# Thermal and electrical analysis of superconducting magnets Some available tools and results

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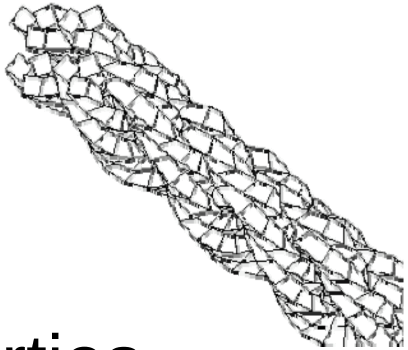
Review on the Thermal Stability of Superconducting Accelerator Magnets, November 14th, 2006

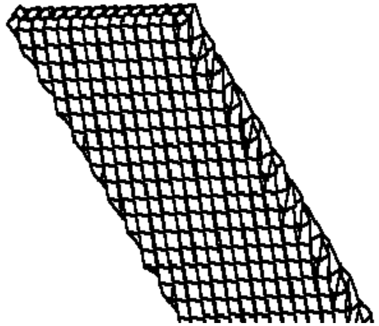
# Outline

- Cable design codes
  - CID
  - OPTICON
- Cable analysis codes
  - ZERODEE
  - GANDALF
  - THEA
- Heat and mass transfer in magnet systems
  - FLOWER
- Field, force, inductance, AC loss
  - M'C
- An example: parametric study of LHC inner cable

# CID



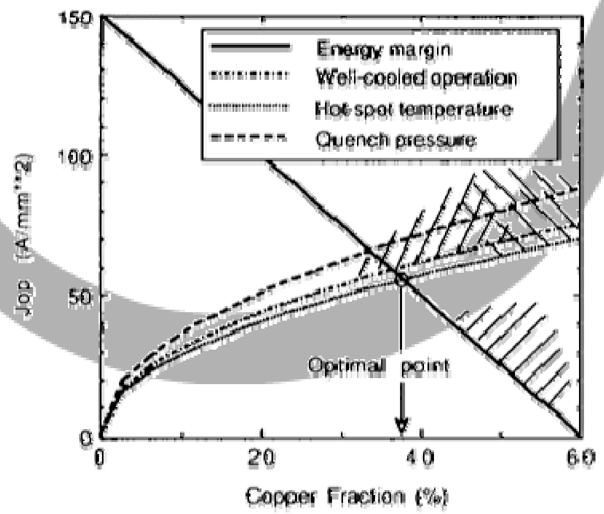
- Cable geometry and electrical properties modeled with 3-D volume elements
  - Twisted cables with or without core
  - Flat cables with or without keystoning



- Calculation of cable:
  - Cross sections
  - Contact resistance matrix (line and cross contacts)
  - Inductance matrix
- Pre-processor for electrical calculation of cables (e.g. current distribution analysis with THEA)

L. Bottura, M. Breschi, C. Rosso, "Analysis of Electrical Coupling Parameters in Superconducting Cables" Cryogenics, 43(3-5), 233-240, 2003.

# OPTICON




Example of copper fraction optimisation in a force-flow cooled cable

L. Bottura, "Stability, Protection and AC Loss of Cable-in-Conduit Conductors. A Designer's Approach", Fus. Eng.ng Des., 20, 351-362, 1992.

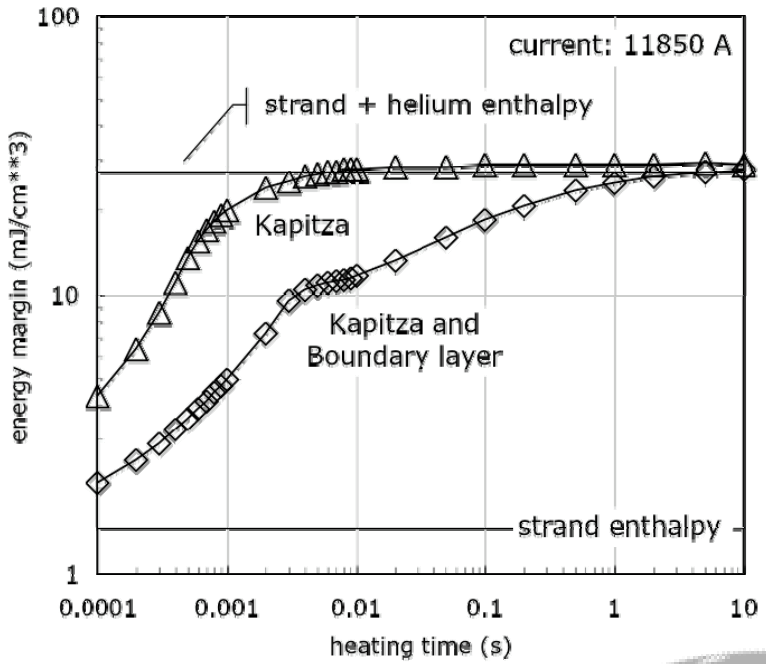
- Cable fraction optimization for force-flow cooled conductors
- Select optimal quantity of components
  - stabilizer
  - superconductor
  - helium

to achieve requested minimum stability margin and limit hot-spot temperature to maximum allowed


L. Bottura, "Stability, Protection and AC Loss of Cable-in-Conduit Conductors. A Designer's Approach", Fus. Eng.ng Des., 20, 351-362, 1992.
L. Bottura, "Limiting Current and Stabilty of Cable-in-Conduit Conductors", Cryogenics, 34(10), 787-794, 1994.
L. Bottura, "Parametric Study of Design of Cable-in-Conduit Conductors", IEEE Trans Mag., 30, 4, 1982-1985, 1994.
L. Bottura, "Stability and Protection of CICC's: an Updated Designer's view", Cryogenics, 38(5), 491-502, 1998.

# ZERODEE

- Stability analysis of SC cables:
  - *lumped* heat capacities
  - thermal contact through
    - convective heat exchange (strands-helium)
    - thermal resistances (strands-structure-insulation)
  - Uniform current distribution in the cable
- Quick estimate of stability margin for long normal zone
- Allows extensive parametric study



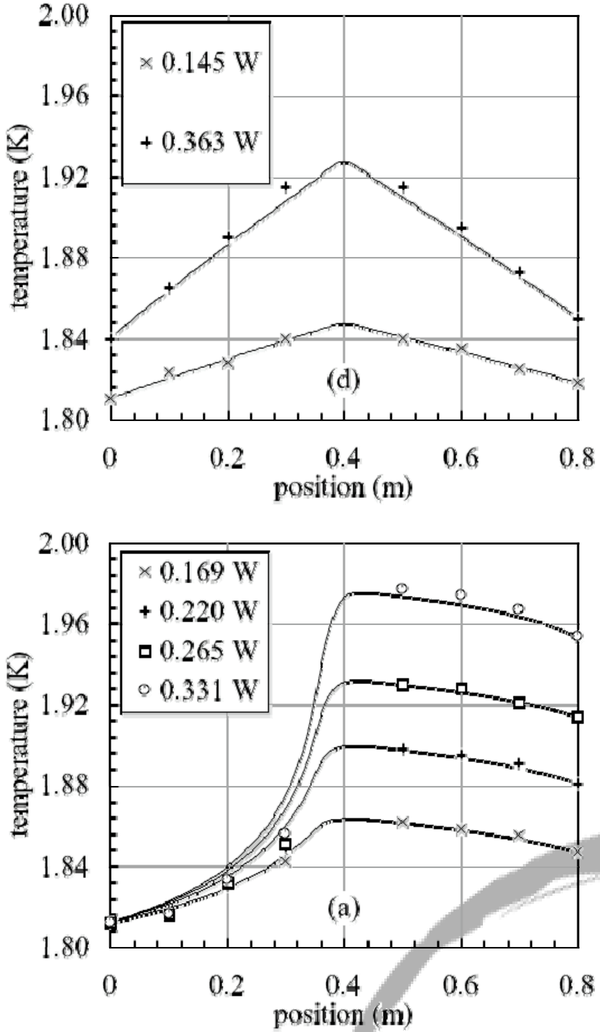

Example of stability analysis of an LHC inner cable considering different heat transfer models

L. Bottura, M. Calvi, A. Siemko, "Stability Analysis of the LHC Cables", Cryogenics, 46(7-8) 481-493, 2006.

J.V. Minervini, L. Bottura, "Stability Analysis of NET TF and PF Conductors", IEEE Trans. Mag., 24, 1311-1314, 1988.
L. Bottura, J.V. Minervini, "Modelling of Dual Stability in a Cable-in-Conduit Conductor", IEEE Trans. Mag., 27, 2, 1900-1903, 1991.
L. Bottura, "Modelling Stability in Superconducting Cables", Physica C, 310(1-4) 316-326, 1998.

# GANDALF

- 1-D compressible helium flow and heat conduction in SC cable
- Uniform current distribution in the cable
- Stability, quench, cooling of force-flow cooled coils
- Realistic evaluation, including non-linear heat transfer phenomena and coupling with electrical and cryogenic supply



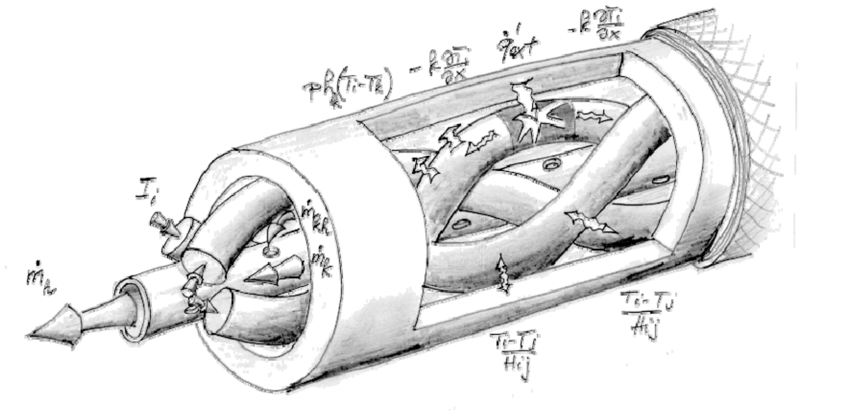

Example of steady state temperature distribution in a He-II channel

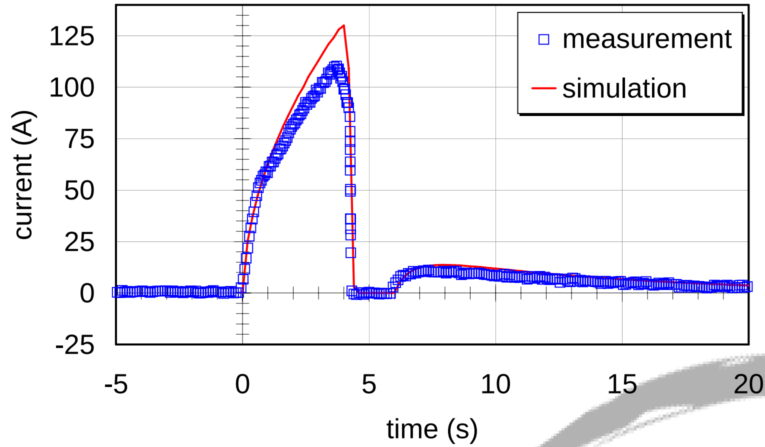
Data: Srinivasan and Hoffman, Cryogenics, 25, pp. 641-657, (1985).


L. Bottura, "A Numerical Model for the Simulation of Quench in the ITER Magnets", J. Comp. Phys., 125, 26-41, 1996.
L. Bottura, A. Shajii, "Numerical Quenchback in Thermofluid Simulations of Superconducting Magnets", Int. J. Num. Methods Eng., 43, 1275-1293, 1998.
L. Bottura, C. Rosso, "Finite Element Simulation of Steady State and Forced Convection in Superfluid Helium", Int. J. Num. Methods Fluids,

# THEA

- Parametric cable model, including an arbitrary number of:
  - Strands (or super-strands)
  - Structural or electrical components (barriers, jackets, insulations)
  - Cooling channels
- Multi-physics model:
  - Heat conduction in solid components
  - Compressible flow in cooling channels
  - Current distribution in electrical components
- Detailed cable analysis






Example of current distribution analysis in a two-strand sample with external dB/dt and sudden quench


Data: L. Krempaski and C. Schmidt, Cryogenics, 39 pp. 23-32 (1999).

L. Bottura, "Modelling Stability in Superconducting Cables", Physica C, 310 (1-4), 316-326, 1998.

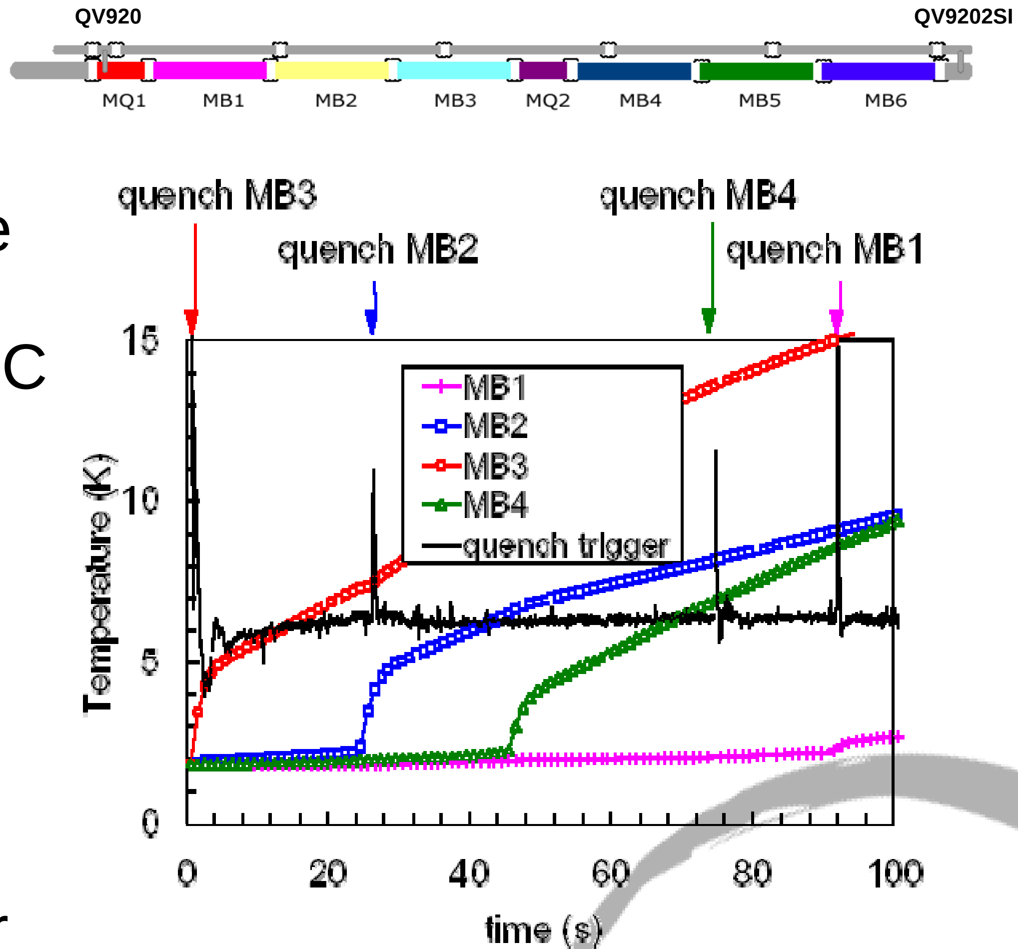
L. Bottura, C. Rosso, M. Breschi, "A General Model for Thermal, Hydraulic, and Electric Analysis of Superconducting Cables", Cryogenics, 40(8-10), 617-626, 2000.

A. Akhmetov, L. Bottura, M. Breschi, "A Continuum Model for Current Distribution in Rutherford Cables", IEEE Trans. Appl. Sup., 11(1), 2138-2141, 2001.

L. Bottura, C. Marinucci, P. Bruzzone, "Application of the Code THEA to the CONDOPT Experiment in SULTAN", IEEE Trans. Appl. Sup., 12 (1),

# FLOWER

- Simplified model of the hydraulic (Lhe or LN2) network that feeds a SC magnet
  - Pipes, pumps, valves, heat exchangers, volumes
- Model of the key features of the cryogenic system
- For stand-alone use or coupled with a cable/magnet analysis code



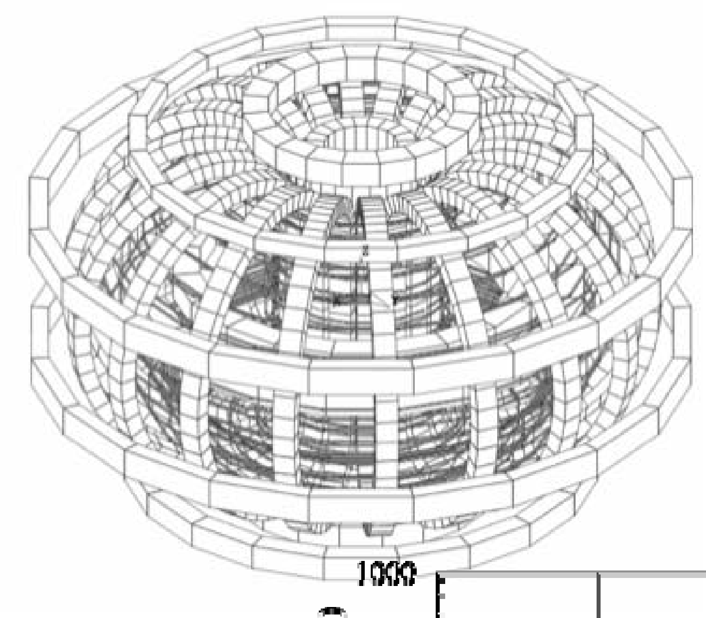

Example of quench simulation in String II

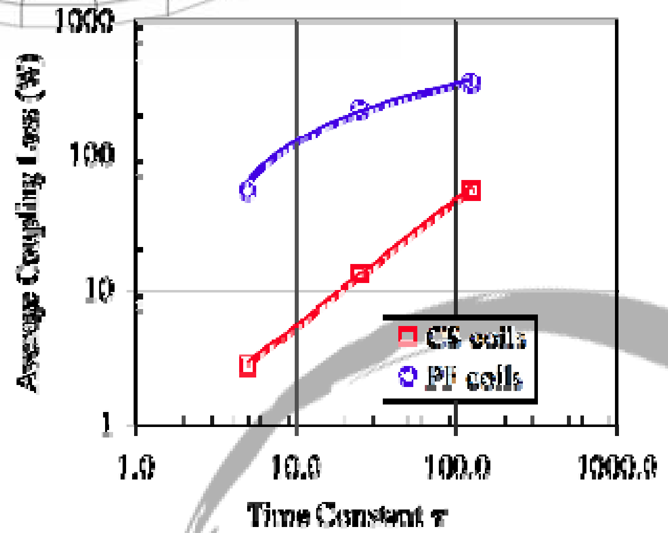
Data: courtesy of R. van Weelderen


L. Bottura,"Quench Propagation Through Manifolds in Forced Flow Cooled Coils", IEEE Trans. Appl. Sup., 3, 1, 606-609, 1993.
L. Bottura, C. Rosso, "Flower, a Model for the Analysis of Hydraulic Networks and Processes" Cryogenics, 43(3-5), 215-224, 2003.

# M'C

- Magnetic field, vector potential, AC loss, loadline, inductance and magnetic energy, forces and resultants calculation in superconducting coil systems of arbitrary 3-D shape in the absence of iron
- isoparametric, 8-nodes brick elements
- Shielding model for coupling currents and hysteresis loss






Example of AC loss calculation in the ITER pulsed coil system

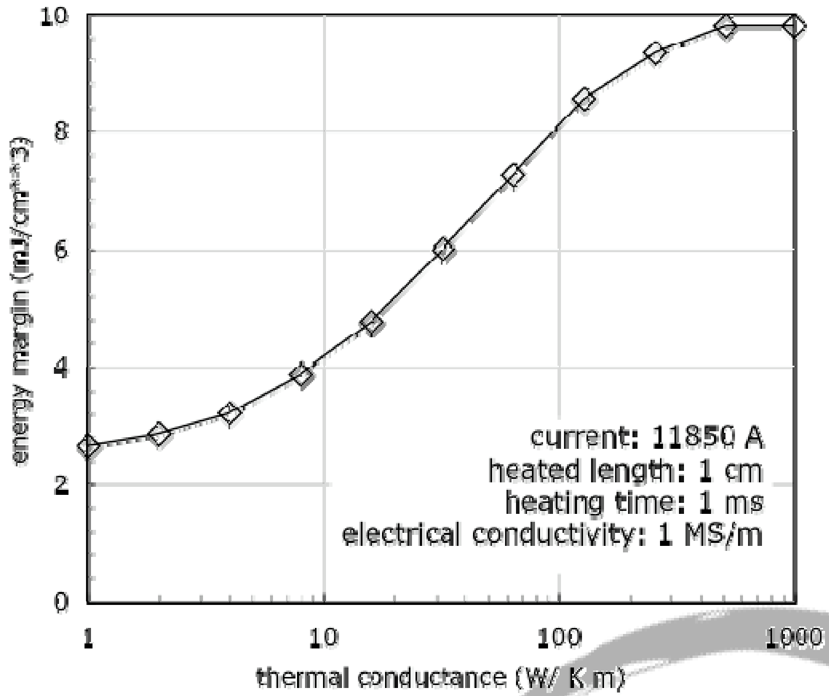

L. Bottura, J.V. Minervini, "Detailed Distribution of AC Loss in the NET TF Coils", IEEE Trans. Mag., 25, 1730-1733, 1989.

L. Bottura, U. Mszanowski, N. Mitchell, " Analysis of the ITER Superconducting Coils: Magnetic Field, AC Losses and Cooling", IEEE Trans. Mag., 28, 1, 230-233, 1992.

L. Bottura, J.V.Minervini,"Calculation of Magnetization, Hysteresis and Power Dissipation in a Superconductor During Bipolar Field Cycles", IEEE Trans. Appl. Sup., 3, 460-463, 1993.

# LHC inner cable - 1/3

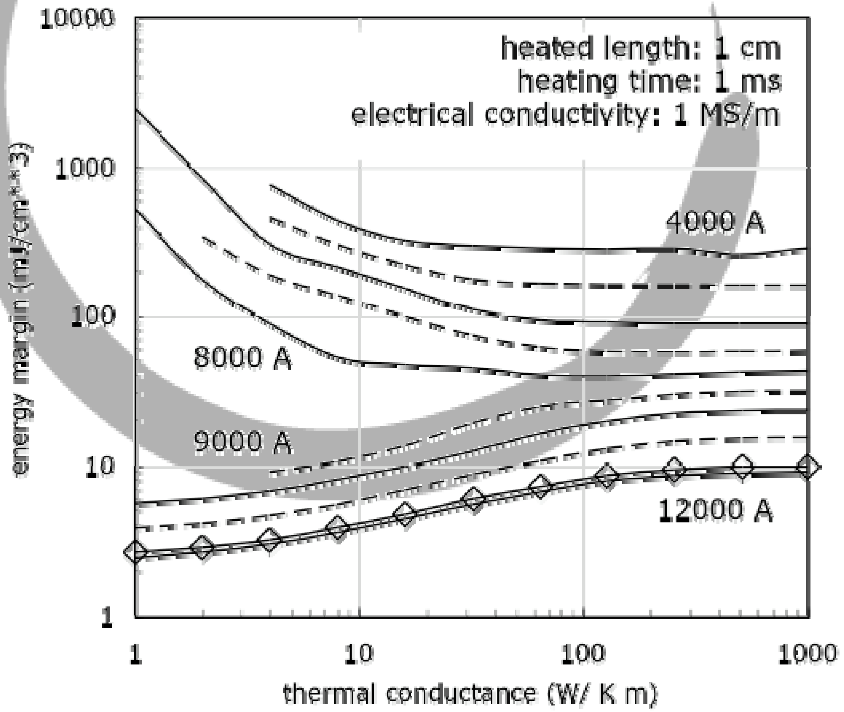
- Parametric analysis of stability margin
  - Heat transfer model
  - Thermal coupling among strands
  - Electrical coupling among strands
- 0-D (ZERODEE) and 1-D (THEA) analysis
- Test the tools and identify critical parameters for a systematic evaluation of the LHC magnets (see talk of A. Siemko for the motivation)

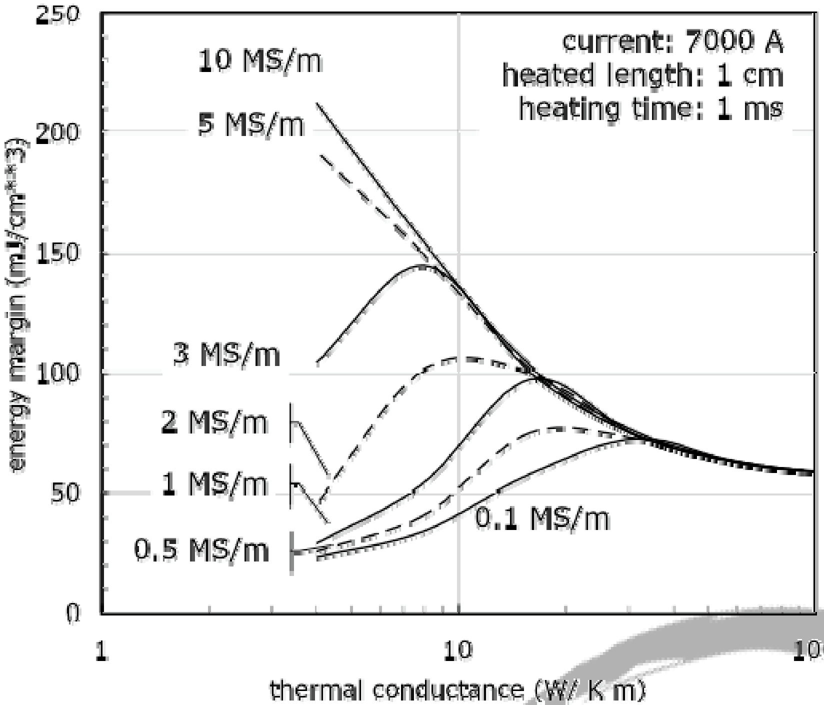



Thermal coupling among strands governs the transition from *single strand* to *collective cable* behavior for a single strand quench…

L. Bottura, M. Calvi, A. Siemko, "Stability Analysis of the LHC Cables", Cryogenics, 46(7-8) 481-493, 2006.

# LHC inner cable - 2/3



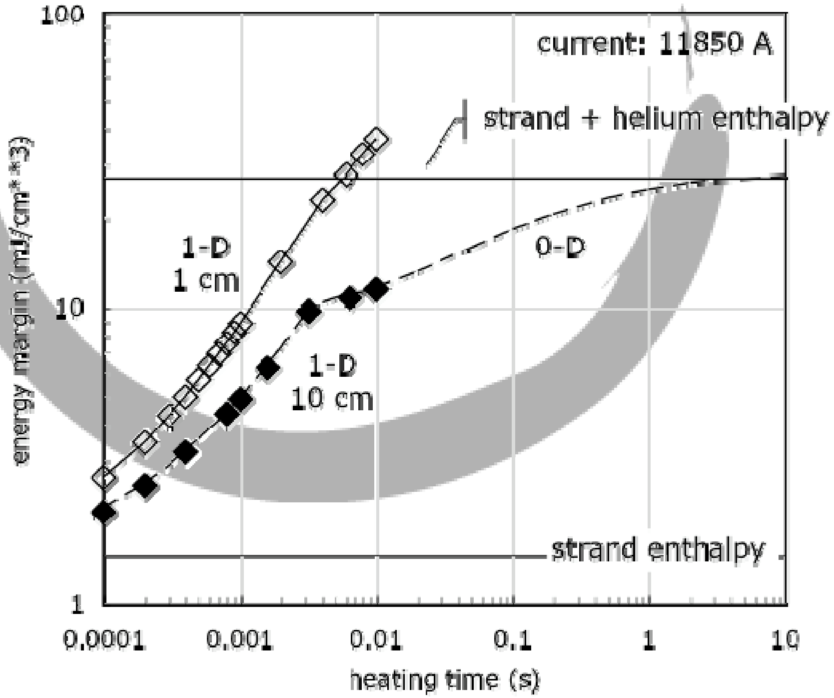




… at low current, and if the strands are well-coupled electrically, the single strand quenched can make use of the current carrying capacity of the neighbours…

… but the benefit of thermal de-coupling is lost once the strands are also electrically de-coupled

L. Bottura, M. Calvi, A. Siemko, "Stability Analysis of the LHC Cables", Cryogenics, 46(7-8) 481-493, 2006.

# LHC inner cable - 3/3

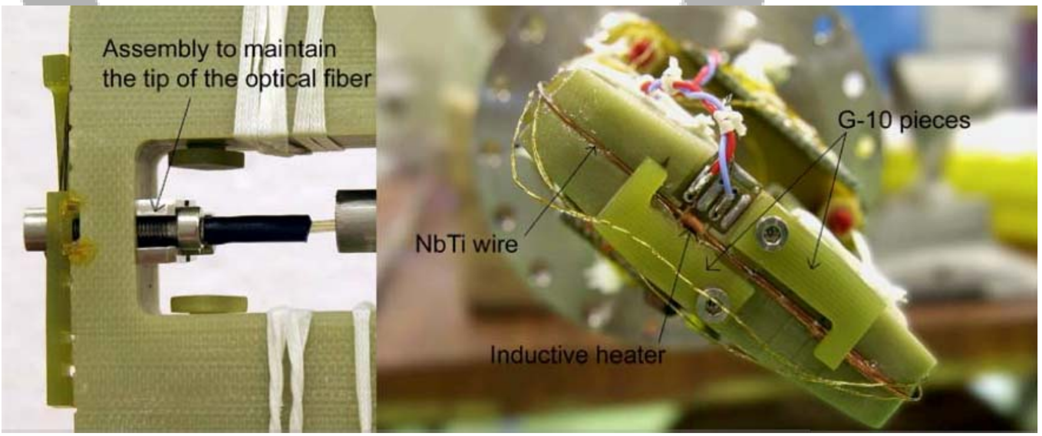



0-D and 1-D simulations give identical results for sufficiently long INZ (i.e. INZ>10 cm for the LHC inner cable)

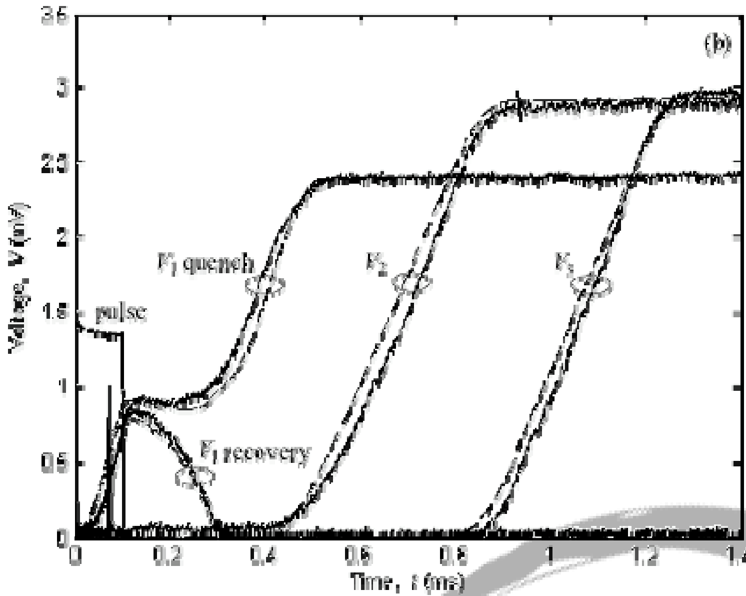
- The value of the stability margin of the LHC inner cables depend critically, and in order of importance, on:
  - The quantity of helium included in the cable and accessible for stabilization
  - The details of heat transfer from the strands
  - The coupling among strands
    - thermal resistance
    - conductance

L. Bottura, M. Calvi, A. Siemko, "Stability Analysis of the LHC Cables", Cryogenics, 46(7-8) 481-493, 2006.

# Heat transfer details


NbTi strand stability experiment, set-up at CEA-Saclay




Simulations performed at Bologna University, using a heat transfer model for nucleate-film boiling based on space-weighted properties

M. Breschi, L. Trevisani, M. Boselli, L. Bottura, A. Devred, P.L. Ribani, F. Trillaud, Minimum Quench Energy and Early Quench Development in NbTi Duperconducting Strands, paper 4MW01 presented at ASC 2006

# Conclusion

- The tools listed can **provide a useful input for the study of the LHC cables**, as well as the design of the LHC upgrades or cables and magnets for the post-LHC era
- Although they have been validated as far as reasonably feasible (some are in use since > 10 years), the understanding of the physics evolves qualitatively as well as quantitatively: **keep them up-to-date**
- Some key issues were, are and will be critical:
  - **Helium heat transfer**
  - **Interstrand resistance**

  and no tool can be better than our understanding of the underlying physics: **give priority to experiments on the above subjects**