Using of B-dot probe for z-pinch plasma diagnostics

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Abstract. We present experiments performed on the IMRI-5 generator (450 kA, 450 ns) with a metallic gas-puff Z-pinch with a power-law density profile. The experiments were carried out in a preembedded axial magnetic field $B_z$ that was varied from 0 to 0.6 T. To determine the initial pinch radius $r_0$, we used the function $r(t)$ that was found from the time dependence of the pinch inductance $L(t)$. The time-dependent inductance $L(t)$, in turn, was determined as a function of load voltage $V_{\text{load}}(t)$ and pinch current $I(t)$. The function $r(t)$ was verified by a B-dot probe diagnostics. Measurements showed that for the “first shot” the initial radius of the metallic gas-puff Z-pinch decreased from 4 cm at $B_z=0$ to 2.1-1.7 cm at $B_z=0.15$ T. We believe that the decrease it $r_0$ is related to the field effect on the ion gyroradius.

1. Introduction

The studies of the interaction of a Z-pinch plasma with an axial magnetic field have a long history [1]. Interest in this problem has rekindled in connection with the Magnetized Liner Inertial Fusion (MagLIF) project (see [2] and references therein). Recent experiments on gas-puff Z-pinch implosions have demonstrated that an applied axial magnetic field $B_z$ stabilizes substantially the pinch compression [3, 4]. However, it turned out that the field $B_z$ not only produces a stabilizing effect on the pinch, but also reduces its compression velocity [4-7]. By the radius $r_0$ we imply a certain effective radius of a conductive layer whose inductance equals the inductance of an infinitely thin cylinder located coaxially inside a multi-post return conductor. Obviously, for the case of a weakly ionized material, this model representation of the dimensions of the conductive region may substantially different from the dimensions of an actual Z-pinch shell. However, for the conditions of significant conductivity, and, hence, a thin skin layer, this representation can be used to give a reasonably adequate description of the behavior of an imploding Z-pinch shell. To interpret the results of our experiment [12], we have estimated the conductivity of the material of a plasma jet having parameters close to those of the plasma jet produced in the experiment. According to our estimates, the initial conductivity of the conductive shell should be $\sigma=5\cdot10^3 \, \Omega^{-1} \cdot \text{m}^{-1}$. In view of the rise time of the IMRI-5 generator current, the initial thickness of the skin layer for our conditions should be 1.4 cm. This is the margin of error that should be considered in estimating the initial shell radius. The material conductivity increases during implosion, whereas the skin layer thickness accordingly decreases, thus making the model representation more correct.
In this paper, we performed the measuring the initial radius $r_0$ of an imploding Z-pinch with a pre-embedded axial magnetic field $B_{z0}=0-0.6$ T. For the goal we used two methods. In the experiment [5], metallic gas-puff Z pinches with a power-law density profile were produced using the IMRI-5 generator capable of generating current pulses of amplitude 450 kA with a 450-ns rise time. First, to estimate $r_0$, we used the time-varying inductance $L(t)$ determined as a function of load voltage $V_{\text{load}}(t)$ and pinch current $I(t)$. Secondly we used a B-dot probe diagnostics. We compare two methods in the paper.

2. Experimental arrangement

The experimental arrangement is shown in figure 1. Metallic gas-puff Z pinches were produced using a Bi (bismuth) plasma gun [5, 6]. The external magnetic field $B_{z0}$ was created by a pair of solenoids spaced 1.5 cm apart, which were driven by a slow (about 500-μs rise time) capacitor. The field $B_{z0}$ was varied by varying the time interval $\Delta t$ between the onset of current passage through the solenoids and the onset of current passage through the pinch. Measurements were performed at $B_{z0}=0.15$ T ($\Delta t=47$ μs), $0.3$ T (114 μs), $0.45$ T (200 μs), and $0.6$ T (360 μs).

The current flowing through the pinch, $I(t)$, and the voltage across the load, $V_{\text{load}}(t)$, were measured, respectively, with a Rogowski coil (RC) and a resistive voltage divider (VD). The position of the plasma boundary was sensed using five B-dot probes. One probe, $\hat{B}_{150}$, was built in a reverse current post at a distance of 150 mm from the pinch axis. Previously we have shown that the radius corresponding to the initial position of the pinch boundary at $B_{z0}=0$ is not greater than 3–5 cm. Therefore, it could be expected that probe $\hat{B}_{150}$ would always be outside the pinch boundary. The other three probes, $\hat{B}_{15}$, $\hat{B}_{29}$, and $\hat{B}_{36}$ were placed in the holes drilled in the stainless steel anode at $r_{\text{Bdot}}=15$, 29, and 36 mm away from the axis, respectively (see figure 1). For each of the probes, the distance from the loop center to the anode plane was about 3 mm. To visualize an imploding Z pinch, we performed time-gated imaging of the visible pinch radiation. A 4-frame HSFC Pro camera was used to take successive images (3 ns) in a single shot.

![Figure 1. Experimental arrangement. The IMRI-5 generator current is switched, via the Bi plasma jet, to a stainless-steel grid cathode. The B-dot probes, $\hat{B}_{15}$, $\hat{B}_{29}$, and $\hat{B}_{36}$ are 15, 29, 36, and 150 mm away from the axis. RC denotes a Rogowski coil and VD a resistive voltage divider.](image)

3. Experimental results

It was shown [1, 7-9] that the time-depending inductance $L_{\text{load}}(t)$ can be found from the $V_{\text{load}}(t)$ and $I(t)$ waveforms as

$$L_{\text{load}}(t) = \frac{\epsilon^2}{2I(t)} \int_0^t V_{\text{load}}(t') dt'.$$  

(1)
In turn, $L_{\text{load}}(t)$ is related with the current sheath radius $r_{\text{ind}}(t)$ as

$$L_{\text{load}}(t) = L_d + 2l_{\text{pinch}} \ln \frac{r_{\text{rcp}}}{r_{\text{ind}}(t)} \ (\text{nH}) \tag{2}$$

where $l_{\text{pinch}}$ is the pinch length, $r_{\text{rcp}}$ is the radius of location of the return current posts, and $L_d$ is the self-inductance of the diode in which the pinch is formed. In our experiment, $L_d$ corresponds to the inductance of the coaxial line section between the voltage divider and the plane of the HV electrode grid, $L_d=8 \ \text{nH}$. According to (2), the inductive pinch radius $r_{\text{ind}}(t)$ can be estimated as

$$r_{\text{ind}}(t) = A \cdot \exp \left( -\frac{L(t)-L_0}{2l_{\text{pinch}}} \right) \tag{3}$$

Figure 2 presents plots of $L_{\text{load}}(t)$ and $r_{\text{ind}}(t)$ for a Bi gas-puff Z pinch imploded at $B_{z0}=0$. Formally, the calculation of $L_{\text{load}}(t)$ can be started from the time of voltage application to the diode. According to relations (1) and (2), at times $t<70 \ \text{ns}$, the load inductance $L_{\text{load}}(t)$ should be either equal to or somewhat greater than the diode inductance $L_d$. However, as can be seen from the respective plot in figure 2, $L_{\text{load}}(t)$ is lower than $L_d$ up to $t=60-70 \ \text{ns}$. As the value of $L_{\text{load}}(t)$ is underestimated, the value of $r_{\text{ind}}$ cannot be considered reliable up to $t=70 \ \text{ns}$. In light of the above we assumed that $r_0=r_{\text{ind}}(t)$ at $t=70-80 \ \text{ns}$. Note that a similar approach to estimating $r_{\text{ind}}$ was used in [1, 10].

The values of $r_0$ were measured at $B_{z0}$ equal to 0.15, 0.3, 0.45 and 0.6 T. When performing the experiment, we took into account that the gas-puff pinch dynamics is sensitive to the material desorbed from the electrodes [5]. For each field value, four shots were made and the evacuation of the vacuum chamber was stopped and the pressure in the chamber increased to atmospheric pressure. Thus, for each value of the field, the “first” shot was made with the electrodes exposed to the atmosphere. The measurement results for $r_0$ are presented in figure 3: blue asterisks refer to the value of $r_0$ in the “first” shot and red asterisks to its values in the subsequent shots. It turned out that for most of the “first” shots, $r_0$ was significantly greater than that for the subsequent shots. However, the behavior of the initial radius was the same for the “first” shot and for the subsequent shots: at $B_{z0}=0.15 \ \text{T}$, $r_0$ almost halved, and as the field was increased, its value remained almost equal to $r_0$ at $B_{z0}=0$.

The position of the outer boundary of the current sheath was determined by the method using a set of B-dot probes that is described in detail in [7]. Analysis has shown that as the current sheath passed by a probe, the $dB/dt$ signal of the probe had a bell-shaped waveform and the time $t_{\text{peak}}$ at which $dB/dt$ was a maximum coincided with the time of passage of the sheath boundary by the probe. Figure 4 presents the waveforms of $V(t)=dB/dt$ obtained for the “first” shots at different values of $B_{z0}$. It can readily be seen that the signals sensed by the probes $B_{29}$ and $B_{36}$ at $B_{z0}=0.15 \ \text{T}$ (see figure 4b) look absolutely differently than that sensed by the same probes at $B_{z0}=0$ (see figure 4a). The signal $V(t)$ for $B_{36}$ in figure 4b coincides in waveform with the signal $V(t)$ sensed by the probe $B_{150}$. The signal $V(t)$
for $B_{29}$, having executed several oscillations, starting from $t=100-150$ ns approaches in waveform the signal $V(t)$ sensed by the probe $B_{150}$. At the same time, the amplitude of the signal of the probe $B_{15}$ starts increasing only after the 100th ns and has a pronounced maximum at $t=175$ ns. Consequently, it can be assumed that at $B_{z0}=0.15$ T the initial plasma boundary radius $r_0$ was between 29 and 15 mm, which is close to $r_0=2$ cm given for this mode in figure 3 (blue asterisk for $B_{z0}=0.15$ T).

Figure 3. Initial pinch radius versus axial magnetic field: blue asterisks refer to the value of $r_0$ in the “first” shot and red asterisks to its values in the subsequent shots.

Figure 4. B-dot probe signals for the “first” shots. One probe, $B_{150}$, was built in a reverse current post at a distance of 150 mm from the pinch axis. The other three probes, $B_{15}$, $B_{29}$, and $B_{36}$, were placed in the holes drilled in the stainless steel anode at $r_{Bdot}=15$, 29, and 36 mm away from the axis, respectively.

We estimated $r_0$ for the “first” shots using the relation

$$r_0 = r_{Bdot} + v(t_{peak} - \Delta t),$$

(4)

where $r_{Bdot}$ is the B-dot position, $v$ is the compression velocity of the Z-pinch, and $\Delta t=70$ ns is the time period during which the current sheath was formed. The values of $v$ were taken from [6]. The estimates obtained with the use of (4) are presented in table 1.
Table 1. The measured specific deposited energy averaged over seven shots. As discussed above, energy is deposited in a foil during the initial resistive heating stage.

| $B_{z0}$, T | $r_{lidot}$, cm | $v \times 10^7$, cm/s | $t_{peak}$, ns | $r_0$, cm |
|------------|----------------|----------------------|--------------|----------|
| 0          | 3.6            | 1.45                 | 145          | 4.6      |
| 0.15       | 1.5            | 1                    | 180          | 2.6      |
| 0.3        | 2.9            | 0.75                 | 175          | 3.7      |
| 0.45       | 3.6            | 0.6                  | 227          | 4.5      |

The values of $r_0$ given in table 1 are somewhat greater than that obtained by determination of the pinch radius as a function of the time-varying pinch inductance $L(t)$ (see figure 3). Nevertheless, the trend is the same as in figure 3: at $B_{z0}=0.15$ T the radius $r_0$ nearly halves compared to that at $B_{z0}=0$.

4. Conclusion

Experimental results allow the following conclusion: The values of $r_0$ obtained with the use of B-dot probes agree with the results obtained by determining the pinch radius as a function of the time-varying pinch inductance $L(t)$.

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