Quench Test Analysis Working Group (QTAWG), August 23, 2013

Quench limit calculation:

- based on heat transfer tests (slow losses)
- on THEA code (fast losses)

Comparison to FLUKA values
for different quench tests

Pier Paolo Granieri

Ack.: L. Bottura, M. Breschi, F. Cerutti, L. Esposito, P. Galassi, M. Massimini, L. Skordis, R. van Weelderen

and B. Auchmann, V. Chetvertkova, A. Lechter, A. Priebe, S. Redaelli, M. Sapinski, A. Verweij, N. Vittal
for discussing QT results & analysis

CERN

Quench limits

transient state, mJ/cm^3
(fast losses)

steady-state, mW/cm^3
(slow losses, typically > 1 s)

Dominant stability mechanism

Local heat transfer from strand to He inside the cable

↓

No conclusive experiments (yet) → we rely on **numerical codes**:
- 1-D (THEA) and 0-D (ZeroDee)
- QP3 (Arjan - Bernhard)

Heat transfer from cable to He bath (through cable electrical insulation)

↓

Experiments and modeling ongoing

Outline

- Steady-state quench limits
  - Experimental method and results
  - Comparison to 2013 collimation QT
- Transient quench limits
  - Numerical methods and results
  - Comparison to different QT's:
    2013 ADT and Q6, 2010 wire scanner

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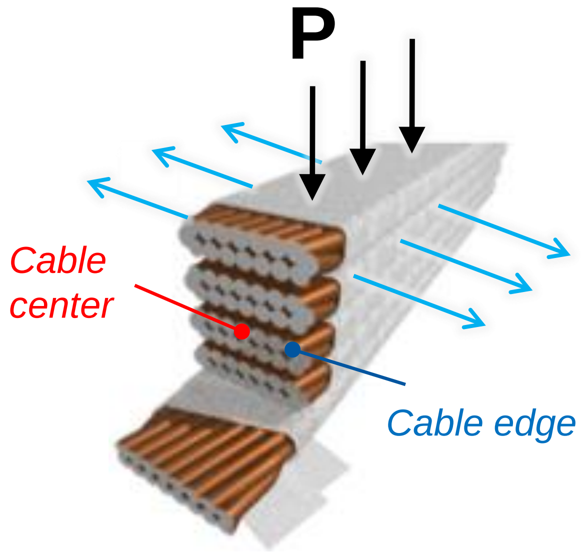
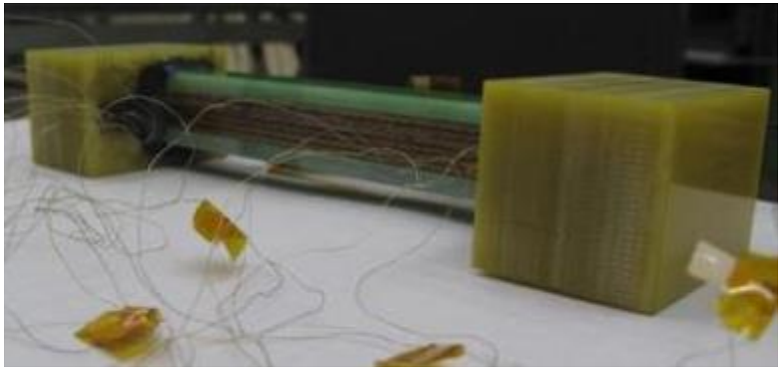
Experimental method

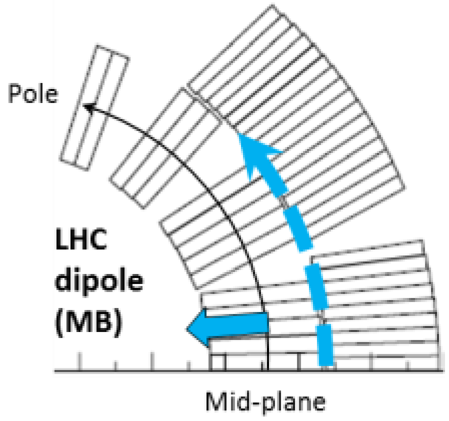
- The *stack method* allows to thermally characterize SC coils, and determine
- It allows to measure the heat transfer through the cable's electrical insulation
  - typically the most severe barrier for heat extraction from the magnet
- Measure heat extracted as a function of the cable temperature, in 2 locations
  - under a controlled pressure
- The deduced quench limits refer to a **uniform heat deposit** over the cable



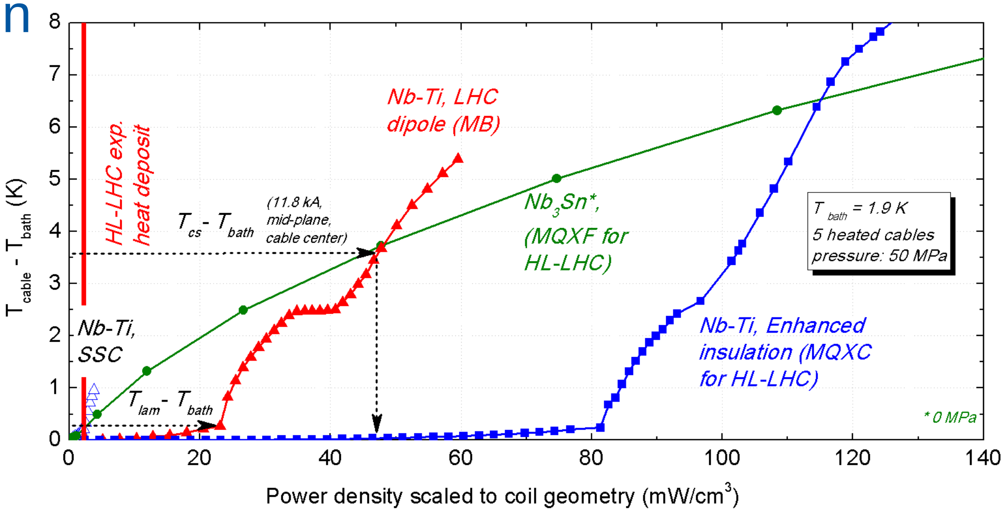


Deduction of cable steady-state quench limits

- For steady-state beam losses, a quench occurs if T_{cable} exceeds T_{cs} (~ 4 K for Nb-Ti, ~ 7 K for Nb_3Sn in a 1.9 K bath)
  - not T_λ (2.16 K), which is instead a design limit for Nb-Ti coils



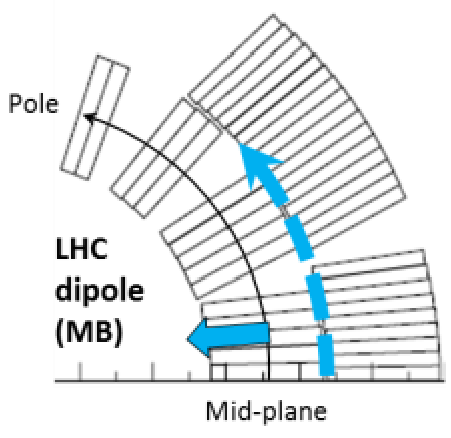
- The cable quench limits depend on
  - Heat extraction:
    - cable cooling within the magnet
    - mechanical pressure, if Nb-Ti coil
    - stack heating configuration
  - Operating conditions:
    - transport current
    - magnetic field, thus cable and strand considered

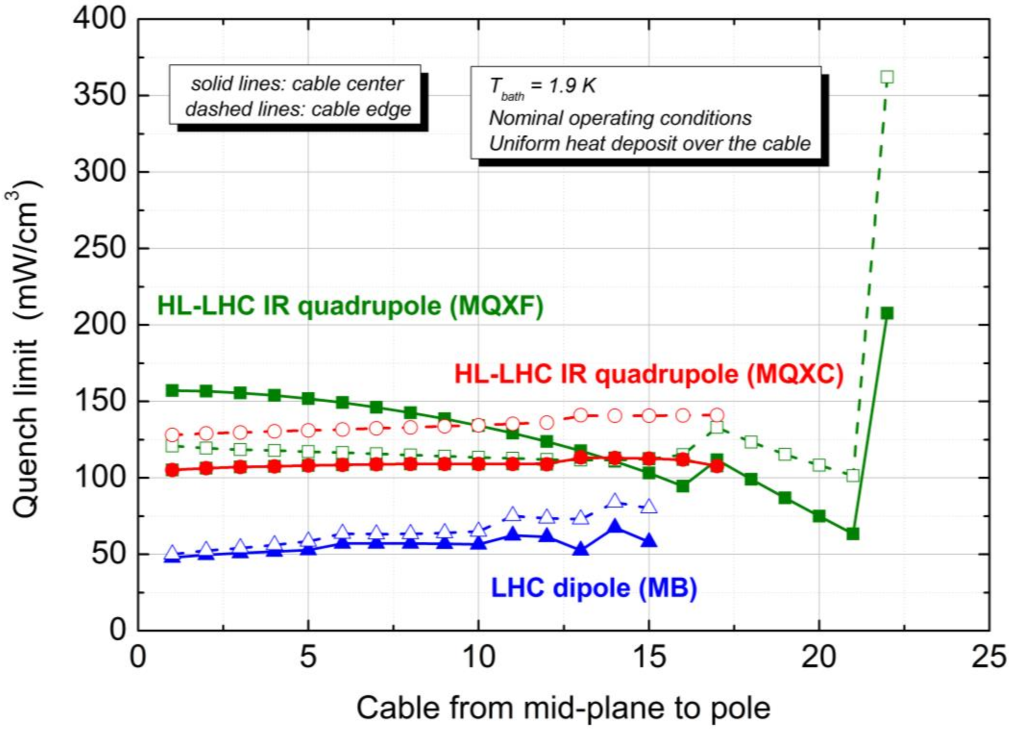


Method reported in: P.P. Granieri and R. van Weelderen, "Deduction of Steady-State Cable Quench Limits for Various Electrical Insulation Schemes with Application to LHC and HL-LHC Magnets", *IEEE Trans. Appl. Supercond.* 23 submitted for publication

Results: QL along the azimuthal direction

- T_{bath} = 1.9 K, held constant during heat removal

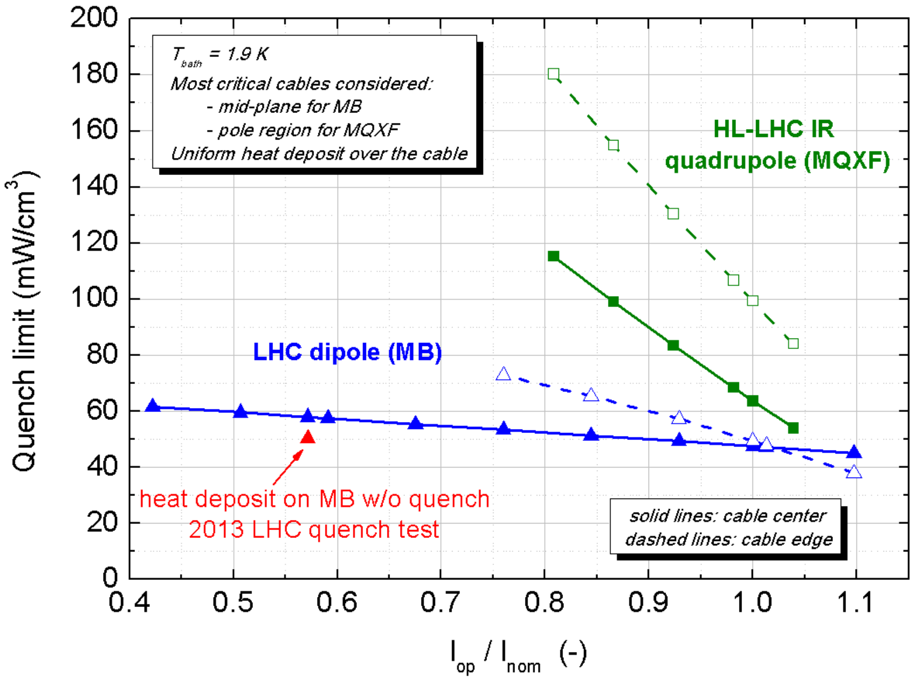




- Next magnes to be studied: MQXA, MQ

Comparison to 2013 collimation QT

- Quench limit as a function of the transport current
  - in the most critical regions, i.e. mid-plane for MB and close to the pole for MQXF
  - in agreement with the LHC collimation quench test, performed in 2013



2013 collimation quench test

Experiment: S. Redaelli, B. Salvachua, R. Bruce, W. Hofle, D. Valuch, E. Nebot

Simulations: F. Cerutti, E. Skordis

LHC collimation Review 2013:
http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=251588

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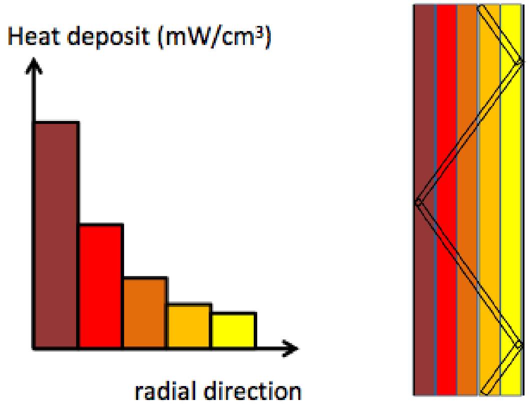
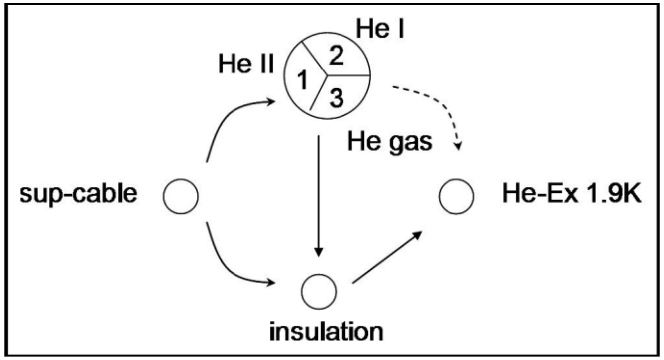
Numerical methods

- Need to distinguish the code used from the physics implemented (i.e. the parameters used), which is fundamental ! See next slide

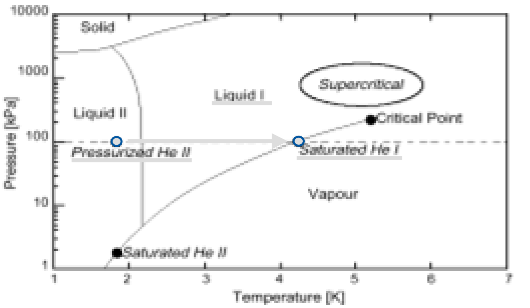
- We use two different approaches:
  - 1-D code (THEA): a single strand experiencing a heat deposit and field variation along its length
    - Similar to QP3



  - 0-D code (ZeroDee): a local balance of energy, without longitudinal direction

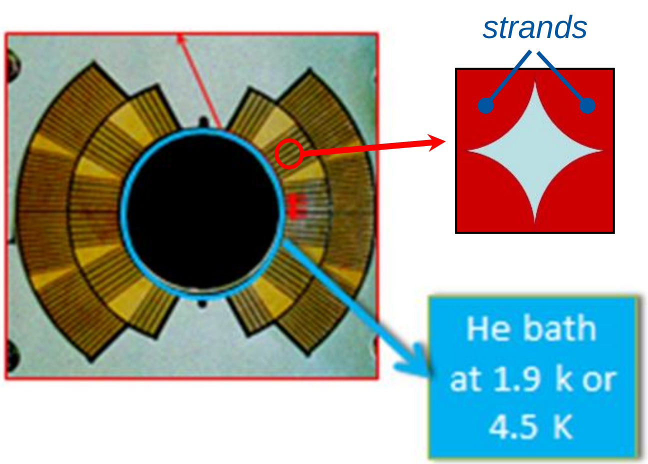


Heat transfer models



- Transient heat transfer between strands and He inside the cable
  - From experimental results of each He phase. But the model of the whole process

$$
h_{s,h} = \begin{cases}
h_K & \textbf{He II} & T_h \leq T_\lambda \\
h_{HeI} & \textbf{He I} & T_\lambda < T_h < T_{Sat} \\
h_{nucl.boil.} & \textbf{Nucleate Boiling} & T_h = T_{Sat} \\
h_{film} & \textbf{Film Boiling} & E_{film} = E_{\lim} \\
h_{gas} & \textbf{Gas} & E_{gas} = E_{lat}
\end{cases}
$$



- Steady-state heat transfer between cable and external He bath
  - From experimental results (see first part of the talk)

Results

- With the 0-D code we studied all the most critical LHC magnets: MB, MQ, MQXA, MQXB, MQXF, MQM, MQY, D1, D2, D3, D4, MQTLI, MQTLH

- We have performed a systematic scan of each magnet, as a function of: heating time, beam energy, magnetic field, effect of He bath

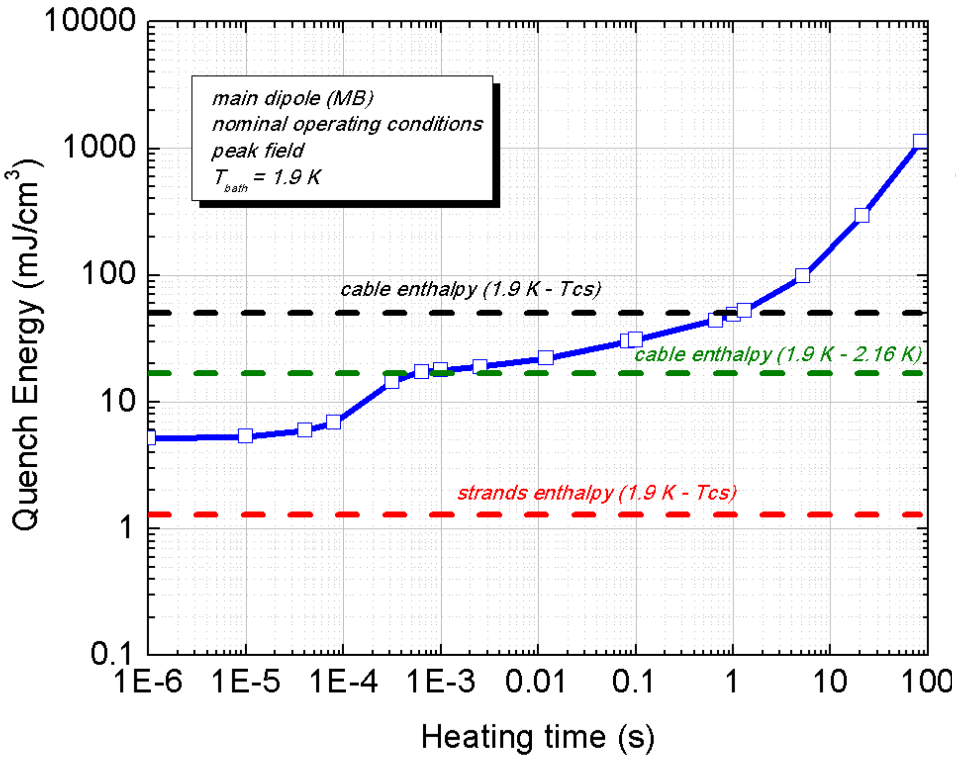
- Work on the 1-D THEA code started just before the summer holidays
  - The following results were obtained with 0-D, except the ADT analysis performed using both codes
  - More work with the THEA code to be done

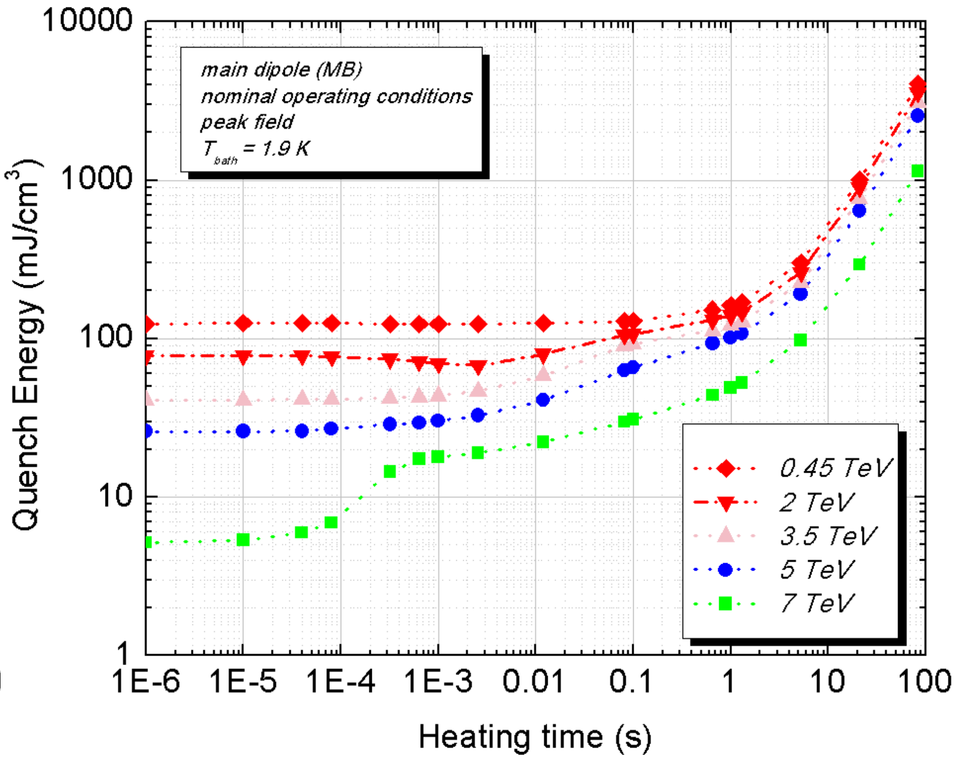
- A complete report of all the results will be ready within few weeks

Brief overview of results

Heating time

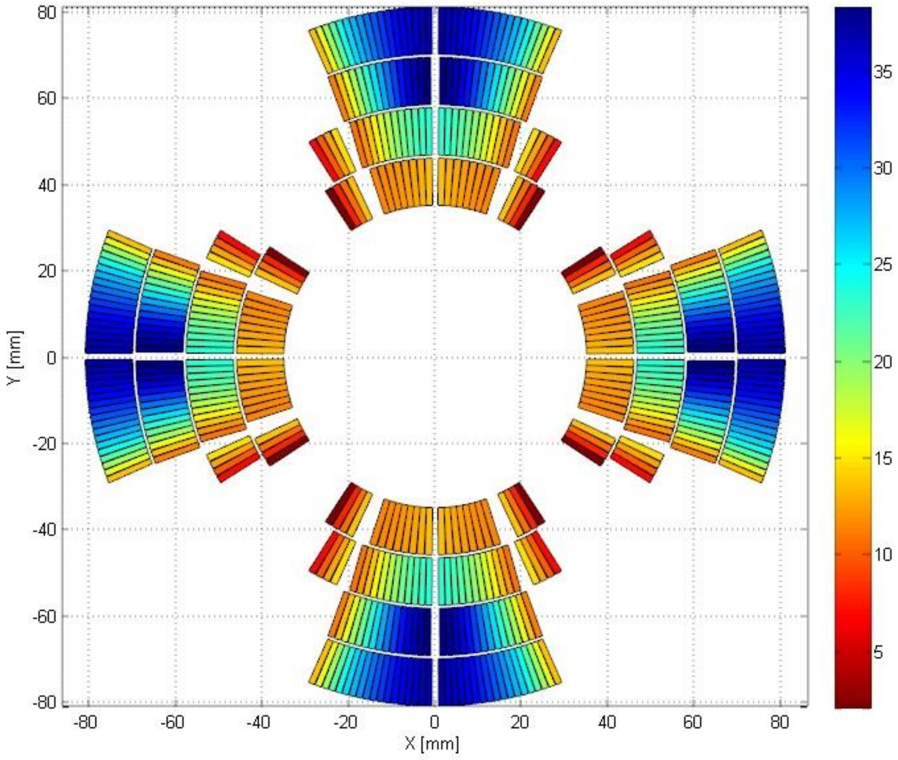
Beam energy



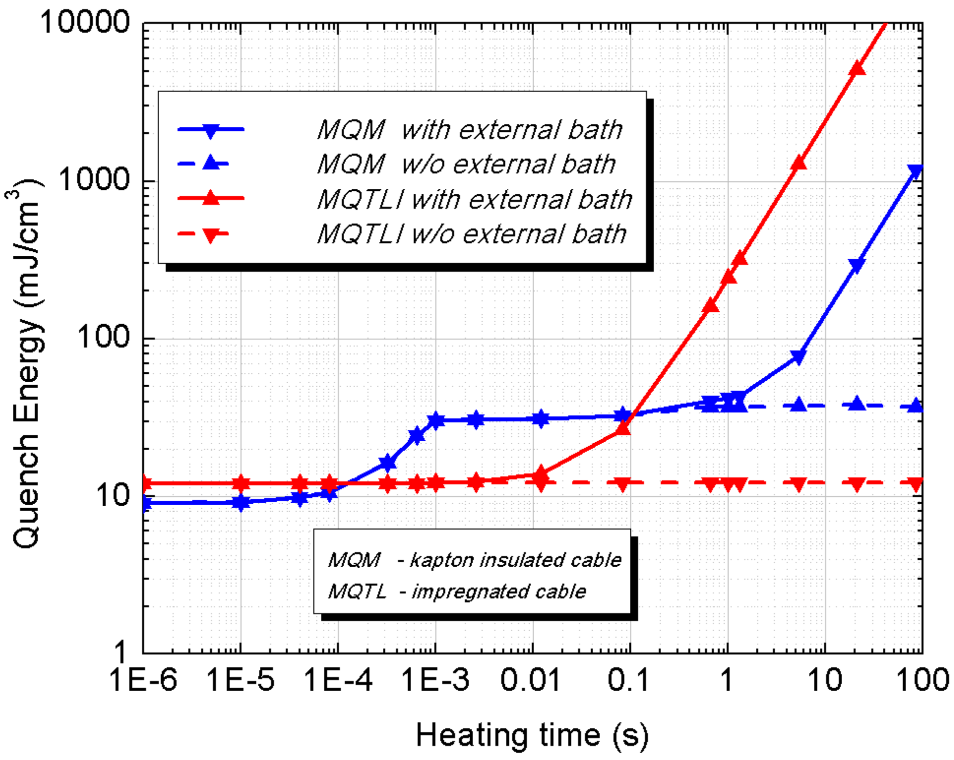


Brief overview of results

Magnetic field

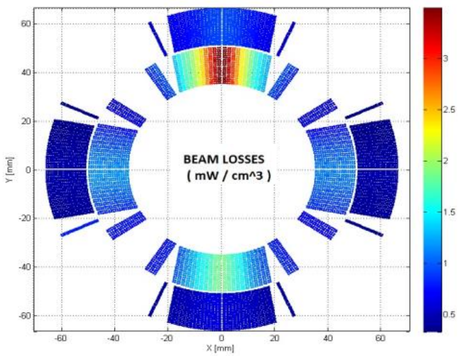


Effect of He bath



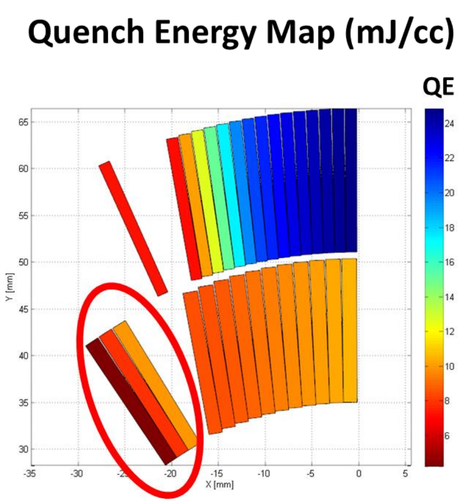
What is the most critical cable?

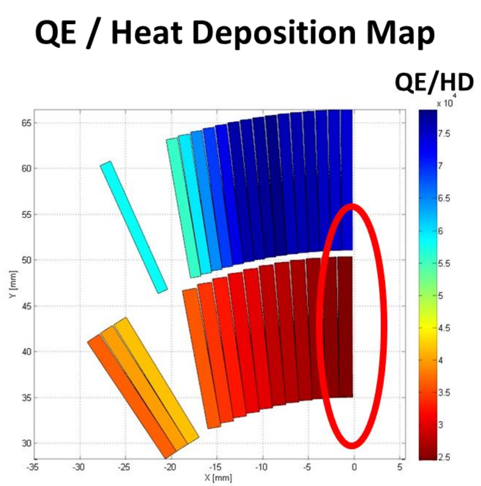
- It is determined by the interplay of:
  - Magnetic field
  - Cooling
  - Heat deposit

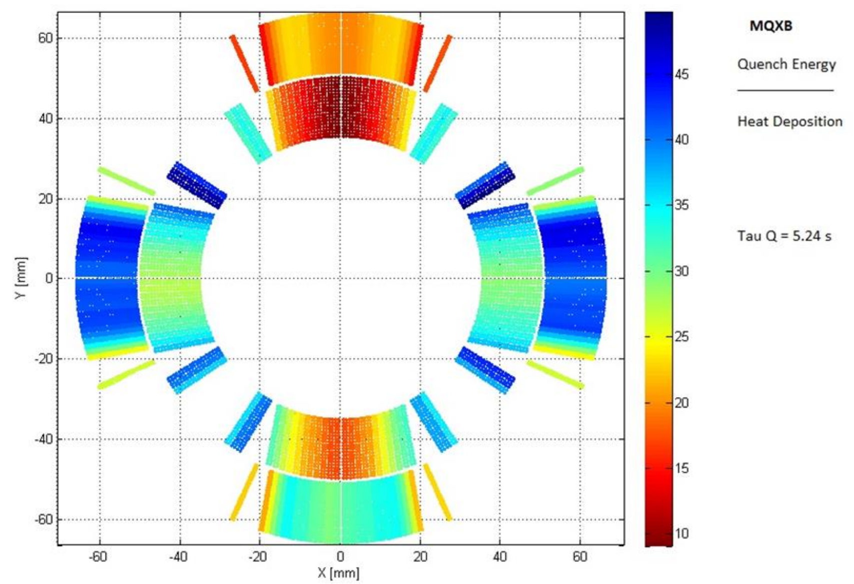


Short heating time: the most critical cable is the mid-plane cable instead of the the cable at the pole

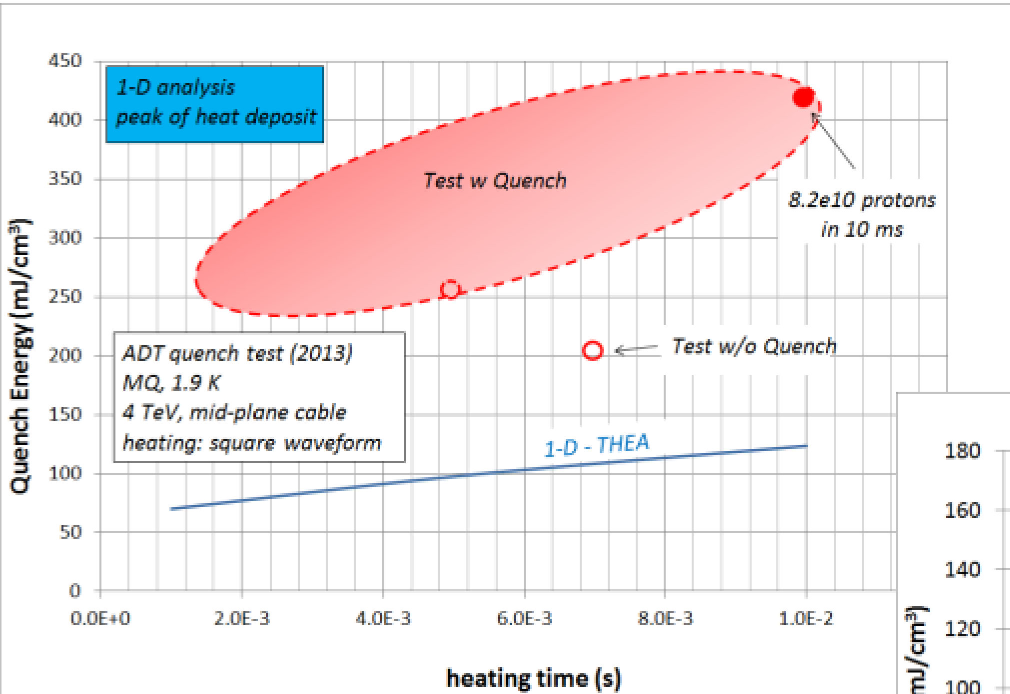
Long heating time:
the outer layer can become critical as well

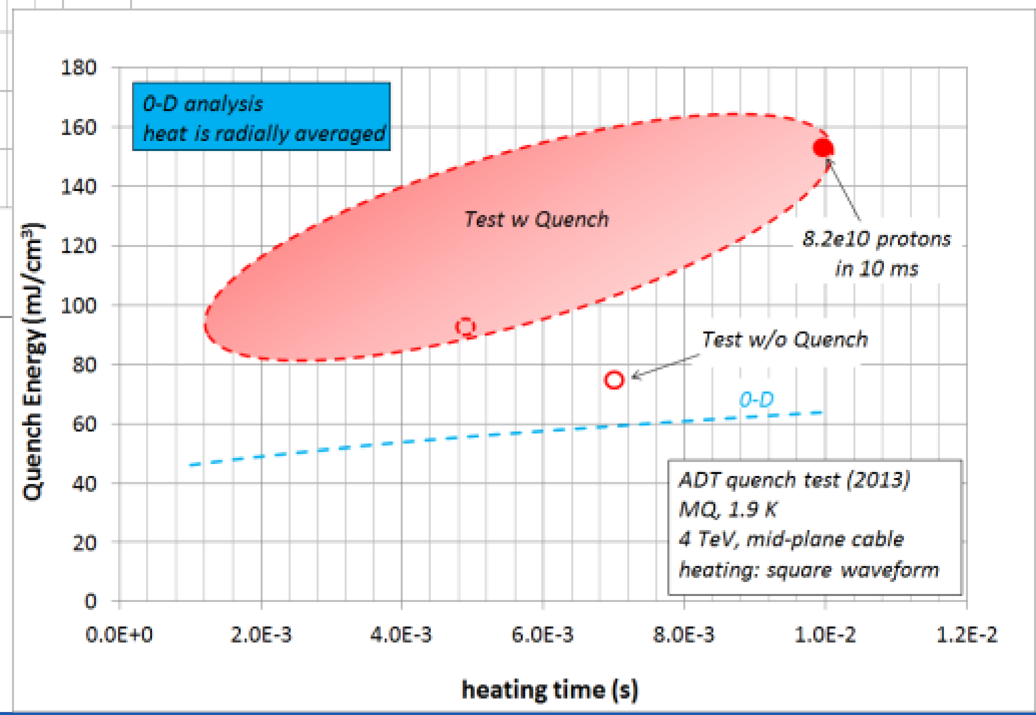






Comparison to 2013 ADT-fast loss QT





2013 ADT-fast loss quench test

Experiment: D. Valuch, W. Hofle, T. Baer, B. Dehning, A. Priebe, M. Sapinski

Simulations: A. Lechner, N. Shetty, V. Chetvertkova

Comparison to 2013 Q6 QT

MQM, 4.5 K

Heat deposit ~ ns

I = 2000 A, no quench

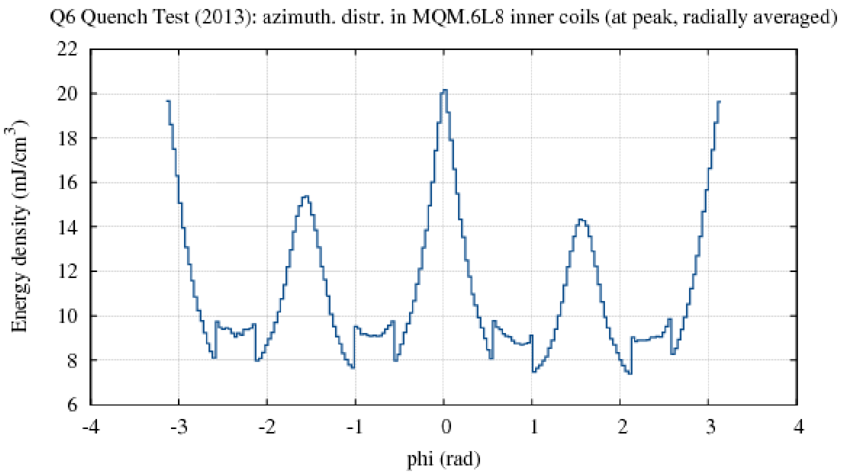
Quench limit mid-plane: 23 mJ/cm^3

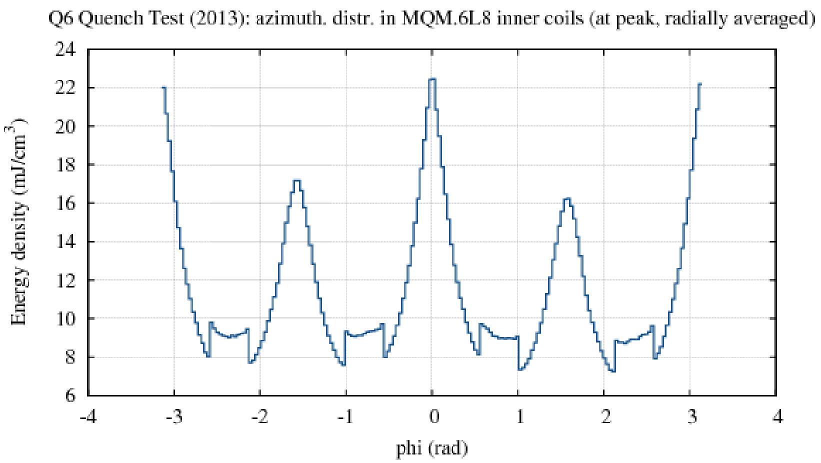
Quench limit pole: 21.8 mJ/cm^3

I = 2500 A, quench

Quench limit mid-plane: 20 mJ/cm^3

Quench limit pole: 18.5 mJ/cm^3





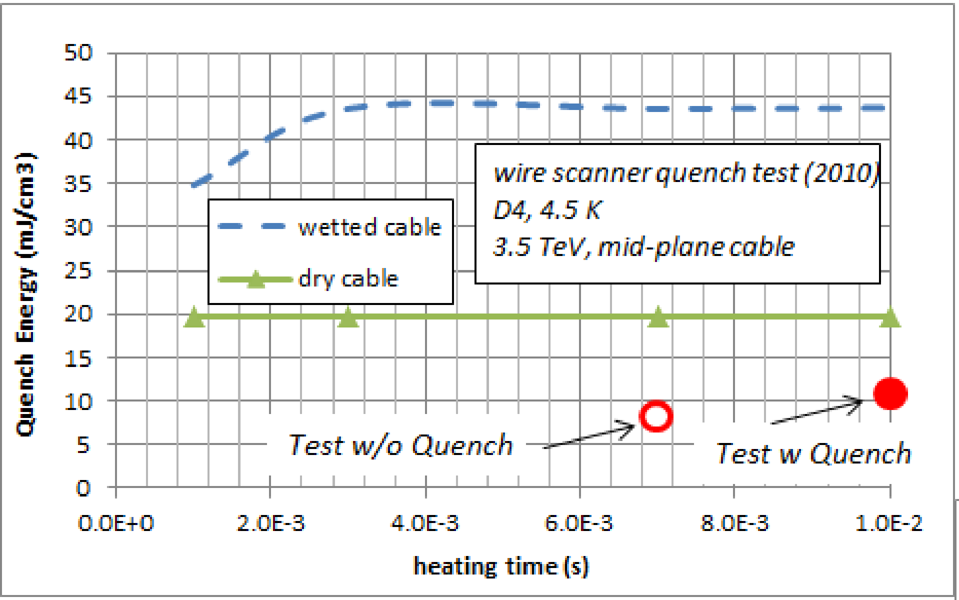
2013 Q6 quench test

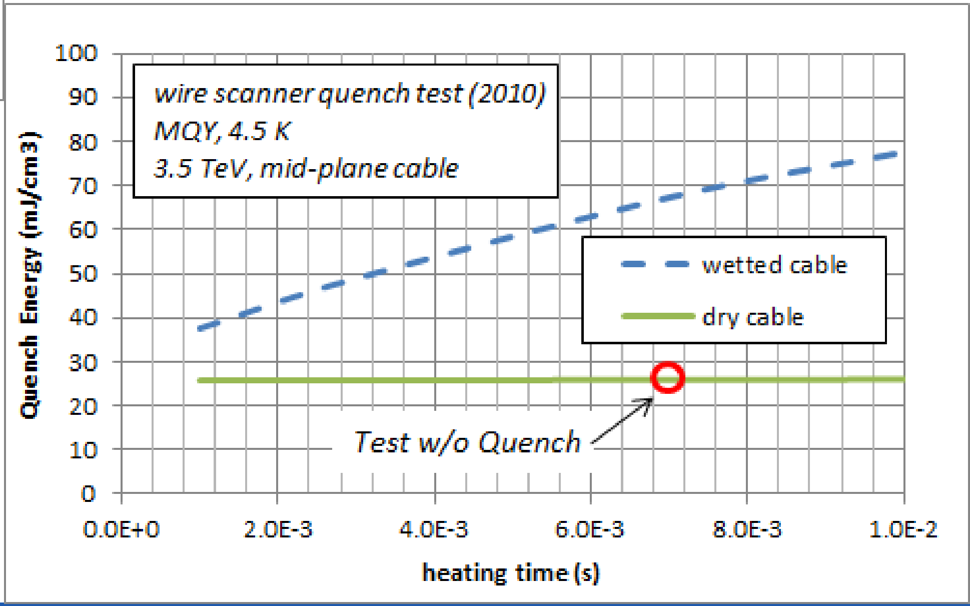
Experiment: C. Bracco, M. Solfaroli, M. Bednarek, W. Bartmann

Simulations: A. Lechner, N. Shetty

Very good agreement

Comparison to 2010 wire scanner QT





2013 wire scanner quench test

Experiment: B. Dehning, A. Verweij, K. Dahlerup-Petersen, M. Sapinski, J. Emery, A. Guerrero, E.B. Holzer, E. Nebot, J. Steckert, J. Wenninger

Simulations: A. Lechner, F. Cerutti

Conclusion

- Pretty good agreement btw computed quench limit and the 4 Quench Tests analyzed
  - except in a couple of cases where we have a factor 2 of disagreement

- How can we further improve the quench limit computation?

Steady-state:

  - by further improving the measurement technique (coil geometry rather than a stack) as well as by extending the numerical model of heat transfer in the coil above the T_λ region → simulate the actual heat extraction from the coil and heat deposit pattern
  - A conclusive test would need the actual radial beam loss profile (not necessarily a quench test, can be a heat transfer test) → something might be done in the lab. Or testing an instrumented sample with the beam?

Transient state:

  - Transient heat transfer experiments in confined volumes to validate or correct the whole model of heat transfer between strands and He inside the cable
  - A conclusive test has to be a stability test. Also in this case we would ideally need the actual radial beam loss profile

Backup slides

Steady-state results

- Summary of the determined steady-state cable quench limits

Magnet	SC	Operating current (kA)	Heat extracted at T_λ (mW/cm³)	Quench limit (mW/cm³)
MB	Nb-Ti	6.8 (4 TeV)	23	58
		11 (6.5 TeV)	23	49
		11.8 (7 TeV)	23	47
MQXF	Nb_3Sn	17.3	2.2	63

- The "T_λ limit" depends of course on the cable cooling witin the magnet
  - by the way, this design limit is meaningless for Nb_3Sn
- The provided quench limits refer to the cables: e.g. for MQXF, they correspond to the magnet quench limits as long as the channels through the Ti piece do not saturate