Thermodynamics Modeling of New LHC Quadrupole Magnet

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LARP CM13 Collaboration Meeting
Port Jefferson, NY, November 4-6, 2009

OUTLINE

- Motivation
- Heat sources in the accelerator magnets
- Thermodynamics of magnet structure
  - Heat evacuation path and heat flow barriers
  - Helium in the magnet
- Modeling of heat flow in the magnets
  - Network model construction
  - Helium modeling
  - Model validation
- New inner triplet phase I simulation status
- New inner triplet phase II simulation status
- Conclusions
- Future plans

MOTIVATION

- Particles coming from proton-proton collision debris impacts the inner triplet magnets

  → energy deposition in the coils.

- Heat flow paths and heat flow barriers identification in the magnet

  → need to give a feedback to the magnet designers.

- Phase I LHC upgrade → enhanced insulation scheme → open helium paths between the bath and the cable

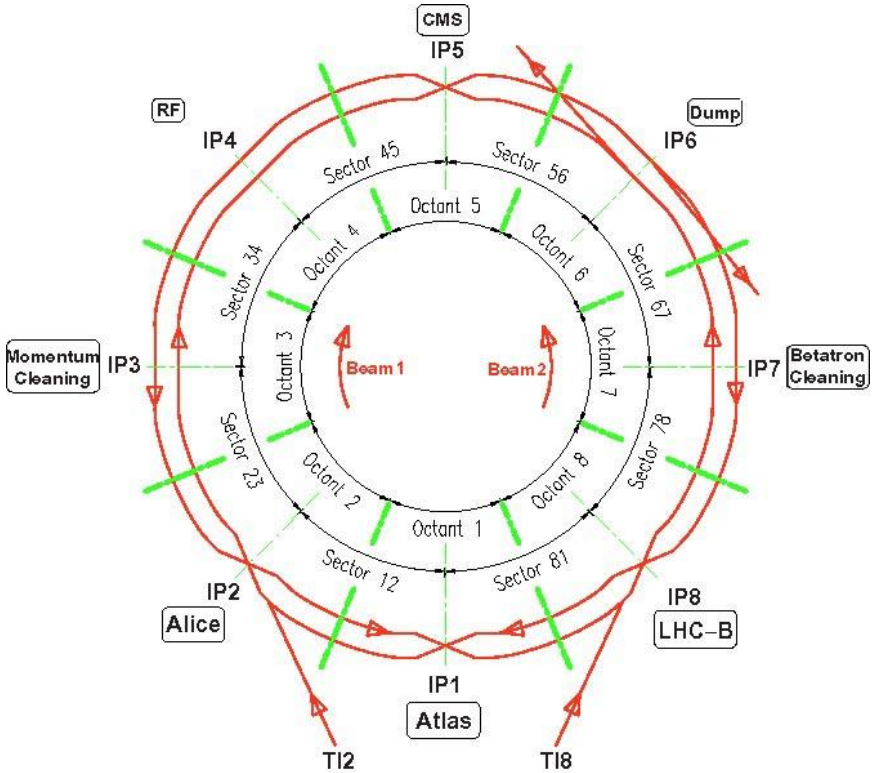
  → necessary studies of magnet thermodynamics

- Thermal studies of LARP Nb_3Sn LHC upgrade phase II magnets

  → implement method used in phase I magnet studies

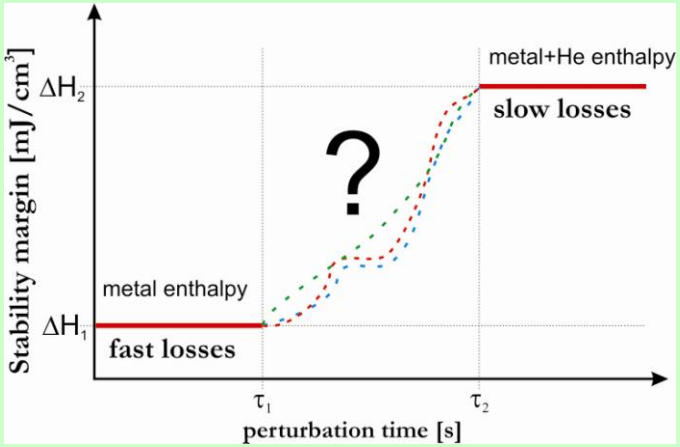
Heat sources in the LHC magnets

- Debris of the proton-proton interactions at accelerator interaction regions
- Interaction of lost protons with collimators
- Physics processes – BFPP (ion beam case)
- Accidental beam losses



• Transient losses ~ns to ~ms

- Enthalpy of the cable materials (~ns)
- Heat transfer to helium volume inside the cable (~μs)
- Enthalpy of the cable (~ms)



• Steady-state losses

- **Transfer of the heat from cable to the heat reservoir (~s)**
- **Magnet structure is vital**

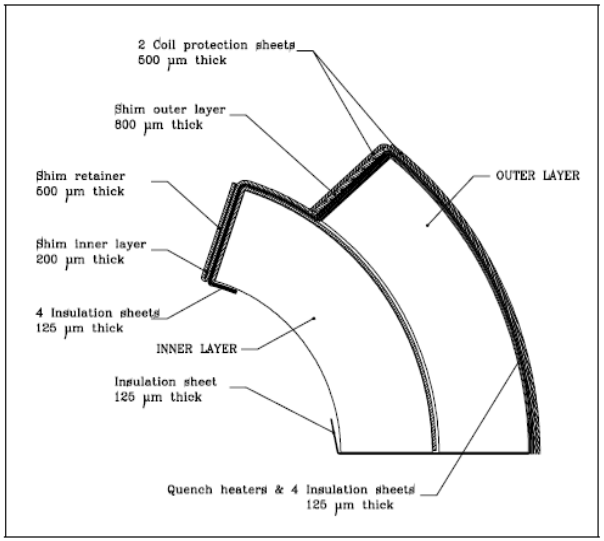
References:

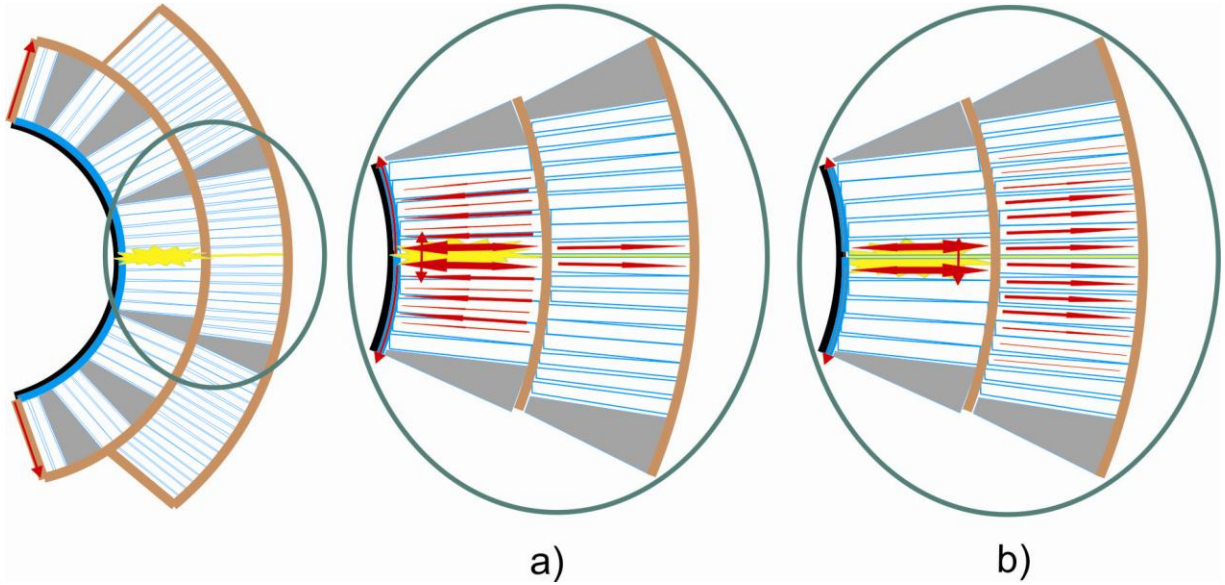
D. Bocian, CERN AT-MTM note, EDMS 750204
P.P. Granieri, (D. Bocian), et al., CERN-LHC-PROJECT-Report-1089
D. Bocian et al., CERN-AB-2008-006

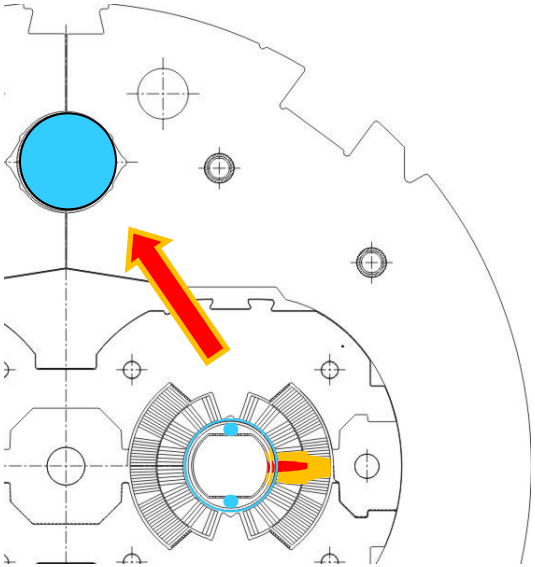
Heat evacuation paths & heat flow barriers

HEAT FLOW BARRIERS

- cable insulation
- interlayer insulation
- ground insulation
- helium channel around cold bore
  For temperatures above 2.16 K: transition HeII → HeI:
  helium channels are blocked = less effective heat flow
  due to the changing of heat evacuation path

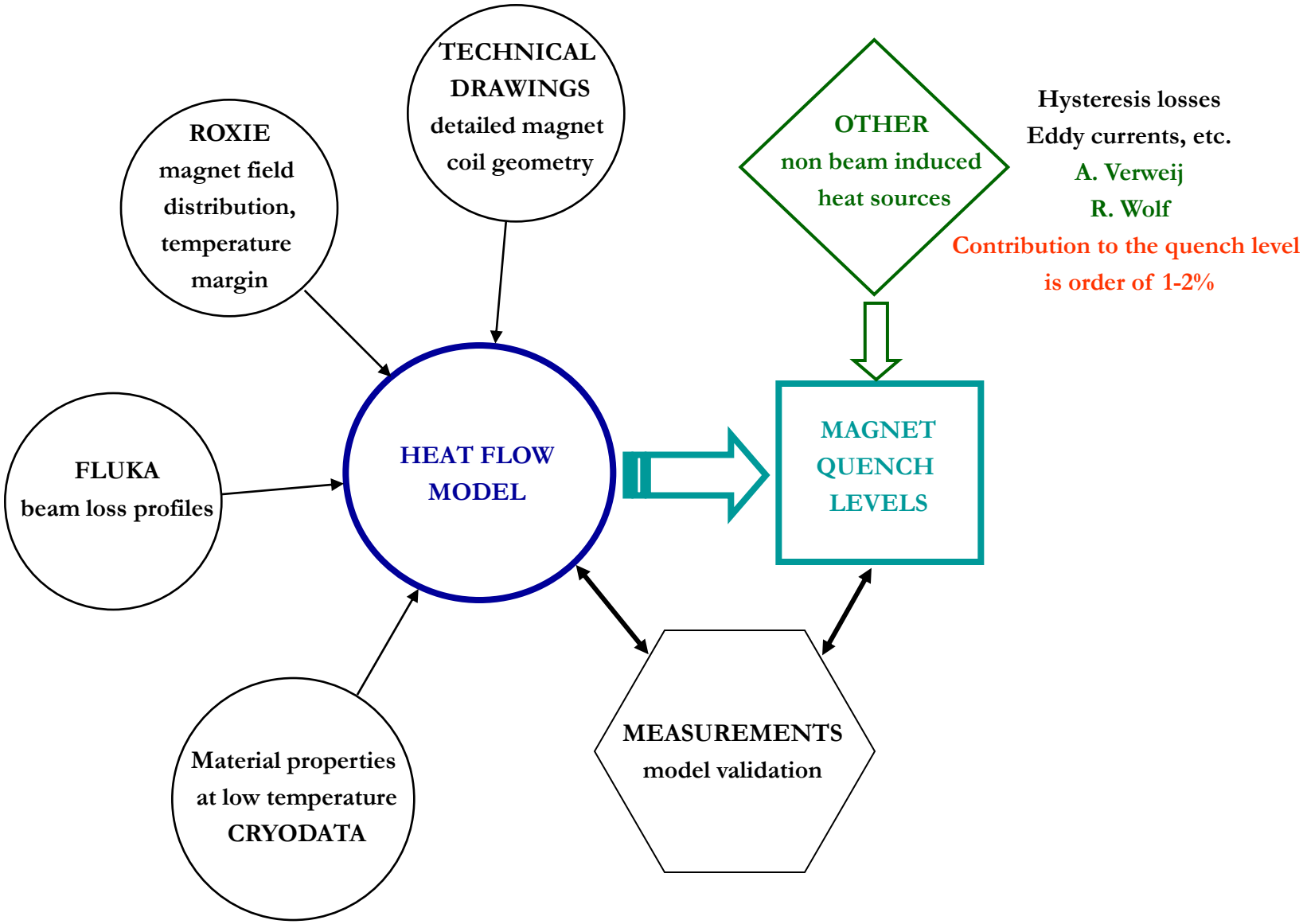






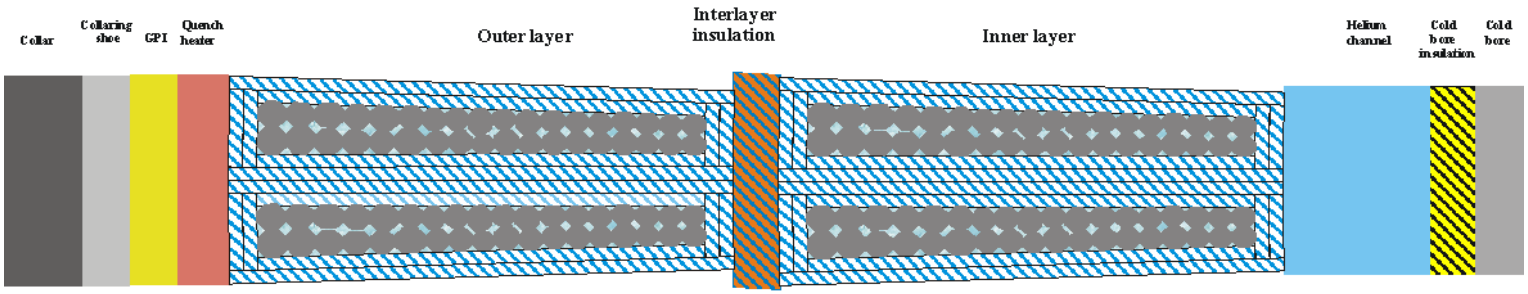
A sketch of the heat transfer in the magnet at nominal operations (a) and at quench limit (b).

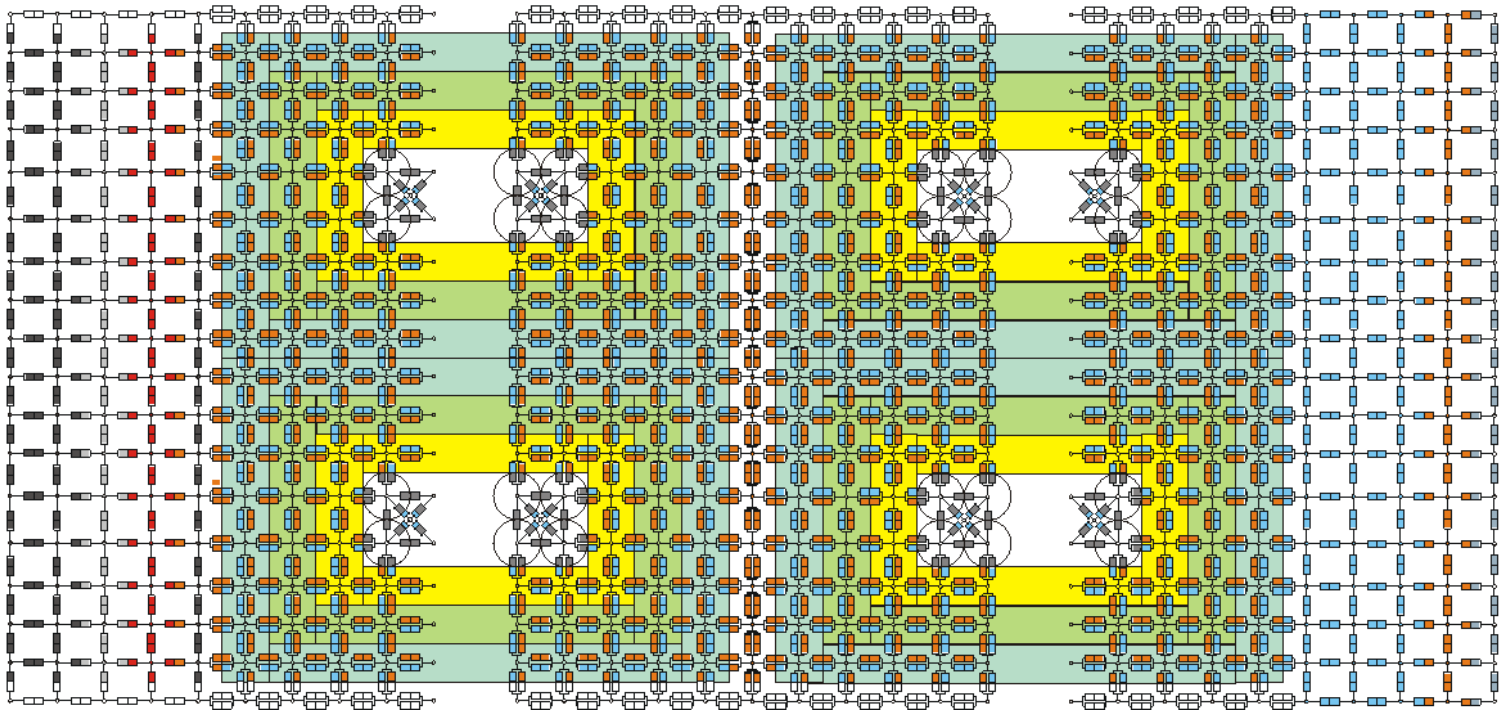
NETWORK MODEL

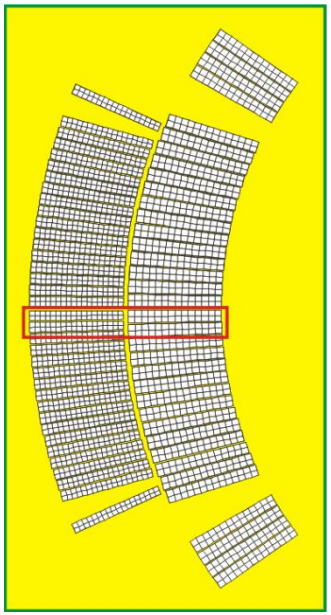


Network Model

coil model

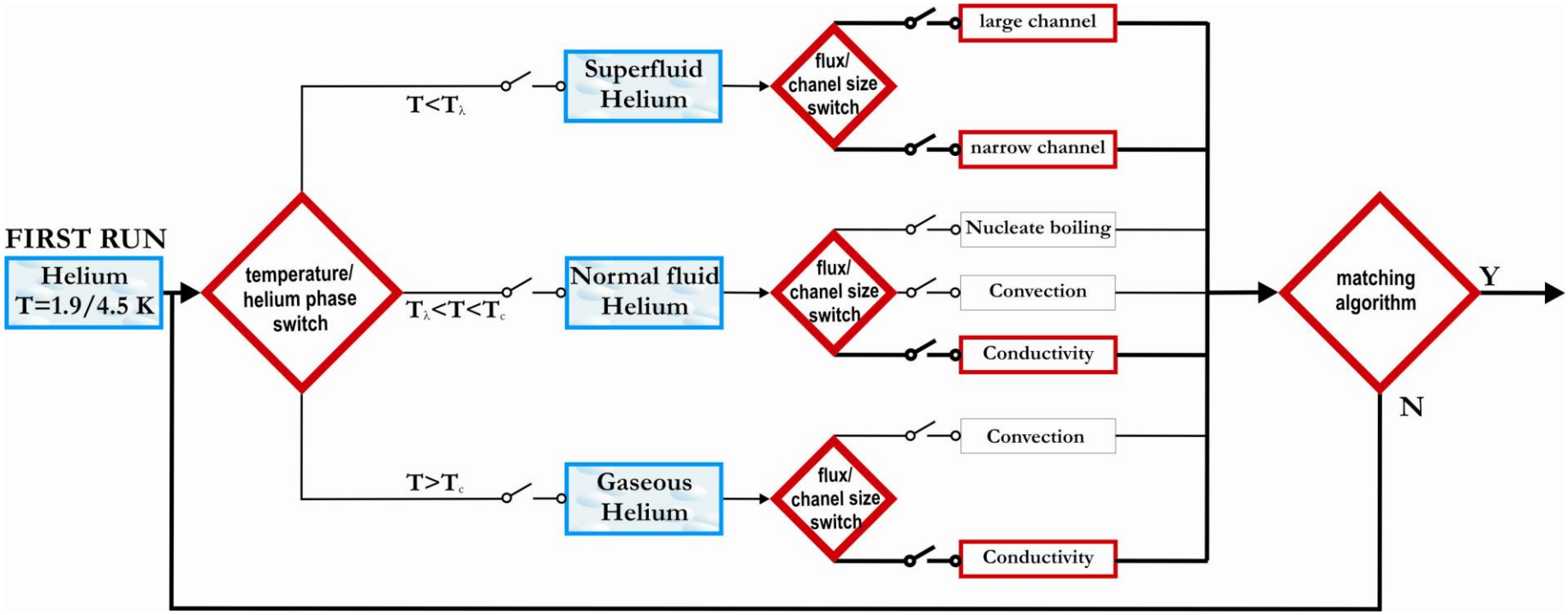






Network Model

Helium modeling



The volumes occupied by helium in the magnet are considered as:

-narrow channels,

-semi-closed volumes = inefficient inlet of fresh helium.

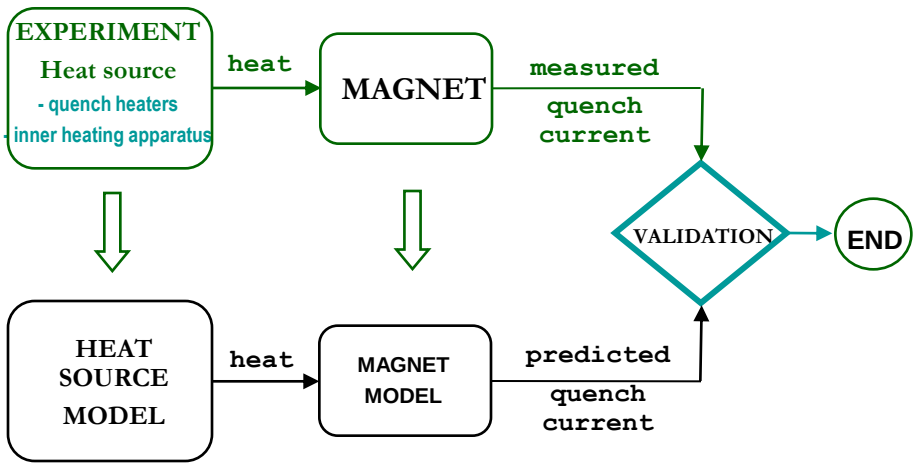
The steady heat load, heat up the helium in the semi- closed volumes:

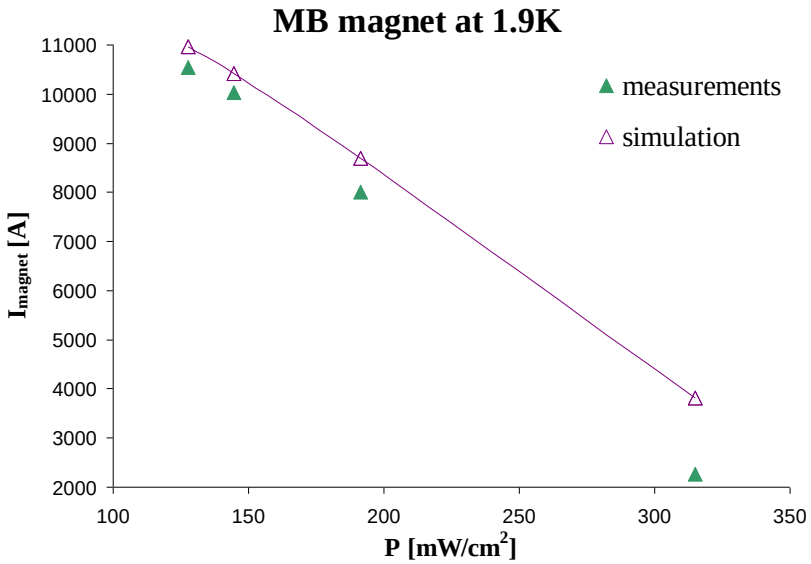
- Helium temperature well above superfluid helium temperature at T_b=1.9K

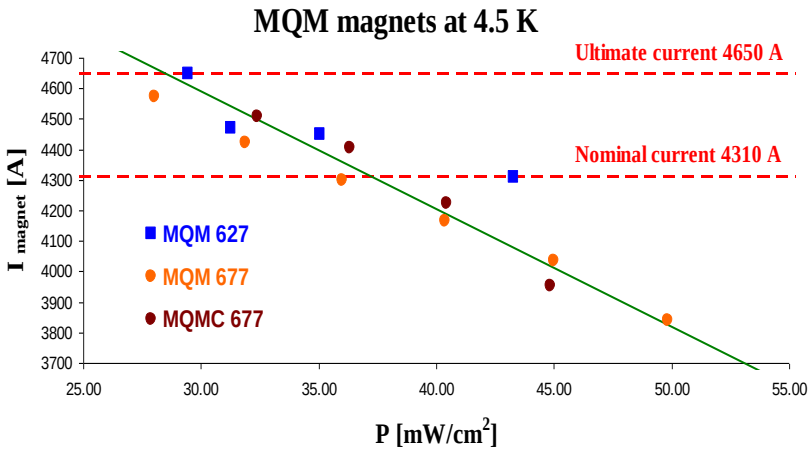
- Critical helium temperature reached already below the calculated quench limit

Network Model Validation

Model validation





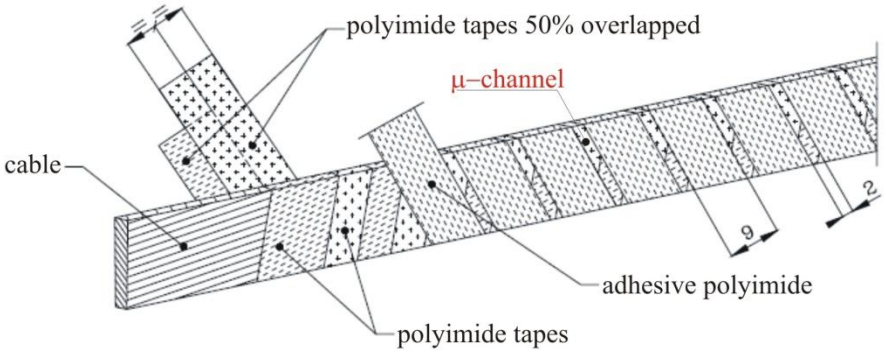


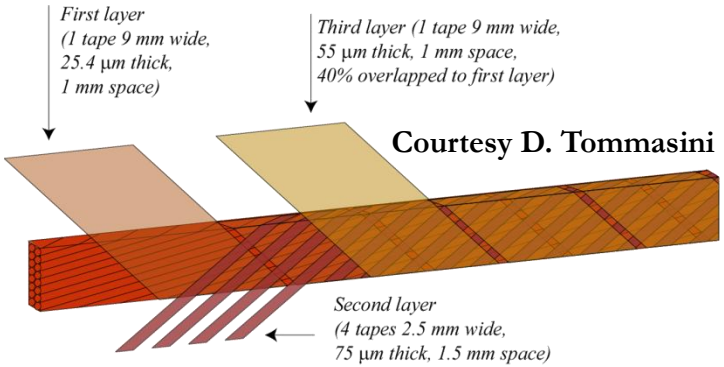
More details:

D. Bocian, B. Dehning, A. Siemko, *Modeling of Quench Limit for Steady State Heat Deposits in LHC Magnets*,IEEE Transactions on Applied Superconductivity, vol. 18, Issue 2, June 2008 Page(s):112 – 115; CERN-AB-2008-006, 2008;

D. Bocian, B. Dehning, A. Siemko, *Quench Limit Model and Measurements for Steady State Heat Deposits in LHC Magnets,* IEEE Transactions on Applied Superconductivity, vol. 19, Issue 3, June 2009 Page(s):2446 – 2449;

New inner triplet phase I simulation status





The nominal LHC cable insulation:

⇨ two 11 mm tapes overlapping by 50%

⇨ one 9 mm tape with 2 mm spacing

The enhanced insulation:

⇨ one 9 mm tape with 1 mm spacing

⇨ four 2.5 mm tapes with 1.5 mm spacing

⇨ one 9 mm tape with 1 mm spacing

Details: M. La China, et al., Phys. Rev. Spec. Top. Accel. Beams 11 (2008)

Nominal parameters for current and phase I design of LHC inner triplet

	Current design	Phase I design
Operating temperature [K]	1.9	1.9
Nominal gradient [T/m]	205	120
Aperture diameter [mm]	70	120
Quadrupole length [m]	5.5 / 6.37	10

Nominal parameters for current and enhanced LHC cable insulation

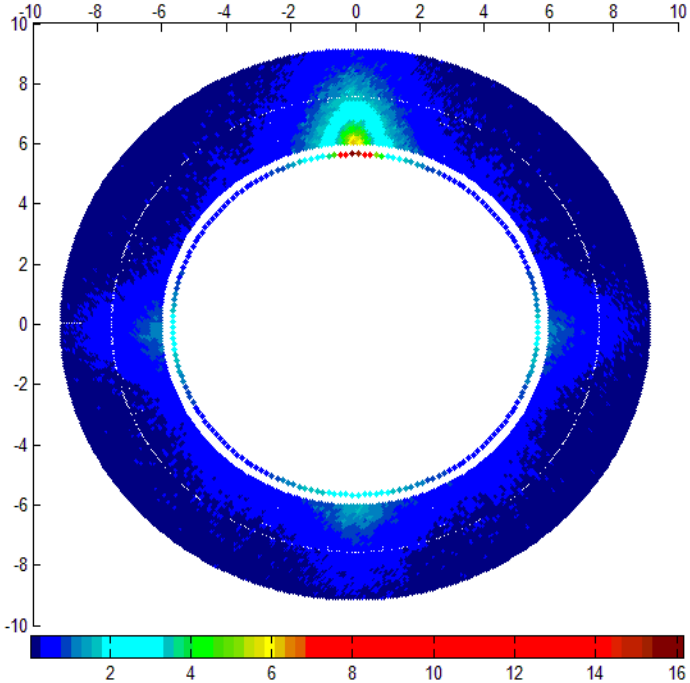
	Nominal		Enhanced	
	Cable 1	Cable 2	Cable 1	Cable 2
Radial thickness	0.150	0.150	0.160	0.160
Azimuthal thickness	0.120	0.130	0.135	0.145

New inner triplet phase I simulation status

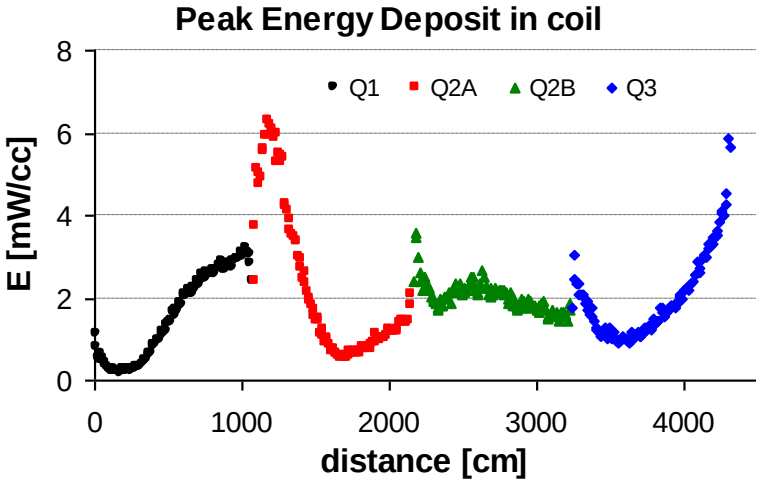
A combining particle tracking, FLUKA shower simulations in a single magnet coil

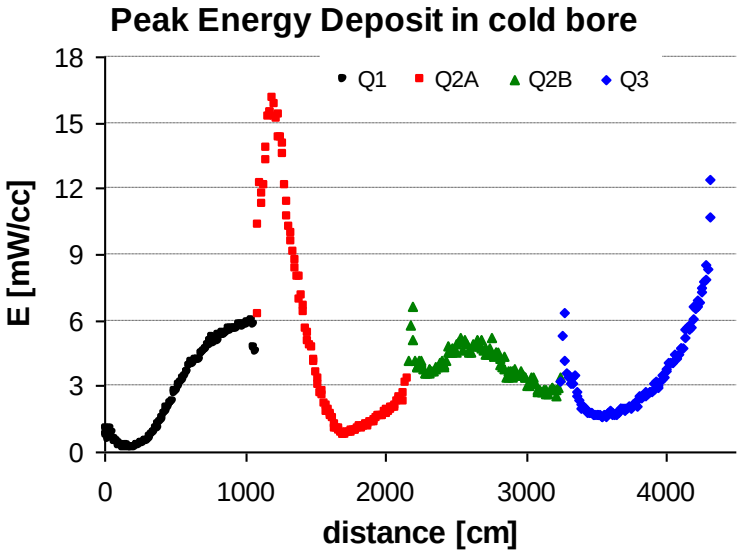
The inner triplet quadrupole FLUKA simulations were ran with a thick Beam Screen (BS) in Q1 (10.15 mm extra stainless steel shield added to the usual 2mm thick BS).

$L=2.5*10^{34}\ cm^{-2}s^{-1}$

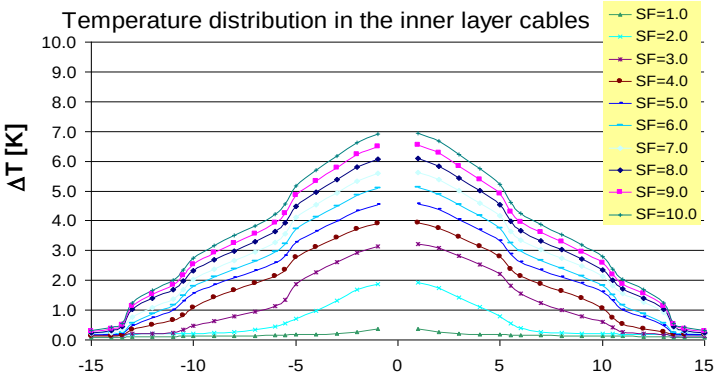


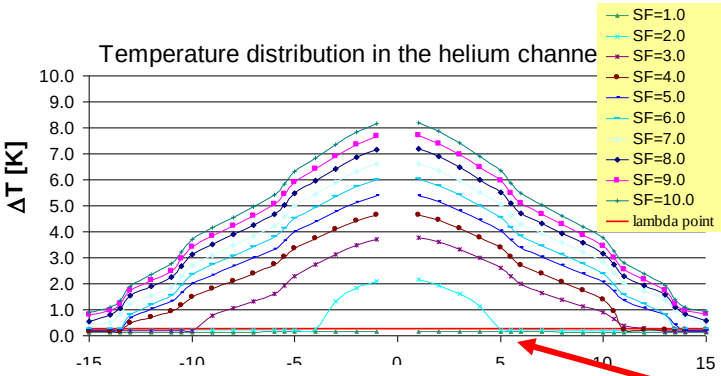
Energy deposits in selected bin of magnet cross section with peak value. Magnet has been divided longitudinally into 108 bins (~10 cm)

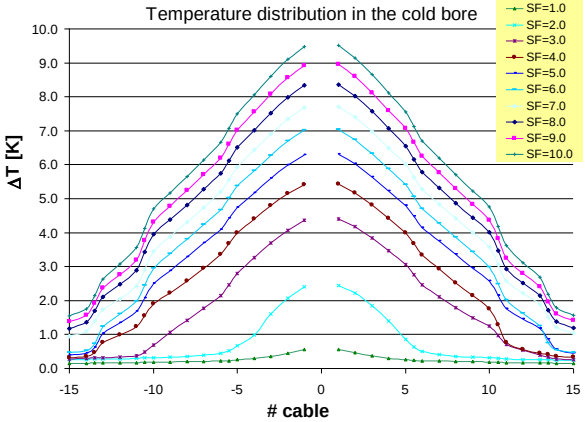




Temperature distribution in the magnet



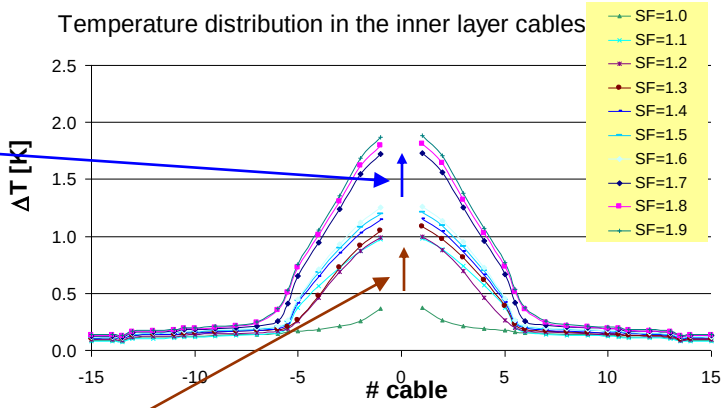


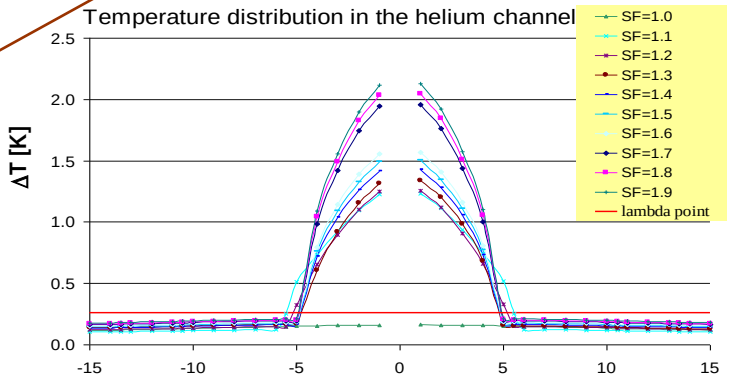


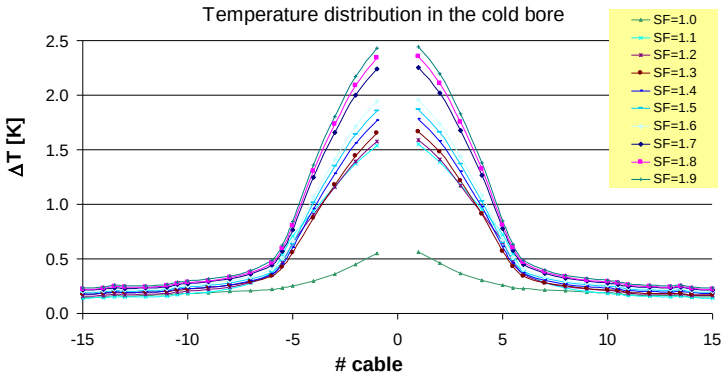
Temperature jump due to normal fluid helium heat conduction decrease

Temperature jump due to superfluid to normal fluid pahse transition

Temperature jump due to normal fluid helium zone expansion in the channel around cold bore

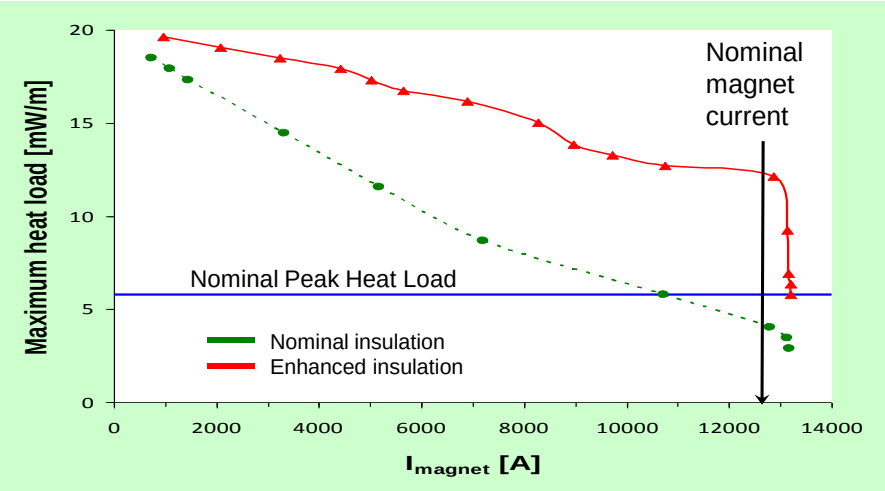






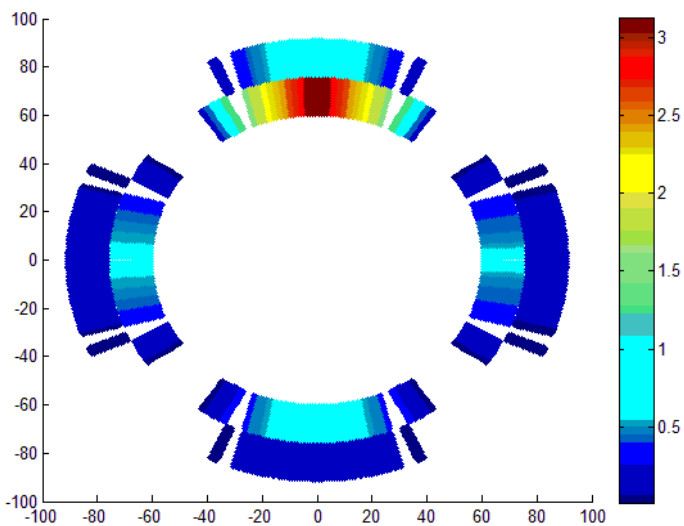
New inner triplet phase I simulation status

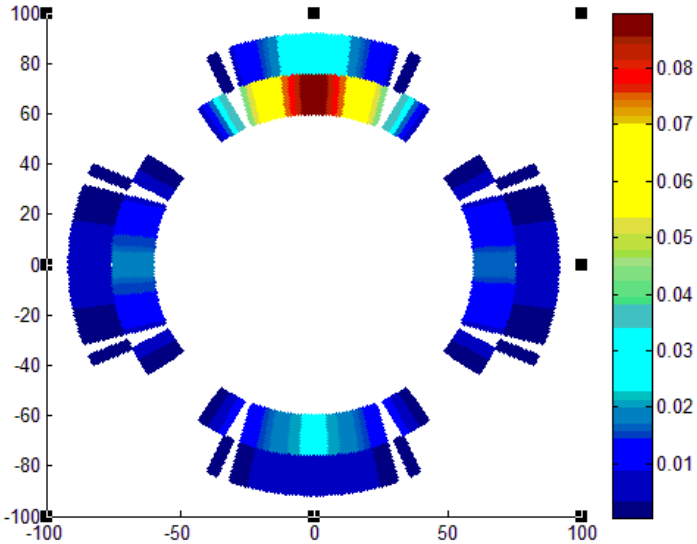
Quench limit in the phase I quadrupole magnet



Cable insulation and helium channel around cold bore are the most critical parameters limiting heat flow from the magnet coil at steady state heat load

Temperature increase in the coil at nominal heat load for nominal and enhanced LHC cable insulation





New inner triplet phase II simulation status

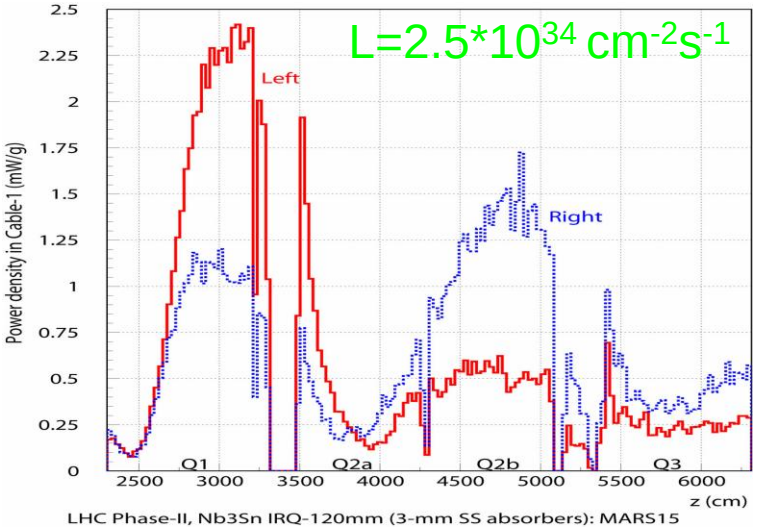
Work presented by V. Kashikhin on CECICMC09.

The COMSOL simulation included:

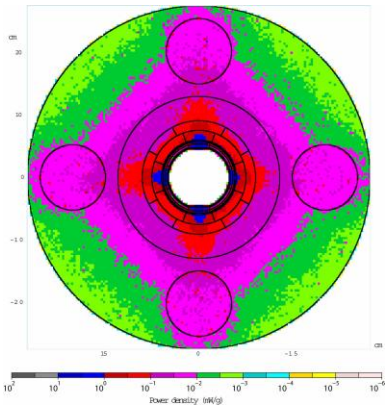
- **energy deposits in the coil**
- **cable material and insulation.**

The simulation did not included:

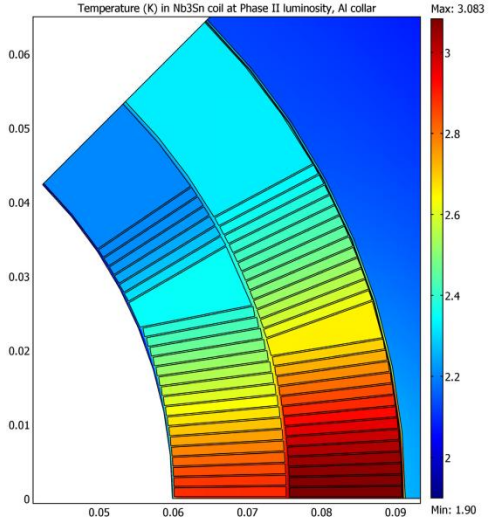
- **helium in the magnet (channel around cold bore)**
- **energy deposits in the coldbore**

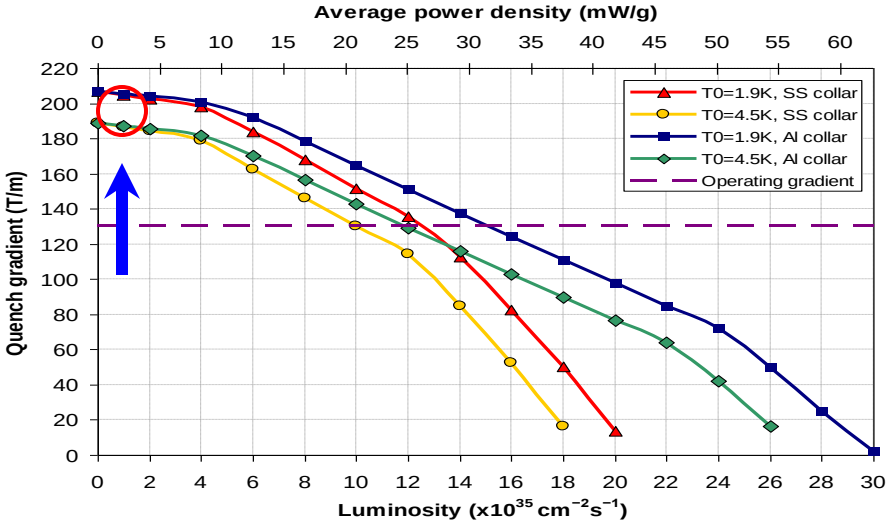


Courtesy N. Mokhov



Nb_3Sn





Arrow indicates phase II nominal luminosity

Conclusions

- The analysis of thermal bahaviour of the phase I quadrupole magnet was presented.
- The heat flow paths and heat flow barriers were identified with the thermal network simulation.
- There is significant impact on magnet performance from energy deposits in cold bore.
- **The size of helium channel around cold bore and cable insulation are the most critical parameters.**

Future Plans

- Implementation of the thermal network to phase II Nb_3Sn magnet is needed to calculate quench limits and compare with phase I simulation.
- The analysis of impact of helium channel around cold bore is necessary to optimize the channel width.
  - An experiment devoted to study of helium channel around cold bore is welcome
- Possible use of network model to study different Nb_3Sn cable insulation properties, for instance radiation hardness.

Modeling of Nb_3Sn coil length change during heat treatment

D. Bocian, G. Ambrosio, F. Nobrega, M. Whitson / FNAL

A. Bonasia, L. Bottura, L. Oberli / CERN

B. Walsh / NHMFL, M. Wake / KEK

To be presented at Low Temperature Superconductor Workshop
Monterey, CA, November 10-11, 2009

Introduction

Presented results are the part of general studies leading to understanding coil elements behavior during heat treatments.

Work has been divided into several steps:

I. Collection of relevant data and material properties for simulations

II. Preparation and conduct of necessary measurements

III. FEM simulation of the strand/cable/coil behavior during reaction

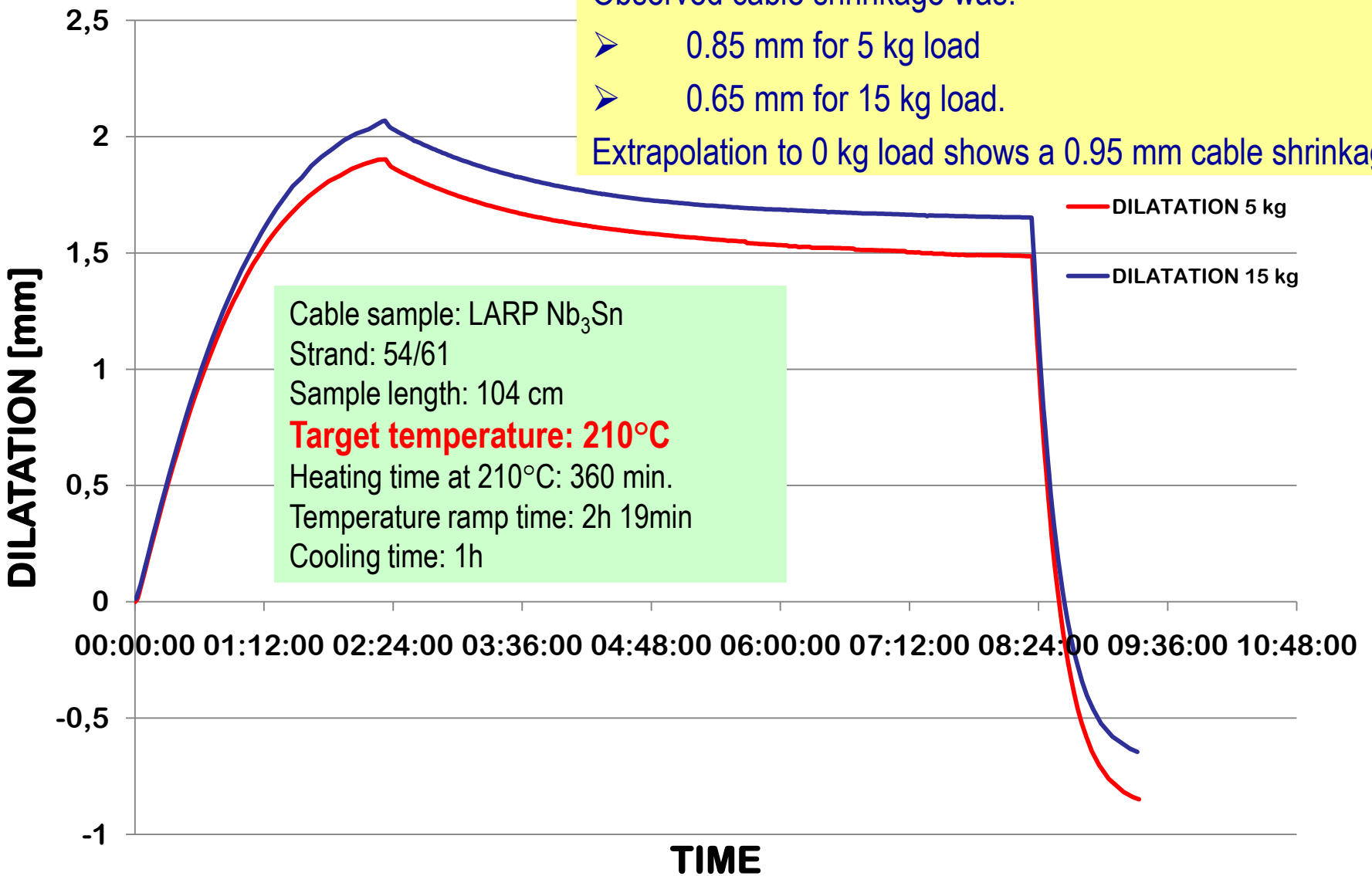
IV. Feedback to the coil fabrication technology

Cable sample measurement

Observed cable shrinkage was:

- 0.85 mm for 5 kg load
- 0.65 mm for 15 kg load.

Extrapolation to 0 kg load shows a 0.95 mm cable shrinkage.



Cable sample: LARP Nb_3Sn
Strand: 54/61
Sample length: 104 cm
Target temperature: 210°C
Heating time at 210°C: 360 min.
Temperature ramp time: 2h 19min
Cooling time: 1h

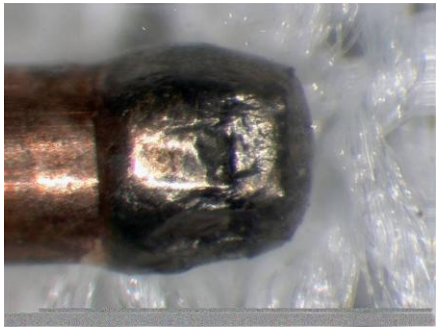
Strand sample measurement

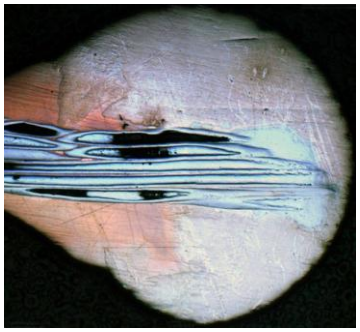
Sample preparation:

⇨ Weld the ends of strand sample.

⇨ Resize the ends of strands to fit required diameter.

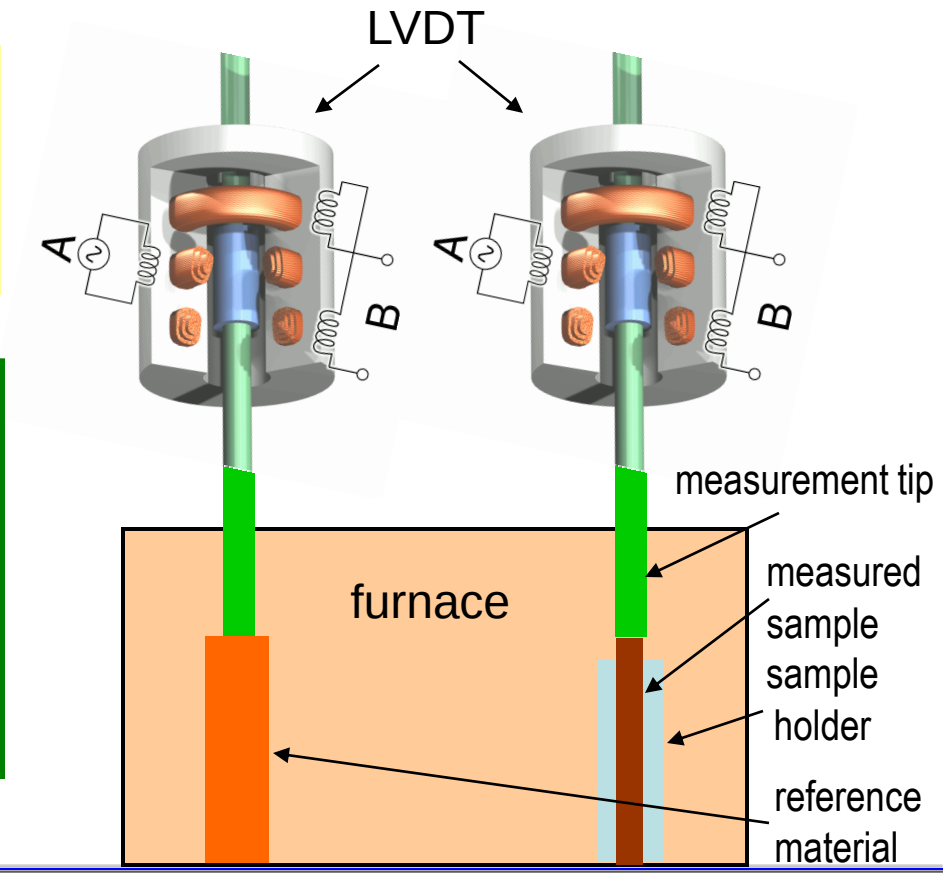
⇨ Chosen sample length ~ 48 mm Nb_3Sn strand.





- **measurement of ΔL after HT - done**
- **measurement during HT - in progress**

Results of nominal LQ heat treatment of strand smaple			
	Sample 1	Sample 2	Sample 3
Before HT [mm]	48.400	47.900	47.710
After HT [mm]	48.450	47.950	47.733
ΔL/L [%]	0.1	0.1	0.05



BACKUP TRANSPARENCIES

Backup - Electrical equivalent

The analogy of the equivalent thermal circuit

Thermal circuit			Electrical Circuit		
T	**[K]**	**Temperature**	V	**[V]**	**Voltage**
Q	**[J]**	**Heat**	Q	**[C]**	**Charge**
q	**[W]**	**Heat transfer rate**	i	**[A]**	**Current**
κ	**[W/Km]**	**Thermal Conductivity**	σ	**[1/Ωm]**	**Electrical Conductivity**
R^{Θ}	**[K/W]**	**Thermal Resistance**	R	**[V/A]**	**Resistance**
C^{Θ}	**[J/K]**	**Thermal Capacitance**	C	**[C/V]**	**Capacitance**

The analogy between electrical and thermal circuit can be expressed as:

-steady-state condition *Temperature rise* ⇔ *Voltage difference*

$$\Delta T = qR^{\Theta} \quad \Leftrightarrow \quad \Delta V = iR$$

-transient condition *Heat diffusion* ⇔ *RC transmission line*

$$\nabla^2 T = R^{\Theta} C^{\Theta} \frac{\partial T}{\partial t} \quad \Leftrightarrow \quad \nabla^2 V = RC \frac{\partial V}{\partial t}$$

Backup - Non beam loss heat loads

A. Siemko, 14th "Chamonix Workshop", January 2005

- **Heat generated by electrical sources**
  - For main dipole during ramp (R. Wolf) [J/m]
    - **Hysteresis loss** **240**
    - **Inter-strand coupling (Rc = 7.5 μΩ)** **45**
    - **Inter-filament coupling (τ = 25ms)** **6.6**
    - **Other eddy currents (spacers, collars..)** **4**
    - **Resistive joints (splices)** **30**
  - ***Total (per meter)*** *~325*

The first estimations shows contribution at the level of 0.5 mW/cm^3

A detailed studies are ongoing (A. Verweij, R. Wolf)

Helium in the magnet

Superfluid helium

The heat flow in He II is calculated according formulae [Claudet et al., CRYOGENIE et ses applications en supraconductivite, IIF/IIR]

$$\frac{\dot{Q}}{s} = \left[\frac{X(T_c) - X(T_h)}{l}\right]^{0.29} \left[\frac{W}{cm^2}\right]$$

and X(T) is an experimental results fitting

$$X(T) = 520\left[1 - e^{-[3\cdot(2.16-T)]^{2.5}}\right]$$

The heat conductivity of superfluid helium is very high at low heat currents, but since it is non-linear it can be much reduced at high heat currents.
(W. F. Vinen. Superfluidity. *CERN CAS School on Superconductivity*, 1995.

At high heat currents the superfluid helium in the channel can „quench" resulting in transition to the normal fluid helium means that heat evacuation from the coil is reduced significantly resulting in quenching of the magnet.

Normal fluid and gaseous helium

In case of channels inside of the cable and μ-channels which are of the order of 0.2 mm and 0.07 mm respectively, a typical nucleate boiling flux becomes much lower than that for helium bath which is 10 000 W/m^2 [1]. The gaseous phase in the narrow channels is described by a constant heat transfer coefficient and is of the order of 70 W/m^2/K as extrapolated from [2]. The convective heat transfer in steady state mode is restricted to heat fluxes not greater than a few mW/cm^2 [3] as it is only relevant for large volumes. In case of helium inside the cable and in the μ-channels this mode is negligible.

[1] S.W. Van Sciver, Helium Cryogenics.
[2] M. Nishi et all., Boiling helium heat transfer characteristics in narrow cooling channel, IEEE TRANSACTIONS ON MAGNETICS, VOL. MAG-19, NO. 3, MAY 1983.
[3] C. Schmidt, Review of steady state and transient heat transfer in pool boiling helium I.

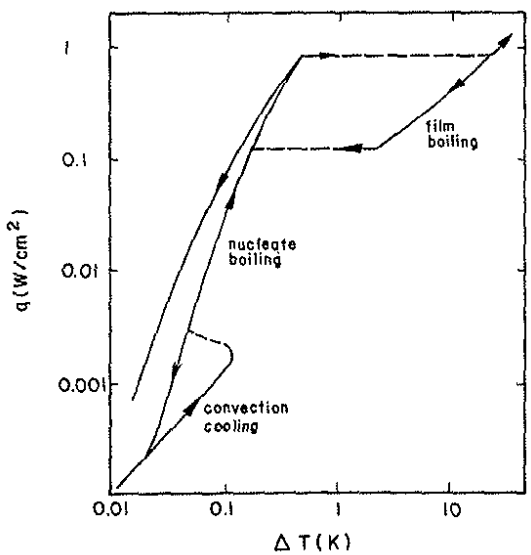


Fig. 6.2. Typical heat transfer relationship for pool boiling liquid.

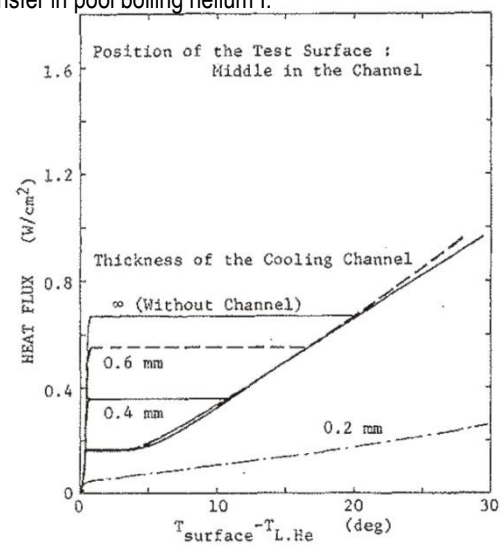


Fig.2 Steady state boiling helium heat transfer characteristics in narrow cooling channels

Cable parameters

Table 1: Cables parameters

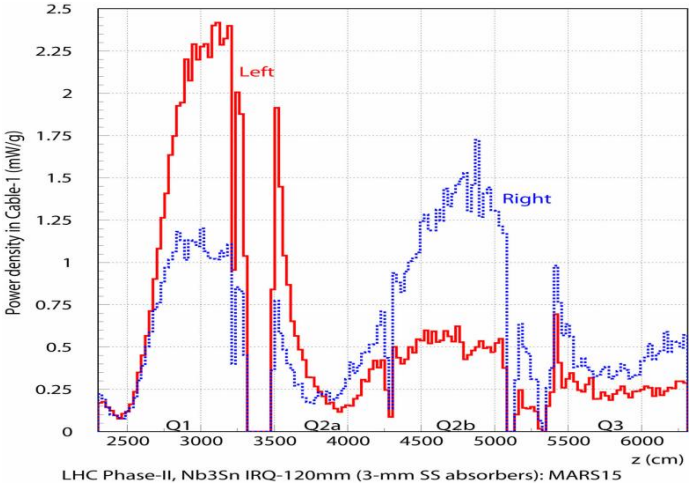
	unit	Inner layer	Outer layer
w	mm	15.100	15.100
thick in	mm	1.736	1.362
thick out	mm	2.064	1.598
rad. insulation	mm	0.160	0.160
az. insulation	mm	0.135	0.145
n. strand		28	36
strand diameter	mm	1.065	0.825
Cu/Sc ratio		1.65	1.95
I_{ss}	A	14800 (10T)	14650 (9T)
$\Delta I_{ss}/\Delta B$	A/T	4680 (10T)	4050 (9T)

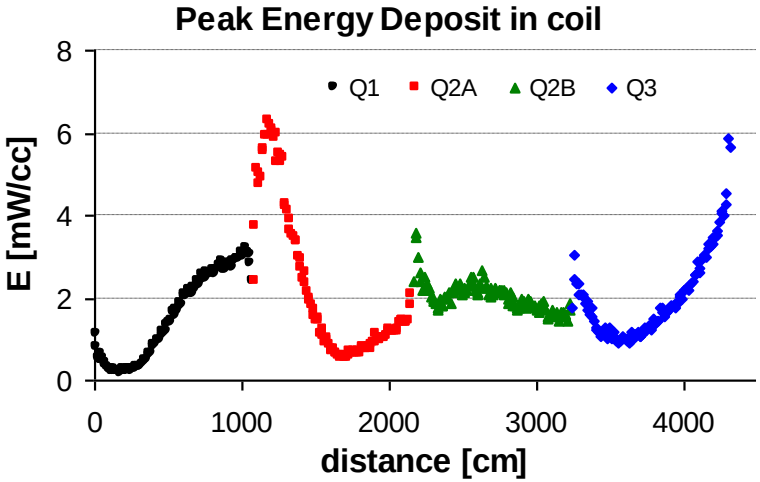
New inner triplet E deposits simulation

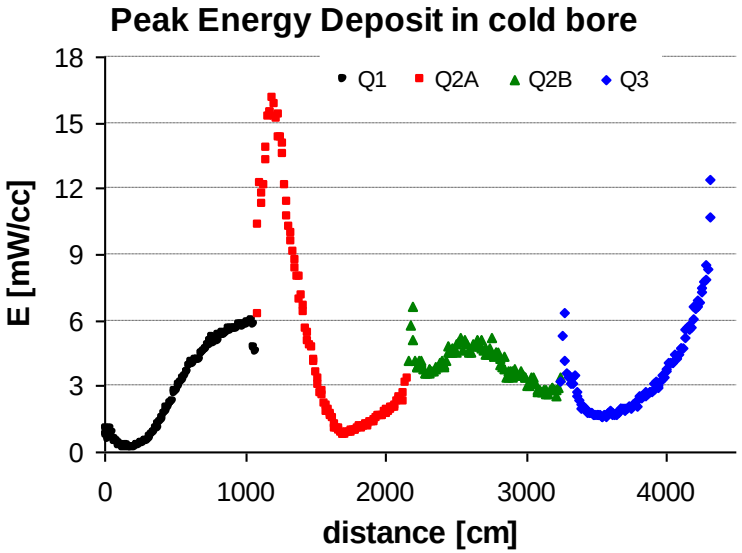
MARS

$L=2.5*10^{34}\ cm^{-2}s^{-1}$

FLUKA



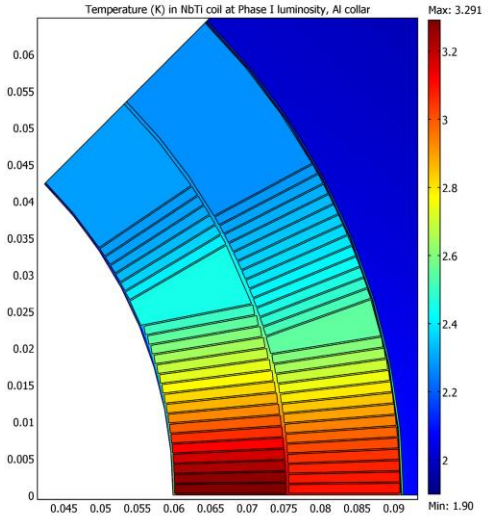


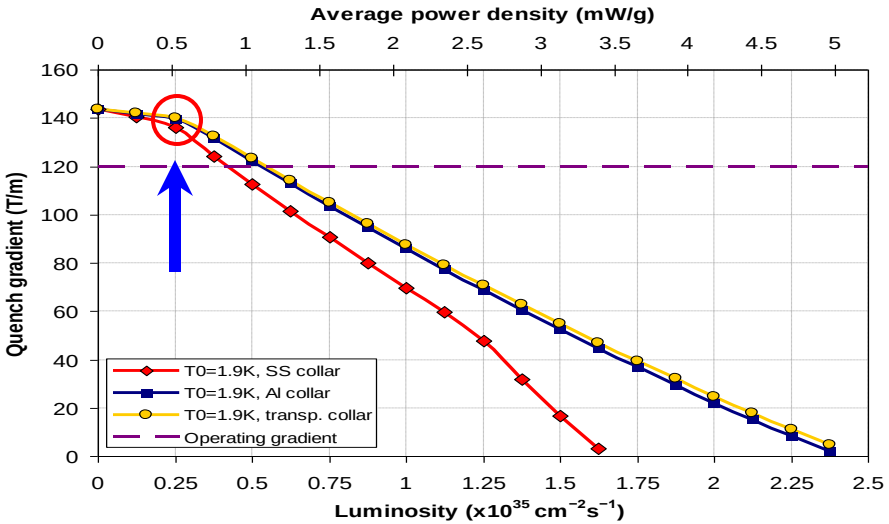


New inner triplet phase II simulation status

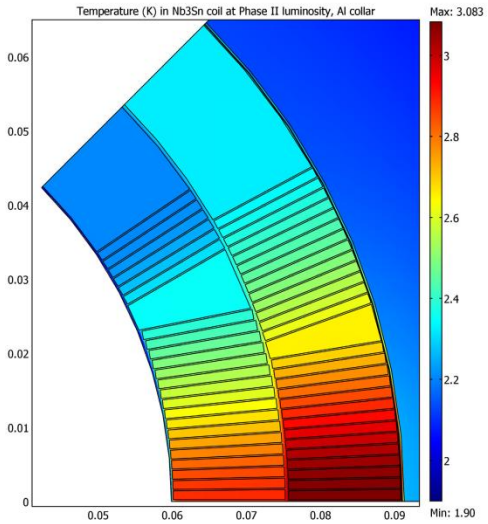
Work presented by V. Kashikhin on CECICMC09.

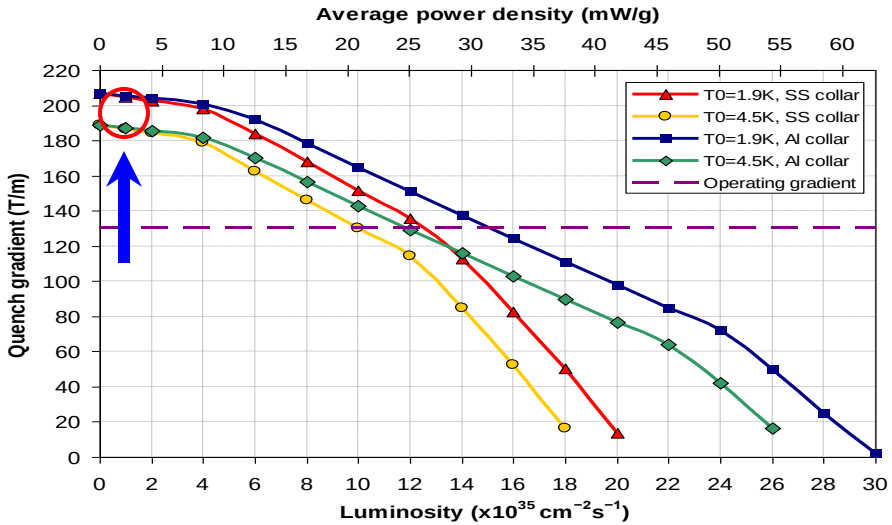
NbTi





Nb_3Sn





Arrow indicates nominal luminosity