THE ZAP FLOW *Z*-PINCH: PLASMA FLOW SHEAR AND STABILITY

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The ZaP Flow Z-pinch plasma device at the University of Washington produces a small diameter (20–30 mm) dense Z-pinch plasma with typical electron density 10^{22}–10^{23} m^{-3} and ion plus electron temperature 100–200 eV. The plasma is stable, with relatively low magnetic mode activity, for tens of microseconds. This is orders of magnitude longer than predicted by a simple ideal magnetohydrodynamic calculation. The probable stabilizing mechanism is radial shear in the axial plasma flow. The axially flowing Z-pinch is generated with a coaxial accelerator coupled to a pinch assembly chamber. After the pinch assembles a quiescent period occurs, during which the mode activity is significantly reduced. 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 plasma has a sheared axial flow that exceeds the theoretical threshold for stability during the quiescent period and is lower than the threshold during periods of high mode activity. The Z-pinch plasmas are globally stable for 700–2000 times the theoretically predicted kink growth time of a static Z-pinch. The end of the quiescent period corresponds to a decrease in acceleration of plasma and possibly suggests a means to extend the experiment to quasi-steady-state operation.

I. INTRODUCTION

The *Z*-pinch plasma configuration has been studied for at least 80 years, and was intensively investigated during the early years of fusion research [1-4]. The *Z*-pinch was largely abandoned as a magnetic confinement configuration due to violent magnetohydrodynamic (MHD) instabilities (gross $m = 0$ "sausage" and $m = 1$ "kink" modes). However, the *Z*-pinch is an attractively simple configuration; a stable, high-density *Z*-pinch would have important implications for fusion research.

Several methods have been developed to stabilize the *Z*-pinch. Unfortunately each method has drawbacks. A close-fitting conducting wall limits the energy content of the plasma. Application of an axial magnetic field connects field lines to material surfaces and limits the plasma current [5]. A gradually decaying pressure profile stabilizes $m = 0$ modes, but not $m = 1$ modes [5].

An intriguing result from several past experiments was the production of a stable *Z*-pinch with inherent axial plasma flow [6,7]. Linear stability analysis has shown that $m = 1$ kink modes in a *Z*-pinch can be stabilized by the application of an axial plasma flow with linear shear $dv_z/dr > 0.1kV_A$, where k is the axial wave number and V_A is the Alfven velocity [8]. Nonlinear analysis indicates that the $m = 0$ mode is also stabilized by radial flow shear of this same magnitude [9]. These analyses included the effect of plasma compressibility. Flow shear can lead to plasma compression, which may convert the energy from the statically unstable mode to acoustic waves. The acoustic waves transport energy away and thus may decrease the energy available to drive an unstable mode.

The ZaP (*Z*-pinch) experiment at the University of Washington was designed to test these predictions. The *Z*-pinch plasmas produced in ZaP are globally stable for 700–2000 times the predicted kink mode growth time of a static *Z*-pinch. The plasma has a sheared axial flow that exceeds the theoretical threshold for stability during the period in which mode activity is quiescent and is lower than the threshold during periods of high mode activity.

II. THE ZAP EXPERIMENT

In ZaP, an axially flowing *Z*-pinch plasma is generated with a coaxial accelerator coupled to a pinch assembly chamber (Fig. 1). Hydrogen gas is puffed into the midpoint of the acceleration region between the two coaxial electrodes, and a voltage is applied between the electrodes. The gas breaks down and forms an annular current sheet (Fig. 2), which is accelerated by the **J**×**B** force. When the plasma reaches the end of the inner electrode in the acceleration region, it collapses onto the *z*-axis in the assembly region. The plasma in contact with the outer electrode continues to move axially until it reaches the electrode end wall where it moves radially inward to complete the pinch formation. Axial plasma flow in the pinch is maintained by inertia. Plasma is continuously accelerated and incorporated into the pinch by current in the acceleration region. The plasma

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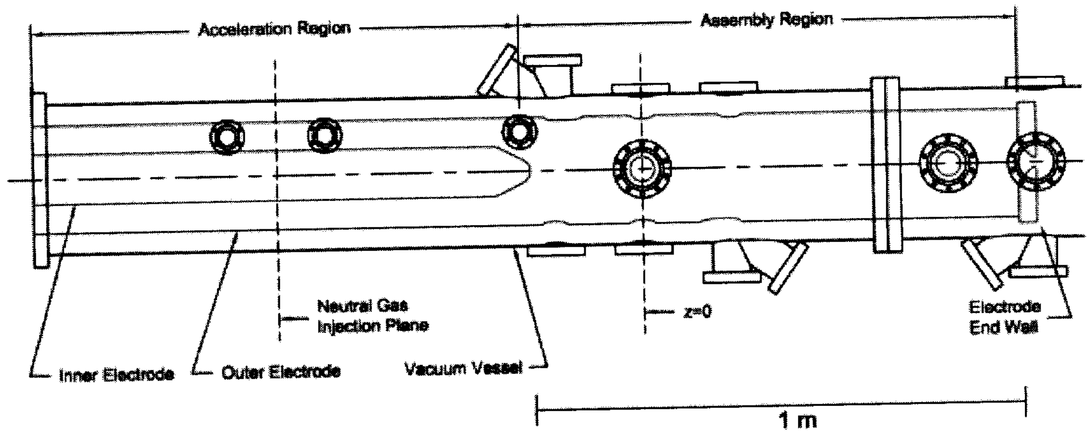

Fig. 1. The ZaP Flow Z-pinch experiment initiates a plasma with a one meter coaxial accelerator which has a 20 cm diameter outer electrode and a 10 cm diameter inner electrode. The plasma current is supplied by a 17.5 kJ capacitor bank configured as a pulse-forming network. Note the locations of the acceleration and assembly regions.

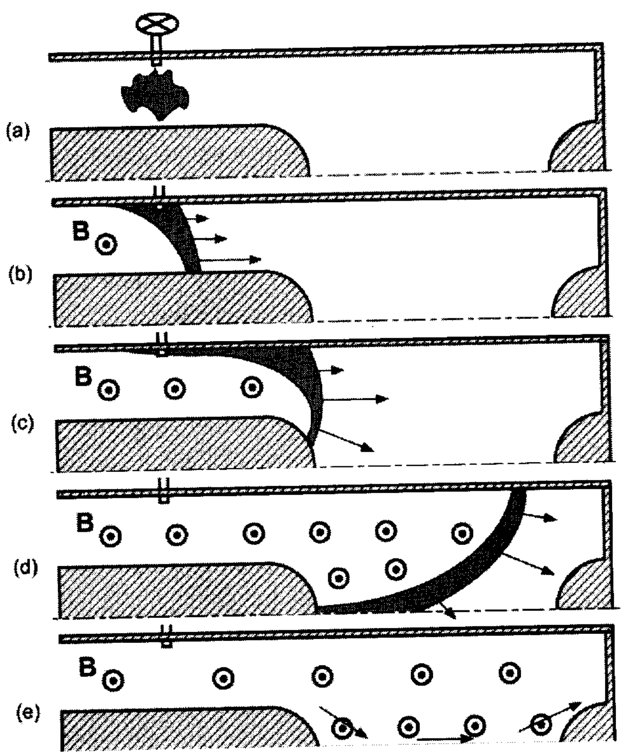

Fig. 2. Schematic representation of Z-pinch plasma formation in ZaP: a) neutral gas is injected into the annulus of the coaxial accelerator, b) the gas breaks down and the **J**×**B** force of the current accelerates the plasma axially, c) plasma moves radially toward the axis at the end of the accelerator, d) plasma assembles along the axis, e) plasma is attached between the inner electrode and outer electrode end wall and inertia maintains the axial plasma flow. Plasma is continuously accelerated and incorporated into the pinch by current in the accelerator.

exhausts through a hole in the electrode end wall.

Plasma flow is passively measured in ZaP by recording the Doppler shift of lines emitted by intrinsic carbon impurities in the majority hydrogen plasma. These measurements are made at the $z = 0$ location in the assembly region (Fig. 1). Spectra are dispersed with a 0.5 m imaging spectrometer and recorded with an intensified charge-coupled device (ICCD) detector. The ICCD camera is set to a gate time of 0.1–1 μs and the trigger time is varied between plasma pulses. To obtain radially resolved profiles of the axial flow velocity in ZaP, the plasma is viewed through two telescopes. The radial telescope views perpendicular to the axis of the ZaP plasma, and thus provides the non-Doppler-shifted reference spectra (radial and azimuthal flows are small relative to axial flow). The oblique telescope views 35° off the ZaP axis, and is sensitive to Doppler shifts induced by axial flows. These viewing telescopes are telecentric [10], meaning that all object chords in the plasma, including those laterally displaced from the optical axis, are formed by ray bundles whose chief ray is parallel to the optical axis. Thus, all 20 light collection chords passing through the ZaP plasma are parallel and equally spaced, simplifying calibration and data reduction, particularly inversion of the chord-average profile to local flow velocities. A deconvolution technique based on a shell model, which includes the effects of the instrument function, is used to deduce the local plasma parameters as function of radius [11].

Plasma stability is diagnosed with an azimuthal array of eight surface-mounted magnetic probes that measure the magnetic structure of the plasma. Data from these probes are Fourier analyzed to determine the time-dependent evolution of the low-order azimuthal modes ($m = 1, 2, 3$).

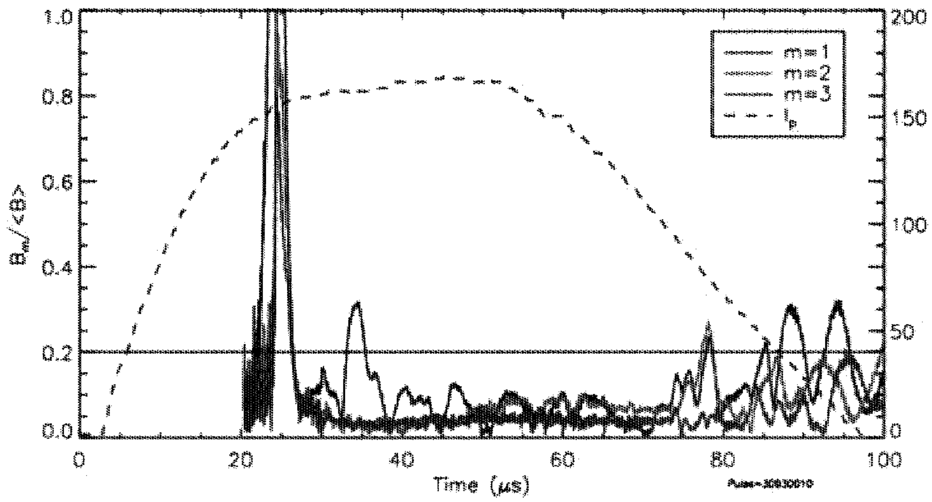

Fig. 3. The *Z*-pinch typically exhibits a quiescent period of approximately 35 μs duration. $B_m(t)$, the amplitude of the $m = 1, 2, 3$ Fourier modes of the magnetic field, is normalized by the average magnetic field $<B(t)>$.

III. RESULTS FROM A STABLE *Z*-PINCH

The magnetic mode activity from a typical ZaP discharge is shown in Fig. 3. The plasma arrives at the pinch midplane at approximately 20 μs. After the pinch has formed the initially large magnetic fluctuation levels drop below the empirical level of 0.2 and the pinch enters a quiescent period. During this period the amplitude of all mode activity is substantially reduced and mode frequency is decreased. At approximately 70 μs the quiescent period ends and mode activity increases in magnitude and frequency, and remains so until the discharge terminates. Optical emission images of the pinch midplane obtained with a fast framing camera show a stable pinch during the quiescent period. At the end of the quiescent period the pinch becomes visibly unstable to a kink mode [12].

The plasma flow velocity profile evolves throughout the *Z*-pinch discharge. This is illustrated versus normalized time in Fig. 4. Only one radial profile of the axial flow can be measured per discharge and the timing of the quiescent period is not exactly reproducible, therefore the time axis is normalized such $\tau = 0$ marks the start of the quiescent period and $\tau = 1$ the end. Thus the time containing the quiescent period is described by $\tau = [0,1]$. As the *Z*-pinch forms, a uniform 100 km/s velocity is seen. As the quiescent period begins the velocity of the center slows to 40 km/s, forming a positive velocity shear. In the second half of the quiescent period the edge velocity slows to 0 km/s, forming a negative velocity shear. Then at the end of the quiescent period the velocity profile becomes uniform. During the quiescent period plasma is present in the acceleration region and maintains the flow in the *Z*-pinch. The quiescent period ends as the plasma exits the acceleration region and no longer maintains a sheared velocity profile in the assembly region.

The observed velocity shear during the quiescent period is consistent with the theoretical expectation that an axial plasma flow with linear shear $dv_z/dr > 0.1kV_A$ will stabilize the kink mode. Using measured parameters from the experiment, $a \approx 0.01$ m and $V_A \approx 1.5 \times 10^5$ m/s.

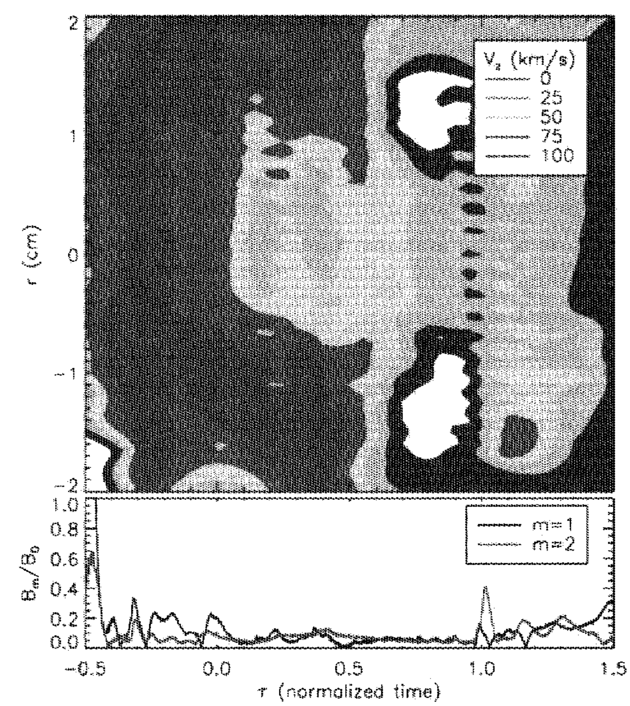

Fig. 4. The radial profile of the axial plasma flow evolves throughout the ZaP discharge, showing substantial shear throughout the quiescent period. Time $\tau = [0,1]$ contains the quiescent period.

For a static *Z*-pinch ideal MHD instabilities should grow on a timescale of $(kV_A)^{-1}$, which for ZaP parameters is 21 ns assuming $ka = \pi$. The ZaP plasma is stable with low mode activity for a quiescent period up to 2000 times this ideal growth time. Using the theoretical expectation, the axial velocity shear required for stability is 5×10^6 s^{-1}. The experimentally measured axial velocity shear is between 6.5–12 $\times$ 10^6 s^{-1} during the stable period τ = [0,0.9], drops to 3–6 $\times$ 10^6 s^{-1} at the end of the quiescent period ($\tau \approx 0.95$), and below 3×10^6 s^{-1} after the quiescent period ($\tau > 1$) when the magnetic mode fluctuations are large.

IV. SUMMARY AND FUTURE WORK

The ZaP Flow *Z*-pinch uses a coaxial plasma accelerator coupled to an assembly region to form *Z*-pinches with a sheared plasma flow profile. The accelerator supplies plasma to the *Z*-pinch to maintain the sheared flow profile. The plasma is stable with low magnetic mode activity for up to 2000 times the growth time of the ideal MHD modes that destabilize a static *Z*-pinch. Experimental results from ZaP confirm that stable operation of the pinch is strongly correlated with the presence of radial shear in the axial flow velocity profile. The observed threshold of shear necessary for stability is consistent with theoretical predictions.

Future work on ZaP will include characterization of the fastest growing mode at the end of the quiescent period, and measuring the plasma pressure profile to enable more accurate stability analysis. A continuing goal is to increase the length of the quiescent period in order to approach quasi-steady-state operation. A flow-stabilized *Z*-pinch has the potential to provide a simple fusion reactor design, requiring neither close-fitting conducting walls nor an axial magnetic field.

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