# Evolution of Plasma Flow Shear and Stability in the ZaP Flow Z-Pinch

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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 ZaP Flow Z-pinch experiment. An azimuthal array of surface mounted magnetic probes measures the fluctuation levels of the azimuthal modes $m = 1$, 2, and 3. After pinch assembly a quiescent period is found where the mode activity is significantly reduced. The quiescent period lasts for over 2000 times the expected instability growth time in a static Z-pinch. Optical images from a fast framing camera, a two-chord HeNe interferometer, and a ruby holographic interferometer indicate a stable, discrete pinch plasma during this time. Multichord Doppler shift measurements of impurity lines show a large, sheared flow during the quiescent period and low, uniform flow profiles during periods of high mode activity. The value of the velocity shear satisfies the theoretical threshold for stability during the quiescent period and does not satisfy the threshold during the high mode activity. Experiments are conducted with varying amounts of injected neutral gas to gain an understanding of the Z-pinch formation and lifetime.

## 1. Introduction

The ZaP Flow Z-pinch experiment at the University of Washington investigates the concept of using sheared flows to stabilize an otherwise unstable plasma configuration. The stabilizing effect of a sheared axial flow on the $m = 1$ kink instability in Z-pinches has been studied numerically using linearized ideal MHD theory. The principal result reveals that a sheared axial flow stabilizes the kink mode when the shear exceeds a threshold value, $dV_z/dr > 0.1\ kV_A$.[1] Nonlinear simulations support the stabilizing effect. Previous experiments have generated Z-pinch plasmas that exist for times longer than theoretically predicted by static plasma theory.[2,3] These experiments have generated Z-pinch plasmas which inherently contain an axial plasma flow.

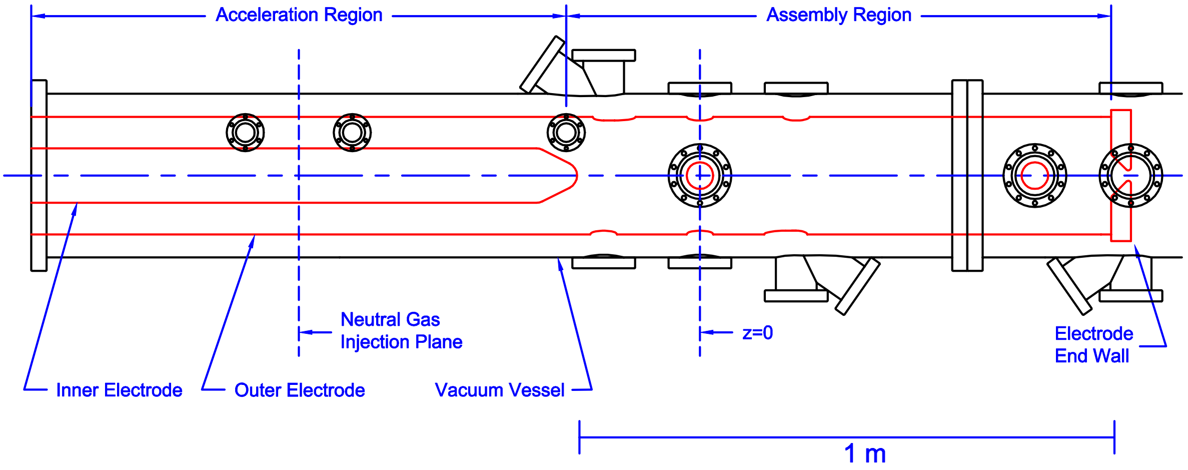

*Fig. 1 – Side view drawing of the ZaP Flow Z-Pinch experiment identifying the relevant features. The acceleration and assembly regions are identified. A 1 m scale is included for reference.*

## 2. ZaP Flow Z-Pinch Experiment

The ZaP Flow Z-pinch experiment at the University of Washington initiates a plasma with a 1 m long coaxial accelerator which has a 20 cm diameter outer electrode and a 10 cm diameter inner electrode. Neutral gas, typically hydrogen, is injected with fast gas puff valves into the midplane annulus of the coaxial accelerator. A side view drawing is shown in Fig. 1. The amount of injected neutral gas is controlled by varying the plenum pressure in the puff valves. An electrical potential of 5 – 9 kV is applied to the accelerator to breakdown the neutral gas. The plasma is accelerated to a large axial velocity. The plasma exits the accelerator and forms a Z-pinch plasma 1 m long with an approximately 1 cm radius. Current in the accelerator continues to accelerate plasma into the Z-pinch, replacing plasma as it exits from the Z-pinch. Inertia maintains the axial flow within the Z-pinch plasma column. The plasma current is supplied by a 17.5 kJ capacitor bank configured as a pulse-forming network. The peak current is 150 - 200 kA with a rise time of 25 μs, a flat-top of 35 μs, and a fall time of 40 μs. Data presented here are primarily from the r-θ plane of the Z-pinch defined at $z = 0$. (The Z-pinch extends from the end of the accelerator at $z = -25$ cm to the electrode end wall $z = 75$ cm.) Diagnostics on the ZaP experiment are designed to measure the plasma flow profile and the stability of the plasma pinch, as well as the plasma equilibrium parameters.

The electron number density in the Z-pinch is measured with a two-chord, HeNe interferometer with a heterodyne, quadrature detector. One chord traverses the plasma along a diameter, and the second chord is parallel to and 2 cm above the first chord. The plasma density is assumed to be spatially uniform for all $r \geq 2$cm. The average plasma density in the Z-pinch ($r < 2$ cm) is determined from the line-integrated densities from the two chords. The maximum plasma density is approximately $2\times10^{22}$ m$^{-3}$. Figure 2 shows the evolution of the plasma density for a puff valve plenum pressure of 4650 torr. Data are recorded for ten pulses and averaged together.

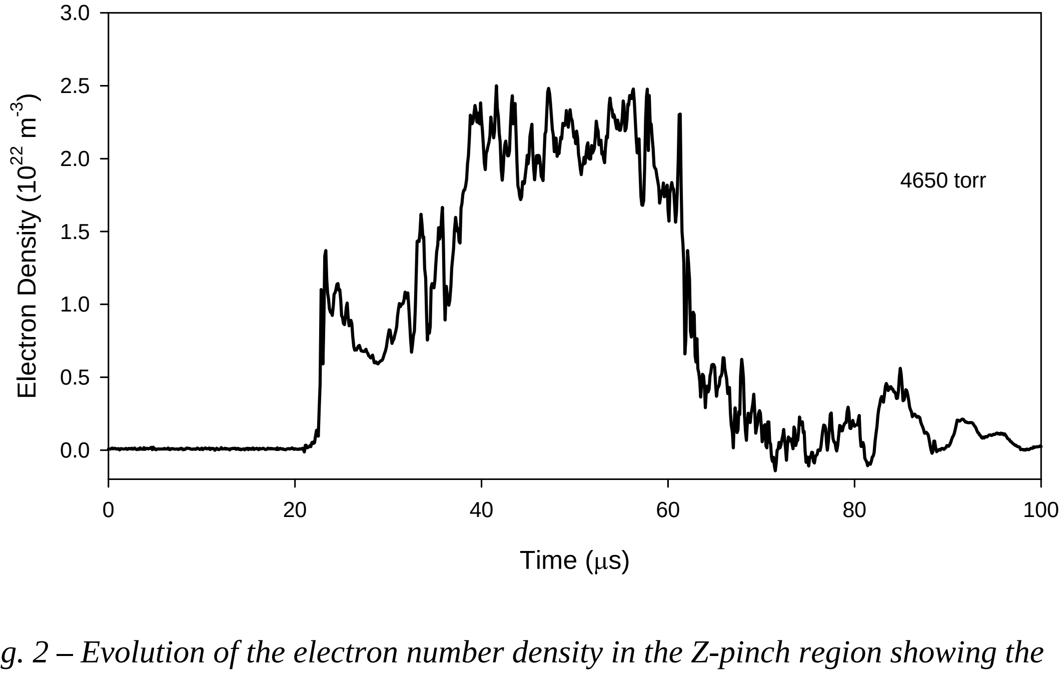

*Fig. 2 – Evolution of the electron number density in the Z-pinch region showing the formation of the Z-pinch plasma.*

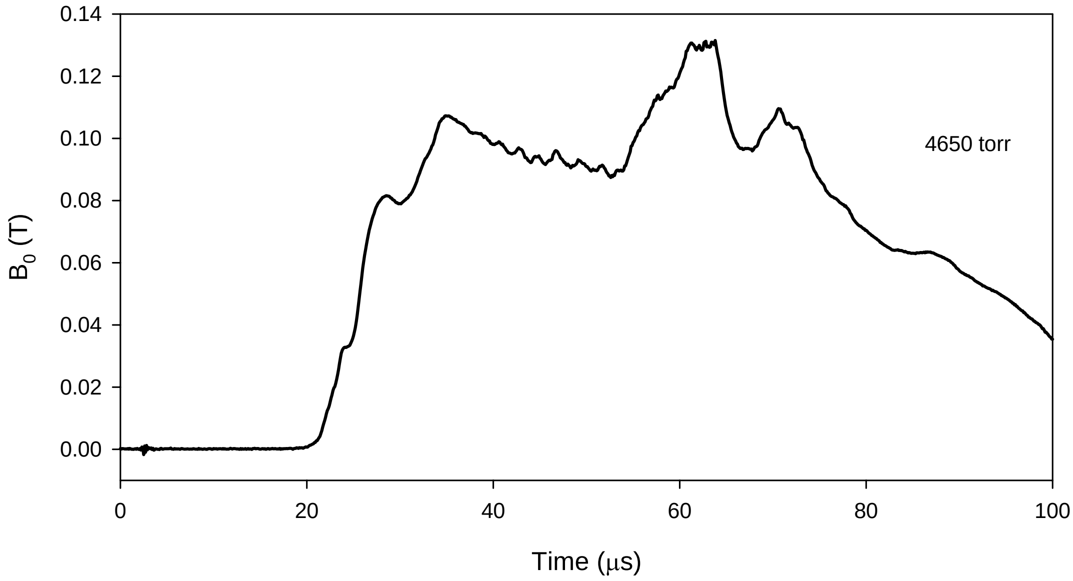

*Fig. 3 – Evolution of the average magnetic field measured at the outer electrode by eight surface-mounted probes. The magnetic field at the Z-pinch radius is approximately 10 times the value measured by the probes at the outer electrode.*

The magnetic field is measured with an azimuthal array of eight surface-mounted magnetic probes located in the outer electrode. The values are averaged to give $B_0(t)$. Figure 3 shows the evolution of the wall magnetic field for a puff valve plenum pressure of 4650 torr. Data are recorded for ten pulses and averaged together. The plasma pinch radius is approximately 1 cm. Therefore, the magnetic field at the edge of the Z-pinch plasma is 10 times the value measured at the outer electrode (10 cm radius) if no current flows between the Z-pinch and the outer electrode. The magnetic field at the edge of the pinch is approximately 1 T during the lifetime of the Z-pinch.

Plasma flow velocity profiles are determined by measuring the Doppler shift of plasma impurity lines using an imaging spectrometer with an intensified CCD camera (ICCD) operated with a 100 nsec gate. The spectrometer images 20 spatial chords spaced 1.78 mm apart through the plasma pinch at a $35^o$ angle to the plasma axis providing a measurement of the axial velocity profile. The chord-integrated data are deconvolved to determine the axial velocity profile.[4] The velocity profile is measured at one time during a pulse. Varying the ICCD trigger time between pulses provides a measure of the plasma flow evolution throughout the plasma pulse. The upper plot of Fig. 4 shows the evolution of the axial velocity profile of the plasma pinch as a function of time $\tau$ normalized by the plasma quiescent period. The C III impurity line at 229.7 nm is used here. Profiles are shown during the pinch assembly ($\tau<0$), through the quiescent period (defined as $\tau=[0,1]$), and through transition from quiescence to instability ($\tau>1$). The velocity profile evolves from a large uniform flow for $\tau<0$ to one that is sheared with a higher velocity at the edge. Late in the quiescent period, $\tau\approx0.8$, the edge velocity decreases towards zero. At the end of the quiescent period, $\tau=1$, the center velocity quickly decays, resulting in a plasma flow profile that is low and uniform. Note there is a brief time during the quiescent period when the flow profile becomes uniform.

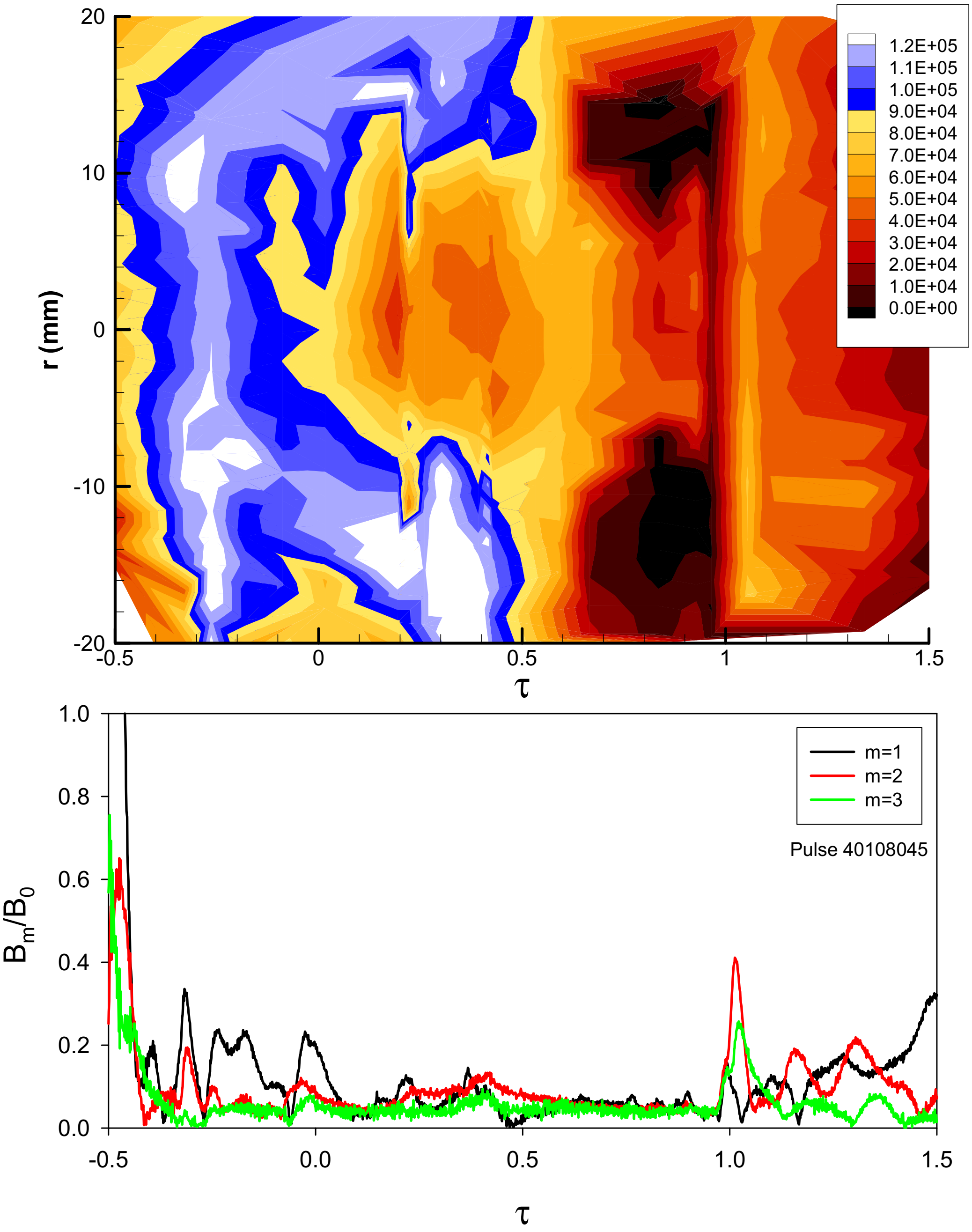

*Fig. 4 - Contours showing the evolution of the axial velocity (m/s) profiles in time normalized to the quiescent period. (The plot is constructed from data of many pulses.) Magnetic fluctuation levels for m=1, 2, & 3 for one plasma pulse. The quiescent period is 36.5 μsec. The C III impurity line at 229.7 nm is used here.*

Time-dependent plasma flow velocities are measured during a single pulse with an Ion Doppler Spectrometer (IDS) instrument. The instrument consists of a sixteen-anode PMT detector connected to a 1 m spectrometer that views the plasma pinch along a single $35^o$ chord through the machine axis. The spectrometer is tuned to plasma impurity lines. The sixteen signals from the PMT are fit with a Doppler shifted and broadened Gaussian distribution to provide a measure of the chord-averaged plasma velocity and temperature as a function of time. The O IV impurity line at 306.3 nm is used here.

Plasma stability is diagnosed with the azimuthal array of magnetic probes described earlier. The measurements from the probe array determine 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). The lower plot of Fig. 4 shows the evolution of the $m$ = 1, 2, 3 Fourier modes of the magnetic field $B_m(t)$ normalized by $B_0(t)$. Large magnetic fluctuations occur during pinch assembly, after which the amplitude and frequency of the magnetic fluctuations diminish. This stable behavior continues for 35 - 45 μs and defines the 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. The time scale in Fig. 4 is normalized by the duration of the quiescent period to allow data comparison among pulses. The quiescent period defines $\tau$=[0,1]. Data from other diagnostics are consistent with this description of the plasma behavior. Visible emission from the pinch is recorded with a fast framing camera and a photodiode array. The data show a stable pinch that becomes unstable. The timing of the stable period corresponds to the stable time shown in the magnetic mode data.

## 3. Comparison to Theoretical Threshold for Stability

The measured axial flow shear is compared to the required threshold predicted by linear theory. Using the experimental data, $V_A = 1.5\times10^5$ m/s. The theoretical growth time for a static Z-pinch is approximately $(kV_A)^{-1}$ which for the experimental values obtained in the ZaP experiment gives $\tau_{growth}$ = 21 nsec for ka = $\pi$. The axial velocity shear required for stability according to the theory is $4.7\times10^6$ s$^{-1}$. The experimental results show a stable period of 40 μs, almost 2000 growth times. The experimentally measured axial velocity shear is between 6.5-12$\times10^6$ s$^{-1}$ during the stable period $\tau$=[0,0.9]. The shear drops to 3-6$\times10^6$ s$^{-1}$ at the end of the quiescent period $\tau\approx0.95$ and below $3\times10^6$ s$^{-1}$ after the quiescent period $\tau>1$ when the magnetic mode fluctuations are high. The correlation of the experimental stability data with the plasma flow measurements is consistent with the sheared flow stabilization theory.[5, 6]

## 4. Plasma Control through Neutral Gas Injection

Further insight into the Z-pinch stabilization is obtained by varying the plenum pressure of the gas puff valves and, thereby, controlling the amount of injected neutral gas in a pulse. The plenum pressure is varied between 2150 – 4650 torr and a series of pulses are performed. On each pulse the plasma velocity and temperature are determined from the IDS instrument data. The instrument only records velocity and not velocity shear. However, if we assume the shear length is approximately the pinch radius a and the mode of interest has ka = $\pi$, the theoretical stability threshold can be expressed as $V_z / 0.1\pi V_A > 1$. The time-dependent Alfvén speed in the Z-pinch is computed using the instantaneous density measured from the two-chord interferometer and the instantaneous $B_0$ measured from the magnetic probes. Figure 5 shows the velocity shear normalized by the theoretical threshold as a function of time for three different plenum pressures. The $m$ = 1 component of the magnetic field measured at the outer electrode is also shown. For the plenum pressures of 3650 and 4650 torr, a period of time exists when the normalized velocity shear is above unity. This time is coincident with the quiescent period described above and evident in the magnetic fluctuations $B_1$. The quiescent period ends at approximately the same time when the normalized velocity shear drops below unity. For the case with a plenum pressure of 2650 torr, the normalized velocity shear never exceeds unity and only briefly approaches unity. The magnetic fluctuations have a high amplitude and high frequency except when the velocity shear approaches the threshold.

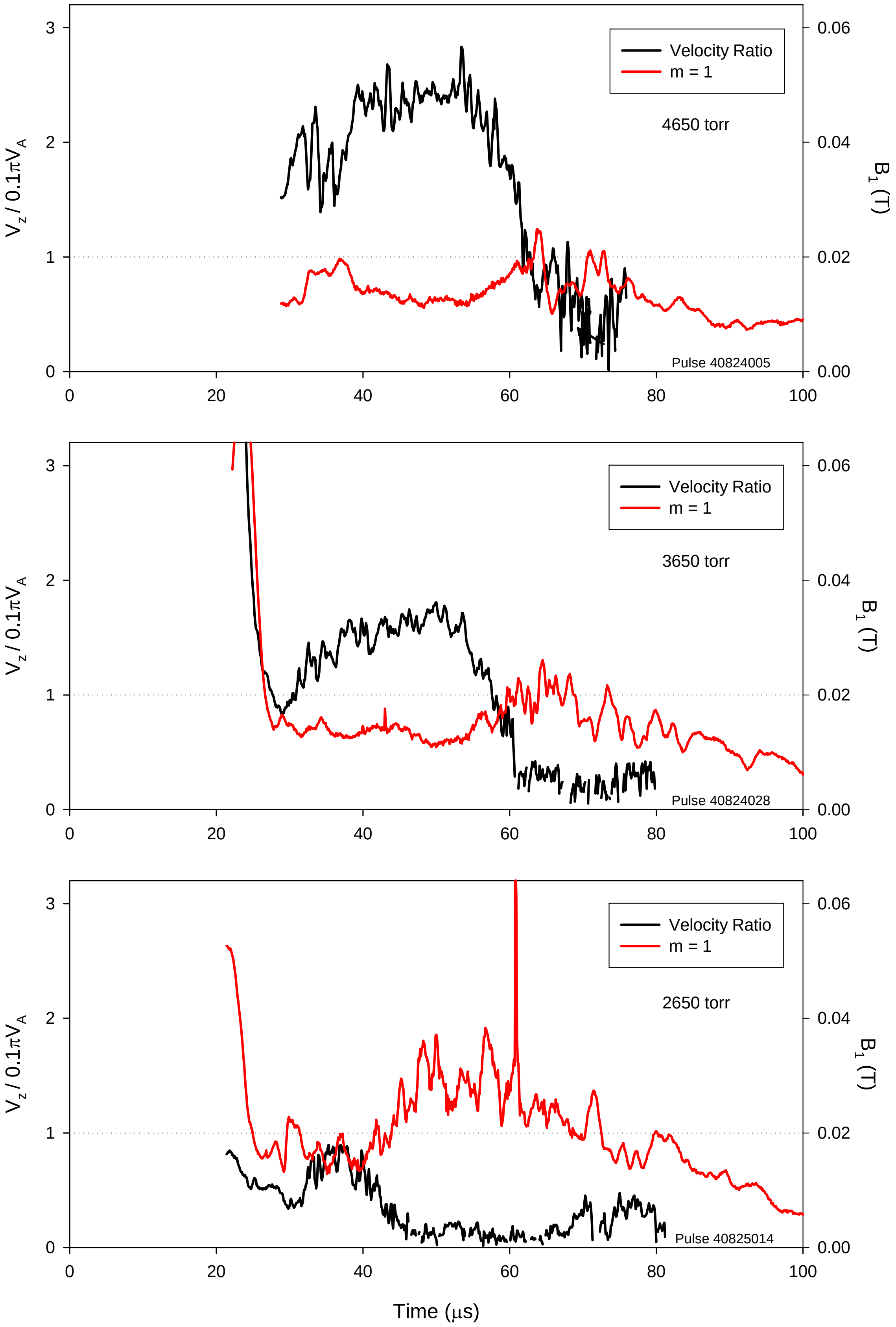

*Fig. 5 – Velocity shear normalized by the theoretical threshold as function of time. The O IV impurity line at 306.3 nm is used here. The plenum pressure in the gas puff valves is varied. The m = 1 component of the magnetic field at the outer electrode is also plotted.*

## 5. Discussion

If it is assumed that velocity shear is playing the critical role of providing stability for the otherwise unstable Z-pinch, then two possible mechanisms that limit the lifetime of the plasma confinement are decay of plasma current and loss of plasma flow or flow shear. These two mechanisms may not be completely independent. However, the experiments conducted with different plenum pressures in the puff valves appear to discount the decay of plasma current as the lifetime limiting mechanism. The bank configuration is identical for the experiments. Different neutral gas injection alters the plasma dynamics and, thereby, alters the plasma current. However, the plasma current pulse is generally similar. The current pulse length is approximately 100 μs and the peak current varies between 150 – 200 kA.

Loss of plasma flow is a more likely mechanism that limits the plasma lifetime. The loss of plasma flow may result from stagnation on the electrode end wall, shown in Fig. 1. A plasma exhaust hole is installed to reduce flow stagnation. Previous experimental measurements indicate a decrease of plasma acceleration in the acceleration region of the experiment that is approximately coincident with the end of the quiescent period in the Z-pinch plasma.[6] Specifically, the azimuthal magnetic field values measured at several axial locations converge to the same value indicating a decrease of radial current in the acceleration region. Plasma density in the acceleration region is also observed to decrease during these same experiments.[6] While not conclusive, the experimental results suggest the loss of plasma flow may be caused by a depletion of the injected neutral gas. The experimental results presented here further support this conjecture. The results presented in Fig. 5 show shorter quiescent periods for less injected neutral gas. A distinct quiescent period is not observed when the gas puff valve plenum pressure is lowered to 2650 torr. Experiments are on-going to further investigate the dependence of the plasma lifetime on injected neutral gas. Future experimental modifications include additional gas puffing capacity to approach a quasi steady-state operation of the ZaP Flow Z-Pinch experiment. True steady state is not likely to be possible with gas puff valves; however, using plasma injectors may be feasible.

Z-pinch plasmas have high plasma densities and can reach high plasma temperatures. However, plasma stability has limited their usefulness as a magnetic fusion configuration. The flow Z-pinch may provide a unique solution if the Z-pinch can be stabilized with a sheared plasma flow and the equilibrium state can be sustained with a steady, or even quasi steady, flow. A flow-stabilized Z-pinch has many important implications for a simple reactor design and other magnetic confinement concepts.

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