# MICE Spectrometer Solenoid (Pre-) Review Initial Impressions

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RAL, Oct 27, 2015

On behalf (but not checking) of Tom Taylor (CERN, ret.), Amallia Ballarino (CERN), Vladimir Kashikhin (FNAL), Andrew Twin (Oxford Instruments), and Josef Boehm (RAL)

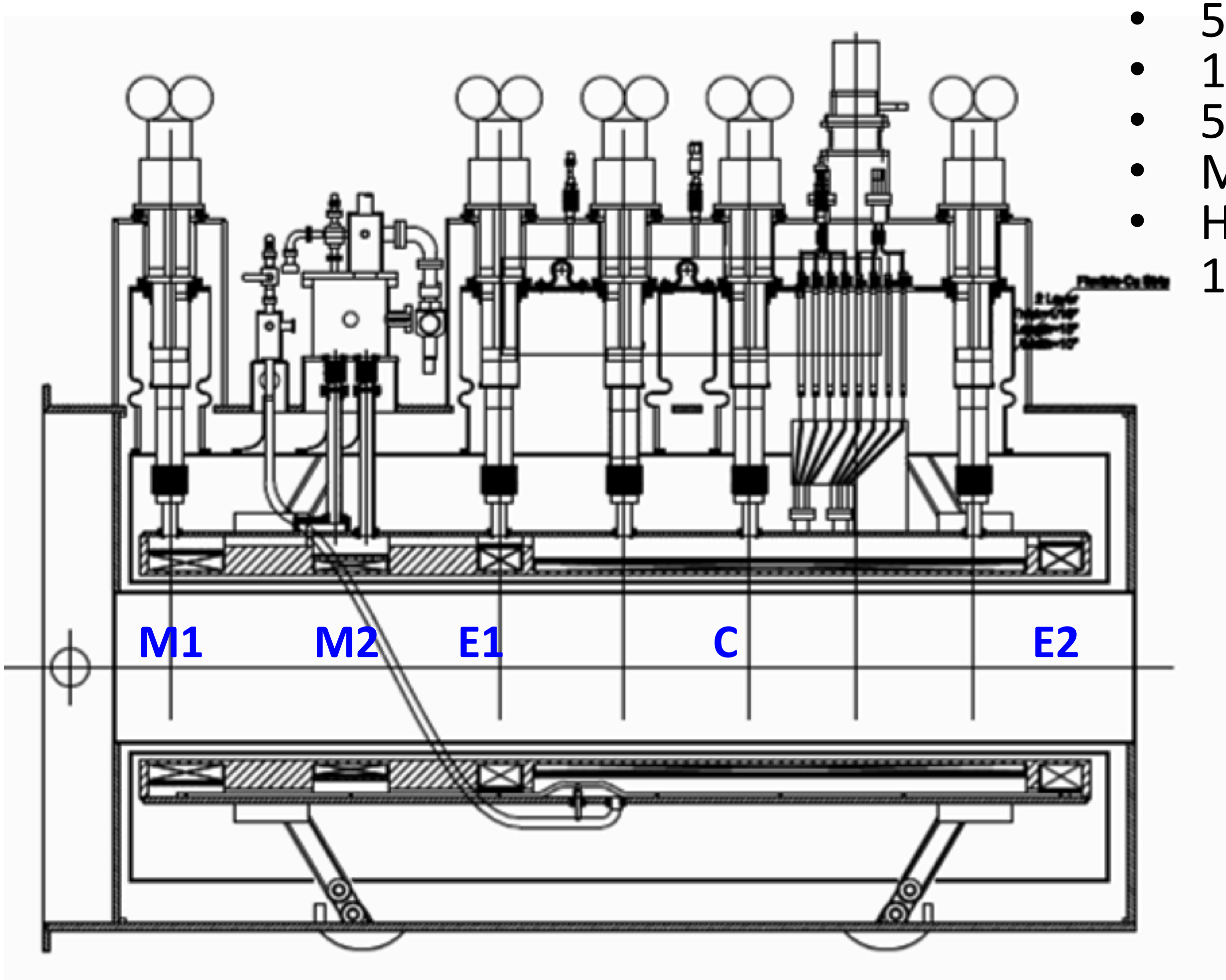
With thanks to Ken, Alan, Steve, Soren, Roy and Mark for talks (& slides) yesterday

# Outline

- Summary of what happened
- What's next?
  - What does MICE need?
  - What are reasonable paths forward?
- Next for the ad hoc committee (+?)

- → if it's in green it's an impression. If it's not I grabbed the slide and probably have not given appropriate credit to the speaker in this set (apologies in advance)

# Reminder: Basic design




- 5 2-stage CCs
- 1 single-stage CC
- 5 Coils
- Max current ~300A
- High inductance 10-40H

# Magnet Protection: basic scenarios

Quench

Normal zone growth

Detection

Power supply switched off

Trigger protection options

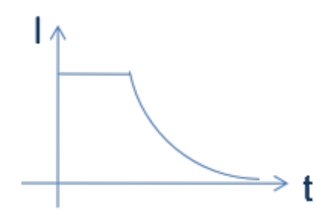
Protection heaters | Extraction | Quenchback

Current decay in the magnet

Magnetic energy $\frac{1}{2}LI^2$

Converted to heat by Joule heating

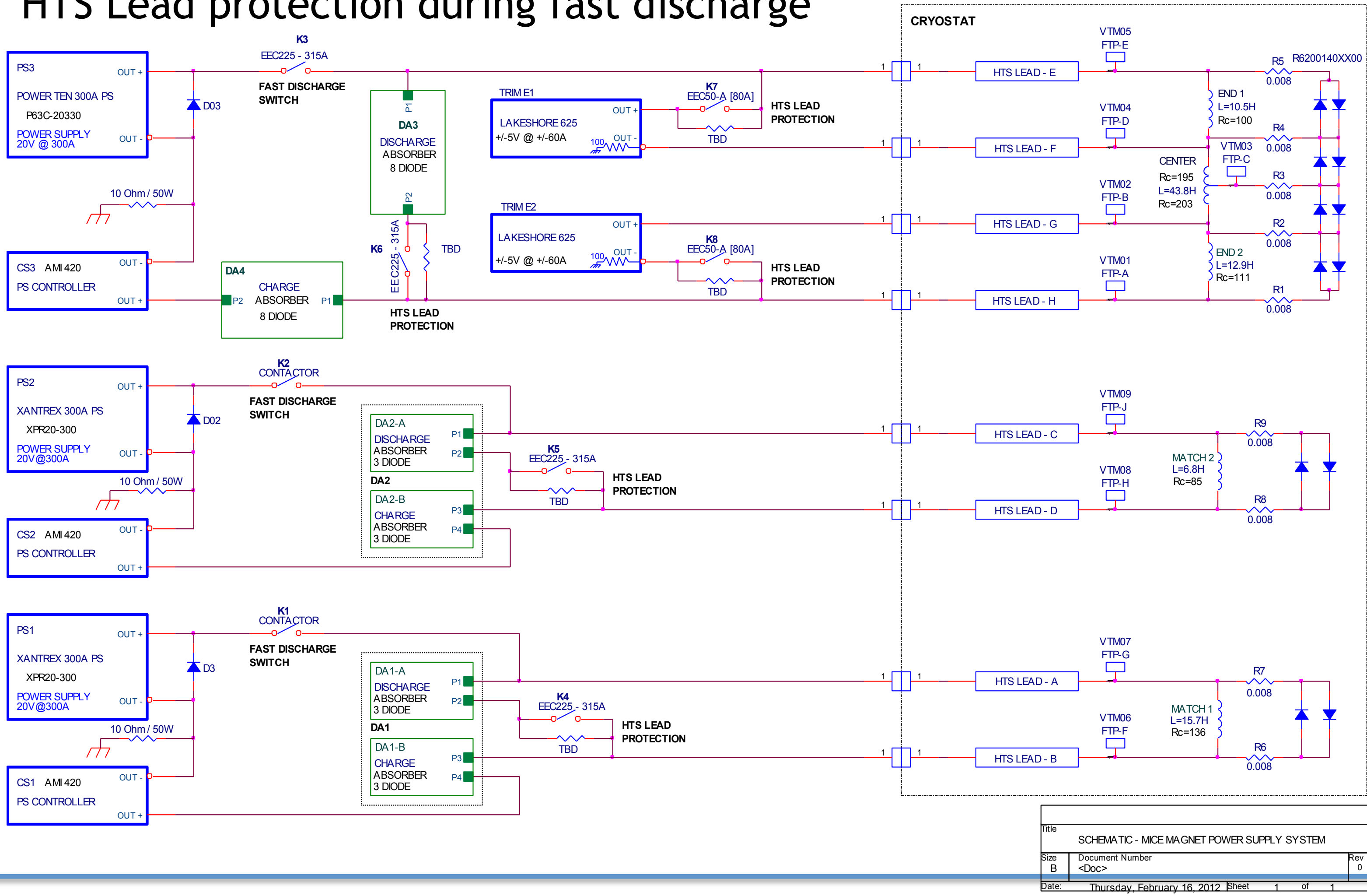
$\int_0^{\tau} R(t)I(t)^2\,dt$



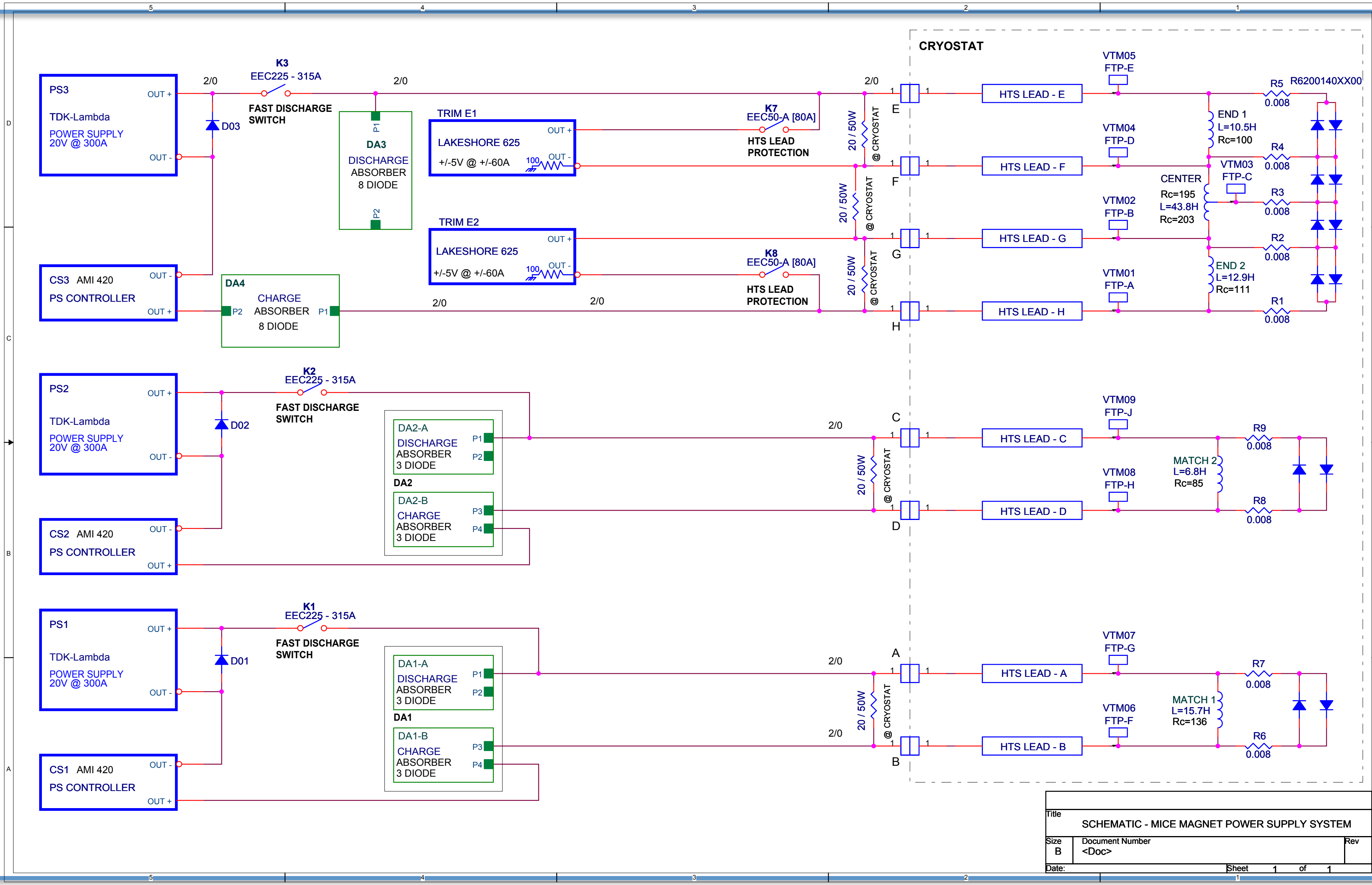

The faster this chain happens the safer is the magnet

# LBNL/MICE: DC PATH [“As Built”]

- Added 5 contactors to system
  - HTS Lead protection during fast discharge



# Schematics as-operated



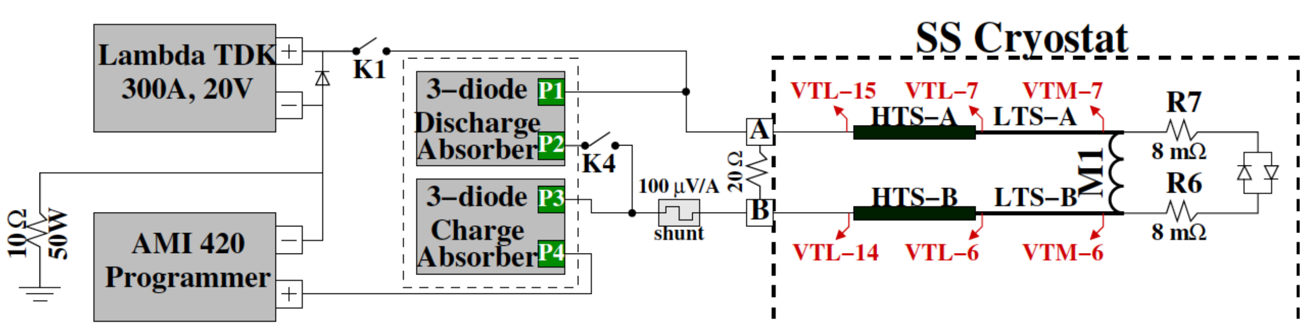
# Training SSD

- SSD has been a bit problematic at RAL
  - Some vacuum issues
  - Lost voltage tap on LTS lead of M2 coil
- In the training run of September 13th, 2015 all was going very well.
  - Implementation of additional QP for the M2 lead had not yet been done, so a decision was made to ramp only M1 and ECE
  - A quench occurred at ~ 260A in ECE (much higher than expected, next slide).
- QP system performed as expected, nothing outwardly unusual except for the large current.

# Lead failure

- However, upon entering the hall the odor of burnt FR4/G10 was extremely strong. Strongest at He relief valve
- After a great deal of analysis, it has now been determined that (see diagram on next slide):
  - One leg of M1 dead short to ground. This is LTSA lead.
  - LTSB lead not connected to coil (open), but connected to LTSA with ~ 2.4KOhm resistance.
  - M2 coil OK.
  - No damage seen anywhere else.
    - However, M2 coil has 1.3 KOhm resistance to M1 (& ground)
  - AC measurements show that QP on M1 not active indicating a break in the internal QP circuit. Most likely point is indicated in the figure on the next slide (x next to diodes) because there is another short to ground on this leg of the circuit.
  - All other coils OK (including their QP circuit).

# M1 circuit after fault



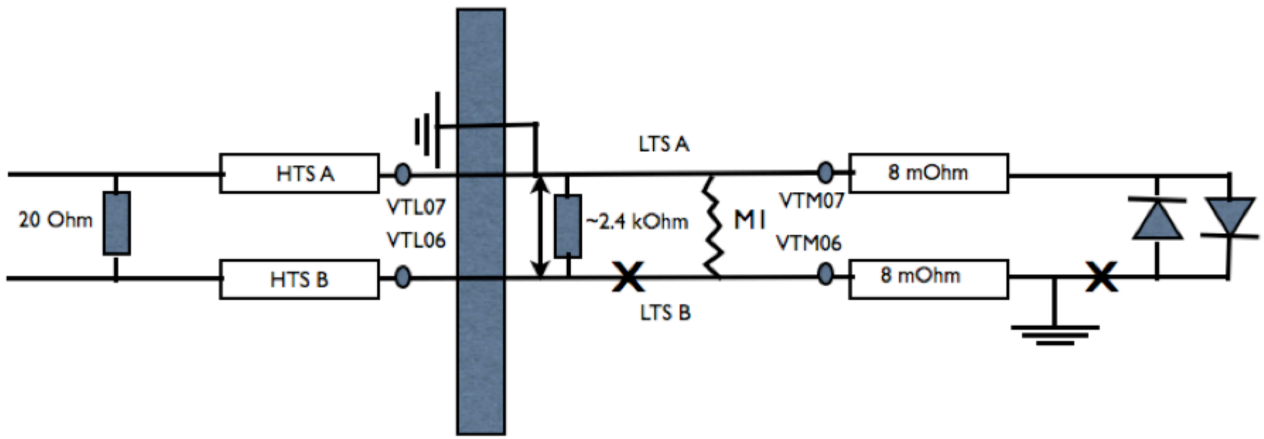



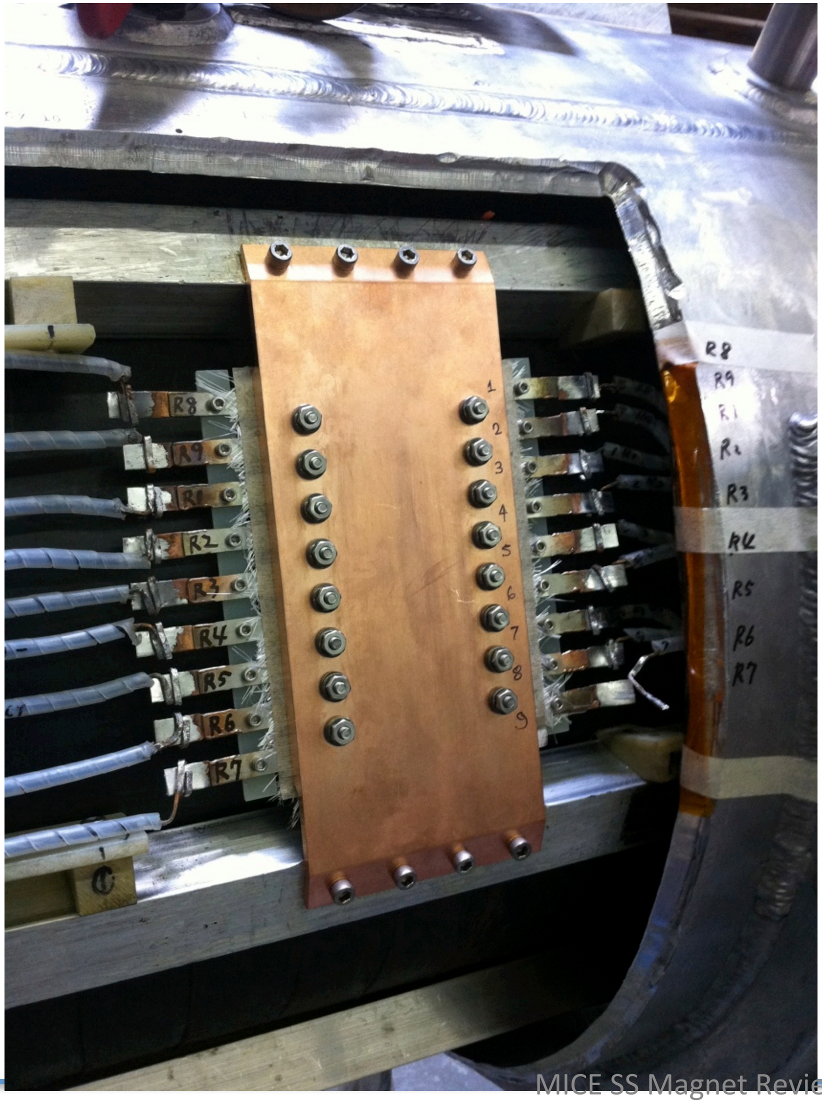

Diagram of the M1 circuit. Resistance (four wire and two wire) measurements revealed:

i) Lead A has hard short to ground,

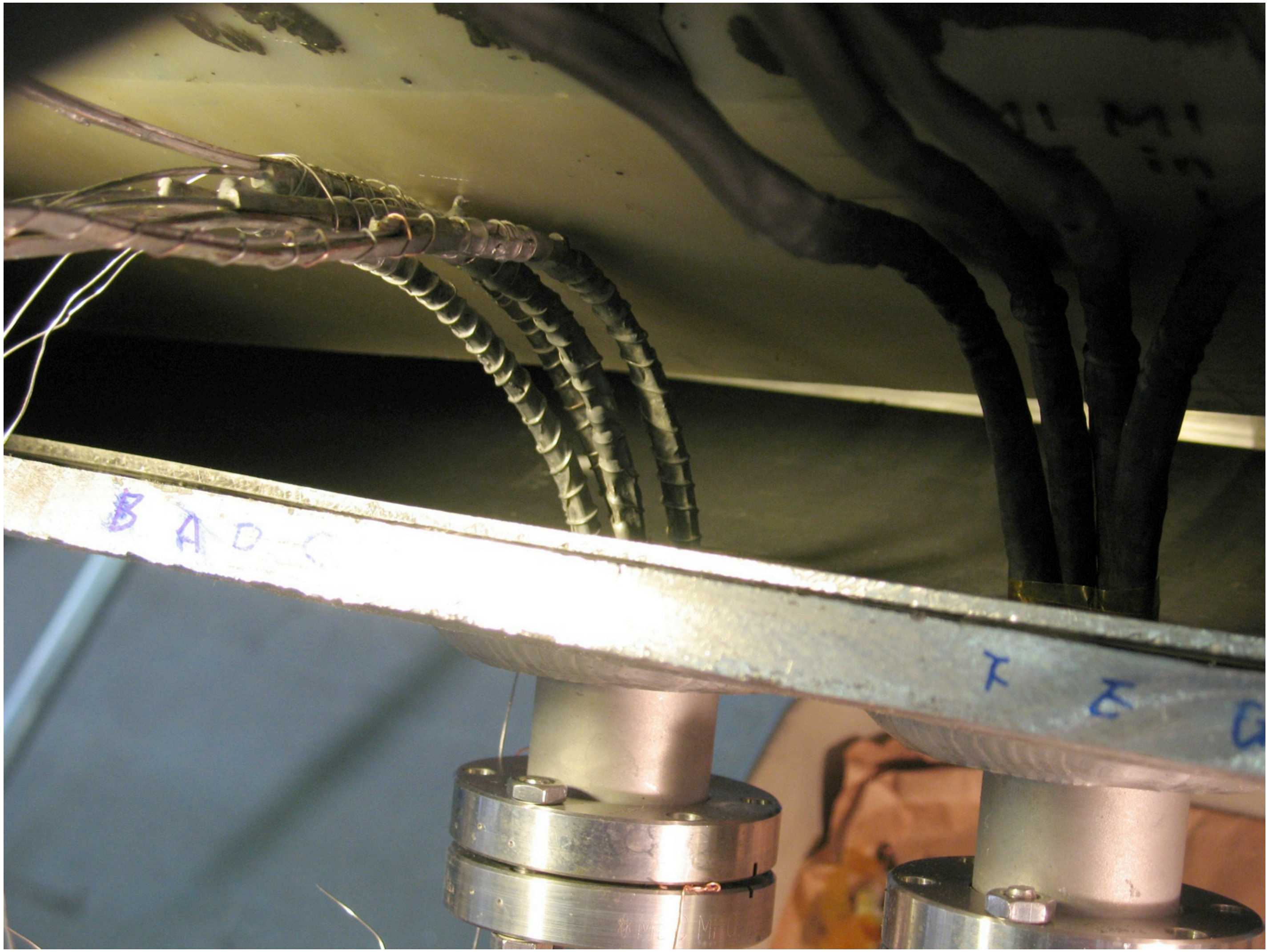
ii) LTSB is shorted to LTSA through 2.4 kOhms and LTSB is not connected to the M1 coil on the Lead B side.

# SS1/SSD Diode Pack

This is a photo of the QP pack for SSD/SS1. What  is not known at this time is exactly how the terminations were made. Did Wang follow the procedures used on SSU/SS1?



# Feedthrough



# Summary

Many contributing factors (in no particular order):

- QA at vendor
- Electrical system implementation
- Not powering M2, causing a delay in quenchback

All together → M1 failure

# Going Forward

- What does MICE need?
- What can be done?

# What does MICE need?

- MICE programme:
  - Step IV:
    - Measurement of material properties
    - Observation of reduction in normalised transverse emittance
  - Cooling demonstration:
    - Study of cooling demonstration effect

- Principal components of Step IV programme can be (and currently are being) carried out w/o SSD/M1

- Cooling demonstration requires recovery of full functionality of SSD

# What Can Be Done?

- Addressing the Key Questions
  1. Step IV?
  2. Repair Path?
  3. Schedule?
  4. Cost?
  5. Risks?

# 1. Step IV?

Can we operate MICE Step IV with the SSD as is?

- Optics designs sufficient for characterizing absorber materials are in hand (assuming SSD M2 coil is operational):
  - Critical SSD checks:
    - SSD E-C-E quench and reasonable response of vessel
      - ⇨ He vessel and feedthrough integrity satisfactory
    - SSD M2 low current checkout
      - ⇨ No anomalous resistive behavior observed
      - – Next step is a careful ramp to high current
  - ⇨ Viable optics and likely viable magnet with M2 and E-C-E coils
- Plan is to proceed with modified Step IV run plan for ~1 year
  - ⇨ Time to prepare for a repair

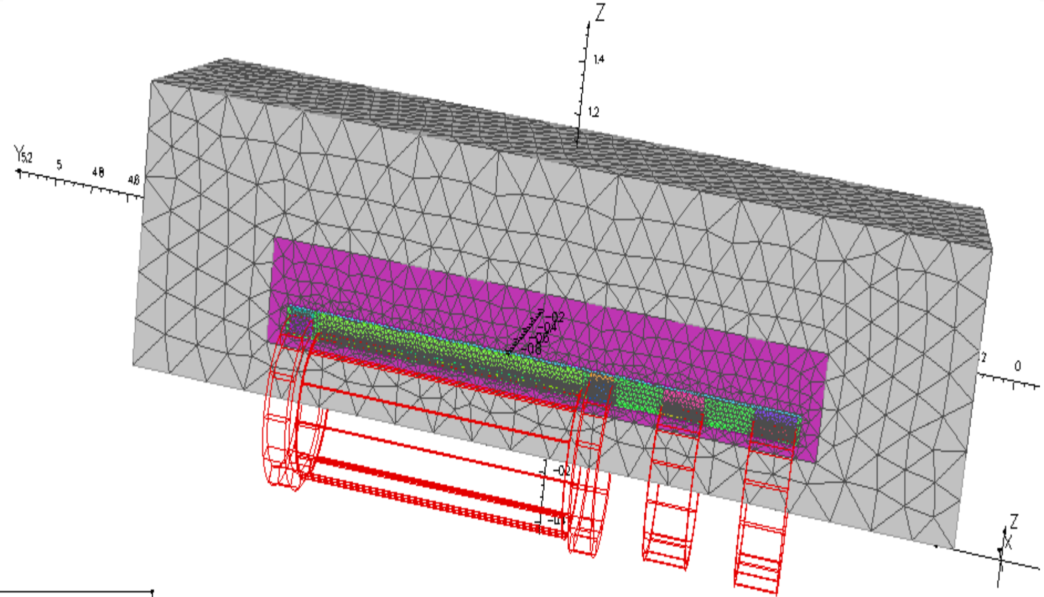
**Answer: YES**

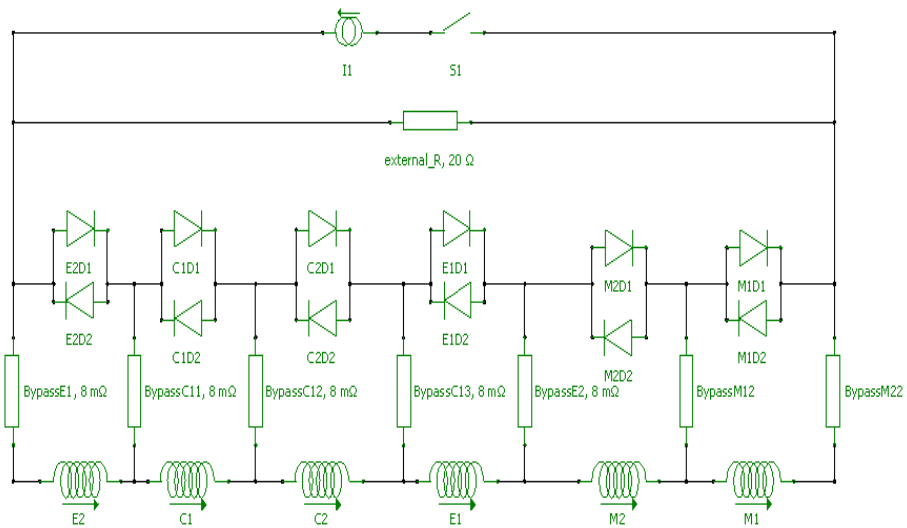
- Caveats:
  - Still need to validate magnet at currents required by alternative optics
  - Need to confirm that we have a power supply configuration that is "safe" for operations

# PSU Configuration (Preliminary for SSU)

Heng Pan (LBNL)

- Quad model built in VF
- Quench initiated in the inner layer of the E2 coil.






- All coils are powered by a single powers supply.
- A 20 Ω external resistor goes across all the coils.
- Switch opened when the overall voltage across the E2 coil exceeds 0.2V.

# Committee Initial Comment

- We suggest no further full powering of SSD or SSU occur until a revised power system is designed, understood, tested, and implemented.
- Proceeding with the Step IV program is probably fine after this change.
  - Risk for further incremental damage is probably contained to the area already damaged and in need of repair.
  - Some noticeable portion of Step IV can be accomplished without M1 or M2 if needed...

# Potential Technical Paths Forward

- Option 1 – Repeat previous repair scenario
  - Assumptions
    - NO changes to magnet design
    - Repair starts at conclusion of Step IV running
    - Suitable repair team available – magnet moved to team location
  - Schedule
    - Magnet could be at RAL for installation/commissioning prior to end of US FY17. Would fully become RAL responsibility at end of US FY17.
  - Cost
    - Nominally appears to use 100% of MAP management reserve funds. Plausible.
  - Risk
    - QA issues (believed to be known) could be addressed
    - Surprises when cold mass is inspected?
    - Are we comfortable with sticking to the current design untouched?

# Potential Technical Paths Forward

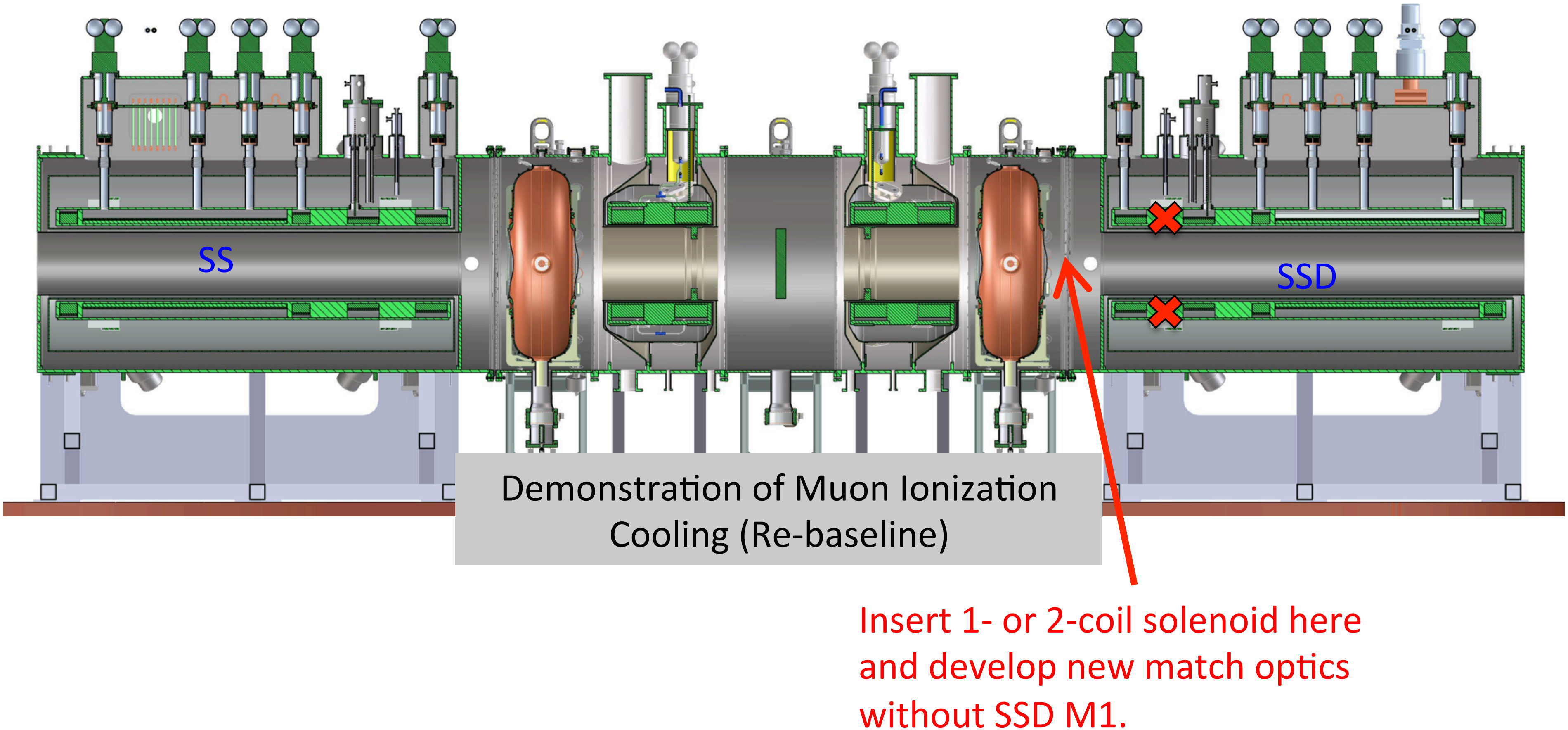
- Option 2 – Fabricate new cold mass
  - Assumptions
    - Only allow *modest* changes to cold mass design
      - Examples:
        - » Minor change in bobbin length to control thermal distortion
        - » Allow for vacuum-impregnation of coils
        - » Allow for addition of active quench heaters
    - Integration with existing cryostat starts at conclusion of Step IV running
    - All required superconductor is on hand (enough SC is in FNAL storage to wind 2 new cold masses)
  - Schedule
    - Cold mass fabrication could start as soon as revised drawings approved.
    - Budgetary quote from Al forging vendor indicates 10 week delivery.
    - With SC on hand, new cold mass could be machined, wound and outfitted before August 1, 2016 (preliminary estimate of 8 months)
    - Potentially could be cold-tested/trained in dewar in advance of August 1, 2016 (a realistic schedule needs to be confirmed)
      - Could also be carried out while magnet disassembly under way
    - Final Installation
      - Installation of prepped cold mass would likely save ~2 months in baseline disassembly/reassembly schedule for magnet (vs. slide 8)
      - A trained cold mass would likely save ~3 weeks in training time (vs. slide 8)
      - <u>Consistent with completion before end of US FY17</u>

# Potential Technical Paths Forward

- Option 2 (cont'd) – Fabricate new cold mass
  - Cost
    - ***Very preliminary*** estimate of $500K to prepare a new cold mass with SC on hand
    - Would we want to wind 2 cold masses as risk mitigation???
    - Would still require most of the $700K base cost estimate to disassemble/reassemble the magnet
  - Risk
    - A chance to address identified risks with minimal modifications
    - Testing before installation would provide certainty – however, only one chance is realistic unless 2 bobbins are prepped
    - Opportunity – Potential reduction in training costs (save ~$150K)
    - Opportunity – Possibility of retrofitting existing SSD cold mass as a spare after SSD repair complete

# Potential Technical Paths Forward

- Option 3 – Do **NO** repair and instead insert



# Potential Technical Paths Forward

- Option 3 (cont'd)
  - Assumptions
    - Magnet can handle longitudinal forces of cooling channel
    - Magnet cryostat can be modified for integration into cooling channel
    - Magnet bore is sufficiently large
    - Magnet cooling can be managed in the RAL Hall
      (Is there a magnet available which can be operated without a refrigerator system? – none available at RAL right now)
  - Schedule
    - One year to prep magnet
    - One year to prep PRY modifications
    - Installation should be fast
  - Cost
    - Would require further modification to the PRY extension
    - Would require additional design and fabrication work to integrate the new magnet
  - Risk
    - Modest as long as both SSU and SSD operating reasonably thru Step IV
    - (SSD in it's current form would remain; M2 has 1.3kohm resistance to M1/ground)

Possibilities: ~~MuCool Test Area Magnet~~; new FC

# Potential Technical Paths Forward

- Option 4 – Cut SSD open (through vacuum vessel, sheild, cold mass) and repair
  - Assumptions
    - Would require acquisition of used refrigerator because thermal losses likely to exceed what could be handled with cryocoolers
    - Would require modifications to work with refrigeration system
  - Schedule
    - Relatively fast assuming that refrigeration system could be installed/ commissioned during Step IV running
  - Costs
    - TBD
    - Utilize surplus refrigerator system to control overall costs
  - Risks
    - Not clear that this could be done safely without damaging the cold mass support structure

# Potential Technical Paths Forward

- Option 5 – Construction of new SS magnet
  - Assumptions
    - Would allow for implementation of (some) lessons learned
    - Would not allow for a major change in configuration to a more reliable magnet style (e.g. high current SC cable with refrigerator)
  - Schedule
    - Difficult to imagine a scenario, with proper contingency assessment, that could deliver a magnet in time
  - Costs
    - Difficult to imagine a scenario where costs would not be significantly higher than a simple repair
  - Risks
    - Depending on scale of modifications from present design, would require an entirely new test program

# Committee Initial Comment

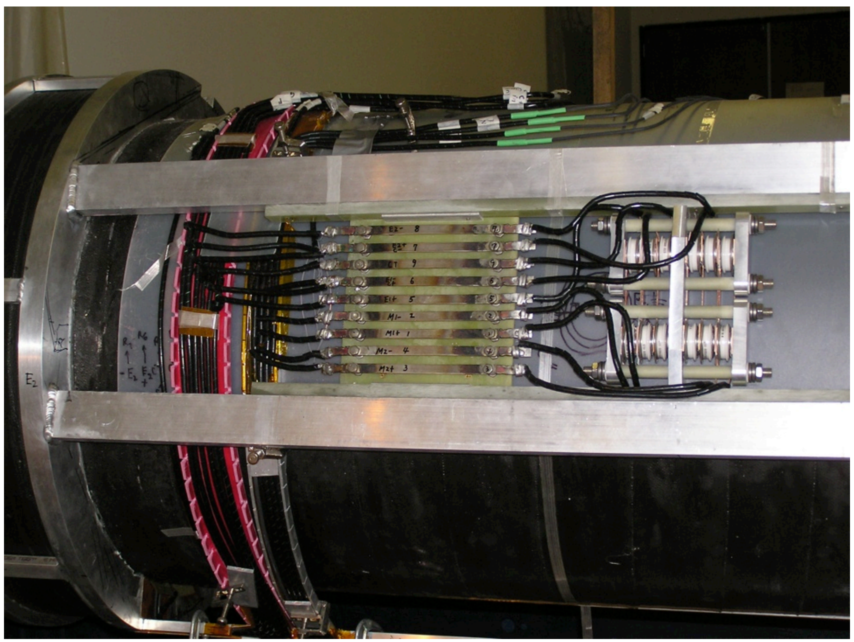
- Options 4 and 5 do not appear viable for technical or funding issues.
- Option 3 requires more beam physics studies for starters and complete understanding of hall interfaces
- Option 1 looks least expensive (?)
- Option 2 buys some schedule and potentially better performance of one of the installed SS

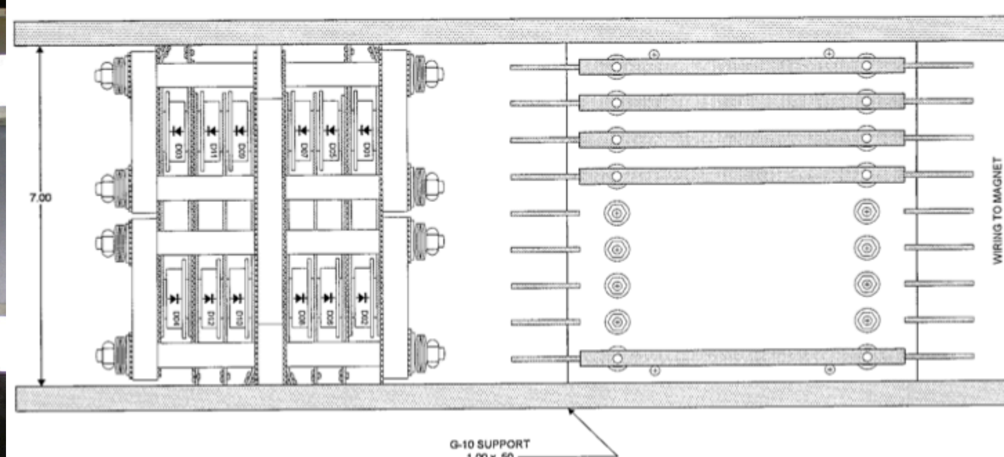
# Committee Initial Comment

- MICE collaboration has done considerable work in the past month to understand problem
- While the SS probably includes a basic design problem, the assembly was tested sufficiently to assure some confidence
- The failure may have resulted from not having a clear understanding of the actual margin in the SS concerning quenchback and the integration of the SSD with the overall power supply / system and having M2 not powered
- Step IV appears achievable with minimal incremental risk
- Beyond Step IV there are several options (2,1,3), though at most 3 look viable and deserve further review over the next month (noting that 2 and 1 are closely related).
- We look forward to more detailed discussion Nov 23-24

# Protection circuit: diodes+resistors

- >3V forward voltage drop  (needs to be measured cold)
  - Forward voltage drop decreases as temperature of diodes increases
- Resistor: strip of Stainless Steel
  - Designed to comfortably support bypass current during “normal” quench decay (~6s)
  - Temperature rise during ~6s decay is <~300K





# Analysis

- Quench initiated on ECE and initially proceeded normally
  – There is no evidence that any LTS leads were involved initially
- At ~ 20 sec, the internal QP for coil M1 failed
  – The voltage on the coil increased rapidly and, it appears that an arc at the LTS power feed through (from vacuum to LHe volume) occurred which burned out the lead and effected M2 (the power leads for M1 and M2 utilize the same 4 pin feed through).
- What caused the QP failure?