

TRIDENT - A MEGAVOLT PULSE GENERATOR USING INDUCTIVE ENERGY STORAGE

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A megavolt level pulse generator, TRIDENT, has been constructed utilizing an inductive store as the primary pulse forming device. The 2.5 μ H coaxial storage inductor can be energized with up to 500 kA obtained from a 500 kJ, 60 kV capacitor bank. Current interruption is accomplished using a three stage opening switch comprised of an explosively actuated switch in parallel with foil and wire fuses. The generator has been operated at the 410 kA charge level (70% energy) to produce 700 kV pulses with risetimes of 150 nsec. Energy has been deposited into a 7.5 Ω resistive load at a rate of 5×10^{10} W. Operation with optimized fuse dimensions and at full charge is anticipated to approach megavolt outputs at powers of 10^{11} W. Future experiments include utilizing a homopolar generator as the current source.

Introduction

The development of high power pulse generators using capacitive energy storage has achieved levels of tens of terawatts at energies of a few megajoules.^{1,2} The next generation of experiments to be performed using pulse power technology will require energies of several tens of megajoules. The combination of size, complexity, cost, and, in some cases, limitation of electrical parameters of such machines is prohibitive. In anticipation of this requirement, NRL has undertaken a program to develop compact inductive energy storage pulse generators which utilize inertial energy stores, i.e. homopolar generators,^{3,4} as the primary energy source.

As recognized in every previous experiment applying inductive energy storage, the major component problem

is the opening switch. Our approach to this problem has been to begin with those types of switches which have exhibited the most promising characteristics (e.g. opening times, high current capabilities, rapid high hold-off recovery, low loss, etc.) with respect to the present state of technology. The results of this work indicated that an effective opening switch could be designed by paralleling explosively actuated switches with foil and wire fuses. As a demonstration of this switching scheme, the TRIDENT pulse generator was designed and fabricated. The goals of this experimental pulse generator were to demonstrate megavolt capabilities at 500 kA current levels with 100 nsec risetimes while delivering a few tens of kilojoules to a resistive load. The remainder of this paper describes the switching scheme, the design of the pulser, operation to date, and future experimental plans.

Three Stage Opening Switch

The three stage opening switch was developed especially to be compatible with the slow risetimes (seconds) typical of homopolar generators, but yet retain the fast opening potential (10's of nsecs) of wire fuses. A schematic diagram of the three stage switch circuit is shown in Fig. 1. The first stage of this switch is an explosively actuated switch. This switch has been described in detail elsewhere.^{5,6} Briefly, it consists of a thick wall aluminum tube which acts as a current conductor. Sharp edged rings (cutters) and full radiused rings (benders) are alternately placed around the tube and spaced using polyethylene insulators. A length of primer cord is placed along the axis of the tube and

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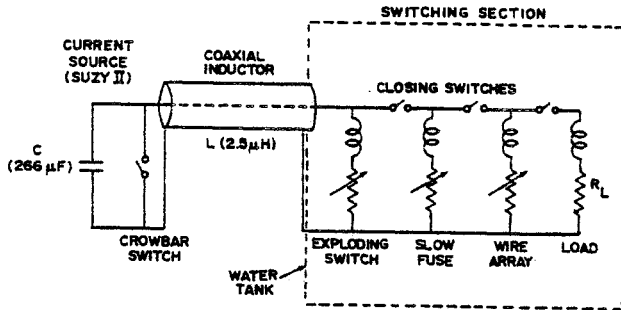


Fig. 1. Schematic diagram of the TRIDENT inductive storage pulse generator.

the tube is then filled with paraffin. Detonation of the primer cord by an exploding bridgewire detonator forces the paraffin against the tube which is then severed circumferentially by the cutting rings and folded around the bending rings. For operation in water, the region immediately adjacent to the bending rings is filled with styrofoam to exclude the water and thus provide a compressible medium into which the severed aluminum rings can be driven. Each gap generates an arc voltage of 200–700 V, depending on the current carried, with a risetime of approximately 20 μsec (opening time). The outstanding characteristic of this switch is its low loss in the conducting state. This feature allows the storage inductor to be charged at relatively slow rates. Its slow opening time and relatively low resistance in the open state are the reasons that succeeding stages are required for high voltage, fast pulse applications. If this switch is to be operated in high voltage applications, current must be commutated away from the switch for a time period of 40–50 μsec before any high voltage is applied. During this interval the switch has recovered to a hold-off level of 10 kV/cm.

Commutation for this interval has been accomplished with fuse elements chosen with appropriate cross sections. The majority of our work has employed water tamped aluminum foil fuses for this element. Fuses with this duration time to explosion generate maximum voltages of 6 kV per cm length of fuse. Current interruption times for these fuses range from 3 to 5 μsec . These times are still too slow

for many applications and, in order to achieve the high voltages, the mass of the fuse material to be vaporized accounts for a significant amount of system energy.

The 100 nsec risetime, high voltage pulses can be generated by commutating the current from the foil with another fuse element with a small cross section designed to explode in the microsecond time range. These fast fuses can generate self-field stresses approaching 20 kV/cm without restrike. Most of the work at NRL has employed wire fuses for this element. Copper wires have been used over aluminum wires mainly because of the fragile nature of aluminum wires. Ideally, wires of minimum mass should be used, however, the actual cross section necessary is dependent on the recovery characteristic of the slower preceding foil fuse. A small scale experiment conducted at the 10 kA level using a two stage foil and wire fuse arrangement has produced the foil fuse recovery characteristic shown in Fig. 2. The two curves were for commutation out of the foil in the 3 and 4 kV/cm self stress range because at lower fields the fuse is not completely vaporized and at higher fields unnecessary energy dissipation occurs. The significant feature of this data is that after 2 μsec of commutation the foil fuse can withstand electric fields of 20 to 25 kV/cm without restrike. The reason for the decrease in the recovery characteristic at times out to 10 μsec is not understood,

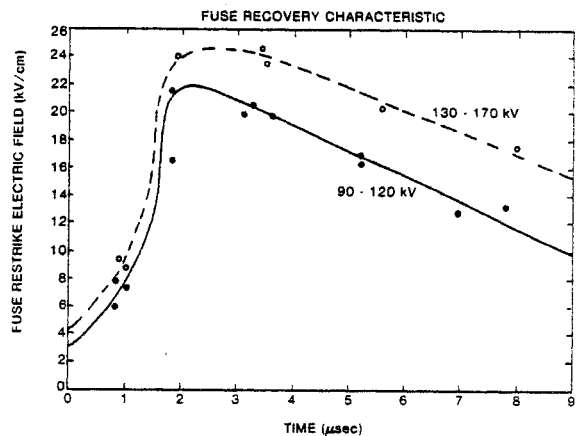


Fig. 2. Foil fuse high voltage recovery characteristic.

but has not been pursued because these longer times are presently not of interest. The factor of six gained in hold-off electric field over the self generated electric field matches, by coincidence, the factor of six in voltage multiplication typically measured from the wire fuse in our two stage switching experiments.⁶ This rapid recovery to a high hold-off voltage minimizes the volumes of both foil and wire fuses required and hence minimizes the energy required. It also allows for a fast time to explosion to be used on the last stage and consequently the capability of attaining submicrosecond output pulses exists. Voltage waveforms from the operation of a three stage switch at the 340 kA level are shown in Fig. 7 and described in the experimental results section.

Design of the TRIDENT Pulse Generator

The design of the TRIDENT pulse generator was based on the requirement that voltages of 1 MV were to be produced and that currents in the sub-megampere range be employed. Additionally, the current source was to be the NRL SUZY II capacitor bank which stores 480 kJ at 60 kV (266 μ F). Calculations to predict the operation of the generator were performed at two levels. First, inasmuch as several switch component designs would be used, simple calculations based on the exploding switch arc characteristic and abrupt resistance changes for fuse elements were performed to permit construction of the inductor and tank for containing the switches. Following construction, inductances of actual switch circuits were measured and calculated. These inductances were inserted into equivalent circuits along with empirical descriptions of fuse vaporization characteristics for more precise simulations. Comparison of these calculations with actual circuit performance provides information for the design of future generators. The remainder of this section provides a description of the pulse generator which was constructed on the basis of the simple calculations. It is followed by a sample calculation in which detailed switch descriptions are used and stray inductances are included.

The early calculations indicated that a storage inductance of 2.5 μ H energized with 500 kA would pro-

duce output pulses of greater than 1 MV with rise-times of 100 nsec when discharged through the three stage opening switch. In order to eliminate mechanical problems arising from forces generated by the high currents, the storage inductor was constructed as an oil filled, 18 ft long coaxial line with an outer conductor diameter of 14 in and an inner conductor diameter of 2 in. This choice facilitated connection of the bank collector plate to the tank containing the switching arrangement as is shown in the experiment plan view of Fig. 3. The inductance of this line is 2.2 μ H. All mechanical forces acting during pulsing will tend to center the inner conductor as opposed to the coil type design in which the forces would deform the coil. The dimensions of the coaxial line were chosen so that electric breakdown would not occur for 500 nsec wide pulses until the voltage exceeded 2.2 MV. The expected pulse rise-times were long enough that transit time effects in the line would not be a major problem.

The bulk of the fuse work performed at NRL used de-ionized water as the tamping medium. To continue using this medium, the entire three stage switch system was placed in a 6 ft x 10 ft x 6 ft water tank. The switches themselves only occupy approximately 1/3 of the tank. A larger tank was fabricated to accommodate future experiments. The oil filled coaxial inductor was interfaced to the water tank through a 1 in polyurethane diaphragm to a short water insulated coaxial line. The total inductance of the circuit through a switch channel is 3.5 μ H.

To more precisely control the transfer of current between switch stages and to allow each switch to open to a desired state before the application of high voltage, closing switches are placed between elements. Because the arc voltage of the exploding switch is low and the opening times are relatively long, a solid dielectric, detonator-triggered switch is used to commutate the current to the foils. Commutation from the foils to the wires and the wires to the load is accomplished using self closing water gaps.

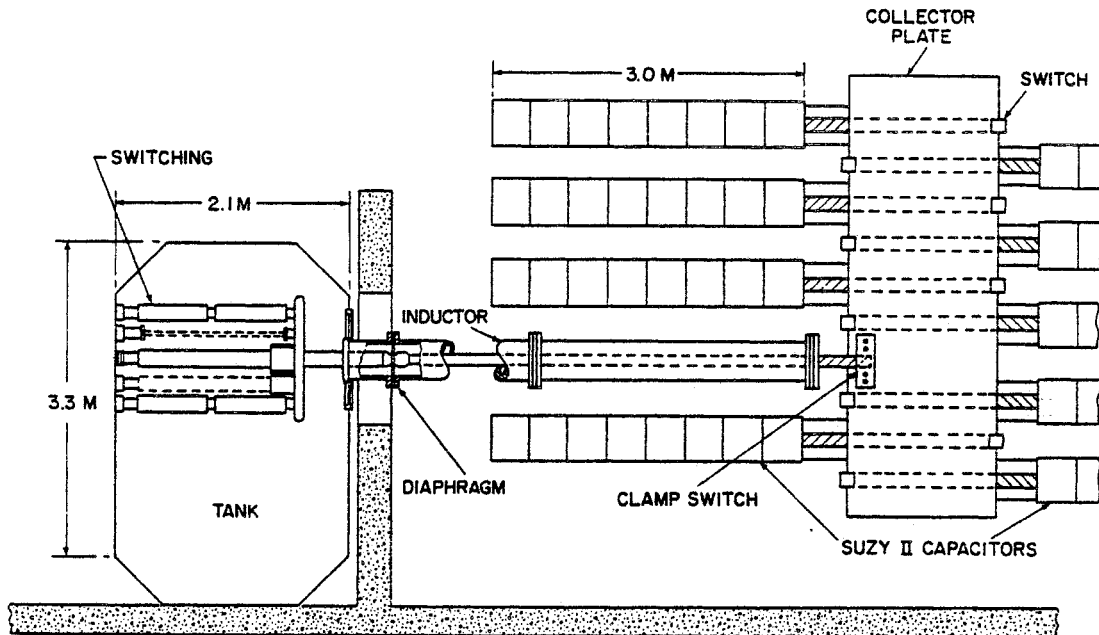


Fig. 3. TRIDENT experiment floor plan.

The quarter cycle period of the capacitor bank ringing through the inductance is approximately $50 \mu\text{sec}$. To provide a DC current through the inductor, the capacitor bank is crowbarred (clamped) using an explosively driven switch when the current in the inductor reaches its peak value. The e-folding decay time for the crowbarred inductor is $500 \mu\text{sec}$. Since the commutation time for the exploding switch is approximately $50 \mu\text{sec}$, the capacitor bank can be operated in the non-crowbarred mode to test the performance of the final two fuse stages independently of the explosively actuated switch.

To accommodate the switches, the inner conductor of the coaxial inductor was terminated in a "T" shape in the tank (Fig. 3). Five equally spaced 2.5 inch saddles were welded to the "T", with a similar saddle attached to the opposite wall of the tank 55 inches away. A current shunt is incorporated into the mount at the wall so that the current through each stage could be measured independently. The switching elements and a cylindrical copper sulfate resistive load could be arranged in any configuration on this "T". Typically, the switches and load were arranged to provide the most favorable for current

commutation between successive stages.

The explosively activated switches, because they employ a 2.5 in diameter tube for conduction, fit directly into the saddle shaped sockets. The fuse elements were stretched on various rack type devices. The most successful of these racks is designed around the same tube used for the exploding switches. The center section of a tube is removed and replaced with an appropriate length of insulator, usually polyethylene. Plates with clamps for foils or pegs for wires are machined so that they slide over the aluminum tube sections. They can be clamped at any location on the aluminum tube as dictated by the fuse lengths.

Measurements and calculations show that each switch stage has an inductance of approximately $1 \mu\text{H}$, thus forming a $3.5 \mu\text{H}$ total loop inductance with the coaxial line. The inductance of the loops between adjacent switches is approximately $.5 \mu\text{H}$. This is the inductance which determines the commutation time between stages. Circuit analysis has been performed using these values and allowing the fuse conductivity to vary according to an empirically determined con-

ductivity vs. energy relationship (Fig. 4). The conductivity curve was obtained from current and voltage measurements of single aluminum foil fuses operated in an open circuit (i.e. no load) condition at a peak current level of 10 kA and a time to explosion of 200 μ sec. The aluminum wires are assumed to follow the same relationship. Figure 5 shows the results of this analysis for a resistive load of 14 Ω with .5 μ H of inductance. The voltage is approximately 1 MV at the peak current of 70 kA for a peak power of 7×10^{10} W. For this simulation the initial inductor current was 490 kA. The explosively actuated switch arc voltage was 13 kV with a total conduction time of 80 μ sec. The aluminum foil fuses were .5 m long with a cross-section designed to explode in 40 μ sec. The aluminum wire fuses were .5m long with a cross-section designed to explode in 2.5 μ sec. The current was commutated away from the foil when the self-generated electric field was 3.2 kV/cm. These waveform shapes are characteristic of inductive energy store pulsers. The load risetimes show the opening characteristics of the final switching stage slowed by the commutating inductance.

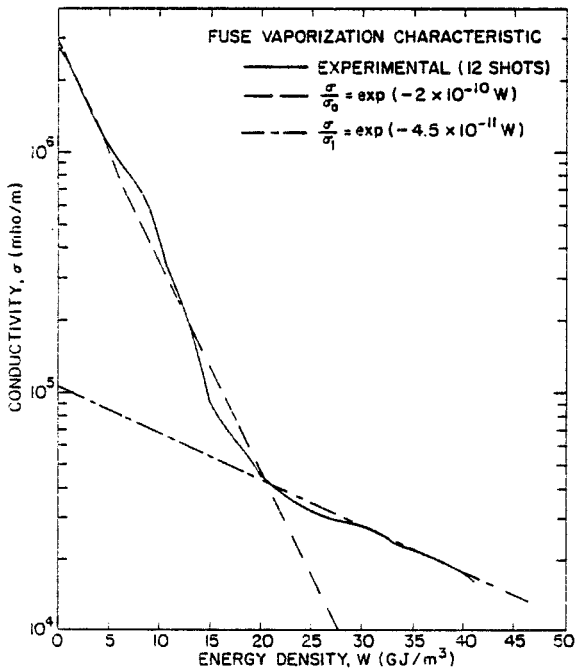


Fig. 4. Conductivity vs. internal energy relationship for aluminum foil fuse. Zero energy corresponds to the onset of vaporization.

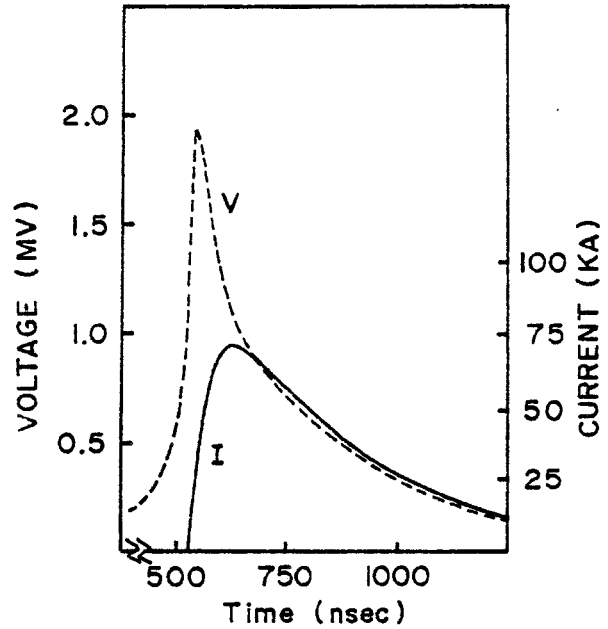


Fig. 5. Computer simulation for TRIDENT experiment driving a 14 Ω resistive load with .5 μ H of series inductance.

The fall times are the L/R decay times of the storage inductance plus load inductance through the load resistance.

Experimental Results

To date the TRIDENT experiment has been operated with a maximum voltage of 50 kV on the capacitor bank (388 kJ stored) which corresponds to a peak current of 410 kA in the storage inductor. This level of current has produced output pulses of 700 kV with risetimes of approximately 150 nsec. Energy has been deposited into a 7.5 resistive load at a rate of 5×10^{10} W. This is a power multiplication of 90 over the power level being dissipated by the resistance of the initially crowbarred inductor.

Early TRIDENT data showed that the arc resistance of the exploding switch was much lower at high currents than expected and the excessive burning in the switch degraded the recovery characteristic. For example, early prototype switches had arc resistances of approximately 300 m Ω at 50 kA, while TRIDENT shots using similar switches at 240 kA and

400 kA had arc resistances of 50 m Ω and 20 m Ω , respectively. To overcome this problem the switch was divided into two modules, a short module containing only 16 switch gaps and a long module containing 31 gaps. (Fig. 6) For circuit operation, the short module, which was placed on the ground end of the switch, was fired first. The number of sections for this module was chosen so that the voltage was sufficient for a reasonable commutation time to the foil fuse. The timing for the firing of the second module was chosen so that it would start opening just prior to complete commutation out of the exploding switch. Since this switch is opening under essentially zero current conditions, there is no burning in the switch and it presents a clean open switch to the high voltages reflected by the succeeding fuse stages.

The long module has operated at least at a recovery voltage of 10 kV/cm. The actual stress across open gaps may be higher. Due to the relatively slow propagation time of the detonation along the primer cord (7-8 mm/ μ sec), only 60% of the gaps are probably open when the high voltage is applied. Future switches will be detonated in several locations along its length to decrease the time for complete switch opening.

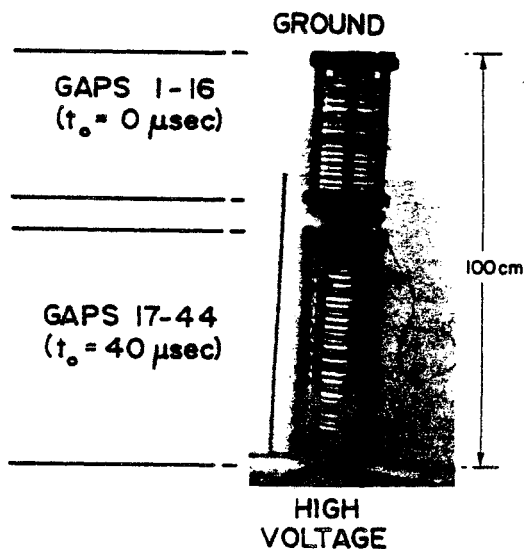


Fig. 6. Photo of double module explosively actuated switch.

Commutation of current to the foil fuse has had good success. Failure to commutate has usually been caused by a failure of the closing switch in the foil path. The inductance of the commutation circuit is approximately .5 μ H and the arc voltage generated by the exploding switch is 3-7 kV, so commutation times range from 20 to 40 μ sec. A representative oscilloscope trace showing commutation from exploding switch to foil is shown in Fig. 7.

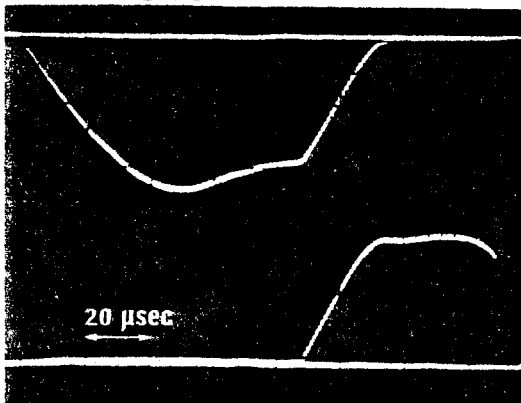
Two problems which have been associated with the operation of the large foil fuses (e.g. 50 cm (W) x 60 cm (L) x .0006 cm (τ)) have been non-uniform explosion of the foils apparently caused by non-uniform current distributions in the foil and damage to the fuses inflicted when the delicate thicknesses are immersed. The first problem, evaluated using time integrated open shutter photographs and examination of the clamped ends of the foils, has been improved by mounting the foils in cylindrical and hexagonal geometries which promote symmetrical current distributions. Handling of the foils has been facilitated by sandwiching the foil between fiberglass screens which are spot welded at the foil edges to form a fuse package with strength equal to that of the fiberglass. The screen transparency allows the water to come into intimate contact with the foil and tests have shown that operation of the foil is unaltered by the screen.

Wire fuses of both aluminum and copper have been used as the final fuse stage in thicknesses ranging from 1 to 5 mils. Wire currents have ranged from 75 kA for shots with 240 kA in the exploding switch just prior to commutation to the foil fuse to 150 kA for shots with 365 kA measured in the exploding switch. The lower level shots used 28, 5 mil diameter aluminum wires, while the high current shots used 53, 3 mil diameter copper wires. The maximum self stress generated by the wires to date in the TRIDENT experiment has been 13 kV/cm, a value well below their previously demonstrated capability.

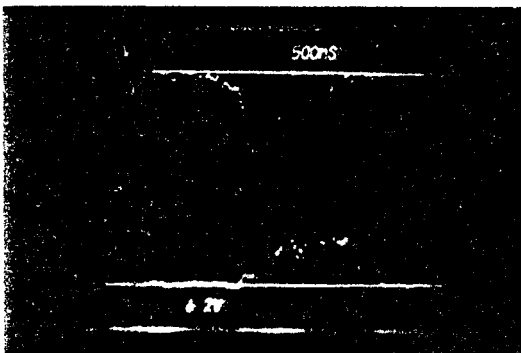
A set of typical current and voltage waveforms from a shot where the peak current through the storage

inductor was 340 kA is shown in Fig. 7. The current just prior to commutation to the foil was 270 kA. This reduction from peak is due to the combined effects of the crowbar resistance and losses in the exploding switch circuit. The commutation time to the foil was 20 μ sec. Although not shown in the photos, the arc voltage was 6.6 kV. The voltage trace shows that the self closing water switch to the wires closed when the foil voltage was 125 kV (saw-tooth ramp on extreme left of voltage trace). The wire fuse exploded 1.75 μ sec after the closure of this switch generating a peak voltage pulse of

EXPLODING SWITCH CURRENT 340 KA PEAK



FOIL FUSE CURRENT 195 KA PEAK OUTPUT VOLTAGE 605 KV PEAK



WIRE FUSE CURRENT 85 KA PEAK

Fig. 7. Representative current and voltage waveforms from the TRIDENT pulse generator.

605 kV. The current commutated to the wires is shown in the bottom trace of the figure. The signal has been delayed 1.5 μ sec and therefore must be shifted three divisions to the left for time correlation with the voltage pulse.

An accurate analysis of the TRIDENT circuit was performed, as described earlier, to evaluate the experimentally observed values of current transfer to the wires against those current levels which should be expected on the basis of circuit parameters and switch properties. This analysis assumed a total exploding switch opening time of 80 μ sec, 5 kV of arc voltage, a foil fuse time to explosion of 50 μ sec, and an initiation of current commutation from the foil to the wire when the foil fuse self generated stress was 3.3 kV/cm. The results of this analysis is shown in Fig. 8 for foil fuse lengths of .5 and 1.0 meters. Fairly good agreement is shown between the analysis and TRIDENT data points. This result indicated to us that we had a good understanding of the operation of the switching elements, and, not surprisingly, the inductance associated with the switch elements and in the commutation circuits must be reduced to increase efficiency to the final stage.

Future Experiments

Immediate plans for the TRIDENT experiment include operating the system at full charge on the capacitor bank (60 kV). This will increase the peak current in the circuit to approximately 500 kA. This is

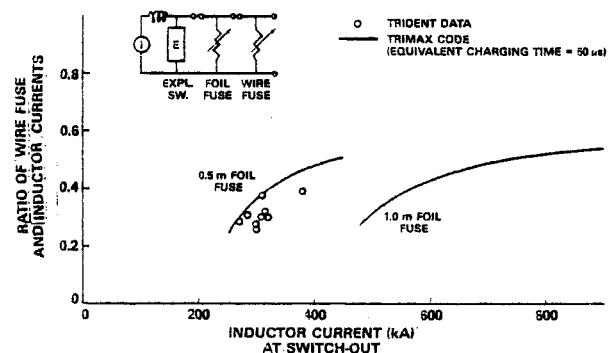


Fig. 8. Comparison of TRIDENT data to computer simulation of current transfer to wire fuse.

expected to generate output pulses of over 800 kV. In order to attain this level, a folded version of the exploding switch will be employed which will have a higher voltage hold-off capability with a very small change in the circuit inductance. Additionally, a falsework arrangement has been proposed to reduce the inductance of the switches and commutation circuits. This modification to improve energy transfer to the wires along with optimized switching between stages should produce output pulses approaching the desired goal of 1 MV.

Later in the year, the TRIDENT switching tank will be connected to the NRL homopolar generator for operation at 600 kA with an initial stored energy of 1 MJ.⁷ This will provide the first demonstration of a complete, compact, high energy inductive storage pulser with an inertial energy store as the primary source.

Following the homopolar generator tests, a demonstration of pulse charging the capacitance of a 1 MV, moderate energy pulse forming line is planned.

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