OMEGA EP System Operations Manual
Volume VII–System Description
Chapter 4: Power Conditioning

Chapter 4
Power Conditioning

4.0 INTRODUCTION

The power conditioning system provides the electrical energy to the flash lamps in the laser amplifiers. The 500-kVA substation supplies power to the power conditioning system at 208 V. This power is converted to high voltage and used to charge a bank of capacitors for subsequent discharge into the flash lamps in the laser amplifiers. The power conditioning unit (PCU) is the building block of the power conditioning system. Each of the 74 glass amplifiers is supported by a PCU, and there is an additional PCU in the Capacitor Bay that is used to support testing. OMEGA EP has 72, 40-cm disk amplifiers in the Laser Bay or 18 for each of the 4 beamlines. Additionally, Beamlines 1 and 2 each use one 15-cm disk amplifier in the Laser Sources area for a total of 74 glass amplifiers. The power conditioning control module (PCM) in the PCU provides for timing of the discharge into the flash lamps, diagnoses the performance of the equipment during the shot, and provides data to the Power Conditioning Executive (PCE) software.

Each PCU is a self-contained, pulsed-power system that includes the following:

- high-voltage power supplies to convert incoming ac to high-voltage dc,
- pulse-forming networks (PFN's) for energy storage and pulse shape,
- preionization and lamp check circuits (PILC's),
- high-energy switching devices to discharge the energy, and
- an embedded controller with associated control circuits and diagnostics to safely sequence the charge and discharge functions under control of a higher level executive software program running on a Sun workstation in the OMEGA EP Control Room.

A PFN is a RLC (resistance, inductance, capacitance) electrical circuit that stores energy to power the lamps and controls the shape of the electrical pulse that fires the lamp. There are 12 PFN's for each power conditioning unit and a total of 900 PFN's. The 15-cm disk amplifier has 12 lamps and each PFN energizes one lamp, whereas the 40-cm disk amplifier has 36 lamps and each PFN energizes a set of three lamps that are connected in series. An example of an energy pulse for the 40-cm disk amplifier is shown in Fig. 4.1. The PILC provides a low energy pulse (~400 J) to the flash lamps about 200 μs before the main energy discharge. This preionization helps to reduce the production of harmful UV radiation in the amplifier cavity and lessens the propensity for damage to the lamp because of the thermal shock of the main pulse. The PILC can be used alone as a lamp check diagnostic.

This chapter discusses the basis of the PCU design for the 40-cm disk amplifier as well as the system that is used to control the PCU. Operational and amplifier facilities controller (AFC) interfaces with PCU's are discussed as well as safety features and the grounding and support systems.

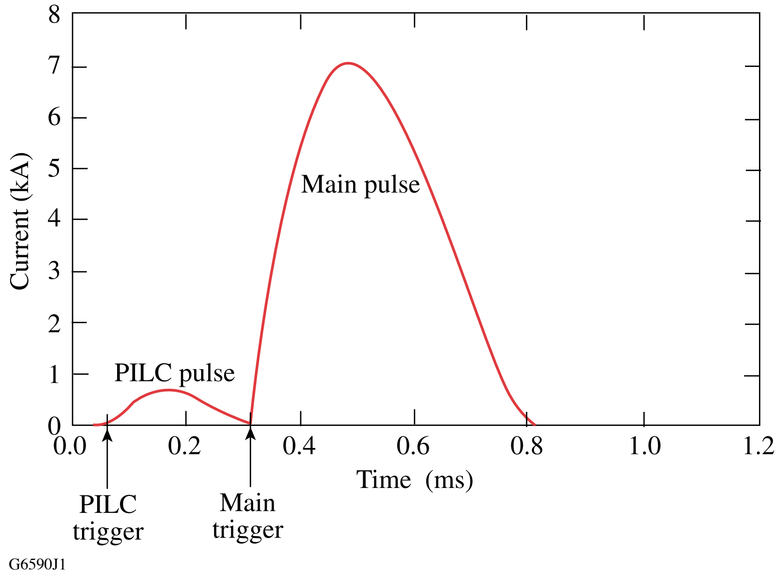

Figure 4.1
An example of the PILC and main discharge pulse from a power conditioning unit. The main pulse's peak amplitude is timed to coincide with the arrival of the laser pulse in the amplifier.

4.1 Disk-Amplifier Power Conditioning Design Basis

The power conditioning design basis for OMEGA EP's 40-cm disk amplifiers is derived from the NIF amplifier prototype tested in Amplab.[1] The LLNL design approach has been tempered with LLE operational and amplifier design experience.[2] The resulting power conditioning specifications for the OMEGA EP 4-cm amplifier are given in Table. 4.1.

Table 4.1: Power conditioning baseline specifications for the OMEGA EP 40-cm amplifier.

Requirement	Specification
Gain	1.05
Pulse full width at tenth-maximum (μs)	360
Number of flash lamps per PFN	3
Number of flash lamps (all external)	36
Energy delivered to flash lamps per PFN (kJ)	12.16
Energy delivered to flash lamps per disk (kJ)	146
Flash-lamp length (cm)	43
Flash-lamp bore (cm)	1.9

The NIF amplifiers are arranged in a 4 × 2 configuration and contain one inboard and two outboard arrays of flash lamps. ("Inboard" arrays are placed between two laser disks.) The OMEGA EP amplifier is arranged in a 1 × 1 configuration and contains only outboard flash lamps. The baseline energy requirements per disk are obtained from reported Amplab measurements for the outboard flash-lamp arrays. Based on these measurements, the per-disk energy requirement is 52 kJ. The per-disk pump energy must be adjusted to compensate for design features that are different in the OMEGA EP configuration and for electrical losses, as summarized in Table 4.2.

Table 4.2: Adjustments to the NIF per-disk pump energy necessary to accommodate the OMEGA EP configuration.

Performance Adjustments	**Multiplier**
Cavity transfer efficiency	2.0
Remove antireflection-coated blast window	1.076
Flat reflectors instead of shaped reflectors	1.120
Account for all LHG-8 laser glass	1.066
Account for preionization and lamp check (PILC)	1.015
Additional lamp length	1.075
Total adjustments to bank energy	2.804

These adjustments result in a per-disk pump energy of 146 kJ for OMEGA EP. The required bank energy is then determined by the linear losses in the PFN. A linear resistance of 75 mΩ has been measured for OMEGA's SSA power conditioning and cabling. This linear resistance combined with the nonlinear resistance of the flash lamp, which is a function of lamp bore, current density, and fill pressure, leads to a required bank energy ranging from 160 to 175 kJ.

The remaining electrical parameters are the pulse width and the flash-lamp fill pressure of the xenon gas. The pulse full width at tenth-maximum (FWTM) is 360 μs, the same as the NIF specification. The optimal fill pressure, which is bore dependent,[3] was determined by extrapolating fill pressures for both NIF 4.3-cm-bore and LLE 1.9-cm-bore flash lamps. This calculation leads to a fill pressure of 300 Torr.

The number of flash lamps of any given bore that will fit along one side of a disk is determined by the lamp wall thickness and the water jacket wall thickness. The OMEGA water-cooled flash-lamp assembly[4] has demonstrated a high degree of operational reliability. On this basis, the hoop stresses[5] for both the flash-lamp wall and water jacket wall have been extrapolated to the larger bore assemblies. For bores of this size, 18 flash lamps can fit along the length of a single disk as shown in Fig. 4.2. The flash lamps are water-cooled and can run at a higher explosion fraction (the operational energy divided by the maximum energy a lamp can survive and not explode). Water-cooled lamps are operated at 26% to 34% of their explosion fraction, whereas air-cooled lamps are normally operated at 20% to 25%. See "Chapter 3: Laser Amplifiers," S-AD-M-007 for additional information on the flash lamps and their function in the OMEGA EP amplifiers.

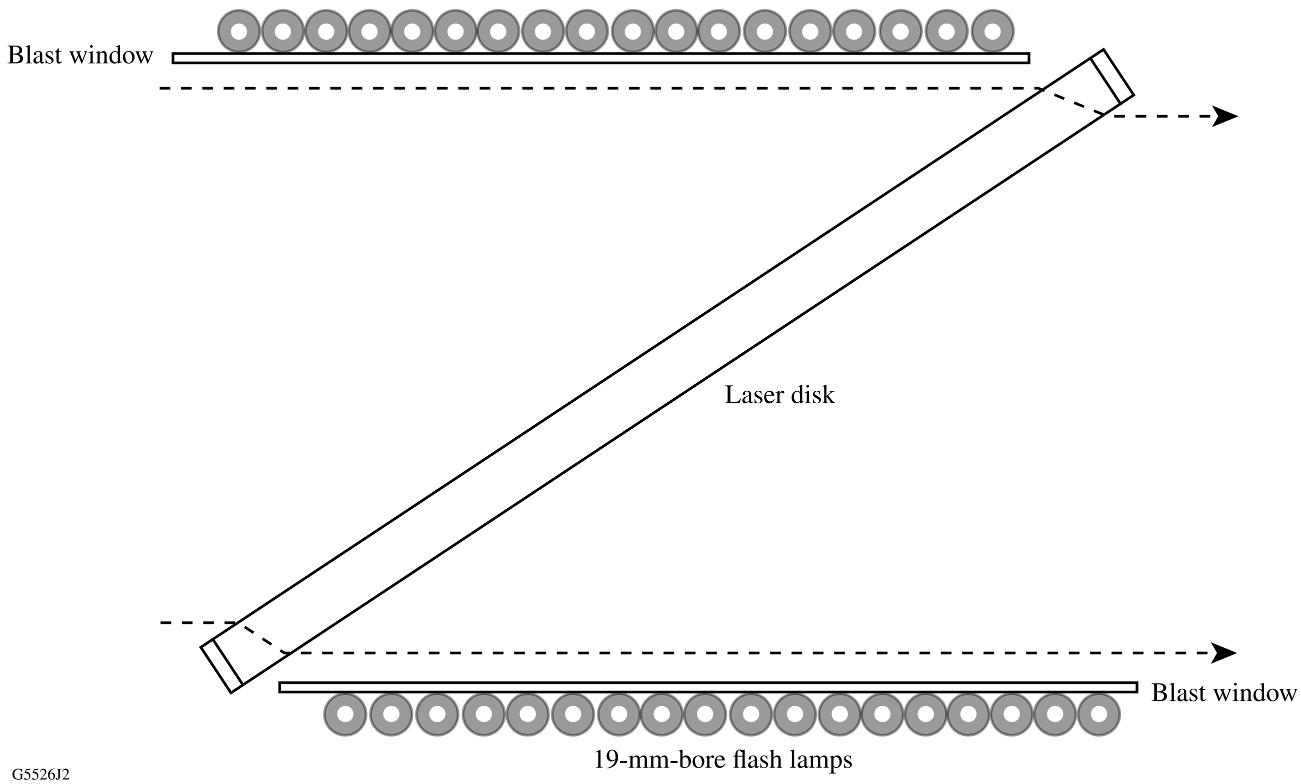

Figure 4.2
Schematic plan view of a 40-cm disk amplifier module containing a laser disk with the 19-mm-bore flash lamps. The path of the laser beam is also shown. All the flash lamps on each side of each laser disk are housed within a single pump module. A blast window in front of the flash lamps protects the laser glass in case of lamp failure.

4.2 DISK-AMPLIFIER POWER CONDITIONING UNIT (PCU)

4.2.1 Reliability, Serviceability, and Manufacturability

A number of improvements were made based on experience gained from the OMEGA power conditioning system, which is described in "Chapter 4: Power Conditioning," of the OMEGA Systems Operations Manual Volume I–System Description S-AA-M-12. In particular, the PCU's for the disk amplifiers are designed to be more reliable, less difficult to build, and easier to service than the PCU's in OMEGA. These and other design objectives were met by using the following approaches:

- minimize the use of discrete wiring
- maximize the use of solid aluminum buss work
- single-point system ground
- single-point enclosure ground
- all charging and dump components are located together
- control modules are clustered at one end of the PCU
- control modules are interconnected via fiber optic
- control modules are designed to mitigate effects of RFI/EMI
- painted steel weldment with steel skin panels
- mirror image PCU's for back-to-back placement

- main and PILC high-energy switches are clustered in a central cavity
- all controls and charge/dump panel on one end
- see-through door over the charge/dump panel
- insulating feet
- discharge cable clamp, shield termination, and entry on top of the PCU

The enclosure design allows two mirror-image units to be positioned back-to-back and accessed from either side (Fig. 4.3). These mirror-image pairs are lined up along the Capacitor Bay wall with a service space between them. Quad-fold doors allow unrestricted access to the PFN area (Fig. 4.4).

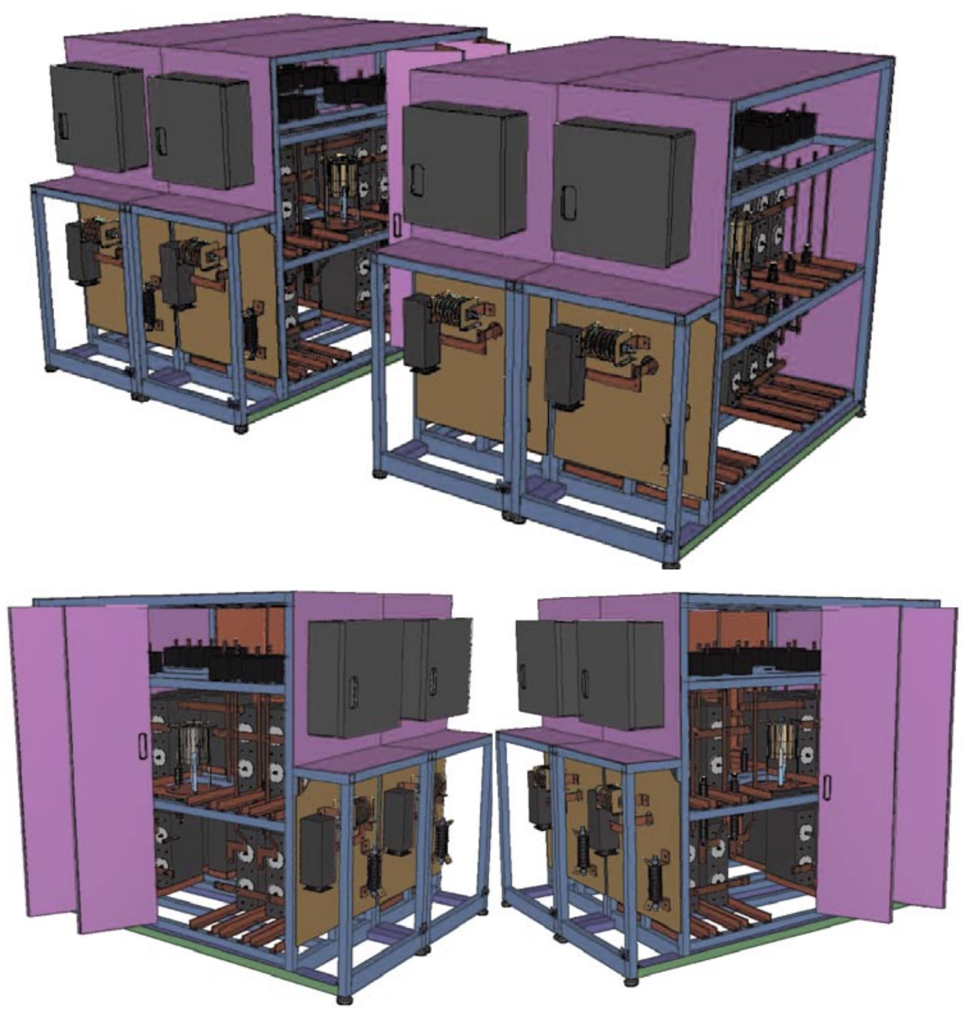

Figure 4.3
Power conditioning units are designed as mirror image pairs of each other to facilitate back-to-back placement in the Capacitor Bays. This design enhances serviceability. Eight PCU's are shown in the figure above. HV-discharge cables to the flash lamps in the amplifiers exit the top of each module (not shown).

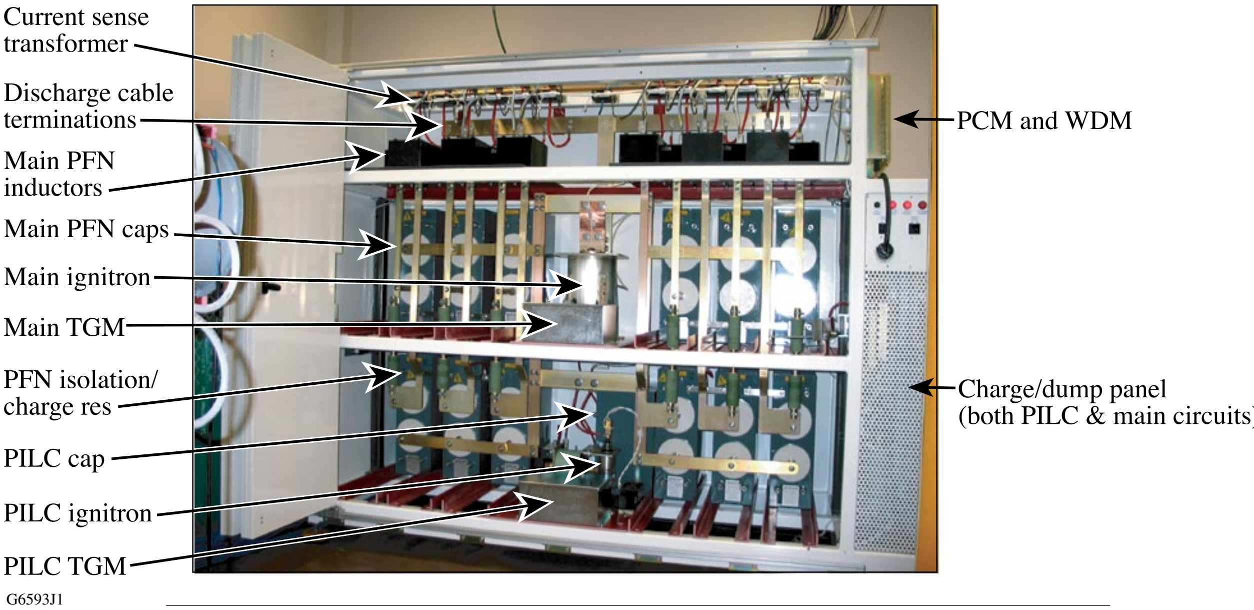

Figure 4.4
A quad-fold front door allows unrestricted access to repair the power conditioning unit.

Figure 4.5 illustrates layout of the PCU's in the Capacitor Bay. The PCU nomenclature corresponds 1:1 with the amplifier nomenclature described in Volume VII, "Chapter 3: Laser Amplifiers," S-A-D-M-007. The 44 PCU's for the main amplifiers are designated M11 for Main, Beamline 1, Amplifier 1 to M4B for Main, Beamline 4, Amplifier 11. The 28 PCU's powering the booster amplifiers are named B11 for Booster, Beamline 1, Amplifier 1 to B47 for Booster, Beamline 4, Amplifier 7. The two PCU's for Laser Sources are designated S11 and S21.

4.2.2 Pulse Power Circuit and Power Supply

The power conditioning pulse power circuits (Fig. 4.6) are nearly identical to those of OMEGA except that inductance was added to the PILC circuit for a more restrained PILC pulse. Each PFN that powers three amplifier lamps connected in series is a critically damped circuit made up of a single inductor, capacitor, and resistor. The specifications for the PFN components used to build the 40-cm (main and booster) amplifier PCU's are shown in Table 4.3, and the PFN energy levels are shown in Table 4.4.

Each PCU is supplied with power from a 2-kW, 15-kV dc output, high-voltage power supply. The main switch releases the main energy pulse, which is typically supplied at 13.6 kV and delivers 14.8 kJ/PFN or 178 kJ for a 40-cm disc amplifier. For the 11-main, 7-booster amplifier configuration, the main amplifiers each provided with 1.96 MJ and the booster amplifiers 1.25 MJ, for a total of 12.8 MJ with full four-beamline operation.

4.2.3 PCU Components and Requirements

The PFN capacitors are constructed using metalized polypropylene film technology. This technology is the industry standard for energy-storage capacitor construction and provides high energy density and excellent reliability compared with the layered paper and metal-foil construction used in older designs.

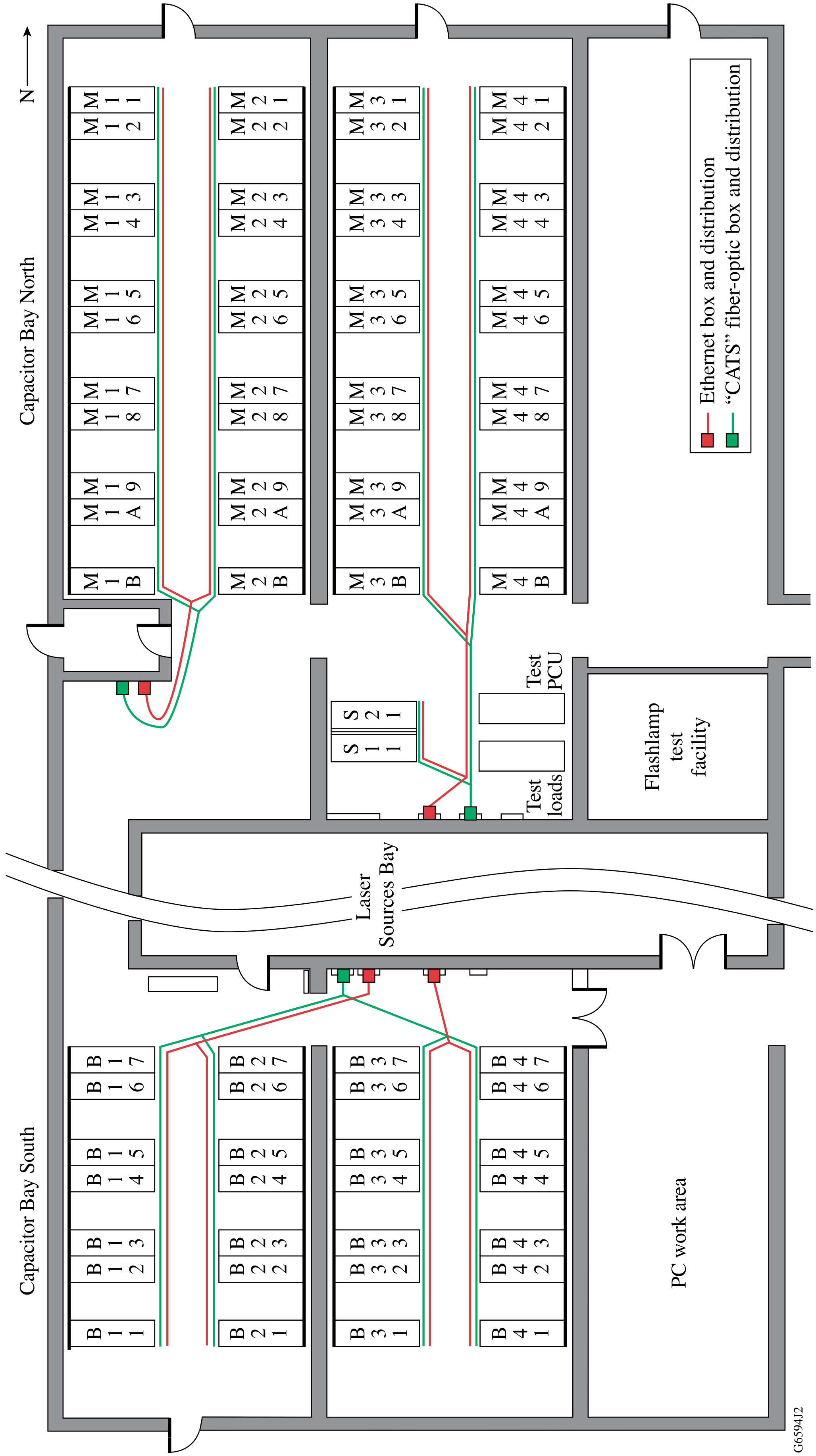

Figure 4.5
PCU layout in the Capacitor Bay: Each PCU identification corresponds 1:1 to amplifier nomenclature; e.g., PCU "B21" supports Beamline 2's first booster amplifier, B21. Ethernet and fiber optic cables are distributed to each PCU from boxes in the North and South Capacitor Bays. PCU's "S1" and "S2" support the Laser Sources amplifiers.

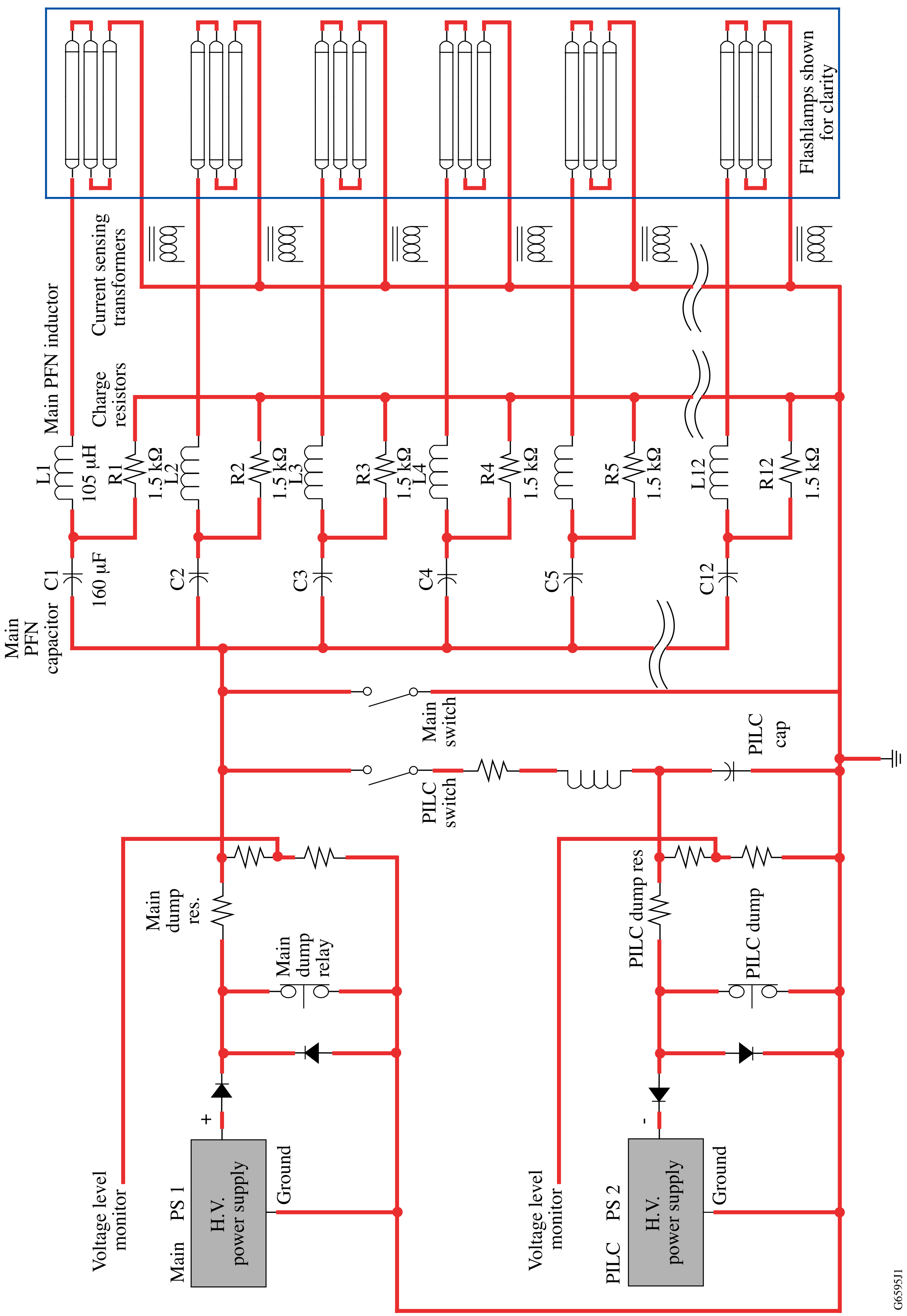

Figure 4.6
Schematic diagram of the PCU's pulse power system. Main and PILC pulse forming networks (PFN) are shown. Each PFN consists of a RLC circuit, HV power supplies, and ignitrons to switch the high current (~8 kA) and voltage (~14 kV) into the amplifier's flash lamps.

Table 4.3: Main and booster amplifier PFN build-to specifications.

Capacitor	160 μF
Inductor	105 μF
Maximum charge voltage	14.5 kV
Peak current	8.8 kA
Pulse width	369 μs
Maximum energy	16.8 kJ
Maximum circuit impedance	0.081 ohm

Table 4.4: Main and booster amplifier energy levels.

% Energy	kJ/PFN	PFN kV
10	1.7	4.6
20	3.4	6.5
30	5.0	7.9
40	6.7	9.2
50	8.4	10.2
60	10.1	11.2
70	11.8	12.1
80	13.4	13.0
88*	14.8	13.6
90	15.1	13.7
100	16.8	14.5

*Nominal operating conditions.

Switching-style power supplies are used for charging the storage capacitors. These power supplies are mounted within each PCU enclosure. The A size (e.g., National Electronic NL-7218H-100) ignitron switches energy for the PILC pulse, and the larger Richardson NL8900R Ignitron switches energy into the flash lamps for the main pulse. These ignitrons are also used in the OMEGA Laser System and are proven, robust, and reliable devices. De-ionized water stabilizes the temperature of the ignitron switches by cooling the cathode. The anode of the ignitron is heated with a 50-W resistive heater. A 208-V/6-V step-down transformer that has a secondary high-voltage isolation in excess of 30 kV supplies the 6-V ac power for this heater. This heater keeps the anode in the range of 35ºC–40ºC. This temperature differential across the tube helps to clear any condensed mercury vapors from the anode or the insulating glass between it and the cathode. This, in turn, helps prevent unexpected high-voltage breakdown (pre-fire) of the tube.

Energy stored in the PCU is delivered to the flash lamps via cables consisting of two #6 AWG silicon-insulated wires twisted together and shielded by an aluminized Mylar film with a #10 AWG drain wire as specified in “Requirements High Voltage Discharge Cable,” A-AL-R-007.

The power conditioning unit requirements for the 15-cm and 40-cm amplifiers are specified in “Requirements Power Conditioning Unit for the 15-cm SSA,” A-AL-R-003 and “Requirements Power Conditioning Unit for the 40-cm SSA,” A-AL-002. The PCU’s were built to the specifications shown in Table 4.5.

Additional background information about OMEGA EP power conditioning can be found in “Power Conditioning Training (OMEGA EP),” A-AL-M-111 and “FDR OMEGA EP Power Conditioning Unit for OMEGA EP,” A-AL-M-113.

4.3 PCU Control System

The PCU control system consists of five subsystems: the PCU control module (PCM), the charger control modules (CCM’s), the waveform digitizer module (WDM), the hardware control module (HCM), and the trigger generator modules (TGM’s) (Fig. 4.7). There are two TGM’s: one for the PILC and another to trigger the main pulse.

4.3.1 PCU Control Module (PCM)

An onboard microprocessor controls the PCU. This processor and its associated interface circuits make up the PCU control module or PCM. A block diagram of the PCM is shown in Fig. 4.8. The PCM is driven by a PC/104 single-board computer and communicates with the PCE via fiber-optic Ethernet. Three PCU ID switches are set to provide PCU identification through hex output to the PCM and PCE. The custom PCM interface board handles the conversion of processor I/O to fiber optics. Firmware controls the sequencing of the charge and discharge cycle as instructed by the PCE. The delay sync trigger properly times the PILC and PFN discharges. The PCM provides diagnostic data and communicates with other control modules. All input/output from the PCM is transmitted by means of fiber optics.

The PCM is housed in a dedicated EMI-hardened enclosure mounted on the end of the PCU. The PCM controls all aspects of the charge and firing operation of the PCU. It performs tests during charge and discharge sequences to ensure proper operation and has the ability to abort the sequence if

Table 4.5: Comparison of the PCU build-to specifications for the 15-cm and the 40-cm disk amplifiers at the nominal and maximum voltages.

	15-cm Disk Amplifer (laser sources)		**40-cm Disk Amplifier (main and booster)**	
PFN Parameters	Nominal Voltage	Maximum Voltage	Nominal Voltage	Maximum Voltage
Bank voltage (kV)	10	14.5	13.6	14.5
Capacitance (μF)	210	210	160	160
Inductance (μH)	160	160	105	105
Lamp arc length (cm)	132	132	129	129
Lamp bore (mm)	19	19	19	19
Lamp fill pressure (Torr)	300	300	300	300
Lifetime exponent	8.5	8.5	8.5	8.5
Impedance parameter ($\Omega A^{0.5}$)	82	82	80.1	80.1
Circuit impedance (Ω)	0.075	0.075	0.075	0.075
PFN stored energy (kJ)	10.5	22.1	14.8	16.8
Lamp energy (kJ)	9.9	20.5	13.7	15.5
Resistance energy (J)	571	1525	1032	1220
Energy left on bank (J)	28	28	2	10
Pulse length (μs)	183.3	183.3	129.6	129.6
Explosion energy (kJ)	68	68	55.8	55.8
Fraction of explosive energy (%)	14.6	30.1	24.6	27.8
Circuit impedance (Ω)	0.873	0.873	0.81	0.81
Full pulse width (μs)	550	550	389	389
True pulse width (μs)	474	466	331	330
Power pulse width at FWTM (μs)	534	520	370	369
Damping parameter	0.88	0.73	0.76	0.74
Peak current (kA)	5.1	8.3	8.1	8.8
Total number of PCU's	2	2	72	72
Number of PFN's per PCU	12	12	12	12
Total number of PFN's	24	24	864	864
Total PFN stored energy (MJ)	0.25	0.53	12.79	14.52

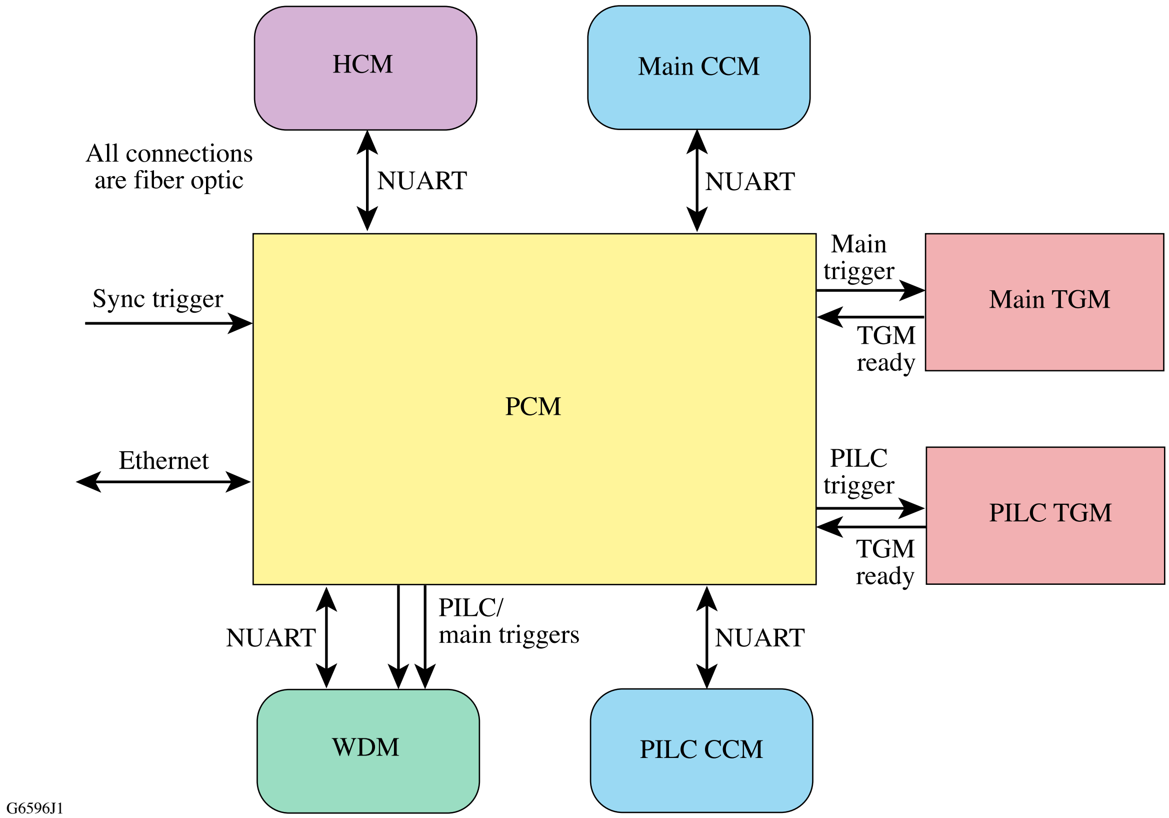

Figure 4.7
The power conditioning control module (PCM) interfaces with the main and PILC trigger generator modules (TGM), the main and PILC charger control modules (CCM's), the waveform digitizer module (WDM), and the hardware control module (HCM). LLE's Ethernet provides communications with the power conditioning executive (PCE) and the synchronous triggers are provided by the master timing generator (MTG).

problems arise. It also provides diagnostic data to the PCE during and after a proper or aborted charging sequence. See "PCU Control Module Requirements," A-AL-R-004 for more detailed information about the PCM.

4.3.2 Charger Control Module (CCM)

The OMEGA EP power conditioning unit utilizes two stand-alone charger control modules (CCM's): one for the PILC charger and another for the main bank. The CCM's purpose is to control the operation of its charger. It contains all the necessary electronics to accomplish proper charging. The PCM communicates with the chargers through the CCM via a dedicated fiber-optic link. Field programmable gate arrays (FPGA's) are used to control these modules. The internal functions of the charger controller include analog signal conditioning and filtering, D/A and A/D conversions, fiber-optic link watchdog, PCM control watchdog, and fiber-optic NUART (nonuniversal asynchronous receiver-transmitter) communication. Figure 4.9 shows a block diagram and external interconnects for this module. Two control modules are required: one for the main bank charger and one for the PILC charger. Functionally, these modules are the same, however, there are differences in the charger I/O signals and the analog programming levels between the two control modules. See "Requirements Charger Control Module," A-AL-R-005 for more detailed information about the CCM.

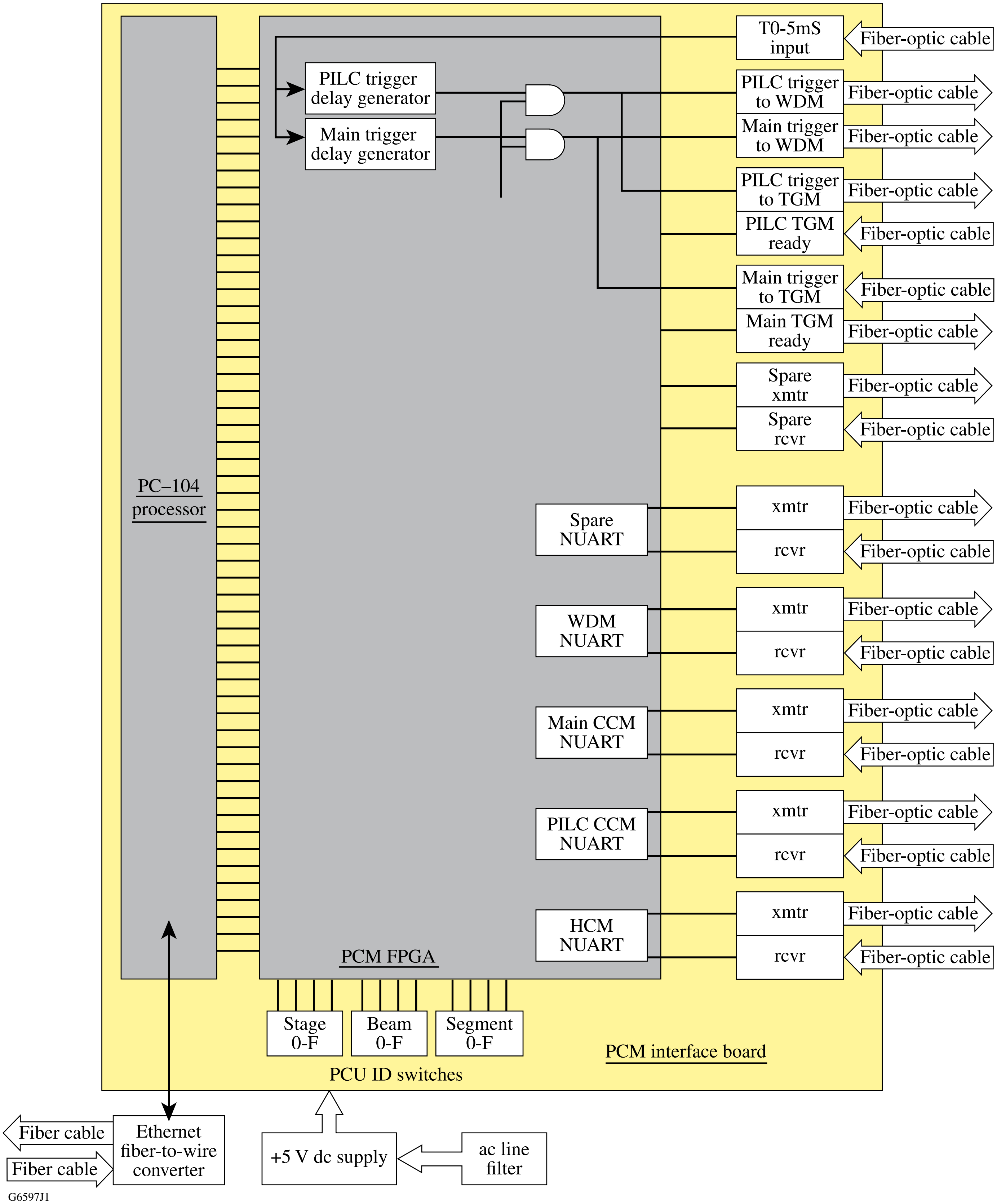

Figure 4.8
A block diagram of the PCU control module shows the Linux-based PC104 microprocessor communicating through the PCM's field programmable gate array (FPGA) to the various control modules. Fiber-optic cables are utilized to minimize electromagnetic interference (EMI).

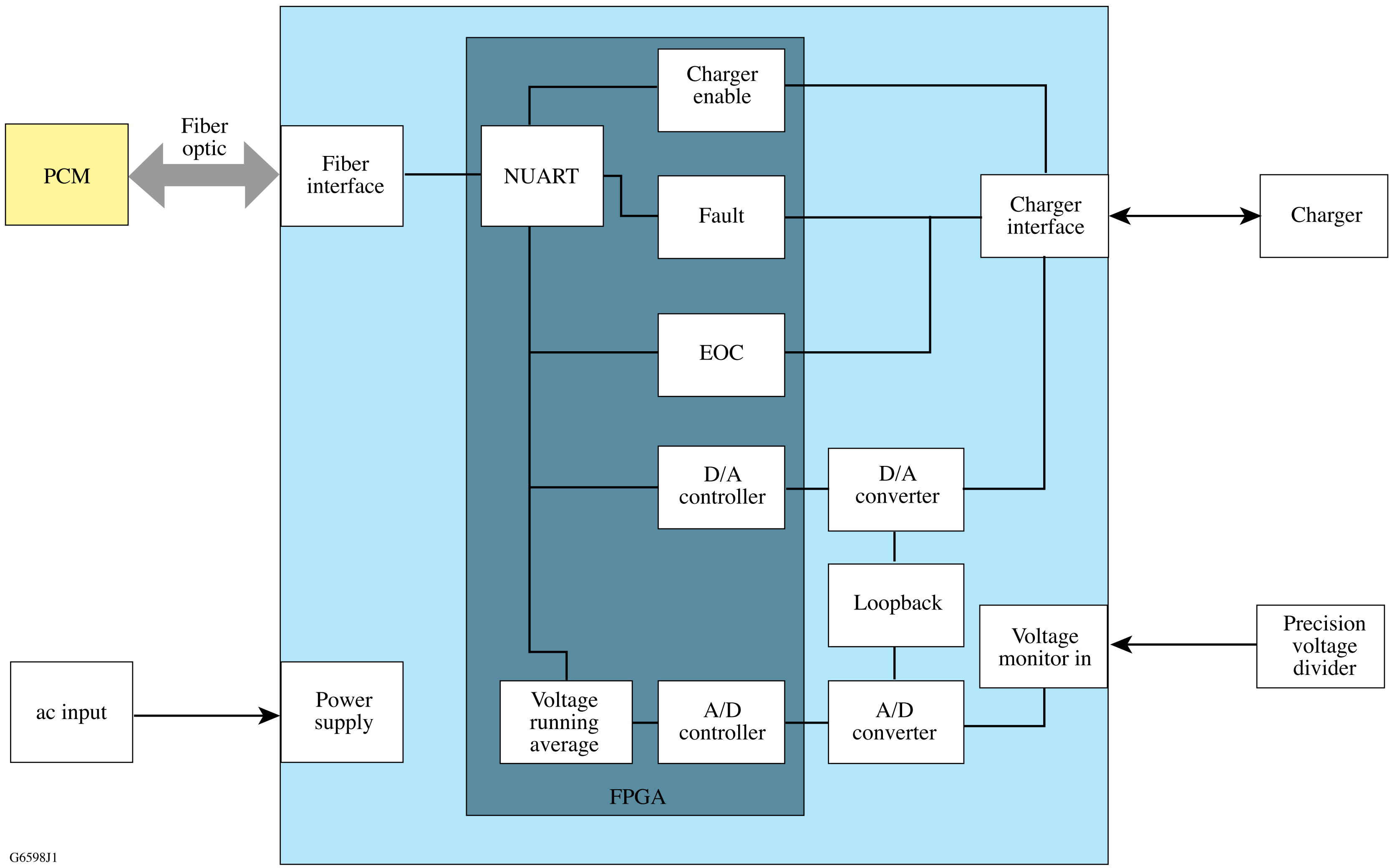

Figure 4.9
Charger control module (CCM) block diagram. The functions internal to the CCM include analog signal conditioning and filtering, D/A and A/D conversions, fiber-optic link watchdog, PCM control watchdog, and fiber-optic NUART. The figure above shows a block diagram and external interconnects for this module. Two different control modules are required, one for the main bank charger and a second for the PILC charger. Functionally, these modules are the same; however, there are differences in the charger I/O signals and the analog programming levels.

4.3.3 Waveform Digitizer Module (WDM)

The purpose of the WDM is to digitize and store PFN current waveforms for each shot. The data collected is used to assess the performance of the PFN's. Each PFN's current waveform contains two pulses, a PILC pulse followed by a larger main pulse as shown in Fig. 4.1. During the shot, a current-sensing probe samples the returning current on each circuit and couples it to the WDM. After a shot, the PCM uploads this information from the WDM for transmission to the OMEGA EP database. The WDM performs both a pre-fire monitor and a waveform digitization function. When the PCU starts charging, the WDM begins to monitor the 12 PFN inputs for a current level above a preset pre-fire threshold. A signal above this level would indicate that a PFN had experienced current flow prematurely. This condition is called "pre-fire" and is reported to the PCM. When the WDM receives the PILC trigger signal, it starts recording the digitized waveform data into memory. This recording continues for 3 ms; then the PCM is notified of the completed digitization. The WDM has sixteen (16) analog inputs. In addition to the 12 PFN inputs previously mentioned, one input monitors the ground fault current waveform, another the discharge cable shield buss current, and two monitor the high-energy switch triggers.

A WDM block diagram is shown in Fig. 4.10, and the WDM is described in more detail in "Requirements Waveform Digitizer Module," A-AL-R-006, which includes a WDM timing diagram. Also, see PCU Waveform Digitizer Module FDR, "A-AL-M-121".

4.3.4 Hardware Control Module (HCM)

The HCM interfaces with the PCM to control and sense various discrete devices within the PCU. The HCM supplies switched and fused 208-V ac power for the dump relays, the power contactor, and the trigger generator modules. It also provides fused, 208-V ac power for the CCM's, the PCM, the WDM, and the ignitron heaters. The HCM senses the status of the "Amp OK" signal, PCU door interlock, the safing contactor, and the dump relays. It interlocks out the power to the charger contactor and the dump relays if the PCU doors are not closed and/or the proper "Amp OK" signal is not present and provides fiber-optic drivers to relay "Safe" and "Charging" signals to the associated AFC in the laser bay. This module communicates with the PCM via a fiber-optic NUART and it drives the control panel status LED's. A block diagram of the HCM is shown in Fig. 4.11. See "Hardware Control Module Requirements," A-AL-R-056 for more detailed information.

4.3.5 Trigger Generator Module (TGM)

The OMEGA EP power conditioning units (PCU's) contain stand-alone trigger generator modules (TGM's) located at both the preionization (PILC) and pulse forming network (PFN) ignitrons. The purpose of these modules is to enable the power conditioning control module (PCM) to trigger each of the ignitrons at the appropriate time. Each TGM contains the electronics to trigger either of these ignitrons via a dedicated fiber-optic link. The internal functions of the TGM include logic voltage generation, high-voltage generation, trigger pulse-forming network, high-voltage isolation, and fiber-optic trigger input and output logic. Silicon-controlled rectifiers (SCR's) are used in the circuit to control the firing conditions. The TGM block/interconnect diagram is illustrated in Fig. 4.12. See "Requirements Definition, Trigger Generator Module," A-AL-R-001 for more detailed information.

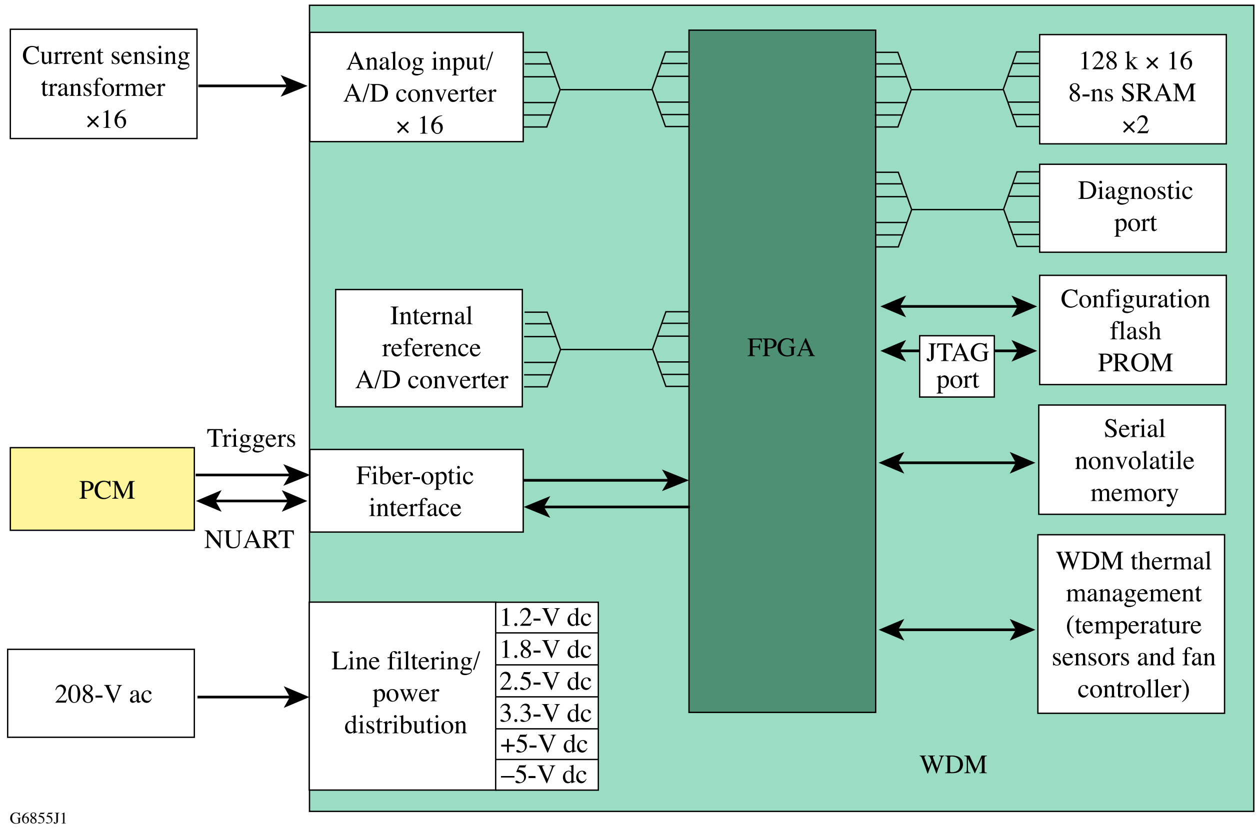

Figure 4.10
Waveform digitizer module (WDM) block diagram. The primary purpose of the WDM is to digitize and store PFN current waveforms during the shot sequence. Each PFN's current waveform contains two pulses: a PILC pulse followed immediately by a larger main pulse as shown in Fig. 4.1. After a shot, the PCM will upload this information from the WDM for later transmission to the Power Conditioning Executive. Each WDM can handle up to 16 independent channels of on-shot data collection.

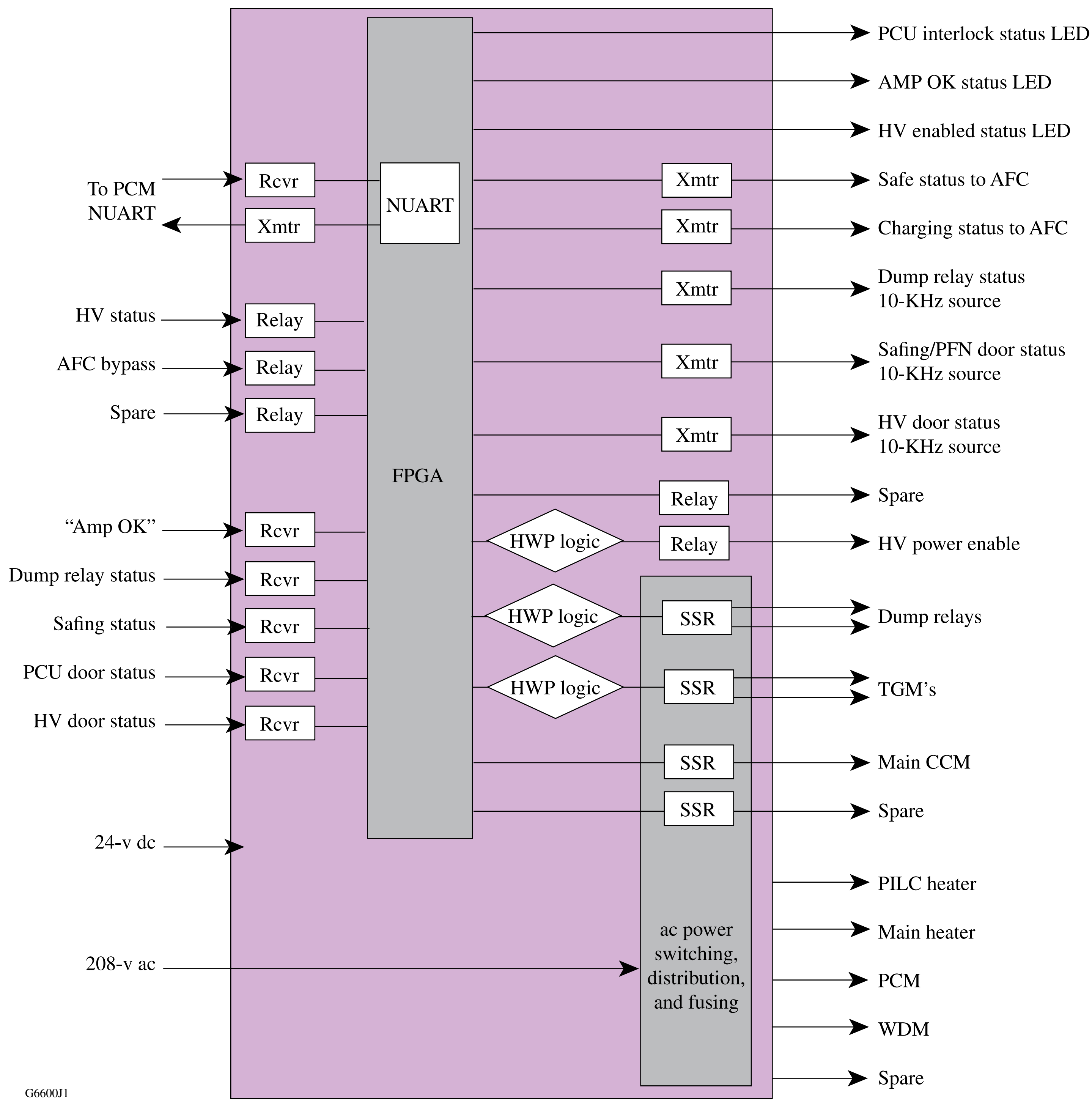

Figure 4.11
The hardware control module (HCM) controls all the miscellaneous digital I/O and interlocks including switched and unswitched ac power, panel indicator drivers, interlock status inputs, and the interface to the AFC.

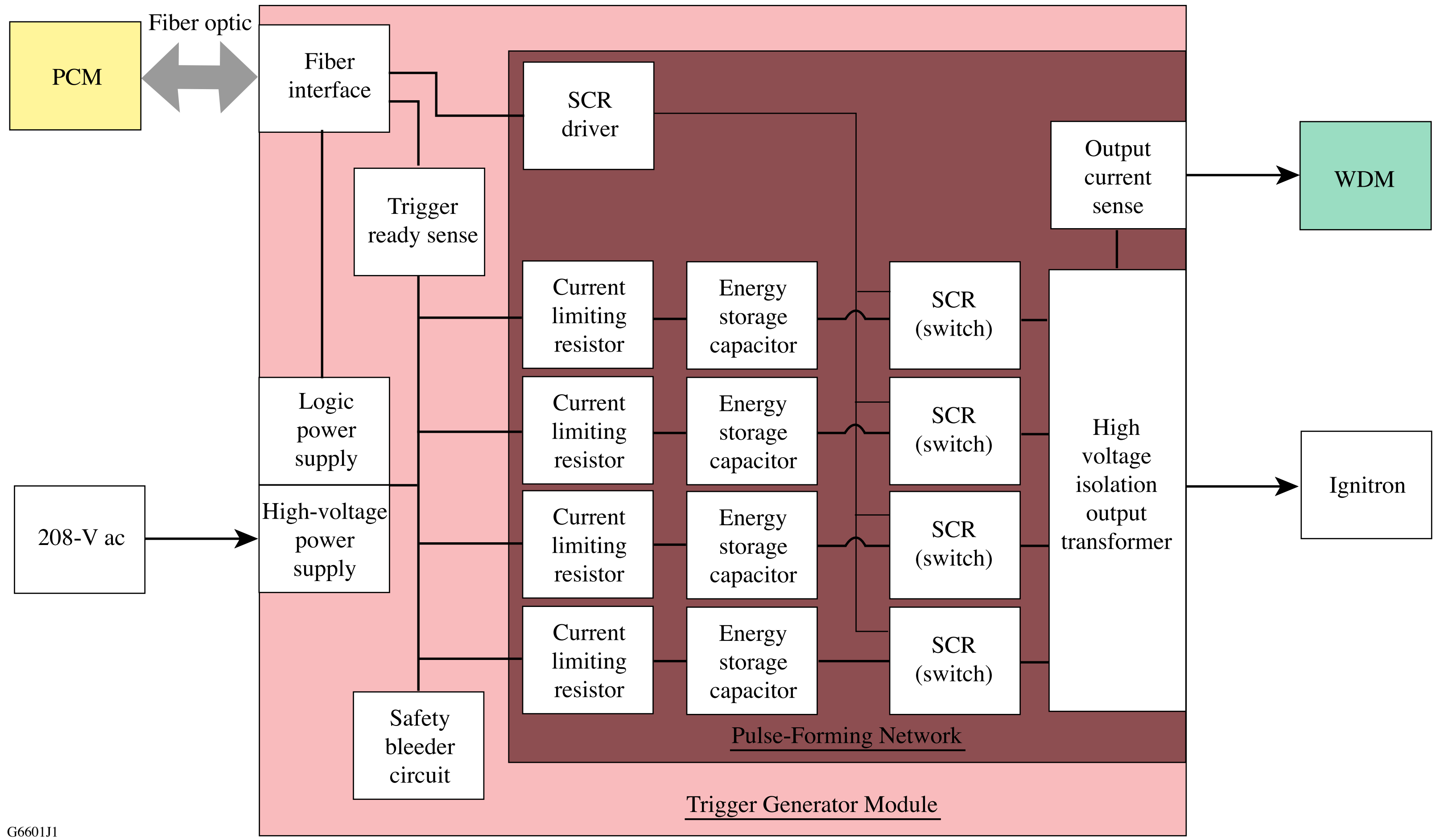

Figure 4.12
The PCU's require stand-alone trigger generator modules (TGM) located at both the pre-ionizing (PILC) and Pulse Forming Network (PFN) ignitrons. This module allows the PCM to trigger each of the ignitrons at the appropriate time via a dedicated fiber-optic link. Each TGM contains all necessary electronics to properly trigger either of these ignitrons. The functions internal to the TGM include logic voltage generation, high voltage generation, trigger pulse forming network, high voltage isolation, and fiber optic trigger input and output logic.

4.3.6 Power Conditioning Executive (PCE)

The OMEGA EP Power Conditioning Executive (EP-PCE) is an executive software program running on a Sun workstation (Sol) in the OMEGA EP Control Room. Detailed requirements of the EP-PCE and a brief description of shot operations are given in “OMEGA EP Power Conditioning Executive Software Specifications,” C-AU-G-001. The primary function of the EP-PCE software is to integrate the 74 PCU’s into shot operations of the overall laser system. It is similar to the OMEGA Power Conditioning Executive in appearance and function. The fewer number of PCU’s in OMEGA EP (74) compared to OMEGA (218) enables the EP-PCE’s user interface and status screens to be combined, as shown in Fig. 4.13. The functions of the EP-PCE are identical to the OMEGA PCE. Each PCU provides the high-voltage power conditioning necessary for one SSA and is represented by a single icon on the status screen.

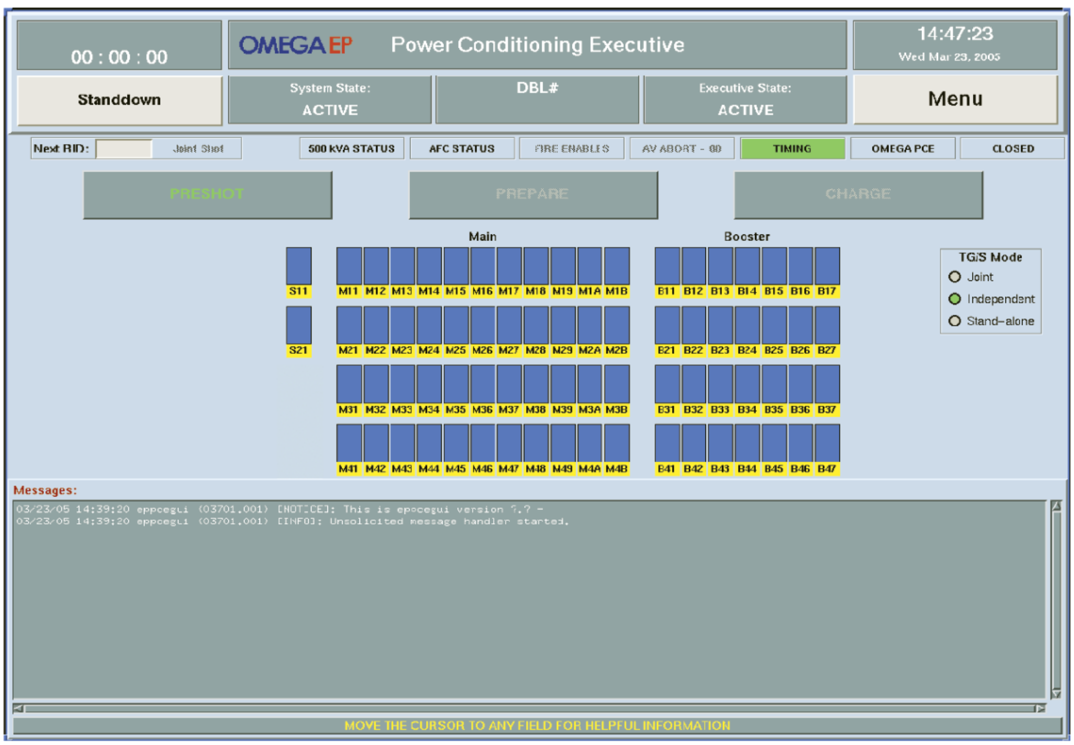

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Figure 4.13
The OMEGA EP Power Conditioning Executive (PCE) graphical user interface (GUI) is similar to the OMEGA PCE GUI. With 66% fewer PCU’s in OMEGA EP, the user interface and status screen could be combined.

Unlike OMEGA, the OMEGA EP Shot Director controls the EP-PCE, effectively becoming the power conditioning operator (PCO): The Shot Director builds the power conditioning template. The EP-PCE selects and controls all of the PCU's in the shot by communicating with their PCM's via the LLE Ethernet. The EP-PCE enables the configuration of the PCU's main and PILC circuits for the shot, including their charge voltages and charge and trigger delays. The EP-PCE is an OMEGA Intercommunication Protocol (OIP) client of the OMEGA EP Shot Executive and also communicates with OMEGA's PCE during joint shots via the LLE Ethernet. In joint shots, the OMEGA PCE is superior, calculates charge delays for both systems, and starts the charge sequence at the command of the OMEGA Shot Director.

The EP-PCE also interfaces to the trigger generator/selector (TG/S) via the timing interface unit (TIU) in order to select the shot mode (independent, joint, or stand-alone), the source of the 0.1-Hz pulse, and the shot triggers [OMEGA Master Timing Generator (MTG) or OMEGA EP MTG]. Figure 4.14 describes the relationships of the EP-PCE to the PCM's and the hardware timing system (HTS). The trigger generator/selector (TG/S) and the TIU are part of the HTS and are discussed in more detail in Volume VII, "Chapter 8: Control System," S-AD-M-012; "CDR OMEGA EP Power Conditioning Executive Software," C-AU-M-004; and "FDR OMEGA EP Power Conditioning Control Executive," C-AU-M-005. A brief description of PCU timing is provided in Sec. 4.3.7.

4.3.7 PCU Timing System Interface

Figure 4.14 provides a block diagram of the power conditioning computer control system. The two 38-MHz RFG's are synchronized through a phase-locked loop. The OMEGA EP RFG, MTG, and TG/S are rack-mounted in the Laser Sources Bay of the new facility. The OMEGA EP MTG is redundant under typical operating conditions and used only when the OMEGA MTG is inoperative. The 0.1-Hz clock pulse and the T-10 and T-0 triggers propagate through the TG/S via the TIU to the EP-PCE in the Control Room. The TIU and its display are located at the Shot Director's console. All connections up to the parallel port of the Sun workstation are optical fiber.

The EP-PCE sends the mode select (joint, independent, or stand-alone), the T-10_Enable, and the T-0_Enable to the TG/S and the MTG. The mode select informs the TG/S from which MTG to receive the 0.1-Hz clock and the T-10 and T-0 triggers. The TG/S responds to the EP-PCE with the 0.1-Hz clock and verifies the selected mode. The TIU interfaces the Sun workstation to the TG/S and converts the signals from wire to optical fiber. The TG/S also passes the T-0 trigger to the PCM's via optical fiber from the selected MTG.

The T-0 trigger is synchronous with the signals that control the pulses from Laser Sources and precedes the next actual light pulse by about 5 ms. When all of the PCU's have completed charging, the EP-PCE sends signals to the MTG that cause it to issue a "T-0" trigger synchronized to the next 0.1-Hz pulse. This event is used to sequence the PCU's and other elements of the system that operate on the shot. Additional information can be found in "OMEGA EP Hardware Timing System Electronics Requirements Specification," E-HR-R-001.

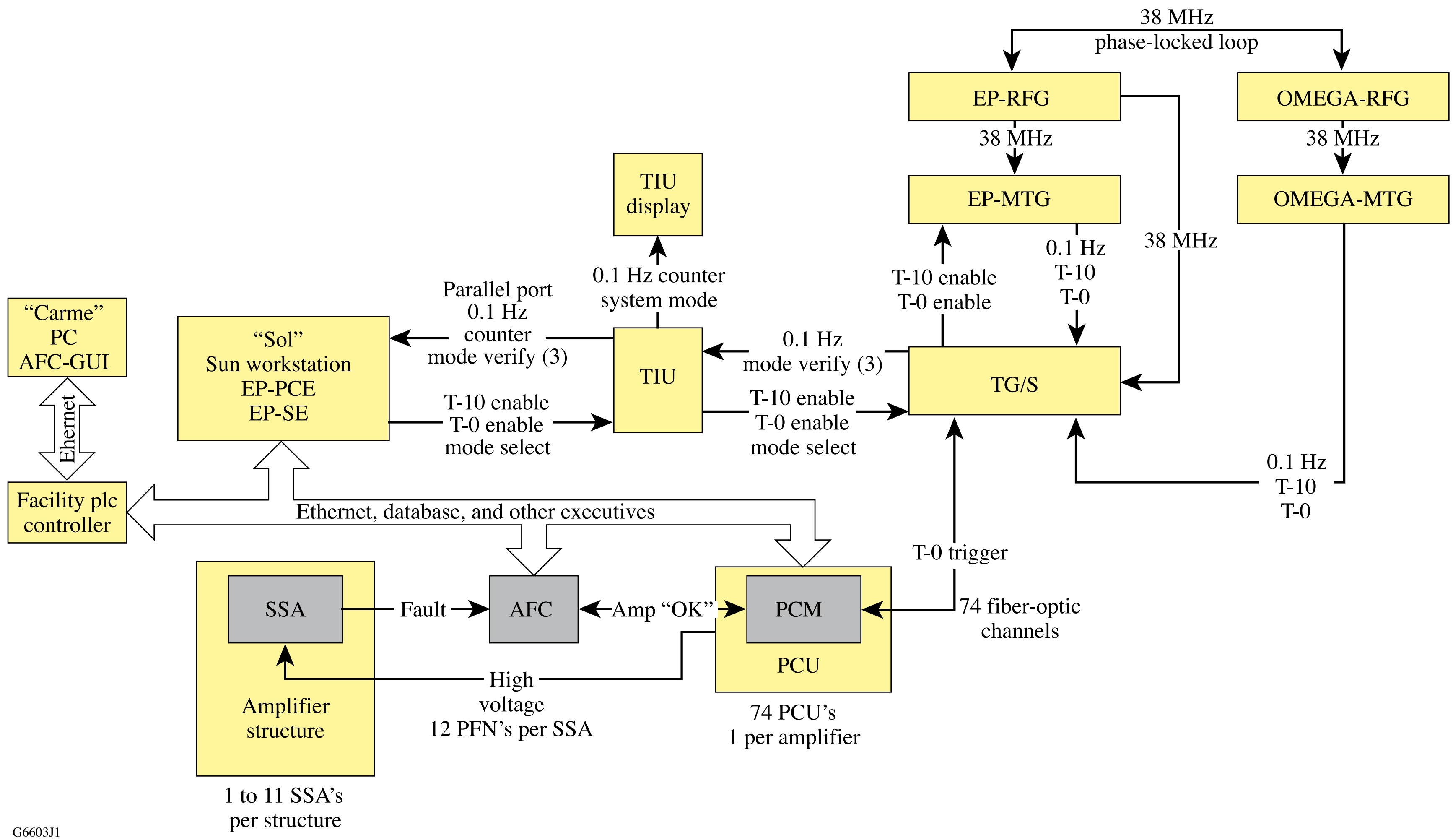

Figure 4.14
The power conditioning control configuration shows the source of the timing signals and the T-0 trigger that discharges the PCU's. The TG/S selects which MTG will provide the source of the T-0 trigger. Ethernet connections between the Power Conditioning Executive and the PCM facilitate configuring the PCU's prior to the shot. The AFC-GUI monitors that status of the amplifiers. If an amplifier error state is detected, the "Amp_OK" message is broadcast so that the PCU's cannot be charged.

4.4. Power Conditioning Operational Interface

While the Laser Sources subsystem produces a shaped optical pulse suitable for amplification by the laser power amplifiers five times per second, charging the PCU's takes about 2.5 min and the power amplifiers can be fired only once every 2 hours (approximately). When the system is ready for a shot, the PCE is able to coordinate charging of the PCU's so that they all arrive at the desired charge voltages within about 10 s of each other. It is then necessary to synchronize firing of the PCU's with each other and with the laser drivers so that the gain in the laser glass is at its peak at the point in time when a sources pulse propagates through the laser amplifier. To achieve this, the PCE monitors a 0.1 Hz signal relayed from the MTG. This signal is synchronous with the signals that control the sources pulses and precedes the next actual light pulse by about 5 ms. When all of the PCU's have completed charging, the PCE sends signals to the MTG that cause it to issue a "T-0" trigger synchronized to a subsequent 0.1-Hz pulse. This event is used to sequence the PCU's and other elements of the OMEGA EP system that operate on the shot.

When the charge command is given, each PCM counts off its charge delay before activating its charger. During that time, the EP-PCE checks the status of each PCM and displays the results to the operators. The PCM's also send the messages to the EP-PCE when they detect a problem or complete the charge process. When all of the PCU's are "At Volt," the EP-PCE initiates the trigger synchronization process. At the T-16 s mark, the PCM's are authorized to trigger the ignitrons in response to the trigger signal from the fiber-optic system (fire enable). After it has triggered, aborted itself, or been commanded to abort by the EP-PCE, the PCM assembles its post-shot reports and transmits them to the EP-PCE. The PCM then transitions to the "on-line" state and is logically ready for another charge cycle.

Communications between the EP-PCE and the PC104 controller in the PCM are via Ethernet as a series of synchronous and asynchronous network variable messages. These messages are defined in requirements document "Power Conditioning Unit Control Module," A-AL-R-004.

4.5 Power Conditioning Unit—Amplifier Facility Controller (AFC)

Each beamline consists of 11 SSA's that form the main amplifier and 7 SSA's that form the booster amplifier. (Additionally, Beamlines 1 and 2 each have a single 15-cm glass amplifier.) In each grouping, the SSA's are mechanically attached to one another and their support structure. High-voltage (HV) discharge cables are connected to each SSA from their respective PCU. Each SSA has two door interlocks, a de-ionized water flow meter, and a leak sensor. The AFC monitors the status of these devices. Each main and booster amplifier is associated with an AFC. Two 15-cm glass amplifiers in Lasers Sources are monitored by an AFC. Software allows Control Room operators to monitor the AFC's and determine of the status of the amplifiers.

Since the beamline SSA's are mechanically attached, the signals coming from the SSA's pass through the AFC and are integrated together in the fiber distribution boxes to ensure that if any one amplifier has a fault, all of the adjoining SSA's are also reported in a fault state, preventing their PCU's from charging them. Each PCU, in turn, returns the "safe" or "charging" signal back to the AFC after being monitored individually and collectively, in the fiber distribution box. In the event of fault detection, the PCM will communicate an "Amp OK" error message to the EP-PCE. The PCU's in the amplifier will not initiate charging if this signal is present. If charging has started when a fault is detected, the PCM will cause the charge to be aborted and the error will be reported to the EP-PCE. Fiber communications are designed such that in case of a break in a fiber, the loss of signal will be reported as a fault condition. The amplifier facility controller and interlocks are discussed in more detail in Volume VII, "Chapter 3: Laser Amplifiers," S-AD-007.

4.6 DIAGNOSTIC CAPABILITY OF THE POWER CONDITIONING SYSTEM

The PCM monitors the charge and fire sequence for proper operation and provides performance data to the PCE during the sequence when polled, and after the sequence in a post-shot report.

4.6.1 PFN Performance

By analyzing data from the WDM, which digitizes and stores data representing discharge currents, the PCM calculates the following information for each PFN:

- PILC current peak value
- Total charge
- Main current peak value
- Width of main pulse @ 1/3 FWTM
- Time to main pulse peak
- Peak current value of any reversal
- Lamp fired (yes/no)
- Performance meets specs for charge voltage level (yes/no).

The system allows for precision calibration of the lamp current data. The WDMs' current transformers are serialized and calibrated against a known standard. The PCM uses these stored calibration factors to correct waveform data to achieve a calibrated accuracy of 0.1%. The drift is less than 0.025% after a 30-min warm-up.

4.6.2 Voltage Readings

By communicating with the CCM's, the PCM continuously monitors the voltage levels on both the PILC and main bank capacitors during the charge sequence. These values are used by the PCM to insure that the charge is progressing as expected (dv/dt), and also made available to the PCE. An auto-calibration routine, included in the Power Conditioning Test Unit (PCTU), creates a table of calibration factors to be stored in the PCM. PCU voltages are calibrated with an automated system using an external high precision voltage probe. The PCM uses these stored calibration factors to correct for the non-linearities in the analog voltage monitoring circuits and achieve a calibrated accuracy of 0.02%. Shot-to-shot repeatability is nominally 2 V over a 300-V to 15-kV range. PCU voltage levels are monitored and regulated using precision voltage dividers connected directly to the capacitor banks rather than the HV charger's internal monitors.

4.6.3 Fault Reporting

The PCM communicates to the PCE any faults as they occur. Certain faults will cause the PCM to abort the charge cycle automatically. These include:

- Dump relay fault – dump relay in the incorrect position
- AFC fault – proper signal is not being received from the AFC
- Failure of charger to enable
- Ramp too slow – charging profile out of bounds, charging too slow
- Ramp too fast – charging profile out of bounds, charging too fast
- Negative charging ramps – bank voltage decreases while charging
- Over-volt conditions – bank voltage above the acceptable level
- Under-volt conditions – bank voltage below the acceptable level
- Pre-fire Fault – one or more PFN's experiences premature current flow.

4.6.4 Timers

Certain functions are timed to ensure that they do not take too long or that the PCM does not remain in a certain state for too long. The PCM has this functionality and the values for most of these timers are set through the PCE interface. Each has a default value set in the PCM's firmware. If these timers do expire, the PCM automatically aborts or prevents charging to put the PCU in a safe condition. The following timers are incorporated:

- Charge time counter – This countdown timer keeps track of the actual time in seconds required to charge the PCU. This countdown timer is set to 180 s in PCM firmware, and starts to count down upon start of charge.

- At-Volt timeout – This countdown timer prevents the PCU from sitting in the fully charged state for more than one minute without advancing to the ready-to-fire state (Fire Ready State). This timer starts when the end-of-charging (End-of-Charge) signal has been received from the chargers that have been enabled for the sequence. This timer is reset when the Fire Ready command is received. This timer is programmable from 0 to 60 s and the default value is 60 s. If this timer reaches 0, the PCM aborts the sequence.

- Trigger wait timeout – This timer prevents the PCU from being in the Fire Ready State for more than 20 s. This timer starts when the "Ready-to-Fire" command is received from the PCE. It is reset when input is received on the synchronizing (T–0) trigger (Sync Trigger Input), which was discussed in Sec. 4.3.7. The PCM aborts the sequence if this timer reaches 0. This timer is programmable from 0 to 20 s and the default value is 20 s.

- Charge delay timer – This timer allows a delayed start of charge after receiving the charging (Charge) command from the PCE. If a value has been set to this timer, the PCM will not actually start the charging sequence until it has timed out. If this timer value ≠ 0, it will start to count down upon receipt of the Charge command from the PCE. When this timer = 0, the PCM goes to the "Charge State." This timer is programmable from 0 to 180 s and the default value is 0 s.

Additional information can be found in “PCU Control Module Requirements,” A-AL-R-004 and “Requirements Power Conditioning Unit for the 40-cm SSA,” A-AL-002.

4.7 Grounding and Support Systems

Figures 4.15, 4.16, and 4.17 illustrate the grounding configuration that applies to the PCU’s for all laser and glass amplifiers and their structures. Each laser amplifier is served by a PCU that includes a control module, interface electronics, and 12 pulse forming networks (PFN’s). Each PFN is connected to a set of flash lamps in the amplifier by a shielded discharge cable.

The HV discharge cable shield and the ground (positive) side of the PFN’s are connected directly to the isolated internal ground buss in each PCU, which, in turn, is connected to an integrated PCU ground buss in the Capacitor Bay. This internal PCU ground buss is bolted directly to all PCU enclosures that serve one amplifier and is grounded to either the facility NKGB or SKGB ground bar. The body of each amplifier is grounded back to its PCU through the ground bar on the amplifier I-beam structure, which is connected to the integrated PCU ground buss (Fig. 4.17). Each structure that supports one or more laser amplifiers is independently connected to the integrated ground buss that serves the PCU’s for that amplifier. Grounding is discussed in more detail in “Chapter Nine: “Facility and Safety Interlocks,” and in the “OMEGA EP System Grounding Plan,” S-AC-G-018.

4.8 Safety Features

High-voltage dump relays provide for the discharge of any stored energy within the PFN’s when conditions warrant such action. The relay is connected in a fail-safe mode: It must be powered open to allow charging and, when it is de-energized, a resistive load is connected across the capacitors to bleed off any stored energy. The load ensures that the capacitor voltage is below 100 V in less than 10 s when dumping from 14 kV. The circuit also prevents buildup of any charge on the capacitor when in the de-energized mode. There is an automatic safing system in place in each PCU that hard shorts the main bank to ground when the front enclosure door is opened. A spring-loaded arm that is operated when the door closes permits normal operation. As the door is opened, this arm is allowed to swing forward until a ground contact on its far end contacts a PFN high-voltage buss contact. Once this has happened, each PFN capacitor is shorted to ground through its own 1.5-kΩ charging resistor (Fig. 4.6) If one or more of the PCU enclosure doors are open, the PCU is prevented from entering a charge state. If a door is opened when a PCU is already charged or charging, the PCM goes to an abort condition. Additional information on how interlocks and fault conditions are managed can be found in “Requirements Power Conditioning Unit Control Module,” A-AL-R-004.

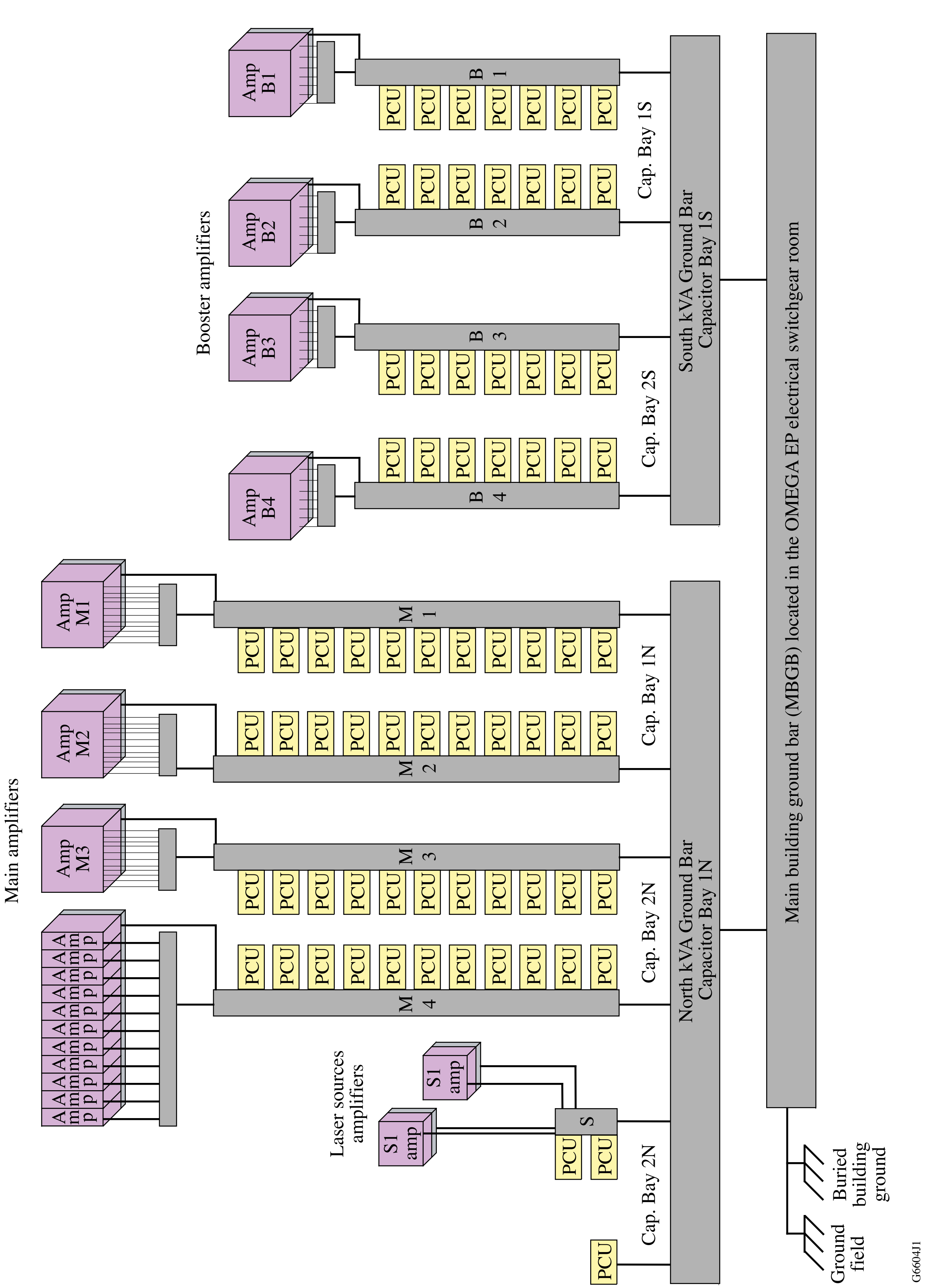

Figure 4.15
The power conditioning ground system starts at the MBGB and then branches to the north and south Capacitor Bays. These branch out to each main and booster amplifier and PCU's connect to these branches. The Laser Sources and test PCU devices are connected to the north kVA ground bar in the north Capacitor Bay.

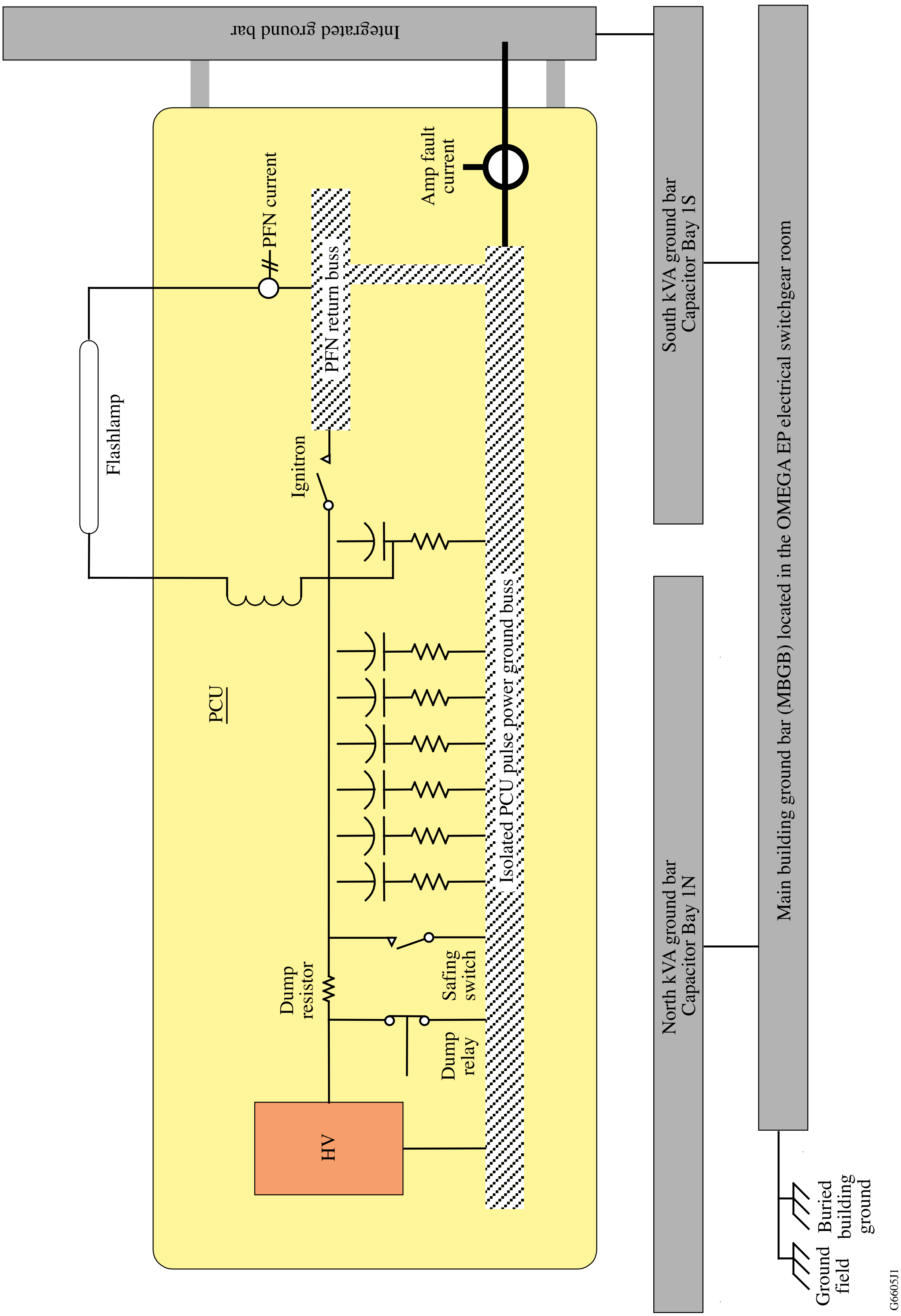

Figure 4.16
Each PCU has an internal buss ground wire connected to the integrated ground bar that circles the Capacitor Bay. This ground, in turn, is attached to either the north or south kVA ground bar.

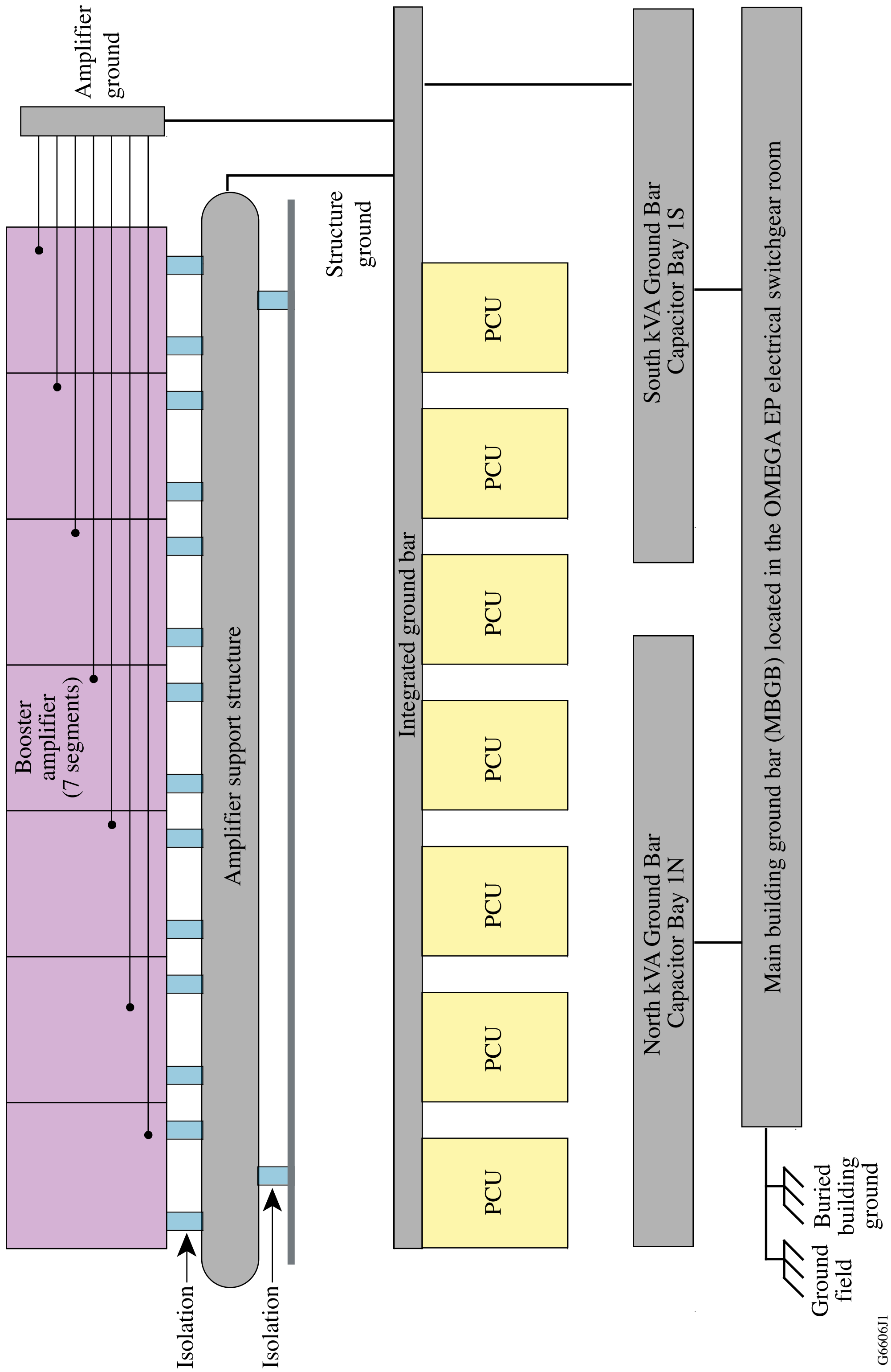

Figure 4. 17
The amplifiers and their support structures return their ground wire to the integrated ground bars that circle the Capacitor Bays. This ground in turn is attached to either the north or south kVA ground bar.

4.9 REFERENCES

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3 A. C. Erlandson and H. T. Powell, "Dependence of Flashlamp Performance on Gas Fill and Bore Size," *Laser Program Annual Report 1984*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-50021-84, 6-27 (1985).

4 R. S. Craxton, ed., *OMEGA Upgrade Preliminary Design*, Laboratory for Laser Energetics, Report DOE/DP 40200-101, University of Rochester (1989).

5. Hoop stress is the normal stress in the circumferential or hoop direction of a cylindrical shell.

Appendix A

Glossary of Acronyms

AFC	Amplifier facility controller
"AMP OK"	An interlock status that indicates the laser amplifier is not in a safe state to operate
AWG	American wiring gauge
CATS	PCU fiber-optic box, named for status conditions communicated: "charge", "Amp OK", "trigger", "safe"
CCM	Charger control module
EMI	Electromagnetic interference
EOC	End of charge
EP-PCE	OMEGA EP Power Conditioning Executive
EP-SE	OMEGA EP Shot Executive
FPGA	Field programmable gate array
FWTM	Full width at tenth maximum
GUI	Graphical user interface
HCM	Hardware control module
HTS	Hardware timing system
HV	High voltage
HWP	Hardwired protection
I/O	Input/output
ID	Identification
IEEE	Institute of Electrical and Electronic Engineers
JTAG	Joint Test Action Group (An IEEE standard for boundary scan technology)
LED	Light-emitting diode
LLE	Laboratory for Laser Energetics
LLNL	Lawrence Livermore National Laboratory
MTG	Master timing generator
NIF	National Ignition Facility
NKGB	North kVA ground bar
NUART	Nonuniversal asynchronous receiver-transmitter
NV	Network variable
OIP	OMEGA intercommunication protocol
PC	Power conditioning
PCE	Power Conditioning Executive
PCM	Power conditioning unit control module
PCO	Power conditioning operator
PCTU	Power conditioning test unit
PCU	Power conditioning unit
PFN	Pulse-forming network
PILC	Preionization and lamp check
PLC	Programmable logic controller
POF	Plastic optical fiber

PROM	Programmable read-only memory
PW	Pulse width
Rcvr	Fiber-optic receiver
RFG	Reference frequency generator
RFI	Radio frequency interference
RLC	Resistor, inductor (L), and capacitor (circuit)
SCR	Silicon-controlled rectifier
SKGB	South kVA ground bar
SRAM	Static random access memory
SSA	Single-segment amplifier
SSR	Solid-state relays
TG/S	Trigger generator/selector
TGM	Trigger generator module
TIU	Timing interface unit
UART	Universal asynchronous receiver-transmitter
WDM	Waveform diagnostic module
Xmtr	Fiber-optic transmitter