Spectrometer solenoid quench protection

MICE Collaboration Meeting #29
Rutherford Appleton Laboratory

Soren Prestemon

Lawrence Berkeley National Lab

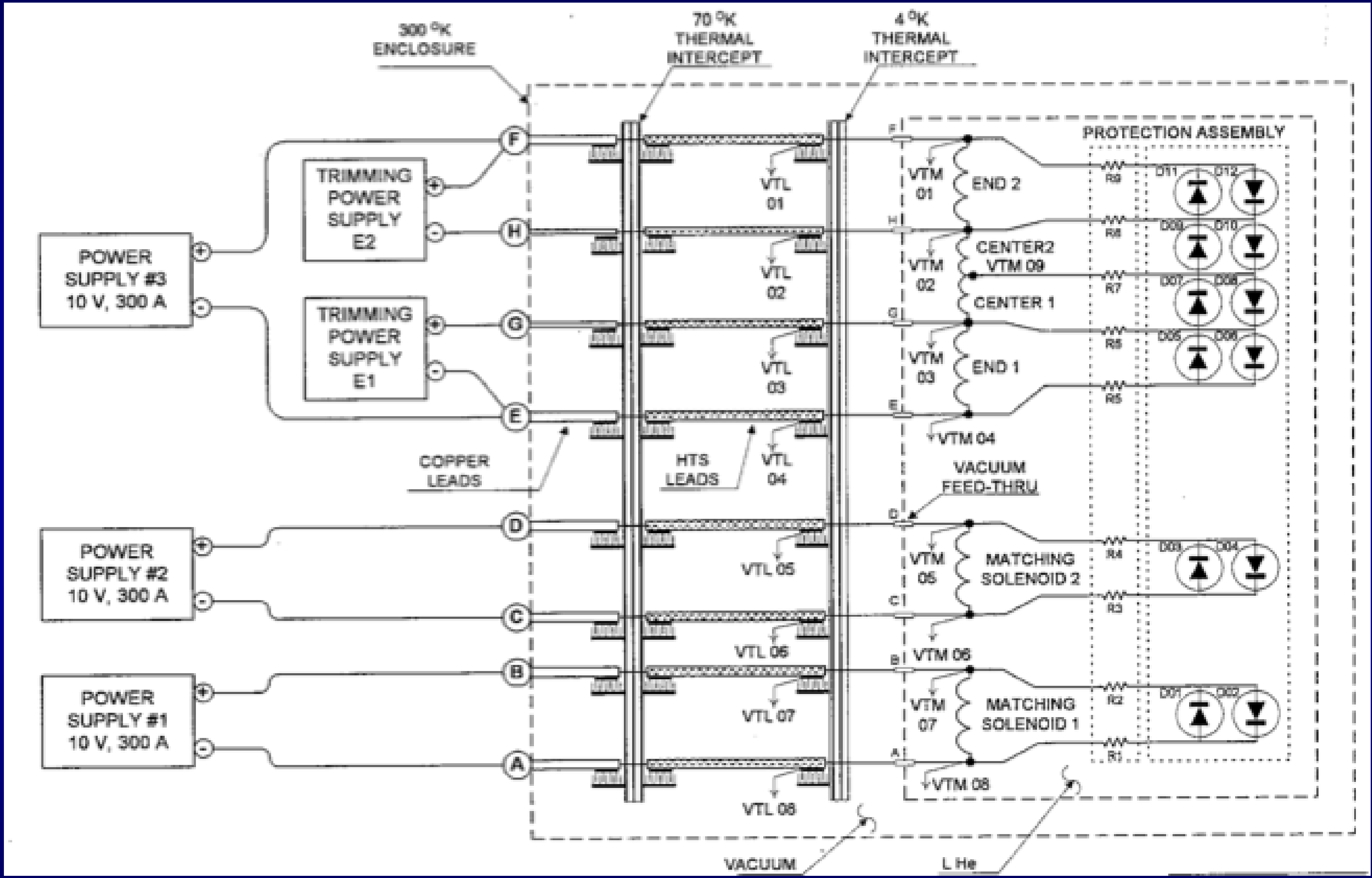
Outline

- Major recommendations from reviewers
- Review of protection circuitry
- Review of simple Wilson-code analysis
  - Simulation results: predictions and caveats
- Key protection issues
  - Protection resistors: value and design
  - HTS leads: discussion
- Status of 3D analysis

Review

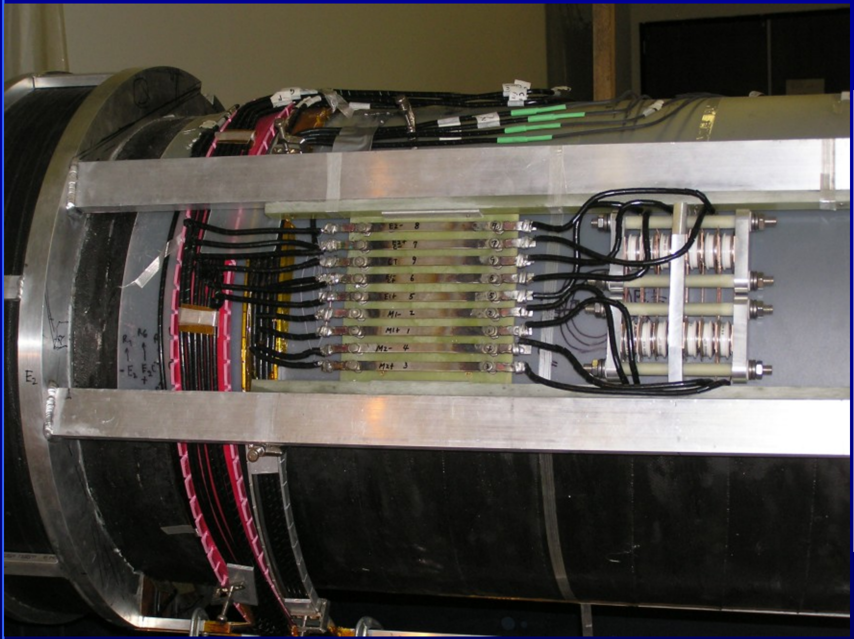
- The review committee recommends:
  - to continue the analysis of the quench protection system, including Coupled transient magnetic and thermal calculations, eddy currents in the Aluminium mandrel, external circuits with shunt resistors.
  - Investigation of different quench scenarios and definition 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.

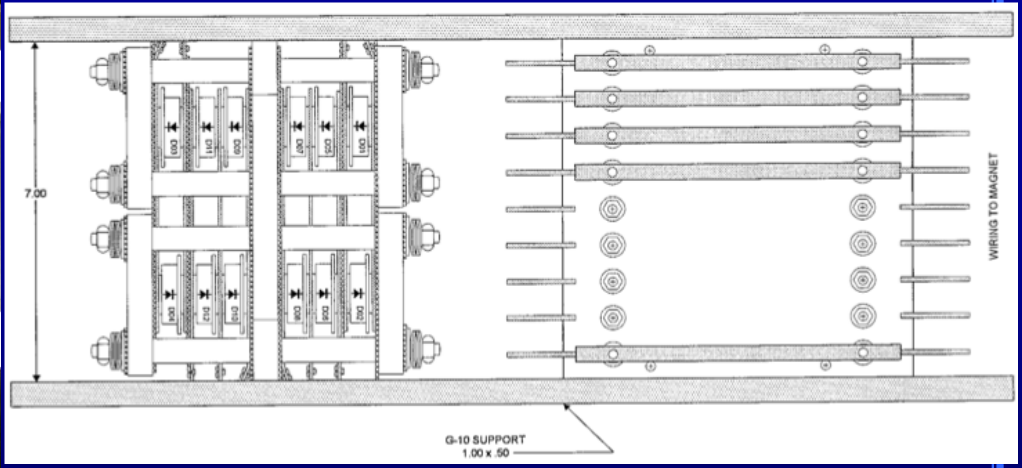
Review of Spectrometer protection circuit



Protection circuit: diodes+resistors

- 3-5V forward voltage drop
  - 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





Simple Wilson-code calculations

- Basic input parameters:
  - Cu:SC=3.9
  - Fractional areas: Copper: 69%; SC: 17.7%; insulation: 13%
  - Area of unit cell (1 turn): 0.0178 cm^2
  - Relative transverse propagation velocities: 1%

Turn and geometry info

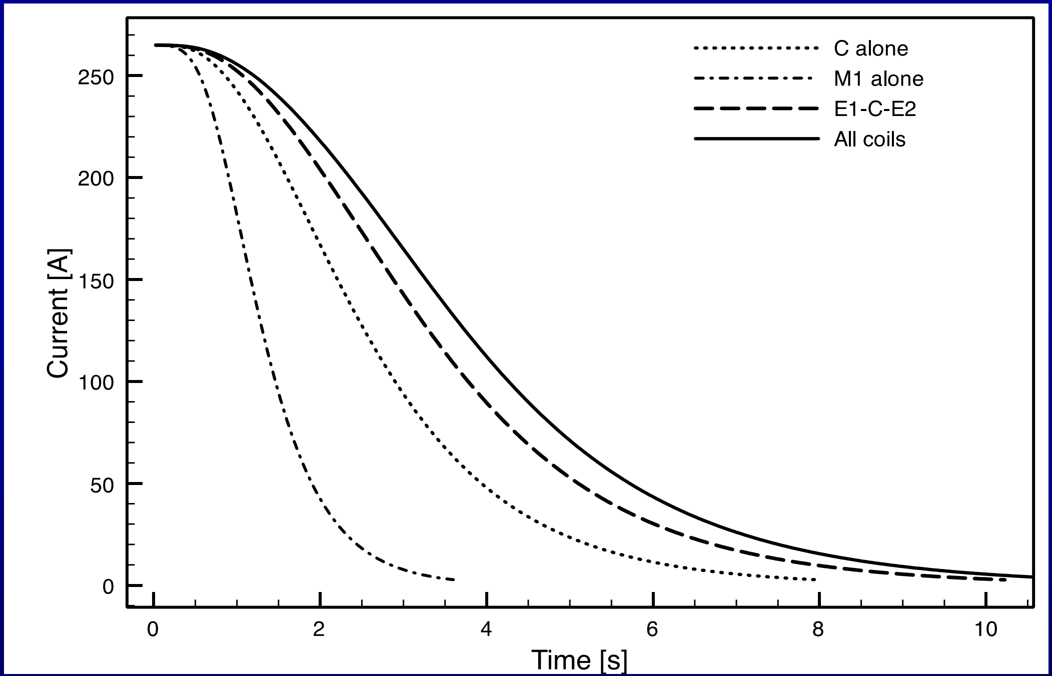
	R1	R2	Z1	Z2	Turns	I [A]	Je[A/mm2]
M1	0.258	0.3027	3.5104	3.7116	5040	269.6	151.11
M2	0.258	0.2878	3.9513	4.1508	3332	245.3	137.5
E1	0.258	0.3176	4.3957	4.5063	3696	227.2	127.37
C	0.258	0.2793	4.5439	5.8582	15680	268.1	150.15
E2	0.258	0.324	5.8957	6.0063	3960	253.4	137.48

Inductance matrix

Coil	M1	M2	E1	C	E2
M1	15.68				
M2	1.14	6.84			
E1	0.31	1.01	10.48		
C	0.28	0.57	3.50	43.77	
E2	0.02	0.02	0.05	3.79	12.01

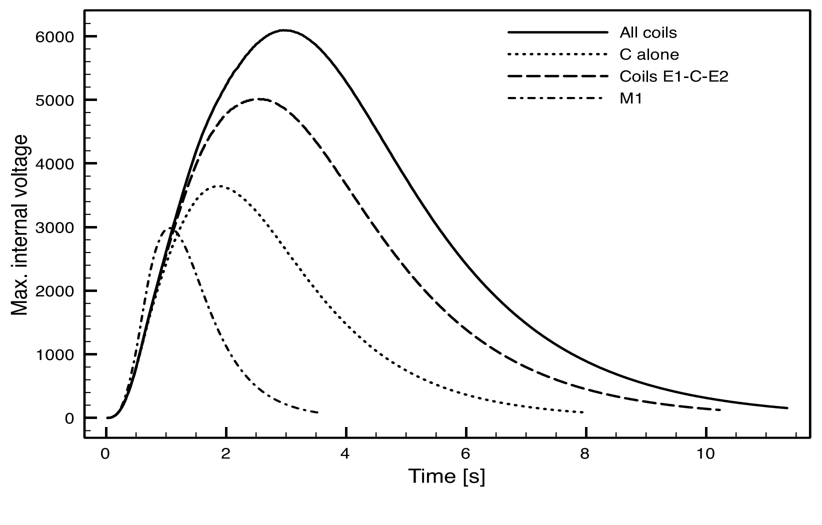
Wilson code results

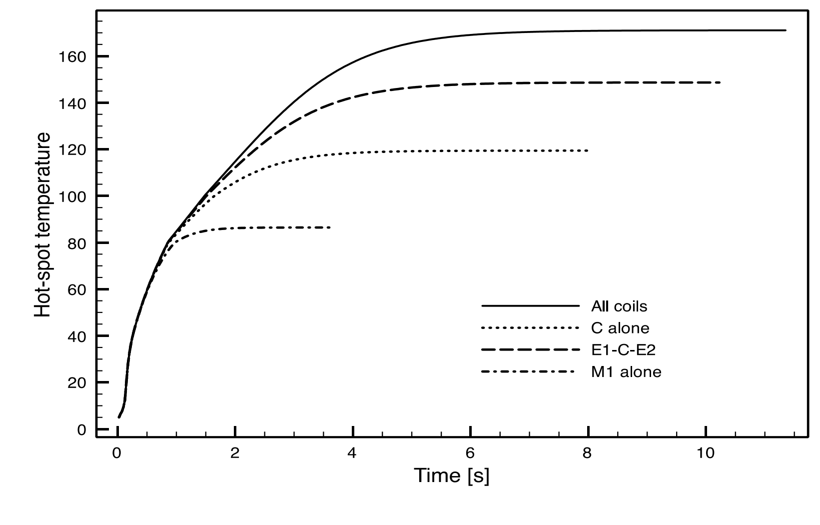
- Note: transverse propagation was “tweaked” to ~match 5s decay time for case “C alone”
  - Sensitivity of derived values, e.g. Tmax and Vmax, is not strong
  - Peak dI/dt~40A/s



Hot-spot temperature and Peak internal voltage

- Code limitations:
  - No quench back
  - Transverse propagation "fit"
  - "Lumped" stored energy; real quench events more complicated
    - Actual hot spot temp significantly lower, due to bypass current
  - No detailed information on size of resistive zone, voltage gradients

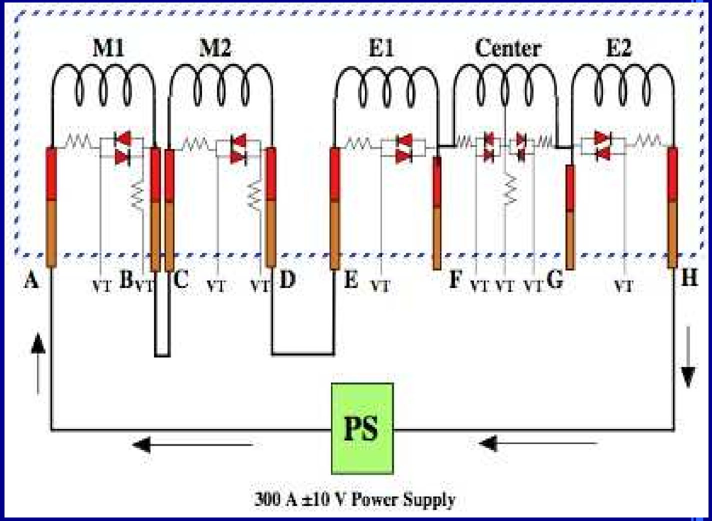




Protection circuit: test condition

- 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
    - Probably also generate bypass currents
  - Other coils either…
    - Quench - very likely, due to quenchback
    - Remain superconducting
      - Current continues to decay due to bypass resistance, but with very long time constant
      - Most likely to occur due to low-current quench, when significant margin available

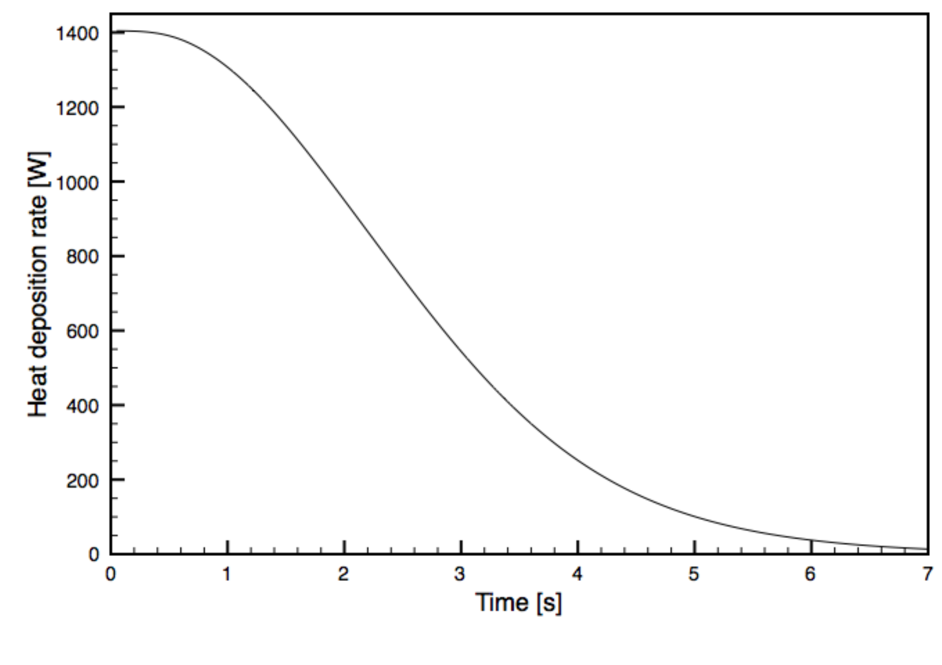
Schematic by V. Kashikhin



Protection resistors: temperature rise

- Characteristic quench decay time ~5s
  - M. Green, from experiment
  - Geometry: ~20cm long, 2cm wide, 0.35mm thick *(need to check with vendor)*
  - Assume all current in bypass:

  => Tmax<300K



- Possible concerns:
  - Anomalous quench scenarios
  - Is 0.02Ω optimal (define)
  - Power supply not shut-off

HTS leads

- 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: make access to HTS leads "reasonable"

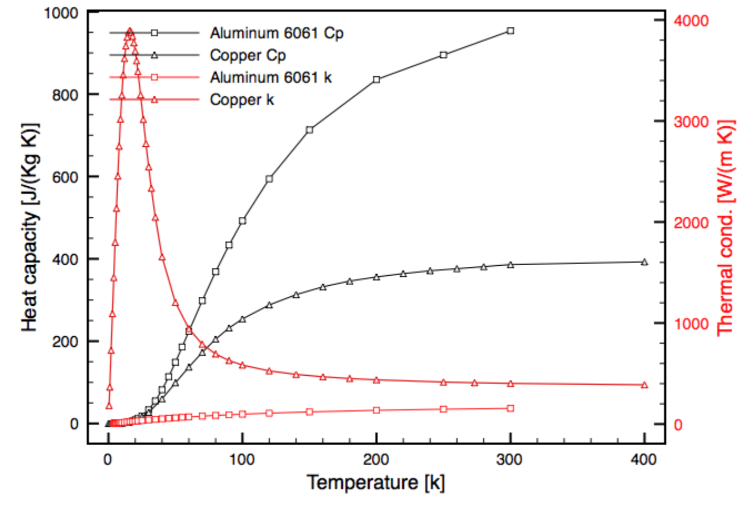
  - Other: how fast di/dt is needed to protect quenching leads?

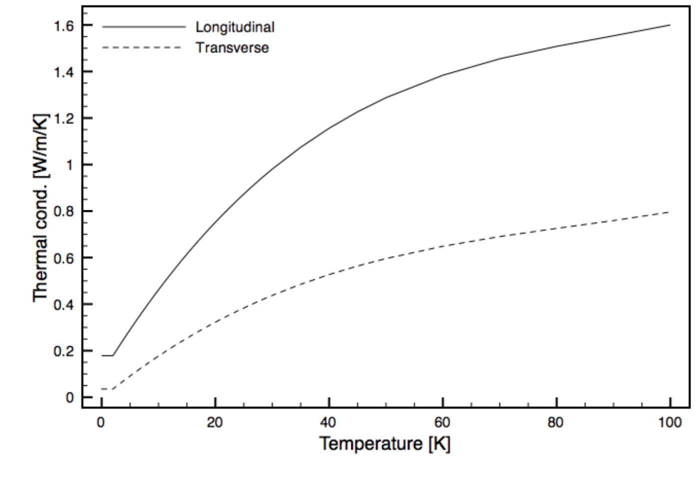
3D simulations

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

Status of 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 series test configured
  - Allows diode + resistor
  - Other (e.g. operational) configurations easily produced
- First 3D model simulations underway
  - checking quench initiation process
  - Calibrating code with Wilson code

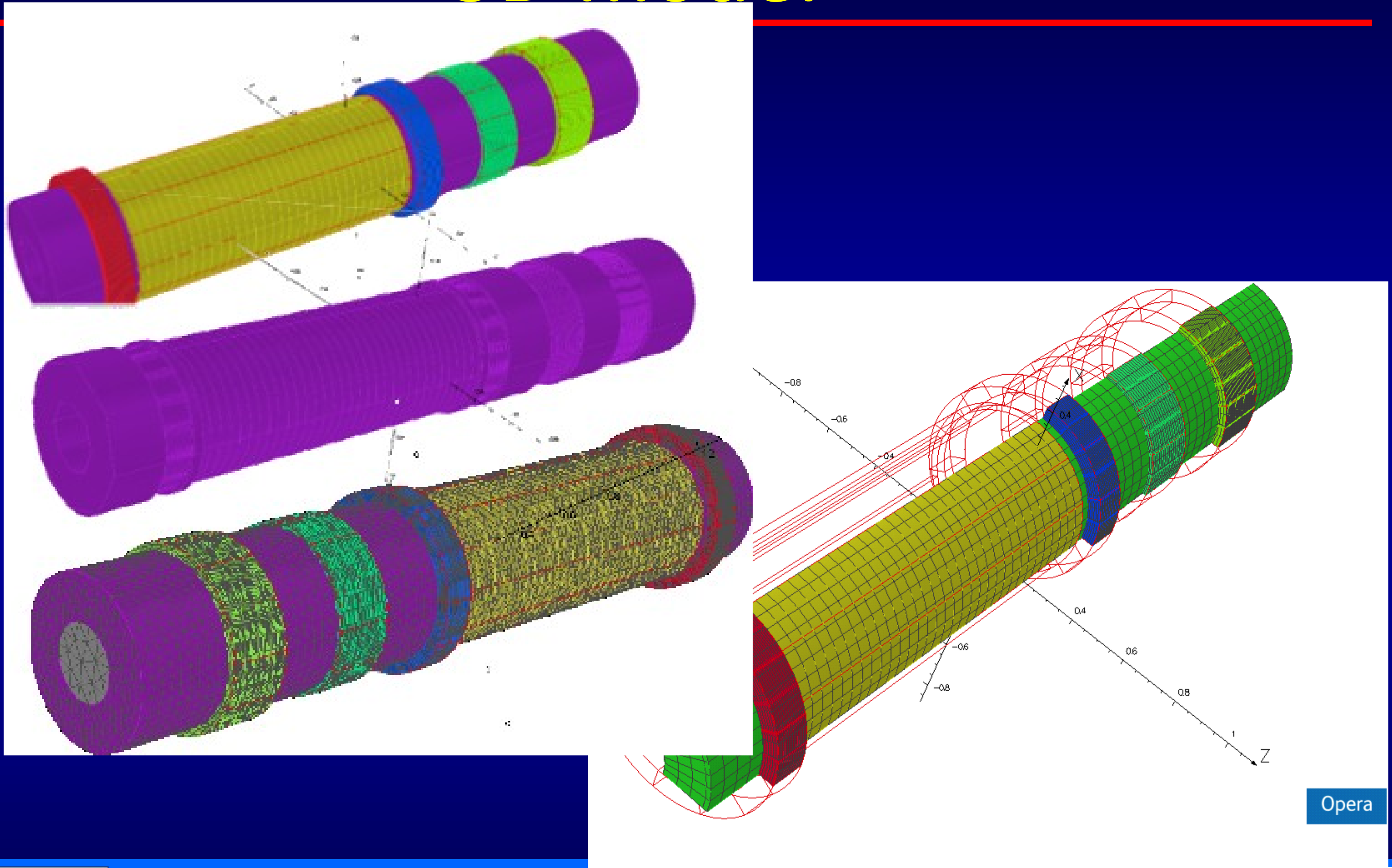




Planned simulations

- Code validation:
  - Comparison with Wilson code for single coil case
- Evaluate current fluctuations, decay, voltages, hot-spot temperature throughout circuit in:
  - Test configuration
  - Operating configuration
- Evaluate role of quench-back from mandrel:
  - Temperature rise and distribution in mandrel during a coil quench

3D model



Goals of simulations

- Main questions to be answered by 3D simulations:
  - What are the maximum turn-to-turn and coil-to-ground voltages seen during a quench?
  - Are there scenarios where a subset of coils quench, but others remain superconducting, resulting in slow decay through bypass diodes and resistors?
  - What dI/dt will be “certain” to generate quench-back?
  - What modifications to the existing system should be incorporated to minimize/eliminate risk to the system in case of quench

General approach towards repair

- Address reviewer concerns
  - essentially same as the project team's
- Use simulations to guide final decision on protection system repairs
  - Allow repair strategy to crystallize based on results
- Develop clear strategy for protection modifications
- Develop test and operational controls to support magnet protection