COMPUTATIONAL CHALLENGES IN PRESENT AND FUTURE PROJECTS (FROM A ROXIE DEVELOPER'S PERSPECTIVE)

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Abstract

The CERN field computation program ROXIE has evolved into a comprehensive design and simulation environment for superconducting and resistive magnets. We give an overview of the latest improvements in the software, in particular in the field of quench simulation. A discussion of the challenges and limitations of today's approaches to numerical field calculation is followed by our views on the future development of the discipline.

EVOLUTION OF ROXIE

ROXIE** was started in 1992 as a tool for the optimization of coil cross-sections in cosine-theta type magnets. The code consisted of an optimization loop, a set of geometry macros, a Biot-Savart solver, and a routine for the harmonic analysis of aperture fields [1]. At the time, the design effort for LHC magnets was at full swing. Numerous features were added at the request of magnet designers. It became apparent that ROXIE was filling a niche: commercial software cannot provide the specific models and post-processing options that are required in the design of accelerator magnets. All the superconducting magnets of the LHC apart from D1 and D2 have been designed with ROXIE; two examples are shown in Fig. 1.

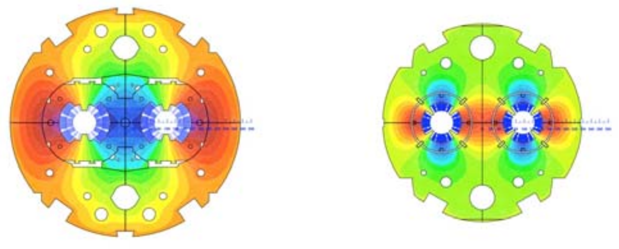

Figure 1: Main Bending- (left) and Main Quadrupole- (right) magnet cross-sections, as designed with ROXIE.

Important extensions to the initial features include:

- ROXIE supports two solvers for the numerical calculation of fields in the nonlinear iron yoke: The finite-element method (FEM) using a reduced vector-potential formulation, that was implemented in collaboration with the university of Graz, Austria [2]; and the coupling of FEM with the boundary-element method, using scalar- and vector-potential formulations, implemented in collaboration with the university of Stuttgart and the Robert Bosch GmbH, Germany [3].
- Models for transient effects in superconducting cables were implemented. We can consider the effect of persistent currents, inter-filament coupling currents, and inter-strand coupling currents on field quality and in terms of thermal losses during a ramp cycle. Special care is taken to solve the interdependence of coil-fields, iron-yoke magnetization, and cable eddy-currents in an efficient, accurate, and numerically stable way [4].
- The latest addition to the ROXIE framework is the simulation of quenches in superconducting magnets. This feature builds upon the transient field-calculation modules in ROXIE, and adds thermal modelling and electric-network simulation.

In the following sections we will give details on the computational challenges in the simulation of quenches, discuss the bottle-necks in 3-dimensional field computation as well as possible remedies, and mention some of the challenges in the field of multi-physics simulations for accelerator magnets.

COMPUTATIONAL CHALLENGES IN QUENCH SIMULATION

A quench is the resistive transition of a superconductor that occurs if the current density, the magnetic field in the cable, or the cable temperature exceeds a critical value. From this description it is evident that quench simulation requires a multi-physics approach.

Modelling Challenges

Fig. 2. displays the different models that interact in the ROXIE quench simulation module [5]. The models are characterized by:

- Coupling: Coupling occurs in two ways: a) the state of one model is the source in another model, e.g., the electric network drives the current in the coil cross-section, the field of which drives the BEM-FEM problem, the result of which drives the transient models, the losses of which drive the thermal computation. b) the state of one model influences the nonlinear material parameters in another model, e.g., field and temperature influence the magnetic permeability, electric resistivity, heat capacity, and many more.
- Nonlinearity: The material properties in the various models exhibit very nonlinear behaviour. Moreover, material values may jump at the transition points between different quantum-mechanical regimes.

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** Acronym for Routine for the Optimization of X-sections, Inverse problems, and Endspacer design.

- Time scale: Most mathematical models are given in the form of first-order systems of differential equations. The time-constants of the individual systems can be on different scales. Moreover, during one simulation the nonlinear materials can make the time constants vary by orders of magnitude.
- Computational cost: There is a large difference in computational cost between the solution of an electrical-network equation, and that of a BEM-FEM coupled system.
- Achievable accuracy: The achievable accuracy is determined by a) the sophistication of the model, and b) the accuracy of the input data, mostly material parameters. Many parameters are notoriously difficult to determine, e.g., cross-over and adjacent resistances in Rutherford-type cable, and heat-conductivities.
- Required accuracy: The most important output of quench calculation being hot-spot temperature, current-decay curve (for comparison with measurement), and internal voltages, the exact solution of the electromagnetic field problem is only of secondary importance.

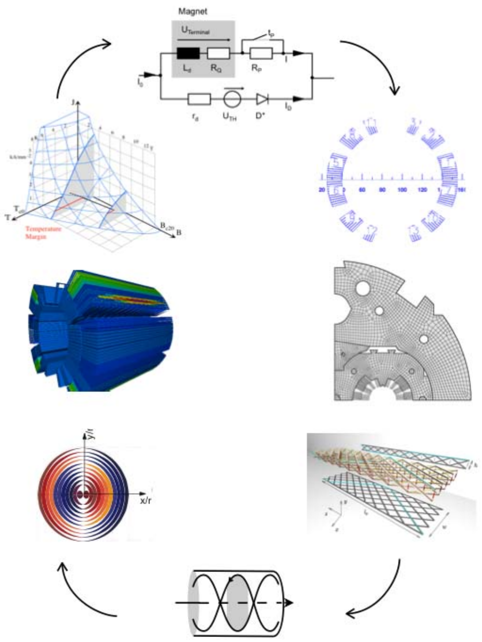

Figure 2: Different models interacting in a quench simulation. Clockwise starting at 1h00: a) geometrical model of the coil, analytical field calculation, b) BEM-FEM model of the nonlinear iron yoke, c) network model of inter-strand coupling currents, d) magnetization model of inter-filament coupling currents, e) magnetization model of persistent currents, f) thermal network model of heat conduction and quench heaters, g) fit of the critical surface of the superconductor, h) electrical network of powering and protection measures.

We identify two big challenges in the simulation of quenches in superconducting accelerator magnets. The first challenge is the accurate, computationally efficient, and numerically stable solution of the above-characterized dynamic models. To this end, adaptive time stepping, iteration schemes, and event-control loops (for the detection of resistive transitions) need to be implemented. Nonetheless quench simulations may take up to several days to be carried out on standard 2.5 GHz desktop computers.

The second challenge is found to be the procurement of all necessary input data for a simulation. The user must supply data for the characterization of quench-heater systems, protection circuits and –electronics, electrical and thermal properties of compound cable materials and insulators, geometrical and magnetic data of the magnets, and many more components. The data must be available at different cryogenic temperatures, and for a range of fields and pressures.

The quench module in ROXIE was written by Nikolai Schwerg in the course of his PhD thesis.

Modelling Results

The above-mentioned dynamical models are implemented in the ROXIE framework. Given the large number of empirical parameters in the models, it must be noted a large part of the simulation work consists in the determination of parameters such that the simulation matches the measurement. It is important to realise that only when

- all relevant phenomena have been taken into account,
- all material parameters have been chosen realistically and within the given range of uncertainty,
- the simulation result match the measured data,

we are able to reproduce the internal states of a quenching magnet, i.e., observe quantities that evade measurement (hot spot temperature, internal voltages).

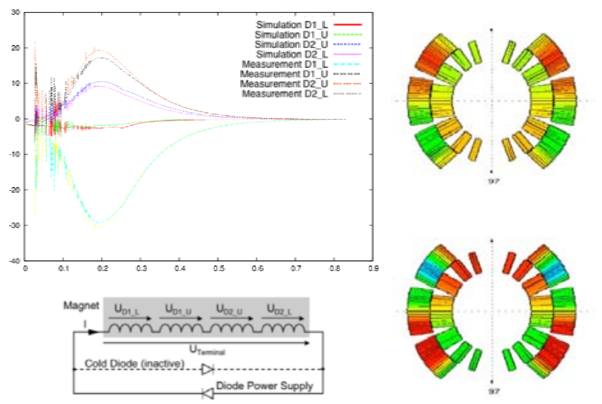

Figure 3: Left: Measured and simulated voltages on the four coils of a LHC main bending magnet on the test bench during a quench. Below: Electric circuit representing the four coils, short-circuited by the power-supply's diode. Right: Electric potentials of conductors in the cross-section at two points in time during a quench.

Fig. 3 shows voltages on the four coils of an LHC main bending on a test bench. We observe spikes in the first third of the measured voltage curves. Interestingly, the spikes are reproduced by simulation [6]. They are explained by the fact that the voltage over all four coils is fixed to the voltage on the diode (compare Fig. 3 bottom). Whenever a conductor quenches, an additional resistive-voltage term emerges in the circuit, which needs to be counter-balanced by a redistribution of inductive voltages in all four coils. We therefore find that the spikes disappear once the whole magnet is quenched.

COMPUTATIONAL CHALLENGES IN 3-D SIMULATIONS

The available RAM on today's workstations limits the accurate 3-D simulation of accelerator magnets. We give two examples and discuss current developments in the computational-electromagnetism community.

3-D Static Simulation

At the request of the CERN AB department, a 3-D electromagnetic model of the PS (proton synchrotron) resistive main magnet should be created. The task was carried out in ANSYS [7], using first-order edge elements and a reduced vector-potential formulation. The PS main magnet is a conventional combined-function magnet, consisting of 10 blocks of C-shaped yokes and a number of different coils for powering and correction. The goal of the exercise was to predict the exact integrated field quality of the magnet for any combination of input currents.

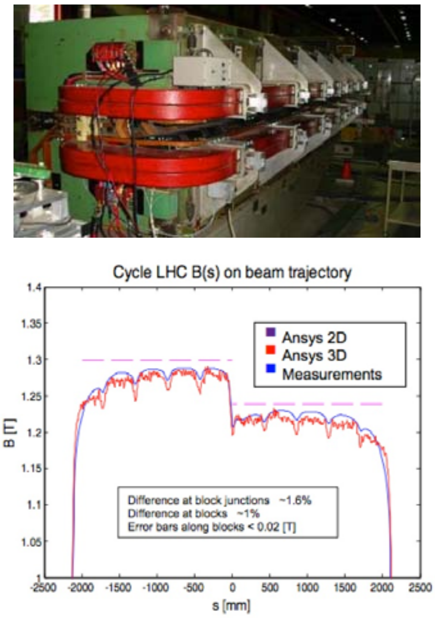

Figure 4: Top: Photo of a PS combined-function magnet. Bottom: Comparison of measured and simulated main field on the beam orbit, [8].

A geometrical model of the yokes and the coils was created with ANSYS workbench and the mesh-density was progressively increased, with a strong bias on the beam tube. By the time the simulation exhausted the ANSYS server's memory, the results were still far from convergence, compare Fig. 4. No reliable field quality could be extracted from the simulated fields.

3-D Transient Simulation

Another example for the limitation of today's field computation algorithms is given by the simulation of eddy currents in the end parts of accelerator magnets. The fast-ramping SIS100 magnets at GSI, Germany, have been the subject of several simulation campaigns on this topic, e.g. [9] [10]. We refer to [11] for the data on convergence and computation time that is presented in Table 1.

The bottom line is that, although a highly-advanced parallelized 2^{nd} order finite-element solver was used, the results only just converge when the memory limit is reached at 4,600,000 degrees of freedom. For field quality simulations in the aperture of the magnet, this accuracy would still not be sufficient.

Table 1: Integrated eddy-current losses over one cycle with simulation times and numbers of degrees of freedom on a 4-processor shared memory workstation.

# Degrees of Freedom	Time [h]	Losses/Cycle [J]
22,000	0.09	54.96
82,000	0.75	45.84
526,000	6.00	30.16
1,537,000	18.75	25.51
3,100,000	40.00	23.98
4,600,000	54.00	23.37

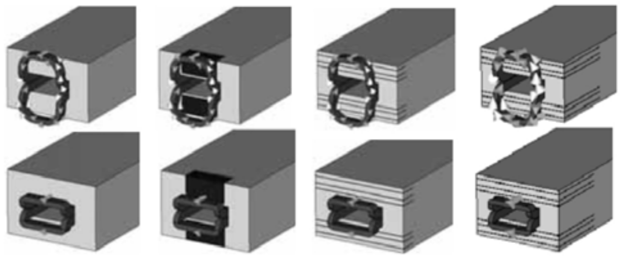

Figure 5: Eight considered magnet-end configurations of the SIS100 magnet, [11]. Picture courtesy of H. de Gersem, S. Koch and T. Weiland.

Numerical Techniques for Future Field Computation Tools

Possible solutions to the above-mentioned memory limitation are given below:

- The coupling method of boundary elements and finite elements (BEM-FEM) needs only to mesh the nonlinear and/or conductive material, i.e., air regions need not be meshed. The number of degrees of freedom is reduced dramatically. The accuracy in the air domain and thus in the magnet aperture is increased by the use of the boundary element method. The coils are modelled as sets of line-currents in the BEM domain. The drawback of the method is that the boundary-element matrices are fully populated, i.e., they consume large amounts of memory. A remedy this problem lies in compression techniques of the BEM matrices, than can reduce memory consumption to as little as 4% of the initial storage [12].

- The coupling of finite elements and spectral elements is a promising candidate for the simulation of very long magnets. Spectral elements are well suited to represent field distributions that vary only very little over long stretches of a domain. Those end-regions that see important field changes could be modelled with finite elements.
- Whichever method is chosen, distributed computing will be the way to solve memory and runtime limitations in the future. Yet, efficient parallelization of field computation programs is difficult and is mastered today only by a small number of research institutes. It is commonly believed that the commercialization of such tools will take another few years.

COMPUTATIONAL CHALLENGES IN MULTI-PHYSICS SIMULATIONS

Eventually we want to mention the challenges related to complex multi-physics phenomena and their simulation:

- Thermal-electromagnetic coupling: In quench-simulations, an accurate model of the cooling by helium is required. Yet the properties of super-fluid, super-critical, boiling, and fluid helium and the phase transitions are difficult to cast into a reasonably complex model.
- Beam losses: the energy-deposit of beam losses in the superconducting coil depends strongly on the electromagnetic field distribution in the coils. In turn, the beam losses can be taken into account in quench simulations. An interface to, e.g., the FLUKA software [13] is a desirable feature for the ROXIE program.
- Mechanics-electromagnetic coupling: Lorentz forces are a crucial input for the mechanical simulation of a magnet [14]. Yet, the internal stress distribution also affects the material properties in the electromagnetic simulation. In a comprehensive simulation, both ways of interaction needs to be taken into account. To this end, a tight interface between, e.g., ANSYS and ROXIE needs to be established.

CONCLUSIONS

Future accelerator projects will require the simulation of fast-ramping superconducting magnets, as well as high-field magnets and magnets with new materials (other than Nb-Ti). The computational challenges lie in the integration of various dynamic models, the user-friendly input of a multitude of empirical parameters, the simulation of the protection measures in case of a quench, and the accurate 3-D simulation of static and transient problems. Some of these challenge are within reach, others will not be met until several years of research and development. The high degree of specialization in the field of superconducting accelerator magnets requires the creation of specialized, well-integrated models. This can be best done in an integrated development and simulation environment such as the ROXIE program at CERN.

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