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TITLE  HIGH-PERFORMANCE, HIGH-CURRENT FUSES FOR FLUX COMPRESSION
GENERATOR DRIVEN INDUCTIVE STORE POWER CONDITIONING
APPLICATIONS

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HIGH-PERFORMANCE, HIGH-CURRENT FUSES FOR FLUX COMPRESSION GENERATOR DRIVEN INDUCTIVE STORE POWER CONDITIONING APPLICATIONS*

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I. INTRODUCTION

Large-scale helical flux compression generators deliver energies in the range of 10–50 MJ in economical, flexible packages for powering a variety of plasma and electron beam experiments. While conventional, end-detonating, helical generators are simple and reliable, they have the disadvantage of delivering their energy over long timescales, up to 400–500 μs, and at relatively low output voltages. Many experiments require faster risetimes than can be delivered by a helical FCG directly, and inductive systems utilizing high current interrupting switches can be employed to match generator performance to load requirements.

Conventional, electrically exploded fuses are among the simplest opening switch concepts appropriate for very high current applications, and they have been used in very high current (20 to 30–1 MA) capacitor bank experiments. In this paper, we report the design and testing of a power conditioning system for a 15-MJ class flux compression generator which employs a fuse interrupting 15–20 MA. The power conditioner is expected to deliver in excess of 10-MA to a 25-nH load with a current risetime of 4–8 μs. The fuse is a cylindrical, multilayer combination of metal foil and plastic film insulation carrying axial current. Fuse parameters are chosen from elementary scaling relationships, and confirmed by zero-dimensional MHD calculations using latest available equation-of-state and conductivity data. These analytic and computational techniques have permitted the design of flux compression generator driven fuse experiments in which 1-MA currents were interrupted producing 300 KV across the fuse, and in which 6 to 7-MA currents were interrupted producing 40 KV across the fuse. The latter experiments, using a combination helical/cylindrical flux compressor, subject the fuse to about the same action timescale, the same axial electric fields upon interruption, the same peak magnetic forces (though not the same mechanical timescale) at peak currents of 6–7 MA as the fuse will experience at 15–20 MA. These experiments are used to benchmark the scaling relationships and the MHD calculations. The scaling experiments and the calculations shed light on issues such as maximum foil thickness which can be expected to yield adequate current interruption and upon the effects of mass loading (tamping) on the expected performance of the fuse.

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FLUX COMPRESSOR

For this experiment, a 15-MJ class helical flux compression generator was selected as the primary energy source. This flux compressor is a modification of a design proposed by Pavlovski in 1979 and used routinely in Los Alamos programs. The generator consists of a multiple conductor, multiple pitch, helical stator and a hollow copper armature containing a 60-kg charge of PBX 9501 high explosive (HE) which is initiated by a small plane wave lens at the end opposite the output. A schematic of the generator is shown in Fig. 1.

The stator coil is wound from #2/0 solid, bare, copper wire (9.3 mm in diameter) which is insulated with two layers of "Thermofit" tubing which is shrunk onto the wire. The coil is 35.6-cm inside diameter, 111.8-cm long and contains a total of 8 turns. The winding begins (near the input end) with five parallel conductors which are wound for four turns. After the fourth turn, the number of wires is doubled (to ten) by adding an additional wire in parallel with each continuing wire and the winding continued for an additional two turns. The conductors are doubled twice more to reach a total of 40 parallel wires completing the 8-turn, 7.2-μH coil as shown in Table I. The spatial inductance gradient $\partial L/\partial x$ decreases from input to output thus moderating the generator gain, tending toward a more constant $dI/dt$ in, and more constant voltage across, a fixed inductance load while at the same time providing more conductor area to carry the increasing current near the end of generator operation. The armature is a copper cylinder, 17.3 cm in outside diameter with a 0.9-mm wall which is annealed to soft condition. When accelerated by the PBX-9501 charge, the armature expands just over a factor of two, and assumes a cone angle of about 14° which advances at just over 8 mm/μs.

Initial flux is produced by discharging a pair of 0.5-MJ capacitor banks charged to 18.6-kV (each) in series for an equivalent capacitance of 1500 μF. At the beginning of its operation, the generator is loaded in 163 μs to an initial current of 425 kA, initial energy of 625 kJ, and an initial flux of about 3.0 Webers.

This generator has been the object of several characterization experiments into 120-, 56-, and 35-nH, fixed inductance loads. For design purposes, an approximate $L(t)$ and $dL/dt$ is computed using models which range from simple geometric ones to quite general models based on solving inductance matrix equations for an array of current sheets and closed rings. From currents measured in characterization experiments and calculated $L(t)$, a total loss function treating all flux losses as a time-varying resistance $R(t)$ is found. Figure 2 shows $L(t)$, $dL/dt$, and $R(t)$, from Ref. 3, which are subsequently used in circuit codes and in zero dimensional MHD codes to design opening switch experiments. From the Figure, we see an initial inductance of 7.2 μH, a peak $dL/dt$ of -200 mΩ, and a loss function which closely mirrors the $dL/dt$ function from the calculations. The total operating time of the generator, $t_\text{op}$, is about 205 μs.

When operated into a fixed load of about 60 nH both circuit model and experiments suggest that the current waveform is approximately

$$I(t) = I_0 e^{\frac{at}{r}}.$$

For an initial current of about 425 kA, a peak current of about 23 MA and a flux of about 1.4 Webers is expected giving an overall flux efficiency of about 40%.

POWER CONDITIONER

Using this description of the large helical generator phrased in terms of circuit parameters $L(t)$, $dL/dt$, and $R(t)$, the parameters of a suitable fuse opening switch
can be defined and performance estimated. The behavior of fuse opening switch circuits energized by a source delivering current $I_{(t)}$ can be described in terms of an equivalent action timescale.\(^4\)

$$\tau_{eq} = \frac{1}{I_{(t)}^2} \int_{0}^{t} I_{(t)}^2 dt$$

$\tau_{eq}$ describes the time for the accumulation of action in a way that allows comparison among currents which have dramatically different waveforms. For example, for a sinusoidal current of quarter period $\tau_q$,

$$\tau_{eq} = \frac{\tau_q}{2}$$

and for an exponential current, $I = I_o e^{\gamma t/\tau_r}$,

$$\tau_{eq} = \frac{\tau_r}{2\gamma}$$

For the large flux compressor used in these experiments, $\tau_r = 205$ $\mu$s and $\gamma = 4$, thus, $\tau_{eq} = 25.6$ $\mu$s. An inductance of 65 nH was chosen for the storage inductance and 24 nH for the load inductance into which current is to be transferred after fusing. We estimate 425-KA initial current and the 7.2 $\mu$H inductance of the generator will give rise to currents of $I_s = 21.5$ MA and flux $\Phi_o = 1.4$ Weber in the storage inductor at the time of peak current.

From first principles, we estimate that to achieve current interruption at maximum current, we choose the area of a copper fuse from:

$$A_f = 2.8 \times 10^{-9} I_s \tau_{eq}^{1/3} = 3.0$ cm$^2$ .

To transfer maximum current to the load, we select a fuse whose mass is such that, at vaporization energy density, $\xi$, the fuse has dissipated just the amount of energy necessary to conserve flux between the store and the load inductance. For this case, that energy is $\alpha = 27\%$ of the energy stored in the storage inductance at peak current. The fuse length is:

$$l_f = \alpha 3.3 \times 10^{-3} \Phi_o \tau_{eq}^{-1/2} = 25$ cm .

And we calculate that it has an initial resistance of 15 $\mu$Ω. From preliminary experiments conducted at the 0.5 to 1.0-MJ energy level\(^6\) we have observed a factor of $M_f = 200$–300 increase in resistance from initial burst conditions for action timescales of about 20 $\mu$s. Thus, the peak resistance is projected to be about 3.7 mΩ.

On the other hand, the fuse needed to produce maximum voltage would be quite different. It would be designed to dissipate 100$\%$ ($\alpha = 1$) of the inductively stored energy. In order to interrupt at maximum current, its area would be unchanged, but its length would be about 91 cm, its initial resistance would be 55 $\mu$Ω, and its final resistance would be about 14 mΩ. The time to interrupt the current and the peak voltage would be:

$$\tau_{sw} = 94 \tau_{eq}/\alpha M_f = 9.6$ $\mu$s ,

$$V_m = 1.2 \alpha M_f \Phi_o/94 \tau_{eq} = 175$ kV .

The first principals analysis assumes a linear increase in fuse resistance, which results in $I(t) I_s e^{-t^2}$ current decay, and is useful for initial estimates of performance. For detailed design a new computational tool named CONFUSE\(^6\) is employed. This tool
couples a zero dimensional magnetohydrodynamic treatment with ohmic heating, an
electrical circuit, and density and temperature dependent thermodynamic and electrical conductivity from the Los Alamos atomic data base SESAME. Using \( L(t) \), \( \frac{dL}{dT} \), \( R(t) \), and the circuit model, storage and load inductances and one of several SESAME models for copper, specific fuse dimensions were selected:

\[
A = 2.5 \text{ cm} : \quad l = 27 \text{ cm}.
\]

Preliminary experiments conducted with copper foil in thicknesses of \( 1.27 \times 10^{-3} \) (0.5 mil) and \( 2.54 \times 10^{-3} \) cm (1.0 mil) produced satisfactory current interruption at currents of 5-7 MA. For 1-mil foil, a fuse of area \( 2.5 \text{ cm}^2 \) is 1000-cm wide (32.8 ft in the direction transverse to the current flow). If fabricated as an axial current carrying cylinder, the diameter would be an unwieldy 10 ft. For practicality, the fuse is constructed in a multiple layer configuration in which a copper foil 32-feet wide by 30-cm long and a polyester film 32-ft wide and 27-cm long were wound (like a role of ribbon) onto an insulated metal cylinder. Connections were made to the ends of the foil by split ring clamps bolted radially with 24 screws at each end.

The complete store/fuse/load configuration is shown in Fig. 3 with the inductive store volume outside the fuse and the metal form on which the fuse is wound comprising the inner conductor of a coaxial output geometry. The metal center conductor is insulated with 30 layers of \( 1.27 \times 10^{-3}-\text{cm} \) (5-mil) polyester film which supports the fuse output voltage at the right end and which continues axially into the 24-nH coaxial load region. Immediately outside the fuse foil, the magnetic field at 20-MA would be 28 Tesla (280 kGauss) compressing the fuse and polyester insulation with a pressure of 312 MPa.

As shown in Fig. 4, the load consists of a coaxial cavity with an ID of 10 cm. At a peak load current of 15 MA, the field on the surface of the aluminum inner conductor would be 60 Tesla (600 kGauss). This value is near the limit of fields easily supported by conventional conductors.

The load is isolated from the storage circuit by a self-closing, surface-tracking switch (STS)\(^7\) for which the rightmost wall of the inductive store is one electrode and the rightmost wall of the load provides the other. The same cylindrical polyester insulation that supported the fuse output voltage and the load voltage comprises the tracking surface for the STS. Closure voltage is determined by the location of a trigger foil which establishes the electric field at the leftmost electrode. This trigger foil is connected to the rightmost STS electrode and separated from the leftmost electrode by four layers of \( 5.00 \times 10^{-5} \) (2-mil) polyester film. The trigger foil/insulator parameters were chosen to produce closure at 15-20 KV which is much less than the 50-200 KV that simple estimates suggest could be produced by the fuse. The relatively low STS voltage was chosen, as were the fuse parameters to optimise energy transfer to the load and not the voltage impressed across the load. The isolation switch is not essential for a maximum energy experiment (and indeed its presence costs a small amount of peak load energy). CONFUSE calculations show that, lacking such a switch, the load current would include a 3 to 5-\( \mu \text{s} \)-long, 1 to 2-MA precursor before the main current transfer. Such a precursor is inconvenient for ultimate applications and demonstration of a suitable load isolation switch adds to the usefulness of the experiment.

Diagnostics for the experiment include Rogowski coils in the storage inductor loop and a matched (counter circling) pair of coils in the load. Current measurements are further confirmed by independent, optical measurements of store and load currents using detectors based upon Faraday effect in long fibers. The geometry precludes
direct observation of voltage across the fuse, but voltage across the STS is recorded and mirrors the fuse voltage up to the time of STS closure.

RESULTS

The design concepts described in the previous sections were tested in an experiment in which the generator, fuse and closing switch functioned properly and current was successfully transferred to the load. While designed for 20-MA peak currents in the inductive store, the experiment suffered a partial malfunction of the capacitor bank system supplying initial flux to the generator and initial current was about 343-kA (80% of the design value of 430 kA). As a result, the peak current was lower than the design value and the time of burst was somewhat later and occurred at lower currents as well.

Figure 5 shows dI/dt in the store loop of the circuit from the time of generator crowbar (when the input of the generator is deliberately short circuited in order to trap flux), through generator run time and fuse interruption time. For dI/dt calculated by CONFUSE is also plotted. The CONFUSE calculation use L(t) and R(t) from Fig. 2, the actual value (343 kA) of current in the generator at crowbar, the physical dimension of the fuse and a copper equation of state (for the fuse) from the SESAME library that has been successfully used to describe the preliminary experiments. The calculation uses values of the adjustable parameter comparable to those found in the previous experiments. Time correlation between experiment and calculation is made with reference to the relatively distinctive features in the generator run phase. The agreement between model and experiment is quite good, indicating that the Mark IX performed as expected (despite slightly lower initial loading). The fuse model employed in CONFUSE correctly predicted the time of current interruption (burst) and, with the use of one adjustable parameter, the magnitude and width of the negative-going dI/dt describing current interruption.

Figure 6 shows the current measurement from a digital integration of the dI/dt information. Sensitivity factors for Rogowski coils are found from careful measurements of coil dimensions and assume (for this trace) complete diffusion of magnetic flux into the conductors that comprise the coil. As a check on the accuracy of these measurements, an independent measurement of the current was made using the Faraday effect in an optical fiber co-located with the Rogowski coil. The figure shows good correspondence between the optical and Rogowski measurements. The currents differ slightly at low currents (where there are very few cycles of polarization rotation and at one point near the peak where it is difficult to distinguish the precise point of reversal of polarization rotation. The peak measured current is 16 MA — 8.2 MJ — occurring at about 206 μs. Since the monitors measure current in the store (not the fuse) we expect the current to drop to (no more than) 72% of the peak current to satisfy flux conservation between the 65-nH store and the 24-nH load.

Figure 7 shows dI/dt measured in the load and that computed by CONFUSE. Data are recorded from two counter encircling coils in the load region. The “clockwise” and “counterclockwise” records are averaged to eliminate any common mode signals resulting from extraneous pickup or ground currents. The load shows a peak dI/dt to the load of about 10^{12} amps/sec and a double-peaked waveform. As seen in the figure, the CONFUSE model also produces similar features and the implication of the double peaked waveform for the path which the fuse takes through density and temperature space is one of the topics discussed in a companion paper.
Figure 8 shows the digitally integrated average of two Rogowski coil traces and an optically measure of the current in the load made using a fiber co-located with the pair of Rogowski coils. For the relatively large dI/dt encountered in these experiments, Rogowski coils of small diameter were fabricated. For small coils, the center conductor occupies a relatively larger fraction of the total coil area than is the case for larger coils. Therefore flux penetration into, or exclusion from, the center conductor can have correspondingly larger impact on the measurements. For the long timescales of the store current (Fig. 5) complete flux diffusion is the appropriate treatment. For the faster currents in the load, some flux exclusion is probably appropriate — but the exclusion is probably not complete. In Fig. 8 we plot the integrated Rogowski coil data scaled for complete diffusion (a) and complete exclusion (b) along with the optically measured current. Taking the optically measure as a reliable measure of current amplitude, the figure suggests that some, but not complete flux diffusion into the conductor in the Rogowski coil is occurring on the time scale of the current transfer in the experiment. For subsequent analysis, we choose a value of sensitivity of the (averaged) Rogowski coils in the load that matches the value of the optically measured signal and the peak load current is measured to be about 9.8 MA.

At the time that the current begins to transfer to the load (210-μs) current in the store is about 15.6 MA, thus the peak load current of 9.8 MA represents 63% of the store current as compared with the 71% (maximum) required to satisfy flux conservation. At 9.8 MA the peak energy in the load is 1.15 MJ.

The configuration of the experiment precludes direct observation of the current in the fuse. In Fig. 10, we find the current in the opening switch branch of the circuit from the difference between the current in the load and the current in the store.

As with current in the fuse it is impractical to directly measure the voltage across the fuse in the coaxial arrangement. We record the voltage across the surface tracking switch. This measure directly reflects the opening switch voltage until the STS closes at 210 μs. The STS voltage is measured by connecting a resistor of known values across the terminals of the switch and measuring the current in the resistor with a precision current transformer. For high-voltage integrity, the voltage probe (and its leads) constitute a relatively large loop, and while the coaxial load, store and switch geometry should have no appreciable (B_φ) magnetic field outside the return conductor, the large helical FCG produces sizable (B_r, B_θ, and B_z) fields outside its windings. Those fields change significantly in magnitude over time as the circuit current grows, and they change significantly in both magnitude and direction as the generator geometry changes. We expect the fields attributable to the helical generator current to vanish altogether when the last of the helical windings are removed from the circuit. The STS voltage trace in Fig. 11 contains a substantial negative component which we attribute to coupling between the loop comprising the voltage diagnostic and these generator external fields. For analysis we ignore the negative component and assume that it vanishes at about 220 μs when the last of the helical winding of the generator is removed. We conclude that the STS closed at about 16 kV — within the 15 to 20-kV window for which the switch was designed.

The voltage across the fuse is equal to the sum of the STS voltage and the L dI/dt voltage across the load. In addition to the STS voltage in Fig. 11, we also plot the inductive voltage (L dI/dt) across the 24-nH load, and the sum of STS and load voltage to give an approximation to the fuse voltage.

From the STS voltage and load current we can infer an impedance for the closing switch. By dividing the STS voltage by the load current we find that the closing switch has dropped in impedance to 10 mΩ at 209-ns (i.e., at closure) to 10 mΩ at
microsecond later, and to less than 1 mΩ by 216 μs. Ultimately the switch resistance falls to 0.8 mΩ and remains constant at that level for at least 10 μs.

The resistance of the fuse inferred from the relation of the fuse voltage in Fig. 11 to the fuse current in Fig. 10 is shown in Fig. 12, scaled to the 19.8-μΩ initial resistance of the copper fuse. Figure 12 shows the resistance multiplication to be 350 — more than that observed in the small scale experiments.

Finally in Fig. 13, we calculate the action integral for the fuse. We see that at the time of peak voltage, 210–215 μs, the action integral is about $1.7 \times 10^{17}$ amperes$^2$ s/m$^4$ which is in good agreement with the value of $1.7 \times 10^{17}$ expected for copper fuses. We also plot the action timescale showing that at the time of current interruption the action timescale was about 15 μs.

CONCLUSIONS

From the data, we conclude that fuses can be used to shorten the current pulse delivered by 10-MJ class flux compressors from hundreds of microseconds to about 10 μs with current transfer efficiency within a few percent of those required for flux conservation. In this experiment, the fuse interrupted 16 MA, withstood 30–40 kV and delivered almost 10 MA to the load in about 10 μs. Perhaps more important is the extent to which the CONFUSE model was capable of reproducing experimental results even when the experimental condition differed (by 20%) from the nominal design value. Fuse resistance multiplication actually exceeded those in smaller scale tests and the action integral and action timescales provided good predictive measures of performance.

REFERENCES


FIGURE CAPTIONS

Fig. 1. Schematic of the Mark IX Generator.

Fig. 2. Calculated \( L(t) \), \( dL/dt \) and inferred \( R(t) \) for the Mark IX.

Fig. 3. The inductive store/fuse/surface switch/load configuration.

Fig. 4. Detail of surface switch and load configuration.

Fig. 5. \( dI/dt \) for the inductive store circuit: Experiment and CONFUSE.

Fig. 6. Current for the inductive store circuit: Rogowski and Optical diagnostics.

Fig. 7. \( dI/dt \) for the load circuit (expanded time scale): Experiment and CONFUSE.

Fig. 8. Current for the load circuit: Rogowski and Optical diagnostics.

Fig. 9. Store and Load currents and Fuse Current from the difference.

Fig. 10. STS Voltage and Fuse Voltage from the sum of STS and \( L \ dI/dt \).

Fig. 11. Resistance multiplication \( (M_f) \).

Fig. 12. Actio: Integral and \( \tau_{eq} \) from the experimental data.
Figure 2.
Figure 1.
Figure 8.
Figure 9.
Figure 10.