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Low-Compression Theta Pinch with Separated Shock Heating

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I. MOTIVATION

The present classes of high-voltage θ pinches, including Scyllac, are objects in which ion heating is done by a two-stage process: (a) Shock heating by means of a fast implosion during the first few hundred nanoseconds after switching on the main capacitor bank, and (b) adiabatic compression of the shock products. Largely as a result of technological history, processess (a) and (b) derive from the application of a single capacitor bank which does both the shocking and compression. The final plasma has undergone a volume compression by about a factor of 20 and fills approximately 5 percent of compression coil volume.

Technological studies show that a larger filling ratio is a great advantage in producing a pulsed reactor (also a steady-state one), and it is important to initiate experiments to develop the θ pinch in this direction, while keeping it hot and collisionless. Greater proximity of the plasma surface to the wall is also a distinct aid to stabilizing high-β toroidal geometries. One would expect simultaneously to raise the ion temperature from its present 2-5-keV range to the neighborhood of 10 keV, which is in the reactor range. Such experiments provide a follow-on to Scyllac, whose object is to study the containment of hot, high-β plasmas as produced by presently-known methods in long linear and toroidal geometries. It is proposed to produce the new plasmas in a linear geometry of sufficient length (about 1 meter) that their properties can be studied in the presence of end-loss, as was done in the past. The coil diameters will be 20-30 cm, as compared to 10 cm at present, the plasma will be hotter, somewhat less dense, and probably of somewhat lower beta. The filling factor will be of the order of 20 percent--a value more appropriate to a reactor than present plasmas.

These objectives can be accomplished by producing greater ion temperatures during the shock phase of the discharge, thus requiring less compression. Since ion energy after the shock is proportional to E_θ, we need to increase this appreciably over its present value of 1 kV/cm. The design outlined below, producing a transient pulse of 400-500 kV, will give $E_\theta \simeq$ 5-6 kV/cm. It will produce the shocked plasma from a separated electrical pulse, followed by compression to a field of about 55 kG. Thus we expect ion energies of the order of 7-9 keV at standard 10-20 mTorr filling pressures. At 5 mTorr we might achieve 10-13 keV.

An important point is to be made regarding the separation of the shock and compression functions in relation to a pulsed reactor. The technological studies have shown that it would be uneconomical to furnish the compression field by means of capacitors. Some form of magnetic energy storage will be necessary, It will probably be necessary to use high-voltage capacitors (perhaps in conjunction with fast initial magnetic storage) to shock heat the plasma in a separate phase, but this will not require a capacitor energy comparable to that for compression. An important additional object of the proposed experiment will be to determine the feasibility of this separation of the functions. Even though we continue to use capacitors for compression in the proposed experiment, we visualize the success of the experiment as opening the door to eventual magnetic energy storage for the compression phase.

The proposed experiment is somewhat comparable with present collisionless shock experiments which use a multi-MV pulse in larger vessels, with no follow-on compression. We do not propose to go to these extremes but to make a sufficient extension of our present technology to extrapolate from known present parameters to those given above. In particular, by not increasing our tube diameter a great deal we expect to be able to preionize by means of Z current. Our filling pressures will remain in the range of present practice (somewhat lower) rather than representing the entirely new values found in the conventional collisionless-shock experiments.

II. SCHEMATIC ENGINEERING DESIGN

By employing transmission-line techniques it is possible to obtain high θ-pinch voltages while retaining the adiabatic-compression and confining magnetic fields presently used in Scylla experiments. Figure 1 illustrates one possibility. Four Blümlein lines are connected in series to produce a coil voltage 9.6 times that on the capacitors. A factor of 2 occurs due to voltage doubling at the coil and the factor 1.2 arises from the choice of impedances. The latter factors could be increased by increasing the characteristic impedance Z_1 of Fig. 1 through increasing the plate separation or by using an insulator of lower dielectric constant. The lengths of the transmission line sections were chosen to provide a pulse duration of 80-nsec at the coil.

At present the multiarc switches shown in Fig. 1 do not exist at Los Alamos. However, a group at the Culham Laboratory has made such switches. The only requirement for obtaining many arc channels along the parallel electrodes is that triggers be placed at the desired arc positions and that the trigger voltage rise time be less than the spark channel formation time. To achieve such fast rise times ($\lesssim$ 2 nsec) the master trigger gap must itself have several arc channels. This can be achieved by using a Q-switched laser with beam splitters and lenses to focus at several different spots on the gap cathode. This technique has been used by A. Guenther, et al., at the Kirtland Armed Forces Special Weapons Development Laboratory where sub-nanosecond megavolt pulses are obtained from low-impedance transmission lines.

If the present Scylla IV capacitor bank were used for this experiment, the 324, 2-μF, 50-kV capacitors would be divided into 4 groups of 81 capacitors each. For a 50-kV charge the peak current and field would be 4.3 MA and 55 kG. The period would be 11.7 μsec. Since the fast switches are not installed on the capacitors, the capacitors could be further stacked in series to obtain higher voltages. To obtain more than 1 MV at the coil, more transmission lines must be added to the coil at the expense of added series inductance and consequent lowering of the confining field. In any event it will be necessary to immerse the coil in oil or Sylgard and perhaps the transmission lines as well.

The length of the transmission lines were chosen so that the driving conditions for the shock would be particularly simple (see Fig. 2).

$$i_f Z_o - i_b Z_o = i_b \frac{dL}{dt} + L \frac{di_b}{dt} , \qquad (1)$$

where i_f is the forward current wave in the transmission line and is constant for the first 80 nsec, and i_b is the backward current wave reflected from the compression coil and is dependent on L and $\dot{L}$ (L is the coil inductance with plasma). The dynamic plasma relations provide the L(i,t). The price paid for the pulse line source in the proposed experiment is the lower energy transfer efficiency from the capacitor bank to the coil. Only 47% of the bank energy is transferred to the coil in the circuit of Fig. 1.

For high filling pressures (10-40 mTorr) 80 nsec may be too short, while at lower pressures it may be longer than necessary. Provision should be made for varying the line lengths and perhaps Z_o. One should also be able to disconnect the capacitor banks so that only shock heating of the plasma occurs. To obtain optimum pulses it may be necessary to shape the parallel plate lines and the switches for matching transit times along current flow lines. It is anticipated that a Garching-type Z-discharge would be used for preionization.

III. PHYSICAL LOCATION AND COST ESTIMATE

During the first year and a half this experiment will occupy some of the space previously used for Scylla III. In FY-72 and FY-73 the present Scylla IV bank will be divided into two sections, disposed on either side (north and south) of the Bluemlein structure. This will require removing most of the low-voltage Zeus bank from the Scylla IV area. The additional manpower and major procurement cost as follows:

	FY-70	FY-71	FY-72	FY-73	FY-74	FY-75
Manpower (C.P.)*	1.5	3	5	5	5	5
Scientific Man Years	1	2	3	3	3	3
Manpower Cost	65 K	130 K	230 K	240 K	250 K	260K
Major Procurement Cost	25 K	50 K	150 K	250 K	250 K	250K
Total Cost	90 K	180 K	380 K	490 K	500 K	510K

* C.P. Ceiling point, one scientist/engineer or two technicians

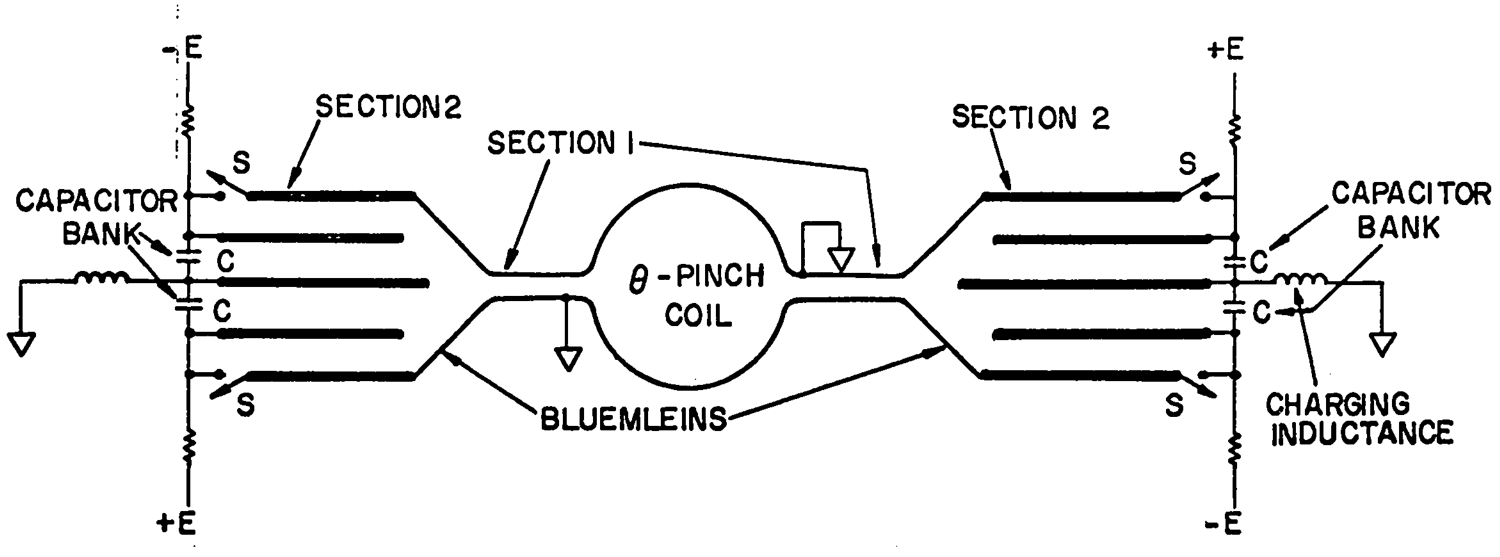
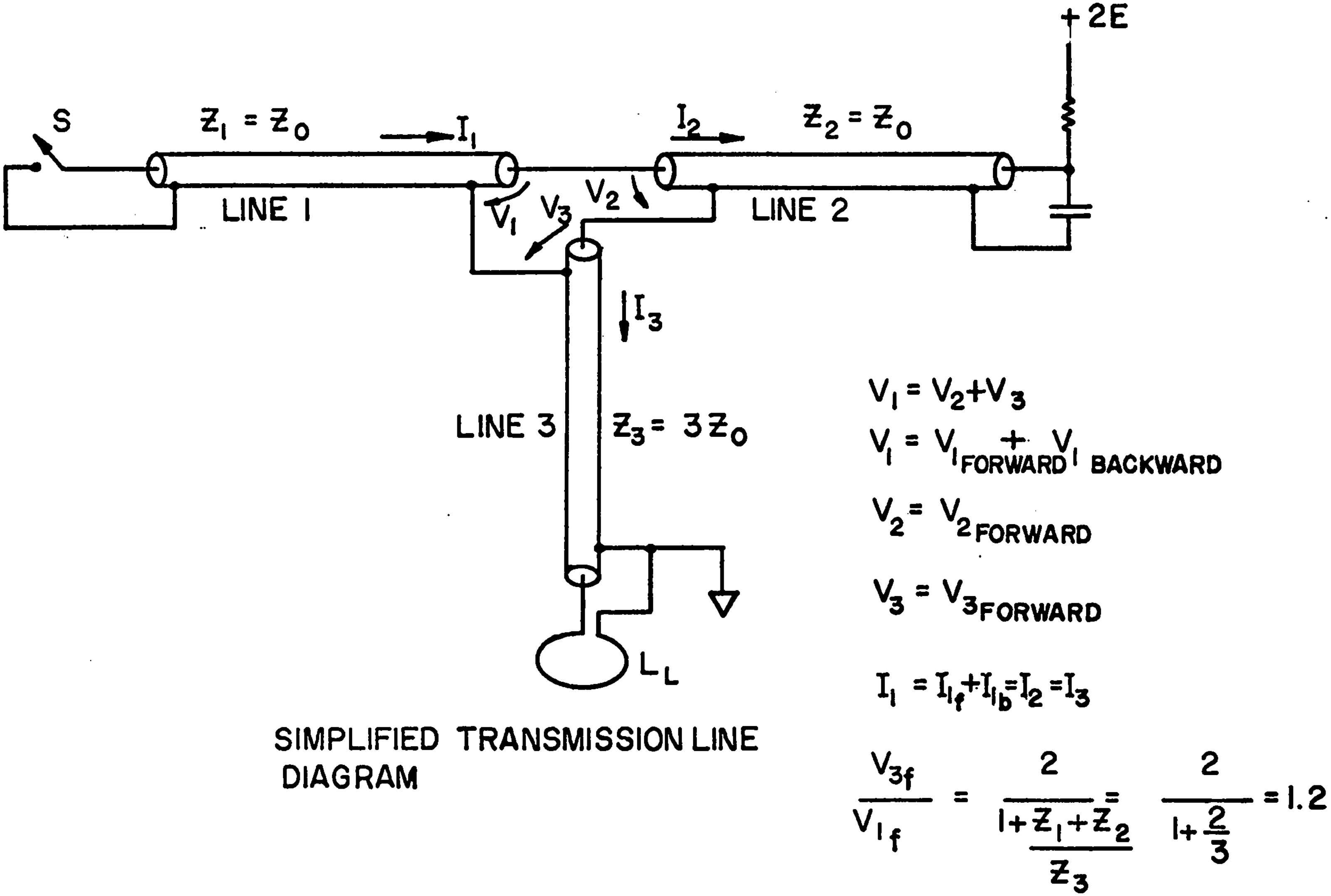


Fig. 1

Characteristics:

1) Coil: 1-meter long by 20-cm dia (or more), L $\approx$ 40 nH
2) Section 1: 6-meter line, 2-meters wide, 3-mm insulation
3) Section 2: (Double modified Blümlein), 4-meters wide, 1-mm insulation, 6-meters long
   Each part, Z_o = 0.047 ohm, L = 0.31 nH/meter, C = 0.144 µF/meter
4) Switches S: Linear, 4 meter, in-plate, pressurized air gaps with 20 arc channels each all switched within ~ 2 nsec of each other.
5) Voltage at θ-pinch coil = 9.6 E = 480 kV for E = 50 kV, using 50 kV capacitors.
   Duration of 9.6 E at coil is ~ 80 nsec



$$V_1 = V_2 + V_3$$

$$V_1 = V_{1\,FORWARD} + V_{1\,BACKWARD}$$

$$V_2 = V_{2\,FORWARD}$$

$$V_3 = V_{3\,FORWARD}$$

$$I_1 = I_{1f} + I_{1b} = I_2 = I_3$$

$$\frac{V_{3f}}{V_{1f}} = \frac{2}{1 + \frac{Z_1 + Z_2}{Z_3}} = \frac{2}{1 + \frac{2}{3}} = 1.2$$

Fig. 2. Simplified Transmission Line Diagram.