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SOME FACTORS BEARING ON THE DECAY AND REVERSAL
OF THE PLASMA CURRENT IN Z PINCHES

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ABSTRACT

The decay and reversal of currents in Z-pinch equivalent circuits are examined. It is shown that the physically observed effects do not require special plasma properties for their explanation because they are the normal behavior of the electrical circuit.

Oomans and Meddens¹ examined the behavior of the plasma current in Z pinches as a function of the external circuit and reported the possibility of generating a short-term rising plasma current after the crowbar switch is closed if a parallel circuit is added to the usual circuit. This short-term plasma-current rise is called a pseudopower crowbar. This report provides an explanation of this phenomenon and explains the current reversal observed in the Z pinch in terms of the plasma inductance and resistance.

When we close the series switch S_1 in Fig. 1, the current divides between the two parallel legs according to their impedance. Because this is an oscillating circuit, this impedance is primarily inductive reactance; therefore, the circuit with the smaller inductance will carry the larger current. However, after the crowbar switch S_2 is

closed, the current will redistribute itself. In fact, it will approach the current division determined by the resistance of the legs as the circuit approaches a direct current state. If the resistance R_a is less than R_b and L_z is greater than L_b , the result will be a rising current in L_a . This effect is apparent in Fig. 2 of Oomans and Meddens' report, although apparently not noticed by them.

In their figure it is the current in the primary that rises after the crowbar switch is closed. We have recalculated their case for the circuit shown in Fig. 1 using their values along with a small value of R_m . To conform to their notation we have reidentified the circuit components as follows: $L_a = L_m$, $R_a = R_m$, $L_b = L_{zp}$, and $R_b = R_{zp}$. The result of our recalculation is plotted in Fig. 2. The calculation was done using the Net-2 circuit analysis code. The time of crowbar switch closing was 12 μ sec. Here the rise in the current in L_m after crowbar switch closing is noticeable.

From the discussion above, the reason for the pseudopower crowbar phenomenon is apparent. The significance of Oomans and Meddens' work is that it shows how to obtain this phenomenon in the plasma leg by adding a third leg in parallel with the primary of the transformer. When this third leg is connected in parallel with L_a and L_b , its inductance is sufficiently low with respect to L_b , and its resistance is greater than R_b , a rise in current

Fig. 1. Simplified Z-pinch circuit.

Fig. 2. Net-2 calculation of currents in the circuit of Fig. 1. $C = 120 \mu F$, $L_e = 300 \text{ nH}$,
 $R_e = 2.7 \text{ m}\Omega$, $L_a = L_m = 630 \text{ nH}$, $R_a = R_m = 10^{-7} \Omega$, $L_b = L_{zp} = 265 \text{ nH}$, $R_b = R_{zp} = 10 \text{ m}\Omega$.

in L_a is to be expected provided L_a is large enough that the current through it cannot change as rapidly as the plasma current.

The reversal of the current in a Z pinch is also related to the circuit values but not necessarily to the plasma properties. To show this we have considered the circuit of Fig. 3. This is the

Fig. 3. Equivalent circuit for Z pinch after crowbar time.

part of the circuit of Fig. 1 that needs to be examined after the switch S2 is closed. We assume current I_{02} and I_{03} flowing at $t = 0$ in the directions shown. If this system is solved, we find that the currents I_2 and I_3 are given by the following equations.

$$I_2 = \left\{ \frac{\gamma I_{03}}{M_2 - M_1} + \frac{(M_2 + \delta)}{M_2 - M_1} I_{02} \right\} e^{M_1 t} - \left\{ \frac{M_1 + \delta}{M_2 - M_1} I_{02} + \frac{\gamma}{M_2 - M_1} I_{03} \right\} e^{M_2 t} \quad (1)$$

$$\text{and } I_3 = \frac{1}{\gamma(M_2 - M_1)} \left\{ -[(M_1 + \delta) \gamma I_{03} + (M_1 + \delta)(M_2 + \delta) I_{02}] e^{M_1 t} + [(M_2 + \delta) \gamma I_{03} + (M_1 + \delta)(M_2 + \delta) I_{02}] e^{M_2 t} \right\} \quad (2)$$

$$\text{where } \gamma = (R_1 L_3 - R_3 L_1) / (L_1 L_2 + L_1 L_3 + L_2 L_3)$$

$$\delta = (R_2 L_3 + R_1 L_3 + R_2 L_1) / (L_1 L_2 + L_1 L_3 + L_2 L_3),$$

$$\text{and } M_1 = -\frac{(\alpha + \delta)}{2} + \frac{1}{2} \sqrt{(\alpha + \delta)^2 + 4(\gamma R - \alpha \delta)}$$

$$M_2 = -\frac{(\alpha + \delta)}{2} - \frac{1}{2} \sqrt{(\alpha + \delta)^2 + 4(\gamma R - \alpha \delta)},$$

$$\text{where } \alpha = (R_1 L_2 + R_3 L_1 + R_3 L_2) / (L_1 L_2 + L_1 L_3 + L_2 L_3)$$

$$\beta = (R_1 L_2 - R_2 L_1) / (L_1 L_2 + L_1 L_3 + L_2 L_3).$$

In the above we have assumed that $M_1 \neq M_2$.

From this we can determine how long it will be after closure of the crowbar switch until the current I_3 passes through zero. This time is given by

$$t = \frac{1}{\sqrt{(\alpha + \delta)^2 + 4(\gamma \beta - \alpha \delta)}} \log \left\{ \frac{(M_2 + \delta) \left(\gamma I_{03} + \frac{(M_1 + \delta)}{(M_2 + \delta)} I_{02} \right)}{(M_1 + \delta) \left(\gamma I_{03} + \frac{(M_1 + \delta)}{(M_2 + \delta)} I_{02} \right)} \right\}.$$

For example, if we use the values given for Fig. 2 with I_{03} and I_{02} taken from the Net-2 calculation,

we find that t equals 96.14 μsec after crowbar time or 108.14 μsec after closing the start switch. The Net-2 calculations graphed in Fig. 2 give the time as $\sim 108.15 \mu\text{sec}$. Equations (1) and (2) demonstrate that the Z-pinch current reversal is purely a matter of the circuit parameters and has nothing to do with the plasma properties other than in how these properties affect the inductance and resistance of the plasma.

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REFERENCE

1. A. A. M. Oomens and B. J. H. Meddens, "The Influence of the External Circuit on the Decay of the Induced Plasma Current," in Proc. of Second Topical Conf. on Pulsed High-Beta Plasmas, W. Latz, Ed., Munchen, Germany, July 3-6, 1972, pp. 201-204.