B. Auchmann (CERN/PSI)
22. April, 2021, GetDP Workshop

Simulation Needs and Challenges for Accelerator Magnets

Some of the work supported by the Swiss State Secretariat for Education, Research and Innovation SERI.

Overview

- Accelerator magnets have “always” been frontier applications for numerical methods.
  - Brief intro to accelerator magnets
  - Numerical-challenges timeline
    - Normal-conducting era
    - LHC
    - HiLumi
    - FCC
    - HTS
- What are the main numerical challenges for the accelerator-magnet community today?

Caveat: this talk does not pretend to present an exhaustive historical overview of numerical challenges, software tools, or contributions. Selected examples are meant to elucidate the above questions.

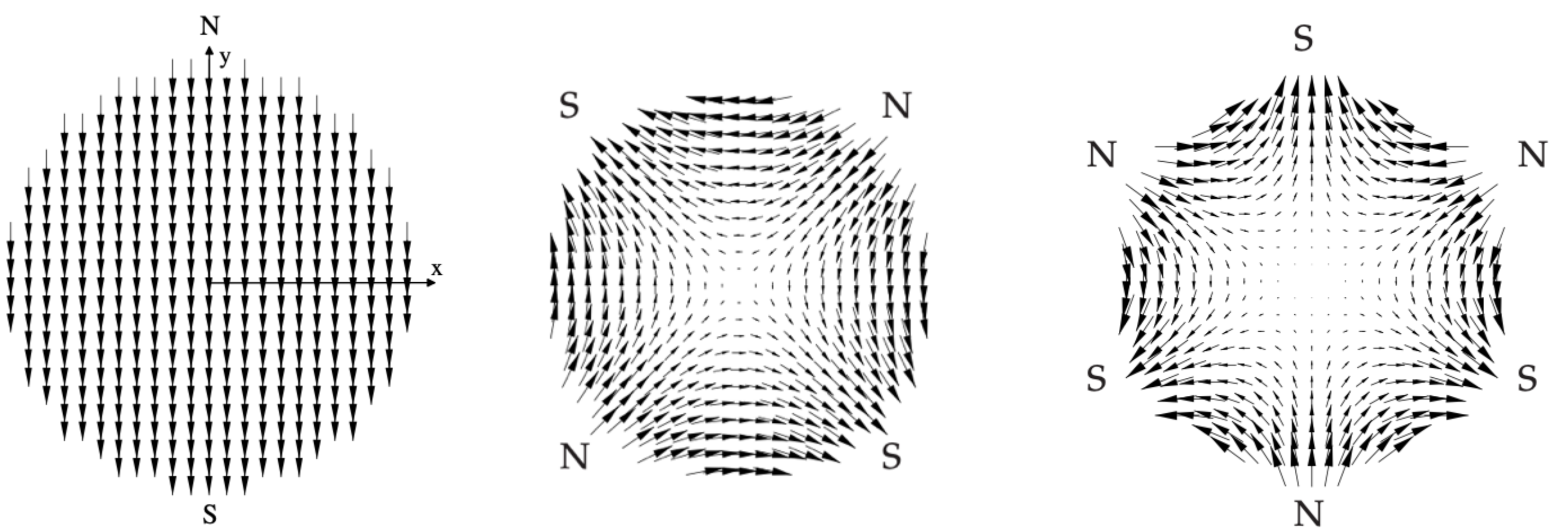
LHC Accelerator Magnets - Intro

Field Quality

- The beam is guided by magnetic fields.
- Ideal field components for steering and focusing correspond to the first and second harmonic in a Fourier decomposition of the radial field.
- Field quality requirement: main field / unwanted field component $\leq 10^{-4}$.

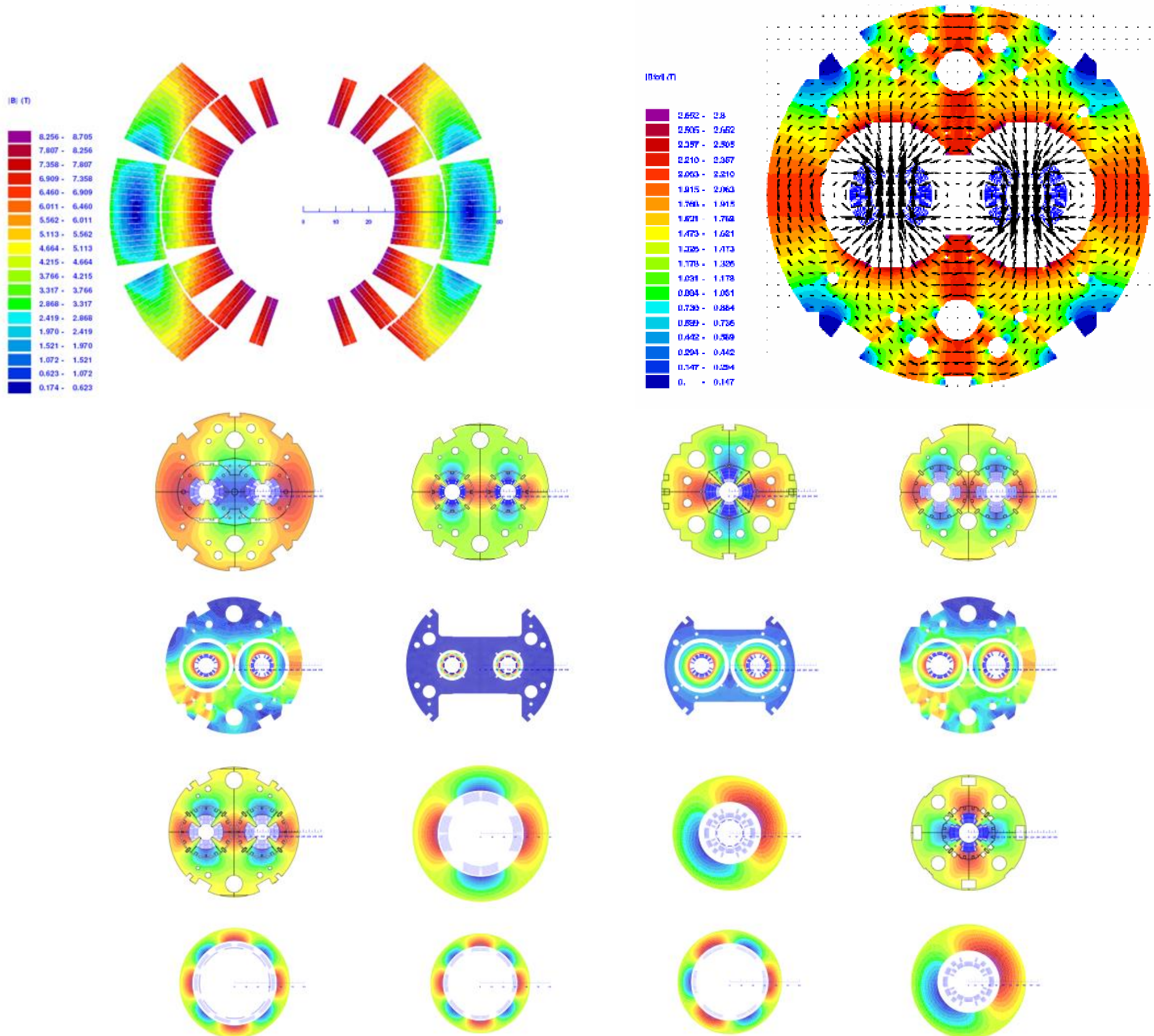
$$B_r(r_0, \varphi) = \sum_{n=1}^{\infty} \left(B_n(r_0) \sin n\varphi + A_n(r_0) \cos n\varphi\right)$$

$$B_n(r_0) = \frac{1}{\pi} \int_0^{2\pi} B_r(r_0, \varphi) \sin n\varphi \, \mathrm{d}\varphi, \qquad n = 1, 2, 3, \ldots .$$

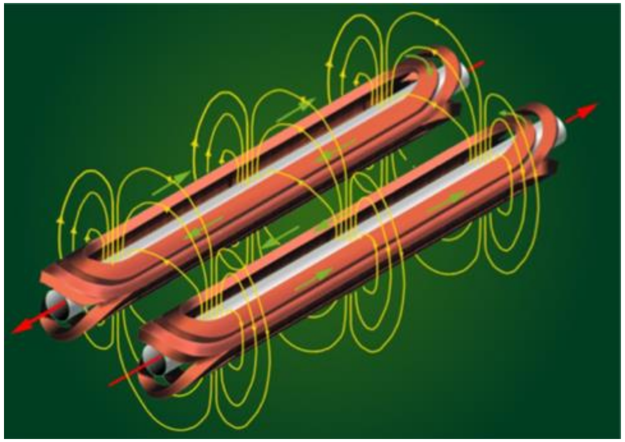


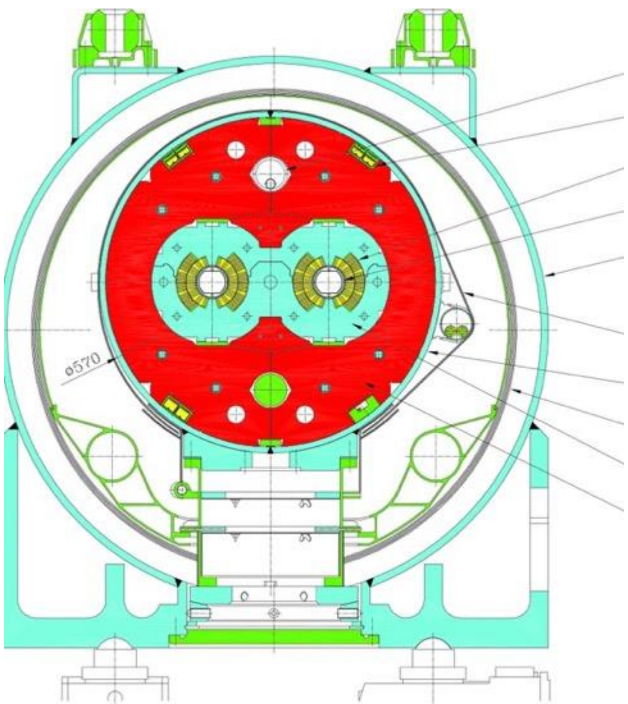
Pictures from S. Russenschuck, Field Computation for Accelerator Magnets, Wiley VCH, 2010.

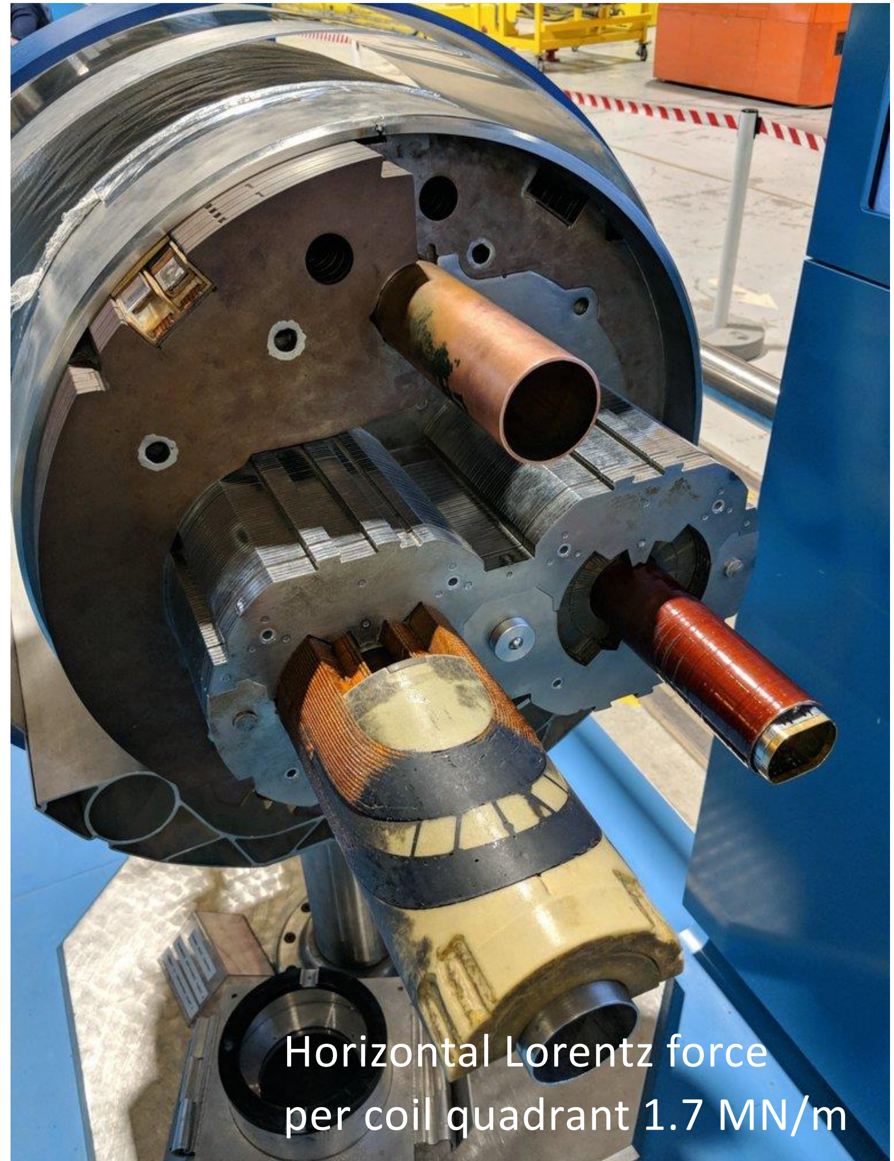
LHC SC Magnet Zoo – the Cos-Theta Coils



Accelerator Magnets







Conductor Motion and Quench

- Conductor motion (following M. Wilson):

work per unit length of strand if moved by

$$W = F\,\delta s = B\,I\,\delta s$$

heating per unit volume

$$Q = B.J.\delta s$$

LHC inner-layer peak field and strand current-density

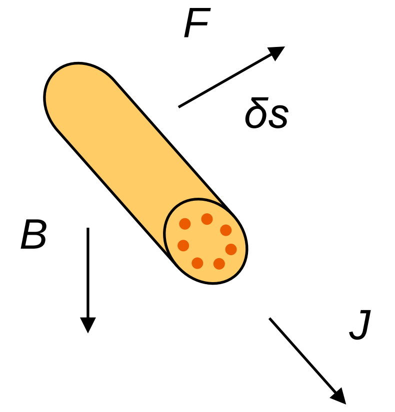
$$B = 8.7\,\mathrm{T}$$

So, if $\delta = 10\,\mu\mathrm{m}$

then $Q = 4.1 \times 10^4\,\mathrm{J/m^3}$

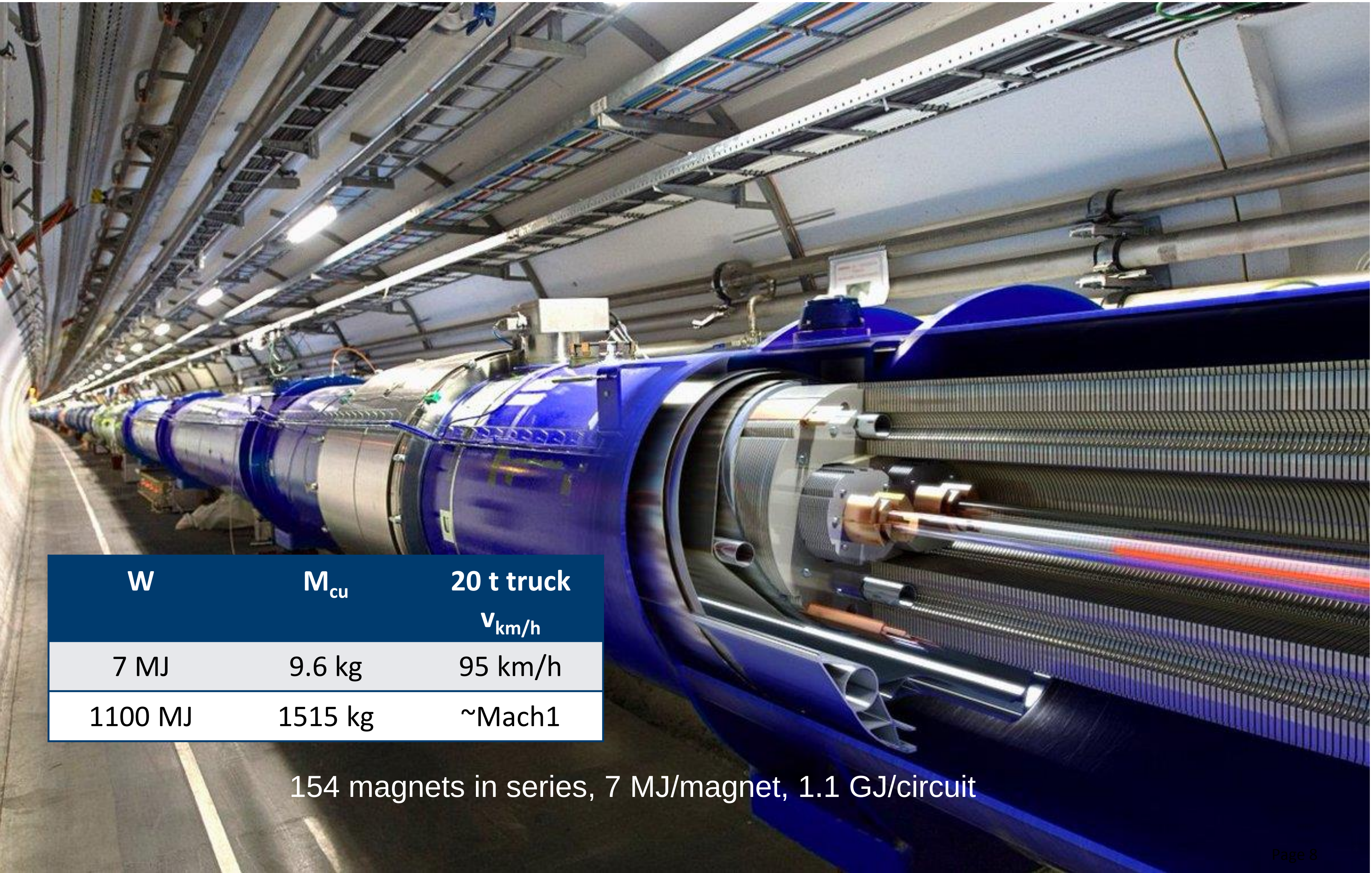
and from $T_0 = 1.9\,\mathrm{K}$

the temperature is increased to $T = T_0 + Q/C(T) \approx 9\,\mathrm{K}$



- We must ***control sudden strand motion to better than 10 µm***!

Magnet Circuits



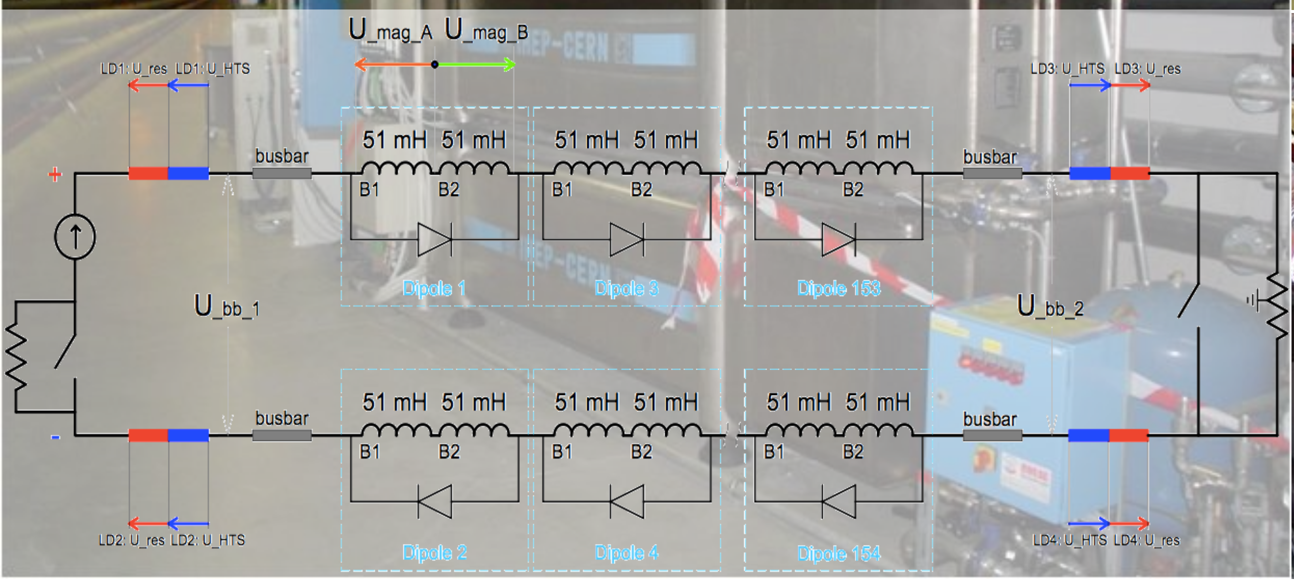
W	M_{cu}	20 t truck $v_{km/h}$
7 MJ	9.6 kg	95 km/h
1100 MJ	1515 kg	~Mach1

154 magnets in series, 7 MJ/magnet, 1.1 GJ/circuit

Protecting an LHC Main Dipole Circuit

The circuit energy is extracted into water-cooled resistors with 100 s time constant.

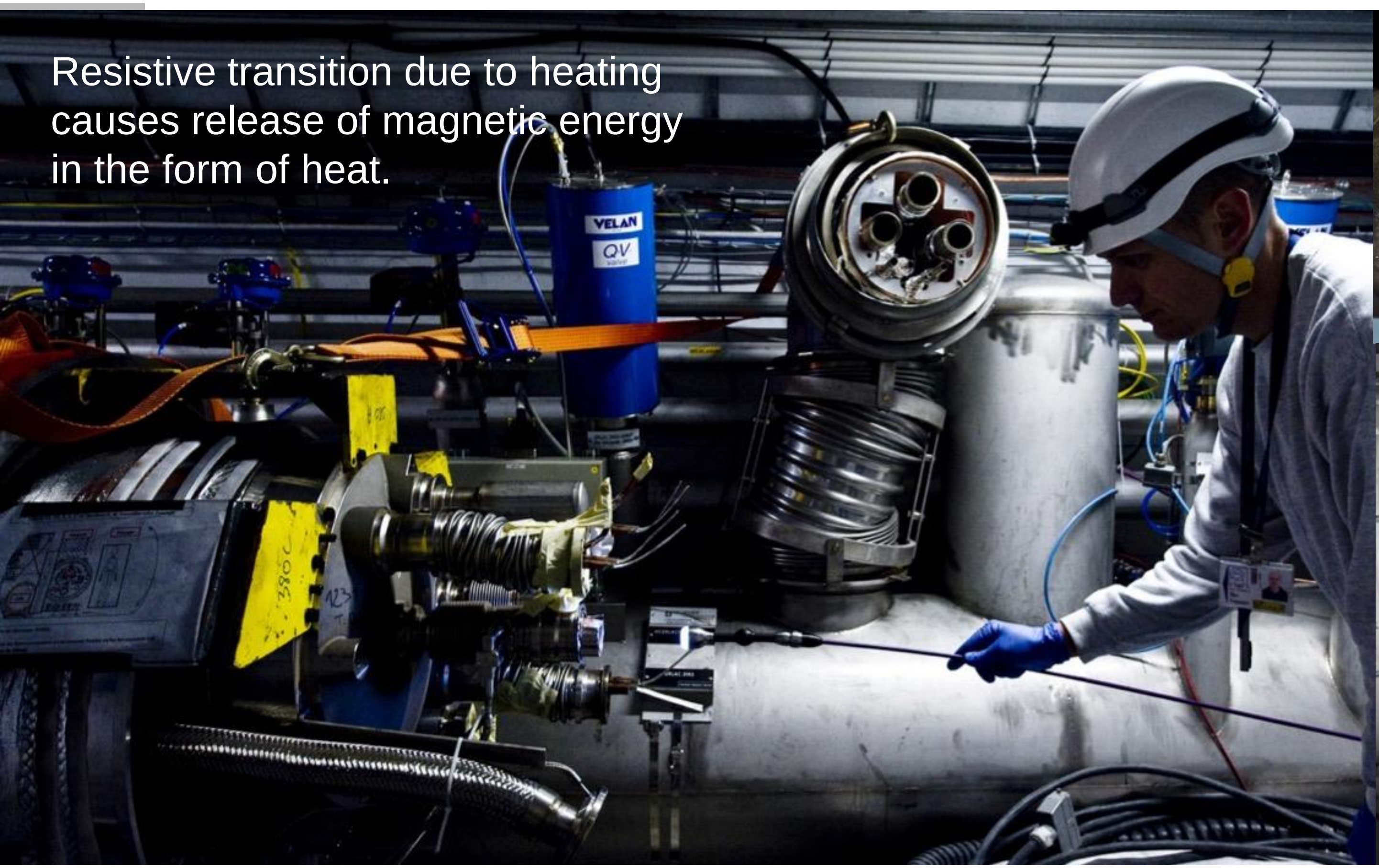
Quenching magnets are isolated via a diode and heated up to distribute the energy.



PAUL SCHERRER INSTITUT
PSI

Protecting an LHC Main Dipole Circuit

Resistive transition due to heating causes release of magnetic energy in the form of heat.

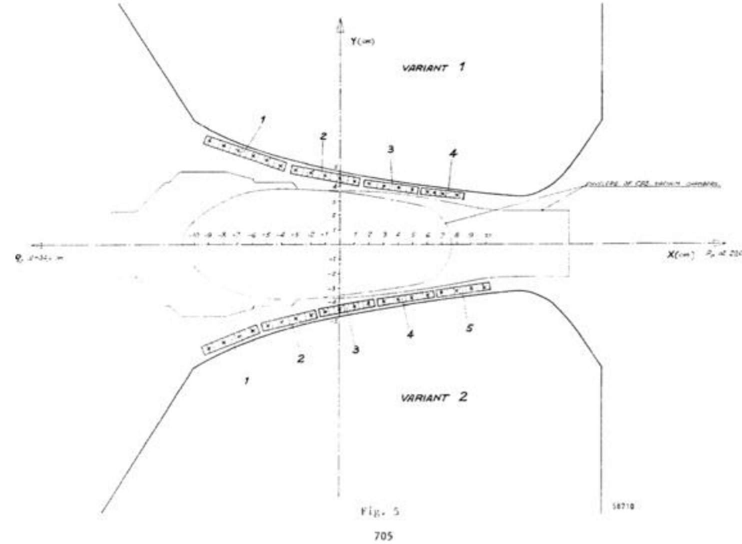


Numerics for Accelerator Magnets - the Beginnings

PAUL SCHERRER INSTITUT

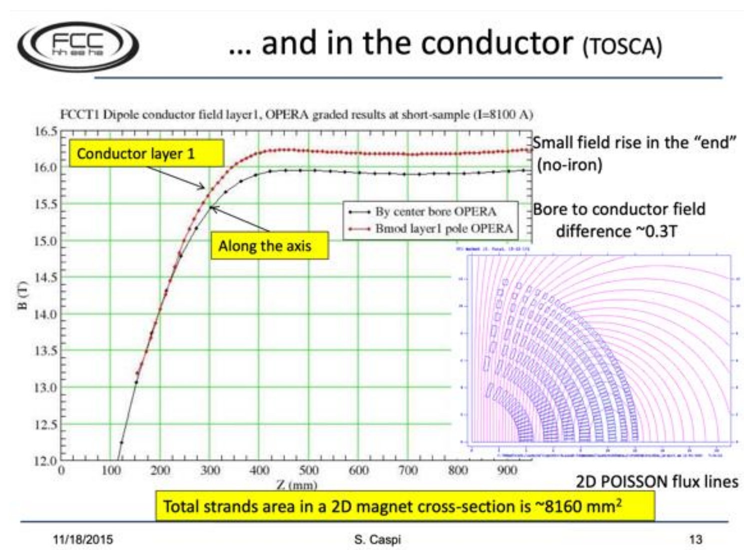
The Beginnings

- Iselin, 1973, computer program MAGNET, PS poleface-winding optimization (MINUIT) for multipole control.



A. Asner, R. Holsinger, Ch. Iselin, The Computation of Poleface Winding Systems Yielding Independent Multipole Fields within the Aperture of Notably Alternatig Gradient Synchrotron Magnets, IEEE Trans. Nucl,. Sci. 20, 3, 1973.

- Holsinger and Iselin, 1984, Poisson
  - Az / rAphi method
  - Still in use today.

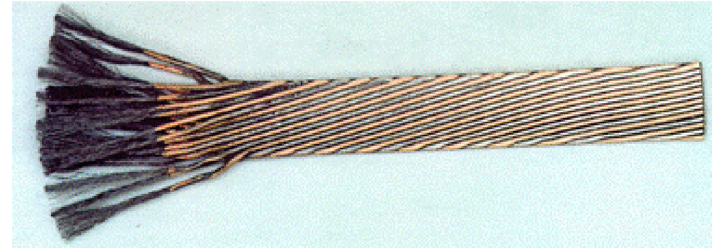


S. Caspi, A 16 T Canted-Cosine-Theta (CCT), An option for the FCC, Nov 2015.

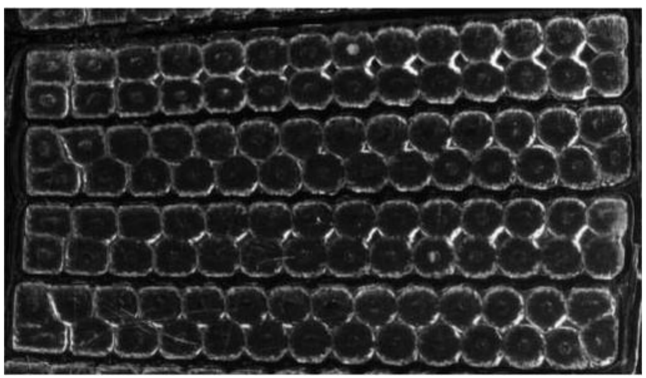
LHC Accelerator Magnets - Numerics

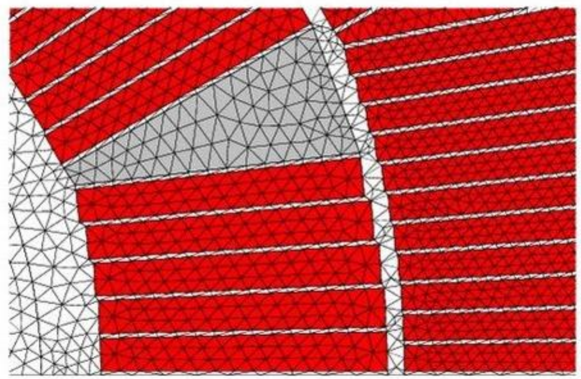
PAUL SCHERRER INSTITUT

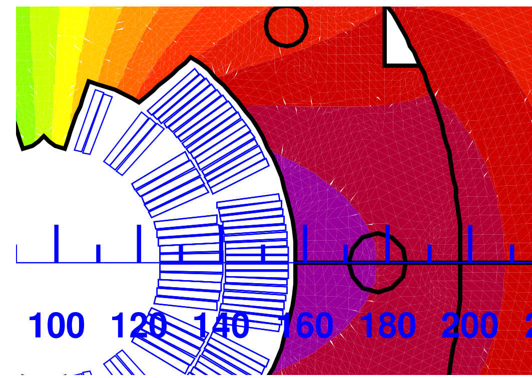
LHC Magnetic Design



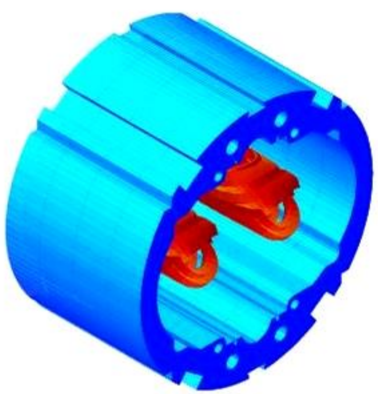
- Line-current models enable fast and accurate representation of SC strands in a Rutherford cable.
- Efficient optimization of coil geometry for field quality with 1000s of iterations.
- Addition of iron yoke by means of FEM and FEMBEM.

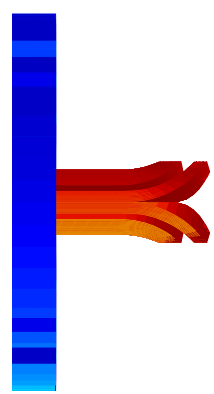


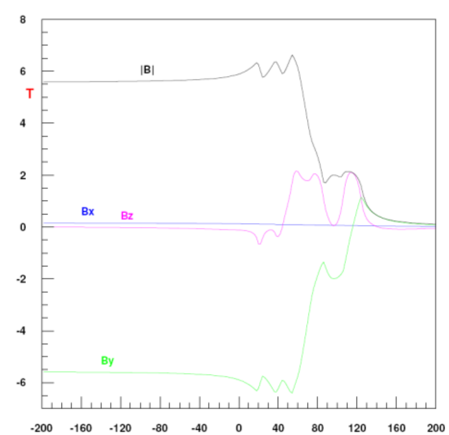




- 3D optimization for windability and integrated field quality.

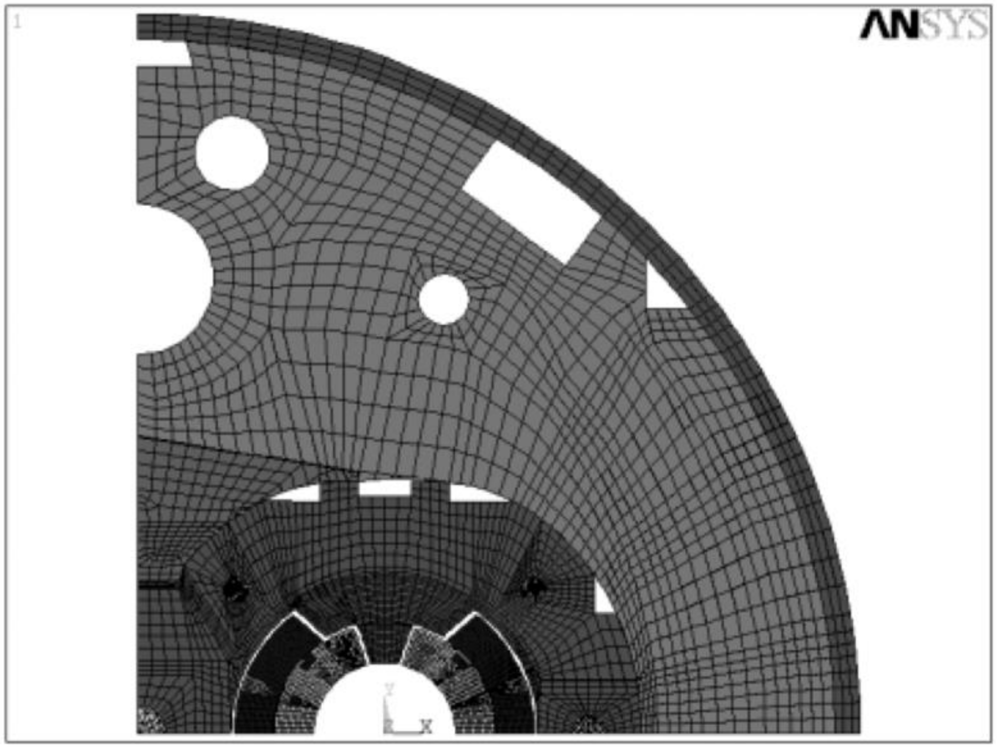






LHC Mechanics in ANSYS Classic (APDL)

- Mostly linear(ized) material properties.
- 2D and 3D optimization.



P. Ferracin, Mechanical and Magnetic Analysis of the Large Hadron Collider Main Dipole. PhD Thesis. 2002.

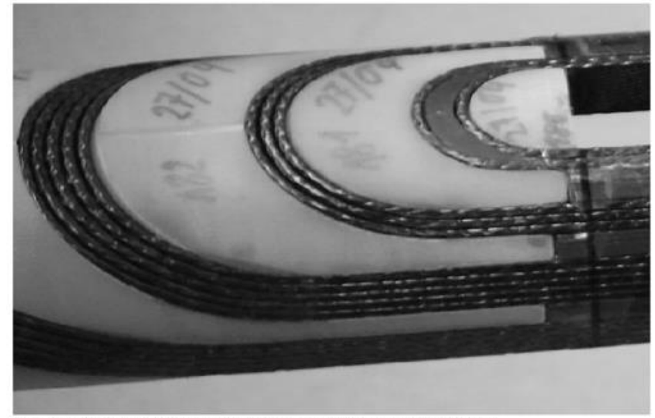


Fig. 2. Detail of inner layer coil non connection side head

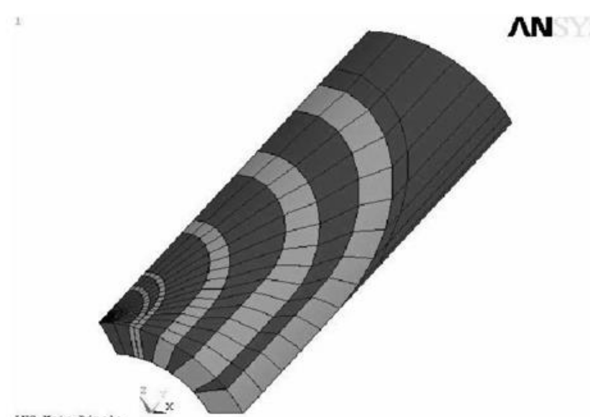


Fig. 3. The inner layer model extracted from the pole model. In light color the superconducting windings, in dark the composite spacers.

P. Fessia, I. R. Canseco, 3D FEM Modeling of the Coil Ends of the LHC Main Dipole, MT19, 2005.

Quench Protection

- Network models / finite differences, e.g., SPQR, ROXIE, Thea.
- Advantages:
  - Readily programmable by engineers and physicists.
  - Relatively simple inclusion of thin layers (insulation, heaters).
  - Relatively efficient.
- Disadvantages:
  - No fully-fledged numerical analysis – but do we mind?
  - Less than ideal for including non-linear iron behavior, bulk eddy-current effects, where relevant.
- Challenges:
  - Modeling of heat transfer in porous coils, filled with superfluid helium, hence conservative assumptions are used for design.

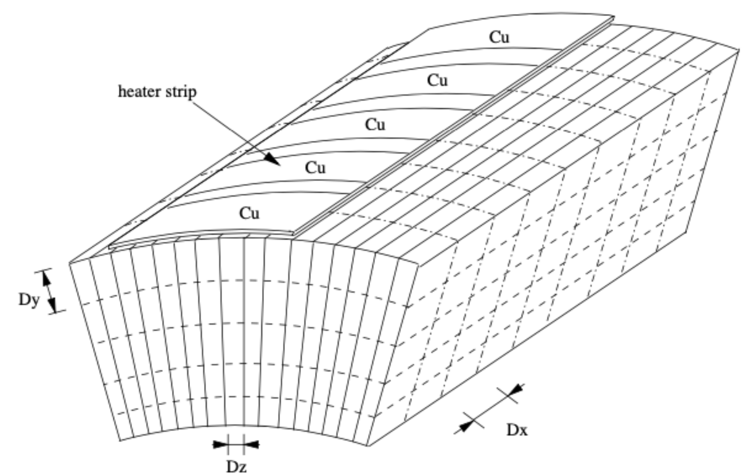
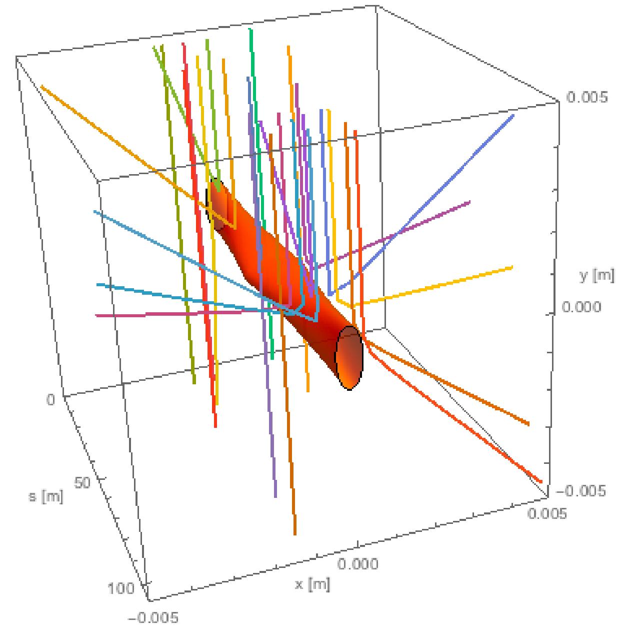


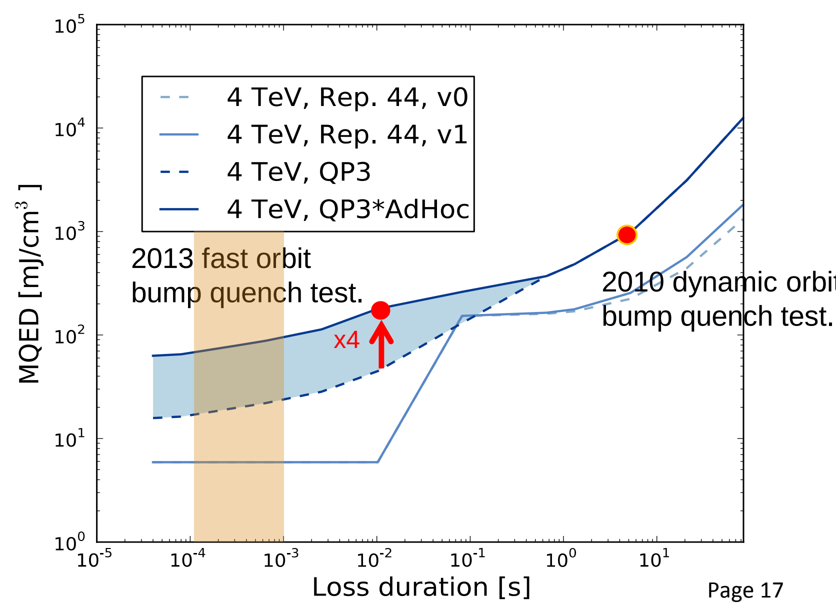
Figure 5: Discretisation of the coil geometry including quench heater strips.

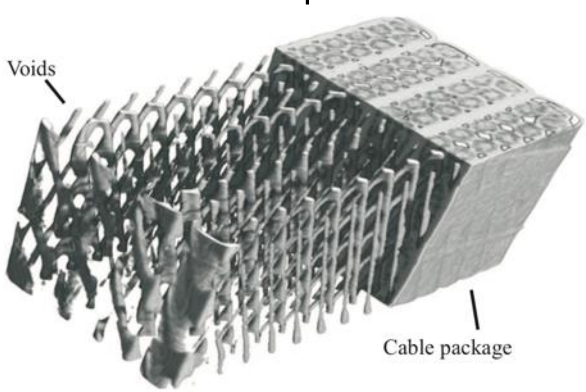
F. Sonnemann and M. Calvi. Quench simulation studies: Program documentation of SPQR simulation program for quench research. LHC Project Note 265, CERN, July 2001.

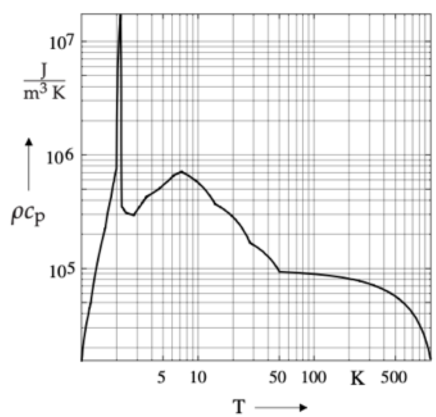
UFOs and MQE

- Unidentified Falling Objects, i.e., dust particles interact with the beam, causing particle showers to hit the SC coils and occasional magnet quenches.
- Modeling involves transient cooling mechanisms into confined volumes of superfluid helium:
  - Non-linearities and Helium phase transition
  - Kapitza heat transfer
  - Nucleate- and film boiling
  - Heat transport in superfluid and fluid helium
- Much modeling and experimental work exists on Minimum Quench Energy simulation.
  - Rutherford-cable shaped non-planar electro-thermal network models in QP3, Thea.
  - Some FEA work with COMSOL and OpenFoam.







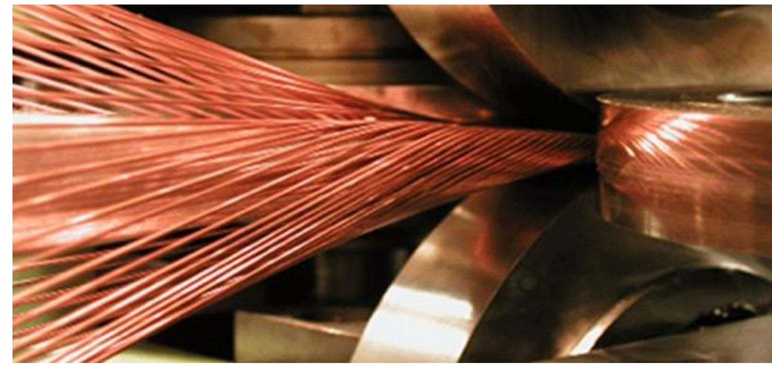


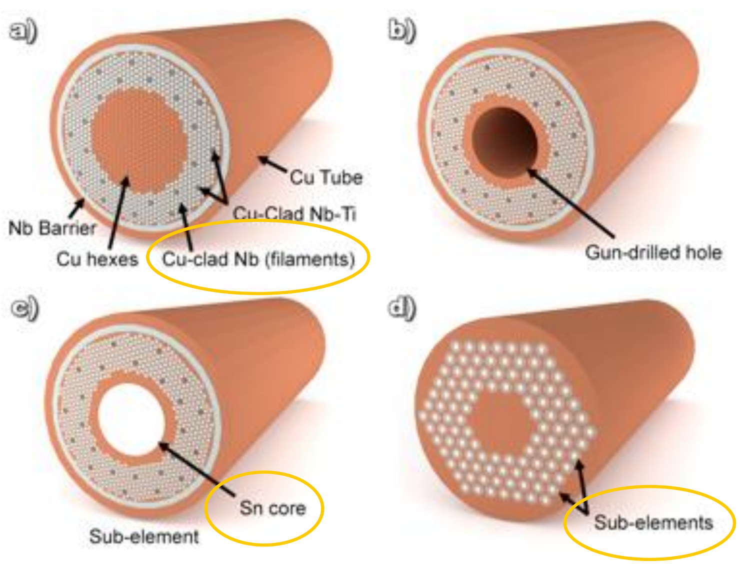
High-Luminosity LHC Nb_3Sn Magnets

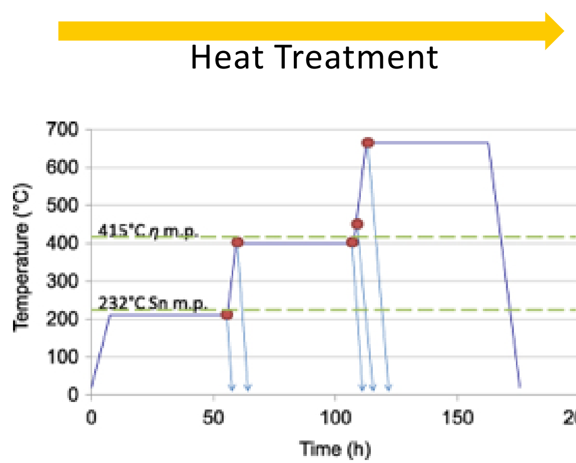
PAUL SCHERRER INSTITUT

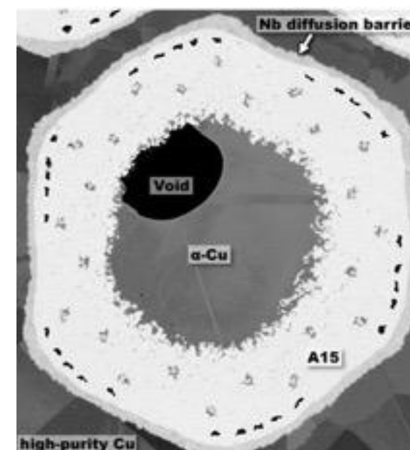
Nb3Sn Technology

- The superconducting A15 phase is brittle and strain sensitive. Niobium and Tin are, therefore, co-extruded in the Rod-Restack Process into a strand.
- In wind-and-react processes, several 10s of strands form a Rutherford cable, that is insulated and used to wind a coil.
- The A15 phase is created during a heat treatment of 180 h at up to 660ºC.





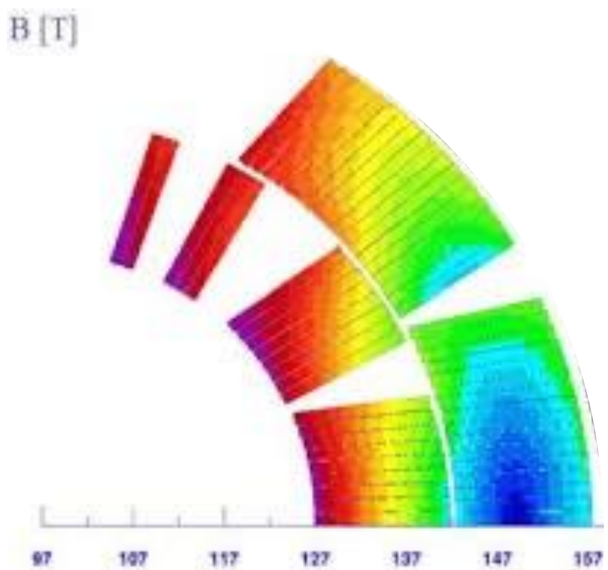


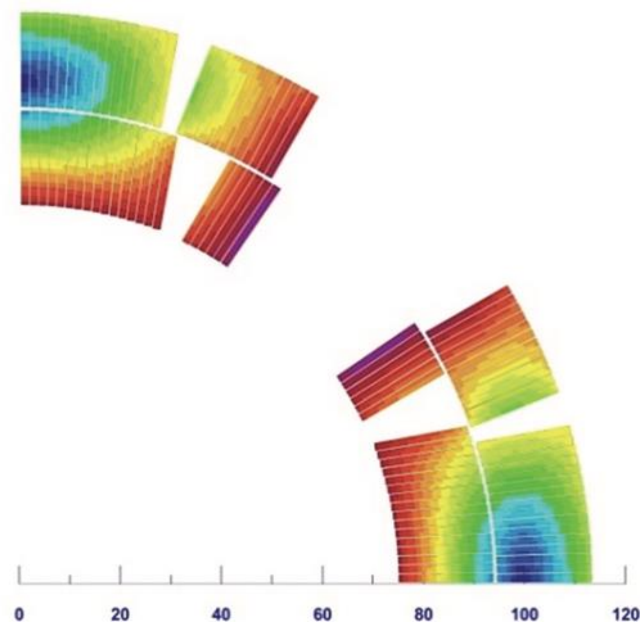


Subelement with A15 Phase

HiLumi Magnetic Design

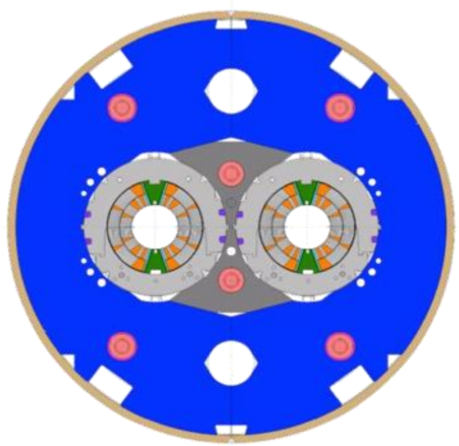
- For HiLumi Nb3Sn magnets 11 T and MQXF, cable design included approximative protection considerations.
- The magnetic design followed the LHC-magnet process, i.e., was carried out following only magnetic design criteria, without mechanical or protection considerations.

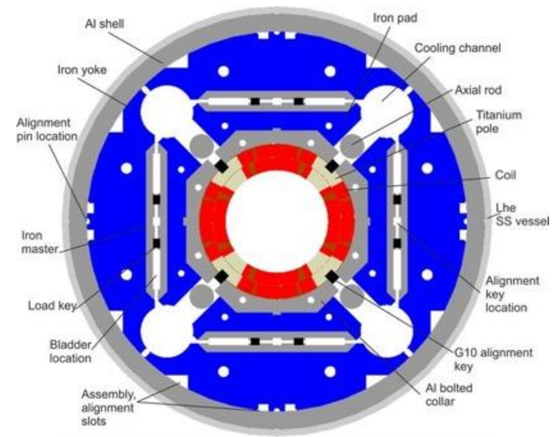


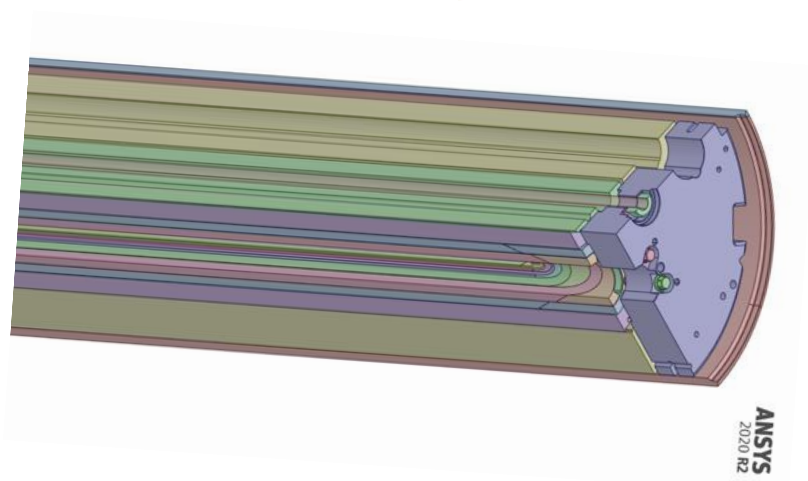


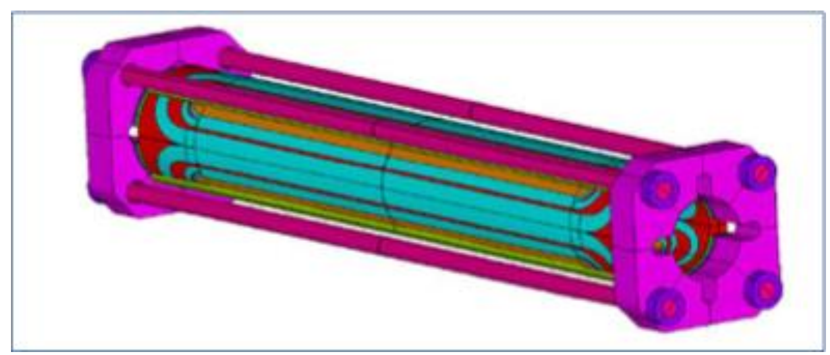
HiLumi Mechanical Design

- ANSYS classical and some workbench with CAD interfaces

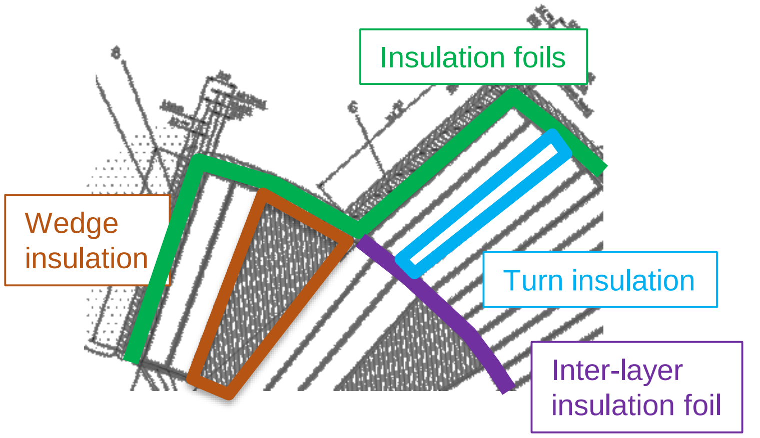








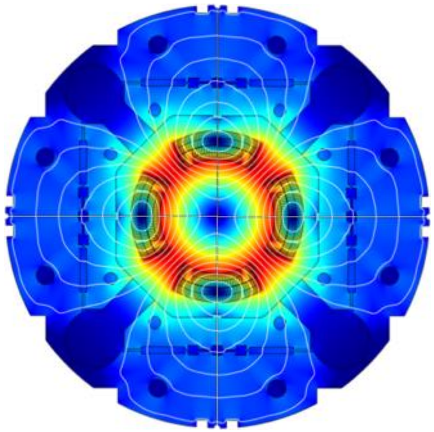
HiLumi Protection – Thin Layers

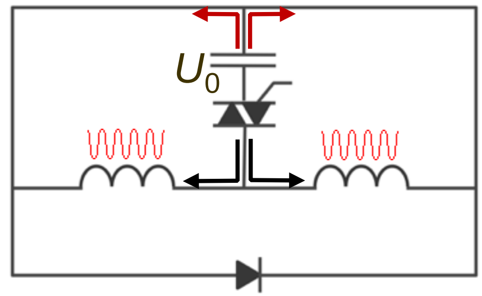


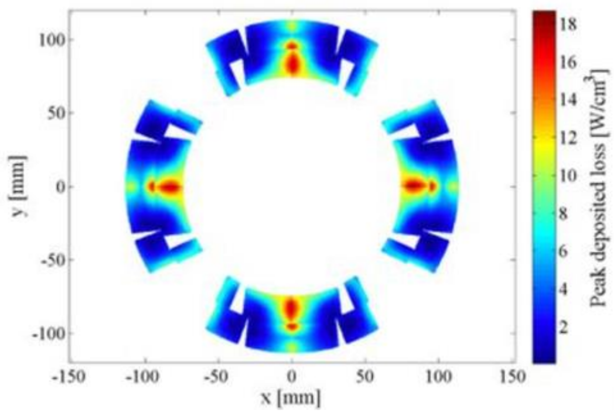
- Quench heaters
  - 20-50 µm stainless steel
  - 100 µm Kapton / G10
  - RC-discharge
  - Extreme non-linearities
  - Explicit-solver time step 10^{-7} s
- FEM thin-layer approximations frequently unstable.
- Network models generally stable and efficient.
- However, automatic layer—to-layer network generation, heat transfer to structural elements and eddy-current in bulk components are hard to include.

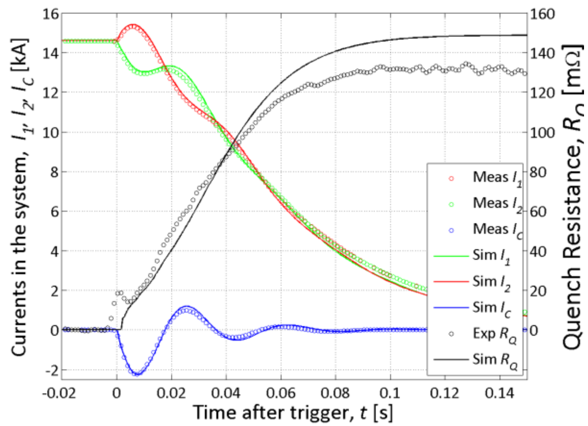
HiLumi Protection – CLIQ

- Heating through inter-filament coupling currents.







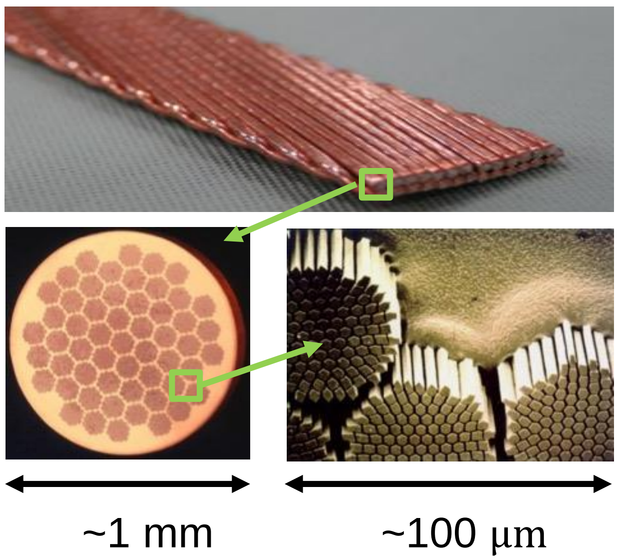


E. Ravaioli, et al. New, coupling loss induced, quench protection system for superconducting accelerator magnets. IEEE Transactions on Applied Superconductivity, 24, 500905, 2013.

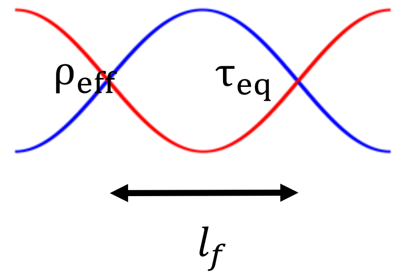
L. Bortot, et al. STEAM: A Hierarchical Co-Simulation Framework for Superconducting Accelerator Magnet Circuits, IEEE TASC 28(3), 2017.

Inter-filament Coupling

- Fully-transposed superconducting cable



When eddy-current paths are known a priori, an equivalent magnetization can be directly related to the change of magnetic flux density.



Equivalent time constant per filament loop

$$\tau_{\mathrm{eq}} = \frac{\mu_0 \mu_{\mathrm{r}}}{\rho_{\mathrm{eff}}} \left(\frac{l_f}{2\pi} \right)^2$$

- Formulation

$$\mu_0 \mu_{\mathrm{r}} \, \vec{M}_{\mathrm{IFCC}} = -\, \tau_{\mathrm{eq}} \partial_t \vec{B}$$

- Constitutive law

$$\vec{B} = \mu_0 \mu_{\mathrm{r}} \left(\vec{H} + \vec{M}_{\mathrm{IFCC}} \right)$$

- Ampere-Maxwell Law

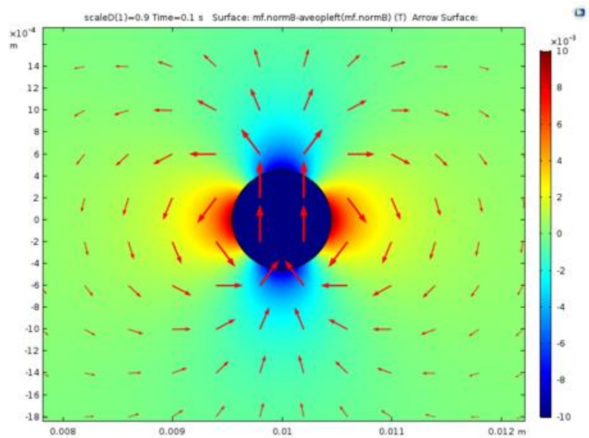
$$\sigma \frac{\partial \vec{A}}{\partial t} \longrightarrow -\nabla \times \vec{M}_{\mathrm{IFCC}} = -\, \nabla \times \frac{1}{\tau} \nabla \times \partial_t \vec{A}$$

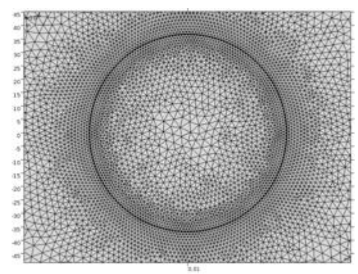
[1] H. D. Gersem and T. Weiland. Finite-element models for superconductive cables with finite inter-wire resistance. IEEE Transactions on Magnetics, 40(2):667–670, March 2004.

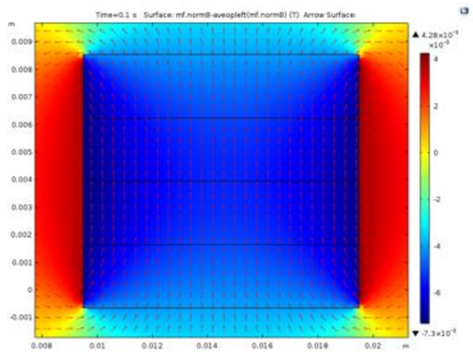
[2] A. Verweij. Electrodynamics of Superconducting Cables in Accelerator Magnets. PhD thesis, University of Twente Enschede, 1995.

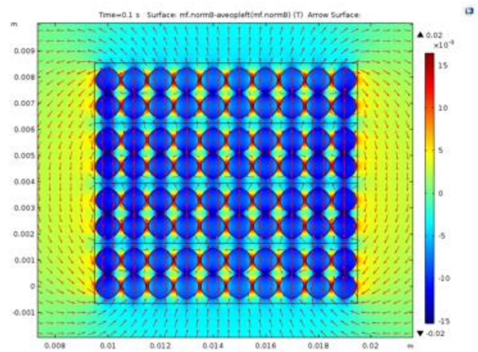
CLIQ IFCL Modeling - FEM

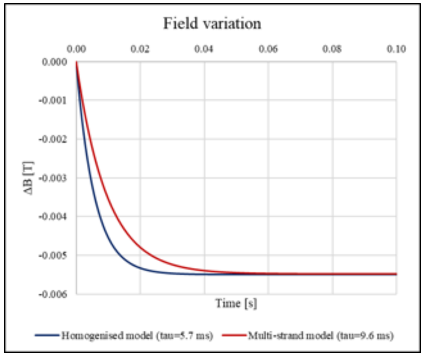
- Inter-filament coupling magnetization in COMSOL.











$$\vec{M}_{\mathrm{IFCC}} = -k_{\mathrm{ht}} \nu \tau_{\mathrm{IFCC}} \frac{\partial \vec{B}}{\partial t}$$

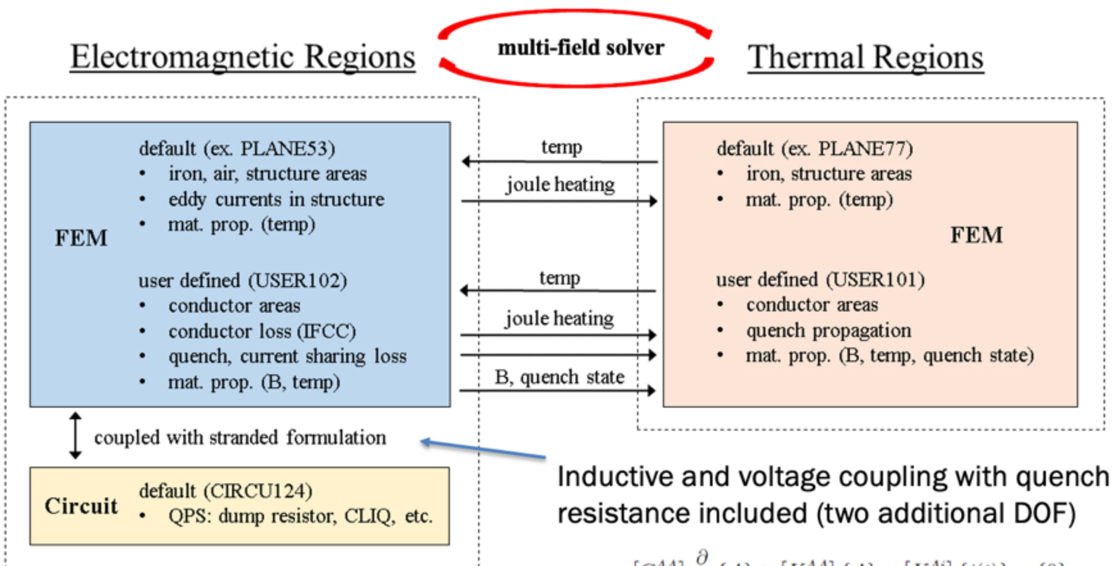
$$\vec{M}_{\mathrm{IFCC}} = -\nu \tau_{\mathrm{IFCC}} \frac{\partial \vec{B}}{\partial t}$$

	ΔB [T]	τ_{IFCC} [ms]
Homogenised model	5.47E-03	5.7
Multi-strand model	5.47E-03	9.6

H. De Gersem, Ad-hoc Homogenisation for Interfilament Coupling Currents, priv. comm. 2019.

ANSYS UDEs

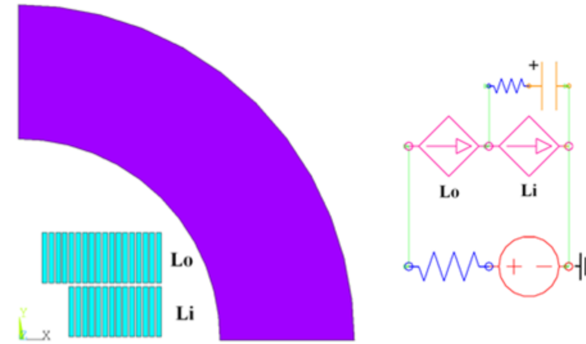
- Capturing multi-dependency material properties and the equivalent-magnetization term in Fortran programmed User Defined Elements.

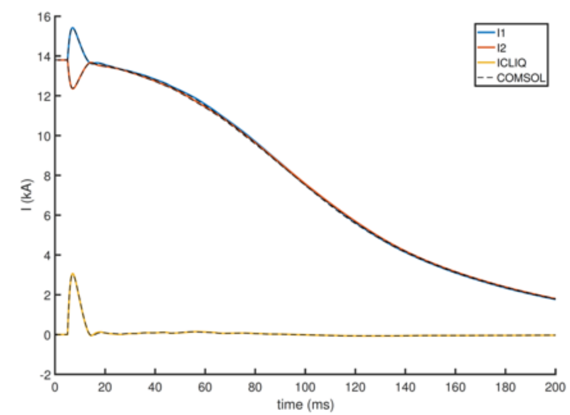


Inductive and voltage coupling with quench resistance included (two additional DOF)

$$[C^{AA}]\frac{\partial}{\partial t}\{A\}+[K^{AA}]\{A\}+[K^{Ai}]\{i(t)\}=\{0\}$$

$$[C^{eA}]\frac{\partial}{\partial t}\{A\}+[K^{ee}]\{e(t)\}+[K^{ei}]\{i(t)\}=\{0\}$$

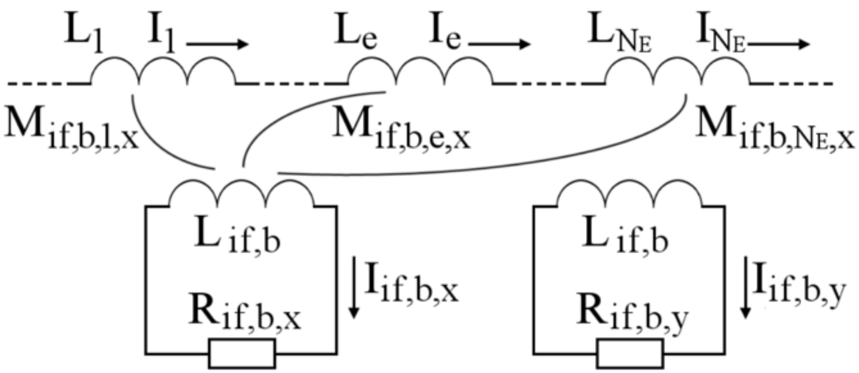


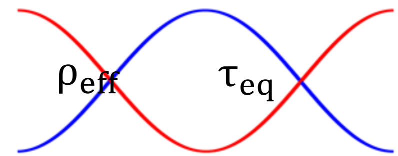


L. Brouwer et al. User defined elements in ANSYS for 2D multiphysics modeling of superconducting magnets, SC Science and Technology 32(9), 2019.

LEDET Network Model

- E. Ravailoli developed an equivalent network model, representing IFCC magnetization via inductively coupled RL loops.





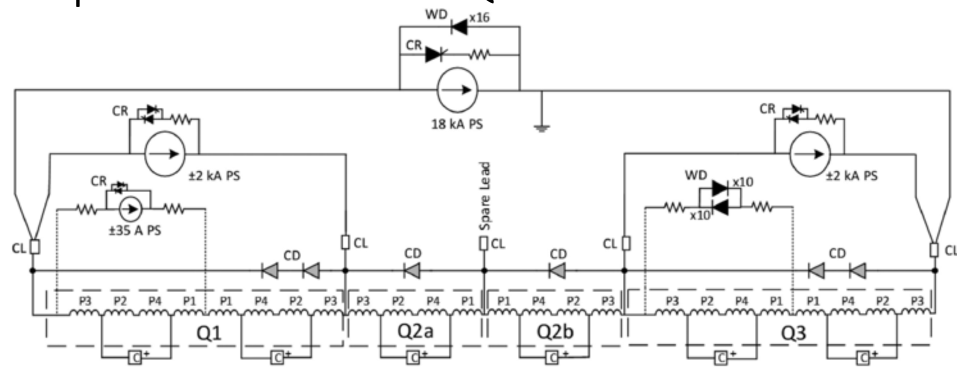
- All strands are represented without need to mesh them.
- A thermal model completes the model.
- Computationally highly efficient.
- Non-linear iron yoke, coil inductances, and field map taken into account via look-up tables and superposition. Strongly non-oinear situations cannot be captured accurately.

E. Ravaioli, et al., Lumped-Element Dynamic Electro-Thermal model of a superconducting magnet, Cryogenics 80(3), 2016.

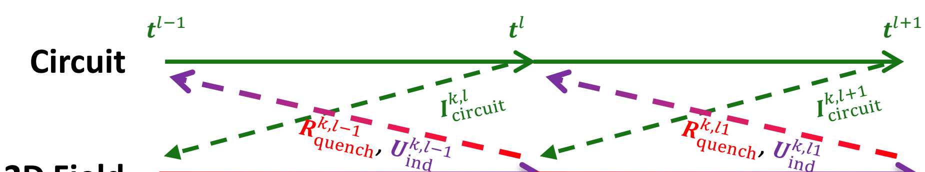
HiLumi Circuit-Wide Cosimulation

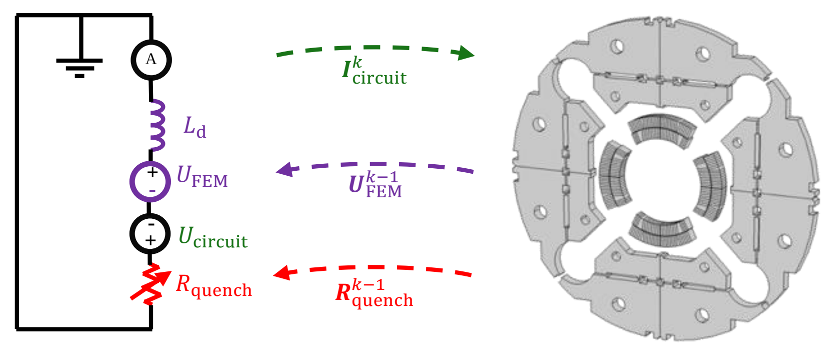
- Final-Focussing Quadrupole Circuit contains six quadrupole magnets. All magnets must be quenched in order to protect the initially quenching one.
- Magnets are protected by combination of quench heaters and CLIQ units.
- A plethora of failure scenarios ensues.

R^{k-1}_{quench}



- Co-simulation via waveform relaxation of six LEDET models in a PSpice circuit.



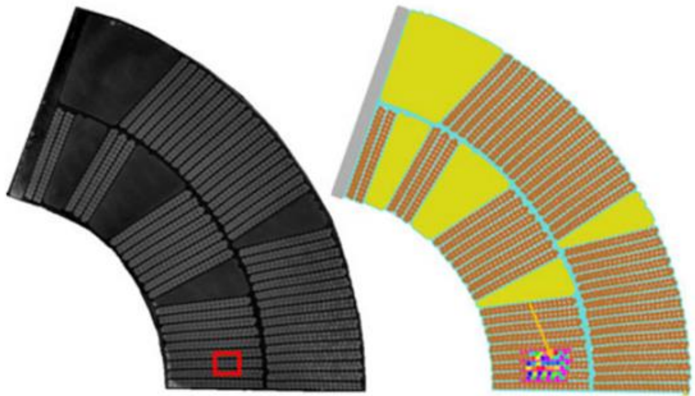


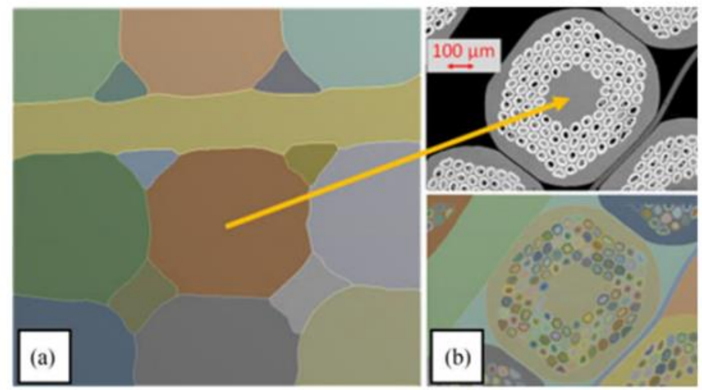
$U_{\text{circuit}} = L_{\text{d}}\, \partial_t I^{k}_{\text{circuit}}$

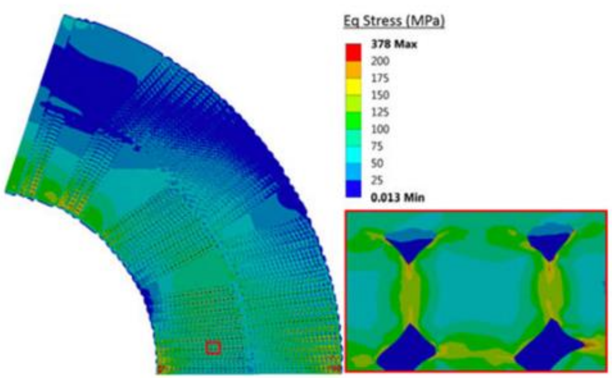
E. Ravaioli et al., Quench Protection Studies for the High Luminosity LHC Nb3Sn Quadrupole Magnets, IEEE TASC 31(5), 2021.
M. Maciejewski, Co-Simulation of Transient Effects in Superconducting Accelerator Magnets, PhD Theses, Lodz University, 2018
I. Cortes Garcia, et al. Optimized Field/Circuit Coupling for the Simulation of quenches in Superconducting Magnets.
IEEE Journal on Multiscale and Multiphysics Computational Techniques, accepted for publication, 2017.

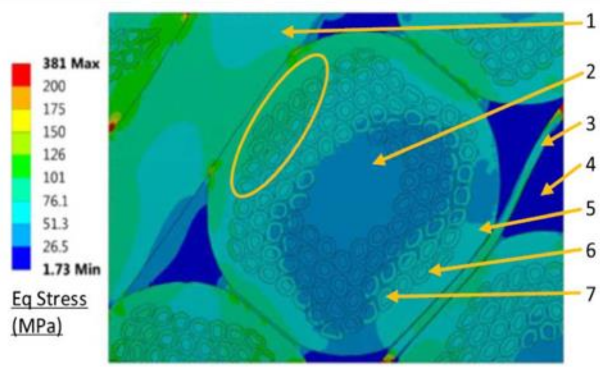
Conductor degradation and sub-modeling

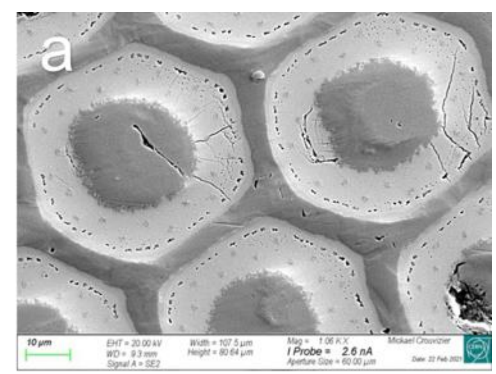
- Image-based models and sud-modeling – to be combined with failure criterion for irreversible degradation modeling.









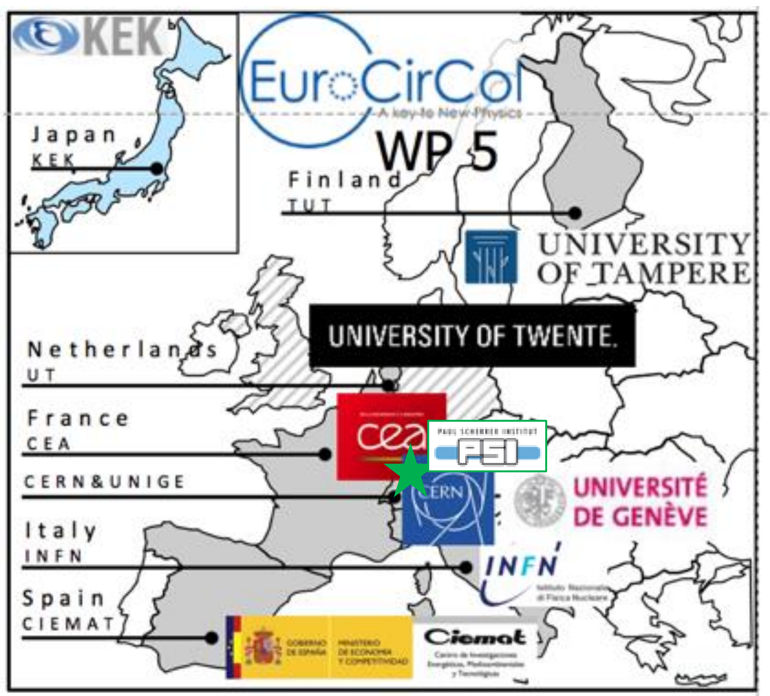


M. Daly et al., Multiscale Approach to the Mechanical Behavior of Epoxy Impregnated Nb3Sn Coils for the 11 T Dipole, IEEE TASC, 28(3), 2018.

FCC Design of Nb3Sn Magnets

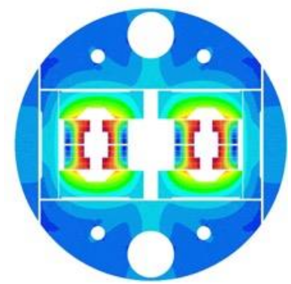
FCC Dipole Magnet Designs, 16 T

- European Circular Energy-Frontier Collider Study started 2015
- PSI joined the effort in 2016 as an "associate member" of WP5
- Magnets fulfill specs for both, FCC-hh and HE-LHC.

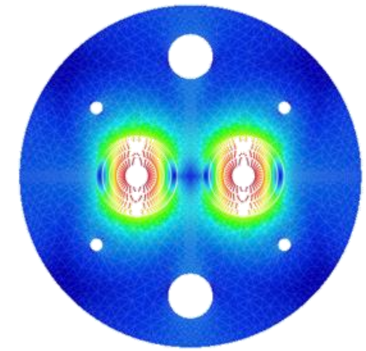


[D. Tommasini, http://cern.ch/fcc/eurocircol]

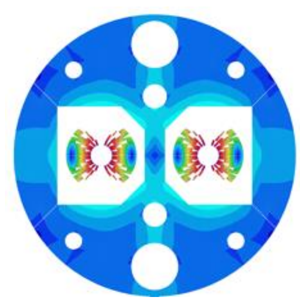
Block coil



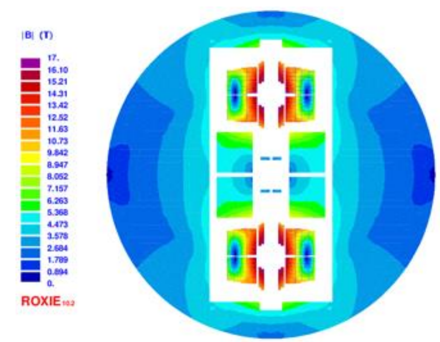
Canted Cosine Theta



Cos-theta



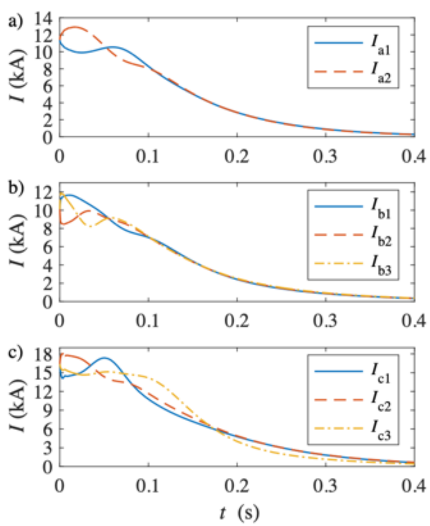
Common coils

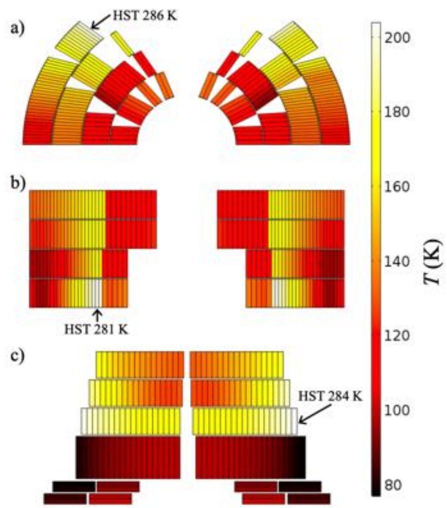


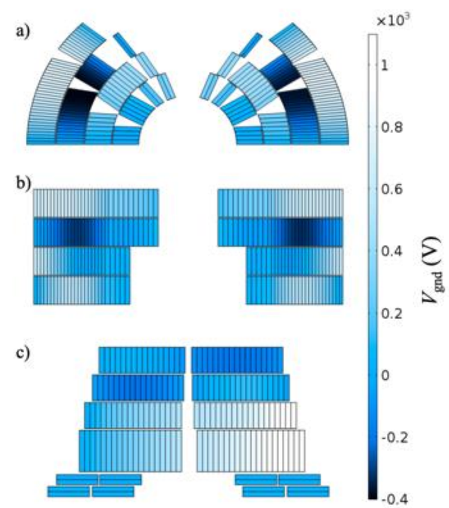
Magneto-Mechanical-Thermal-Electrical Design

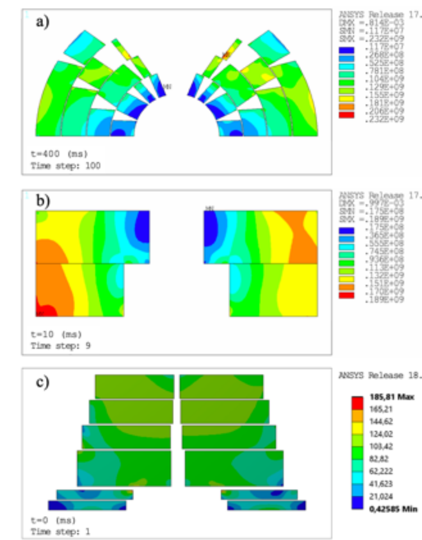
STEAM

- Initial Coil designs based on magnetic and efficiency (cost) considerations and worst-case protection approximations.
- Mechanical and detailed protection design are closely interwoven. Here using MpCCI mesh transfer to ANSYS.







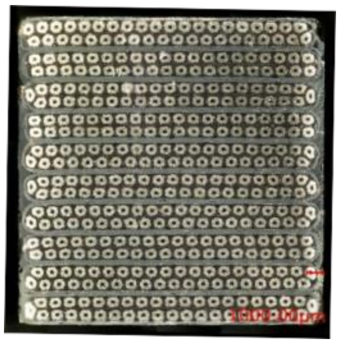


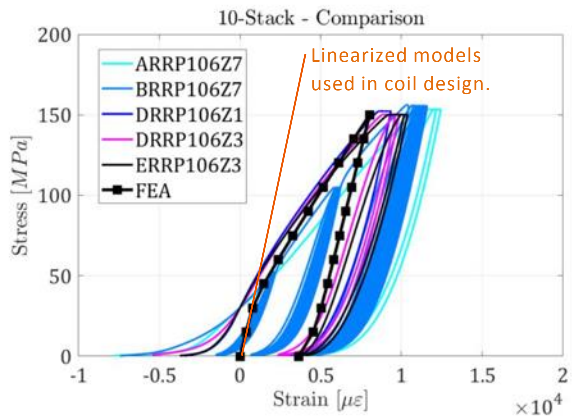
M. Prioli, et al., The CLIQ quench protection system applied to the 16 T FCC-hh dipole magnets, IEEE TASC, 29(8), 2019.
M. Maciejweski, et al., Coupling of Mechanical and Magneto-Thermal Models of Superconducting Magnet by Means of Mesh Based Interpolation , IEEE TASC, 28, 2017.

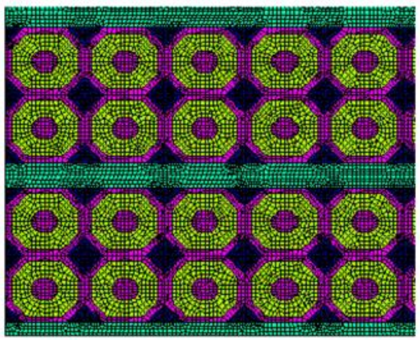
- Lately, coil-layout is optimized for both, field quality and mechanical peak stresses simultaneously.

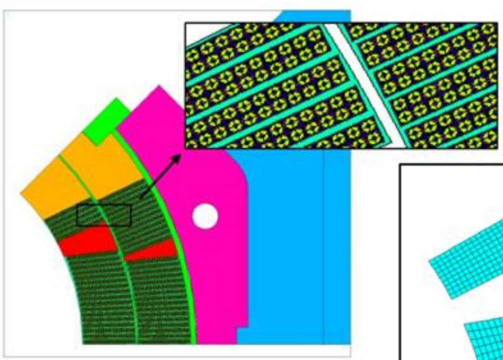
Mechanical Homogenization Techniques

- Improved modeling of mechanical coil models are emerging from HiLumi project.
- Plastic aniostropic coil properties are extracted from validated 10-stack simulations.

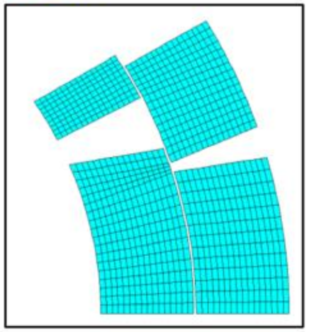




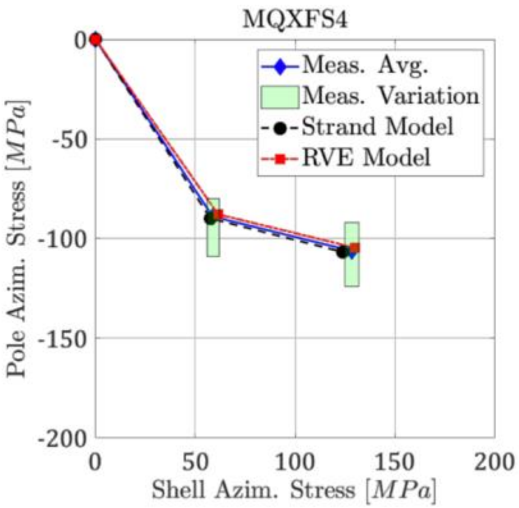




Strand Model



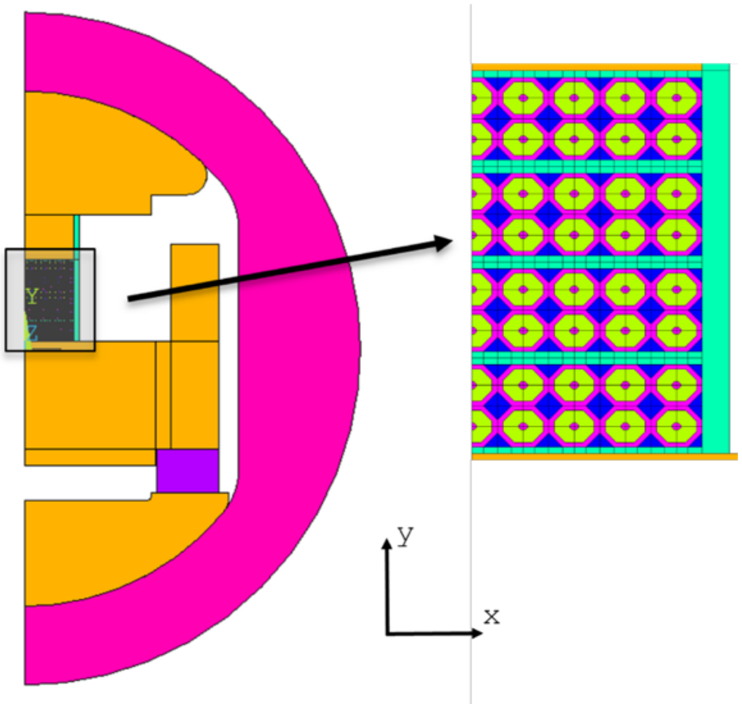
'RVE' Model

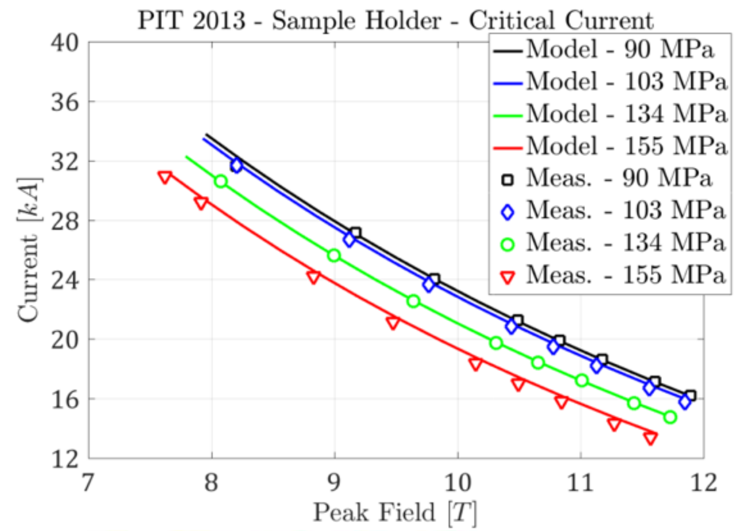


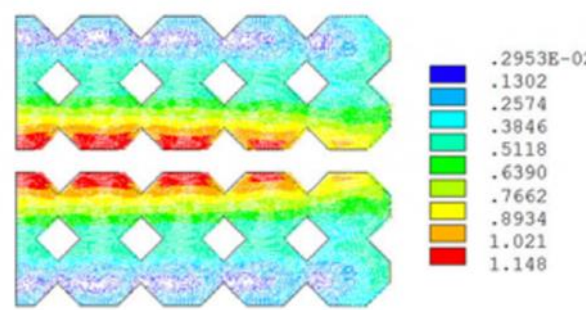
G. Vallone, Coil Composite and Interface Engineering, presentation at the HFM State of the Art Workshop, 2021.

11 T Conductor Degradation

- Conductor degradation on the midplane turn leads to detailed investigations.

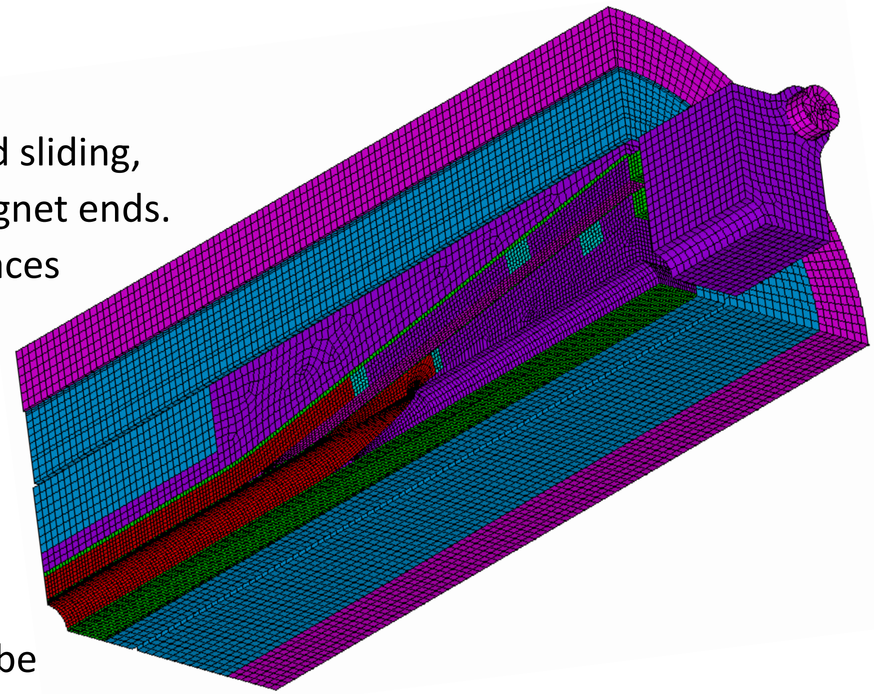




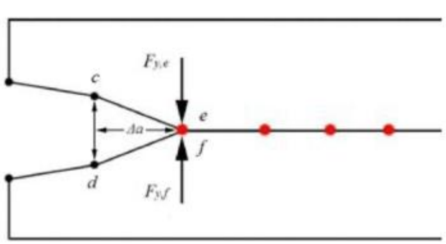


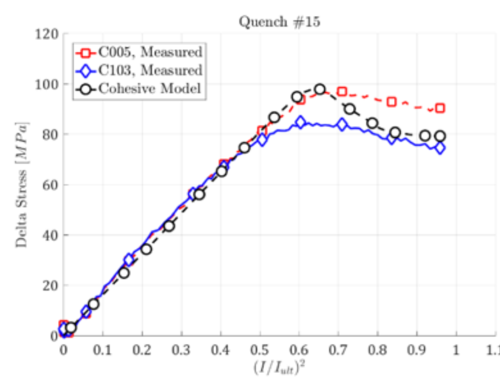
G. Vallone et al, Computation of the Reversible Critical Current Degradation in Nb3Sn Rutherford Cables for Particle Accelerator Magnets, IEEE TASC, 28(6), 2018.

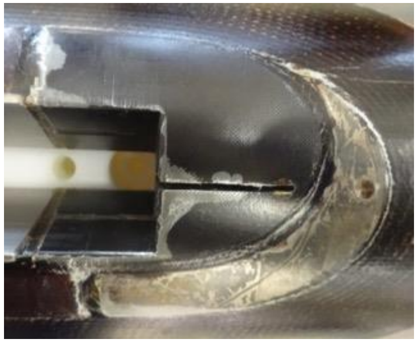
Interface Modeling and End Loading



- Dozens of interfaces, nominally bonded and sliding, determine the strain distribution in the magnet ends.
- Sudden de-bonding of highly-loaded interfaces as well as stick-slip motion cause quences.
- Uncontrolled distribution of relative thermal contraction can cause localized strain and conductor degradation.
- Transverse pre-load influences end load.
- Ends and straight section should no longer be designed sequentially.
- Submodelling and damage criteria need to be introduced in 3D!

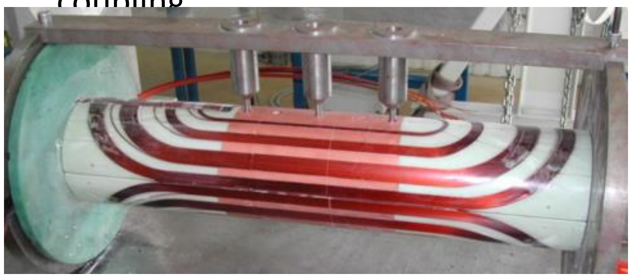


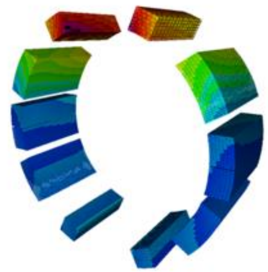


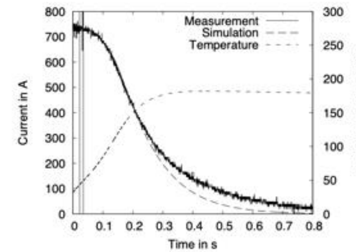


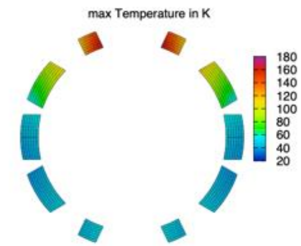
Quench Propagation

- Relevant for initial hot-spot evolution as well as self- and passively protected magnets.
- Typically electro-thermal network models, not including magnetic effects such as inter-filament coupling

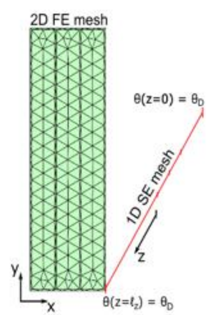


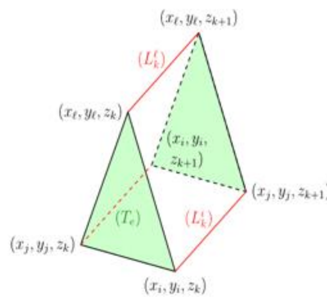


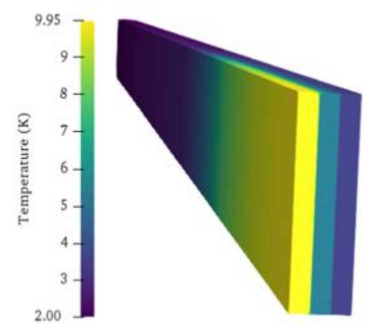




- STEAM/LEDET3D includes IFCLs.
- Quasi-3D FEM with spectral elements







L. D’Angelo, Quasi-3D Discretization of Thermal Hot-Spot Propagation in Superconducting Models, submitted for publication, 2001.

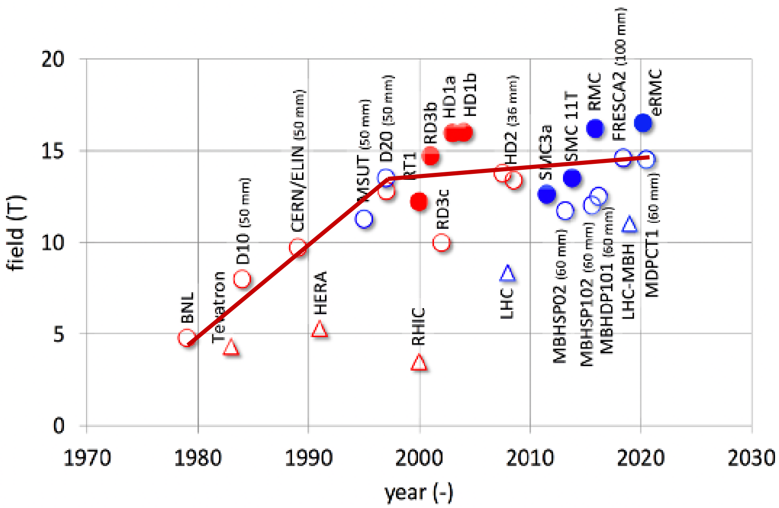
- 3D hp-adaptive FEM, see plans to use http://sparselizard.org (Alexandre Halbach) at Tampere.

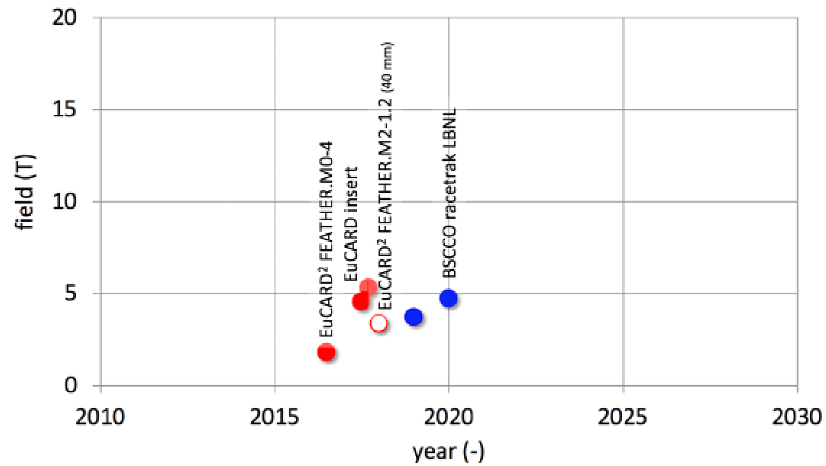
PAUL SCHERRER INSTITUT

Nascent HTS Magnet Technology for Accelerators

Genealogy of LTS and HTS Magnets

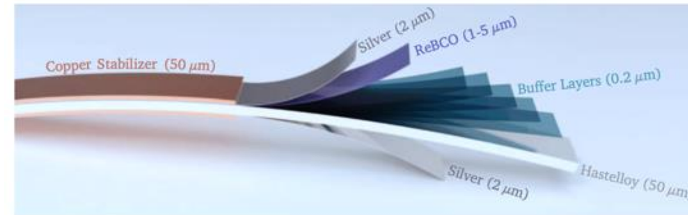
- We witness the early infancy of HTS technology for accelerator magnets.

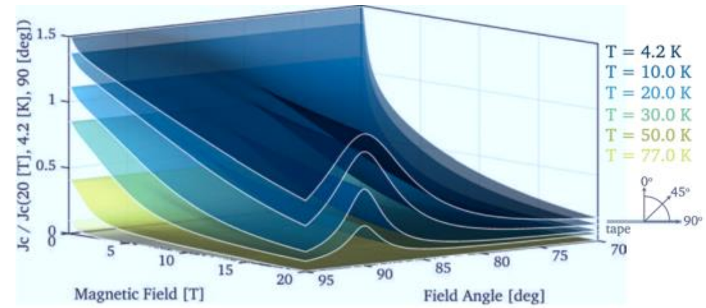


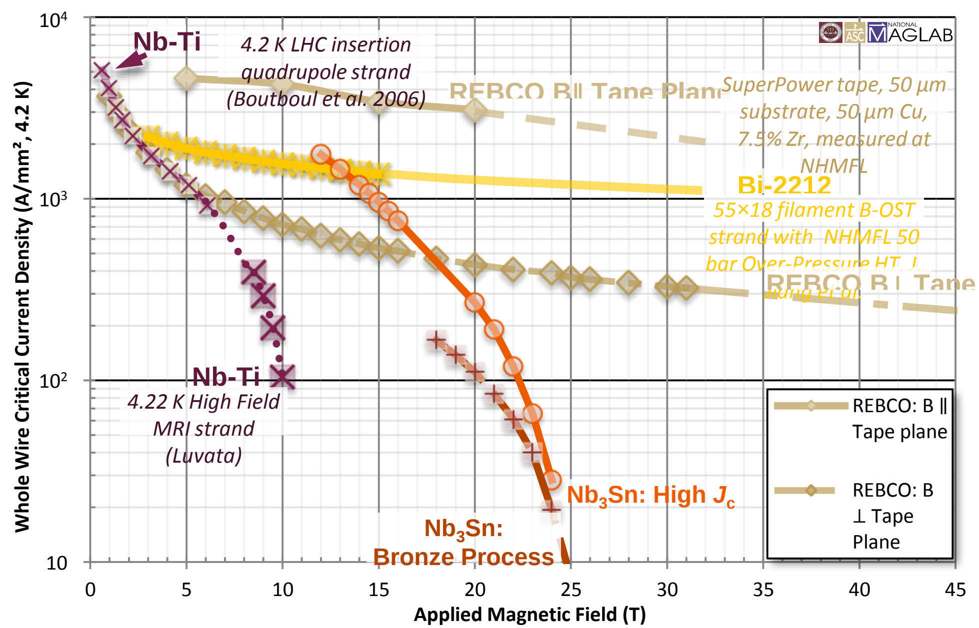


REBCO Tape Conductor – Challenges

- Angular dependency of Jc.
- Very high Bc0 → dream of 20 T accelerator magnets and more.
- Many practical challenges ahead:
- $V = R(\ell, T)I$ → voltage detection only at high temperatures!
- High current margins at low fields lead to very high screening currents.
  - Field quality issues.
  - Force issues.
- Quadratic scaling of forces on structure needs to be managed.
- Jointing techniques required to feed the magnets safely.
- Etc.

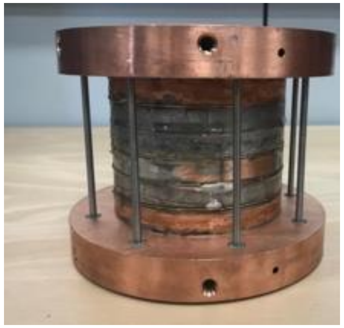


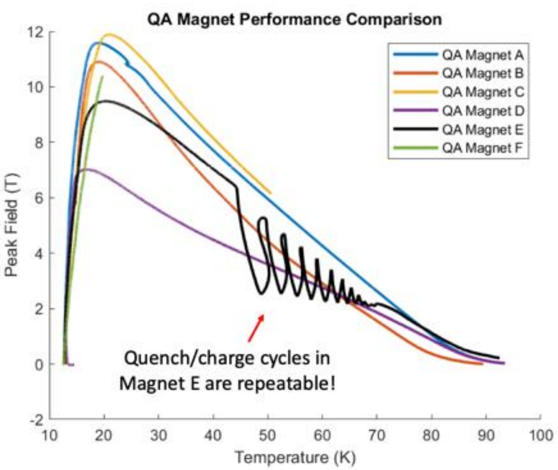


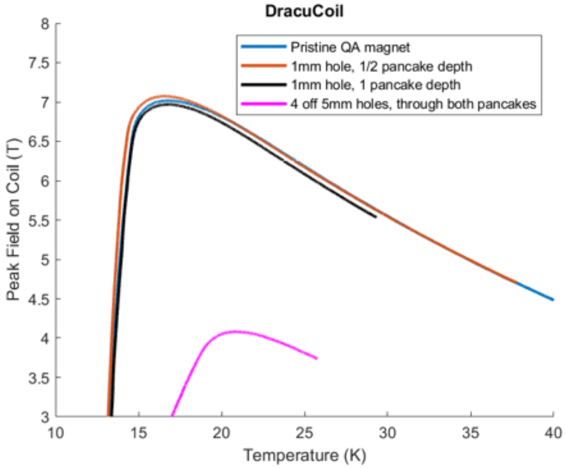


NI and PI Coils - Quench Mayhem

- Non-insulated or solder-impregnated coils promise incredible robustness for static applications (no ramping with beams).



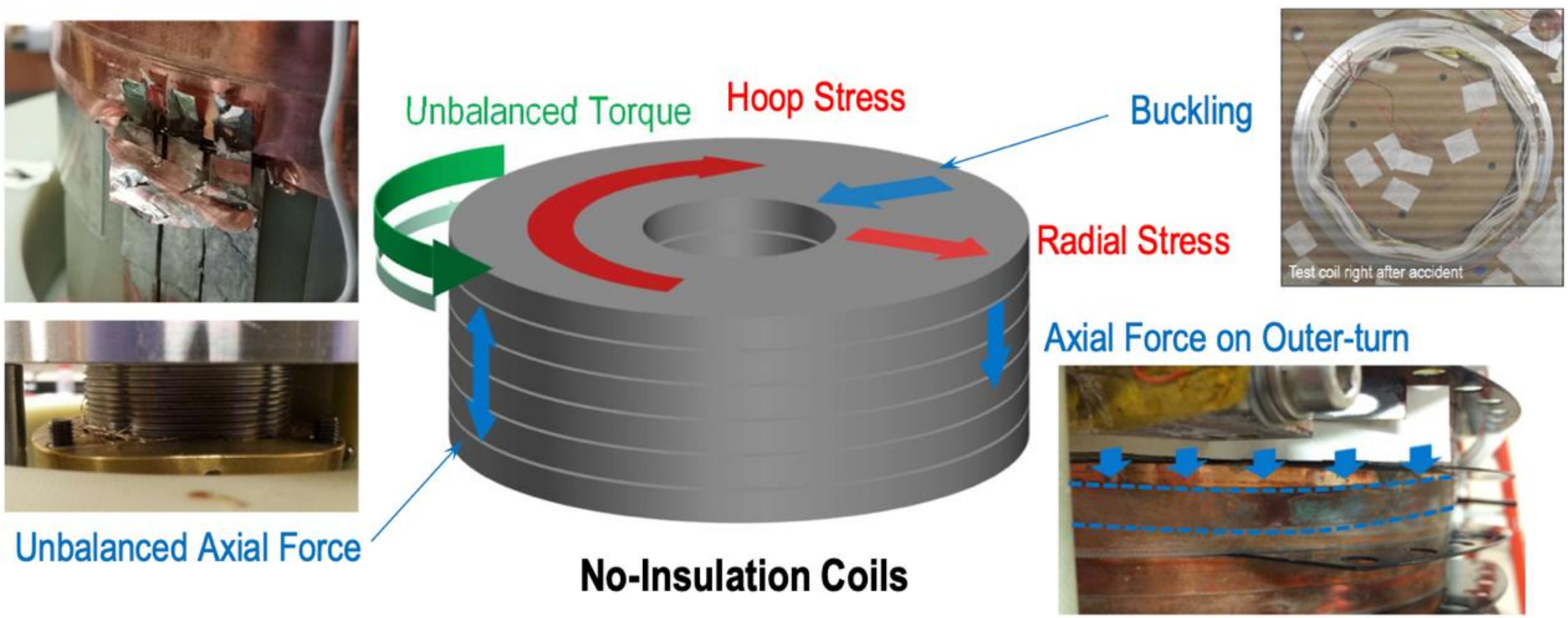




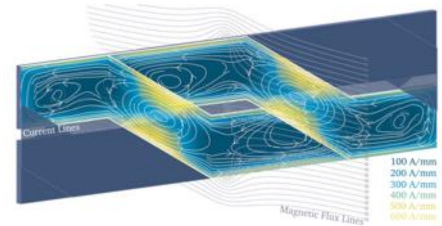
G. Brittles, et al, Stability and quench - dynamic behaviour of Tokamak Energy REBCO QA coils, https://indico.cern.ch/event/775529/contributions/3334053/

NI Coil Disadvantages

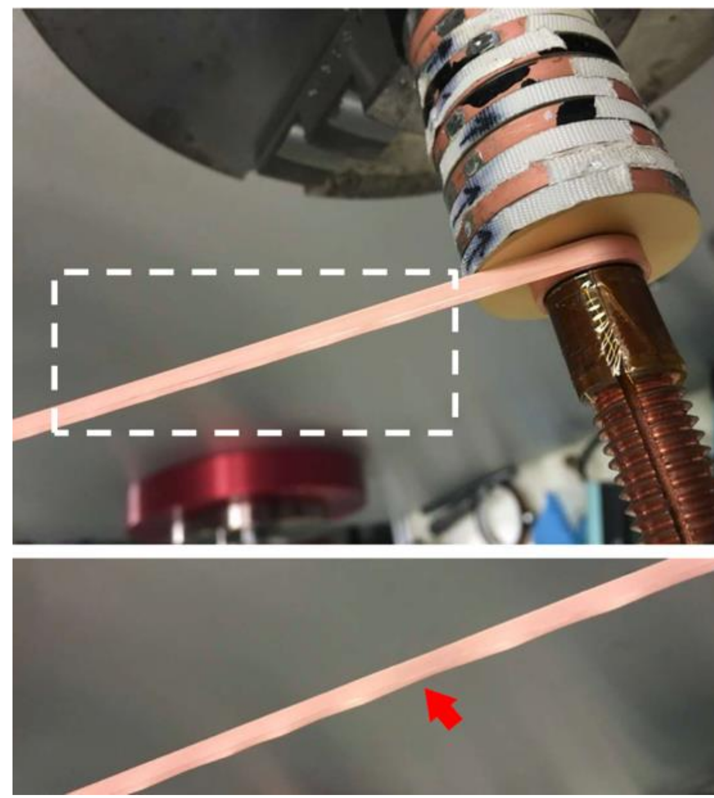
- Charging time constant scales quadratically number of turns and length – charging times quickly grow from hours on sample magnets to years on accelerator magnets.
- Unbalanced forces in case of quench.

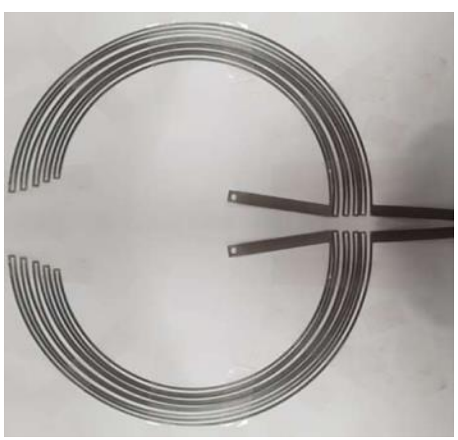


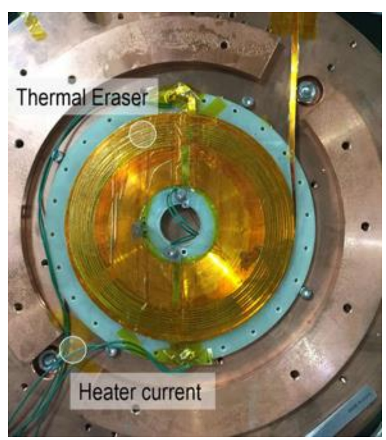
Screening Currents – Field Quality and Forces



- Screening Current problem:
- High Jc of REBCO is problematic in many zones of the magnet:
  - Excessive current margins enable large screening currents to be induced during ramping.
  - Field quality deteriorates.
  - In high fields (e.g. ~30 T high-field solenoid) mechcanical damage was observed due to resulting Lorentz forces.
- Different grading methods are studied to manage margins.
- Interesting approach: Thermal Eraser







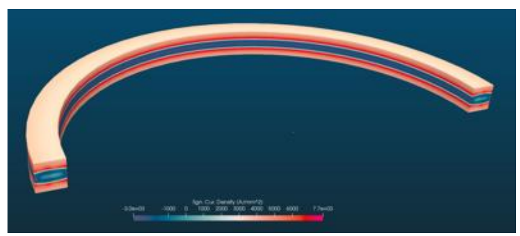
J. Bang et al., "Thermal Eraser to mitigate screening current in an HTS coil," MT26 International Conference on Magnet Technology, Vancouver, Canada, 2019

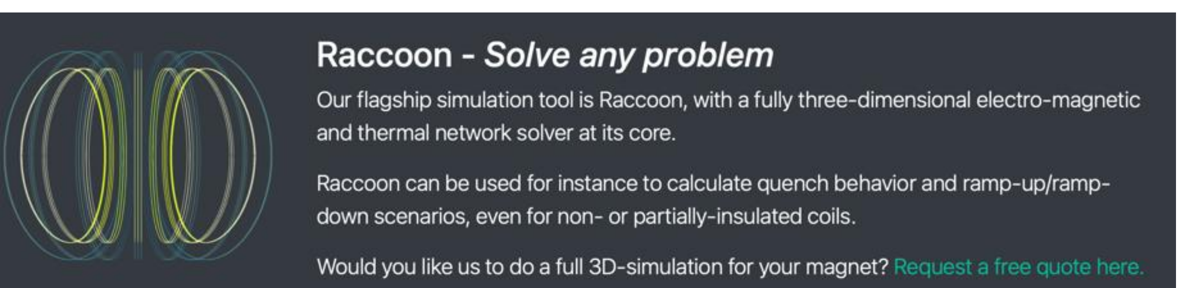
Modeling NI Coils – A Recurring Theme

- As happens frequently, network models (PEEC) are used for frontier applications.
- Raccoon (with Rat magnetic solver, free, http://littlebeastengineering.com) is the most advanced PEEC solver.
- TEMF/CERN develop the A-H formulation with appropriate dimensional reduction for a clean FEM approach.
- Simplistic homogenized FEM models may cover much the same areas at lower computational cost.

A Coupled A-H Formulation for Magneto-Thermal Transients in High-Temperature Superconducting Magnets

L. Bortot, B. Auchmann, I. Cortes Garcia, H. De Gersem, M. Maciejewski, M. Mentink, S. Schöps, J. Van Nugteren, and A.P. Verweij





Letters
IOP Publishing
Superconductor Science and Technology
Supercond. Sci. Technol. 33 (2020) 08LT01 (8pp)
https://doi.org/10.1088/1361-6668/ab9688

Letter

Finite-element modelling of no-insulation HTS coils using rotated anisotropic resistivity

R C Mataira[1], M D Ainslie[2], R A Badcock[1] and C W Bumby[1]

[1] Robinson Research Institute, Victoria University of Wellington, 69 Gracefield Road, Lower Hutt 5010, New Zealand
[2] Bulk Superconductivity Group, Engineering Department, Trumpington Street, Cambridge CB2 1PZ, United Kingdom

E-mail: ratu.mataira@vuw.ac.nz

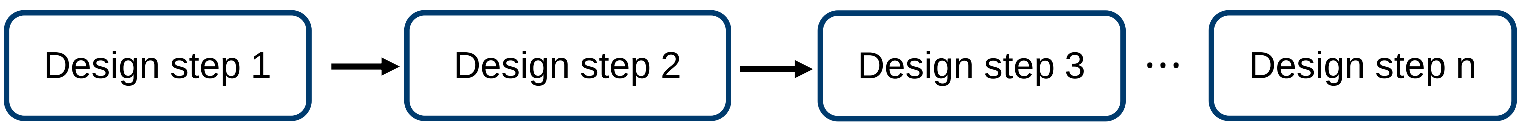
Received 30 January 2020, revised 4 May 2020
Accepted for publication 26 May 2020
Published 19 June 2020

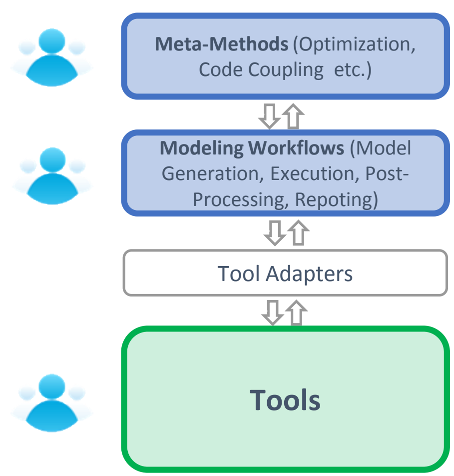
PAUL SCHERRER INSTITUT

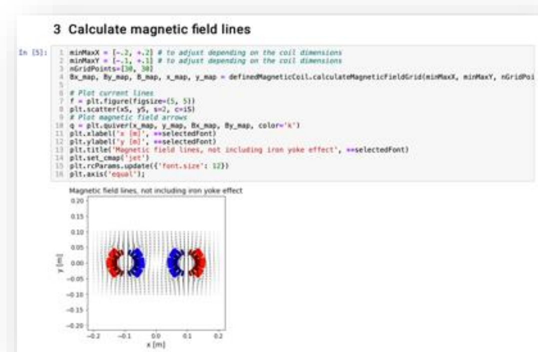
From numerics to design – an MBSE framework approach

MagNum Project: Sustainable Design and Development

- Flexible coupling of numerical tools and streamlining of complex workflows.
- Workflows with
  - end-to-end documentation of input parameters, tool versions, figures of merit, etc. via parameterized notebooks.
  - defined interfaces that can be implemented with different tools and modeling depths.
- Auto-run execution pipelines for code-testing and design-reproducibility.
- Workflow develoment and maintenance shall become a decentralized community effort.





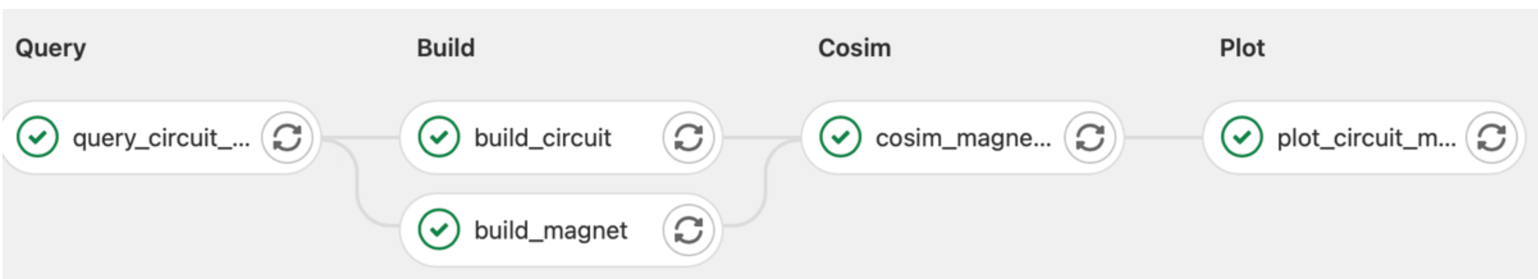


MagNum Example: LHC Main Dipole Digital Twin

An example of this approach is a modelling pipeline for the LHC main dipole circuit.
Given a timestamp of a quench event in the LHC, the pipeline automatically:

- **queries** over 500 signals from the magnet and circuit protection hardware
- **builds** and simulates monolithically circuit and magnet models
- **cosimulates** both models to obtain non-measurable signals (e.g., temperature, resistance)
- **plots** and compares selected signals for model validation

GitLab



Model-Based Project Lifecycle Management: Auto-run execution of the digital twin pipeline on parameter change as well as for code-testing and design-reproducibility.

Take-Aways 1/2

- With every generation of accelerator magnets, we see an increase of:
  - interconnectedness between physical disciplines,
  - need for sub-modeling and homogenization,
  - need for 3D simulations,
  - transient simulations with extreme non-linearities,
  - all of which becomes important already in the earliest stages of magnet design.
- Numerical tools
  - **Network / Finite Differences**, discretizing along and transverse to the coil winding
    - tend to spearhead development and innovation in our field:
      - many engineers/appl. physicists “need” to code in order to develop intuition,
      - most intuitive form of numerics.
      - reduces meshing difficulties.
      - generally good performance.
    - typically run into limitations related to
      - non-linear iron yokes
      - bulk superconductivity
    - can be linked to reduced-vector-potential FEM or FEM/BEM by means of Biot Savart solver to overcome this.

Take-Aways 2/2

- **Fully integrated commercial codes** (ANSYS, COMSOL) are of increasing importance.
  - in particular, when tight link to mechanical simulation is needed.
  - many young engineers have key competence in one tool (Swiss knife).
- **Open FEM tools** play a role in electromagnetic and thermal modeling, implementing transient problems and workflows that involve submodelling and/or homogenization.
  - encapsulation of numerics setup in easy-to-use and license-(cost)-free workflows will serve the wider community of magnet engineers.
  - openness allows student to implement new features.
  - license-(cost)-free workflows can run on clusters to cover a wider design space.

- **MagNum**: the framework for sustainable and flexible workflow development and design. Project under way at ETHZ – will open up to the community in the coming 1-2 years.