Spectrometer solenoid quench protection

MAP review of MICE Spectrometer Repair Plan

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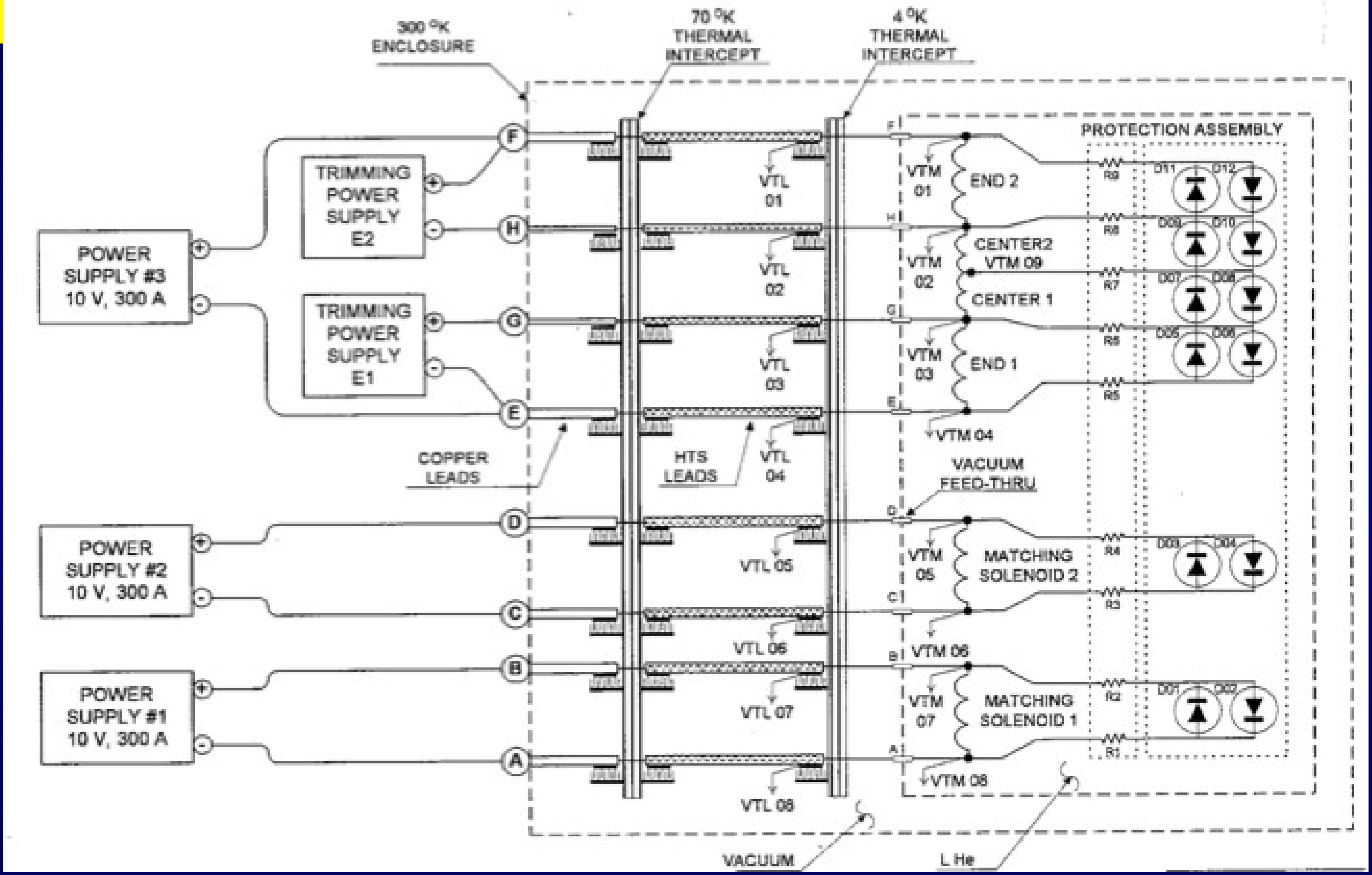
Outline

- Review of protection circuitry
- Review of protection scheme concerns
- Major recommendations from reviewers
- Key protection issues
  - Protection resistors: value and design
  - Voltages seen by coils during quenches
  - HTS leads
- 3D analysis
  - Results and discussion
- Proposed plan

Review of Spectrometer protection ci



Review of Spectrometer protection circuit

- Comments:
  - System as designed is passive
  - No “need” to trigger any circuitry
  - No direct ability to initiate quenches
  - Bypass resistors allow each coil / coil section to decay at their own speed
    - Reduces hot –spot temperatures, peak voltages
  - What we want:
  - A system that protects coils well during quenches (e.g. training)
  - A system that avoids damage to the cold mass during serious faults

Protection circuit: diodes+resistors

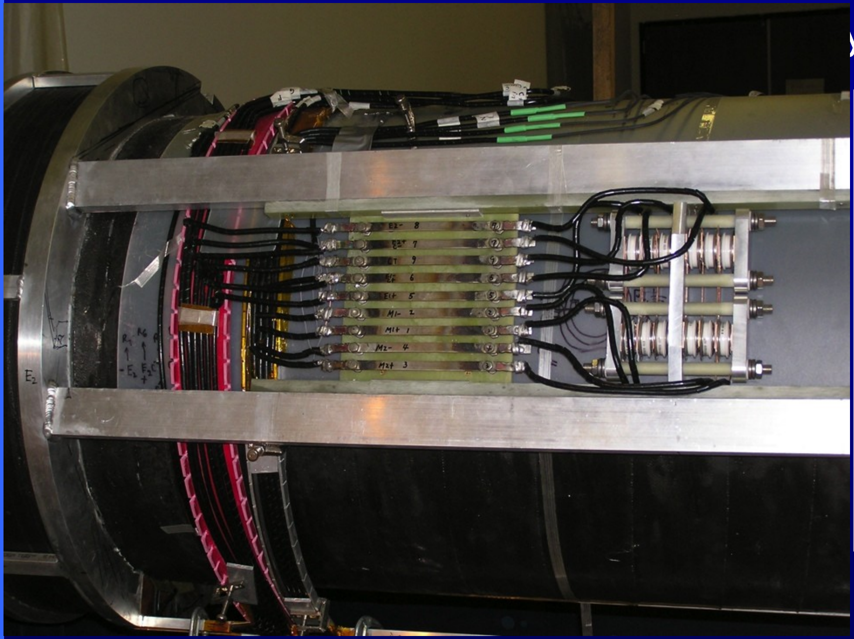
3-5V forward voltage drop (needs to be measured cold)

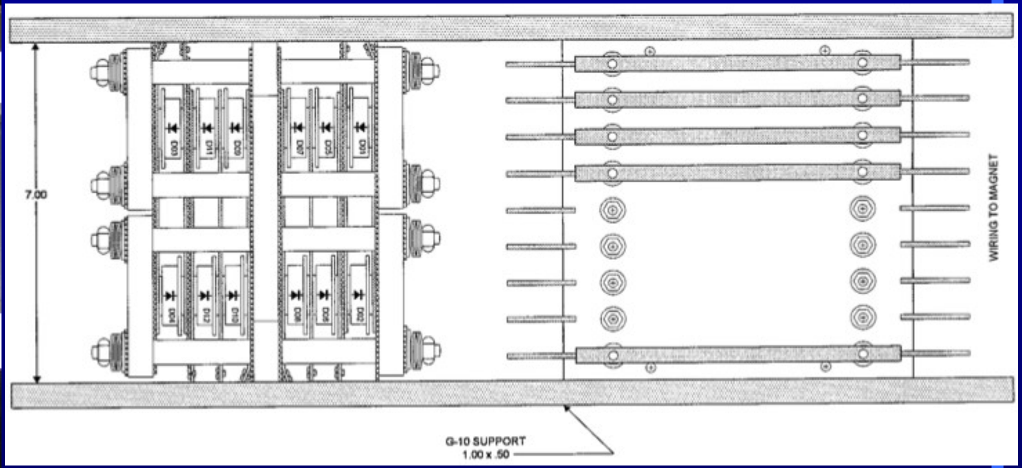
Forward voltage drop decreases as temperature of diodes increases

Resistor: strip of Stainless Steel

Designed to comfortably support bypass current during “normal” quench decay (~6s)

y is <~300K





Review

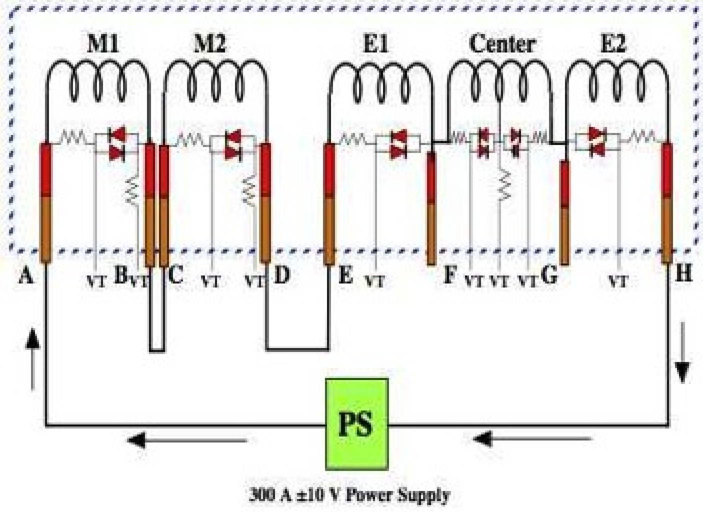
- The review committee recommends:
  - to continue the analysis of the quench protection system, including Coupled transient magnetic and thermal calculations, eddy currents in the Aluminium mandrel, external circuits with shunt resistors.
  - Investigation of different quench scenarios and definition of the hotspot temperatures of coils, leads and shunts.
  - Definition of peak voltages: to ground, and layer to layer
  - Definition of the optimal shunt resistor values for all coils to reduce risk.
  - Definition of the allowable peak operating current to eliminate the risk of coil damage.
  - Measurement of the leakage current to ground for each coil, to check the status of electrical insulation.
  - Limitation of the test current to 200 A until all points above are verified and understood.
  - Design of the magnet test procedure ensuring a minimal risk of cold mass damage.

Protection circuit: test condition example

Circuit with most stored energy

If a quench occurs in E1:

- Current shunts via diode+resistor across E1
- Coil current in E1 decays
- Coil currents in neighboring coils increase
    - Due to mutual inductance
    - Generate bypass currents
- Other coils either…
    - Quench - very likely, due to quenchback
    - Remain superconducting
        - Unlikely except for very low-current quench, when
            - significant margin is available
            - Energy in quenched coil is insufficient to boil off stored helium
        - Current continues to decay due to bypass resistance, but with very long time constant



Limitations of “Wilson code” simulation:

Does not consider mutual coupling and full electric circuit

Does not take into account quenchback from mandrel heating

Does not provide means of determining turn-to-turn or layer-to-layer voltages

Vector Field Quench module:

Provides for mutual coupling and full electric circuit

Provides for quenchback from mandrel heating

Can use “Wilson-code” for validation on simple system (e.g. single coil with no quenchback)

3D simulations

- Material properties are defined
  - Specific heat:
    - Cu, NbTi, Al6061
  - Thermal conductivity:
    - Cu, Al6061
    - Coil effective bulk - longitudinal and transverse
  - Jc(B,T) of NbTi conductor
- Electric circuit for various conditions
  - Allows diodes + resistors
  - Various models have been tried
- Independent analysis from:
  - Heng Pan (LBNL)
  - Vladimir Kashikhin (FNAL)
- Some cross checks highlighted:
  - Importance of mesh (space and time) refinement
  - Some insight into sensitivity (or lack thereof) with respect to properties

Electric circuit definition

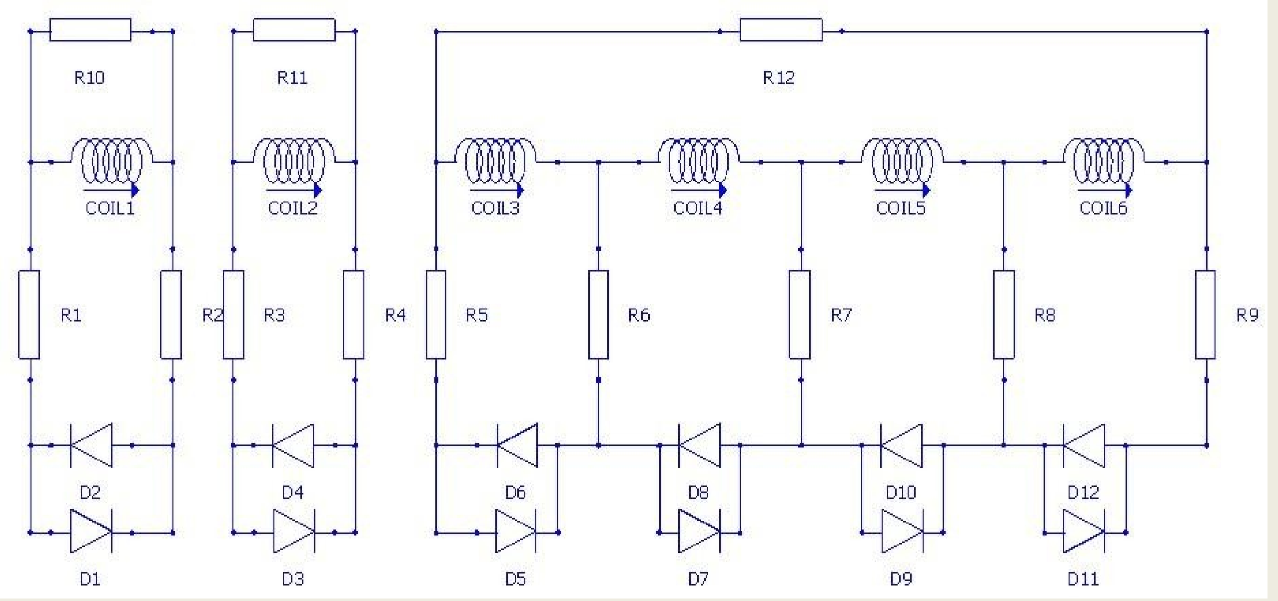
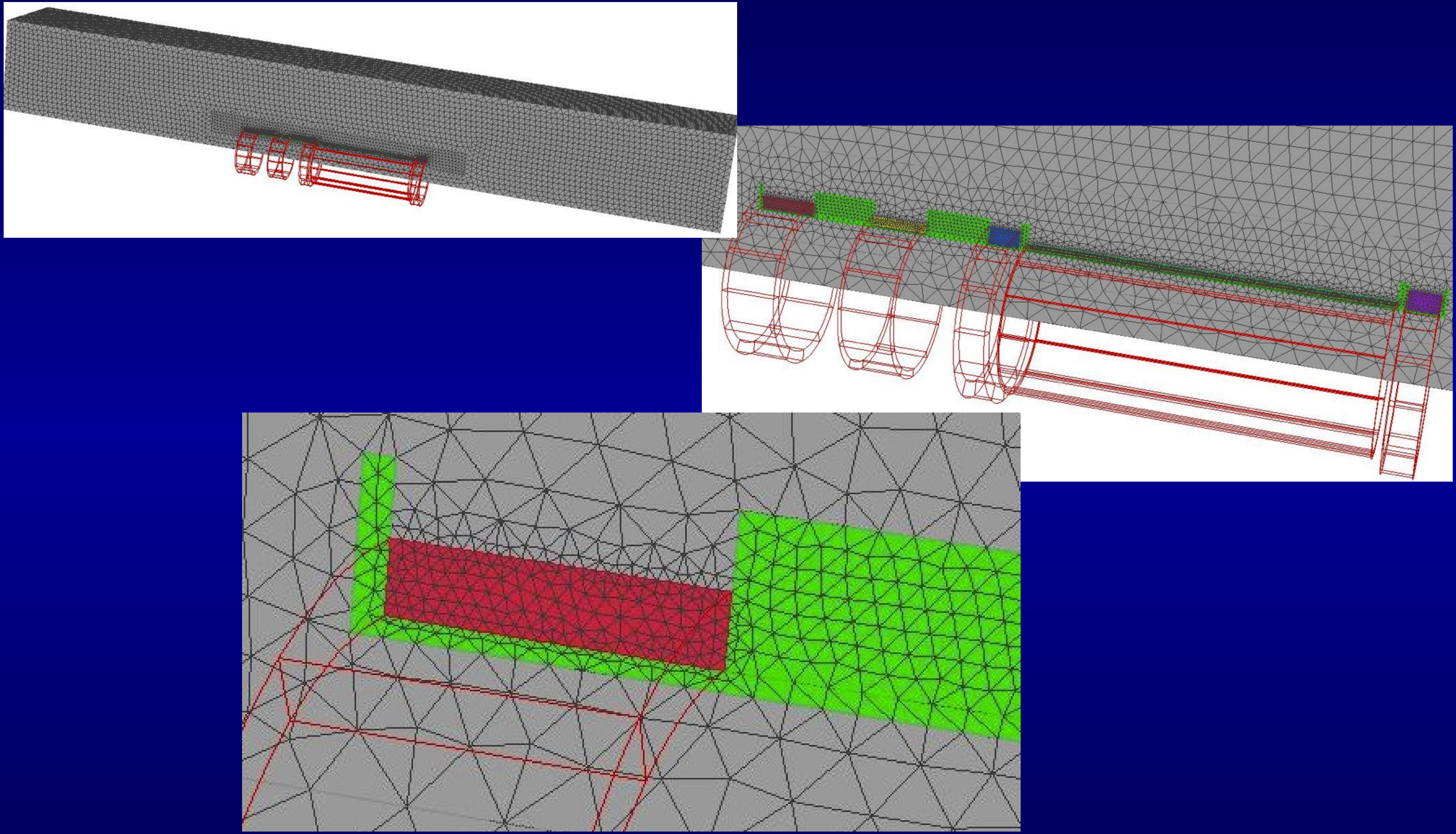


Fig. 9. Electrical scheme for simulations.

Shunt resistors R1-R9 have the resistance 0.015 Ohm, and external resistances R10-R12 are 1.0 Ohm. Diodes D1-D12 has 4V forward voltage.

From Kashikhin

Model mesh (LBNL)



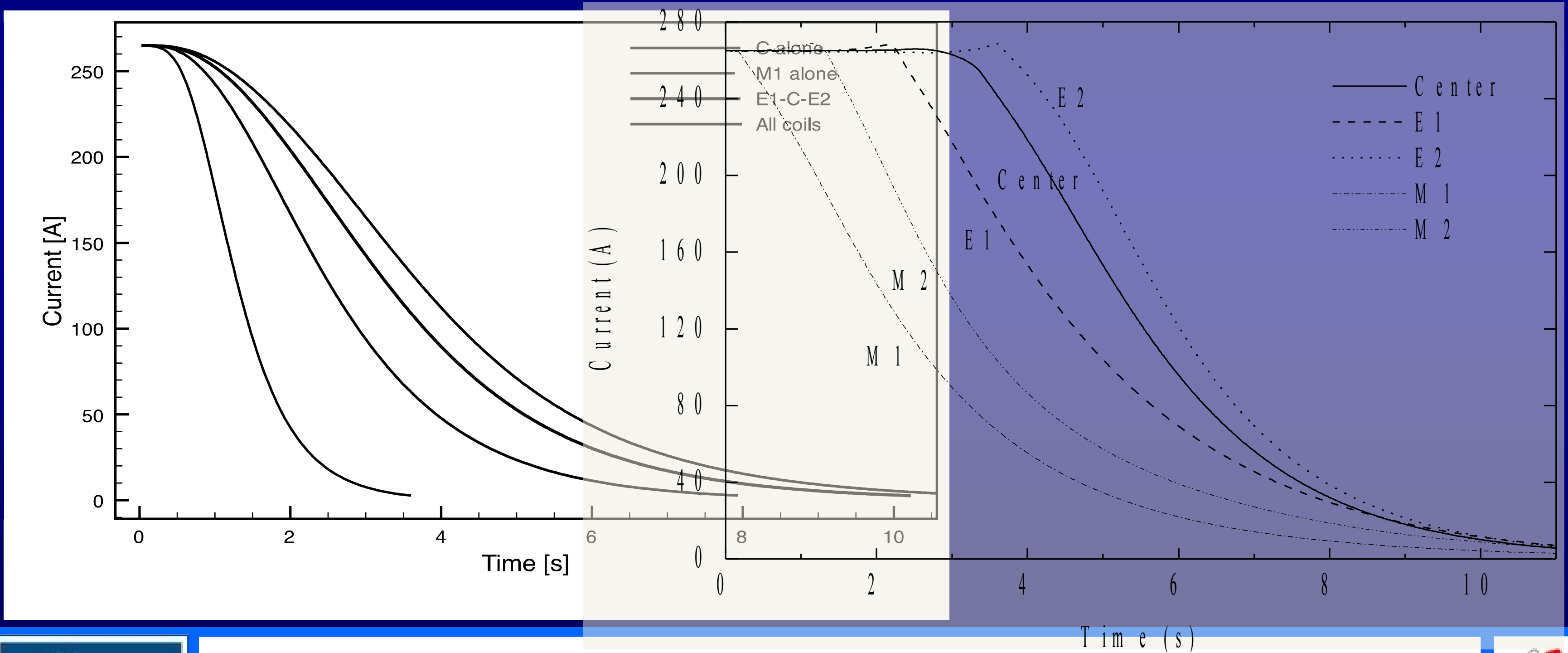
Simulations: validation

Code validation:

Comparison with Wilson code yield reasonable agreement of coil normal zone growth

Wilson code

LBNL VF model



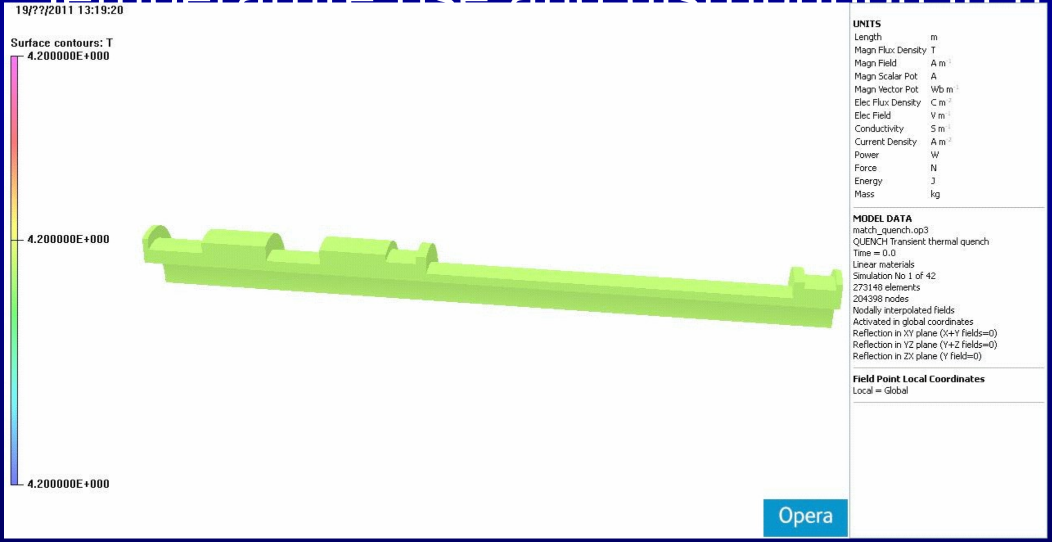
Simulations

Evaluate current fluctuations, decay, voltages, hot-spot temperature throughout circuit:

Dependence on quench current

Evaluate role of quench-back from mandrel:

- Temperature rise and distribution in mandrel during



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Surface contours: T

UNITS

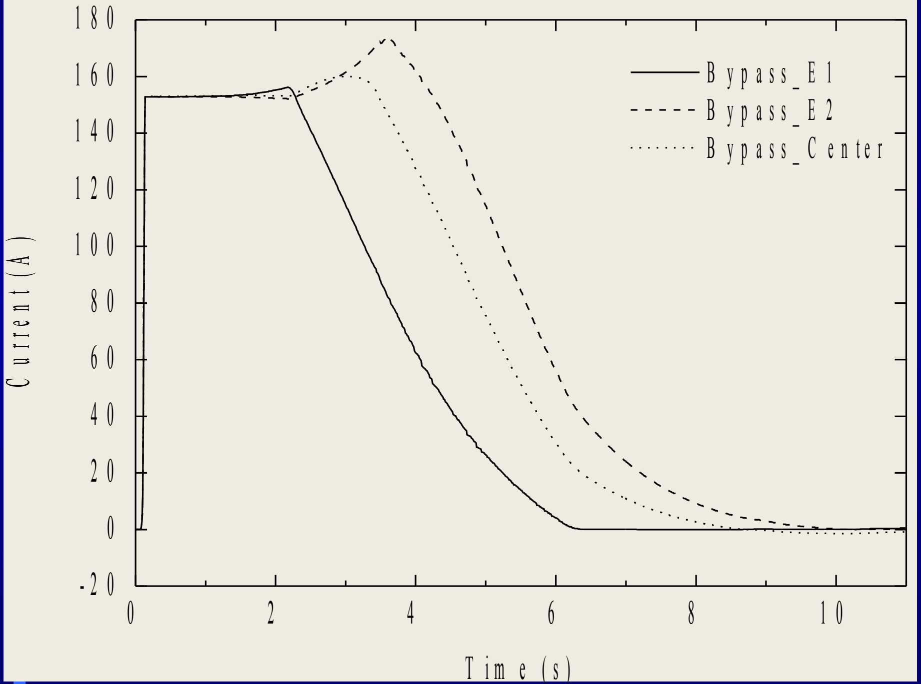
Length	m
Magn Flux Density	T
Magn Field	$A\,m^{-1}$
Magn Scalar Pot	A
Magn Vector Pot	$Wb\,m^{-1}$
Elec Flux Density	$C\,m^{-2}$
Elec Field	$V\,m^{-1}$
Conductivity	$S\,m^{-1}$
Current Density	$A\,m^{-2}$
Power	W
Force	N
Energy	J
Mass	kg

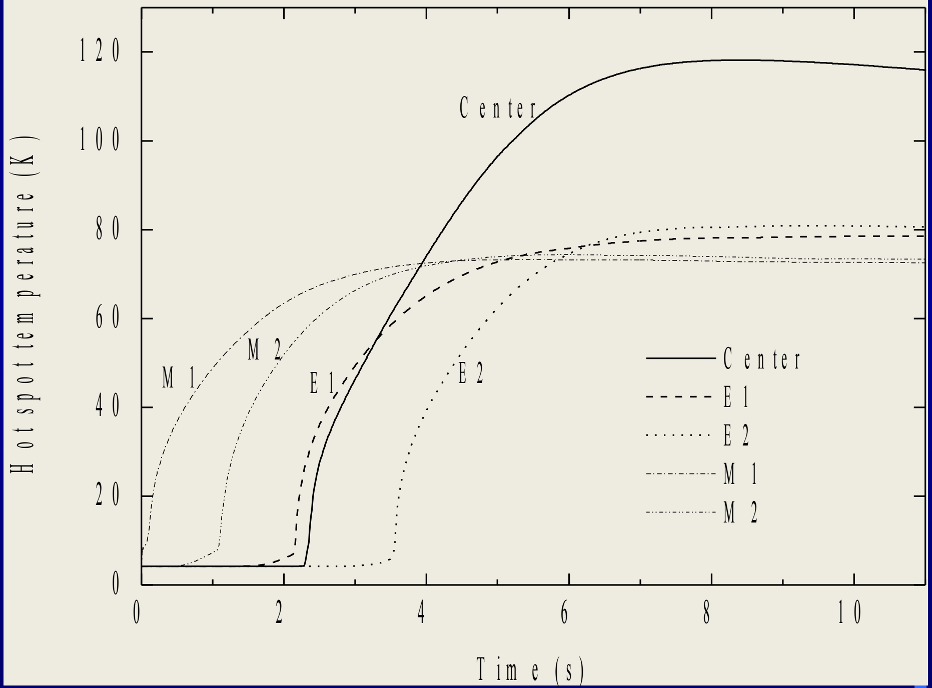
MODEL DATA
match_quench.op3
QUENCH Transient thermal quench
Time = 0.0
Linear materials
Simulation No 1 of 42
273148 elements
204398 nodes
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (X+Y fields=0)
Reflection in YZ plane (Y+Z fields=0)
Reflection in ZX plane (Y field=0)

Field Point Local Coordinates
Local = Global

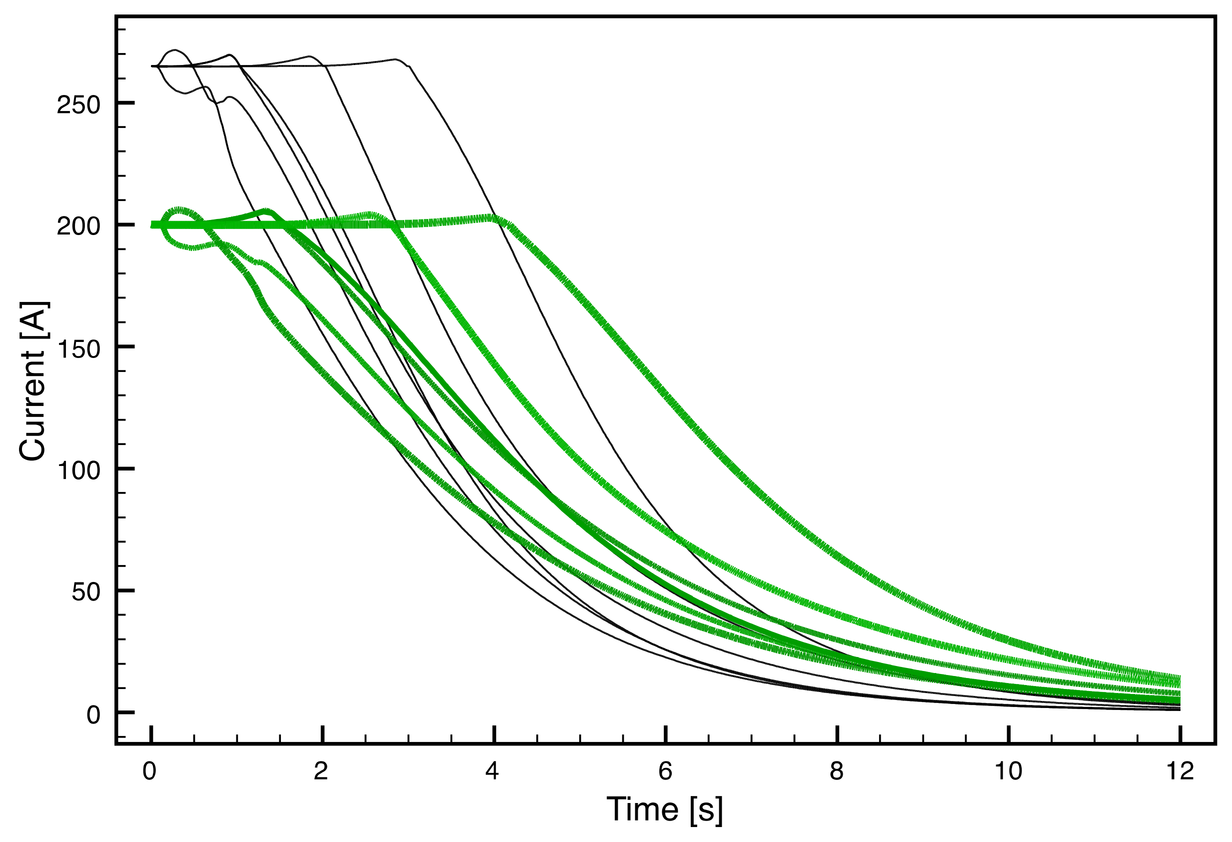
Current evolution for an M1 solenoid quench

265A initial current





Quench Scenarios at Different Currents



Main questions to be answered by 3D simulations:

What are the maximum turn-to-turn and coil-to-ground voltages seen during a quench?

What are the peak hot-spot temperatures under various scenarios?

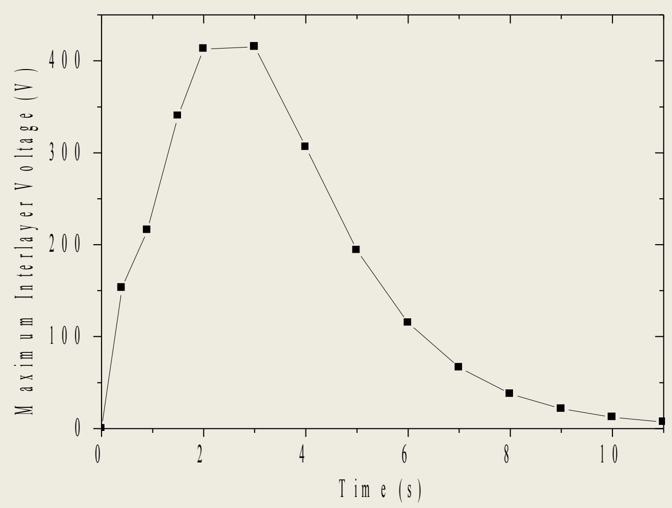
Are there scenarios where a subset of coils quench, but others remain superconducting, resulting in slow decay through bypass diodes and resistors?

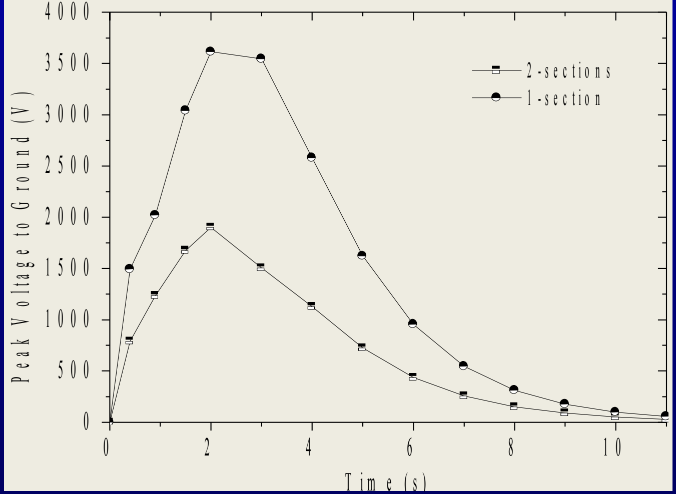
=>What modifications to the existing system should be incorporated to minimize/eliminate risk to the system in case of quench

Results of simulations: Voltages

- Turn-to-turn voltages:
  - Remains negligibly small throughout quenches (<1 volt)
- Layer-to-Layer voltages:
  - Maximum in Central solenoid
  - Reaches ~450V - occur in outer layers!
- Coil-to-ground voltages:
  - Maximum in Central solenoid
  - Reaches ~1.3kV (~2kV resistive)
  - Values are lower than Wilson code
    - Segmentation and Quenchback help

Note: Coil hi-potted to 5kV

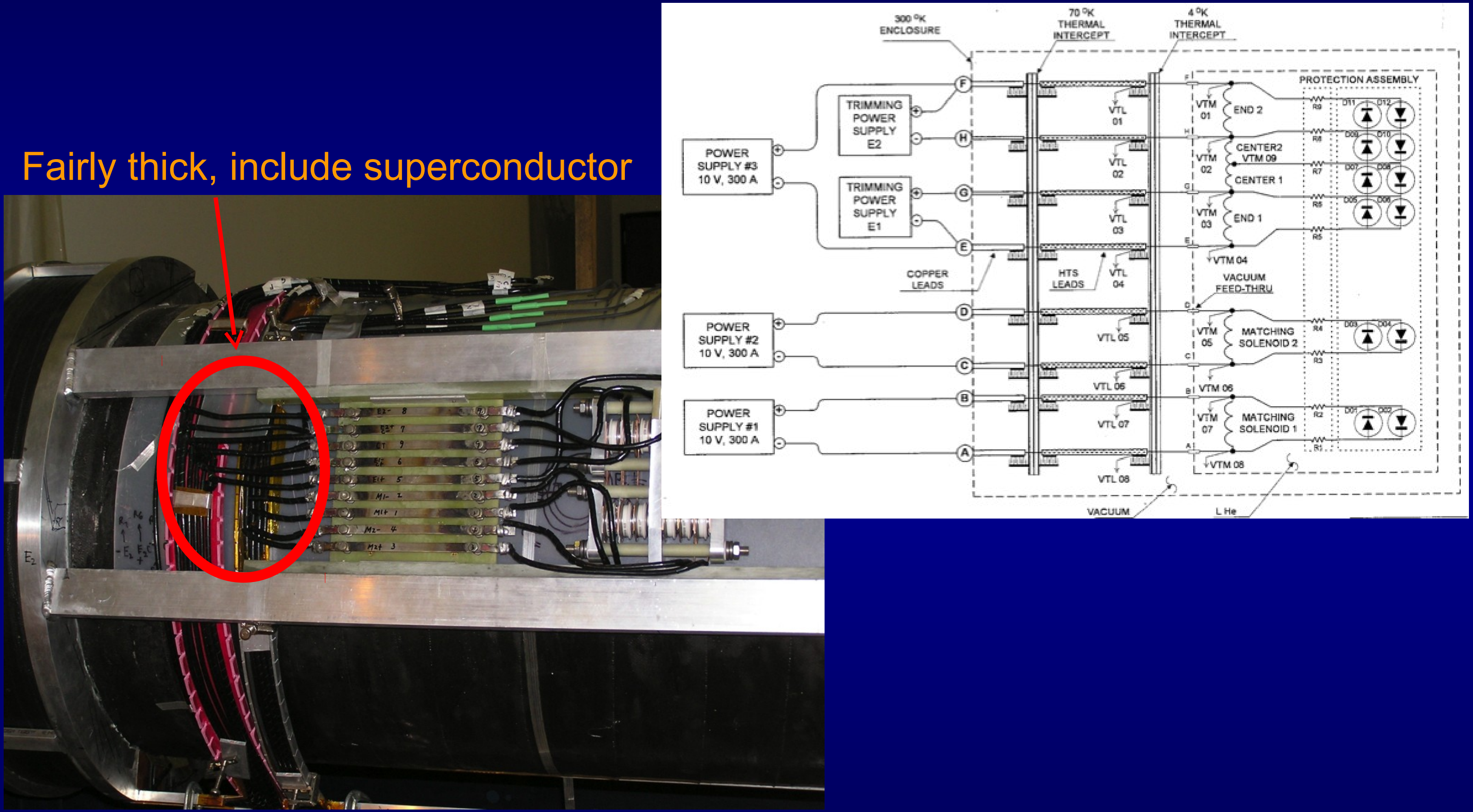




Protection: bypass resistors

- Improved passive protection: general rationale
  - System has survived many quenches
  - HTS burn-out and lead burn out resulted in very high bypass-resistor temperatures
  - No problem has been observed at joint area
- Proposed cooling of bypass resistors will:
  - Lower temperature at bypass resistors (lower driving force)
  - Speed up heating of mandrel => produce earlier “quenchback”
- Issues:
  - Must demonstrate that no shorts / new faults will be introduced

View of protection circuitry

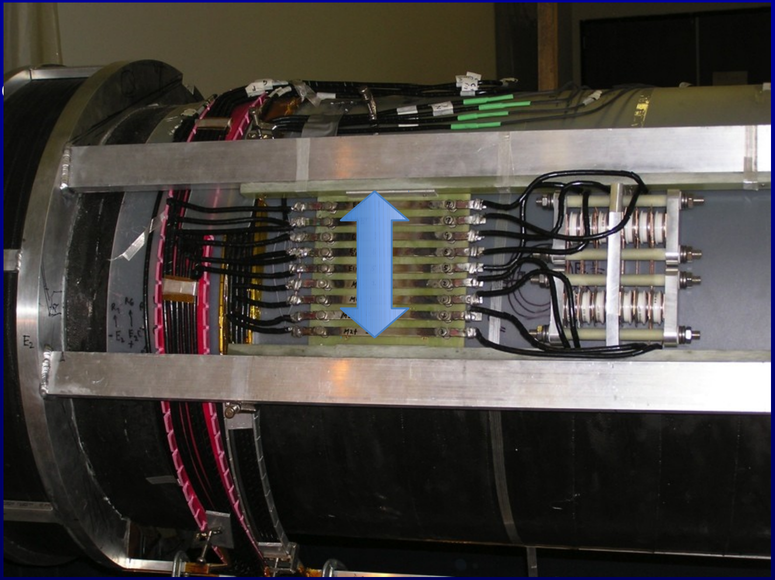


Fairly thick, include superconductor

Conclusions on bypass resistors:

Protect resistors from

- Open circuit
- Low-current quench
- => need to sink resistors
    - Preferably to mandrel ne
        - large heat capacity,
        - access all helium,
        - induce coil quenche



Proposed modification to bypass resistors

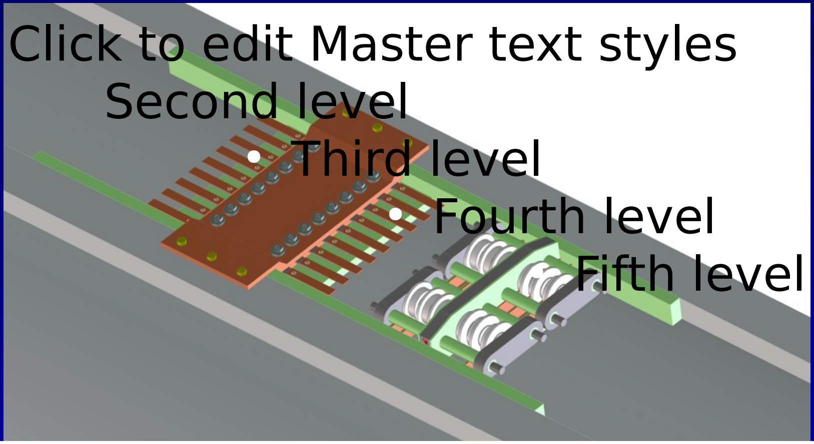
Provide a path for thermal transport from resistors to cold mass:

Simple design that minimizes risk to resistors

- Avoid shorts
- Avoid significant deformations
- Allow resistors to flex

=> Leverage strength of original design, compensate for weaknesses

Thermal link model



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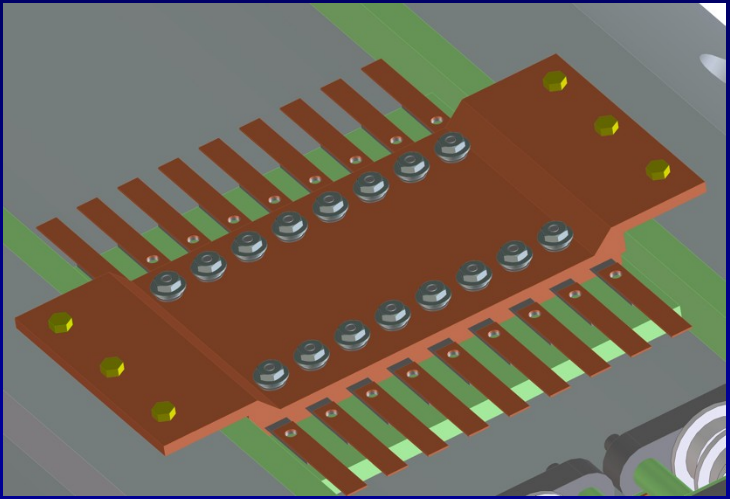
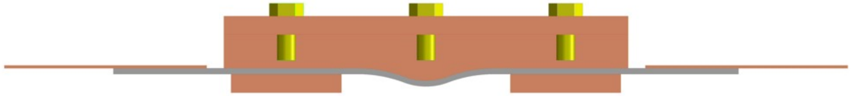
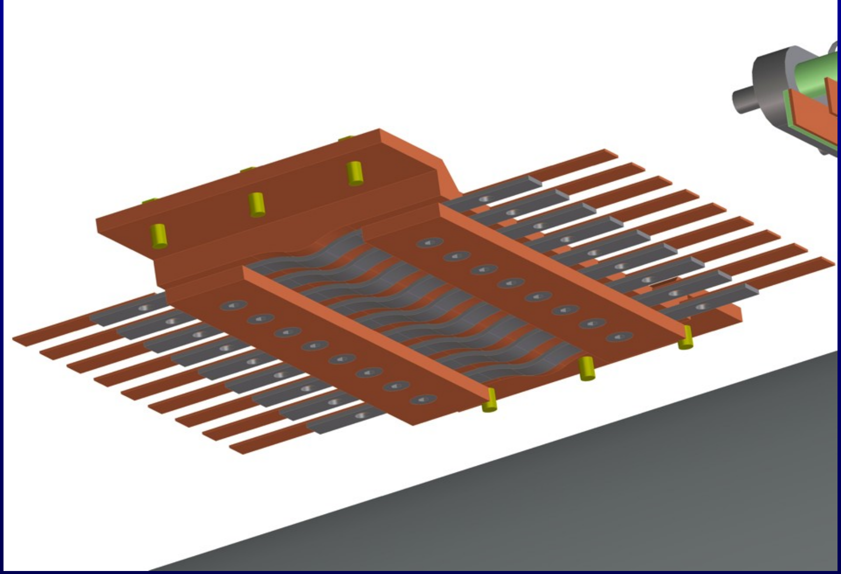
  - Third level
    - Fourth level
      - Fifth level



Capable of >2kW with dT=300K





HTS lead protection

Protection concept:

First: avoid quench by providing margin!

- No energizing until high-end temp. sufficiently low

Second: trigger spin-down if issue arises

- Interlock PS to high-end temperature
- Interlock PS to voltage drop

Third: active lead protection via warm switch

- External switch and resistor will cause internal cold diodes to pass current, thereby protecting HTS leads

Fourth: make access to HTS leads "reasonable"

- And design protection to avoid damage to cold-mass in case of such faults

Proposed plan

Finish test of bypass resistor cooling scheme ✓

Demonstrate reduction in peak temperature

Demonstrate no electrical shorts under cycling

Finalize, with detailed engineering note, all 3D simulations ✓

Find sources of the few discrepencies between various models/codes

Give serious consideration to adding active protection ✓

Weigh pros and cons – evaluate risks

Implement bypass resistor cooling scheme on spectrometer solenoids

Implement active external protection of HTS leads

Implement strict controls:

Temperature limits on HTS leads

Automate PS shut-off based on quench voltage signals