LA-UR- 73-1752

Conf-731114--37

TITLE: THE DESIGN OF A HIGH-VOLTAGE GENERATOR FOR THE LASL IMPLOSION-HEATING EXPERIMENT

AUTHOR(S): J. E. Hammel, Ivars Henins, John Marshall, and A. R. Sherwood

SUBMITTED TO: FIFTH SYMPOSIUM ON ENGINEERING PROBLEMS OF FUSION RESEARCH to be published by the Nuclear and Plasma Sciences Society of the IEEE.

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

MASTER

n Nc. 836
Jo. 2629

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

J. E. Hammel, Ivars Henins, John Marshall, and A. R. Sherwood

Los Alamos Scientific Laboratory, University of California

Los Alamos, New Mexico

Summary

The goals of the LASL implosion-heating experiment are to learn more about the physical processes involved in the initial implosion of a theta pinch and to find ways of enhancing the amount of implosion heating. The design parameters chosen for the experiment are: an initial plasma density of 10^{15} deuterons per cm^3, a 40-cm-diameter discharge tube, a coil length of one-meter, an initial electric field of 2 kV/cm applied to the inside of the discharge tube, and a magnetic field of 10 kG having a fast risetime and lasting for 500 nsec. This experiment differs from the collisionless shock experiments which have been conducted over the past few years at other laboratories in that we have a much higher initial plasma density. The higher density reduces the effective impedance of the plasma and thus requires a lower impedance current source.

The unusually large diameter for a theta pinch is designed to allow time and distance for study of the implosion process, but it has the disadvantage of requiring a voltage of 250 kV around the discharge tube in order to attain the desired field of 2 kV/cm. At the 800-kA design current (10-kG magnetic field) the plasma impedance is calculated (as described below) to be about 0.3 Ω.

The design of a high-voltage pulse generator which meets these requirements is described. Systems which have been considered are: 1) Mylar-insulated stripline Blumlein generators, 2) simple Mylar striplines, 3) combinations of Mylar striplines with capacitors, 4) water-insulated coaxial transmission lines, 5) capacitors, and 6) lumped-constant transmission lines. The system finally selected is a hybrid of a peaking-capacitor system with a curtailed, lumped-constant delay line. All systems were investigated by computation, mostly using the NET-2 code. The calculation takes into account the changing impedance of the load due to the motion of the imploding plasma sheath. Plasma dynamics were simulated using the bounce model, which assumes perfect elastic reflection of all ions from impinging magnetic piston.

The final design employs four coil feed points with a 125-kV generator at each one, totaling 500 kV. Each 125-kV generator consists of a pulse-charged two element lumped-constant line. An essential feature of the circuit is fast charging from Marx generators through the inductance of the Marx and of the connecting cable system. The load switches are fired when the voltage on the lumped-constant line reaches 125 kV, at this time the voltage is still rising rapidly. At the peak load current about 300 kA is contributed by the charging current from the Marx bank and 500 kA comes from the capacitors of the lumped constant line.

Implosion Heating Experiment

The primary goal of the implosion heating experiment is to study the physics of the initial implosion of a theta pinch; therefore, it is desirable to provide simple reproducible conditions for the magnetic field during the implosion. We have chosen to use as nearly as possible a square current pulse, raising the magnetic field inside a ~ 400-mm-diameter tube to 1 T with as short a rise as possible and maintaining it for ~ 500 nsec, somewhat longer than the anticipated implosion time. The coil length has been chosen to be 1 m so as not to lose too large a fraction of the ions through the ends of the coil during the implosion. The coil current required is then 800 kA.

LASL theta pinches have mostly been operated with an initial electric field at the inside of the discharge tube of ~ 100 kV/m. We hope to raise this in the future to ~ 200 kV/m, so the present experiment is designed for that field strength. This requires ~ 200 kV/m, so the present experiment is designed for that field strength. This requires ~ 250 kV around the 400-mm-diameter tube, and it must be applied to an imploding plasma which has a non-linear resistive impedance of ~ 0.3 Ω during the first part of the implosion. The resistive plasma impedance is actually the result of a rapidly increasing inductance of 0.3 H/sec caused by the effective increase of coil area accompanying the implosion of a current sheath separating preionized unmagnetized deuterium plasma from the magnetic field. We have assumed, for design purposes, that the plasma interacts with the magnetic piston by a bounce model, i.e. that in the moving frame of the piston, ions are elastically reflected. This gives the maximum possible momentum transfer and thus the slowest inward sheath velocity possible. The 0.3 Ω plasma impedance cited above corresponds to a filling density of 10^{21} deuterons/m^3. A snowplow model for the imploding plasma, or any substantial amount of field diffusion, leads to a larger effective plasma impedance.

Our first idea for a pulse generator to operate the experiment was mylar stripline Blumlein generators, following the lead of the Garching group[1] and others studying collisionless shock phenomena in theta-pinch geometry. Our experiment differs from these earlier ones in that we hope to use 100 to 1000 times the plasma density at several times the magnetic field strength. The higher density of our plasma gives it a lower impedance according to either the bounce or the snowplow models. If, as seems likely, field diffusion is smaller at higher density, this also will lower the effective plasma impedance. The result is that our generator impedance must be several times lower than that of the Garching experiment in order to apply a reasonable fraction of the generator emf to the load. A Blumlein generator is arranged with two line sections in series so that its effective impedance is twice that of the lines. This is compensated to some extent because it delivers twice the charging voltage. The Garching experiment is driven at four feed slots each one being fed by a Blumlein generator using 44-m-long line sections 1.5-m wide, insulated with 2 mm of polyester film, and immersed in water. The lines have 0.29 Ω impedance and are charged to 125 kV. The total emf in the circuit is then 10^6 V and the generator impedance is ~ 2.3 Ω. In order for this generator to drive 800 kA through our load it would have to be charged to 260 kV instead of 125 kV. Presumably it should then have double the insulation thickness and, to have the same impedance, it would have to be 3-m wide. This seemed difficult, although in principle it could have been done. An unattractive feature of Blumlein generators on our low-impedance load is that failure of preionization or firing onto an evacuated discharge tube would apply nearly all of a ~ 2 MV emf to the coil, so as to make insulation flashover and tube destruction likely.

An alternative scheme using simple transmission lines, switched at the lower end, suffers from the same disadvantage of bulk as the Blumlein system. It is not subject to the voltage doubling problem, but the lines uld have to be somewhat lower impedance because of is, and would probably end up ~ 5-m wide. Again the heme seems unattractive.

A scheme using a low-inductance capacitor in place one of the Blumlein line sections was also consider- . This has the advantage of voltage doubling like a umlein system, but with the generator impedance equal that of the line section instead of being twice as rge. An alternative is to drive a line section from e far end with a capacitor through a switch. The oblem here, as in the Blumlein system, is line bulk, though the line need not have so low an impedance.

Water lines were also considered. The most reason- le system appeared to be a two feed slot coil with a ttery of coaxial water lines feeding each slot. Be- use of the high dielectric constant (~ 80) of water e lines need be only about 5-m long instead of 44 m with polyester (Mylar). The dielectric strength of ter, however, is quite small, with the result that a fficiently low impedance could be attained only with very bulky assembly. In our case we considered nine 0-mm-diameter lines having a radial separation of 50 feeding each feed slot. The lines would have been arged to ~ 250 kV, and we estimated that there was ae probability of dielectric breakdown every 100 shots. ough energy appeared to be available in a breakdown do serious damage to a line, even though they were be switched through individual spark gaps. The large lk of this system made it difficult to connect to a -meter coil and almost impossible to feed a much ger theta pinch, assuming it would be used for large ged theta pinches in the future, so it was dropped.

A system using lumped constant delay line modules a series-parallel arrangement was considered. The acitors were to have been the small plastic case h-voltage capacitors frequently used in high-voltage x generators. It appeared that this system would be essively expensive because of the large number of acitors required.

The system finally chosen uses pulse-forming net- ks driving the coil through four feed points. The se-forming networks (PFNs) resemble curtailed lumped stant lines. The circuit is shown in Fig. 1. The acitors used are modifications of a design developed preionization use in Scyllac, the modification being eduction of capacity from the original 0.7 μF to 0.2 or 0.4 μF with very little effect on the original uctance. In Scyllac use the capacitors are dc rged to 75 kV, but must hold 120 kV pulsed, because a voltage doubling effect when the much larger main llac bank is connected across them after preioniza- n. C_1 in Fig. 1 actually consists of four 0.2-μF acitors. The paralleling is to reduce the inductance an acceptable value. Similarly C_2 consists of three μF capacitors. The connection between the capaci- s and the collector plate involves modification of original capacitor insulator by cutting off a flange, the use of silicone rubber voltage gaskets. It is cribed in the following paper. This produces an in- tance of ~ 30 nH per capacitor, but will hold off kV.

The capacitor shown on the left in Fig. 1 is actual- wo Marx generators in parallel, each capable of pro- ing 240 kV. They use 20-kV, 14.7-μF capacitors in es. The Marx are erected with field distortion k gaps triggered in parallel through resistors by -kV pulse derived from a master gap. With two generators in parallel feeding each PFN, eight are ired altogether. Because of limited space they are ked in pairs, one on top of the other, the upper connected with high voltage at its lower end and lower one with high voltage at the top. Most of 5-μH inductance shown in series with the Marx is internal inductance of the capacitors. The generators are cable connected to the PFNs.

Circuit analysis for designing the PFNs has been carried out using the NET-2 computer code. NET-2 performs transient analysis of complicated networks, and is capable of handling time-dependent non-linear impedance elements. By coupling the equation for the plasma motion into the circuit analysis we include the effects of the imploding plasma, according to the bounce model, until the sheath has reached one-third of its original radius. From this point on the sheath radius is assumed to be constant. This simplifies a bouncing plasma situation which is too complicated to predict accurately and of which the effects are small in any case.

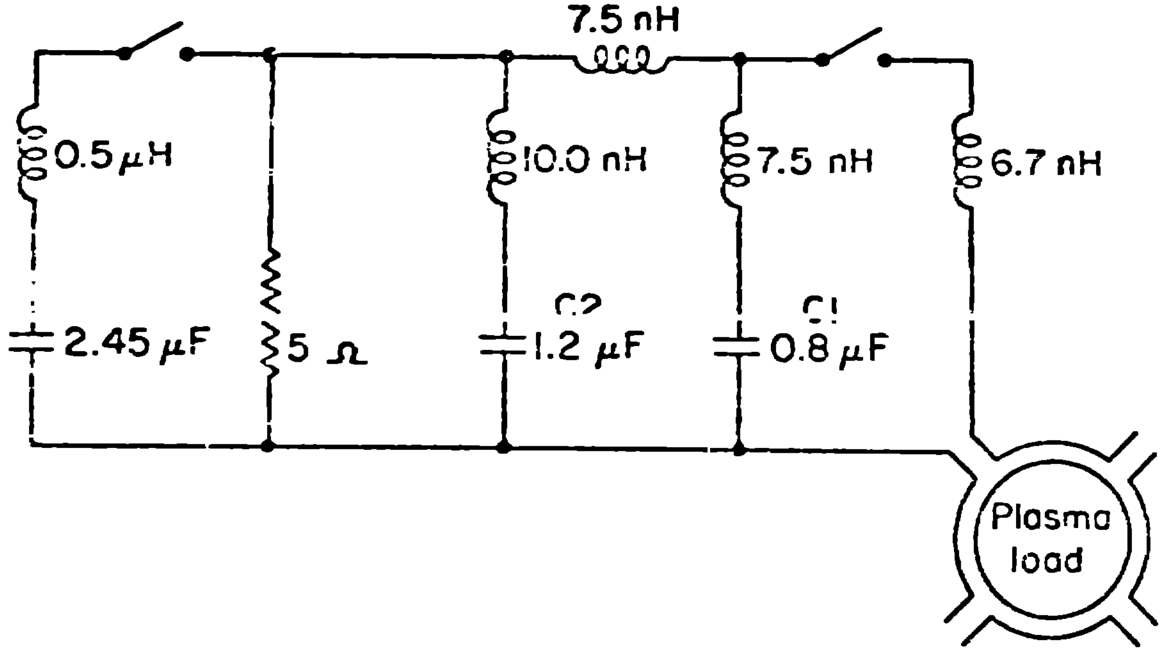
In the study of the water line system mentioned above it was necessary to consider fast high-current charging from the Marxes. This was because of the known degradation of dielectric strength of water with exposure time, and because of the conductivity of water, which leads to a short charge decay time of a water-insulated capacitor. It became apparent that a high charging current at firing time contributes substantially to system performance. As in a peaking capacitor system, the charging current can be diverted to the load without degradation by capacitor inductance. This principle will be applied to our PFN system by charging the Marxes so that if the load switches were not fired the capacitors would be charged to 184 kV by 2.28 μsec, substantially above their voltage rating. The load switches are fired at 1.37 μsec, when the capacitors reach 125 kV. The charging current is about 280 kA at this time, a little bit past its peak. It stays above 250 kA for the full pulse time of the coil, and thus contributes at least this much to the coil current. The time behavior of the more important voltages and currents are shown in Fig. 2 as computed. The curve marked V_{Marx} is the voltage at the high-voltage end of the Marx generators where it is substantially decreased from its open circuit value by the Marx internal inductance.

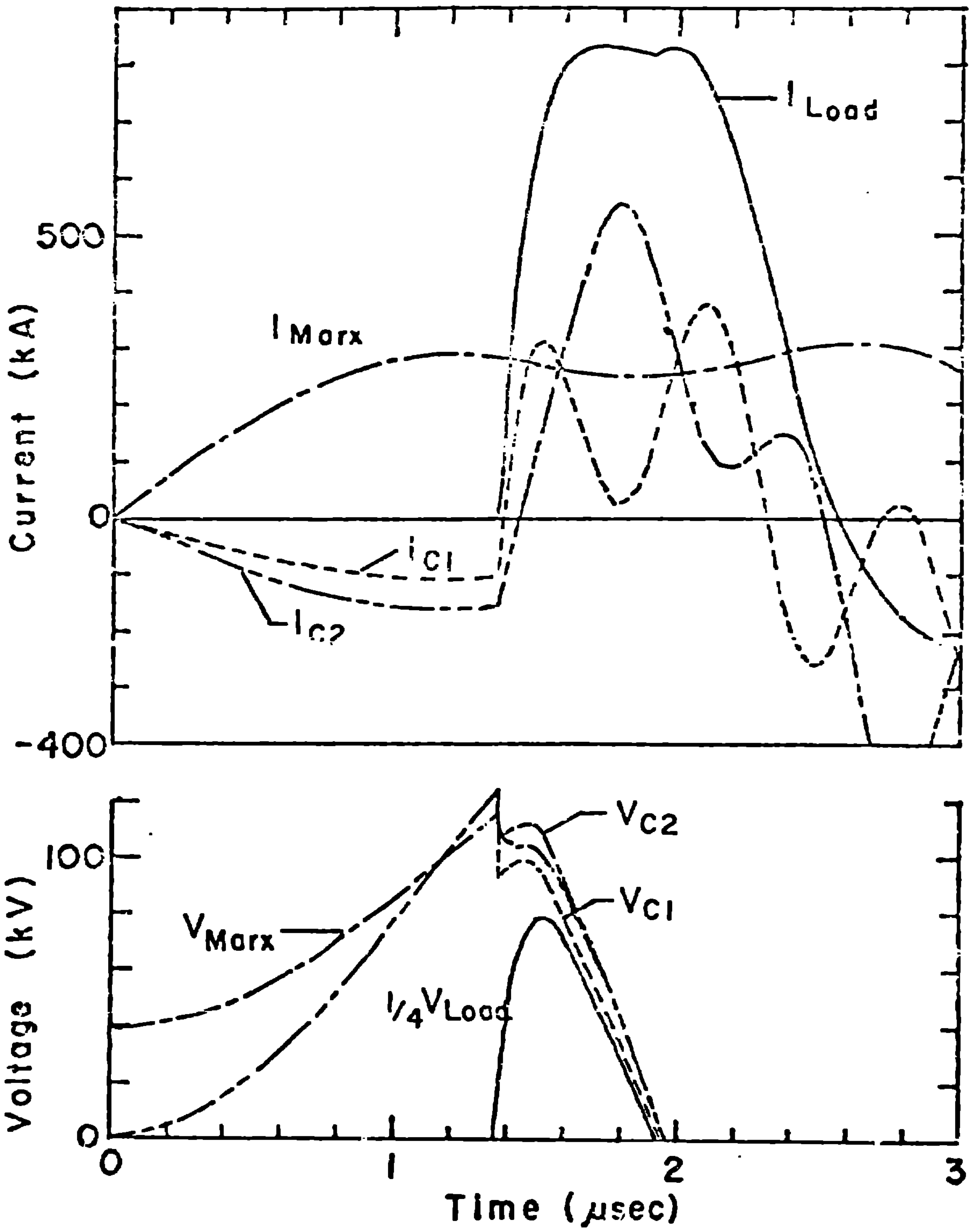
The main load switches are multi-channel field distortion rail gaps built by Physics International (PI). They are used in pairs, two of them connecting each PFN to its coil feed slot. The rail gaps are a modification of a design used under water by PI for switching considerably higher voltages. Extensions on the acrylic plastic spark gap bodies allow operation in air at 125 kV with voltage grading described in the next paper. The gaps are filled with high purity dry N_2 to about 5 atmospheres and can be triggered so as to have 10 to 20 spark channels in parallel. All eight gaps will be triggered from a single master gap. The full system has not yet been triggered or even assembled, but the master gap with all eight load cables has been used to trigger one gap successfully. The trigger pulse at the load end of an unterminated trigger cable rises at about 30 kV/nsec.

It should be emphasized that the load current and voltage will depend on the dynamic and resistive characteristics of the actual plasma, and that those characteristics are unknown and are precisely what the experiment is designed to measure. Another important question is that of preionization. Present plans are to use a relatively low frequency theta-pinch discharge isolated through cable inductance from the high voltage of the PFNs. A full scale test system is in operation at the time of writing this paper.

Reference

1. G. Herppich, "Projekt 500 kV-Theta-Pinch (500 kV Theta Pinch Project)", Inst. fur Plasma-Physik, Garching, Report IPP 4/68, November 1969.





<u>Captions</u>

Fig. 1 Pulse Forming Network

C1 is 4 0.2 µF 125 kV capacitors in parallel. C2 is 3 0.4 µF 125 kV capacitors in parallel. Inductances above C1 and C2 are capacitor plus header inductance. 6.7 nH inductance on right is that of switch and coil feed. Network at left represents 2 Marx generators in parallel with bleed resistors. Identical networks connected to all 4 coil feed slots.

Fig. 2 Calculated wave forms of circuit of Fig. 1 driving plasma load assumed to have 10^{21} deuterons/m^3. Bounce model perfect magnetic piston starting at inner wall of tube (a = 0.18 m). Coil 1-m long with inner radius 0.20 m. Plasma motion stopped at 1/3 of initial radius. Marx no-load voltage 190 kV.