# Evidence of Flow Stabilization in the ZaP Z Pinch Experiment

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**Abstract.** The stabilizing effect of an axial flow on the $m = 1$ kink instability in Z pinches has been studied numerically with a linearized ideal MHD model to reveal that a sheared axial flow stabilizes the kink mode when the shear exceeds a threshold. The sheared flow stabilizing effect is investigated with the flow-through Z pinch experiment, ZaP. An azimuthal array of surface mounted magnetic probes located at the midplane of the 50 cm long pinch plasma measures the fluctuation levels of the azimuthal modes $m = 1$, 2, and 3. After pinch formation a quiescent period is found where the mode activity is reduced to a few percent of the average field. Optical images from a fast framing camera and a HeNe interferometer also indicate a stable pinch plasma during this time. Doppler shift measurements of a C-III line correspond to an axial flow velocity of $9.6\times10^4$ m/s internal to the pinch. During the time when the axial plasma flow is high, the plasma experiences a quiescent period which lasts approximately 800 exponential growth times predicted by linear theory for a static plasma.

## 1. Introduction

The stabilizing effect of a sheared axial flow on the $m = 1$ kink instability in Z pinches has been studied numerically by reducing the linearized ideal MHD equations to a one-dimensional eigenvalue equation for the radial displacement. The principal result reveals that a sheared axial flow stabilizes the kink mode when the shear exceeds a threshold value which is inversely proportional to the wavelength of the mode, namely $dV_z/dr > 0.1\ kV_A$.[1] Nonlinear simulations support the stabilizing effect of a sheared axial flow.[2] Previous experiments have generated Z pinch plasmas that exist for times longer than theoretically predicted by static plasma theory.[3,4] These experiments have generated Z pinch plasmas which inherently contain an axial plasma flow.

The role of plasma flow may have a profound impact on the design of current magnetic plasma confinement configurations for fusion energy. The result could be devices that are smaller, simpler, and more economical. The sheared flow stabilizing effect is investigated directly with the flow-through Z pinch experiment, ZaP.

## 2. ZaP Z Pinch Experiment

The ZaP Z pinch experiment is designed to generate Z pinch plasmas with a large axial flow. This is accomplished by coupling a coaxial accelerator gun with a pinch assembly region. FIG. 1 shows a scale machine drawing of the ZaP Z pinch experiment showing the major features of the experiment. A 1 m scale is provided for reference. Neutral hydrogen gas is injected through puff valves into the annulus of the coaxial accelerator gun. A 44 kJ capacitor bank is then discharged across the inner and outer electrodes to initiate the plasma and accelerate it. Once the plasma is initiated the one meter coaxial gun accelerates the plasma to a large axial velocity. The plasma exits the gun and forms a Z pinch plasma between the inner gun electrode and the outer electrode end wall. The pinch plasma is 50 cm in length and approximately 1 cm in radius in the assembly region. Inertia maintains the axial flow within the Z pinch plasma. The plasma remains stable for many growth times

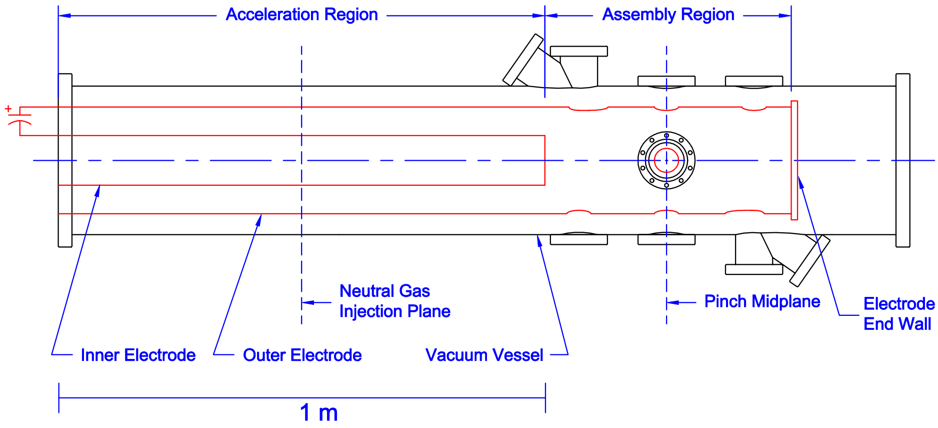


*FIG. 1 – Machine drawing of the ZaP Z pinch experiment showing the major features. A 1 m scale is provided for reference.*

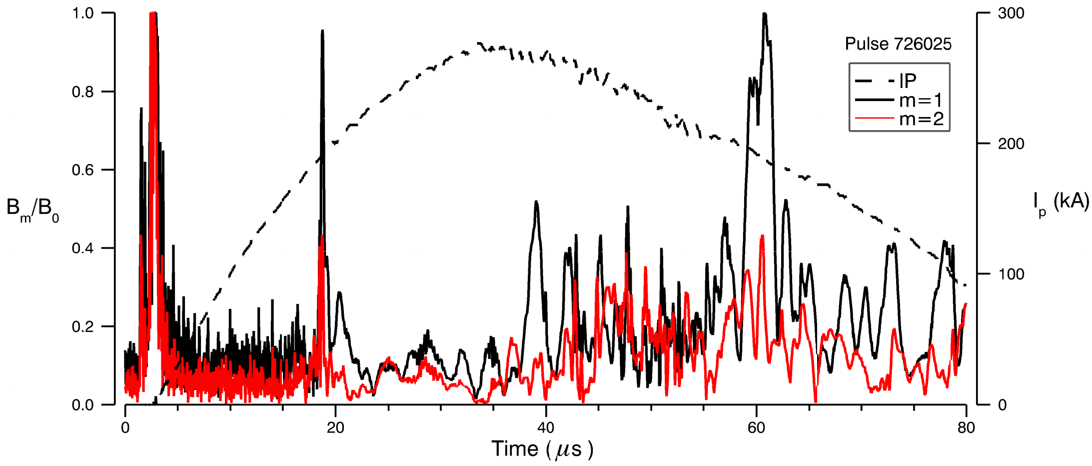


*FIG. 2 - Evolution of the magnetic mode activity. Plasma current is shown for timing reference.*

predicted by linear theory for a static plasma. The data presented in this paper are acquired from the midplane of the pinch shown in FIG. 1.

The speed of the current sheet is measured with an axial array of 23 surface mounted magnetic probes. The probes are spaced 5 cm apart in the coaxial gun and throughout the pinch assembly region. The probes measure acceleration of the current sheet along the outer electrode to an axial velocity of approximately $10^5$ m/s at the exit of the coaxial gun.

The plasma current peaks to 270 kA at 35 μsec, 32 μsec after the initial capacitor bank discharge. The current waveform is shown as a dashed line in FIG. 2. The current sheet arrives at the last surface mounted magnetic probe (5 cm from the electrode end wall) at 20 μsec. The evolution of the plasma's magnetic structure is measured with an azimuthal array of surface mounted magnetic probes located at the midplane of the 50 cm long pinch plasma. The azimuthal array data measures the magnetic activity levels of the azimuthal modes $m$ = 1, 2, and 3 at the outer electrode at the midplane of the pinch. Evolution of the magnetic mode activity for a typical pulse is shown in FIG. 2. ($m$ = 3 data are not presented, but are lower than $m$ = 2 levels.) The plasma current is shown for timing reference. The mode activity signals are also given as values at the outer electrode and have been normalized to the average value of the magnetic field at the outer electrode along the pinch midplane. The pinch forms at 20 μsec and exhibits high levels of mode activity. The pinch then experiences

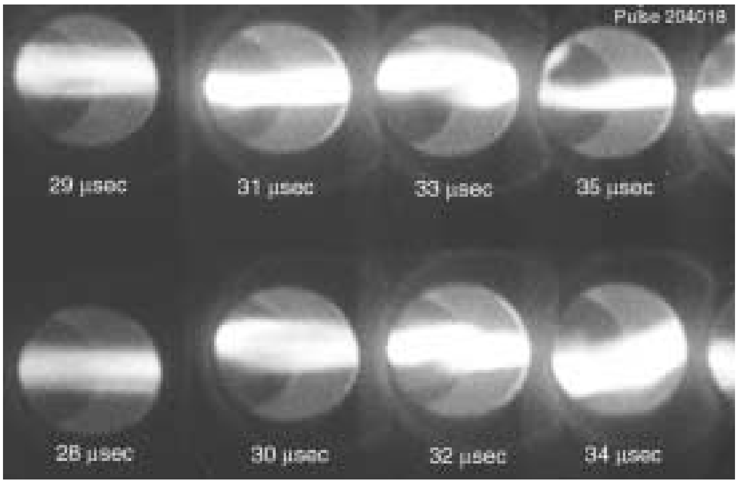


*FIG. 3 - Optical images from a fast framing camera view the plasma through a $H_\alpha$ filter and show a stable pinch plasma.*

a quiescent period of approximately 15 µsec where the mode activity is significantly reduced. After the quiescent period the mode activity increases again.

Optical images acquired with a fast framing camera through a $H_\alpha$ filter are consistent with the magnetic mode activity data. FIG. 3 shows a typical series of optical images acquired for one pulse. The images are obtained at the midplane of the 50 cm long pinch plasma viewed through a 4.7 cm diameter hole in the outer electrode. The front and back holes in the outer electrode are visible in the images and provide a reference scale. The images show a stable pinch through 33 µsec at which point the pinch becomes unstable. The images in FIG. 3 were for a plasma pulse with lower capacitor bank energy (28 kJ) than those shown in FIG. 2.

Electron number densities are measured with a two chord visible HeNe laser interferometer. The data are not shown. The density oscillates as the pinch forms. The density remains relatively constant during the quiescent period at a value of $10^{22} – 10^{23}$ $m^{-3}$. Oscillations in the density are again present after the quiescent period. From force balance the total plasma temperature is estimated at $T_i + T_e = 100 – 200$ eV.

Plasma flow velocity profiles are determined by measuring the Doppler shift of plasma impurity lines using an intensified CCD (iCCD), 0.5 m imaging spectrometer. The iCCD camera is set to a gating time of 1 µsec and the trigger time is varied between plasma pulses. The spectrometer images 20 spatial chords through the plasma onto the iCCD camera using telecentric viewing telescopes.[5] The telecentric design insures that the principle rays for each of the viewing chords are parallel to the optical axis in the plasma and on the imaging fibers. The chords are spaced 1.34 mm apart and image 20 points along a diameter through the pinch. The chords span 2.55 cm across the pinch. Optical access to the midplane of the plasma column is provided through radial view ports that are positioned perpendicular to the axis and oblique view ports that are positioned at a 35° angle to the plasma column. The radial and oblique optical view ports are shown in FIG. 1. In practice the view ports along the bottom of the machine are used.

Doppler shifts are calculated by viewing the plasma through the radial view port to locate the unshifted impurity line and then viewing the plasma through the oblique view port. The oblique view has a directional component along the axis and, therefore, is sensitive to Doppler shifts due to axial flows. FIG. 4 shows the output from the iCCD spectrometer tuned

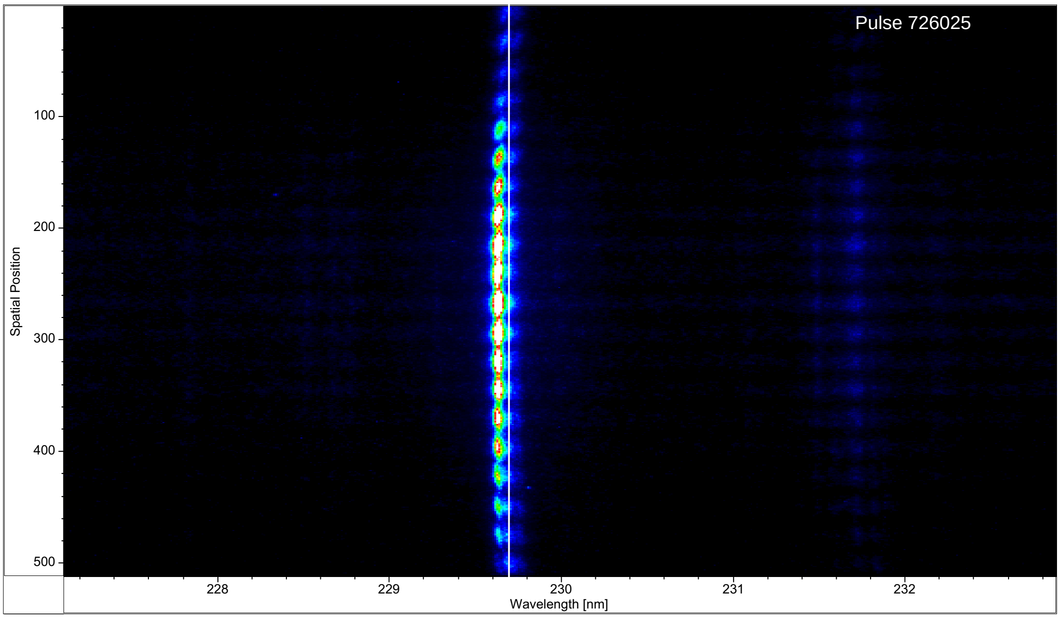


*FIG. 4 - C III line (229.7 nm) emission at 30 μsec as viewed oblique to the plasma column using the iCCD imaging spectrometer. The spectra show Doppler shifts towards blue of the central plasma indicating an axial flow velocity of 9.6×10$^4$ m/s and no Doppler shift of the outer plasma. The solid line is positioned at 229.7 nm for reference.*

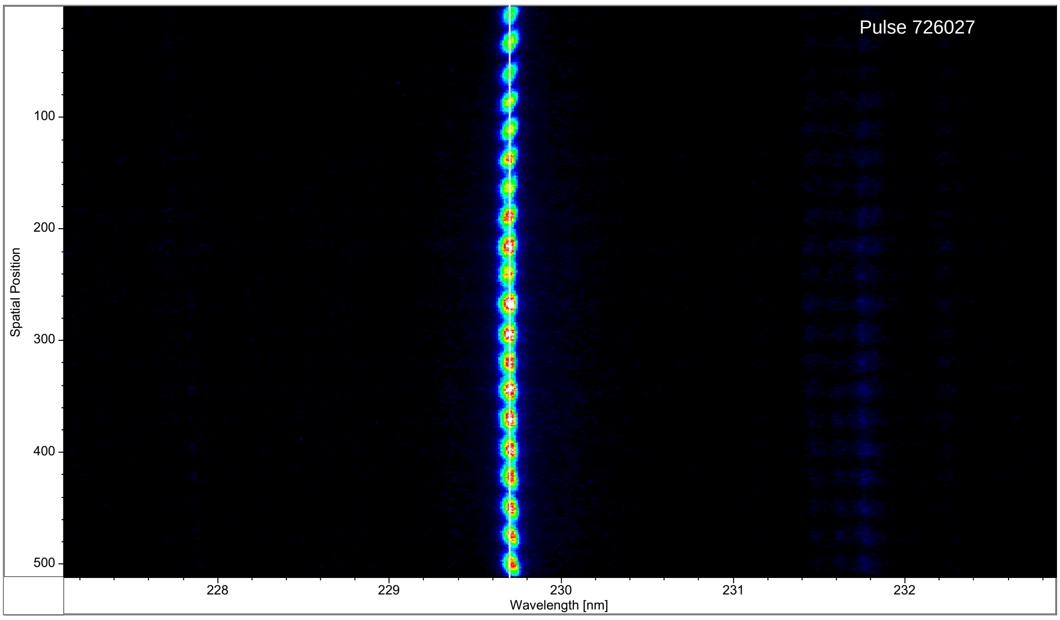


*FIG. 5 - C III line (229.7 nm) emission at 38 μsec as viewed oblique to the plasma column using the iCCD imaging spectrometer. The spectra show significantly reduced Doppler shifts and broader lines. The solid line is positioned at 229.7 nm for reference.*

to the C-III line at 229.7 nm and viewing the plasma through the oblique view port. The trigger time for the iCCD is 30 μsec which is during the quiescent period. (This pulse is the same presented in FIG. 2.) The data shows a 0.06 nm blue shift of the C-III line being emitted from the central plasma, chords 5-18, and an insignificant shift of the line being emitted from the edge plasma, chords 1 and 20. Since the bottom oblique view port is being used, the plasma has a component of the axial velocity that is moving towards the view port and produces the expected blue shift. The axial velocity of the inner plasma is calculated by $V_z = c\,\Delta\lambda/(\lambda \cos\theta) = 9.6\times10^4$ m/s at 4 mm from the edge which gives a shear of $dV_z/dr \approx \Delta V_z/\Delta r = 2.4\times10^7\ s^{-1}$. It should be noted that the data has not been inverted to resolve the spatial dependence of the line shift, and, therefore, no conclusions about the flow shear between chords 5 and 18 can be drawn at this time. The variation of the emitted light intensity also indicates the radial dependence of the plasma temperature.

After the quiescent time the plasma flow velocity is significantly reduced. FIG. 5 shows the output from the iCCD spectrometer tuned to the C-III line at 229.7 nm and viewing the plasma through the oblique view port. The trigger time for the iCCD is 38 μsec which is after the quiescent period and when the magnetic mode activity is high. The spectra for all of the spatial locations are centered on the 229.7 nm reference line in the figure. The peaks are also broader indicating random plasma motion and plasma heating due to flow stagnation on the electrode end wall, shown in FIG. 1.

**3. Comparison to Linear Theory**

The experimental results can be compared to the theoretical results. The theoretical exponential growth time for the static Z pinch is $\approx(kV_A)^{-1}$ which for the experimental values obtained in the ZaP experiment gives $\tau_{growth} = 19$ nsec for $ka = \pi$. The linear stabilization theory requires a sheared axial flow of $dV_z/dr > 0.1\ kV_A$ [1], which for these experimental parameters requires $dV_z/dr > 5.3\times10^6\ s^{-1}$. The data from the iCCD spectrometer in FIG. 4 shows that a shear of approximately $2.4\times10^7\ s^{-1}$ exists in the outer portion of the pinch. No comparison can be made at this time for the inner portion of the pinch. The extent of the shear and of the role that the shear in the outer plasma plays in stabilizing the pinch or reducing mode growth and amplitude is not yet known.

**4. Discussion**

The ZaP experiment has generated Z pinch plasmas which are stable with low mode activity for approximately 800 exponential growth times predicted by linear theory for a static plasma. Furthermore, the mode activity in the plasma is higher when the plasma flow velocity is small as shown in FIG. 5. During the quiescent period the plasma maintains a stable structure as seen from the fast framing camera, the magnetic probes, the interferometer, and the spectrometer data. After the quiescent period the electron number density oscillates and the emission of the C-III line appears to be uniform across the field of view. The results presented here seem to provide direct supporting experimental evidence of a connection between sheared flow and MHD stability.

A sheared flow stabilized Z pinch has many important implications for a simple fusion reactor design.[6] The primary advantages are no external magnetic coils, linear system, and high plasma density. The fundamental principal of sheared flow stabilization also has important implication and applications to other magnetic confinement concepts.[7]


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