Protection Studies of the HL-LHC Circuits with the STEAM simulation framework

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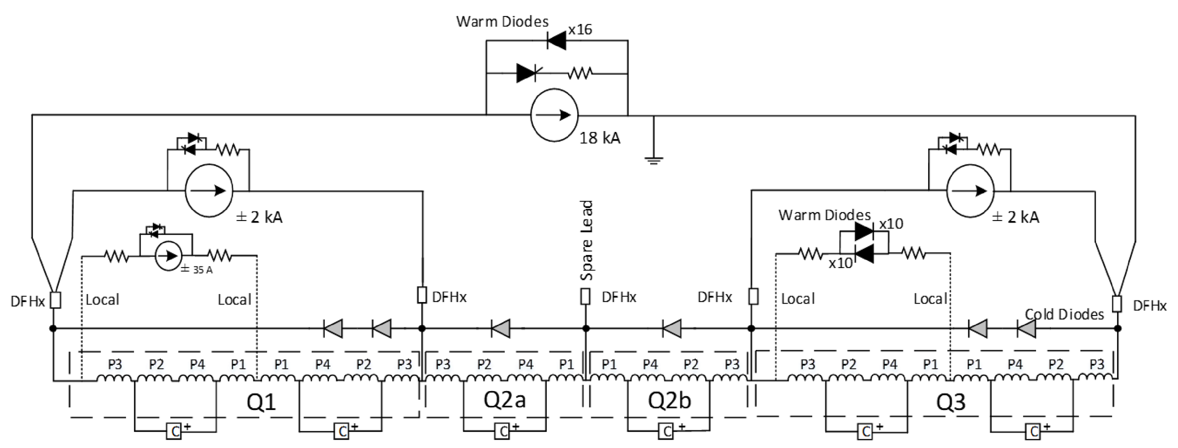
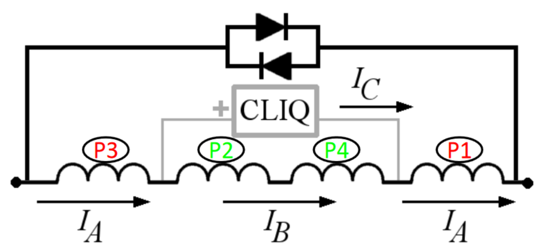
Introduction

- High-Luminosity Large Hadron Collider Upgrade: CERN Upgrade to achieve ten times higher luminosity
- Circuits powering ten different superconducting magnet types, with often more than one variant per magnet type
- Within STEAM project: Extensive simulation effort, cross-checked against experimental observations where possible, toward understanding the transient behavior of the HL-LHC circuits and their components, and to ensure their proper protection

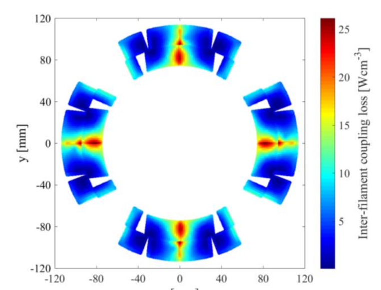
Inner triplet circuit



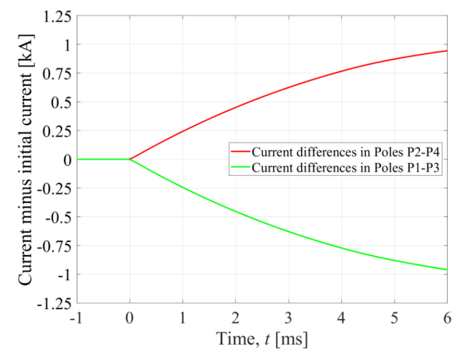
Latest proposed HL-LHC Inner Triplet Circuit Layout



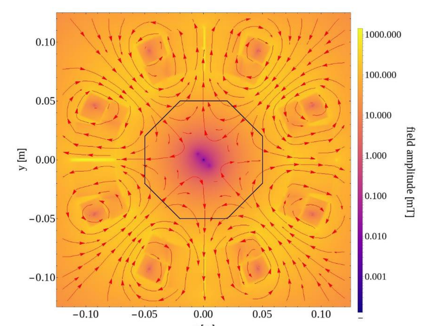
MQXF magnets protected with Quench Heaters, CLIQ (Coupling-Loss-Induced-Quench) and diodes



Inter-filament coupling losses in Nb_3Sn MQXF quadrupole magnets (LEDET)



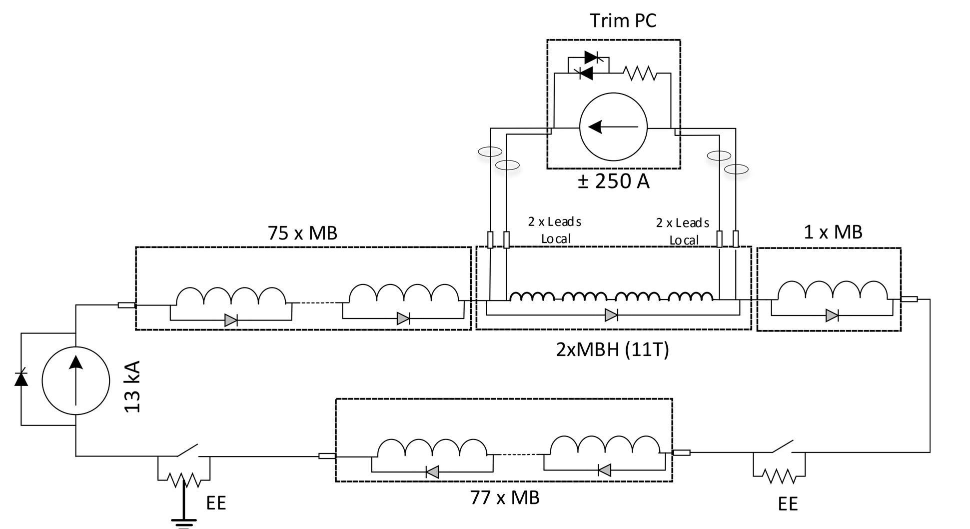
Transient behavior of IT circuit with power supplies, crowbars, diodes, six different MQXF magnets (Co-simulation of LEDET + PSPICE)



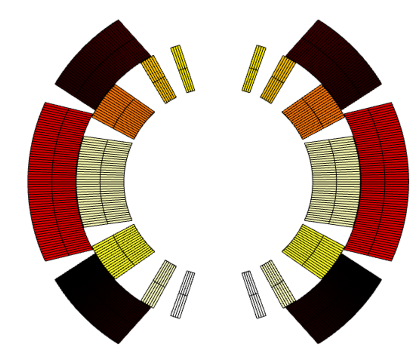
Effect of QHs and CLIQ on the beam, (Here: CLIQ discharge, simulated with SIGMA)

- Simulated hotspot temperature and peak voltage-to-ground at elevated temperatures, comparison with experimentally observed insulation voltage tolerance at elevated temperatures, also considering fault scenarios and compositional inhomogeneity (LEDET)
- Effect of a spurious CLIQ or quench heater discharge on the beam (SIGMA)
- Effect of collimator material choice on the local voltages-to-ground, in case of asynchronous beam dumps (Co-simulation: LEDET + PSPICE)
- Interaction between crowbars and cold diodes (PSPICE)
- Busbar studies (BBQ), etc. etc.

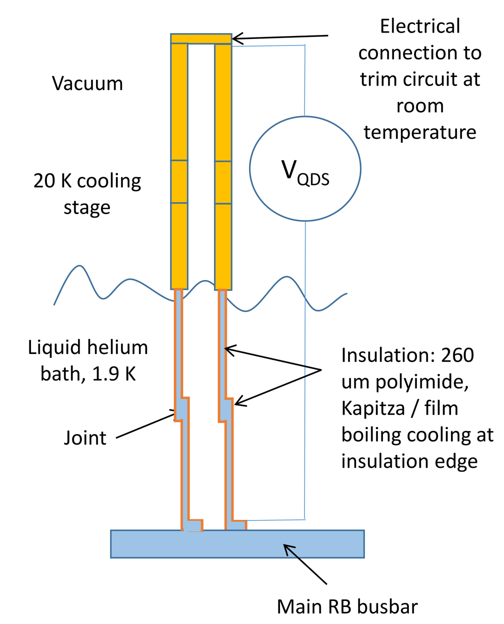
Main dipole circuit + 11 T cryo-assembly



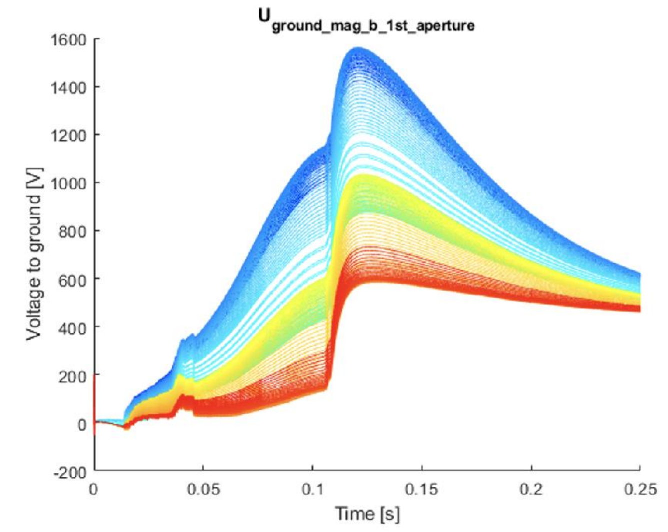
Main dipole circuit with 11 T cryo-assembly and trim circuit



Nb_3Sn 11 T dipole magnets, protected with Quench Heaters and a by-pass diode



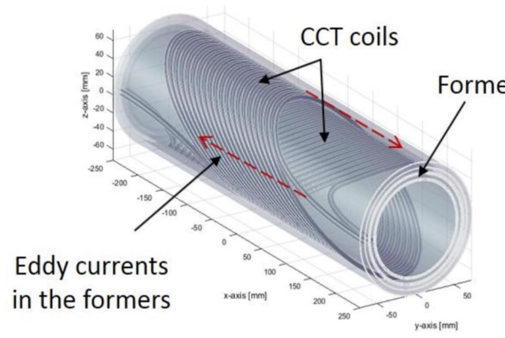
Simulations of transient behavior of trim circuit current leads + busbars (BBQ)



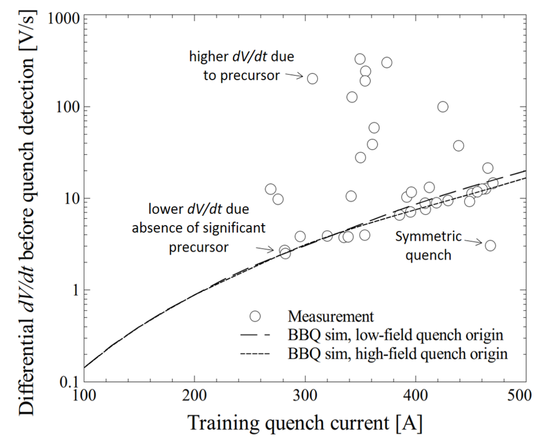
Voltages-to-ground in the circuit under fault conditions (LEDET)

- Transient behavior of 11 T cryo-assembly in case of a quench or a component failure (Co-simulation: LEDET + PSPICE)
- Resulting hotspot temperatures and voltages-to-ground in the circuit, also considering fault scenarios and compositional inhomogeneity in the conductor (Co-simulation: LEDET + PSPICE)
- Trim circuit transient behavior (PSPICE), and protection of the trim circuit busbars and current leads (BBQ)

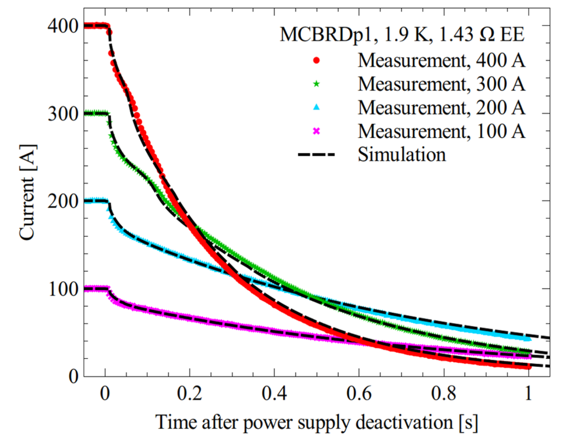
Twin Aperture Orbit Correctors



Canted-cosine-theta-type magnets, protected with energy extraction + quench-back



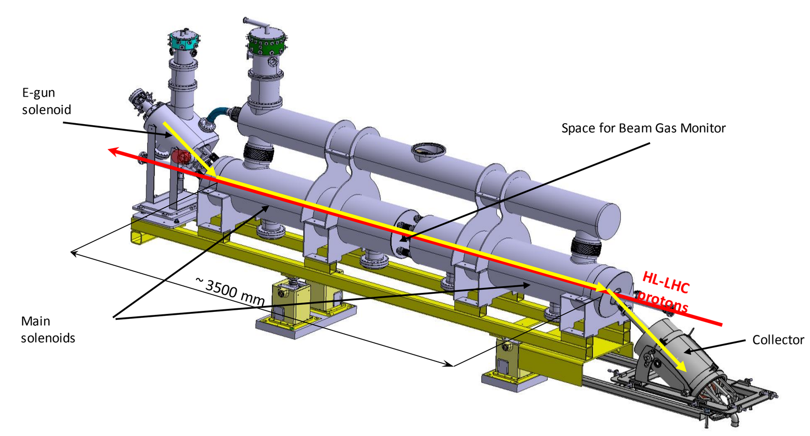
Initial voltage development after a quench (BBQ)



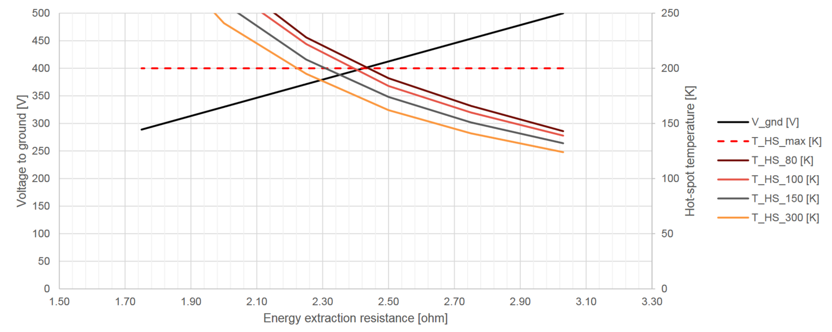
Discharge behavior of the magnets (ProteCCT)

- Twin Aperture Orbit Correctors: Protected by combination energy extraction and quench back
- Definition of energy extractor characteristics for proper protection
- Initial voltage development after a quench (BBQ)
- Discharge behavior of the magnet (ProteCCT)

Hollow Electron Lens



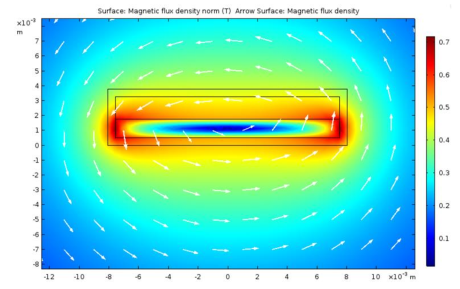
Hollow Electron Lens Circuits: Six main circuits + Ten corrector circuits, protected with energy extraction



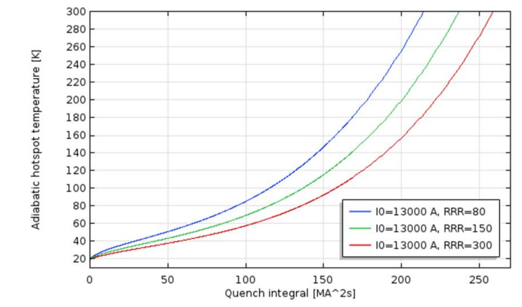
Simulations of the peak voltage-to-ground and resulting hotspot temperature for different energy extractor values (Main solenoid, BBQ simulation)

- Hollow Electron Lens: 16 circuits powering superconducting magnets, protected with energy extraction
- For different energy extraction values, simulation of the resulting hotpot temperatures and voltages to ground (BBQ)

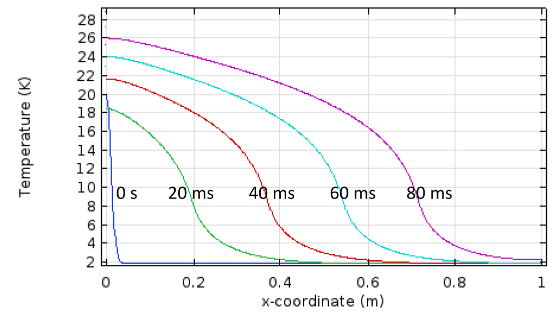
Superconducting busbars



Self-field the RD1/RD2 superconducting busbar



Adiabatic hotspot for a given quench integral, RD1/RD2 superconducting busbar



Temperature evolution during a quench

- Quench simulations of the various superconducting busbars
- Consideration of quench-stoppers, local cooling conditions, expansion loops, etc.
- Initial voltage development, quench propagation velocity, effect of compositions, resulting hotspot temperature (BBQ)

Summary

- Extensive simulation effort to understand the transient behavior of the HL-LHC circuits (HL-LHC Work Package 7)
- Simulation tools developed for this purpose: Co-simulation, LEDET, SIGMA, BBQ, ProteCCT, amongst others
- Purpose: To ensure proper protection and introduce adjustments to the circuits as needed, **to contribute to the success of the HL-LHC upgrade**
- These studies were made possible through collaboration within the CERN Technology department and with the external collaborators. We thank everyone for their support.