UCRL-MA-150291

NIF Amplifier Power Conditioning System (PCS) Design Basis Document

G. Hammon III, M. A. Newton

January 1, 2001

U.S. Department of Energy

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This work was performed under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

Laser Engineering Division

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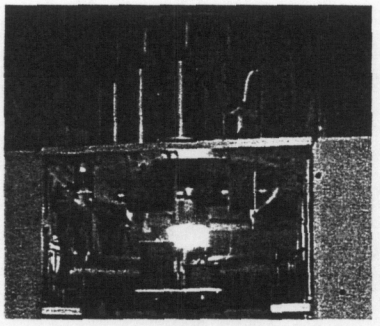
NIF-0081294

June 2002



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1.0 POWER CONDITIONING MODULE SUB-SYSTEM CONFIGURATION

This section of the Design Basis Document describes the configuration of the Power Conditioning Module Sub-System (PCMS) for the NIF Large Aperture Amplifier as of June 2002. The PCMS consists of the following main subsystems: The Main Energy Storage Module (MESM), Local Controls, a set of Output Cables, the Main Trigger Generator, and the Pre-Ionization Lamp Check (PILC) pulser. The modules are designed to meet the specification described in NIF Subsystem Design Requirement 1.3.4.

This section of the document is organized into the following sub-sections:

1.1 PCMS System Overview

- Frame/Enclosure
- Main Energy Storage Module
- Controls
- Diagnostics
- Main Trigger Generator (TG-803) (See Section 1.5 for additional details)
- Output Cables
- Pre-Ionization/Lamp Check (PILC) Module (See Section 1.4 for additional details)
- Connections to Facility Grounds (See Section 1.3 for additional details)

1.2 PCMS Performance Predictions

1.3 Power Conditioning System Grounding

1.4 PILC System Description

1.5 TG-803 Trigger Generator System Description

1.1 PCMS System Overview

1.1.1 FRAME / ENCLOSURE

Most components of the MESM are contained in a heavy-duty welded-steel enclosure designed to allow the assembled MESM to be transported assembled, from the assembly location to the NIF building. The enclosure is also designed to safely contain any shrapnel that may be produced in the event of a catastrophic component failure inside the enclosure while venting pressure that may build up in the enclosure.

1.1.1.1 Transportability

The MESM has been designed to allow the module to be assembled, pre-tested, then transported to the NIF facility and installed, with only minimal confirmation testing required after installation. Design features included for this purpose include a stiffened frame, capacitor hold-downs, supports at both ends of the damping elements, and vibration-resistant fasteners. The enclosure includes fork-lift points, as well as a set of slots for air bearings, visible in Figure 1-1, to be used for transport of the module within the Capacitor Bays.

1.1.1.2 Seismic Restraints

The various component restraint features described above also provide restraint for seismic events. For protection of the assembled module, the module frame is held down by a set of seismic restraints, visible in Figure 1-1, that are bolted into the capacitor bay floor.

1.1.1.3 Blast Doors

Vented blast doors mounted on the front and the rear of the module allow rapid relief of pressure that can build up in the module in the event of a catastrophic failure, such as a capacitor rupture at high voltage. The doors, visible in Figure 1-1, include shrapnel traps in the vents and inspection doors to allow inspection of the safety dump circuits.

1.1.1.4 Drip Tray

A metal drip tray is an integral part of the module frame, and will contain up to 30 gallons of oil that may leak from damaged or defective capacitors. The tray is visible in Figure 1-6.

1.1.1.5 Shrapnel Protection

Outer surfaces of the enclosure are made from 3/8 steel, to prevent high-energy shrapnel from exiting the module. Steel cable-cover boxes, visible in Figure 1-1, are used to protect the signal and control cable access ports. Thick polycarbonate plates cover the openings for the HV power supply cable and main trigger generator entry points.

1.1.2 MAIN ENERGY STORAGE MODULE (MESM)

1.1.2.1 Capacitors

Capacitors are installed in two columns, each three capacitors wide and four high, for a maximum of 24 capacitors. In the baseline configuration, 20 capacitors are installed. Four empty positions remain in the top level, two on each side of the module. The opening in the frame for installing and removing capacitors is 21" high x 40" long. Space has been allowed for the cans to grow two inches in each dimension, beyond anticipated initial bowing, and still be removed. (Gas can build up in the capacitor cans during self-clearing operations, resulting in pressure build-up and resultant bowing of the can, over the life of the capacitor.) Capacitor access is via bolt-on panels on the front of the module, which are shown removed in Figure 1-4. Panels on the rear of the module are welded in place. Capacitors are insulated to >30 kV from the module frame by kydex trays, 1/8 thick, with a 2.125 lip.

Modules will be assembled using one of two different capacitor types. Capacitors will be built by ICAR (Italy) and General Atomics (USA). Capacitors are tied down to the frame for transportability and seismic protection, using a pair of polyester straps (5/8 wide, 0.04 thick) for each capacitor. Characteristics of the two capacitor types are summarized in Table 1-1 below.

Table 1-1 Main Capacitor Prameters

Capacitance Specification	290 μF, —0 + 10%
Maximum Voltage	26 kV
Normal Operating Voltage	24 kV
Rated Life	> 20,000 normal shots before 5% loss in capacitance
Maximum Recommended Charge Time to 24 kV	≤ 80 seconds
Maximum Hold Time at 24 kV	15 seconds
Equivalent Series Resistance	15 mΩ
Nominal Initial Capacitance: ICAR General Atomics	 299 μF 320 μF

1.1.2.2 High Voltage Bus

The high voltage bus is a 23.5" wide x 0.5" thick aluminum plate. It is supported above the floor by the Bus Foot; a 0.5" thick G-10 plate. The bus is visible in Figure 1-2 and Figure 1-3. The Bus Foot is visible in Figure 1-2 and Figure 1-6. When properly installed, the bottom of the bus is approximately 8 above the bolts in the bottom angle and 9.7 above the floor. During installation, the bus is held above the floor using a hydraulic jack, providing additional pre-load to the ST-300 spark gap.

1.1.2.3 Module Pulsed-Power-Return Buswork

Current return buswork to the capacitors consists of pairs of steel bars, 1" x 0.25" - - one on each side of each capacitor. The steel bars are connected to two capacitor case terminals of each capacitor through 1.5 wide, 0.064 thick copper straps. The bars connect to the top of the module frame via 2 x 2 steel angles welded to the frame near the top hat and are tied together across each side of the module by an insulating bar near the bottom of the capacitor column. These elements are shown in Figure 1-4 and Figure 1-6.

1.1.2.4 Damping Elements

Capacitors are protected from internal capacitor faults by the Damping Elements, 25 mΩ ± 1.5 mΩ, 9 H ± 0.5 H each. The damping elements must maintain mechanical integrity through a 390 kA fault. **In the event of such a fault, the affected damping element must be replaced prior to resuming operation.**

Each damping element is connected to its associated capacitor bushing and to the center High Voltage Bus through 1.5 wide. 0.125 thick copper straps. The damping elements are supported and tied down at each end, to allow transportation of the assembled module and to prevent damage to the capacitors in a seismic event. These items are shown in Figure 1-4.

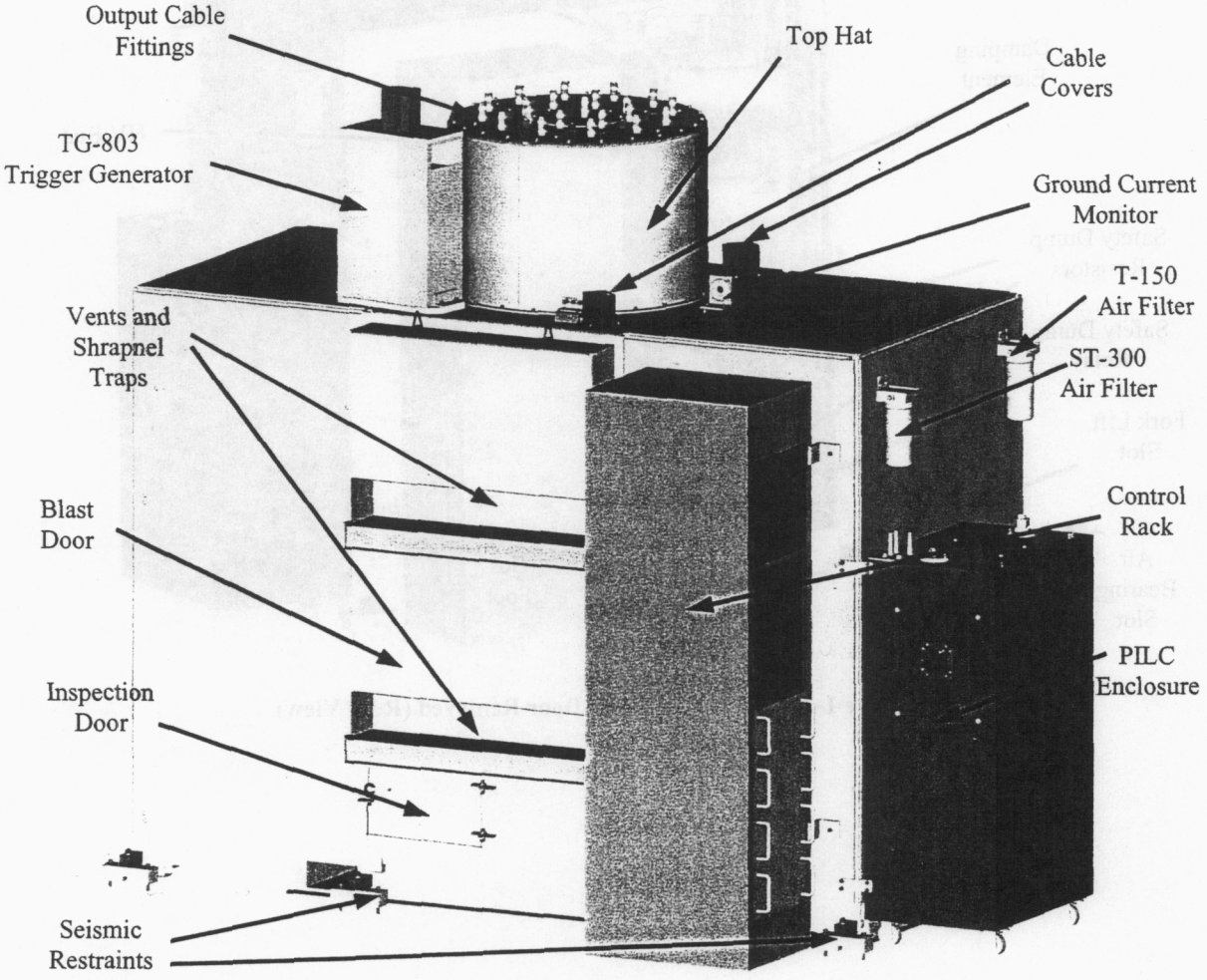


Figure 1-1 MESM Exterior (Rear View)

Module Frame: 134 x 60 Footprint -- 98.9 High
Overall Height: 130.9 to top of Top Hat -- 136.2 to top of TG-803

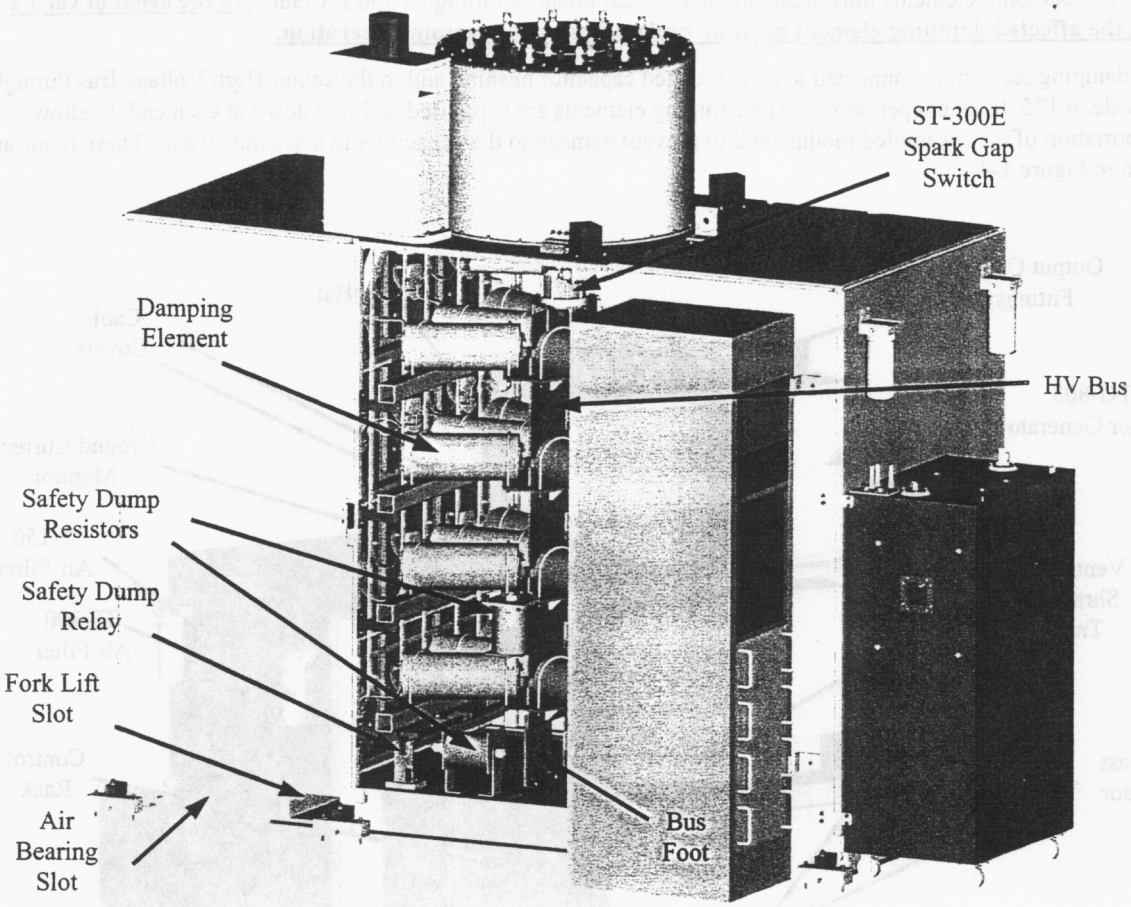


Figure 1-2 MESM with Blast Door Removed (Rear View)

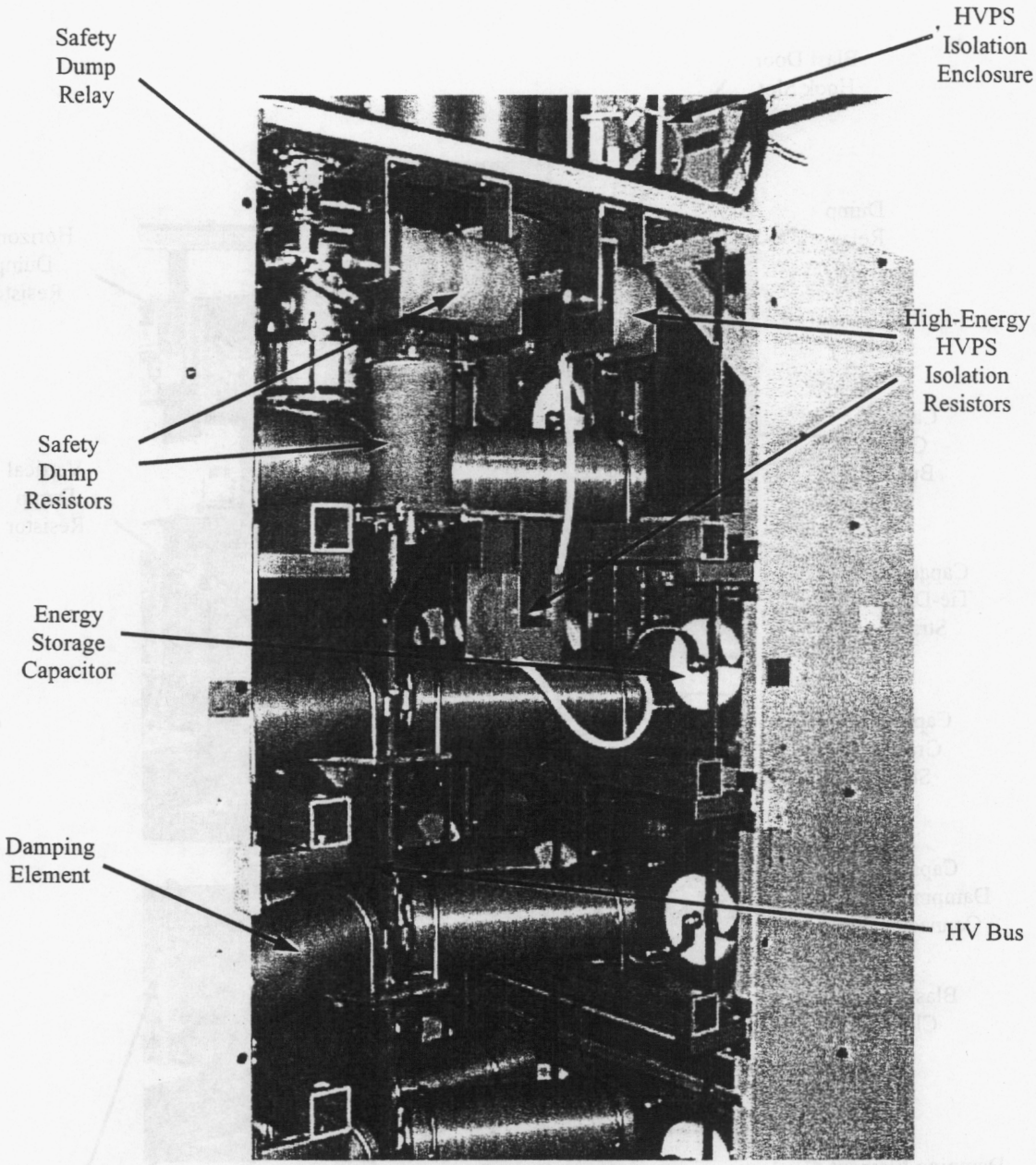


Figure 1-3 MESM Interior (Front View) with Blast Door removed

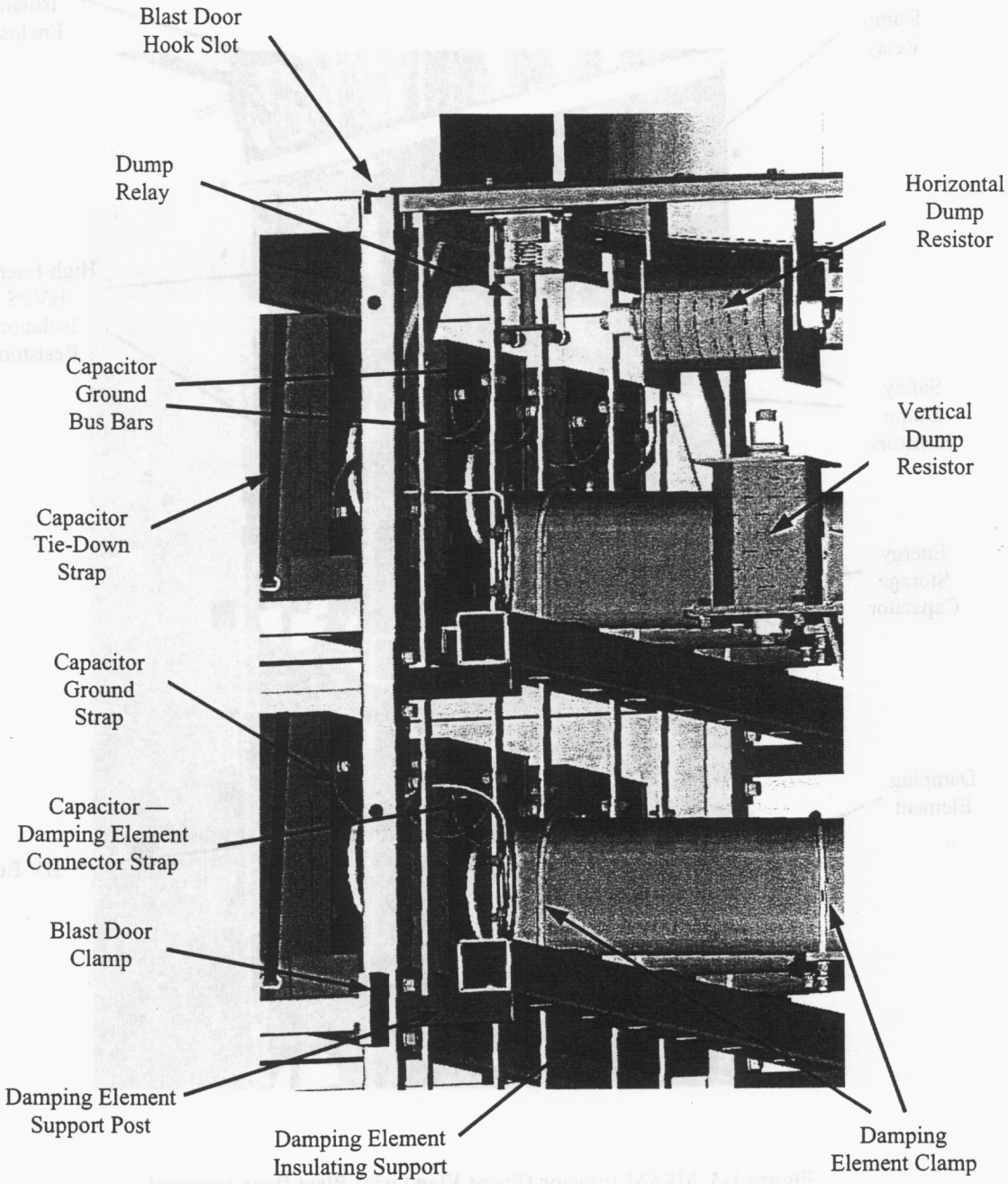


Figure 1-4 Upper MESM - - Front View

1.1.2.5 Output switch

The output switch is a Titan Pulse Sciences ST-300E spark gap. The switch uses a steel housing, with a 1/8 inch initial gap between the high-density graphite electrodes, and uses dry, oil-free air as the switching gas. The electrodes erode in the switching process, progressively increasing the electrode gap. The electrode gap is estimated by the control system, based on calculated charge transfer, and switch gas pressure is automatically adjusted to compensate for the increasing switch gap. The switch will be removed and replaced with a new or refurbished switch after the switch transfers approximately 283,000 Coulombs (approximately 1,800 shots, depending on module capacitance and charge voltage). In addition, the switch will be inspected and the UV-illumination spark plug replaced after approximately 150,000 coulombs. The switch is visible in Figure 1-2, Figure 1-5, and Figure 1-8.

1.1.2.6 Trigger Isolation Cores

The series-injection-trigger for the ST-300 switch requires at least 6 μH of inductance between the switch and a low-impedance load, to support the required trigger voltage. In the MESM, this isolation is provided by a Ceramic Magnetics CMD 5005 Ferrite core, 4" thick, 3.5" ID, 10 OD. The core is split to allow installation and held together by plastic straps. The core is insulated from the metal base flange by 1/8 of nylon. The core is visible in Figure 1-5.

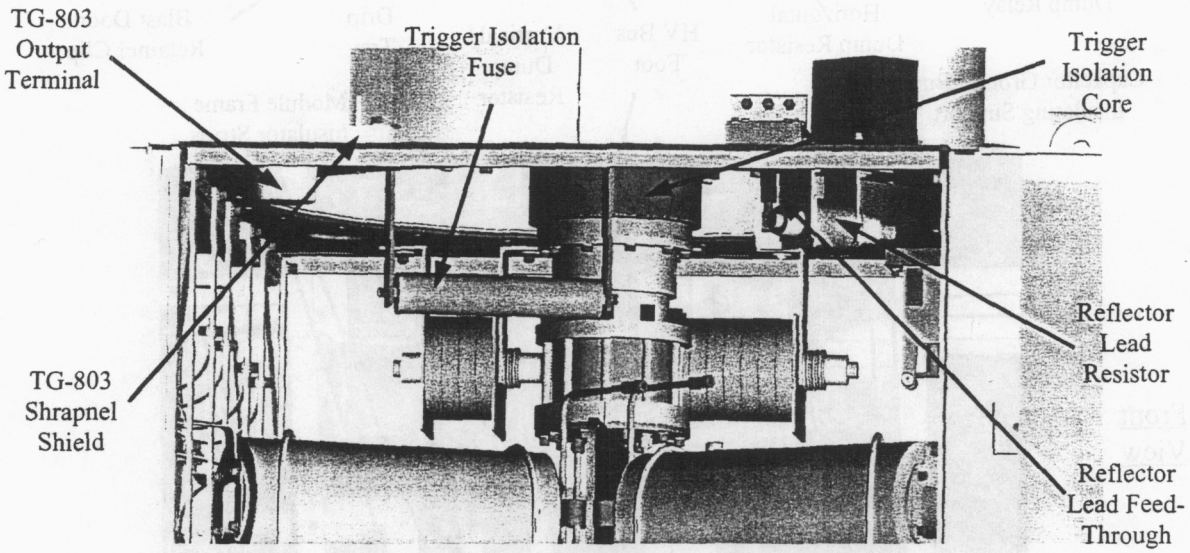


Figure 1-5 Upper MESM -- Rear View

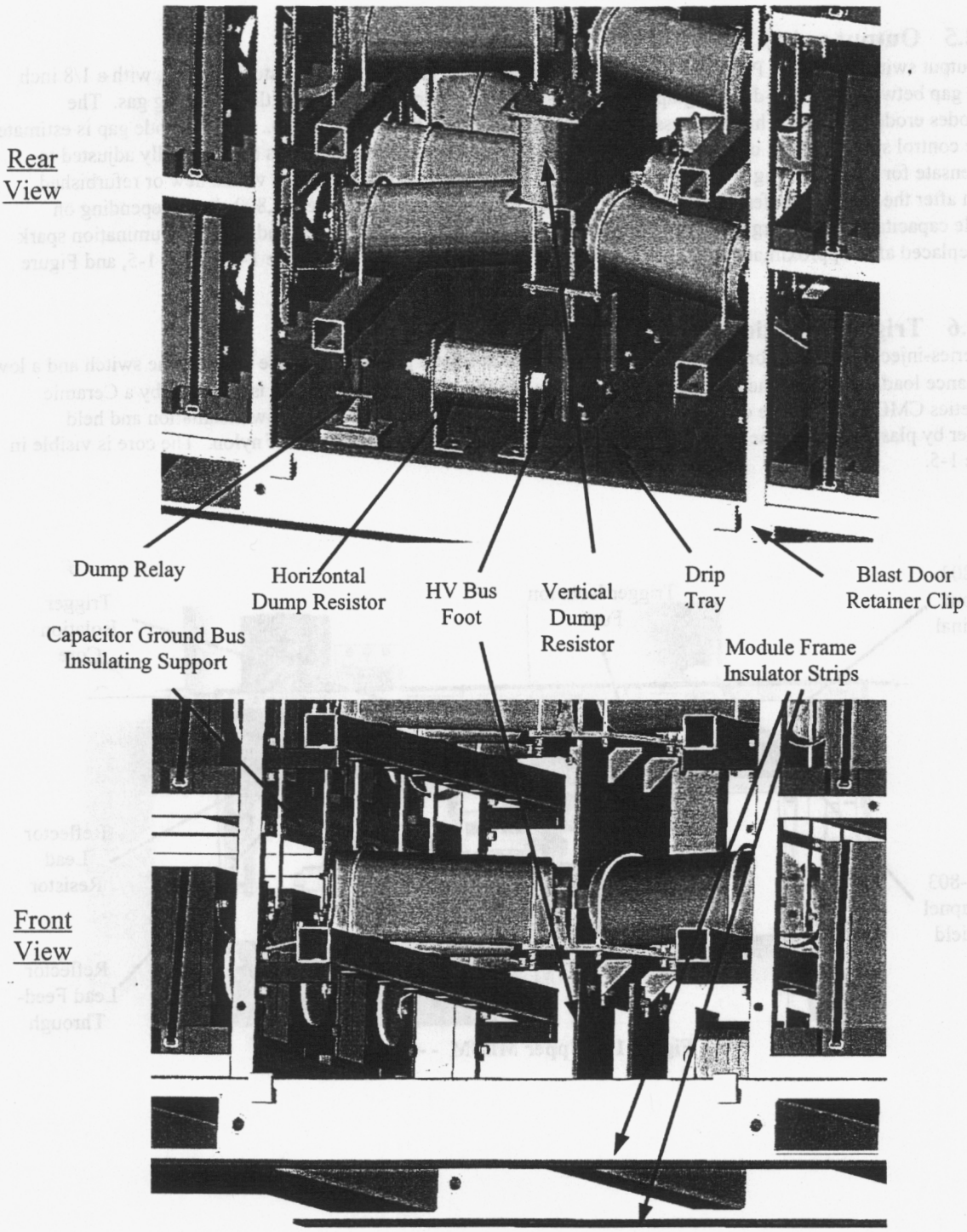


Figure 1-6 Lower MESM Detail

1.1.2.7 Ballast Inductors

The module includes 20 ballast inductors, one for each cable. The inductors are visible in Figure 1-7 and Figure 1-8. A photo of an inductor is shown in Figure 1-9. Each inductor is formed from _ DIA copper solid wire, and is contained in a fiberglass-reinforced cylinder. The inductors have been demonstrated to survive 130 kA simulated lamp faults, but may be damaged in such a fault. **An affected ballast inductor must be replaced after such a fault.**

The module design calls for a nominal 30 H total inductance for the combination of the ballast inductor, cable, and a pair of flashlamps. Different inductance values will be used to compensate for the different inductances associated with different cable lengths. Each module will have only one cable length, and thus one ballast inductance value. The ballast inductance values associated with different cable lengths are summarized in Table 1-2.

Table 1-2 Ballast Inductor Parameters

Cable Lengths	Ballast Inductance	Number of Turns
66 ft — 87 ft	8.2 μH	15
92 ft — 119 ft	10.3μH	18
121 ft — 151 ft	13.8 μH	22
152 ft — 180 ft	15.5 μH	24

1.1.2.8 Ballast Inductor Adapter Plate

The set of 20 ballast inductors is connected to the module through the Ballast Inductor-Spark Gap Adapter Plate, a 0.5 aluminum plate shown in Figure 1-7 and Figure 1-8. The plate is supported from above by a set of 8 each 3/4" DIA fiberglass threaded rods. A stainless steel screen is used between the bottom of each coil and the aluminum plate, to assure good current contact. A silicon rubber gasket is used at the top of each coil, to prevent loosening of the coils during transportation.

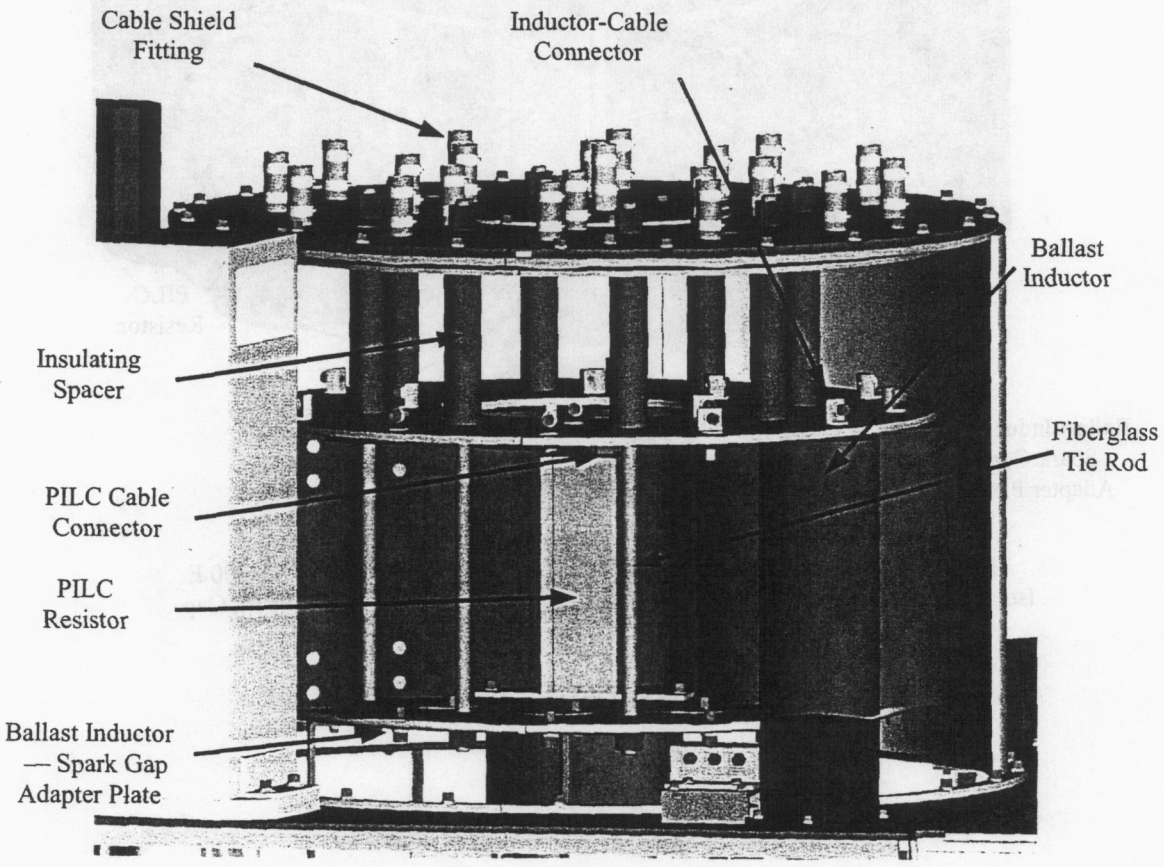


Figure 1-7 Top Hat Assembly (Rear View) with Panel Removed

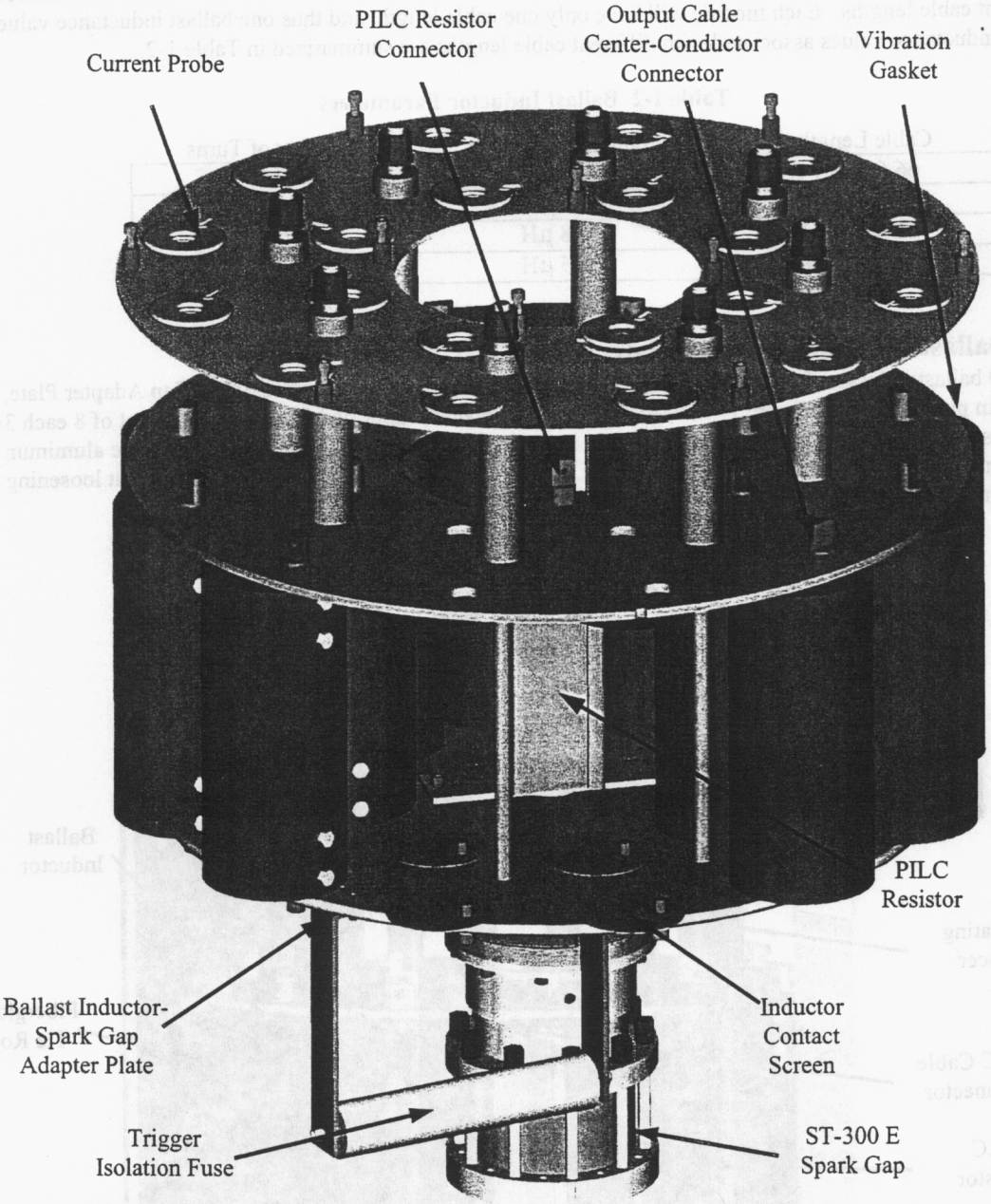


Figure 1-8 Top Hat Interior Detail - - Rear View

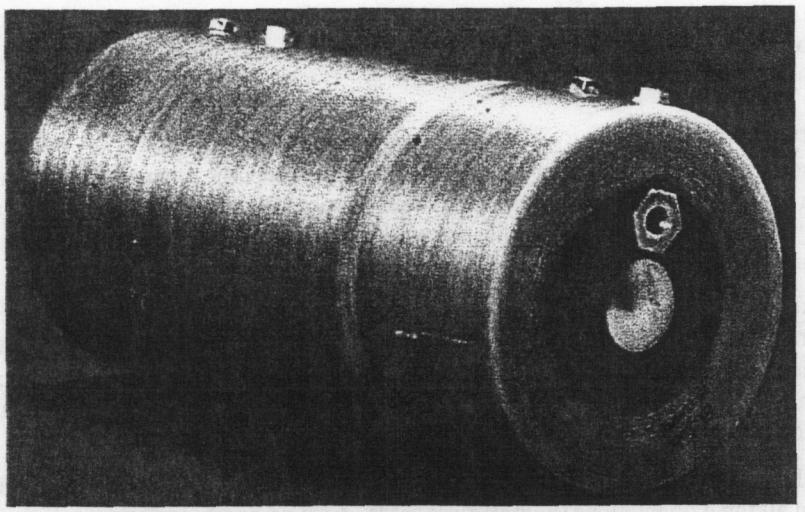


Figure 1-9 Ballast Inductor After Encapsulation

1.1.2.9 High Voltage Power Supply Protection Circuit

The power supply protection circuit is shown schematically below. As noted in this figure, a portion of the circuit is located in a separate acrylic enclosure, mounted on the top of the MESM, partially visible in Figure 1-3.

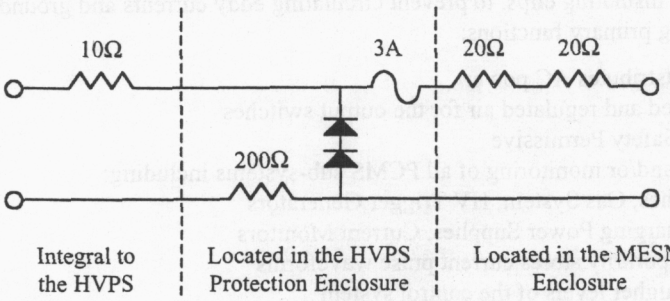


Figure 1-10 HVPS Protection Circuit Schematic

The key components in the HVPS Protection circuit are:

Crowbar Diode Assembly:

- Two block-type diode assemblies in series, each block rated for 50 kV, 1 kA surge-current: HV Components Associates #6HV-50KC. The use of two 50 kV units in series assures protection against the transients produced when the output switch is triggered and fired. There were problems in early testing with only a single diode block; there have been no problems using the two blocks in series.

Current-Limiting Resistors:

- The 10 Ω resistor is located inside the power supply chassis.
- The 200 Ω resistor is a 100 W Dale HL-100
- Two each 20 Ω, 0.44 MJ resistors: HVR Advanced Components assemblies: # J04PFA200L. Each assembly is formed from 4 series 6 DIA disks
    - High-energy resistors are used in this location to assure safe dissipation of the full module energy in the event of a failure of the VHPS feed-through at the top of the MESM enclosure. The high-energy resistors are located inside the MESM enclosure, as shown in Figure 1-3.

Series Protection Fuse:

- The fuse is a Pulse Power Components #PPC-FU-212-173 fuse rated for 3 A rms and 173 A^2-second let-through action. The same fuse design is used in the protection circuit for the main switch trigger generator.

1.1.2.10 Safety Dump

The MESM includes two independent dump assemblies; one at the top, the other at the bottom of the module. Each is designed for an RC-discharge time constant of less than 10 seconds for the highest-energy bank, at 7.7 mF (24 capacitors). That is, when both dump assemblies are working in parallel, the system voltage is reduced to a safe level in approximately 40 seconds.

Each assembly uses a series pair of 560 Ω resistor assemblies (10 series disks, 6 OD ceramic resistors). Each 560˚Ω resistor is rated for 1.1 MJ, to allow repeated dumps. A single resistor pair can safely dump a full 2.2 MJ high-energy module two times in a 30 minute interval. Two resistors are used in series to assure that the flashover or breakdown of a single resistor will not tie the module directly to ground. This limits fault current, and assures that a failed resistor will not produce shrapnel.

The solenoids in the dump switches use ac for opening and spring drives to close, providing fail-safe closure, and are rated for use in all three orientations (both vertical cases - base up and base down - and the horizontal case).

1.1.3 CONTROLS

Separate and independent controls are provided for each Power Conditioning Module Subsystem. The local controller is located in the Control Rack, attached to the module as shown in Figure 1-1. The relationships between the local controller and other systems is shown in the block diagram of Figure 1-11. The control rack is attached to the MESM enclosure with insulating clips, to prevent circulating eddy currents and ground currents. The control rack provides the following primary functions:

- Conditions and distributes AC power
- Provides controlled and regulated air for the output switches
- Implements HV Safety Permissive
- Provides control and/or monitoring of all PCMS sub-systems including:
  - Dump Switches, Gas System, HV Trigger Generators
  - Capacitor Charging Power Supplies, Current Monitors
- Acquires and temporarily stores current pulse waveforms
- Interfaces to the higher levels of the control system
- Houses the Main and PILC Charging Power Supplies

The PCMS local controls provide only the low level functionality needed to operate the PCMS. Connection to a Control Station (for stand alone operation) or connection to the NIF Integrated Computer Control System (ICCS) is required in order for the PCMS to operate. These required higher level functions include: HV Permissive generation; Control Network Services; EC Processor Boot Server; Graphical User Interfaces (GUIs); Trigger Generation; Control Sequences; Waveform Data Analysis and Archive; Databases for Machine History, Calibration Factors, and other programmable control parameters.

The control rack includes the following major items:

1.1.3.1 AC Power Distribution

The AC Breaker Panel of the control rack accepts 480 VAC 3-phase wye connected, 100 A service from the facility utilities. The panel provides independent circuit breakers with lockouts for the HV power supplies and independent fuses for the Embedded Controller and Gas Pressure Controller. Two 480/120 step-down transformers deliver 120˚VAC to the Embedded Controller and Gas Pressure Controller.

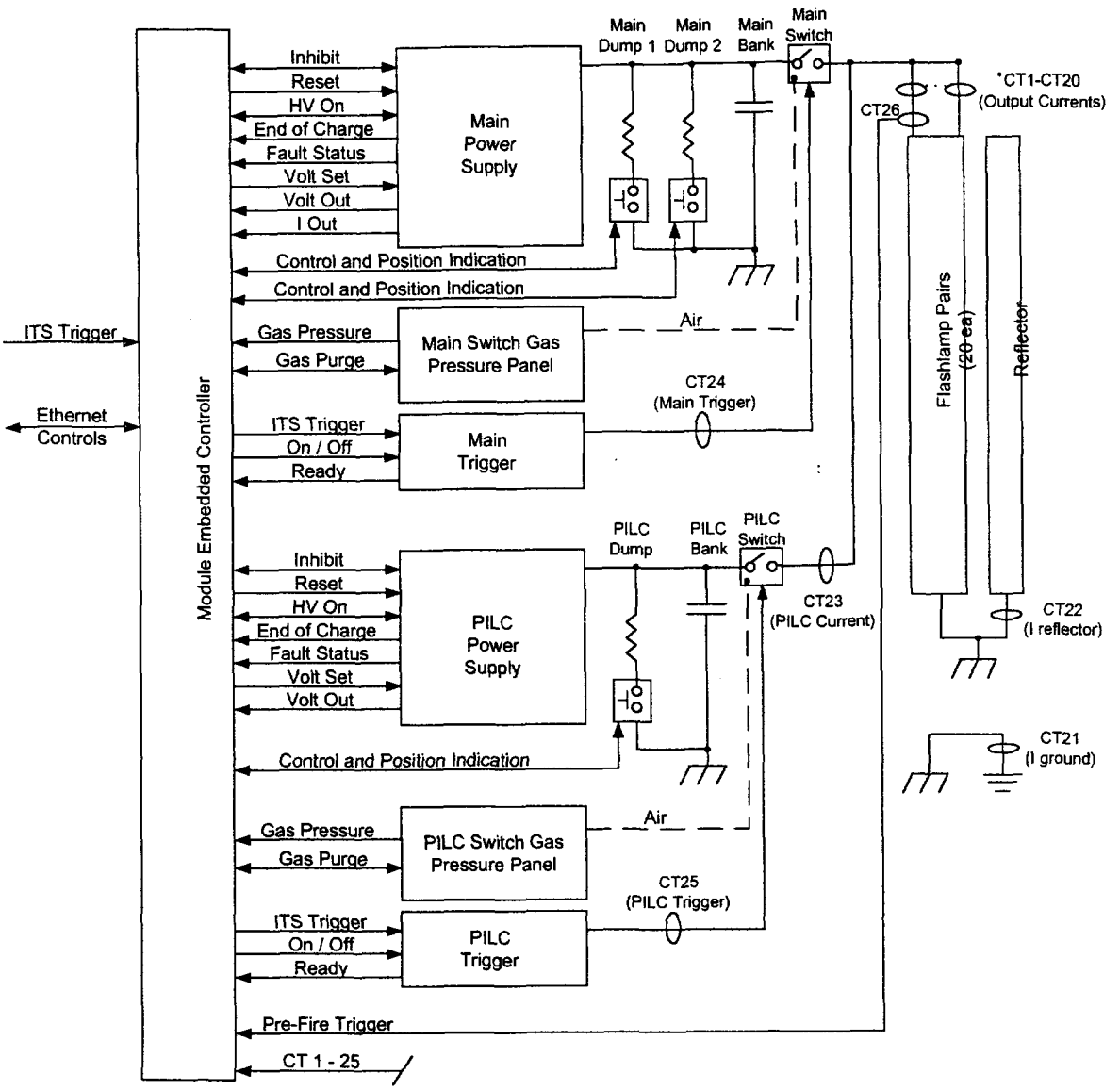


Figure 1-11 PCMS Local Controls Block Diagram

1.1.3.2 Gas Pressure Controller

The Gas Pressure Controller provides two independent air pressure regulation and purging systems, one for the MESM and one for the PILC spark gap switches. The two systems share a common air supply. Two separate exhaust lines are returned to the facility. Exhaust air from the switches passes through filters (mounted on the MESM enclosure) prior to returning to the gas control chassis, to remove powder produced during switch operation.

An additional circuit breaker is provided on the front of the Gas Pressure Controller chassis, which provides power to the HV Trigger Generators only. This circuit breaker allows HV Trigger Generator lockout when controls are operated with personnel present in the vicinity of the PCMS. This chassis also provides a 110 VAC control interface for the trigger generators and the dump switches.

1.1.3.3 Embedded Controller

The Embedded Controller (EC) receives commands from the higher level controls (either the control station or the NIF ICCS) which it transforms into control signals for the various PCMS devices. It reads status inputs from these devices and (upon command) provides this status back to the higher level controls. The EC utilizes a commercial pentium- class single board computer.

All control signals between the EC and the devices are isolated. Communication with the higher level controls is through a fiber optic ethernet network using TCP/IP.

The EC contains a high-speed digitizer system referred to as the DAS (data acquisition system). On each shot (or pre-fire), this system captures signals from twenty five current probes located through-out the PCMS: 20 output currents, plus reflector, ground, PILC, Main trigger and PILC trigger currents. Upon command, the EC reads and transmits the data to the higher-level control system.

The DAS is used as a module performance diagnostic and a lamp integrity diagnostic. The EC compares the twenty acquired output waveforms with a reference waveform and provides a pass/fail indication to the higher-level control system. The individual diagnostics are discussed further under Diagnostics below.

1.1.3.4 Triggers

The PCMS requires three separate triggers, one each for Diagnostics, PILC and Main. The diagnostic trigger is provided from the external timing system via a fiber-optic cable. Strictly speaking, the PILC and Main Triggers are not part of the Control Rack - - they merely pass through the rack on their way to the PILC and Main Trigger Generators. These are fiber optic signals generated by the external timing system. Each directly triggers its respective PILC or Main Trigger Generator. Each trigger generator provides a fiber optic status signal to the EC, which indicates whether or not the trigger generator is ready to fire.

1.1.3.5 Main Charging Power Supply

The power supply for the MESM capacitors consists of two modules operating in parallel, mounted in the control rack. The power supply system will charge the bank of up to 24 each, 320 F capacitors to 24 kV in approximately 80 seconds. The power supplies are rated for 26°kV, 25 kJ/second, nominal.

Note: Modules may have different capacitances and charge voltages. Modules can be assigned different start charge times, to roughly synchronize the charge complete times for all modules.

1.1.3.6 PILC Power Supply

The PILC power supply is also located in the control rack. This power supply must be able to charge the PILC capacitors (130 μF total) in ≤ 60 seconds to a selectable voltage up to 30 kV. The specification calls for 2 kJ/second rating.

1.1.4 DIAGNOSTICS

The PCS module includes a variety of sensors that are used to monitor system performance and to identify possible fault conditions. The diagnostics signals and their use within the control system are listed below.

Table 1-3 Diagnostics

Output Current (One on each output cable)	Current is compared to a standard waveform. Anomalous current is flagged as a fault and must be analyzed to identify the problem.
Pre-Fire Detector (Second current probe on one output cable)	Provides an early DAS trigger in the event of an output switch pre-fire, to assure that data will be collected in the event of a pre-fire
Reflector Lead Current	Current is compared to a threshold level. Any significant reflector current implies a lamp failure.
Ground Lead Current	Current is compared to a threshold level. Any significant ground lead current implies a ground fault.
PILC Output Current	Signal is available for recording. No processing/evaluation is done.
PILC Trigger Current	Signal is available for recording. No processing/evaluation is done.

TG-803 Trigger Current	Signal is available for recording. No processing/evaluation is done.
Main HVPS Charge current	Charge voltage profile is monitored: Detection of an anomaly (e.g., sudden change of charge rate before set-point) will raise a fault flag.*
Main HVPS Charge voltage	Charge voltage profile is monitored: Detection of an anomaly will raise a fault flag.*
PILC HVPS Charge voltage	Charge voltage profile is monitored: Detection of an anomaly will raise a fault flag.
ST-300 Output Switch Pressure	Pressure is monitored and compared to computer-selected pressure. Out-of-range pressure raises a fault flag.
PILC Switch Pressure	Pressure is monitored and compared to standard pressure. Out-of-range pressure raises a fault flag.
Dump Relay Status	Sensor switches establish the status of the three safety dump relays. If any of the relays is not in the commanded position, a fault flag is raised.
Trigger generator status (2 each)	Trigger generator status F/O signals are monitored for both trigger generators. If the status is not as commanded, a fault flag is raised.
Controller communications status	The communications link between the Front End Processor (which controls the module) and the module s Embedded Controller is monitored routinely. A drop-out of the communication link will initiate a process to disable the power supplies and drop the safety dump switches.

1.1.5 TRIGGER GENERATOR

The trigger generator for the ST-300 spark gap is a TG-803 trigger generator, visible in Figure 1-1. It is mounted on the top of the MESM near the Top Hat. It uses an SCR for its main switch, pulse-charging an output capacitor, through a pulse-transformer, to approximately 105 kV. This capacitor is discharged through a UV-illuminated, sealed gas (N_2) spark-gap output switch. The high-voltage bushing of the trigger generator passes through a hole in the top plate of the module enclosure, as shown in Figure 1-5. The _ inch-thick polycarbonate output plate of the TG-803, combines with the _ inch-thick plate of polycarbonate between the TG-803 and the top plate of the module to provide shrapnel protection.

The trigger generator includes an output blocking capacitor in the output bushing, and is further isolated from the module by a high-current fuse, Pulsed Power Components #°PPC-FU-212-173, which has a let-through action of 173 A^2-sec. The fuse is shown in Figure 1-5. Another fuse of the same design is also used in the HVPS protection circuit.

1.1.6 OUTPUT CABLES

The output cables must be able to survive 130 kA lamp faults without damage or degradation, and have reasonably low resistance. Each module will use a set of 21 concentric-neutral 28 kV-rated URD Cables, one for each of 20 flashlamp pairs and one as the reflector lead (see below). Overall diameter of a cable is ≤ 1.32 - - additional details on the cable construction are listed in Table 1-4 below.

Cable lengths range from 66 ft to 180 ft. No service loops are planned for the cables, and no spare cables will be installed.

Table 1-4 Cable Specification Summary

Center Conductor	#1 AWG Solid Copper	0.289 DIA
Center Conductor Shield	Semiconducting polymer	≥ 0.016 thick
Insulation	Extruded cross-linked Polyethylene	~ 0.28 thick
Insulation Shield	Semiconducting polymer	≥ 0.030 thick
Return Conductor	≥ 23 ea #14 AWG copper wires	~ 0.064 DIA each

* In the present Bldg 391 test bed, the Main HVPS voltage and current signals are combined to calculate the module capacitance. This process is not planned for the NIF system.

Outer Jacket	Chlorosulphonated Polyethylene or PVC over linear low-density polyethylene	~ 0.08 thick
Overall Diameter		≤ 1.32

Most modules drive a pair of FUAs that are close to each other, either in the Power Amplifier or the Main Amplifier. However, six modules in each capacitor bay drive one FAU in the Power Amplifier through half of the module s cables and one in the Main Amplifier with the remaining cables. These modules are often called split modules. In these cases, one half of the cables could, in principle, be significantly shorter than the remaining cables. Such a difference in cable length would result in un-equal currents in the two sets of lamps. Some form of resistive and inductive balancing would be required.

The simplest solution is to keep the cable lengths the same for both cable sets of the split modules. Any excess cable lengths will be laid out on the mezzanine deck, assuring that all cables of any given module have the same inductance and resistance, thus allowing all the ballast inductors in each module to have the same inductance value and eliminating any need for balancing resistors.

1.1.6.1 Correction for losses in longer output cables

Modules with longer cables experience higher cable losses than modules with shorter cables. Compensation for these higher losses will be accomplished through a combination of: 1) Selection of the higher-capacitance Maxwell GA capacitors, and 2) operation at increased charge voltage. Examples are listed in the performance predictions of Section 1.2.

1.1.6.2 Reflector Lead and Resistor

A separate cable, of the same design as the twenty output cables, is connected to the set of reflectors in the FAU at one end of the cable (through buswork in the Big T), and to a 10 Ω resistor inside the MESM enclosure at the other end. This cable/resistor set provides a path back to ground at the MESM in the event of a flashlamp failure in the FAU, while limiting the current in the event of this fault. This current limiting will minimize the probability of damage to the reflector. The resistor is an HVR model J03FFA100K resistor formed of three series 3 DIA disks, and is rated for 75°kJ.

It is important to note that the reflector structures of groups of FAUs (six or eight, depending on location) are tied together, meaning that the reflector current will actually come back through several modules in the event of a fault. Circuit modeling and testing shows that the energy deposited in the resistor during such a fault will be less than 10°kJ, well below the 75 kJ resistor rating.

1.1.7 Connection to Facility Grounds

The flashlamp load for the PCS module is isolated from ground. The ground connection for the pulsed power system is at each MESM module. Each MESM is connected to Facility Ground through a 4/0 insulated lead to the nearest facility ground connection. This lead is connected to the MESM at the bottom of the Top Hat. This places the facility ground connection as close as possible to the connection point of the capacitor ground buses inside the enclosure, minimizing voltage in the event of a fault.

To minimize the risk of injury to facility personnel, a low-inductance, effectively co-axial return is used to surround the sets of output cables between the module and the laser bay. This Cable Enclosure is tied to the top of the MESM with a set of insulated leads surrounding the output cable set, and an additional set of leads connect the enclosure to the Laser Bay grounds at the location of the associated FAUs. The Cable Enclosure is also tied to the facility ground grid at a number of locations, through the structural steel of the mezzanine.

See Section 1.3 for further details.

1.1.8 PILC Module

The Pre-Ionization Lamp-Check (PILC) module will be installed adjacent to the Main Energy Storage module, and connected to it through the Top Hat. The PILC module has a capacitance of 130 F, a net series inductance of approximately 3.2 H (including the output cable and connections in the MESM Top Hat), and a net series

resistance of approximately 0.10 Ohm. When charged to 24 kV charge voltage, it will deliver a nominal 500 J per lamp. The PILC module is designed to allow operation at up to 28.5 kV charge voltage, for a nominal 700 J per lamp.

The PILC module is contained in an EMI enclosure, visible in Figure 1-1 and Figure 1-2. The enclosure is tied to facility ground through the MESM enclosure. The PILC pulsed power system is electrically floating relative to its enclosure. The PILC pulsed power ground is tied to MESM pulsed power ground through the shield of the PILC output cable at the Top Hat. The PILC output cable is double-shield RG-220 coaxial cable. The design of the PILC module is discussed in more detail in Section 1.4.

1.1.9 POWER CONDITIONING SYSTEM DRAWING TREE

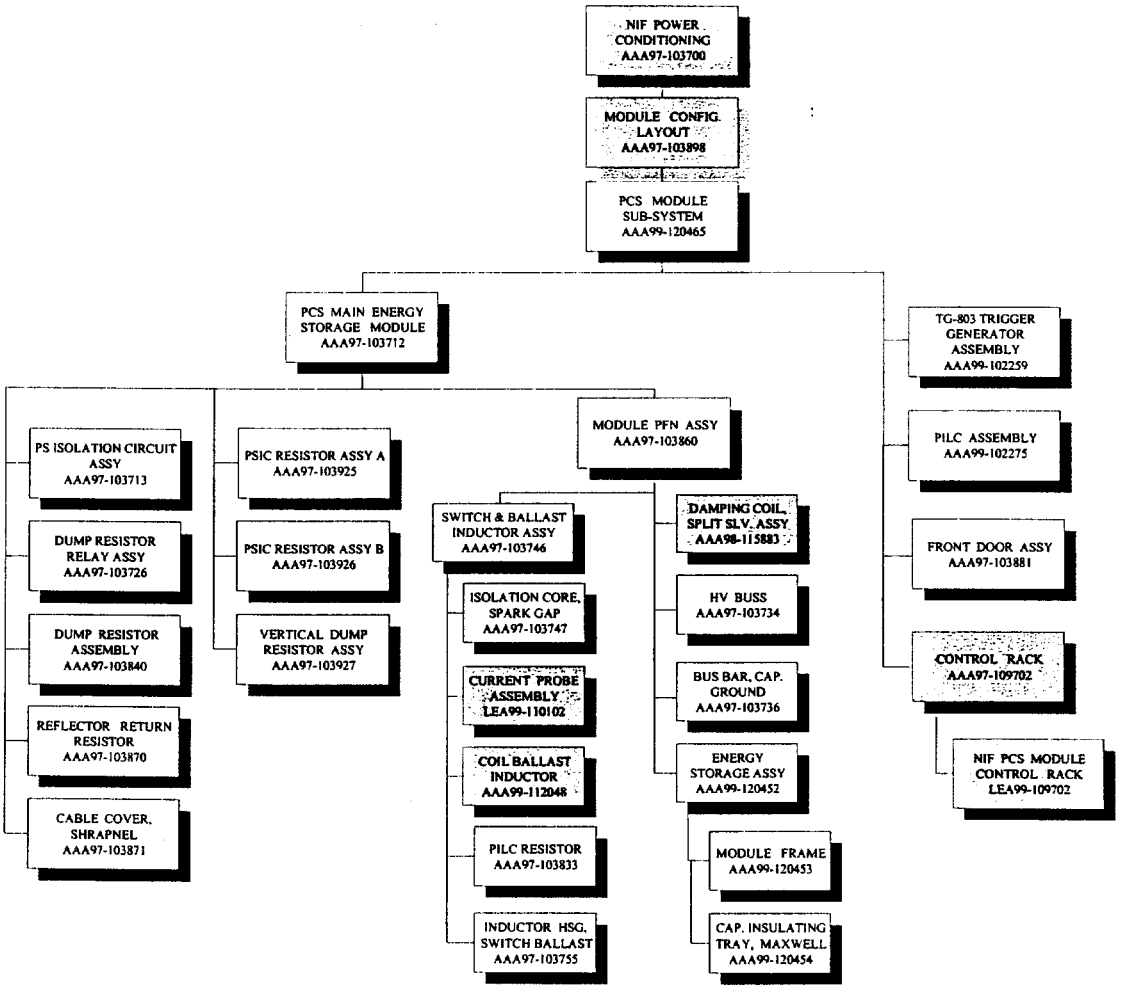


Figure 1-12 Simplified Drawing Tree

This simplified version of the PCMS drawing tree shows the basic organization of the drawings. It is not complete, and has not been updated since early 2001. All Branches of the tree are shown, but a significant number of lower-level drawings have been deleted from each branch, for simplicity of viewing.

1.2 PCS Module Performance Predictions

The figures below summarize the performance of the module described in the main text, as predicted with the PSpice circuit modeling code. Also given is the Average Gain Coefficient, predicted by using the power pulse from the PSpice run (beginning at the firing of the output switch, thus deleting the PILC pulse) as the source file for the GainCalc code supplied by LLNL. Section 1.2.1 summarizes modeling results for normal operation. Section 1.2.2 summarizes results for several key fault modes. Section 1.2.3 shows the detailed circuit schematic used for the modeling,. The circuit shown is one of the cases for normal operation. Changes for the other cases can be inferred from the summary tables and texts of the relevant sub-sections below.

1.2.1 NORMAL OPERATION

Table 1-5 summarizes the module circuit parameters used in the model. The following two tables summarize the modeling results for the baseline module with different ballast inductor/cable length configurations. Two cases are considered for each ballast inductor/cable length configuration. Table 1-6 summarizes the predicted performance of modules configured for a predicted gain coefficient of approximately 5.0°%/cm (20 capacitors and 24 kV charge, plus a 21-capacitor case for the longest cables). Table 1-7 summarizes the predicted performance of modules configured for a predicted gain coefficient of at least 5.2°%/cm (24 capacitors at 24 kV charge).

For normal shots, the load is taken to be a set of 20 series pairs of flashlamps, with a resistance versus current profile for a series pair of lamps assumed to be given by:

$$R = 78.7 / I^{1/2}$$

The data of Table 1-6 and Table 1-7 and are summarized in the graphs of Figure 1-13, Figure 1-14, and Figure 1-15, following the tables. Some observations made from the table are:

- Gain coefficient increases with energy delivered to the lamps (See Figure 1-13).
- Gain coefficient goes down as cable length goes up.
  - Gain coefficient for a fixed stored energy depends primarily on total series resistance, but also depends weakly on inductance, due to changes in pulse duration. Increasing resistive losses reduces delivered energy and thus reduces gain (see Figure 1-14). Longer pulses, due to higher inductance, have slightly lower gain, even at constant cable resistance (see Figure 1-14 and Figure 1-15).
  - That is, while gain is primarily dependent on the energy delivered to the flashlamps, it is also dependent on the pulse duration for the delivery of the energy. Increasing pulse duration beyond the 357 μs minimum evaluated here reduces the predicted gain, at constant delivered energy.
- "Tapered" ballast inductance values (using lower ballast inductance for modules with longer cables, as in the present approach) reduces the gain losses associated with longer cables (See Figure 1-15).
  - The lower-inductance ballast inductors used with the longer cables minimize the inductance (pulse duration) impact of the longer cables and also have lower internal resistance.

Table 1-5 Module Circuit Parameters

Capacitor Value (μF)	Capacitor ESR (mΩ)	Damping Inductance (μH)	Damping Resistance (mΩ)	Output Switch Resistance (mΩ)	Cable Inductance (nH/ft)	Added Inductance per Branch (μH)	Cable Resistance (μΩ/ft)	PILC Capacitance (μF)	PILC Inductance (μH)	PILC Resistance (mΩ)
300	15	9.2	26	0.885	100	3.0	300	130	1.5	110

Table 1-6 Predicted Performance Details — 20 and 21-capacitor Cases

Number of Capacitors		20	20	20	20	20	20	20	20	21
Module Capacitance	mF	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.3
Charge Voltage	kV	24	24	24	24	24	24	24	24	24
Ballast Inductance	H	16.0	16.0	14.4	14.4	11.3	11.3	9.1	9.1	9.1
Ballast Ind. Resistance	mΩ	6.0	6.0	5.5	5.5	4.5	4.5	3.8	3.8	3.8
Internal Bus Inductance (Eff.)	H	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	
Internal Bus Resistance (Eff.)	mΩ	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	
Switch Bus Inductance	H	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375
Cable Length	ft	66.0	82.9	86.6	114.9	118.8	146.4	151.0	180.0	180.0
Cable Resistance	mΩ	19.8	24.9	26.0	34.5	35.6	43.9	45.3	54.0	54.0
Cable Inductance	H	6.6	8.3	8.7	11.5	11.9	14.6	15.1	18.0	18.0
Eff. Inductance per branch	H	48.2	49.9	48.6	51.5	48.8	51.5	49.8	52.7	
Eff. Resistance per branch	mΩ	54.7	59.8	60.4	68.9	69.0	77.3	78.0	86.7	
Source Impedance per branch	mΩ	0.40	0.41	0.40	0.41	0.40	0.41	0.41	0.42	
PILC Current (1st peak)	kA	98.5				97.7			96.1	
PILC Reverse Current	kA	76.6				77.2			79.1	
PILC Charge Transfer	Coul	10				10			10.2	
PILC Capacitor Reverse V	kV	-3.6				-3.5			-3.9	
Peak Power, one Lamp Pair	MW	328				318			298	
10% Power Pulse Width	s	357				360			376	
Energy per Lamp (Less PILC)	kJ	37.4				36.1			35.3	
Lamp/Ballast Peak Current	kA	26.0				25.5			24.4	
Time to Peak Current	s	159				155			162	
ST-300 Peak Current	kA	519				508			487	
ST-300 Charge Transfer	Coul	137				136			136	
ST-300 Action	MJ/Ω	53.6				51.9			49.5	
Predicted Peak Gain Coeff.	%/cm	5.116	5.094	5.096	5.059	5.067	5.031	5.034	4.998	5.068

Table 1-7 Predicted Performance Details — 24-capacitor Case

Number of Capacitors		24	24	24	24	24	24	24	24
Module Capacitance	mF	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Charge Voltage	kV	24	24	24	24	24	24	24	24
Ballast Inductance	H	16.0	16.0	14.4	14.4	11.3	11.3	9.1	9.1
Ballast Ind. Resistance	mΩ	6.0	6.0	5.5	5.5	4.5	4.5	3.8	3.8
Internal Bus Inductance (Eff.)	H	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Internal Bus Resistance (Eff.)	mΩ	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Switch Bus Inductance	H	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375
Cable Length	ft	66.0	82.9	86.6	114.9	118.8	146.4	151.0	180.0
Cable Resistance	mΩ	19.8	24.9	26.0	34.5	35.6	43.9	45.3	54.0
Cable Inductance	H	6.6	8.3	8.7	11.5	11.9	14.6	15.1	18.0
Eff. Inductance per branch	H	47.4	49.1	47.8	50.7	47.9	50.7	49.0	51.9
Eff. Resistance per branch	mΩ	54.4	59.5	60.1	68.6	68.8	77.0	77.7	86.4
Source Impedance per branch	mΩ	0.36	0.37	0.36	0.38	0.36	0.38	0.37	0.38
PILC Current (1st peak)	kA	98.5				97.7			96.1
PILC Reverse Current	kA	80.4				80.1			82.6
PILC Charge Transfer	Coul	10.1				10			10.3
PILC Capacitor Reverse V	kV	-3.6				-3.5			-3.9
Peak Power, one Lamp Pair	MW	367				355			332
10% Power Pulse Width	s	386				392			410
Energy per Lamp (Less PILC)	kJ	44.9				43.5			42.4
Lamp/Ballast Peak Current	kA	28.1				27.5			26.3
Time to Peak Current	s	172				166			176
ST-300 Peak Current	kA	559				54.7			523
ST-300 Charge Transfer	Coul	160				159			158.4
ST-300 Action	MJ/Ω	67.0				64.7			61.6
Predicted Peak Gain Coeff.	%/cm	5.363	5.341	5.343	5.306	5.314	5.280	5.283	5.247

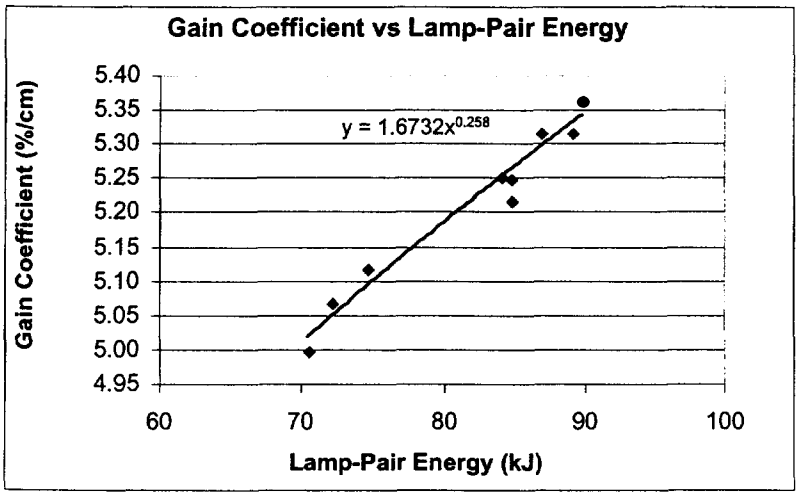


Figure 1-13 Gain coefficient vs energy delivered to a pair of lamps. Variations in delivered energy were produced by variations in the losses caused be cable resistance

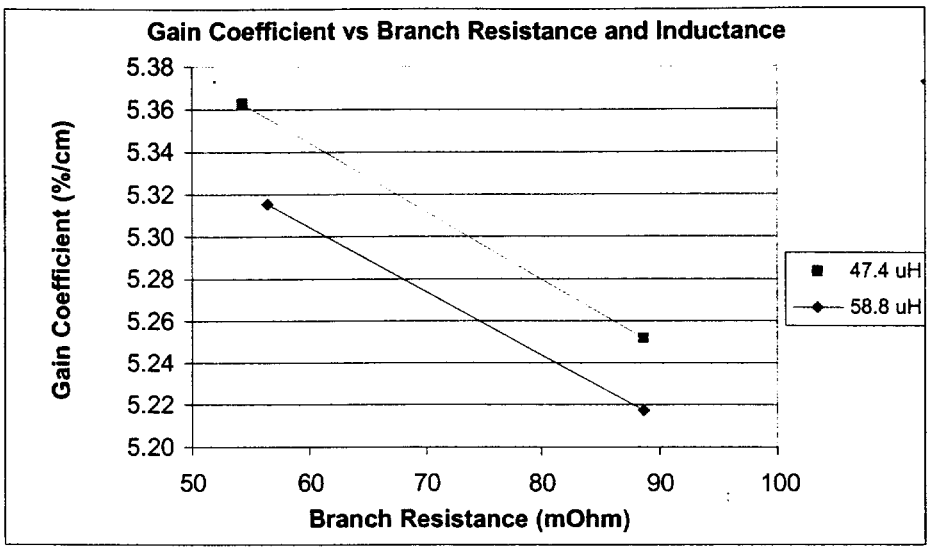


Figure 1-14 Gain coefficient vs total resistance per branch (including resistance in the PCMS module and the cables, but not the flashlamp resistance), for two different cases of total branch series inductance.

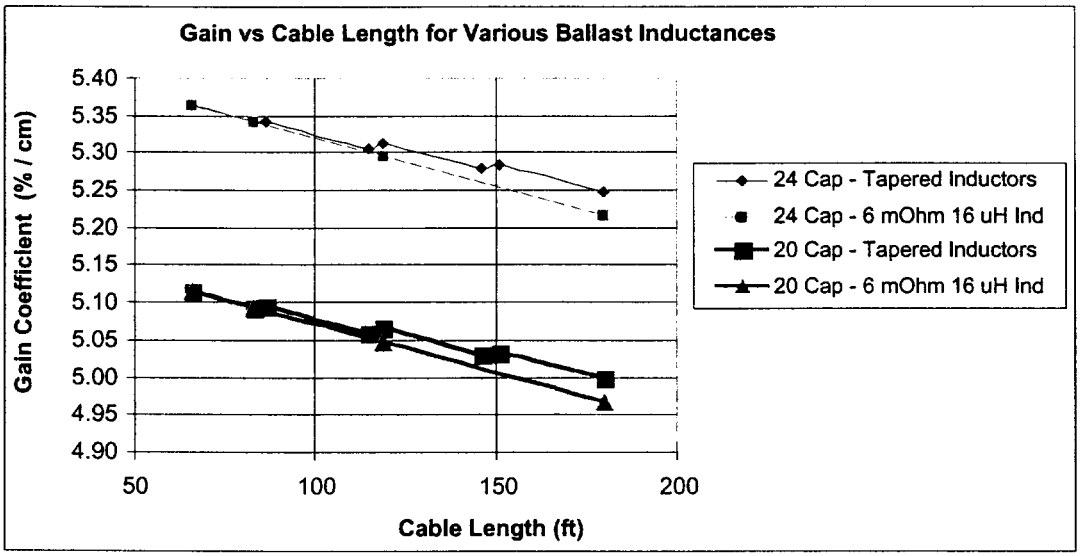


Figure 1-15 Gain coefficient vs cable length, for 20 and 24 capacitor cases, with a fixed 16°µH ballast inductance (independent of cable length) and for the planned tapered ballast inductance, with lower inductances compensating for longer cables.

1.2.1.1 Predicted Waveforms

Predicted waveforms for one of the cases (20 capacitors and mid-range cable length) are shown below. Measured waveforms for the prototype module tested in Bldg. 391, are shown in Section 1.2.1.2. The detailed circuit schematic used in the circuit modeling is shown in Section 1.2.3. The circuit model was constructed to include the distributed nature of the capacitor assembly and output cables, as well as the PILC module.

20-capacitor, 24 kV charge voltage case
with 118.8 ft cables and 11.3 μH ballast inductors.

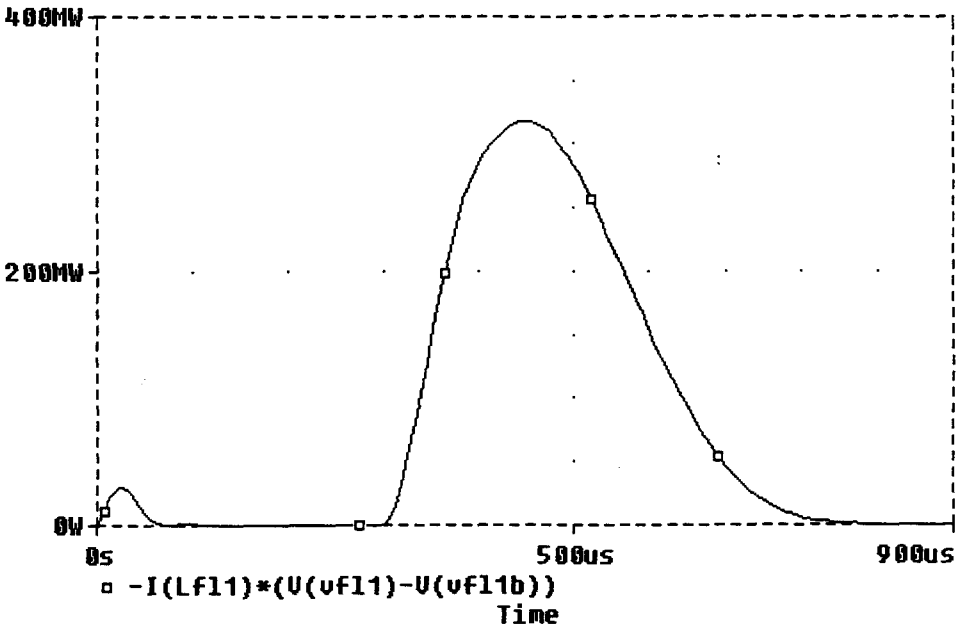


Figure 1-16 Power pulse to a single flashlamp pair.
Peak value is 318 MW. Pulse width at the 10% of peak point is 360 μs.

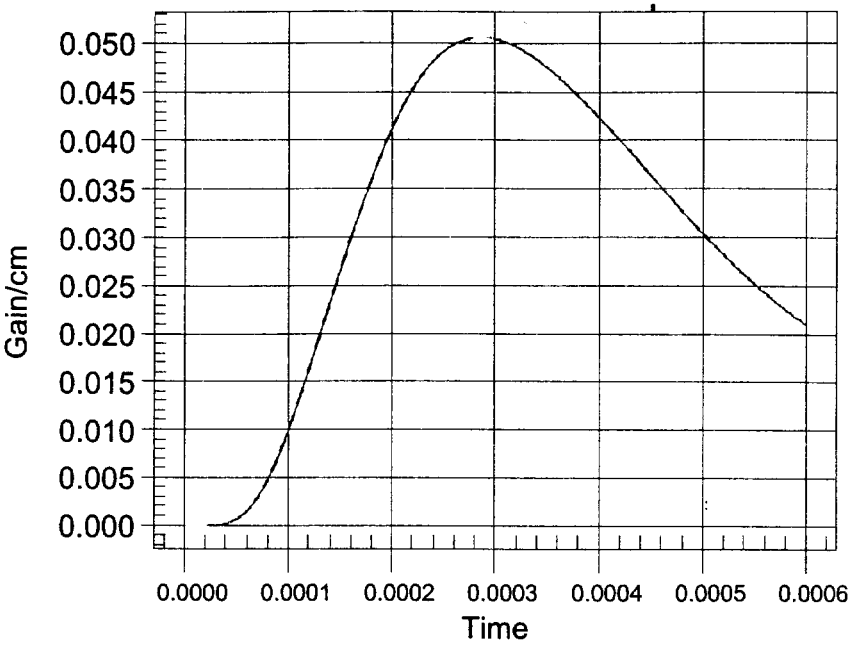


Figure 1-17 Average Gain Coefficient, as predicted by the LLNL GainCalc code, based on the predicted power pulse given above. The time scale here begins with the firing of the main output switch (at t = 200 μs in the remaining waveforms). Peak value is 5.067°%/cm at 286 μs after switchout.

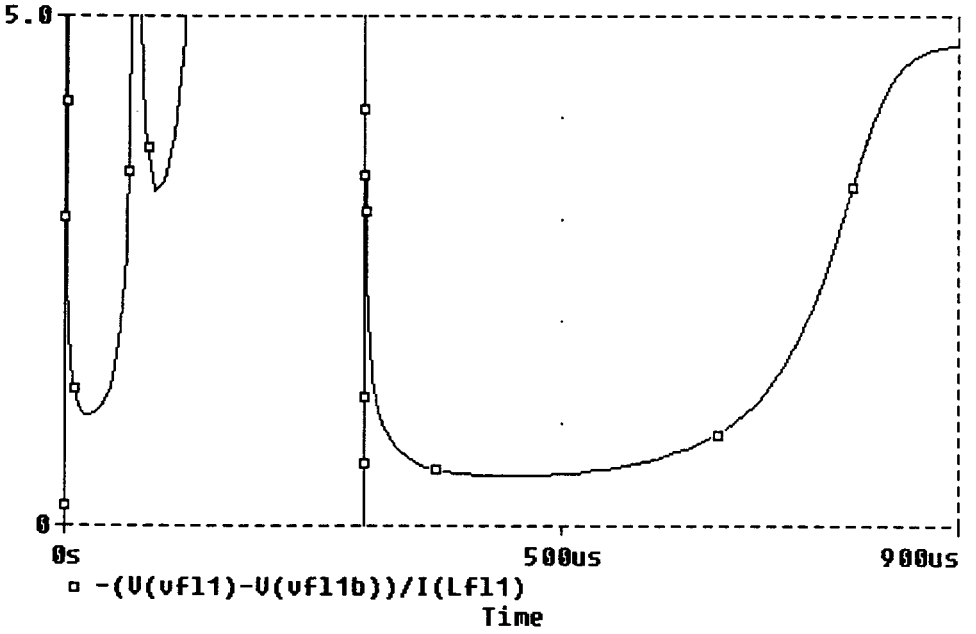


Figure 1-18 Resistance profile of a flashlamp pair. Minimum value is 488 mΩ.

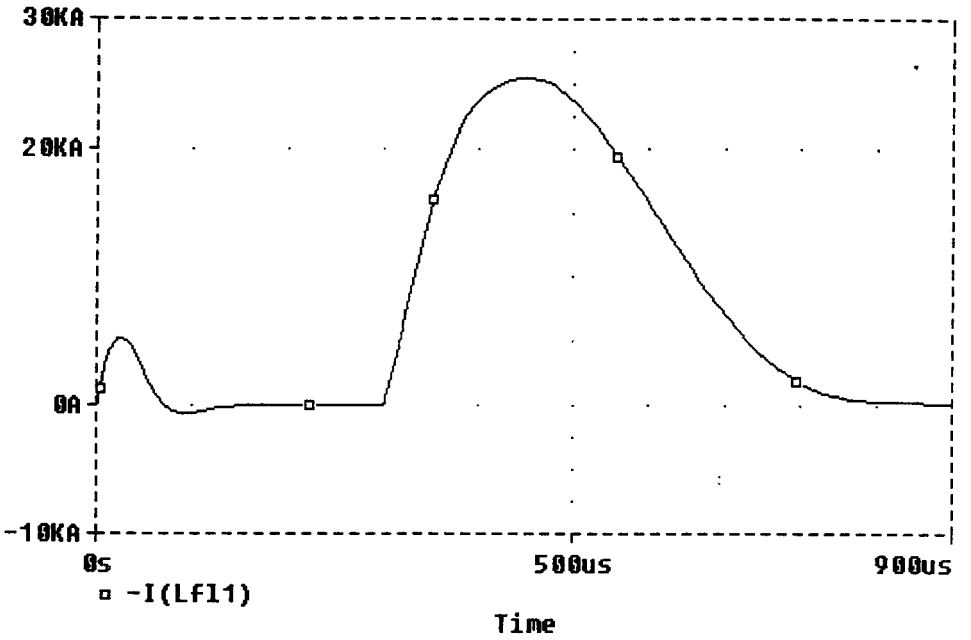


Figure 1-19 Current in a single flashlamp (also the current in a single ballast inductor) Peak value is 25.5 kA.

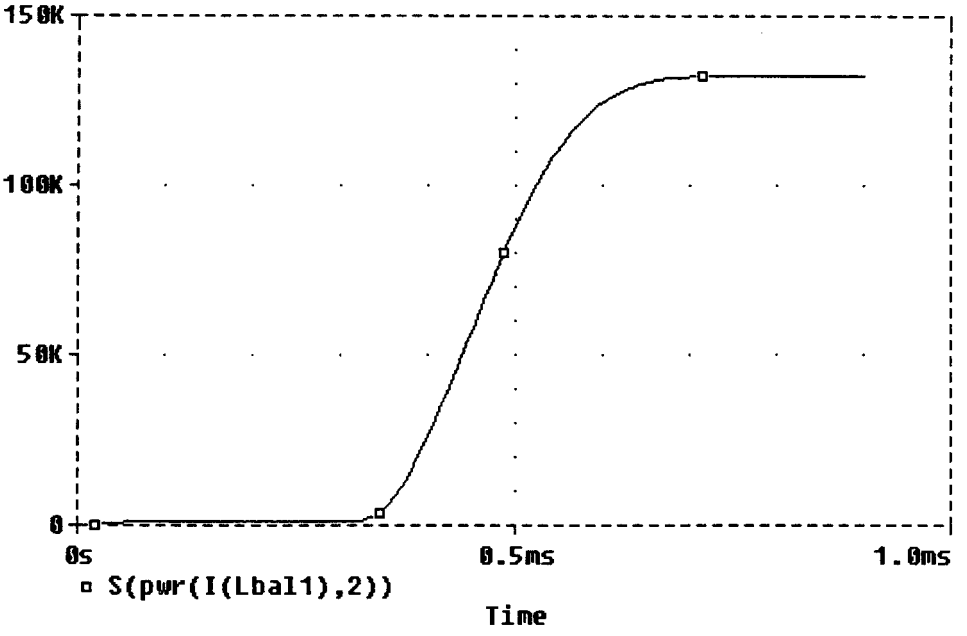


Figure 1-20 Action in a ballast inductor. Peak value is 1.3 x 10^5 A^2-sec

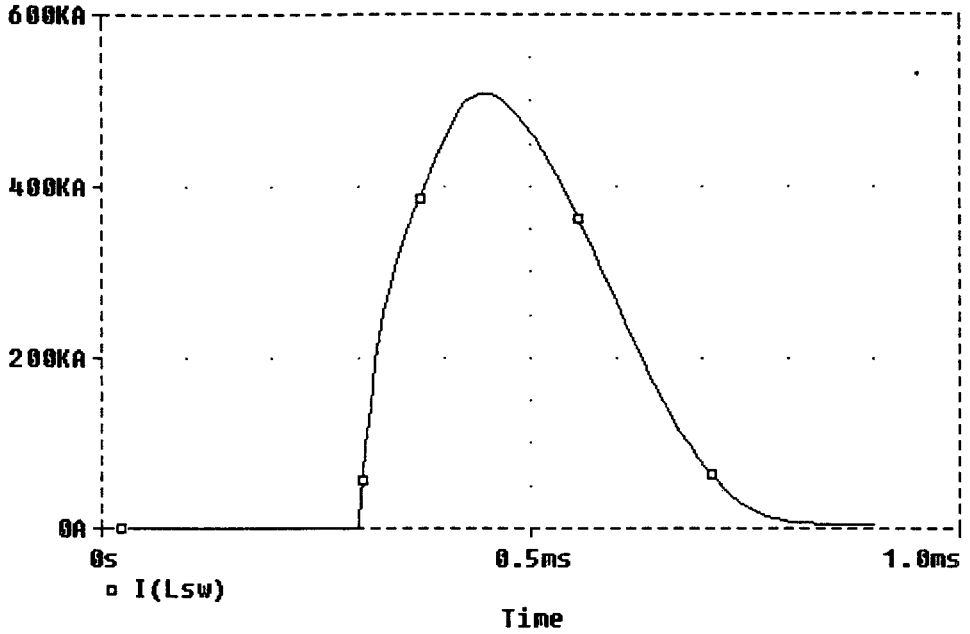


Figure 1-21 Current in the output switch. Peak value is 508 kA.

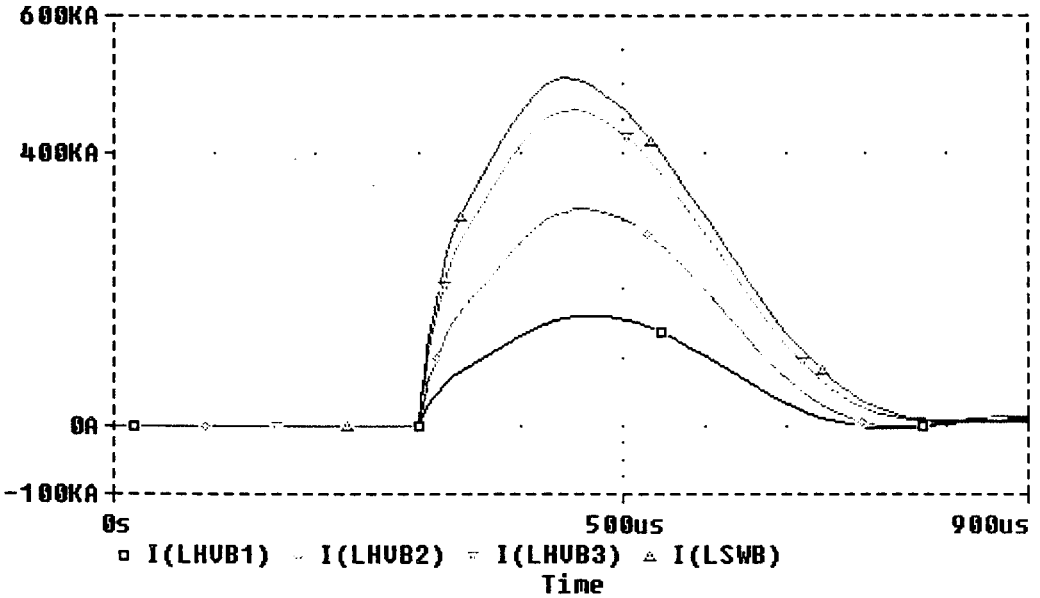


Figure 1-22 Currents at four locations in the hot bus.

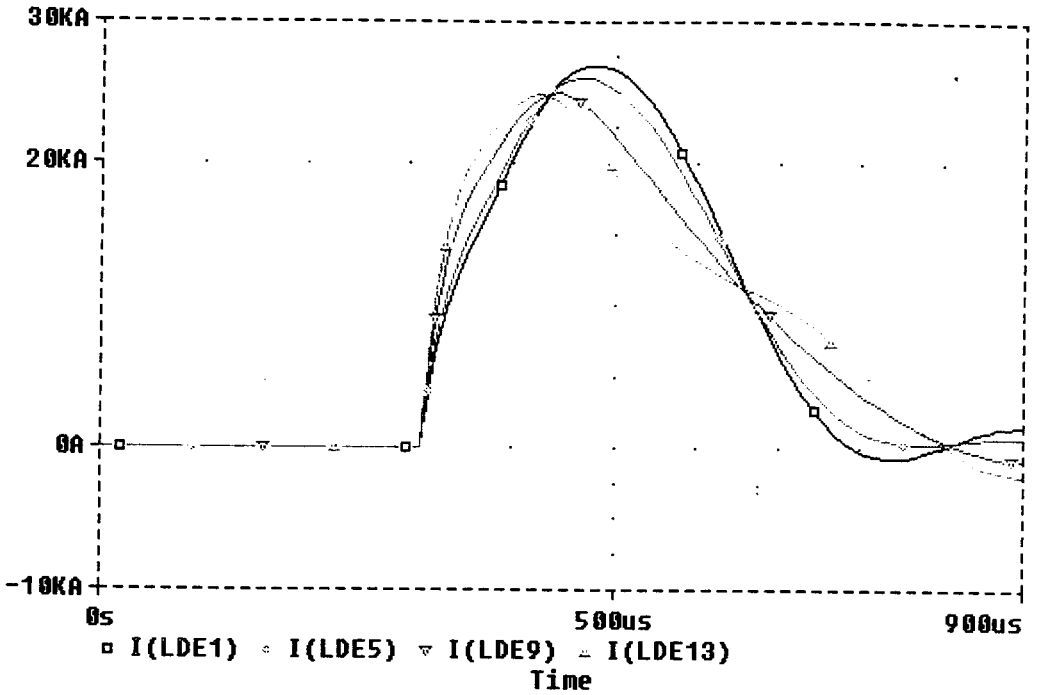


Figure 1-23 Damping element currents.
Currents in different units vary somewhat, as a function of position in the module. This variation is caused primarily by the inductance of the High Voltage Bus, plus a small contribution from the ground buses, which have less equivalent inductance, as there are several in parallel.

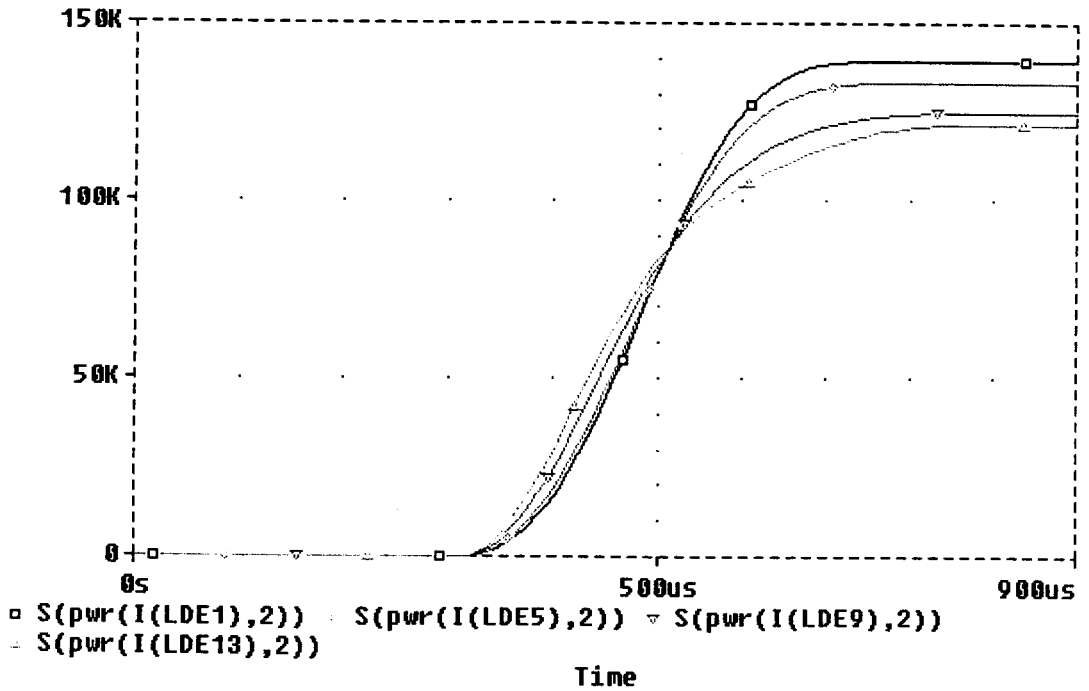


Figure 1-24 Damping element actions

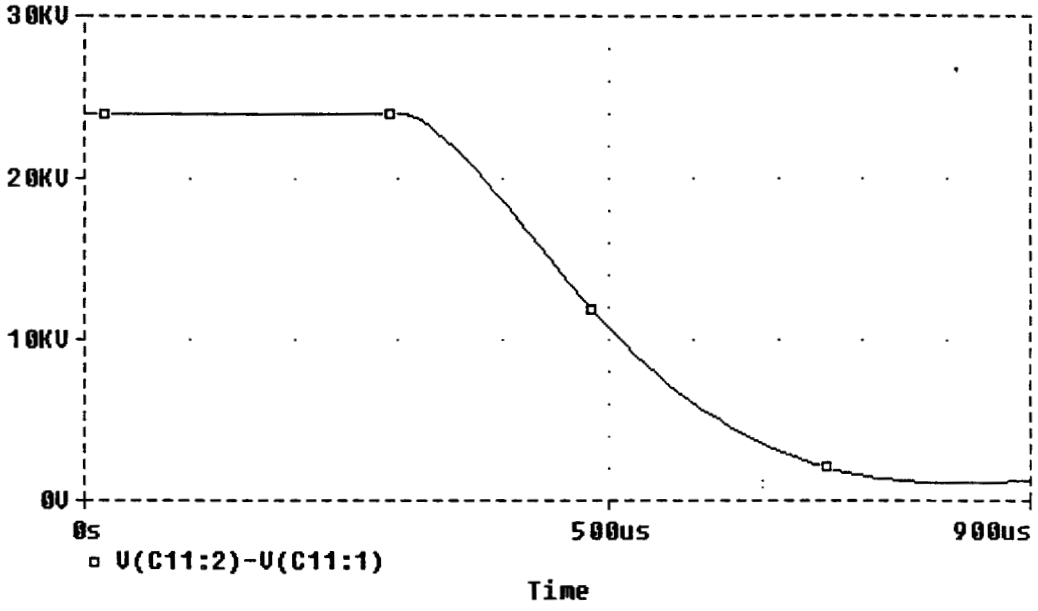


Figure 1-25 Capacitor voltage.

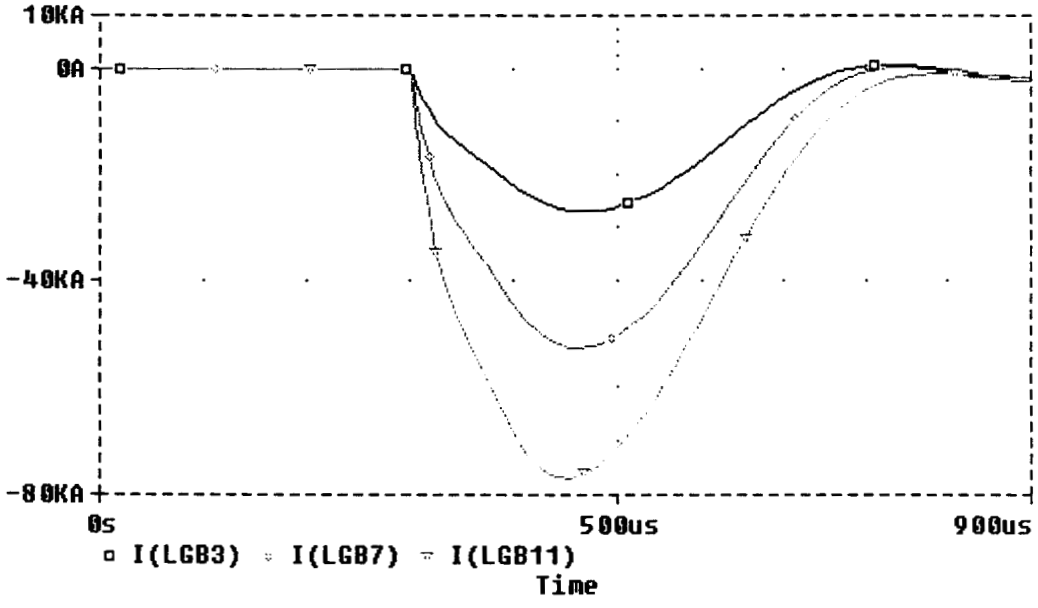


Figure 1-26 Currents in ground bus straps at three locations; bottom, middle, and top. The model uses one ground strap per capacitor column; six straps, total.

1.2.1.2 Measured Waveforms

Measured waveforms for the prototype module tested in Bldg. 391, are shown below; 1) a shorted shot (shorted at the top of the Top Hat) and 2) a normal shot in to the flashlamps. The PSpice circuit model was refined to assure an accurate match to the shorted-shot case. Modeled waveforms depart somewhat from actual measurements for the flashlamp case, due to the complex behavior of the flashlamps.

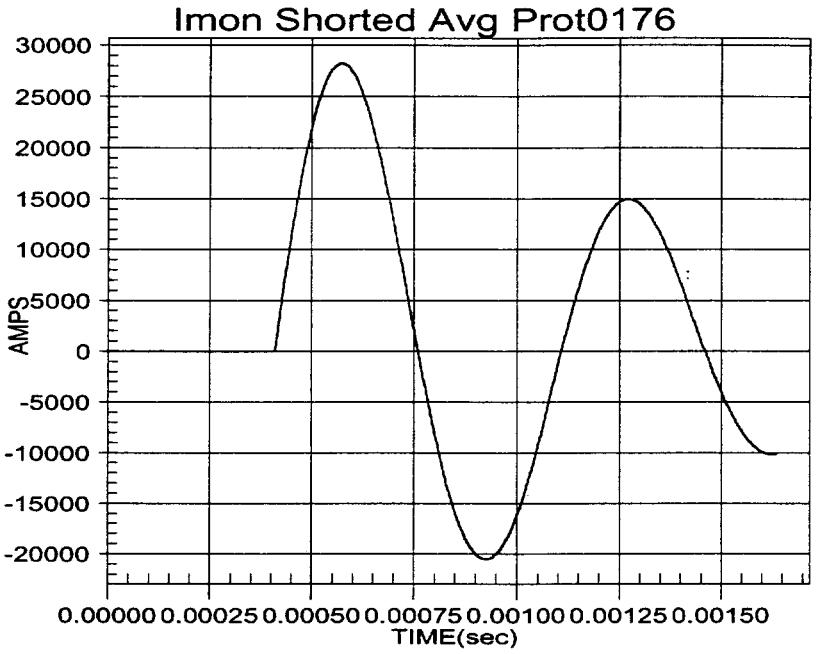


Figure 1-27 Measured Shorted-Shot Current per Ballast Inductor; averaged over the 20 outputs: Shorted at the Top Hat; 24 capacitors, 10 kV charge, no PILC

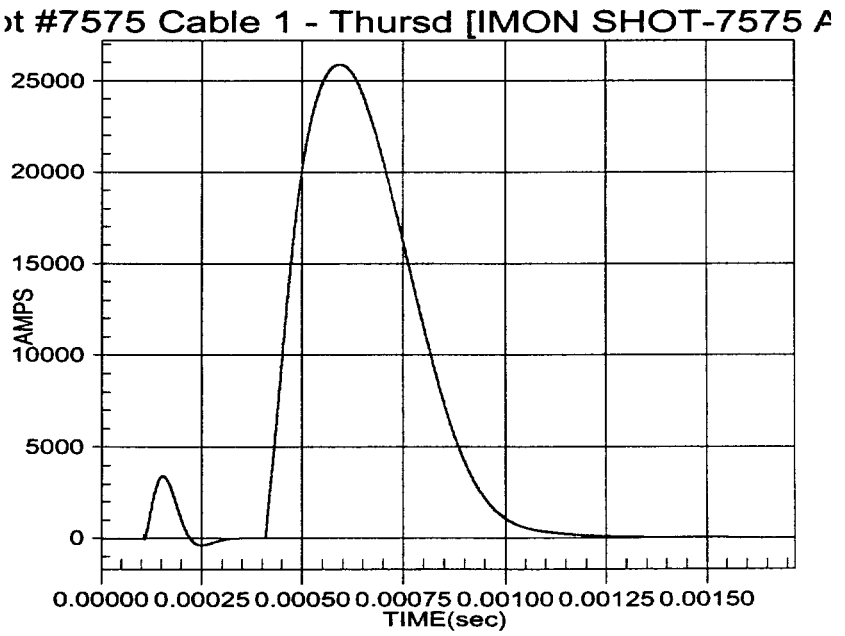


Figure 1-28 Measured Current per Ballast Inductor; averaged over the 20 outputs: Normal shot into flash lamps; 24 capacitors, 180 ft cables Main charge voltage: 23.8 kV PILC charge voltage: 28.5 kV

1.2.2 FAULT MODELING

Fault cases considered are:

- Big T Fault: A low-resistance (1 mΩ) breakdown from the hot conductor of one cable to the return conductor of the same cable through the circuits within the Big T. The peak current in this fault mode is limited by the combination of the ballast inductance and the cable inductance. Lamp energies in the remaining circuits are reduced, due to the diversion of current to the fault.
- FAU Ground Fault: A low-resistance (1 mΩ) breakdown from the hot center conductor of one cable to facility ground and the cable tray ground at the location of the FAU, without making an electrical connection to the return of the coaxial output cable. Again, lamp energies in the remaining circuits are reduced, due to the diversion of current to the fault. Ground current implications of this fault are discussed further in Section 1.3.
- PILC Fault: A low-resistance (1 mΩ) breakdown from the hot terminal to ground inside the PILC enclosure. Peak current is limited by the combination of the inductance of the PILC cable and the 85 mΩ PILC output resistor, plus the fact that the flashlamps will still fire normally, absorbing most of the PCMS energy. If few or none of the flashlamps were to fire, this would become a very serious fault.
- Reflector Fault: This represents a flashlamp failure, and the resultant plasma connection from hot to reflector for one of the twenty output branches/cables of the module. The fault current returns to the PCMS through the reflector cable and the reflector resistor. The fault current is limited primarily by the reflector resistor. Since the remaining lamps still function normally, very little energy is deposited in the reflector resistor. In the absence of this resistor, reflector fault currents are much higher, and the blast shield between the lamps and the laser glass would fail.
- Capacitor Fault: Internal failure of a capacitor in the MESM. Most of the energy in the module is dissipated in the damping element of the failed capacitor.
- Bus Fault (Lower and Upper): A breakdown from the high-voltage bus of the MESM to ground at the bottom and top of the bus, respectively.

Table 1-8 lists the circuit parameters used in the fault runs. Table 1-9 summarizes the results of the fault simulations.

Some observations made from the summary of Table 1-9 are:

- Capacitor voltage reversals are less than 50% for all cases modeled.
- Damping Element current is high only for the case of capacitor failure, and then only for the damping element attached to the failed capacitor.
  - Æ **Note: The damping element is to be replaced after a capacitor failure.**
- The reflector cable resistor limits the current in the event of a lamp failure to about 6.1 kA; low enough to protect the blast shield.
  - Æ Note: Voltage at the reflector is nearly the full capacitor charge voltage in this fault, but still well below to 30 kV insulation/isolation of the FAU.
- The PILC output resistor (in the Top Hat) sees high current and action in the event of a PILC ground fault or a capacitor failure in the PILC module.
  - Æ **The resistor is designed to handle this energy, but should be replaced after such a fault.**
- In the event of a fault at the Big T or the FAU, the ballast inductors limit fault current to reasonable values (See Figure 1-29).
  - Æ **Note that the ballast inductor is to be replaced after a Big T or FAU fault.**
  - Æ Additional fault scaling information is included in Figure 1-29, showing the effect of cable length and ballast inductor values on Big T fault current.
- The highest fault currents are created by bus faults in the MESM.
  - Æ In general, the damping element currents are still low, so the damping element generally will not require replacement after a bus fault, unless some other event causes damage to one or more of the damping elements.

Table 1-8 Fault Run Model Parameters

Number of Capacitors	24
Module Capacitance	7.2 mF
Charge Voltage	24 kV
Ballast Inductance	16.0 H
Ballast Ind. Resistance	6.0 mΩ
Eff. Internal Bus Inductance	0.25 H
Eff. Internal Bus Resistance	0.09 mΩ
Switch Bus Inductance	0.375 H
Added Inductance	0.15 H
Cable Length	66.0 ft
Cable Resistance	19.8 mΩ
Cable Inductance	6.6 H
Eff. Reflector Resistance	3 Ω
Eff. Inductance per branch	47.4 H
Eff. Resistance per branch	54.4 mΩ
Source Impedance per branch	0.36 mΩ

Table 1-9 Fault Run Results

		Normal Baseline	Big T Fault	FAU Gnd Fault	PILC Fault	Reflector Fault	Capacitor Fault	Bus Fault Upper	Bus Fault Lower
Peak Power, one Lamp Pair	MW	367	341	343	314	378			
10% Power Pulse Width	s	386	347	348	354	390			
Energy to 1 Lamp Pair (Less PILC)	kJ	89.9	75.6	76.6	69.2	92.7			
Ballast Peak Current (Fault / Normal)*	kA	28.1	135 / 26.8	129 / 26.7	25.3	6.1 / 28.6			
Time to Peak Current (Fault / Normal)*	s	172	360 / 160	358 / 168	150	70 / 169			
Ballast Inductor Energy (Fault / Normal)*	kJ	0.8	55.8 / 0.8	50.7 / 0.9	0.8	0.04 / 1.0			
ST-300 Peak Current	kA	559	600	598	629	545			
ST-300 Charge Transfer	Coul	160	250	226	167	166			
ST-300 Action	MJ/Ω	67.0	83	82	80.0	65			
PILC Forward Current	kA	98.5							
PILC Reverse Current	kA	80.4			140				
PILC Switch Action	MJ/Ω	0.52			3.6				
PILC Switch Charge Transfer	Coul	10.1			37				
PILC Capacitor Reverse V	kV	-3.6			-17				
PILC Cap Resistor Energy	kJ	3.9			123				
PILC Output Resistor Energy	kJ	44			305				
Reflector Voltage	kV					18.4			
Relfector Resistor Energy	kJ					21			
Reflector Action	kJ/Ω					7.1			
Reflector Resistor Current	kA					6.1			
Main Cap Reverse Voltage	kV		-4.1	-3.2			-2.6	-7.4	-8.6
Arc Peak Current	kA							982	856
Pulsed Power Return Voltage Bounce	kV						-105	-1.4	6.9
Damping Element Current	kA	28.1					320	43	56
Damping Element Energy	kJ	3.7					1,200	10	13.4

Entries for lamp power and energy are for the branches unaffected by the fault

* Values in these three rows are given for the branch/cable experiencing the fault ("Fault") and for each of the remaining branches ("Normal").

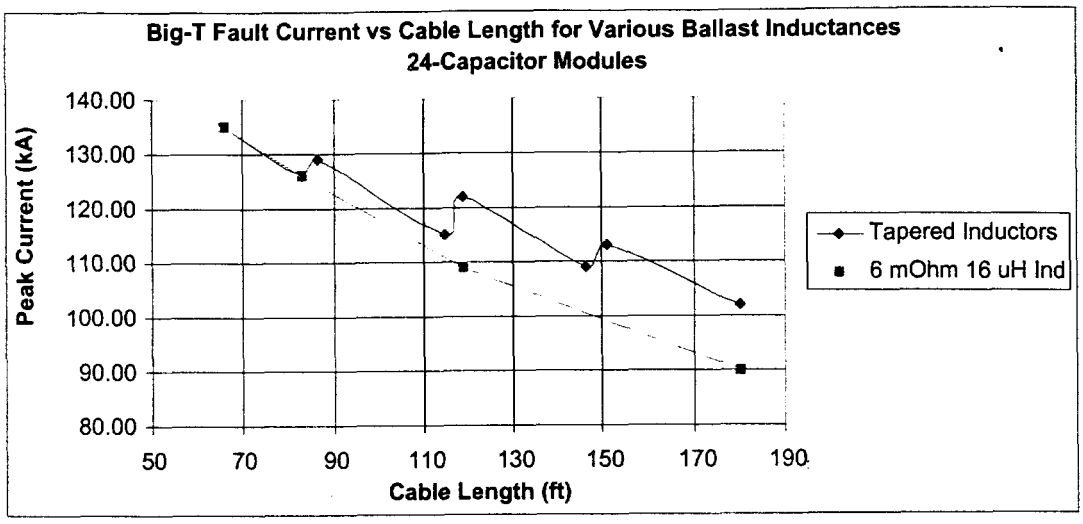
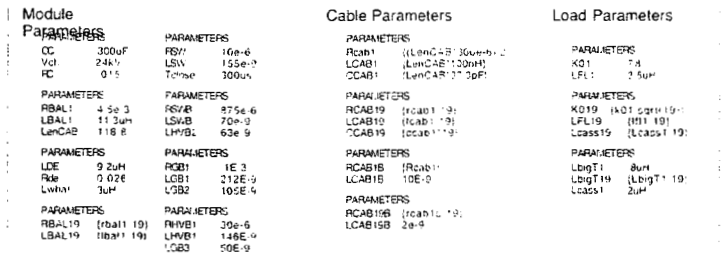


Figure 1-29 Big-T fault currents vs cable length, for a fixed 16 μH ballast inductance and for the planned tapered ballast inductances

1.2.3 CIRCUIT SCHEMATIC FROM PSPICE MODEL

1.2.3.1 Main Capacitor Bank Module



20 Capacitors, 15 mOhm ESR each
First-Article Internal Buswork
9uH 26 mOhm damping elements
Baseline ballasts
Underground Utility Cables
Flashlamp Load
Fast 130uF, 3.23uH, 0.1 Ohm PILC
Load Floating
Module grounded at Top Hat

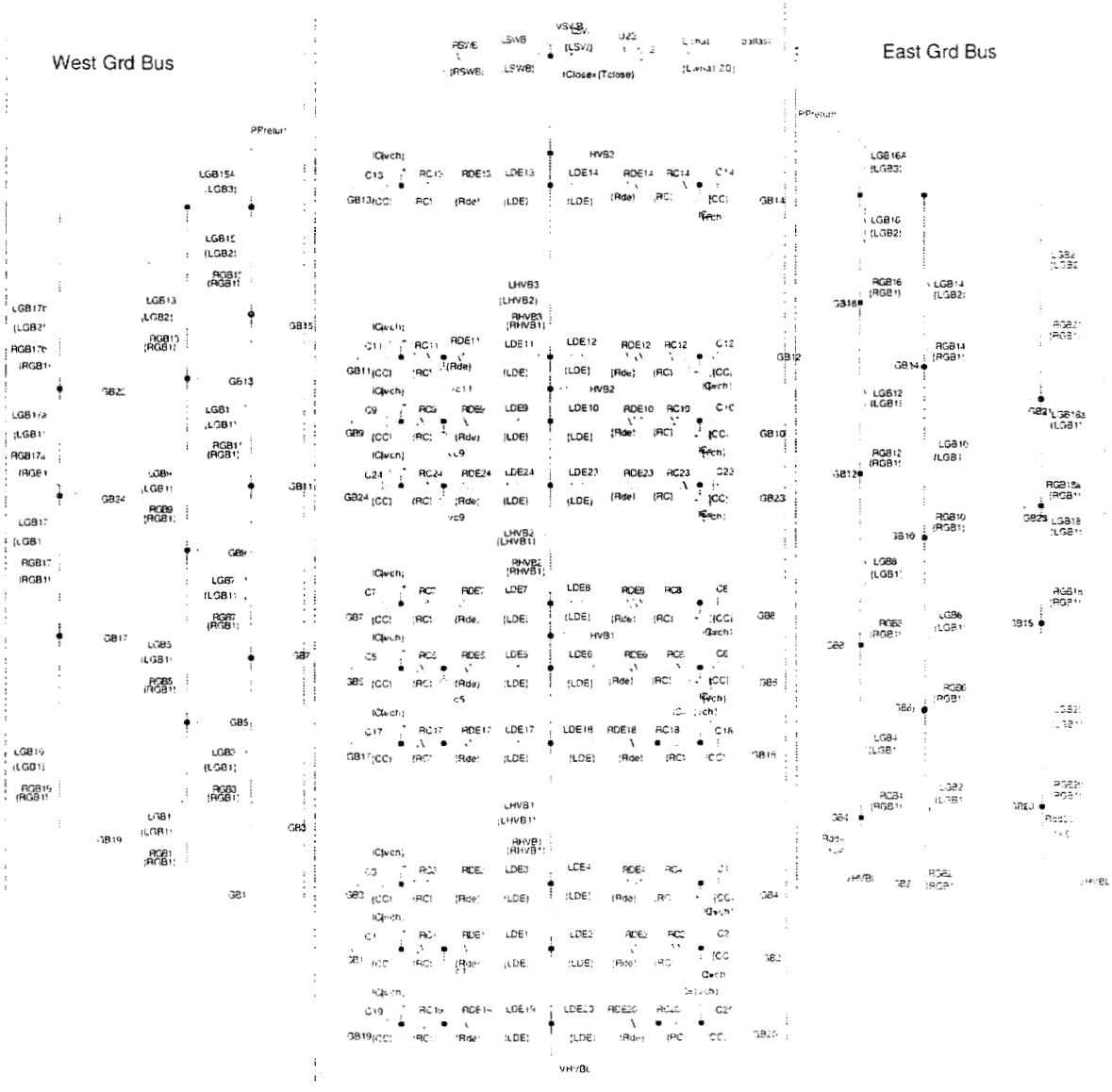


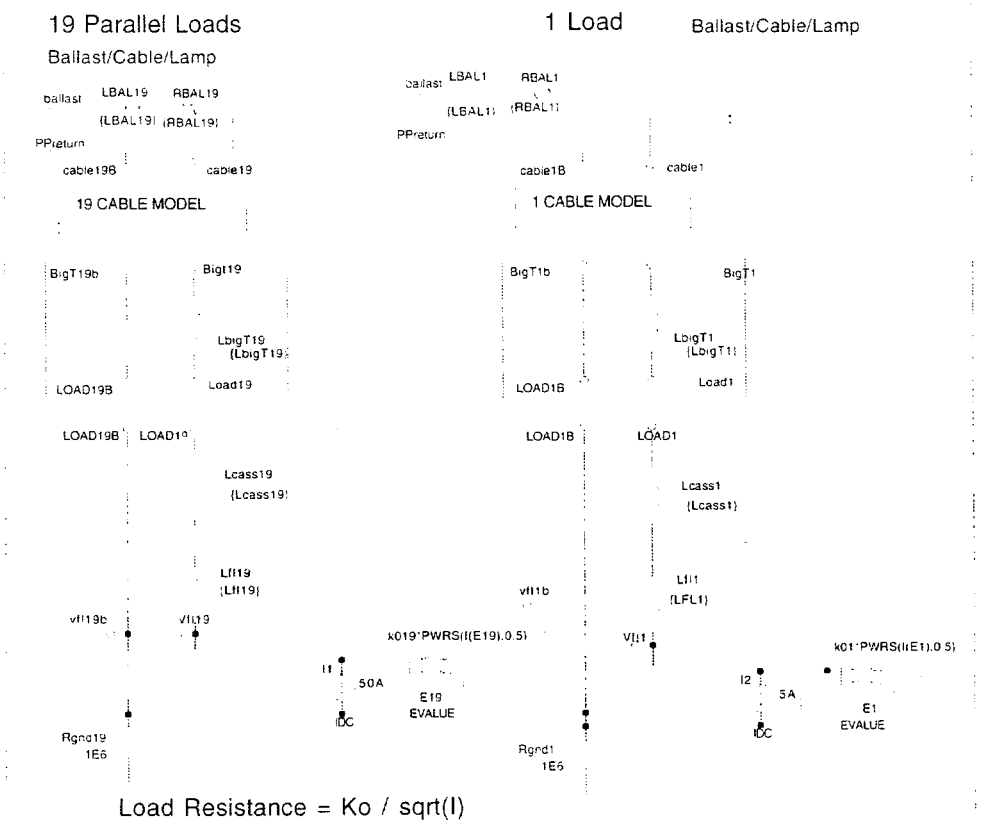
Figure 1-30 Circuit model of main capacitor bank section

1.2.3.2 Loads and Module Ground Cable

Trigger Generator and PILC simplified, and grounded only at the Top Hat

Coupled capacitances between output cables and cable tray

Simple, grounded Cable Tray



Grounding Cables

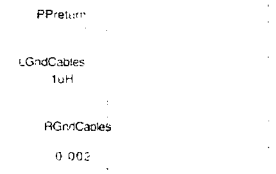


Figure 1-31 Circuit model of output section and loads

1.2.3.3 Pre-Ionization Pulser, Output Cables, and Cable Tray

Figure 1-32 Circuit model of PILC, output cables, and cable tray

1.3 Power Conditioning System Grounding

1.3.1 Overview

This section summarizes a set of analyses performed to evaluate approaches to provide a robust grounding system in the NIF facility. This grounding system must minimize touch potentials associated with operation of the Power Conditioning System (PCS), even in the event of severe faults, and assure that the energy delivered to a person through contact with grounded structures is very low.

As is described below, we conclude that the most effective approach is some form of enclosure around the PCS output cables. Some form of covered cable tray surrounding several bundles of cables, with a metal floor and cover, was selected as the most cost-effective approach meeting all safety requirements.

1.3.2 Grounding Objectives/Policy

At a NIF Off-Site meeting in February 1998, Doug Larson proposed the following NIF grounding policy:[1]

Proposed NIF Grounding Policy

1. **Design to keep touch potentials during ground faults less than 500 V.**
   - This keeps the voltage in a range where skin resistance seems likely to remain in the circuit.
2. **Design to keep energy delivered to a 90 Ω load (a person where skin resistance is ignored) less than 3 Joules**
   - This is $^1/_3$ — _ of the published energy standard
3. **Administratively prohibit the routing of conductors into or out of the capacitor bay or amplifier region of the Laser Bay without a dielectric break**
   - This minimizes the possibility of propagating a touch potential outside of the Laser and Capacitor Bays

1.3.3 Candidate Grounding Approaches

In the same briefing, he noted four basic approaches to meeting this safety objective:

1. Tightly bond the PCS modules to the grounded laser support structures using a conductive enclosure around the cables.
2. Tightly bond the PCS modules to facility ground, using an improved ground mat in the slab.
3. Fully insulate the equipment in the Laser Bay, so that a ground fault in the laser bay need not be considered.
4. Float the pulsed power system from facility ground, using a high-value resistor or inductor to provide the safety ground.

Approaches 3 and 4 were rejected as being impossible to implement in such a way that their viability is assured.

Approach 2 was rejected due to the cost of modifying the building design to incorporate a fine ground grid in the slab. Bob Anderson and Bill Gagnon showed that the planned grounding grid, with 4/0 wires on a grid 12.5 ft on a side, would result in touch potentials as high as 3 kV between the PCS module and a fault in the Laser Bay, and still 800 V — 1,600 V at significant distances away from this line. They concluded that a grid spacing of 6 would reduce the peak touch potential to ~ 200 V, likely an acceptable value.[2]

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[1] NIF Capacitor Bank/Amplifier Grounding Strategy, Part II, D. Larson, February 19, 1999 PCS 0140

[2] Executive Summary —Flashlamp Fault Current Estimates for Different System Ground Configurations, R. Anderson, February, 1998 PCS 00018

Mark Rhodes performed a separate analysis of this approach, including magnetic-field modeling and experimental measurements, and reached a similar conclusion, with touch potentials falling below 500 V for wide, continuous ground planes.[3]

With the building construction well under way, however, the viability of a fine-grid ground plane was a moot point.

The following analysis thus focuses on Approach 1; some form of close-coupled grounding structure around the cables from the PCS to the flashlamp assembly, bonded to the PCS modules at one end and to the laser support structures (which must be bonded to the facility ground grid), at the other end.

1.3.4 Summary of Results

A detailed PSpice model was developed to include the details of the PCS module, the cables to the flashlamps, the dynamic performance of the flashlamps, and the distributed ground-return paths back to the PCS module from the laser bay, including a rough representation of the coupling capacitances, and stray inductances and resistances. Several different versions of cable trays and enclosures were considered.

The touch potentials and the energy delivered to a person through contact with the grounding structures are predicted to be significantly below the guidelines above for normal shots, for any of the considered grounding approaches, as no significant current couples into the building ground grid. However, ground faults, particularly ground faults in the laser bay, result in much higher voltages and person energies than for normal operation. As a result, the NIF design was modified to include a cable enclosure system to carry fault currents back to the PCS modules, significantly reducing touch potentials.

It is important to note that the cable enclosure system plays a significant role in system grounding only in the event of a fault from the hot conductor of a PCS output cable to a grounded structure in the Laser Bay, and then only if the fault occurs in such a way that very little current can flow back on the return conductor of the affected cable. This is an unlikely fault, but it could occur, for example, if an output cable was not plugged into the Big T, but left with its output terminal near a grounded structure in or near the FAU.

A set of calculations was performed using a 2-D Maxwell solver, to establish the self-inductances and coupling coefficients for a number of geometries for cable trays and cable enclosures. These results, along with measurements at LLNL and at Maxwell Physics International (now Titan Pulse Sciences), confirmed that an enclosure around the cables results in the minimum possible touch potential. The outer portion of enclosed transmission line, such as a coaxial cable or cables inside a conduit, effectively has no inductance, because it eliminates flux outside the enclosure. As a result, only the resistive component of the voltage drop along the enclosure remains.

The PSpice circuit model of the system was used to estimate voltages, currents, and person energies in the event of a fault from the hot terminal of an output cable to the cable tray/enclosure near the Laser bay. For this fault case, we assumed that the fault current reaches the cable tray/enclosure without connecting to the return side of the coaxial cable. (If the fault ties to the cable return conductor, little or no current flows in the facility ground, and touch potentials and person energies would be very low.) Four cases were modeled; a simple ground plane under the cables (assumed to be approximately 40 wide), two different cable troughs, and a full cable enclosure.

A highly schematic version of the circuit model, shown in Figure 1-33, summarizes the parameters used in the detailed model. The model assumes that 19 of the loads are driven more or less normally, with a breakdown from the remaining cable to a grounded structure near the FAU. Note that the fault at issue here, breakdown to ground without involving the cable return conductors, can only occur at the end of the cable, where the cable outer conductor has been stripped back from the center conductor, for connection to the Big T. This is also where the cable enclosure is tied to the facility ground through the FAU structures. This constraint was taken into consideration in constructing the circuit model.

---

[3] Modeling and Experiments of Ground Return Voltages in the NIF Pulse Power System, M. Rhodes, February 1998, PCS 0141

The inductances of the cable center conductor and of the return through the cable tray/enclosure were taken from the 2-D Maxwell-solver modeling. The values are given in Table 1-10. The full PSpice model used for one of the cases (20 capacitors, enclosed trough) is given at the end of this section. Table 1-11 summarizes the results of the PSpice modeling. Example waveforms are given in Figure 1-34 and Figure 1-35.

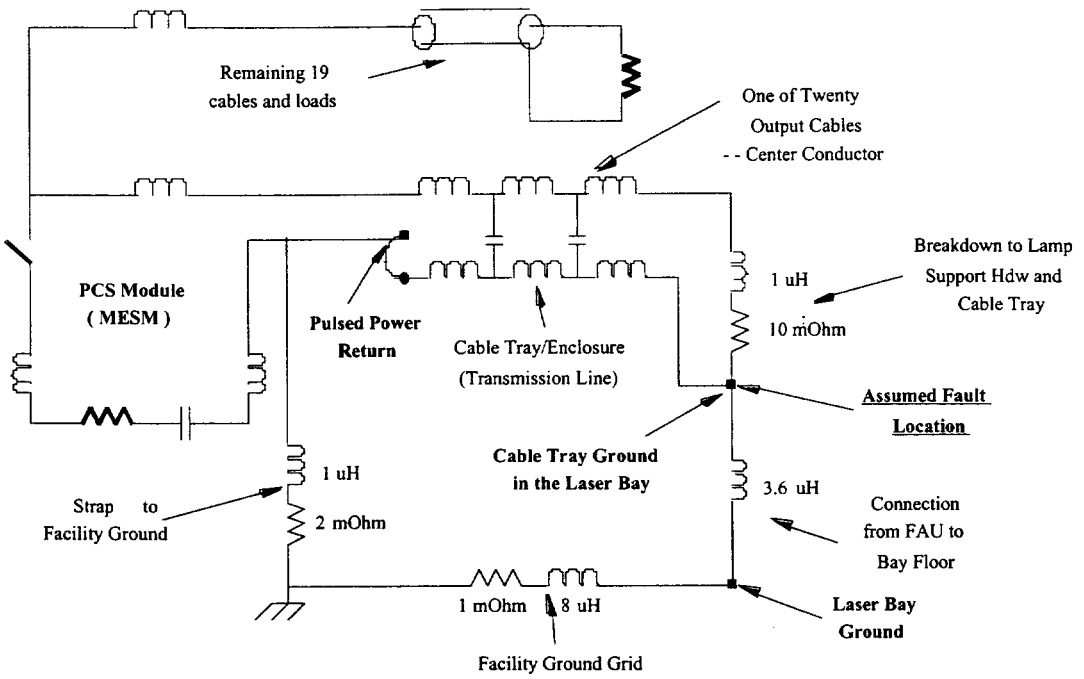

Figure 1-33 Simplified Circuit Model for the Fault Runs

Table 1-10 Wire and Cable Tray/Enclosure Inductances

	Wire Inductance	Plate/Trough Inductance
Wire 8 above a 40 -wide plate	43 μH	3.4 μH
Wire _ above a 24 -wide plate	21 μH	0.3 μH
Wire 8 above the bottom of a 10 x 10 Trough	42 μH	1.7 μH
Wire 8 above the bottom of a 24 -Deep Trough	42 μH	0.3 μH

1.3.4.1 Cable Trays

Within the context of the selected approach, the simplest level of touch potential reduction would be installing a flat conductive cable tray under the cables between the PCS modules and the flash lamp assemblies. The tray would be bonded to the PCS module at the Top Hat and to the laser support structures in the Laser Bay, which are bonded to the facility ground grid. Both the hot and return sides of the cables would be isolated from the tray for all normal shots, but might break down to the tray in the event of foreseeable faults.

As is shown in Table 1-11 below, this approach comes close to meeting the Grounding Policy. Voltages are somewhat too high, but person energies are low enough, with a small margin. However, given the difficulty of modeling systems of this complexity, we cannot be confident that the actual system will perform this well. Therefore, this approach was considered too risky.

1.3.4.2 Cable Enclosures

To ensure safety of personnel and equipment, the selected and implemented NIF design includes a conducting enclosure around the cables. The 2-D Maxwell solver analysis showed that the enclosure need not be fully closed, to achieve the desired effect. For example, the voltage drops are very nearly equal along a 150 ft length of cable tray if the tray is a fully-enclosed 10 square cross-section trough or an open-top trough 10 wide and extending 16 above the top cable.

Similarly, several bundles of cables can be enclosed in a common enclosure using metal plates both above and below the cables. Similar to the open-topped trough, side walls are not needed if the cables near the outside edges of the enclosure are not too close to the opening at the edge; about a distance 1.6 times the spacing between the plates.

The selected design takes advantage of these observations at the ends of the enclosure and at a few short sections along the run from the PCS modules to the FAUs. Most of the enclosure, however, is fully closed, to minimize touch potentials.

Table 1-11 summarizes the results of the PSpice modeling and also includes a comparison between the model results and a low-voltage test using the prototype First Article PCS module under test in the basement of Building 391.[4] Both the model and the test show that the planned approach will meet the safety criteria listed above.

1.3.5 Enclosure Design Summary

Good current contacts are required between sections of the tray/enclosure to prevent sparking, even in normal shots, due to eddy currents and the charging of stray capacitances through the tray/enclosure. This means that casual contact between sections of the tray/enclosure should be avoided. The selected design ensures that individual pieces will either be separated by a clear gap (1/8 or more) or will be held tightly together. This is achieved by separating adjacent pieces by a nominal _ and connecting the pieces together with bolted straps. Spacing between the straps could be as much as 2 ft along edges parallel to the current flow direction, but will be approximately 4 along edges perpendicular to the current flow, to limit current per connection point to less than 50 kA. Straps are formed from 1/8 thick aluminum for most connections, but use _ copper wire for the transitions at the ramps and for the drops to the PCS module and the FAU.

The material used for the enclosure and the thickness of the material have been selected to keep the resistive component of the voltage along the tray to ~ 150 V or less. Since the peak current can be as high as 90 kA, this means the resistance of the tray/enclosure should be less than 1.5 mΩ. For the case in which the tray length is approximately 150 ft, it will not be possible to meet this resistance budget with steel, and aluminum plate or conduit should be at least 1/8 thick. The selected design uses aluminum plates of _ thickness for most of the run, with 3/16 plate used for the bottom plates over the Laser Bay. Sides of the enclosure are formed from aluminum I beams or channel, depending on the locations, with _ web thickness.

High currents, in the range of 90 kA, also mean large forces on the enclosure, requiring adequate structural strength to prevent deformation of the enclosure. Forces in the event of a fault can be as high as 6,000 lb per lineal foot. This, again, leads to the selection of thicker plates for the system.

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[4] B391 First Article System Grounding Test, S. Fulkerson, July 2000 PCS 0048

Table 1-11 Predicted Voltages, Currents, and Energies for a Cable-to-Tray Fault

	20 Capacitors, 150 ft cables					24 Caps 66 cables
	Flat Cable Tray	10 Deep Open-Top Trough	24 Deep Open-Top Trough	Closed Enclosure	Bldg. 391 Enclosure Test *	Closed Enclosure
Voltage at P. P. Return (V)	50	45	20	20		30
Voltage at Laser end of Cable Tray (V)	670	460	130	150		210
Voltage at Laser Bay Ground (V)	460	320	190	190	370	310
Current in Cable Tray (kA)	65	65	65	65	67	92
Current in Ground Grid (kA)	12	6	4	4	5	6
Person Energy; Laser Bay end of Cable Tray (J)	1	0.4	0.08	0.08	~ 0.3	0.22
Person Energy; Laser Bay Ground (J)	0.4	0.2	0.04	0.04	~ 0.1	0.10

Note: Cable tray current values shown in the table are for the case in which the cable is treated as located only _ above the metal of the tray/enclosure, as this gives the higher currents. Voltages and energies are shown for the case of the faulted cable located 8 above the tray or the bottom of the trough, as this results in the higher voltages, ground grid currents, and energies.

* This column summarizes a scaling of a set of low-voltage measurements with the prototype First Article module under test in the basement of Building 391. The system has the same architecture as the NIF design, including an enclosed cable tray, and has a set of 150 ft cables. Person energies were estimated based on the closed-enclosure Spice model, scaling the calculated energies with the square of the ratio of measured to predicted voltages.

1.3.6 WAVEFORMS FROM PSPICE MODELING

Predicted waveforms below are for the ground fault case. That is, a breakdown from the hot center conductor of one of the output cables to grounded structures at the FAU. Specifically, these waveforms are for the case of a cable 1/2 up from the bottom of an enclosed trough (Run 61C).

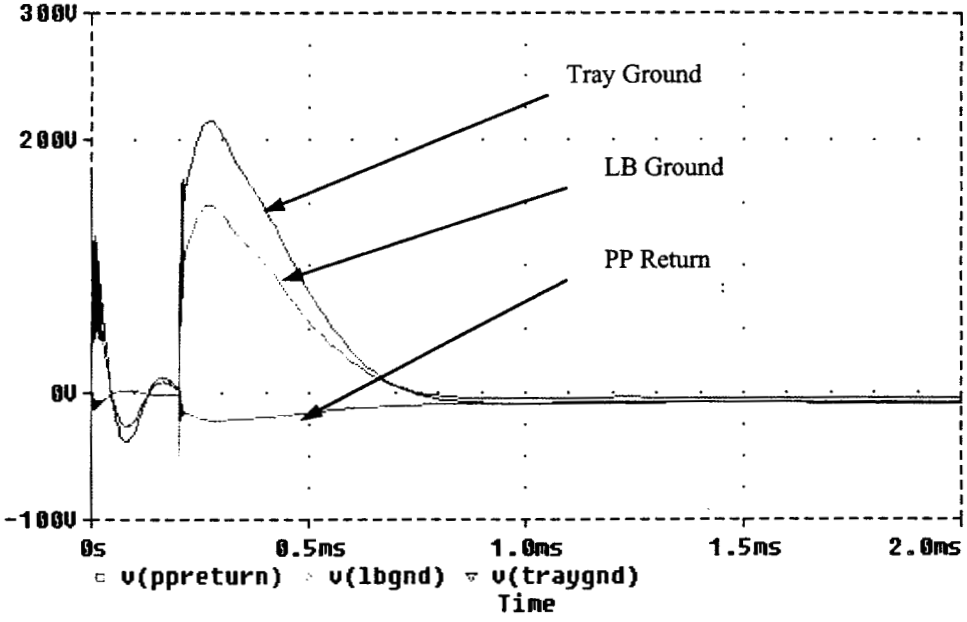


Figure 1-34 Voltages at three ground locations
PPreturn; Pulsed Power Return (the Top Hat), LBgnd; the floor ground grid, in the Laser Bay, and TrayGnd; the cable tray or enclosure, at the Laser Bay end.

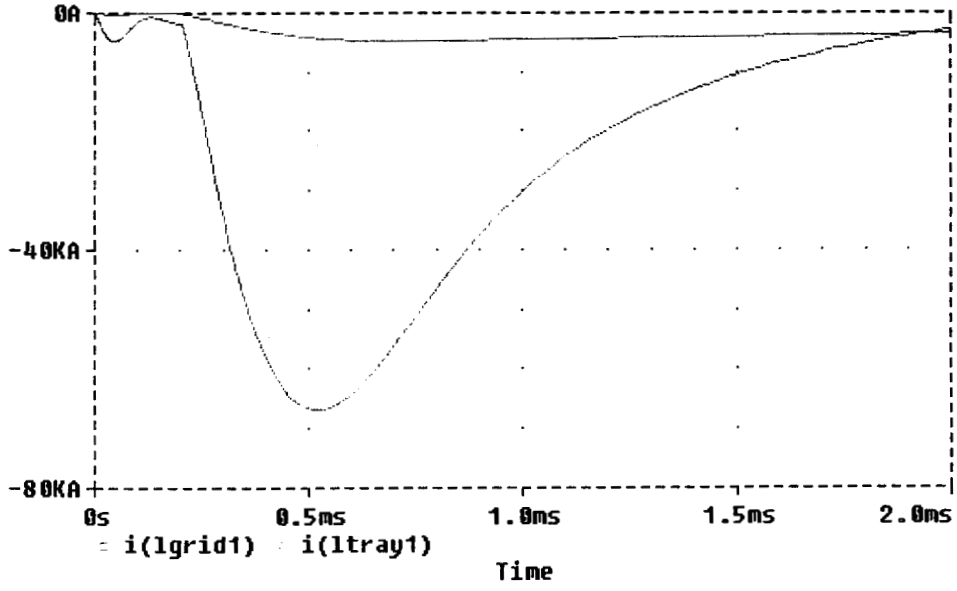


Figure 1-35 Currents in the floor grounding grid (Lgrid1) and in the cable enclosure (Ltray1). Note that the time of peak current in the Ground Grid is considerably after that for the Cable Tray. The Cable Tray peak current is at the same time as that for the cable, itself.

1.3.6.1 PSpice Model for Run 61C

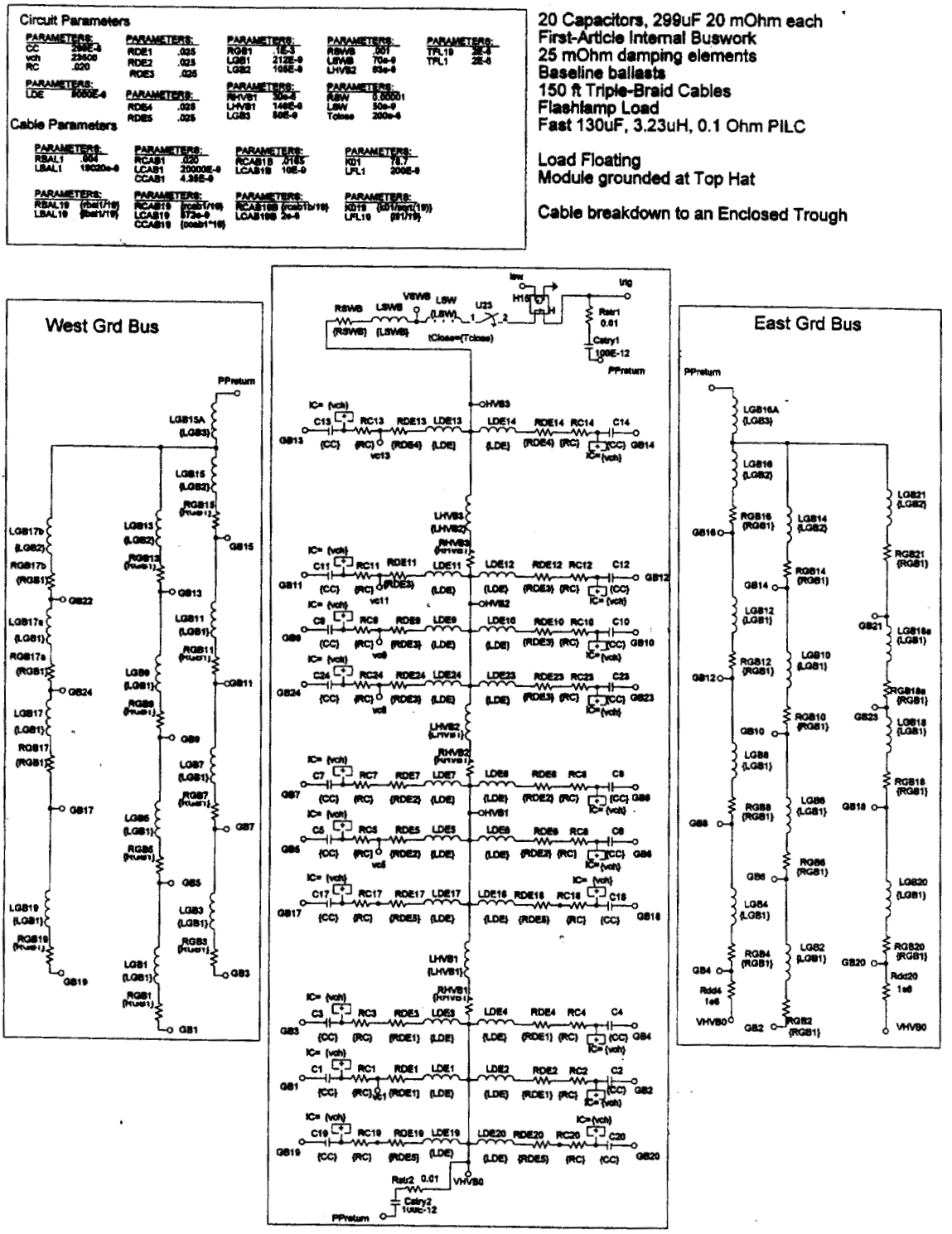


Figure 1-36 Spice circuit model, part 1

Trigger Generator and PILC simplified, and grounded only at the Top Hat

Coupled capacitances between output cables and cable tray
Simple, grounded Cable Tray

Distributed stray capacitances to ground

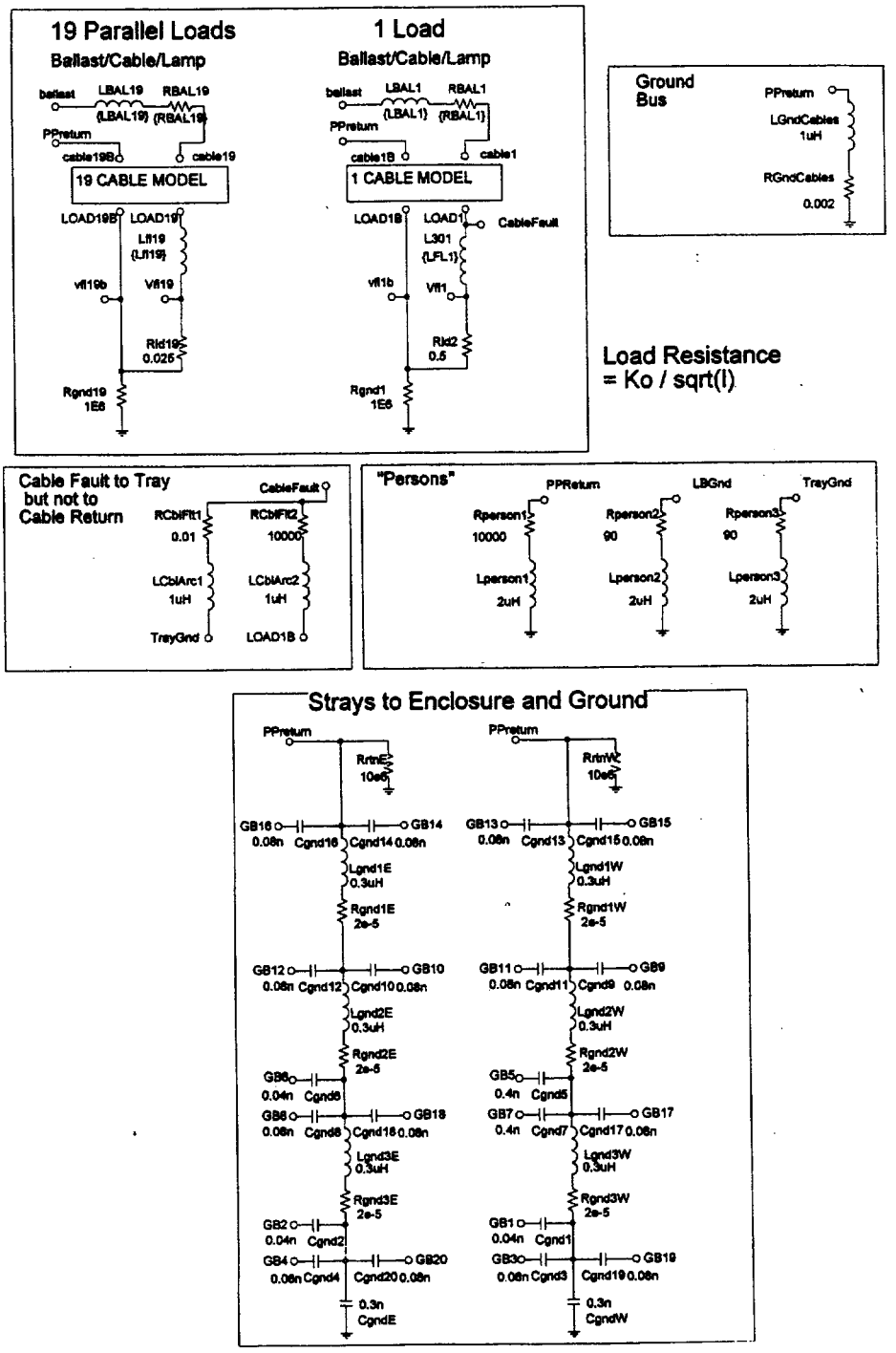


Figure 1-37 Spice model, part 2

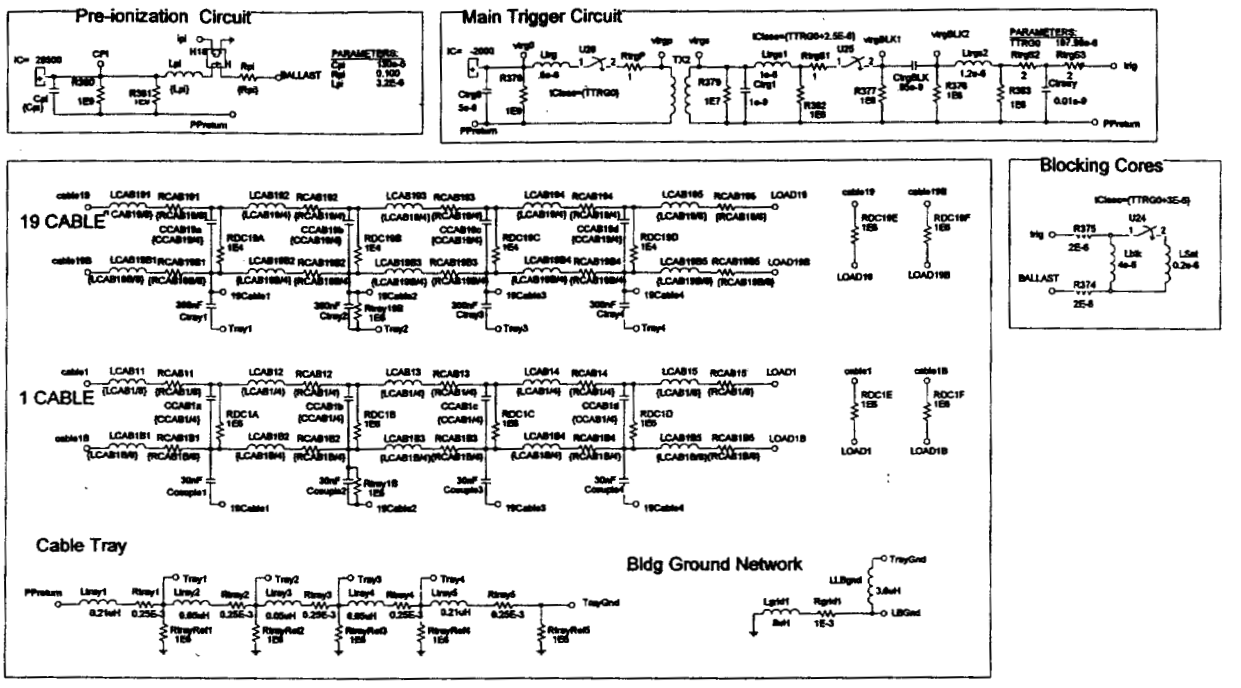


Figure 1-38 Spice model, part 3

1.4 PILC System Description

This section summarizes the design and configuration of the Pre Ionization/Lamp Check (PILC) system for the Main Amplifier Power Conditioning System, as of June 2002.

The Pre-Ionization Pulser is a single-loop capacitor-bank circuit, as shown in the simplified circuit schematic of Figure 1-39. The indicated 3 μH inductance is distributed in the internal buswork, the output cable, and the connections inside the PCS module Top Hat. Typical operating parameters, when connected through the PCS module to the flashlamp set, are as summarized in Table 1-12.

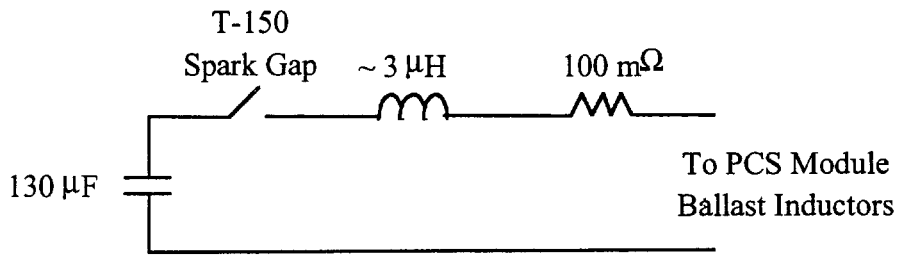


Figure 1-39 Simplified Pre-Ionizer Pulser Circuit

Table 1-12 Typical Operating Parameters, through the PCS Module to the Flashlamp Set

Maximum Charge Voltage	28.5 kV
Stored Energy at 28.5 kV	57 kJ
Nominal Peak Current with 28.5 kV charge	70 kA
Current Pulse Duration	110 μs
Fault Current	140 kA

The block diagram of Figure 1-40 shows the Pre-Ionization Pulser and its association with the control system and the Power Conditioning System module. The bold lines in the figure indicate the primary discharge circuit of the Pre-Ionizer into the PCS module. The general layout of the pulser is shown in Figure 1-41. A circuit schematic showing the key elements of the PILC pulser is shown in Figure 1-42.

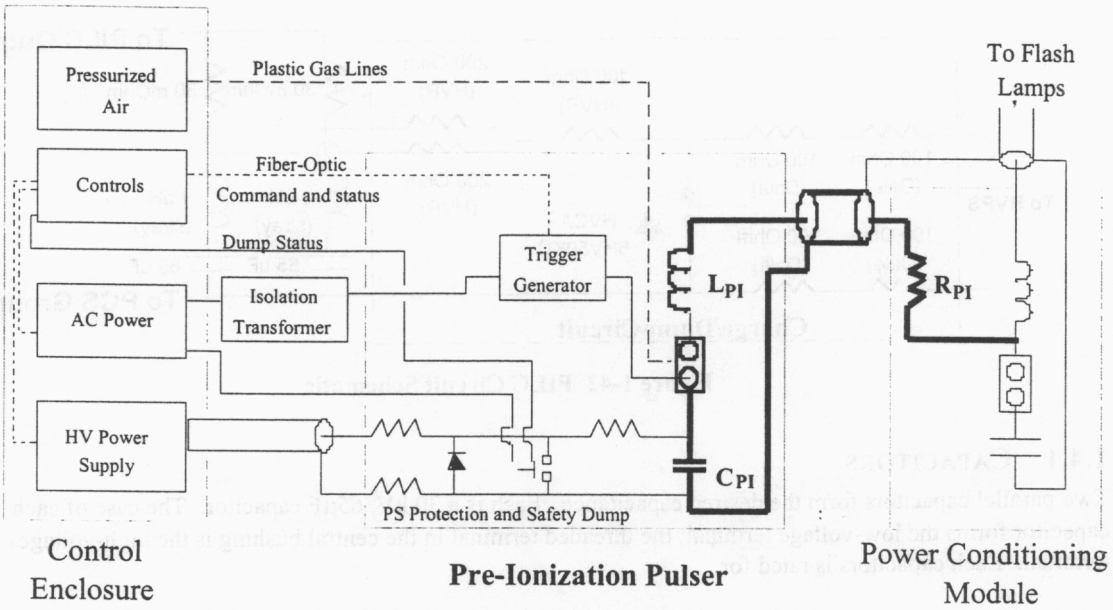


Figure 1-40 Pre-Ionization Pulser System Block Diagram.

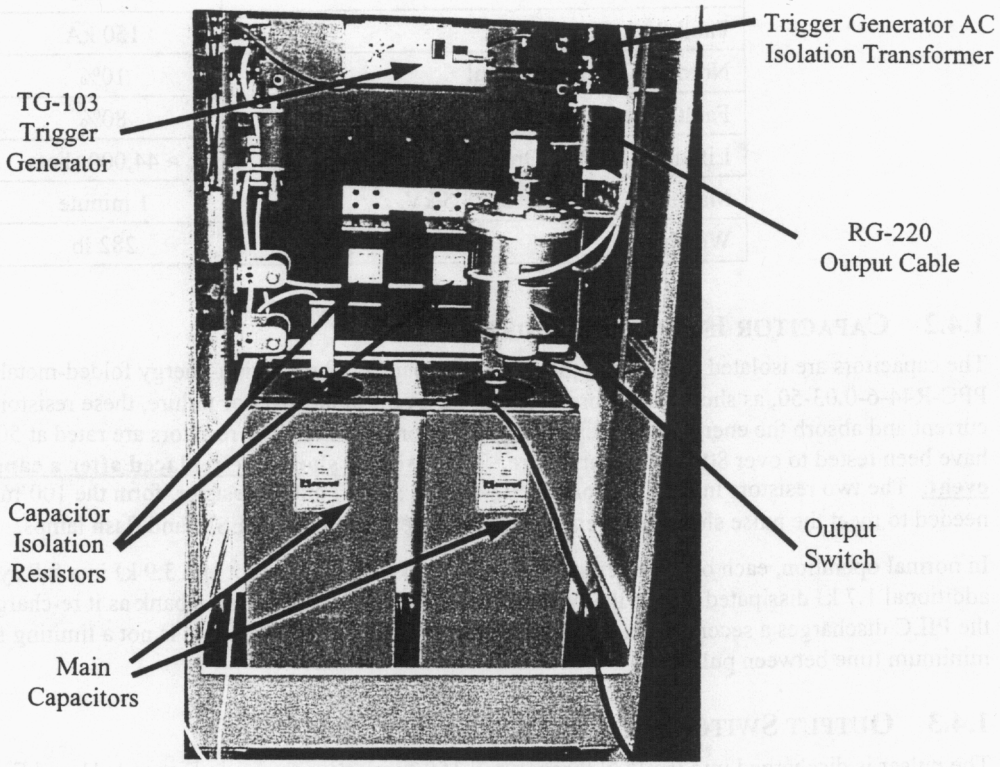


Figure 1-41 PILC Cabinet Interior

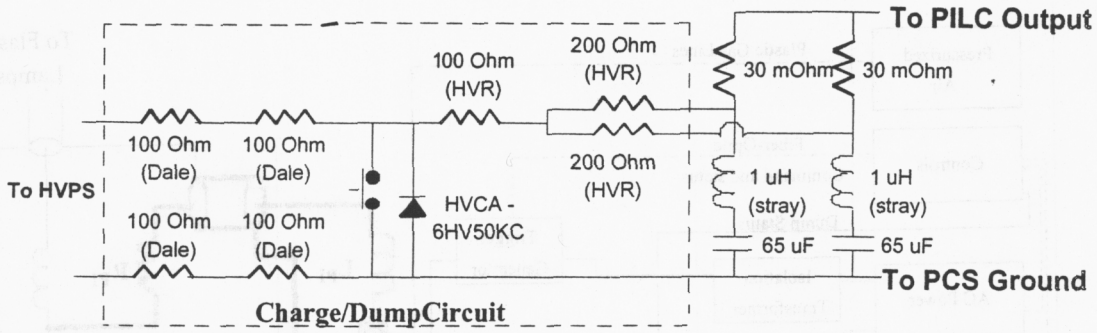


Figure 1-42 PILC Circuit Schematic

1.4.1 CAPACITORS

Two parallel capacitors form the desired capacitance. Each is a 30 kV, 65μF capacitor. The case of each capacitor forms the low-voltage terminal; the threaded terminal in the central bushing is the high-voltage terminal. Each capacitors is rated for:

Table 1-13 Capacitor Ratings

Charge Voltage	30 kV
Normal Peak Current	75 kA
Fault Peak Current	150 kA
Normal Voltage Reversal	10%
Fault Voltage Reversal	80%
Lifetime (Normal Operation, 28.5 kV)	> 44,000 shots
Maximum hold time at 28.5 kV	1 minute
Weight	282 lb

1.4.2 CAPACITOR ISOLATION RESISTORS

The capacitors are isolated from each other through a pair of 30 mΩ, high-energy folded-metal resistors, model PPC-R44-6-0.03-50, as shown in Figure 1-42. In the event of a capacitor failure, these resistors limit the fault current and absorb the energy of the remaining capacitor (~30 kJ). The resistors are rated at 50 kJ each, and have been tested to over 80 kJ, without failure. **The resistors should be replaced after a capacitor failure event.** The two resistors in parallel, combined with the 85 mΩ output resistor, form the 100˚mΩ resistance needed to meet the pulse shape requirement for low reversal into the MESM and flash lamps.

In normal operation, each of these resistors absorbs 2.2 kJ in a PILC shot and 3.9 kJ in a full system shot. The additional 1.7 kJ dissipated during the full system shot comes from the main bank as it re-charges the PILC and the PILC discharges a second time. Average-power heating in these resistors is not a limiting factor for the minimum time between pulses.

1.4.3 OUTPUT SWITCH

The pulser is discharged into the PCS through a T-150 spark gap, shown in Figure 1-41 and Figure 1-43. The switch, rated for operation at up to 40 kV, 300 kA, and 120 Coulombs per shot, uses a triggatron trigger geometry. The switch uses pressurized dry air as the switching gas. The switch body and the triggered electrode are connected to the output cable. The other switch electrode is connected to the capacitor hot bus. The switch body is at dc ground during the charging of the capacitors, and floats to high voltage during the output pulse. Note that the trigger generator for the T-150 also floats to high voltage during the output pulse. Hence the requirement for the AC isolation transformer to supply power to the trigger generator.

Switch electrodes wear during the switching operation. Based on test results to date (June 2002), it is recommended to replace the trigger pin after 20,000 Coulombs (1,000 shots PILC + PILC & Main) and the main electrodes, along with the trigger pin, after 40,000 Coulombs (2,000 shots PILC + PILC & Main).

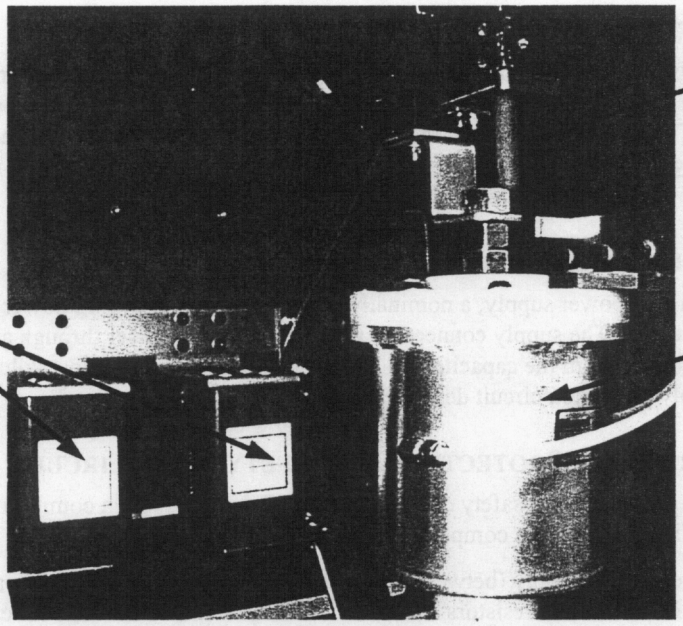


Figure 1-43 Output switch and associated buswork.

1.4.4 TRIGGER GENERATOR

The T-150 spark gap is triggered by a TG-103 trigger generator. The TG-103 uses a solid state switch (an SCR) to discharge a 5 μF capacitor charged to 1.2 kV into the primary of an 8:1 step-up transformer. The secondary of the transformer is connected, through a set of protection resistors and a short section of RG-223/U coaxial cable, to the trigger terminals of the T-150 spark gap. The TG-103 has an open-circuit voltage of approximately 10kV. Trigger generator charge status is indicated through a fiber-optic cable, and the input trigger pulse is provided through a fiber optic cable.

NOTE: The trigger generator, which is fully isolated from ground, floats to the PILC output voltage during the output pulse. Power for the trigger generator is provided through a Stangenes Industries SI-13636 isolation transformer.

1.4.5 SERIES LIMITING RESISTOR

The 85 mΩ series limiting resistor, PPC-R44-0.085-130, is located in the Top Hat of the PCS. In addition to influencing the shape of the normal-shot output pulse, the series limiting resistor protects against excessively high current and energy from the MESM into the pre-ionization pulser in the event of a fault in the pulser. Modeling with the Spice circuit code shows that the current in such a fault will be limited to 170 kA, assuming that the flash lamp loads remain in normal operation. In the event of such a fault, the energy dissipated in the series limiting resistor would be 480 kJ, for the full 24-capacitor MESM at full 24 kV charge voltage. (The resistor has been tested to over 550 kJ dissipation, simulating this fault mode.) **The resistor is to be replaced after such an event.**

In a normal shot, the energy dissipated per pulse is approximately 20 kJ during a PILC-only shot, and 36 kJ during a full system shot (PILC + Main). The additional 18 kJ dissipated during the full system shot comes from the main bank as it re-charges the PILC and the PILC discharges a second time. This means that a normal PILC pre-shot, followed by a PILC + Main shot delivers 70 kJ of energy to the resistor.

The resistor is located inside the Top Hat, with no active cooling and rather restricted convective cooling. The resistor should not be operated at an average power exceeding 120 W under these circumstances. **Resistor heating limits the shot rate to no more than one full shot set (PILC only and PILC + Main) per 10 minutes, or 1 PILC + Main shot per 7 minutes.**

1.4.6 Output Cable

The output cable is a double-braid RG-220 cable, to give long life at nominal current and a high tolerance for fault current. The cable center conductor is connected to the T-150 switch output bus, which is connected to the switch housing. The return conductor of the cable is connected to the cases of the capacitors. **Note: The PILC pulsed power circuit is electrically isolated from the enclosure.** The PILC high-current ground is made through the shield of this output cable at the Main Energy Storage Module.

1.4.7 Capacitor Charging Power Supply

The capacitor charging power supply, a nominally 30 kV, 2 kJ/sec switching power supply, is located in the MESM control console. The supply connects to the Pre-Ionization pulser through an RG-8U coaxial cable. The power supply is isolated from the capacitors in the pulser and protected against voltage reversals of the capacitor by the power supply protection circuit described below.

1.4.8 Power Supply Protection and Safety Dump Circuit

The power supply protection and safety dump circuits are combined into a common circuit, as shown schematically in Figure 1-42. The components are mounted on the fiberglass panel shown in Figure 1-44.

The safety dump resistor assembly (between the safety dump relay and the capacitors, in Figure 1-42) is a set of three high-energy HVR ceramic resistors, each rated for 30 kV and 85 kJ. The set can safely dissipate the energy of the capacitors charged to the full 30 kV rated voltage of the capacitors and power supply, for two dumps in rapid succession. If additional dumps at full energy are required, allow 5 minutes between events.

The series limiting resistors (between the power supply and the safety dump relay, in Figure 1-42) are each formed from a series pair of 100 Ω Dale RS-10 wire-wound resistors. Each 200 Ω resistor set is rated for 10 Watts continuous, well over the 1.8 W dissipated in the resistors at full rated current from the power supply, and have been routinely used at similar or higher operating voltage.

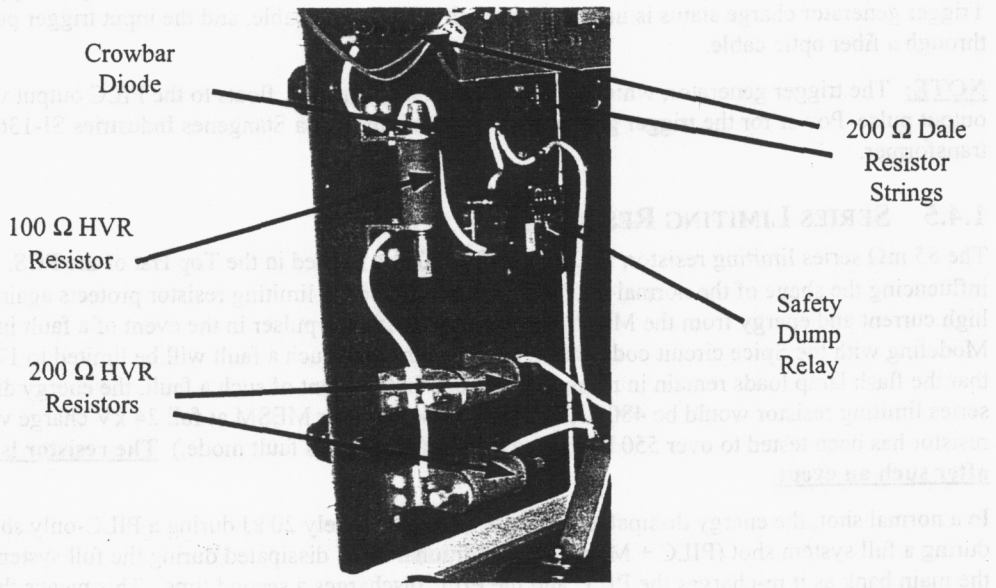


Figure 1-44 PILC Charge-Dump Panel

The crowbar diode is a High Voltage Component Associates HVCA-6HV50KC block diode assembly rated for 50 kV, 2.5 A average, and 400 A surge current.

The safety dump relay is a Ross E-40-NC-40-2C-0-T relay, a normally-closed relay rated at 40 kV holdoff. The contacts are rated for 125 A continuous and 1 kA surge. With the 200 Ω dump resistor, maximum surge current during the dump process is 150 A. The unit includes position sensors for both the OPEN and CLOSED positions. Operation of the relay is through a 115 V solenoid. Maximum inrush current is 5 A; hold current is 0.5 A. The relay is electrically actuated, but is spring-driven to the closed position, assuring the switch will safely discharge the capacitors in the event of a power failure.

1.4.9 ENCLOSURE

The system is mounted in a Hofmann enclosure. It is important to note that the pulser is electrically isolated from the enclosure. This allows the enclosure to be tied to a safety ground, for personnel safety, without introducing a ground loop. The pulser within the enclosure is intended to be grounded, through the RG-220 output cable, at the Top Hat of the MESM. The system includes a safety grounding strap used to tie the pulsed power ground bus to the enclosure for personnel safety during inspection and maintenance. This strap must be removed prior to operation of the system.

1.5 TG-803 Trigger Generator System Description

This section summarizes the design and configuration of the TG-803 Trigger Generator, which is used to trigger the ST-300E output switch of the MESM. The key components in the unit are listed in Table 1-14 below.

Table 1-14 Key TG-803 components

Primary Capacitor	5 μF, 2 kV	Condenser Products
Primary Switch	3.6 kV, high dI/dt SCR	Westcode
Secondary Capacitor	2 series 2 nF, 50 kV	Condenser Products
Pulse Transformer	1:46.3	Stangenes
Output Switch	UV-Illuminated, Sealed Switch	Titan Pulse Sciences
Blocking Capacitor	Potted assy of 3 series 50 kV capacitors	Titan Pulse Sciences
AC Isolation Transformer	120V AC	Stangenes

The TG-803 is mounted on the top of the MESM at the rear side, as shown in Figure 1-1 (see Section 1.1). A simplified circuit diagram of the unit is shown in Figure 1-45.

The 5 μF primary capacitor is charged to approximately 2 kV by a power supply internal to the TG-803. A high-dI/dt SCR is used as the main switch, pulse-charging the output capacitor through a pulse-transformer to approximately 105 kV. The output capacitor is formed from a series pair of high-voltage capacitors. This capacitance is discharged through a UV-illuminated, sealed gas (N_2) spark-gap output switch. The pressure in the switch is set (at the factory) so that the switch self-fires at approximately 105 kV. The UV-illuminator significantly improves the repeatability of the firing voltage of the switch. Tests have shown the switch lifetime to exceed 60,000 shots.

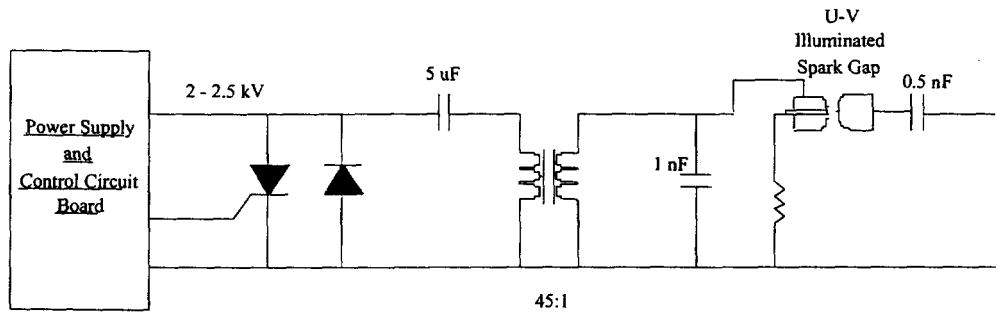


Figure 1-45 TG-803 Simplified Circuit Schematic

Figure 1-46 shows the key features of the TG-803. The high-voltage bushing of the trigger generator includes an output blocking capacitor, to isolate the trigger generator circuit from the rest of the MESM circuit during the relatively long discharge time of the MESM. This isolation is critical, as the TG-803 output transformer would otherwise place a short-circuit across the output of the MESM. Clearly, this would be a disaster. Due to the importance of isolation from the MESM, a second-level of isolation from the module is provided by a high-current fuse; Pulsed Power Components #°PPC-FU-212-173, which has a let-through action of 173 A^2-sec.

Protection against possible shrapnel from the MESM is provided by the _ polycarbonate output plate of the TG-803 in combination with a _ polycarbonate plate placed between the TG-803 and the top plate of the MESM.

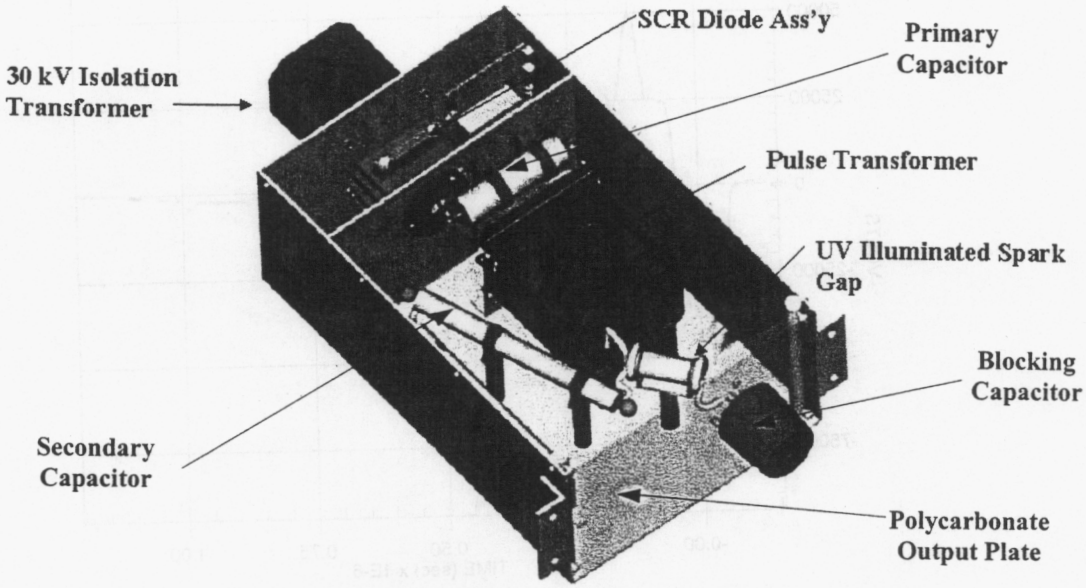


Figure 1-46 TG-803 Trigger Generator

Figure 1-47 shows the voltage on the secondary capacitor for a fairly typical shot. Figure 1-48 and Figure 1-49 show fairly typical output voltages of the trigger generator, measured at the ST-300 in the MESM, when the ST-300 pressure has been set high enough to prevent it from firing, so that the full trigger generator voltage pulse can be seen.

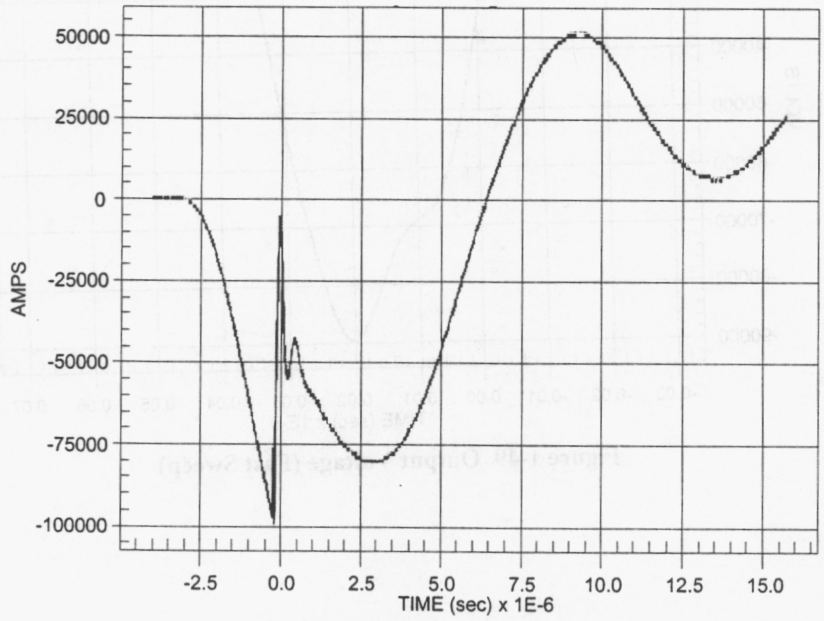


Figure 1-47 Secondary Voltage

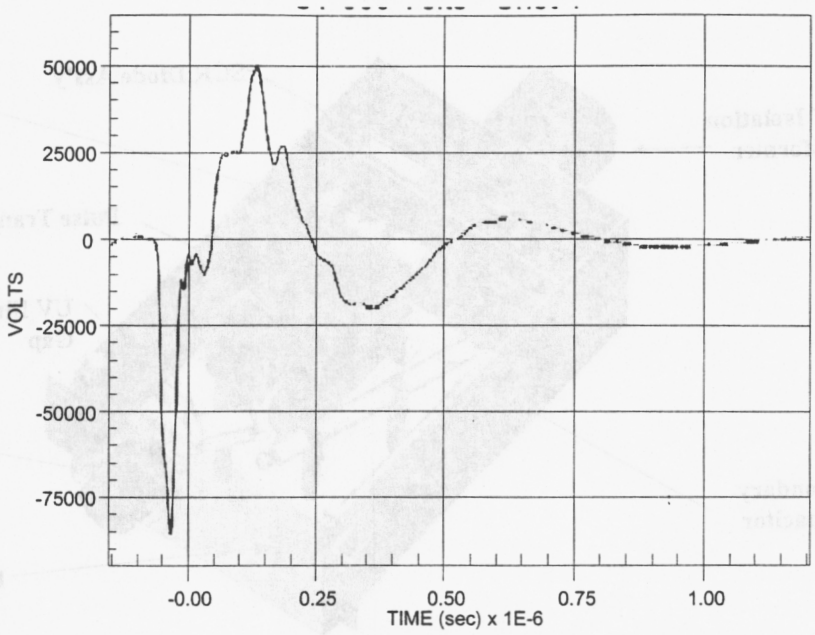


Figure 1-48 Output Voltage (Slow Sweep)

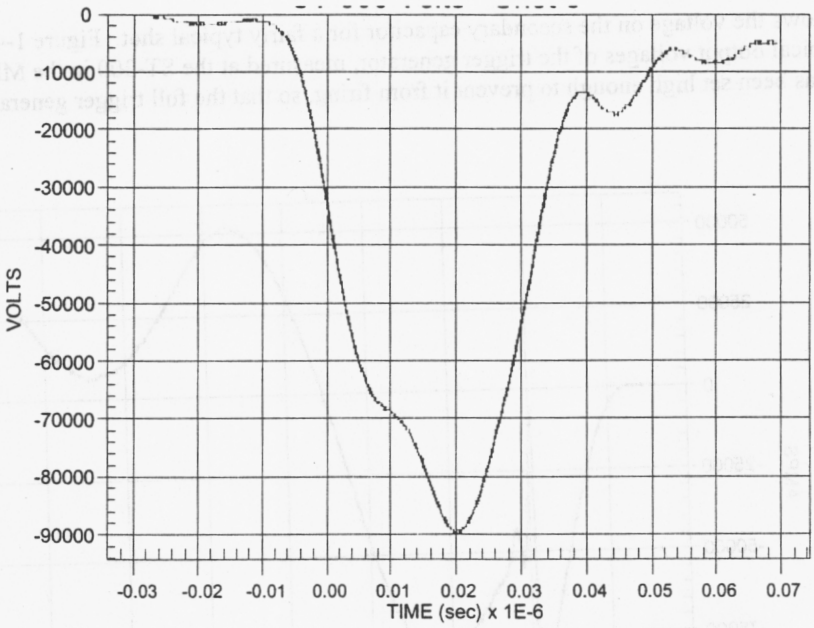


Figure 1-49 Output Voltage (Fast Sweep)

2.0 MAINTENANCE REQUIREMENTS

2.1 Periodic Inspections

Assembly/ Component	Inspection Interval	Comments
MESM	150,000 Coulombs transferred by MESM Output Switch	Check all high current connections for damage or soot due to arcing. Identify and repair poor connections. Inspect dump relays and resistors -- Replace if tracked or damaged.
PILC	40,000 Coulombs transferred by PILC Output Switch	Check all high current connections for damage or soot due to arcing. Identify and repair poor connections. Inspect dump relays and resistors -- Replace if tracked or damaged.

2.2 Routine Maintenance

Component	Maintenance Action	Maintenance Interval	Maintenance Procedure
ST-300 MESM Output Switch	Replace with new or re-furbished switch	After 283,000 Coulombs (Approx. 1,800 shots)	MESM Gas Switch Replacement and Inspection *(Document xxx)*
ST-300 MESM Output Switch	Check electrode gap and replace spark plug	Between 150,000 — 155,000 Coulombs	PCS Module Operating and Maintenance *(Document xxx)*
T-150 PILC Output Switch	Replace with new or re-furbished switch	After 40,000 Coulombs (Approx. 4,000 PILC shots + 2,000 Main shots)	PILC Gas Switch Replacement and Inspection *(Document xxx)*
ST-300 Air Filters	Replace with new filter element	During ST-300 replacement	MESM Gas Switch Replacement and Inspection *(Document xxx)*
ST-300 Gas Lines	Replace with new gas lines	During ST-300 replacement	MESM Gas Switch Replacement and Inspection *(Document xxx)*
T-150 Air Filters	Replace with new filter element	During T-150 replacement	PILC Gas Switch Replacement and Inspection *(Document xxx)*

2.3 Special Maintenance -- Mandatory Maintenance/Repair

Component	Mandatory Action	Off Normal Event	Maintenance Procedure *Need Doc #s xxx*
Ballast Inductor	Replace with new inductor	After flashlamp failure or other faults resulting in a current over 50 kA in the inductor	PCS Module Operating and Maintenance *(Document xxx)*
Damping Element	Replace with new inductor	After a capacitor failure or ground fault on the capacitor side of the Damping Element. After any event that damages the Damping Element	PCS Module Operating and Maintenance *(Document xxx)*

Power Supply Isolation Resistors and Safety Dump Resistors	Replace with new resistor	After module failure that may have contaminated resistor with oil or hit resistor with projectiles. After any condition which dumps the module into the power supply isolation resistors or a single dump resistor	PCS Module Operating and Maintenance *(Document xxx)*
MESM Capacitor	Replace with new capacitor	Capacitance dropped from initial value by more than 5%	Procedure for Removal of Failed Capacitors NIF-0058472

3.0 OPERATIONAL CONSTRAINTS

Assembly	Parameter	Normal Operation	Limit	Controlling Component or Sub-System	Source Documents
MESM	Charge Voltage	22-24 kV	15 seconds @ 24°kV	Capacitors	MESM Capacitor Specification NIF-0005095
MESM	Charge Voltage for Shorted Load Tests	N/A	400 kJ stored (~10 kV) or 30 kA / ballast inductor	Shrapnel and blast effects with doors off Ballast Inductor current limit	PCS System Operation and Safety Plan, OSP 581.03
MESM	Charging Interval	15 minutes	10 minutes	Charging Power Supply	Main Power Supply Specification, NIF-5001464
MESM	Shot Interval	15 minutes between PILC + PILC & Main shot sets	10 minutes between PILC + PILC & Main shot sets	PILC Output Resistor heating	
MESM	Dump Interval	Wait 30 minutes after a full-energy dump	Wait 15 minutes after full-energy dump	Dump Resistor Assy heating	HVR Data Sheet
MESM	Dump Interval for a Single dump assy	One Dump at End of Day	Wait 30 minutes after full-energy dump	Dump Resistor Assy heating	HVR Data Sheet
MESM	Spark Gap Pressure	5-95 psig	120 psig	Tie Rods (?)	Set By Manufacturer
MESM	Spark Gap Purging	30 seconds at 2.2 CFS	120 psig	Air Supply Allocation	See ICD *(Document xxx)*

PILC	Charge Voltage	28.5 kV	60 seconds @ 28.5 kV	Capacitors	*(Document xxx)*
PILC	Shot Interval - - PILC only	N/A	4 minutes	PILC Output Resistor heating	
PILC	Dump Interval	N/A	Can do two dumps close together - - Wait 5 minutes after second full-energy dump	Dump Resistor Assy heating	HVR Data Sheet
PILC	Spark Gap Pressure		100 psig	Nylon Insulator	Set by Manufacturer
PILC	Spark Gap Purging		100 psig		

4.0 SAFETY FEATURES / CONCERNS

4.1 Introduction

This section of the Design Basis Document is meant only as a top-level overview of the safety concerns associated with the NIF Power Conditioning System and the safety features implemented to mitigate these concerns. Additional information on the safety features of individual components/subsystems can be found in the relevant sections of this document. More details on system hazards and hazard mitigation can be found in *NIF Amplifier Power Conditioning System (PCS) Hazard Analysis and Safety Implementation Plan, EESN02-002 NIF-0079483.*

The philosophy followed during the design and development of the NIF PCS system can be characterized as follows:

- Design the system components to be safe.
- Test individual components and entire modules extensively.
- Provide redundant protection in high-risk areas.
- Establish procedural controls and perform personnel training.

The system and its components are designed to be safe to use and maintain. However, anyone working on the NIF Power Conditioning System must be aware of the hazards associated with the system, and must be appropriately trained. Operation and maintenance procedures have been developed to allow safe, appropriate use and maintenance of the system. These procedures must be adhered to as written.

The operator or worker must *never* assume the system is safe nor overlook or ignore any subtle changes in performance.

Should situations arise which are uncertain or for which no procedure exists, the responsible personnel are required to stop and develop a safe course of action.

It is critical to recognize that the NIF PCS modules are designed for safe operation only within an appropriately armored room. Personnel should never be allowed in the same room as a charged module. Although the module enclosure is designed to contain all shrapnel from internal module failures, it was not possible to perform adequate testing to ensure the safety of personnel in the vicinity of the module during a fault. As a result, PCS modules should always be operated in a room with secondary containment (at least 1 1/8 plywood) for shrapnel, and personnel should be excluded from the room whenever modules are charged.

Many component designs are the result of years of testing and development. Components are designed to survive the worst-case fault scenarios, but some must be replaced after severe faults, such as the damping elements, ballast inductors, and dump resistors (see Section 2.3). Designs of the components in this system should not be altered without a thorough review of the requirements, additional analysis, verification testing and evaluation of the personnel and hardware safety implications of making any changes.

As large systems age and personnel originally involved in the system design move on to other projects, there is a tendency to forget why decisions were made and what their safety implications are. We hope that those who at a later date are called upon to maintain or modify the facility will find this document and the NIF Amplifier Power Conditioning System (PCS) Hazard Analysis and Safety Implementation Plan, EESM02-002 NIF-0079483 to be useful references.

4.2 Summary of Safety Features and Concerns

The bulk of this section is arranged as a set of tables, summarizing types of hazards presented by the Power Conditioning System and hazard mitigation features designed into the system to protect against these hazards.

Relevant documents with additional safety-related information, including safety-related procedures that are critical in supplementing the safety design features, are listed in Section 4.3.

4.2.1 EXPLOSION: FIRE, SHRAPNEL, TOXIC FUMES

The MESM and PILC contain high voltage capacitors that store sufficient energy to present the risk of explosion and/or fire, and thus the potential to create shrapnel and toxic fumes. **The capacitors must be considered potentially hazardous even if the modules have been discharged through their safety dump systems.** It is particularly important that only trained personnel should perform service on these systems. Established procedures should be followed at all times.

Source of Hazard	Mitigation Features
Main Energy Storage Module - Capacitors - Dump Resistors - HV Breakdown	- Personnel are excluded from the capacitor bay whenever PCS modules are charged. - MESM enclosure is designed to prevent shrapnel from exiting the module, while venting over-pressure associated with an explosion. - Capacitor Bays include secondary shielding — 1"1/8 plywood on walls. - Capacitor Bay is vented, to prevent build-up of fumes.
PILC - Capacitors	- Personnel are excluded from the capacitor bay during whenever PCS modules are charged . - Capacitor Bays include more-than-adequate shielding for PILC explosions — 1"1/8 plywood on walls. Note: The PILC enclosure does **not** provide primary shrapnel protection.

4.2.2 ENERGETIC SPARKS FROM A HV BREAKDOWN

Sparks may be created during the operation of the system. Some sparks, such as those associated with eddy currents and displacement currents, have little energy associated with the spark. Others, such as sparks created in the event of a high-voltage breakdown, can be very energetic. Sparks may also be created at poor connections between the cables and their terminations.

Source of Hazard	Mitigation Features
Main Energy Storage Module - Capacitors - Dump Resistors - HV Breakdown	- Personnel are excluded from the capacitor bay whenever PCS modules are charged. - Enclosures prevent sparks

PILC - Capacitors - Dump Resistors - HV Breakdown	created inside the MESM or PILC from escaping the system. - Note: Some sparks may be created from loose connections or poor contacts on the outside of the enclosure.
HV Cables	- Personnel are excluded from the capacitor bay and laser bay whenever PCS modules are charged.
Big T	- Personnel are excluded from the capacitor bay and laser bay whenever PCS modules are charged.

4.2.3 ELECTRICAL SHOCKS - - HIGH VOLTAGE SYSTEMS

The MESM, PILC, Control Rack, and TG-803 all contain high voltage capacitors and/or high voltage power supplies, and thus present hazards for high-voltage shocks. In addition, it is possible under some circumstances for residual high voltage to remain on the PCS output cables. It is particularly important that only trained personnel should perform service on these systems. Established procedures should be followed at all times.

Particular attention must be paid to MESM capacitors that read partially or fully open. That is, capacitors that show part or all of the internal capacitor sections to be disconnected from the capacitor terminals. Such a capacitor may be storing internal energy that cannot be discharged. It is possible for the capacitor to re-connect without warning, thus presenting an unknown high-voltage hazard. Special procedures established for this circumstance[5] must be followed.

Source of Hazard	Mitigation Features
Main Energy Storage Module - Main Capacitors - Buswork	- Procedures restrict personnel access to high voltage components. - Enclosures isolate personnel from the high voltage components. - Interlocks disable high-voltage power supplies and discharge the MESM and PILC capacitors if personnel enter the capacitor bay. - Circuit breakers include Lock-out / Tag-out features. - Automatic safety dump relays discharge capacitors whenever the system is shut down, if interlocks open, or if AC power is lost. - Capacitor Bay entry procedures and module safing procedures must be followed.
PILC - High Voltage Capacitors - Buswork	

[5] Procedure for the Removal of Failed Capacitors NIF-0058472

TG-803 - Blocking Capacitor - Internal Capacitors	- Procedures restrict personnel access to high voltage components.
High Voltage Power Supplies	- Enclosures isolate personnel from the high voltage components. - Interlocks disable high-voltage power supplies discharge capacitors if personnel enter the capacitor bay. - Circuit breakers include Lock-out / Tag-out features. - Capacitor Bay entry procedure and module safing procedures must be followed.
High Voltage Cables	- Coaxial cables enclose the high-voltage conductor within a low-voltage return conductor. - Established procedures call for discharging cables taken out of use. - Protective covers are used for cables not in use. - Capacitor Bay entry procedure and cable shorting procedures must be followed.

4.2.4 ELECTRICAL SHOCKS - - AC POWER SOURCES

There is an electrical shock hazard from the 480 VAC three-phase and 120 VAC single-phase power in the control rack and the 120 VAC power in the MESM, PILC, and TG-803. AC power sources are protected by enclosures and/or covers. Breakers include lock-out/tag-out capability. **Operations and maintenance staff should be alert to the fact that most electrical shock incidents in pulsed-power facilities occur from the AC power, not the high-voltage systems, due to the mistaken perception that the much lower voltage of the AC power makes it relatively safe.**

Source of Hazard	Mitigation Features
- Main Energy Storage Module - PILC - TG-803 - HVPS - Control Rack	- Enclosures and/or Terminal Cover Strips protect personnel from AC power sources. - Circuit breakers include Lock-out / Tag-out features. - Capacitor Bay entry procedure must be followed

4.2.5 PRESSURIZED GAS

The spark gaps used in the MESM and the PILC require pressurized air for operation. The pressurized gas is supplied and controlled through the control rack. The normal hazards associated with pressurized gases apply.

Source of Hazard	Mitigation Features
Main Energy Storage Module - ST-300 Spark Gap - Air Filters - Gas lines	- Spark gap housings and the associated gas lines, filters, and fittings are rated for pressures well above those applied by the

PILC - T-150 Spark Gap	gas system. - Pressures are below levels where special procedures and controls are required
Control Rack - Air Panel	

4.2.6 Toxic Gases

The spark gaps in the MESM and the PILC create small quantities of toxic gases when the switches fire. These gases are exhausted outside the building, through an exhaust system in each capacitor bay.

Source of Hazard	Mitigation Features
- MESM output switch (ST-300) - PILC output switch (T-150) - Air Panel	- Air filters capture particulate powders produced in the spark gap switches. - Contaminated air is exhausted outside the building, through the facility exhaust system. - Quantities and concentrations of toxic elements in the exhaust gases have been determined to be low enough to be exhausted into the atmosphere.

4.2.7 Handling Heavy Objects

The Main Energy Storage Module, PILC, and Control Rack are heavy objects, and in turn contain heavy objects. The normal hazards associated with handling and moving heavy objects apply.

Source of Hazard	Mitigation Features
Main Energy Storage Module	- Fork Lift Points are provided on the MESM enclosure for safe handling with a folk lift. - Air Pad points are provided to allow the use of air pads for the transport of the MESM inside buildings. - **NOTE: Air pads should not be used to transport the module on sloping surfaces.** - An electric Tug is available to assist in transporting the MESM when using the air pads.
Main and PILC Capacitors	- MESM Capacitor Handling Fixture should be used
Control Rack	- Follow standard procedures for handling heavy objects
PILC	- The PILC is supplied with heavy-duty wheels to simplify transport of the PILC within buildings.

4.3 Source Documents

The documents below generally address several of the hazards described above.

Report #	Subject
PCS 0146	NIF Safe Potential Study, W. DeHope, Primex Physics International, Feb. 1998
PCS 0106	National Ignition Facility Project, Title I Review, Oct. — Nov. 1996
PCS 0108 —0117	National Ignition Facility Project, Title II Review, April 1998
NIF-0018457 — NIF-0018463 inclusive	National Ignition Facility Project, Title II, 100% Review, Feb. 1999
MESN99-066-0A NIF-0063594	Analysis and Control of Hazards Associated with NIF Capacitor Module Events , LLNL Mechanical Engineering Safety Note, Sandra Brereton et al., Sept. 1999
PCS 0085 and 0086	Recent Explosive Failures at the FANTM Facility, M. Wilson,
UCRL-ID-133180	Fire Risk Analysis for the NIF Capacitor Containment Design, Feb. 1999
PCS 0147	Internal Memorandum, Mar. 1, 2000, Open Capacitor Failures Bill Moore Sandia National Laboratory
EESN02-002 NIF-079483	NIF Amplifier Power Conditioning System Hazard Analysis and Safety Implementation Plan LLNL Electronics Engineering Safety Note, June 2002

5.0 SEISMIC RESTRAINT AND TRASPORTABILITY

The PCS Module has been designed to survive a seismic event consistent with requirements described in *LLNL Mechanical Engineering Design Safety Standards*, and to allow the module to be transported assembled. Additional detail on seismic restraint and transportability features of the module design can be found in *Module Frame Re-Design 100% Review* PCS 0131. The primary features of the module design addressing these requirements are:

- Capacitor rack design
- Capacitor hold-down straps and trays
- Damping Element supports and clamps
- Seismic Anchors
- PILC and Control Rack attachment hardware

Some temporary bracing is used to prepare the module for shipping. All such temporary bracing must be removed prior to operating the module or its sub-systems. The installation and removal of these items are discussed in the shipping and installation procedures.

5.1 Capacitor Rack Design

A portion of the module frame (or capacitor rack) design is shown in Figure 5-1. Stiffening features include:

- Welded end and rear panels
- 45° stiffening braces at the top interior section of each side of the frame
- 3/8-16 inserts in the frame tubing for attachment of the removable front panels

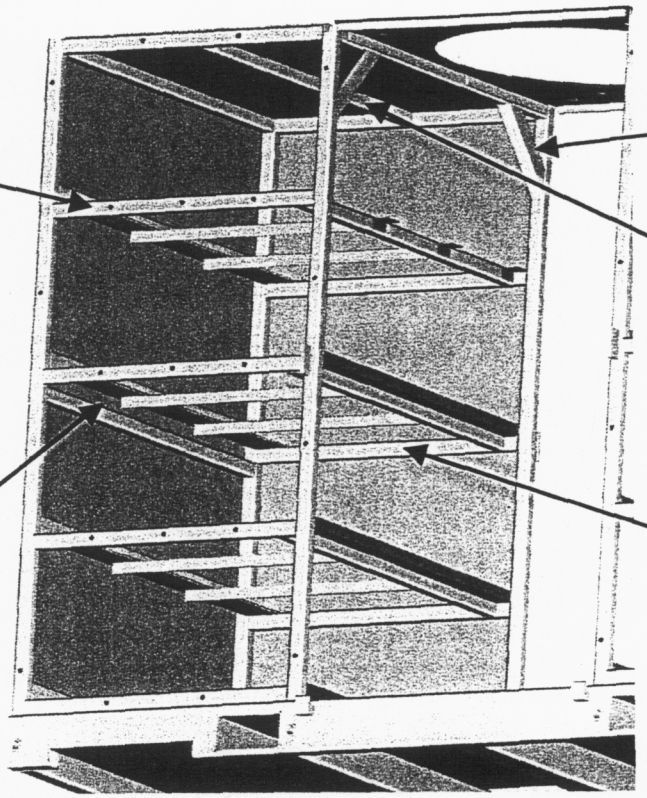


Figure 5-1 Module Frame

A detailed analysis of the seismic and gravity responses of the capacitor rack was performed. Results are summarized in *Analysis of NIF capacitor Racks for Gravity & Seismic Loading,* NIF-0072430. The capacitor rack design was analyzed by finite element computer methods for both gravity and seismic loads, in both fully and partly populated conditions (24 and 20 capacitors per rack, respectively). Calculated stresses in the steel framework are comfortably within acceptable levels, with factors of safety of not less than 7.5 on yield for gravity alone, and not less than 2.1 on yield for gravity plus seismic. Calculated stresses in the plate and shell materials (steel panels and top hat) are also comfortably within acceptable levels, with factors of safety of not less than 25 on yield for gravity alone, and not less than 9.2 on yield for gravity plus seismic. These factors of safety are above the minima specified in the *LLNL Mechanical Engineering Design Safety Standards* manual (Chapter E, page 5), which are: 3.0 on yield for general purposes, and 1.0 on yield for rare events such as seismic. Further information on the seismic requirements for NIF equipment can be found in: *Seismic Provisions for NIF*, NIF-0000214 and *Additional Seismic Provisions for NIF Equipment and Operations*, NIF-0002715.

5.2 Capacitor Hold-Down Straps and Trays

Capacitors are held in place by a combination of the insulating capacitor tray, which indexes the capacitors both side-to-side and front-to back, and the tie-down straps, which prevent vertical motion. **The tie-down straps should be replaced when new/replacement capacitors are installed, as they serve as both transportation and seismic restraints.**

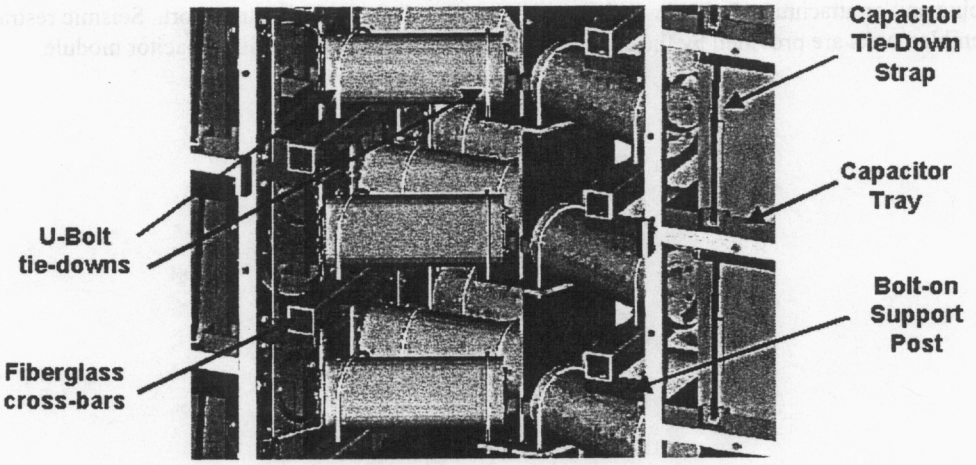


Figure 5-2 Module Internal Seismic and Transport Support Features

5.3 Damping Element Supports and Clamps

The damping elements are supported at both ends; by the metal shelves of the HV Bus at one end, and by fiberglass cross bars at the other end, as shown in Figure 5-2. They are attached to the supports using steel U bolts. **The U bolts should be re-installed when new/replacement damping elements are installed, as they serve as both transportation and seismic restraints.**

5.4 Seismic Anchors

A set of eight seismic restraints provides horizontal and vertical restraint for each corner of each capacitor rack. The hold-down fittings are arranged so that 8 fittings share longitudinal (model X-direction) loads, while any 4 fittings resist transverse (model Z-direction) loads. The X- and Y-forces produce bending in the pin, while Z-forces are resisted by bearing against the steel bar on top of the fiberglass block. **The effectiveness of the seismic restraints relies on the anchor bolts installed into the concrete floor of the capacitor bays, which must be installed in accordance with the installation procedure.**

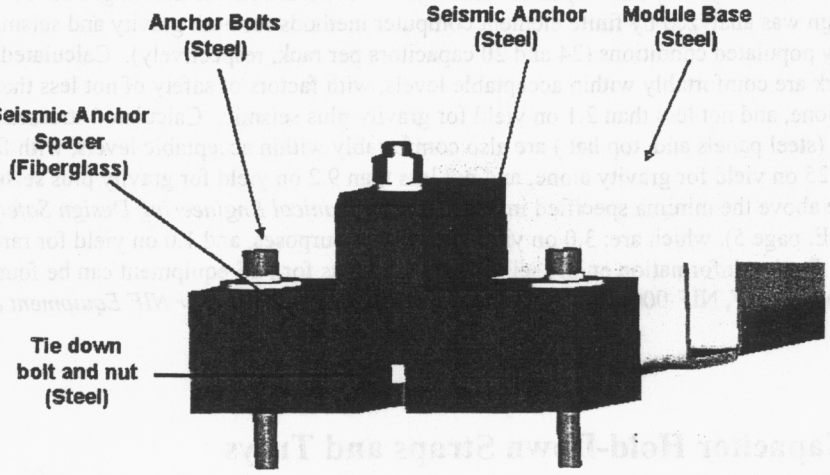


Figure 5-3 Seismic Anchor

5.5 PILC and Control Rack Attachment Hardware

The PILC and the Control Rack are transported separate from the PCS Module. Each unit has its own internal bracing and/or attachment/hold-down features to prevent damage during transport. Seismic restraints for the assembled units are provided by the clamps that attach the units to the main capacitor module.

6.0 BLAST AND SHRAPNEL PROTECTION

The following paragraphs, taken from the Mechanical Engineering Safety Note (MESN99-066-OA 'NIF-0063594 N.M. 6.4) Analysis and Control of Hazards Associated with NIF Capacitor Module Events, summarize the approach to blast and shrapnel protection for the PCMS module. Figure 6-1 shows a view of the PDMS Module isometric rendering, showing several of the key features discussed. The isometric rendering of the module frame shown in Figure 5-1, shows protection features in the frame, itself. Additional details can be found in the engineering safety note.

The NIF capacitor module was reviewed with respect to pressure venting and shrapnel containment during failures. A modified module concept was proposed that would adequately vent the pressure, yet be effective at containing shrapnel. Two large vents are provided on each side of the module. These have fixed vent areas, and are immediately accessible for pressure venting at the beginning of a pressure transient. A shrapnel shield is located on the outside of each vent opening, forming a chute. The chute contains a collimator. This increases the number of bounces that shrapnel must take on the way out, and directs the shrapnel to the trap beneath. The trap contains a depth of clear pine, sufficient to completely absorb the energy of even the most energetic fragment considered.

Based on a review of the evidence from past capacitor failures at the FANTM facility at Sandia National Laboratory, Albuquerque, and additional theoretical estimates, the peak pressure generated in the module during explosive events was estimated to be less than 40 psig. This internal pressure in the FANTM module appears to be tolerable, as only minor damage to the module and to internal components was observed after events. The new module concept proposed here provides increased venting area, fully available at the initiation of an event. It is expected that even less damage would be observed if an event occurred in a module with this design. The module joints and connections were formally reviewed with respect to their tolerance to a brief internal pressure as high as 40 psig. With minor modifications that have been incorporated into the design, the module was shown to maintain its integrity during such events.

Some of the calculations performed estimated the quantity of dielectric oil that could be involved in a capacitor failure. It was determined that a very small amount of the available oil would contribute to the explosive event, on the order of 500 g or less. This is a small fraction of the total free oil available in a capacitor (approximately 11,200 g), on the order of 5% or less.

The estimates of module pressure were used to estimate the potential overpressure in the capacitor bays after an event. It was shown that the expected capacitor bay overpressure would be less than the structural tolerance of the walls. Thus, it does not appear necessary to provide any pressure relief for the capacitor bays.

The ray tracing analysis showed the new module concept to be 100% effective at containing fragments generated during the events. The analysis demonstrated that all fragments would impact an energy absorbing surface on the way out of the module. Thus, there is high confidence that energetic fragments will not escape the module. However, since the module was not tested, it was recommended that a form of secondary containment on the walls of the capacitor bays (e.g., 1.0 inch of fire-retardant plywood) be provided. Any doors to the exterior of the capacitor bays should be of equivalent thickness of steel or suitably armed with a thickness of plywood. Penetrations in the ceiling of the interior bays (leading to the mechanical equipment room) do not require additional protection to form a secondary barrier. The mezzanine and the air handling units (penetrations lead directly to the air handling units) provide a sufficient second layer of protection.

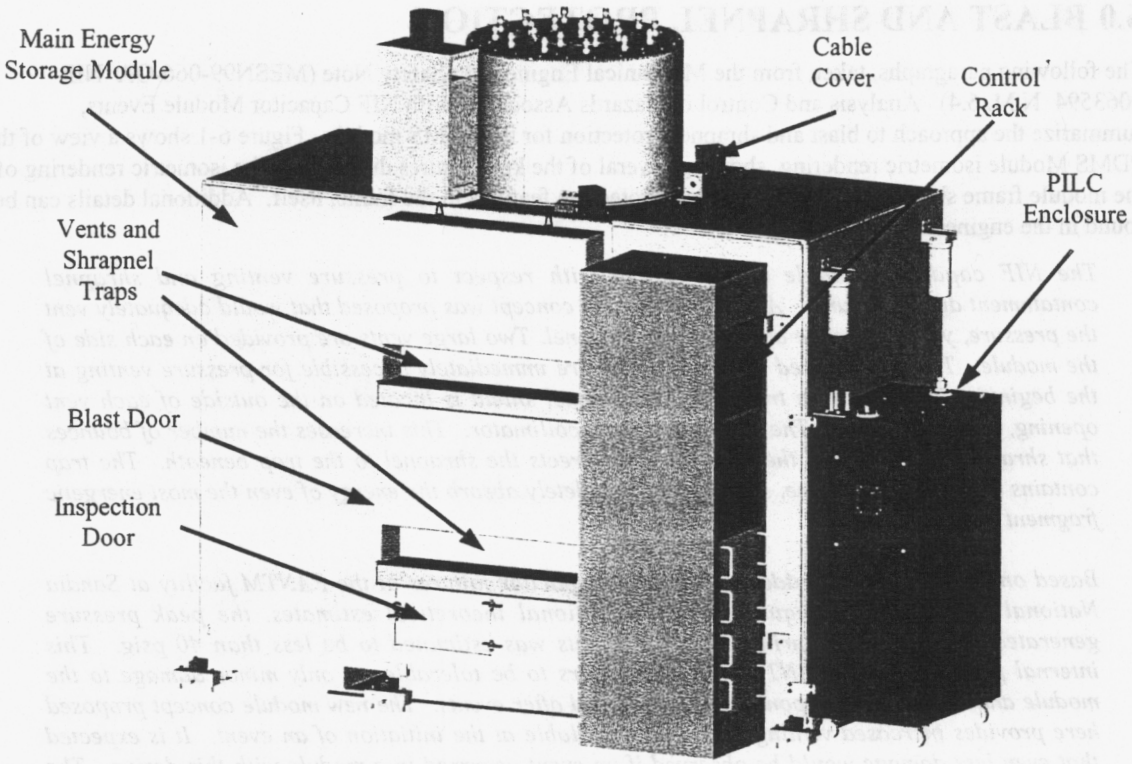


Figure 6-1 Power Conditioning System Module - - Exterior (Rear View)

Additional features of the blast and shrapnel protection not already described above include:

- All panels are 3/16 in-thick steel.
- All panels are welded to the frame, except for the removable panels at the front (for access to the capacitors) and the blast doors.
- Panels are attached with 3/8-16 grade 8 bolts. Thread inserts in the frame increase thread engagement.
- Cables and fiber-optics enter the module through the open face of one of the steel protection cubes, each of which is open only on the side facing the Top Hat.

7.0 CONTROL SYSTEM FEATURES

7.1 Overview

Separate and independent controls are provided for each Power Conditioning Module Subsystem (PCMS). The block diagram of Figure 7-1 shows the module controls and their interconnection to the MESM and PILC. Additional details on internal control rack wiring and functions are shown in the simplified schematic of Figure 7-2. A photograph of the control rack is shown in Figure 7-3.

It should be noted that the PCMS controls described here only provide the low level functionality needed to operate the PCMS. Connection to a Control Station (for stand alone operation) or connection to the NIF Integrated Computer Control System (ICCS) is required in order for the PCMS to operate. These required higher level functions include:

HV Permissive generation
Control Network Services
EC Processor Boot Server
Graphical User Interfaces (GUIs)
Trigger Generation; Control Sequences
Waveform Data Analysis and Archive
Databases for Machine History
Calibration Factors
Other programmable control parameters
Check for off-normal conditions during a shot
- Provide automatic shutdown and alert messages

The module control system provides the following primary functions:

Conditions and distributes AC power
Provides controlled and regulated air for the output switches
Implements HV Safety Permissive (from the NIF Integrated Computer Control System)
Provides control and/or monitoring of all PCMS systems:
- Dump Switches, Gas System, HV Trigger Generators
- Capacitor Charging Power Supplies, Current Monitors

Interfaces to the higher levels of the control system
Houses the Main and PILC Charging Power Supplies
Aborts charging, if capacitors are held at charge longer than pre-set time

Functions of the module control system are summarized in the shot sequences described in Table1 (a full system shot, MESM and PILC) and Table 2 (a lamp-check shot, PILC only), located at the end of this document.

7.2 Key Control System Assemblies and Components

7.2.1 CONTROL RACK

PCMS module controls are provided by the control rack, which is attached to the PCMS module frame. The control rack houses the following equipment:

AC Breaker Panel
Gas Pressure Controller
Embedded Controller
Main Capacitor Charging Power Supply (consists of 2 units)
PILC Capacitor Charging Power Supply
480/120 Step-down Transformers

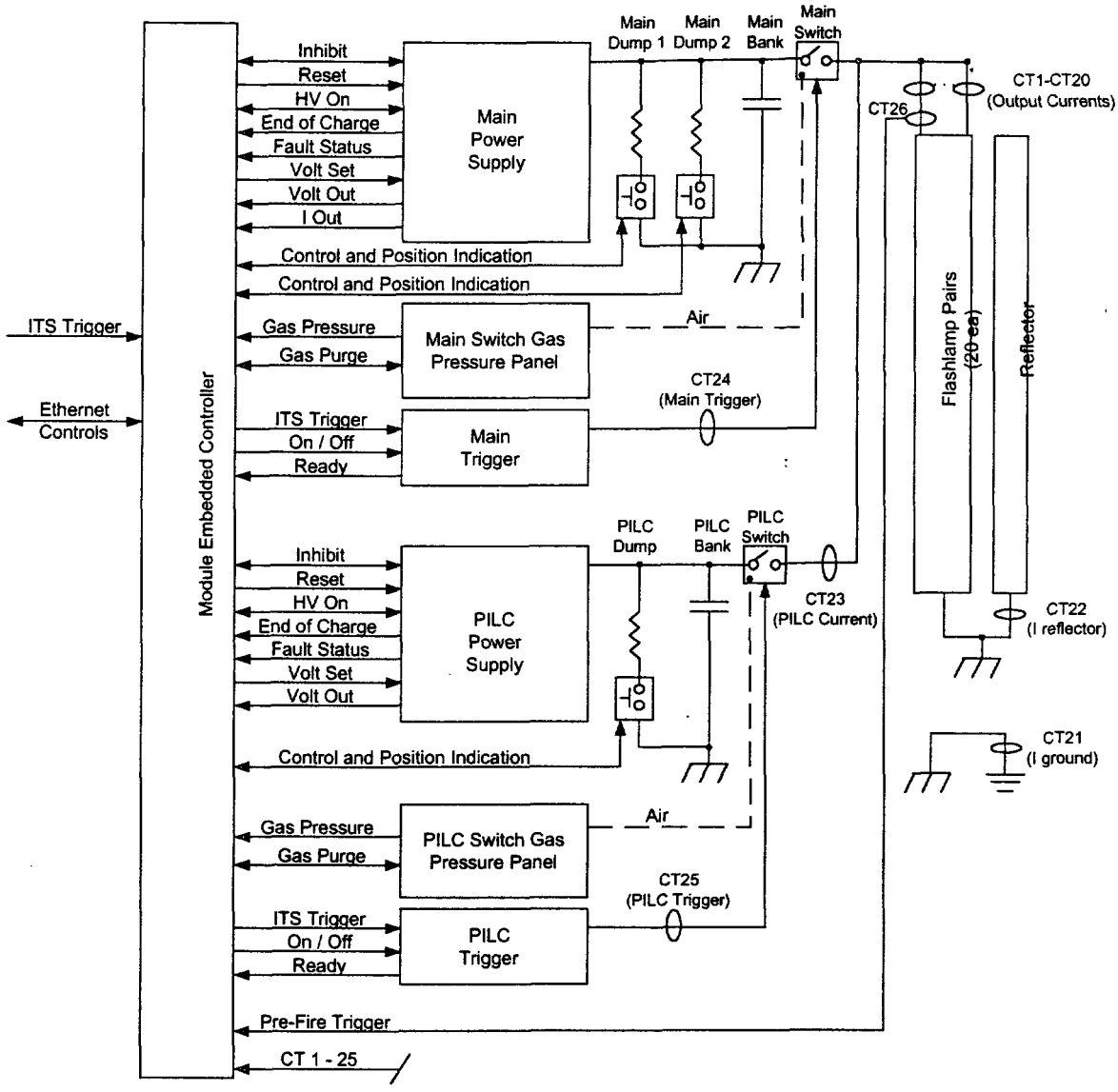


Figure 7-1 Module Controls Block Diagram

7.2.2 AC Breaker Panel

The AC Breaker Panel of the control rack accepts 480 VAC 3phase wye connected, 100 A service from the facility utilities. This service is typically delivered on a 4/C 2awg with 1/C 6awg GND high flexibility cable. Neutral is not used in the present design, however there is the ability to land a neutral wire.

The AC Breaker Panel provides independent circuit breakers with lockouts for the HVPSs and independent fuses for the Embedded Controller and Gas Pressure Controller. The HVPS breakers feed directly to the HVPSs. The fuses feed two 480/120 step-down transformers, discussed further below.

A circuit breaker with lockout is provided on the front of the Gas Pressure Controller chassis. This breaker provides power to the HV Trigger Generators only. It is used as a HV Trigger Generator lockout when controls are operated with personnel present in the vicinity of the PCMS and the HV Permissive is temporarily enabled.

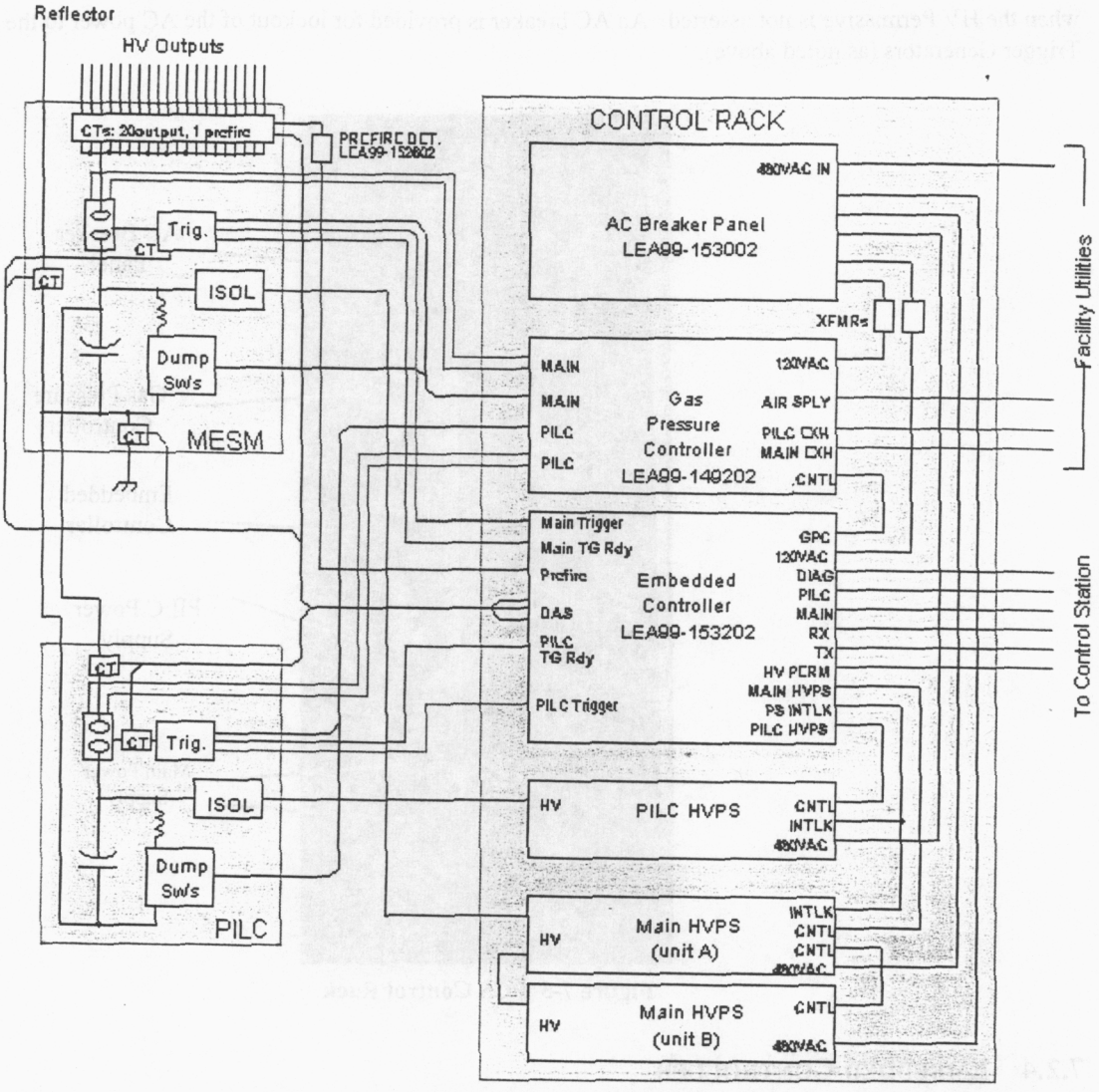


Figure 7-2 Module Controls Simplified Schematic

7.2.3 GAS PRESSURE CONTROLLER

The Gas Pressure Controller serves two functions. It controls the gas (air) pressure to the Main and PILC spark gap output switches, and provides a control interface for 110 VAC devices (dump switches and HV Trigger Generators.).

For the gas system, the Gas Pressure Controller provides independent air pressure regulation for both switches. The Main Switch pressure is set through the control system. The PILC pressure is manually set from the front of the chassis. The controller also provides a means to purge the switches in order to flush out debris. The chassis houses all the valves, regulators and pressure sensors, as well as controls interfaces for these components. House air (at 100 psig nominal) is brought into the chassis, regulated and delivered to the switches. Air from the switches is returned to the chassis through filters, which filter out debris resulting from switch operation. Except for a common air supply, the two air systems are independent, one for the MESM and one for the PILC. Two separate exhaust lines are returned to the facility.

The Gas Pressure Controller also provides power and control interfaces for the two MESM dump switches, the PILC dump switch, the Main HV Trigger Generator and the PILC HV Trigger Generator (which are 110°VACdevices). A hard wired interlock interrupts AC power to all dump switches and HV Trigger Generators

when the HV Permissive is not asserted. An AC breaker is provided for lockout of the AC power to the HV Trigger Generators (as noted above).

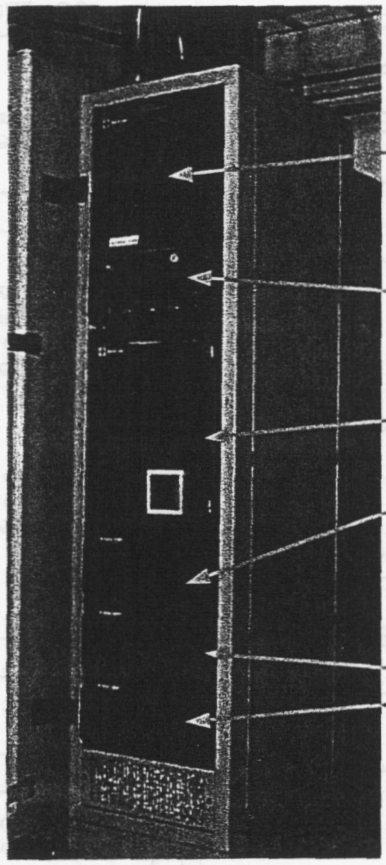


Figure 7-3 PCS Control Rack

7.2.4 EMBEDDED CONTROLLER

The Embedded Controller (EC) is the heart of the PCMS controls. In general, it receives commands from the higher level controls (either the control station or the NIF ICCS) which it transforms into control signals for the various PCMS devices. It reads status inputs from these devices and (upon command) provides this status back to the higher level controls. All control signals between the EC and the devices are isolated. Communication with the higher level controls is through a fiber optic ethernet network using TCP/IP. The EC utilizes a COTS Pentium-class single board computer running VX Works. It is a diskless system that downloads its operating system and applications from a boot server which is part of the higher level controls. Boot-up and execution of the control application is automatic upon power-up of the EC. Analog and digital I/O is provided by COTS I/O boards. Independent digital and analog modules provide electrical isolation of all control and monitor signals.

The EC implements a HV interlock based on the state of the HV Permissive, which it receives via a fiber optic cable. The permissive is typically used to disable all HV at the module when the personnel safety interlocks are not made up. The HV Interlock is hard wired to the Main and PILC HVPSs, and the Gas Pressure Controller. A watch-dog timer is also hardwired in series. If the EC does not strobe the timer at least every two seconds, the HV interlock is opened. The EC can read the status of the HV Interlock. Loss of communication with the ICCS control or termination/lock-up of the EC software will cause drop-out of the watch-dog timer.

7.2.5 DATA ACQUISITION

The EC contains a high-speed digitizer system referred to as the DAS (data acquisition system). On each shot (if armed by the control system), this system captures signals from twenty five current probes located throughout

the PCMS: twenty output currents plus a duplicate output current used for pre-fire detection, pulsed-power ground and FAU reflector currents, PILC output current, and the Main trigger and PILC trigger currents (these two are summed at the DAS). A fiber optic trigger from the external timing system triggers the acquisition of the signals. Upon entering the EC cabinet, these signals pass through a transient protection circuit, which is designed to protect the digitizer inputs. The digitizers simultaneously capture 24 channels at 5 M samples per second and store the 12 bit data in on-board 8k x 12bit buffers. Additional, slower, digitizers record the Main HVPS charge voltage and current and the PILC charge voltage at 2 samples per second. Upon command, the EC reads and transmits the data to the higher-level control system.

The DAS is used as a module performance diagnostic and a lamp integrity diagnostic. The EC compares the twenty acquired output waveforms with a reference waveform and provides a pass/fail indication to the higher-level control system. There is one extra current probe on output cable one. This signal is used as a pre-fire detector. It is connected to a prefire detector fiber-optic transmitter, which is connected to the DAS system. This signal serves to trigger DAS system data capture if premature output current is sensed (which would be the case if the module fired before it was triggered by the timing system).

7.2.6 High Voltage Charging Power Supplies

The high-voltage charging power supplies for the Main and PILC capacitors are located within the control rack and controlled by the embedded controller. The Main HVPS consists of two modules, running in a master-slave configuration. The PILC power supply is a single module. Both the Main and PILC power supplies use 480 VAC 3-phase input power. Isolation and power supply protection circuits for the two power supply systems are located on the top of the MESM frame and within the PILC cabinet, respectively.

7.2.7 480/120 Step-Down Transformers

Two step-down transformers, located in the bottom of the Control Rack, deliver 120 VAC to the EC and Gas Pressure Controller for control rack functions, and to the Main and PILC cabinets for control of the safety dump switches and for power to the Main and PILC trigger generators. An additional transformer, a Sola/Hevi-Duty Inc. CSV transformer, is used to provide clean regulated line voltage with harmonic protection for the embedded controller, the heart of the PCMS controls.

7.2.8 Triggers

The PCMS requires three separate triggers, one each for Diagnostics, PILC and Main. The diagnostic trigger was discussed above. The PILC and Main Triggers are not created or manipulated in the Control Rack. These fiber optic signals are generated by the external timing system. They pass through the rack on their way to the PILC and Main Trigger Generators. Each directly triggers its respective PILC or Main Trigger Generator. Each generator provides a fiber optic status signal back to the EC, which indicates that the trigger generator is ready to fire.

7.2.9 Charge Voltage Status Monitor

The EC software will abort the charge cycle if the MESM remains charged to the HVPS set point for longer than 15 seconds or if the PILC remains charged to its HVPS set point for longer than 90 seconds.

7.3 Shot Sequences

Table 7-1 Full Shot Sequence (MESM and PILC)

Parameter	Monitor	Control	Required Level / Status	Pre Shot	Ready to Charge	Charging	Ready to Fire	Discharge Pulse	Post Shot	Data Archive	Comments
MESM Switch Pressure	•	•	Set point determined by # of shots on output switch	•					•		Set under software control.
	•		Verify: set point ± 2 psig		•						
			-			•	•	•			Regulator & pressure sensor a isolated by valves during char
	•	•	Purge cycle						•		
MESM Charge Voltage	•	•	Ramp to set point (typ. 23.8 kV)			•				•	Monitor V_{ch} profile at 2 Hz ra during charging.
	•	•	At set point ± 0.2 %				•			•	
			-					•			
	•	•	0 V + 20 V						•	•	HVPS commanded off post sh
MESM Dump Switches	•	•	Closed	•					•		
	•	•	Open		•	•	•	•			
MESM Trigger Gen.	•	•	Off	•					•		
	•	•	Charged		•	•	•	•			
PILC Switch Pressure		•	Set point determined by # of shots on output switch	•	•				•		Manually set regulator.
	•		Verify: set point ± 2 psig		•						
			-			•	•	•			Regulator & pressure sensor a isolated by valves during char
	•	•	Purge cycle						•		
PILC Charge Voltage	•	•	Ramp to set point (typ. 24 kV)			•				•	Monitor V_{ch} profile at 2 Hz ra during charging .
	•	•	At set point ± 2 %				•			•	
			-					•			
	•	•	0 V + 20 V						•	•	HVPS commanded off post sh
PILC Dump Switch	•	•	Closed	•					•		
	•	•	Open		•	•	•	•			
PILC Trigger Generator	•	•	Off	•					•		
	•	•	Charged		•	•	•	•			
DAS Status	•	•	Armed			•	•				
	•	•	Acquire					•			

Table 7-2 Lamp-Check Shot Sequence (PILC only)

Parameter	Monitor	Control	Required Level / Status	Pre Shot	Ready to Charge	Charging	Ready to Fire	Discharge Pulse	Post Shot	Data Archive	Comments
MESM Switch Pressure	•	•	Set point determined by # of shots on output switch	•					•		Set under software control.
	•		Verify: set point ± 2 psig		•						
			-			•	•	•			Regulator & pressure sensor a isolated by valves during char
	•	•	Purge cycle								No purge on LC shot.
MESM Charge Voltage	•	•	0 kV + 20V	•	•	•	•	•	•	•	Monitor V_{ch} profile at 2 Hz ra during charging.
MESM Dump Switches	•	•	Closed	•	•	•	•	•	•		
MESM Trigger Gen.	•	•	Off	•	•	•	•	•	•		
PILC Switch Pressure		•	Set point determined by # of shots on output switch	•	•				•		Manually set regulator.
	•		Verify: set point ± 2 psig		•						
			-			•	•	•			Regulator & pressure sensor a isolated by valves during char
	•	•	Purge cycle								No purge on LC shot.
PILC Charge Voltage	•	•	Ramp to set point (Typ. 28.5 kV)			•				•	Monitor V_{ch} profile at 2 Hz ra during charging .
	•	•	set point ± 2 %				•			•	
			-					•			
	•	•	0 V + 20V						•		HVPS commanded off post sh
PILC Dump Switch	•	•	Closed	•					•		
	•	•	Open		•	•	•	•			
PILC Trigger Generator	•	•	Off	•					•		
	•	•	Charged		•	•	•	•			
DAS Status	•	•	Armed			•	•				
	•	•	Acquire					•		•	

8.0 KEY SUBSYSTEMS AND COMPONENTS

8.1 Main Capacitors

The main energy storage capacitors for NIF are a self-healing, metalized dielectric. A summary of the performance specifications is given below:

Nominal capacitance	290 µF, - 0% + 10%
Nominal stored energy	85 kJ
Nominal operating voltage	24 kV
Maximum operating voltage	26 kV
Maximum rep-rate	1 discharge every 2 minutes
Maximum normal discharge current	30,000 A
Voltage reversal during normal operation	10%
Nominal discharge period for normal operation (critically damped sine)	400 µs
Maximum fault discharge current	95 kA
Voltage reversal during fault	65%
Nominal discharge period for fault discharge	350 — 450 µ
Number of fault discharges during capacitor life	25 shots
Capacitor life	> 20,000 shots

8.1.1 CAPACITOR AGING

Due to the self-healing technology of the capacitors, combined with the high dielectric stress required for the high energy density of the NIF capacitors, it is expected that the capacitors will slowly loose capacitance throughout their operational life. At some point (planned to be 5% capacitance loss), the loss of capacitance will cause the capacitor to be defined as at end of life.

8.1.2 CAPACITOR FAILURE MODES

In addition to this aging process, there are numerous possible failure modes internal to the NIF capacitor. These failures usually manifest themselves as either a shorted capacitor or a capacitor that has lost a significant amount of capacitance, i.e., sections are open.

The capacitors can short internally due to an insulator or, possibly, dielectric winding breakdown. The insulator breakdown can occur across the inner surface of the high-voltage terminal insulator. This breakdown may be caused by impurities in the impregnation oil, air bubbles in the oil, or over-voltage of the capacitor. Shorts may also occur due to catastrophic failure of a section of dielectric windings.

Capacitor failure due to capacitance loss is generally caused by the disconnection of one or more capacitor sections, due to failures of interconnections between windings or sections, which results in lost capacitance. Each winding is connected to the other windings by a soldered conductor on the end of the winding. This conductor has been sprayed with an Al or Al-Zn endspray. The bonding between the endspray and the winding may fail because of over-current, excessive mechanical stress on the endspray connection (such as may occur during shipping), or incorrect manufacturing processes.

8.1.3 NIF CAPACITOR DEVELOPMENT HISTORY

Capacitor development for NIF has occurred over several years and included extensive testing. During early phases of the development, many capacitor failures were experienced both during individual capacitor testing and during module testing. The following summarizes efforts in developing high-energy-density capacitors and the relationship of this effort to the production capacitors that will be used in NIF:

- Preproduction Capacitors
  - Six capacitor failures were experienced on the "First Article NIF Test Module" (FANTM).
  - All FANTM capacitors were prequalification units.

- One of the vendors supplying capacitors for this prototype was eliminated from the bid list because of failures during qualification testing.
- Qualification Capacitors
  - Qualification tests were conducted to qualify capacitor designs and manufacturing processes.
  - Extensive testing was performed on units from four vendors to qualify each vendor to be on the bid list. Seventeen units were tested for a minimum of 25,000 shots each.
  - Total qualification shots on production units: 1,500,000 shots with zero failures.
- Production Capacitors
  - Each production capacitor is tested for 500 shots before acceptance.
  - One capacitor in every 1—2 shipments is life-tested (0.5% sample).
  - Acceptance testing to date (June 2002): 600,000 shots with two failures.

Analysis of the qualification test data indicates that the mean time to failure, averaged over the life of NIF, will be on the order of 35,000 shots. This is believed to be a very conservative number based on life-test data. The sample of capacitors that have been tested have individual lifetimes in excess of 65,000—100,000 shots.

8.1.4 CAPACITOR SUPPLIERS

The NIF capacitors are being manufactured by two vendors, ICAR SpA in Monza, Italy and Sorrento Electronics in San Diego, California. The internal construction and dielectric systems utilized by each vendor are different. The capacitors are shown in the photograph of Figure 8-1.

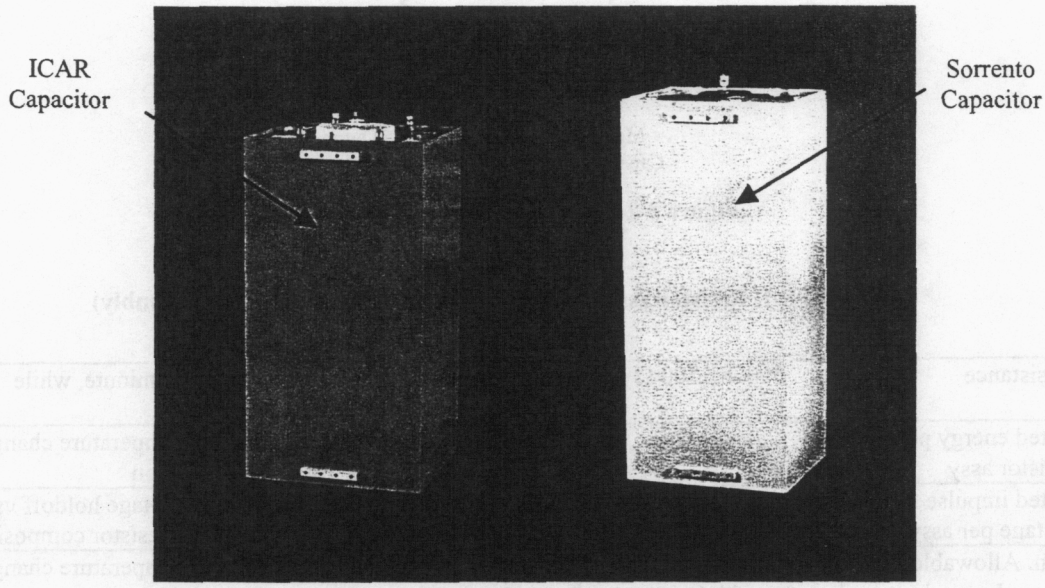


Figure 8-1 Main Energy Storage Capacitors

Relevant Reports

Report #	Subject
NIF-0005095	NIF Main Energy Storage Capacitor Specification
NIF-0058472	Procedure for Removal of Failed Capacitors
NIF-0077342 PCS 0129	NIF Main Energy Storage Capacitors Hazard Documentation, Maxwell Technologies Energy Products
NIF-00077482 PCS 0130	NIF Capacitors Safety Documentation, ICAR S.P.A.

8.2 Dump Resistors

The MESM safety dump system uses a set of four resistor assemblies. The resistor assemblies are used in series pairs, to assure that the flashover or other failure of a single resistor will not result in a direct short of the module hot bus to ground. A single resistor is capable of supporting the full voltage of the module and can dissipate the full energy of the module without catastrophic failure. **Dissipation of the full module energy in one resistor will, however, stress the resistor to the point that it is to be replaced after such an event.**

In addition, two separate assemblies are used in parallel, each with its own safety dump relay, as shown in the simplified schematic of Figure 8-2. This reduces the "cool-down" time required between full-energy dumps and provides redundancy in the safety discharge circuit. Details of the resistor design parameters are given in Table 8-1. Capacitor bank residual voltage as a function of time during the dump process for single and two parallel dump assemblies is given in Table 8-2.

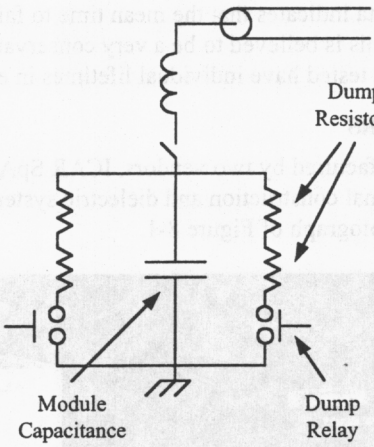


Figure 8-2 Dump Circuit Simplified Schematic

Table 8-1 Resistor assembly design summary (each 10-disk assembly)

		Design Basis
Resistance	560Ω ± 100 Ω	Selected to assure full discharge in < 1 minute, while keeping discharge current < 100 A
Rated energy per resistor assy	1.1 MJ	Based on HVR general data base on temperature change vs energy, mass, and resistor composition
Rated impulse voltage per assy	50 kV	Based on HVR general data base on voltage holdoff vs assembly length, resistor coating, and resistor composition
Min. Allowable Dump Interval	Wait ≥ 30 minutes after a high-energy dump	Based on HVR general data base on temperature change vs energy, mass, and resistor composition Note: The full set of two parallel dump resistor assemblies can absorb two high-energy dumps close together, but it is not possible to be certain that both sets will share the energy of both dump events.
Supplier and Part #	HVR Advanced Components. Part # J10PFA561L (with insulating brackets) and J10PFB561L (no brackets)	

NOTE: **Resistor must be replaced in the event of a fault resulting in contamination of the resistor with capacitor oil or discharge of a full module (>1.5 MJ) into a single 10-disc resistor**

One dump assembly is near the top of the module, at the front (normal service) side. The other assembly is at the bottom of the module, at the rear. Access hatches are provided in the blast doors for each assembly. The location of the front (upper) dump circuit is shown in Figure 8-3. The two resistors can be clearly seen in the figure. The only difference between the two assemblies is the addition of the fiberglass L brackets for use in

the upper assembly. The rear (upper) resistor assembly (visible in Figure 1-2) has essentially the same format, but inverted for mounting on the floor. The dump relay and the resistor with the L brackets are mounted on the floor of the module.

Table 8-2 Residual capacitor voltage versus time after dump relays drop

Two Parallel Dump Assemblies

Time (sec)	Voltage (V)
0	24,000
5	7,527
10	2,361
20	232
30	23
40	2
60	-

Single Dump Assembly

Time (sec)	Voltage (V)
0	24,000
5	12,698
10	6,718
20	1,881
30	526
40	147
60	12

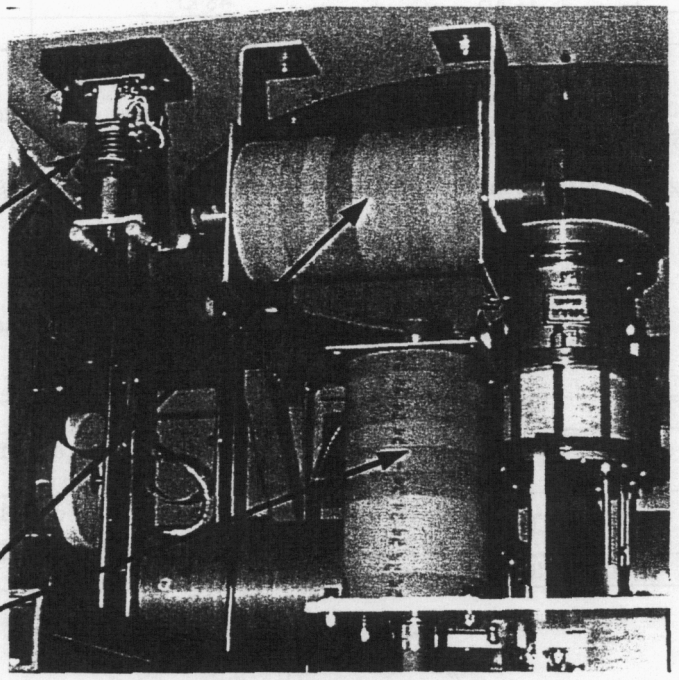


Figure 8-3 Location of Front Dump Resistors and Relay

Relevant Reports

PCS Report #	Subject
PCS 0088	10-Disc Assembly Ratings - - Reviews calculated temperatures and cooling rates for various energy dissipation levels
PCS 0086	Thermal Performance of Resistor Assemblies - - Reviews calculated temperatures and cooling rates for various energy dissipation levels for the earlier 8-disc resistor assemblies
PCS 0080	Resistor Assembly High Temperature Test - - Discusses energy dissipation and high-temperature damage to similar resistors.

PCS Report #	Subject
PCS 0057	Modification of the FANTM Dump Resistors - - Discusses failure of the single-resistor FANTM assembly and the rationale for going to two resistors in series

8.3 Reflector Resistor

The Reflector Cable Resistor was selected to limit the current through the reflector cable in the event of a fault to the reflector. It was determined that in the absence of this resistor, currents will often be high enough (in the range of 100 kA) to fracture the glass blast shield, possibly causing damage to the laser glass. Tests were performed on FANTM to confirm the current predicted by circuit modeling. Table 8-3 summarizes predicted current and voltage, as a function of the added resistance.

Table 8-3 Predicted Reflector Fault Paramaters

Added Resistance	Peak Current	Resistor Energy	Peak Reflector Voltage
0	100 kA	-	10.5 kV
0.1 Ω	64 kA	170 kJ	11 kV
1 Ω	12 kA	48 kJ	12 kV
5 Ω	3 kA	11 kJ	13 kV

Since there may be as many as 6 FAUs that are connected in parallel, up to 8 reflector resistors may combine in parallel in the event of a fault. Thus the effective resistance may fall as low as 1.25 Ω.

Table 8-4 summarizes the design parameters of the selected resistor, shown in its installed orientation in the isometric drawing of Figure 8-4 and mounted in the MESM in Figure 8-5.

Table 8-4 Resistor assembly design summary (3-disk assembly)

		Design Basis
Resistance	10Ω	See Table 8-3
Rated energy per resistor assy	75 kJ	Based on HVR general data base on temperature change vs energy, mass, and resistor composition
Rated impulse voltage per assy	15 kV	Based on HVR general data base on voltage holdoff vs assembly length, resistor coating, and resistor composition
Supplier and Part #	HVR Advanced Components Part # J03FFA100K	

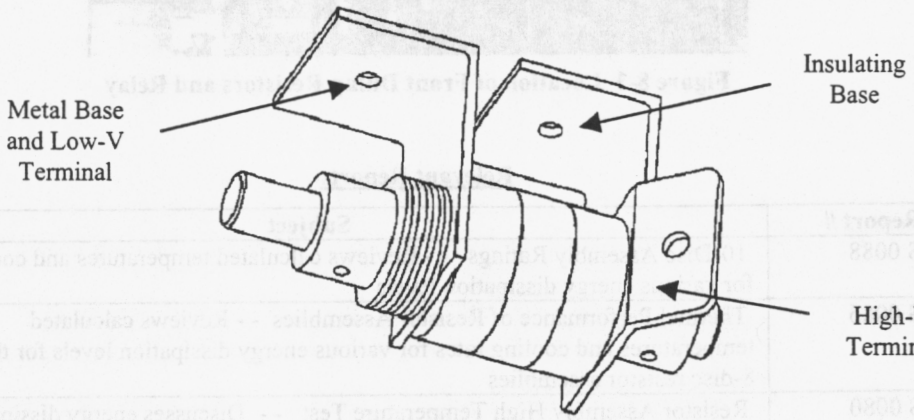


Figure 8-4 Reflector resistor in its installed orientation

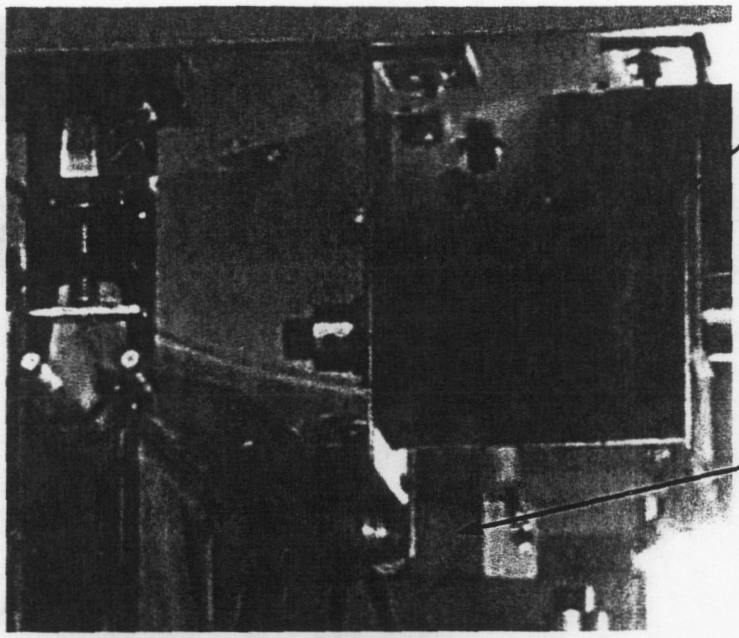


Figure 8-5 Reflector Resistor Mounted in the MESM

Relevant Reports

PCS Report #	Subject
PCS 0070	FANTM Reflector Resistor Test Results , E. S. Fulkerson, July 1999

8.4 Damping Elements

The damping elements in the NIF module were designed and developed to limit the fault current associated with the failure of a MESM capacitor to less than 400 kA and to absorb fault energy in the internal resistance of the damping element. If a capacitor fails by shorting (internally or externally), the one damping element that is in series with the failed capacitor absorbs more than 80% of the energy initially stored in the remaining capacitors. With up to 2.2 MJ stored, a single damping element can dissipate over 1.8 MJ in a capacitor failure.

The energy deposited in the damping element during a fault causes extreme internal heating of the coil and high mechanical stresses on the containment sleeves. This results in significant degradation of the structural integrity of the damping element. **The damping element connected to the failed capacitor will be damaged during the fault and *must* be replaced before operation resumes. It should *never* be reused.**

The stainless-steel coil used in the damping element is shown in Figure 8-6. The two ends of the coil are attached to split stainless steel sleeves (visible in the figure) which form the connection points for the inductors. The coils are designed to fit into a very robust fiberglass-reinforced plastic sleeve, and are potted in place. High-strength spacers are placed between the coils prior to the encapsulation. An assembled coil is shown in Figure 8-7. Figure 8-8 shows the key features of the coil assembly.

Note: The design of this coil went through several iterations before reaching this successful design. Modifications to the design would require extensive re-certification prior to implementation.

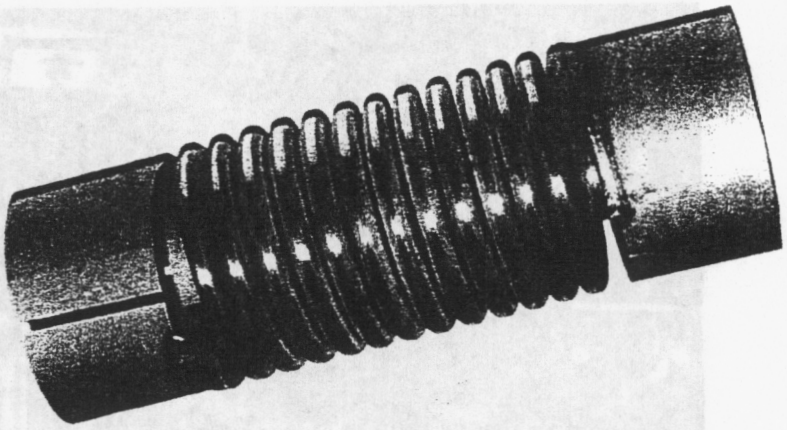


Figure 8-6 Split-Sleeve Damping Coil

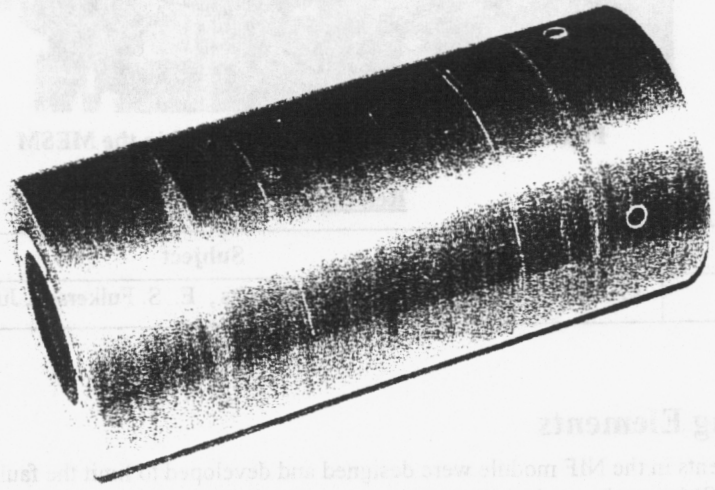


Figure 8-7 Damping Element, after Encapsulation

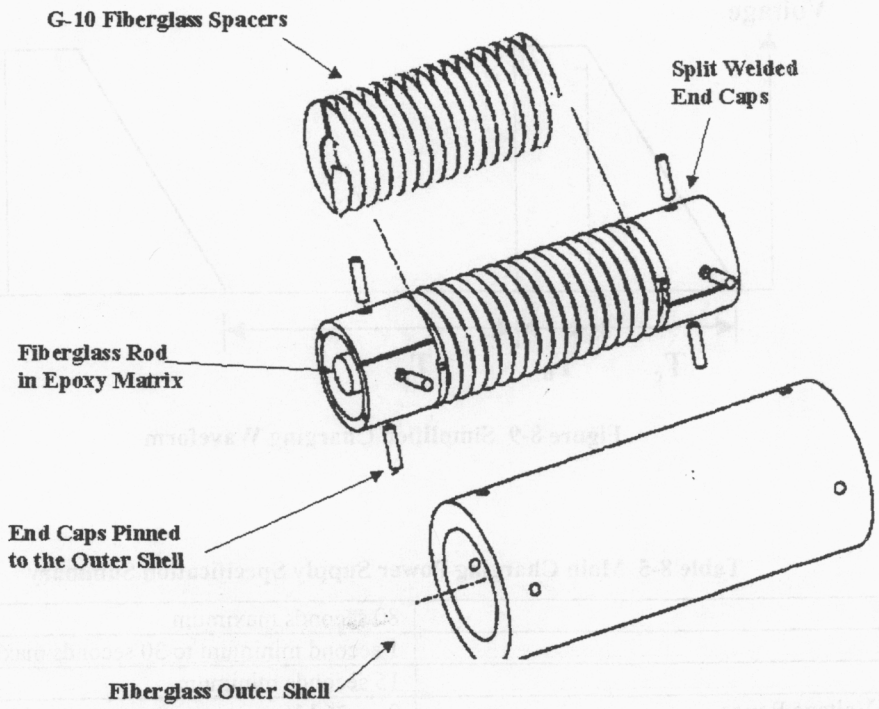


Figure 8-8 Damping Element Construction Features

Relevant Reports

PCS Report #	Subject
PCS 0027	Damping Element Tests of Split-Sleeve Design, R. Anderson, February 1999
PCS 0035	Damping Coil Welding Information
PCS 0036	Damping Coil Design Sketches and Information

8.5 Main Charging Power Supply

Each NIF amplifier power conditioning module is charged to a nominal 24 kV with high voltage switching supplies built by Sorrento Electronics (formerly Maxwell Technologies). Each module has a capacitance of 5.5 – 7.7 mF, stores a maximum of 2.2 MJ of energy, and is charged by a power supply formed of 2 modules, located in the control rack, as shown above in Figure 7-3.

The power supplies charge the NIF capacitor modules prior to discharge into the flashlamp loads. The operating cycle is shown in Figure 8-9 where T_c is the time required to charge the capacitor bank, T_h is the time that the capacitor bank must be held at the requested voltage and T_d is the time between shots. The specification for the power supply is summarized in Table 8-5.

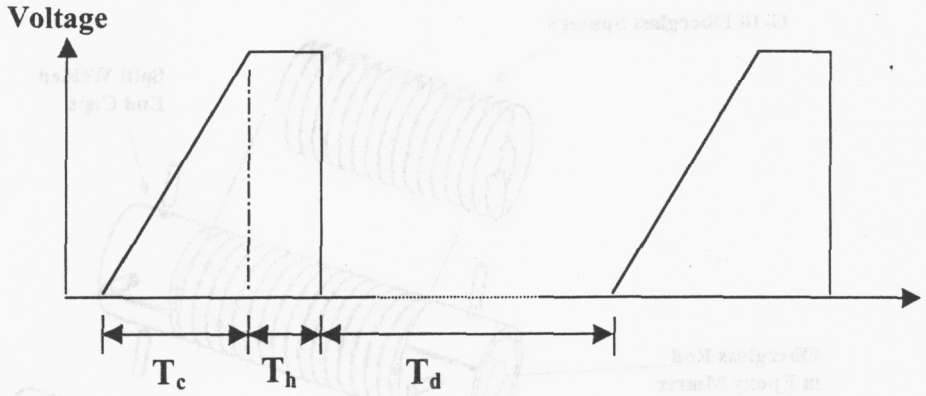


Figure 8-9 Simplified Charging Waveform

Table 8-5 Main Charging Power Supply Specification Summary

Tc	80 seconds maximum
Th	1 second minimum to 30 seconds maximum
Td	15 seconds minimum
Operating Voltage Range	0 — 26 kV
Nominal operating voltage	23.5 kV
Load capacitance	5.5 mF to 7.7 mF
Voltage regulation	± 0.05% of nominal operating voltage
Output voltage stability	± 0.05% of nominal operating voltage for 144 hours
Efficiency	> 85%
Power Factor	> 0.90
Polarity	Positive output voltage with respect to case
Input Power	480 VAC, wye-connected three phase
Output setpoint accuracy	– 0.1%
Specification Number	NIF5001464

The design of the power supplies has gone through several iterations during the development process, and a few important fault modes have been found. The primary fault modes that may be important in de-bugging the system in the future have been: 1) failure of the high voltage diodes and 2) failure of the series-resonant capacitors. Further details are given in the two reports listed below.

Relevant Reports

PCS Report #	Subject
PCS 0015	Voltage Reversal Testing of the NIF First Article HV Power Supply, R. Anderson
PCS 0148	Capacitor Charging Power Supply Testing, S. Fulkerson, April 24, 2002

8.6 Output Cables

The output cables for the NIF Power Conditioning System carry the output current from the PCMS modules to the flashlamp assemblies. Coaxial cables are used, to meet system inductance and EMI budgets. Each module uses 20 output cables. Each cable is connected at one end to a ballast inductor at the Top Hat of the PCMS

module, and to a series-connected pair of flashlamps through the Big T of the associated Frame Assembly Unit (FAU) at the other end. Over 500,000 feet of this cable will be used in the completed NIF system. A photograph showing details of the cable construction is shown in Figure 8-10.

An underground residential distribution (URD) cable, designed for 28 kV operation at 60 Hz, has been selected. The outer conductor of the URD cable consists of concentric wires spiraled around the dielectric, unlike the braided outer conductor of RG-220 originally used in the pre-prototype system. A semiconducting layer covers both the center conductor of the cable and the outer surface of the cross-linked polyethylene dielectric material, which increases the voltage holdoff capability of the cable.

The URD cable has been thoroughly tested for high-voltage integrity under the normal PCS operating condition, as well as under fault conditions, where the currents can be in excess of 100 kA. It is important to note that the cable will probably not be usable after a fault in which the ballast inductor shorts. This failure mode is considered to be extremely unlikely. However, if it were to occur, the cable would probably be damaged and need replacement.

During normal operation, each cable will be pulsed with high voltage (up to 60 kV from the PILC ring-up) and high current (25kA nominal) pulses. Lifetime of the NIF PCS transmission line cable is 30 years and 40,000 shots. Voltage waveforms are shown in Figure 8-11, Figure 8-12, and Figure 8-13.

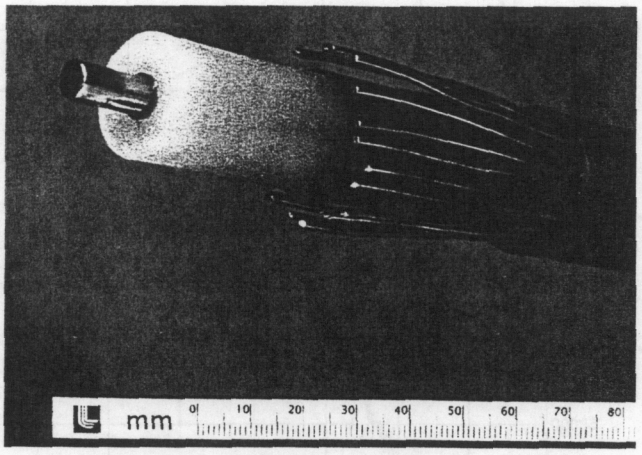


Figure 8-10 PCS Output Cable

The center conductor of the cable is a single solid bare annealed copper wire with an overall diameter of 0.289 inches +/-0.002 in, coated with an extruded semiconducting shield to reduce risk of high-voltage cable failure. The cable insulation is extruded extra-clean crosslinked polyethylene, with an average insulation thickness of 0.280 inches. The outside diameter of the insulator is 0.940 inches. To further reduce breakdown risk, the insulation is shielded by an extruded semiconducting cross-linked coating between the insulation and the return conductor. The return conductor is formed of 23 each, 14 AWG solid bare annealed copper wires (0.0641 +/- .001 inches diameter), evenly spaced, and spiral-wound around the insulation.

The return wires are enclosed in a tough jacket of BICC CPE 24-2 or a combination of a linear low density polyethylene (LLDPE) jacket with a minimum thickness of 0.050 inches and an extruded PVC jacket over the LLDPE. The total jacket thickness is to be 0.080+/-0.010 inches.

The overall diameter of the cable, including the jacket, is approximately 1.34 inches. The cable is marked at a maximum of two-foot intervals with the manufacturer s name and part number, NIF specification number, Batch or lot code, and Date code. The initial purchase of cable is from Pirelli Corp., Colussa, CA. BICC General Cable was also qualified as an alternative supplier

The cable has been designed to assure that it will meet all of the required specifications after storage for 30 years within the following range of environmental conditions:

Temperature	-15 C to +60 C (dry bulb)

Relative humidity	5% to 95% non-condensing
Altitude	200 ft below Sea Level to 8,000 ft

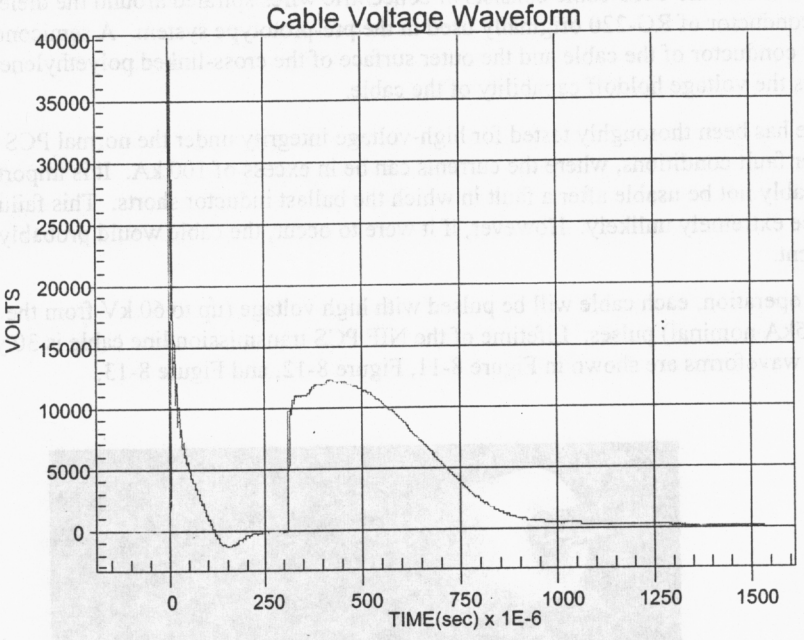


Figure 8-11 Cable voltage waveform.
The initial high-voltage spike is due to voltage ring-up into the initially open-circuit flashlamps. See Figure 8-12 for more details.

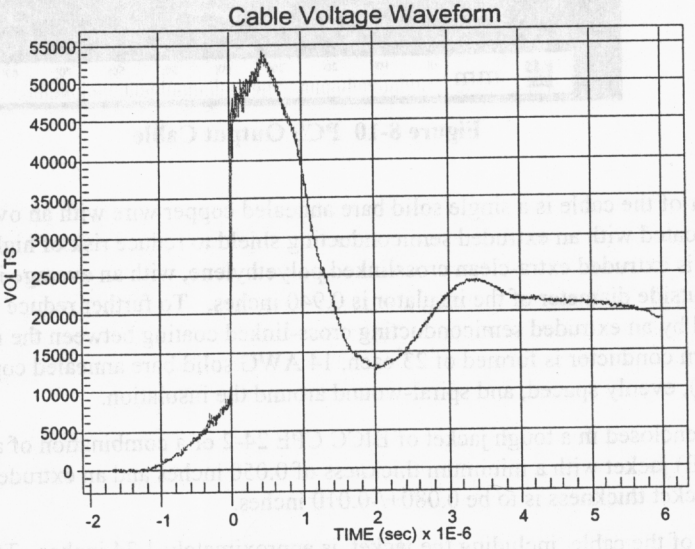


Figure 8-12 Higher time/voltage resolution of the first 7 microseconds of the cable voltage waveform

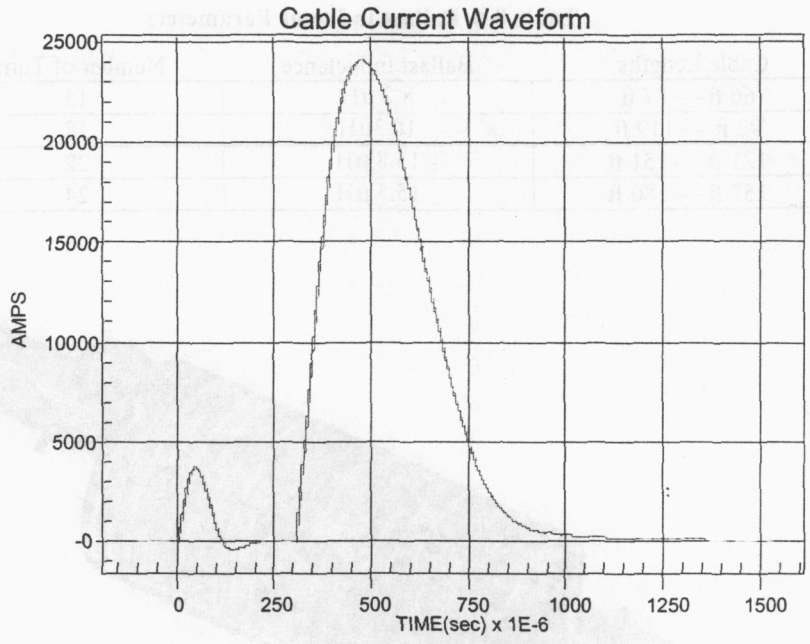


Figure 8-13 Cable current waveform

Relevant Reports

Report #	Subject
NIF-5005133	Specification of Transmission Line URD Cable for NIF Power Conditioning System
AEIC CS5-94	Specifications for Cross-Linked Polyethylene Insulated Power Cables rated 5 through 46 kV
ICEA S-66-524	Cross-Linked Thermosetting Polyethylene Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy

8.7 Ballast Inductors

The module includes 20 ballast inductors, one for each cable. The inductors help to keep current uniform, cable to cable, and minimize fault current in the event of a flashlamp failure or other short at the output of the module. The inductors must be able to survive 130 kA lamp faults, but will be replaced after such a fault. The inductors are formed from _ DIA copper solid wire, as shown in the coil photo of Figure 8 -14, and are contained in fiberglass-reinforced cylinder, visible in the photo of the assembled inductor in Figure 8-15.

The module design calls for a nominal 30 H total inductance for the combination of the ballast inductor, output cable, and a pair of flashlamps, including the flashlamp connection inductance. Different inductance values will be used to compensate for the different inductances associated with the different cable lengths required for different relative locations of the PCS module and its associated set of flashlamps. Each module will have only one cable length, and thus one ballast inductance value. The ballast inductance values associated with different cable lengths are summarized in Table 8-6.

Table 8-6 Ballast Inductor Parameters

Cable Lengths	Ballast Inductance	Number of Turns
66 ft — 87 ft	8.2 μH	15
92 ft — 119 ft	10.3μH	18
121 ft — 151 ft	13.8 μH	22
152 ft — 180 ft	15.5 μH	24

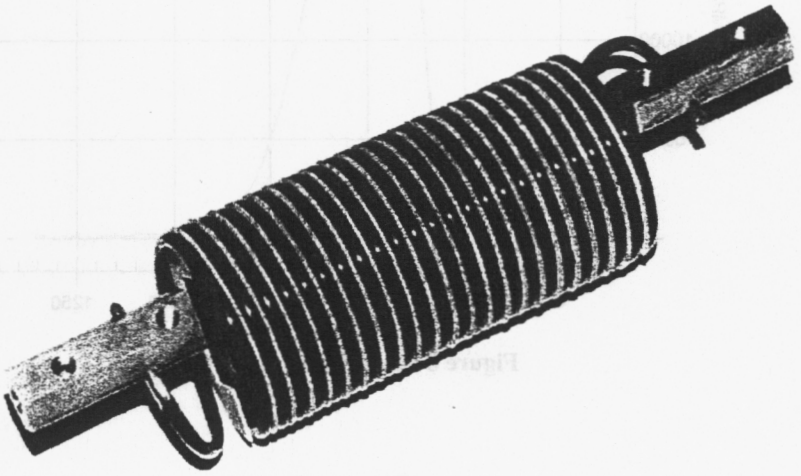


Figure 8-14 Ballast Coil, Showing Termination and Insulation Details

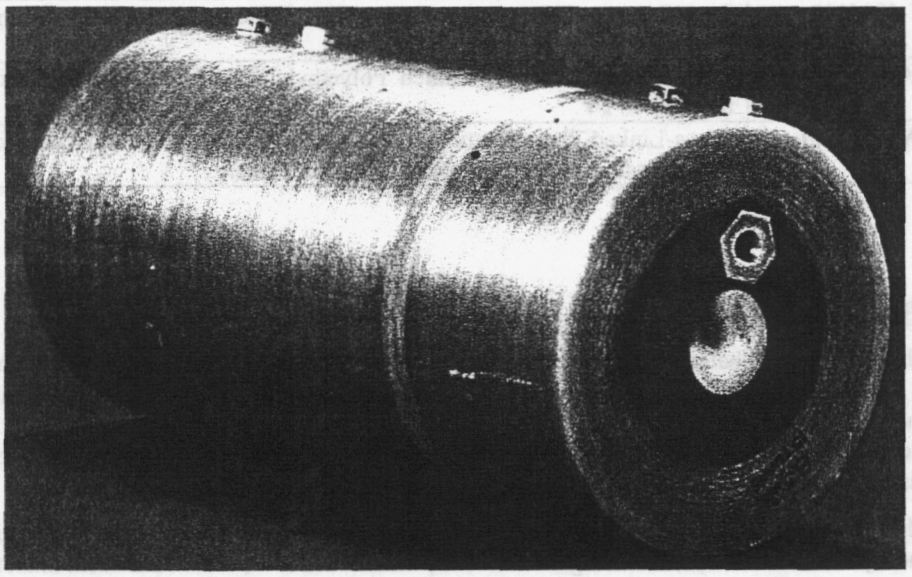


Figure 8-15 Ballast Inductor Assembly, After Encapsulation

Relevant Reports

PCS Report #	Subject
PCS 0003	Ballast Coil Value Engineering Results, R. Anderson, August 1999

8.8 Main Power Supply Isolation Resistors

The MESM power supply protection circuit includes a pair of high-energy resistor assemblies mounted within the MESM. Both resistors are visible in the photograph of Figure 8-16. The resistor assemblies are used in series pairs, to assure that the flashover or other failure of a single resistor will not result in a direct short of the module hot bus to ground through the rest of the power supply protection circuit or the power supply.

Occasional failures of the power supplies during prototype MESM testing in Building 391 were believed to be caused by transients produced by the sudden fall of the output bus voltage when the output switch was fired. This transient was dramatically reduced by moving the power supply connection point from its original location, on the High Voltage Bus, to the capacitor side of the damping element of one of the upper-row capacitors, as shown in Figure 8-16.

The full power supply protection circuit is shown in Figure 8-17. Note that there are two other resistors in the power supply protection circuit; a 200 Ω resistor, mounted in the power supply protection circuit box on the top of the MESM, and a 10 Ω resistor integral to the power supply. These two other resistors are low-energy resistors.

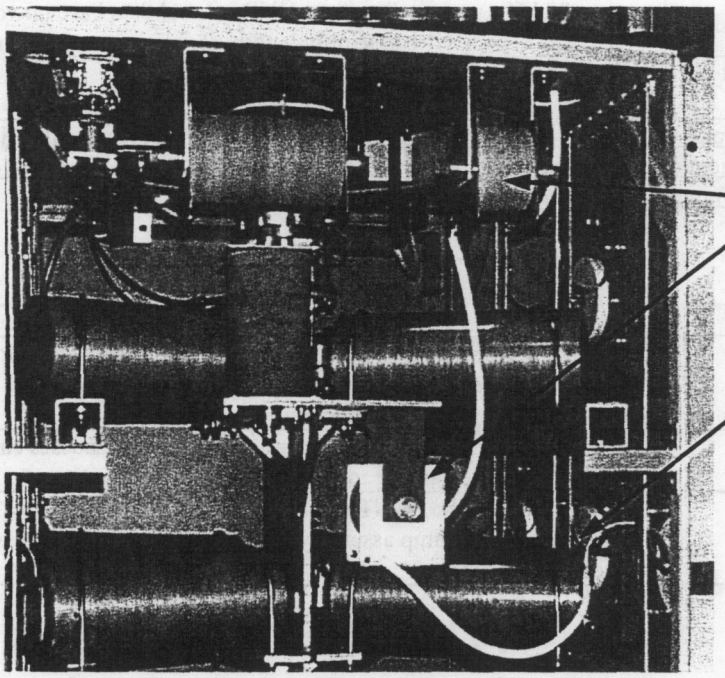


Figure 8-16 Isolation Resistors and HVPS Protection Circuit Box

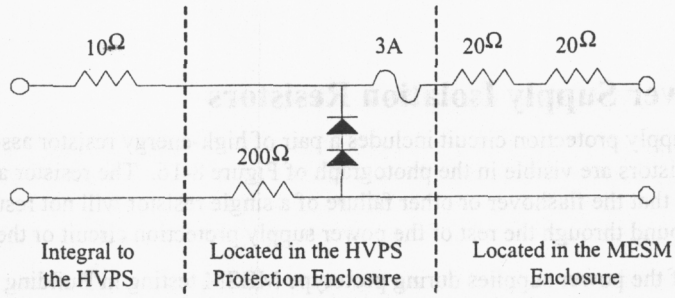


Figure 8-17 Power Supply Isolation Circuit

Table 8-7 Main power-supply high-energy isolation resistor assembly design summary (each 10-disk assembly)

		Design Basis
Resistance	20Ω ± 4 Ω	
Rated energy per resistor assy*	440 kJ	Based on HVR general data base on temperature change vs energy, mass, and resistor composition
Rated impulse voltage per assy	20 kV	Based on HVR general data base on voltage holdoff vs assembly length, resistor coating, and resistor composition
Supplier and Part Number	HVR Advanced Components. #J04PFA200L	

* NOTE: Resistors will survive the discharge of a full module through the pair of resistors, but must be replaced in the event of a fault that causes contamination of the resistor with capacitor oil or discharge of a full module (>0.8 MJ) into a short through these resistors.

Relevant Reports

Report #	Subject
PCS 0086	Thermal performance of resistor Assemblies - - Reviews calculated temperatures and cooling rates for various energy dissipation levels for the 8-disc resistor assemblies used in the dump circuit
PCS 0080	Resistor Assembly High Temperature Test - - Discusses energy dissipation and high-temperature damage to similar resistors.
PCS 0057	Modification of the FANTM Dump Resistors - - Discusses failure of the single-resistor FANTM dump assembly and the rationale for going to two resistors in series

8.9 PILC Charging Power Supply

As of June 2002, the selection of the PILC charging power supply had not been finalized. The initial set of PCS modules was built using Main Charging supplies that had been modified for use as PILC supplies.

8.10 PILC Output Resistor

The PILC Output Resistor, shown in the configuration drawing of Figure 8-18, serves two functions: 1) shaping the normal output pulse, by limiting current reversal, and 2) as a fault mitigation component. The resistor is formed from a folded strip of metal, restrained by a pair of fiberglass channels, and using heavy brass end plates for connection terminals.

The 85 mΩ resistance combines with the parallel pair of 30 mΩ resistors attached to the capacitors, forming a net series resistance of 100 mΩ, which was selected to limit the current reversal to approximately 10% when firing into the set of 20 flashlamp pairs.

In the event of a fault to ground in the PILC module, current will flow from the MESM through this fault when the MESM output switch fires. Since the PILC fault is in parallel with the PCS flashlamp set, only a fraction of the MESM energy can be driven into the PILC fault. Spice modeling predicts the energy dissipated in the PILC output resistor to be up to 430 kJ, depending on the MESM configuration and the location of the PILC fault.

The PILC resistor can safely dissipate the energy associated with such a fault, but will be degraded in the process, and must be replaced after the fault.

The resistor dissipates energy during normal shots (about 43 kJ on a normal PILC + Main shot), and should be allowed to cool between shots. See Table 8-8 for additional details.

Table 8-8 PILC Output resistor design summary

		Design Basis
Resistance	85 mΩ	
Rated energy	43 kJ normal Tested to 550 kJ Fault	Tested to 550 kJ fault case at American Control Engineering. Resistor is to be replaced after a fault
Rated impulse voltage	30 kV	
Min. Allowable Firing Interval	10 minutes between shots	Resistor should be actively cooled (blowing air) if operating sequence is faster than 1 PILC + 1 PILC and Main per 10 minutes
Supplier and part Number	Pulse Power Components. Part # PPC-R44-12-0.085-130	

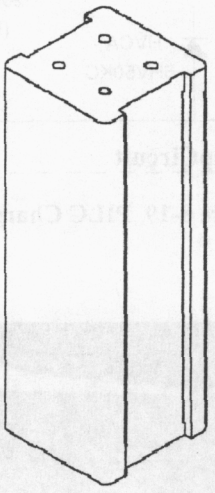


Figure 8-18 PILC Output Resistor Configuration

Relevant Reports

PCS Report #	Subject
PCS 0143	Test of 85 mΩ and 30 mΩ High-Energy PILC Resistors (Tom Naff, 9/6/99)

8.11 PILC Dump Resistors

The PILC dump resistor circuit is designed:

- To safely discharge both capacitors through the safety dump switch when desired.
- To protect the second capacitor from over-current or reversal in the event of failure of the other capacitor.
- To assure that the flashover or other failure of a single resistor will not result in a direct short of the module hot bus to ground.

To meet these objectives, the dump resistor set is formed by effectively putting two resistors in series for each capacitor, and with a dedicated resistor for each capacitor. The PILC dump resistors, and their relationship with the rest of the PILC circuit are shown in Figure 8-19. The two 200 Ω HVR resistors, one for each capacitor, assure that both of the capacitors can be dumped, even in the event that one of the two 30 mΩ output resistors should become open. The 100 Ω resistor, in series with each of the two 200 Ω resistors, assures that a flashover of any one high-energy resistor will not result in a short of the capacitor to ground through the dump relay.

Note: In the event of a failure of the power supply or the power supply cable, the 100 Ω Dale resistors (10 W wire-wound resistors) are very likely to fail. This is not a catastrophic failure, as the energy can still be safely absorbed in the HVR resistors, which will still work properly as dump resistors. However, the Dale resistor strings will have to be replaced after the fault.

A photograph of one of the HVR resistors is shown in Figure 8-20. The design basis for the resistors is summarized in Table 8-9. Currents and energies for each HVR resistor in normal and fault cases are shown in Table 8-10.

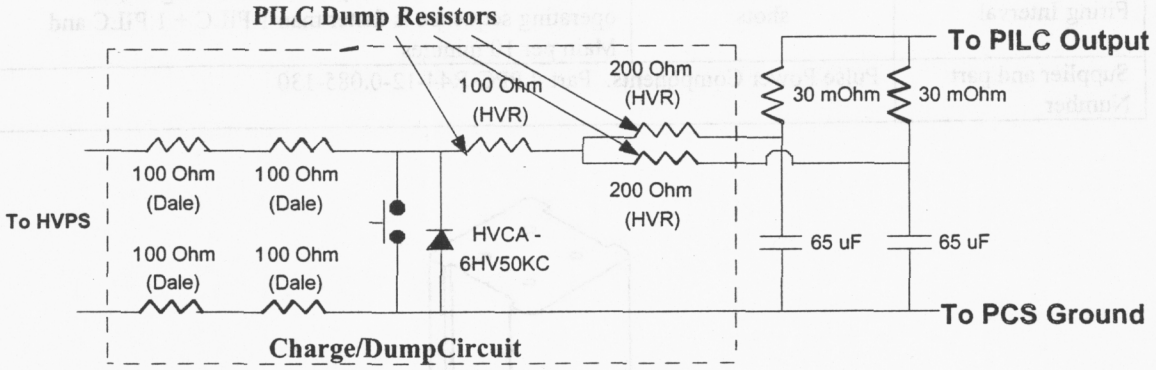


Figure 8-19 PILC Charge-Dump Circuit

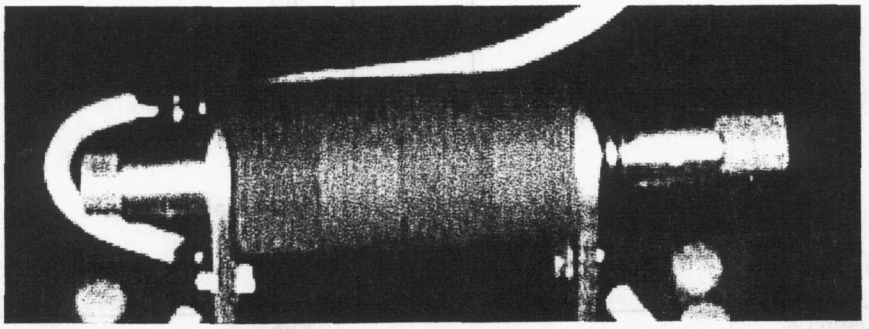


Figure 8-20 PILC Dump Resistor

Table 8-9 PILC Dump resistor assembly design summary (each 4-disk assembly)

		Design Basis
Resistance	100 Ω 200 Ω	Selected to assure full discharge in < 1 minute, while keeping discharge current < 200 A
Rated energy per resistor assy	85 kJ	Based on HVR general data base on temperature change vs energy, mass, and resistor composition
Rated impulse voltage per assy	40 kV	Based on HVR general data base on voltage holdoff vs assembly length, resistor coating, and resistor composition
Supplier and Part Number	HVR Advanced Components #J04DDA101L 100 Ω HVR Advanced Components #J04DDA201L 200 Ω	

Table 8-10 Resistor Currents and Energy Dissipation

Normal Capacitor Energy Dump

100 Ω HVR	150 A	30 kJ
200 Ω HVR	75 A	15 kJ
Each 100 Ω Dale	-	-

Power Supply Short (Cable or internal)

100 Ω HVR	75 A	15 kJ
200 Ω HVR	37.5 A	7.5 kJ
Each 100 Ω Dale	37.5 A	15 kJ

Capacitor Failure (Short)

100 Ω HVR	-	-
200 Ω HVR	150 A	30 kJ
Each 100 Ω Dale	-	-

8.11.1 Information from HVR Resistor Spreadsheet

The system can allow one dump every 5 minutes for at least 3 full-energy dumps. With a maximum rated energy of 85 kJ for one pulse, the resistors can allow two dumps very close together (<~60kJ) without damage to the resistors. Results of the HVE spreadsheet analysis are given in Table 8-11 and Figure 8-21 and Figure 8-22

Table 8-11 HVR Spreadsheet Summary for PILC Dump Resistors

Part number	J04DDA201L
Number of disks in stack	4
Mass (grams)	708.8
Length (cm)	7.6
Diameter in (cm)	1.9
Diameter out (cm)	7.5
Volume (cc)	315.0
Exposed Surf. Area (incl. fins.	307.5
Resistance (ohms)	198.0
Pulse width (us)	50000.0
Peak voltage (kV)	73.3
Peak current (A).	370.0
Max. energy (J)	85059.8
Max. power (W)	38.4
Modeling conditions	
Energy per pulse (J)	29250.0
Time between pulses (s)	300.0
Ambient temp. (deg. C)	24.0
Average power (W)	97.5

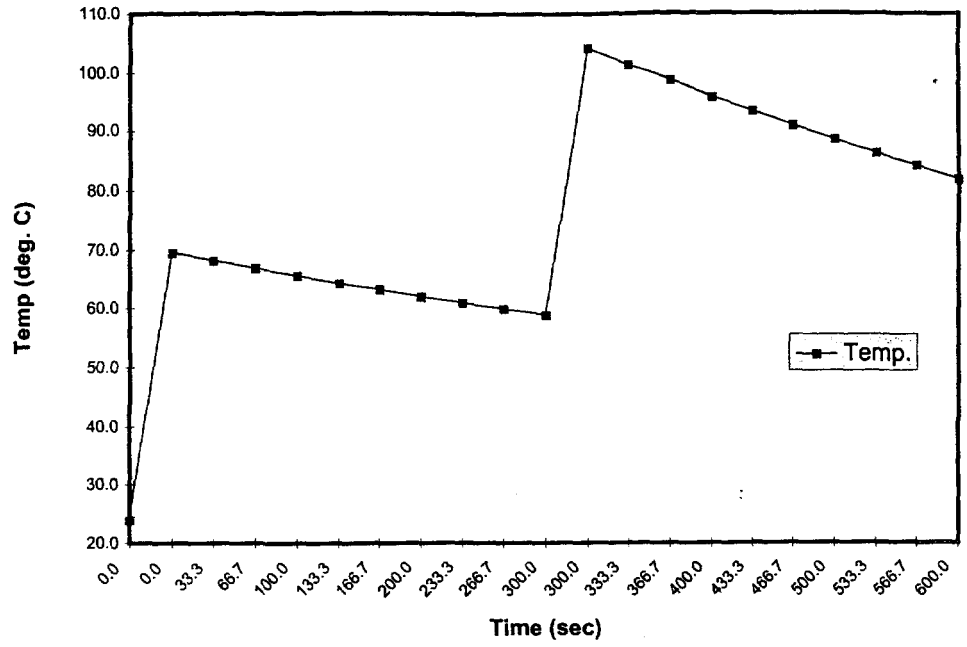


Figure 8-21 PILC Dump Resistor Temperature for First Two Dumps From Room Temperature

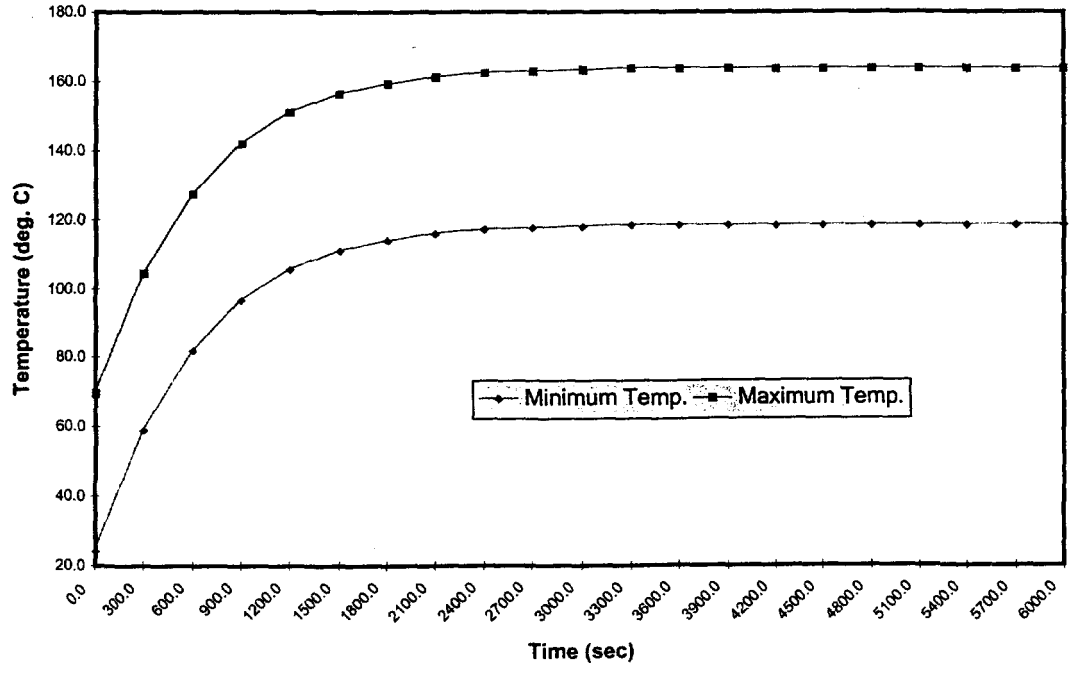


Figure 8-22 PILC Dump Resistor Temperature for a Dump Every 5 Minutes

8.12 TG-803 Trigger Protection Circuit

8.12.1 Protection Circuit

The TG-803 trigger generator effectively presents a short circuit across the output of the MESM after the TG-803 output switch has fired. This can be seen in the simplified circuit diagram of Figure 8-23. The secondary of

the pulse transformer will saturate well before the end of the output pulse, and then will be a short to ground. Without some form of isolation between the TG-803 and the MESM, very high currents would flow through the trigger generator after it fires the MESM output switch. Two redundant elements prevent this fault from occurring: 1) the TG-803 output blocking capacitor, and 2) the PPC output fuse. Both items are shown in Figure 8-23.

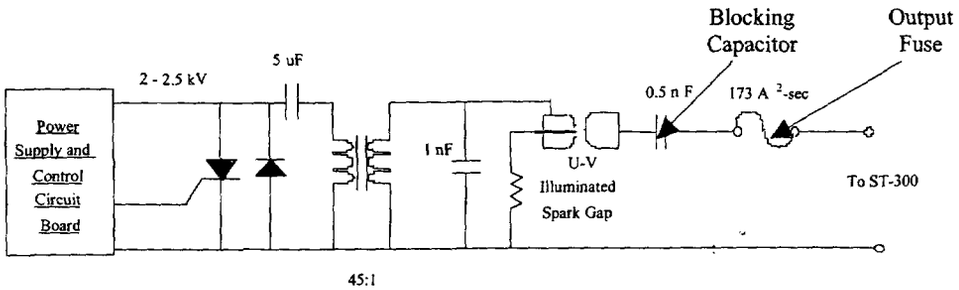


Figure 8-23 TG-803 Trigger Circuit

8.12.2 Blocking Capacitor

The blocking capacitor is an integral part of the TG-803, and consists of a set of three 50 kV ceramic capacitors in series, potted in epoxy. The capacitor also serves as the output bushing of the TG-803. Prior to installation into the TG-803, each capacitor sassembly is hi-potted to 100 kV for several seconds, to confirm its voltage-holdoff ability. There have been no failures of these capacitors in test units to date.

Table 8-12 Blocking Capacitor Design Summary

		Design Basis
Capacitance	0.5 nF	
Voltage rating	135 kV	Significantly exceeds the TG803 pulse output voltage (Approx. 100 kV).
Hi-Pot Test Level	100 kV	This several-second test is performed in transformer oil, to confirm the integrity of the capacitors and potting material.
Supplier and part number	Titan Systems Corporation, Pulse Sciences Division Part # 6680-113-A	

8.12.3 Fuse

The fuse action (173 A^2-sec) significantly exceeds the TG803 action (~ 1 A^2-sec), but allows very little action/energy to be dissipated in the trigger circuit in the event of a blocking capacitor failure. All pre-prototype (FANTM) tests at Sandia were performed with a fuse of 8,000 A^2-sec action. This fuse did open on several occasions, due to flashovers of a different design for the blocking capacitor. No damage was observed in any of the events; in fact, the operators were not aware the fuse had opened until they observed that they were unable to trigger the ST-300 switch.

All LLNL tests have been performed with the smaller, 173 A^2-sec fuse, and no premature fuse openings have been observed.

Table 8-13 Output Fuse Design Summary

		Design Basis
Let-Through	173 A^2-sec	Significantly exceeds the TG803 action (~ 1 A^2-sec), but allows very little action/energy to be dissipated in the trigger circuit in the event of a blocking capacitor failure
Voltage rating	40 kV	Significantly exceeds the MESM operating voltage (24 kV)
Supplier and part number	Pulse Power Components Part number PPC-FU-212-173	

Appendix 1
PILC System Description

This document summarizes the design and configuration of the Pre Ionization/Lamp Check (PILC) system for the Main Amplifier Power Conditioning System, as of November 20, 2000.

The Pre-Ionization Pulser is a single-loop capacitor bank circuit, as shown in the simplified circuit schematic of Figure 1. The indicated 3 μH inductance is distributed in the internal buswork, the output cable, and the connections inside the PCS module Top Hat. Typical operating parameters, when connected through the PCS module to the flashlamp set, are as summarized in Table 1.

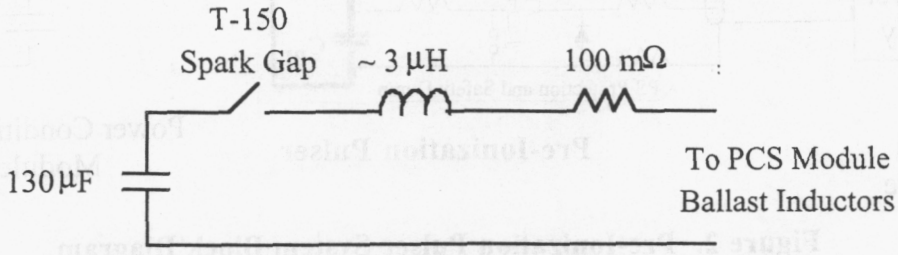


Figure 1: Simplified Pre-Ionizer Pulser Circuit

Table 1: Typical Operating Parameters, through the PCS Module to the Flashlamp Set

Maximum Charge Voltage	28.5 kV
Stored Energy at 28.5 kV	57 kJ
Nominal Peak Current with 28.5 kV charge	70 kA
Current Pulse Duration	110 μs
Fault Current	140 kA

The block diagram of Figure 2 shows the Pre-Ionization Pulser and its association with the control system and the Power Conditioning System module. The bold lines in the figure indicate the primary discharge circuit of the Pre-Ionizer into the PCS module. The general layout of the pulser is shown in Figure 3. A simplified circuit schematic of the PILC pulser is shown in Figure 4.

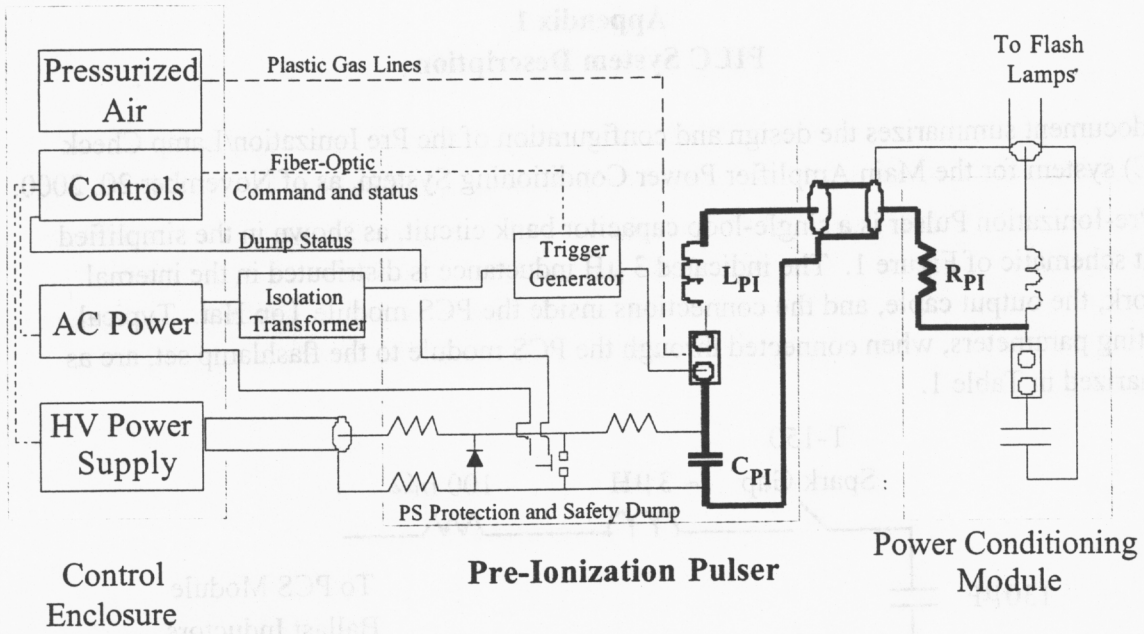


Figure 2. Pre-Ionization Pulser System Block Diagram.

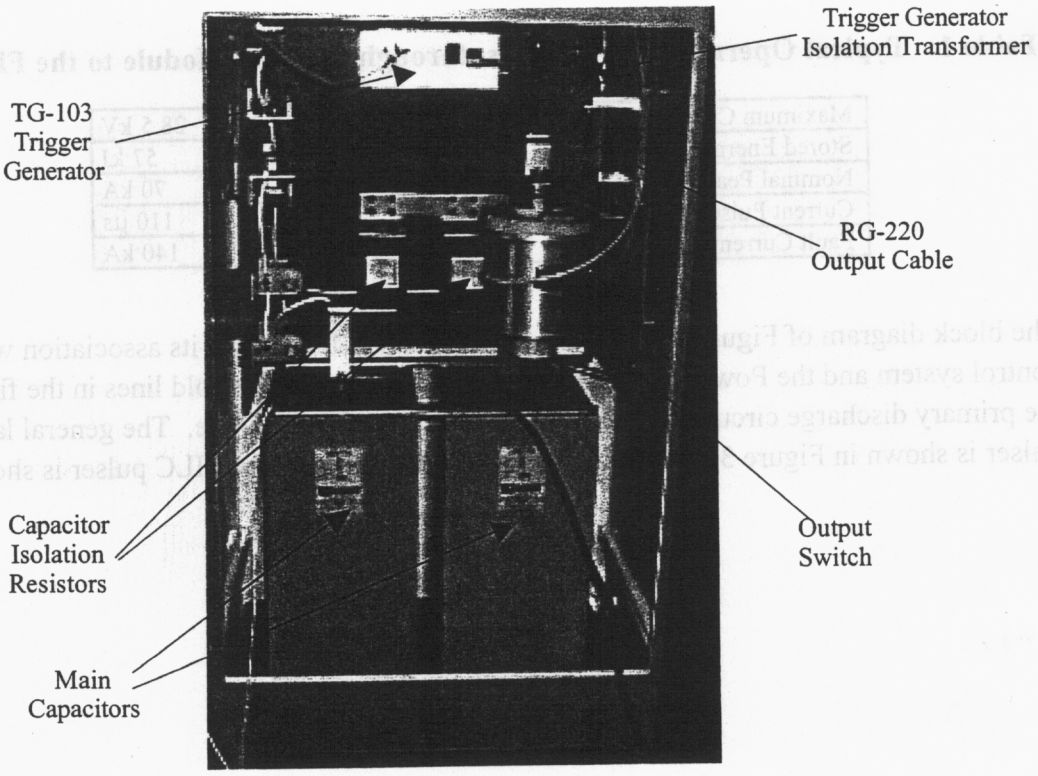


Figure 3. PILC Cabinet Interior

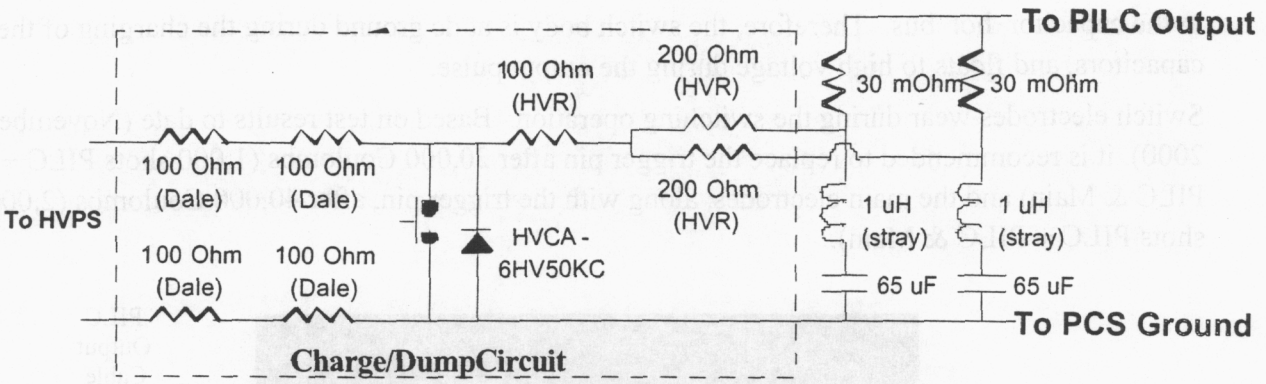


Figure 4. PILC Simplified Circuit Schematic

Capacitors

Two parallel capacitors form the desired capacitance. Each is a 30 kV, 65μF capacitor. The case of each capacitor forms the low-voltage terminal; the threaded terminal in the central bushing is the high-voltage terminal. The capacitors are rated for:

Table 2. Capacitor Ratings

Charge Voltage	30 kV
Normal Peak Current	75 kA
Fault Peak Current	150 kA
Normal Voltage Reversal	10%
Fault Voltage Reversal	80%
Lifetime (Normal Operation, 28.5 kV)	> 44,000 shots
Maximum hold time at 28.5 kV	1 minute
Weight	282 lb

Capacitor Isolation Resistors

The capacitors are isolated from each other through a pair of 30 mΩ, high-energy folded-metal resistors, model PPC-R44-6-0.03-50, as shown in Figure 4. In the event of a capacitor failure, these resistors limit the fault current and absorb the energy of the remaining capacitor. The resistors should be replaced after a capacitor failure event. The two resistors, in parallel, combined with the 85 mΩ output resistor, form the 100 mΩ resistance needed to meet the pulse shape requirement for low reversal into the MESM and flash lamps.

In normal operation, each of these resistors absorbs 2.2 kJ in a PILC shot and 3.9 kJ in a full system shot. The additional 1.7 kJ dissipated during the full system shot comes from the main bank as it re-charges the PILC and the PILC discharges a second time. Average-power heating in these resistors is not a limiting factor for operation rate.

Output Switch

The pulser is discharged into the PCS through a T-150 spark gap, shown in Figure 5. The switch is rated for operation at up to 40 kV, 300 kA, and 120 Coulombs per shot uses a triggatron trigger geometry. The switch uses pressurized dry air as the switching gas. The switch body and the triggered electrode are connected to the output cable. The other switch electrode is connected

to the capacitor hot bus. Therefore, the switch body is at dc ground during the charging of the capacitors, and floats to high voltage during the output pulse.

Switch electrodes wear during the switching operation. Based on test results to date (November, 2000), it is recommended to replace the trigger pin after 20,000 Coulombs (1,000 shots PILC + PILC & Main) and the main electrodes, along with the trigger pin, after 40,000 Coulombs (2,000 shots PILC + PILC & Main).

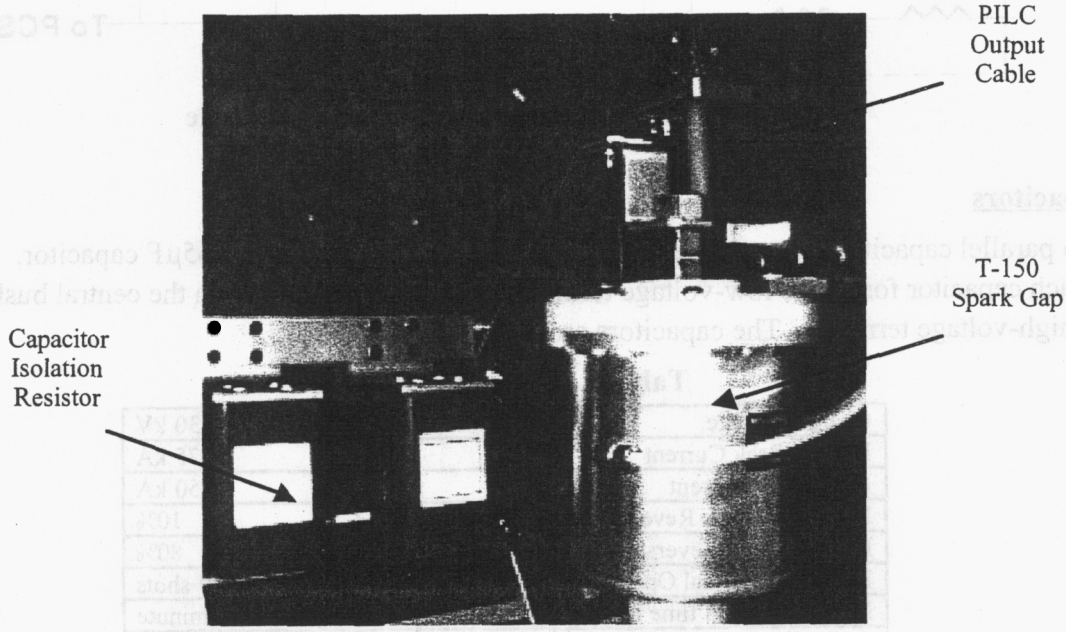


Figure 5. Output switch and associated buswork.

Trigger Generator

The T-150 spark gap is triggered by a TG-103 trigger generator. The TG-103 uses a solid state switch (an SCR) to discharge a 5 μF capacitor charged to 1.2 kV into the primary of an 8:1 step-up transformer. The secondary of the transformer is connected, through a set of protection resistors and a short section of RG-223/U coaxial cable, to the trigger terminals of the T-150 spark gap. The TG-103 has an open-circuit voltage of approximately 10kV. Trigger generator charge status is indicated through a fiber-optic cable, and the input trigger pulse is provided through a fiber optic cable.

NOTE: The trigger generator, which is fully isolated from ground, floats to the PILC output voltage during the output pulse. Power for the trigger generator is provided through a Stangenes Industries SI-13636 isolation transformer.

Series Limiting Resistor

The 85 mΩ series limiting resistor, PPC-R44-0.085-130, is located in the Top Hat of the PCS. In addition to influencing the shape of the normal-shot output pulse, the series limiting resistor protects against excessively high currents from the MESM into the pre-ionization pulser in the

event of a fault in the pulser. Modeling with the Spice circuit code shows that the current in such a fault will be limited to 170 kA, with the 85 mΩ resistor, assuming that the flash lamp loads remain in normal operation. In the event of such a fault, the energy dissipated in the series limiting resistor would be 480 kJ, for the full 24-capacitor MESM at full 24 kV charge voltage. The resistor is to be replaced after such an event.

In a normal shot, the energy dissipated per pulse is approximately 20 kJ during a PILC-only shot, and 36 kJ during a full system shot (PILC + Main). The additional 18 kJ dissipated during the full system shot comes from the main bank as it re-charges the PILC and the PILC discharges a second time. This means that a normal PILC pre-shot, followed by a PILC + Main shot delivers 70 kJ of energy to the resistor.

The resistor is located inside the Top Hat, with no active cooling and rather restricted convective cooling. The resistor should not be operated at an average power exceeding 120 W under these circumstances. This limits the shot rate to no more than one full shot set (PILC only and PILC + Main) per 10 minutes, or 1 PILC + Main shot per 7 minutes.

Output Cable

The output cable will be a double-braid RG-220 cable, to give long life at nominal current and a high tolerance for fault current. The cable center conductor is connected to the T-150 switch output bus, which is connected to the switch housing. The return conductor of the cable is connected to the cases of the capacitors. The pulsed power system is electrically isolated from the enclosure, and is intended to be grounded through the shield of this output cable at the PCS Module.

Capacitor Charging Power Supply

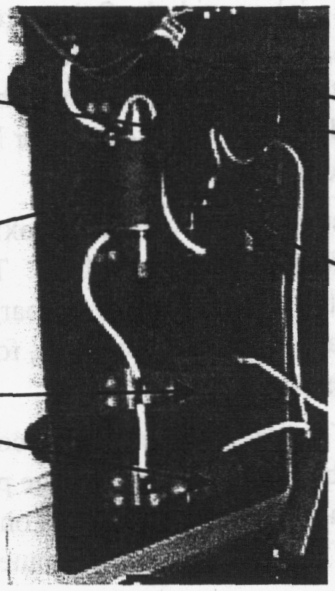
The power supply, a nominally 30 kV, 2 kJ/sec switching power supply, is located in the MESM control console. The supply connects to the Pre-Ionization pulser through an RG-8U coaxial cable. The power supply is isolated from the capacitors in the pulser and protected against voltage reversals of the capacitor by the power supply protection circuit described below.

Power Supply Protection and Safety Dump Circuit

The power supply protection and safety dump circuits are combined into a common circuit, as shown schematically in Figure 4. The components are mounted on the fiberglass panel shown in Figure 6.

The safety dump resistor assembly (between the safety dump relay and the capacitor) is a set of three high-energy HVR ceramic resistors, each rated for 30 kV and 85 kJ. The set can safely dissipate the energy of the capacitors charged to the full 30 kV rated voltage of the capacitors and power supply, for two dumps in rapid succession. If additional dumps at full energy are required, allow 5 minutes between events.

The series limiting resistors (between the power supply and the safety dump relay) are each formed from a series pair of 100 Ω Dale RS-10 wire-wound resistors. Each 200 Ω resistor set is rated for 10 Watts continuous, well over the 1.8 W dissipated in the resistors at full rated current from the power supply, and have been routinely used at similar or higher operating voltage.



The crowbar diode is a High Voltage Component Associates HVCA-6HV50KC block diode assembly rated for 50 kV, 2.5 A average, and 400 A surge current.

The safety dump relay is a Ross E-40-NC-40-2C-0-T relay, a normally-closed relay rated at 40 kV holdoff. The contacts are rated for 125 A continuous and 1 kA surge. With the 200 Ω dump resistor, maximum surge current during the dump process is 150 A. The unit includes position sensors for both the OPEN and CLOSED positions. Operation of the relay is through a 115 V solenoid. Maximum inrush current is 5 A; hold current is 0.5 A. The relay is electrically actuated, but is spring-driven to the closed position, assuring the switch will safely discharge the capacitors in the event of a power failure.

Enclosure

The system is mounted in a Hofmann enclosure. It is important to note that the pulser is electrically isolated from the enclosure. This allows the enclosure to be tied to a safety ground, for personnel safety, without introducing a ground loop. The pulser within the enclosure is intended to be grounded, through the RG-220 output cable, at the Top Hat of the PCS. The system includes a safety grounding strap used to tie the pulsed power ground bus to the enclosure for personnel safety during inspection and maintenance. This strap must be removed prior to operation of the system.

Appendix 2
PCS Module Performance Predictions

The figures below summarize the performance of the module described in the main text, as predicted with the PSpice circuit modeling code. Also given is the Average Gain Coefficient, predicted by using the power pulse from the PSpice run (beginning at the firing of the output switch, thus deleting the PILC pulse) as the source file for the GainCalc code supplied by LLNL.

Table 1 summarizes the module circuit parameters used in the model. Table 2 summarizes the modeling results for the baseline module with different ballast inductor/cable length configurations. Two cases are considered for each configuration, one set configured for a predicted gain coefficient of approximately 5.0 %/cm (20 capacitors and 24 kV charge, plus a 21-capacitor case for the longest cables), and a second set configured for a predicted gain coefficient of at least 5.2 %/cm (24 capacitors at 24 kV charge).

For normal shots, the load is taken to be a set of 20 series pairs of flashlamps, with a resistance versus current profile for a series pair of lamps assumed to be given by:

$$R = 78.7 / I^{1/2}$$

The data of Table 2 are summarized in Graphs 1 — 3, following the tables. Some observations made from the table are:

- Gain coefficient increases with energy delivered to the lamps (See graph 1).
- Gain coefficient goes down as cable length goes up.
  - Gain coefficient depends on both total series resistance (increasing resistive losses reduce gain - - see Graph 2) and on pulse duration (longer pulses, due to higher inductance, have lower gain - - see Graph 3).
- "Tapered" ballast inductance values (using lower ballast inductance for modules with longer cables, as in the present approach) reduces the gain losses associated with longer cables (See Graph 3).

Table 3 lists the circuit parameters used in the fault runs. Table 4 summarizes the results of the circuit model, when used to assess fault conditions. Some observations made from the table are:

- Capacitor voltage reversals are less than 50% for all cases modeled.
- Damping Element current is high only for the case of capacitor failure; and then only for the damping element attached to the failed capacitor.
  - Æ Note: the damping element is to be replaced after a capacitor failure.
- The reflector cable resistor limits the current in the event of a lamp failure to about 6.1 kA; low enough to protect the blast shield.
  - Æ Note that the voltage at the reflector is nearly the full capacitor charge voltage in this fault.
- The PILC output resistor (in the Top Hat) sees high current and action in the event of a ground fault or capacitor failure in the PILC module.
  - Æ The resistor is designed to handle this energy, but should be replaced after such a fault.

- In the event of a fault at the Big T or the FAU, the ballast inductors limit fault current to reasonable values (See Graph 4, which follows the fault tables).
  - Æ Note that the ballast inductor is to be replaced after such a fault.
- The highest fault currents are created by bus faults in the MESM.
  - Æ In general, the damping element currents are still low, so the damping element generally will not require replacement unless some other event causes damage.

Additional fault scaling information is included in Graph 4, following table 4, showing the effect of cable length and ballast inductor values on Big T fault current.

The detailed circuit schematic used is also included, at the end of this section. The circuit model was constructed to include the distributed nature of the capacitor assembly and the output cables, and the PILC module.

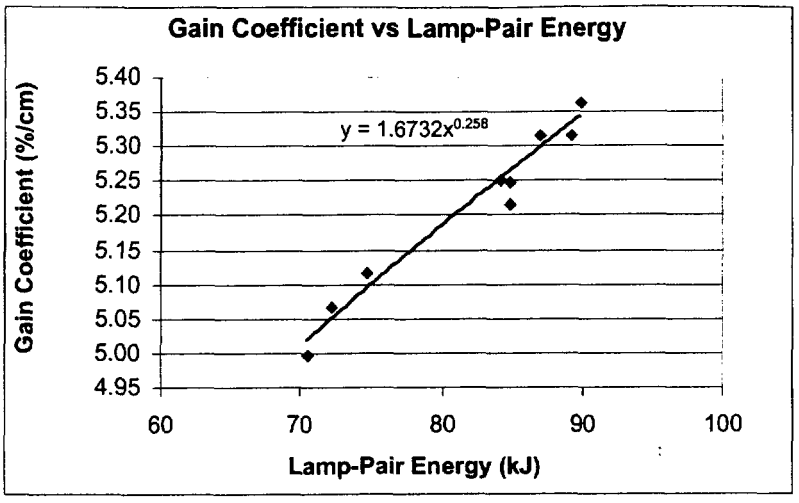
Waveforms for one of the cases (20 capacitors and mid-range cable length) are shown, following the summary tables. Measured waveforms for the prototype module tested in Bldg. 391, are also shown; a shorted shot (shorted at the top of the Top Hat) and a normal shot in to the flashlamps. The model was refined to assure an accurate match to the short-shot case. Modeled waveforms depart somewhat from actual measurements for the flashlamp case, due to the complex behavior of the flashlamps.

Table 1. Module Circuit Parameters

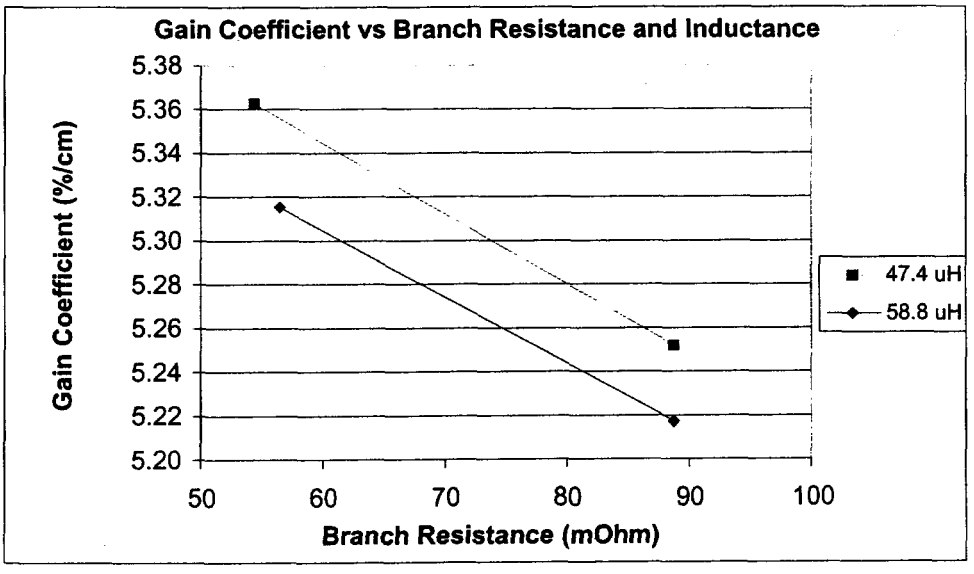
Capacitor Value (μF)	Capacitor ESR (mΩ)	Damping Inductance (μH)	Damping Resistance (mΩ)	Output Switch Resistance (mΩ)	Cable Inductance (nH/ft)	Added Inductance per Branch (μH)	Cable Resistance (μΩ/ft)	PILC Capacitance (μF)	PILC Inductance (μH)	PILC Resistance (mΩ)
315	15	9.2	26	0.885	100	3.0	300	130	1.5	110

Table 2. Predicted Performance Details

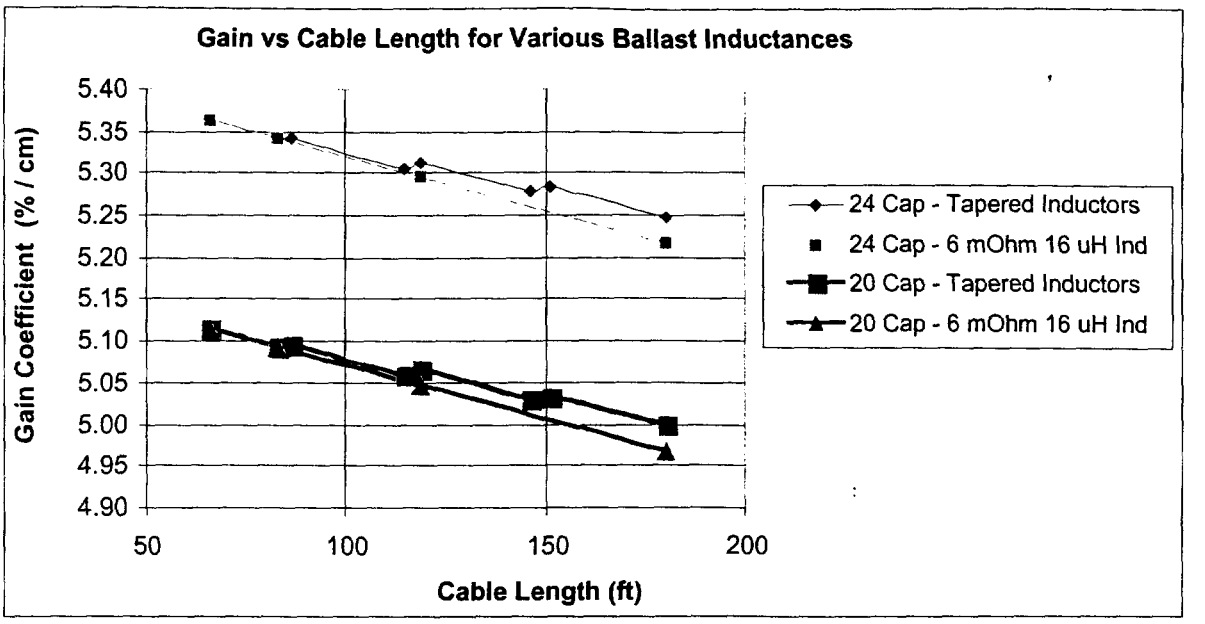
Number of Capacitors		20	20	20	20	20	20	20	20	21	24	24	24	24	24	24	24	24
Module Capacitance	mF	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.3	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Charge Voltage	kV	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
Ballast Inductance	H	16.0	16.0	14.4	14.4	11.3	11.3	9.1	9.1	9.1	16.0	16.0	14.4	14.4	11.3	11.3	9.1	9.1
Ballast Ind. Resistance	mΩ	6.0	6.0	5.5	5.5	4.5	4.5	3.8	3.8	3.8	6.0	6.0	5.5	5.5	4.5	4.5	3.8	3.8
Internal Bus Inductance (Eff.)	H	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29		0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Internal Bus Resistance (Eff.)	mΩ	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10		0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Switch Bus Inductance	H	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375
Cable Length	ft	66.0	82.9	86.6	114.9	118.8	146.4	151.0	180.0	180.0	66.0	82.9	86.6	114.9	118.8	146.4	151.0	180.0
Cable Resistance	mΩ	19.8	24.9	26.0	34.5	35.6	43.9	45.3	54.0	54.0	19.8	24.9	26.0	34.5	35.6	43.9	45.3	54.0
Cable Inductance	H	6.6	8.3	8.7	11.5	11.9	14.6	15.1	18.0	18.0	6.6	8.3	8.7	11.5	11.9	14.6	15.1	18.0
Eff. Inductance per branch	H	48.2	49.9	48.6	51.5	48.8	51.5	49.8	52.7		47.4	49.1	47.8	50.7	47.9	50.7	49.0	51.9
Eff. Resistance per branch	mΩ	54.7	59.8	60.4	68.9	69.0	77.3	78.0	86.7		54.4	59.5	60.1	68.6	68.8	77.0	77.7	86.4
Source Impedance per branch	mΩ	0.40	0.41	0.40	0.41	0.40	0.41	0.41	0.42		0.36	0.37	0.36	0.38	0.36	0.38	0.37	0.38
PILC Current (1st peak)	kA	98.5				97.7			96.1		98.5				97.7			96.1
PILC Reverse Current	kA	76.6				77.2			79.1		80.4				80.1			82.6
PILC Charge Transfer	Coul	10				10			10.2		10.1				10			10.3
PILC Capacitor Reverse V	kV	-3.6				-3.5			-3.9		-3.6				-3.5			-3.9
Peak Power, one Lamp Pair	MW	328				318			298		367				355			332
10% Power Pulse Width	s	357				360			376		386				392			410
Energy per Lamp (Less PILC)	kJ	37.4				36.1			35.3		44.9				43.5			42.4
Lamp/Ballast Peak Current	kA	26.0				25.5			24.4		28.1				27.5			26.3
Time to Peak Current	s	159				155			162		172				166			176
ST-300 Peak Current	kA	519				508			487		559				54.7			523
ST-300 Charge Transfer	Coul	137				136			136		160				159			158.4
ST-300 Action	MJ/Ω	53.6				51.9			49.5		67.0				64.7			61.6
Predicted Peak Gain Coeff.	%/cm	5.116	5.094	5.096	5.059	5.067	5.031	5.034	4.998	5.068	5.363	5.341	5.343	5.306	5.314	5.280	5.283	5.247



Graph 1. Gain coefficient vs energy delivered to a pair of lamps



Graph 2. Gain coefficient vs total resistance per branch (including resistance in the PCMS module and the cables, but not the flashlamp resistance), for two different cases of total branch series inductance.



Graph 3. Cain coefficient vs cable length, for 20 and 24 capacitor cases, with a fixed 16°µH ballast inductance (independent of cable length) and for the planned tapered ballast inductance, with lower inductances compensating for longer cables.

Table 3. Fault Run Model Parameters

Number of Capacitors		24
Module Capacitance	mF	7.2
Charge Voltage	kV	24
Ballast Inductance	H	16.0
Ballast Ind. Resistance	mΩ	6.0
Eff. Internal Bus Inductance	H	0.25
Eff. Internal Bus Resistance	mΩ	0.09
Switch Bus Inductance	H	0.375
Added Inductance	H	0.15
Cable Length	ft	66.0
Cable Resistance	mΩ	19.8
Cable Inductance	H	6.6
Eff. Reflector Resistance	Ω	3
Eff. Inductance per branch	H	47.4
Eff. Resistance per branch	mΩ	54.4
Source Impedance per branch	mΩ	0.36

Table 4. Fault Run Results

		Normal Baseline	Big T Fault	FAU Gnd Fault	PILC Fault	Reflector Fault	Capacitor Fault	Bus Fault Upper	Bus Fault Lower
Peak Power, one Lamp Pair	MW	367	341	343	314	378			
10% Power Pulse Width	s	386	347	348	354	390			
Energy to 1 Lamp Pair (Less PILC)	kJ	89.9	75.6	76.6	69.2	92.7			
Ballast Peak Current (Fault / Normal)*	kA	28.1	135 / 26.8	129 / 26.7	25.3	6.1 / 28.6			
Time to Peak Current (Fault / Normal)*	s	172	360 / 160	358 / 168	150	70 / 169			
Ballast Inductor Energy (Fault / Normal)*	kJ	0.8	55.8 / 0.8	50.7 / 0.9	0.8	0.04 / 1.0			
ST-300 Peak Current	kA	559	600	598	629	545			
ST-300 Charge Transfer	Coul	160	250	226	167	166			
ST-300 Action	MJ/Ω	67.0	83	82	80.0	65			
PILC Forward Current	kA	98.5							
PILC Reverse Current	kA	80.4			140				
PILC Switch Action	MJ/Ω	0.52			3.6				
PILC Switch Charge Transfer	Coul	10.1			37				
PILC Capacitor Reverse V	kV	-3.6			-17				
PILC Cap Resistor Energy	kJ	3.9			123				
PILC Output Resistor Energy	kJ	44			305				
Reflector Voltage	kV					18.4			
Relfector Resistor Energy	kJ					21			
Reflector Action	kJ/Ω					7.1			
Reflector Resistor Current	kA					6.1			
Main Cap Reverse Voltage	kV		-4.1	-3.2			-2.6	-7.4	-8.6
Arc Peak Current	kA							982	856
Pulsed Power Return Voltage Bounce	kV						-105	-1.4	6.9
Damping Element Current	kA	28.1					320	43	56
Damping Element Energy	kJ	3.7					1,200	10	13.4

Entries for lamp power and energy are for the branches unaffected by the fault

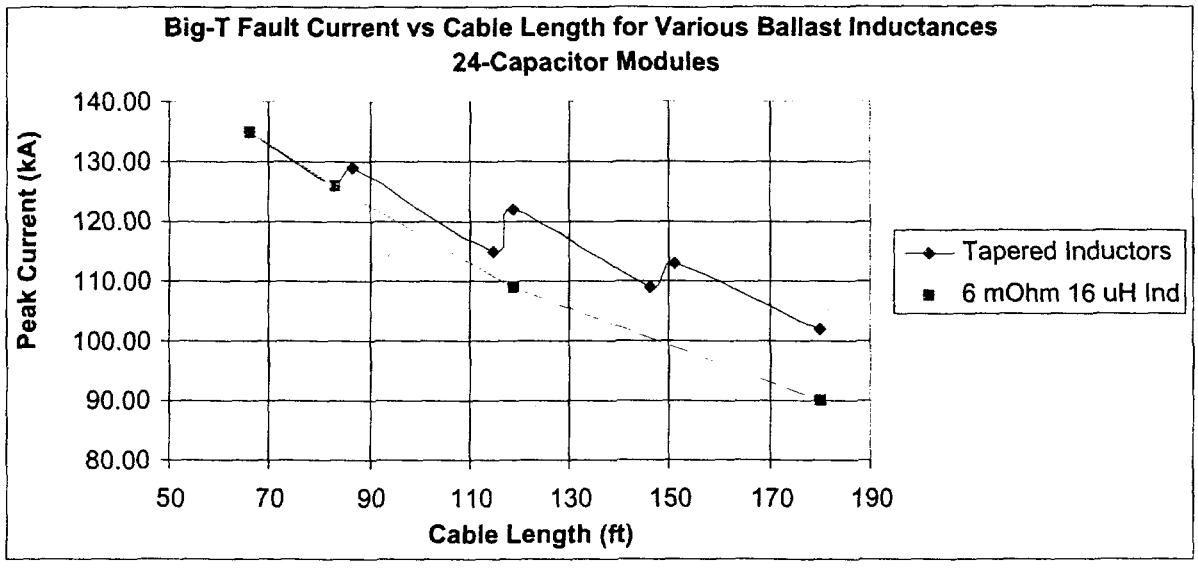
* Values in these three rows are given for the branch/cable experiencing the fault ("Fault") and for each of the remaining branches ("Normal").

Fault cases considered are:

- Big T Fault: A low-resistance (1 mΩ) breakdown from the hot conductor of one cable to the return conductor of the same cable through the circuits within the Big T. The ballast inductor limits the peak current of the fault, along with the cable inductance. Lamp energies in the remaining circuits are reduced, due to the fault.
- FAU Ground Fault: A low-resistance (1 mΩ) breakdown from the hot center conductor of one cable to facility ground and the cable tray ground at the location of the FAU, without making an electrical connection to

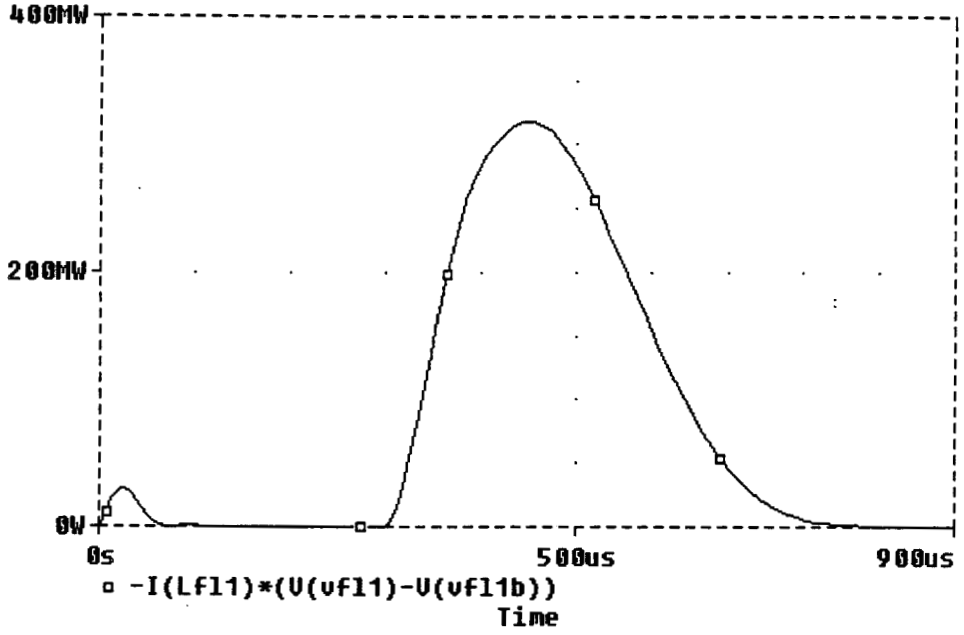
the return of the coaxial output cable. Again, lamp energies in the remaining circuits are reduced, due to the fault. Ground current implications of this fault are discussed further in Appendix 3 of the Overview to this document.

- PILC Fault: A low-resistance (1 mΩ) breakdown from the hot terminal to ground in the PILC enclosure. Peak current is limited by the combination of the inductance of the PILC cable and the 100 mΩ PILC resistance, plus the fact that the flashlamps will still fire normally, absorbing most of the PCMS energy. If few or none of the flashlamps were to fire, this would become a very serious fault.
- Reflector Fault: This represents a flashlamp failure, and the resultant plasma connection of the hot of one branch to the reflector. Current returns to the PCMS through the reflector cable and the Reflector Resistor. Current is primarily limited by the resistor. Since the remaining lamps still function normally, very little energy is deposited in the reflector resistor. In the absence of this resistor, reflector fault currents are much higher, and the blast shield between the lamps and the laser glass would fail.
- Capacitor Fault: Internal failure of a capacitor in the MESM. Most of the energy in the module is dissipated in the damping element of the failed capacitor.
- Bus Fault (Lower and Upper): A breakdown from the high-voltage bus of the MESM to ground at the bottom and top of the bus, respecively.

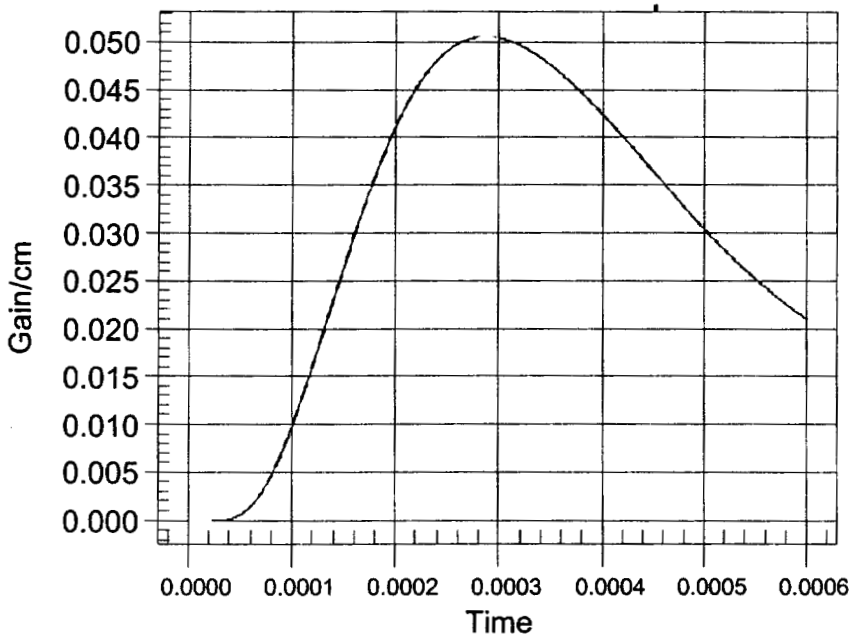


Graph 4. Big-T fault currents vs cable length, for a fixed 16 μH ballast inductance and for the planned tapered ballast inductances

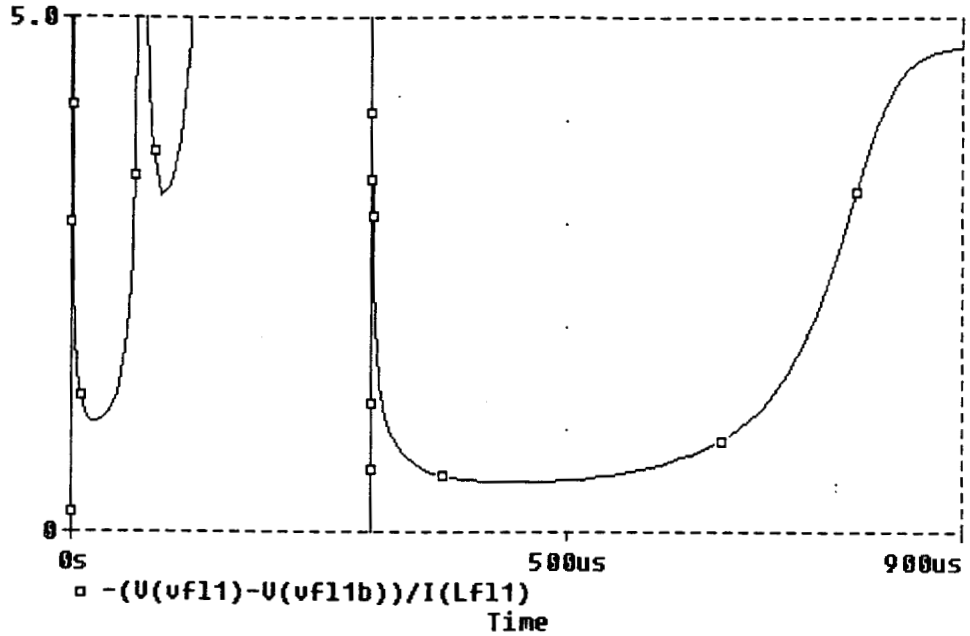
Predicted Waveforms
20-capacitor, 24 kV charge voltage case
with 118.8 ft cables and 11.3 μH ballast inductors.



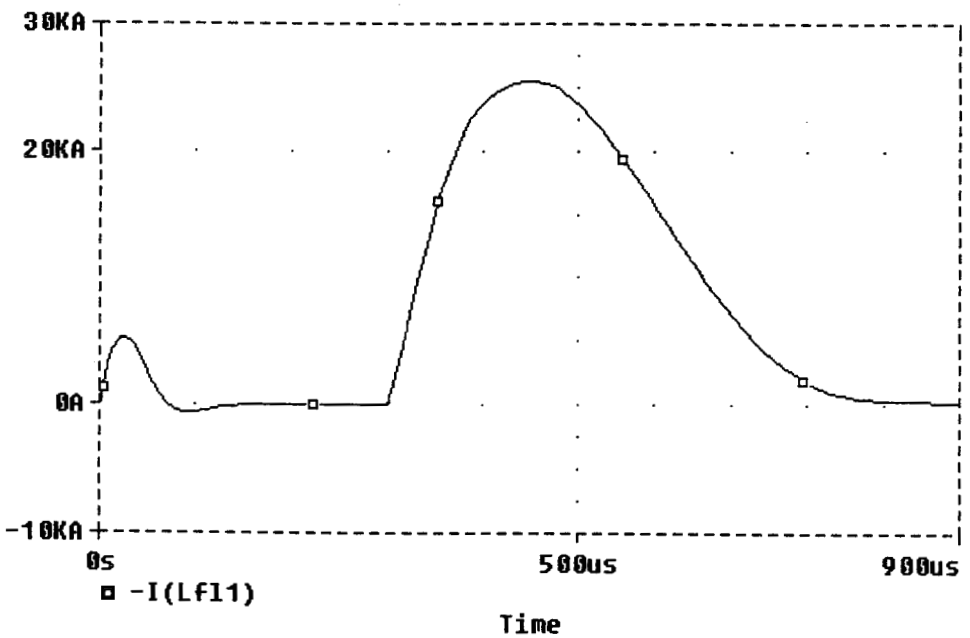
Power pulse to a single flashlamp pair. Peak value is 318 MW. Pulse width at the 10% of peak point is 360 μs.



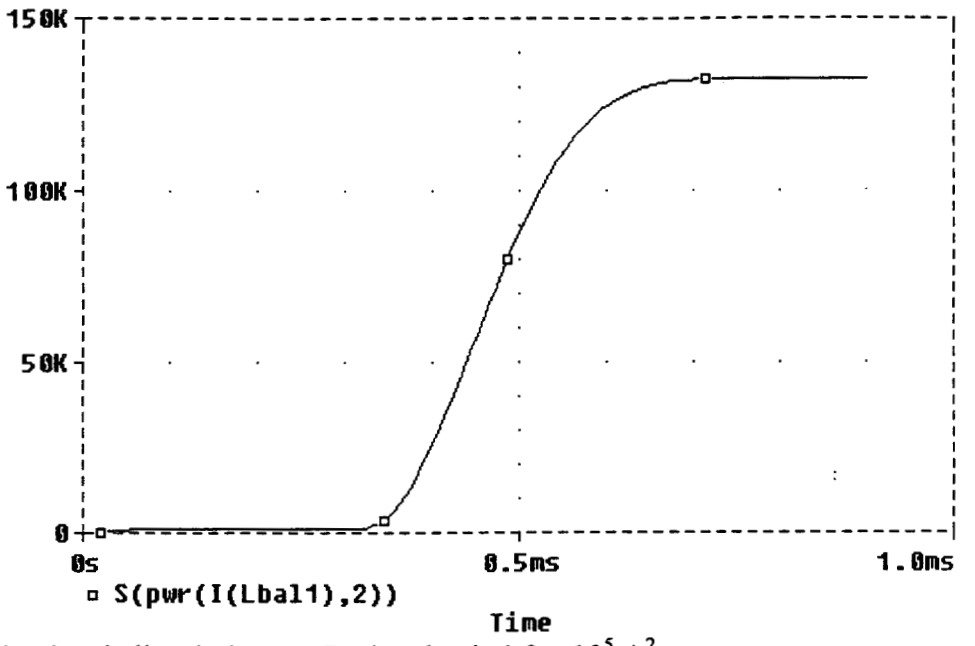
Average Gain Coefficient, as predicted by the LLNL GainCalc code, based on the predicted power pulse given above. The time scale here begins with the firing of the main output switch (at t = 200 μs in the remaining waveforms). Peak value is 5.067%/cm at 286 μs after switchout.



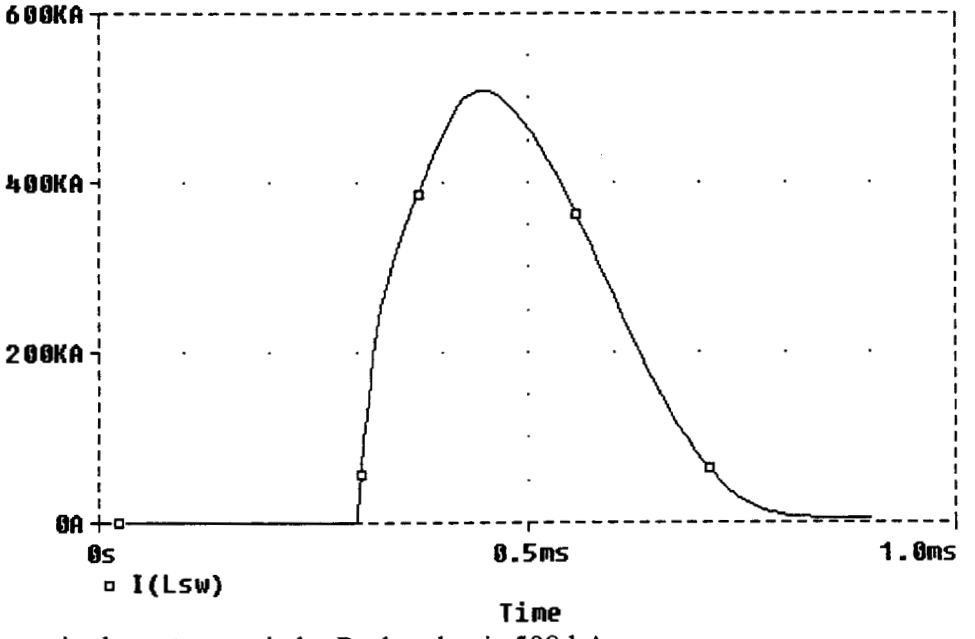
Resistance profile of a flashlamp pair. Minimum value is 488 mΩ.



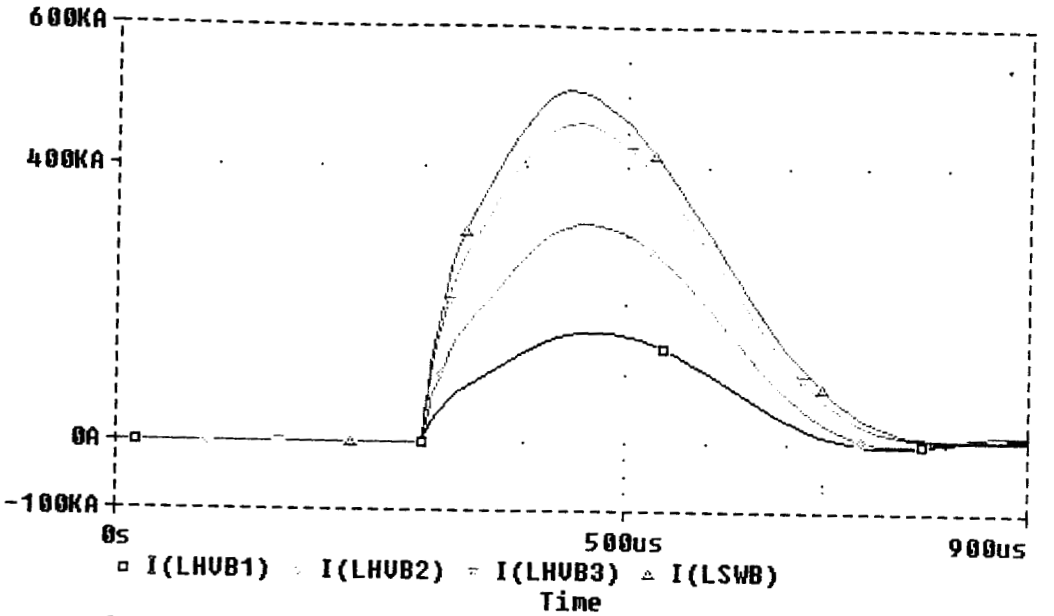
Current in a single flashlamp (also the current in a single ballast inductor) Peak value is 25.5 kA.



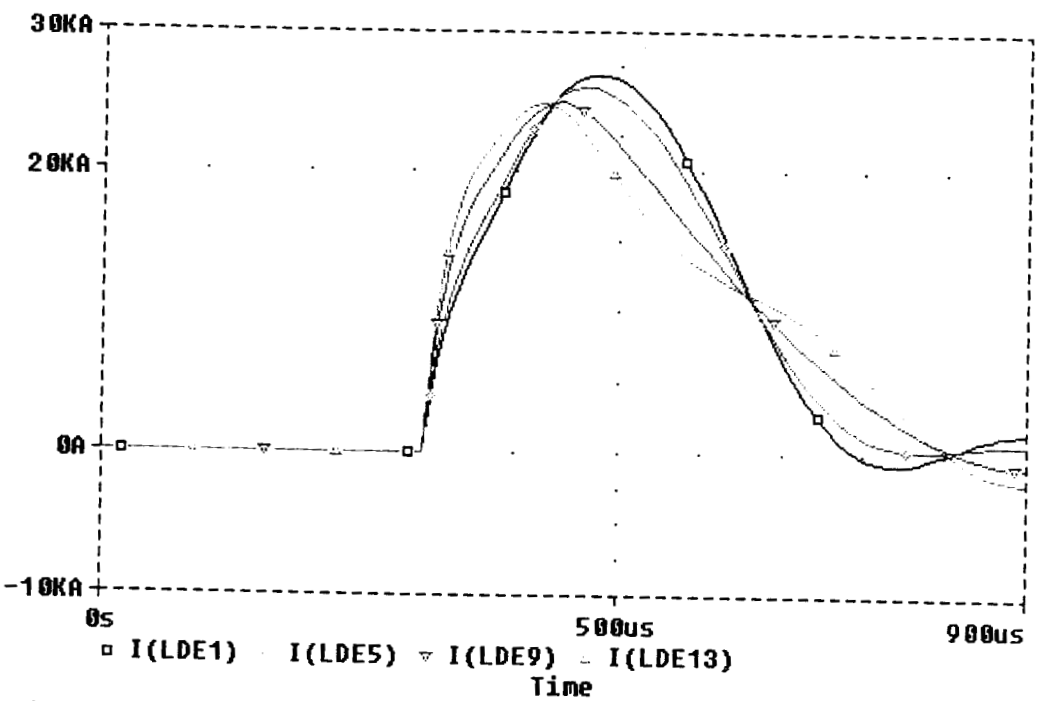
Action in a ballast inductor. Peak value is 1.3 x 10^5 A^2-sec



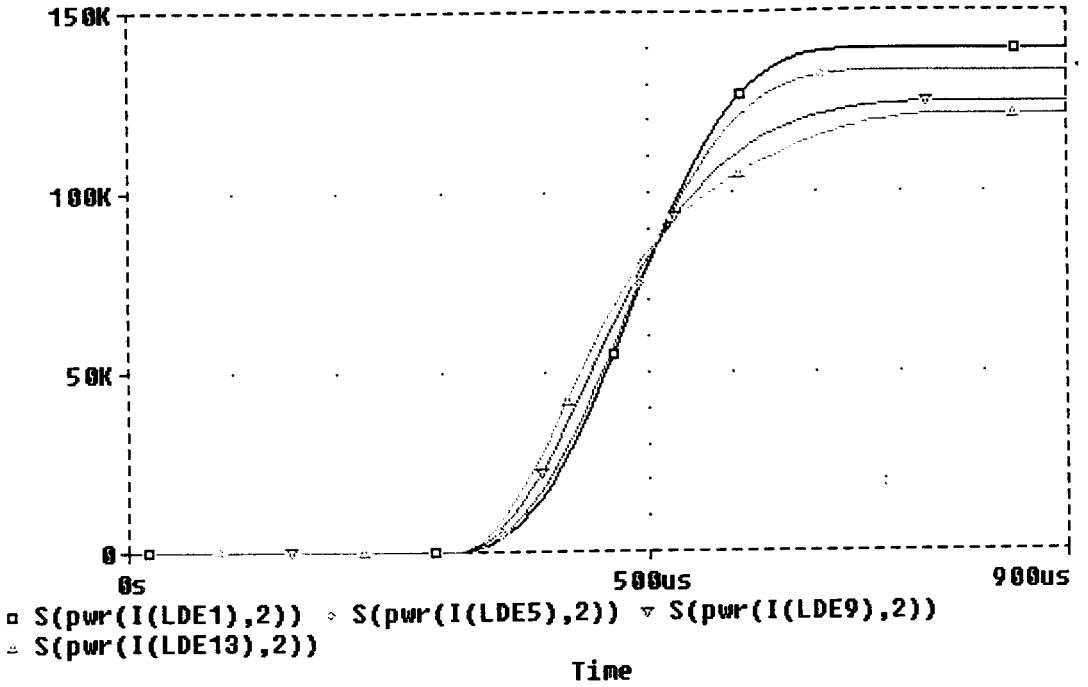
Current in the output switch. Peak value is 508 kA.



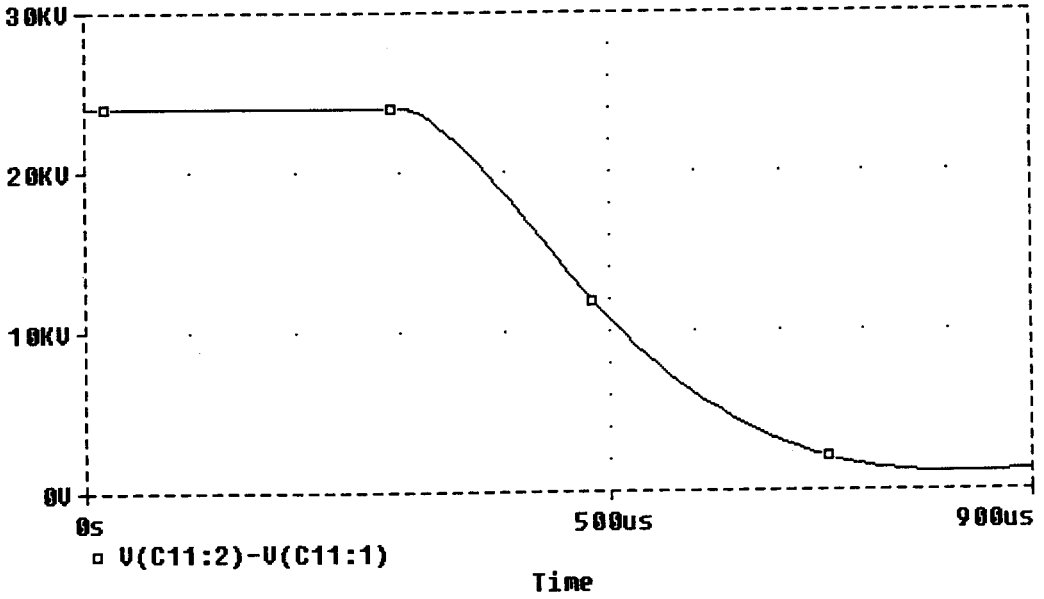
Currents at four locations in the hot bus.



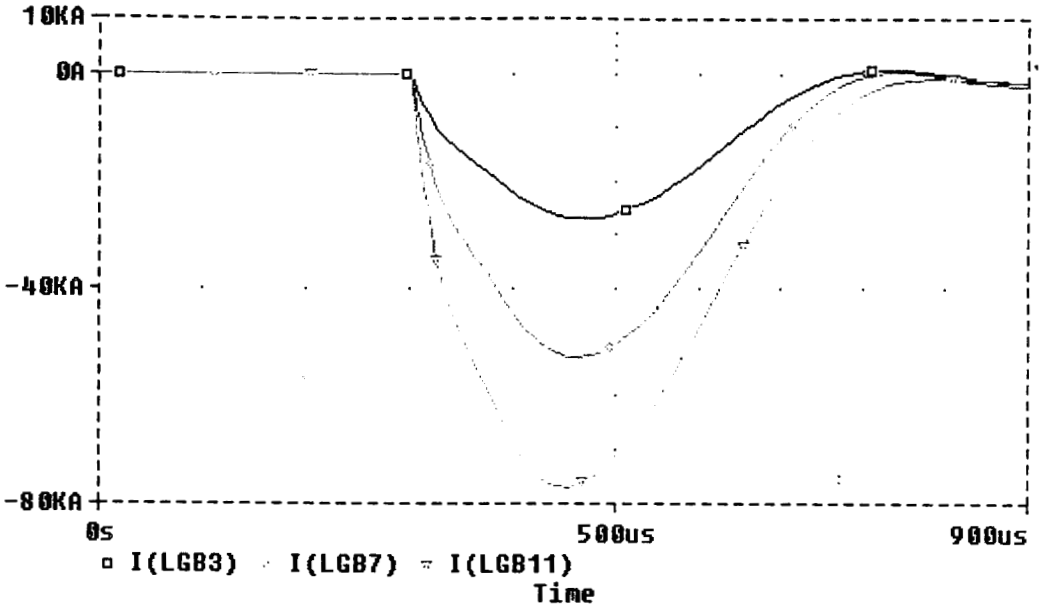
Damping element currents. Currents in different units vary somewhat, as a function of position in the module. This variation is caused primarily by the inductance of the High Voltage Bus, plus a small contribution from the ground buses, which have less equivalent inductance, as there are several in parallel.



Damping element actions

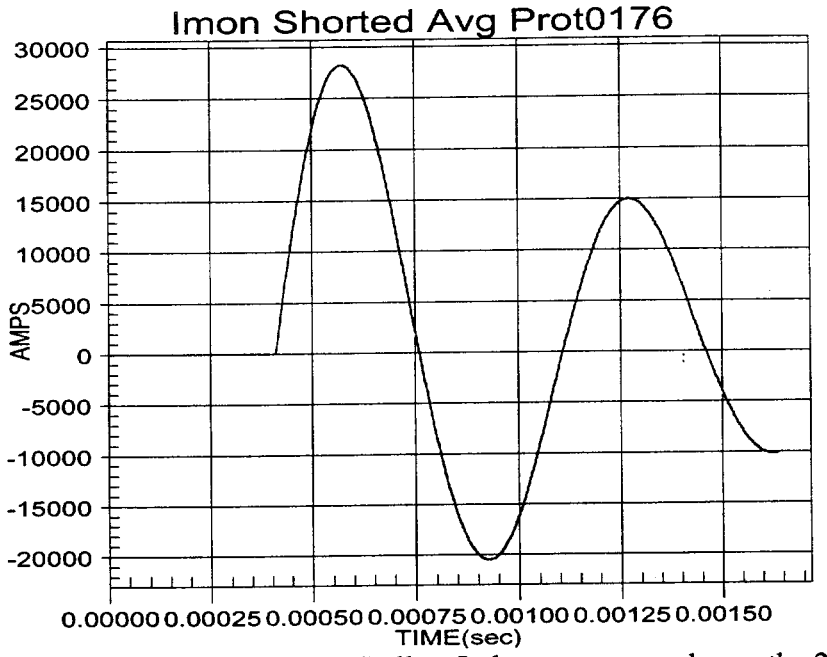


Capacitor voltage.

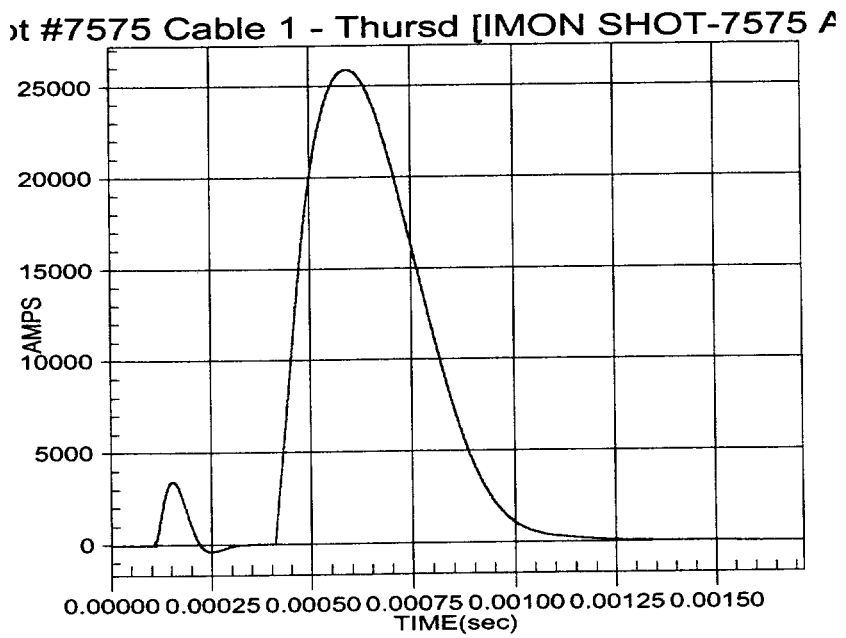


Currents in ground bus straps at three locations; bottom, middle, and top. The model uses one ground strap per capacitor column; six straps, total.

Measured Waveforms



Measured Shorted-Shot Current per Ballast Inductor; averaged over the 20 outputs:
Shorted at the Top Hat; 24 capacitors, 10 kV charge, no PILC



Measured Current per Ballast Inductor; averaged over the 20 outputs:
Normal shot into flash lamps; 24 capacitors, 180 ft cables
Main charge voltage: 23.8 kV PILC charge voltage: 28.5 kV

Circuit Schematic from PSpice Model

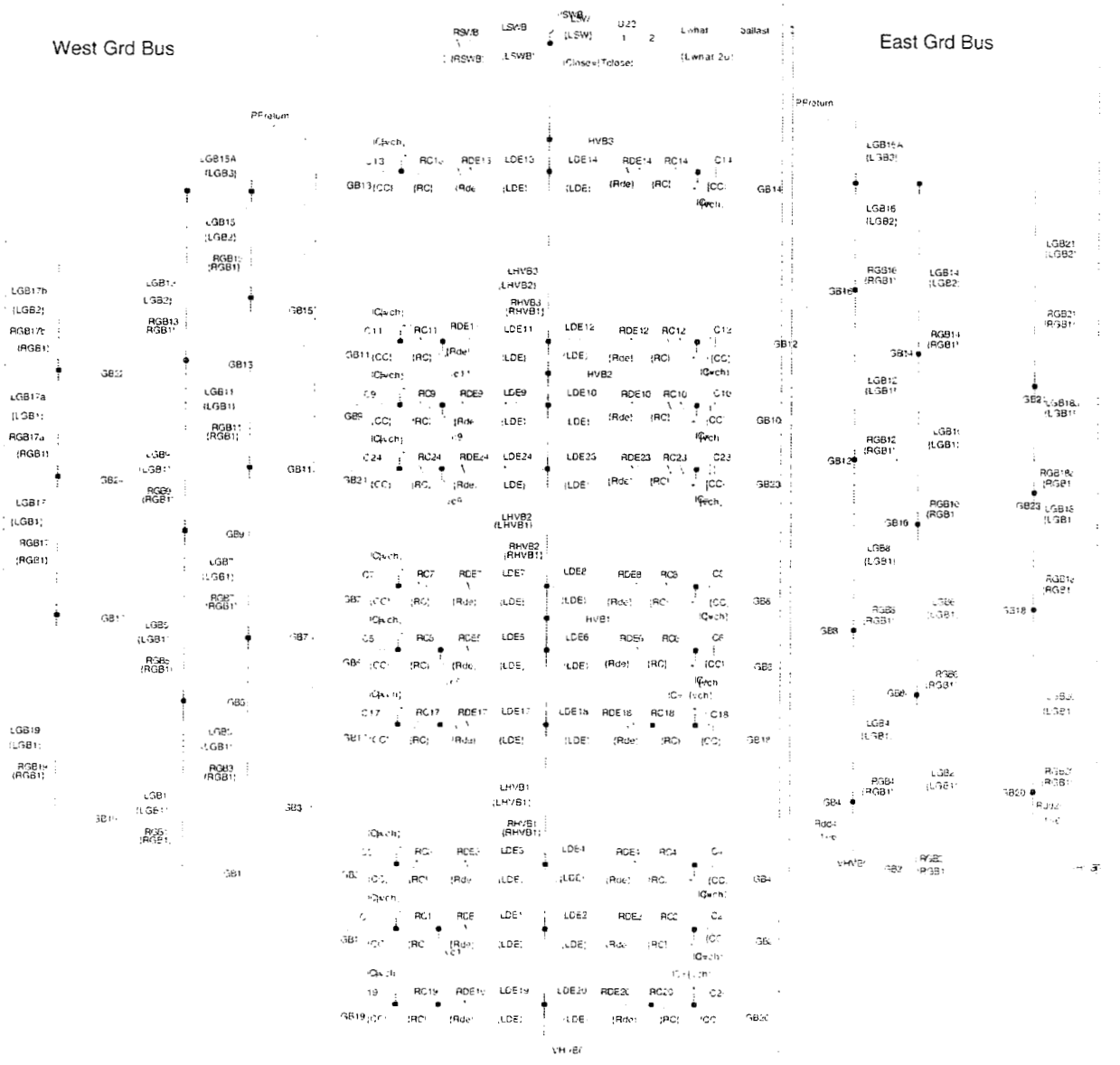
Main Capacitor Bank Module

Module Parameters

Cable Parameters

Load Parameters

20 Capacitors, 15 mOhm ESR each
First-Article Internal Buswork
9uH 26 mOhm damping elements
Baseline ballasts
Underground Utility Cables
Flashlamp Load
Fast 130uF, 3.23uH, 0.1 Ohm PILC
Load Floating
Module grounded at Top Hat

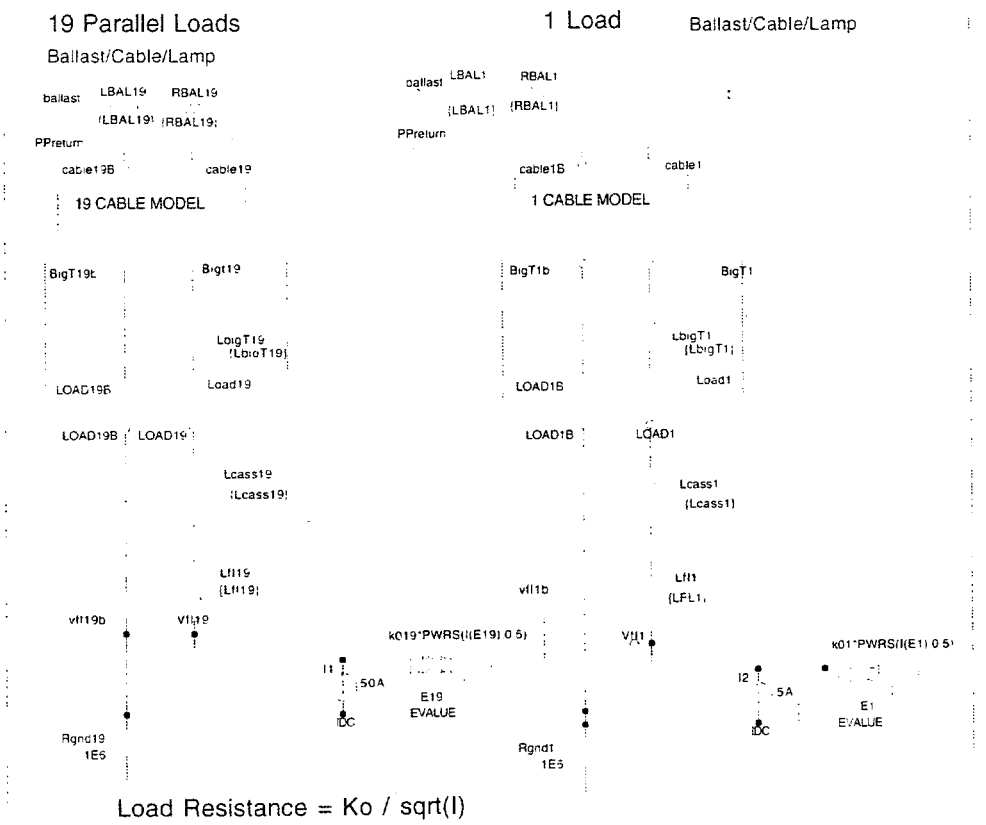


Loads and Module Ground Cable

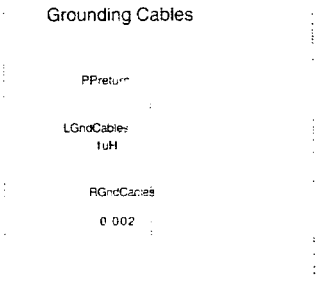
Trigger Generator and PILC simplified, and grounded only at the Top Hat

Coupled capacitances between output cables and cable tray

Simple, grounded Cable Tray

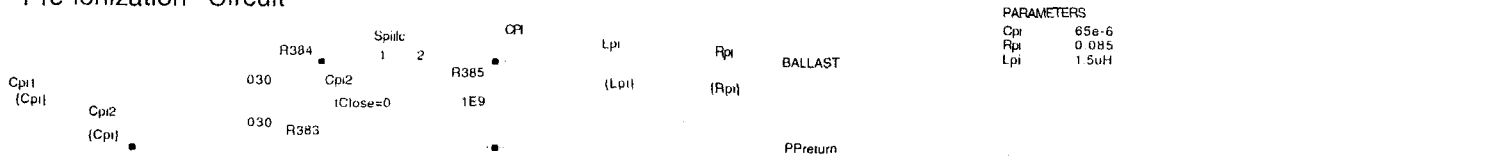


Grounding Cables

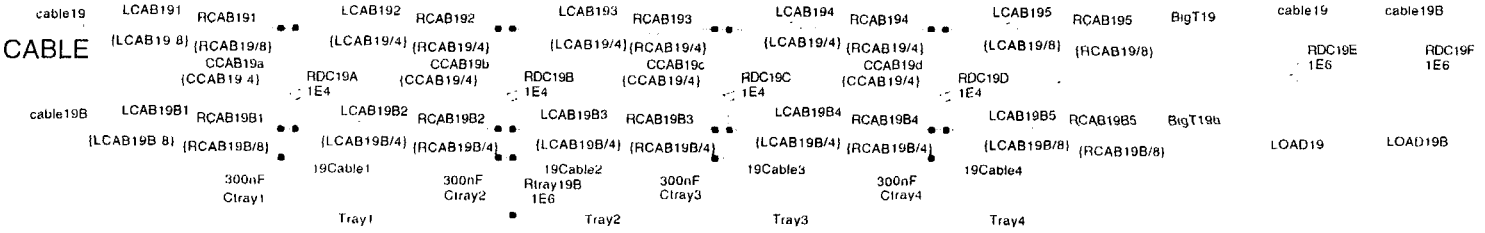


Pre-Ionization Pulser, Output Cables, and Cable Tray

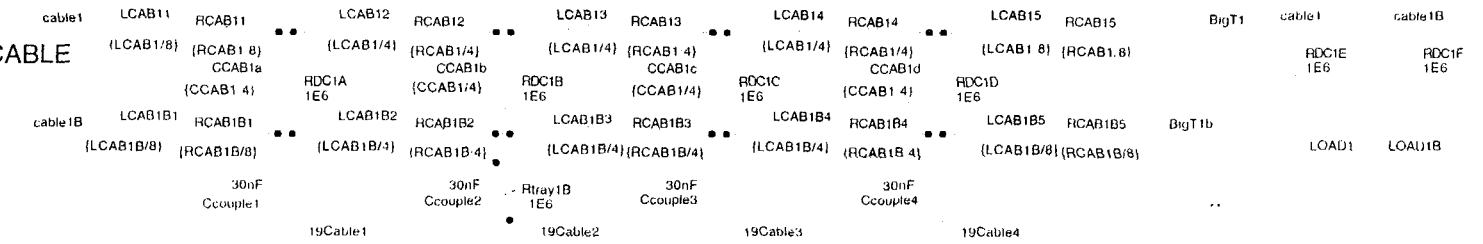
Pre-ionization Circuit



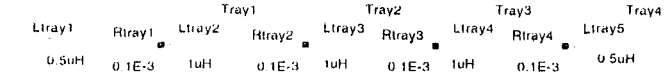
19 CABLE



1 CABLE



Cable Tray



Appendix 3
Power Conditioning System Grounding

Overview

This appendix summarizes a set of analyses performed to evaluate approaches to provide a robust grounding system in the NIF facility. This grounding system must minimize touch potentials associated with operation of the Power Conditioning System (PCS), even in the event of severe faults, and assure that the energy delivered to a person through contact with grounded structures is very low.

As is described below, we conclude that the most effective approach is some form of enclosure around PCS output cables. Placing each bundle of cables in a dedicated conduit or trough appears to be an effective approach, but may be expensive to implement, due to the requirements for good current contacts and structural strength. Some form of covered cable tray surrounding several bundles of cables, with a metal floor and cover, may be the most cost-effective approach.

Grounding Objectives/Policy

At the February, 1998 NIF Off-Site meeting, Doug Larson proposed the following NIF grounding policy:

Proposed NIF Grounding Policy

1. **Design to keep touch potentials during ground faults less than 500 V.**
   - This keeps the voltage in a range where skin resistance seems likely to remain in the circuit.
2. **Design to keep energy delivered to a 90 Ω load (a person where skin resistance is ignored) less than 3 Joules**
   - This is $^1/_3$ — _ of the published energy standard
3. **Administratively prohibit the routing of conductors into or out of the capacitor bay or amplifier region of the Laser Bay without a dielectric break**
   - This minimizes the possibility of propagating a touch potential outside of the Laser and Capacitor Bays

Candidate Grounding Approaches

In the same briefing, he noted four basic approaches to meeting this safety objective:

1. Tightly bond the PCS modules to the grounded laser support structures using a conductive enclosure around the cables.
2. Tightly bond the PCS modules to facility ground, using an improved ground mat in the slab.
3. Fully insulate the equipment in the Laser Bay, so that a ground fault in the laser bay need not be considered.

4. Float the pulsed power system from facility ground, using a high-value resistor or inductor to provide the safety ground.

Approaches 3 and 4 were rejected as being impossible to implement in such a way that their viability is assured.

Approach 2 was rejected due to the cost of modifying the building design to incorporate a fine ground grid in the slab. Bob Anderson and Bill Gagnon showed that the planned grounding grid, with 4/0 wires on a grid 12.5 ft on a side, would result in touch potentials as high as 3 kV between the PCS module and a fault in the Laser Bay, and still 800 V — 1,600 V at significant distances away from this line. They concluded that a grid spacing of 6 would reduce the peak touch potential to ~ 200 V, likely an acceptable value.

Mark Rhodes performed a separate analysis of this approach, including magnetic-field modeling and experimental measurements, and reached a similar conclusion, with touch potentials falling below 500 V for wide, continuous ground planes.

With the building construction well under way, however, the viability of a fine-grid ground plane was a moot point.

The following analysis thus focuses on Approach 1; some form of close-coupled grounding structure around the cables from the PCS to the flashlamp assembly, bonded to the PCS modules at one end and to the laser support structures (which must be bonded to the facility ground grid), at the other end.

Summary of Results

The touch potentials and the energy delivered to a person through contact with the grounding structures are significantly below the guidelines above for normal shots, for any of the considered grounding approaches. Several faults, however, can result in much higher voltages and person energies than those associated with normal operation. As a result, the NIF design includes a cable enclosure system to carry fault currents back to the PCS modules while significantly reducing touch potentials.

It is important to note that the cable enclosure system plays a significant role in system grounding only in the event of a fault from the hot conductor of a PCS output cable to a grounded structure in the Laser Bay. Furthermore, the fault must occur in such a way that very little current can flow back on the return conductor of the affected cable. This is an unlikely fault, but it could occur, for example, if an output cable was not plugged into the Big T, but left with its output terminal near a grounded structure in or near the FAU.

Mark Rhodes performed a set of calculations to establish the self-inductances and coupling coefficients for a number of geometries for cable trays and cable enclosures. These results, along with measurements at LLNL and at MPI, confirmed that an enclosure around the cables results in the minimum possible touch potential. The outer portion of enclosed transmission line, such as a coaxial cable or cables inside a conduit, effectively has no inductance, because it eliminates flux outside the enclosure. As a result, only the resistive component of the voltage drop along the enclosure remains.

Based on the inductances Mark calculated, we have used the PSpice model of the system to estimate voltages, currents, and person energies in the event of a fault from the hot terminal of an output cable to the cable tray/enclosure near the Laser bay. For this fault case, we assumed that the fault current reaches the cable tray/enclosure without connecting to the return side of

the coaxial cable. We modeled four cases; a simple ground plane under the cables (assumed to be approximately 40 wide), two different cable troughs, and a full cable enclosure.

A highly schematic version of the circuit model is shown in Figure 1. The model assumes that 19 of the loads are driven more or less normally, with a breakdown from the remaining cable to a grounded structure near the FAU. Note that the fault of concern, breakdown to ground without involving the cable return conductors, can only occur at the end of the cable, where the cable enclosure is tied to the facility ground through the FAU structures. This constraint was taken into consideration in constructing the circuit model.

The inductances of the cable center conductor and of the return through the cable tray/enclosure were taken from modeling done by Mark Rhodes. The values are given in Table 1. The full PSpice model used for one of the cases is given at the end of this appendix. Table 2 summarizes the results of the PSpice modeling. Example waveforms are given in Figures 2 and 3.

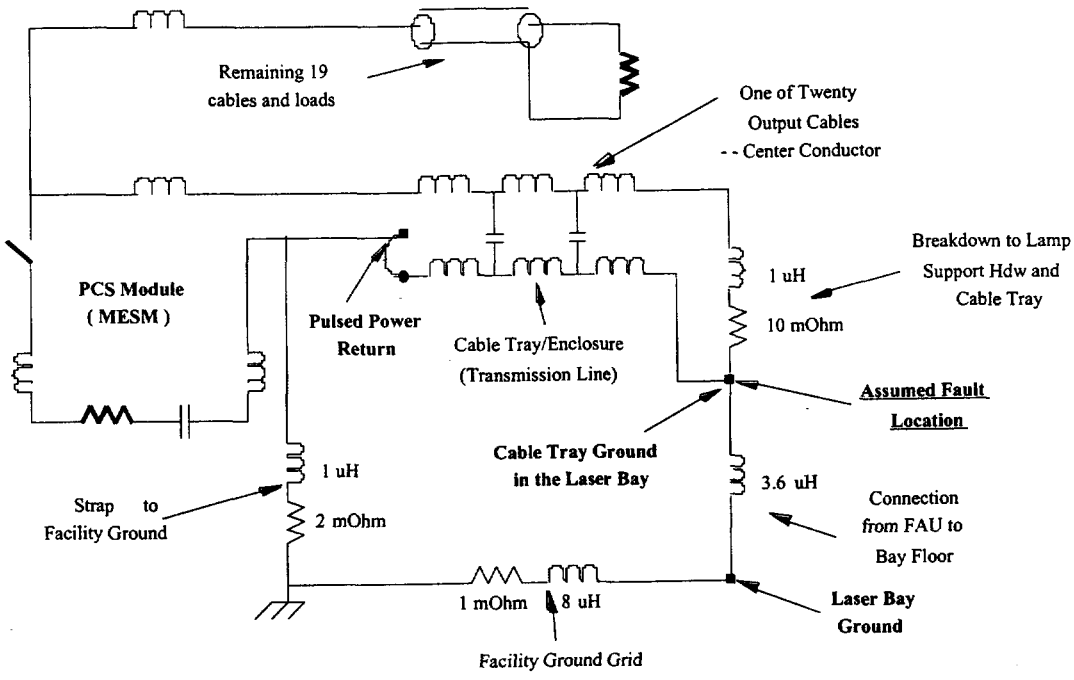


Figure 1. Simplified Circuit Model for the Fault Runs

Table 1. Wire and Cable Tray/Enclosure Inductances

	Wire Inductance	Plate Inductance
Wire 8 above a 40 -wide plate	43 µH	3.4 µH
Wire above a 24 -wide plate	21 µH	0.3 µH
Wire 8 above the bottom of a 10 x 10 Trough	42 µH	1.7 µH
Wire 8 above the bottom of a 24 -Deep Trough	42 µH	0.3 µH

Cable Trays

Within the context of the selected approach, the simplest level of touch potential reduction would be installing a flat conductive cable tray under the cables between the PCS modules and the flash lamp assemblies. The tray would be bonded to the PCS module at the Top Hat and to the laser support structures in the Laser Bay, which in turn would be bonded to the facility ground grid. Both the hot and return sides of the cables would be isolated from the tray for all normal shots, but might break down to the tray in the event of foreseeable faults.

As is shown in Table 2 below, this approach comes close to meeting the Grounding Policy. Voltages are somewhat too high, but person energies are low enough, with a small margin. However, given the difficulty of modeling systems of this complexity, we cannot be confident that the actual system will perform this well. Therefore, this approach was considered too risky.

Cable Enclosures

To ensure safety of personnel and equipment. The NIF design includes a conducting enclosure around the cables. Mark s analysis showed that the enclosure need not be fully closed, to achieve the desired effect. For example, the voltage drops are very nearly equal along a 150 ft length of enclosure if the enclosure is a 10 square cross-section enclosed trough or a open-top trough 10 wide and extending 16 above the top cable.

Similarly, several bundles of cables can be enclosed in a common enclosure using metal plates both above and below the cables. Similar to the open-topped trough, side walls are not needed if the cables near the outside edges of the enclosure are not too close to the opening at the edge; about a distance equal to the spacing between the plates.

The selected design takes advantage of these observations at the ends of the enclosure and at a few short sections along the run from the PCS modules to the FAUs. Most of the enclosure, however, is fully closed, to minimize touch potentials.

Table 2 summarizes the results of the PSpice modeling and also includes a comparison between the model results and a test with the prototype First Article PCS module under test in the basement of Building 391. Both the model and the test show that the planned approach will meet the safety criteria listed above.

Enclosure Design Summary

Good current contacts are required between sections of the tray/enclosure, to prevent sparking, even in normal shots, due to eddy currents and the charging of stray capacitances through the tray/enclosure. This means that casual contact between sections of the tray/enclosure should be avoided. The selected design ensures that individual pieces will either be separated by a clear gap (1/8 or more) or will be held tightly together. This is achieved by separating adjacent pieces by a nominal _ and connecting the pieces together with bolted straps. Spacing between the straps could be as much as 2 ft along edges parallel to the current flow direction, but will be approximately 4 along edges perpendicular to the current flow, to limit current per connection point to less than 50 kA. Straps are formed from 1/8 thick aluminum for most connections, but use _ copper wire for the transitions at the ramps and for the drops to the PCS module and the FAU.

The material used for the enclosure and the thickness of the material have been selected to keep the resistive component of the voltage along the tray to ~ 150 V or less. Since the peak current

can be as high as 90 kA, this means the resistance of the tray/enclosure should be less than 1.5 mΩ. For the case in which the tray length is approximately 150 ft, it will not be possible to meet this resistance budget with steel, and aluminum plate or conduit should be at least 1/8 thick. The selected design uses aluminum plates of _ thickness for most of the run, with 3/16 plate used for the bottom plates over the Laser Bay. Sides of the enclosure are formed from aluminum I beams or channel, depending on the locations, with _ web thickness.

As is shown in Table 2, the fault currents can be in the range of 90 kA. High currents mean large forces on the enclosure, requiring adequate structural strength to prevent deformation of the enclosure. Forces in the event of a fault can be as high as 6,000 lb per lineal foot. This, again, leads to the selection of thicker plates for the system.

Table 2. Predicted Voltages, Currents, and Energies for a Cable-to-Tray Fault

	20 Capacitors, 150 ft cables					24 Caps 66 cables
	Flat Cable Tray	10 Deep Open-Top Trough	24 Deep Open-Top Trough	Closed Enclosure	Bldg. 391 Enclosure Test *	Closed Enclosure
Voltage at P. P. Return (V)	50	45	20	20		30
Voltage at Laser end of Cable Tray (V)	670	460	130	150		210
Voltage at Laser Bay Ground (V)	460	320	190	190	370	310
Current in Cable Tray (kA)	65	65	65	65	67	92
Current in Ground Grid (kA)	12	6	4	4	5	6
Person Energy; Laser Bay end of Cable Tray (J)	1	0.4	0.08	0.08	~0.3	0.22
Person Energy; Laser Bay Ground (J)	0.4	0.2	0.04	0.04	~0.1	0.10

Note: The table gives the cable tray current values for the case in which the cable is treated as located only _ above the metal of the tray/enclosure, as this gives the higher currents, and the voltages and energies for the case of the faulted cable located 8 above the tray or the bottom of the trough, as this results in the higher voltages, ground grid currents, and energies.

* This column summarizes the results of a set of measurements with the prototype First Article module under test in the basement of Building 391. The system has the same architecture as the NIF design, including an enclosed cable tray, and has a set of 150 ft cables. Person energies were estimated based on the closed-enclosure Spice model, scaling the calculated energies with the square of the ratio of measured to predicted voltages.

Fault Case: Breakdown from cable hot to grounded structures at the FAU for a cable 1/2 up from the bottom of an enclosed trough (Run 61C)

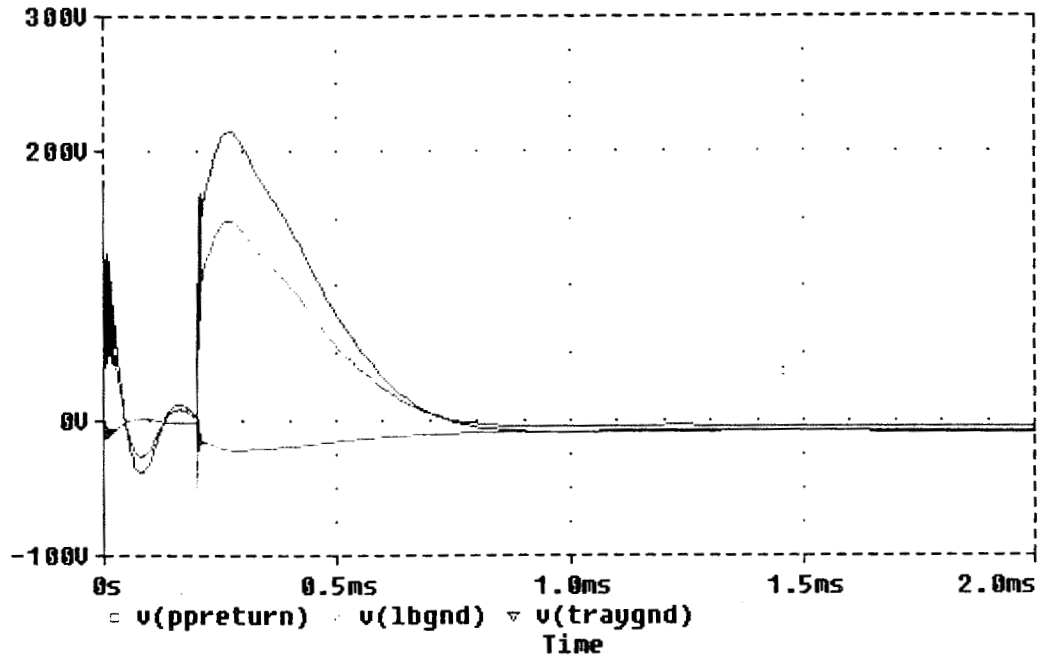


Figure 2. Voltages at three ground locations PPreturn; Pulsed Power Return (the Top Hat), LBgnd; the floor ground grid, in the Laser Bay, and TrayGnd; the cable tray or enclosure, at the Laser Bay end.

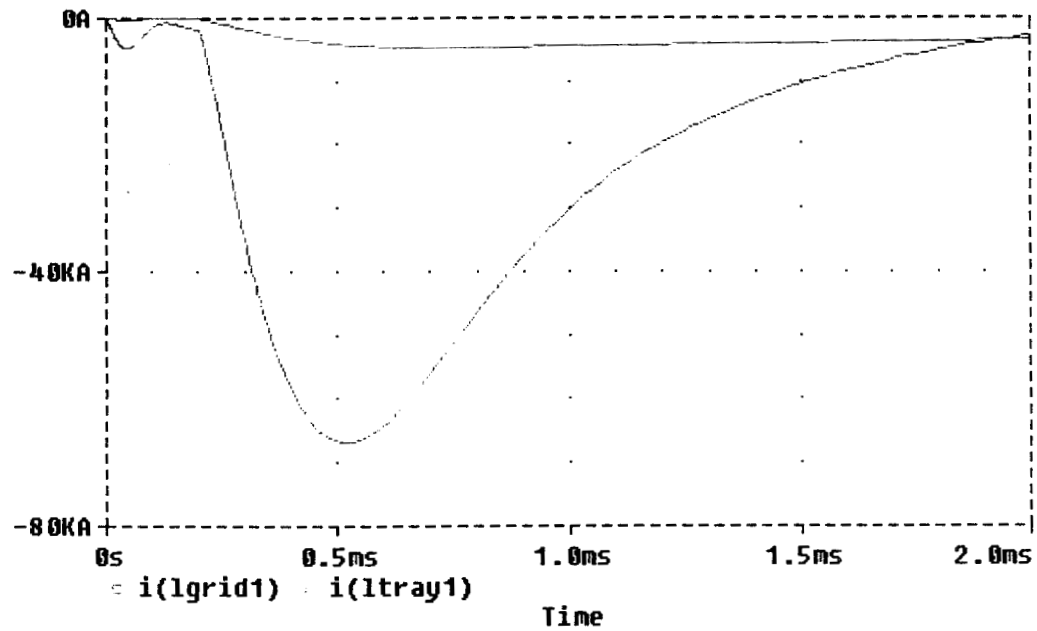


Figure 3. Currents in the floor grounding grid (Lgrid1) and in the cable enclosure (Ltray1). Note that the time of peak current in the Ground Grid is considerably after that for the Cable Tray. The Cable Tray peak current is at the same time as that for the cable, itself.

PSpice Model for Run 61C

Circuit Parameters

PARAMETERS:		PARAMETERS:		PARAMETERS:		PARAMETERS:		PARAMETERS:	
CC	299E-6	RDE1	.025	RGB1	.15-3	RSWB	.001	TFL19	2E-6
vch	23600	RDE2	.025	LGB1	212E-6	LSWB	70e-9	TFL1	2E-6
RC	.020	RDE3	.025	LGB2	108E-6	LHVB2	83e-6		

PARAMETERS:		PARAMETERS:		PARAMETERS:		PARAMETERS:	
LDE	9000E-6	RDE4	.025	RHVB1	30e-6	RSW	0.00001
		RDE5	.025	LHVB1	148E-6	LSW	50e-9
				LGB3	80E-6	Tclose	200e-6

Cable Parameters

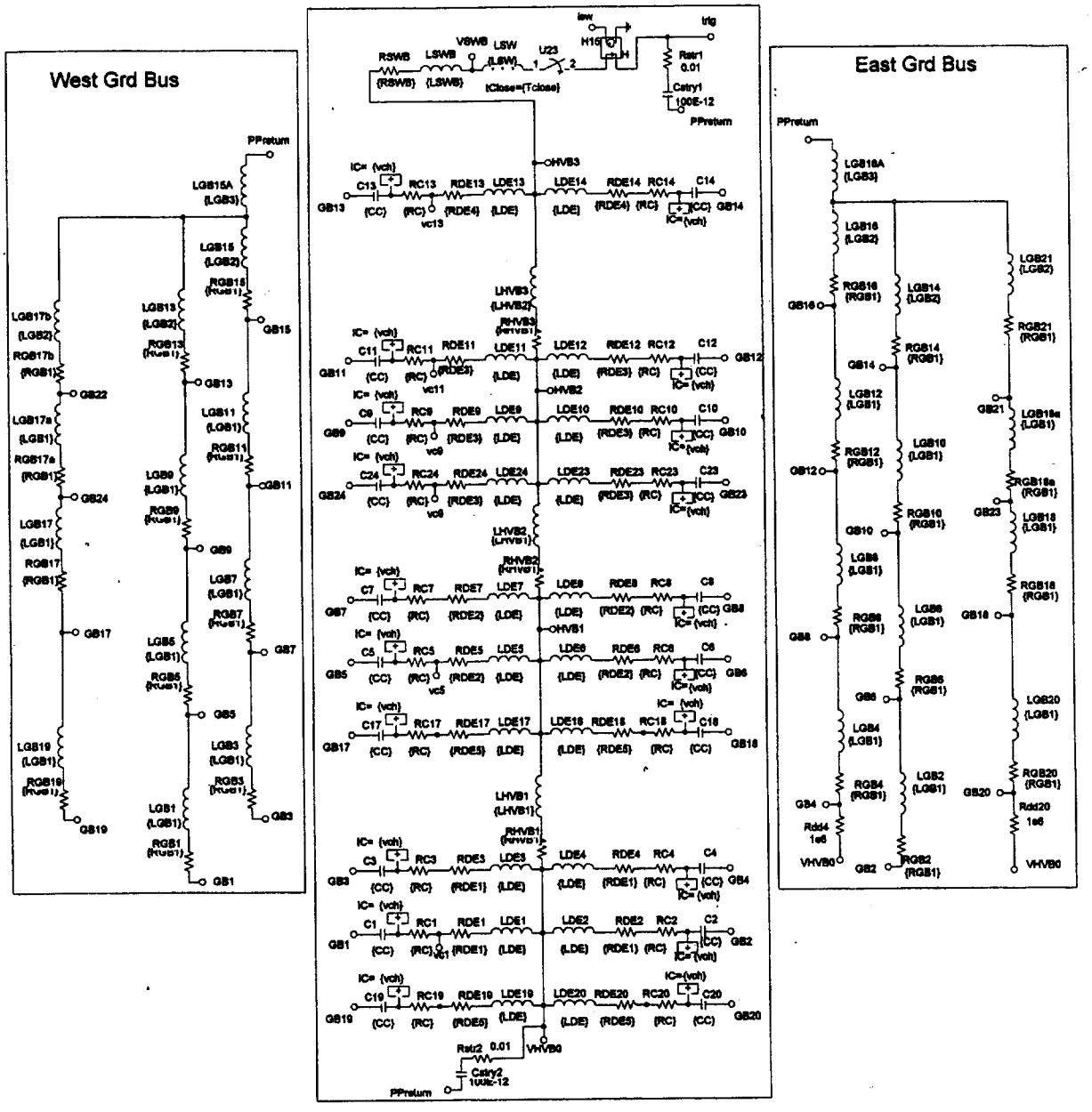
PARAMETERS:		PARAMETERS:		PARAMETERS:		PARAMETERS:	
RBAL1	.004	RCAB1	.020	RCAB1B	.0185	K01	78.7
LBAL1	19020e-9	LCAB1	20000E-9	LCAB1B	10E-9	LFL1	200E-9
		CCAB1	4.35E-9				

PARAMETERS:		PARAMETERS:		PARAMETERS:		PARAMETERS:	
RBAL19	(rbal1/19)	RCAB19	(rcab1/19)	RCAB19B	(rcab1b/19)	K019	(k01/sqrt(19))
LBAL19	(lbal1/19)	LCAB19	572e-9	LCAB19B	2e-6	LFL19	(lfl1/19)
		CCAB19	(ccab1*19)				

20 Capacitors, 299uF 20 mOhm each
First-Article Internal Buswork
25 mOhm damping elements
Baseline ballasts
150 ft Triple-Braid Cables
Flashlamp Load
Fast 130uF, 3.23uH, 0.1 Ohm PILC

Load Floating
Module grounded at Top Hat

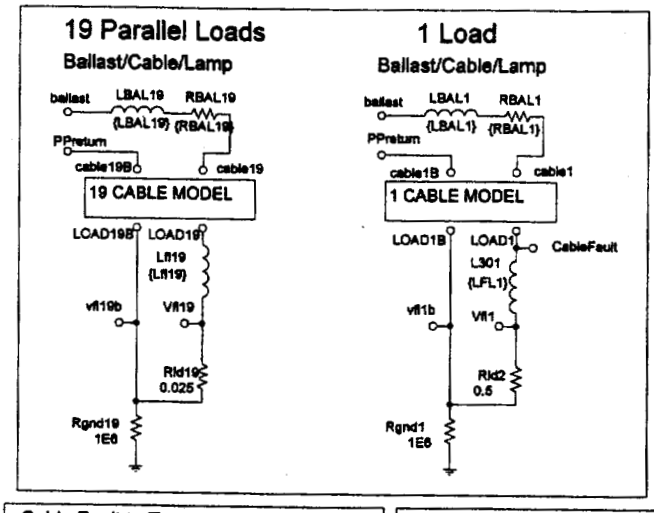
Cable breakdown to an Enclosed Trough

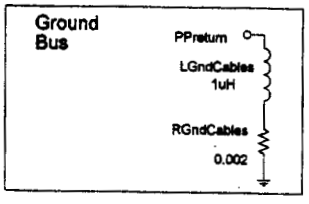


Trigger Generator and PILC simplified, and grounded only at the Top Hat

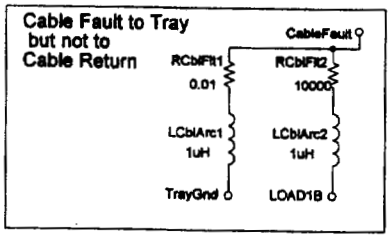
Coupled capacitances between output cables and cable tray
Simple, grounded Cable Tray

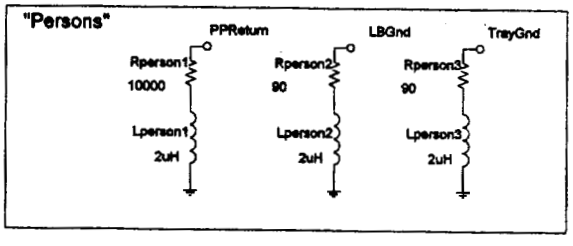
Distributed stray capacitances to ground

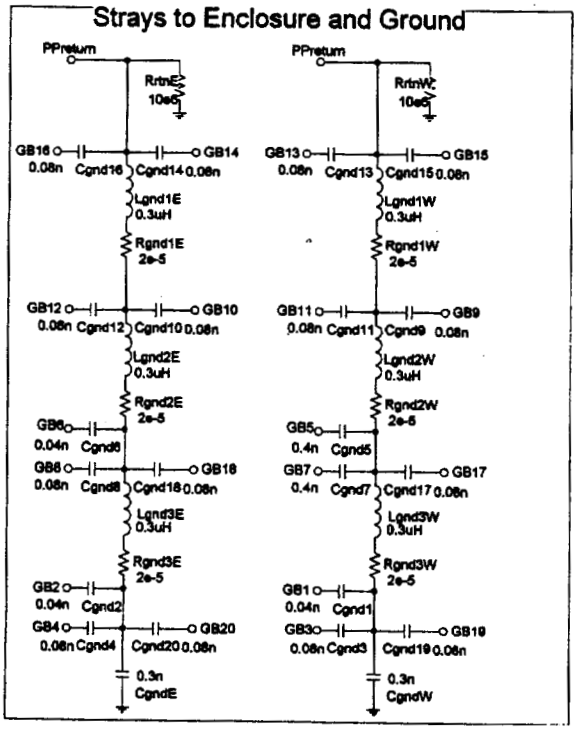


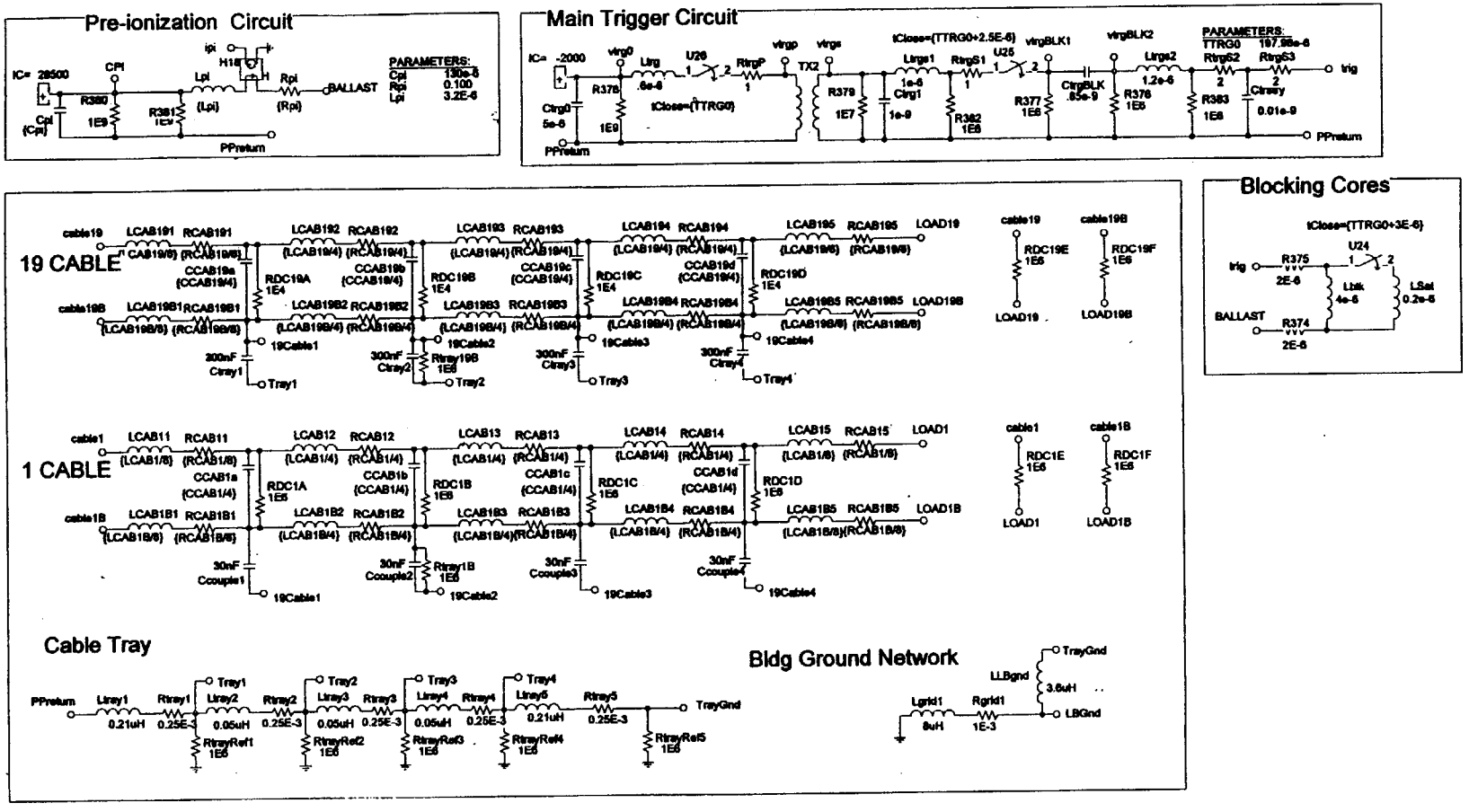


Load Resistance
= Ko / sqrt(I)








Pre-ionization Circuit
Main Trigger Circuit
Blocking Cores
19 CABLE
1 CABLE
Cable Tray
Bldg Ground Network
PARAMETERS:
PPreturn
BALLAST
TrayGnd
LBGnd

Appendix 4
TG-803 Trigger Generator System Description

This document summarizes the design and configuration of the TG-803 Trigger Generator, which is used to trigger the ST-300E output switch of the MESM. The key components in the unit are listed in the table below.

Primary Capacitor	5 μF, 2 kV	Condenser Products
Primary Switch	3.6 kV, high dI/dt SCR	Westcode
Secondary Capacitor	2 series 2 nF, 50 kV	Condenser Products
Pulse Transformer	1:46.3	Stangenes
Output Switch	UV-Illuminated, Sealed Switch	Titan Pulse Sciences
Blocking Capacitor	Potted assy of 3 series 40 kV capacitors	Titan Pulse Sciences
AC Isolation Transformer	120V AC	Stangenes

The TG-803 is mounted on the top of the MESM at the rear side, as shown in Figure 1 of the main section text. A simplified circuit diagram of the unit is shown in Figure A4-1.

A 5 μF capacitor is charged to approximately 2 kV by a power supply internal to the TG-803. A high-dI/dt SCR is used as the main switch, pulse-charging the output capacitor through a pulse-transformer to approximately 105 kV. The output capacitor is formed from a series set of capacitors. This capacitor is discharged through a UV-illuminated, sealed gas (N_2) spark-gap output switch. The UV-illuminator significantly improves the repeatability of the firing voltage of the switch. Tests have shown the switch lifetime to exceed 60,000 shots.

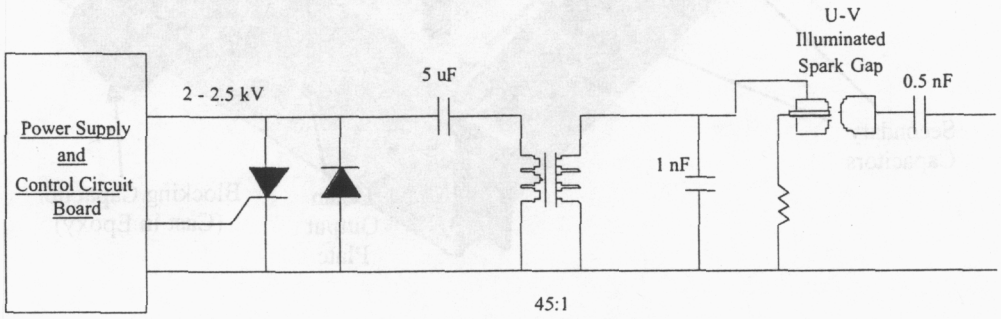


Figure A4-1. TG-803 Simplified Circuit Schematic

Figure A4-2 shows the key features of the TG-803. This figure was created prior to the recent re-configuration of the UV illumination of the output switch, which re-located the illuminator to the input side of the switch, as shown in the schematic of Figure A4-1. The UV-illuminator is now near the transformer, and the associated resistor string is routed to the ground side of the output capacitor.

The high-voltage bushing of the trigger generator includes an output blocking capacitor, to assure isolation of the trigger generator circuit from the rest of the MESM circuit during the relatively long discharge time of the MESM. Further isolated from the module is provided by a high-current fuse; Pulsed Power Components #°PPC-FU-212-173, which has a let-through action of 173 A^2-sec.

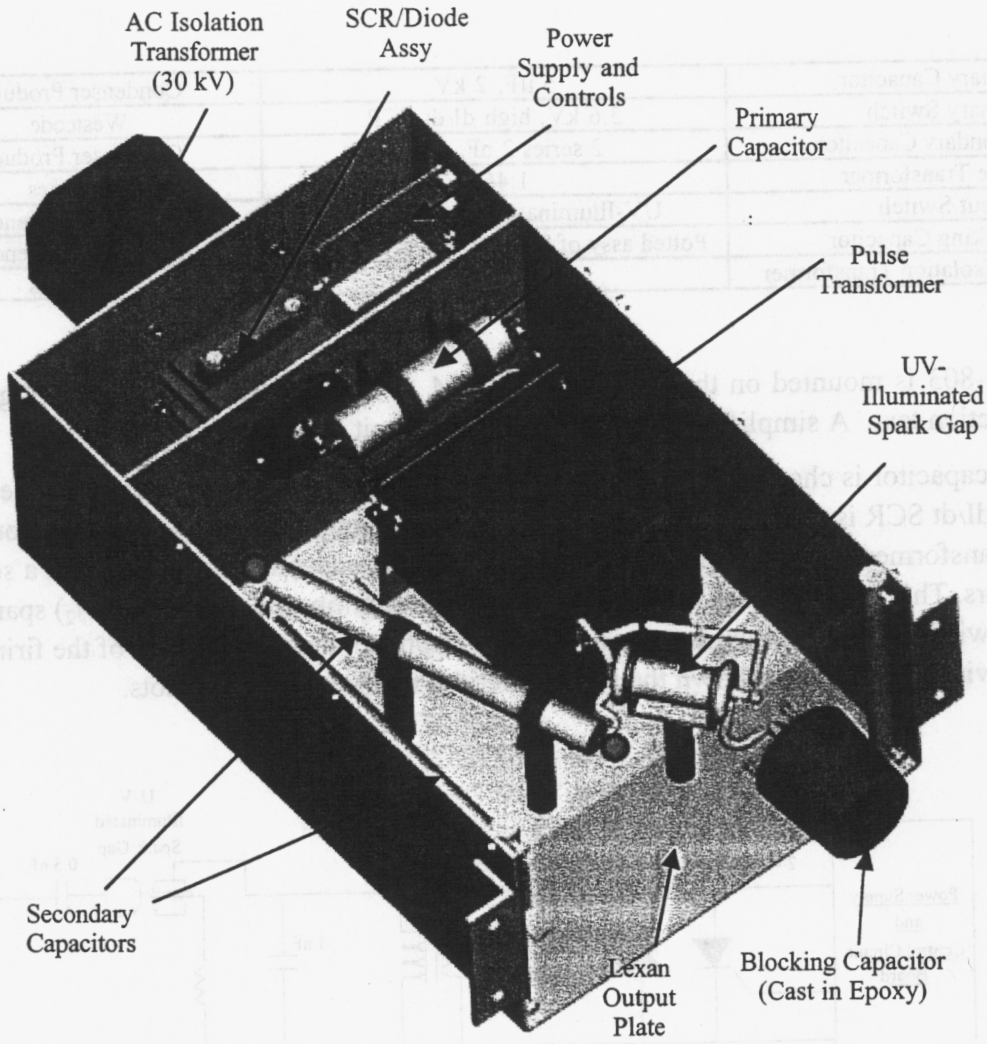


Figure A4-2 TG-803 Trigger Generator

Need new Photo or Drawing

Figure A4-3 shows the voltage on the secondary capacitor for a fairly typical shot. Figures A4-4 and A4-5 show fairly typical output voltages, measured at the ST-300, when the ST-300 pressure has been set high-to prevent the switch from firing.

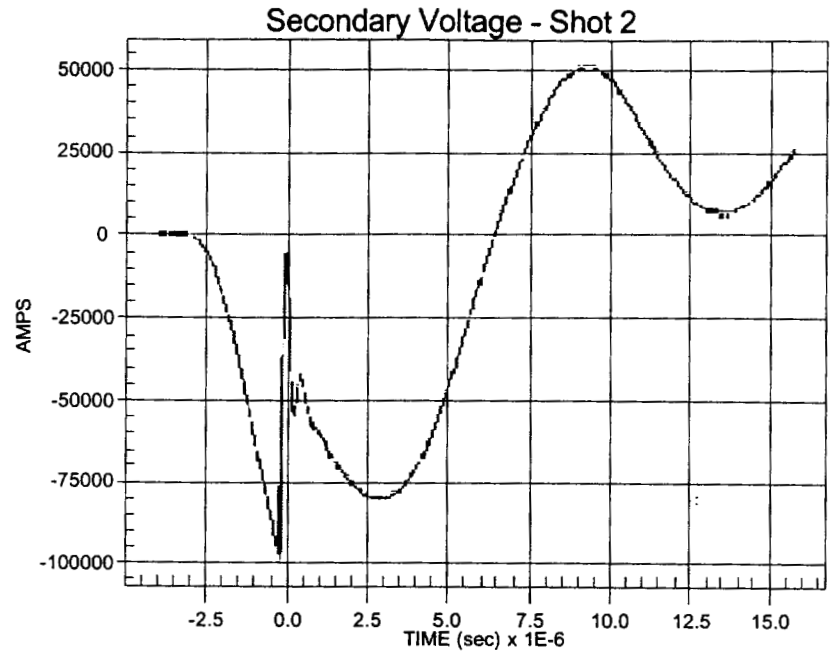


Figure A4-3. Secondary Voltage

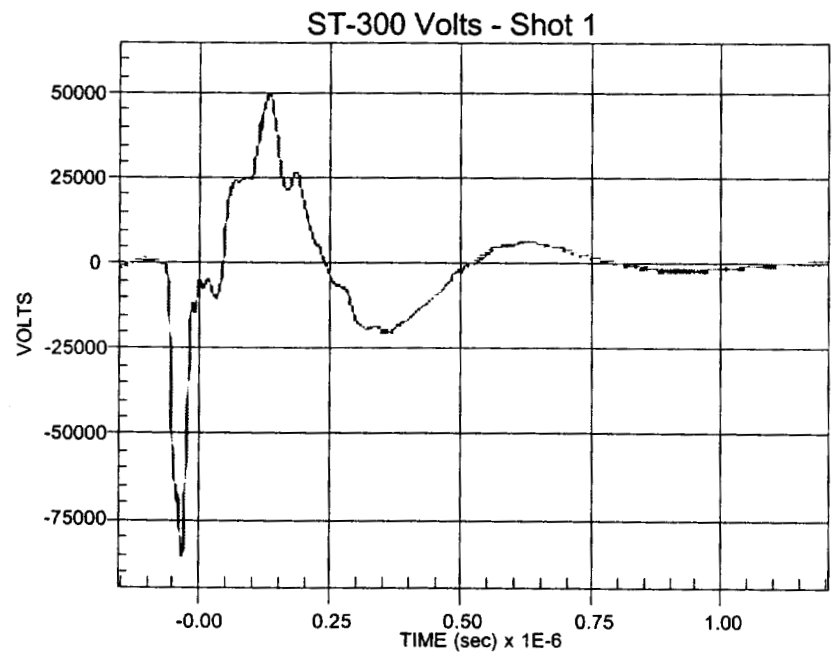


Figure A4-4. Output Voltage (Slow Sweep)

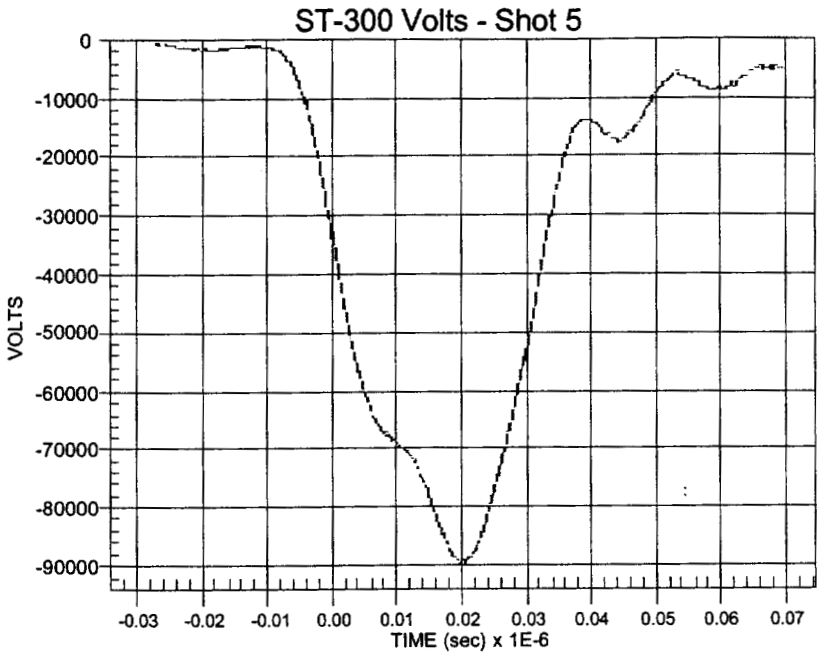


Figure A4-5. Output Voltage (Fast Sweep)