Simulation of Quench Behavior of the 11 T Superconducting Dipole for HL-LHC

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With lots of inputs from: 11 T design, construction, and testing teams at CERN

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Overview

• Introduction: HL-LHC Nb$_3$Sn 11 T magnet for the Large Hadron Collider

• Quench protection

• Comsol simulations

• Comparison with experimental observations

• SIGMA model generation tool

• Summary
CERN accelerator complex

Biggest ring = 27 km circumference
Protons=stripping electrons form hydrogen

Large Hadron Collider: Lots of superconducting magnet needed to manipulate the particle beam and fix its trajectory!
First Nb$_3$Sn-based accelerator magnet to be installed in the LHC

- Typical magnets in the LHC: Either Nb-Ti (superconducting) or copper (normal) electromagnets
- Nb$_3$Sn allows for generation of much higher magnetic fields due to superior superconducting properties of Nb$_3$Sn compared to Nb-Ti
- Together with another Nb$_3$Sn-based magnet (MQXF), constitutes significant part of one billion CHF High Luminosity Upgrade of the Large Hadron Collider (HL-LHC)
What is a quench?

Low-temperature-superconductor-based magnets

- Run with very high current density in the windings, on the order of 500 – 1000 A/mm²
- Only superconducting at extremely low temperature (typically run at 1.9 K)
- If conductor heats up by some Kelvins → No longer superconducting and heating up very fast due to high current density, so-called quench
- Quench protection: Detect quench and discharge magnet as fast as possible, to keep the peak temperature below 350 K
- Discharge time given by $L/R$ → Rapid increase of resistance for quick discharge
Quench protection methods

- Quench heaters (resistive heater strips), glued to the side of superconducting windings → Heat flow through insulation into the windings → Magnet is brought to normal state and stored magnetic energy is distributed over the magnet.

- Coupling Loss Induced Quench (CLIQ): Discharge of capacitor across half the magnet coils → Produces current oscillations and inter-filament coupling losses (special type of eddy current loss) → Magnet is brought to normal state and stored magnetic energy is distributed over the magnet.

- Energy extraction (Discharge over a dump resistor) → Conceptually straight-forward but leads to larger voltages, due to non-distributed nature.
Comsol simulations

- Physics: 2D component for magnet, 1D component for quench heaters, coupled together
- Stationary initial condition + transient simulation
- Strongly non-linear properties (temperature and magnetic-field dependent) + iron BH-curve
- 2D component: Electro-magnetic (mf), heat transfer (ht), internal circuit (ge), quench integration (dode)
- 1D component: Heat transfer (ht)
- All modules coupled together
Do the simulation results make sense?

**Measurement versus simulation**
- Measurements performed on 11 T model magnet (performed at CERN magnet test facility)
- Protection studies: Quench heater only versus quench heater + CLIQ
- In spite of uncertainty in material properties, close consistency between calculation result and measurement
- **Simulation model captures the relevant physics needed for simulating this type of magnet**
What is the relevance?

SIGMA model generation tool
- Java-based tool for automatically generating simulation models of accelerator magnets
- Generates simulation models (Comsol), with correct geometry, material properties, and physics
- Allows for interface with other typical tools used for simulation magnet, such as the Roxie magnet design tool
- Developed at CERN and used by other institutes: CEA Saclay, INFN, Fermi lab, Lawrence Berkeley National Laboratory, Tampere University of Technology, NHMFL, ...
- Powerful tool for simulating transient behavior of accelerator magnets: Hotspot temperature, voltage to ground, power supply to beam transfer function, eddy currents in beam screen, mechanics, etc...
- All transient physics combined in reproducible models
Comsol application

- For sharing simulation tools with collaborators, for example for quickly comparing experimental observations to simulation results by the magnet test teams
- Under development
Summary

• For High-Luminosity upgrade at CERN: Development of new Nb$_3$Sn-based accelerator magnets with very challenging quench protection

• Quench heaters and coupling-loss-induced-quench (CLIQ): Effective methods for quickly bringing the superconducting magnet to normal state, thus protecting it from permanent damage

• Comsol simulation: Multi-physics (electro-magnetic, thermal, ...), with non-linear properties and coupled 1D and 2D components

• Simulation results validated against experimental measurements

• SIGMA model generation tool: Used for transient simulations of a wide variety of superconducting magnets and used by a growing number of institutes