

Generation of high magnetic fields using a gas-puff Z pinch

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The imploding plasma column of a gas-puff Z pinch was used to compress an embedded axial magnetic field. Field compression ratios up to 180 times and peak compressed fields up to 1.6 MG were measured by Faraday rotation. Field compression by this method has the advantage of high repetition rate for applications in the controlled production of high-energy densities, solid-state studies, generation of short-wavelength radiation, reducing the ignition threshold for fusion, and particle acceleration.

This letter summarizes flux compression experiments, performed on a gas-puff Z pinch at the University of California, Irvine, in which an axial magnetic field B_0 was compressed hundredfold to levels exceeding 1 MG. In these experiments the B_0 field was injected between two vacuum electrodes that are subsequently energized, in the presence of an annular gas puff, to establish a Z discharge. As the J_z current increases the plasma column implodes to a small final radius by the action of a $\mathbf{J}_z \times \mathbf{B}_\theta$ self-magnetic force. The high conductivity of the plasma column traps the injected magnetic flux, compressing the axial field.

To date the highest documented fields are in the range of 15–20 MG and were achieved using explosive-driven generators to implode metallic liners or foils.^{1,2} The method described in this letter is scaleable to higher fields and ameliorates many of the difficulties of these alternate approaches. Specifically this method is controllable, has a high repetition rate, and is characterized by a high-temperature plasma, 0.1–1 keV, with implosion velocities in the range 10–100 cm/ μ s, the latter of which is desirable to reduce flux diffusion losses.

Figure 1 displays a schematic illustration of the Z-pinch facility.³ In this device a fast-gas valve⁴ injects an annular gas puff between two vacuum electrodes driven by a capacitor bank and parallel plate transmission line ($C = 12 \mu\text{F}$, $L = 58 \text{ nH}$, $\tau_{1/4} = 1.25 \mu\text{s}$, $I = 470 \text{ kA}$ at $V = 32 \text{ kV}$). The repetition rate of this pinch is approximately one shot every 3 min, limited principally by capacitor bank charging times.

To accommodate the magnetic field experiments the Z pinch was modified with (1) a Helmholtz coil to inject the B_0 field, (2) high-resistivity anode/cathode (AK) electrodes to enhance diffusion of the B_0 field into the electrodes, and (3) diagnostics to measure the high fields. The Helmholtz coil consisted of two fiberglass reinforced coils (seven turns each, #18 gauge copper wire, 1.5 cm coil spacing) wound on a G-10 form (10.4 cm o.d.) and energized by a capacitor bank ($C = 68 \mu\text{F}$, 13 kJ, $\tau_{1/4} = 65 \mu\text{s}$). Machined into the G-10, between the coils, were several slots to allow diagnostic radial viewing of the pinch. The cathode electrode was fabricated from a carbon-carbon fiber composite,⁵ the choice of which was motivated both by its high electrical resistivity and our desire to evaluate erosion-resistant electrode materials for pulsed, high-current applications; this material displayed superior erosion resistance with little ap-

parent damage after hundreds of shots. The cathode electrode also served as a nozzle to collimate the gas puff into a 2-cm radius annular flow between the AK electrodes. The grounded-anode electrode was fabricated from 0.7-cm-thick stainless-steel honeycomb and was axially displaced from the cathode by 1 cm.

Standard diagnostics include dB/dt (B -dot) magnetic probe, vacuum x-ray diode (XRD), Mach-Zehnder laser interferometer,⁶ and Faraday rotation. The B -dot probe measures the time derivative of the pinch current and when used in conjunction with the XRD evaluates the "hardness," reproducibility, and timing of the pinch. The nitrogen laser interferometer measures the density, radius, and dynamics of the plasma column during implosion. The magnitude of the compressed B_0 field was measured by Faraday rotation in a fused silica quartz fiber mounted coaxial with the pinch. The fiber was 35 cm long, 0.725 mm in diameter, with an opaque cladding. Depending on the value of B_0 , a single fiber survived multiple Z-pinch firings with little or no apparent damage. The polarized laser beam was the green line (514.7 nm) of a 2-W (coherent) argon ion laser, detected by a (Hamamatsu S1722, 1.5-ns rise time) photodiode with a 1.0-nm bandpass filter.

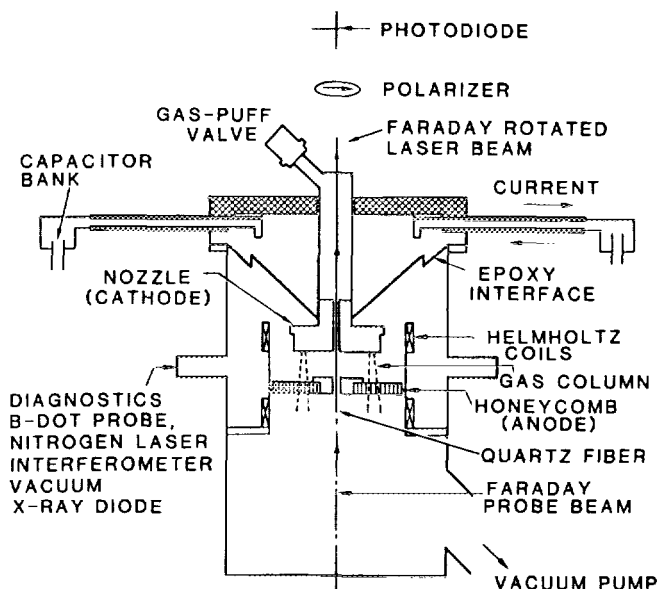


FIG. 1. Schematic illustration of the gas-puff Z pinch and diagnostics.

The effects on the pinch of increasing the B_0 field at fixed mass per unit length M/L were to (1) delay the onset of the pinch, (2) increase the final compressed radius of the pinch, (3) decrease the x-ray intensity at pinching, and (4) stabilize the plasma column before and after the pinch. Effects #1 and #2 are due to the larger initial (magnetic) pressure inside the plasma column which results in a slower and softer constriction of the plasma column at pinching, effect #3. Effect #4 was noticeable by injecting even a small amount of axial field, $B_0 \approx 1$ kG. Normally, with $B_0 = 0$ kG the laser interferometer revealed radial asymmetries in the plasma column approximately 75 ns before pinching, characteristic of small-amplitude Raleigh-Taylor instabilities. However, as a function of increasing B_0 field the amplitude of these instabilities decreased considerably. Time-integrated pinhole photographs confirmed these trends revealing a distinct lack of hot spots as B_0 increased. The unusual stability that has been observed will be reported in detail elsewhere.⁷

The highest compressed fields were measured in krypton and xenon discharges. In all we documented 16 shots in which the peak field intensity exceeded 1 MG. For lower Z gases the compressions were not as good since the value of M/L was smaller, causing the pinch to bounce off the compressed field early in the current pulse. In these experiments we observed multiple, periodic radial bounces of the plasma column due to the strong compressional force that remains after the first pinch.

If we neglect diffusion and assume that the initial radius of the plasma column is defined by the annular radius of the cathode nozzle, r_0 , then a rough estimate of the peak field strength is given as $B_f = B_0(r_0/r_f)^2$, where r_f is the column final radius measured by the laser interferometer. However, this method underestimates the peak field since the interferometer has limited ability to resolve the inner radius of the plasma column at maximum compression. Nevertheless, this method gave values of final field that were consistent with the Faraday rotation measurements to within a factor of 1.6.

The Faraday measured field intensity and plasma column radius are displayed in Fig. 2 for a typical high-field shot in which the peak compressed field is 1.6 MG and the field compression ratio is $B_f/B_0 = 180$. These data display a noticeable (~ 100 ns) time delay between the minimum column radius and peak field that is attributed to field diffusion into the Faraday fiber through a current sheath J_θ that surrounds the fiber. This current is induced on the outer surface of the fiber by the rapidly rising magnetic flux and ionizing radiation produced by the pinch. The diffusion of field through this sheath limits the measured field to a value below that which might exist on axis if the fiber were not present.

The interferograms of Fig. 3 were made of a krypton pinch in a region of small M/L to reveal the dynamics of the J_θ and J_z sheaths during plasma pinching. In Fig. 3(a), taken prior to energizing the pinch, the pinch axis is vertical and the dark central region outlines the axial quartz fiber. The interferogram of Fig. 3(b) was taken at maximum compression and demonstrates that the J_θ sheath, identified with the increased diameter central dark region, uniformly sur-

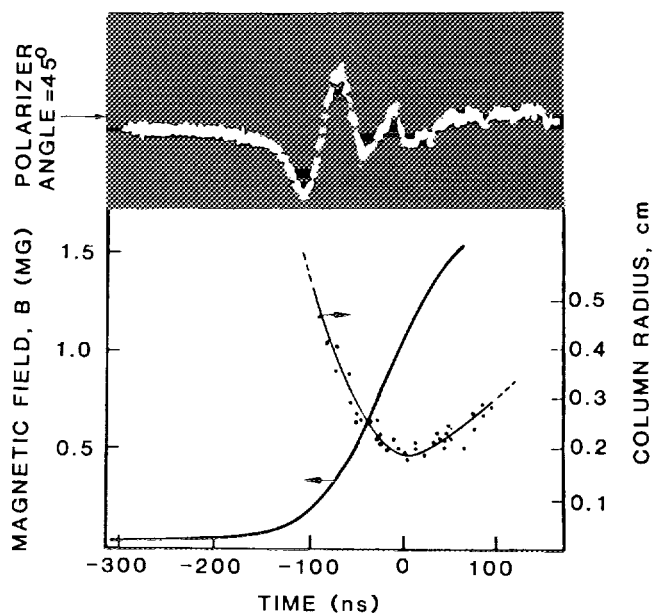


FIG. 2. Faraday rotation trace, compressed field strength, and column radius vs time. Pinch parameters: krypton, $B_0 = 9$ kG, $r_0 = 2$ cm.

rounds the fiber and has a thickness on the order of $\Delta x = 0.4-0.8$ mm; the dark region at larger radius corresponds to the J_z sheath. Interferograms taken at earlier and later times during pinching indicated that the J_θ sheath was compressed during column implosion. A direct result of sheath compression was the coupling of a large impulse into the fiber, of a magnitude of 100 kbar, that caused the fiber to lose its polarization-preserving properties on a time scale comparable to the implosion of the plasma column. The loss of polarization gave the Faraday signal the appearance of a damped oscillating waveform symmetric about the 45° bias

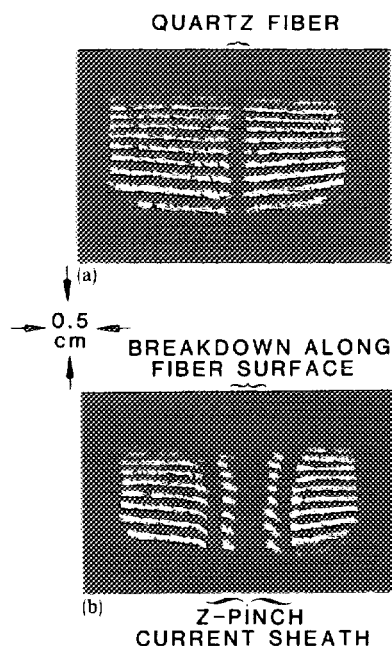


FIG. 3. Laser interferograms (a) before energizing the Z pinch and (b) at maximum field compression. The quartz fiber is coaxial with the pinch.

level (see Fig. 2). The effects of pressure-induced depolarization are described in more detail elsewhere.⁸

By taking a series of time-delayed laser interferograms we were able to evaluate the time evolution of the pinch axial profile and observe "bowing" and "zippering" of the plasma column during implosion; bowing is due to entrainment of the axial magnetic field lines in the discharge electrodes and is apparent in Fig. 3(b), while zippering arises from asymmetries in the initial breakdown path of the gas column and occurs as the location of the minimum column radius propagates from one axial extreme of the pinch to the other. Column bowing and zippering both decrease the axial length of the compressed high-field region and hence, the line-averaged value of the Faraday-measured field; our measurements are uncorrected for these effects.

In conclusion, we have demonstrated a novel method for producing controlled ultrahigh magnetic fields, where a gas-puff Z pinch implodes onto an axial field, that ameliorates many of the difficulties associated with conventional methods of field compression. Relying on the 10 ns resolution of laser interferograms, Faraday rotation, and high shot-to-shot reproducibility we noted improved pinch stability and measured peak fields of ≤ 1.6 MG at field compression ratios of ≤ 180 , uncorrected for the effects of field diffusion through the breakdown plasma along the Faraday diagnostic fiber, pressure-induced depolarization of the Faraday signal, and bowing and zippering of the plasma column. Simple scaling⁹ suggests that it should be possible to produce approximately 4 MG of axial field for each MA of current into a gas-puff Z pinch; our experiments produced approximately 3.4 MG/MA. Potential applications of this

method of generating ultrahigh fields include generation of short-wavelength radiation,^{10,11} magnetic field enhanced fusion,¹²⁻¹⁵ and atomic physics and material studies.^{2,16}

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