B. Auchmann, TE-MPE, August. 2014

Quench Simulation for LHC Magnets – Challenges&Goals

Overview

1. Magnet-level quench simulations
   1. Practical example: simulation of symmetric quenches in MB.
   2. Consequences of shortcomings
2. More real-world problems in the accelerator.
3. What is the strategy to tackle all of the above?

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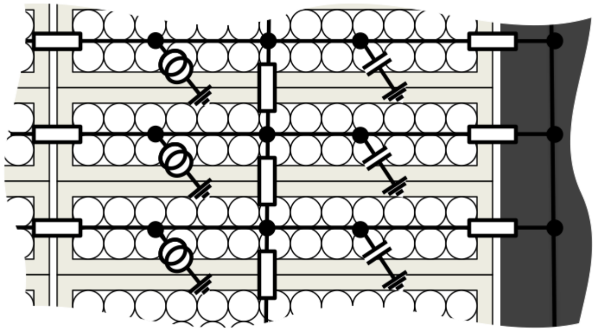
Preamble

- The challenge of quench simulation:
  - to model all relevant physical phenomena
  - with adequate accuracy
- Check 1:
  - Measured quantities can be reproduced
  - with all material- and model-parameters within the range of uncertainty,
- Check 2:
  - The model can be used for the same parameter set to extrapolate a magnet's quench behavior to different working points.
- Only if the above criteria are met, can we be confident to simulate internal states and reproduce observable and hidden behavior.
- Any deviation from this path, and any filling in of unknown and unobservable parameters, must be on the conservative side.

How we simulate a quenching MB

- Coil discretization
  - Transversal:
    - 1 node per half-turn, lumping together cable, insulation, and helium,
    - 1 conductance per insulation layer.
    - Surrounding structure is neglected.
    - Heaters as single nodes, connected to turns and He bath.
  - Longitudinal:
    - Up to 100 subdivisions for full magnet.
    - No coil ends (2-D mag. field).



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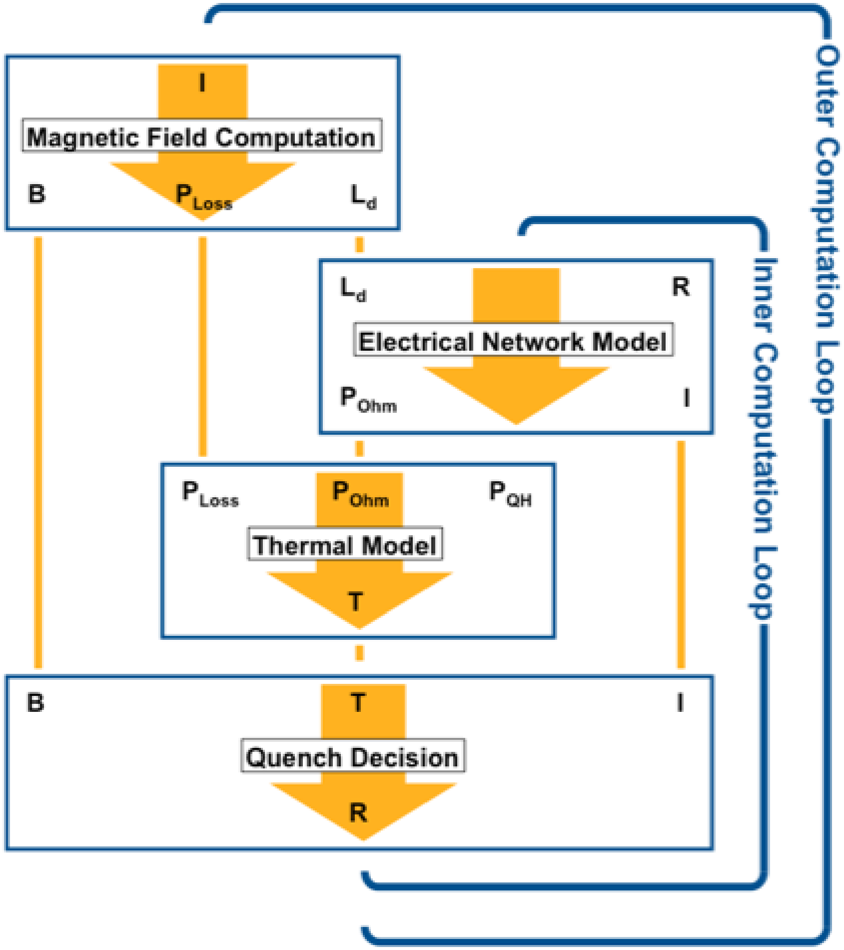
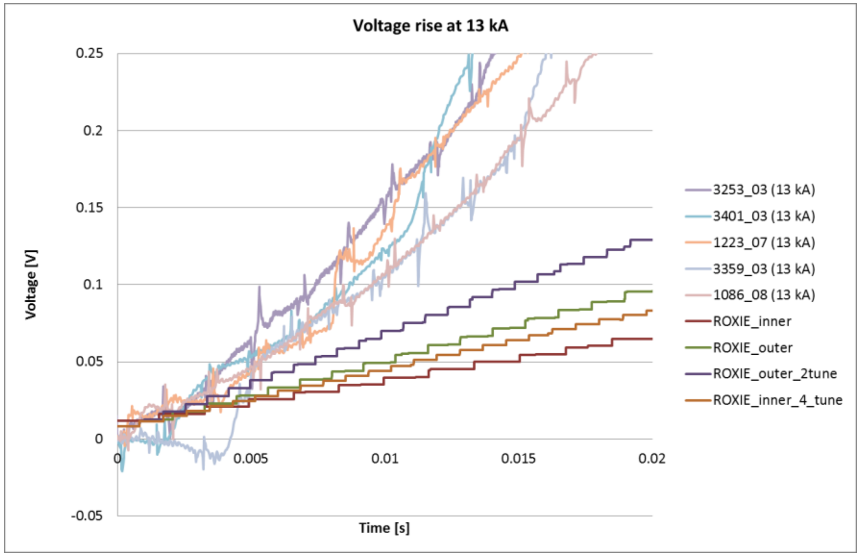
How we simulate a quenching MB

- Time discretization
  - Explicit 4-th order Runge-Kutta with adaptive time stepping.
  - The quench front determines the step size in the entire magnet.
  - Typically 1-10 μs for Nb-Ti magnets, and 0.1-1 μs for Nb_3Sn magnets → tens of thousands of steps.
- Coupling
  - Outer loop only updated after significant change in current.



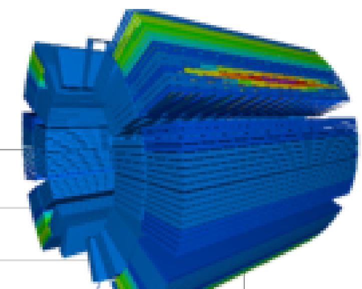
How we simulate a quenching MB

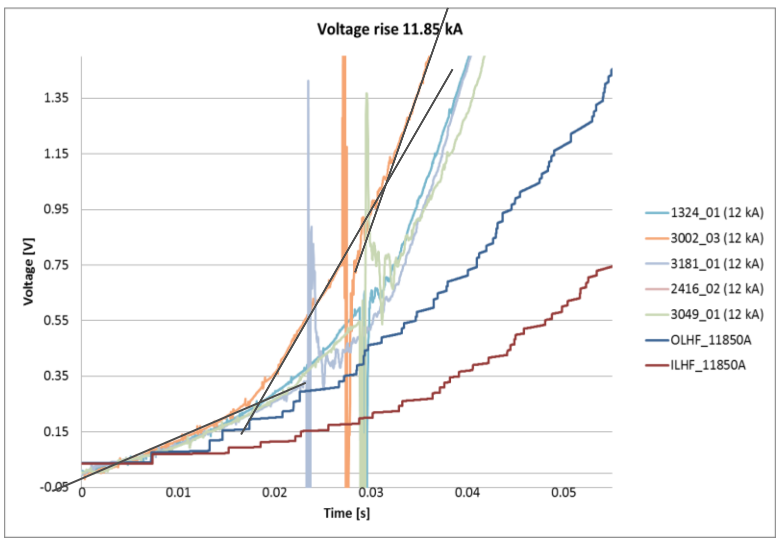
- Step 1: tune the longitudinal model to fit measurement.
  - A predictive model would require to include both, thermal and fluid-dynamics aspects of helium physics.
  - Convergence would require step sizes of 1-5 mm.
  - Tuning factors for models with 5-cm steps: 2-4.

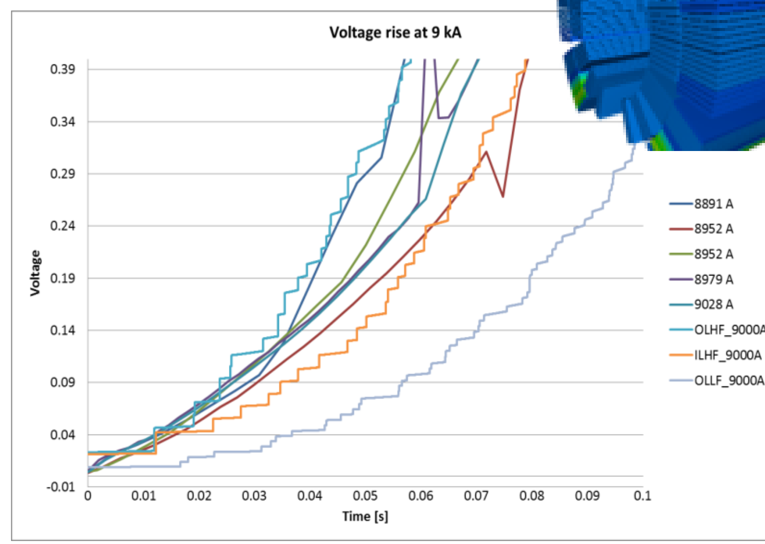


How we simulate a quenching MB

- Step 2: Tune the transverse model
  - Missing detailed helium model (microchannels in the insulation, helium in the Rutherford cable voids) and missing measurement data make this the least predictive part of the model. Tuning by factor 20!!! Does not scale properly with current. The most important effect is neither well known by measurement nor from the model.
- Step 3: Note the time to reach threshold.





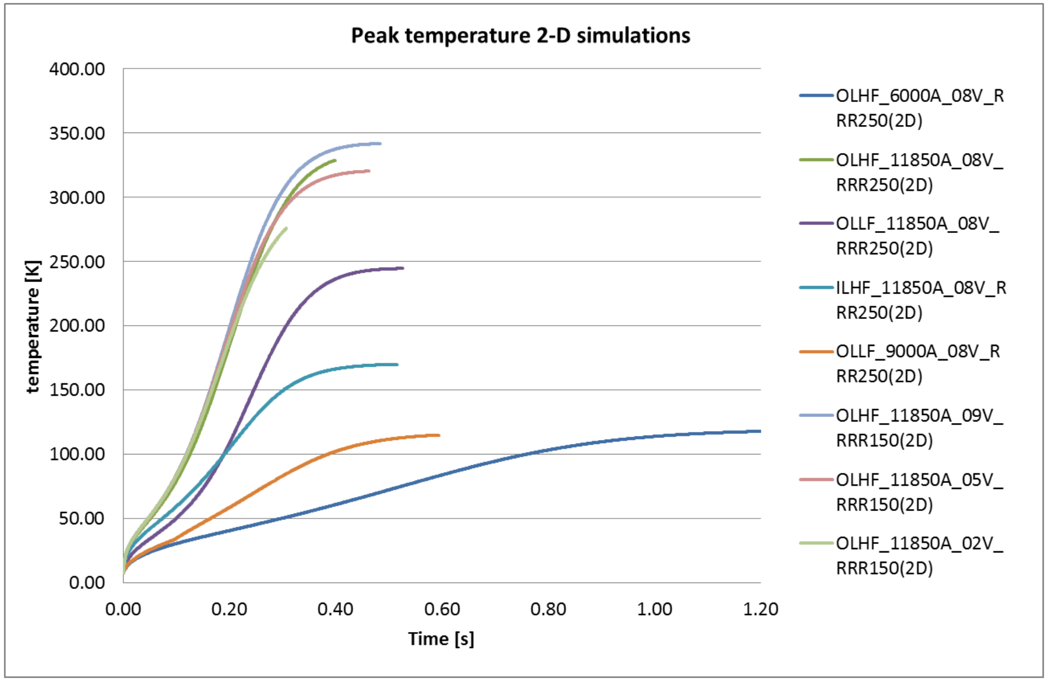


How we simulate a quenching MB

- Step 4: Tune heater-efficiency model based on measurement data.
  - Missing helium model, contact resistances makes tuning by factor ~2 necessary.
- Step 5: 2-D simulation with hard-coded detection delay from 3-D simulation.

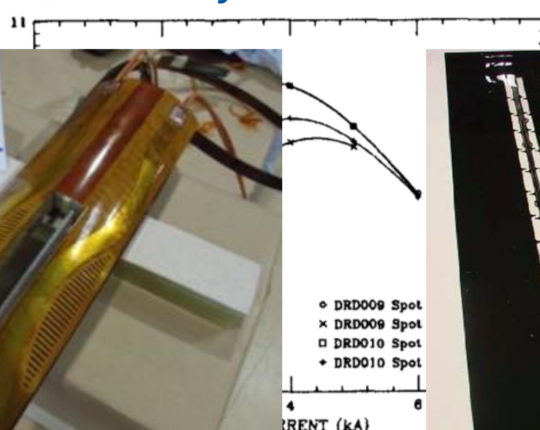
SymQ Threshold	Time to reach threshold
0.1 V	0.007 s
0.2 V	0.0132 s
0.5 V	0.022 s
0.8 V	0.0293 s
0.9 V	0.0297 s

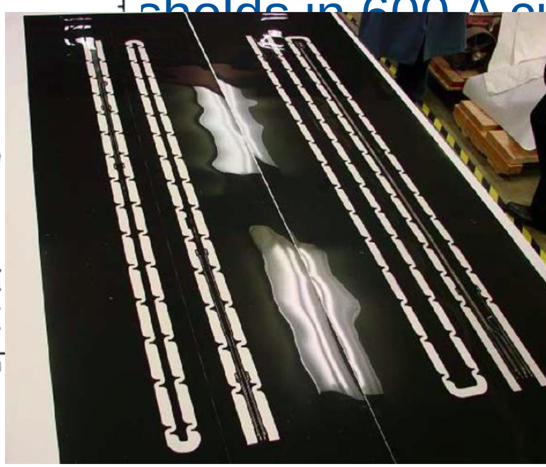
NB: The simulations were performed for one aperture and the SymQ measures the voltage across both apertures.



Consequences

- D1 without heaters
  - *Consequence*: Model vs. measured hotspot discrepancy of ~200 K. Applies to all helium-cooled magnets without heaters (with defective heaters). Hesitation to use spares, magnets with defective heaters.
- Qualify the 11-T protection scheme for the LHC
  - *Consequence*: Critical for magnet R&D program. Validation of the design will come only after many years of R&D. May build more prototypes than necessary.
- Estimation of sa… …sholds in 600 A circuits
  - C… …C.



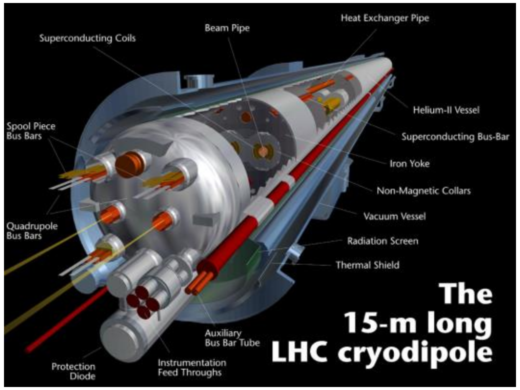


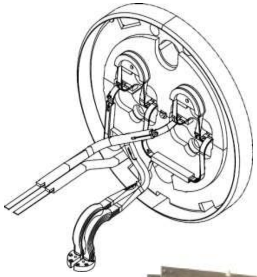
What if we fail?

	E	M_{cu}	$v_{20\ t}$
MB	7 MJ	9.6 kg	95 km/h
RB	1100 MJ	1515 kg	~Mach1
beam	300 MJ	413	620 km/h

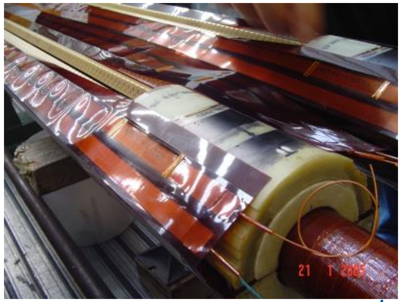
Some real-world aspects

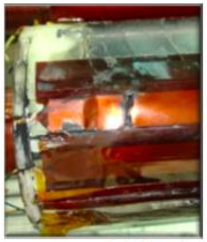
diodes and diode leads



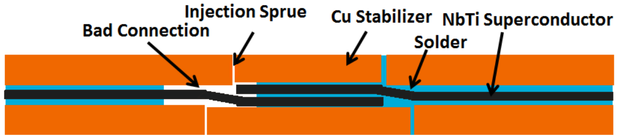


heaters





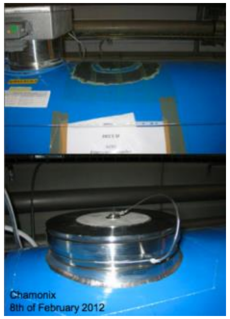
G. D'Angelo



busbars & splices

power converters

pressure valve



dump resistor

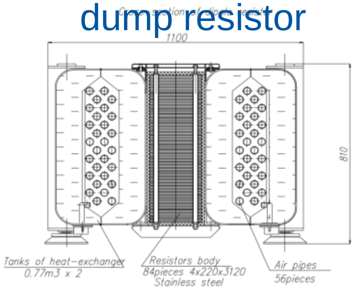


Fig. 1. Cross sections of a 225 mΩ and 3.5 m long dipole resistor

switch

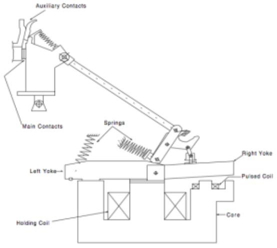
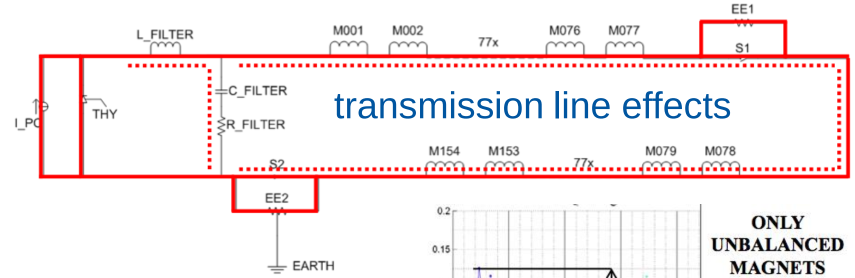
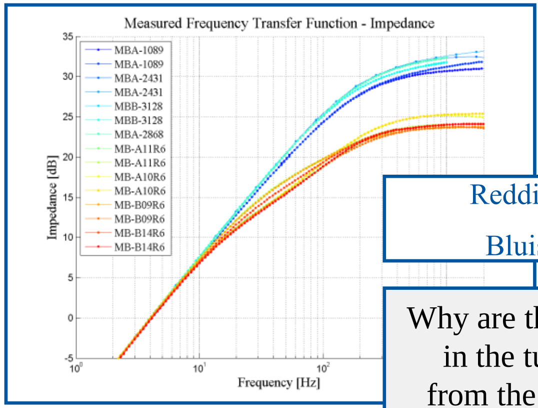


Fig.1. Simplified mechanical and magnetic system of the breaker.

Other EM effects



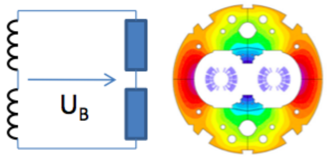


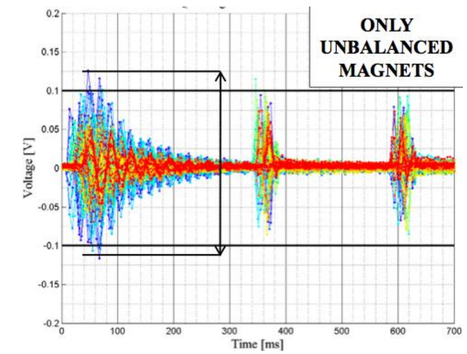
FTFs

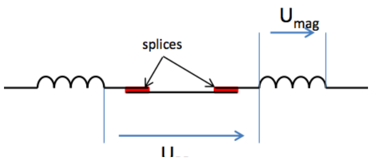
Reddish → Tunnel

Bluish → SM18

Why are the FTF measured in the tunnel different from the ones in SM18?







$$U_{res} = U_{BB} + L_{Bus} * \frac{U_{mag}}{L_{mag}}$$

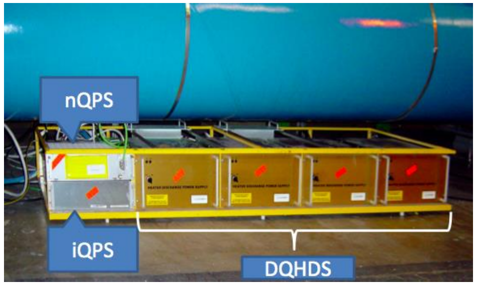
Simplified logic:

FireA : (A-B or A-C or A-R) > Thres

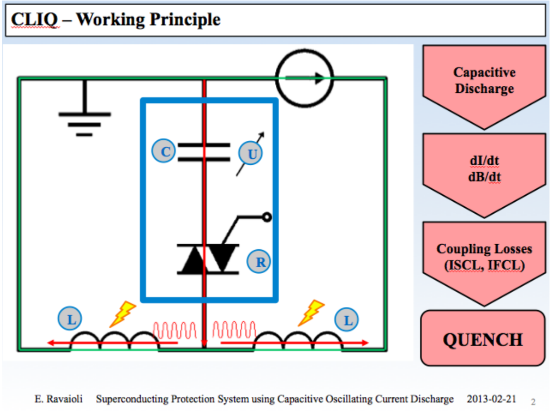
FireB : (B-A or B-C or B-R) > Thres

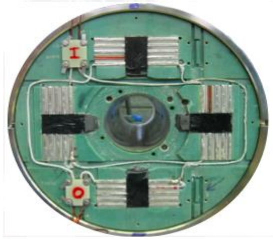
FireC : (C-B or C-A or C-R) > Thres

QPS detection system

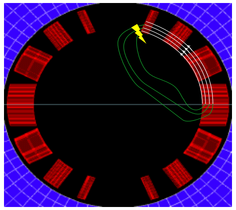


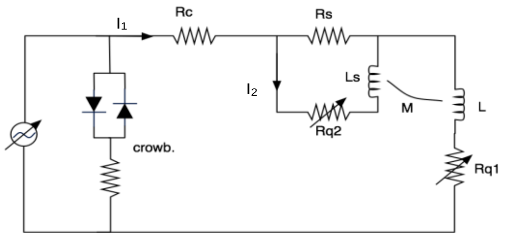
CLIQ system in case of heater failure?



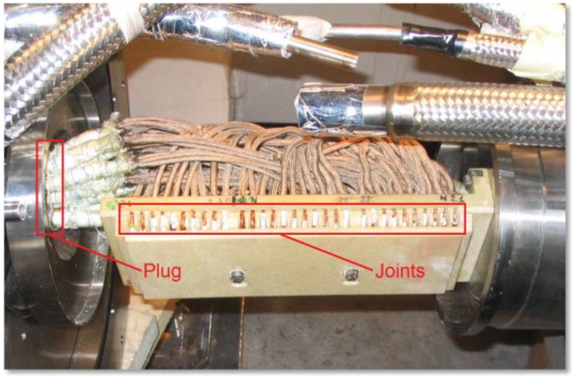


magnets with short circuits.

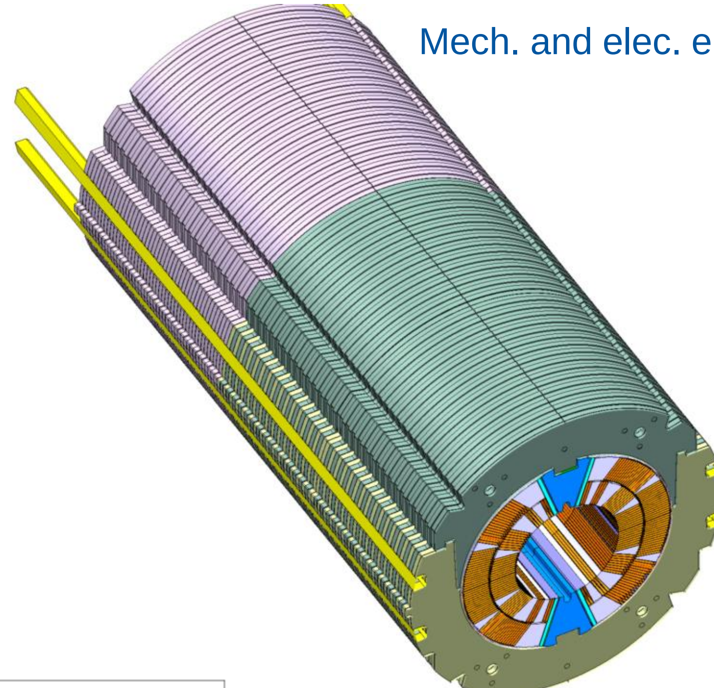




Some more real-world aspects



A mutual-coupling and quench protection problem



Mech. and elec. elements

Magnet-to-magnet propagation.

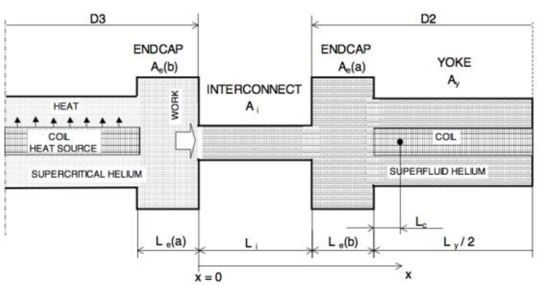


Figure 9: Model schematic with interactions shown.

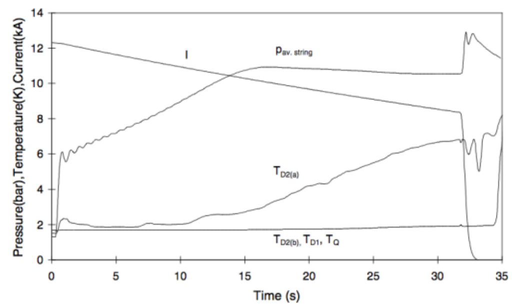


Figure 2: Quench propagation from D3 to D2; $p_{set} = 11$ bar.

Recap real-world features

- Every aspect mentioned above may at any point in the next 20 year require specific attention and modeling.
- The modeling depth for specific aspects needs to be adjusted from problem to problem.
- The problems of proper coupling, adequate modeling depth, efficiency, and convergence are common to all investigations.

Commonalities/Differences

- Most problems have in common:
  - Multi-domain
  - Multi-scale
  - Multi-physics
  - Multi-rate
  - Need for post-processing
- The differences lie in:
  - Data source for geometries (CAD, FEM, custom coded)
  - Modeling depth (scale, method)

Goals strategic

- Framework that allows to develop models for the next 15 years.
- Simulate quenches in MB with numerical convergence.
- Lay the foundations to improve physics in quench models in a sustainable way.
- Avoid maintenance of a large number of different programs.
- Build a strategic partnership with relevant university institute.

Goals tactical

- Co-simulation core providing
  - Iteration algorithms
  - Interpolation algorithms
  - Fast material updates
  - Theory of system coupling (coupling terms, coupling metrics, coupling methods)
- Set of bench-marked solver tools providing variable modeling depth.
- Post-processing setup for network and mesh-based models in multi-domain, multi-rate setting.
- Pre-processing interfaces.
- Validation with R&D magnet data.

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Goals tactical 2

- Surrogate models with experimental validation
- Hybrid FEM
- Sensitivity analysis