SUMMARY OF THE BEAM INDUCED QUENCH WORKSHOP AT CERN

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CERN, Geneva Switzerland

Acknowledgements: L. Bottura

THE WORKSHOP

The aim of this workshop is to

1. survey the operational experience with beam losses in superconducting accelerators and transfer lines,
2. analyze the results of quench tests at the LHC,
3. study the status of experimental work and numerical models for heat transfer in Rutherford-type cable, and
4. review the strategies for beam-loss monitoring in the LHC after the long shutdown.
5. Moreover, we intend to stimulate a discussion on experimental work on quench- and damage levels for transient beam losses in accelerator magnets.

https://indico.cern.ch/event/323249/

Organizers: B. Auchmann, A. Lechner, B. Salvachua, M. Sapinski
Proceedings Editor: E. Todesco
Administration: S. Sapountzi

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- Introduction

- The beam induced quench workshop:
  - Beam losses in SC accelerators
  - Quench tests at the LHC
  - Heat transfer, experiments and models
  - Threshold for the LHC BLM for RUNII

- Outlook

Introduction: types of showers

- Accelerator magnets are affected by two different sources of particle showers
  - Beam losses
    - Protons/ion for the LHC, with wide time range, creating showers of different particles when colliding with collimators, beam screen, …
      - Fast losses (μs) as for instance a kicker wrongly set shooting on the magnets
      - Intermediate losses (ms) as fast instabilities, or the case of UFO (see later)
      - Slow (continuous) losses (s) as given by diffusive phenomena and instabilities
  - Collision debris from the interaction point
    - These are different types of particles γ, π, protons
      - Slow (continuous) losses

L.S. Esposito, F. Cerutti, E. Todesco, `Fluka Energy Deposition Studies for the HL-LHC', *2013 International Particle Accelerator Conference* 1379-81 (2013),

Introduction: Fast losses

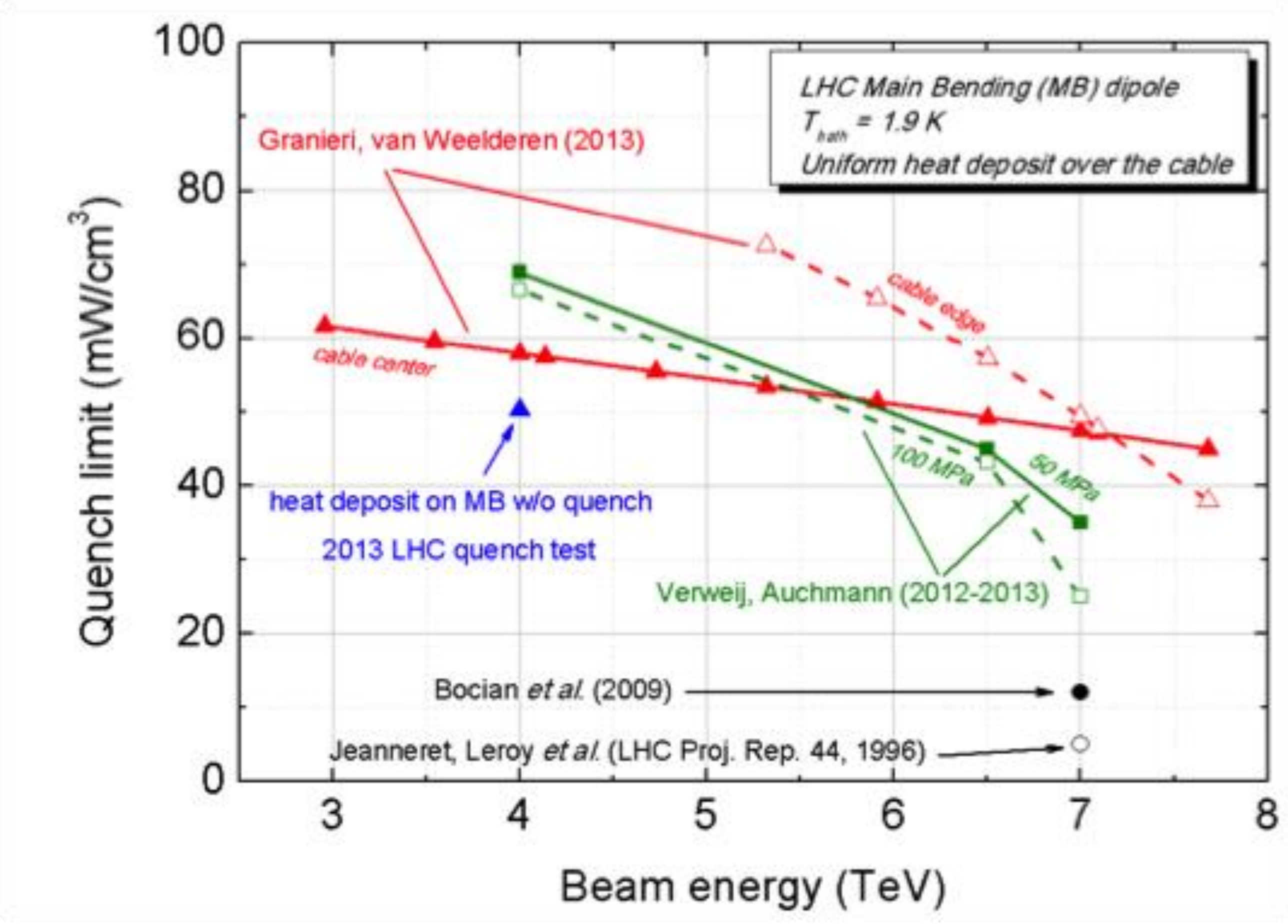
- Fast losses
  - Here limits are given in mJ/cm^3 and peak deposition in the cable cross section.
    - Typically, ~10 mJ/cm^3 for our cases
  - The simulations are adiabatic (no role of cooling)
    - But for non impregnated cable operating at 1.9 K, the He in the voids plays a relevant role
  - Limits depend essentially by
    - Superconductor material
    - Operational margin (temperature), translated in energy margin
- Example: Nb-Ti magnet at 1.9 K
  - Operating at 80% of loadline, ~2 K temperature margin, ~3 mJ/cm^3 for the conductor but ~50 mJ/cm^3 including He
- Example: Nb_3Sn magnet at 1.9 K
  - Operating at 80% of loadline, ~5 K temperature margin, ~12 mJ/cm^3

INTRODUCTION: SLOW LOSSES

- Slow losses
  - Here limits are mW/cm^3 and average power density accross cable
    - Typically, ~10 mW/cm^3 for our cases
  - The simulations must describe the cooling (more complex)
  - Limits depend essentially by
    - Superconductor material
    - Structure of the coil, impregnation, insulation
      - All thermal barriers are critical
- Example: Nb-Ti magnet at 1.9 K
  - With LHC dipole insulation, initial guess of ~12 mW/cm^3 but probably 2-3 times larger [G. Kirby, et al., IEEE TAS 23 (2013) 4002105]
  - Possibility of enhanching the insulation allowing He penetration, enhancement of a factor 3 [P. P Granieri, et al., IEEE TAS 22 (2012) 7700404]
- Example: Nb_3Sn magnet at 1.9 K
  - Best estimate [S. Zlobin, et al.] ~50 mW/cm^3

INTRODUCTION: SLOW LOSSES

- Review of results for the LHC dipoles



Introduction: Intermediate losses

- Intermediate losses
  - Here limits are given on total energy, and on the pattern energy lost versus time
  - Example of the UFO during LHC run I (Unidentified Falling [flying?] Objects)
    - particles of dust that electrostatically charged by the beam, detach from the beam screen, and are rapidly (10 μs – 1 ms) burned by the proton beam inducing showers on magnets

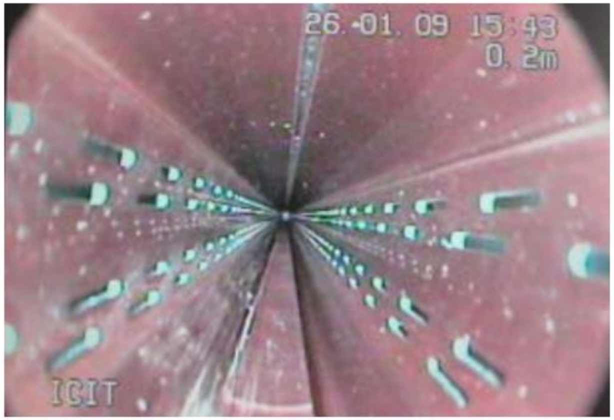
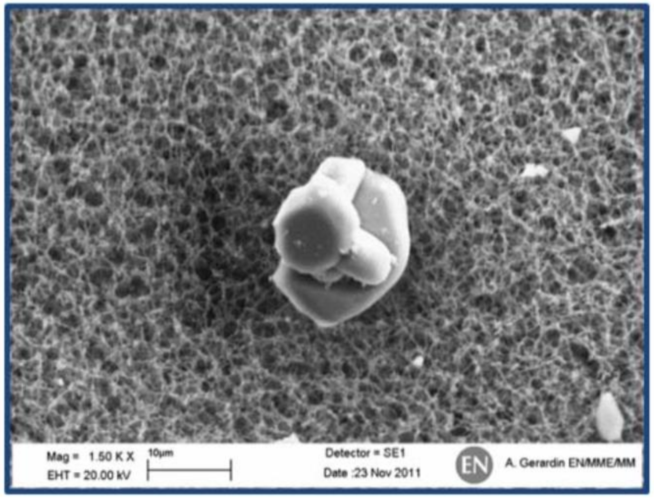


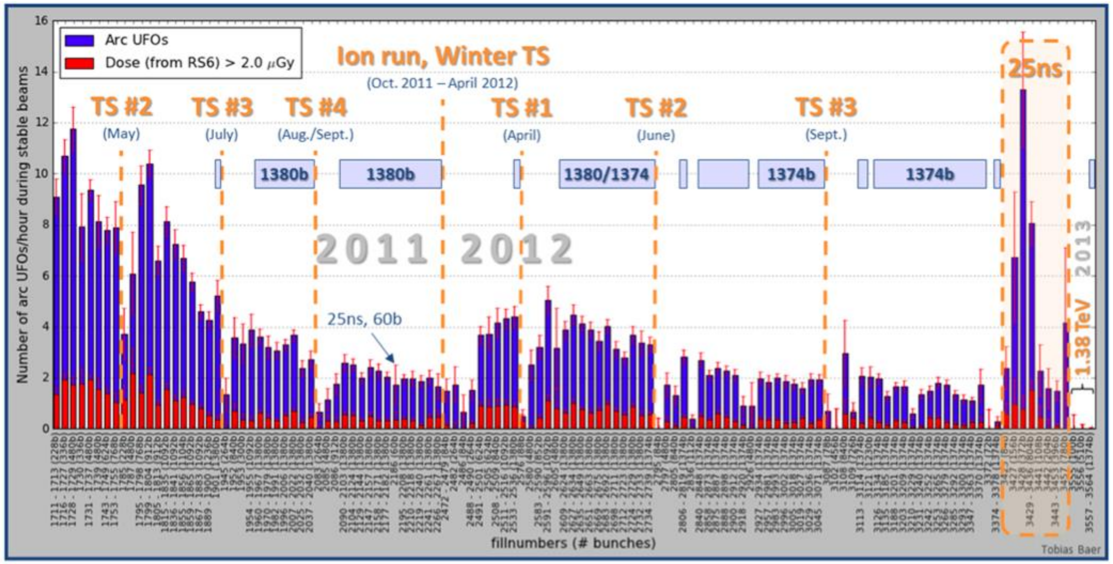
Figure (courtesy by C. Garion, LMC # 170, Oct 2013): MB beam screen interior – endoscopy inspections in LS1.



(b) Zoom of a macro particle.

Introduction: Intermediate losses

- Intermediate losses
  - Example of UFO in the LHC:
    - Visible cleaning during operation in Run I

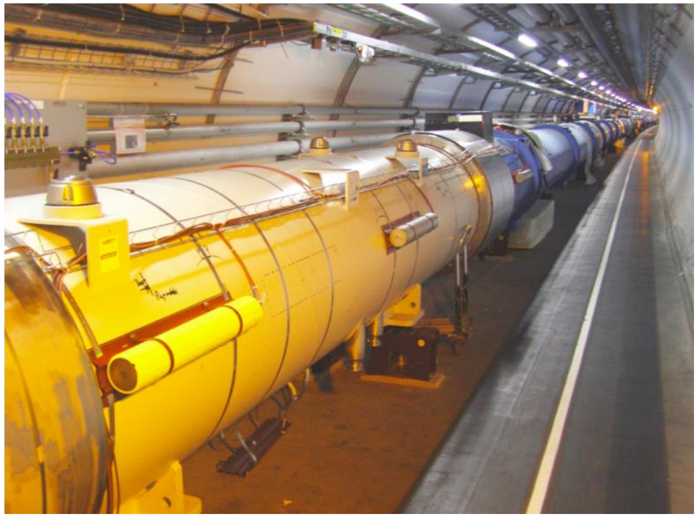


Number of UFO events versus time in 2011 and 2012 LHC operation [T. Baer PhD thesis, from B. Salvachua talk]

  - This is obviously the most difficult to simulate: both from theoretical point of view and experimental
    - Heat-transfer to helium in confined volumes is so far not accessible to direct experimental studies

Introduction: Strategies

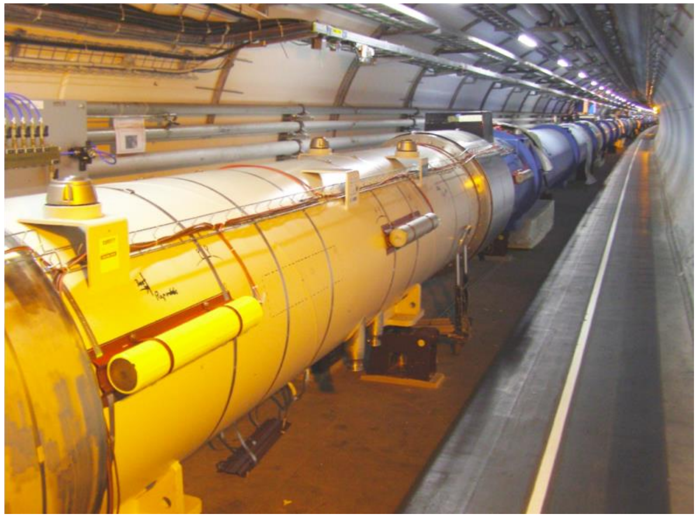
- One wishes to «see» the loss before it quenches the magnet
  - A magnet quench means ~hours to recover, depending on the accelerator and on the magnet
    - This is precious time lost for physics, better to dump the beam before quenching
- BLM: Beam Loss Monitor
  - Detector (in the LHC ionization chambers attached outside the cryostat)
  - Problem is to correlate the BLM signal to the quench level: there are several steps to be done



The LHC tunnel: cryostats and BLM

Introduction: strategies

- BLM reading is Gy/s: the puzzle has two main pieces
  - Knowing the types of beam loss, correlate the signal seen in the BLM to what seen in the coils
    - Done with a code tracking particles , their interaction with matter, and subsequent showers (FLUKA, GEANT, …)
  - Knowing how the magnet is done, how the cooling is done, estimate the quench level based on the loss pattern
    - Done with codes modeling heat transfer in cable/magnets



The LHC tunnel: cryostats and BLM

Introduction: strategies

- Several lines of attack to the problem:
  - Simulations
  - Ad hoc measurements
    - on strand/cables
    - on magnets
    - on accelerators
  - Parasitic analysis of accelerator operation

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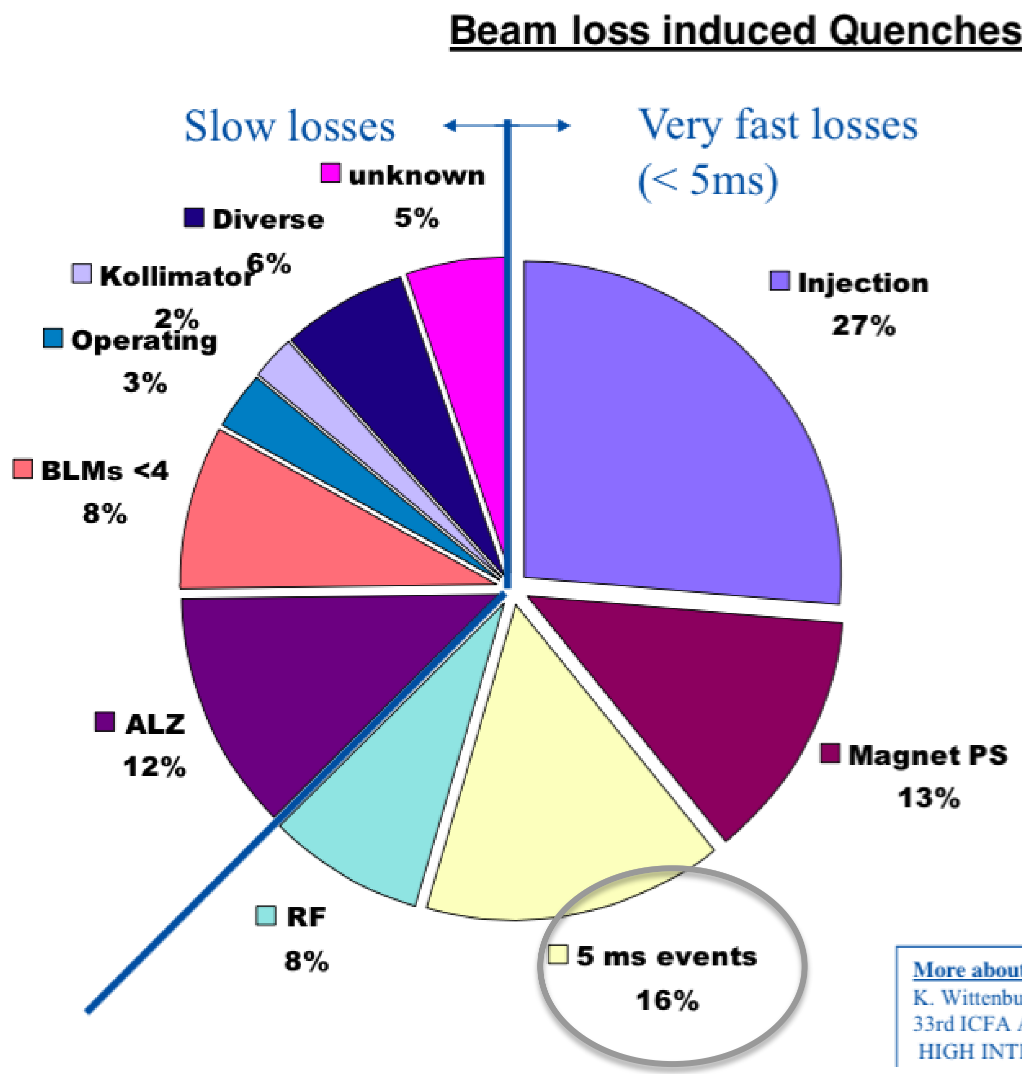
HERA (M. Sapinski based on input from K. Wittenburg)



- Magnets: Nb-Ti, 4.2 K
- PIN diodes
- 5.2 ms integration time
- 1 monitor/magnet; 4 monitors must exceed thresholds
- Blind to very fast or very localized beam losses
- Quench recovery within 1h
- Statistics of 200 BIQs
- UFOs cannot be excluded
- Known fast losses:
  - RF or PC trips
- Known slow losses:
  - Unwanted local bumps
  - Collimation

Tevatron (M. Sapinski based on input from N. Mokhov)

FERMILAB-CONF-11-129-APC

TEVATRON ACCELERATOR PHYSICS AND OPERATION HIGHLIGHTS

A. Valishev for the Tevatron group, FNAL, Batavia, IL 60510, U.S.A.

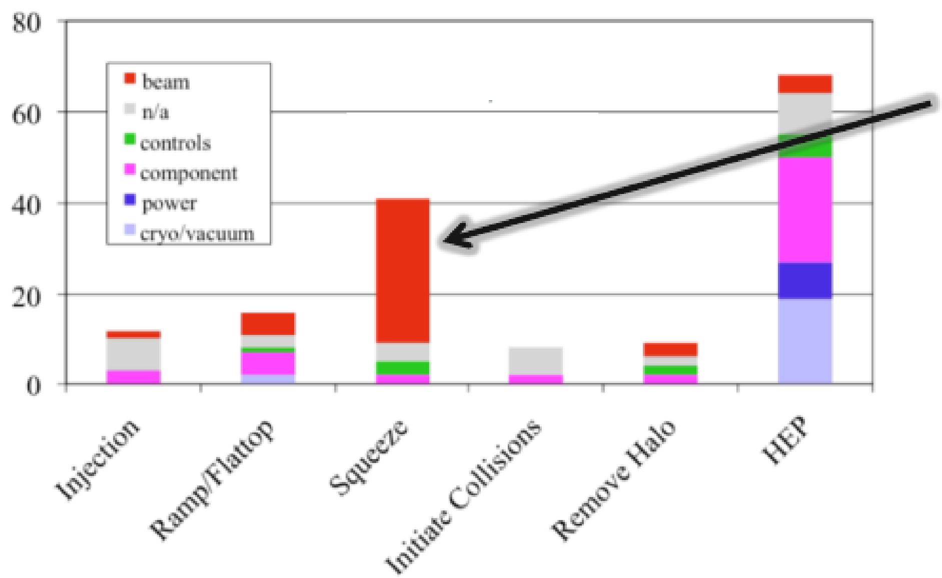
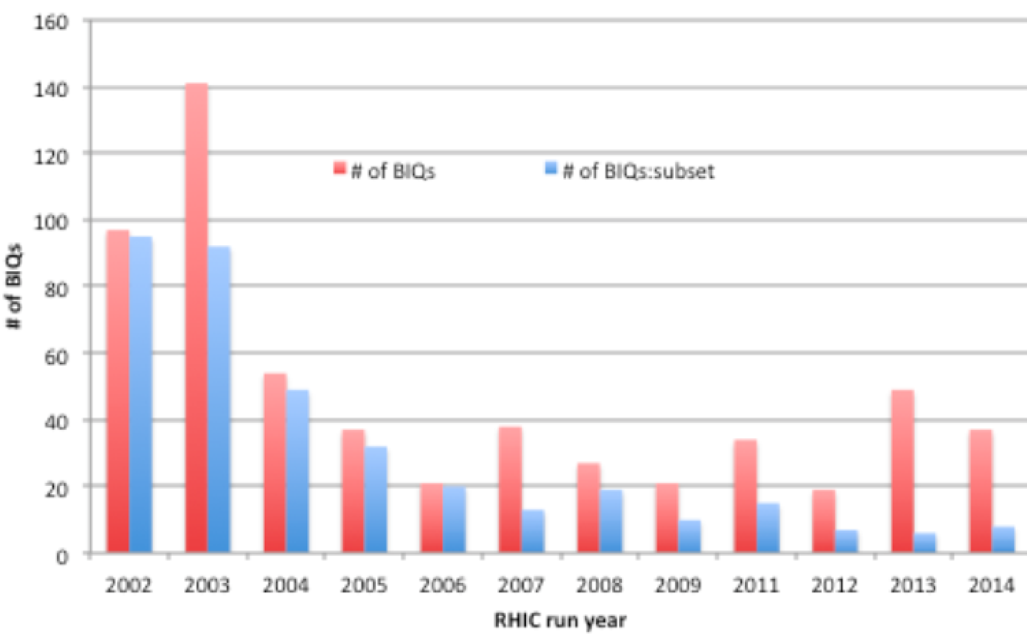


Figure 4: Categorization of Tevatron magnet quenches. Data between October 2007 and March 2011.

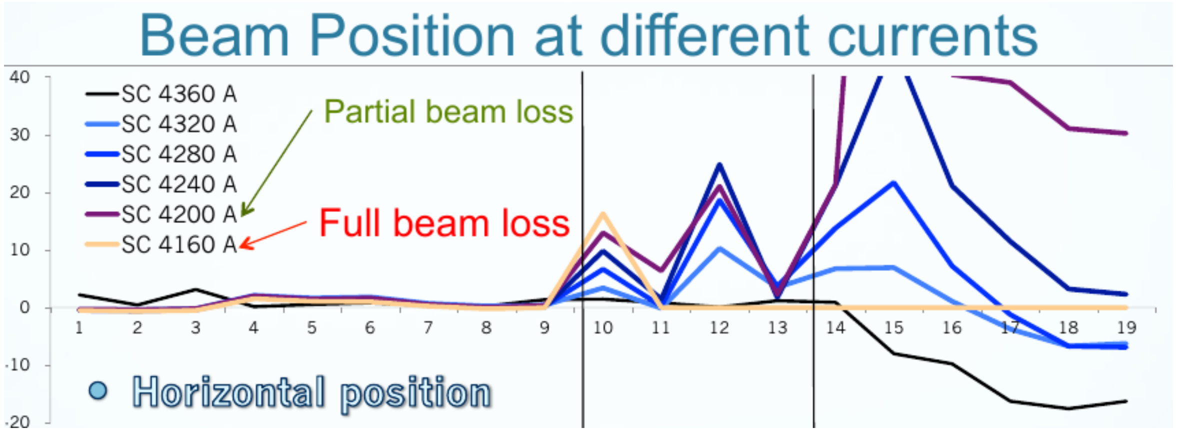
- Magnets: Nb-Ti 4.2 K
- Ionization chambers with 20 µs integration time
- 154 quenches in 4 years, 32 of which during β* squeeze and reduction of beam separation from 6 to 2 σ
- 2010: introduction of collimation at top energy in IRs
- Loss of antiprotons requires lengthy refilling – significant loss of integrated luminosity

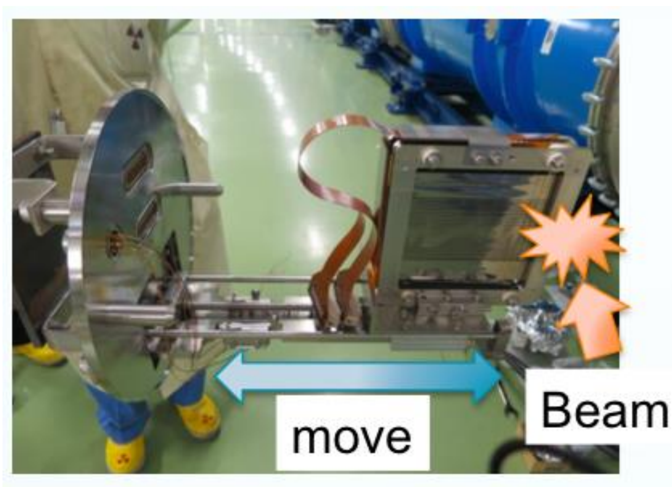
RHIC Experience (M. Bai)



- Magnets: Nb-Ti 4.2 K
- Ionization chamber in between RHIC rings
- Fast- (20 ms) and Slow Thresholds at triplets
- Thresholds are constant for all energies
- Blind to very fast losses. No distinction between beam lines possible. (Separate monitors only at IPs)
- One beam-loss event created damage on helical dipole
- Availability optimization by, e.g., masking BLMs during beginning of ramp. Some avoidable BIQs (blue) are the consequence

KEK JPARC Trasfer Line (K. Sasaki)





- Magnets: Nb-Ti
- Operational beam losses not measurable
- Quench test: As no training quenches occurred in the beam line, current was lowered until quench was observed
- Human error: BPMs were moving in as beam was extracted. Interlock was masked

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LHC Experience (M. Sapinski)

One accidental kick provoking quenches

UFO provoking beam losses above BLM thresholds but no quench

Ad hoc experiments:

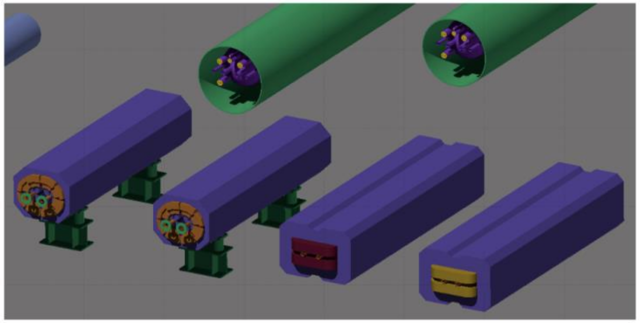
- Injection shooting on a quadrupole (Q6) – fast loss
- ADT excitation to create UFO like losses – intermediate
- Wire scanner

Year	Method	Analysis
2008	Accidental kick	Geant4, D. Bocian quench levels
2010	First beam-dumping UFO	Start thinking about QT in the UFO time-scale
2010	Dynamic orbit-bump (1-6 s)	Geant4, QP3
2010	Wire-scanner (20 ms)	Geant4, QP3
2011	Collimation quench tests with p and Pb (1-10 s)	No quenches. Very short losses for Pb.
2011	Shot on TDI (x ns)	No quench in Q6.
2013	End of run campaign: • Shot on TDI (x ns) • Fast-loss ADT excitation (10ms) • Slow-loss ADT excitation (20 s) • Collimation with ADT (15 s)	MAD-X, SixTrack, FLUKA, QP3, THEA Full analysis in QTAWG ~ 1 year.

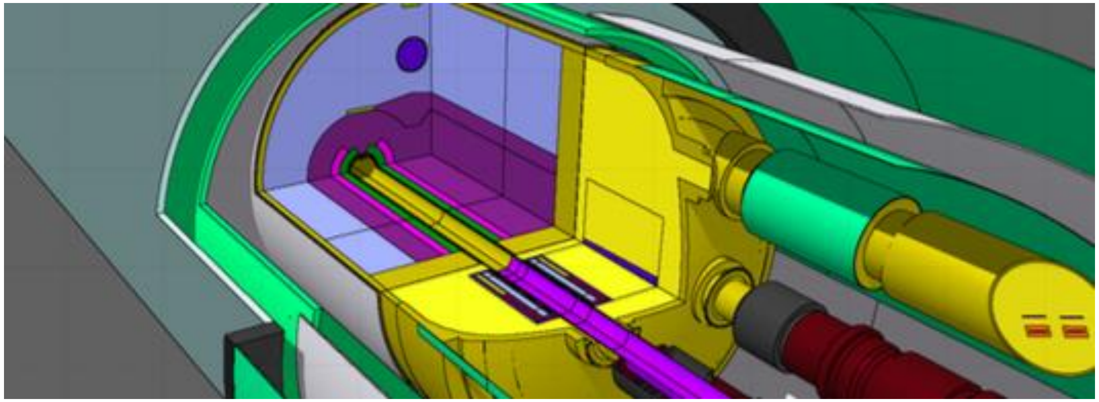
LHC Modeling (A. Lechner)

FLUKA has become the standard tool for machine protection studies, collimation, BLM settings, UFOs, etc.

- A modular element library is available
- Model includes detailed 3D geometry
- Good agreement between simulated values and BLM output for many cases of different losses



modular: FLUKA element database (magnets, colls, etc.)



Quench levels (A. Verweij, B. Auchmann)

First case: injection shooting on a magnet – good agreement [QP3 code by A. Verweij]

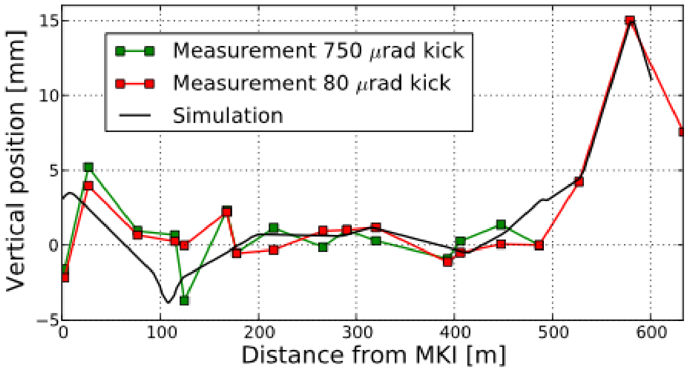
Particle-tracking	Particle-shower	Electro-thermal
Injection to beam screen	Same Magnet	Strand enthalpy

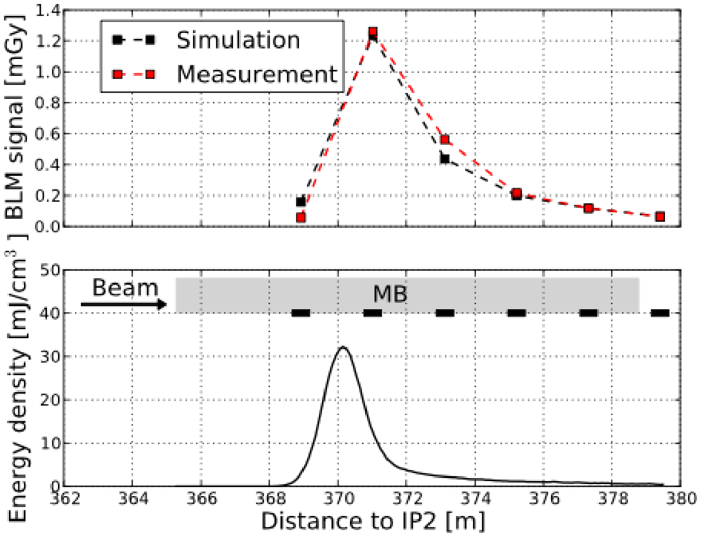
P. Show. [mJ/cm^3]	El.-Therm. [mJ/cm^3]
$\leq$36	38

Challenge: getting the beam trajectory up to the kick right.

Advantage: data for validation available.

Uncertainties in particle-tracking input used to obtain best agreement.

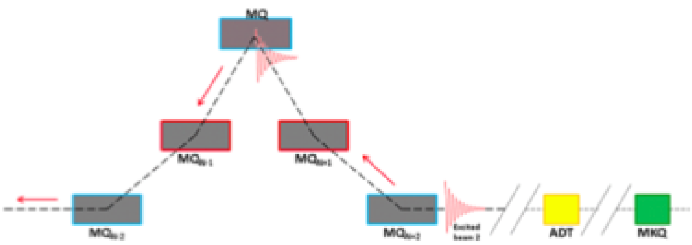




Quench Levels (A. Verweij, B. Auchmann)

Second case: orbit bump with beam blow-up – 4 times larger margin

Particle-tracking	Particle-shower	Electro-thermal
Tracking hundreds of turns, MKI, ADT	Same Magnet	Cooling of μs loss peaks into He II

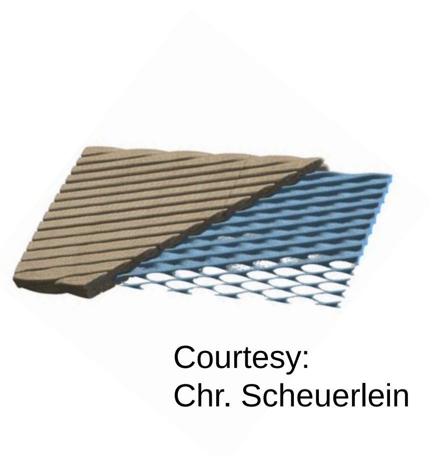


Uncertainty on moment of quench.

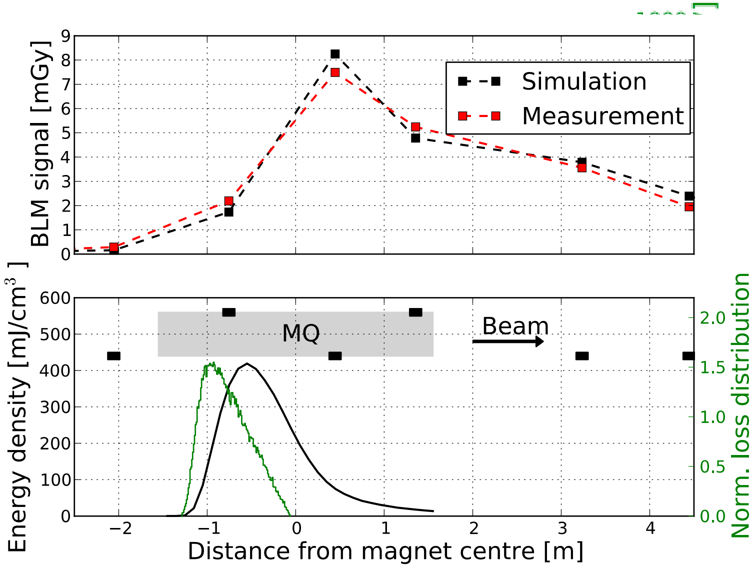
Loss spikes of several μs ➔ even larger uncertainty on cooling model.

Particle tracking tuned to fit BPM data.

N_p	N_q	P. Show. [mJ/cm³]	El.-Therm. [mJ/cm³]
3.5×10^8	n/a	>198	$71^{+?}_{-10}$
8.2×10^8	5.3×10^8	250	$58^{+?}_{-8}$
8.2×10^8	8.2×10^8	≤405	$80^{+?}_{-10}$



Courtesy:
Chr. Scheuerlein



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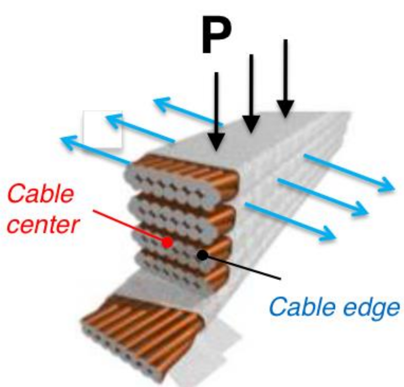
Continuous losses in cables:

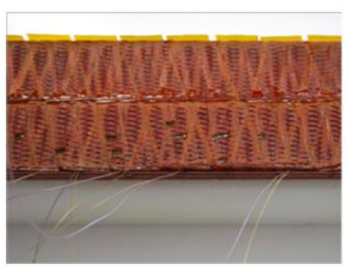
Measurements on stack of cables, heating provided by Cu cable [D. Richter, P. P. Granieri, P. Fessia, D. Tommasini, IEEE TAS **22** (2012) 7700404]

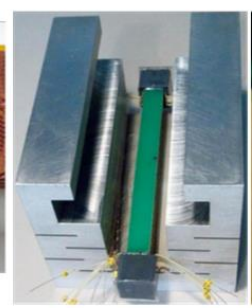
Quench level for different configuration of insulation, stresses, etc.

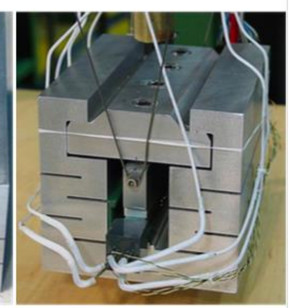
- New specificities wrt previous stack-type experimental setups (CEA, KEK, CERN)
  - thermometry
  - real cable structure
  - controlled pressure
  - heating configurations

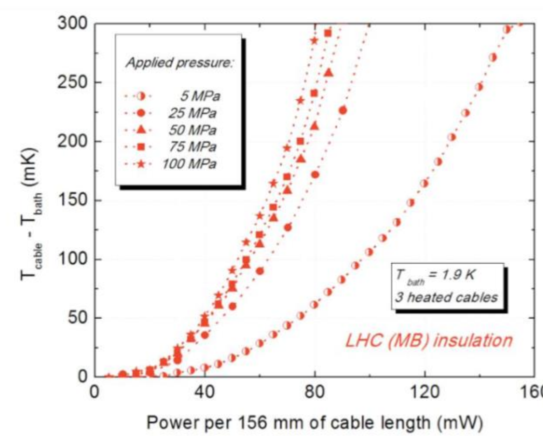


Stack sketch by S. Pietrowicz









N. Kimura *et al.*, "Heat transfer characteristics of Rutherford-type superconducting cables in pressurized He II", *IEEE Trans. Appl. Supercond.*, vol. 9, no. 2, pp. 1097–1100, 1999.

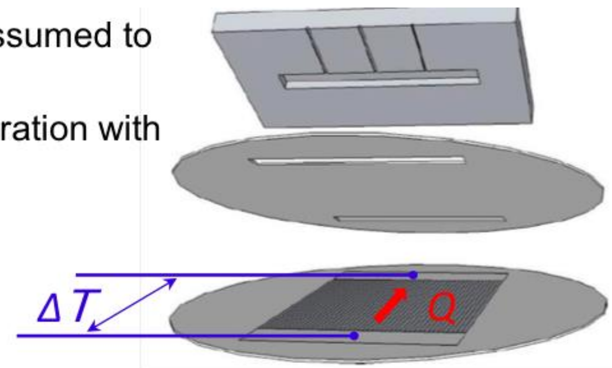
P.P. Granieri, P. Fessia, **D. Richter**, D. Tommasini, "Heat transfer in an enhanced cable insulation scheme for the sc magnets of the LHC luminosity upgrade", *IEEE Trans. App. Sup.*, 20, 201

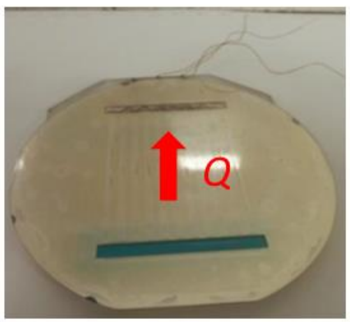
P.P. Granieri, *Heat transfer between the superconducting cables of the LHC accelerator magnets and the superfluid helium bath*, Ph.D. dissertation, 2012.

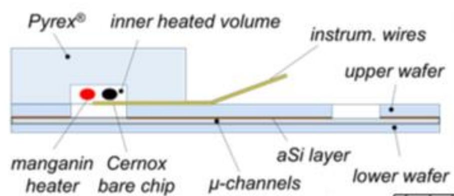
Examples of Experimental Programs

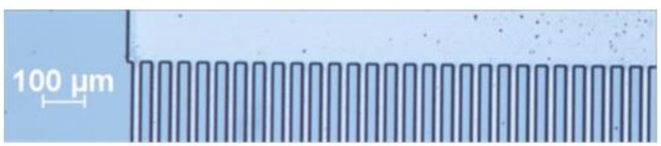
Continuous losses, modeling of He flow in channels:

- In modeling, He II classical heat transport laws were assumed to be valid in narrow channels
- A study is ongoing to validate such hypothesis (collaboration with CEA-Saclay), making use of MEMS techniques

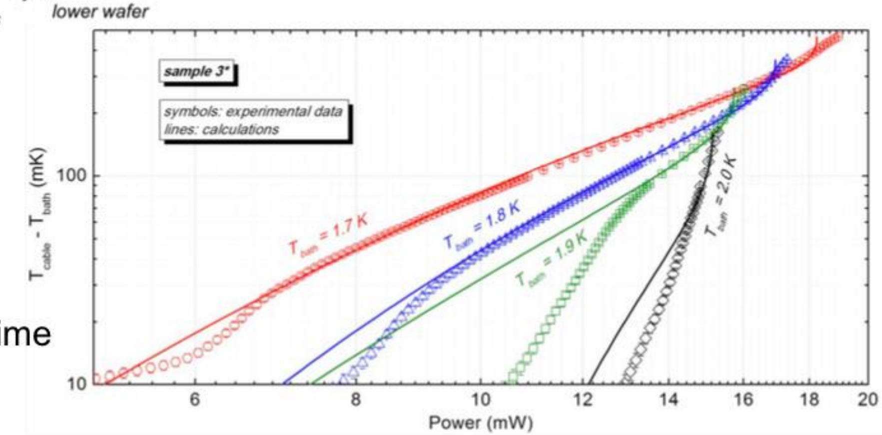








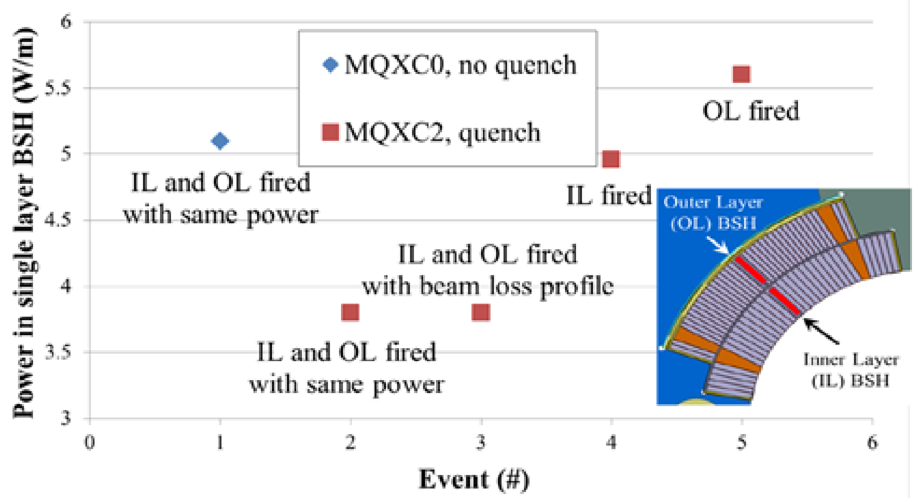
- So far, Landau and Gorter-Mellink regime measured down to 10 µm thickness



P.P. Granieri, B. Baudouy, A. Four, F. Lentijo, A. Mapelli, P. Petagna and D. Tommasini, "Steady-state heat transfer through micro-channels in pressurized He II", Adv. in Cryogenic Engineering.
P.P. Granieri, *Heat transfer between the superconducting cables of the LHC accelerator magnets and the superfluid helium bath*, Ph.D. dissertation, 2012.

Examples of Experimental Programs

- Continuous losses on magnets
  - Spot heaters in the midplane
    - Problem: how much goes into the coil and how in the He bath – model needed to interpret the results
  - MQXC quadrupole in Nb-Ti, 1.9 K, had spot heaters and experiments were made

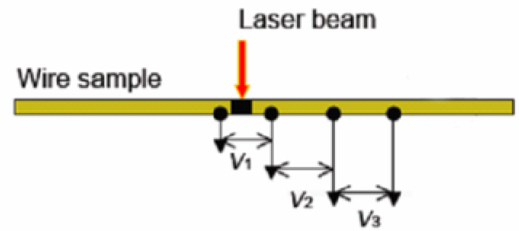


G. A. Kirby et al., "Testing Results for Nb-Ti, 120-mm-Aperture, Low-B Quadrupole Models for the LHC High-Luminosity Insertion." *IEEE Trans. on Appl. Supercond.* 4002105 (2013).

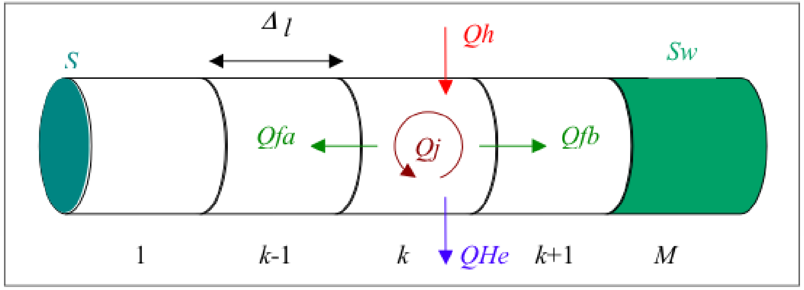
Transient losses:

On single wire, heat deposited by a laser beam [F. Trillaud, et al., *Cryogenics* **45** (2005) 585-8
E. Takala, et al. *IEEE TAS* **22** (2012) 6000704]]

Accurate control of heat deposited, including structure of the pulse



Measurements by F. Trillaud, CEA Saclay, France

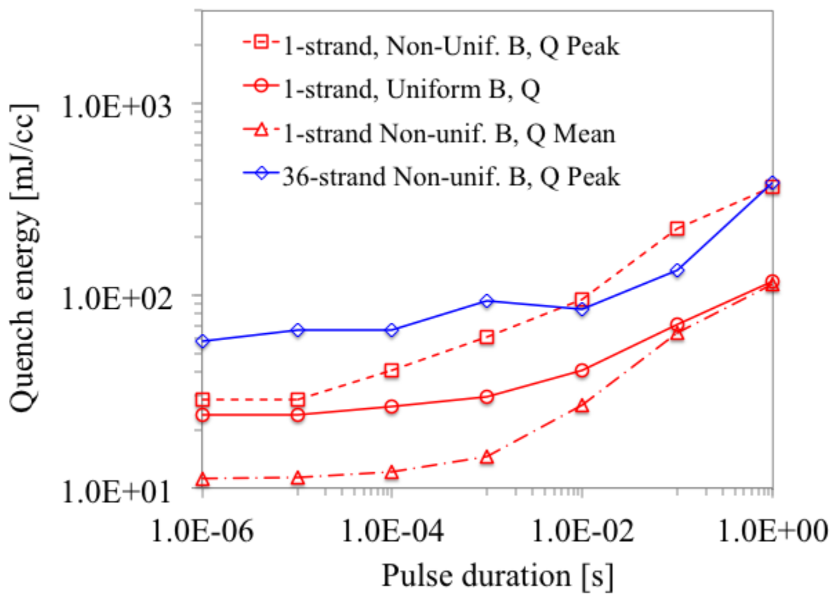


MODELING TOOLS

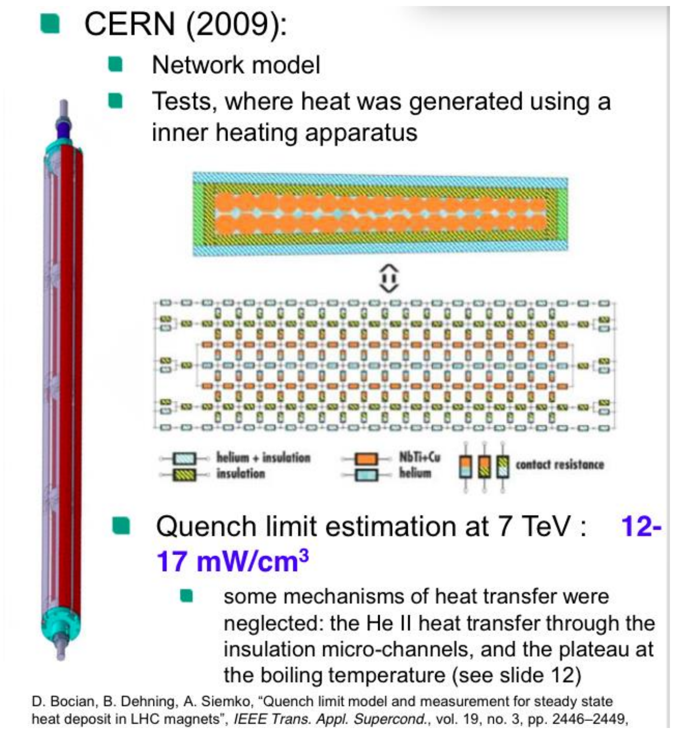
Several modeling tools at CERN, among which

- Network model [D. Bocian, et al, *IEEE TAS* **19** (2009) 2446-9]
- FEM models (ex.: ANSYS) [E. Bielert, et al, *IEEE TAS* **22** (2012) 4701205]
- Multiphysics models (ex.: COMSOL)
- Ad hoc codes integrating the relevant part (ex.: THEA [L. Bottura], QP3 [A. Verweij])

Steady state:
D. Bocian 2009
E. Bielert 2012
P.P. Granieri 2012
B. Baudouy 2013
C. Soulaine 2014



M. Breschi, et al., ASC 2014
IEEE TAS in press



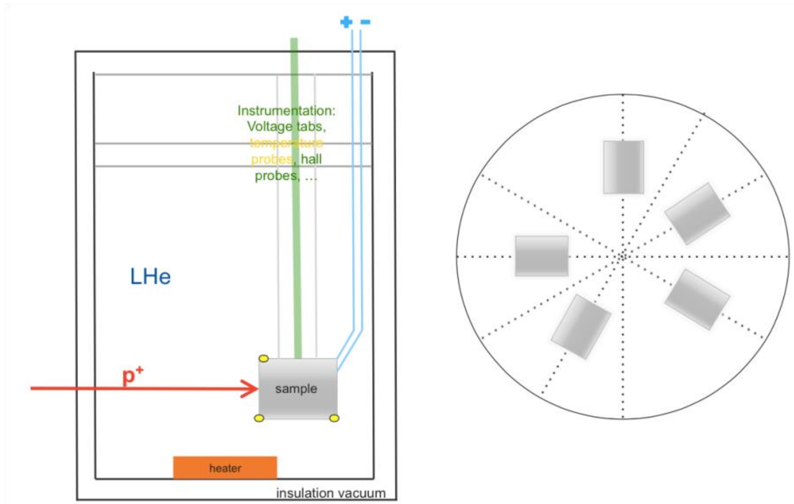
Damage Levels (D. Wollmann)

What is the damage level for instantaneous beam losses into SC accelerator magnets?

No reliable data seems to be available!

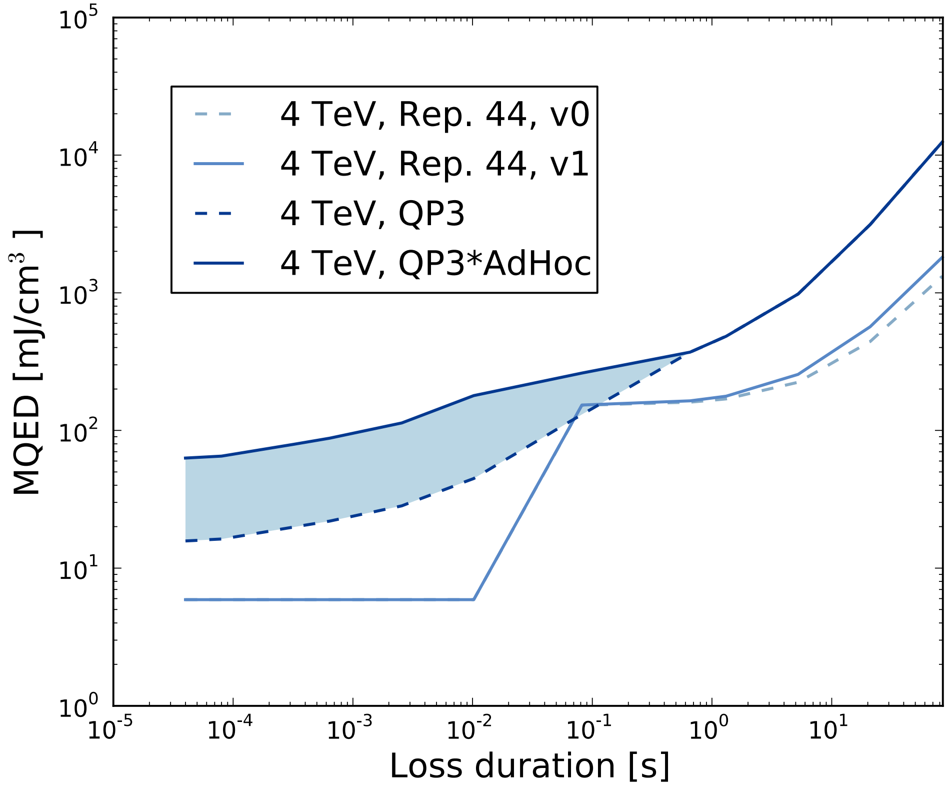
What are the damage mechanisms? He pressure rupturing insulation? Thermal shockwaves? Differential thermal expansion?

Request for beam-time in HiRadMat facility for experiment with He II bath has been made.



Thresholds for LHC Run II

- Final result: the threshold curve
  - This is where are we with the LHC today
    - Previous thresholds will be raised in some time domains by factor ~4



OUTLOOK

- Outlook for HTS magnets
  - Due to the much larger temperature margin we could be in a different domain compared to Nb_3Sn and Nb-Ti
- Lot of experience on several accelerators
  - But all of them made with Nb-Ti
    - One of them at 1.9 K – little data for the moment but much more coming with RunII
- Lot of experience on magnets and cables/strands
  - Many experimental settings adopted for Nb-Ti and Nb_3Sn could be applied to HTS
- The operational temperature is critical 1.9 K? Or 4.2 K? Or more?
  - Superfulid of supercritical helium changes the picture for slow losses

Previous Related Events

- 2005 Stability Workshop (March 4)
  - https://indico.cern.ch/event/0516/
- 2006 Review of thermal stability of acc. SC magnets
  - https://indico.cern.ch/event/7282/
- 2009 Mini-Workshop on Thermal Modeling and Thermal Experiments for Accelerator Magnets CERN
  - https://indico.cern.ch/event/69056/
- WAMSDO 2013 on quench modelling, detection and protection
  - http://indico.cern.ch/event/wamsdo2013
- CHATS-AS Workshops
  - http://indico.cern.ch/event/chats2011,
  - http://sites.tufts.edu/chatsas2013/
- BIQ 2014
  - http://indico.cern.ch/event/BIQ2014