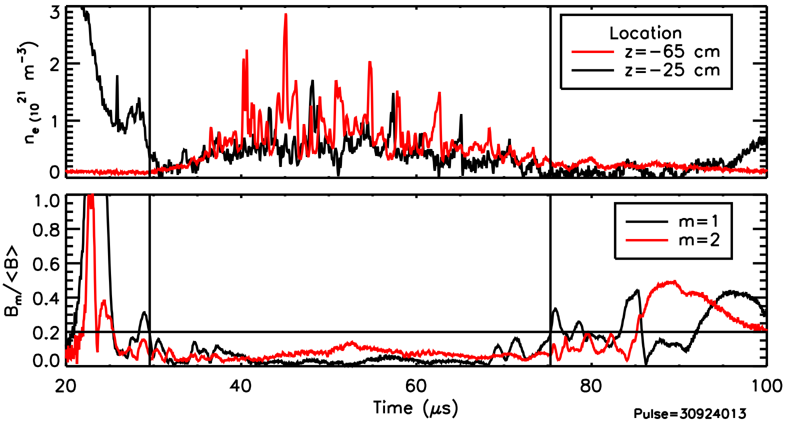
Images obtained through a 5 cm hole at z=0, every 200 ns, left-to-right, top-to-bottom
Pulse 40127041

Z-Pinch Density Peaked During Quiescent Period



r=0 line density higher than r=1.5 cm during quiescent period

Accelerator Continuously Supplies Flowing Plasma

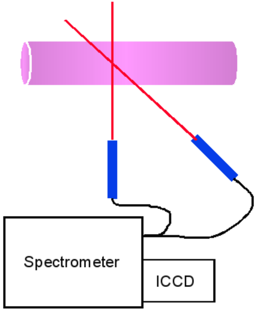


Quiescent period lasts until accelerator plasma flow exhausted

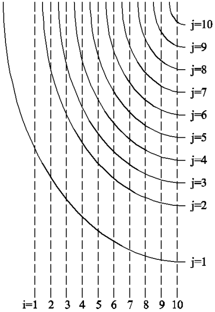
Multichord Spectrometer Measures Velocity Profiles

Data deconvolved with shell model (Golingo *et al.*, *Rev. Sci. Inst.*, 2003)

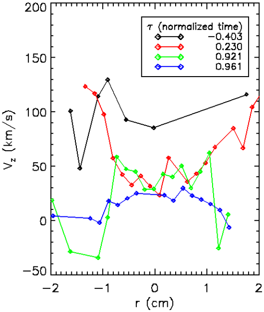
A 20 chord imaging spectrometer is connected to an intensified CCD detector to measure the Doppler shifts of impurity emission lines.



ICCD system schematic



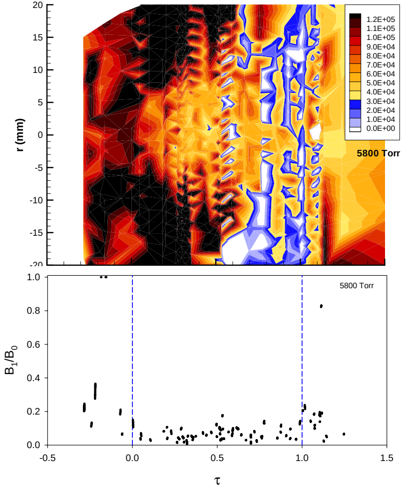
Shell model for deconvolution



Deconvolved $v_z(r)$ profiles, (normalized quiescent time)

Flow Profile is Correlated to Plasma Stability

5800 Torr gas line pressure, one inner puff valve



Plasma assembly (τ<0), the axial plasma velocity is high and uniform. ($v_z' \simeq$ 0–4 $\times 10^6$ s^{-1})

Start of quiescent period (τ=0), the velocity profile is high at the plasma edge and lower at the axis. ($v_z' \simeq$ 7–12 $\times 10^6$ s^{-1})

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

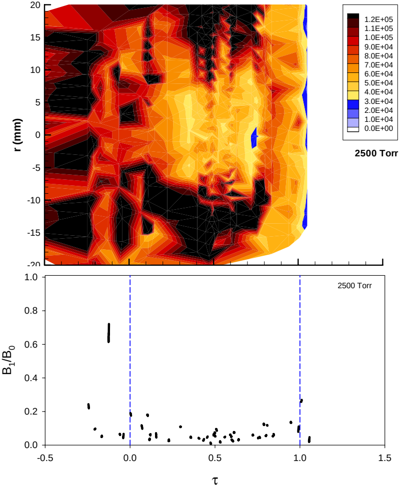
End of quiescent period (τ=1), the plasma velocity profile is low and uniform. ($v_z' \simeq$ 0–6 $\times 10^6$ s^{-1})

Theoretical growth time is $\simeq$ 20 ns.

Shear threshold is $\simeq 5 \times 10^6$ s^{-1}

Flow Profile is Correlated to Plasma Stability (cont.)

2500 Torr gas line pressure, one inner puff valve



Decreasing injected neutral gas does not significantly alter the correlation between flow shear and stability.

Plasma assembly (τ<0): v_z is high and uniform. ($v_z' \simeq$ 0–4 $\times$ 10^6 s^{-1})

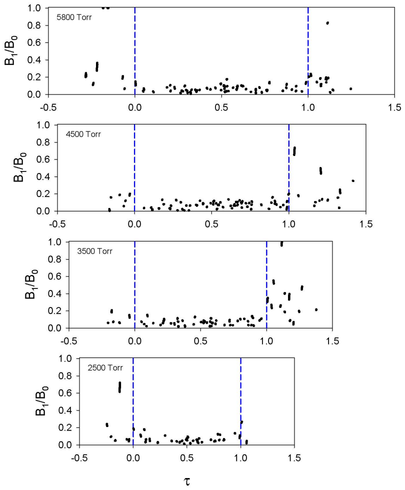
Start of quiescent period (τ=0): v_z' is high at the pinch edge and lower at the axis. ($v_z' \simeq$ 5–12 $\times$ 10^6 s^{-1})

End of the quiescent period (τ=1), the plasma velocity profile is uniform. ($v_z' \simeq$ 0–2 $\times$ 10^6 s^{-1})

Theoretical growth time is $\simeq$ 20 ns.

Shear threshold is $\simeq$ 5 $\times$ 10^6 s^{-1}

Quiescent Period Increases with Injected Neutral Gas



The quiescent period is seen to increase with the amount of injected gas when plotted on the same time base.

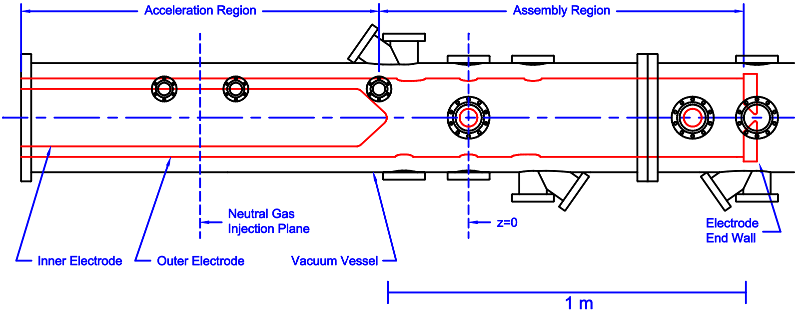
Neutral gas continually ionizes, supplies plasma to the pinch, and maintains the sheared flow Z-pinch state. The shorter quiescent periods suggest the plasma source is being exhausted.

This finding also suggests a means for extending the plasma lifetime.

Mods: Improve Gas Control and Increase Heating

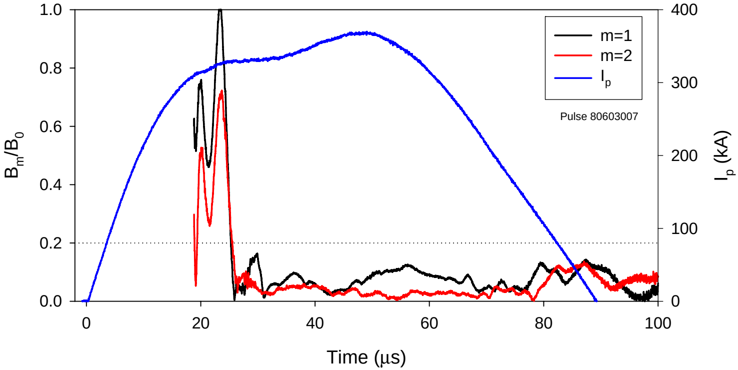
5 cm radius inner electrode replaced with 7.5 cm radius

- Added larger inner electrode and additional gas valves
- Can stagger gas injection to replenish plasma supply
- Larger electrode increases compression



Longer Quiescent Time with Increased Gas Supply

Modified experiment still produces a quiescent period with low magnetic fluctuation levels, with the plasma lifetime now limited by supplied plasma current.



Quiescent period lasts for $\sim$ 75 μs after pinch forms.

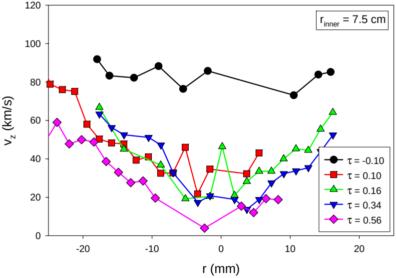
Flow Profile is Still Correlated to Plasma Stability

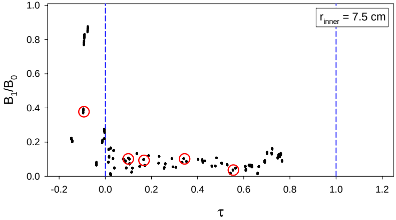
With the modified inner electrode, velocity profiles are measured in the same manner as previously.

Plasma assembly (τ<0), the axial plasma velocity is high and uniform. ($v_z' \simeq 0$–2×10^6 s-1)

During the quiescent period (0<τ<1), the velocity profile is high at the plasma edge and lower at the axis. ($v_z' \simeq 3$–6×10^6 s^{-1})

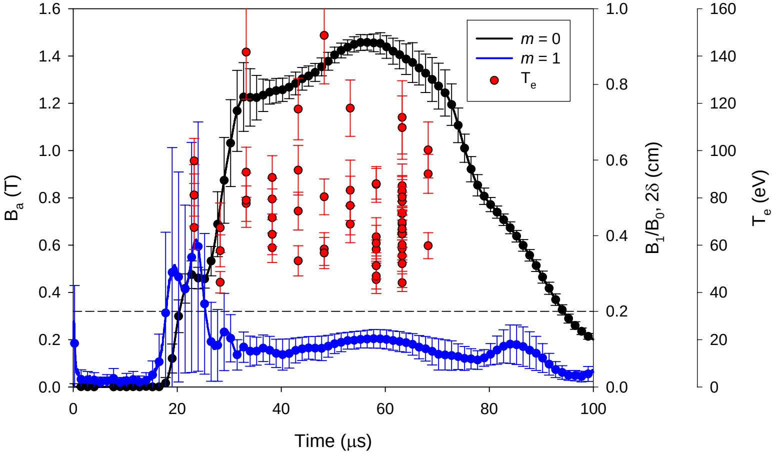
Theoretical growth time is $\simeq$ 25 ns. Shear threshold is $\simeq 4 \times 10^6$ s^{-1}.





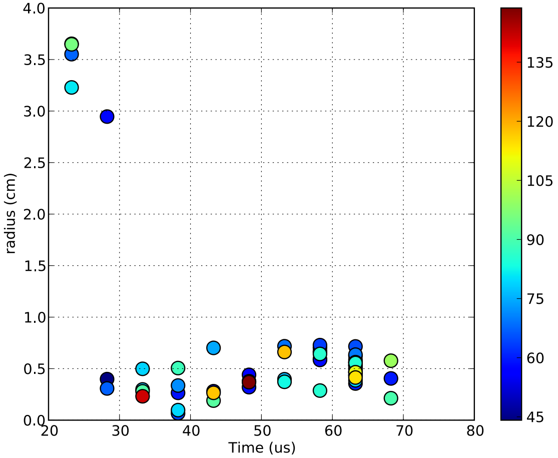
Thomson T_e Evolution Shows a Sustained Hot Plasma

Measured on *machine* axis; pinch can be $\sim$ 0.5 cm off



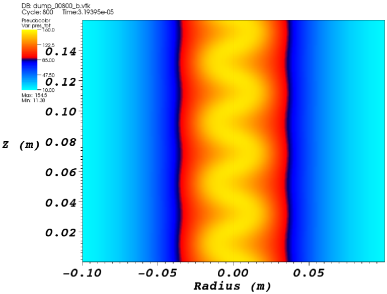
Thomson Data Shows Hottest Plasma Towards Axis

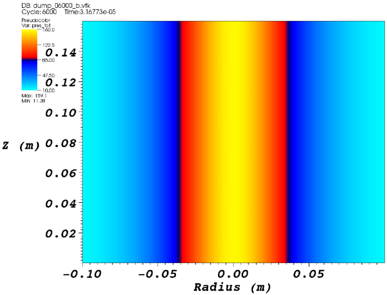
T_e relative to center of pinch, determined from mode data



NIMROD Simulations Suggest Shear Stabilization

Pressure contours from nonlinear resistive MHD, w/o shear and with constant shear





No shear

$v_z = 50\ r/r_{\mathrm{wall}}$ km/s

("Bennett" pinch equilibrium profiles)
Collaboration with Dr. C. C. Kim of the PSI-Center

NIMROD Linear Stability Boundary Studies Underway

Collaboration with Dr. C. C. Kim of the PSI-Center

Initial results see decrease in growth rate for Bennett profiles (constant density; not m=0 stable) with comparable results to $v_z' \simeq 0.1 k v_A$ (need to do convergence studies)

Plans (compare to Shumlak *et al.* results):

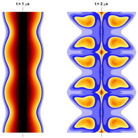
- Use m=0 marginally stable Kadomtsev equilibrium with constant T
- Map out n=1 growth times for constant shear profile, varying r_{wall}/a, k, and v_z'
- Perform convergence studies

$\Rightarrow$ Expand studies to experimental profiles ($P(r)$, $v_z(r)$, *etc.*)

m=0 Also Stabilized with *Non-Constant* Sheared Flow

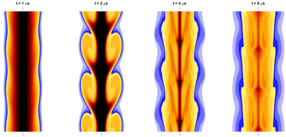
Axisymmetric pressure contours from MACH2 simulations

No flow nor shear



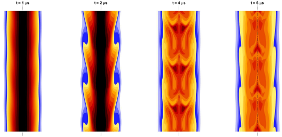
Static Z-pinch simulation shows the growth of the *m*=0 instability.

Flow with uniform shear



Flow Z-pinch with uniform shear simulation shows the stabilization of the instability.

Flow with non-uniform shear



Experiment exhibits shear mostly at the plasma edge. When the simulation is repeated with a shear $\propto r^5$, the plasma still demonstrates the stabilizing effect.

Summary

- ZaP produces Z-pinch plasmas exhibiting gross stability during an extended quiescent period, *thousands* of MHD growth times
- The quiescent period:
  - Is coincident with a sheared plasma flow
  - Lasts as long as plasma and current are flowing in the accelerator region
  - Experimentally satisfies calculated stability criteria
- 3D MHD simulations of flow-shear Z-Pinch stabilization are underway, and will be compared to stability calculations and experimental results

Future Plans

- Double size of PFN capacitor bank
  - Increase flattop duration and/or current level
- Extend solid outer electrode with a short rod array
  - Reduce any wall stabilization, and open optical access
- Extend outer electrode from 1 to 2 m (rods or solid)
  - Explore stabilization at different pinch lengths
  - Allow $v_z(r)$ measurements at other axial locations
- Expand Thomson scattering to multi-point
  - Characterize equilibrium $n_e(r)$ and $T_e(r)$, as well as $T_i(r)$ from existing ICCD Doppler spectrometer
- Design/install LIF Zeeman diagnostic
  - Measure local $B_\theta(r)$ (line-integrated measurements have been made)