

Design and Testing of the Power Electronics for the Cannon Caliber Electromagnetic Gun System

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Design and Testing of the Power Electronics for the Cannon Caliber Electromagnetic Gun System

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Abstract—The University of Texas Center for Electromechanics (UT-CEM) is in the final fabrication and testing phase of a power electronics system required to operate a skid mounted compulsator-driven railgun. Design goals for the self-excited air core compulsator include a 95 MW rectifier/inverter bridge for field coil self-excitation. Initial field coil seed energy is supplied by a 50 kJ capacitive discharge from the field initiation module. The field coil is passively protected from voltage transients by an array of metal oxide varistors. Other system power modules include the gun closing switch and explosive opening switch. This paper presents a brief system overview and detailed design of the rectifier/inverter bridge module with performance data from shots up to #6.

INTRODUCTION

UT-CEM has completed fabrication and is currently testing a lightweight air-core compulsator driving a cannon caliber electromagnetic gun (CCEMG). The final mechanical fabrication and preliminary testing results are presented in references [1,2]. This paper will present a brief system overview and detailed design of the rectifier/inverter bridge module with available performance data.

UT-CEM has fabricated a four-pole, air core compulsator and has tested the machine to 8,250 rpm. This power supply drives a 2.25 m, augmented railgun capable of launching 15, 185 g projectiles at a velocity of 1,850 m/s. The 15-shot sequence will be accomplished with three, 1 s, five-shot salvos with 2.5 s between salvos. At the time of writing this paper, only single-shot testing has been completed to a level of 1,900 m/s.

The CCEMG system uses five different but unique switching mechanisms for the distribution of current during a launch. An overall system schematic is shown in Fig. 1. The air-core compulsator is a self-excited machine and a 50 kJ field initiation module (FIM) produces a seed current for the field coil. The FIM consists of two 3,500 μF capacitors charged to 4 kV and switched by dual 4.5 kV thyristors. The FIM is passively recharged during the rectification phase using anti-parallel high voltage diodes with appropriate resistive current limiting.

Once the firing and fault control monitor (FFCM) has detected adequate FIM charging of the field coil, rectification is initiated. Rectification and inversion are achieved using a 95 MW thyristor bridge. Each leg consists of six 3.8 kV thyristors stacked in two sets of three parallel devices with a peak forward operating current of 25 kA at a 50% duty cycle. The bridge was designed to stand-off sinusoidal voltage of 3.8

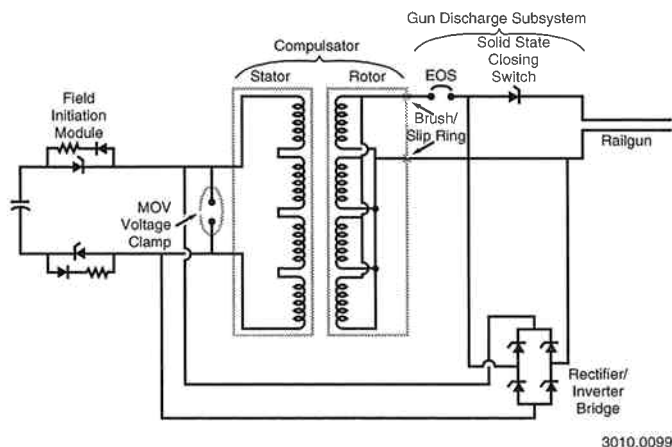


Fig. 1. Overall CCEMG system schematic

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kV. The thyristor bridge not only serves the purpose of rectification but also freewheels during launching and is used as an inverter for field reclamation between rounds. The three tasks of the rectifier/inverter bridge are controlled by the FFCM.

Once the FFCM has detected the field coil level defined by the mission parameters, the rectifier/inverter bridge begins freewheeling and the gun pulse is produced by the gun switch module (GSM). The GSM consists of 40 parallel 4.5 kV thyristors designed for pulse duty with a forward surge of 825 kA [3]. The 77 mm thyristors are arranged in a five layer, interleaved, cylindrical geometry. As the launch package exits the gun, a muzzle crowbar switch with a similar design will be used to snub the muzzle arc. The forward surge rating for the solid-state muzzle crowbar is only 250 kA.

An explosively operated opening switch (EOS) is used for overcurrent and thermal protection of the compulsator and all solid state switches. The EOS is designed to be able to handle the current and action demands of both the field coil and gun circuits. This switch is a semi-circle shaped piece of aluminum with multiple gaps loaded with Primacord[®]. The switch is initiated using standard exploding bridgewire detonators. The EOS is also designed to passively open thermally upon an overcurrent condition inside the compulsator. Therefore the EOS must be able to adequately dissipate all of the inductively stored energy in the system. The physical layout of the power electronics skid can be seen in Fig. 2.

RECTIFIER/INVERTER BRIDGE

Field coil excitation and regenerative field coil dump for the compulsator is achieved using a full wave, single phase rectifier/inverter (R/I) bridge. In the CCEMG system, the initial field coil current is supplied by a capacitor discharge. As the compulsator main armature voltage increases above the threshold for self-excitation, ac current from the armature is

rectified and charges the field coil. Depending on rotor speed and desired field coil current, rectification can last for 50 to 150 ms. In addition to rectification, the bridge also performs inversion. After a discharge, the bridge switches to inverter mode thus reclaiming remaining field coil energy and returning it to the rotor where it is stored as increased kinetic energy. Again, depending on rotor speed and the level of field coil current, inversion will last for 50 to 150 ms. The combined duties of rectification and inversion yield a requirement for a quasi-steady state bridge operation with an instantaneous peak power of 95 MW.

Overall system efficiency was an important consideration in the design of the CCEMG project. The reclamation of field coil current was important to increase efficiency as well as reduce the thermal demands on the bridge and the buswork. The efficiency of the bridge is highly dependent on the thyristor turn-off time. In selecting the bridge thyristors, fast turn-off time and high action capacity were the main criteria. Several candidate devices from different manufactures were evaluated. The selected thyristor is a Powerex TD-20. The device is a 100 mm unit with a 3,800 V rating with surge rating of 56 kA and an action rating of $1.3 \times 10^7 \text{ A}^2\text{s}$. A final configuration of two sets of three in parallel for a total of six thyristors is shown in Fig. 3. The combined thyristor data sheet values yield these parameters for the bridge:

Peak current (surge):	138 kA
Peak voltage:	7.6 kV
Peak action*:	$460 \times 10^6 \text{ A}^2\text{s}$
Total volume:	$112 \times 10^{-3} \text{ m}^3$
Total mass:	125 kg
Peak power:	95 MW

*Assumes an adiabatic system.

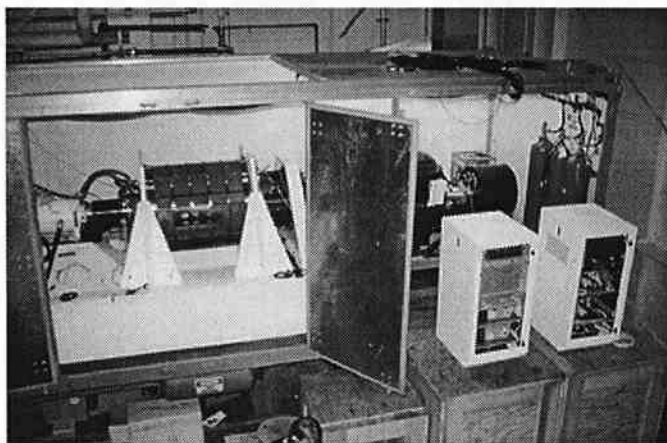


Fig. 2. Layout of CCEMG power electronics skid

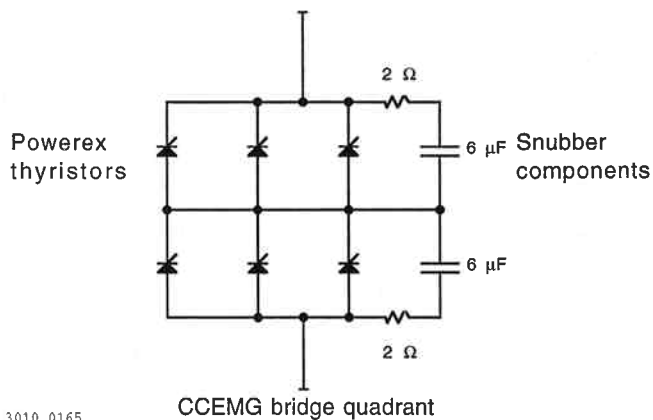


Fig. 3. Detailed schematic of R/I bridge

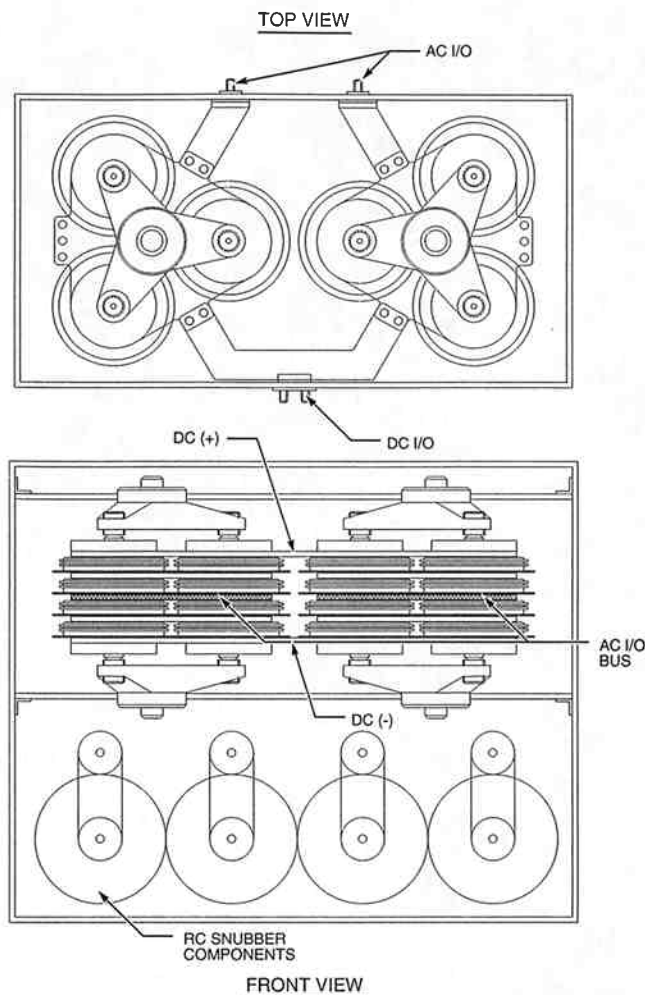


Fig. 4. Mechanical layout of R/I bridge, top and front views

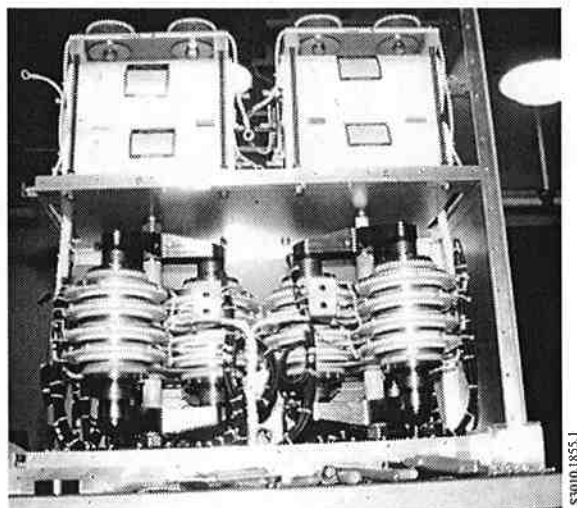


Fig. 5. Assembly of R/I bridge

MECHANICAL PACKAGING

The complete R/I bridge is packaged as one unit. Volume of the complete bridge as well as matching the impedance of the current paths were the main reasons for a single unit design. Thermal issues were also a packaging concern. Copper plates were used as heat sinks in addition to electrical conductors. During multi-shot mode, heating in the thyristors will become an important concern, but should be managed with the packaging design. The complete R/I bridge is made up of four identical quadrants of six thyristors each. The six thyristors of a quadrant are configured in a geometry consisting of two sets of three in parallel (Fig. 3). The bridge input power comes from the main coaxial bus. The ac is fed through flexible hexapolar cable into the center nodes of the thyristor stack. The rectified dc output leaves from the top of the bridge assembly and returns from the field coil on the bottom. Again, all conductors on the bridge output are flexible hexapolar cable up to the field coil terminals. The RC snubber components are arranged above the thyristors in another compartment [4]. The final bridge layout is shown in Fig. 4, and an assembly photo is shown in Fig. 5.

The bridge thyristor is a custom version of the Powerex TD20. The Powerex device was selected for performance and packaging reasons. The Powerex unit was available in a thin ceramic case, saving 30% in thickness compared to a standard press pak. These devices require a preload of 20,000 lb (85 kN) per device. As shown in the layout, the bridge is assembled in two halves. Each half has a gang-clamping system. The gang-clamp uses a single alloy steel tie-rod with a titanium flange at each end. Each titanium flange has three self-aligning tilt pads that provide even pressure distribution across the thyristor stack. The preload is initially applied hydraulically, and maintained in operation by spring washers.

GATE DRIVE

One of the most critical areas of design for power electronic circuitry is proper device gating. Proper gating techniques are very important for reliably turning the thyristor on and off as well as for longevity of the device. Some of the earliest design work done on the CCEMG power electronics was to investigate what type of gate drive circuit would be optimal for this system. This early study found the best gate drive method for this system was a hard drive gate pulse with a 50 μ s back porch for the moderate to high di/dt and dv/dt requirements [4].

The gate drive circuit used for both the bridge and GSM is shown in Fig. 6. The circuit receives the command to gate from the cycle portion encoder (CPE) based on mission parameters. For the hard gate drive pulse, a 60 V, 3.5 A pulse is generated at the output of the pulse transformer. Since the pulse transformer used has a single primary turn and eight secondary turns, an insulated gate bipolar transistor (IGBT) was

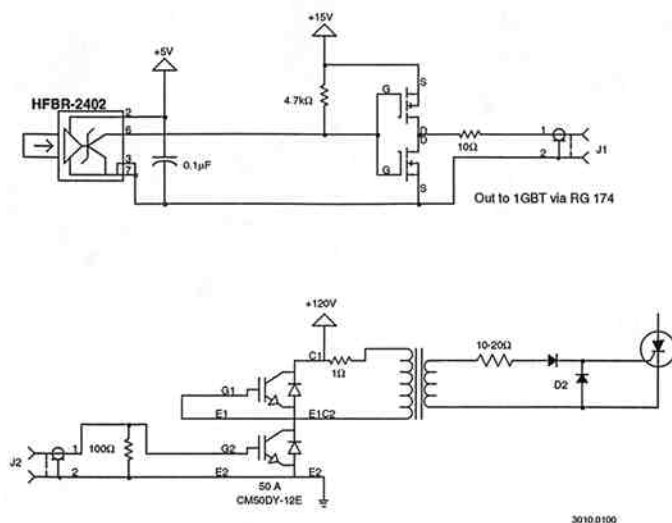


Fig. 6. Schematic of gate drive circuit

needed to drive the primary. The IGBT has strict gating requirements much like a thyristor. To satisfy these requirements, a complementary FET pair was used. The gate drive circuits have turned the thyristors on with 100% reliability as long as there was a sufficient forward voltage drop (at least 40V). The timing of the gate pulses with respect to actual compulsator voltage during a run is shown in Fig. 7. (Note that the gate pulses shown are the output of the pulse transformer and then are optically isolated, therefore, not the actual gate pulse used to drive the thyristor).

CURRENT MONITORS

To determine the actual current distribution during operation between thyristors, Rogowski coils are used to instrument each thyristor. The 24 Rogowski coil signals are conditioned and monitored by the bridge current sharing monitor (BCM). Since the bridge operates in quadrants, all thyristors in a quadrant are gated at the same time. Likewise, the BCM handles the 24 Rogowski signals as four groups of six signals each. After integration of the raw Rogowski signal, the average of each six-channel quadrant is formed. This establishes a quadrant average value for each of the four quadrants. The minimum acceptable sharing threshold is then added and subtracted from each average signal. This process yields a range to which each of the 24 individual integrated Rogowski signals are compared. Any signal from an individual Rogowski falling outside of the range will generate an error condition. The threshold levels are adjustable parameters, as are the gains for each raw Rogowski signal. With both of these items being adjustable, individual monitoring system differences can be calibrated out.

In addition to average current, positive and negative current flow is indicated for each channel using a similar ranging

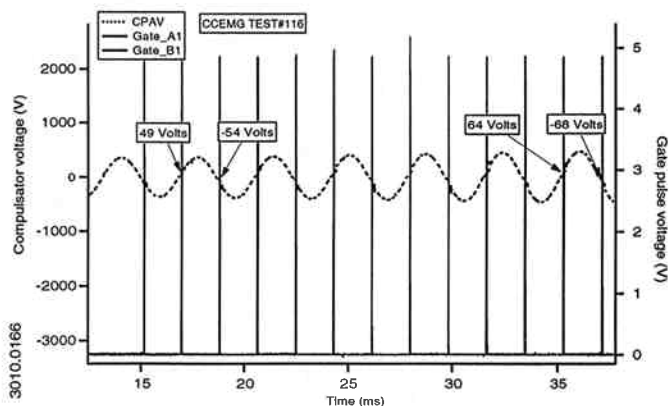


Fig. 7. Gate pulses and compulsator voltage

technique. The positive and negative levels are fixed conduction thresholds for each of the forward and reverse directions. Three resultant signals are possible: high, low, and negative. A fault condition is latched and displayed by quadrant on an array of LEDs. With the BCM system operating, evaluation of switch performance and troubleshooting a failed thyristor is possible.

The BCM also provides buffered individual integrated Rogowski signal outputs for data acquisition. As only six channels of data acquisition were available, bridge currents were sampled in quadrants. One quadrant was analyzed during test #116. It was determined from the data that the six thyristors of the bridge shared current within the desired range of 10%.

FIM PERFORMANCE

The field initiation module (FIM) provides the initial seed current for the field coil. A simplified schematic of the FIM is visible on the overall system schematic (Fig. 1). The FIM consists of two Aerovox KM502EX350D21A capacitors connected in parallel for a total of 7,000 μF . The capacitors are initially charged from a high voltage dc supply, up to 4 kV providing up to 50 kJ of energy. After the compulsator is motored to the desired discharge speed, the FIM is discharged into the field coil through dual Westcode N750CH45 thyristors. As the compulsator output terminal voltage increases, the FIM capacitors are passively recharged through dual high voltage diodes that are connected anti-parallel with the discharge thyristors. To insure long capacitor life, current limiting resistors are included in the charging circuit.

The FIM capacitor must be recharged from the computer terminals to meet CCEMG contract goals. To complete a CCEMG mission of 15 shots fired, the FIM must also discharge 15 times. During initial CCEMG system testing, passive FIM recharging has been demonstrated. Fig. 8 shows the

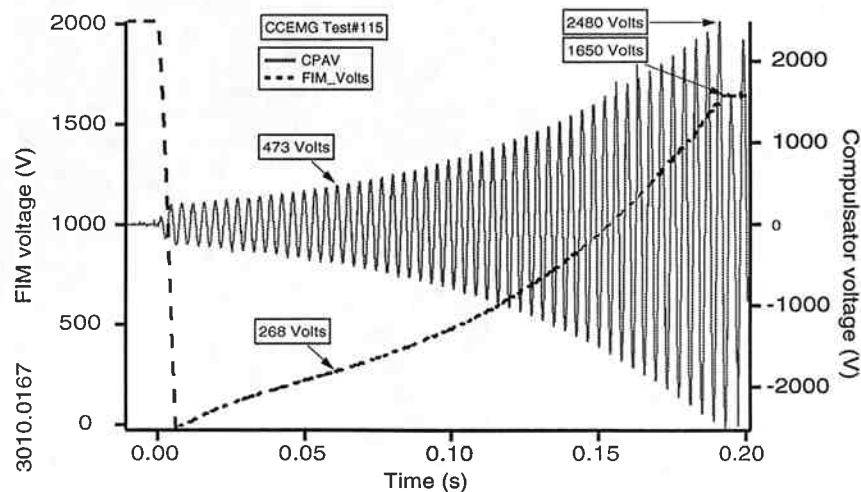


Fig. 8. Passive recharging of FIM with compulsator voltage

2 kV initial capacitor charge, capacitor discharge, and finally the FIM capacitor passively recharging. Final FIM capacitor charge voltage is 67% of compulsator terminal voltage. The FIM recharge energy was limited by a 15 degree bridge gating angle. This means that the energy between zero and 15 degrees was not utilized, therefore lowering the charging efficiency. For achieving CCEMG goals, 67% charge is an acceptable level.

CONCLUSIONS

Although the compulsator has not been tested to rated speed, several key components have been fully tested. As noted above, the bridge has charged the field coil current above its peak rating of 25 kA. During run #116, the bridge rectified the field coil up to 30.5 kA, which should be the highest required current for testing. A summary of significant

test data is shown in Table I. On the same test, each of the instrumented bridge thyristors of one quadrant indicated that current was shared between the devices within a 10% range. These results indicate the bridge has been tested to full design goals (with the exception of the total action rating) and verify that it will be able to handle the CCEMG system requirements for full testing. Fig. 9 shows the results of the bridge rectification from run #84. The full-wave rectification of the bridge can be seen on the field coil current waveform along with resulting compulsator terminal voltage. Due to low compulsator speed, the rectification interval was much longer than at higher speeds. During initial CCEMG system testing, there have been no bridge related component failures.

The three other components of the power electronics skid, the FIM, GSM and EOS, were tested to full single-shot testing requirements and indicate they will meet the needs of full scale multi-shot testing. The FIM was charged to 3 kV on

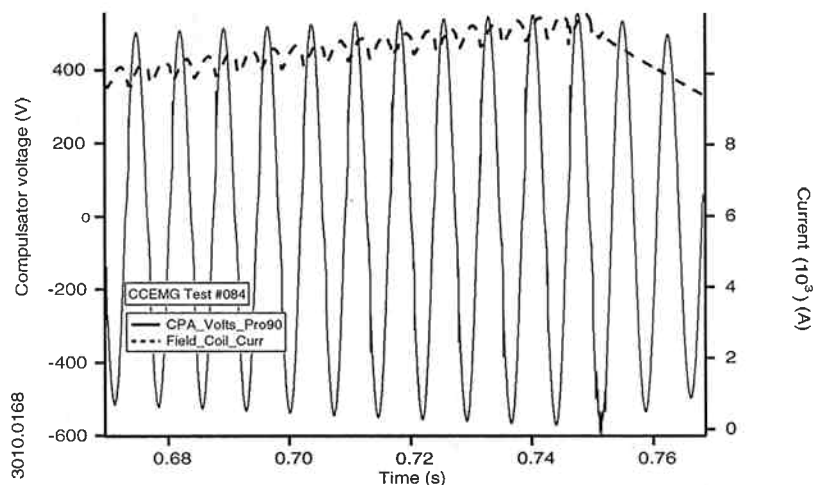


Fig. 9. Field coil current and compulsator

run #116 and successfully seeded current into the field coil for self-excitation. Passive recharging of the FIM was demonstrated on run #115 and achieved a recharging level of 67% of peak compulsator voltage, a level adequate to achieve full-scale goals. In stand-alone testing, the FIM was charged to its peak rating of 4.5 kV and discharged into an inductive load. On run #116, the GSM switched 660 kA into the gun during testing. On this test, the GSM saw a sinusoidal voltage of 2,835 V, 1 kV below its rating. Although preliminary analysis indicates that a snubber may be required for higher peak current discharges, the GSM indicates that it can achieve system goals. The EOS has shown 100% reliability which is important for thermal protection of the compulsator during overcurrent or fault scenarios.

The power electronics skid components have been adequately tested during commissioning of the CCEMG system for full scale, single shot testing. In the initial single shot testing, no thermal problems have occurred. The thermal issues will be explored during the multi-shot testing sequence. Preliminary analysis of all of the components indicate that they should be able to achieve the system to full scale multi-shot testing goals for the CCEMG program.

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Table I. CCEMG selected single shot test summary

Parameter/Shot, Run # & Date	Units	Shot #3 Run #107 1/24/96	Shot #4 Run #114 2/5/96	Shot #5 Run #115 2/7/96	Shot #6 Run #116 2/9/96
CPA Parameters					
CPA Rotor Speed	rpm	7,580	8,021	8,000	8,264
FIM Charge	kV	2	2	2	3
Field Amps	kA	22.0	27.4	27.4	30.5
% Design Field	%	88	110	110	122
Field Rise Time	s	0.192	0.195	0.195	0.160
CPA Peak AC Volts	V	1,910	2,510	2,485	2,835
Rotor Speed @ Discharge	rpm	7,251	7,607	7,653	7,772
Fire Angle (electrical)	°	5	5	5	5
Volts @ Trigger	V	166	221	221	220
Peak Gun Current	kA	496	599	605	660
Pulse width	ms	3.30	2.97	2.97	2.97
Launcher/Armature Parameter					
Primary Flatjack Pressure	ksi	10.0	13.0	13.0	15.0
ILP Mass	g	135.3	148.4	163.3	154.5
Load Force	lbf	3,100	3,200	3,360	3,136
ILP Muzzle Velocity	m/s	1,187	1,729	1,530	1,900
Muzzle Energy	kJ	95.3	222	191	279
Action	MA ² s	322	495	512	589
Breech Efficiency	%	44	53	49	49
Muzzle Current	kA	0.0	125	68	212
Launcher L'	μH/m	1.00	1.04	0.98	1.00