SHEARED-FLOW-STABILIZED Z PINCH AS A COMPACT FUSION DEVICE

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Abstract

The Z-pinch equilibrium radially confines plasma pressure with an axial current. High densities and temperatures should result from plasma compression from increasing the current. However, virulent pressure-driven instabilities quickly destroy the equilibrium and impede the path to a viable fusion device for the traditional Z pinch. Introducing a sheared axial flow to the plasma was theorized to stabilize the Z pinch. Closely coupled with computational studies, a series of Z-pinch experiments (Zalp and Zalp-HD) at the University of Washington were used to test the theory of sheared-flow stabilization. Diagnostic measurements of the plasma equilibrium and stability confirmed that in the presence of a sufficiently large flow-shear, gross Z-pinch instabilities were mitigated, and radial force balance was achieved. Z-pinch plasmas of 50, 100, and 126-cm lengths were held stable for durations much longer than predicted for a static plasma, thousands of growth times. Experimental results were combined with adiabatic scaling relations and detailed single-fluid, multi-fluid, and kinetic computational studies to explore the limits of plasma properties that can be achieved in a sheared-flow-stabilized (SFS) Z pinch. The collaborative FuZE (Fusion Z-pinch Experiment) project between UW and LLNL scaled the SFS Z pinch to fusion conditions. Flow-shear stabilization was demonstrated to be effective even when a 50-cm long plasma column was compressed to small radii (3 mm), and improved understanding of stabilization provided a means of increasing plasma parameters, $n_e > 10^{17}$/cc and $T_i > 1$ keV. Results have demonstrated that fusion reactions are sustained along a 50-cm long Z-pinch deuterium plasma. Steady neutron production was observed for durations up to 8 microseconds during which the plasma was stable, and the current was sufficiently high to compress the plasma to fusion conditions. The neutron production was demonstrated to be consistent with a thermonuclear fusion process. Increasing the pinch current has demonstrated a corresponding increase in neutron yield. The dependence of yield on current is compared to theoretical scaling relations of $I^{1/3}$ and numerical simulations. Experimental observations generally agree with theoretical and computational predictions, indicating that sheared flows can stabilize and sustain a Z-pinch equilibrium and offering a potential path to achieve even higher performing plasmas.

1. INTRODUCTION

The Z pinch offers attractive scaling to fusion energy. The equilibrium has no applied axial magnetic fields and is described by a radial force balance.

$$\frac{dp}{dr} = -j_z B_\theta = -\frac{B_\theta}{\mu_0 r} \frac{d}{dr}(r B_\theta)$$

With no applied axial magnetic field, the plasma beta is unity. Increasing the directly driven plasma current results in a larger azimuthal magnetic field that compresses the plasma to fusion conditions in a compact device – no magnetic field coils.

The increase in plasma parameters as a function of plasma current can be determine through scaling relations $1,2,3$ derived by assuming adiabatic compression and radial force balance. The relations describe the change in density, temperature, and pinch radius between two plasma states 1 and 2 that have the same integrated plasma particles but with different current

$$\left(\frac{n_2}{n_1}\right) = \left(\frac{T_2^{1/2}}{T_1^{1/2}}\right)^{1/1} = \left(\frac{l_2}{l_1}\right)^{2/1},$$
\frac{a_2}{a_1} = \left( \frac{I_1}{I_2} \right)^{\frac{1}{\gamma-1}},

where \( n_1, T_1, \) and \( a_3 \) are the plasma number density, temperature, and pinch radius with current \( I_1 \), and \( \gamma \) is the adiabatic index. The scaling relations are zero dimensional and are predicated on having a stable plasma.

Stabilizing the Z pinch has proven to be challenging. While the equilibrium is attractive, the Z pinch is classically unstable to MHD modes: \( m = 0 \) sausage and \( m = 1 \) kink. Stability can be provided by limiting the pressure gradient [4], introducing an axial magnetic field [5], or installing a close-fitting conducting wall [6]. These approaches are incompatible with magnetically confining a high-temperature, high-density plasma.

Theory suggests that \( m = 1 \) kink mode can be stabilized with a sheared axial flow [7] beyond a threshold value given by

\[
\frac{dv_z}{dr} \geq 0.1 k V_A
\]

where \( v_z \) is the axial flow velocity, \( k \) is the wave number of unstable mode, and \( V_A \) is the Alfvén speed. The value of the required shear and its effectiveness is sensitive to the axis treatment [8]. Flow shear is also observed to stabilize the \( m = 0 \) sausage mode. [9]

2. SHEARED-FLOW-STABILIZED Z PINCH

The sheared-flow stabilization has been investigated through a series of projects that integrated experimental and computational studies: the flow Z-pinch ZaP (1999 – 2009), the flow Z-pinch at high density ZaP-HD (2009 – 2015), and the fusion Z-pinch experiment FuZE (2015 – present). Figure 1 shows a machine drawing of the FuZE device.

![FIG. 1. FuZE (Fusion Z-pinch Experiment) device produces sheared-flow stabilized Z-pinch plasmas (shown schematically in magenta). The device couples a coaxial accelerator to a pinch assembly region to produce and sustain the flow Z-pinch plasma state.](image)

These flow Z-pinch projects explored using sheared flows to stabilize an unstable plasma and magnetically confined the plasma and compressed it to high plasma parameters and eventually to achieve fusion reactions. Sheared-flow-stabilized (SFS) Z-pinch plasmas [10] were generated that were 50 – 126 cm long. Plasma stability was observed to be coincident with a sheared flow state. [11,12] The plasma equilibrium was experimentally characterized and demonstrated to be in radial force balance. [2,13] When compressed to sufficiently high density and temperature, fusion reactions were sustained [3,14] during the quiescent period.

In addition to the experimental investigations, detailed numerical simulations have been critical to gain improved physical understanding into the SFS Z pinch. Nonlinear fluid [15] and kinetic [16] simulations using Mach2 for MHD modeling, WARPXM for multi-fluid plasma modeling, and LSP for kinetic PIC modeling have been used to (a) study sheared flow stabilization, (b) design experimental details, (c) model whole device, and (d) predict neutron yield.
The FuZE device produces stable, high-performance plasmas. Stable plasma behavior is observed during the quiescent period, when the pinch current rises above 200 kA. Digital holographic interferograms indicate pinched plasma density structures with $\alpha \approx 3$ mm, $B_\theta \approx 10$ T, and $T_e + T_i \approx 1.8$ keV using the analysis technique described in Ref. [17]. Spectroscopic measurements show Doppler-broadened spectra during the quiescent period indicating $T_i \approx 1.0 - 1.5$ keV from He-like C V emission. The presence of which suggests high $T_e$ and well confined electrons.

When gas mixtures containing deuterium, $D_2 – H_2$, are used to make FuZE plasmas, sustained fusion neutron production [14] is detected coincident with quiescent period and large pinch current. The neutron production is sustained for approximately 8 μs with measurements indicating an emission at a steady rate to within statistical expectations. See Fig. 2. The neutron yield is observed to scale with the square of the deuterium concentration.

Neutron emission and energy are characterized using plastic scintillators. The detectors are placed at various locations relative to the Z-pinch plasma as shown in Fig. 3. Close placement of the detectors provides a means of neutron imaging to determine the volume over which fusion reactions are occurring. The findings indicate that fusion occurs uniformly along the Z-pinch length (33 cm of the 50 cm long plasma) [18], as a line source.

**FIG. 2.** Experimental measurements from the FuZE device showing low magnetic fluctuation levels (red) during the quiescent period and neutron emission (green) occurring when the pinch current (blue) becomes sufficiently high. The integrated neutron count gives the time-dependent yield (purple) and shows a linear increase, which indicates a steady and sustained fusion neutron production.

**FIG. 3.** Plastic scintillator neutron detectors positioned at various locations relative to the Z-pinch plasma, which allows determination of the neutron emission volume and neutron energy spectra.
Neutron energy spectra are characterized from proton recoil signals of upstream and downstream plastic scintillator detectors that are visible in Fig. 3. The maximum neutron energy is related to the energy of any beams that are present according to

\[ E_{n_{\text{max}}} = \frac{1}{8} \left( \sqrt{E_b} + \sqrt{3(E_b + 2E_f)} \right)^2 \]

where \( E_b \) is the beam energy and \( E_f \) is the fusion energy release, 3.27 MeV for the D-D fusion reaction. Measurements of the FuZE neutron energy spectra from the upstream and downstream detectors are statistically identical. Accounting for a measurement uncertainty of 140 keV limits the maximum deuteron beam energy to below 7.5 keV [19]. Beam energies typically present to induce beam-target fusion are several hundred keV. The measurements from the FuZE SFS Z-pinch device indicate that the observed fusion originates from a thermonuclear process.

The adiabatic scaling relations from Sec. 1 predict a neutron yield that strongly depends on the Z-pinch current. The fusion neutron yield for a deuterium plasma scales as \( Y_n \propto I^{11} \) [3], for the plasma parameters measured on FuZE. The scaling is confirmed by two-temperature MHD simulations. Initial results from an experimental campaign on the FuZE SFS Z pinch to increase pinch current shows yields that may be consistent with this expectation. The data is presented in Fig. 4 on a log-log plot.

3. SCALING THE SFS Z PINCH TO A FUSION REACTOR

Starting with experimentally achieved plasma parameters at 50 kA from the ZaP device, the adiabatic scaling relations indicate that increasing the current rapidly reaches breakeven conditions. Fusion core remains compact [20] even at high Q. The large instantaneous power associated with the high plasma density avails modest duty cycle operation. Adiabatic scaling results can be compared to experimental measurements obtained with higher currents [3] to show that the experimental measurements exhibit higher temperature and lower density, which results in a higher Q.

4. CONCLUSION

The sheared-flow-stabilized (SFS) Z pinch produces equilibrium plasmas that exhibit gross stability during an extended quiescent period. The quiescent period is coincident with a sheared plasma flow that is consistent with sheared flow stabilization theory. Combining fluid and kinetic numerical simulations with well-diagnosed experiments – ZaP, ZaP-HD, and FuZE – has demonstrated scaling of the SFS Z pinch to high energy density...
plasmas. Experimental measurements show an axially uniform, compressed plasma with high parameters: $a \approx 3$ mm, $n_e \approx 10^{17}$ cm$^{-3}$, $B_0 \approx 10$ T, and $T_e \approx T_i \approx 3$ keV. The FuZE device has demonstrated sustained neutron production during the quiescent period with measurement of the neutron energy to indicate a thermonuclear fusion process. The SFS Z pinch has no magnetic field coils resulting in a compact device that could be attractive for terrestrial fusion energy.

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