Simulation Needs and Challenges for Accelerator Magnets

Some of the work supported by the Swiss State Secretariat for Education, Research and Innovation SERI.
• 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
• 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 $\leq 10^{-4}$.

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

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

Accelerator Magnets

Horizontal Lorentz force per coil quadrant 1.7 MN/m
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

\[ B = 8.7 \, \text{T} \]

So, if \( \delta = 10 \, \mu \text{m} \)

then \( Q = 4.1 \times 10^4 \, \text{J/m}^3 \)

and from \( T_0 = 1.9 \, \text{K} \)

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

• We must \textbf{control sudden strand motion to better than 10 \( \mu \text{m} \)!}
Magnet Circuits

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

<table>
<thead>
<tr>
<th>W</th>
<th>$M_{cu}$</th>
<th>20 t truck $v_{km/h}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 MJ</td>
<td>9.6 kg</td>
<td>95 km/h</td>
</tr>
<tr>
<td>1100 MJ</td>
<td>1515 kg</td>
<td>~Mach1</td>
</tr>
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</table>
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.
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
• Iselin, 1973, computer program MAGNET, PS poleface-winding optimization (MINUIT) for multipole control.

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

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.


• 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.

• 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 electrothermical network models in QP3, Thea.
  – Some FEA work with COMSOL and OpenFoam.
High-Luminosity LHC Nb$_3$Sn Magnets
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 660°C.
• 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.
• Heating through inter-filament coupling currents.


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.

\[
\rho_{\text{eff}} \quad \tau_{\text{eq}}
\]

\[
\tau_{\text{eq}} = \frac{\mu_0 \mu_r}{\rho_{\text{eff}}} \left( \frac{l_f}{2\pi} \right)^2
\]

- Formulation

\[
\mu_0 \mu_r \vec{M}_{\text{IFCC}} = -\tau_{\text{eq}} \partial_t \vec{B}
\]

- Constitutive law

\[
\vec{B} = \mu_0 \mu_r (\vec{H} + \vec{M}_{\text{IFCC}})
\]

- Ampere-Maxwell Law

\[
\sigma \frac{\partial \vec{A}}{\partial t} \rightarrow -\nabla \times \vec{M}_{\text{IFCC}} = -\nabla \times \frac{1}{\tau} \nabla \times \partial_t \vec{A}
\]


• Inter-filament coupling magnetization in COMSOL.

\[ \vec{M}_{\text{IFCC}} = - k_{ht} \nu \tau_{\text{IFCC}} \frac{\partial \vec{B}}{\partial t} \]

\[ \vec{M}_{\text{IFCC}} = - \nu \tau_{\text{IFCC}} \frac{\partial \vec{B}}{\partial t} \]


<table>
<thead>
<tr>
<th>Model</th>
<th>(\Delta B) [T]</th>
<th>(\tau_{\text{IFCC}}) [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogenised model</td>
<td>5.47E-3</td>
<td>5.7</td>
</tr>
<tr>
<td>Multi-strand model</td>
<td>5.47E-3</td>
<td>9.8</td>
</tr>
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</table>
• Capturing multi-dependency material properties and the equivalent-magnetization term in Fortran programmed User Defined Elements.

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-linear situations cannot be captured accurately.

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.

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

M. Maciejewski, Co-Simulation of Transient Effects in Superconducting Accelerator Magnets, PhD Theses, Lodz University, 2018
Conductor degradation and sub-modeling

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

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]
• 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.

• Lately, coil-layout is optimized for both, field quality and mechanical peak stresses simultaneously.
• Improved modeling of mechanical coil models are emerging from HiLumi project.
• Plastic anisotropic coil properties are extracted from validated 10-stack simulations.

G. Vallone, Coil Composite and Interface Engineering, presentation at the HFM State of the Art Workshop, 2021.
• Conductor degradation on the midplane turn leads to detailed investigations.

• 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.


- 3D hp-adaptive FEM, see plans to use http://sparselizard.org (Alexandre Halbach) at Tampere.
Nascent HTS Magnet Technology for Accelerators
• We witness the early infancy of HTS technology for accelerator magnets.
• Angular dependency of $J_c$.
• Very high Bc0 $\rightarrow$ dream of 20 T accelerator magnets and more.
• Many practical challenges ahead:
  • $V = R(\ell, T)I \rightarrow$ 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.
- Non-insulated or solder-impregnated coils promise incredible robustness for static applications (no ramping with beams).

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 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) mechanical damage was observed due to resulting Lorentz forces.

- Different grading methods are studied to manage margins.

- Interesting approach: Thermal Eraser
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

Modeling NI Coils – A Recurring Theme
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 development and maintenance shall become a decentralized community effort.

Design step 1 → Design step 2 → Design step 3 → … → Design step n
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

**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.
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.
– **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.