Flow Shear Stabilization Experiments 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 located at the midplane of the 50 cm plasma column 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 700 times the expected instability growth time in a static Z-pinch. Optical images from a fast framing camera 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.

1. Introduction

The stabilizing effect of an 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, $dV_Z/dr > 0.1\ kV_A$.[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.

2. ZaP Flow Z-Pinch Experiment

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 plasma is initiated in the middle of a one meter coaxial accelerator, which has an approximately 20 cm diameter outer electrode and an approximately 10 cm diameter inner electrode. Neutral gas (usually hydrogen) is puff injected in the middle of the accelerator region. A capacitor power supply is connected to the electrodes at $t = 0$ which breaks down the neutral gas and forms plasma. The plasma is accelerated to a large axial velocity. The plasma exits the gun and forms a Z-pinch plasma at $t = 20 - 22$ μsec. The pinch plasma is 50 cm in length and approximately 1 cm in radius. Inertia maintains the axial flow within the Z-pinch plasma column. FIG. 1 shows a machine drawing of the experiment identifying the main features. The power supply is configured either to store 28 kJ with a peak plasma current of 250 kA and a quarter cycle time of 25 μsec or to store 44 kJ with a peak plasma current of 275 kA and a quarter cycle time of 30 μsec. The two configurations produce different timings. Diagnostics are concentrated at the midplane of 50 cm pinch. A plasma current evolution is shown in FIG. 2 as a dashed line.

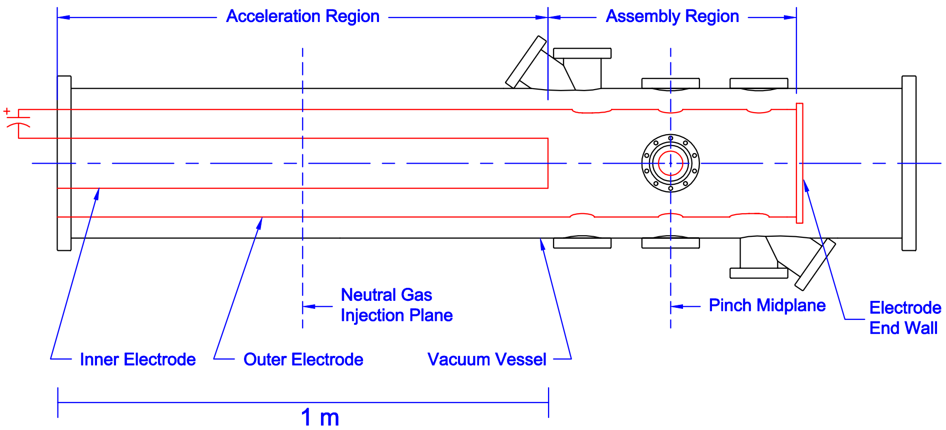

FIG. 1. Machine drawing of the ZaP Flow Z-Pinch experiment identifying the primary features. A 1 m scale is included for reference.

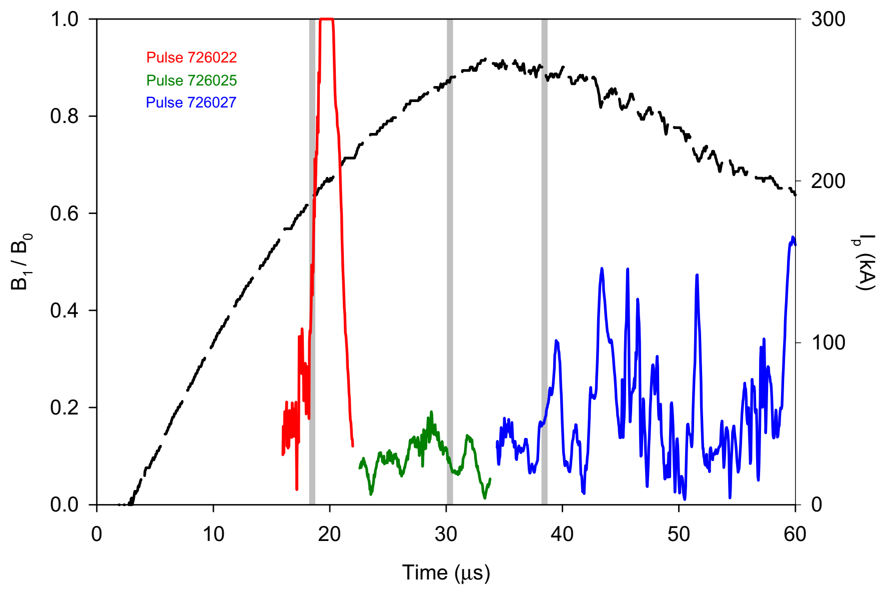

FIG. 2. Evolution of the normalized m=1 magnetic mode activity during formation (red), quiescent period (green), and instability (blue). Plasma current is shown as a dashed line for timing reference.

3. Equilibrium, Plasma Flow, and Stability Measurements

Diagnostics on the ZaP experiment are designed to measure the plasma equilibrium parameters, including the flow profile, and the stability of the plasma pinch. The diagnostics include surface-mounted magnetic field probes, optical emission detectors, interferometers, and spectrometers. An axial array of 23 surface-mounted magnetic probes that are located in the outer electrode and spaced 5 cm apart spans the length of the experiment. The probes indicate the acceleration of the plasma and the distribution and movement of the plasma current. Two azimuthal arrays of surface-mounted magnetic probes are located at the exit of the accelerator and at the midplane of the pinch assembly region. An azimuthal array of eight surface-mounted magnetic probes measures the plasma's magnetic structure at the pinch midplane. Data from these probes are Fourier analyzed to determine the time-dependent evolution of the low order azimuthal modes (m = 1, 2, 3). FIG. 2 shows the evolution of the m = 1 Fourier mode of the magnetic field $B_m(t)$ normalized by the average magnetic field $B_0(t)$. The data presented are compilations of three separate pulses. The m = 2 and m = 3 data are not shown but are generally lower than the m = 1 data at all times. The figure also shows the evolution of the total plasma current for timing reference. The plasma arrives at the pinch midplane at approximately 18 μsec. After the pinch has assembled the initially large fluctuation levels change character for approximately 17 μsec. The change in character is identified by lower levels and decreased frequency during this quiescent period. The fluctuation levels then again change character, increase in magnitude and frequency, and remain until the end of the plasma pulse.

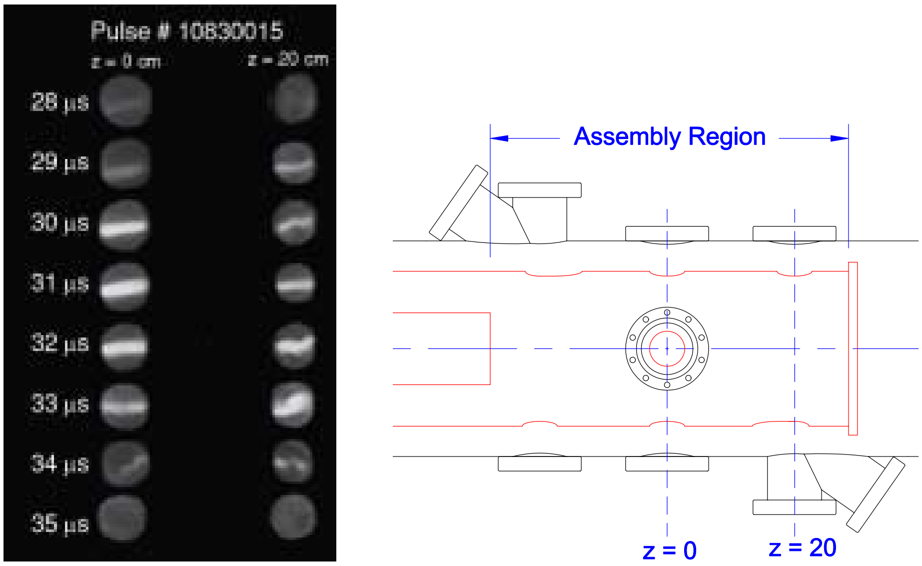

FIG. 3. Optical emission photographs obtained through two viewports simultaneously using an H_α filter which show a stationary plasma pinch extending down the length of the assembly region and kinking late in time. A partial machine drawing shows the locations of the two ports (z =0 and 20 cm) relative to the length of the pinch plasma.

Optical emission images of the pinch midplane obtained with a fast framing camera show a stable pinch that becomes unstable to a kink mode later in time. The timing of the stable period corresponds to the stable time shown in the magnetic data. FIG. 3 shows photographs obtained through an H_α filter through the viewports at z = 0 (midplane) and at z = 20 cm simultaneously.

Time-dependent electron density levels are measured with a two-chord He-Ne heterodyne quadrature interferometer which can be positioned at the pinch midplane, the exit of the accelerator, and before or after the neutral gas injection location. The plasma electron number density at the pinch midplane is determined to be $10^{16} – 10^{17}$ cm^{-3} inside the pinch assuming a 1 cm pinch radius and a uniform density within the pinch radius. If it is assumed that no plasma current flows outside of the pinch radius, then the total plasma temperature can be determined from the magnetic field at the outer electrode and the density information. The magnetic field measured at the 10 cm outer electrode at the pinch midplane is 0.15 – 0.25 T. The magnetic field at the pinch radius is then 1.5 – 2.5 T. The total plasma temperature (T_e + T_i) is estimated from force balance to be 150 – 200 eV. Density profiles at a single time are obtained with a double-pass holographic interferometer that uses a pulsed ruby laser. The laser pulse length is approximately 50 nsec. The integrated density profiles are deconvolved using an Abel method. Deconvolved density profiles are shown in FIG. 4 obtained (a) during the pinch assembly at 22 μsec and (b) during the plasma quiescent period at 27 μsec. The profiles show a discrete plasma pinch with a radius of 0.5 cm during assembly. The plasma density is peaked. During the quiescent period the plasma pinch expands to 1 cm in radius and develops a hollow core structure. The total plasma temperature profile can be calculated using force balance with the magnetic force and assuming a cold plasma outside of the pinch radius and no plasma current flows outside of the pinch radius. The temperature profiles are shown in FIG. 4. The temperature profiles show a cool plasma during pinch assembly that develops a hot core during the quiescent period. The values of the pinch radius, density, and temperature are consistent with the data from the He-Ne interferometer.

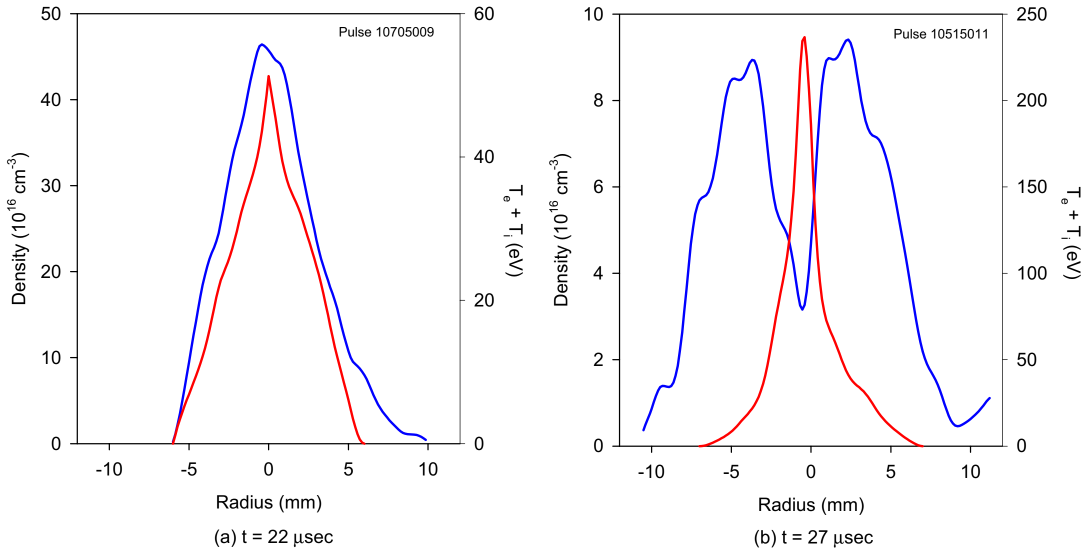

FIG. 4. Deconvolved interferometric holograms (a) obtained during plasma assembly (t = 22 µsec) show a discrete plasma pinch which is small, dense, and cool. (b) During the quiescent time (t = 27 µsec) the plasma develops a hollow, hot core.

Two spectrometers are used to measure the line radiation from the plasma. A 0.5 m Jarrell-Ash spectrometer is connected with a UV-grade fused silica fiber to a telescope that views the pinch plasma. The spectrometer output is split between a CCD camera to record the time-integrated spectrum and a PMT to monitor the evolution of a single emission line. The ion temperature is calculated from Doppler broadening of the C-III impurity line at 229.7 nm to be 50 – 80 eV. When the hydrogen neutral gas is mixed with methane, the C-V triplet lines centered around 227.5 nm can be seen during the quiescent period.

Profile information is determined from a 0.5 m Czerny-Turner imaging spectrometer with an intensified CCD (ICCD) detector. The ICCD camera is set to a gating time of 0.5 – 1 µsec and the trigger time is varied between plasma pulses. The spectrometer images 20 chords separated 1.24 mm apart through the plasma pinch onto the ICCD camera using telecentric viewing telescopes.[4] A telescope uses the lower oblique viewport shown in FIG. 1. which is positioned at a 35^{o} angle to the plasma axis. Since this oblique viewport has a component along the axis, an axial plasma flow produces a Doppler shift of impurity line radiation. The axial velocity profile is determined by measuring the Doppler shift. The data recorded on the ICCD camera have been chord integrated and modified by the instrument function of the spectrometer. The profile information is determined by removing these effects through a deconvolution procedure that fits the data to a plasma model that assumes concentric shells of uniform emissivity, velocity, and temperature within each shell.[5] The deconvolution procedure is only successful when the edge of the plasma is visible. In general, gradients steepen through deconvolution. When the edge of the plasma is not visible an approximate profile information is obtained by fitting the raw data at each chord to shifted and widened Gaussian functions. FIG. 5 shows the axial velocity profiles (not deconvolved) determined from the shift of the C-III impurity line at 229.7 nm. The velocity profiles are obtained at the three times indicated by the shaded lines in FIG. 2 (t = 18, 30, and 38 μsec). The profile obtained during the pinch assembly indicates a mostly uniform velocity profile with values of 3 – 5 cm/μsec. During the quiescent period the plasma exhibits a structured velocity profile with shear at the edge. When the mode activity becomes high the plasma velocity is uniform and low, 0 – 1 cm/μsec.

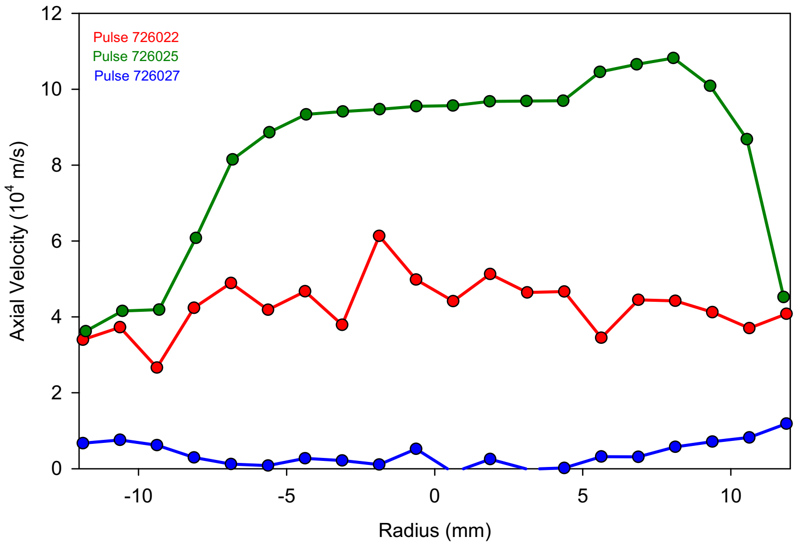

FIG. 5. Axial plasma velocity profiles for the times indicated in FIG. 2 showing a large, sheared flow (green) during the quiescent period at t = 30 μsec and low, uniform flow profiles (red and blue) during periods of high mode activity at t = 18 and 38 μsec.

4. Analysis and Conclusions

The measured axial flow shear can be compared to the required threshold predicted by linear theory. From the experimental data, the Alfvén speed, V_A, is 1.3×10^5 m/s. The theoretical growth time for the m = 1 mode in a static Z-pinch is approximately $(kV_A)^{-1}$ which for the experimental values obtained in the ZaP experiment gives τ_{growth} = 24 nsec for ka = π. The axial velocity shear required for stability according to the theory is 4.2×10^6 s^{-1}. Experimental results show a stable period of 17 μsec, over 700 growth times. The experimentally measured axial velocity shear is 1.9×10^7 s^{-1} during the stable period and approximately zero afterwards when the magnetic mode fluctuations are high. The correlation of the experimental stability data with the plasma flow measurements is consistent with the shear flow stabilization theory.[6] Furthermore, the density and spectroscopic measurements indicate a pinch plasma that has sufficient confinement to demonstrate a heating of the plasma core during the quiescent period. A flow-stabilized Z-pinch has many important implications for a simple reactor design and other magnetic confinement concepts.

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