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0-D and 1-D approaches to investigate the thermal stability of superconducting cables

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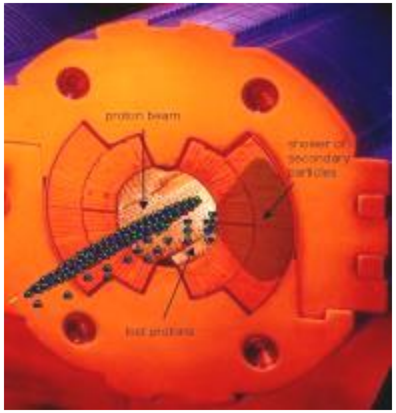
Outline

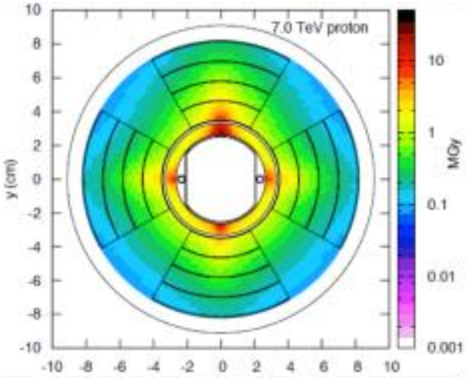
- Stability of accelerator superconducting magnets
- Heat transfer mechanisms
- 0-D approach: description of the model and results
- 1-D approach: description of the model and results
- Comparison to experimental tests
- Conclusions and perspectives

Stability of accelerator SC magnets

Beam loss



Heat deposit



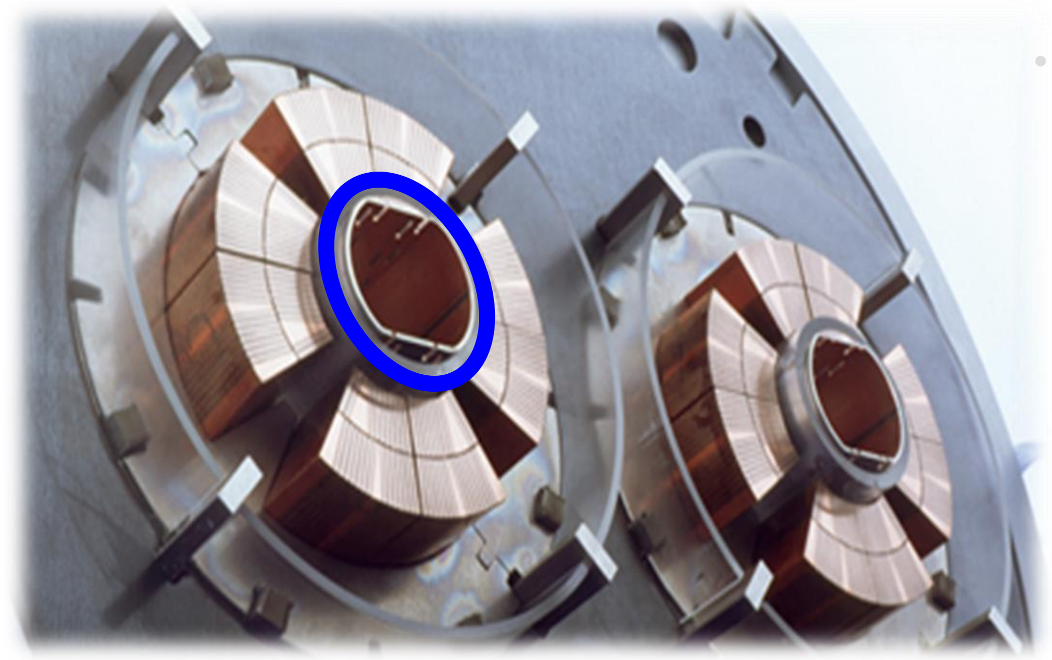
Beam Loss Monitors

Quench Energy

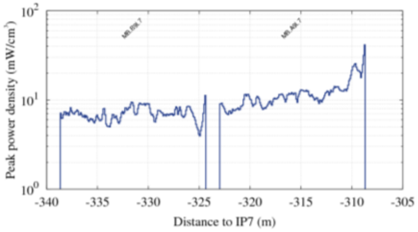
- Beam loss duration ranges from micro-seconds to hours
- Typical beam loss mechanisms:
  - Beam dump (1-100 μs)
  - UFO (ms)
  - Collision, collimator losses (steady-state)
- LHC operation in 2008-13 at ~ half the nominal energy: 17 beam induced quenches (8 of them caused by quench tests)
- Future operation at 7 TeV will be more challenging

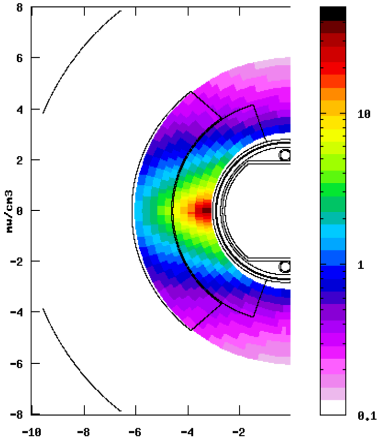
Heat deposit simulation by L. Esposito

Stability of accelerator SC magnets

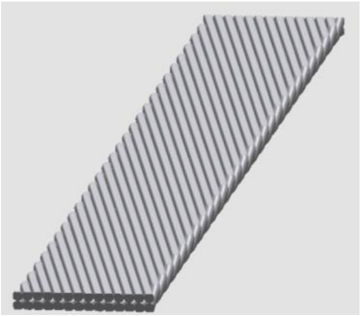


- Heat deposit distribution:
  - radial
  - azimuthal
  - longitudinal

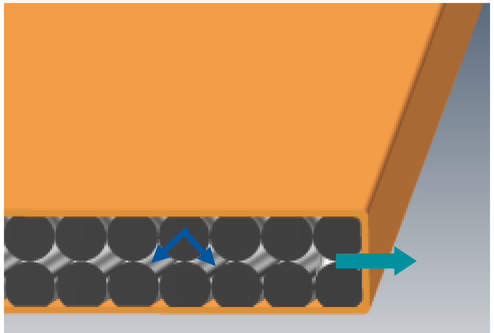




Heat deposit simulations by E. Skordis, F. Cerutti and A. Lechner



- He heat transfer mechanisms:
  - inside the cable
  - towards the external bath



Drawings by D. Santandrea

Quench limits

transient state, mJ/cm^3

(fast losses)

Local heat transfer from strand to He inside the cable

↓

No conclusive experiments (yet) → we rely on **numerical codes**

Dominant mechanism

steady-state, mW/cm^3

(slow losses, > 1-10 s)

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

↓

Experiments and modeling ongoing

Background

Experimental:

- A lot of studies on cable stability of LHC cables, but mainly considering localized heating: Wilson, Baynham, Wolf, Bauer, Ghosh, Kimura, Willering, Verweij, etc

- Heat transfer tests
  - steady-state: running since a few years (CERN Magnets and Cryogenics group)
  - transient: just started (CERN Cryogenics group)

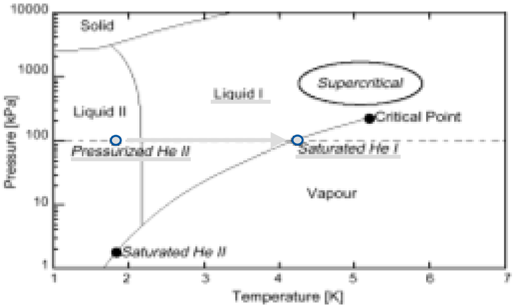
Theroretical / Numerical:

- Bottura's work on stability of CICC's, leading to development of the codes ZeroDee and THEA

- CHATS-AS 2005: Bottura, Calvi, Siemko
- CHATS-AS 2008: Granieri, Calvi, Bottura *et al.*
- CHATS-AS 2011 and MT-23: Granieri *et al.* (heat transfer)

- Parallel work by Verweij and Auchmann at CERN

Heat transfer mechanisms



- Transient heat transfer between strands and He inside the cable
    - From experimental results of each He phase

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

$$\boxed{h_K = \sigma\left(T_s^2 + T_h^2\right)\left(T_s + T_h\right)}$$

$$\boxed{h_{HeI} = \max\left\{\frac{h_K h_{BL}}{h_K + h_{BL}}; h_{ss}\right\}} \quad \boxed{h_{BL} = \sqrt{\frac{K_h \rho_h c_h}{\pi \Delta t}}}$$

$$\boxed{h_{nucl.boiling} = \frac{\beta(T_s^m - T_h^m)}{T_s - T_h}}$$

$$\boxed{h_{film\ boiling} = 250\ \mathrm{W/m^2K}}$$

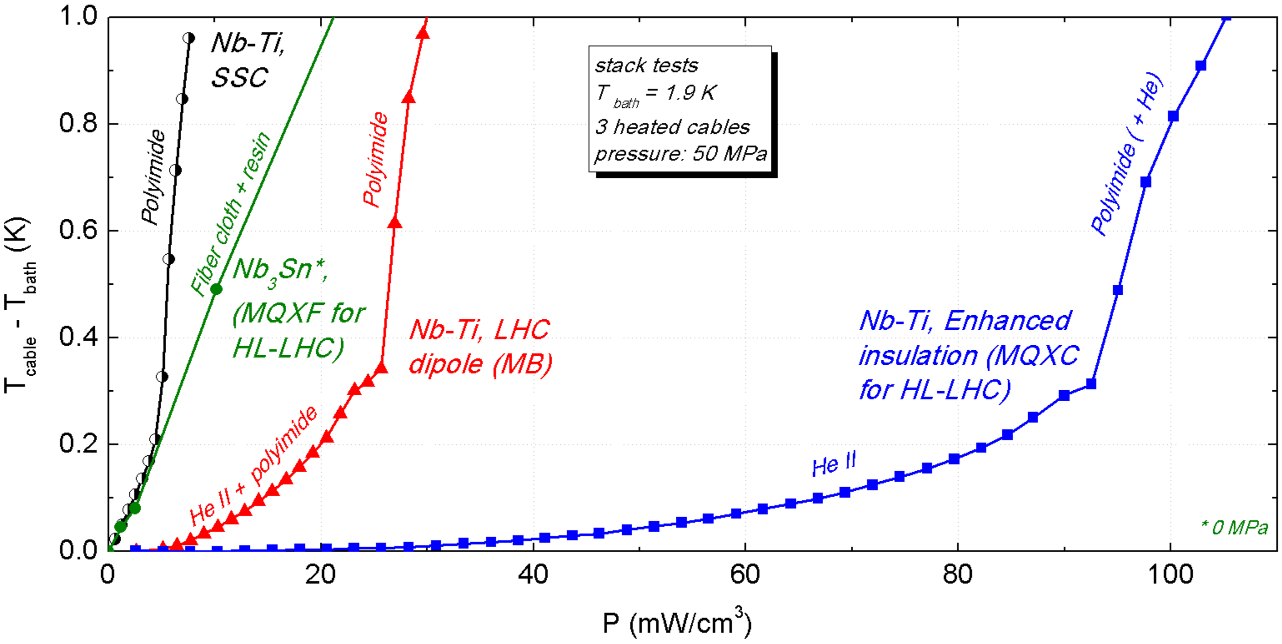
$$\boxed{h_{gas} = 70\ \mathrm{W/m^2K}}$$

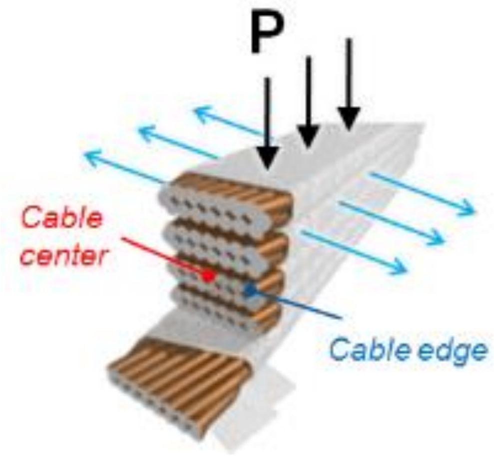
- But the model of the whole process should be validated

P.P. Granieri *et al.*, Stability analysis of the LHC cables for transient heat depositions

Heat transfer mechanisms

- Steady-state heat transfer between cable and external He bath
  - From experimental results on cable-stacks
  - As a function of the mechanical pressure
  - For a radially and longitudinally uniform heat deposit





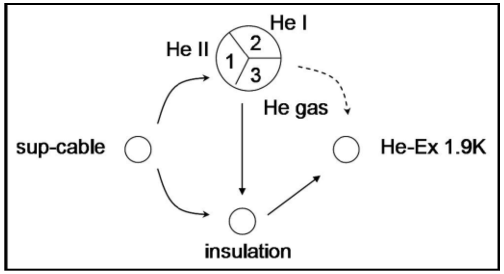
SSC: C. Meuris, B. Baudouy *et al.*
LHC MB & EI4: D. Richter, P.P. Granieri *et al.*
Nb_3Sn: P.P. Granieri, R. van Weelderen *et al.*

0-D approach: description of the model (ZeroDee code)

- The cable components are: strands, He inside the cable, electrical insulation
- They are lumped parameters, featuring uniform temperature, heat deposit and magnetic field over the cable cross-section
- No longitudinal direction, hence no longitudinal heat conduction

- Heat balance equations:

$$\begin{cases} A_s \rho_s C_s \dfrac{\partial T_s}{\partial t} = \dot{q}'_{ext} + \dot{q}'_{Joule} - p_{s,He} h_{s,He} (T_s - T_{He}) - p_{s,i} h_{s,i} (T_s - T_i) \\ A_{He} \rho_{He} C_{He} \dfrac{\partial T_{He}}{\partial t} = p_{s,He} h_{s,He} (T_s - T_{He}) + p_{i,He} h_{i,He} (T_i - T_{He}) - (p_{i,He} + p_{s,i}) Q_{HeII} \\ A_i \rho_i C_i \dfrac{\partial T_i}{\partial t} = -p_{i,He} h_{i,He} (T_i - T_{He}) - p_{s,i} h_{s,i} (T_i - T_s) - p_{i,b} h_{i,b} (T_i - T_b) \end{cases}$$

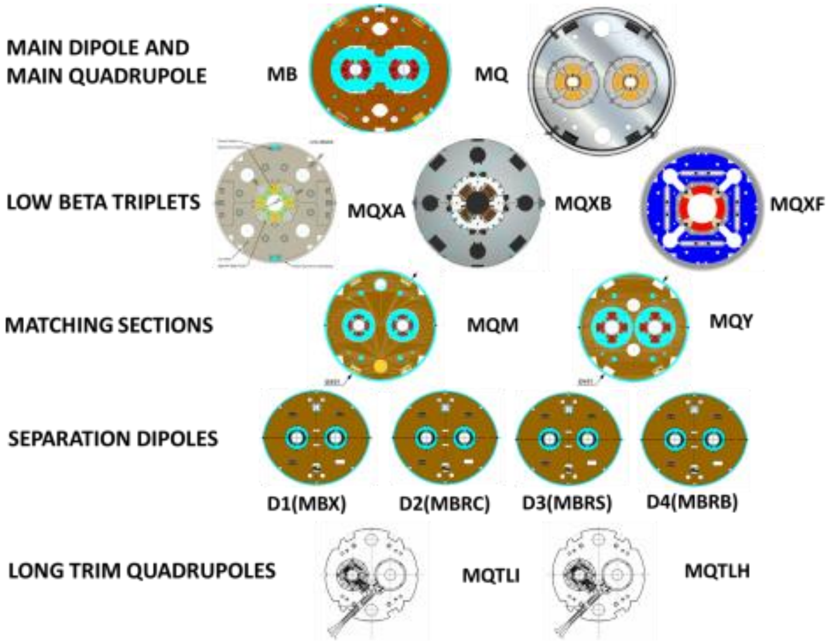


ZERODEE Software, CryoSoft, France, 2001.

Results of the 0-D approach

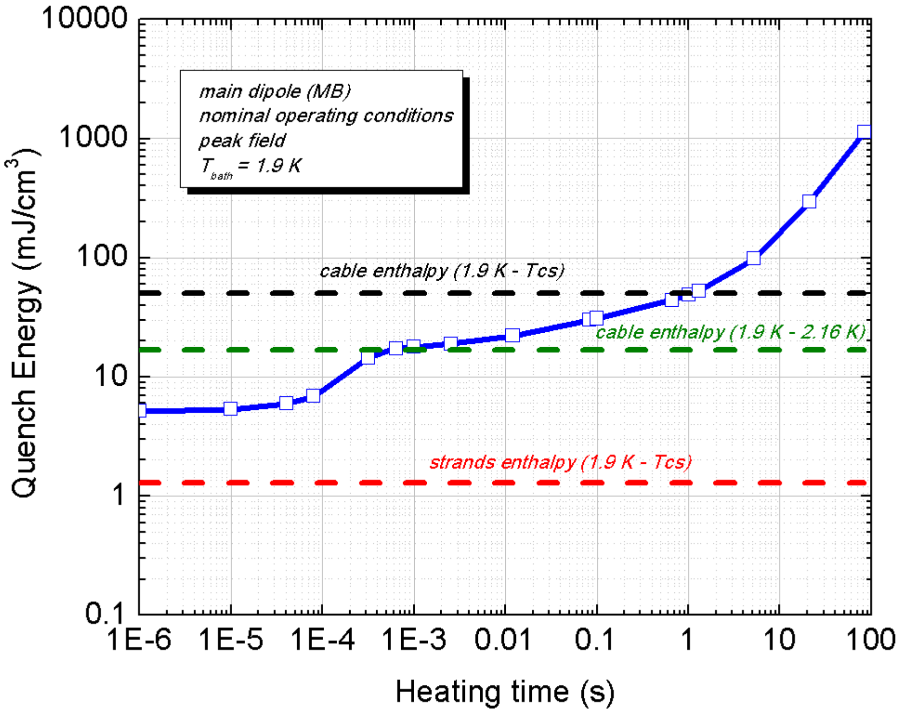
- We have simulated thermal transients to determine the Quench Energy (QE, i.e. minimum energy leading to a quench) as a function of:
  - Transport current → from injection to operating beam energy
  - Magnetic field → from lowest to peak field in the coil cross-section
  - Heating time → from micro-seconds to steady-state
  - Bath conditions → He II, He I, supercritical He
  - Superconductor →Nb-Ti (Rutherford/flat cables), Nb_3Sn cables

Systematic analysis of the most critical LHC (and HL-LHC) magnets



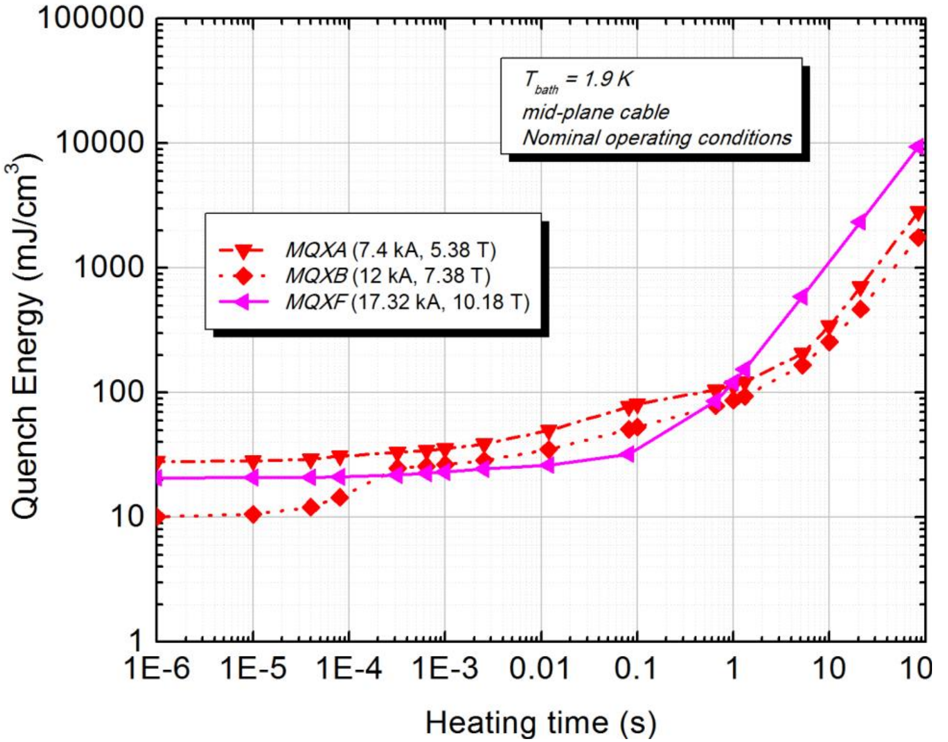
Results of the 0-D approach

Effect of the heating time



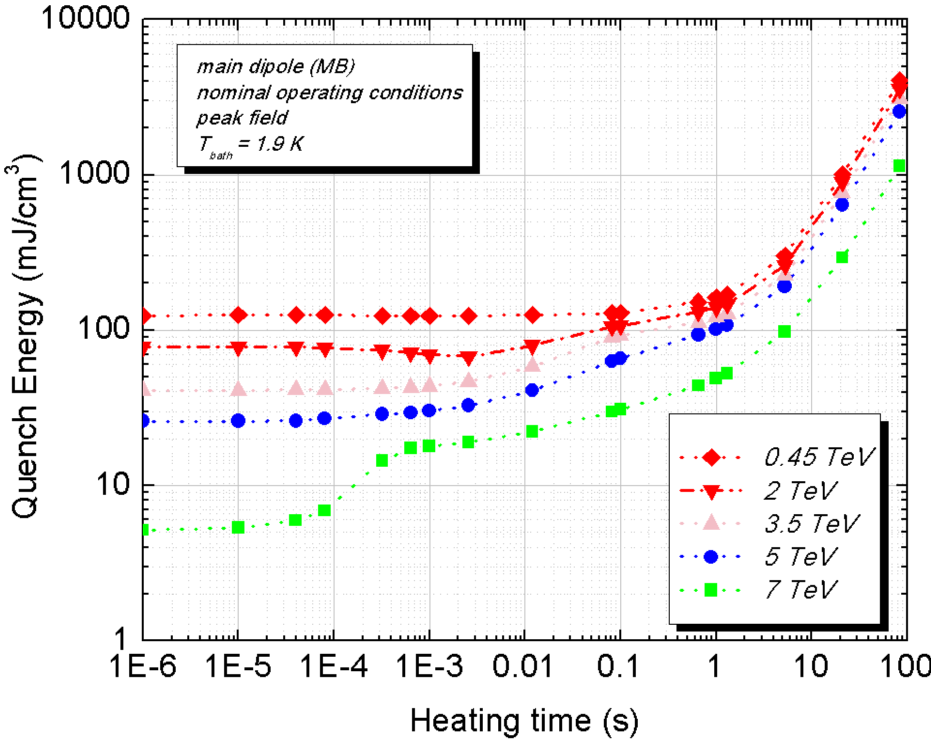
Effect of the external bath

- Steady-state fully developed after 0.1 to 5 s

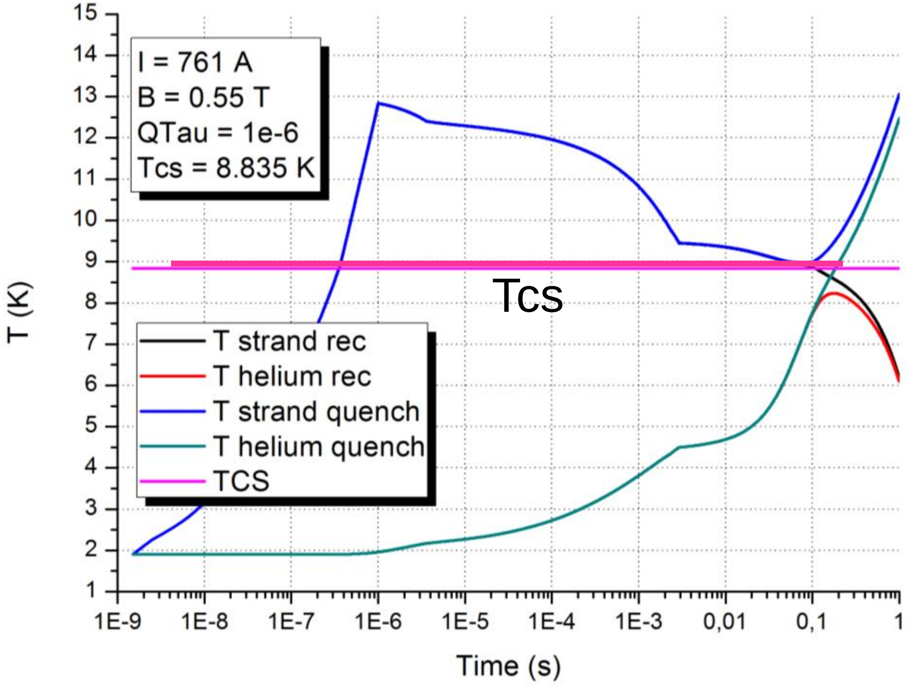


Results of the 0-D approach

Effect of the transport current (beam energy)

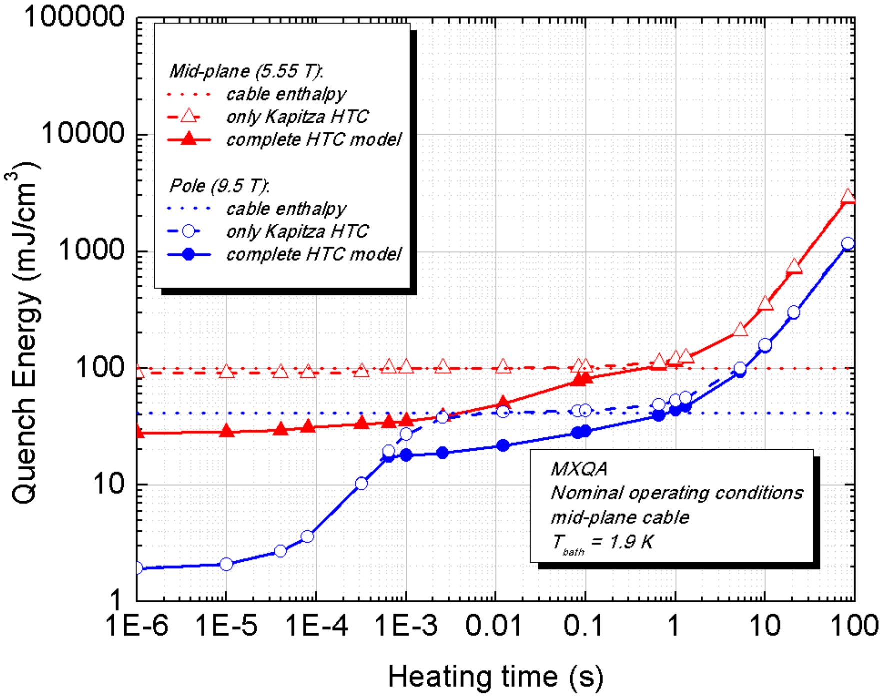


Temperature behavior

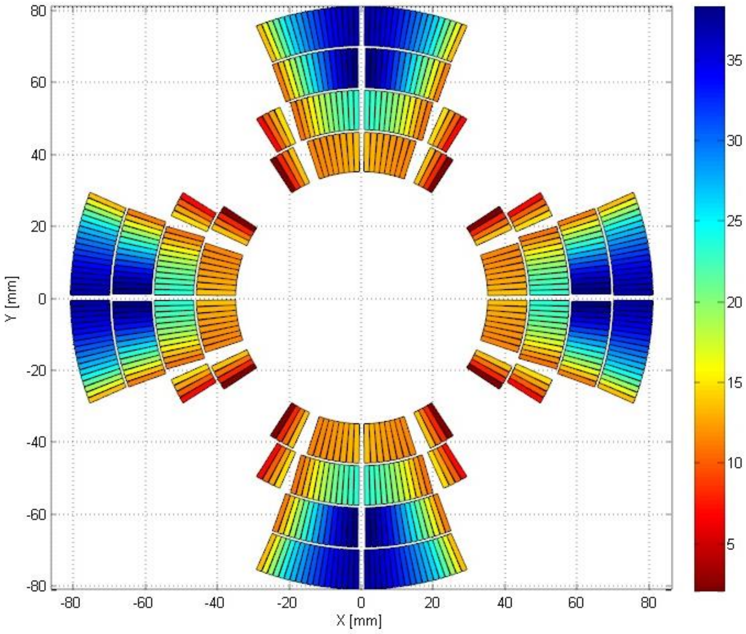


Results of the 0-D approach

Effect of the magnetic field

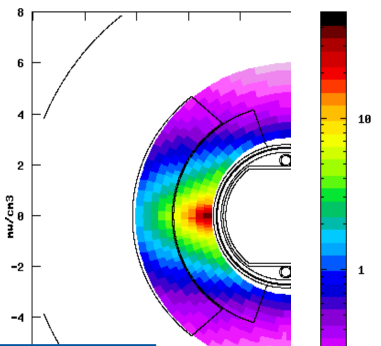


Stability map (QE) over the magnet cross-section

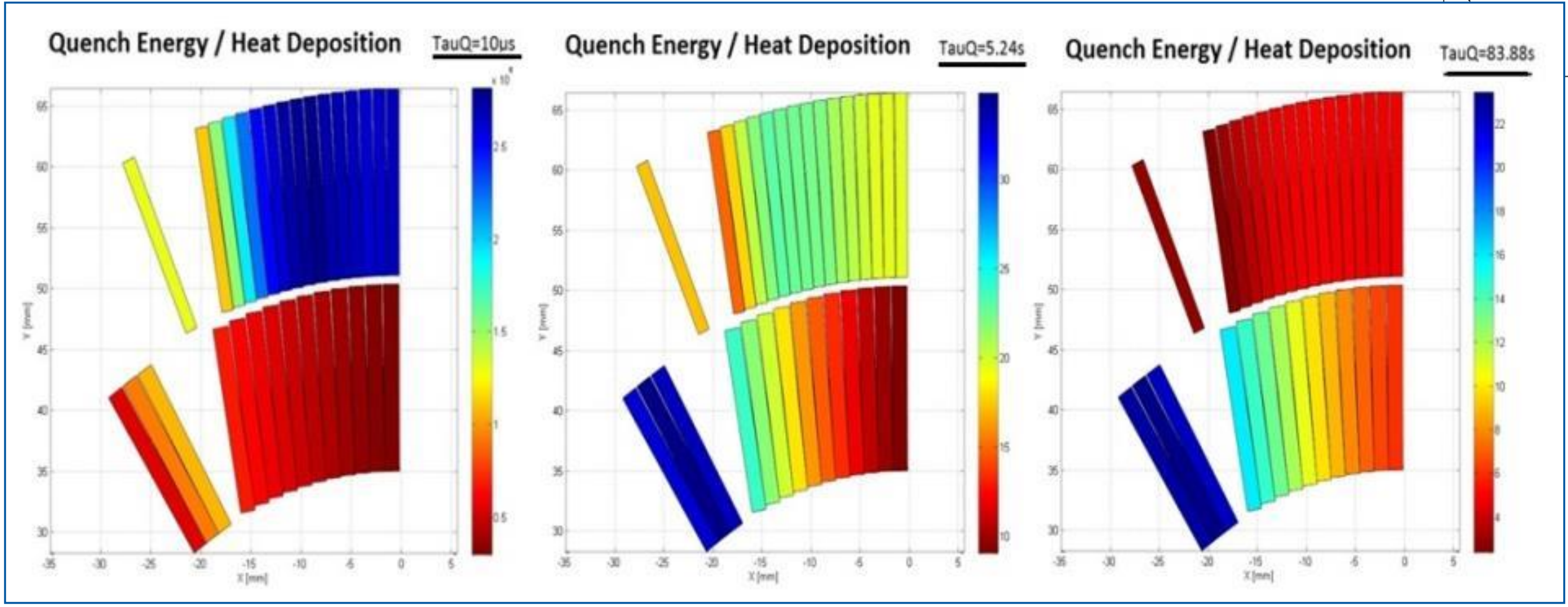


Results of the 0-D approach

Heat deposit



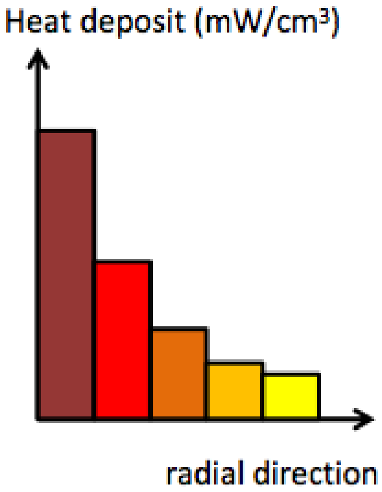
Computation of QE / Heat deposit to determine the most critical cable in the magnet cross-section

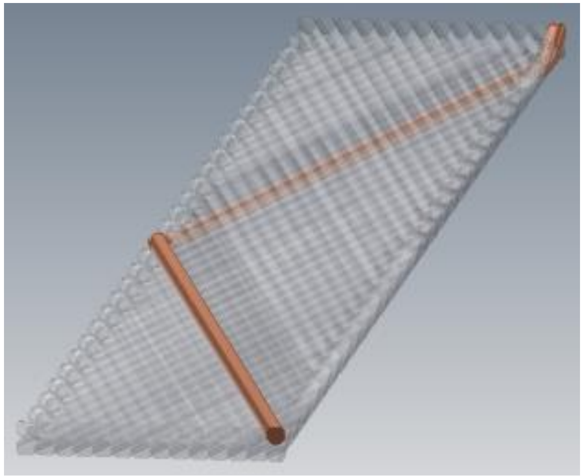


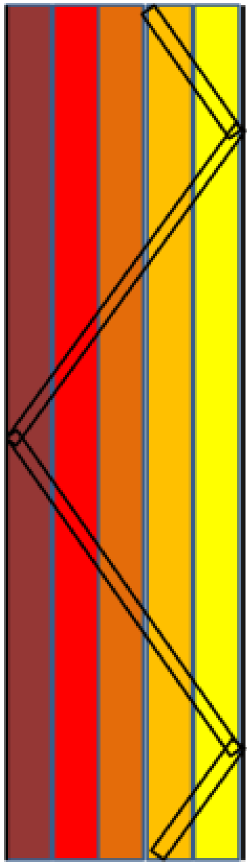
The criticality of a cable in a magnet is an interplay of: magnetic field, cooling and heat deposit

1-D approach: description of the model (THEA code)

- 1-D description of one single strand experiencing heat deposit and magnetic field varying along its length
- The considered amount of He is relative to one strand
- Same heat transfer mechanisms used in the 0-D approach







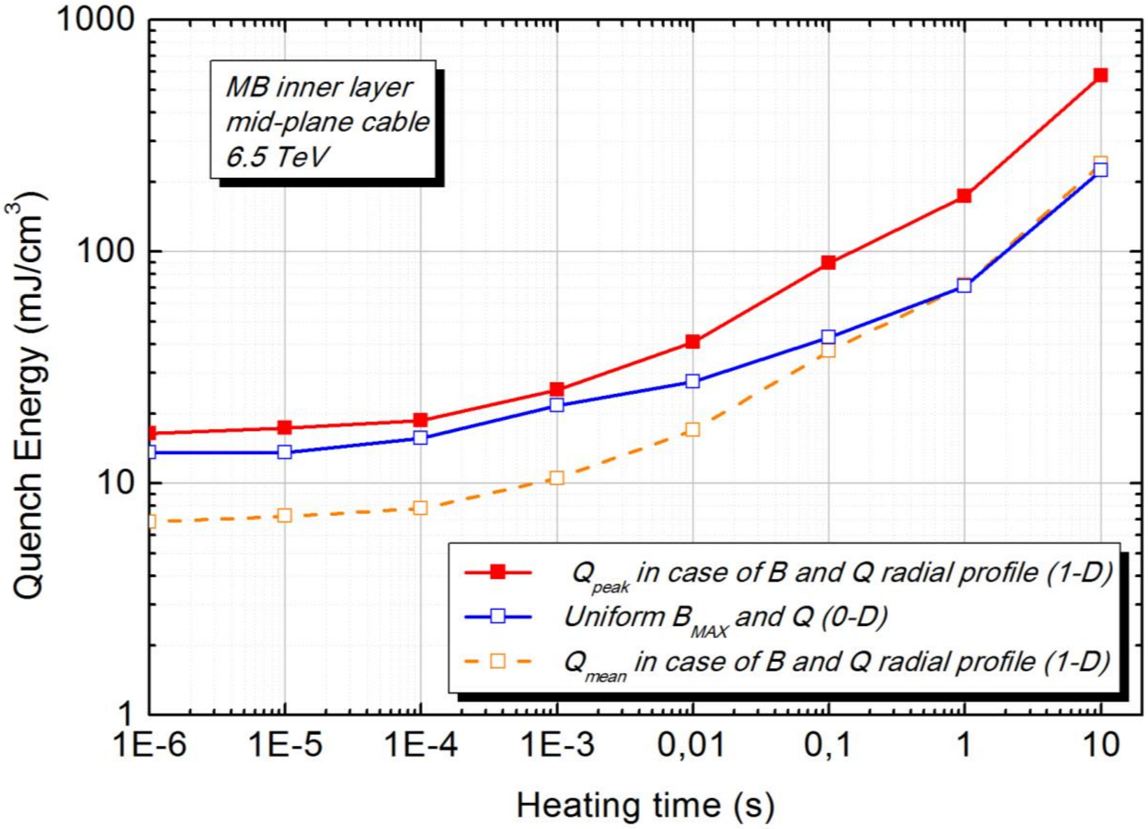
Drawing by D. Santandrea

$$A_i \rho_i C_i \frac{\partial T_i}{\partial t} - \frac{\partial}{\partial x}\left(A_i k_i \frac{\partial T_i}{\partial x}\right) = q_i' + q_{Joule,i}' + \cancel{\sum_{j=1, j\neq i}^{N} \frac{(T_j - T_i)}{H_{ij}}} + \sum_{h=1}^{N} p_{ih} h_{ih} (T_h - T_i)$$

L. Bottura, C. Rosso, M. Breschi, *Cryogenics*, vol. 40 (8-10), 2000, p..617

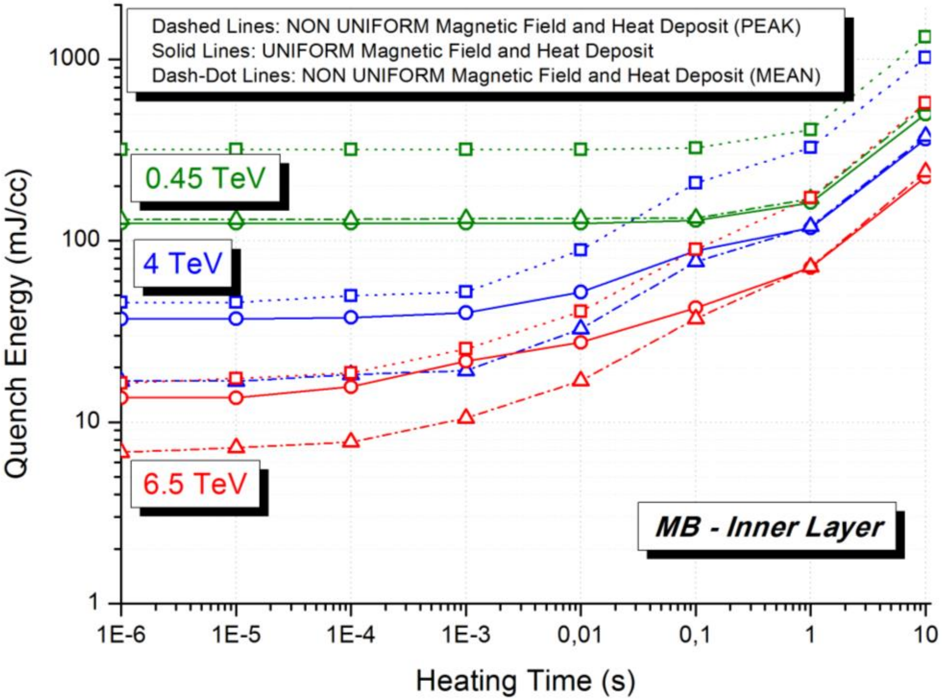
Results of the 1-D approach

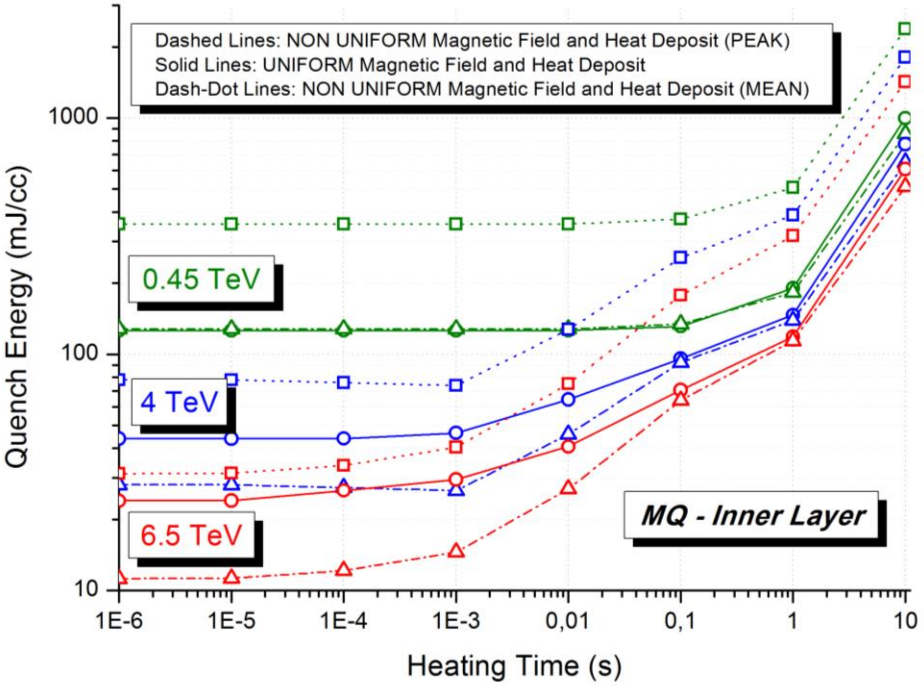
1-D vs. 0-D approach



Results of the 1-D approach

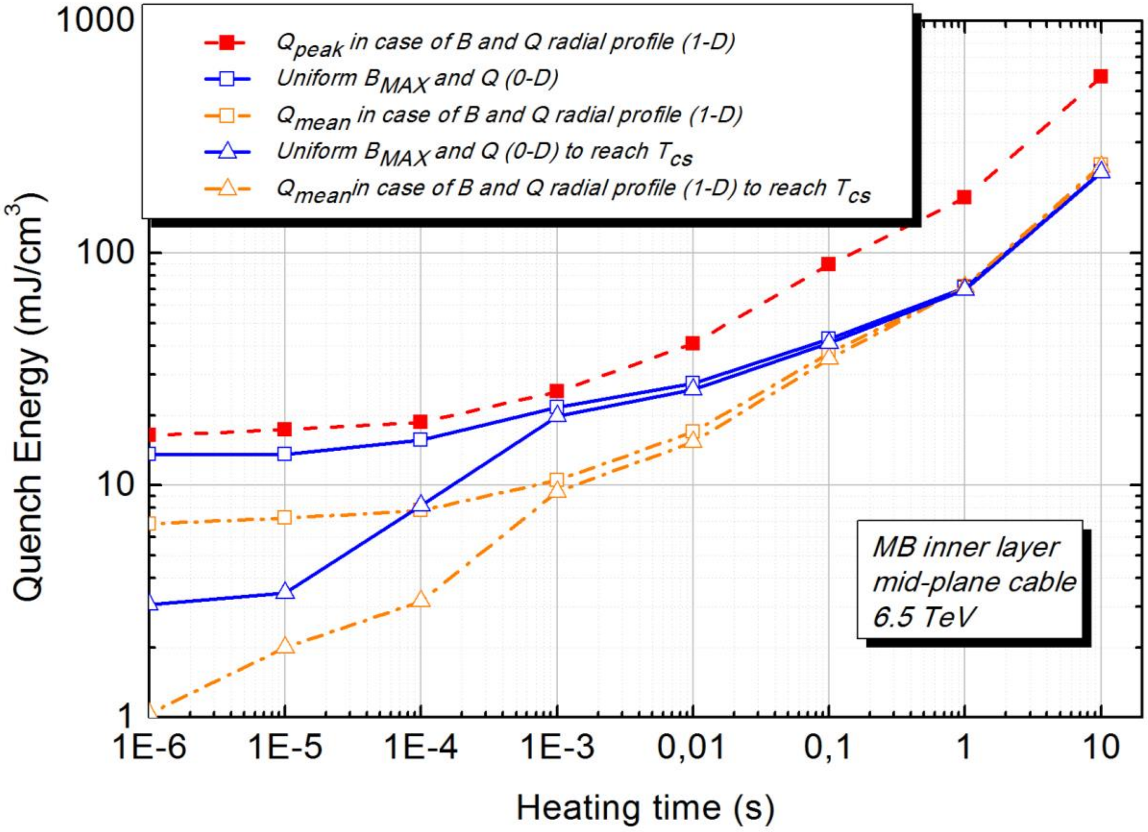
1-D vs. 0-D approach for different transport currents (beam energy), for the LHC main dipoles (MB) and quadrupoles (MQ)





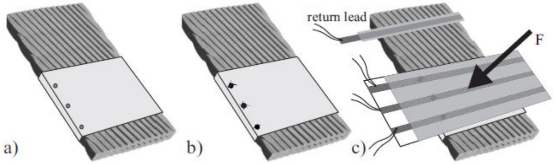
Results of the 1-D approach

Quench vs. development of a normal zone



Comparison to experimental tests

- Power injected into a strand by a graphite paste heater (0.5 mm diameter)
  - For low current, the heat flows through other strands until the cable will quench: *collective regime*
  - For high current, the strand will quench before having time to share current with the near ones:
    single strand regime
  - Our 1-D model can reproduce t



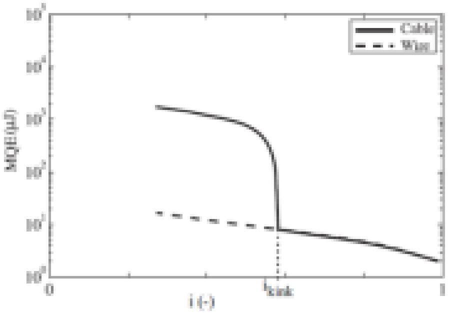
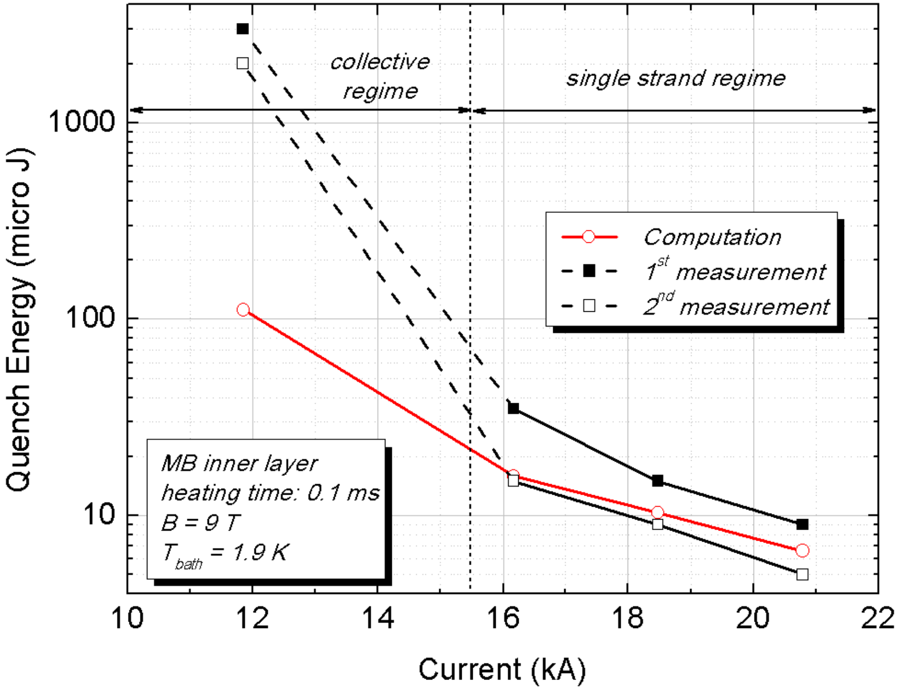
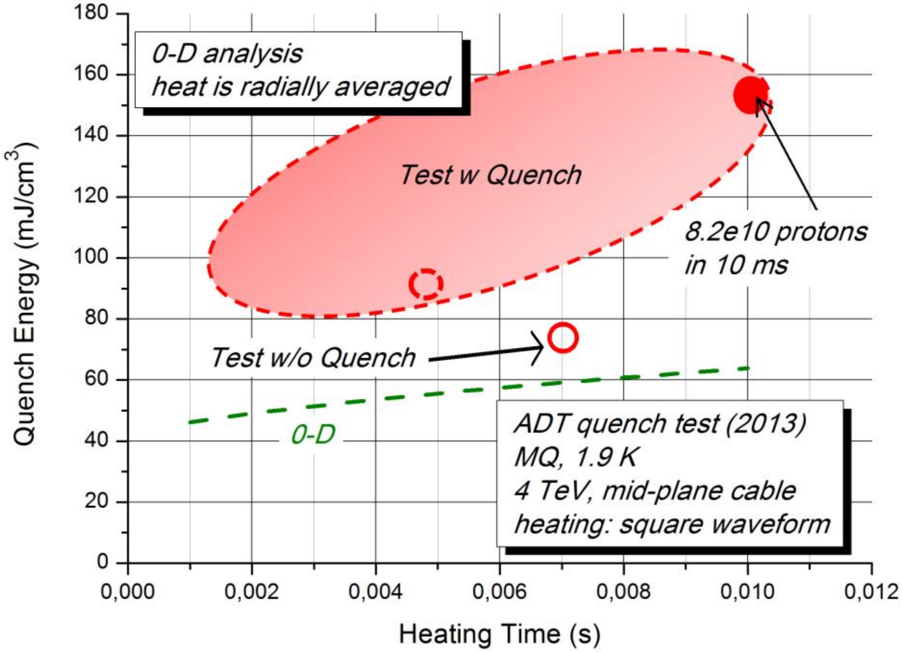


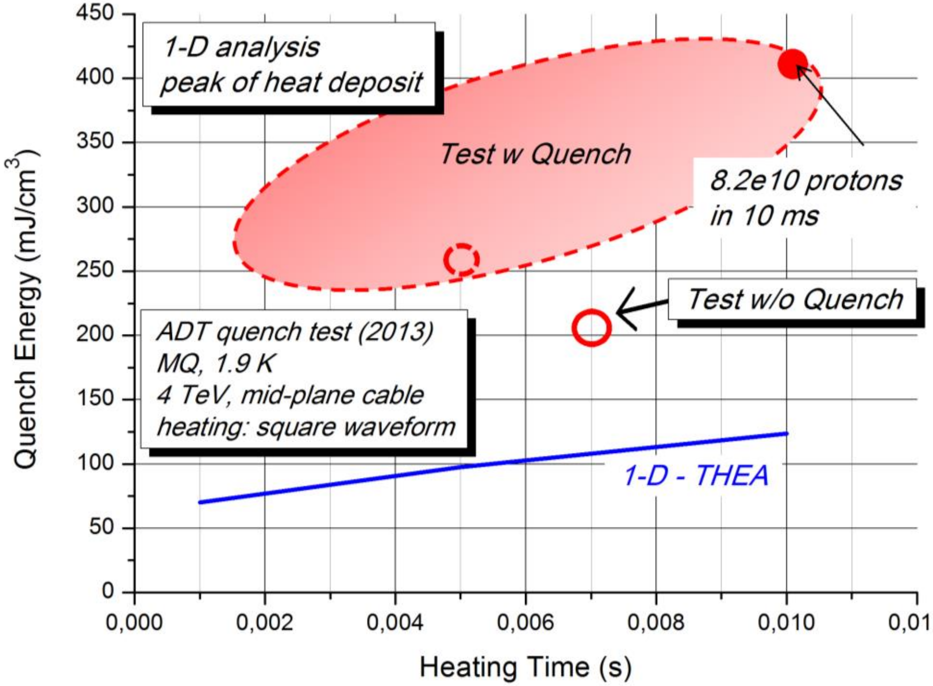
Figure 2.18: Characteristic MQE dependence on the normalized current for a cable (solid line) and a single wire (dotted line).

G. Willering, Ph.D. thesis



Comparison to experimental tests





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

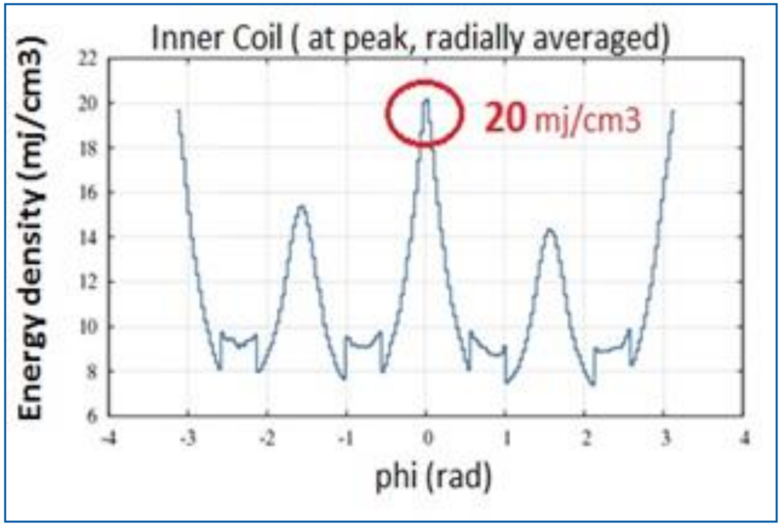
Comparison to experimental tests

MQM, 4.5 K

Heat deposit ~ ns

I = 2000 A, **no quench**

0-D QE (mid-plane): **23 mJ/cm³**



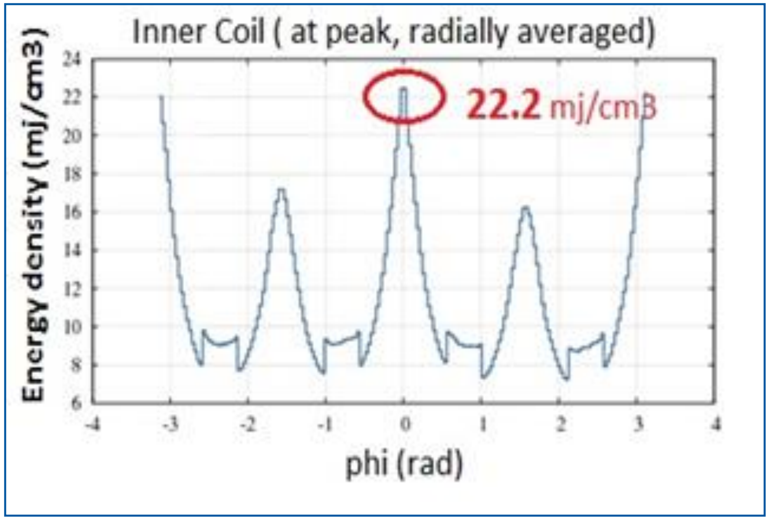
2013 Q6 quench test

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

Simulations: A. Lechner, N. Shetty

I = 2500 A, **quench**

0-D QE (mid-plane): **20 mJ/cm³**



Very good agreement

Conclusion

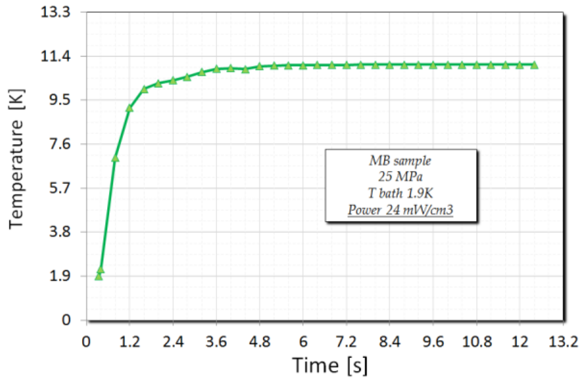
- 0-D model used to perform a systematic analysis of the most critical LHC magnets
  - Description of heat transfer mechanisms improved, though more work is needed
  - Impact of current, field, heating time, cooling bath assessed

- A more refined model 1-D model has been developed, to take into account the magnet field and heat deposit non uniformity
  - 0-D model in good agreement with either the peak or average heat deposit in the 1-D model, depending on the time constants of the system

- Pretty good agreement with experimental results
  - In the worst case a factor 2 of disagreement

Perspectives

- A **3-D model** of the whole cable to investigate the impact of cur varying field, heat deposit and cooling
- **Experimental program** needed to determine the **transient hea** to improve the computation of cable stability against fast beam

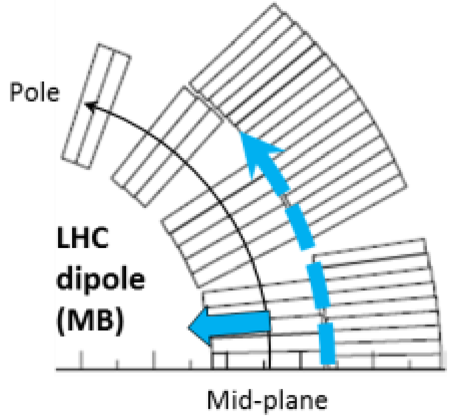


Measurements and analyses by D. Santandrea

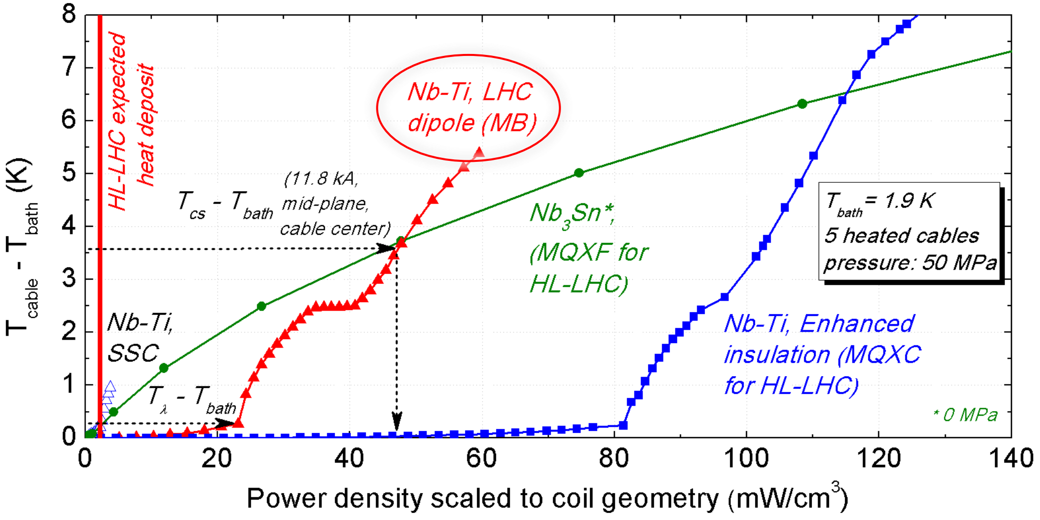
Backup slides

Deduction of cable steady-state quench limits

- For steady-state beam losses, a quench occurs if T_{cable} exceeds T_{cs} (4 - 5.5 K for the LHC MB)



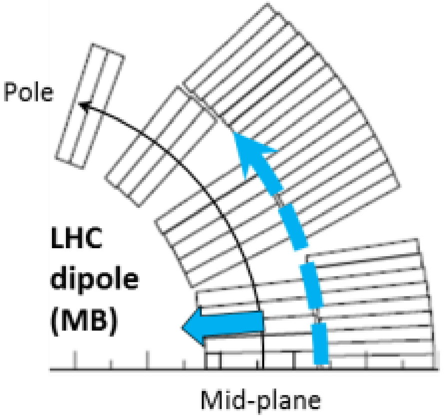
- The cable quench limits depend on
  - Heat extraction:
    - cable cooling within the magnet
    - mechanical pressure, if Nb-Ti coil
    - stack heating configuration
  - Operating conditions:
    - transport current
    - magnetic field, thus cable and strand considered

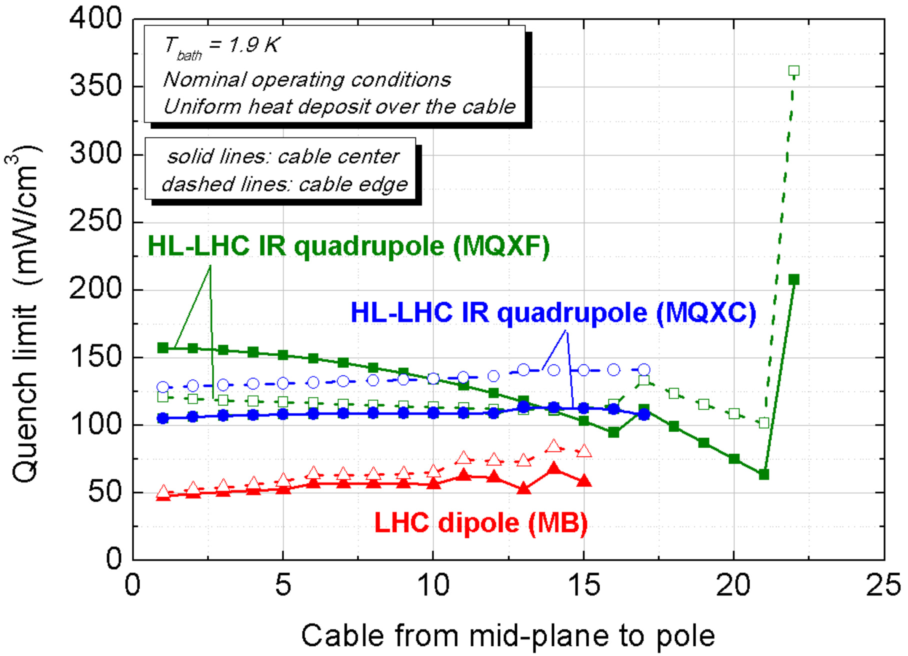


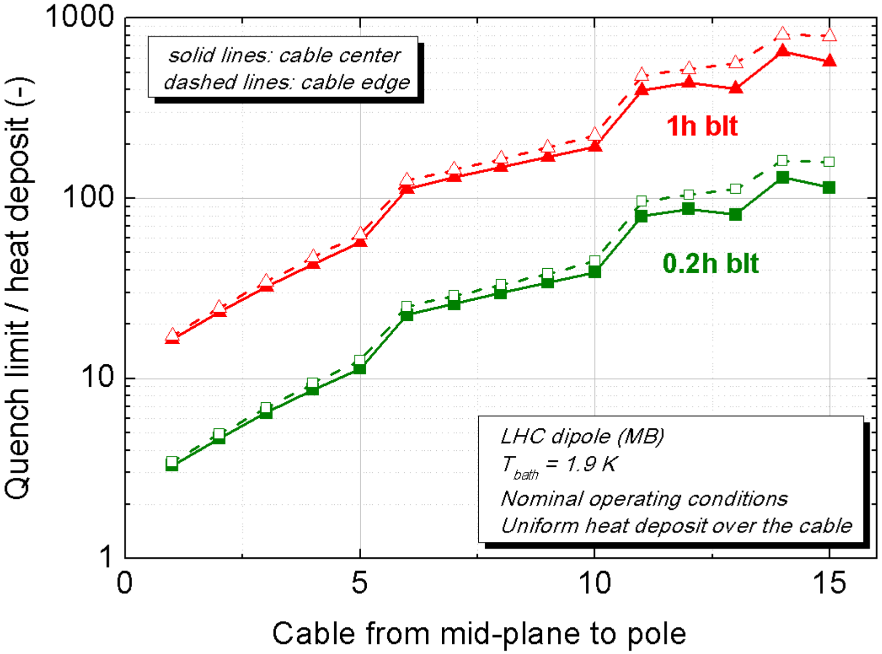
Method reported in: P.P. Granieri and R. van Weelderen, "Deduction of Steady-State Cable Quench Limits for Various Electrical Insulation Schemes with Application to LHC and HL-LHC Magnets", *IEEE Trans. Appl. Supercond.* 23 submitted for publication

Raw data:
- SSC: C. Meuris, B. Baudouy *et al.*
- LHC MB and EI4: D. Richter, P.P. Granieri *et al.*
- Nb_3Sn: P.P. Granieri *et al.*

Results along the azimuthal direction







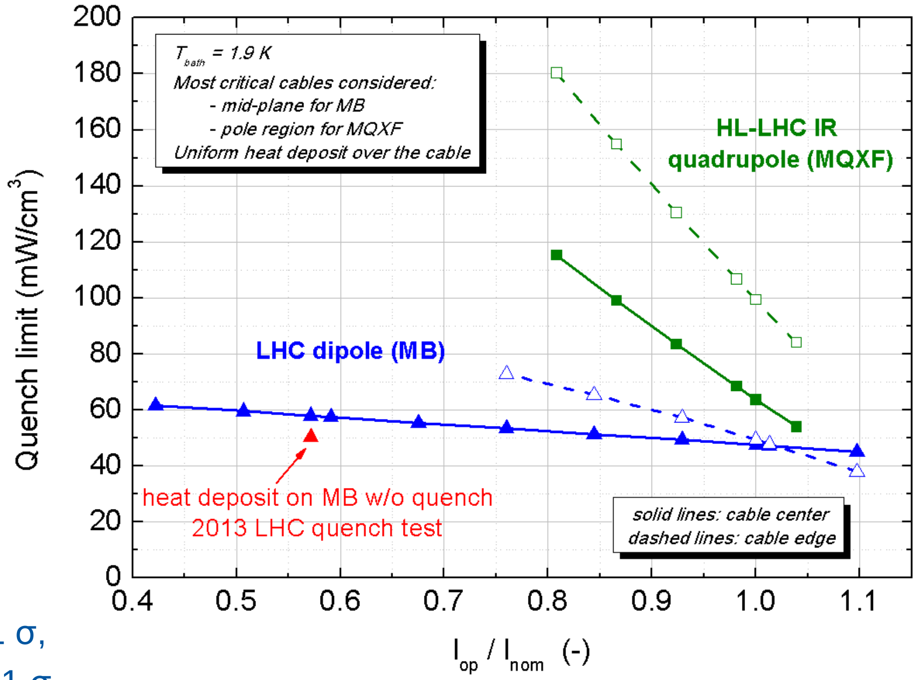
6.5 TeV, 4.5 x 10^11 protons/s

Collimator settings (relaxed): TCP7 @ 6.7 σ, TCS7 @ 9.9 σ

Heat deposit comes from simulations by R. Bruce, B. Salvachua, S. Redaelli, L. Skordis, F. Cerutti, A. Lechner, A. Mereghetti

Results as a function of I_{op}, and comparison to 2013 collimation QT

- most critical regions considered, i.e. mid-plane for MB
- in agreement with the LHC collimation quench test performed in 2013

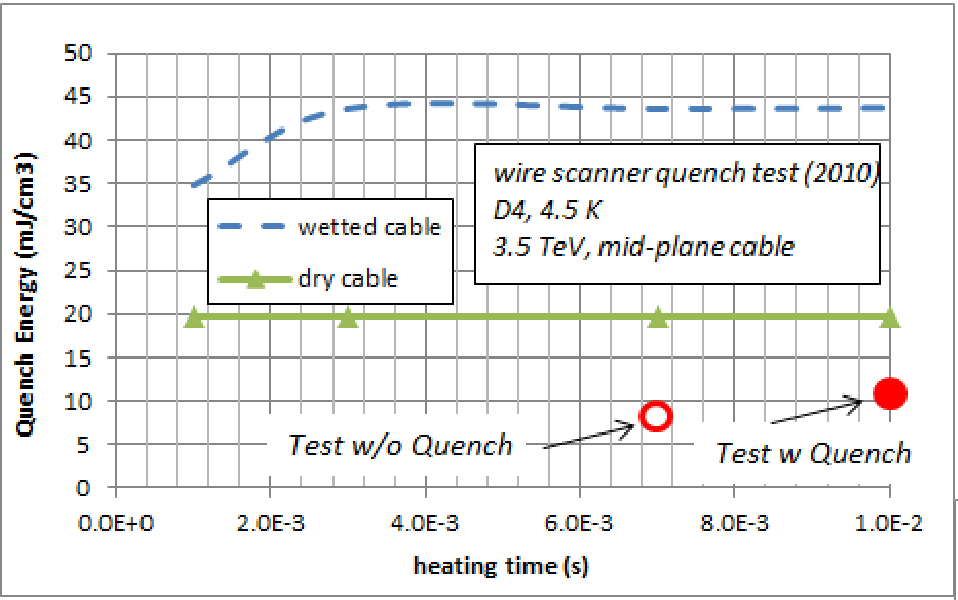


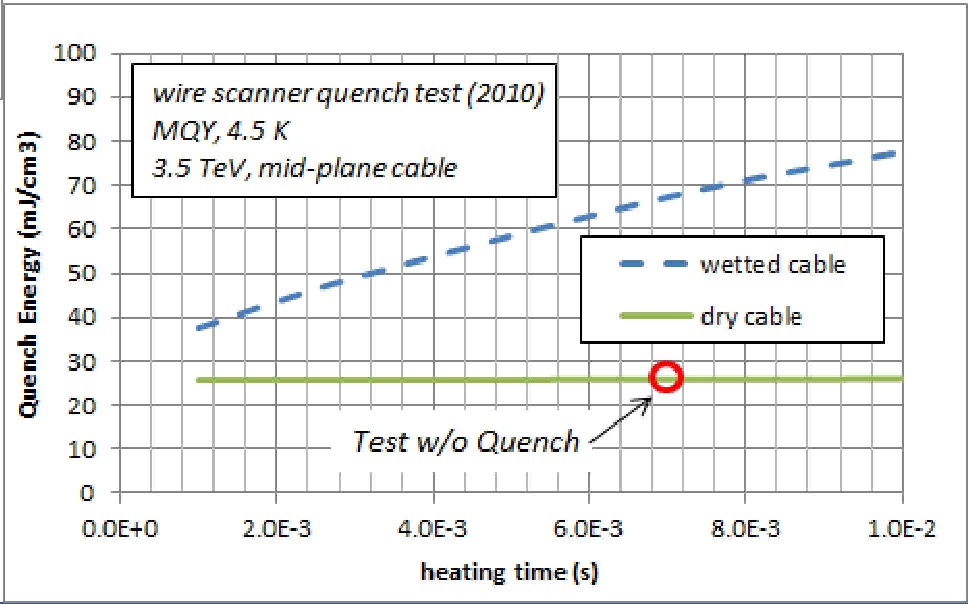
2013 collimation quench test:
4 TeV, 1.63 x 10^12 protons/s
Collimator settings: TCP7 @ 6.1 σ,
TCS7 @ 10.1 σ

Experiment: S. Redaelli, B. Salvachua, R. Bruce, W. Hofle, D. Valuch, E. Nebot
FLUKA simulations: F. Cerutti, E. Skordis

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

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