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

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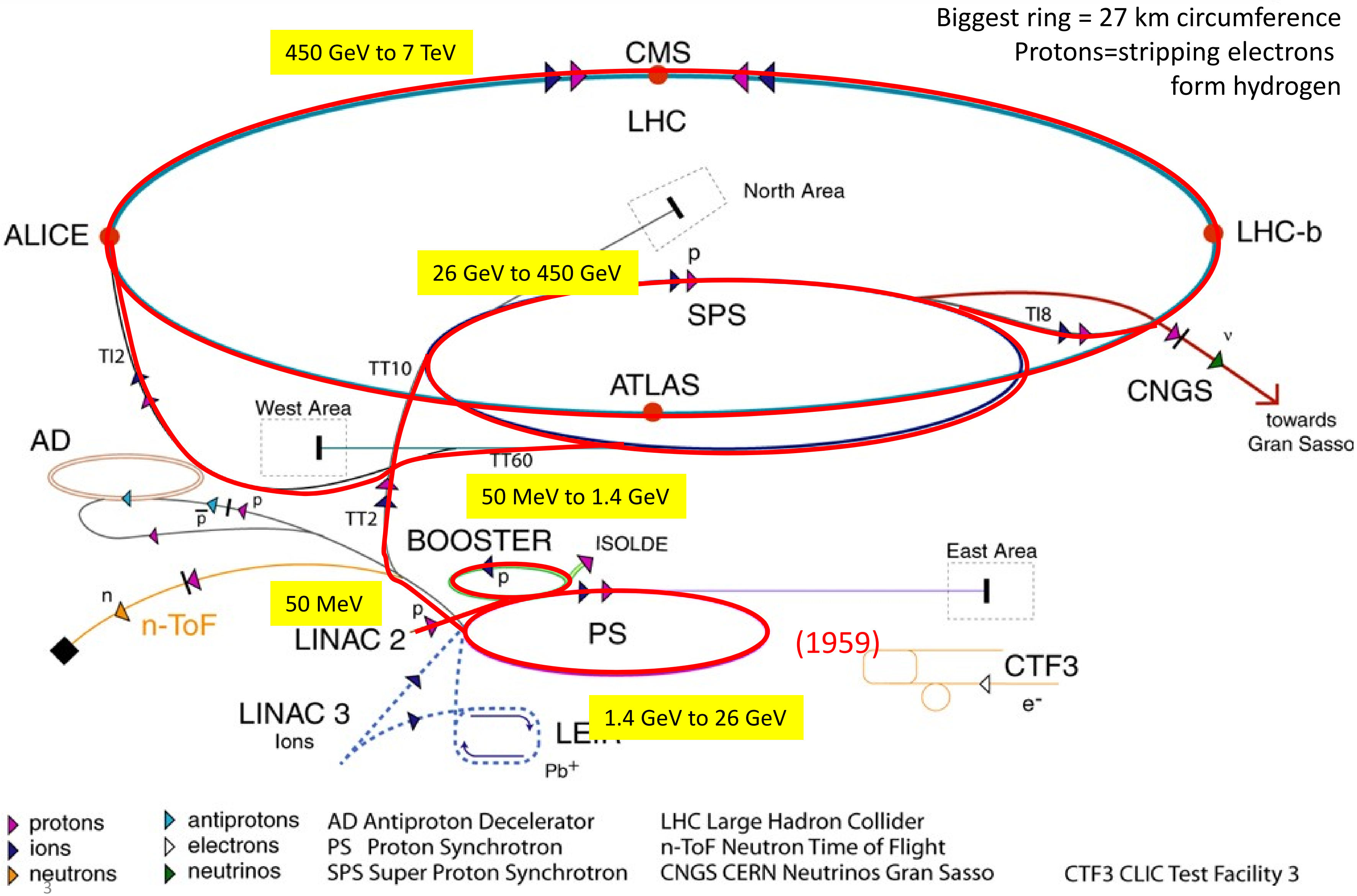
With lots of inputs from: 11 T design, construction, and testing teams at CERN

October 23rd, 2018

Overview

- Introduction: HL-LHC Nb_3Sn 11 T magnet for the Large Hadron Collider
- Quench protection
- Comsol simulations
- Comparison with experimental observations
- SIGMA model generation tool
- Summary

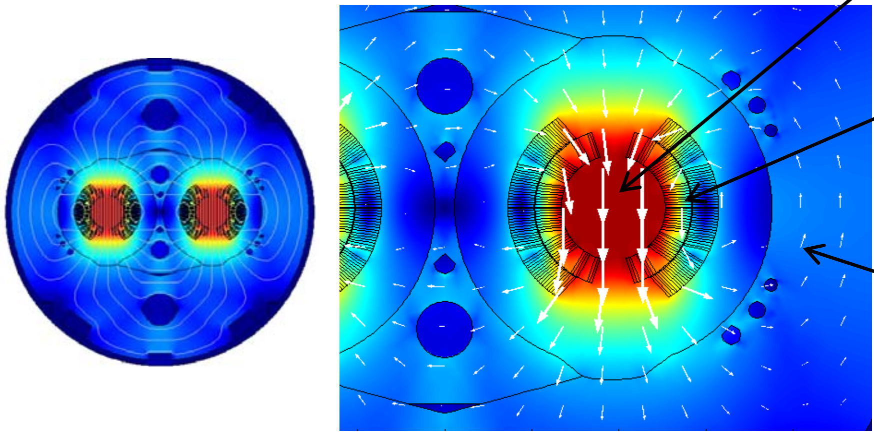
CERN accelerator complex

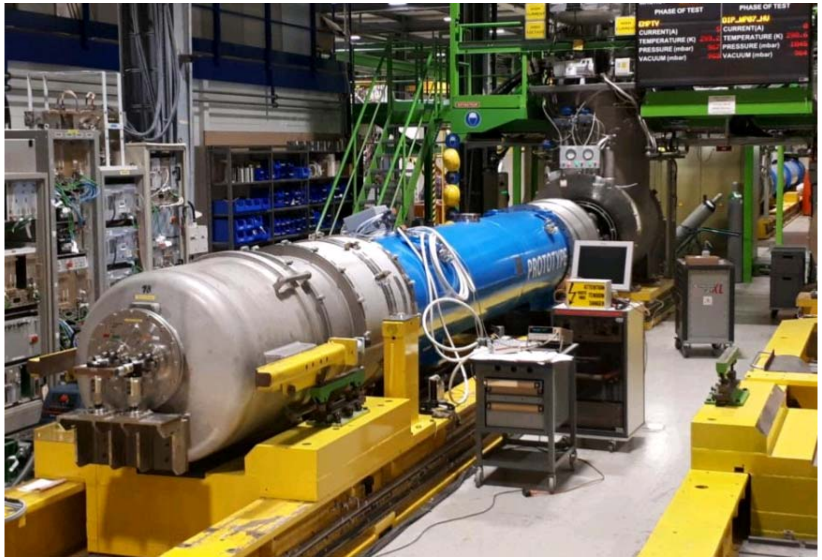


Large Hadron Collider: Lots of superconducting magnet needed to manipulate the particle beam and fix its trajectory!

HL-LHC Nb_3Sn 11 T magnet

Comsol simulation of the 11 T magnet





11 T prototype in SM18 magnet test station, courtesy: F. Savary

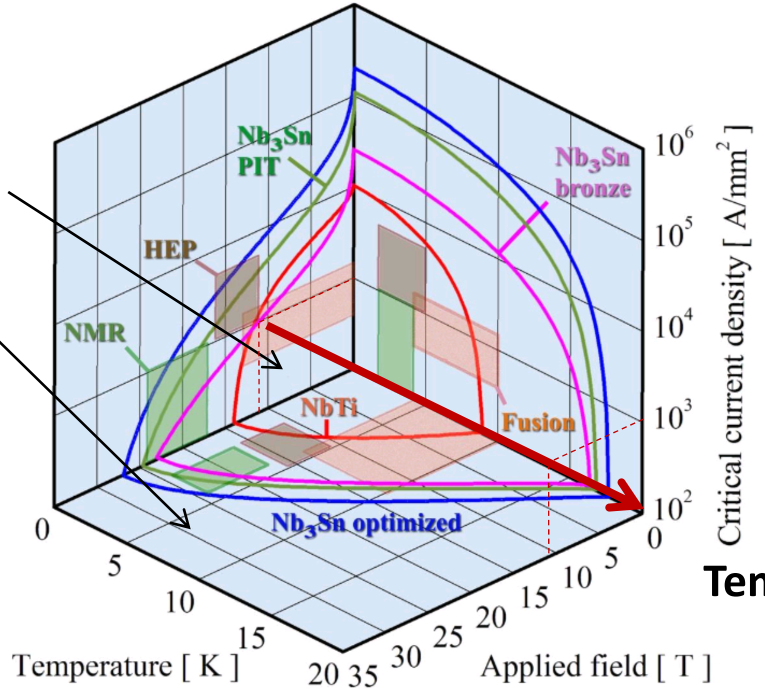
First Nb_3Sn-based accelerator magnet to be installed in the LHC

- Typical magnets in the LHC: Either Nb-Ti (superconducting) or copper (normal) electromagnets
- Nb_3Sn allows for generation of much higher magnetic fields due to superior superconducting properties of Nb_3Sn compared to Nb-Ti
- Together with another Nb_3Sn-based magnet (MQXF), constitutes significant part of one billion CHF High Luminosity Upgrade of the Large Hadron Collider (HL-LHC)

What is a quench?

Superconducting state

Normal state

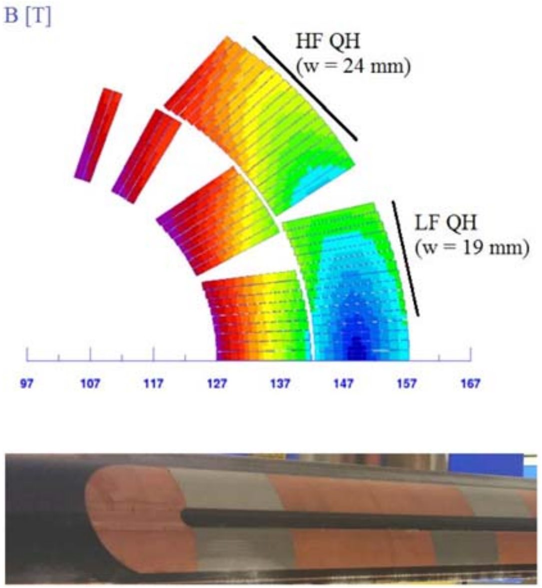


Temperature increase
→ Quench

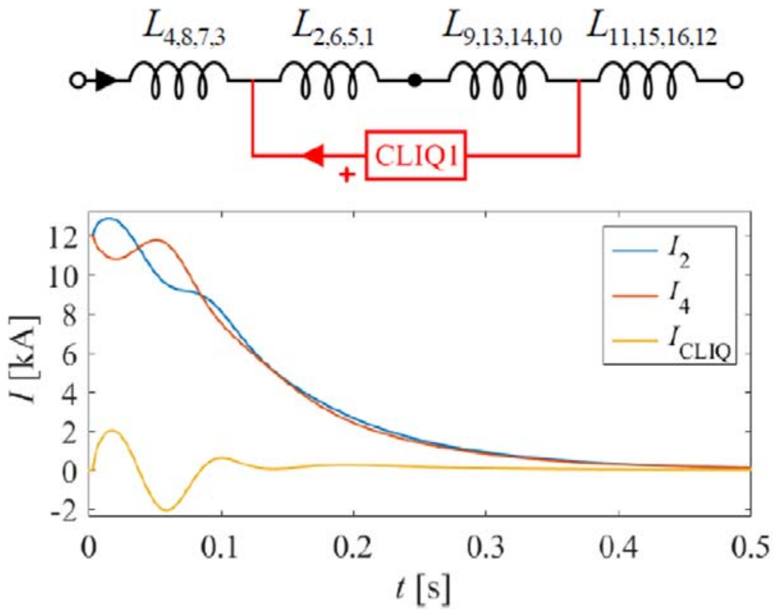
Low-temperature-superconductor-based magnets

- Run with very high current density in the windings, on the order of 500 – 1000 A/mm^2
- 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,
courtesy Susana Izquierdo Bermudez

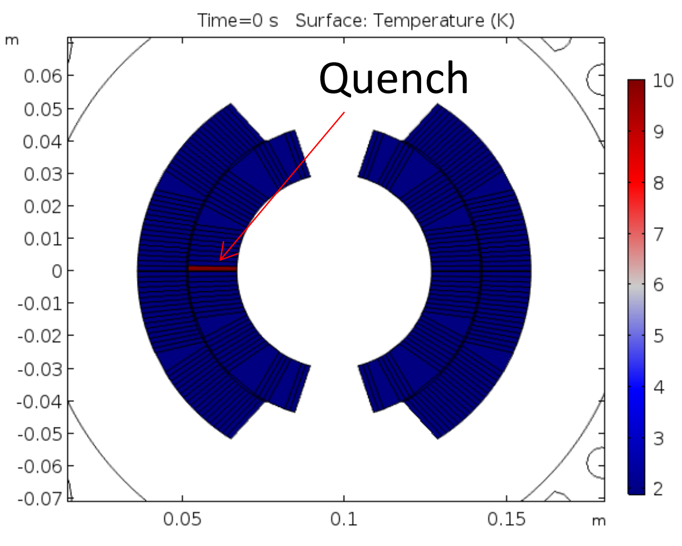


CLIQ: Discharge of capacitor
parallel to half the magnet coils

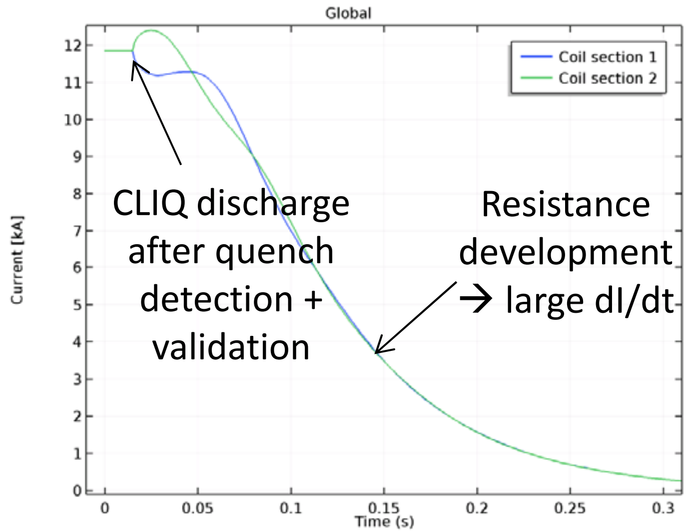
Quench protection methods

- 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

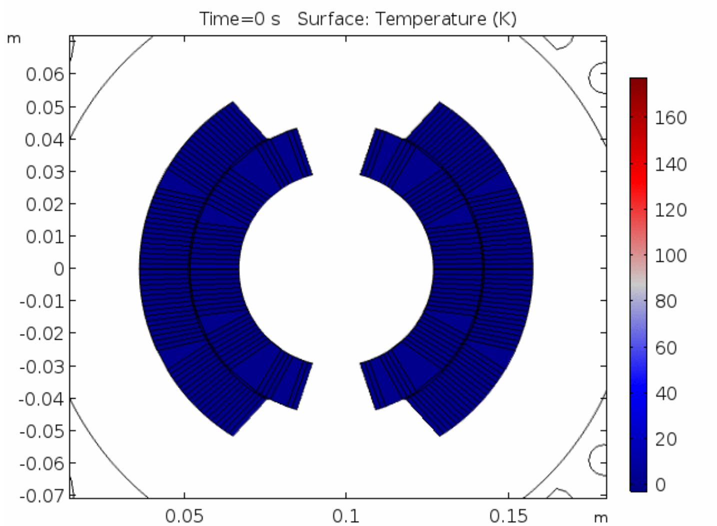
Comsol simulations



Initial conditions



Quench protection response (QH + CLIQ) after quench detection

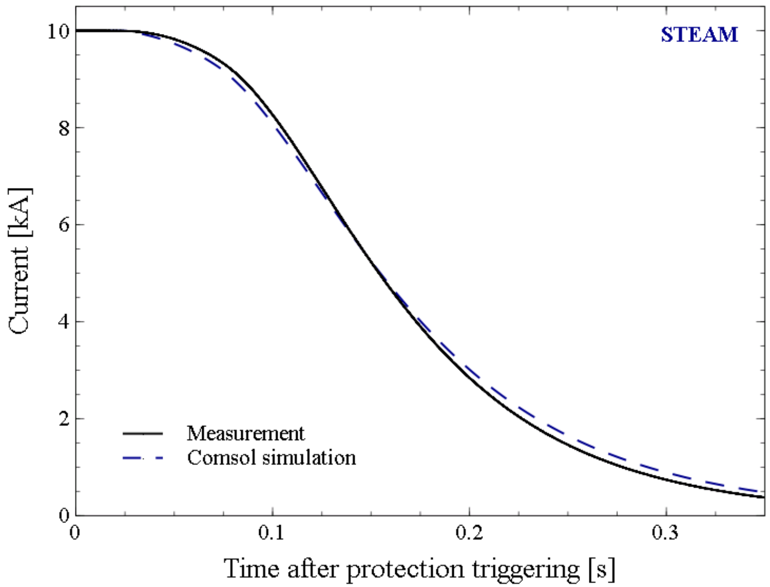


Temperature evolution

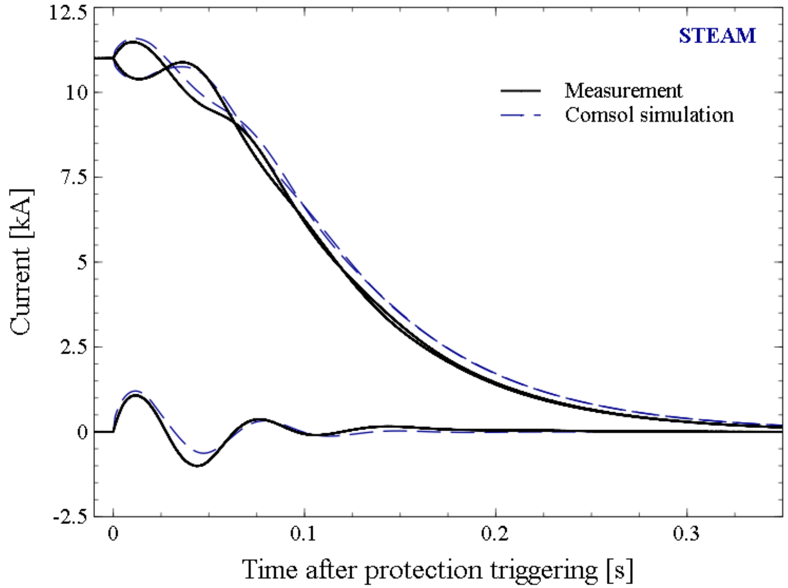
Comsol simulation

- 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?



Simulation versus measurement, quench heater discharge

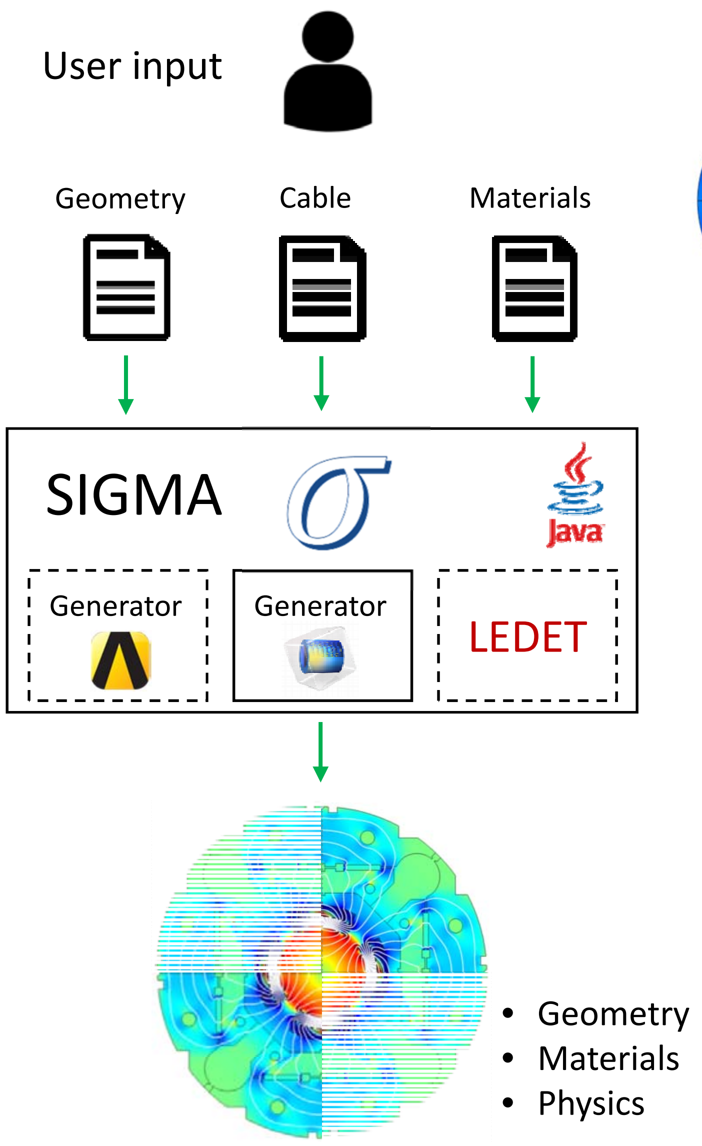


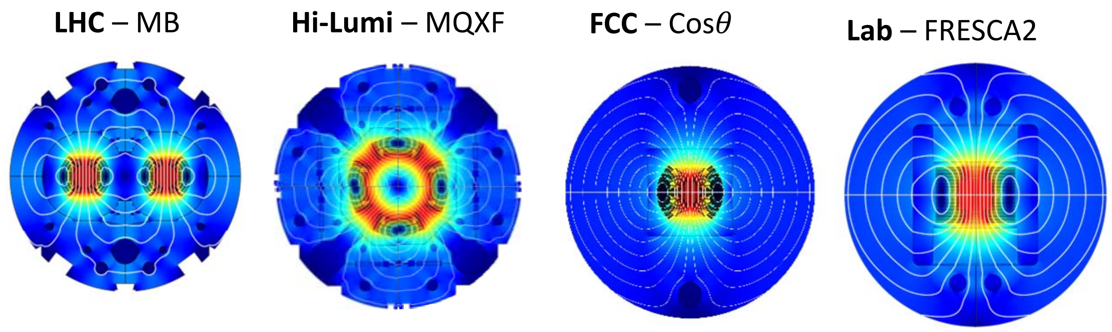
Simulation versus measurement, quench heater + CLIQ discharge

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?



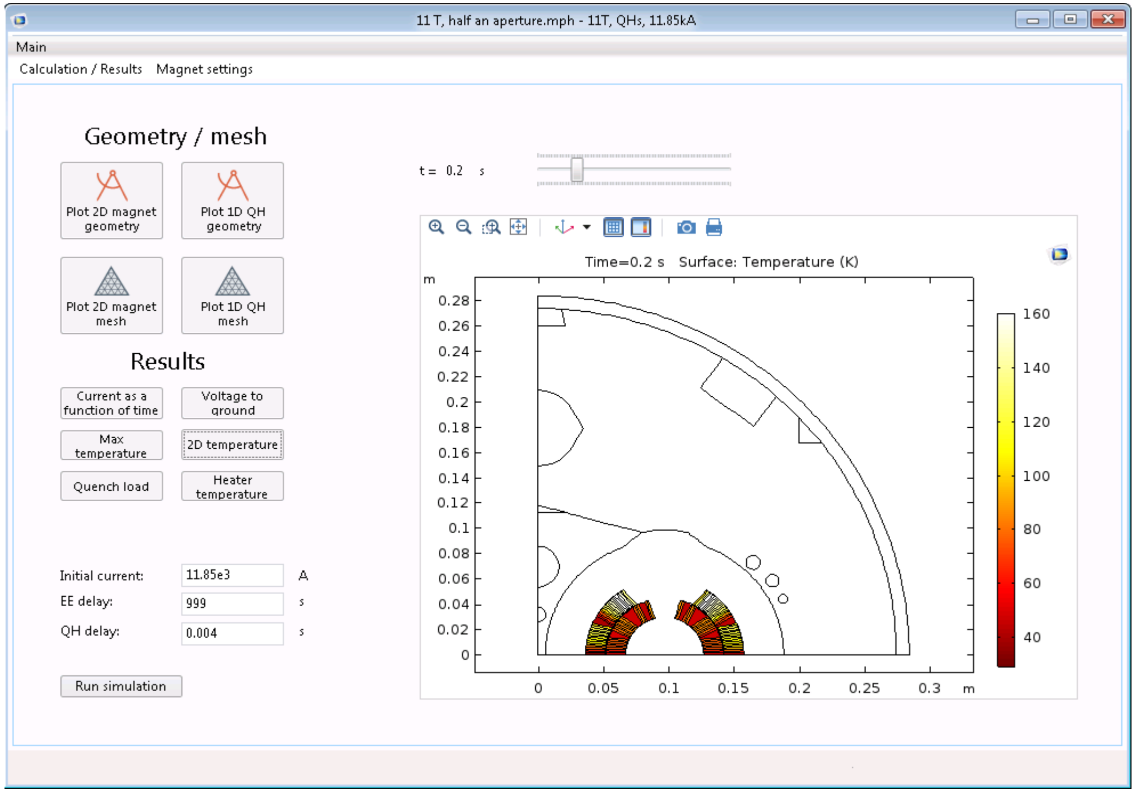


Other models: 11 Tesla, D1 … and many more!

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



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_3Sn-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