Detection of trapped magnetic fields in a theta pinch using a relativistic electron beam

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A novel nonperturbative diagnostic is used to infer the existence of trapped magnetic fields in a θ-pinch plasma. A thin beam of 1.5-MeV electrons from a 9-GHz, X-band linear accelerator is injected along the axis of a θ pinch with a period of 6 μs. The electron pulse duration is approximately 1 μs. Without any fill gas, when the θ pinch is fired, only those electrons within ±50 ns of the second B_{ext} = 0 are transmitted. The rest of the electrons are deflected by the solenoidal field, which acts as a strong lens. When the plasma is present even these transmitted electrons at B_{ext} = 0 are deflected because the plasma can trap some of the field lines. The magnitude and the scale length of these trapped fields can be estimated from the extent of the deflection.

INTRODUCTION

The physics of magnetic field line trapping in a theta pinch received considerable interest in the 60's.\(^1\) It was observed that if plasma breakdown occurs before (after) the second B_{ext} = 0 crossing, the plasma will have reversed (parallel) trapped field imbedded during the implosion stage. At maximum compression, reversed trapped field results in a very hot, field-free plasma, while parallel trapped field gives rise to a less hot plasma still containing field. The importance of determining the presence of trapped magnetic field lines in a plasma can easily be seen for an experiment like the plasma beat wave accelerator (PBWA).\(^2\) The presence of these fields complicates both the electron beam transport and the detection of electrons at the exit plane of the plasma device. For probing the presence of these fields magnetic probes are of very limited use, since high Z impurities boil off from the probe surface, altering the plasma diamagnetism and the magnetic field topology. In this article we describe the use of a low-current relativistic electron beam (REB) as a probe for trapped fields. The measurement is done at a moment that the external magnetic field goes through zero. As the REB propagates through the plasma, it suffers deflections if there are off-axis trapped magnetic fields inside the plasma. From the radial displacement we estimate the strength of the fields when the external magnetic field is zero, and using a simple field diffusion model we obtain the field strength at maximum compression. Applying a pressure balance to data of the radial density profile, taken with holographic Mach–Zender interferometry, gives the same order of magnitude for the trapped field strength at maximum compression.

I. APPARATUS

The theta pinch uses a capacitor bank of 11.1-μF typically operated at 24 kV. The coil is 20 cm long and split into two equal halves with a gap in between them of 2 cm. The period of the magnetic field is 6 μs. The time variation of the induced electric field and, after integration, the magnetic field is monitored with a single turn loop wrapped around the quartz discharge tube 50 cm away from one of the coils. The plasma density has been measured through holographic Mach–Zender interferometry as a function of time within a time interval of -800 to +1200 ns around peak compression (τ = 0).

Correlating the interferometric data with the signal of the pick-up loop and a photodiode monitoring the plasma light has allowed us to identify breakdown, implosion, and compression of the plasma.

The 9-GHz, X-band electron linac emits 1.5-MeV electrons in a micropulse of 1 μs consisting of a train of micropulses approximately 10 ps long separated by 110 ps. The micropulse current is 0.1 A. The beam transport system consists of three magnetic lenses and is shown in Fig. 1. At the exit plane the electron current is attenuated through a 90-mil Al plate and monitored using Polaroid type 52 film or a photodiode. Putting the electron detection system 1.5 m away from the pinch makes it very sensitive to detecting the smallest e-beam deflection.

II. RESULTS

A. Relativistic electron beam injection

Reducing the neutral gas fill pressure in the theta-pinch chamber below 1 mTorr delays plasma breakdown until the beginning of the third cycle of the magnetic field. The theta-pinch magnetic field then simply acts as a magnetic lens in the first two cycles.

As seen in Fig. 2, electrons injected within a time window of 50 ns around the end of the second half-cycle of the B field are guided by the beam transport system, and reach the detector without suffering deflections. When the filling pressure is increased to 120 mTorr, a plasma will be formed in

![Fig. 1. Electron beam transport system.](image-url)
the second half-cycle. As seen in Fig. 2 the electron beam is severely deflected both radially and azimuthally and since the detector looks at a fixed position it results in a decrease of the photodiode signal.

B. Trapping of magnetic field lines

In our experiment breakdown in He is observed after the second \(B_{ex} = 0\) crossing leading to the parallel trapped field\(^{1,2}\) frozen into the plasma. In the hydromagnetic model of the pinch, flux is adiabatically conserved and when the external magnetic field increases, the transverse temperature, the pressure, and the internal \(B\)-field (in the particle coordinate system) increase.\(^{3}\) In reality the field strength increases due to the decrease of the plasma cross section but decreases due to field diffusion.\(^{2}\) The axial symmetry of the theta-pinch plasma and magnetic field line topology is perturbed by the different high-beta plasma instabilities as described in the review paper by Bodin.

The trapped field strength can be obtained from Fig. 2. Since the third lens performs a 1:1 imaging of the exit plane of the theta pinch it is found that the beam suffers a radial displacement of 1 cm over a distance of 40 cm, 20 cm of which is plasma with the magnetic field trapped inside, the rest being vacuum.

We assume azimuthal symmetry of the fields in a coordinate system centered at a small island on the hologram. From the Lorentz equation and a force balance between the centrifugal and the centripetal forces we obtain\(^{6}\)

\[
F_r = m_r \ddot{r} - m_r \dot{\theta}^2 = -e B_\theta \dot{\theta},
\]

where \(B_\theta\) is taken to be zero.

For paraxial relativistic electrons

\[
\frac{d^2r}{dt^2} = \frac{d^2r}{dz^2} \left( \frac{eB_\perp}{2mc} \right)^2 r
\]

and substituting Eqs. (2)–(4) into (1) we obtain

\[
\frac{d^2r}{dz^2} = - \left( \frac{eB_\perp}{2mc} \right)^2 r
\]

or

\[
\frac{dr}{dz} = - \left( \frac{e}{2mc} \right)^2 \int B_\perp r \, dz.
\]

Now \(dr/dz = 1\) cm/40 cm = 0.025 and \(r = 0.5\) cm (from holograms). Then, using a plasma length of 20 cm, we obtain

\[B_r = 630 \text{ G}.
\]

The trapped field strength at maximum compression can now be found by applying a simple field diffusion model\(^{7}\)

\[B_r = B \exp(-t/\tau)
\]

with

\[\tau = \frac{\mu_0 L_r^2}{\eta}.
\]

The plasma resistivity is given by Spitzer's formula

\[\eta = 1.65 \times 10^{-7} Z \ln \Lambda/T_e
\]

with \(T_e\) in keV. Substituting an effective \(Z = 1.6\) and \(\ln \Lambda = 10\) we obtain

\[\eta = 8.4 \times 10^{-8} \Omega - m.
\]

Taking a characteristic dimension \(L_r = n/n' = 2.5\) mm the diffusion time becomes

\[\tau \approx 800 \text{ ns}.
\]

Therefore, the initial trapped field strength is estimated to be

\[B_r \approx 4.5 \text{ kG}.
\]

The trapped field strength can also be obtained using holographic interferometry data. On certain holograms small off-axis closed fringes were observed. Consistent with our picture of off-axis magnetic field lines we assume that field is trapped inside. Furthermore, there is an uncertainty in the density measurement of \(\Delta n = 1.3 \times 10^{16} \text{ cm}^{-3}\) (one fringe shift). An upper limit to the field can then be obtained from a pressure balance that results in

\[B_r = \left[ (\Delta n)(2\mu_0)(KT_e + KT_i) \right]^{1/2}.
\]

Using \(T_e = 20 \text{ eV}\) and \(T_i = 70 \text{ eV}\) we obtain

\[B_r = 6.8 \text{ kG}
\]

consistent with our previous estimate.

III. CONCLUSION

From the radial displacement of a REB injected into a theta-pinch plasma at \(B_{ex} = 0\) we have been able to estimate the magnitude of off-axis localized trapped magnetic field lines inside the plasma. Plasma instabilities can account for the nonaxisymmetry of both the plasma and the magnetic
field line topology. Using a simple diffusion model we have obtained an estimate of the trapped field strength at maximum compression and shown that this is consistent with results from a pressure balance based upon the interferometric density measurements.

Finally, although the electron beam transport through the theta pinch is complicated, preliminary results of the PBWA experiment at UCLA have shown that it is a viable source for this experiment. In future plasma-based accelerators, however, one will need field-free plasma sources in order to obtain a beam quality comparable to the more conventional accelerators.

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