Co-simulation of quench transients in the HiLumi recombination dipole magnet combining STEAM-LEDEET and STEAM-PyBBQ

Lennard Bender (CERN / Hochschule Karlsruhe)

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Acknowledgements
Special thanks to:
B.Caiffi, P.Fabbricatore and MBRD team (INFN-Genoa),
A. Foussat, T.Mulder, E.Ravaoli, G.Willering, M.Wozniak and SM18 team (CERN)
Validation process of co-simulation

Alternative protection of MBRD magnet to decrease hot-spot temperature and voltage to ground

Including longitudinal quench propagation for QH protected magnets
What is the goal of quench protection?
STEAM tools - 2022

BBQ (Comsol) → PyBBQ

Magnet

FiQuS

Conductor

SIGMA

LEDET

PROTECCT

SING → PySING

Circuit

COSIM

Recombination dipole magnet MBRD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore magnetic field</td>
<td>4.5 T</td>
</tr>
<tr>
<td>Peak magnetic field</td>
<td>5.28 T</td>
</tr>
<tr>
<td>Nominal current</td>
<td>12340 A</td>
</tr>
<tr>
<td>Ultimate current</td>
<td>13357 A</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>7.78 m / 1.378 m</td>
</tr>
<tr>
<td>Number of blocks</td>
<td>5</td>
</tr>
</tbody>
</table>
Quench heaters and quench propagation

- After the QH firing, the normal zone is propagating from each heating station into both, longitudinal directions

\[ v_{QH} = 2 \cdot n_{QH, \text{stations}} \cdot v_q \]

**Example MBRDP1 magnet:**

- \( vQ @ \text{nominal current: } \sim 15 \text{ m/s} \)
- \( vQ @ 2 \text{ kA: } 0.39 \text{ m/s} \)

All turns, attached to QH would quench in \( \sim 13.3 \text{ ms at nominal current} \)

All turns, attached to QH would quench in \( \sim 510 \text{ ms at nominal current} \)

Note: quench propagation velocity calculated with PyBBQ including cooling

Marvin Janitschke: 2nd STEAM Workshop (11-October 15, 2021): Thermal analysis of quench-heater heating stations using STEAM-BBQ · Indico (cern.ch)
Introduction of quench propagation scaling at low currents

- Poor fit for STEAM-LEDET 2D model at low currents [1]
- Improvement by implementing 2D+1D extension [2]
- 2D+1D includes longitudinal quench propagation between heating stations [3]

➢ Improved simulation by including scaled quench propagation due to helium cooling

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Validation process of co-simulation

Alternative protection of MBRD magnet to decrease hot-spot temperature and voltage to ground

Including longitudinal quench propagation for QH protected magnets
STEAM-PyBBQ (BusBar Quench in python)

- STEAM-PyBBQ implemented tool in python by T. Mulder [4]

- Able to simulate quench propagation in a cable with and without helium cooling

- Quench initiation through power input at one conductor side

- Crucial to include external and internal cooling of the cable to simulate quench propagation at low currents

Validation of PyBBQ

- Comparison to STEAM-LEDET 3D and STEAM-BBQ [5], [6]

- Good fit for basic case without insulation and cooling

- Analytical calculation not applicable, further investigations necessary

- STEAM-PyBBQ and STEAM-BBQ show similar behaviour for multi-strand cable and cooling

➢ STEAM-PyBBQ can be seen as validated

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QH heating stations in STEAM-PyBBQ

- No quench propagation simulated by STEAM-PyBBQ for low current
- Implementing a heating station leads to detectable quench propagation in the cable at low current
Co-simulation; setting conductor simulation

Analysis_MBRD_co_simulation
- creating analysis_file_conductor
- starting PyBBQ
  - quench propagation calculation
  - calculating analytic_vQ

Calculating_scaling_vQ
- setting quench heater pattern
- calculating f_vq using PyBBQ output, analytic_vQ and heater pattern
- creating analysis_file_magnet
- starting LEDET
  - modelling magnet discharge
  - calculate hot-spot temperature

analysis_file_conductor
- specific variables for PyBBQ are given
- structures PyBBQ simulation

analysis_file_magnet
- specific variables for LEDET are given
- structures LEDET simulation

model_data_conductor
input

model_data_magnet
input

Validation – Co-simulation MBRD magnet
Co-simulation; running conductor simulation

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PyBBQ
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Co-simulation; calculating quench propagation scaling

**Analysis_MBRD_co_simulation**
- creating `analysis_file_conductor`
- starting `PyBBQ`

**PyBBQ**
- quench propagation calculation
  - calculating `analytic_vQ`

**Calculating_scaling_vQ**
- setting quench heater pattern
- calculating $f_{vQ}$ using `PyBBQ` output, `analytic_vQ` and heater pattern
  - creating `analysis_file_magnet`
  - starting `LEDET`

**LEDET**
- modelling magnet discharge
- calculate hot-spot temperature

**analysis_file_conductor**
- specific variables for `PyBBQ` are given
- structures `PyBBQ` simulation

**analysis_file_magnet**
- specific variables for `LEDET` are given
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Co-simulation; setting magnet simulation

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analysis_file_magnet
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Co-simulation; running magnet simulation

➢ Consistent, repeatable and traceable co-simulation based on YAML files

model_data_conductor

input

Analysis_MBRD_co_simulation
- creating analysis_file_conductor
- starting PyBBQ

PyBBQ
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Calculating_scaling_vQ
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analysis_file_magnet
- specific variables for LEDET are given
- structures LEDET simulation
Quench start at high current

- Variation of the amount of helium inside the cable
- Voltage jumps caused by quench heaters
- Manipulation of heater contact to strands possible
Quench start at high current

- Variation of the amount of helium inside the cable
- Voltage jumps caused by quench heaters
- Manipulation of heater contact to strands possible
- Matching quench start for fraction\_inner\_voids at 2 %
- Best fitting discharge at fraction\_inner\_voids = 2 %
- Faster discharge at quench start, slower discharge before energy extraction triggering
• Variation of the amount of helium inside the cable
• Voltage jumps caused by quench heaters
• Manipulation of heater contact to strands possible
• Matching quench start for fraction_inner_voids at 2 %
• Best fitting discharge at fraction_inner_voids = 2 %
• Faster discharge at quench start, slower discharge before energy extraction triggering
• Similar behaviour visible in global differential voltage
Simulation results of the MBRD

- Validated STEAM-LEDET model of the MBRD magnet

- Using the 2D+1D option including quench propagation between heating stations and to turns that are not yet quenched

- Typical RMS error divided by peak value: 1% for the current and 2-10% for the voltage

High current:

- Validated STEAM-LEDET model of the MBRD magnet

![Measured and simulated currents](chart1)

![Measured and simulated differential voltage](chart2)
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- Typical RMS error divided by peak value: 1 % for the current and 2-10 % for the voltage

Low current:

Measured and simulated currents

![Graph showing measured and simulated currents](image)

Measured and simulated differential voltage

![Graph showing measured and simulated differential voltage](image)
Validation process of co-simulation

Alternative protection of MBRD magnet to decrease hot-spot temperature and voltage to ground

Including longitudinal quench propagation for QH protected magnets
Baseline:

<table>
<thead>
<tr>
<th>Case</th>
<th>QH firing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>QH_1; QH_3; QH_6; QH_8</td>
</tr>
<tr>
<td>Ultimate</td>
<td>QH_1; QH_3; QH_6; QH_8</td>
</tr>
<tr>
<td>Failure 1</td>
<td>QH_1; QH_3; QH_6</td>
</tr>
<tr>
<td>Failure 2</td>
<td>QH_1; QH_3</td>
</tr>
<tr>
<td>Failure 3</td>
<td>QH_1; QH_6</td>
</tr>
</tbody>
</table>
**MBRD prototype; Failure 1**

### Baseline:

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<td>QH_1; QH_3</td>
</tr>
<tr>
<td>Failure 3</td>
<td>QH_1; QH_6</td>
</tr>
</tbody>
</table>

![Diagram of MBRD prototype with QH firing points highlighted]
### MBRD prototype; Failure 2

**Baseline:**

<table>
<thead>
<tr>
<th>Case</th>
<th>QH firing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>QH_1; QH_3; QH_6; QH_8</td>
</tr>
<tr>
<td>Ultimate</td>
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</tr>
<tr>
<td>Failure 1</td>
<td>QH_1; QH_3; QH_6</td>
</tr>
<tr>
<td>Failure 2</td>
<td>QH_1; QH_3</td>
</tr>
<tr>
<td>Failure 3</td>
<td>QH_1; QH_6</td>
</tr>
</tbody>
</table>

![Graph showing MBRD prototype configurations](image-url)
Validation – Co-simulation MBRD magnet

MBRD prototype; Failure 3

Baseline:

<table>
<thead>
<tr>
<th>Case</th>
<th>QH firing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>QH_1; QH_3; QH_6; QH_8</td>
</tr>
<tr>
<td>Ultimate</td>
<td>QH_1; QH_3; QH_6; QH_8</td>
</tr>
<tr>
<td>Failure 1</td>
<td>QH_1; QH_3; QH_6</td>
</tr>
<tr>
<td>Failure 2</td>
<td>QH_1; QH_3</td>
</tr>
<tr>
<td>Failure 3</td>
<td>QH_1; QH_6</td>
</tr>
</tbody>
</table>
Simulation results of the MBRD prototype

- In the baseline, 8 QH strips out of 16 are used
- Failure cases simulated at nominal current

<table>
<thead>
<tr>
<th>Case</th>
<th>T_adiabatic [K]</th>
<th>Peak voltage to ground [V]</th>
<th>Peak turn to turn voltage [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>292</td>
<td>76</td>
<td>48</td>
</tr>
<tr>
<td>Ultimate</td>
<td>348</td>
<td>95</td>
<td>64</td>
</tr>
<tr>
<td>Failure 1</td>
<td>336</td>
<td>303</td>
<td>56</td>
</tr>
<tr>
<td>Failure 2</td>
<td>410</td>
<td>335</td>
<td>70</td>
</tr>
<tr>
<td>Failure 3</td>
<td>410</td>
<td>713</td>
<td>70</td>
</tr>
</tbody>
</table>

\[\text{T}_\text{adiabatic} \text{ is calculated by assuming that a quench occurred 27 ms before the quench detection is triggered}\]
Alternative protection; Baseline

### Alternative:

<table>
<thead>
<tr>
<th>Case</th>
<th>QH firing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>QH_1-8</td>
</tr>
<tr>
<td>Ultimate</td>
<td>QH_1-8</td>
</tr>
<tr>
<td>Failure 1</td>
<td>QH_8 fails</td>
</tr>
<tr>
<td>Failure 2</td>
<td>QH_2; QH_6 failing</td>
</tr>
<tr>
<td>Failure 3</td>
<td>QH_3; QH_7 failing</td>
</tr>
</tbody>
</table>

![Graph showing alternative protection cases and QH firing scenarios]
Alternative: 

<table>
<thead>
<tr>
<th>Case</th>
<th>QH firing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
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<tr>
<td>Ultimate</td>
<td>QH_1-8</td>
</tr>
<tr>
<td>Failure 1</td>
<td>QH_8 fails</td>
</tr>
<tr>
<td>Failure 2</td>
<td>QH_2; QH_6 failing</td>
</tr>
<tr>
<td>Failure 3</td>
<td>QH_3; QH_7 failing</td>
</tr>
</tbody>
</table>

Alternative protection; Failure 1
Alternative: "Case | QH firing"

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<thead>
<tr>
<th>Case</th>
<th>QH firing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>QH_1-8</td>
</tr>
<tr>
<td>Ultimate</td>
<td>QH_1-8</td>
</tr>
<tr>
<td>Failure 1</td>
<td>QH_8 fails</td>
</tr>
<tr>
<td>Failure 2</td>
<td>QH_2; QH_6 failing</td>
</tr>
<tr>
<td>Failure 3</td>
<td>QH_3; QH_7 failing</td>
</tr>
</tbody>
</table>

Alternative protection; Failure 2

- Case 1: QH_1
- Case 2: QH_3
- Case 3: QH_5
- Case 4: QH_7
- Case 5: QH_8

Diagram showing the placement of QH_1 to QH_8.
Alternative protection; Failure 3

Alternative:

<table>
<thead>
<tr>
<th>Case</th>
<th>QH firing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
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<td>Failure 1</td>
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</tr>
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</tr>
</tbody>
</table>

![Diagram showing QH firing cases](image-url)
**Alternative protection for the MBRD prototype**

- Significant improvement of hot-spot temperature and voltage to ground

- Alternative: 16 QH strips out of 16 are used
- Failure cases simulated at nominal current

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_{\text{adiabatic}}$ [K]</th>
<th>Peak voltage to ground [V]</th>
<th>Peak turn to turn voltage [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8/16</td>
<td>16/16</td>
<td>8/16</td>
</tr>
<tr>
<td>Nominal</td>
<td>292</td>
<td>219</td>
<td>76</td>
</tr>
<tr>
<td>Ultimate</td>
<td>348</td>
<td>259</td>
<td>95</td>
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$T_{\text{adiabatic}}$ is calculated by assuming that a quench occurred 27 ms before the quench detection is triggered.

---

**Peak temperature distribution during the transient**
Conclusion and lessons learned

- Simulation of QH discharges can be made more accurate, especially at low current, if the quench propagation between heating stations is included in the simulation.
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- STEAM-PyBBQ: New tool is now validated for cases with and without cooling.
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- Co-simulation analysis based on YAML files to be consistent, repeatable, versioned and traceable.
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- HL-LHC MBRD STEAM-LEDET model validated against experimental results
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• Co-simulation analysis based on YAML files to be consistent, repeatable, versioned and traceable.

• HL-LHC MBRD STEAM-LEDET model validated against experimental results.

• Studied nominal and failure cases for the HL-LHC baseline case, and an alternative protection with double the QH units, which allows reducing the hot-spot temperature by 160 K and the peak voltage to ground by 44%.
Annex: Coil and block voltages

- Coil voltages show similar behaviour as differential voltage
- Underestimation before energy extraction triggering not yet understood
- Block voltages of coil 2A show good overall agreement for blocks in contact to quench heaters
- Outer blocks don’t quench but develop inductive voltage
Voltage block 4 and 5

Voltages over blocks of coil 2_A

- V_2A_block_5_meas
- V_2A_block_5_sim
- V_2A_block_4_meas
- V_2A_block_4_sim

approximated quench start

Coil 2A
Annex: Improvements at low currents

- Major improvement of simulated discharge at low currents by including QH in the PyBBQ simulation
- No changes at high currents due to including QH in PyBBQ
Annex: Variation of f_helium at low currents

- No impact on discharge current and differential voltage at low currents for high f_helium
- From certain f_helium quench propagation occurs
Annex: Variation of $f_{\text{helium}}$ at high currents

- No impact at low currents for high $f_{\text{helium}}$
- From certain $f_{\text{helium}}$ quench propagation occurs
- Negligible impact on high currents
Annex: Identifying value of f_helium

- No impact at low currents for high f_helium
- From certain f_helium quench propagation occurs
- Negligible impact on high currents
- Highest visible impact at 6000 A
- Less helium cooling accelerates discharge
- Best fit for f_helium at 0.7
Annex: Difference of simulated and measured quench start

- Time of quench at high current is simulated well
- At low current, the quench start is simulated too early
- Earlier start maybe due to underestimating the cooling along the longitudinal direction of a half turn