CHAPTER 10

DC ENERGIZATION CIRCUIT

10.1 DC Current Regulated Power Supply

The PEI 150 power supply [1] to be provided for the solenoid is a special Fermilab unit designed for superconducting loads. The electrical input requirements of the supply are 480V 3Ø, approximately 240A at rated output. The PEI 150 is a twelve phase thyristor water cooled rectifier unit with precision feedback current regulation; it is provided with series/parallel taps for both primary transformer connections and output SCR grouping.

The power supply taps can be set at 30V/5000A or 15V/5000A. It is preferable to set the power supply taps at 15V/5000A because the overall operation is more efficient, the power factor is better, and the ac loading and dc output ripple voltage are reduced. The differences are listed in Table 10.1.

The feedback regulator has an internal current transductor to regulate current to within 0.05%. The power supply is expected to regulate the current to within 0.01% [2]. An internal shunt is used for the panel ammeter mounted on the front of the supply. The internal transductor measures the sum of the filter current and the load current and therefore in order to regulate the load current an external precision Holec 5000 Amp transductor [3] is to be installed downstream of the ripple filter and dump resistor. This device will provide the current feedback signal to the power supply regulator. Internal status of the power supply is monitored and a summation of its internal interlock string is necessary for turn-on. External permits and interlocks also can be introduced into this summation via an available connector. The power supply is programmable. It can be turned on and off remotely when the interlocks are ready and reset. A precision external reference is used to set the current. A rate control chassis [4] will be installed to limit the rate of current change to the desired value (see Chapter 11) during magnet energization. The rate control chassis must be installed in the power supply at the power supply regulator output. Installing current rate control at the sensitive reference input location will deteriorate power supply current regulation.

The output power circuit of the supply contains freewheeling diodes. These diodes conduct the current decay when the supply is turned off. Because the power supply and filter chokes are not rated to carry the decaying current during a cooling water failure, an extra set of freewheeling diodes sized for a slow discharge from full current without cooling water is therefore added behind the filter. These diodes also prevent polarity reversal at the filter capacitors.

The grounded steel enclosure with interlocked doors and a lockable main power circuit breaker are safety features. A lighted front panel provides operating status.

10.2 Ripple Filter

In order to prevent external electrical noise from being transmitted into the quiet environment of the detector a filter [5] will be installed on the output of the power supply. Each polarity will connect to a 5000 A, 230μH choke [6]. The chokes provide high current capability with low loss in a small package. They are constructed with split laminated cores and use an economical method of construction for air gap reactors.

The shunt capacitance needed is in the range of 9000 to 45000 μF. Further circuit analysis and simulation will be required to finalize the actual component choices and the extent of overvoltage protection required by the capacitors. The electrolytic capacitors are protected from reverse voltages during magnet discharge by the freewheeling diodes. The capacitors are not expected to require an active SCR crowbar circuit to clip surges that would exceed their specifications [5]. The filter capacitor must have a minimum operating working voltage of 250Vdc, and a surge voltage rating of 325Vdc. The filter must be able to withstand 1250Vdc test to ground.

10.3 Dump Switch and Protection Resistor

A 5000Adc/1000V contactor, such as Siemens Allis type 703 [7], is provided as a dump switch. A similar Allis type 703 switch is installed in the proton beamline at PE3Q2. A solid state switch [8] could also be used; such a switch is highly reliable but at 5000A would create about 3kW losses. Because the solenoid is designed to quench without damage without a protection resistor, a backup to to the dump switch will not be installed.

The air-cooled protection resistor will be fabricated of stainless steel bars weighing 120 kg welded in series and installed in a metal enclosure [9]. The resistor provides a resistance of 48×10^{-3} Ohm at 20^0C to limit the fast discharge voltage to 250V maximum; its temperature rises to 100^0C during a discharge of 5MJ. The midpoint of the protection resistor is connected to ground so that the maximum coil voltage to ground does not exceed 125V peak during a discharge from 5000A. The resistor will recool in about 30 minutes following a fast discharge.

A trigger fuse or resistor on the grounded center tap of the protection resistor will limit unexpected ground fault currents to less than 40A. A ground fault detection chassis will be provided for the center tap.

The protection resistor is connected in parallel with the dump switch so that the 5000A dc circuit is never fully interrupted. This arrangement allows the stored energy in the power supply and the filter chokes to escape via the protection resistor. A capacitor of about 1000μF, 500V is installed across the dump switch to suppress spikes.

10.4 Reversing Switch

Reversal of the load polarity will be accomplished with an available 5000A dc mechanical, motorized polarity reversing switch [10] and a switch controller. Polarity reversal requires a slow discharge and recharging of the solenoid. Initiating a fast discharge below the point where the decaying current can no longer cause a quench can speed the discharge. Reversing is expected to take approximately 40 minutes. The switch is presently in storage at Fermilab and will be refurbished for its new installation. It measures approximately 4 feet per side, is floor mounted and requires no water cooling. The controller performs the critical functions which assure that the polarity reversal occurs at zero load current and that the power supply is turned off. Some modification to the operation of the existing mechanical timer system in the controller will be required to interface with the DØ PLC system. A set of maintained closed (forward) contacts or maintained open (reversed) contacts can be monitored and selected by the PLC. Changing the status of the contacts begins a timing sequence in the controller which powers the supply off to initiate a slow discharge of the magnet. The built in timing control of the controller reverses the switch after a preset delay and releases the power supply rate control chassis. The reversing switch timing control uses a motor driven timer with cam switches and is not affected by power interruptions. Once it is started it must complete a sequence before it can be used again.

10.5 Crowbar

An overvoltage protection crowbar [5] will be installed in parallel with the solenoid between it and the reversing switch. This crowbar serves as a safety backup for the interlocks on the reversing switch so that in the event of equipment failure, the operation of the reversing switch under load does not cause destructively high voltages. The crowbar will be set to trip and limit the maximum solenoid voltage to 300V peak, above the normal fast discharge voltage of 250V peak. The crowbar consists of several back to back SCR's in parallel. Each back to back set of SCR's has a series resistor to assure current sharing and at the same time dissipate the stored energy of the solenoid. The combined weight of all the series resistors is about 250 lbs. The crowbar is completely self-contained and does not require any auxiliary power to trip. The crowbar SCR voltage rating should be chosen at 500 V. The SCR's will break down if the crowbar firing fails. This provides two levels of protection: 300 V and 500 V.

10.6 Water Cooled Bus

A 5000A dc copper bus system is provided to connect the power supply system to the superconducting load. The one-way distance from the power supply area to the Assembly Hall Detector location is approximately 21 meters and an additional 23 meters to the location in the Collision Hall. A standard bus construction, widely used in the Fermilab Experimental Area will be used [11]. It consists of supply and return conductors of high conductivity, 3.8 cm square "double extra strong" copper pipe. A high impact PVC (or equivalent) insulating pipe is slipped over the copper pipe for electric insulation. The copper pipes are joined by brazing or silver soldering with straight couplings or elbows as required. The joints are then insulated with shrink-on sleeves. Copper flags are brazed to the ends of the bus for cable attachment. A suspension system of Unistrut and pipe clamps will be required to route the bus. One set of flags taps off the bus at the Assembly Hall location for the detector and another in the Collision Hall. Water cooling is accomplished with LCW hose connections to the bus end caps. Overtemperature switches are installed near the cable connection flags and these are wired to the interlock system. The watercooled bus can dissipate all stored energy if a fast discharge is triggered by a cooling water failure which then fails over to a slow discharge due to failure of the dump switch. The maximum expected temperature of the buses in this instance is 91^0C. From experience with similar installations this bus is simple to install, is rugged in service, and meets all safety requirements.

To equalize test conditions in the Assembly Hall and the operation conditions in the Collision Hall a small length of stainless steel watercooled pipe may be added to the buswork in the Assembly Hall to make the Assembly Hall bus resistance the same as the Collision Hall bus resistance (see table 10.1).

10.7 Quench Detection

Quench detection will be accomplished by providing redundant balanced bridge circuits and voltage taps on the coil, superconducting buses, and vapor cooled leads. As described in Chapter 9, four coil taps are provided on the coil: one each at the start and finish of the coil winding and two additional taps, one near the center and another near the 3/4 point as diagrammed in Figure 10.2. Each bridge must be balanced for zero output during solenoid initial startup to enable the lowest practical threshold levels to be selected thereafter while preventing nuisance trips. The quench detector bridges can use iso-op amp style isolation as shown in Figure 10.2 or a magnetically coupled technique [12] which is presently under development. Both isolation methods are similar but the magnetically coupled type is expected to provide better noise immunity and better personnel safety.

A redundant set of quench detectors is provided. The first set will be monitored by a hardwired QPM chassis and the redundant set will be routed to the PLC for software quench detection. The QPM will provide the first line of defense for quench detection by means of lower threshold reference values. Quench threshold levels will be established during preliminary low-current charging exercises prior to full current operation of the magnet. The quench detectors are fail-safe and must be connected otherwise they will cause an interlock trip.

10.8 Interlocks and Controls

A possible interlock and control flow diagram for the magnet energization system is shown in Fig. 10.3. The diagram shows many interlocks and others may have to be added as the design is finalized. Additional detail on the interlock system is provided in Chapter 9. All controls will be via the PLC as described in Chapter 9. Status monitoring (voltage taps, etc.) from the solenoid must be via a different set of safety isolation resistors and monitoring cables as described in Chapter 9.

References

[1] PEI 150 Model SR-1029, NAL Spec 6065-ES-44047; Engineered Magnetics, Inc 18435 Susanna Road, Rancho Dominguez, CA 90221

[2] A.T. Visser, "Magnet Power Supply Regulation Comments 240 kW and 500 kW Magnet Power Supplies", Fermilab TM 1890, March 1993

[3] Holec, Inc. 12502 Exchange Dr., Suite 404, Stafford, TX 77477

[4] See e.g. Fermilab EED Drawing 6005-ED-172973

[5] E. Drennan, "Ripple Filter for the 10,000 A Superconducting Magnet Test Stand at the Magnet Test Facility", FERMILAB-TM-1764, Nov 1991.

[6] A. T. Visser, "Electrical Design Note for a 5000 ADC, 230 μH Power Supply Filter Choke", FERMILAB-TM-1836, Apr 1993,

[7] Siemens Energy & Automation, Inc., PO Box 8900, Atlanta, GA 30356.

[8] A. T. Visser, "Design Note of a 10,000 A, 1000 V Solid State Dump Switch for the Magnet Test Facility", FERMILAB-TM-1692, Oct 1990.

[9] A. T. Visser, "Design Note of a 10,000 A 2 MJoule Dump Resistor for the Magnet Test Facility", FERMILAB-TM-1611, Mar 1990.

[10] Gould/ITE Model SO 45-03951, Fermilab Spec 2816-ES-38314; Gould Shawmut, 374 Merrimac St., Newburyport, MA 01950.

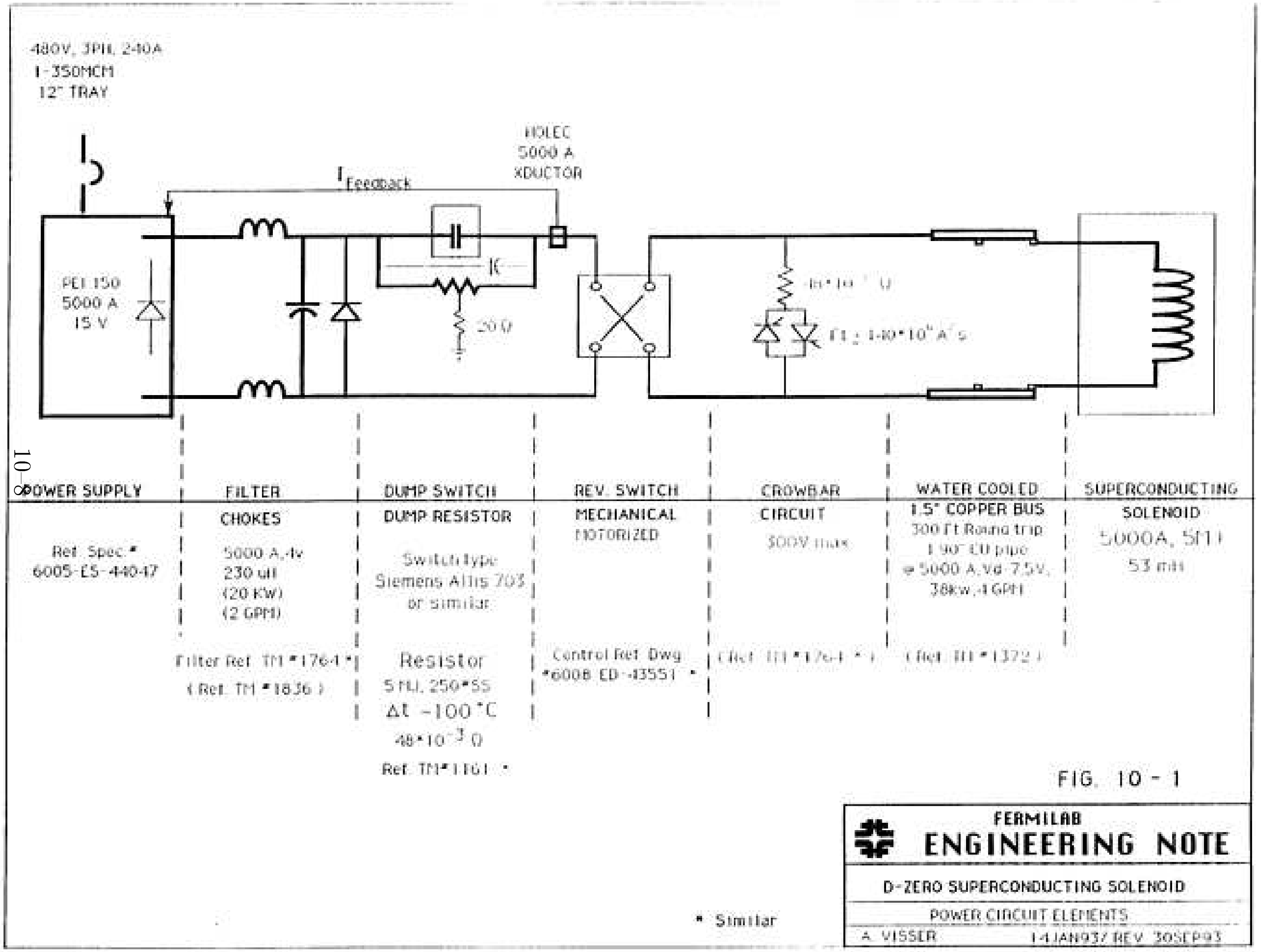
[11] A. T. Visser, "Description of a High Current Water Cooled Bus", FERMILAB-TM-1372, Dec 1985.

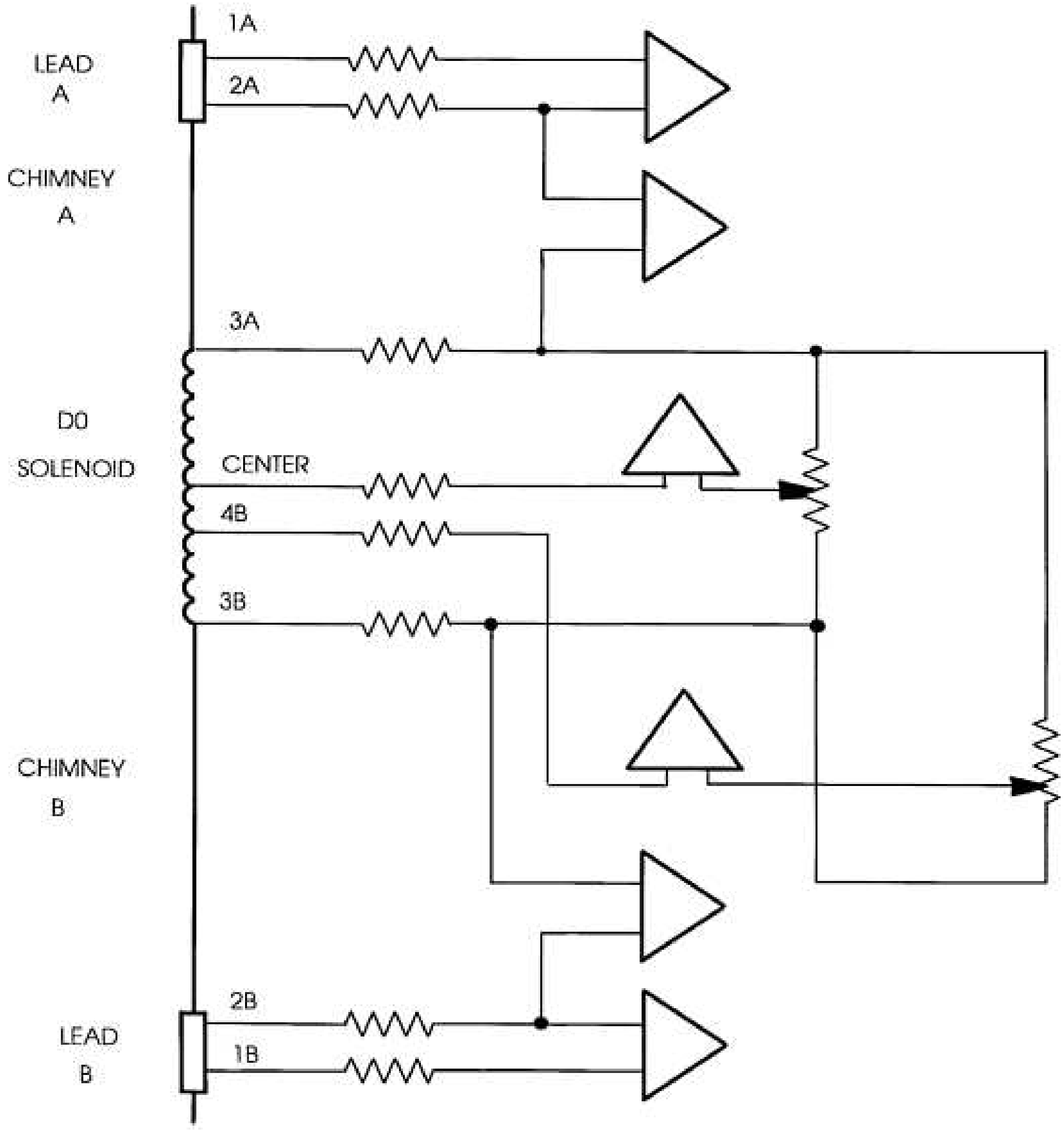
[12] A. T. Visser, *et. al.*, "A Magnetically Coupled Quench Detector for Superconducting Magnets", Fermilab TM 1870, Oct. 1993.

Table 10.1: Electrical System Parameters

Parameter	PS Tap 30 V, 5000 A	PS Tap 15 V, 5000 A
Nominal Operating Current	5000 A	Same
Maximum Allowable dI/dt	≤720 A/min	Same
Maximum Dump Voltage	250 V	Same
Maximum Insulation Test		
Voltage to ground (1 min)	1250 V DC	Same
Magnet Stored Energy	5.6 MJ	Same
Circuit Inductance	0.53 H	Same
Circuit Resistance (CH)	2.3×10^{-3}	Same
Circuit Resistance (AH)	1.5×10^{-3}	Same
CH(AH) Slow Dump Time Constant	230 (353) seconds	Sane
CH(AH) Fast Dump Time Constant	10.5 (10.7)seconds	Same
Charging Time	7 minutes	Same
CH(AH) Slow Dump Time	20 (25) minutes	Same
Fast Dump Time	50 seconds	Same
DC Current Reversing Time	37 minutes	Same
Power Supply		
Max Voltage	34	17
Current Regulation	$\leq$ 100 ppm at $>$ 1000 Adc	Same
External Reference	$\leq$ 5 ppm/^{o}C, $\geq$ 16 bit	Same
	0-10 V dc, 500 A/v	Same
CH(AH)Operating DC Voltage	$\approx$ 8 (12)V	Same
Output Ripple P to P	$\approx$ 5.6 V	$\approx$ 2.2 V
AC Input	480 V, 3Ø, 240 A,60 Hz	Same Except 120 A
Input Power Factor	0.3 (0.2)	0.6 (0.4)
Ripple Filter Chokes	$2 \times 230\mu$H	Same
	$2 \times 0.38 \times 10^{-3}$	Same
CH (AH) Bus	5000 A, 3.8 cm nom. Cu pipe	Same
	1.5×10^{-3} (0.7×10^{-3})	Same
	91 (43) m	Same
Protection Resistor	48×10^{-3}	Same
	120 kg	
	ΔT $\approx$ 100^{o}C at 5.6 MJ	
Dump Switch	5000 A Contactor	Same

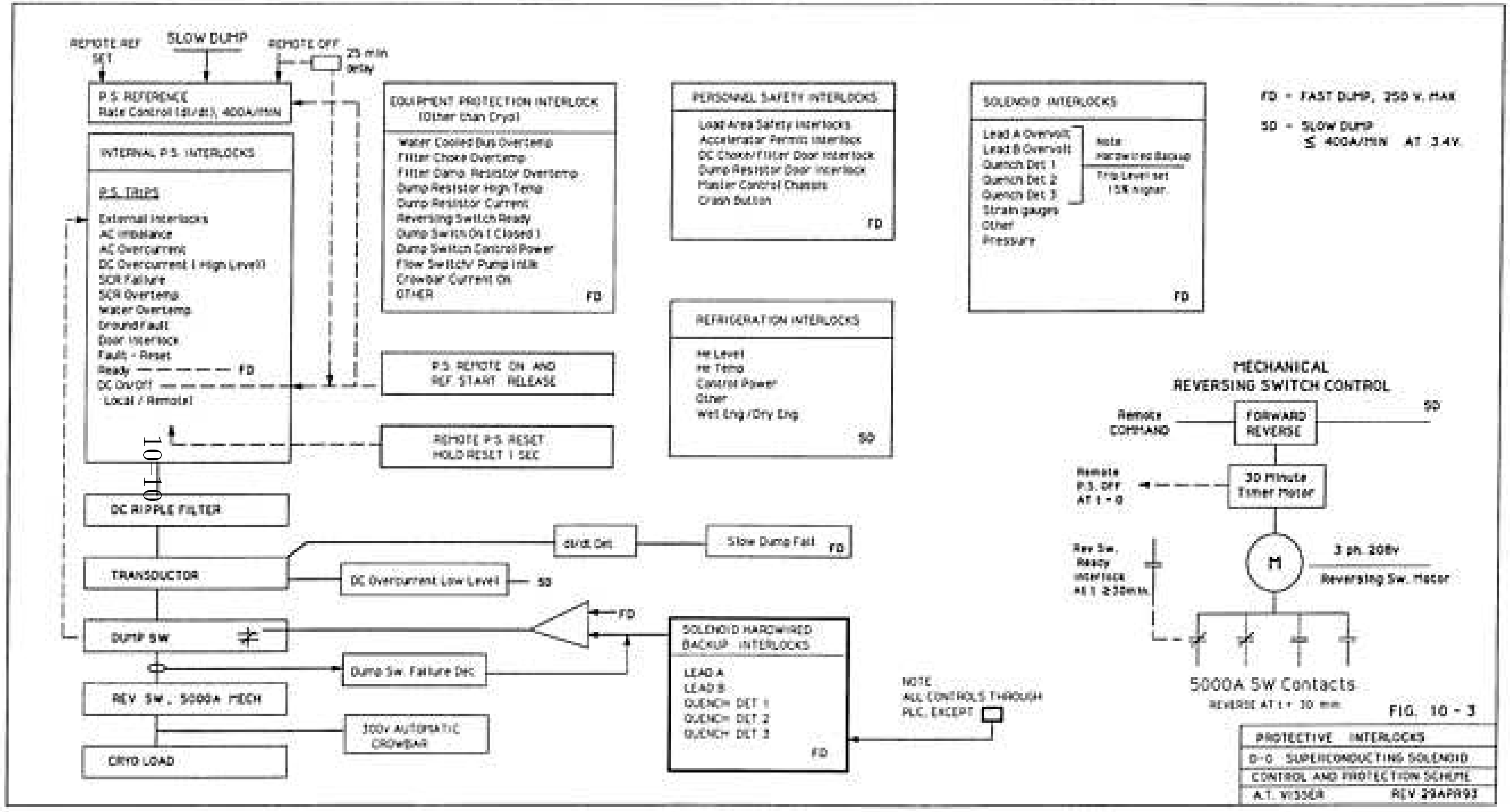
Table 10.1: Electrical System Parameters, cont.		
Parameter	PS Tap 30 V, 5000 A	PS Tap 15 V, 5000 A
Reversing Switch	5000 A Mechanical	Same
Overvoltage Crowbar	300 V, 5000 A peak	Same
Cooling Water		Same
Resistivity	$\geq$ 3 MΩcm, LCW	
Power Supply	19 l/s, ΔP = 690 kPa	
Chokes Each	4 l/s, ΔP = 690 kPa	
Bus at 40^{o}C Rise	15 (8) l/s	
Over Temperature Protection	80^{o}C	Same
Losses	69 kW Total	Same
Power Supply	12 kW	Same
Chokes	19 kW	Same
Bus	38 (18) kW	Same


480V, 3PH, 240A
1-350MCM
12" TRAY
HOLEC
5000 A
XDUCTOR
I Feedback
PEI 150
5000 A
15 V
20 Ω
POWER SUPPLY
Ref. Spec.*
6005-ES-44047
FILTER
CHOKES
5000 A,4v
230 uH
(20 KW)
(2 GPM)
Filter Ref. TM *1764 *
(Ref. TM *1836)
DUMP SWITCH
DUMP RESISTOR
Switch type
Siemens Allis 703
or similar
Resistor
5 NJ, 250*55
Δt -100°C
48*10^-3 Ω
Ref. TM*1161 *
REV. SWITCH
MECHANICAL
MOTORIZED
Control Ref. Dwg
*6008 ED-43551 *
CROWBAR
CIRCUIT
300V max
WATER COOLED
1.5" COPPER BUS
300 Ft Round trip
1.90" ID pipe
@5000 A,Vd-7.5V,
38kw,4GPM
(Ref. TM *1372)
SUPERCONDUCTING
SOLENOID
5000A, 5MJ
53 mH
* Similar
FERMILAB
ENGINEERING NOTE
D-ZERO SUPERCONDUCTING SOLENOID
POWER CIRCUIT ELEMENTS
A. VISSER
14JAN93/ REV 30SEP93
FIG. 10 - 1



QUENCH DETECTION WITH ISO-OPAMPS
An additional set of detectors and taps is needed for redundancy

FIG. 10-2


REMOTE REF SET
SLOW DUMP
REMOTE OFF
25 min delay
P.S. REFERENCE
Rate Control (dI/dt), 400A/MIN
INTERNAL P.S. INTERLOCKS
P.S. TRIPS
External Interlocks
AC Imbalance
AC Overcurrent
DC Overcurrent (High Level)
SCR Failure
SCR Overtemp
Water Overtemp
Ground Fault
Door Interlock
Fault - Reset
Ready
FD
DC On/Off
Local / Remote)
EQUIPMENT PROTECTION INTERLOCK (Other than Cryo)
Water Cooled Bus Overtemp
Filter Choke Overtemp
Filter Damp. Resistor Overtemp
Dump Resistor High Temp
Dump Resistor Current
Reversing Switch Ready
Dump Switch On (Closed)
Dump Switch Control Power
Flow Switch/ Pump Intlk
Crowbar Current On
OTHER
FD
P.S. REMOTE ON AND REF START RELEASE
REMOTE P.S. RESET HOLD RESET 1 SEC
PERSONNEL SAFETY INTERLOCKS
Load Area Safety Interlocks
Accelerator Permit Interlock
DC Choke/Filter Door Interlock
Dump Resistor Door Interlock
Master Control Chassis
Crash Button
FD
REFRIGERATION INTERLOCKS
He Level
He Temp
Control Power
Other
Wet Eng /Dry Eng
SD
SOLENOID INTERLOCKS
Lead A Overvolt
Lead B Overvolt
Quench Det 1
Quench Det 2
Quench Det 3
Strain gauges
Other
Pressure
Note
Hardwired Backup
Trip Level set 15% higher
FD
FD = FAST DUMP, 250 V. MAX
SD = SLOW DUMP ≤ 400A/MIN AT 3.4V
DC RIPPLE FILTER
TRANSDUCTOR
dI/dt Det
Slow Dump Fail
FD
DC Overcurrent Low Level
SD
DUMP SW
FD
Dump Sw. Failure Det
REV SW., 5000A MECH
300v AUTOMATIC CROWBAR
CRYO LOAD
SOLENOID HARDWIRED BACKUP INTERLOCKS
LEAD A
LEAD B
QUENCH DET 1
QUENCH DET 2
QUENCH DET 3
FD
NOTE
ALL CONTROLS THROUGH PLC, EXCEPT
MECHANICAL REVERSING SWITCH CONTROL
Remote COMMAND
FORWARD REVERSE
SD
Remote P.S. OFF AT I = 0
30 Minute Timer Motor
Rev Sw. Ready Interlock AT I ≥ 30min.
M
3 ph. 208v
Reversing Sw. Motor
5000A Sw Contacts
REVERSE AT I + 30 min
PROTECTIVE INTERLOCKS
D-0 SUPERCONDUCTING SOLENOID
CONTROL AND PROTECTION SCHEME
A.T. VISSER
REV 29APR93
FIG. 10 - 3