Electro-thermal simulations of superconductors in case of beam losses

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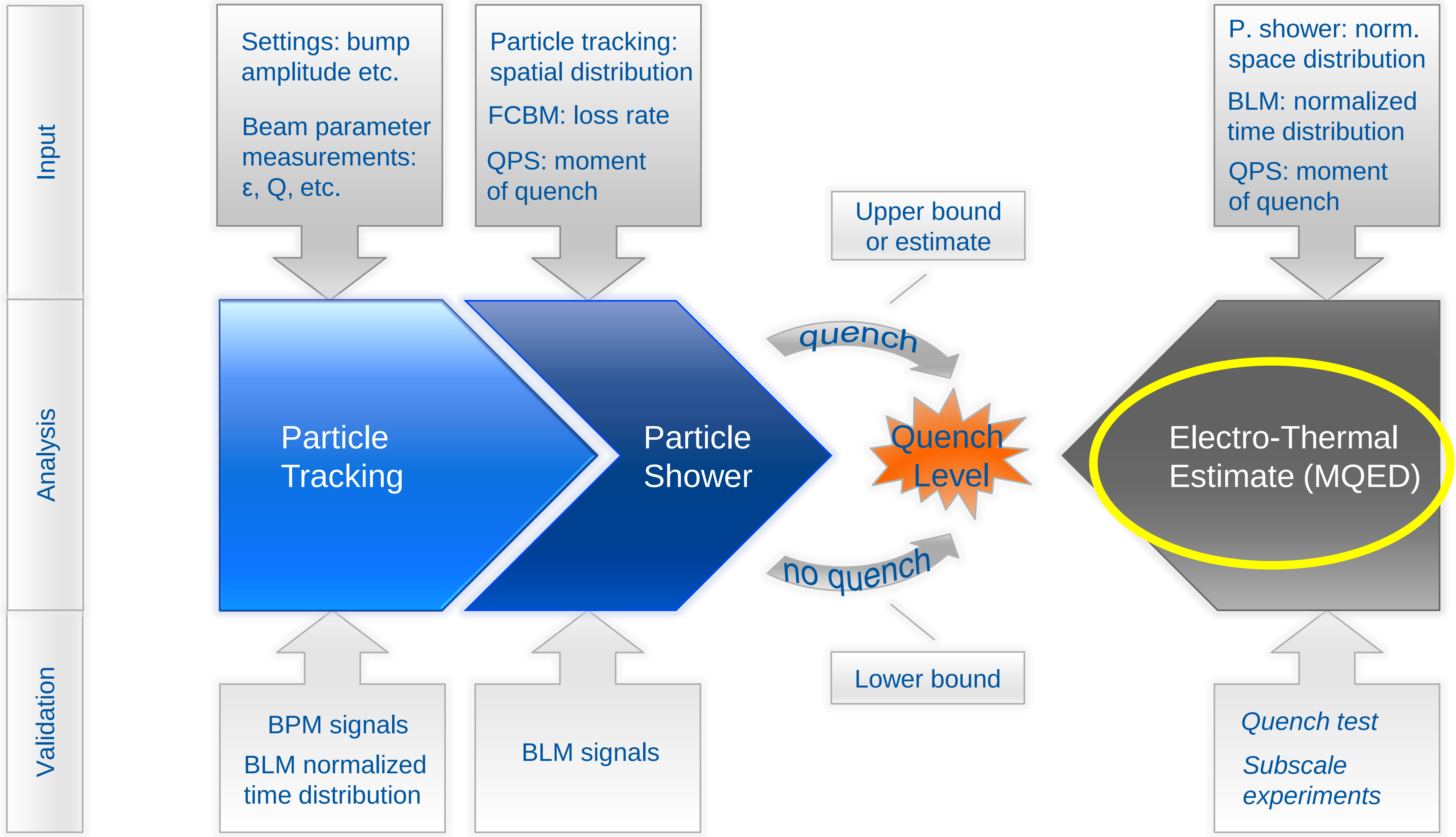
- Intro
- Conductor geometry
- The thermal model in QP3
- MQED results of the quench tests
  - Short duration
  - Intermediate duration
  - Steady-state
- Conclusions

Intro



Input

Analysis

Validation

Settings: bump amplitude etc.

Beam parameter measurements: ε, Q, etc.

Particle tracking: spatial distribution

FCBM: loss rate

QPS: moment of quench

P. shower: norm. space distribution

BLM: normalized time distribution

QPS: moment of quench

Upper bound or estimate

Particle Tracking

Particle Shower

quench

Quench Level

no quench

Electro-Thermal Estimate (MQED)

Lower bound

BPM signals

BLM normalized time distribution

BLM signals

Quench test

Subscale experiments

Intro

The LHC contains a variety of SC coils:

- Wound from Rutherford cables or single strands
- Non-impregnated or impregnated/potted coils
- Operating at 1.9 K or 4.5 K

The simulation code should of course cover all these possibilities, taking also into account that the beam losses can be of arbitrary shape in space and in time.

The main focus is on the main dipoles and quadrupoles, because they cover >90% of the machine.

Other magnets (with impregnated coils or working at 4.5 K) have often less stability margin and should not be forgotten….

Intro

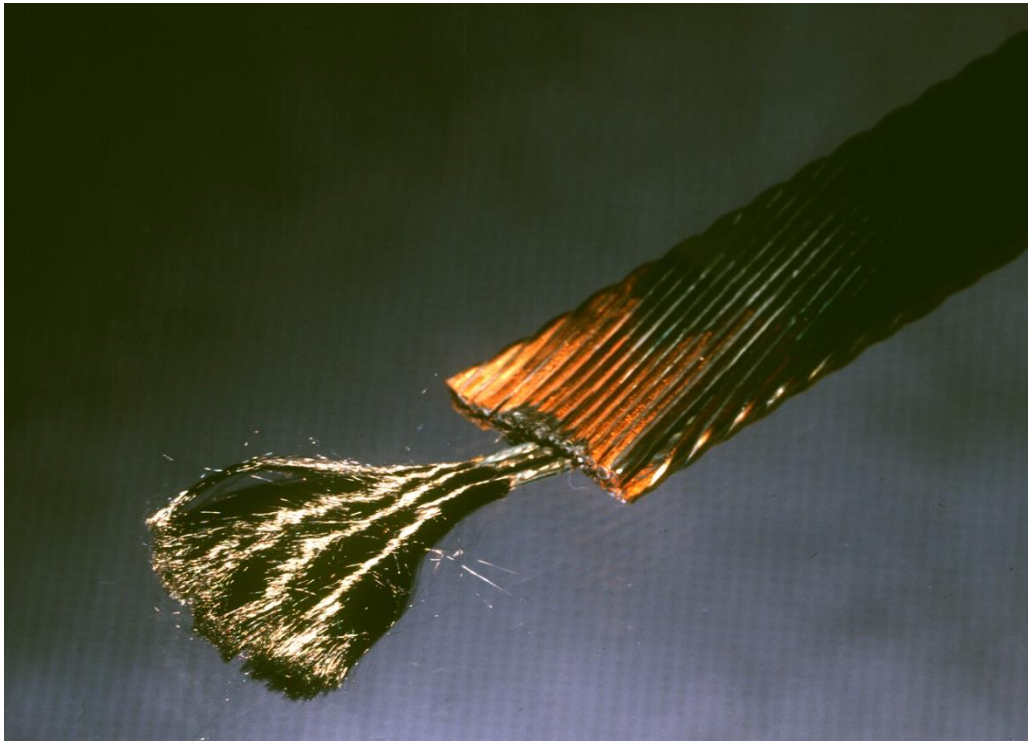
The code QP3 can be used for electrodynamic-thermal calculation of superconductors, especially suitable for uncoiled conductors or coils with small heat transfer between the turns.

The code has been used to calculate:

- Quench propagation in SC's.
- QPS thresholds for busbars/coils.
- Hot-spot temperatures in coils.
- The behaviour of defective joints in the 13 kA circuits (2008 accident, 'safe current', required shunt size for the repair, tests in FRESCA and SM-18).
- **Quench tests in the LHC.**
- Quench thresholds for BLM settings.

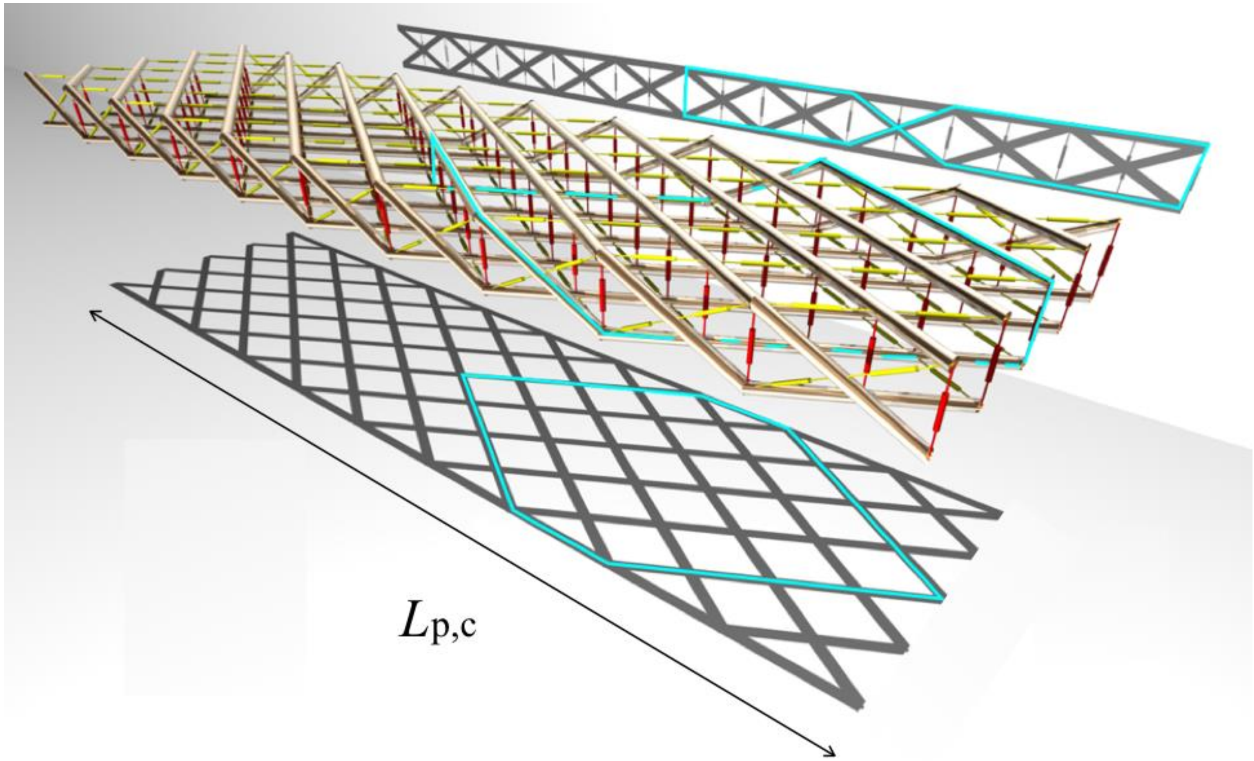
Rutherford cable

The Rutherford cables in the LHC are fully transposed non-potted multi-strand compacted cables with a slightly keystoned cross-section.



Cable model

A 3-D model can be set up for such a cable.



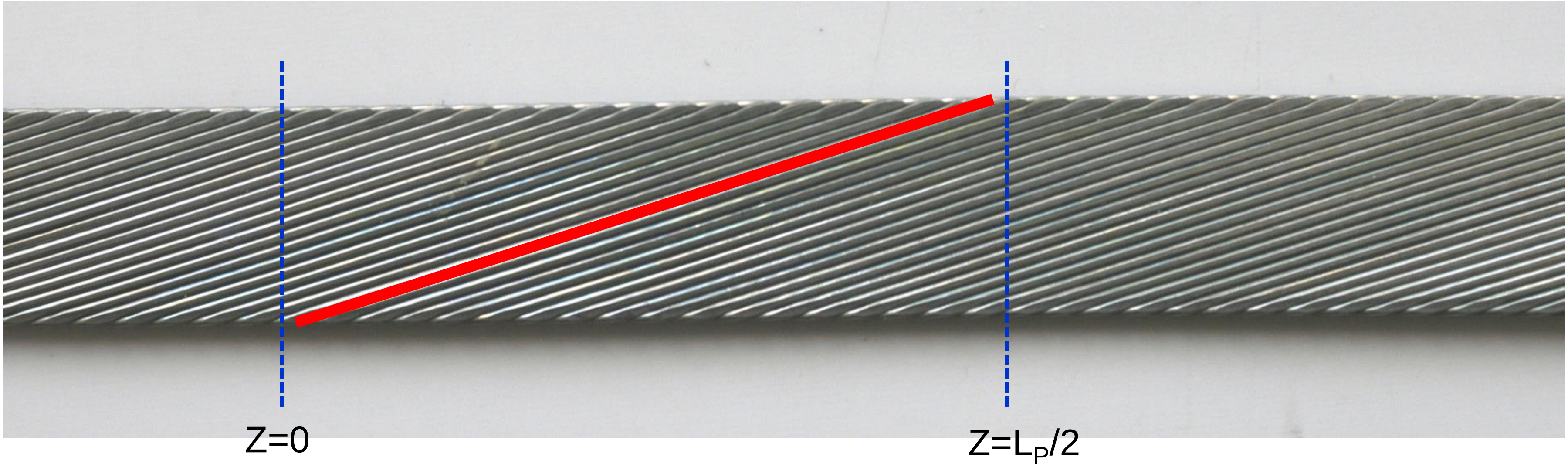
When calculating the response of the cable due to a heat deposition P_{ext}, one can reduce the 3D cable model to a single strand, if:

1. each strand carries the same transport current, and
2. P_{ext} is larger than a twist pitch (typically 10 cm).

Strand model

After averaging the properties over the cross-section of the strand, one can use a simplified **1-D model**.

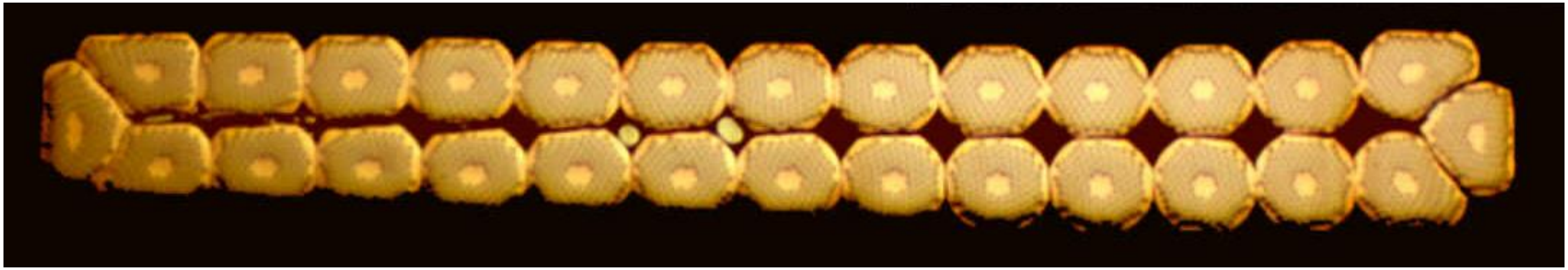
The length of the 1-D model should be such that the heat transfer at both ends is almost zero. A length of half a twist pitch is usually sufficient since most beam losses are rather global. In case of doubt, one should run the model for lengths of $L_P/2$ and $3L_P/2$ and check the difference.



Geometrical variations

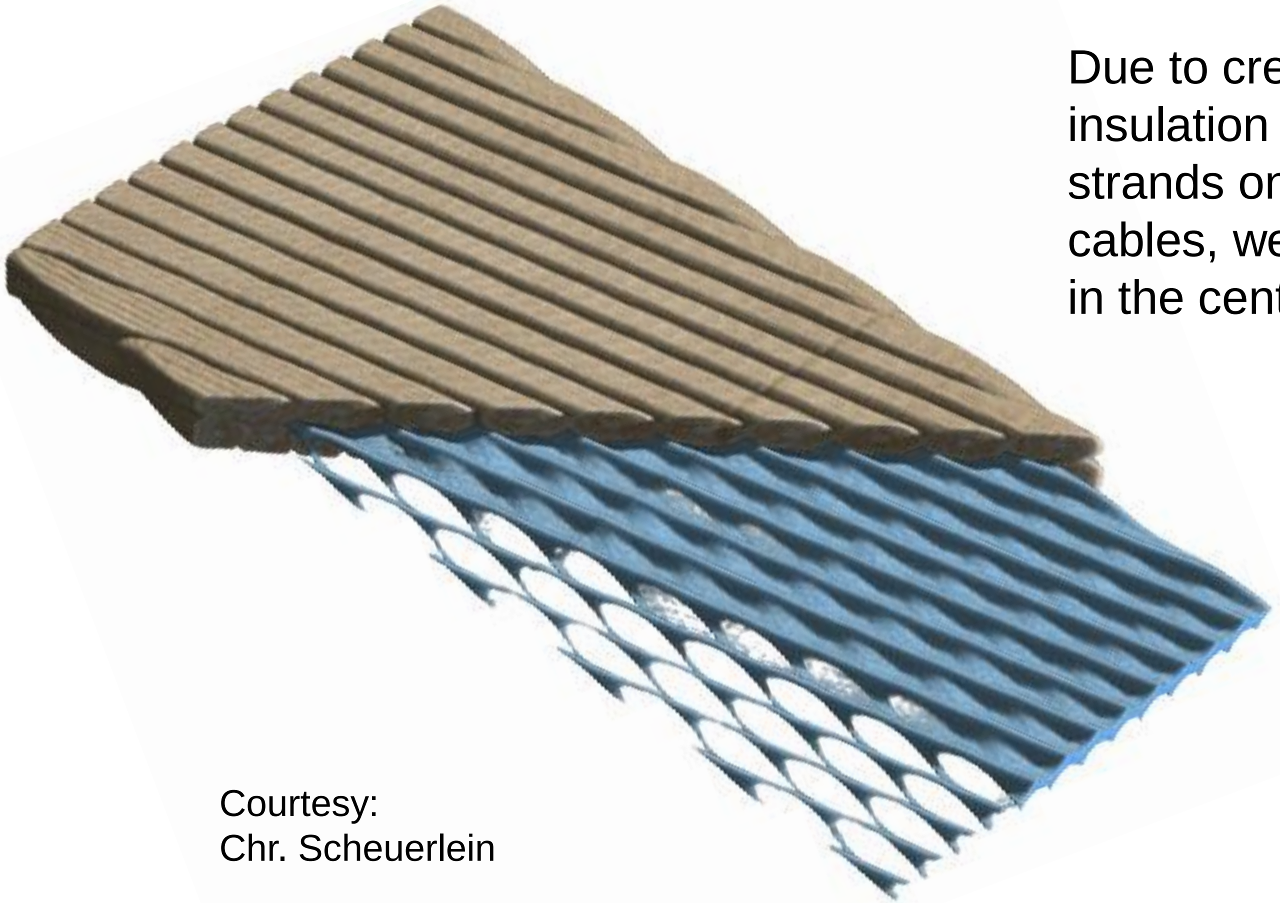
In case of a cable one has of course to take into account that the strands are twisted, so that several parameters vary along the length:

- Field (input from Roxie). Typically factor 2.
- Void volume. Typically factor 3.
- Contact surface with voids. Typically factor 5.
- Beam losses (input from Fluka). Typically factor 10.



Tomography of a Rutherford cable

The volume of the voids and the contact surface between strands and voids are deduced from tomography measurements. We have only data for the dipole inner cable. Other cables are scaled.



Due to creep of the kapton insulation in-between the strands on the outside of the cables, we assume only helium in the centre of the cable.

Courtesy:
Chr. Scheuerlein

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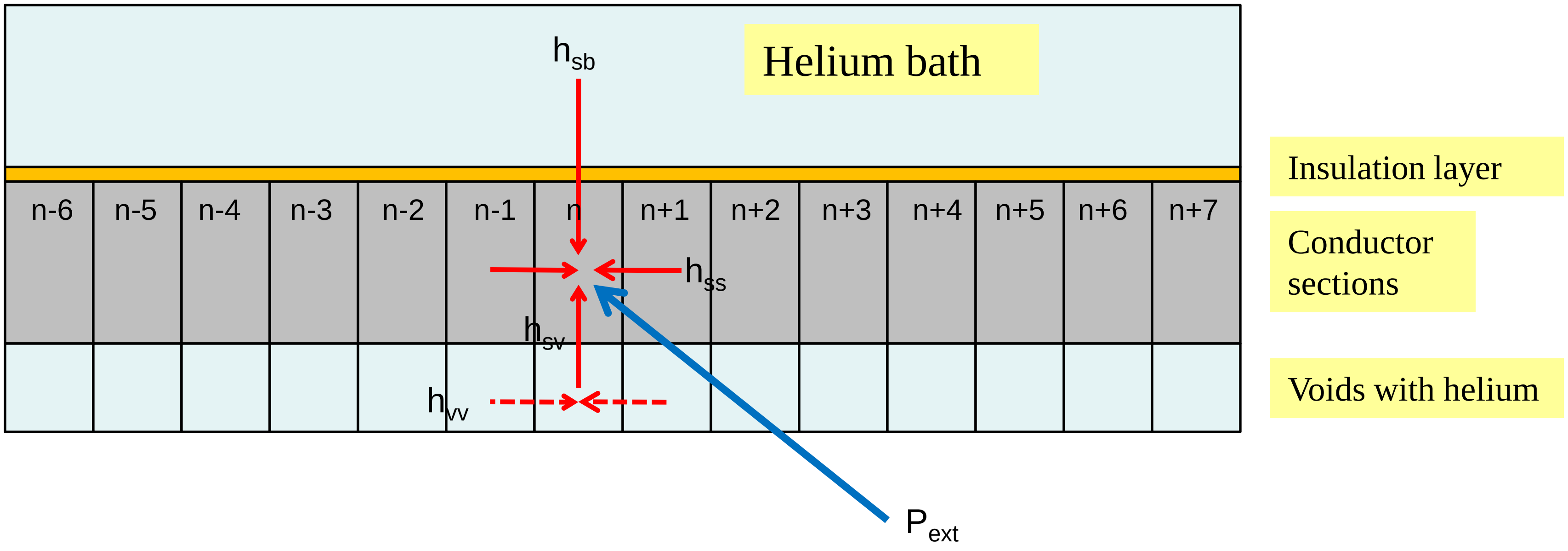
Thermal model

The 1-D strand is discretized and a small volume of helium is put adjacent to each conductor section. An insulation layer and helium bath are added.

The thermal model includes:

- Heat flow along the conductor (h_{ss}).
- Heat flow between conductor and helium voids (h_{sv}).
- Heat flow between conductor and helium bath (h_{sb}).
- Heat flow between the helium voids (h_{vv})
- External heat input, e.g. beam losses (P_{ext})



Thermal model

Heat balance for section n:

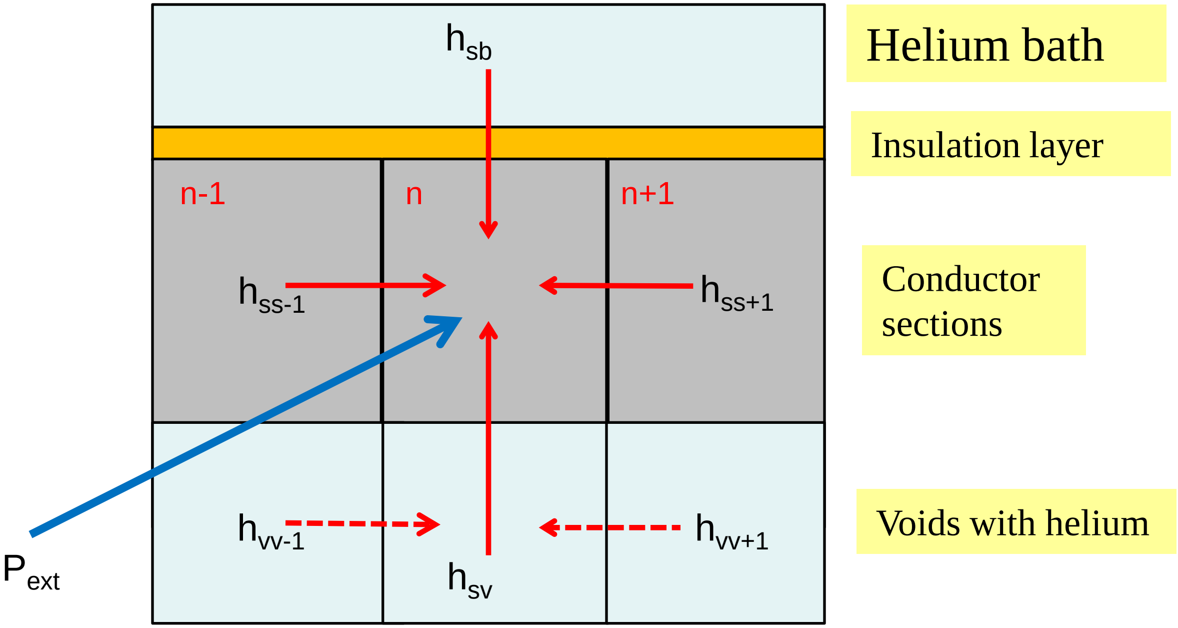
$$V_s C_{P,s} \Delta T_s/\Delta t = P_s + P_{ext} + h_{ss-1} + h_{ss+1} + h_{sv} + h_{sb}$$

Material properties
f(T, B, RRR)

$=I^2R_s(T,B)$

Fluka

Material properties
f(T, B, RRR)



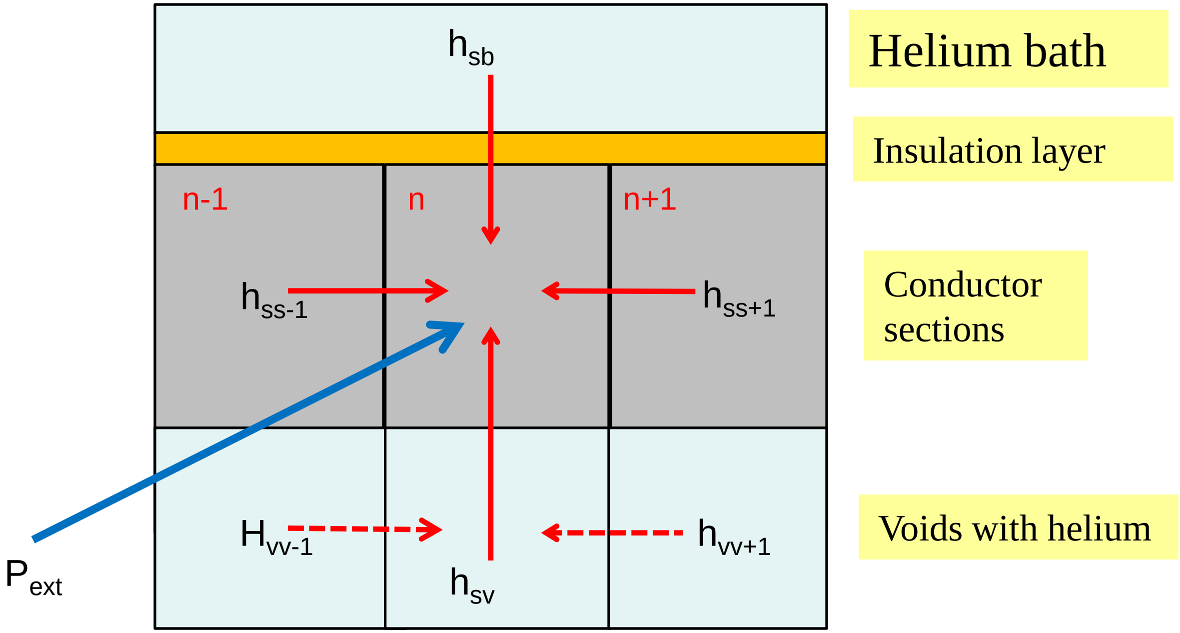
Thermal model

Heat balance for helium void adjacent to a strand section:

$$V_v C_{P,he} \Delta T_v / \Delta t = -h_{sv} + h_{vv-1} + h_{vv+1}$$

Material properties
f(T,B)

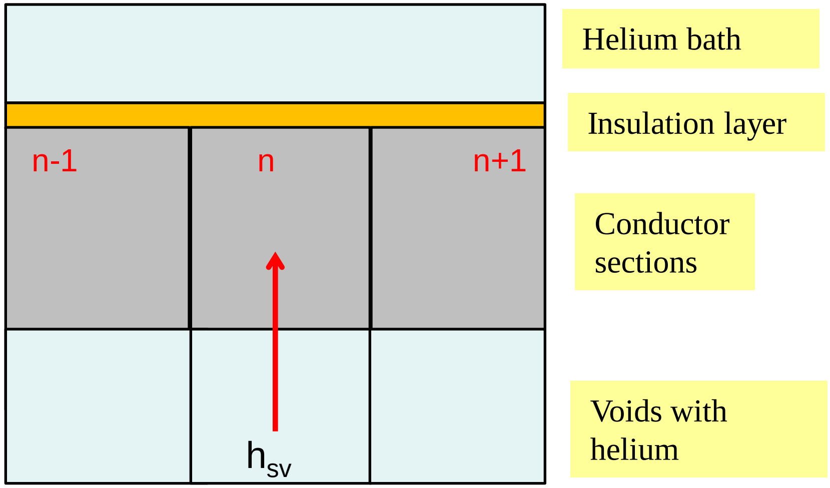
The user can select constant helium mass (varying helium pressure) or constant helium pressure (varying helium mass).



Heat transfer: remarks

h_{sv}: complicated, and poorly understood, especially under transient conditions. QP3 follows the heat transfer mechanisms as described in the PhD thesis of P. Bauer:

- Kapitza cooling
- Film boiling to HeII
- Natural convection
- Nucleate boiling
- Film boiling to HeI



Note:
- C_P of Nb-Ti @ 2 K: 0.4 mJ/K/cm^3
- C_P of He @ 2 K: 800 mJ/K/cm^3

The user can decide which regimes should be taken into account, set the limits and the parameters in the heat transfer equations.

Other type of cooling regimes can be easily added.

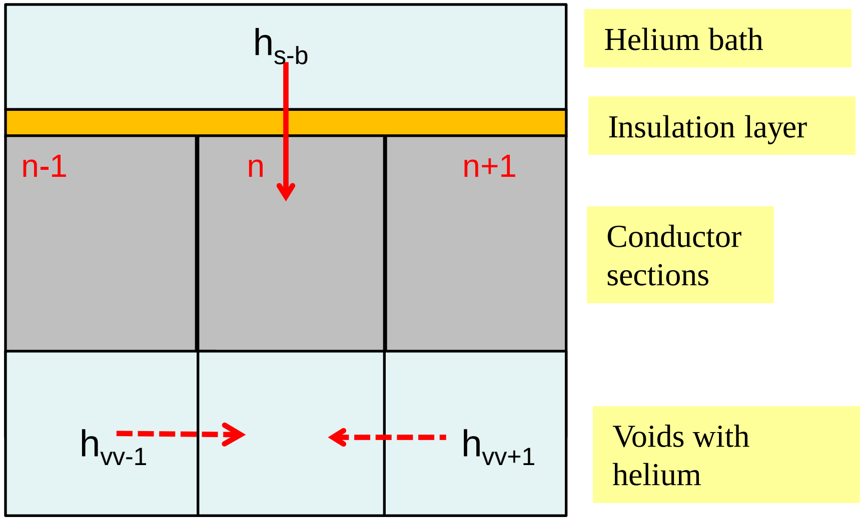
See presentations tomorrow morning.

Heat transfer: remarks

h_{sb} (through the porous cable insulation): Input from heat transfer measurements at CERN and Saclay on dummy LHC coils.

See presentations tomorrow morning.

h_{vv} (along the voids): Only relevant below T_λ. Channels are very narrow on the thin side of the cable. In parallel to the (very efficient) $h_{s\text{-}s}$. Not implemented at present in QP3.



Solving algorithm

- Loop for parametric sweep (e.g. beam energy, loss duration, …)
  - Iterate with different P_{ext} to calculate the MQED (or MQPD)
    - Loop through all time steps
      - Iterate until the time step is small enough (dynamic time stepping)
        - Fix Joule heating based on previous time step (explicit method)
          - Iterate until the thermal module has converged
            - Loop over all the sections of the conductor
              - Iterate until the temperatures of the section and the adjacent helium have converged

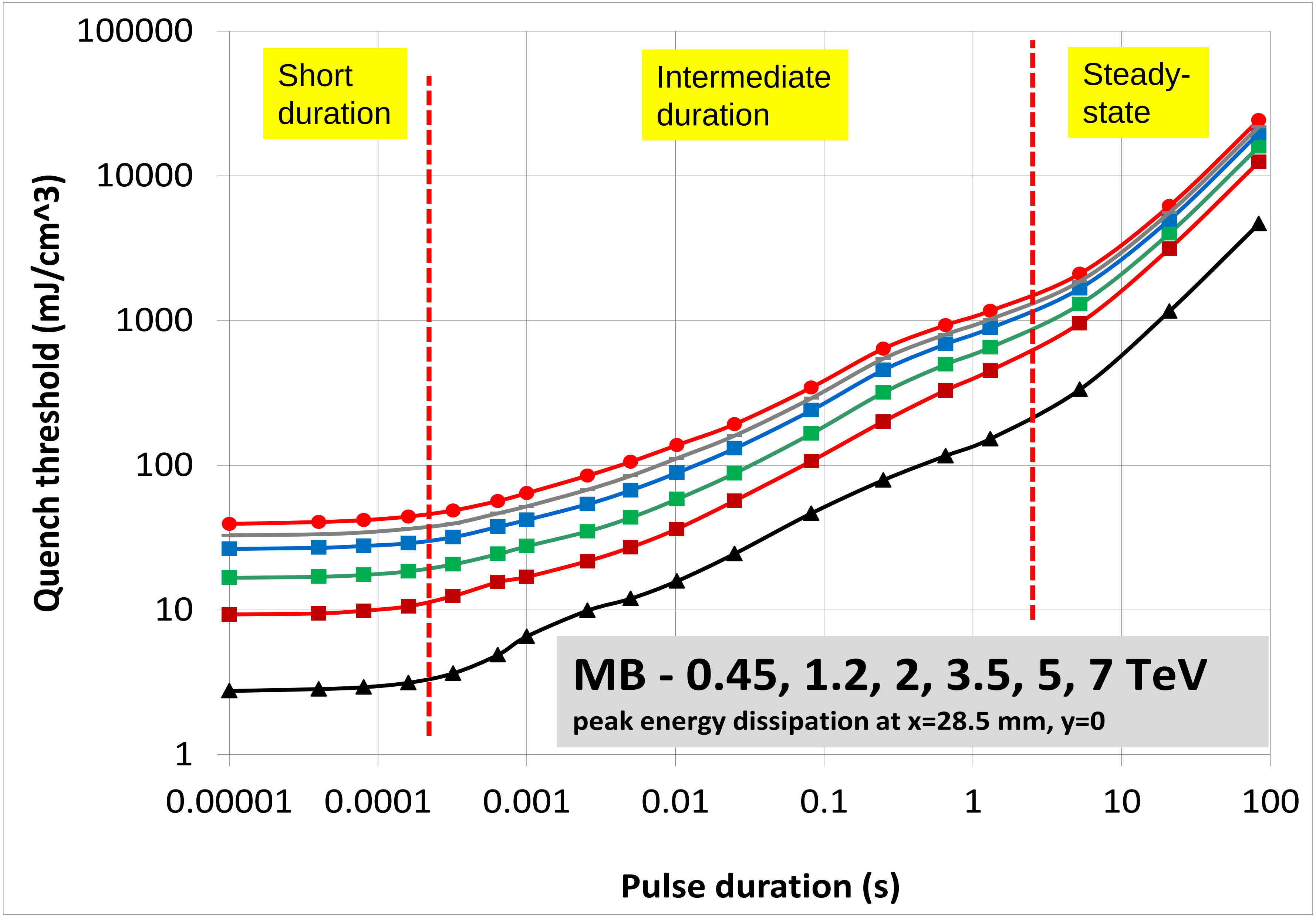
Typical simulation errors *for known beam loss*

- Local variations in RRR, I_C, Cu/SC ratio, void fraction, wetted strand surface, strand surface oxidation,…
- Possible non-uniform current distribution.
- Incorrect heat transfer mechanisms/physics.
- Incorrect modeling of the helium phase transitions.
- Different h_{sb} due to adjacent turns, especially for steady-state losses.

Loss duration	**Adiabatic**	**4.5 K 1.9 K potted**	**1.9 K non-potted**
Short	🟩	🟩	🟩
Intermediate	🟩	🟦	🟥
Steady-state	🟩	🟦	🟦

🟩	Error <20%
🟦	Error <50%
🟥	Error up to a factor 4

Example of “Quench threshold vs duration” plot



MB - 0.45, 1.2, 2, 3.5, 5, 7 TeV

peak energy dissipation at x=28.5 mm, y=0

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Simulation results for the quench tests

Short duration

Name	**Energy [TeV]**	**Magnet**	**Temp [K]**	**I/Inom**	**QP3 [mJ/cm^3]**	**Comments**
Strong-kick	0.45	MB	1.9	6%	38	Error is small and dominated by uncertainties in local strand characteristics.
Collimation	0.45	MQM	4.5	46% 58%	20 16	

See next talk for comparison with Fluka

Simulation results for the quench tests

Intermediate duration

Name	Energy [TeV]	Magnet	Temp [K]	I/Inom	QP3 [mJ/cm^3]	Comments
Wire-scanner 0.15 m/s	3.5	MBRB	4.5	50%	26-37	Tests at 4.5 K, so cooling better known than at 1.9 K. Quench probably in the ends of the magnet, so field and void fraction not accurately known. Exact moment of quench not known.
Wire-scanner 0.05 m/s	3.5	MBRB	4.5	50%	24-42	
Wire-scanner 0.05 m/s	3.5	MQY	4.5	50%	52	
Orbit bump, ~10 ms	4	MQ	1.9	54%	50-80	Error dominated by unknown transient heat transfer to the helium in the cable voids, especially due to the ‘spiky’ loss. Exact moment of quench is also not known.

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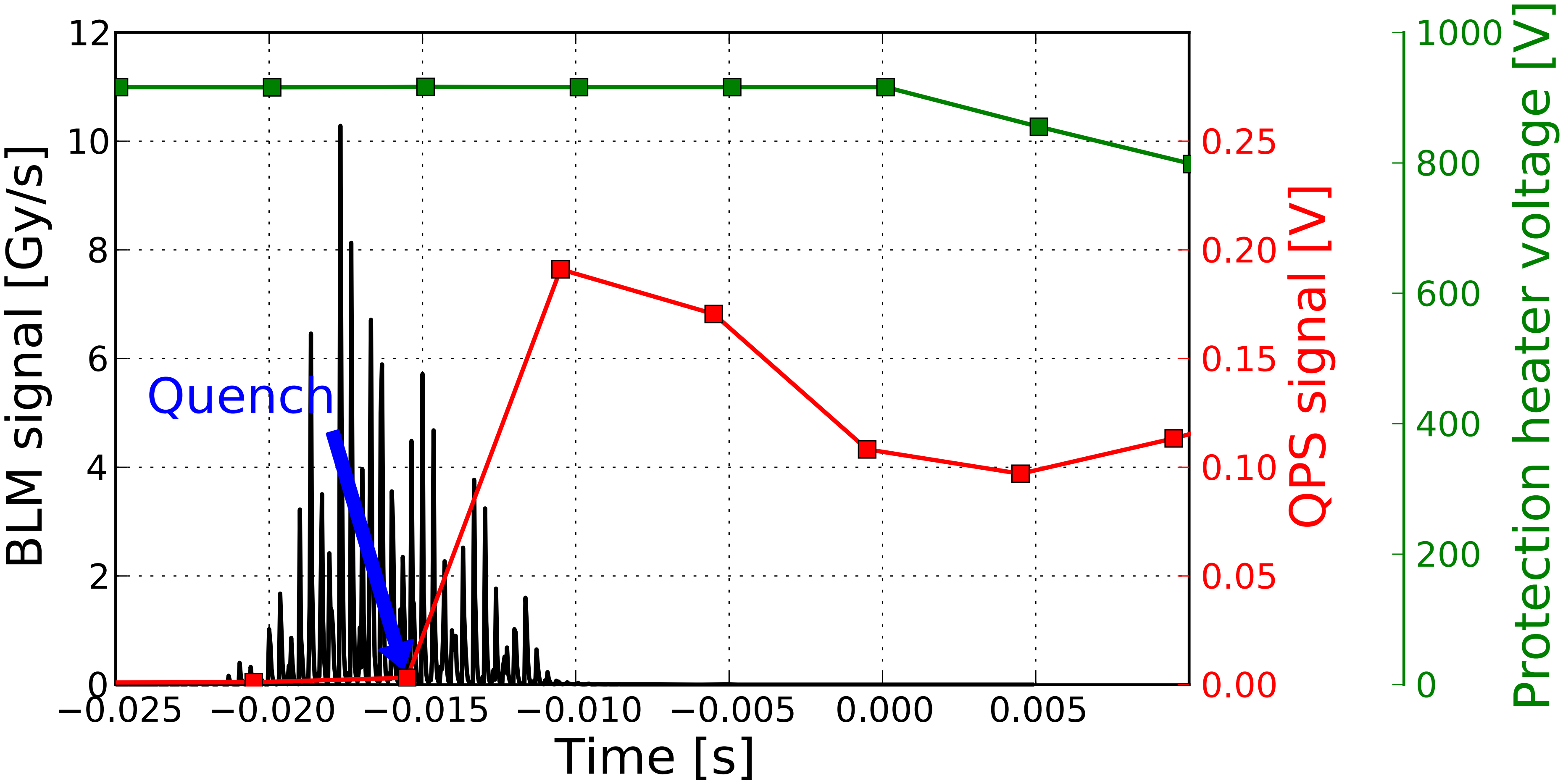
“Spiky heat deposition”, and unknown start of quench



See also talk B. Auchmann

Simulation results for the quench tests

Steady-state

Name	Energy [TeV]	Magnet	Temp [K]	I/Inom	QP3 [mW/cm^3]	Comments
Dynamic orbit-bump ~1 s	3.5	MQ	1.9	54%	190-215	Unknown efficiency of the fish-bones. Unknown effect of adjacent turns. Collimation test: Quench probably in the ends of the magnet, so field and void fraction not accurately known.
Collimation ~5 s	4	MB	1.9	57%	115-140	
Static orbit-bump ~20 s	0.45	MQ	1.9	5%	70-100	

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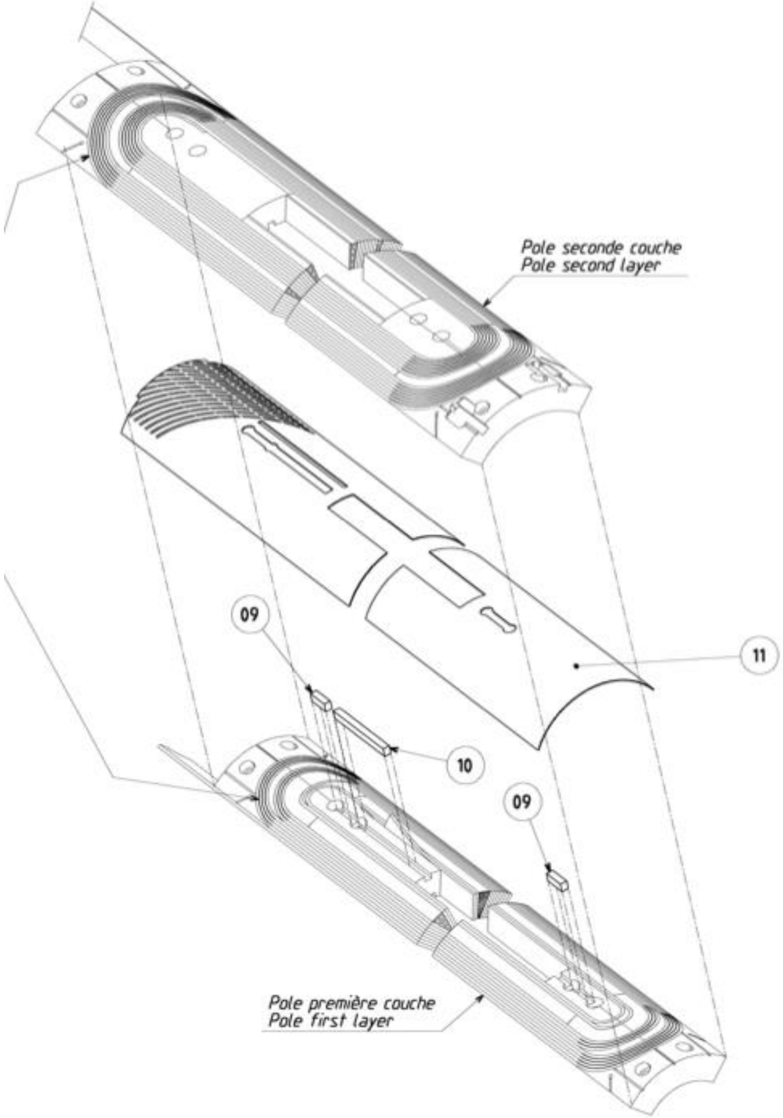
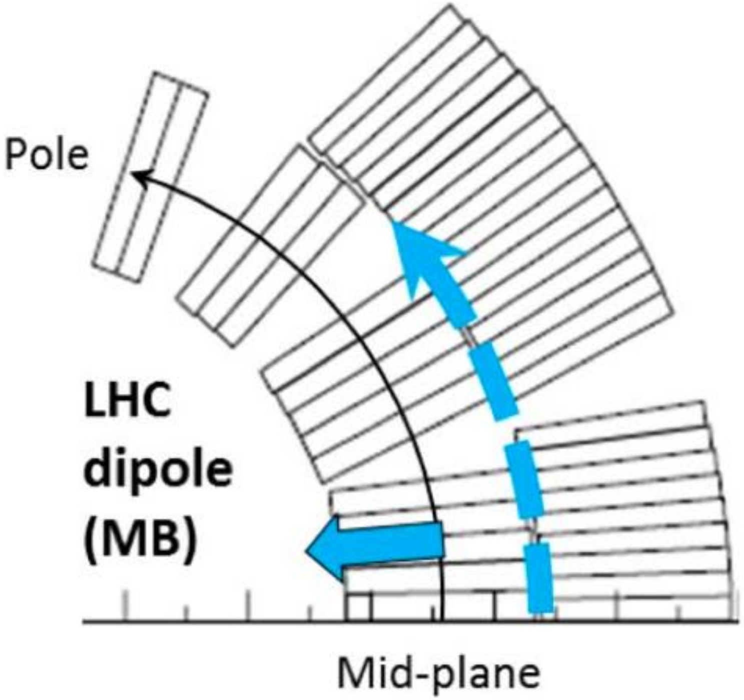
Unknown efficiency of the fish bones





Courtesy: P.P. Granieri

Summary

Using the electro-thermal code QP3 the quench thresholds have been calculated for the various quench tests performed in the LHC.

When simulating these quench tests, often an error is present due to uncertainty in the heat deposition and exact moment of quench.

Due to manufacturing tolerances of the SC strand & cable and possible variations in the transport current among the strands, the calculation of the MQED always contains a certain error.

Additional errors are caused by inaccurate heat transfers, especially the transient heat transfer from the conductor to the helium in the voids.
In QP3 we can easily modify the heat transfer mechanisms, but we need validated experimental data. The focus should be on the 1-10 ms range, which is important for the LHC, and has a large uncertainty at the moment, but is experimentally very demanding.