Radiation Production Notes
Note 7

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Prepulse and Other Factors Affecting Fine Self-focussing of Large Currents

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1. Introduction

Prepulse may be defined as an electric field appearing within the vacuum diode section of a high speed electron pulse generator prior to the arrival of the main generator pulse. Its magnitude may vary between zero and roughly 10% of the main pulse amplitude and its length is of the order of a microsecond.

2. The Origins of Prepulse

Prepulse can arise from several causes which are dependent upon the form of the high speed generator used and which dictate the sign, magnitude and time scale of the prepulse voltage. The pulse forming sections of most generators are based upon either a simple switched co-axial line or a co-axial concentric Blumlein configuration.

2.1 Blumlein Prepulse

Fig. 1 shows a Blumlein system in this co-axial form, together with its effective equivalent circuit. Ideally, in a symmetrical system, no output voltage appears across the diode A-B during the time taken to charge the high speed line and prior to the closure of high speed switch S2. This situation can still be achieved with unequal capacities C_1 and C_2 (in a co-axial system, dielectric breakdown considerations usually lead to this state of affairs) by adjusting L_1 and L_2 to give equal LC products for the two sides. However, because the outer cylinder is usually electrically continuous with the Marx tank, stray capacity between Marx components and the tank leads to a finite voltage appearing across A-B during the charging phase. The magnitude and waveform of this voltage are determined by the stray capacity distribution, the distributed circuit inductance and the manner in which the Marx erects. The duration of the prepulse is that of the charging phase of the generator. Typically, in a 5 MV generator, prepulse voltages of a few hundred kilovolts both positive and negative may be obtained in times of a microsecond or so (Fig. 2(a)).

A further possible source for prepulse fields in Blumlein systems is "shine through". The proximity of the intermediate cylinder end to the RF window structure can cause significant field to leak through into the diode region (Fig. 3), causing an effective voltage to appear across some portions of the window.

2.2 Co-Axial Line Prepulse

Generators employing the simple co-axial pulse forming line with an output switch give rise to prepulse diode voltages which differ both in cause and character from those arising in Blumlein systems. As illustrated in Fig. 4, the cause is now capacitive coupling across the output switch between charged inner line and generator output section. The magnitude of this prepulse voltage is now dependent on the relationship between C_S and C_T and on any parallel damping resistance R_T (such as a monitoring resistor or intentional shunt) across the output end. The waveform is almost identical to that of the main line charging voltage, at least for damping resistances which are not too low, and is hence uni-directional (Fig. 2(b)).

3. Pre-Pulse Simulation

A rapidly dawning awareness of the association between the presence of prepulse voltage across the vacuum diode and inconsistent diode performance between various machines led us to investigate roughly the macroscopic effects of such voltages on polished electrodes in vacuo.

Unidirectional voltages derived from an air-cored transformer were applied for times of a microsecond or so with either polarity to electrodes in an evacuated lucite test cell at pressures in the 1 μ region. Applied voltage, current and photographic diagnostics were used in the tests. The results of these tests may be summarised:

(a) Electrode spacing had little effect on results; at least the gross phenomena tended to be voltage rather than field dependent.

(b) For voltages in excess of about 50 kV, copious local light emission associated with joints, cracks, etc. on the electrodes was observed, indicating the presence of reasonably dense plasma concentrations.

(c) An inter-electrode current which begins to flow virtually from time zero was observed; magnitudes of a few tens of amps at voltages of the order of 30 kV were obtained.

4. Pre-Pulse in the Vacuum Diode Region

While no great reliance should be attached to the actual numbers obtained, it is immediately obvious that significant local plasma concentrations can arise with prepulse voltages of a few tens of kilovolts in the diode region. Such concentrations may well lead to variability in performance as an electron generation system, "parasitic" current flow through regions other than the main diode gap, and catastrophic impedance collapse, depending on their location. This in turn will be determined by the mechanical structure of the system, surface condition and the precise nature of the prepulse. Blumlein generators with their oscillatory prepulse voltage may suffer from the effects of plasma concentrations on both cathode and anode sides of the diode; simple co-axial line generators, with their unidirectional prepulse, may tend to be one-sided.

4.1 Pre-Pulse in 'SPLATTLET'

Recent work on the water generator 'SPLATTLET' has provided our first clear-cut evidence of a direct relationship between pre-pulse and diode performance. In this generator, measurement of pre-pulse voltage, along with line and diode voltage, integrated γ dose and transmission target pinhole radiography, is performed on a routine basis. It was observed that, for a given cathode and diode electrode spacing, occasional abnormal pre-pulse waveforms were obtained which were always associated with abnormal diode performance. Figure 5(a) shows typical 'normal' pre-pulse and diode voltages as functions of time. Figure 5(b) shows the corresponding 'abnormal' forms.

The magnitude of the pre-pulse voltage at the time of arrival of the main pulse τ_p provides an approximate measure of the effective loading impedance existing across the diode at that time. In the 'normal' case, a known 200 Ω shunt resistor provides a 'calibration'. On those occasions where a prepulse waveform of the type illustrated in Fig. 5(b) was obtained, the diode voltage reaches only a fraction of the normal maximum and collapses rapidly back to zero; a large proportion of this voltage will, because of the high value of $\partial I/\partial t$, be inductive, making the actual diode voltage even smaller. Pinhole radiography shows that in these cases an off-axis spot of high current density is obtained, differing greatly from the normal symmetrical distribution of relatively low current density on the anode/target.

Further very limited evidence for a half-way stage between 'normal' and 'abnormal' results exists. In this case a multiple needle (wire) cathode was used and the waveforms of Fig. 6 were obtained. Pre-pulse loading was intermediate, the effective diode impedance being between 50 Ω and 100 Ω at the onset of the main pulse. The latter, though low in amplitude, lasted for about two-thirds of the generator pulse length. Radiography showed that only a few per cent of the available emitters contributed to the final current.

The frequency of these 'abnormal' responses was such that, for diode spacings with one particular plasma cathode of about 1 cm, more than 80% of the shots were normal; for spacings of about 0.7 cm, less than 50% were normal.

4.2 Surface Condition

The most effective treatment of negative polarity surfaces in the diode region has been found to depend strongly upon the magnitude of pre-pulse. For machines with very small pre-pulse levels, a thin oil coating is effective in suppressing electron emission from surfaces other than the cathode itself. Such emission is particularly noticeable in the high impedance machines on which a large proportion of our cathode development work was performed. In the presence of significant pre-pulse voltages, however, such oil coating leads to far greater parasitic emission than a plain polished surface and when such a plain surface gives intolerable emission currents it becomes necessary to change the physical structure of the diode so that the electron emission does no harm. For example, on the MOGUL machine it was necessary to increase the impedance of the transmission line feed to the cathode formed by the diode tube structure to the point where parasitic electrons were prevented from intersecting the anode side of the diode by the magnetic field of the main diode current flow; i.e. the inequality $Z_{tube} > Z_{diode}$ was satisfied.

5. Speculations

5.1 It is obvious that detailed analytic treatment of pre-pulse effects based on the limited evidence available is neither possible nor desirable. The apparently crucial dependence of such effects on surface geometry and conditions alone is sufficient to make this true. However, certain crude hypotheses may be advanced which at least help to explain some of the observed effects.

The pre-pulse loading effects described in Section 4.1 point to the existence and growth during the pre-pulse phase of plasma concentrations on one or both electrodes, which, by effectively bridging the diode gap, form one or more current-carrying channels. This is consistent with velocities of the order of 10^6 cm/sec, as suggested by Mesyats et al.* The main pulse then finds an essentially pre-ionized channel and the diode current rises very rapidly within the channel, raising its temperature, lowering its resistivity even further, and, by virtue of the very large self-generated magnetic field, forming essentially a Z-pinch. The ensuing radial collapse of the channel leads to very high current densities and eventual jetting of electrode material into the channel. This process is seen externally as a rapid impedance collapse.

The random nature of the location of the original plasma concentrations leads to the radiographic result noted in Section 4.1, the development of such concentrations will depend upon surface condition and the diode spacing will have a significant effect on the onset of pre-pulse loading.

The multiple needle experiment is interesting in that it may demonstrate a partial stabilisation process. If pre-pulse

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*Proc, IIIrd Int. Symposium on 'Discharges and Electrical Insulation in Vacuum', Paris, Sept. 1968.

generated positive ion densities and temperatures in the channel are high enough, radial channel collapse may be halted at a stage where particle pressure (nk $(T_i + T_e)$) balances magnetic pressure ($B^2/2\mu_o$) at a radius at which the current density is not high enough to cause significant electrode material injection, and catastrophic impedance collapse is prevented. The situation may have practical application in the production of high current beams of small (~ 1 cm) radius and of reasonably stable impedance. If little or no pre-pulse exists, a rapidly rising (~ 10 nsecs) main pulse may well cause small whiskers to vaporise, elongate and close across the diode at very small radii, and hence collapse to occur.

5.2 Summary

The tentative hypotheses advanced to explain some rather limited experimental data on the relationship between diode performance and pre-pulse suggest that, although prepulse may lead to rapid diode impedance and electron beam radius collapse, it may under certain circumstances be beneficial. Certain very tentative conclusions may be drawn:

(a) In the absence of pre-pulse and with fast rising main pulse voltages, catastrophic impedance collapse following vaporisation of a few small whiskers may occur. Sufficient pre-pulse to form a reasonably uniform cathode plasma distribution filling only a fraction of the diode gap may then be desirable.

(b) For high impedance systems in which pre-pulse is high enough to create a gap filling plasma before the arrival of the main pulse, diode currents may be limited to values which do not allow significant pinching to occur. The radial stabilization process outlined in Section 5 does not occur and impedance collapse may be obtained by virtue of the low pressure 'arc' so formed.

(c) Low impedance (~ 1 Ω) systems may benefit from plasma forming pre-pulse by achieving the stabilized pinch during the main pulse.

6. Pre-Pulse Control

The ability to exert partial, if not complete, control over the magnitude of pre-pulse voltages is obviously desirable. Blumlein systems and switched simple transmission lines differ greatly in this respect. However, the option to include an isolating switch between generator output and diode is common to both systems.

6.1 Blumlein Systems

Some of the factors which influence pre-pulse magnitude have been determined both in model tests and full scale tests. It should be emphasized that because of the origin of pre-pulse in Blumlein generators, the results will be critically dependent on the specific geometry used and effective measures on one system may not be applicable in general.

The measures either found to be influential in the case of MOGUL, or predicted from model tests, may be summarised:

(a) Charging inductor balance. A definite minimum pre-pulse is obtained at a specific tap-off point on the charging inductor.

(b) Damping resistors: the insertion of resistors between the first few stages of the Marx circuit and ground can have a small but significant effect on the pre-pulse voltage, damping the waveform, if not reducing the maximum value.

(c) Marx triggering: model tests have indicated that by triggering the Marx switches somewhere up the stack rather than at the ground end, a significant reduction in pre-pulse voltage may be achieved. This, as previously mentioned, will be very dependent upon the specific distribution of stray capacity between Marx and tank.

6.2 Switched Co-axial Line Systems

In this case the form of the pre-pulse is much more determinate and is readily calculable once the parameters outlined in Fig. 4 are determined. Defining the time constant τ as:

$$\tau = R_L (C_S + C_L) \qquad \ldots\ldots (6.2.1)$$

and assuming a charging voltage of the form

$$V(t) = \frac{V_o}{2} (1 - \cos \omega t) \qquad \ldots\ldots (6.2.2)$$

so that peak charging voltage is V_o, then, if the output switch S_2 is closed when $V(t) = V_o$, peak pre-pulse voltage is given by:

$$\frac{\hat{V}_{pp}}{V_o} = \frac{C_S}{C_S + C_L} \cdot \left[\frac{\alpha^2}{1 + \alpha^2} \cdot \frac{1 + \varepsilon^{-\pi/\alpha}}{2} \right] \qquad ..... \; (6.2.3)$$

where $\alpha = \omega\tau$.

Straightforward capacitive division is modified by the bracketed factor due to the presence of R_L , this factor always being less than unity for finite positive α , and tending to unity as $\alpha \to \infty$.

The extent to which R_L and hence α can be reduced is limited by the increasing amount of energy abstracted from the main pulse by the shunt resistor.

As an illustration of the gain obtainable by use of R_L , the results from SPLATTLET, a co-axial water line of 6 Ω impedance may be quoted. With little significant shunt resistance (a 1.6 kΩ monitor was present) a peak pre-pulse of about 7% was obtained. The addition of a 200 Ω shunt resistor, a value still acceptable from an energy loss point of view, reduced this figure to about 3 1/2%.

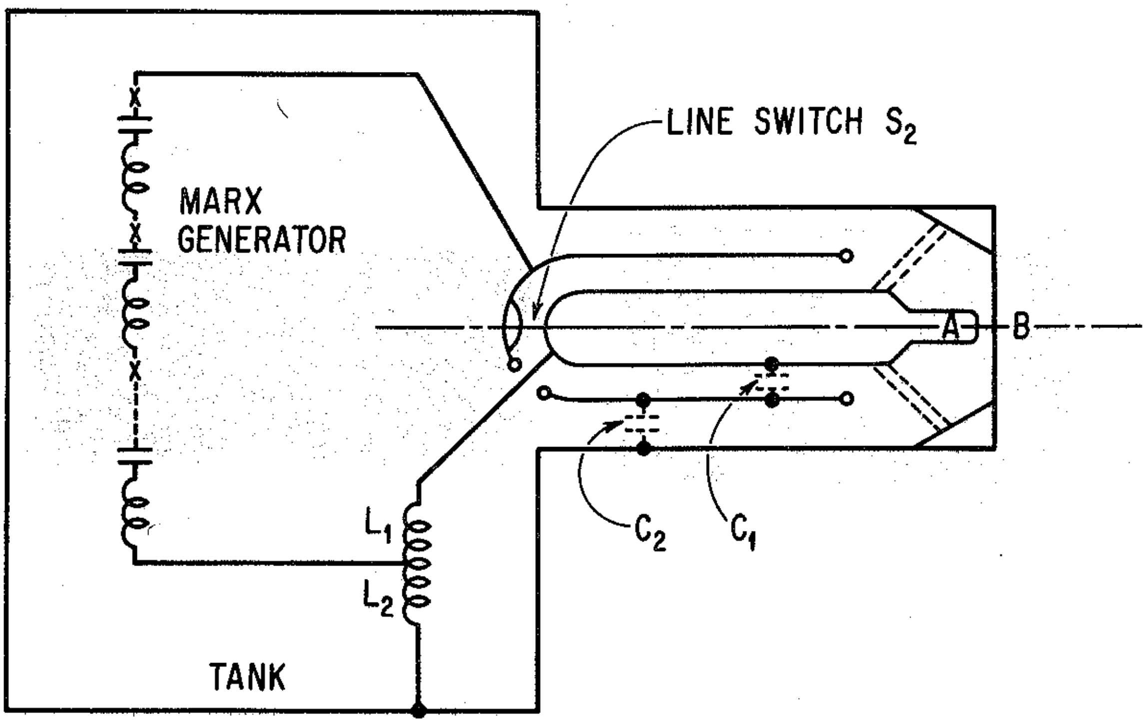
The conclusions may be drawn that pre-pulse is minimised by keeping the ratio C_L/C_S as high as possible, using the minimum value of shunt R_L allowable from energy loss considerations and charging as slowly as possible (small ω) consistent with other requirements.

6.3 Pre-Pulse Isolation Switch

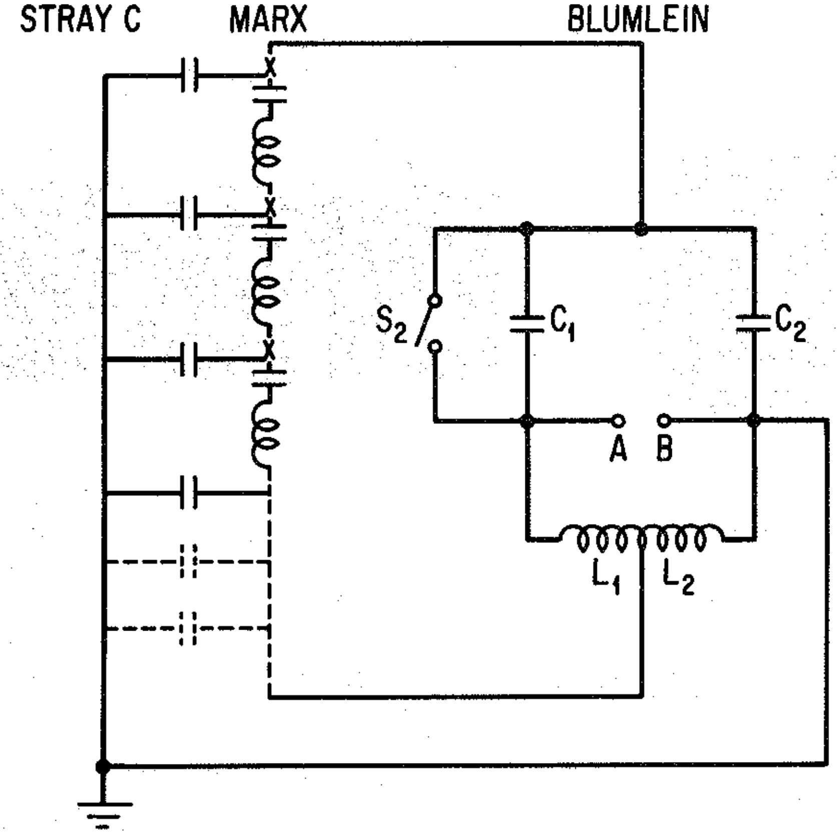
The possibility of effecting further reduction in pre-pulse than that attainable by circuit modifications is admitted by the inclusion of a second switch between generator output and diode input, designed to hold off the pre-pulse voltage but close on arrival of the main pulse in a fast and low inductive manner. This switch may be inserted either on the generator or diode side of the vacuum-dielectric interface. In general, the former is preferable, in that no part of the electrode structure at low pressure is subjected to the pre-pulse, but the latter is more easily achieved in that a fast vacuum interface breakdown can be utilized in a readily accessible position. With the additional capacitive division which takes place in this switch, it becomes possible to reduce pre-pulse to below 1%.

Recently a multiple ball gap isolation switch in transformer oil has been put into SPLATTLET on the generator side of the vacuum-dielectric interface, reducing the prepulse on all components of the evacuated diode structure by a factor of ~ 7 to a level ~ 1/2% of the line charging voltage.

GENERATOR LAYOUT



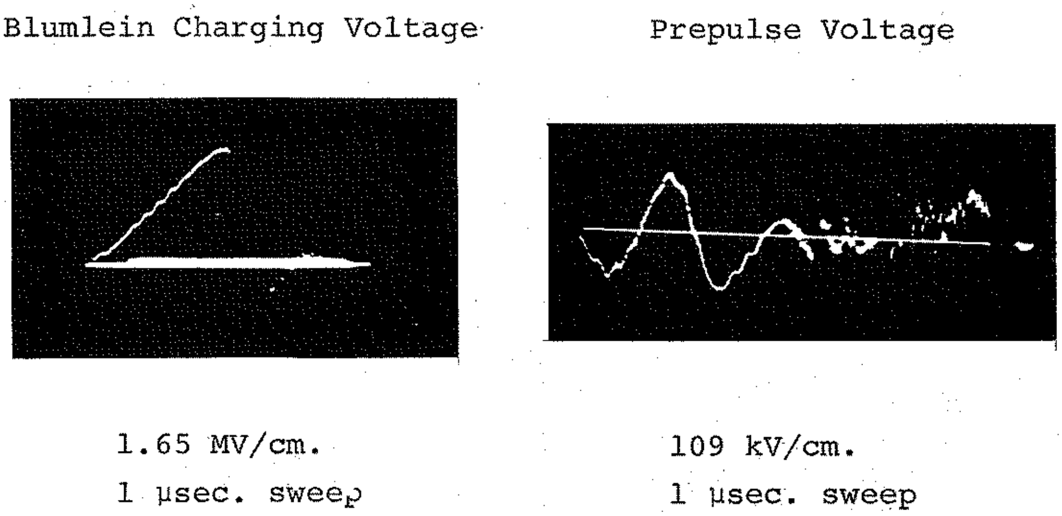
EQUIVALENT CIRCUIT



THE BLUMLEIN GENERATOR

FIGURE 1

2(a). Blumlein Generators.



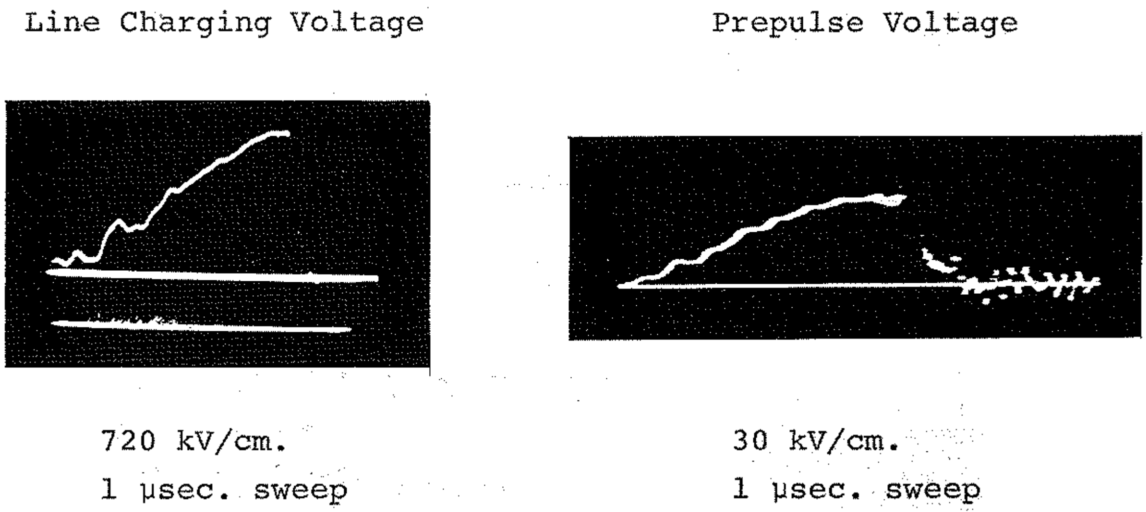
Blumlein Charging Voltage

1.65 MV/cm.
1 μsec. sweep

Prepulse Voltage

109 kV/cm.
1 μsec. sweep

2(b). Switched Co-axial Line Generators.



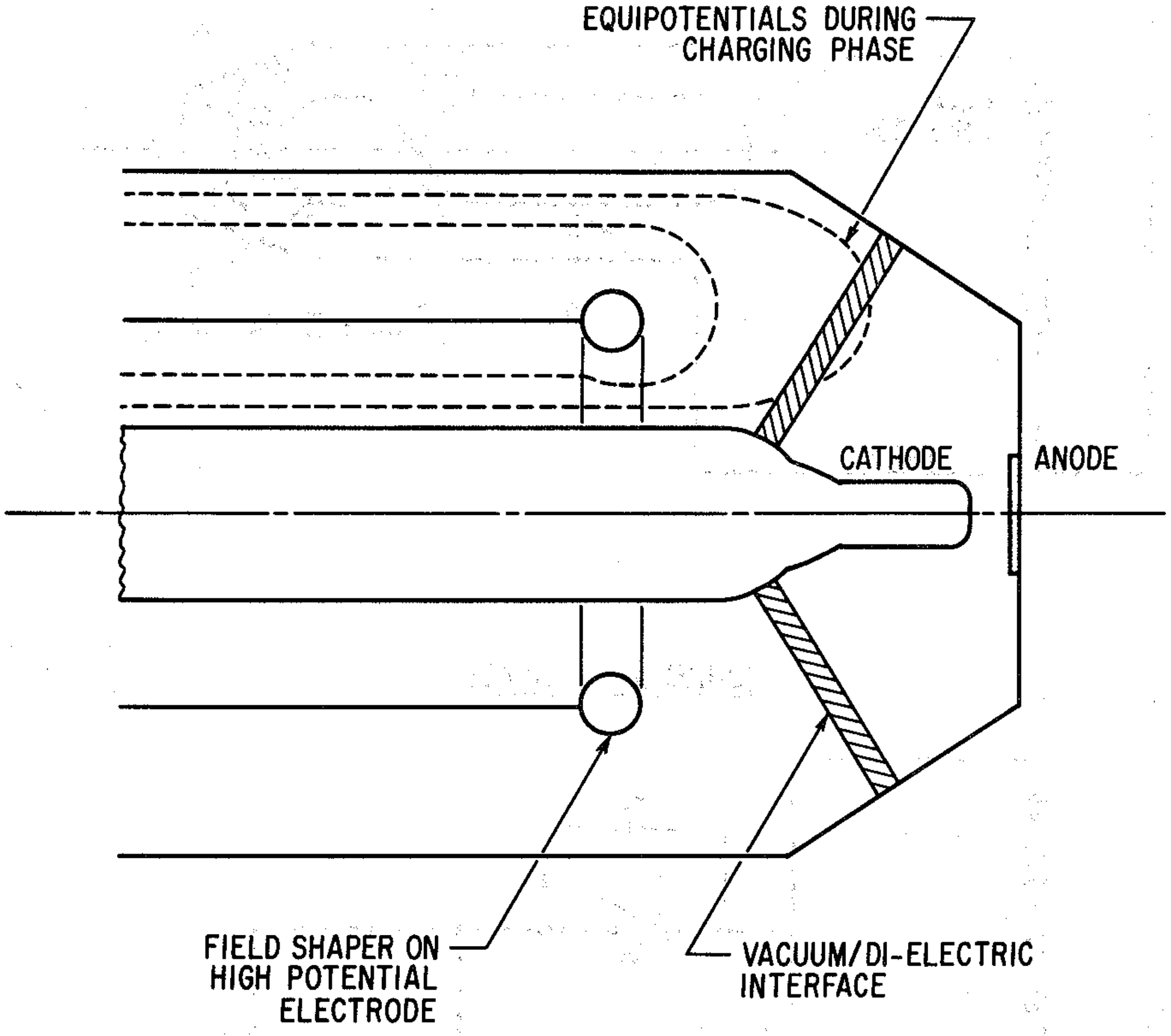
Line Charging Voltage

720 kV/cm.
1 μsec. sweep

Prepulse Voltage

30 kV/cm.
1 μsec. sweep

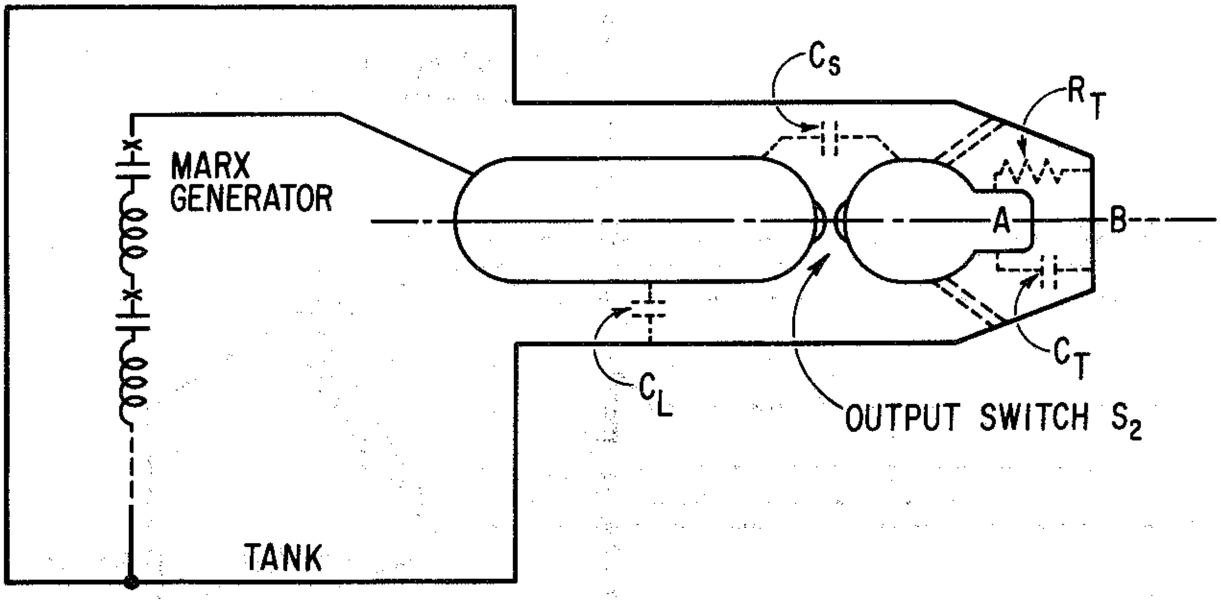
FIGURE 2. TYPICAL PREPULSE VOLTAGE WAVEFORMS.



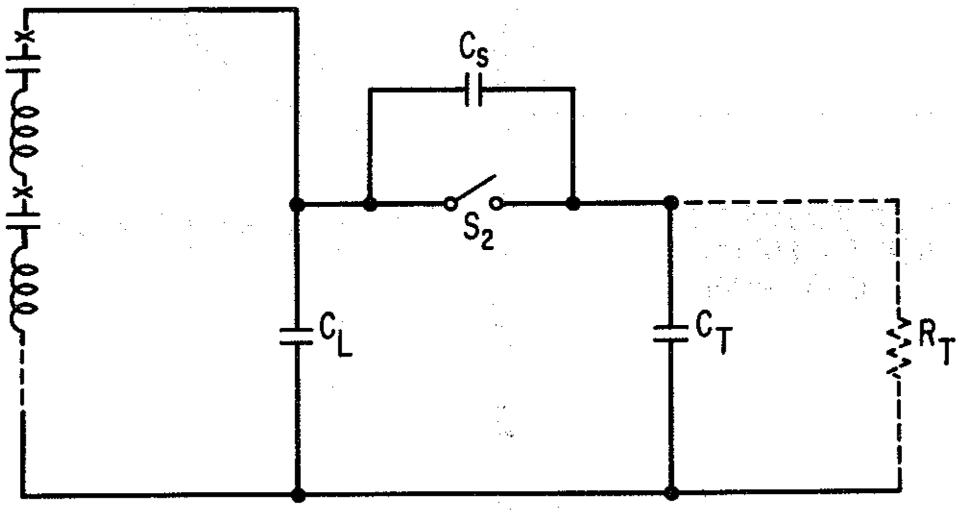
'SHINE THROUGH' IN BLUMLEIN CIRCUITS

FIGURE 3

GENERATOR LAYOUT



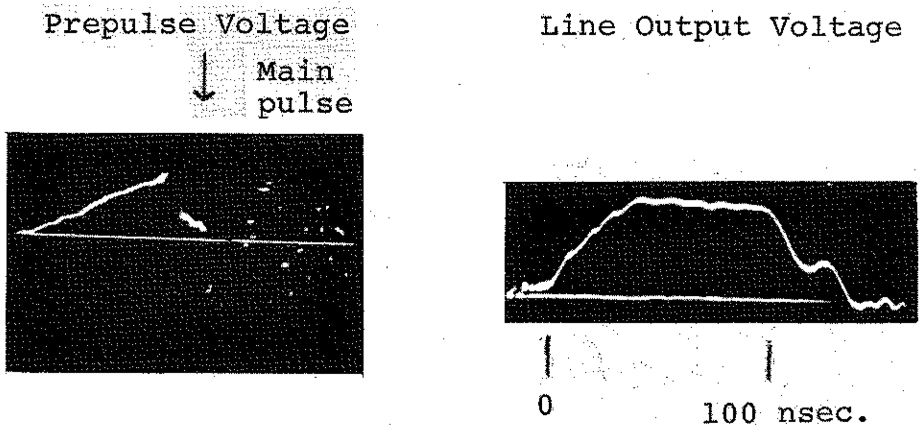
EQUIVALENT CIRCUIT



THE SWITCHED COAXIAL LINE GENERATOR

FIGURE 4

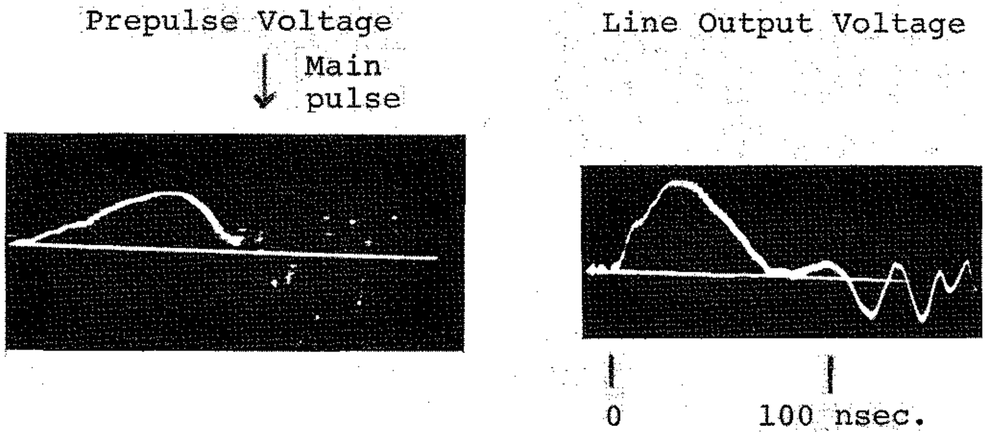
5(a). Normal Prepulse.



44 kV/cm.
1 µsec. sweep

600 kV/cm.
Exponential Sweep

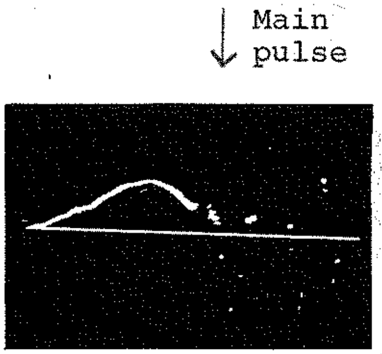
5(b). 'Abnormal' Prepulse.



36 kV/cm.
1 µsec. sweep

600 kV/cm.
Exponential Sweep

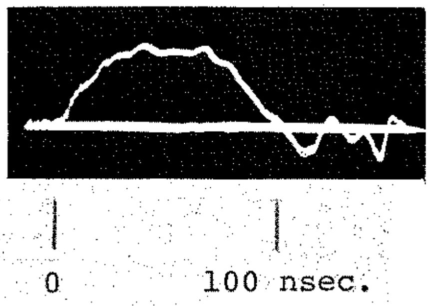
FIGURE 5. PREPULSE IN 'SPLATTLET'.



Prepulse Voltage

41 kV/cm.

1 μsec. sweep



Line Output Voltage

600 kV/cm.

Exponential sweep

<u>FIGURE 6.</u> <u>PARTIAL PREPULSE LOADING IN 'SPLATTLET'</u>.