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DESIGN OF AN EXPLOSIVE PULSED POWER SYSTEM FOR DRIVING 16-MA PLASMA FLOW SWITCH EXPERIMENTS*

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INTRODUCTION

We have described a system that uses a MK-IX helical generator to deliver 11 MA to a 140-nH pulse compression circuit.[1,2,3] The purpose of that system is to drive a plasma z-pinch experiment.[4] Although the system generates ~8-MJ magnetic energy, only ~0.1 MJ are delivered to the load. This inefficiency is for a variety of reasons, among them simplicity in a developing system. Paramount among them, however, is the difficulty in managing the large voltage required to drive our load. The system generates over 200 kV while transferring current out of an inductive store into a 1-μs implosion. To approach 1-MJ implosions using the same technique, at any efficiency, would require generating and sustaining 600–700 kV. Handling such voltages outside the vacuum region of the experiment and at the vacuum/dielectric interface would be difficult since the circuitry must remain low inductance. To circumvent the high-voltage difficulties, we propose a two-stage switching system to couple an inductive store to the implosion load. A relatively slow opening switch will be used to deliver current at modest voltages past a vacuum/dielectric interface to a plasma flow switch (PFS)[5] that will ultimately divert current to the z-pinch load.

We have demonstrated that the MK-IX generator will deliver 23–24 MA to a 56-nH load[6] in a pulse that develops in ~350 μs. We are currently considering two different switching systems for our first stage switch. We have demonstrated that explosively formed fuse (EFF) opening switches can be operated in a more efficient topology[7,8] than used previously and scaling relations indicate that it can withstand the MK-IX current pulse and dissipate the appropriate energy at switching time. We have also demonstrated that a suitably slower EFF can be designed.[7] In addition, conventional foil fuses are under investigation for this application.[9] Fuses are easily designed in the more efficient topology and most of our developmental efforts are aimed

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at sizing fuses for the MK-IX generator waveform. Small-scale tests have shown that pulse compression factors can be much larger for fuses driven by helical generators than the factor of ten which has been a rule of thumb for fuses driven by capacitor banks for many years.[10] To power a system that will drive implosions at energies approaching 1 MJ, we propose to deliver ~22 MA to one of the two slow switches and then divert 14–16 MA to a PFS in 5–10 μs. This system would generate ~1-MJ implosions from 13.5-MJ stored energy. This represents a factor of six increase in efficiency over the previously reported system using components that were largely developed in the less-efficient system. In designing a system that will develop 13.5 MJ from a MK-IX generator and transfer 1 MJ to an implosion, several factors must be taken into account that we have not confronted previously. These arise principally from the large magnetic pressures developed over long periods of time. In this paper, we present the system design and our proposed solutions to some of the more demanding design problems.

SYSTEM DESCRIPTION

Figure 1 is a detailed illustration of the system as constructed with an EFF. The differences between this and the foil-fuse versions are minor, and have to do largely with the explosives system required for the EFF. The foil-fuse version has a fuse where the active switch conductor is shown and a different holder for the fuse. In addition, the extrusion die for the EFF is not required in the fuse version although the volume is still required for storage inductance.

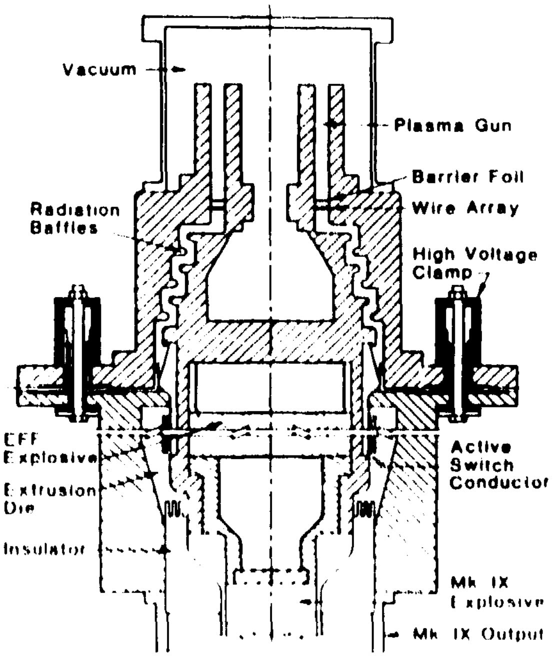

Fig. 1. System with an EFF for driving a plasma flow switch experiment. Detonator-actuated closing switches are interspersed between the high-voltage clamps. Only a small section of the MK-IX generator is shown and the complete MK-IX is ~2 m in length. In addition, the cut lines allow us to show the figure in better detail, but portray the wrong proportion of length to width. With the EFF, which is 76-cm long, the system is nearly 4 m in length. The fuse version is slightly shorter. Both systems will be fired in a horizontal position rather than vertically as shown. The barrier foil and wire array initiate the plasma for the coaxial plasma gun and the radiation baffles prevent restrike at the vacuum dielectric interface.

Although the MK-IX generator will deliver 23–24 MA to a 56-nH load, each of the two switches develops some resistance that reduces the MK-IX output. With the foil-fuse version, our calculations indicate that ~22 MA will be delivered to the magnetic store. The EFF is not designed to fuse, but calculations indicate that the current waveform will cause appreciable heating in the 0.08-mm-thick active switch conductor. As a result, the generator output into the EFF will also be reduced 1 or 2 MA.

The opening switch resistance profiles for either the foil-fuse or EFF will be dependent to some extent on actual experimental conditions. Extrapolations from smaller scale experiments are required to obtain a resistance profile for the purpose of calculating system performance. For the EFF, this profile is obtained by using the scaling constant obtained from small scale experiments for the extrusion die we have chosen[7] and making the appropriate adjustment for physical size. Our foil-fuse resistance profile is obtained calculationally with a computer code which has been used to predict fuse performance for a variety of experiments[11] including a recent test at the 16-MA level with a MK-IX generator.[9] Special attention has been given in both cases to the risetime of the resistance, so that current diversion can be matched to the operating time of a plasma gun. Most of our EFF experience is with switches that operate faster than desirable in this application. We have shown, however, that an appropriately slowed risetime can be obtained.[7] Since foil fuses function off accumulated action of the current pulse, obtaining a fuse design that will divert current in the 5 to 10-μs time scale, when driven by a 350 μs pulse, has required considerable development. A new analysis for characterizing high-gain helical generator waveforms by an "equivalent action timescale" however, has allowed good progress to be made[10] and we feel such performance is possible. In addition to the resistance profile, we must also consider energy dissipation in each opening switch. The switch is required to dissipate ~5 MJ for nominal system performance. Extrapolation from small-scale tests indicate that an EFF of the size we intend will dissipate more than 7 MJ. We are dissipating ~3 MJ in our current application[3] and the 5-MJ level gives us a comfortable margin of error for our extrapolations. While we expend considerable effort in developing EFFs that will dissipate large energies, the energy dissipation of a foil fuse is a straightforward design consideration. However, this still represents a design constraint in choosing the length and cross section of a fuse that will provide small early time losses and still burst rapidly enough.

Ultimately, the best switch for the system will be determined by full-scale tests of each device. In the meantime, we calculate system performance and explore appropriate plasma gun parameters with the resistance waveforms thus obtained. Figures 2 and 3 show calculated system performance based on actual MK-IX generator test data and the extrapolated switch performance curves. Of the 22–23 MA generated, 14–16 should be transferred to the plasma gun which, in each case, produces a 900-kJ implosion in our slug model calculations. Although neither calculation is optimized, each drives the plasma in the PFS gun to a velocity of ~7 cm/μs. In the calculations shown, the foil-fuse has a 15-cm-long plasma gun and the EFF a 10-cm-long gun.

DESIGN CONSIDERATIONS

A system performing like that described above provides some severe design problems for practical size devices. At a peak current of 22 MA the linear current density in our MK-IX armature is 0.39 MA/cm which produces a magnetic pressure of ~0.6 GPa. This, in addition, is considerably enhanced by the cylindrical geometry. Since this pressure far exceeds the material strength of the copper armature, attaching output hardware to the armature is a special design consideration, and making a transition to a larger diameter as quickly as possible a design requirement. For independent design reasons, the diameter of the active conductor in our opening switch is ~30.5 cm. This reduces the current density to 0.23 MA/cm and the pressure to ~0.2 GPa. This is still a large pressure compounded by cylindrical effects, especially on the very thin active conductor cylinder. Finally, the EFF version of our system requires a cylindrical explosive charge, which in turn must be detonated at an appropriate time. This gives rise to another set of design restraints. The output conductor is restricted to a thickness of 1.9 cm so that the EFF will function at the appropriate rate. Because of cylindrical stress concentration effects, when the magnetic pressure is transferred from the active switch conductor through the output insulation to the output conductor, the output conductor will yield. Only the masses of the output insulator, output conductor, and the HE slow the motion of these components. In addition, pressure transmitted to the axial detonation system could prevent proper functioning.

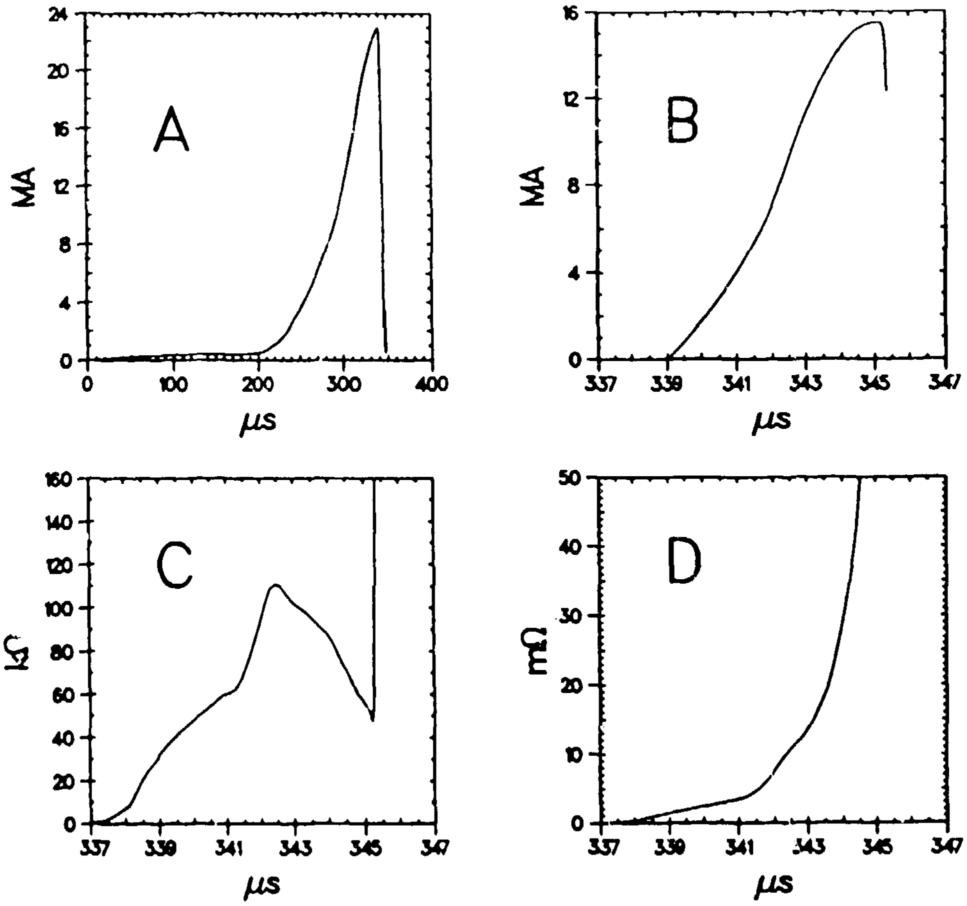

Fig. 2. Calculated (A) total current profile, (B) plasma gun current, (C) driving voltage and, (D) extrapolated switch resistance for EFF version.

Our first major engineering consideration is for the output end of the MK-IX armature. Peak pressure on the armature is 0.6 GPa which, with a stress concentration of seven, is multiplied to ~4 GPa. Fortunately, by peak pressure, all the explosive has detonated and begun to drive the armature outward. However, before the detonation arrives, a magnetic pressure of ~0.22 GPa (1.5 GPa with stress concentration) is still developed. Throughout our system, we have attempted to put a mechanical pressure on current-carrying joints that equals or exceeds peak magnetic pressure. This is our criterion for preventing magnetic pressure from opening up the joint. At the 1.5-GPa pressure level, this is impossible and there are only two things that can be done to prevent the collapse of these components and the opening of electrical joints. The first is to expand the conductor to a larger radius as soon as possible and the second is to provide inertial confinement. Figure 4 is a magnification of the MK-IX output region shown in Fig. 1. In this region we have to deal with the high pressure mentioned and the transition from the copper armature to an aluminum transmission line. After much effort in trying to design a clamp that was not limited by the material properties of copper, we resorted to the joints shown. Our armature is brazed to a massive copper flange that has the function of expanding to a larger radius to make the Cu to Al transition and providing enough mass to slow the collapse appreciably. In addition, high-strength steel is used to line the Cu and Al parts in this region for further support. The diameter of the armature is 17.8 cm. If we assume that the Cu will withstand a pressure of 0.1 GPa before it yields, then the pressure exceeds this level at 3.4 MA. The detonation begins to support the brazed joint when the current reaches 13 MA, and only inertia holds the joint the intervening ~55 μs. At the end of the explosive, the steel provides further support, but the critical joint does not benefit from that. Although this joint does not satisfy our engineering criterion, it does represent what appears to be a best effort and is a considerable improvement over the joint we have used previously in tests up to 24-MA.[6] In addition, a recent test at 16 MA[9] followed nominal generator performance curves and we feel the design is satisfactory at the proposed level.

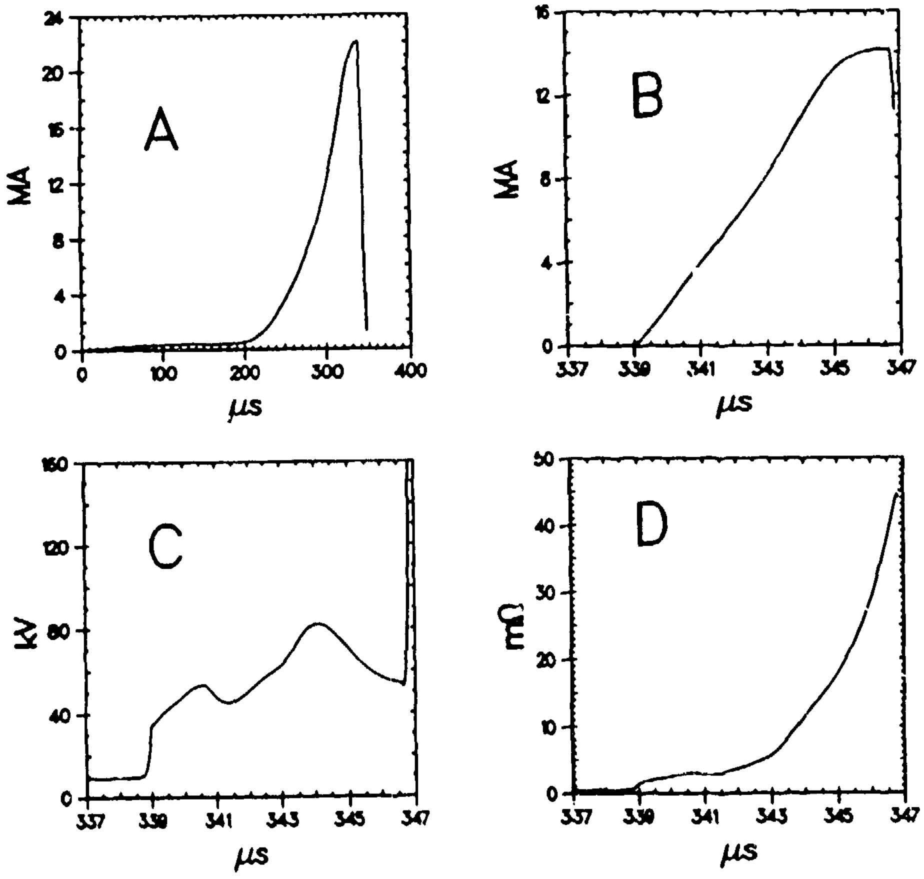

Fig. 3. Calculated (A) total current profile, (B) plasma gun current, (C) driving voltage, and (D) switch resistance for fuse version.

The next major concern is for the active opening switch conductor. The foil-fuse version of our system has a considerable advantage in this respect. Although the fuse is a multilayered wrap of very thin Al, it can lay directly on firm insulation which in turn can be supported by as massive and strong a support structure as desired. The bulk motion of this conductor then is limited to the compression that the insulation will experience, which may still be as much as 2 mm depending on the amount and type of insulation required to withstand the output voltage after being compressed by the fuse. The EFF version requires more attention in this respect. To obtain the appropriate function time, the amount of mass between the HE charge and the extrusion die must be controlled. To satisfy this and the high-voltage requirement, we are using a 1.9-cm-thick Al output conductor and a 1.1-cm-thick Teflon output insulator. The Teflon insulator transfers the pressure to the 1.9-cm Al tube which suffers from a factor of 11 stress concentration. We are using Al with a strength of ~0.3 GPa, but after the pressure reaches this level, the conductor is supported only by the HE system.

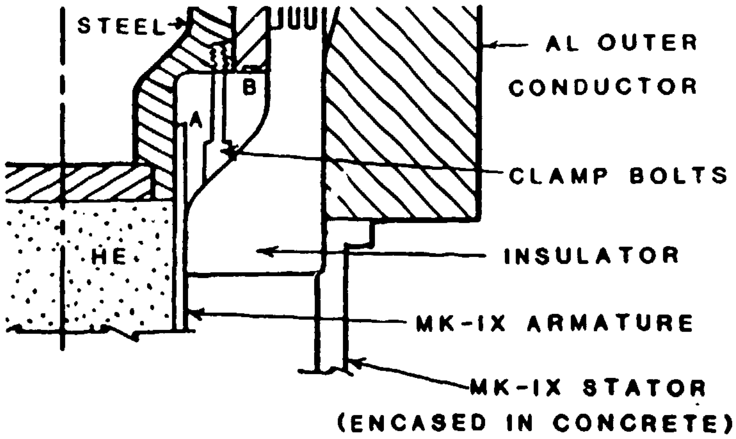

Fig. 4. Magnified view of MK-IX output. Copper armature is brazed to copper flange at (A). Flange expands to larger radius and clamp bolts develop full strength of flange at the joint (B).

The diameter of the 0.08-cm-thick active switch conductor is ~34 cm (107-cm circumference) and the pressure produced will exceed the material strength of the supporting output conductor when the current reaches ~9 MA. Inertially tamped motion will occur in this region for ~50 μs. The motion itself is not a severe problem, but two areas of considerable concern arise as a result of it. The attachment point where the active switch conductor is fastened to the massive return conductor flange is influenced by the motion of the thin conductor as well as the more slight motion of the end flange. Hydrocode simulations indicate that the thin conductor will rupture if attached by the method we have previously used. This is only a hydrodynamic effect, and the effects of current flowing in the ruptured region will make the situation even worse. After several simulations, the joint shown in Fig. 5 was chosen as the best solution to the problem. Bowing of the joint still occurs, but appreciable thinning does not. This contour causes a considerable manufacturing problem, but allows the system to hold together at least hydrodynamically.

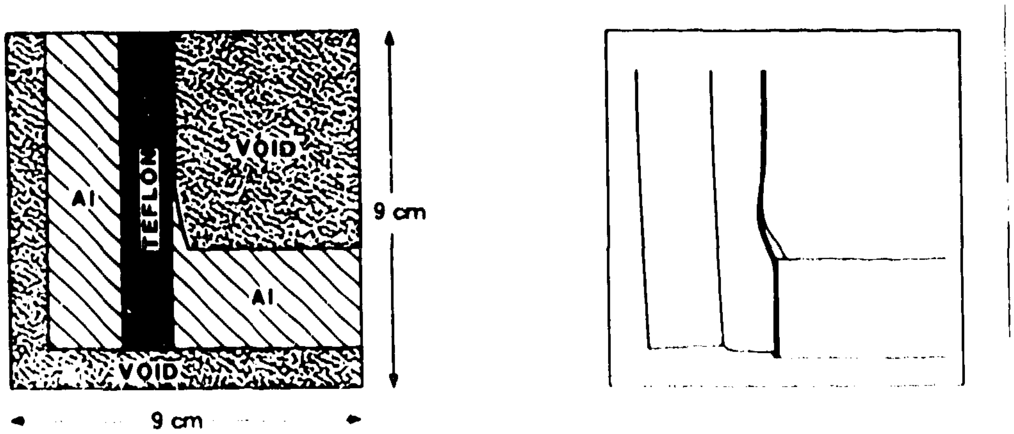

Fig. 5. Computer simulation showing effects of magnetic pressure on attachment point of the active EFF switch conductor. Left shows initial condition and right shows condition after pressure is applied for a representative time.

The other concern is for the integrity of the HE system. Pressure transmitted through the HE could cause problems with our axial slapper detonation system. Our calculations have sufficient errors on axis that it is difficult to know quantitatively how significant the problem is, but sufficient pressures to affect delicate components seem likely. To circumvent this difficulty, we have left an air gap between the two cylindrical explosives layers. A malleable steel tube will contain an inner HE cylinder, and an acrylic tube will line the inner surface of an outer HE cylinder. The steel will be driven across the air gap and detonate the outer charge by transmitting a shock wave into the acrylic tube. The air gap allows the HE to move by as much as 6 mm without passing pressure on to the inner charge, and hence the detonation system. Further, the acrylic will not cause high pressure to build up on the surface where the outer charge is detonated.

The last design feature we will discuss regards detonating the explosive. In initial design considerations, we contemplated passing detonator cables through a hole in the insulator at the MK-IX output. Although this is a low-voltage region, it is a high-magnetic field region as we have discussed, and crushing cables as well as coupling flux into them are both potential problems. Further, armoring and excluding flux from a volume across the stator-armature gap and keeping the armor sufficiently insulated to prevent shorting out the gap also represents a serious difficulty. Highly permeable materials, of course, are undesirable in this region. Our current design is based on a different approach to the problem. We are developing battery-powered detonator firing devices that will fit inside the flux-free volume inside the armature and between the two explosive components. This device can be controlled and operated with only fiber-optic inputs. These control links are not subject to harmful effects, as long as we protect them from the conductors that are moving due to magnetic pressure, and we can pass them through a hole in the MK-IX output insulator as originally planned. A trigger for the circuit is obtained from the MK-IX main charge at the appropriate time.

CONCLUSION

We have completed the design for a system that will ultimately use one of two slow-opening switches to divert up to 16 MA to a plasma-flow switch experiment. High-magnetic fields applied over a long time scale have imposed many design restrictions and we have addressed these to the best of our ability prior to conducting tests. We will perform full-scale tests with each switch and choose the best switch for further tests based on overall complexity, expense, and performance. When it functions properly, the system should deliver ~900 kJ to z-pinch implosion kinetic energy.

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