Solenoid Re-Commissioning Narrative

Introduction:
This document provides the rational for the re-commissioning of the Hall D Solenoid in response to the quench experienced on May 1 at 1460 A. The following topics are covered:

Suppositions on the cause of the quench
Response to the potential causes
Additional Solenoid Magnet System problems
Changes to the Solenoid Magnet System that work the problems

Goal: Our goal is to prove that the Solenoid System is not damaged and can be used without modification for physics over the next few years of physics commissioning. The second goal is to map the solenoid before installed apparatus precludes good mapping and, if possible, map a few traverses at a higher current to base extrapolation to the higher field from the lower field has a basis.

Plan: The plan is to continue low current (15 A) tests when the solenoid is superconducting and fully inductive. These tests continue interlock validation for validations that require a superconducting magnet. The tests look for turn-to-turn shorts, verify the operation of the Ground fault Detector, allow the low current calibration of the quench detectors and verify that the soft ramp and/or tuning of the power supply prevents spurious QD tripping. The second stage of the test is ramps to 140 A to verify superconducting operation and extend the low current validations at a meaningful current. The third stage testing extends earlier tests to the current to be used for operation. This stage requires an operational response to the change in inductance of the solenoid from 28 to 25 H over the current range. The stage requires a balance adjustment of the hard wire QD and a programmed change in inductance values used by the PLC quench detectors. The third stage of testing will ramp and plateau at several currents to look for changes in resistance and cryogen usage and will end in mapping the solenoid. These plans are detailed in Commissioning procedure D000000402-P002, Revision C (up to 140 A) and Revision D (to full current).

Comment [w1]: manual

Suppositions on the cause of the quench
Analysis of the solenoid coils is attached in referenced documents. 1, 2, 3.

The supposed cause of the quench matched to the sequence of the events is as follows:

From the fast data acquisition system (DAQ) voltage tap readings seen in Figure 1, we see the quench started in Subcoil 1AB. Our considered supposition is that the quench was caused by a conductor at the inner bobbin diameter (highest field) in Subcoil 1AB that exceeded its current sharing temperature for the bath temperature and magnetic field surrounding it. We know that once current sharing temperature is reached, no amount of cryo stabilization can stop the quench. The heat transfer characterized by the cryostabilization calculation (heat transferred to helium is greater than heat generated prevents growth of quenching in the presence of at least 0.5 K of temperature margin. The result was a quench of the entire Subcoil within 6 seconds (matching the calculation of Document 1 pX). We also know that the conductors used in this subcoil (at the start of the reels) had short sample values that indicate the conductor is X.X K away from current sharing temperature. But we also know4 that the quality of the superconductor made for the project varied~~, in quality~~. The manufacturers didn't have a good control on even the proportions of niobium to titanium in their product. Hence portions of the superconducting wire on the reels could have lower properties than the short samples indicate.

We suppose that the successful ramp to 1500 A on April 30, the day before the quench, was successful because the temperature was 0.08 K lower. At that current the coil was very near the quench boundary.

Voltage tap readings show the quench remained isolated in the Subcoiil's antechamber volume, not spreading to the remaining subcoils of Coil 1, in their large separate chamber, for 18 seconds. We can conclude the cause of the quench is not coming from the leads connecting to the outer turns of Subcoil AB because, being in a far lower field, the current sharing temperature margin is well above 1 K where cryostabilization works and wetted area on the conductor is more than double of that available when conductor is within the coil. The fact that the quench didn't transmit to the other subcoils shows that heat transfer was enough to squelch quenching in the leads during that time interval.

We also observe that the quench is ~~also~~ probably? not from some sudden motion (generating frictional heat) of the subcoil or multiple turn subunit. We observe no voltage spike near the start of the quench – a necessary indication at a sample rate of 10,000 hertz and sensitivity to microvolts.

There is a possibility the quench may be from a turn–to-turn short that developed at high current.

Comment [w2]: eugene's analysis?

We continue our supposition that conductor reaching current sharing temperature is the cause is validated by the observation that at 13 seconds (5 seconds earlier than the remainder of Coil 1 quenching), a very similar, independent quench started in the largest subcoil (4D) of Coil 4 followed within 2 seconds by its co-joined Subcoil 4C. These Subcoils are isolated away from Coil 1 by two very well stabilized (extra copper) buses plus Coil 3 (which was not quenched at the time.) We conclude there is no transmission of the quench, through the conductor between coils **but rather that Coil 4's quench is an independent quench for the same reason as Subcoil 1AB.** At 13 seconds, the bath pressure increased to 1.44 Atm. and instantaneously increased the saturation bath temperature at the lower bobbin diameter to 4.64 K. We suppose that an inner bobbin winding of Subcoil 4D (a better superconductor, but at an equivalently higher field) was then at **its** current sharing temperature**.** This supposition is further validated by the identical start of the quench voltage curve and then the identical, greater slopes of the voltage tap readings from these two subcoils. The higher slope is consistent with the smaller amount of stabilizing copper in the Coil 4 conductor.

We observe that allowing the quench detector to be disengaged through 22 seconds of the quench allowed us to see the independent quench in Coil 4. The absence of the Coil 4 information would make the current sharing temperature argument more difficult to make.

Coil 4's quench also allowed greater spread of the energy deposition throughout the magnet such that the temperatures reached were less than if most of the energy was dumped into Subcoil 1AB and the dump resistor. Even if the external dump resistor was engaged earlier than 22 seconds, its withdrawal of energy is so slow that it would withdraw only XX% of the energy if engaged at a 1 V threshold. We conclude that the existing dump resistor's (0.06 Ω) rapid use is overrated. In this magnet, the object of the quench detector is only to shut off the power supply and start removing the resistors portion of the total energy.

If the quench were limited to just Subcoil AB for the complete quench the temperature would rise to 88 K, with the hot spot going to 182 K, not a high or destructive temperature.

Response to the Supposed Cause

We **do not** plan to explore the cause of this quench by any experimentation.

Pick a new Maximum Operating Current

The probable helium bath temperature at the bottom of the bobbin for the next two years (before possible refrigerator upgrade) is 4.56 K. From the assumptions below, the current should be 1300 A. Standardization of the magnet should also be taken into account in setting the maximum current where a magnet is taken to a current over its operating current to drive the iron into maximum saturation and then have the current back off to a lower value. This hysteresis process always yields the most consistent field values.

Limited higher operating current

The test should also explore, if possible, the magnetic field at 1350 A, the preferred low limit for physics experiments. Since 1350 A needs a 4.5 K bath, we should take a magnetic map of the magnet at is bore center (and perhaps at the BCal inner radius) for at least one plane through the bore during the limited, lower temperature running time when liquid he can be injected into the refrigerator.

Details of picking the temperature

On April 30, we know that the coils were subject to fields and forces (at 1500 A) no greater than experienced at the SLAC installation when the Solenoid was constituted as the LASS Solenoid and run at 1600 A. The helium bath temperature was XX K lower during our successful 1500 A run than the bath temperature at the lower part of the bobbin at 1460 A at the quench on May 1. The lower bath temperature was lower because of liquid helium injection from a 1000 l Dewar during that test.

A prudent way of not having another quench (with loss of helium and potential damage to the coils) is to (1) select a conservative conductor property value for the conductor less than the short sample data we have for the conductors. (2) Assume those properties are resident at the bobbin of Subcoil 1AB. Create a property surface on the field, current, temperature diagram. Apply the load line surface parallel to and intersecting the temperature axis for Subcoil 1AB. De-rate the current/field along the load surface for the higher temperature of running. Determine the current sharing temperature surface below the short sample surface for this state.

Since we know that the conductor actually quenched at the known temperature, which is below the current sharing temperature we calculate, we want to run the subcoil at a state (temperature/field) where the current sharing temperature is at least 0.4K higher than what we calculate for the state the conductor was when it quenched. Current sharing temperature. And apply a reasonable temperature margin on top of the temperature margin of that conductor as we assume it quenched at in Subcoil AB.

(As determined by short sample), determine its de-rated short sample properties due to temperature, further de-rate these

Commissioning Sequence
We plan to:
Take the Solenoid up to 1350 A in 4 stages from 40 A: (1) 1000 A, (2) 1200 A, (3) 1300 A and (4) 1350 A. using the soft ramp. We plan a thermal settling time of 1 hr between ramps.

For the 1350 A stage, the temperature should be lowered from standard refrigerator running pressure/temperature (1.345 atm/4.56 K) to 4.5 K using the LHe injection mode from the 1000 l Dewar.

Mapping the Solenoid.
We will map the Solenoid per our 4 ~~plain~~ plane? method at 1300 A

Comment [w3]: Will be do centerline at 1350A Ramp to 1360A aqnd back down?

Additional Solenoid Magnet System Problems

Quench Detector usage and sensitivity adjustment

Our first test of the solenoid had difficulty with the use of the Quench Detectors because of two conditions.

(1) Just turning on the power supply produced unbalanced transient voltages across the Subcoils such that at the ± 100 mV sensitivities we were using, the hard wire and software QDs would trip. The QDs needed to be defeated in order to turn on the

power supply. We didn't want to decrease the sensitivity of the long-term measurements.

(1) Any change in the power supply current resulted in unbalanced transient voltages across the Subcoils such that at the ± 100 mV sensitivities we were using, the hard wire and software QDs would trip. Some of the unbalance was due to the induced eddy currents in the yokes that would die down after 10 seconds from any change in ramping speed. Again the QDs needed to be defeated, in this case in, order to ramp. Again we didn't want to decrease the sensitivity of the long-term measurements. Our response during the test was "manning" the hard wire QD momentary defeating switch during ramping. Since the magnet "had never quenched" it seemed to be a safe bet that if a quench occurred, the manning person had time to initiate a fast dump and start extracting the fractional amount of the energy it could take. We also disengaged the PLC quench detectors because "manning" a momentary button on a screen using a mouse button was impractical while also trying to control the magnet from the screen.

The transients caused by the Power Supply when changing ramp rate and possibly when it is turned on are caused by the Power Supply not being impedance matched to the highly inductive load of the this Solenoid. Consultation with the manufacturer (Danfysik) lead to our purchase of a kit to 'tune' the power supply to the load. That kit may or may not be installed in the power supply for the high current tests. A second strategy to minimize transients at ramp changes only is to start and end every ramp using a staged ramp, where initially the ramp is hard ramp and not tuned.

Change in Solenoid Inductance Problem
A second order effect also affected the QDs during a ramp from low to high current. We observed the inductance of the Solenoid changes from 28 H ant 0 current to 25 H at 1500 A. Along with this change the ratio of the inductances of the subcoil sets also changes. Thus the quench detector balance pot, adjusting for the inductance difference between coil sets needs to be changed during the ramp. We disengaged the complicated subcoil set comparisons that used Channel 1 and 2 and used only the Coil 2 & 1 balanced against coil 3 & 4 in Channel 3 of the quench Detector. As current rose, we used hand adjustment of the pot using a micro screwdriver using the "Error Signal" from the QD as read out by a volt meter such that it never went near the 5 V trip limit.

~~He~~ The PLC QDs were totally disengaged during our first commissioning tests.

Changes to the Solenoid Magnet System that Work the Problems

Response to quench detector problems

From our analysis of the quench, the following is the rational course:
Because we calculate that we will not be able to stop a quench mid-quench, the best course of action is to turn off the power supply in a reasonable time and let the

dump resistor extract some of the energy while most of the energy dumps into the magnet. (Maximum is XX %) If high helium pressures raise the bath temperature and force Coil 4 to quench, so much the better. Coil 1AB will end up at a lower temperature if this happens.

Note that the quench in Coil 1AB easily went to 10 V over 6 seconds. So setting the quench detector to a sensitivity of 1.0 V or even 2 volts will easily trip the QD to extract almost all that can go into the Dump Resistor. At the same time, this insensitive setting, probably allows the use of a power supply not tuned to 25 H. The QD would ignore (1) transients from turning-on as well as (2) the transients from initiating a Slow Dump while ramping.

Comment [w4]: Note that the PLC quench detector will be more sensitve

Use of a more resistive dump resistor would raise the voltages to ground during a quench from the 50 V seen now to a proportionally higher voltage. Because there are zones within Coil 2 where raw conductor is facing the un-insulated flange across a 2 mm thick strip of G-10, consultation with the properties of cold helium gas next to a tracking surface~~5~~ shows that it is unwise to raise the dump resistor resistance by a meaningful factor of 10 (~500 V to ground).

We note that voltage taps see only a substantially reduced voltage from real resistive voltage of a quench. The voltage from the resistance from a quenching segment of conductor is nearly overcome by the inductive, and opposite emf from attempting to decrease the current in the subcoil. Thus the voltage taps that see the algebraic sum of these voltages are blind until the resistive voltage becomes dominant. At this point, the quench has run-away and will never be “caught by the quench detector in time to lower the current.

The conclusion is that if a quench starts, all you can do is turn off the power supply and start to extract that portion of the energy that can be dumped into the dump resistor. It follows that the quench detector sensitivity can be set at, say the 1 V level (first 3 seconds of the observed quench) and the results will be that same as if we caught the quench within milliseconds. If we adopt this decreased sensitivity, there are substantial operational benefits. The quench detector will not trip under the 2 nuisance scenarios: (1) tripping the power supply from a voltage spike generated while turning on the power supply, (we will no longer have to defeat the QD by the momentary switch) and (2) the system will probably no longer trip a Fast Dump at the start of a Slow Dump during a ramp because of the difference in voltage transients from the will no longer be greater than the sensitivity setting.

Power supply soft ramp and tuning

Response to change in inductance for the re-commissioning

We changed the screwdriver slot pot to pot with a readable dial for both sensitivity and balance for Channel 3 of the hard wire QD. We will use the error signal from the QD again, but this time we will log the pot dial readings for balance over the current range. We will also log the dial readings for the sensitivity control. The log entries will allow us to characterize and reliably repeat the settings in future operations.

The PLC QDs will be programmed to use changing inductances with increasing current from a look-up table and will not be disengaged during ramping or constant current operations.