***CDF Solenoid Interlocks***
***Component Failure Analysis***

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## I. Introduction

The objective of this analysis is to demonstrate that the failure of any single component in the CDF Solenoid Interlock system will not cause the system to fail to perform the following tasks.

a) Detect quenches in the superconducting solenoid and leads.
b) Turn off the 5000 Amp power supply when it is called for.
c) Open the Slow Dump switches when it is called for.
d) Open the Fast Dump switches when it is called for.

It is also acceptable to have the system shut down the power supply and open the Fast Dump switches when a failure in the quench detection circuits is detected or there is a loss of power.

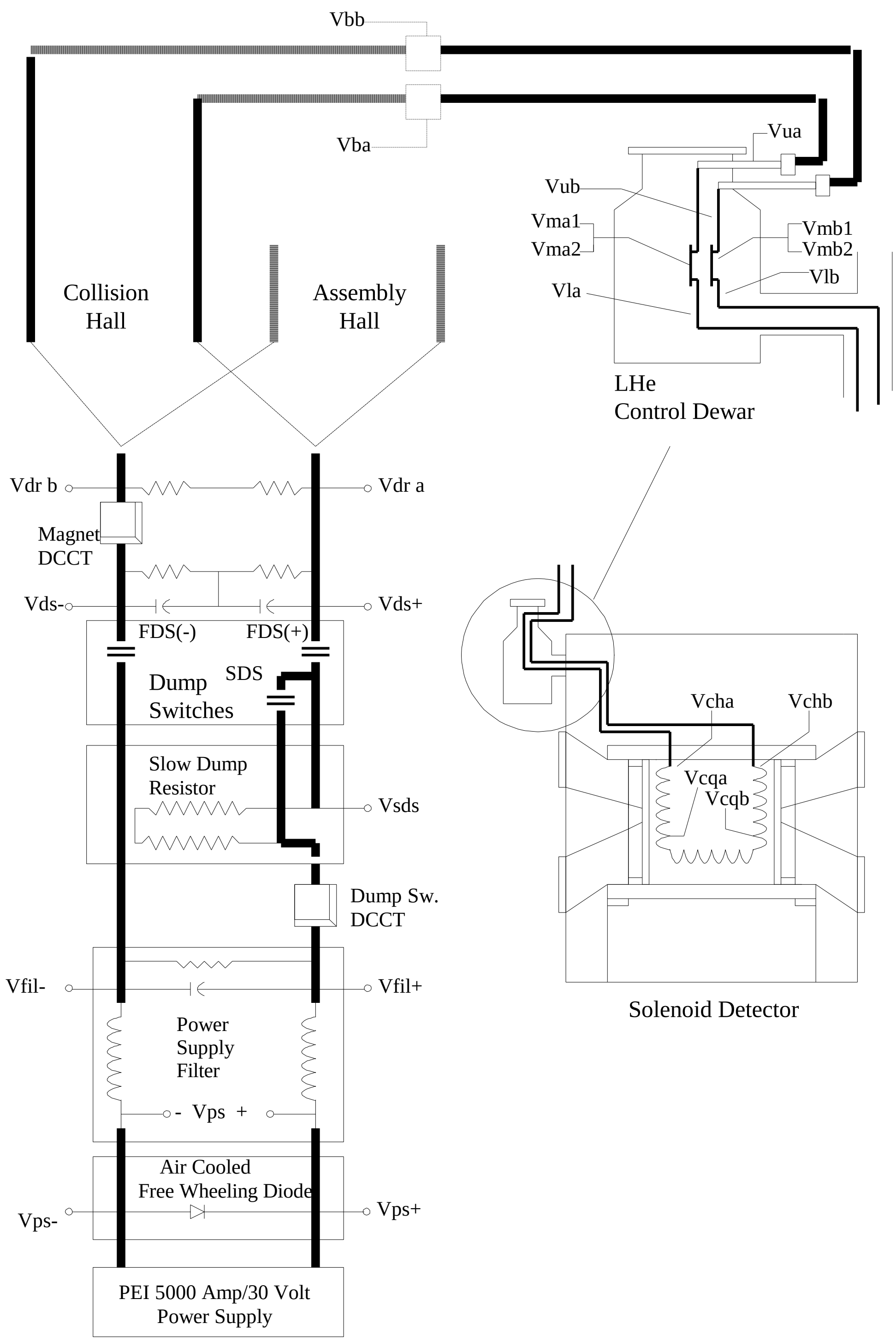



**Figure II.1.1 Solenoid Power Circuit.**

# II. Detecting a Quench

## II.1 Redundant Measurements

When a portion of the superconducting solenoid or superconducting leads loses its cooling or receives excessive flux of energy that causes the material to warm up and become resistive this is when a quench occurs. A voltage drop will appear across the portion of the solenoid that has become resistive. By monitoring all portions of the solenoid for excessive voltage drop we can detect the quench and remove power. We also obtain a voltage across the solenoid when the current through it is ramping up due to its inductance. In order to detect a quench when the current is being ramped we compare the voltage dropped across one portion of the solenoid to another part of the solenoid or to the voltage across a flux pickup coil wrapped around the solenoid. In this manner the ***inductive voltage drop due to the changing current is canceled out and the resistive voltage drop due to a quench in one portion is detectable***. The interlock system quench detection electronics performs the measurements listed below. More details of each measurement is given in Table II.1.1. Refer to Figure II.1.1 for the location of the voltage tap positions.

1. The voltage across the gas cooled leads is determined by measuring the voltage differential (Vua - Vma1) for lead A, and (Vmb1 - Vub) for lead B.
2. The voltage across the superconducting chimney leads is determined by measuring the voltage differential (Vma1 - Vcha) for lead A, and (Vchb - Vmb1) for lead B.
3. A comparison between the voltage drops across the chimney lead A plus the first quarter of the solenoid and chimney lead B plus the last quarter of the solenoid is made using a bridge network. The output of the bridge network is a voltage proportional to (Vma1 - Vcqa) - (Vcqb - Vmb1).
4. The middle two quarters of the solenoid (Vcqa - Vcqb) is compared to the voltage across the flux coil.
5. The voltage across the entire solenoid (Vcha - Vchb) is compared to the voltage across the flux coil.

Table II.1.1 Quench detection monitoring.

| Item | Module | Portion of Solenoid Monitored | Voltage Differential | Threshhold |
|---|---|---|---|---|
| 1. | NIM2A | Gas cooled lead A | (Vua - Vma1) | |
| 2. | NIM2B | Gas cooled lead B | (Vmb1 - Vub) | |
| 3. | NIM3A | Superconducting chimney lead A | (Vma1 - Vcha) | |
| 4. | NIM3B | Superconducting chimney lead B | (Vchb - Vmb1) | |
| 5. | NIM1, NIM5A | Solenoid first quarter plus chimney lead A and last quarter plus chimney lead B | (Vma1 - Vcqa) - (Vcqb - Vmb1) | |
| 6. | NIM4B, NIM6A | Solenoid middle two quarters | (Vcqa - Vcqb) - Vfluxcoil | |
| 7. | NIM4A, NIM6B | Entire Solenoid | (Vcha - Vchb) ) - Vfluxcoil | |

Note that two separate electronic modules monitor each portion of the solenoid and superconducting chimney lead. The chimney leads are monitored in NIM3 and in NIM5A. The measurement of the entire solenoid in NIM6B is redundant to measurements made in NIM5A and NIM6A.

## II.2 Analysis of Quench Detection Modules

### II.2.1 Isolation Amplifiers, NIM2, NIM3, NIM4, and NIM5.

Table II.1.1 lists the portions of the solenoid that are monitored by the isolation amplifiers. The differential measurement is provided by a precision instrumentation amp (INA118) followed by a precision , 3-port isolation amplifier (AD210) which provides isolation of the solenoid signal, and isolated power and ground to the instrumentation amp and the cable monitoring circuitry.

Figure II.2.1 is a simplified schematic of the isolation amplifier input circuits. Shown in this figure are the typical 10K Ohm isolation resistors in the Safety Resistor Box. The Safety Resistor Box is mounted on the CDF detector as close to the solenoid taps as possible. The cable monitoring voltage applied across the isolation resistors, cabling and interconnects results in a voltage drop of 0.1Vdc across these elements. The gain of the instrumentation amp, 50 V/V, results in a fixed 5Vdc offset in the measurement. If a short should result in the cabling or interconnects this bias is lost. If the cabling or interconnects should open, the cable monitoring voltage will drive the instrumentation amp to its high rail near 15Vdc. In each case the voltage shift at the input to the window comparator will cause a Fast Dump to occur.

Since the output of the instrumentation amp and the isolation amp is expected to be 5Vdc in normal operation, nearly all possible failures of these portions of the circuit should be detected. That is failures that cause one of the amps to go to its high or low rail, +/- 15Vdc, or to zero. This also follows for the amplifiers or 2.5Vdc reference that generates the cable monitoring voltage.

Figure II.2.2 is a simplified schematic of the circuit that generates the +/- trip voltages for the window comparator as well as the -5Vdc that cancels the 5Vdc offset just prior to the comparators. All of the amps are part of a single quad package, which means that a power input failure that causes one amp to move to one power rail or the other would cause all of the amps to do so. These conditions will cause the comparators to open the Fast Dump switches.

Relay K1 must be energized in order to hold the Fast Dump switches closed. Relay K1 will be deenergized should the measured solenoid voltage go outside the comparator window, or one or both of the +/- 15Vdc supplies are lost, or the comparators output fail in a shorted state.

### II.2.2 Flux Coil Summation, NIM6.

There are two Flux Coil Summation channels in NIM6. Channel A compares the flux coil voltage to the voltage across the entire solenoid using the differential output of Isolation Amp, NIM4A. Channel B compares the flux coil voltage to the voltage across the inner two quarters of the solenoid using the differential output of Isolation Amp, NIM4B. The Flux Coil Summation channels provide the same cable monitoring as does the Isolation Amplifiers.

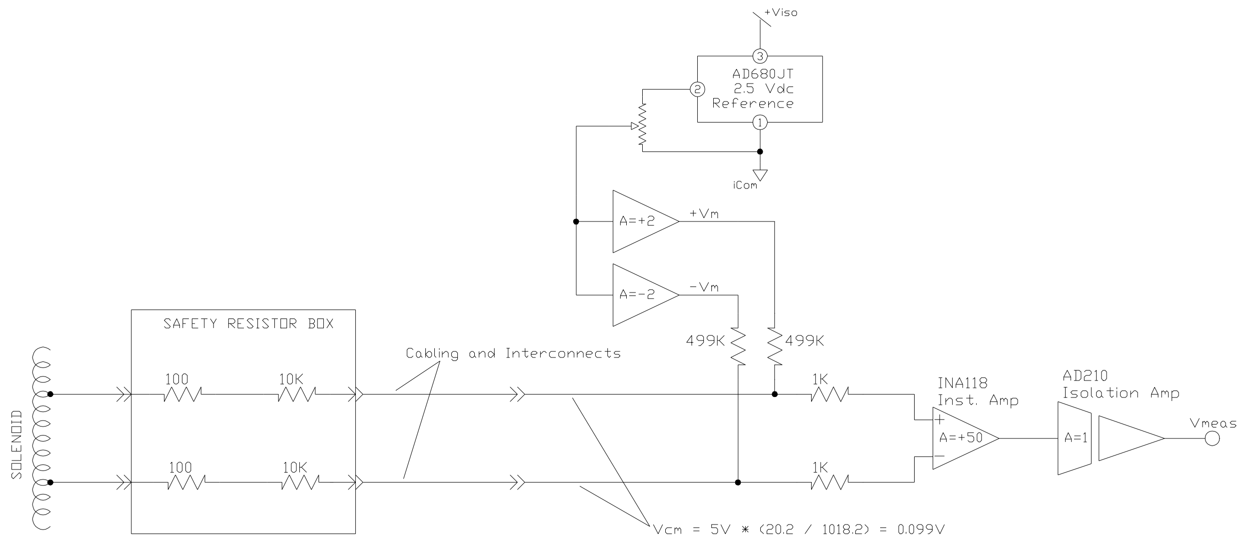



**Figure II.2.1 Simplified schematic of the isolation amplifier input circuits and cable monitoring.**

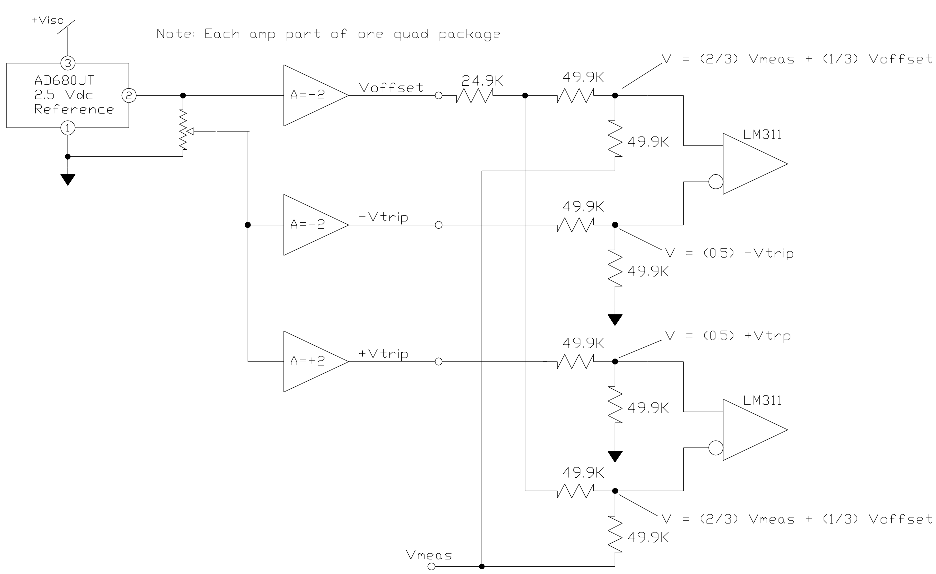



**Figure II.2.2 Simplified schematic of the circuit that generates the +/- trip voltages for the window comparator.**

# III. Shutting Down the Power Supply

## III.1 Means of Shutting Down the Power Supply

The 5000 Amp power supply is to be shut off whenever either the Fast Dump switches or the Slow Dump switch is opened. There are also a number of other conditions where we need to ensure that the power supply is shut off. The power supply can be shut off from the Quadlog programmable logic controller, from any of three NIM Interlock Summation Modules, and contacts in the Fast Dump switches, the Slow Dump switch, and the Filter/Crowbar circuit.

Several events call for the power supply to be shut down. A list of these events and the signal paths used to shut down the power supply are listed below. Figure III.1.1 illustrates different interlock paths that can shut down the power supply.

### 1. Fast Dump Switch (1 or 2) Opens

**Main Interlock Path:** Status contacts from the fast dump switches themselves are inputs of Interlock Summation Module, NIM9. Relay KSD of NIM9, in series with power supply interlock EI#1 will open if the dump switches are open.

**Secondary Interlock Path:** When it is the quench detection electronics which calls for a fast dump, Interlock Summation Module, NIM7 which sums these interlocks opens the contacts of KSD which are in series with power supply interlock EI#1.

### 2. Slow Dump Switch Opens

**Main Interlock Path:** Status contacts from the slow dump switch is an input of Interlock Summation Module, NIM9. Relay KSD of NIM9, in series with power supply interlock EI#1 will open if the slow dump switch is open.

**Secondary Interlock Path:** When it is the quench detection electronics which calls for a slow dump, Interlock Summation Module, NIM8 which sums these interlocks opens the contacts of KSD which are in series with power supply interlock EI#1.

### 3. Current Transducer Failure and DC Over Current

**Main Interlock Path:** Status contacts DC Over Current and Transducer Failure from NIM11 are inputs of Interlock Summation Module, NIM9. Relay KFD of NIM9, in series with power supply interlock EI#2 will open if solenoid over current or transducer failure is indicated.

**Secondary Interlock Path:** Using the same inputs from NIM11 into Interlock Summation Module, NIM9. Relay KSD of NIM9, in series with power supply interlock EI#1 will open if the slow dump switch is open.

**Additional Interlock Path:** The power supply itself provides detection of an over current condition and interlocks internal to the power supply will cause it to shut down. Also, the Quadlog PLC monitors the magnet DCCT and power supply internal DCCT. In the event of overcurrent the PLC will remove the power supply permit at NIM9 independent of NIM11.

## 4. Hi-Pot in Progress

**Main Interlock Path:** Status contacts from the hi-pot chassis are inputs of Interlock Summation Module, NIM9. Relay KFD of NIM9, in series with power supply interlock EI#2 will open if solenoid over current or transducer failure is indicated.

**Secondary Interlock Path:** Using the same inputs from the hi-pot chassis into Interlock Summation Module, NIM9. Relay KSD of NIM9, in series with power supply interlock EI#1 will open if the slow dump switch is open.

**Additional Interlock Path:** When hi-potting is done in an automated manner, it is done using the QuadLog PLC. ***The PLC will initiate an automatic hi-pot only when NIM11's output indicates that the power supply is off and the operators have completed a checklist***. The PLC will shut down the power supply through contacts connected in series with EI#3. When hi-potting is done manually a visual verification that the power supply is off will be part of the procedure.

## 5. Power Supply Mode Interlock

**Main Interlock Path:** This will prevent the power supply from being operated if it is not in the following mode: Remote On/Off control, Current Regulation mode, and External Reference selected. The switches are monitored by the Quadlog PLC.

**Secondary Interlock Path:** ***The event of the switches not being in the proper position also requires operator error. Operators will be trained in this regard and procedures will address the proper setting of these mode switches***

## 6. Power Supply and Buswork Cooling Water Flow Interlock

**Main Interlock Path:** Contacts of each cooling water flow switch are wired in series with EI#3 to shut down the supply in the event that we lose water flow through the buswork.

**Secondary Interlock Path:** Should the water flow stop and the flow switches fail to detect the situation we expect the buswork to get the hottest at the bolted joints. Each bolted joint has a Klixon temperature switch mounted to it. These switches are all daisy chained together and provides an input to the Interlock Summation Module, NIM8. This will cause a slow dump if an over temperature condition is detected by any of the Klixons. Hence the power supply is also shut down as described previously.

## 7. Loss of Watt Can Vacuum

**Main Interlock Path:** Contacts of the Watt Can vacuum readout are wired in series with EI#3 and will cause the power supply to shut down in the event that the Watt Can vacuum gets too high.

**Secondary Interlock Path:** The Watt Can vacuum is also monitored through the PLC and the power supply permit will be removed in the event of the loss of vacuum.

The Interlock Summation Modules monitor eight digital outputs of the NIM Isolation Amplifiers and outputs of other sources. Table III.1.1 lists the items monitored by each Interlock Summation Modules. In each summation module, any of the eight inputs going into a trip state will cause relay KSD to deenergize and open its normally open contacts. The KSD contacts of each of the three summation modules are wired in series with one of the power supply's external interlock relays.  A second independent path to shut the power supply down in the event of a quench is provided using a contact in the Power Supply Filter / Crowbar circuit that is an input of NIM9.

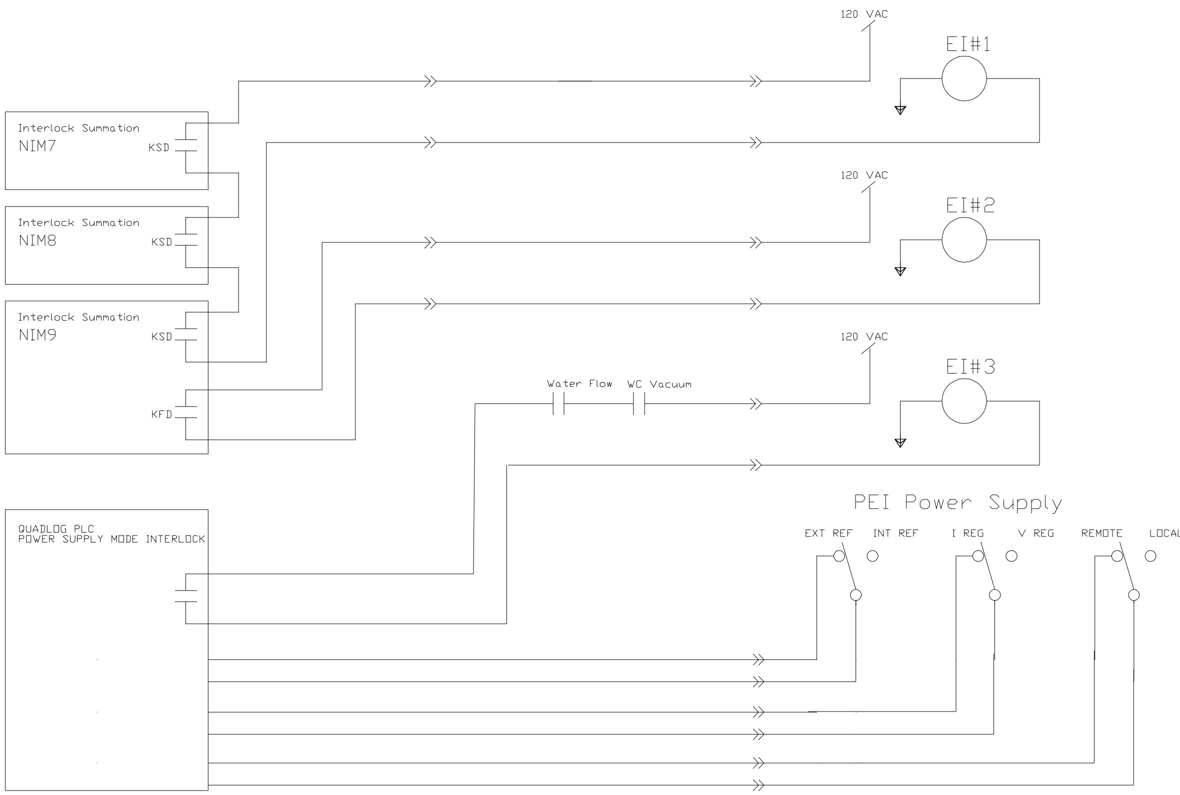



**Figure III.1.1  Power Supply External Interlocks.**

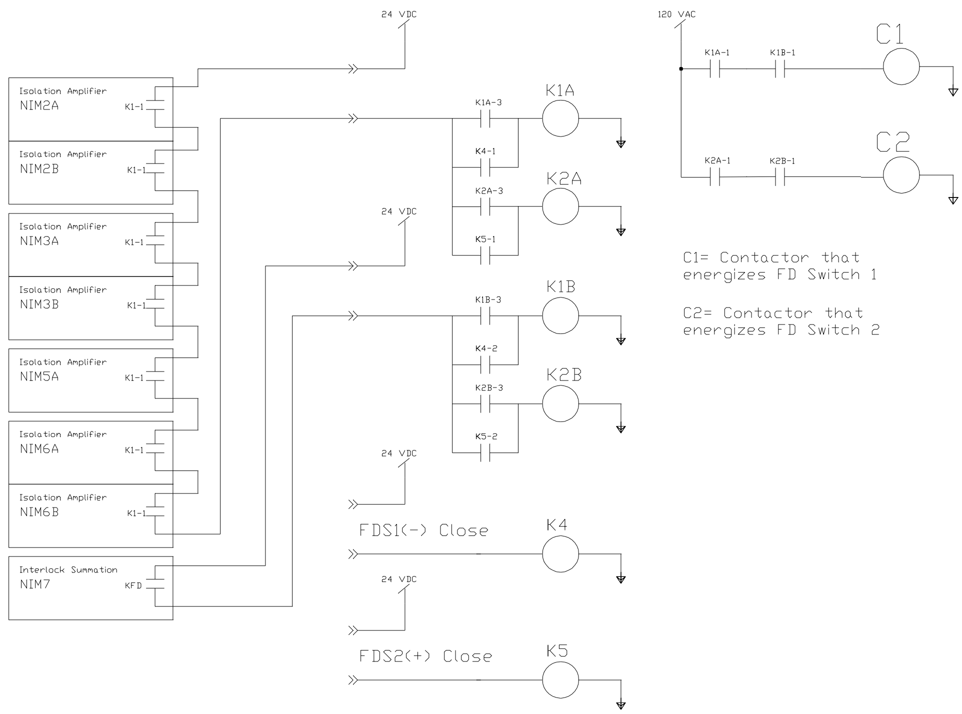
Table III.1.1 Items monitored by each Interlock Summation Modules

| Module | Input No. | Name | Comment |
|---|---|---|---|
| NIM7, Fast Dump | 1 | NIM2A | Gas cooled lead A. |
| | 2 | NIM2B | Gas cooled lead B. |
| | 3 | NIM3A | Superconducting chimney lead A. |
| | 4 | NIM3B | Superconducting chimney lead B. |
| | 5 | NIM5A | Solenoid first quarter plus chimney lead A and last quarter plus chimney lead B. |
| | 6 | NIM6A | Solenoid middle two quarters. |
| | 7 | NIM6B | Entire Solenoid. |
| | 8 | QuadLog Permit, Fast Dump Switches | Permit from the QuadLog PLC to close the Fast Dump switches. |
| | | | |
| NIM8, Slow Dump | 1 | QuadLog Permit, Slow Dump Switch | Permit from the QuadLog PLC to close the Slow Dump switch. |
| | 2 | Klixon Temperature Sum | Klixon interlock summation. Klixons are temperature switches that trip on excessively high temperature. These are used on bolted joints in the bus work and other critical locations. |
| | 3 | NIM10 | Ground Fault Permit |
| | 4 | Not Used | |
| | 5 | Not Used | |
| | 6 | Not Used | |
| | 7 | Not Used | |
| | 8 | Not Used | |
| | | | |
| NIM9, Power Supply Permit Only | 1 | QuadLog Permit, Power Supply | Permit from the QuadLog PLC to enable the power supply. |
| | 2 | NIM11, DC over current | DC over current. |
| | 3 | HiPot in progress | Disable the power supply when doing a hipot. |
| | 4 | NIM11, Transducer failure | Current transducer failure. |
| | 5 | Fast Dump Switch 1 | Fast Dump switch 1 open status. |
| | 6 | Fast Dump Switch 2 | Fast Dump switch 2 open status. |
| | 7 | Slow Dump Switch | Slow Dump switch open status. |
| | 8 | Filter / Crowbar Monitor | Fires during a quench. |

# IV. Opening the Fast Dump Switch

## IV.1 Means of Opening the Fast Dump Switch

If a quench is detected in the solenoid or the superconducting leads the fast dump switches are to be opened. Figure IV.1.1 illustrates the interlocks that hold the fast dump switches closed. Contacts K1-1 of the NIM quench detection isolation amplifiers are in series with the fast dump relay, K1A in the Dump switch Cabinet, that hold Fast Dump Switch 1 and Fast Dump Switch 2 closed. If a quench is detected by any of these modules the fast dump relays are deenergized and the fast dump switches opened. A second contact of each quench detection isolation amplifier, K1-2, is summed with the others in Interlock Summation Module, NIM7. The contacts of relay KFD in NIM7 are wired in series with a second fast dump relay, K1B. As shown in Figure IV.1.1 contacts of both fast dump relays must be closed in order for the fast dump switches to remain closed.




## Figure IV.1.1 Fast Dump Switch Interlocks.

# V. Opening the Slow Dump Switch

## V.1 Means of Opening the Slow Dump Switch

The slow dump switch is caused to opened using contacts of the KSD and KFD relays of the Interlock Summation Module, NIM8. Figure V.1.1 indicates how the two contacts of NIM8 along with an additional slow dump relay are used to provide separate interlock paths.
Review Table III.1.1 for a list of items monitored by Interlock Summation Module, NIM8.

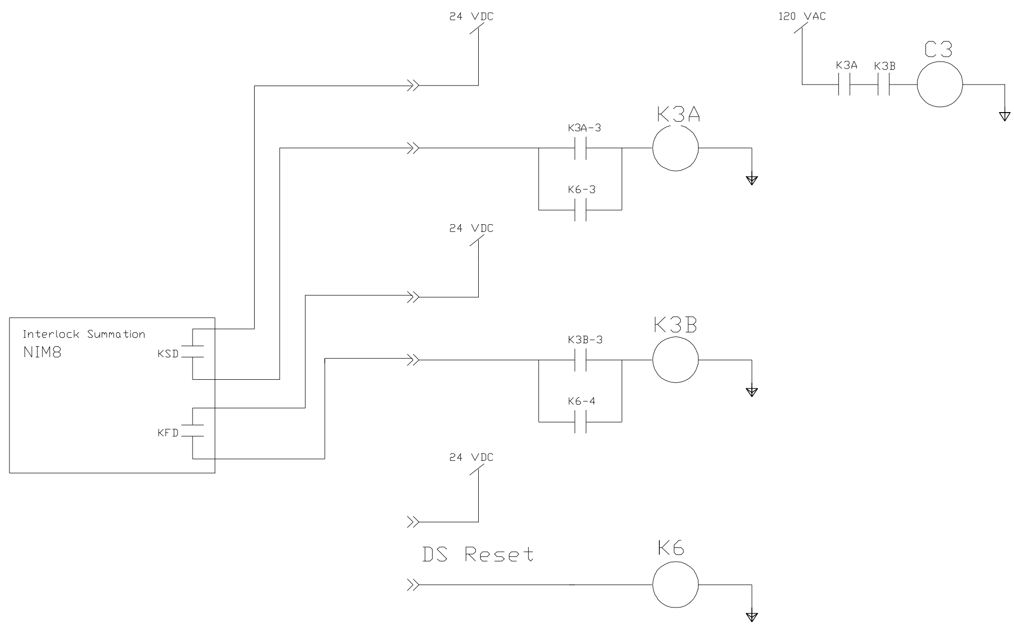



**Figure V.1.1 Slow Dump Switch Interlocks.**

# VI. Conclusions

In Section II.1 we have described how each part of the solenoid and superconducting leads are monitored by two separate sets of electronics. The electronics get their signals from separate sets of cables, whose endpoints at the detector are isolated from one another using series resistors. In Section II.2.1 we also described how shorts and opens in the signal cables can be detected. Such compromises to the quench detection result in the fast dump switches being opened and the power supply being shut down.

In Section III.1 we described how each event that needs to be responded to by shutting down the power supply has at least two interlock paths that will achieve the desired result. The only exception is the event that the power supply is left in the wrong mode, there is only one interlock path to shut down the power supply. For the sake of this single failure analysis, we defend ourselves by pointing out that both the human operator would have to fail in their switch selection and the interlock path would have to short before there would be a problem.

In Section IV.1 we described the redundant interlock paths available for applying the results of the quench detection isolation amplifiers to opening the fast dump switches. There are two separate paths from the two pair of contacts of K1 in the isolation amplifiers to the fast dump switch relays. In addition, all four fast dump relays would need to fail before the fast dump switch would fail to open.

Finally, Section V.1 describes the redundant paths for opening the slow dump switch. Note that some of the events that call for a slow dump do not have redundant sensing of the event at the input to the Interlock Summation Module, NIM8.