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MAGNETIC INSULATION IN SHORT COAXIAL VACUUM STRUCTURES*

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Abstract

Magnetically insulated vacuum structures (MIVS) can be used to overcome the limitation on power flow in liquid dielectrics and dielectric vacuum interfaces in pulsed high power accelerators. A short (1 m), low-impedance (Z_o = 5Ω) coaxial MIVS with a gap of 5 mm was studied experimentally. Power flows of 1.5 x 10^{10} W cm^{-2} were observed. The current pulse showed some erosion before the onset of magnetic insulation. The transverse electron current arising from this erosion was observed with Faraday cups imbedded in the wall. Magnetic insulation was lost about 60-70 ns into the pulse. This loss was also observed in the Faraday cups and radiation diagnostics. This loss of magnetic insulation is associated with closure of the gap by cathode plasma.

Introduction

Magnetically insulated vacuum structures (MIVS) may be used to overcome limitations on power flow in liquid dielectrics and dielectric vacuum interfaces in pulsed high power accelerators. However, there are limitations in the energy transport efficiency in MIVS arising from:

1. Transverse electron flow in the gap as magnetic insulation is established. This electron current erodes the front of the pulse.
2. Current loss to the anode due to instabilities in the longitudinal space charge flow once insulation is established.
3. Loss of insulation due to closure of the gap before the end of the power pulse. This closure is due to motion of the cathode plasma across the gap.
4. Ion flow across the gap once a plasma has been established at the anode by electron leakage current.

An experiment has been designed and diagnostics have been developed to investigate how magnetic insulation is established and lost in a coaxial MIVS, therefore providing some insight on the limitations above.

The measurements revealed that the width of the front which establishes magnetic insulation is much shorter than the length of the MIVS under investigation. Therefore, even though the MIVS is short by the conventional definition[1] ($\ell << c\tau$ where ℓ is the length of the structure and τ is the risetime of the pulse), it exhibits the properties which have been attributed in the literature to a long structure ($\ell >> c\tau$).

It is suggested, therefore, that the distinction between a "short" and "long" structure should be based upon a comparison of the length of the structure and the width of the propagating front which establishes magnetic insulation.

Measurements also revealed that the apparent velocity of the front is substantially lower than that predicted by theory[2,3] for the voltages measured in the experiments.

While bounds have been established on the magnitude of the leakage current which may be due to instabilities in the electron flow, plasma closure has been identified as the cause of loss of magnetic insulation. The current flow across the gap, once magnetic insulation is lost, has been determined to be due to electrons. Calculations show that there is not enough energy

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deposited in the anode to produce a plasma which could be a source of ions.

Experimental Apparatus and Diagnostics

A schematic of the coaxial MIVS, drawn to scale, appears in Figure 1. The figure shows the coax (ℓ = 1.15 m) terminated with a focusing diode

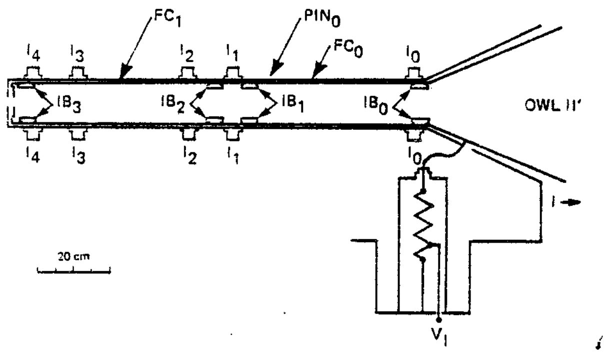

Figure 1 Vacuum coax apparatus.

load. The inner radius r of the coax is 6.2 cm, the radial gap d is 5 mm, and the geometrical factor[4] g equals 12.6 ($g = 60\Omega/Z_0$). To minimize the disturbances to the space charge flow, $g_{bicone} = g_{coax} = g_{diode}$ were chosen.

The coaxial MIVS was attached to the output of the OWL II' accelerator through a biconic adapter. This ~ 1 TW accelerator with a water dielectric coaxial output circuit has an effective source impedance of 1.2Ω. Prepulse was reduced to less than 4.1 kV peak.

The diagnostics used in the experiments were:

1. A vacuum voltage monitor at the input of the transmission line[5].
2. Self-integrating Rogowski coils[6] placed in grooves in the cathode and anode of the structure; their locations are shown in Figure 1.
3. A high-current graphite shunt[7] was placed at the I_4 location where electron bombardment caused the epoxy potted coils to fail.
4. Faraday cups consisting of a 0.32-cm-o.d. collector, nested in a 0.46-cm-diameter hole in the anode, shunted to ground via a ~ 1Ω resistor.

Experimental Results

The solid waveform in Figure 2 is the input voltage to the coax (V_I) with a g = 12.6 diode load. The dashed and dotted waveforms are the

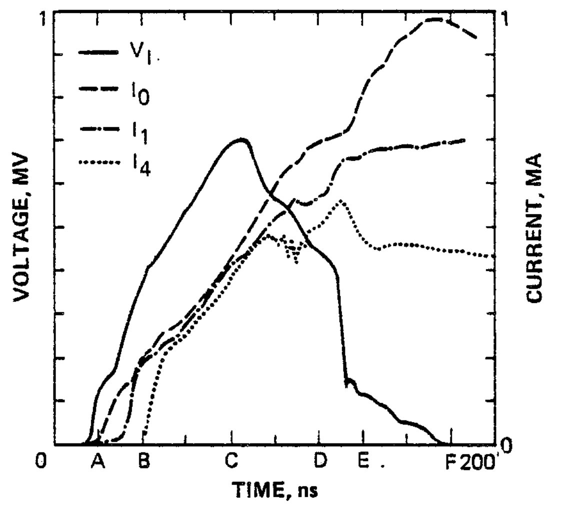

Figure 2 Voltage and current waveforms.

currents I_0 and I_4 at the input and output of the coax, respectively. The most significant features of the waveforms are the following:

a) There are about 120 kV on the line before current (I_0), which is in excess of the displacement current, begins to flow (A in Figure 2). This voltage corresponds to a mean field of 240 kV cm^{-1}. A field of this magnitude is required to achieve field emission from exploding whiskers on the cathode[8].

b) The current at the output (I_4) rises 20 ns after the current at the input I_0 (A→B in Figure 2). It is also 40 kA less than the current at the input until shortly after peak voltage (B→C in Figure 2), when impedance collapse takes place in the structure. It takes place in two phases described below.

c) In the first phase, the current shows an upward inflection as the voltage peaks and then drops (C in Figure 2). As the voltage continues to drop, I_4 diverges from I_0 and some high frequency structure appears on the I_4 waveform (C→D in Figure 2).

d) In the second phase, the input voltage (V_I) drops 300 kV in a few nanoseconds (D→E in Figure 2). The current at the input (I_0) displays an abrupt rise while I_4 at the output rises slightly, at first, then drops and finally clamps.

The signal from the Faraday cups, which yield a local measurement of current density at the anode, explains the difference between the input and output current waveforms displayed in Figure 2. The Faraday cup waveforms appear in Figure 3. The axial locations of FC_0 (dashed waveform) and FC_1 (dotted waveform) are 32 and 80 cm from the cone to coax transition, respectively. The solid line in the same figure shows the difference, I_{loss}, between the input (I_0) and output (I_4) currents.

Both Faraday cups peak at the beginning of the pulse (A→B in Figure 3). These peaks, which fit temporally under the broader peak of I_{loss}, arise from transverse electron current, that is, current flowing across the gap. The signal from FC_0 arises before the signal from FC_1. This transverse electron flow (pulse front) is required to establish magnetic insulation.

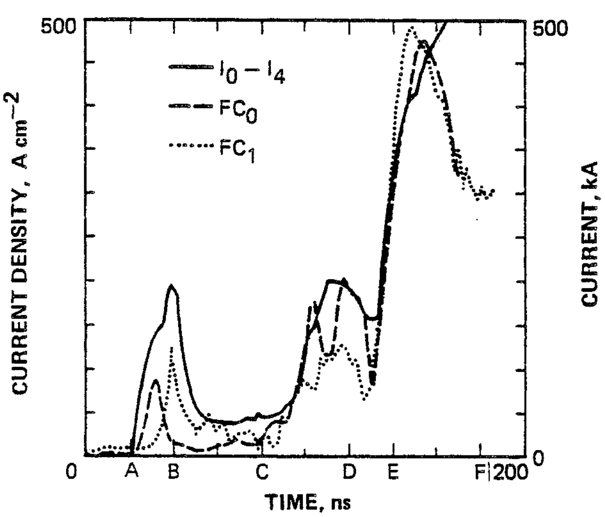

Figure 3 Faraday cup and current loss waveforms.

Another feature of the Faraday cup and current loss waveforms is the rise that occurs simultaneously and has roughly the same duration as the drop in voltage (C→D in Figures 2 and 3). This loss reaches a plateau before there is a rapid rise in the current loss and Faraday cup signals, which is simultaneous with the rapid drop in V_I (D→E in Figures 2 and 3).

The time between the two peaks of the Faraday cup allows a calculation of the apparent velocity of the pulse front, since the distance between the cups is fixed. For the waveforms of Figure 3, the velocity is 6.4×10^7 m s^{-1} while the velocity for seven experiments performed under similar conditions is $5.2 \pm 1.2 \times 10^7$ m s^{-1} corresponding to $\beta = 0.17 \pm 0.4$. The spreads in the results are standard deviations about the mean of the experimental data for seven experiments performed under identical conditions. Since the voltage behind the front is approximately 340 kV, the velocity is substantially below the velocity

$$\beta = \sqrt{\gamma_0 - 1/\gamma_0 + 1} = 0.5$$

predicted by present theories.[2,3]

The spatial extent of the front may be calculated under the assumption of constant apparent front velocity using a straightforward $t = x/u$ transformation. The mean FWHMs of the FC_0 and FC_1 fronts for the same seven experiments are 6.9 ± 2.7 ns and 7.4 ± 1.6 ns, respectively. These values yield a front width of 37 ± 14.3 cm at both locations. This analysis indicates that although the MIVS is short compared to the characteristic time scales of the experiment, it is long compared to the spatial extent of the front, which establishes magnetic insulation.

The difference between I_0 and I_4 (I_{loss}) shows a low level of transverse electron flow in the interval B→C of Figures 2-3 after insulation has been established and before the voltage begins to drop. For the seven experiments, this loss averages 55 ± 20 kA, which is equivalent to 12 ± 4 A cm^{-2}. This loss could arise from instabilities in the electron flow.

Experiments were performed with filters, covering the Faraday cups, to discriminate ion emission current, which could produce a signal distinguishable from electron impact current. The measurements revealed that the signals were indeed due to electron impact.

Gap closure has not been measured in these experiments. Indirect evidence of gap closure, however, was obtained from the current and voltage waveforms. It was observed that the current in the structure agreed very closely with that corresponding to saturated parapotential flow during the time interval B→C of Figure 2 The current became substantially larger thereafter, suggesting that closure of the gap could be responsible for the increase.

The gap in the coax is obtained as a function of time by dividing the current corresponding to saturated flow[4] $I_p/g = I_\alpha \gamma \ln [\gamma + (\gamma^2 - 1)^{1/2}]$ by the measured input current (I_0) and multiplying the quotient by R. Since g = R/d, the result of the calculation is d(t). In the calculation $\gamma = eV_I/m_oc^2 + 1$ and I_α = 8500 A. Figure 4 displays the result of the calculation with the waveforms of Figure 2. The plot shows that d remains equal to 5 mm for 40 ns after magnetic insulation has been established in the coax. Then gap closure begins shortly before peak voltage as

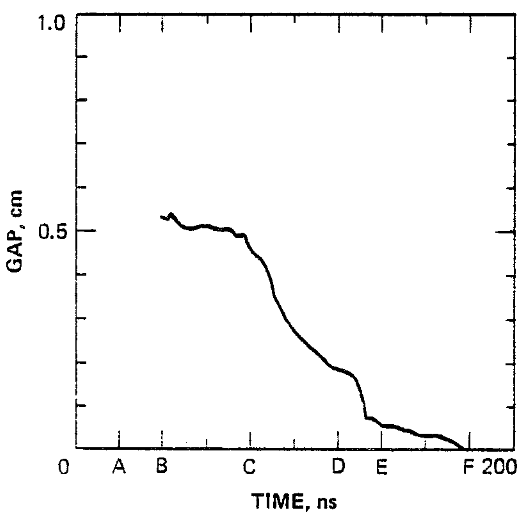

Figure 4 Coax gap as a function of time.

the Faraday cup signals start to rise. The gap in the coax has been calculated by this method for the seven experiments for which the Faraday cup data have been discussed. Before closure begins, the calculated average gap is 5.3 ± 0.2 mm, which compares well to the 5 mm gap in the coax. The average closure velocity for 5 mm > d > 2 mm is 4.6 ± 0.8 cm μs^{-1}.

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