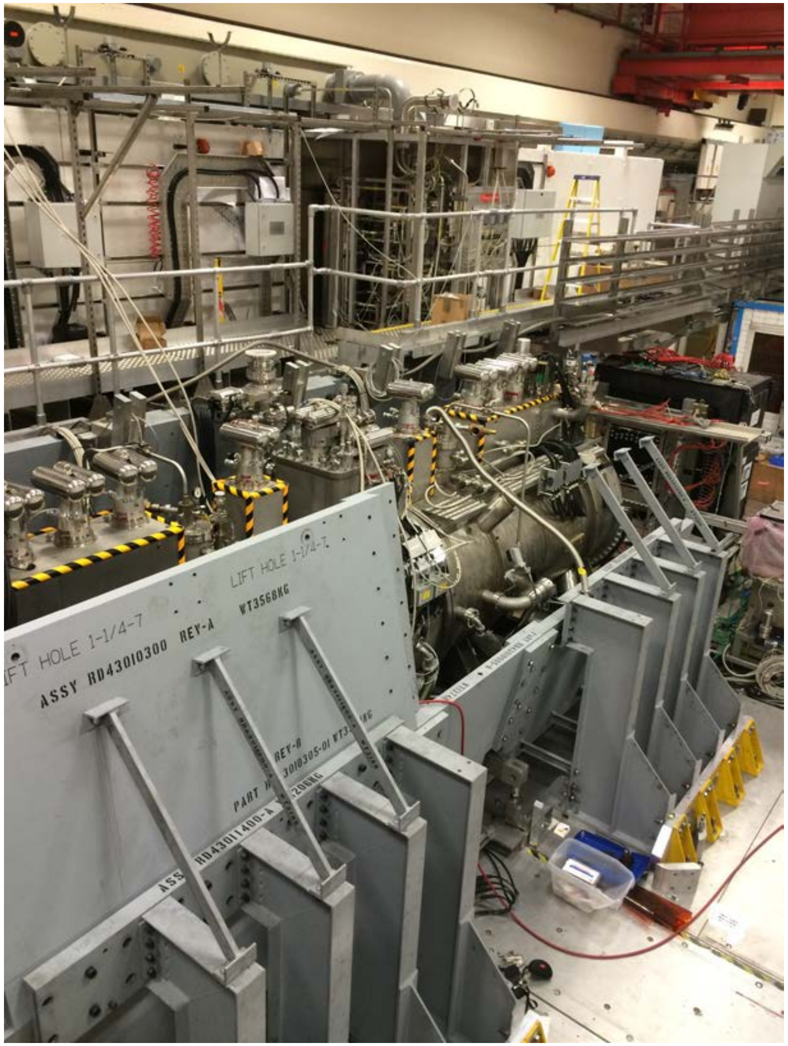
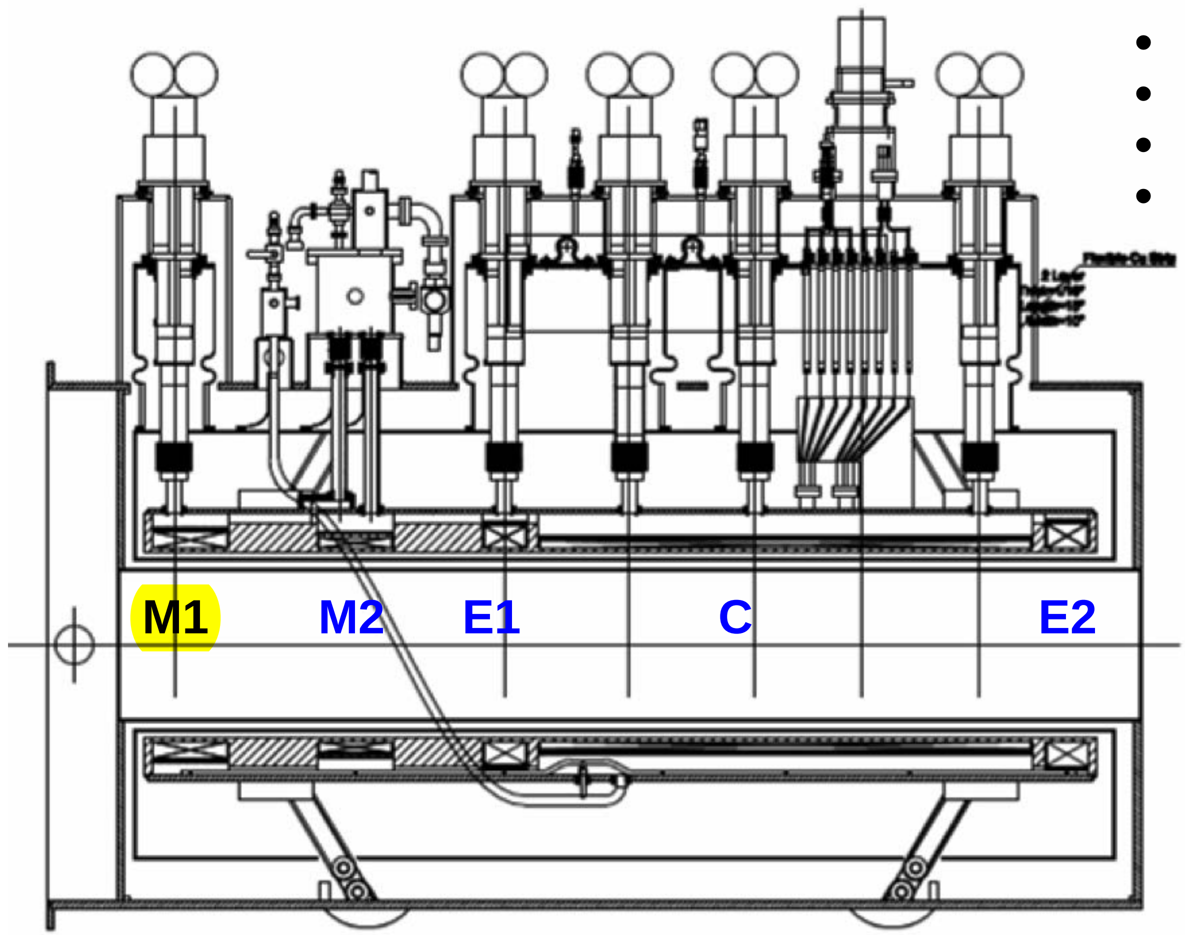
MICE Spectrometer Solenoid Repair



MICE Spectrometer Solenoids

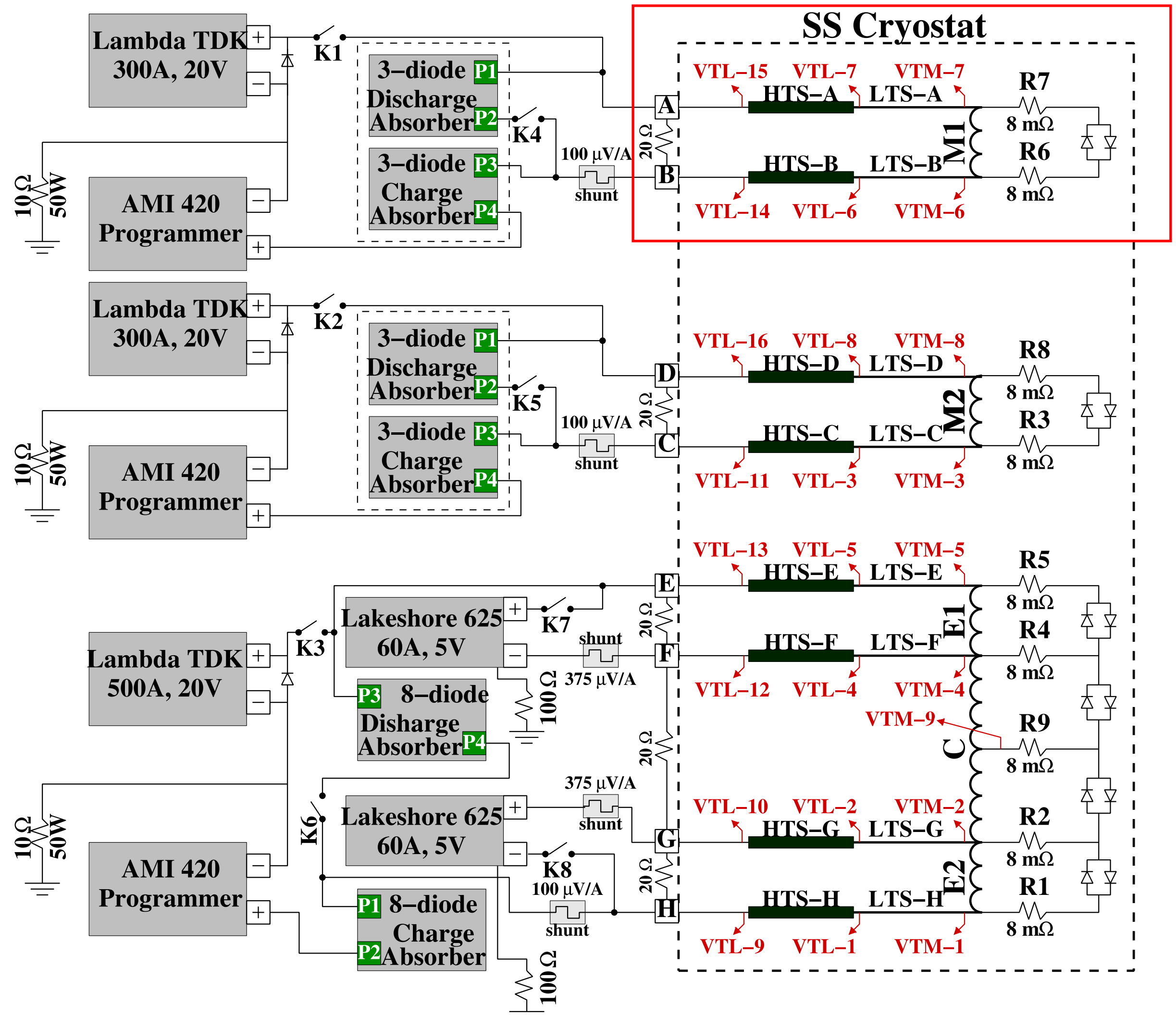
- These magnets have had a long history and I will make NO attempt to review it in any detail here.
  - Steve and Soren will fill in some of the details
- Both magnets met the full specification at the vendor and were fully mapped.
  - Cryogenic operation was very good. Both magnets had significant cooling headroom (SS2 more than SS1)
- SS2 (in upstream position of the beam line – SSU) has reached full operating current at RAL, but full training (soak, solenoid mode) has not been completed.
- SS1 (in downstream position – SSD) had a lead failure during training.
- What is the optimal path forward?

Reminder: Basic design



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

Power system



Power delivery system

- 2 Vacuum feedthroughs bring power into vacuum space
  - One for ECE, one for M1 and M2
- Copper leads to HTS
  - $IL/A = 3.6 \times 10^6$ A/m
- HTS:
  - HTS-110 500A (M1, M2, C) and 250A E1 and E2
- LTS:
  - Vacuum feedthrough: Proprietary Wang design based on SSC superconductor
  - Inside He space: Cu stabilized conductor

He? liquid or gas?
breakthrough
voltage here ?

Training SSD

- SSD has been a bit problematic at RAL
  - Some vacuum issues
  - Lost voltage tap on LTS lead of M2 coil

vac feedthroughs related?

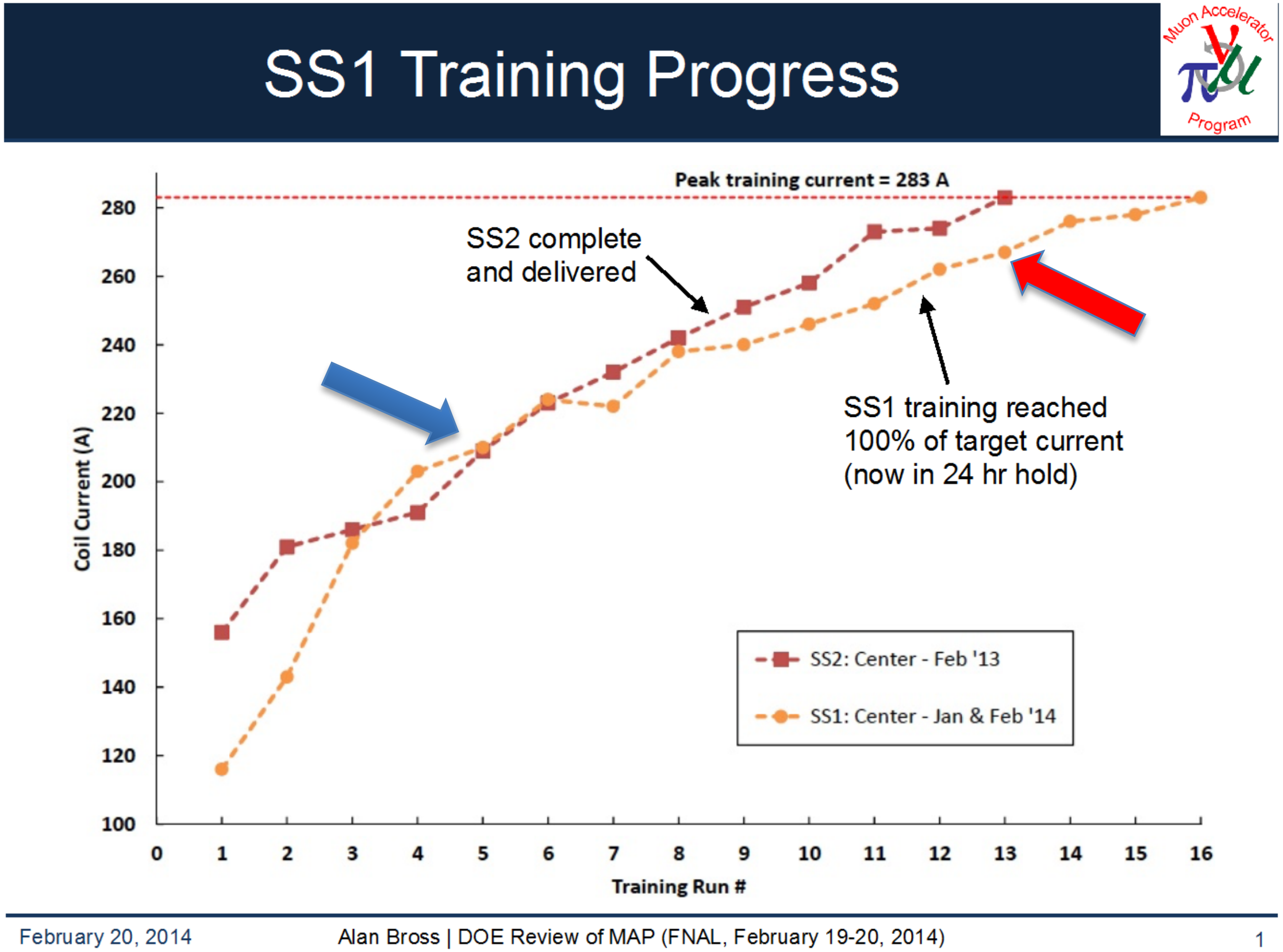
- In the training run of September 12th, 2015 all was going very well.
  - Implementation of additional QP for the M2 lead had not yet been done, so a decision was made to ramp only M1 and ECE
  - A quench occurred at ~ 260A in ECE (much higher than expected, next slide).

M1 only, so status of M2 feedthroughs unknown, any indications?

- QP system performed as expected, nothing outwardly unusual except for the large current.

What is QP on the vac feedthroughs? How protected, thresholds?

Training history



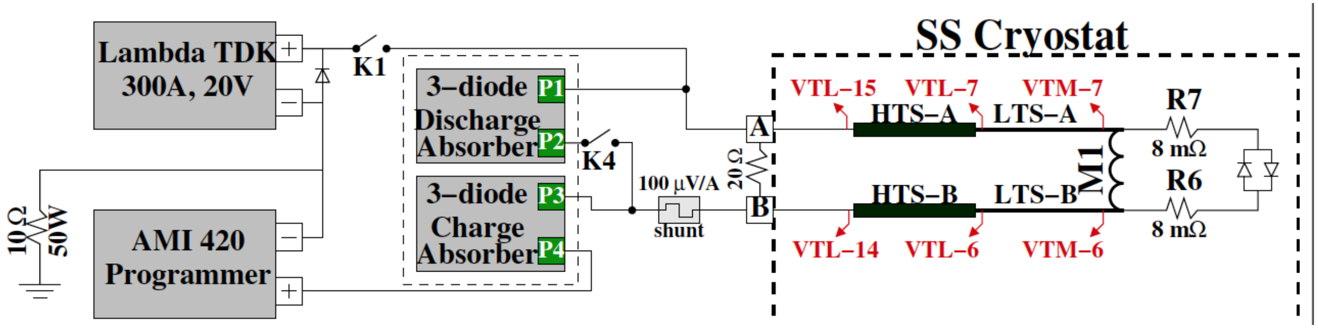
Lead failure

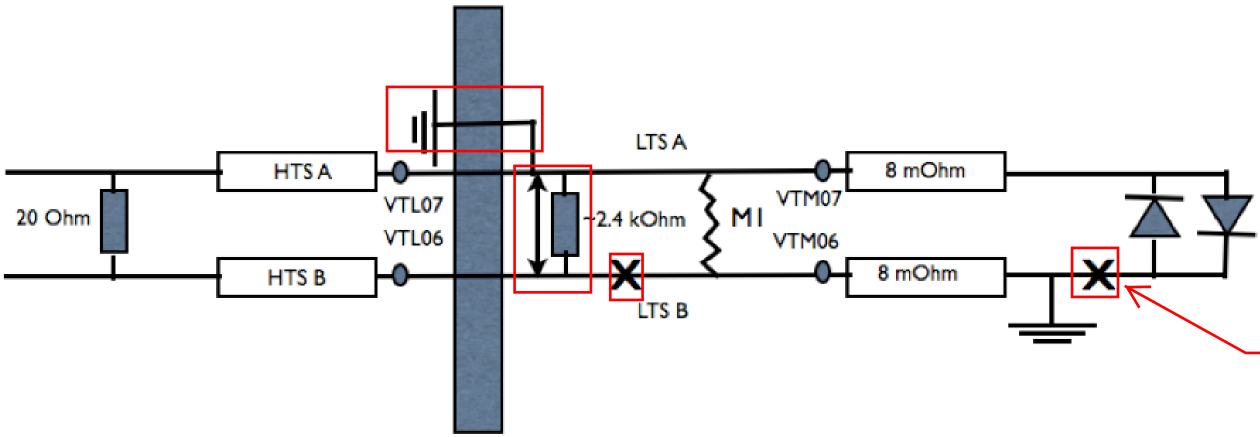
- However, upon entering the hall the odor of burnt FR4/G10 was extremely strong. Strongest at He relief valve
- After a great deal of analysis, it has now been determined that (see diagram on next slide):
  - One leg of M1 dead short to ground. This is LTSA lead.
  - LTSB lead not connected to coil (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).

? what does this mean? coil not tested, how are you sure?

? 2nd feedthrough damaged as well, but how, explanation? apparently

M1 circuit after fault





True picture? is the X in the main lead or in one of the two diode branches?

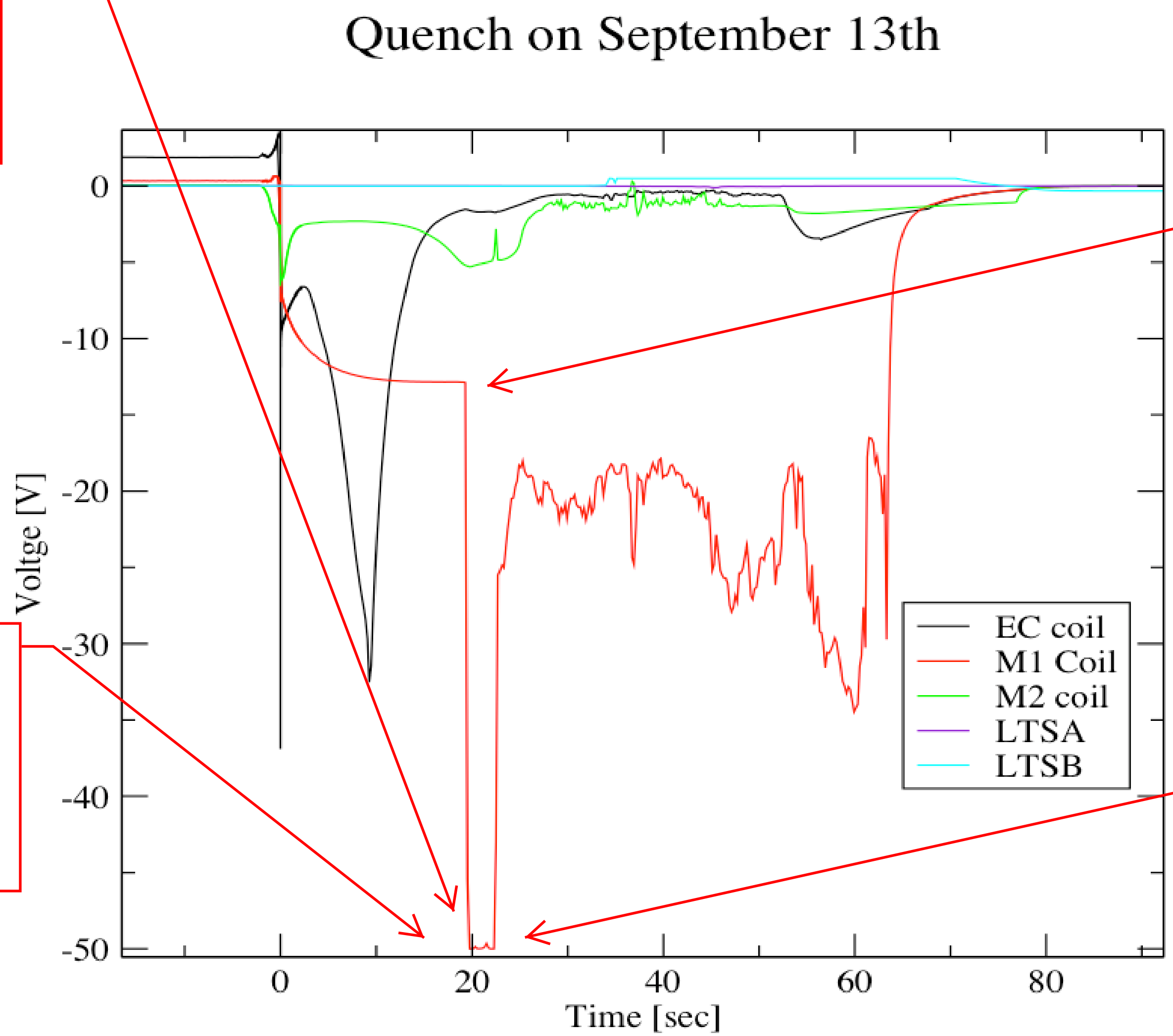
Diagram of the M1 circuit. Resistance (four wire and two wire) measurements revealed:

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.

QP data – M1

I would guess the following: the diode lead burned out first (why) and then a high voltage on the leads caused the breakdown of the feed through area. Do we have evidence, pictures?



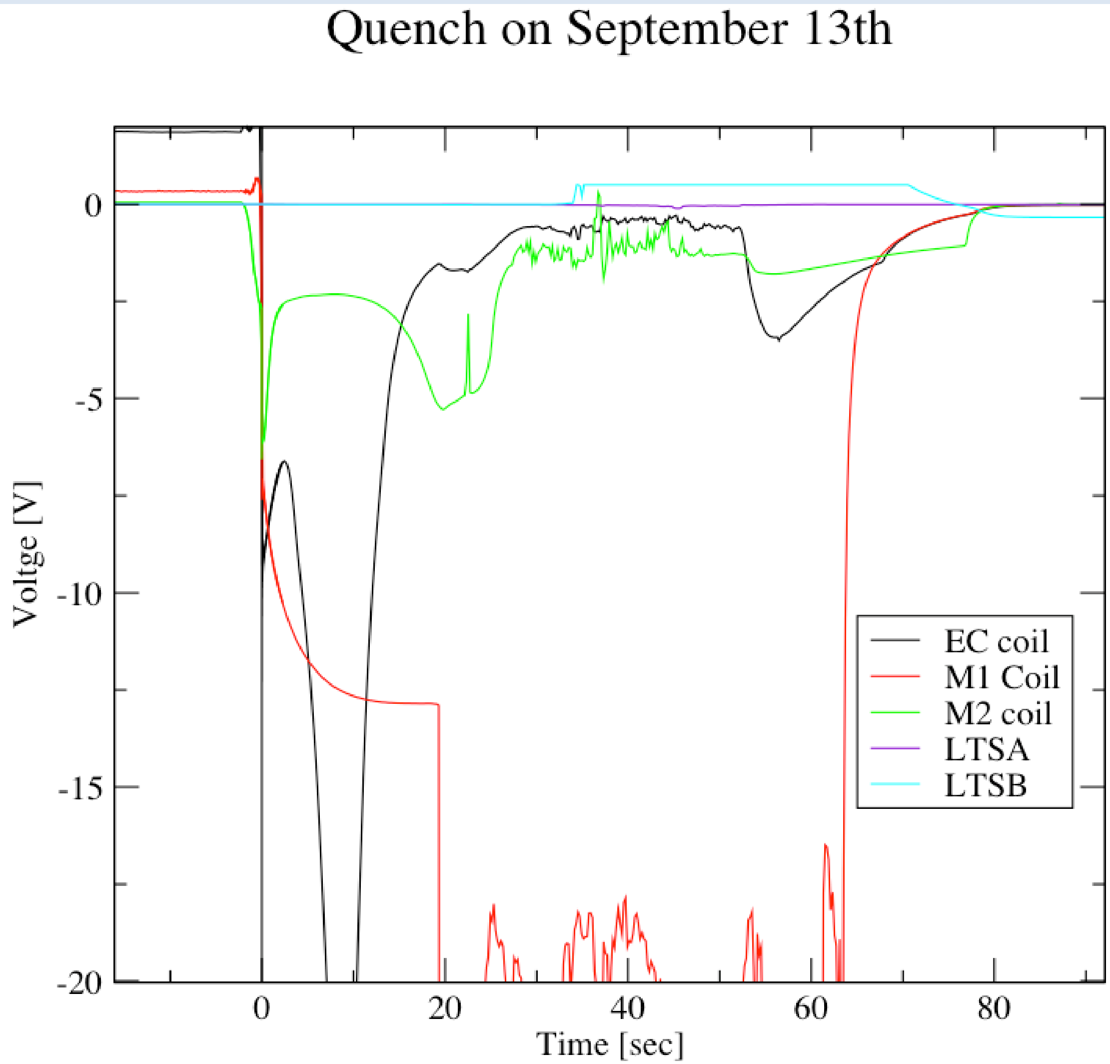
20 s point!

I have no where seen an explanation of the high cause of the high voltage, not explained, or not known, or?

why 50V, real or saturated channel, if so, what is the real voltage? and why?

QP data – M1

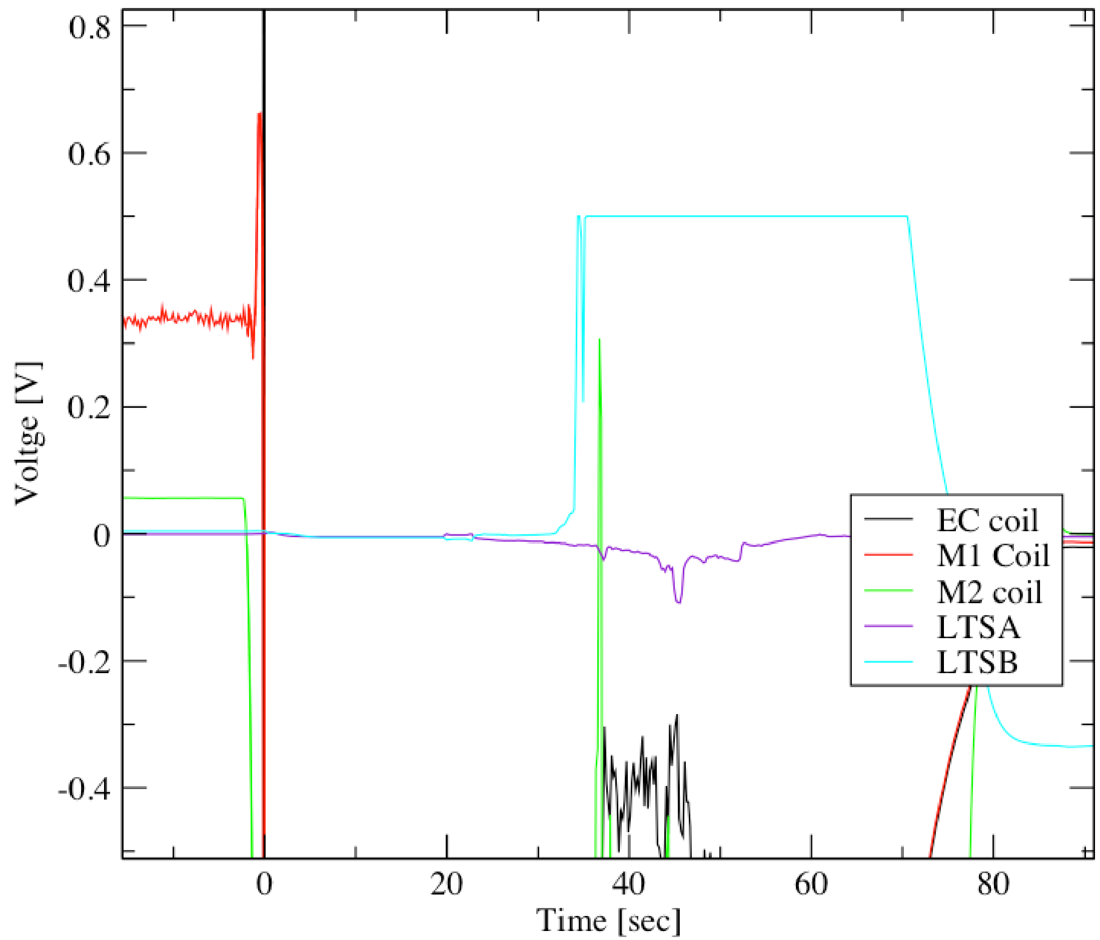
Expanded V scale



QP data – M1

Expanded V scale II

Quench on September 13th



Analysis

- Quench initiated on ECE and initially proceeded normally
  - There is no evidence that any LTS leads were involved initially

? which failure? understood?

- 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).

why did it increase? diodes did not work, disconnected, by what?

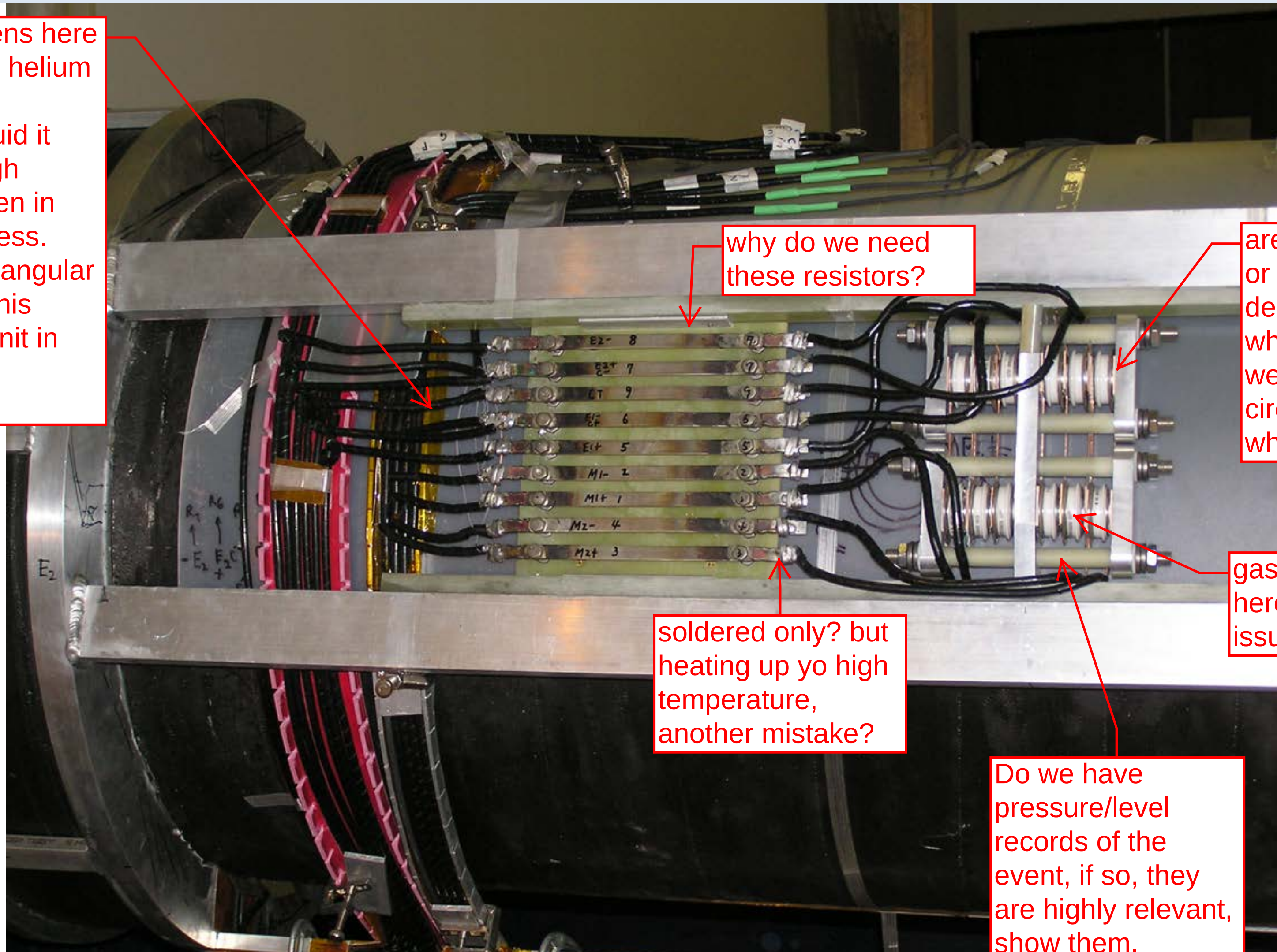
- What caused the QP failure?

= mistake, should not be done!

Internal QP

Original Wang configuration

What happens here with varying helium conditions? When in liquid it can hold high voltage, when in gas, much less. What is the angular position of this protection unit in operation?



why do we need these resistors?

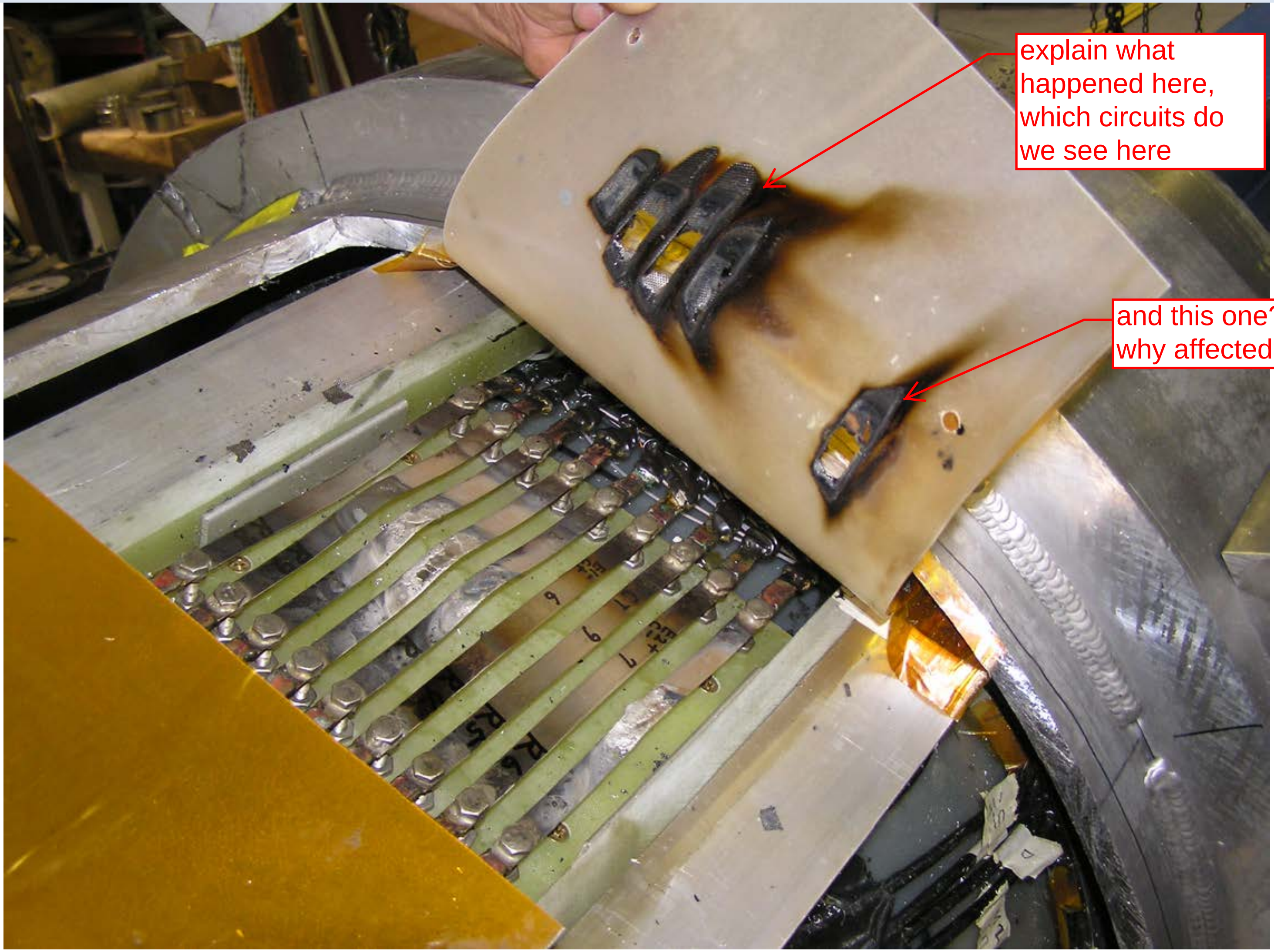
are these in liquid or in gas, or it depends, if so, on what, and what were the circumstances when it failed?

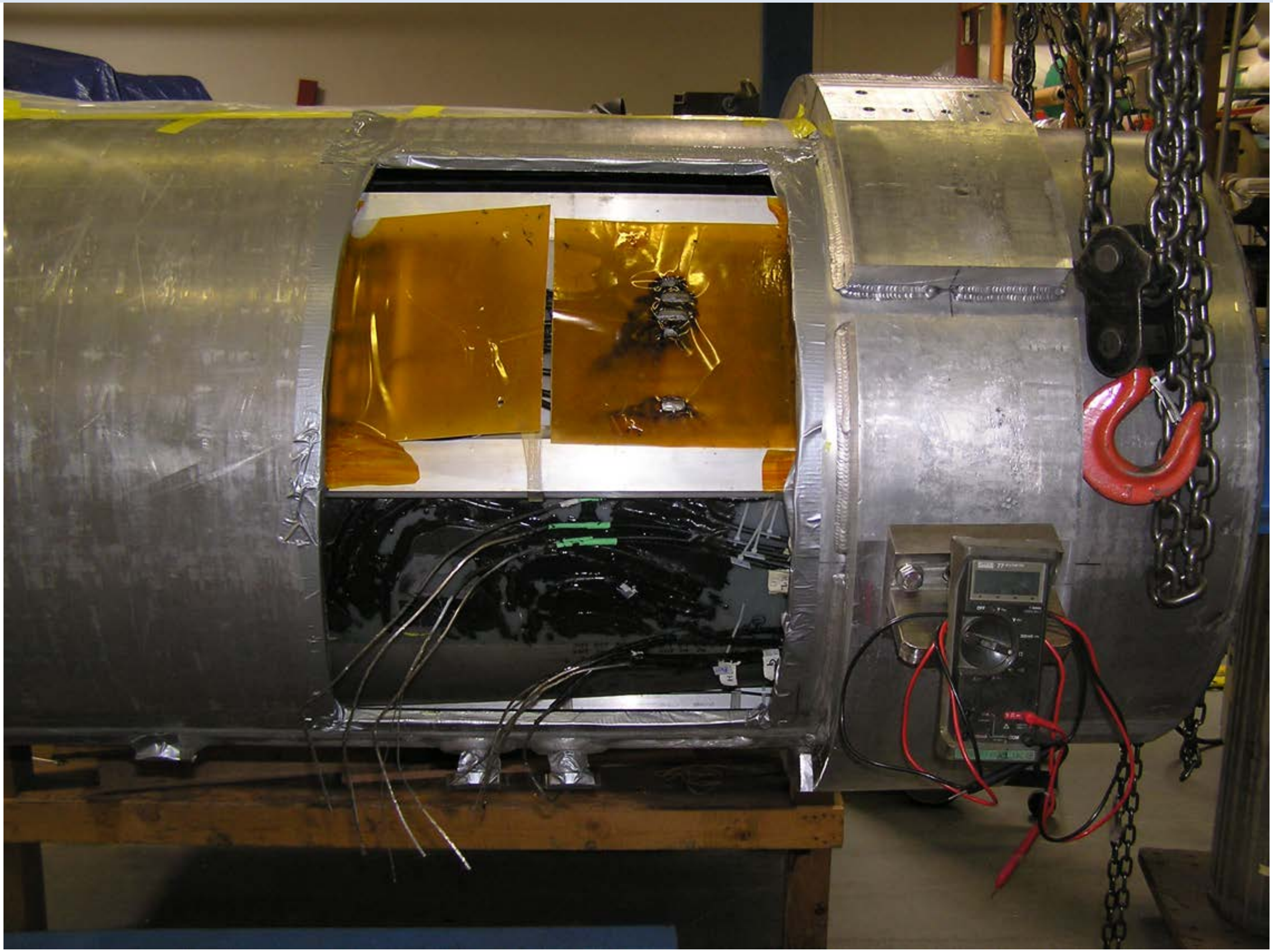
gas environment here? pressure issues?

soldered only? but heating up yo high temperature, another mistake?

Do we have pressure/level records of the event, if so, they are highly relevant, show them.

We have add previous issues



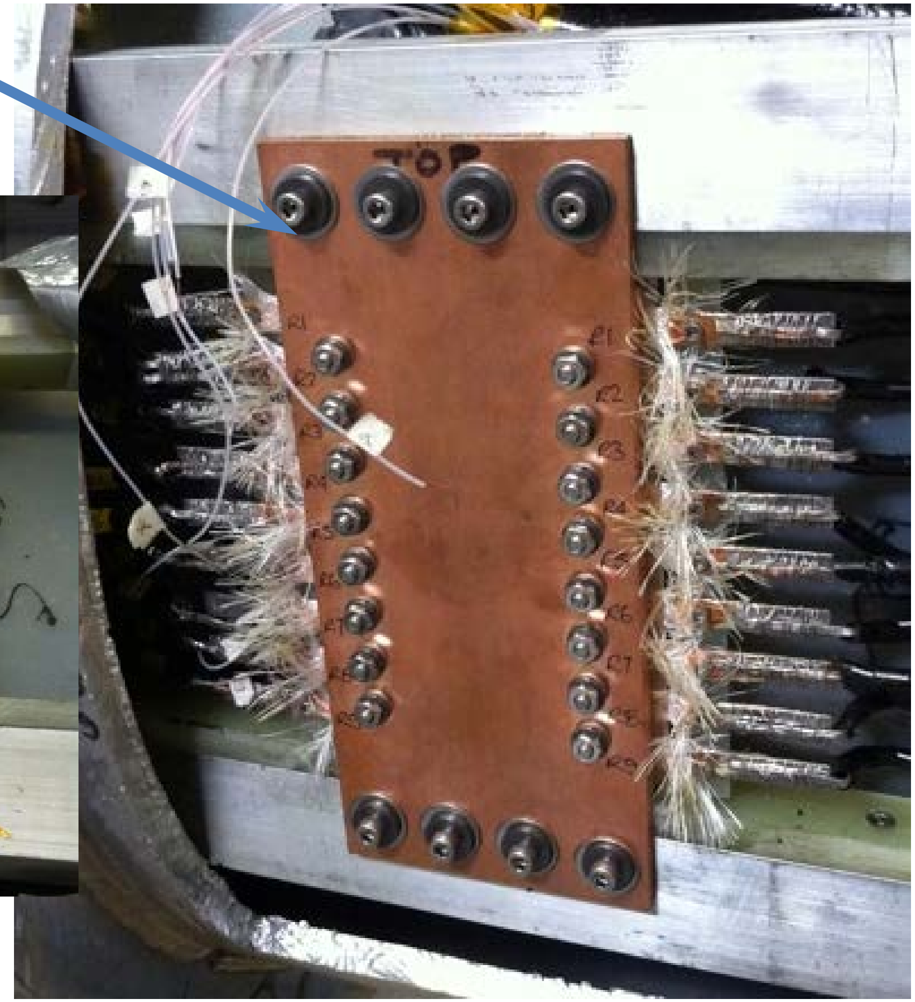


LBNL re-design

Picture of final configuration for SS2/SSU

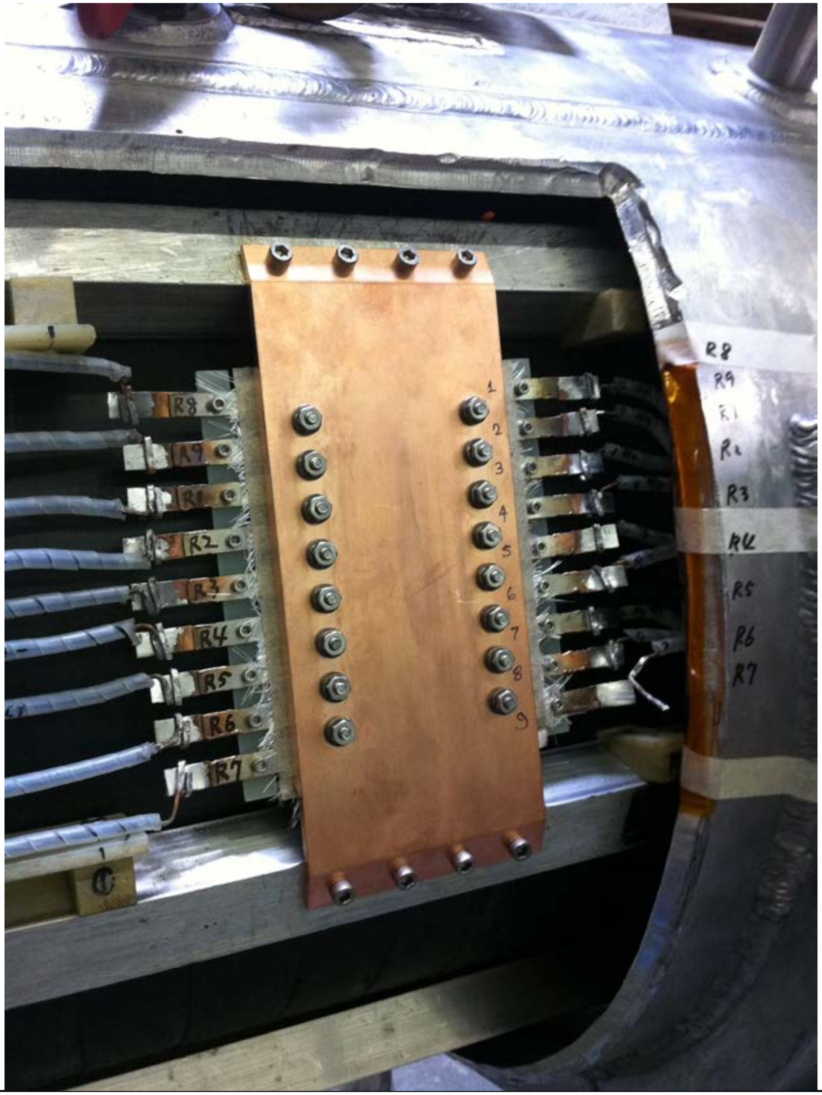
Conductively cooled resistors

Quench protection circuitry

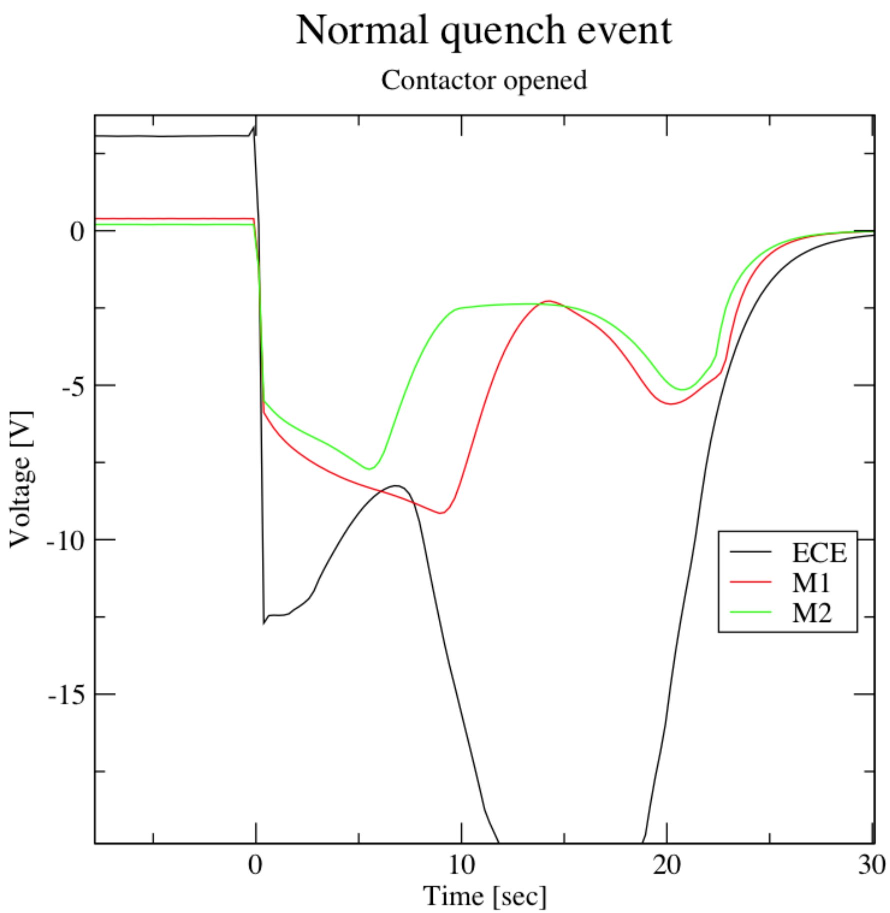


SS1/SSD

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?

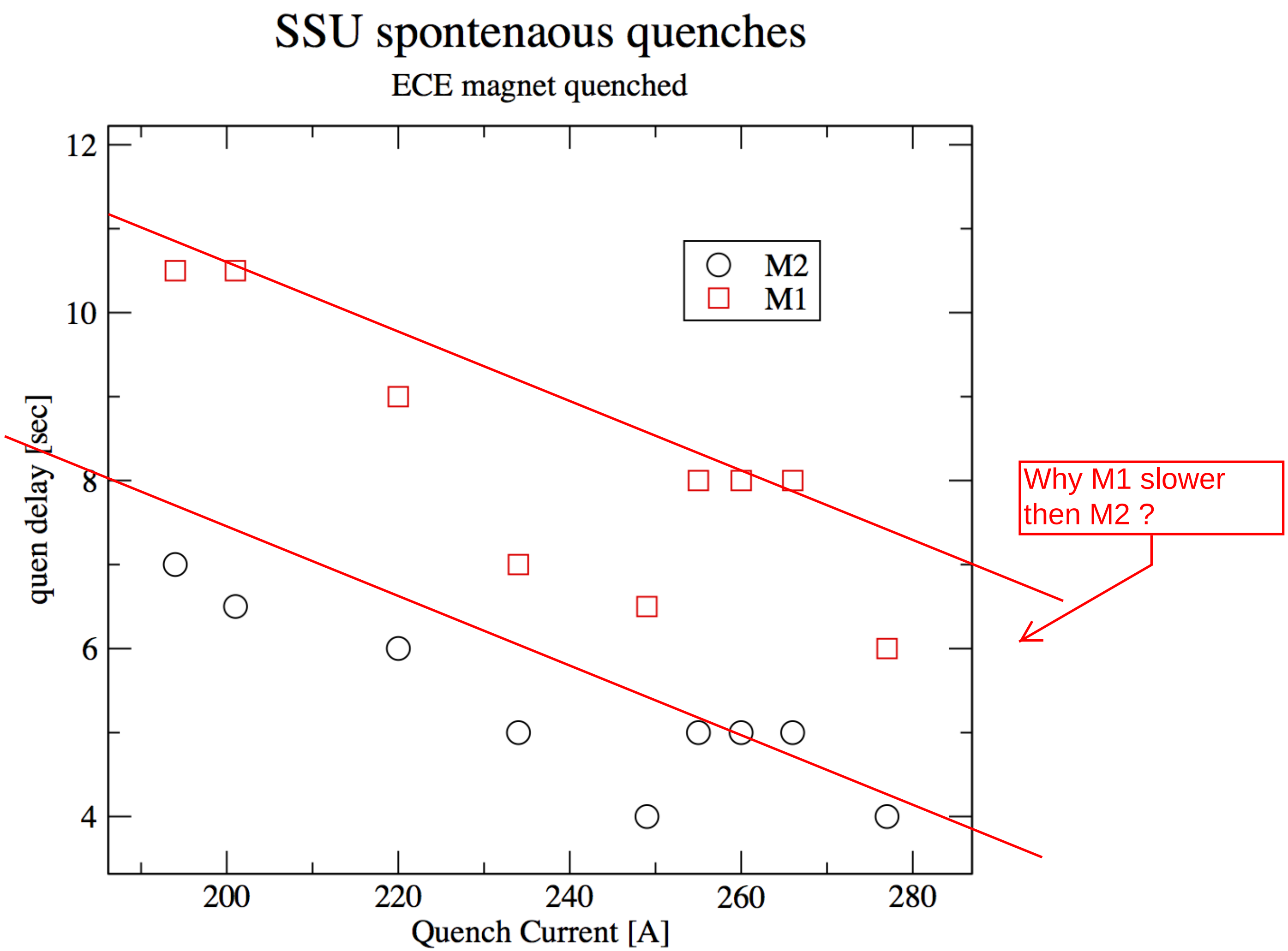


Normal Quench



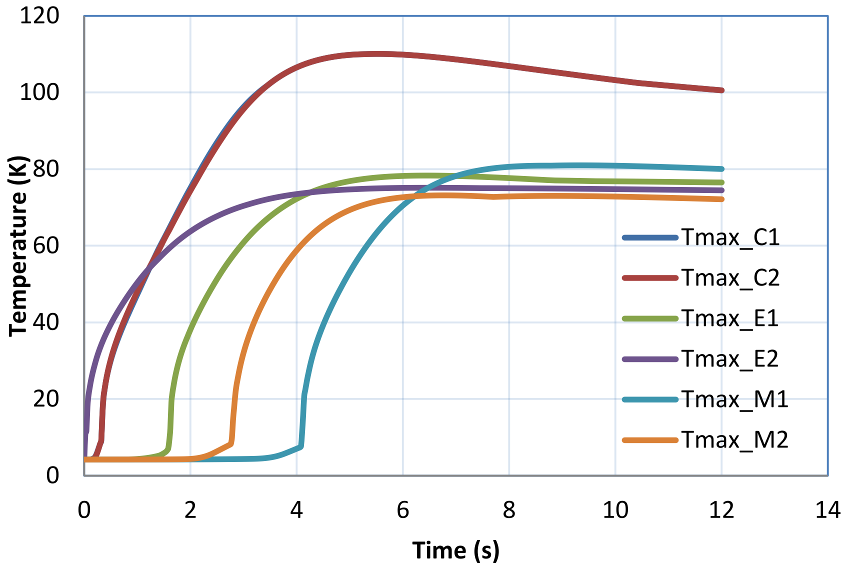
- These are data from a normal quench
  - All coils ramping together to their design current
  - NOTE: In this case, the quench occurred as the currents were ramping down
- ECE initiated the quench (QP system detected and sent trigger to open contactors)
- M2 followed, then M1
  - As predicted.

Quench delay
M1 & M2

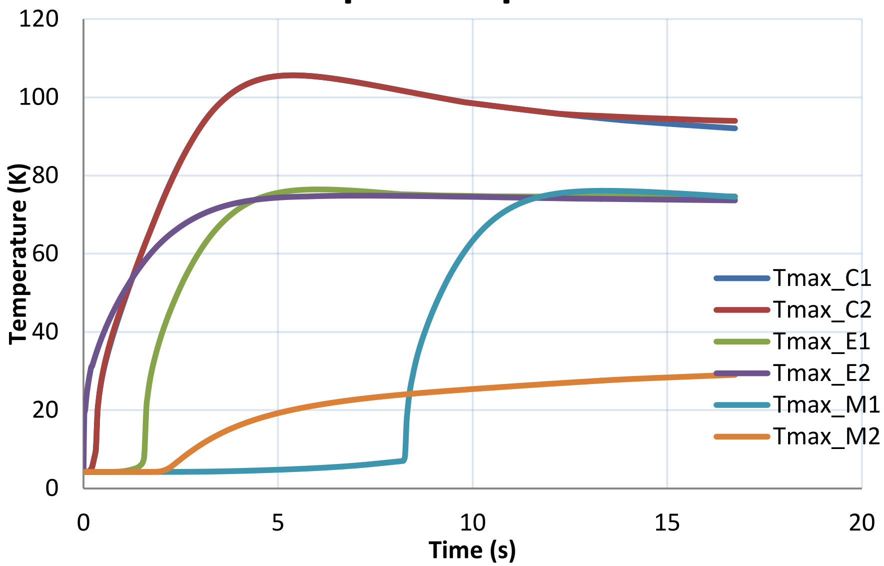


Quench propagation analysis without M2 powered

Case I
Hot Spot Temperature



Case II
Hot Spot temperature



- Compared the results with (case I)and without (case II) M2 powered.
- Quenches were initiated in E2 in both cases.
- The quench current in case I is 265A in all coils.
- In case II, the quench currents in ECE and M1 are 260A and 250A, respectively.

Quench delay

- Time to Q for M1 increased by ~ 2X
- However, overall scale in simulation does not agree with data
  - There is a qualitative understanding
    - LHe & gas not modeled exactly
    - The thermal properties of the mandrel + insulation between coils and the bobbin are not precisely known
    - The starting location of the quench will affect the heat propagation from the hot spot to the mandrel, this will cause time difference. The model is always set so that the innermost layer initiates the quench.

Is NOT the worst case! = in a lead, coil entry!

- Given the above, there is qualitative agreement:
  - The quench delay of M1 increased by ~2X, from 10 seconds to 20+ seconds.

Moving Forward

- Can obtain lattice to allow MICE Step IV running without SSD M1 coil. However, limits momentum scan
- Harder when RF is added
  - Impossible?
- However, risk that a M2 lead will fail must be considered high at this point
  - M2 has been powered at low current (5A) and all looked good.
- Need guidance on how to proceed

Pg. 5: He space is filled with liquid to the ~ 98% level. Leads and QP pack are covered in liquid before ramping and remain so up to the quench. LTS leads and power feedthrough (vacuum to LHe vessel) are always in liquid during normal operations.

Pg. 6: Vacuum issue: Power feedthrough from air to vacuum (Copper leads). M2 feedthrough (vacuum to LHe volume) OK. LTS voltage taps across LTS leads on all coils (one missing on M2) part of QP. Threshold set at < 10mV.

Pg 8: DC and AC measurements on M2 all show normal readings. 5A power test passed. This is extent of testing to date. NO – second feedthrough not affected.

Pg. 9: Yes, data taken indicate that the open is in the position as shown – between diode pack and 8 mOhm SS resistor.

Pg. 10: Scenario: Quench originated in ECE, onsite of quench in M1 delayed due to M2 not being powered; at ~ 20 sec a connection in the diode/resistor pack for M1 failed (open created), with contactors open – no place for current to go – voltage builds rapidly. QP detection system saturates at 50V. Arcing begins. Most likely place is at the He side of the power feedthrough. Arcing continues until ~ 63 sec. No pictures. Have to open the magnet first.

Pg. 13: See page 9 of the presentation. Failure as indicated. Most likely the connection between the diode stack and the resistor (see photo pg. 18 of presentation, lower left – as marked R7).

Pg. 14: Normal running conditions indicate a LHe level that is >= 95% in the upper LHe level sensor. In this case, the QP pack (resistors and diodes) and feedthroughs are always in liquid. In the event of September 13th, the upper LHe level sensor was reading > 98%. QP system was submerged in LHe up to the time of the quench. Yes, soldered only in this case. In the case of SSU, however, the SC lead was attached to the resistor with multiple wraps of Cu wire. See picture on pg. 17.

Pg. 15: Upper 4 burns – M1+/M1-/M2+/M2-. Lower one is E2 (+ I believe).

Pg. 20: M1 always lags M2 (in ECE initiated quenches which occur in > 80% of all quenches). This is the quench back effect and is supported by simulation (multiple simulations). See slide 21.

Pg. 22: Yes, lead quench is worse. However, we have seen no quenches in the leads in final testing at Wang (both magnets) nor in any training run performed at RAL.