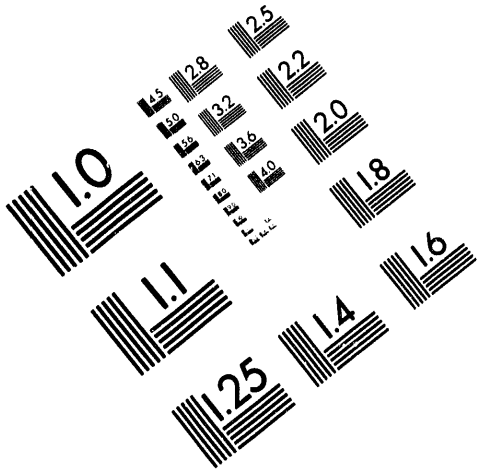

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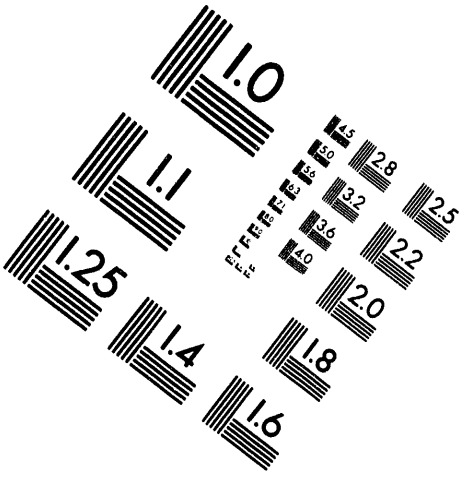

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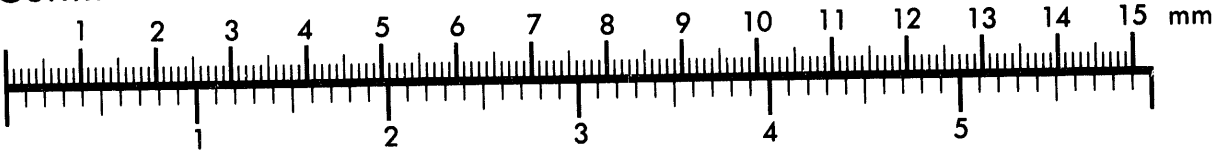

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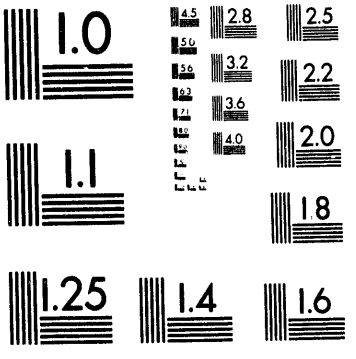

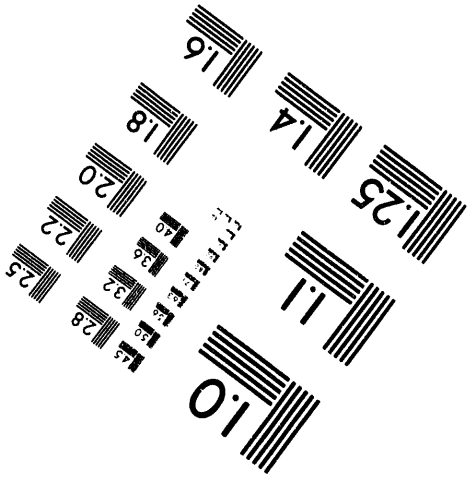

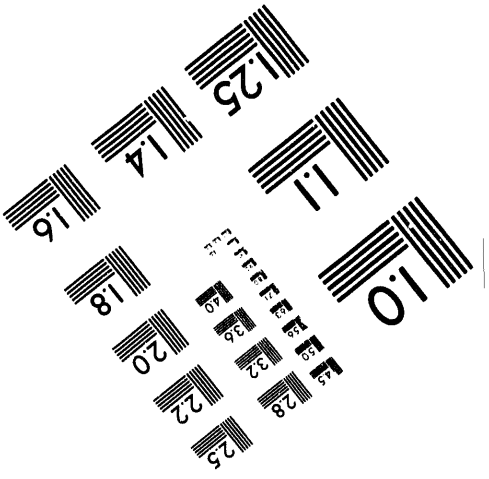

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CONTROL OF A LARGE VACUUM WAVE PRECURSOR ON THE SABRE VOLTAGE ADDER MITL AND EXTRACTION ION DIODE *

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Abstract

SABRE is a ten-cavity magnetically insulated voltage adder (6 MV, 300 kA) used to study ion beam production in high voltage extraction applied-B ion diodes. Observations indicate that the machine power initially propagates in a large-amplitude vacuum wave prior to electron emission. This vacuum wave "precursor" has an important impact on the turn-on and impedance history of ion diodes. Some typical precursor characteristics are shown using transmission line, diode, and beam current and voltage data and are compared to TWOQUICK simulations. Two techniques are under investigation to control the precursor and its effects on diode performance. A plasma opening switch (POS) has been used to erode the precursor. Field enhancing inserts are also planned to decrease the macroscopic fields required for electron emission from the cathode. This will limit the distance over which vacuum and insulated waves separate by propagation at different velocities. Experimental data from the POS technique and TWOQUICK simulations of the insert technique are presented and discussed.

Introduction

SABRE is a ten-cavity magnetically insulated voltage adder operated in positive polarity (6 MV, 300 kA) [1] to study ion beam production in high voltage extraction applied-B ion diodes [2,3]. Observations indicate that power propagates along the coaxial output transmission line as a large vacuum wave prior to electron emission [1]. The vacuum wave is identified as the region where transmission line anode and cathode currents are equal indicating no electron emission. After the electron emission threshold is reached locally, power propagates in a magnetically insulated wave. The faster vacuum wave "precursor" ($\beta=v/c=1$) and slower magnetically insulated wave ($\beta\leq0.8$) separate as they propagate to the load over 9.7 m. In the worst case this can result in two separate pulses at the extraction diode.

The precursor initiates diode load plasma formation and dominates the first 20-30 ns of the impedance history since the precursor voltage is large enough to cause electron emission from both the cathode feed and cathode tips [2]. The elimination of this precursor is considered a prerequisite for the development of active ion sources. Precursor elimination is also desired to stop premature formation of electrode plasmas to impede gap closure, and to delay neutral production leading to charge exchange production of fast neutrals. Precursor elimination may give a higher rate of rise of the beam power. Application of this magnetically insulated inductive adder technology to ion beam fusion will require elimination of the precursor, since the proposed systems have very long magnetically insulated transmission line (MITL) delivery systems resulting in two electrical pulses at the load.

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Precursor Characteristics

Fig. 1 shows that the precursor dominates the first 20-25 ns of the diode voltage and current. Fig. 1 gives the diode voltage VDIODE, a composite of the inductively-corrected MITL voltage from a magnetic spectrometer and diode voltage from a range-filtered Faraday cup array, upstream MITL cathode current IMCAT from shunts, diode cathode current IDCAT from B-dots, and ion beam currents IIBDOT and IIFCUP from B-dots and scaled Faraday cups respectively. The precursor drives a low enhancement (≈ Child-Langmuir) ion beam at the diode because the sheath electrons are overinsulated during the precursor ($V_c/V \approx 2.5$) and the high vacuum wave impedance (about 100 Ω in Fig. 1) restricts diamagnetic sheath compression [4]. The line labeled VCL in Fig. 1 represents a Child-Langmuir (CL) scaling of IIFCUP to voltage, agreeing well with the measured precursor voltage. We also observe that the precursor current depends on diode impedance which is a function of diode geometry, ion species, and magnetic field profile and strength.

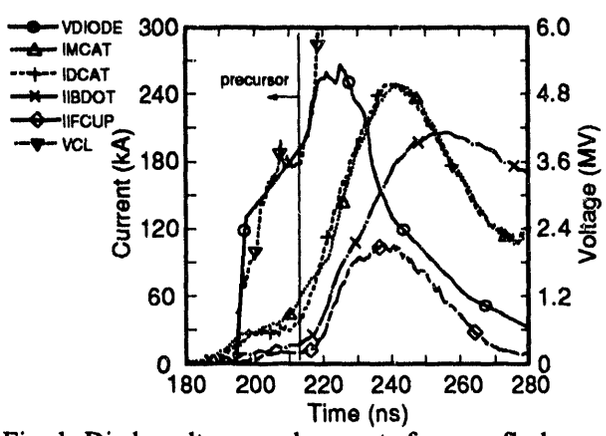

Fig. 1. Diode voltages and currents for wax flashover with precursor (extended cathode tip diode [3]).

The SABRE inductive adder consists of two sets of five cavities, each cavity charged to a nominal 850 kV. Each set of five cavities is charged through a single electrically triggered gas switch. Firing of the downstream set is delayed to compensate for wave transit time between the two cavity sets. Different output voltage waveshapes are observed depending on this delay interval.

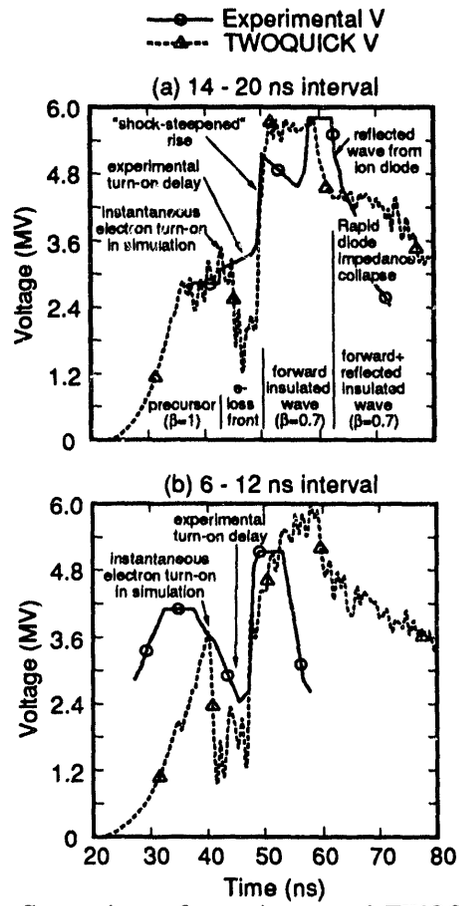

Fig. 2. Comparison of experiment and TWOQUICK simulations for different switching intervals.

Fig. 2 compares time-resolved MITL voltages measured 1 m from the diode with TWOQUICK PIC-code simulations [5] for two different switching intervals. The MITL electron emission threshold electric field was 300 kV/cm for these simulations. The data is obtained using a magnetic spectrometer to measure the energy and arrival times of protons accelerated across the MITL gap, with a correction for the particle transit time. Fig. 2a compares data and simulation with a 14 ns switching interval. The data features are typical of switching intervals in the 14-20 ns range. Fig. 2b compares data with an interval of 8 ns to a simulation for a 0 ns interval. The data features are typical of intervals of 6-12

ns. Significant features of the data and simulation are labeled on the figure. We make the following observations:

(1) Switch intervals of 14-20 ns optimally add the insulated waves from the two sets of cavities for wave velocities of β=0.6 to 0.8. The result is a precursor blended into the insulated pulse (Fig. 2a). Switch intervals of 6-12 ns add the vacuum waves from the two sets, giving a lower amplitude insulated pulse and a well separated precursor of larger amplitude (Fig. 2b). MITL, diode, and ion beam currents and Faraday cups also show these waveshape differences.

(2) The simulations show a greater separation between precursor and insulated wave in contrast to experiments. Electron turn-on in the idealized simulation is instantaneous once the threshold is exceeded. A 5-10 ns sheath development period can account for the smoother transition between the measured precursor and insulated wave.

(3) The simulations do not show as clear a difference for various switching intervals in separation and amplitude of precursor and insulated wave as do the experiment, although shorter intervals do give a larger separation. Differences can be explained by use of a simulation cavity input voltage that is about 15-20 ns too wide and by the instantaneous sheath turn-on in the simulation.

(4) The separation of precursor and main wave is larger than can be accounted for strictly on the basis of propagation times. Erosion of the electron loss front, and shock steepening of the insulated wavefront as the velocity increases with wave voltage both contribute to the larger separation.

(5) The simulations show that the peak precursor voltage varies with threshold field. The measured amplitude of the precursor is consistent with threshold fields of 200-300 kV/cm.

In summary, the precursor is a prominent aspect of the SABRE data in amplitude and timing for several reasons:

(1) The MITL gaps and therefore impedances ($\approx$ 9 cm and 40 Ω at output) are large and hence the electric field threshold for electron emission (200 to 300 kV/cm) is not reached until 40-60% of the maximum voltage is present. The emission voltage is related to the emission threshold field by:

$$V_{emission} = E_{threshold} r_c \ln(r_c/r_a),$$

where r_c and r_a are the radii of the cathode and anode. The peak amplitude of the precursor in Fig. 2 agrees with this analytical estimate. The scaling of this formula with r_c implies that positive polarity operation will have a larger precursor in comparison with negative polarity.

(2) The rapidly falling forward wave and diode impedance for the ion diode further reduces the ratio of insulated pulse voltage to precursor voltage.

(3) SABRE is long (9.7 m) allowing ample distance for precursor and insulated wave to separate and the voltage of the insulated wave gives a slower propagation velocity compared to β=1. Note that positive polarity lowers the voltage compared to negative polarity [1], slowing the insulated wave by comparison.

(4) Wave addition effects from different gas switch timings, erosion of the electron loss front and shock steepening of the insulated wavefront all contribute to the large separation of precursor and insulated wave.

Precursor Elimination

Two techniques are under investigation to control the precursor and its effects on ion diode operation. A plasma opening switch (POS) located 20 cm upstream of the diode has been used to erode the precursor by filling the MITL gap with plasma. Field enhancing inserts are planned for the transmission line cathode to decrease the macroscopic fields required for electron emission. These inserts will be located in the 4.2-m long coaxial extension transmission line downstream of the voltage adder region.

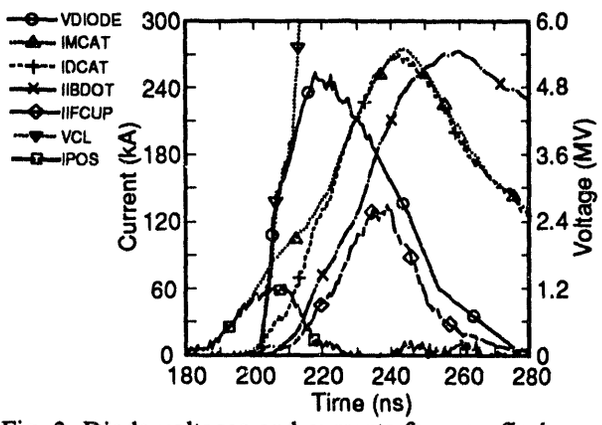

Fig. 3. Diode voltages and currents for wax flashover with optimal POS precursor erosion (extended cathode tip diode [3]).

Fig. 3 shows diode voltage and currents for a wax flashover source with optimal precursor erosion ($\approx$ 1.2 mCoul) by POS. The waveforms in Fig. 3 can be compared directly to those in Fig. 1 with a full precursor. The

additional signal IPOS is the POS current, the difference between IMCAT and IDCAT. A detailed comparison between Fig. 1 and Fig. 3 shows:

(1) Elimination of the precursor allows the ion current to quickly exceed the CL level (10 ns vs. 25 ns).
(2) The increase of peak cathode current from 240 to 270 kA and peak ion beam current from 94 to 130 kA is due to undermatching of the POS/diode system to the MITL [1].
(3) The peak ion power is essentially the same (≈ 0.5 TW) but the voltage at peak ion power is decreased from 4.6 to 3.8 MV.

We also note that the POS may be able to simultaneously provide the necessary charge (A-s) for erosion of the precursor while also providing an appropriate range of timing and action (A^2-sec) for ohmically vaporizing a metal film as an active plasma source, with the film thickness as the adjustable parameter.

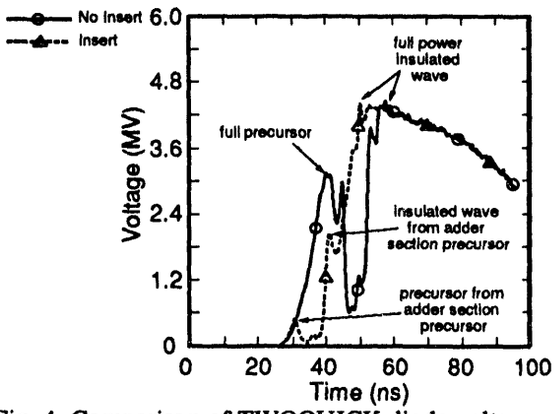

Fig. 4. Comparison of TWOQUICK diode voltage with and without cathode inserts in extension MITL.

Fig. 4 shows TWOQUICK simulated diode voltage behavior where a 300 kV/cm emission threshold in the entire machine (No Insert) is compared with the case of 300 kV/cm in the adder and 30 kV/cm cathode insert in the extension MITL (Insert). Note that the insert starts formation of the insulated wave earlier in the forward wave and limits the distance over which the vacuum and insulated waves can separate by propagation at different velocities. There is still a small vacuum wave of about 500 kV launched before electron sheath turn-on in the extension MITL. This could be eliminated with a either a low-level POS or a dielectric flashover insert on the anode if it appears to adversely affect diode performance.

Other precursor mitigation/elimination techniques are also possible. Increasing the cavity voltage on SABRE to 1 MV would result in a faster insulated wave and a less prominent precursor at the diode. SABRE could be made into a vacuum wave adder with no electron flow if the threshold for electron emission could be increased by about a factor of two to 400-600 kV/cm by surface coating or treatment of the MITL cathode.

Summary

A high impedance vacuum wave precursor has been observed on the SABRE MITL, diode, and beam current and voltage data. Its appearance and characteristics are well understood. The TWOQUICK simulations show that the data are qualitatively consistent with a 200-300 kV/cm turn-on threshold and a 5-10 ns development period of the electron sheath. The precursor drives a 20-30 ns long Child-Langmuir level ion beam at the diode. A low-level POS effectively erodes the precursor. TWOQUICK simulations show the promise of field enhancing inserts for precursor modification. This concept will be tested in future experiments.

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