Sheared Flow Stabilization in the 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 Alfven 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.

1. Introduction

The Z-pinch provides a simple magnetic confinement configuration for plasma that has many advantages both as a possible fusion reactor and as a test bed to conduct basic plasma science research. The pure Z-pinch is simply connected, has unity average beta, and directly drives the plasma current. The only magnetic field present is the field generated by the plasma current. All magnetic field lines are closed, even though the plasma has open ends. However, the pure Z-pinch is classically unstable to the m = 0 sausage and m = 1 kink modes. Conventional techniques to provide stability have drawbacks. The sausage mode can be stabilized if the pressure gradient is limited.[1] Controlling the pressure profile is difficult and the technique does not stabilize the kink mode. A close-fitting, conducting wall can provide stability if the wall is located close to the plasma edge, $r_{wall}/a < 1.2$,[2] which is incompatible with a hot, fusion-grade plasma. An axial magnetic field can be applied to provide stability. However, the plasma current and the pressure are limited by the strength of the axial magnetic field according to the Kruskal-Shafranov limit.[3] Furthermore, the axial magnetic field opens all field lines and connects the electrodes to all regions of the plasma. Flow shear can stabilize the MHD modes in a pure Z-pinch without the drawbacks of the conventional stabilization techniques. If the flow is axial, it does not affect the radial force balance that describes a Z-pinch equilibrium. Since the plasma geometry is simple, i.e. described by a one-dimensional force balance, the Z-pinch configuration is ideal for studying stability characteristics.

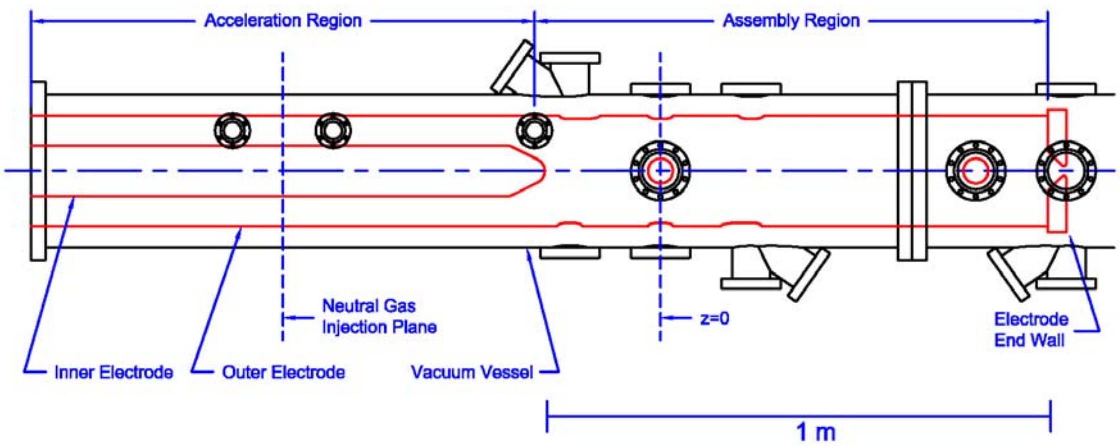

FIG. 1. Side view drawing of the ZaP Flow Z-Pinch experiment identifying the relevant features. The acceleration and assembly regions are identified. The ports at z = 0 are used by the holographic interferometer and the spectrometer used for Zeeman splitting measurements. A 1 m scale is included for reference.

Linear stability analysis demonstrates a stabilizing effect of a sheared axial flow on the $m = 1$ kink instability in Z-pinches when the shear exceeds a threshold value, $dV_z/dr > 0.1kV_A$ [2], assuming a uniform shear throughout the plasma. In addition, previous experiments have generated Z-pinch plasmas that exist for times longer than theoretically predicted by static plasma theory.[4,5] These experiments have generated Z-pinch plasmas which inherently contain an axial plasma flow.

2. ZaP Flow Z-Pinch Experiment

Experiments are conducted with the ZaP Flow Z-pinch experiment at the University of Washington to investigate using sheared flows to provide stability in a pure Z-pinch. As described in Ref. [6], the ZaP Flow Z-pinch experiment initiates a plasma with a one-meter coaxial accelerator that has a 20 cm diameter outer electrode and a 10 cm diameter inner electrode. Neutral gas is injected through puff valves into the acceleration region. The plasma is accelerated to a large axial velocity by a Lorentz force, exits the accelerator, and forms a Z-pinch plasma 1 m in length and 1 cm in radius. Current in the accelerator continues to accelerate plasma into the Z-pinch assembly replacing plasma as it exits the Z-pinch. Inertia maintains the axial flow within the Z-pinch plasma column. A machine drawing of the experiment is shown in Fig. 1 that identifies the relevant hardware features.

Experimental results reported here also include results from the recently modified ZaP experiment. The inner electrode of the coaxial accelerator has been replaced with a larger diameter electrode, approximately 15 cm. The new inner electrode also has added capacity and control for neutral gas injection.

3. Velocity Profile and Magnetic Fluctuation Measurements

Diagnostics on the ZaP experiment are designed to measure the plasma flow profile and the stability of the pinch, as well as the plasma equilibrium parameters. Plasma stability is diagnosed with an azimuthal array of eight magnetic probes that measures the plasma's

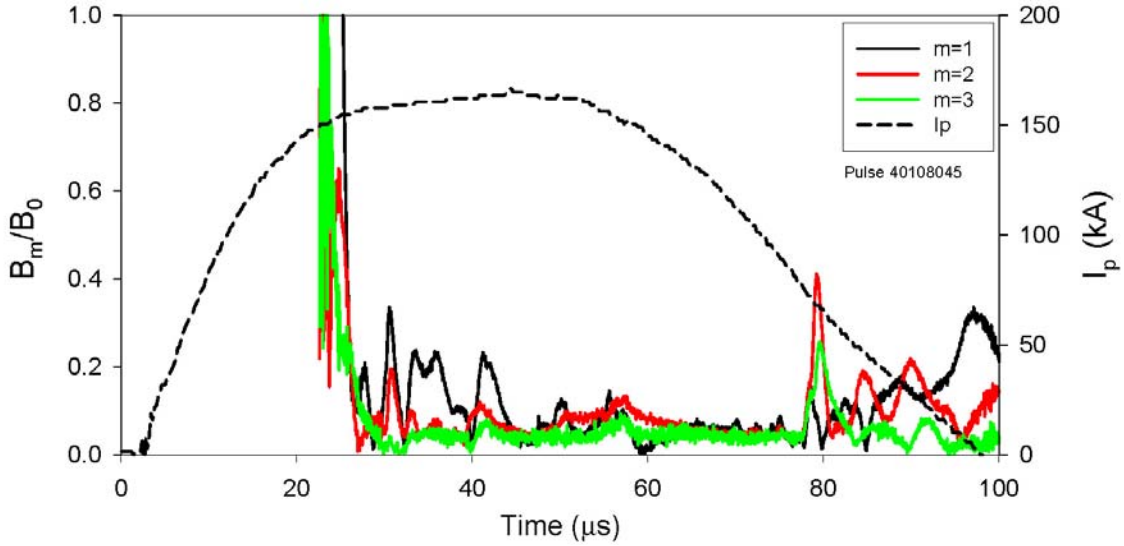

FIG. 2. Time evolution of the Fourier components of the magnetic field fluctuations at z = 0 for the m = 1,2,3 modes. The values are normalized to the average magnetic field value. A quiescent period is evident from 42 to 79 μs which defines τ = 0 to 1 for this pulse. The evolution of the plasma current is included for reference.

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), as shown in Fig. 2. 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. The quiescent period is defined as m = 1 fluctuation levels sustained below a threshold of 0.2, which corresponds to a 1 cm displacement of the plasma current from the geometric axis. A 37 μs quiescent period is seen in Fig. 2. 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. A normalized time is defined to account for small pulse-to-pulse variations and to allow detailed comparisons between the pulses. Time is normalized to the quiescent period to allow comparison between pulses. $\tau = 0$ is defined as the beginning and $\tau = 1$ is defined as the end of the quiescent period. The quiescent period is coincident with a sheared axial flow that satisfies the theoretical threshold. [2,6,7,8]

The plasma velocity profiles are determined by measuring the Doppler shift of impurity line radiation with an imaging spectrometer connected to an intensified CCD camera (ICCD) operated with a 100 ns gate. Typically, the C III impurity line at 229.7 nm is used. Light is collected along 20 parallel chords through the pinch plasma viewed at an oblique angle, through the bottom, angled viewport shown in Fig. 1. The chord-integrated data are deconvolved using a shell/matrix method to give the radial profiles of the axial velocity.[9] The trigger times of the ICCD camera are varied between pulses to determine the evolution of the velocity profiles. The trigger times are also expressed using the normalized time τ. Figure 3 presents a contour plot of the axial velocity as a function of radius (for both sides of the axis) and of normalized time compiled for many pulses. The corresponding magnetic mode data for m = 1 collected during the same gate time as the spectroscopic data is shown in Fig. 4.

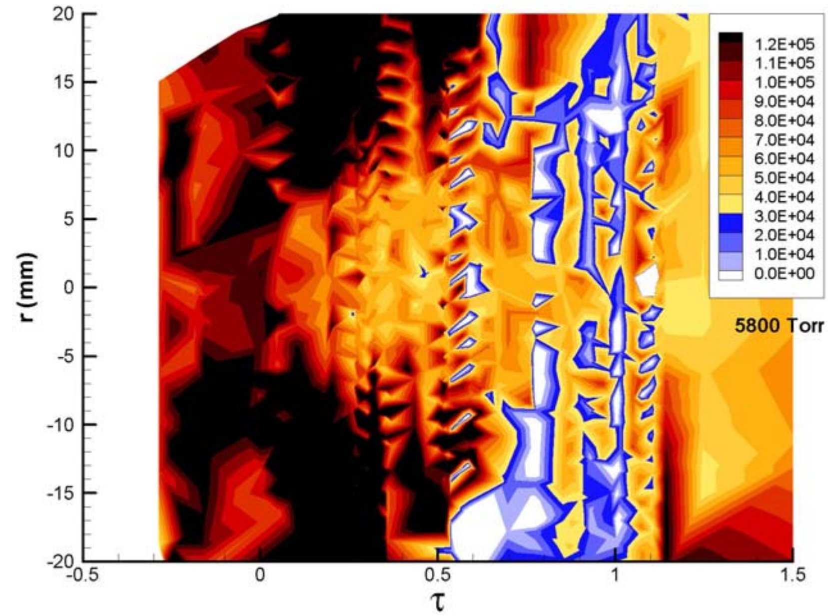

FIG. 3. Contours of axial velocity as a function of radius (for both sides of the axis) and of normalized time compiled for many pulses. A sheared plasma flow is evident during the quiescent period $0 < \tau < 1$.

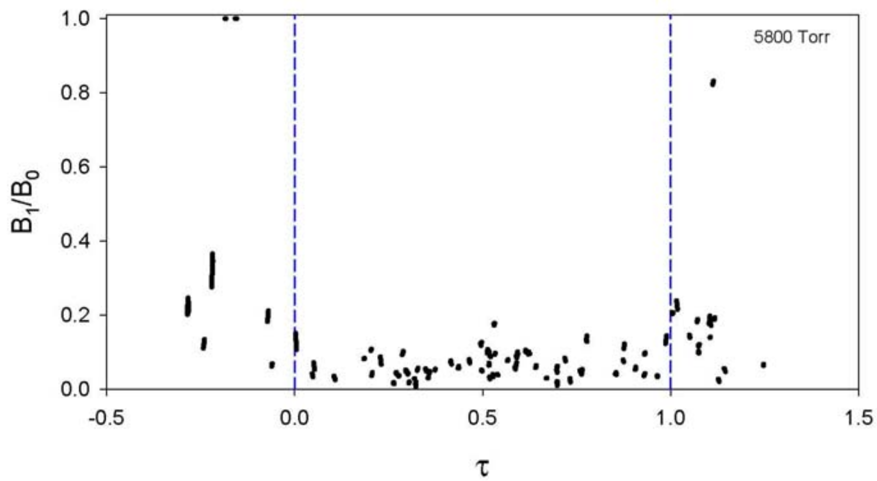

FIG. 4. Magnetic mode data for m = 1 showing fluctuation levels collected during the same gate time as the spectroscopic data as shown in Fig. 3. The length of the data segment for each time is indicative of the radial displacement of the plasma current during the ICCD gate time.

The density measurements are made with a holographic interferometer and with a two-chord He-Ne interferometer.[10] During the quiescent period a peaked electron density profile is measured with maximum values in the range of $10^{16} – 10^{17}$ cm^{-3}. The interferometer also indicates a pinch radius of approximately 1 cm. Using the experimentally measured density, plasma radius, and magnetic field, the Alfven speed is calculated. The theoretical growth time for the kink mode in a static Z-pinch is 20 ns for these plasma parameters. The theoretical flow shear for these plasma parameters has a threshold value of $5\times10^{6}\text{s}^{-1}$.

The axial velocity is high and uniform during the assembly of the Z-pinch plasma ($\tau < 0$). The flow shear is $dV_z/dr \approx 0 - 4\times10^6\,\mathrm{s}^{-1}$, as compared to the theoretical threshold $5\times10^6\,\mathrm{s}^{-1}$ required for stability. At the start of the quiescent period $\tau = 0$, the velocity profile is high at the plasma edge and lower at the axis. The flow shear is $dV_z/dr \approx 7 - 12\times10^6\,\mathrm{s}^{-1}$. The flow shear exceeds the theoretical threshold throughout the quiescent period, except for a brief time when the velocity at the edge slows so the velocity is higher along the axis and lower at the edge. At the end of the quiescent period $\tau = 1$, the velocity profile is low and uniform. The flow shear is $dV_z/dr \approx 0 - 6\times10^6\,\mathrm{s}^{-1}$. The corresponding magnetic mode data shows low fluctuations during the sheared flow plasma state and high fluctuations before and after the quiescent period. Furthermore, the length of the data segment for each time is indicative of the radial displacement of the plasma current during the ICCD gate time. The general finding shows 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 amount of neutral gas injected is varied to test the consistency of the observed plasma behavior and of the correlation between the sheared plasma flow and the quiescent period. The nominal gas line pressure is 5800 torr. Experiments are conducted with gas line pressures at 4500, 3500, and 2500 torr. The quiescent period is seen to increase with the amount of injected neutral gas. The neutral gas continually ionizes, supplies plasma to the pinch, and maintains the sheared flow Z-pinch state. The lower gas line pressure produces shorter quiescent periods, which suggests the plasma source is being exhausted. The finding suggests a means for extending the plasma lifetime.

Measurements of the plasma velocity profile and magnetic fluctuations are repeated with the modified experimental geometry. Magnetic fluctuation data are presented in Fig. 5, which shows a behavior similar to that for the original experimental geometry. As in Fig. 2 for the

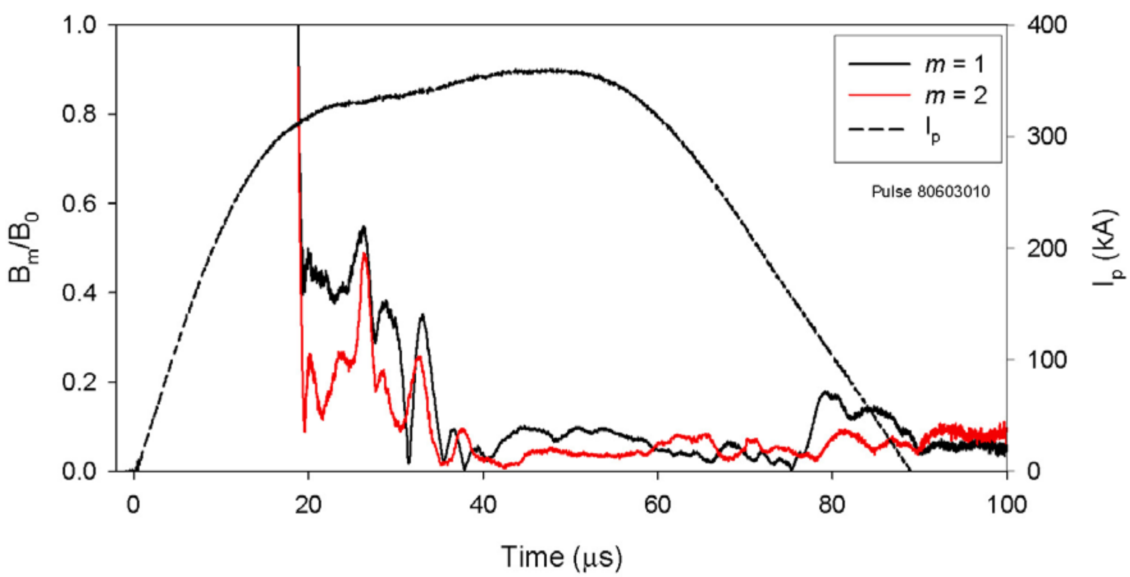

FIG. 5. Time evolution of the Fourier components of the magnetic field fluctuations at z = 0 for the m = 1,2 modes for the modified experimental geometry. The values are normalized to the average magnetic field value. A quiescent period is evident from 34 to 78 μs which defines τ = 0 to 1 for this pulse. The evolution of the plasma current is included for reference.

original geometry, large magnetic fluctuations occur during pinch assembly, after which the amplitude and frequency of the magnetic fluctuations diminish. This stable behavior continues for 34 – 78 μs. A 44 μs quiescent period is seen in Fig. 5. 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 stabilizing effect is evident in the modified experimental geometry, which has a 50% larger inner electrode, different neutral gas injection, and a plasma current that peaks at 360 kA compared to 170 kA for the original geometry.

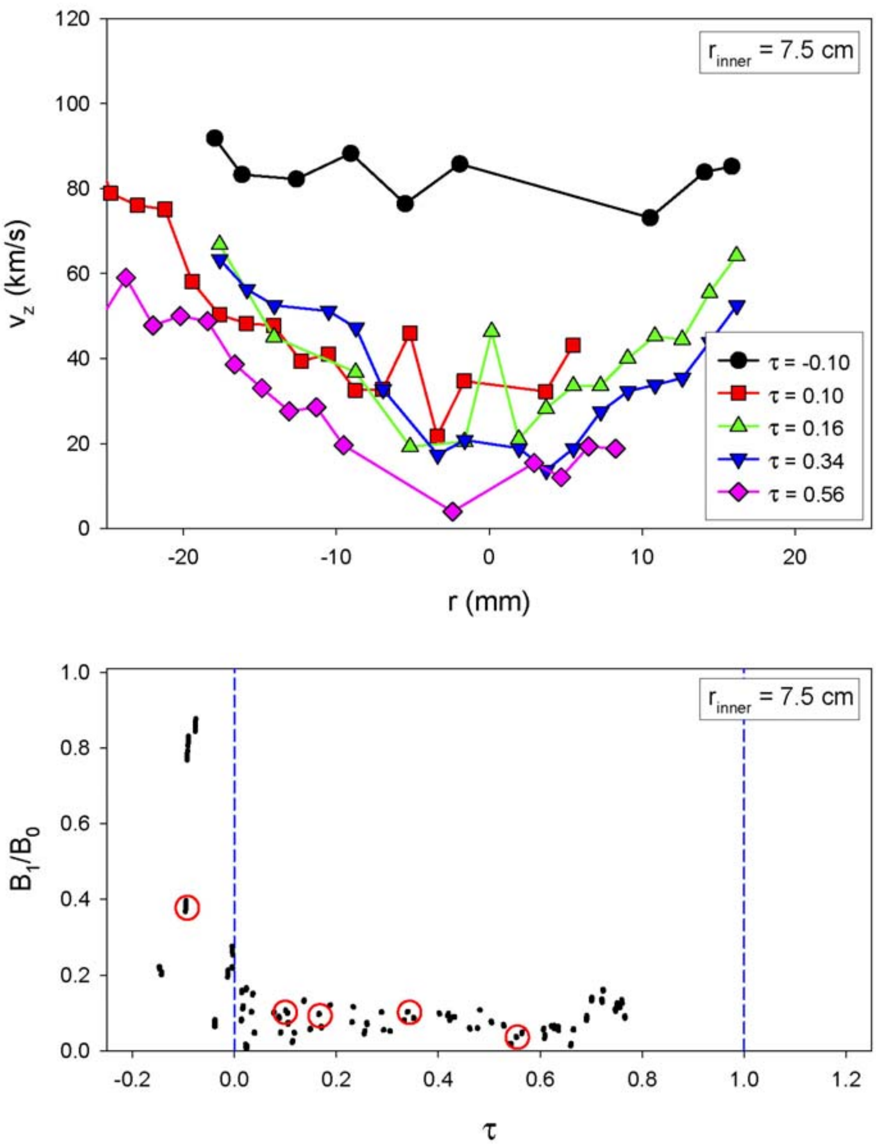

FIG. 6. (upper plot) Axial velocity profiles (for both sides of the axis) at different values of normalized time for several pulses. (lower plot) Magnetic mode data for m = 1 showing fluctuation levels collected during the ICCD gate time for several pulses. The lengths of the data segments are indicative of the radial displacement of the plasma current during the ICCD gate time. Circled data corresponds to the spectroscopic data used in upper plot. A sheared plasma flow is evident during the quiescent period, 0 < τ < 1, indicated by the dashed vertical lines.

The plasma velocity profiles in the modified experimental geometry are measured and deconvolved in the same manner as described previously. Figure 6 (upper plot) presents axial velocity profiles (for both sides of the axis) at different values of normalized time for several pulses. The corresponding magnetic mode data for $m = 1$ collected during the same gate time as the spectroscopic data is shown in the lower plot of Fig. 6. The axial velocity is high and uniform during the assembly of the Z-pinch plasma ($\tau < 0$). The flow shear is $dV_z/dr \approx 0-2\times10^6\,\mathrm{s}^{-1}$. Using experimentally measured density and magnetic field, the Alfven speed is calculated. The theoretical growth time for the kink mode in a static Z-pinch is 25 ns for these plasma parameters. The theoretical flow shear required for stability for these plasma parameters has a threshold value of $4\times10^6\,\mathrm{s}^{-1}$. During the quiescent period, $0 < \tau < 1$, the velocity profile is high at the plasma edge and lower at the axis. The flow shear is $dV_z/dr \approx 3-6\times10^6\,\mathrm{s}^{-1}$. The corresponding magnetic mode data shows low fluctuations during the sheared flow plasma state and high fluctuations before and after the quiescent period. The general finding is consistent with the original experimental geometry – 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.

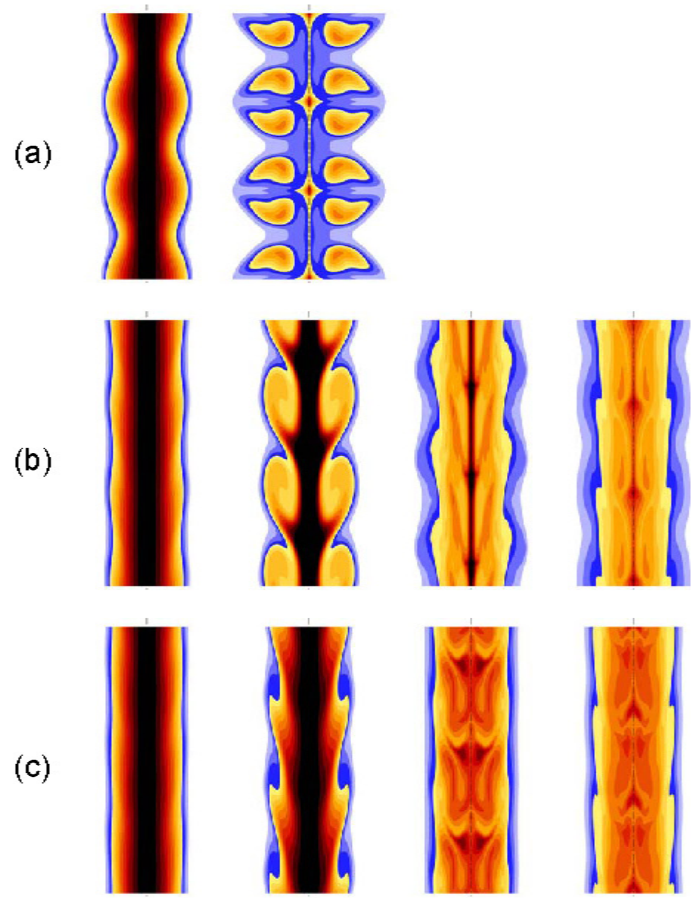

FIG. 7. Nonlinear simulation results showing the pressure contours in a Z-pinch. The results for each simulation time is aligned vertically. (a) No equilibrium axial flow is initialized. The plasma quickly develops an m = 0 mode and loses confinement. (b) An equilibrium axial flow with a uniform shear through the pinch is initialized. The m = 0 mode is significantly less developed than the static plasma case. (c) An equilibrium axial flow with a shear increasing towards the plasma edge is initialized. The stabilizing effect is again evident.

4. Z-Pinch Simulations with Nonuniform Flow Shear

The velocity profile throughout the quiescent period generally does not produce a uniform flow shear across the pinch radius as assumed in the linear stability analysis. To test the effect of nonuniform flow shear on stability, nonlinear simulations of the *m* = 0 mode in a Z-pinch plasma are performed using Mach2, a time-dependent, resistive MHD code. An equilibrium is initialized with a parabolic pressure profile and an axially periodic density perturbation. A series of simulations are performed with varying plasma flow shear. Figure 7 shows Z-pinch simulation results (a) for a static plasma, (b) for a plasma with a uniform flow shear (peak $V_z = 0.2kaV_A$), and (c) for a plasma with a flow shear localized at the plasma edge (peak $V_z = 0.2kaV_A$). The uniform flow shear produces a substantially reduced *m* = 0 instability as compared to the static plasma.

The experimentally measured flow velocity profiles typically show a flow shear that is localized at the edge of the pinch plasma. Computer simulations are used to test shear flow stabilization with flow profiles similar to the experimental flow profiles. Figure 7(c) shows simulation results for a plasma with a flow shear that varies as r^5. The stabilizing effect is evident. The stabilizing results for a nonuniform shear are consistent with other research that indicates the local shear is important for stability.[11]

5. Conclusions

The ZaP project is producing Z-pinch plasmas that exhibit gross stability during a extended quiescent period, consistent with flow stabilization theory. The quiescent period is coincident with a sheared plasma flow. The magnitude of the sheared plasma flow is consistent with flow stabilization theory, even for different amounts of injected neutral gas. Neutral gas supply appears to limit the plasma lifetime and suggests a technique to produce long-lived plasmas. The behavior holds as the diameter of the inner electrode of the coaxial accelerator is increased by 50%. Plasma simulations demonstrate stabilization with flow profiles similar to experimental measurements. A flow-stabilized Z-pinch has many important implications for a simple reactor design and other magnetic confinement concepts. Understanding the physical effects of sheared flows on stability is important to advancing our general understanding of plasma physics and specifically magnetic fusion science, beyond the flow Z-pinch concept alone.

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