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Towards to Quench Limit Determination of Superconducting Magnet with use of Thermal-Electrical Analogy

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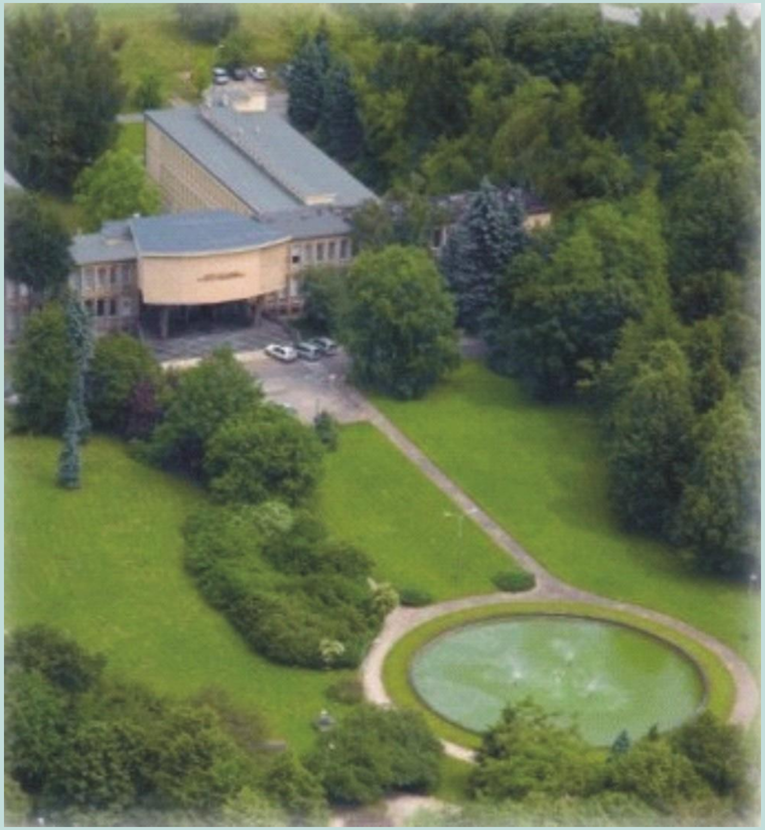
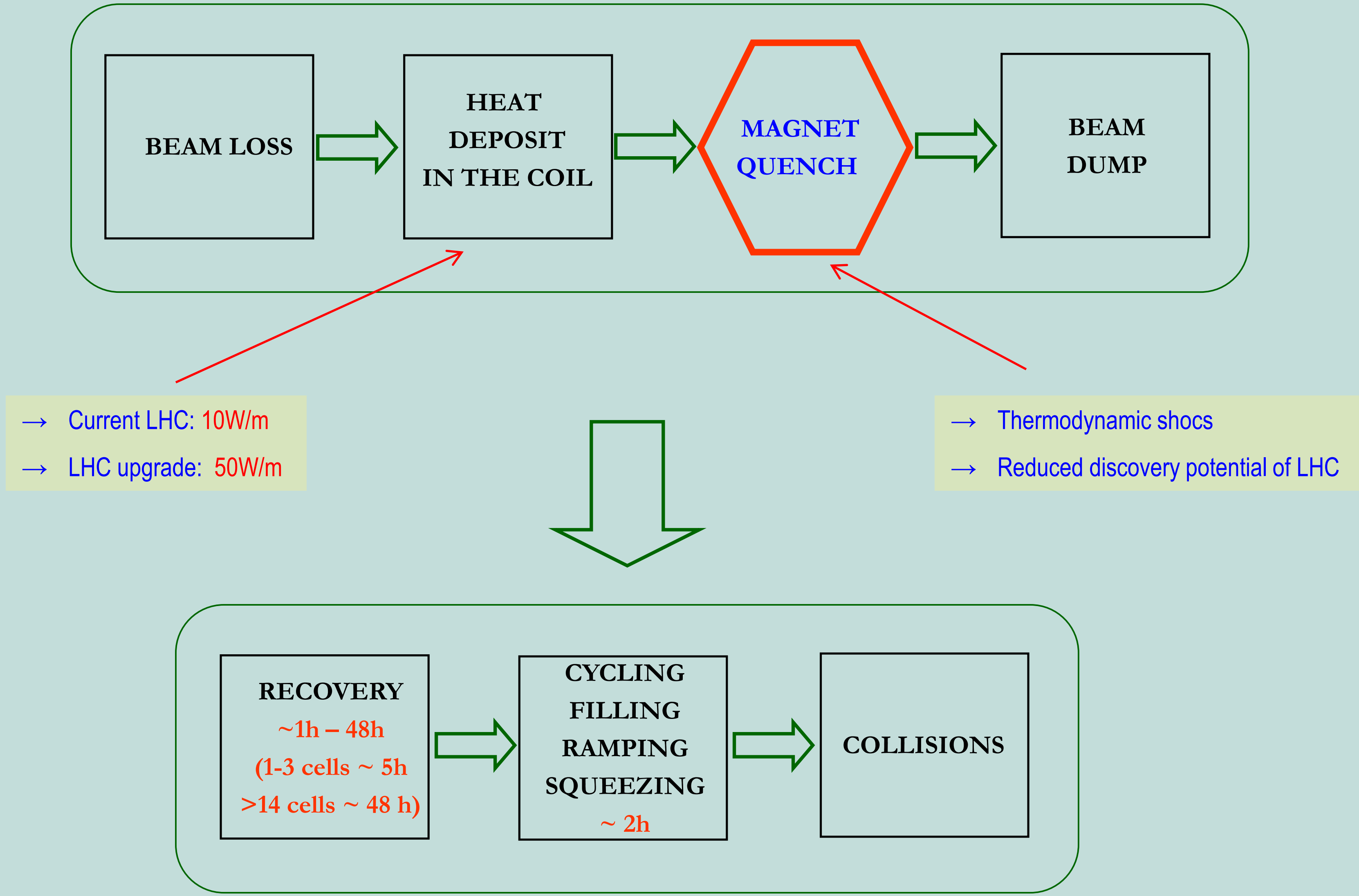
CHATS on Applied Superconductivity 2019

Szczecin, *9th July, 2019*

- Introduction
  - Motivation
- Thermal-electrical analogy
  - Magnet model
- Implementation
  - Comparison with measurements
  - Comparison with ANSYS model
- Outlook



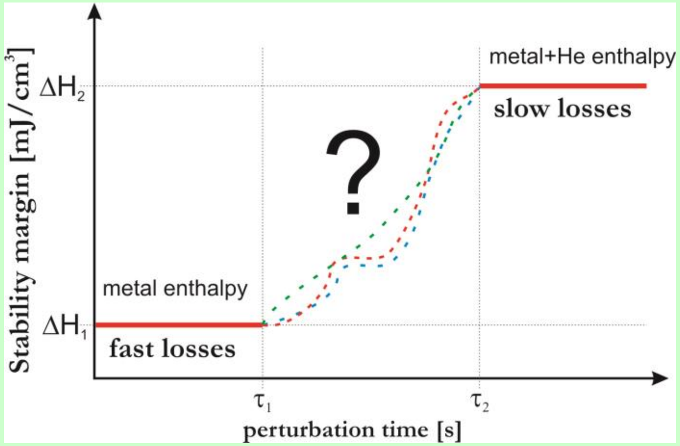
Accelerator operation scheme



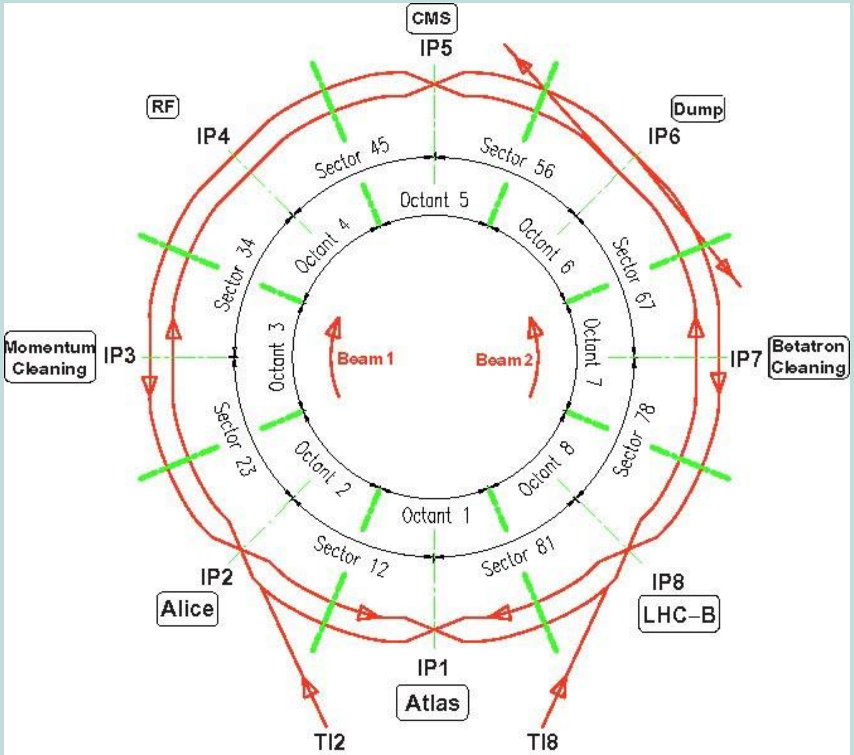
Numbers: Introduction

- **Particles from proton-proton collision debris**
- **Interaction of lost protons with collimators**
- **Physics processes – BFPP (ion beam case)**
- **Accidental beam losses**

- Transient losses ~ns to ~ms
  - Enthalpy of the cable (metal only) (~ns)
  - Heat transfer to helium volume inside the cable (~μs)
  - Enthalpy of the cable (metal + He) (~ms)



- Steady-state losses
  - Transfer of the heat from cable to the heat reservoir (~s)
  - Magnet structure and geometry of cooling channels



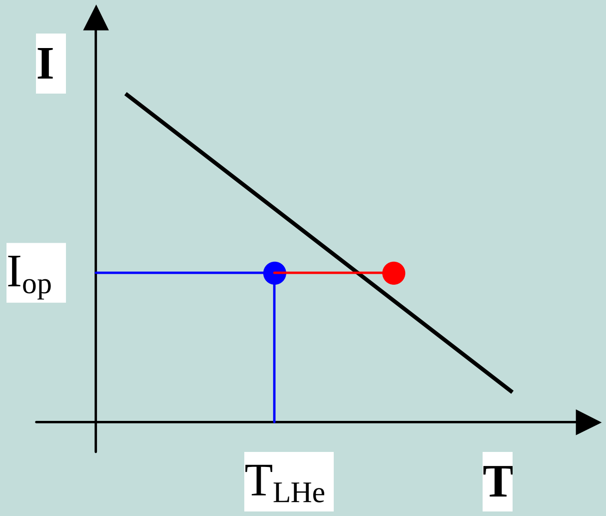
GOAL:

⇒ **NUMBERS** for accelerator protection system (BLM's, etc)

Superconducting magnets characteristics

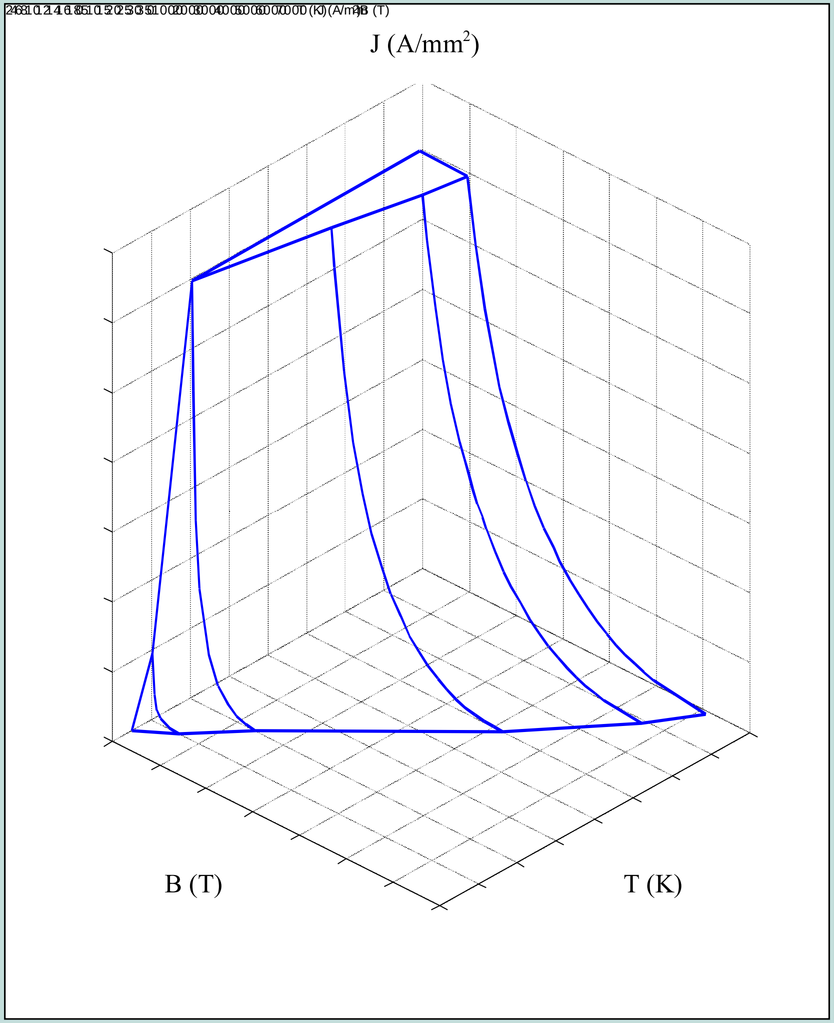
- Three parameters characterizing superconductor:
  - Critical current density
  - Critical magnetic field
  - Critical temperature

operating point of the magnet beyond critical surface
⇒ **QUENCH**

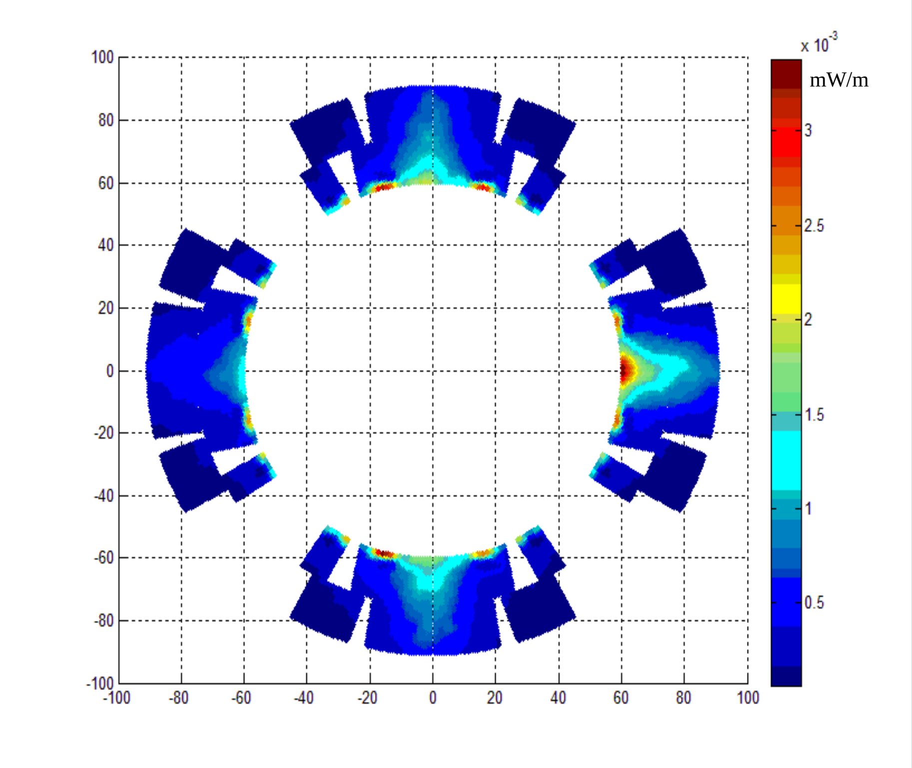


Accelerators: conductor temperature rise due to beam induced heat load ⇒ QUENCH

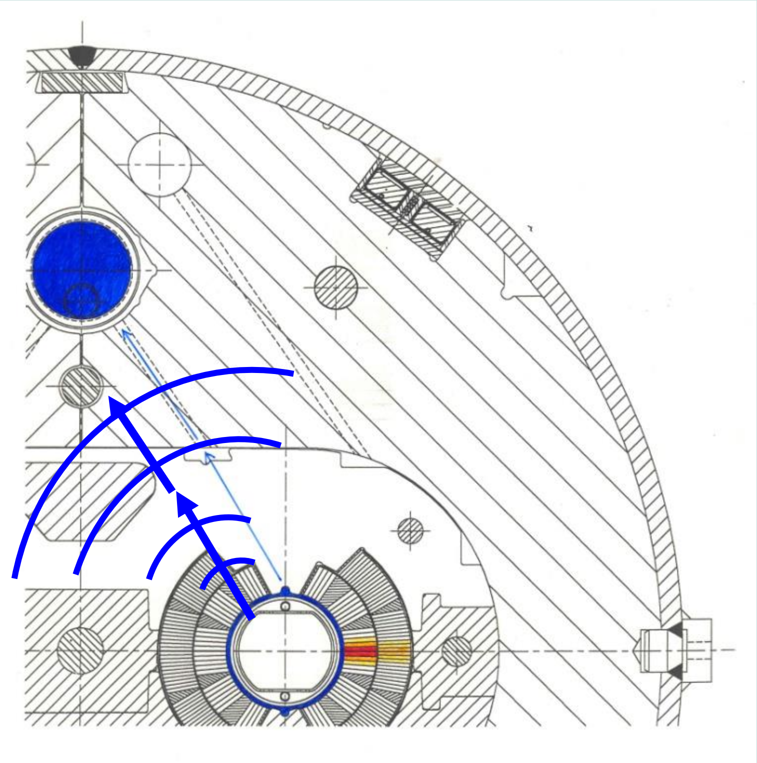
Critical surface



Heat load in the LHC magnets



A heat transfer in the magnet



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D. Bocian, CERN AT-MTM note, EDMS 750204

D. Bocian et al., IEEE Trans. on Appl. Supercond.,18, (2008) 112 – 115;

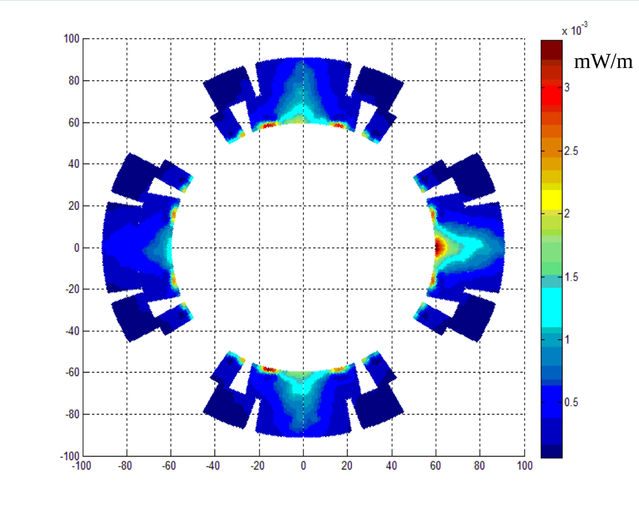
P.P. Granieri, (D. Bocian), et al., IEEE Trans. on Appl. Supercond.,18, (2008) 1257 – 1262;

D. Bocian et al., IEEE Trans. on Appl. Supercond.,19, (2009) 2446–2449;

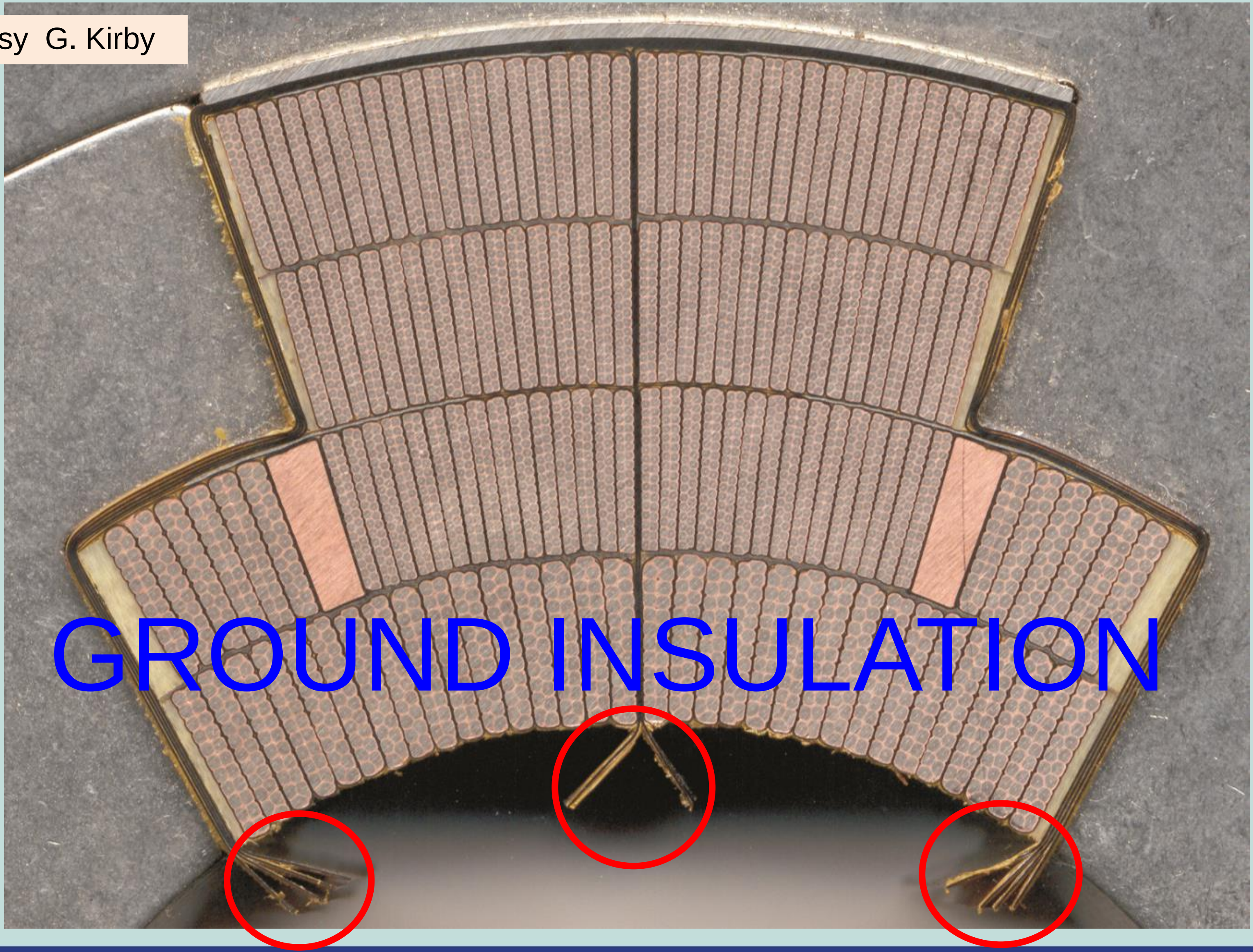
R. Bruce, (D. Bocian), et al., Phys. Rev. ST Accel. Beams 12, (2009) 071002;

Motivation

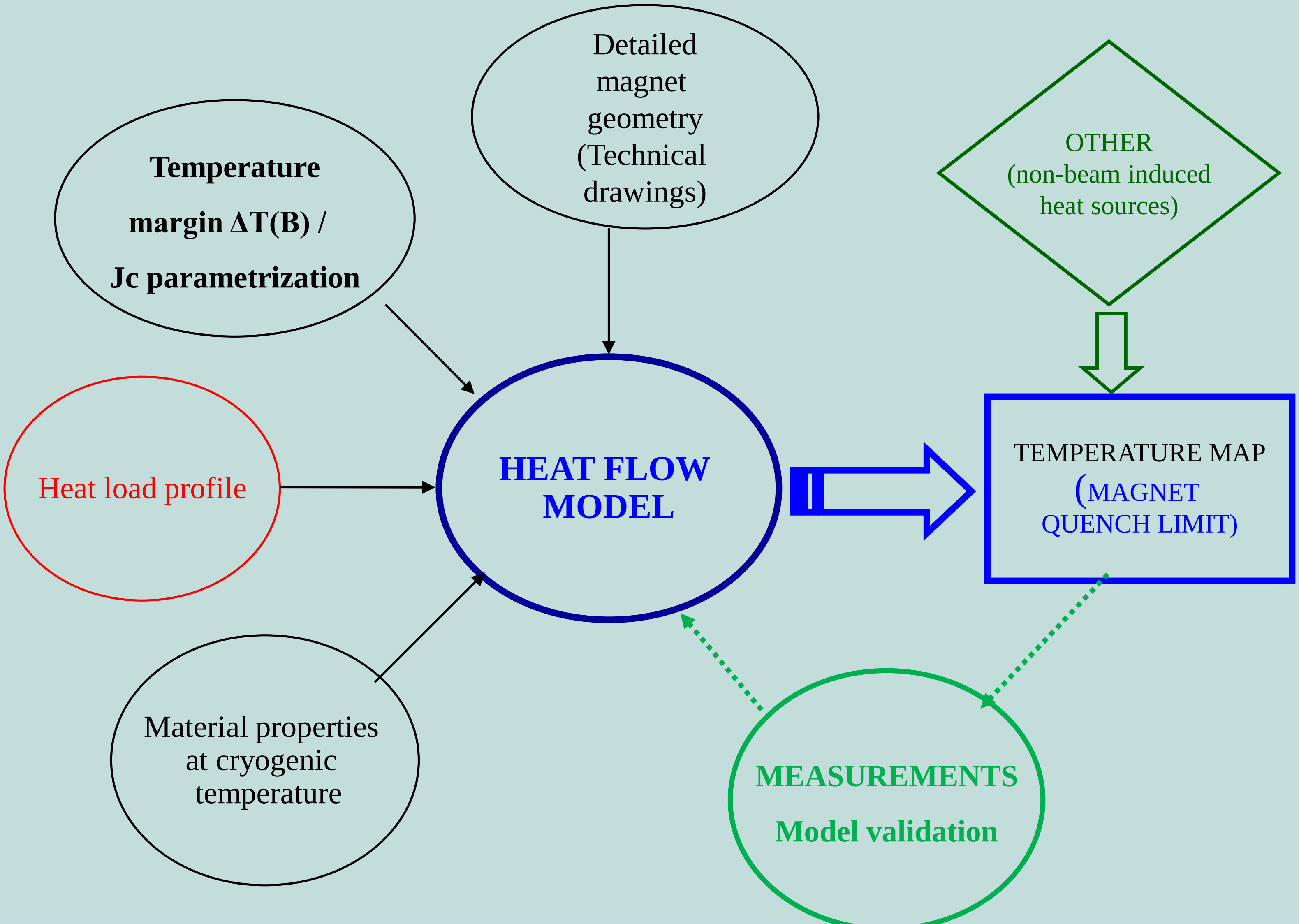
- Energy deposits in the accelerator magnets
- Heat load calculations for LHC IR magnets show:
  - → Current LHC: 10W/m
  - → LHC upgrade: 50W/m
- Thermal study objectives:
  - → Optimise Beam Loss Monitors threshold settings (gain the time and money)
  - → Integrated luminosity (increase discovery potential of LHC)
  - → Reduce of quench number (reduce the number of thermodynamic shocks)
  - → Optimise magnet cooling scheme in future accelerator magnets
    - **<u>LARP Nb_3Sn quadrupole design</u>**
      - → impregnated coil → no helium link between the bath and the cable
    - New CERN N-Ti quadrupole design
      - → enhanced insulation scheme → open helium paths between the bath and the cable



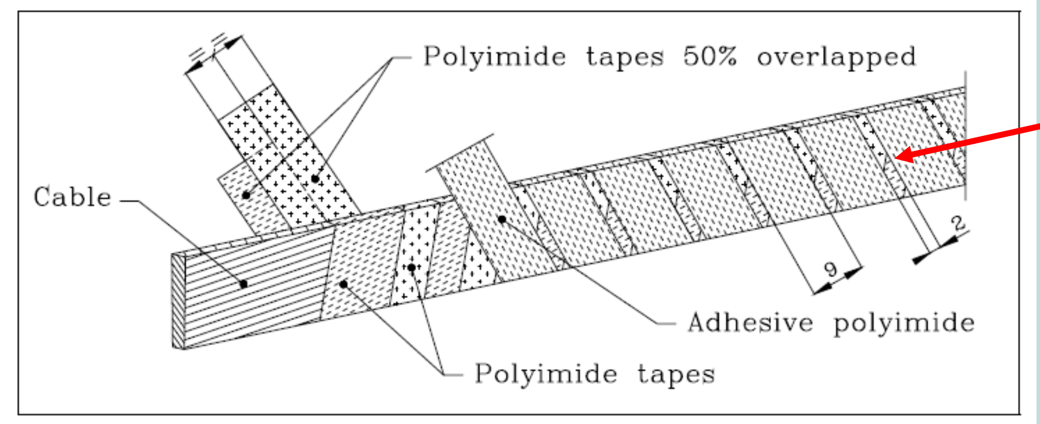
Thermal Model: coil cross section



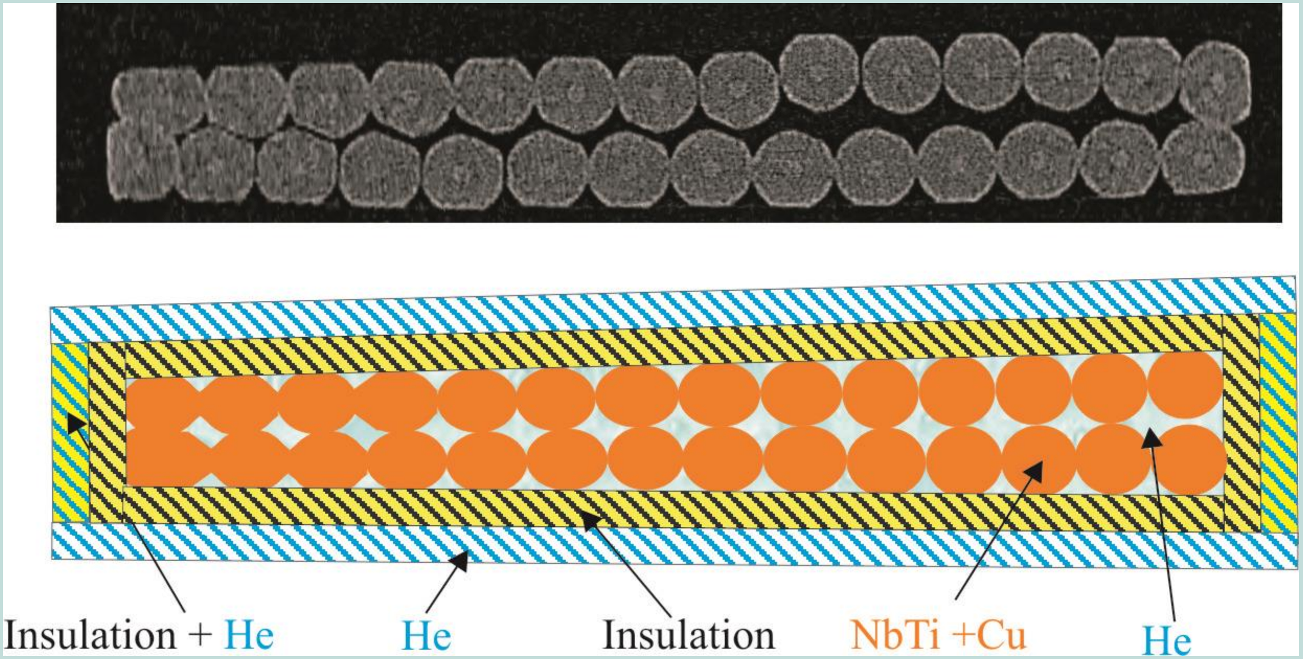
Thermal model: construction



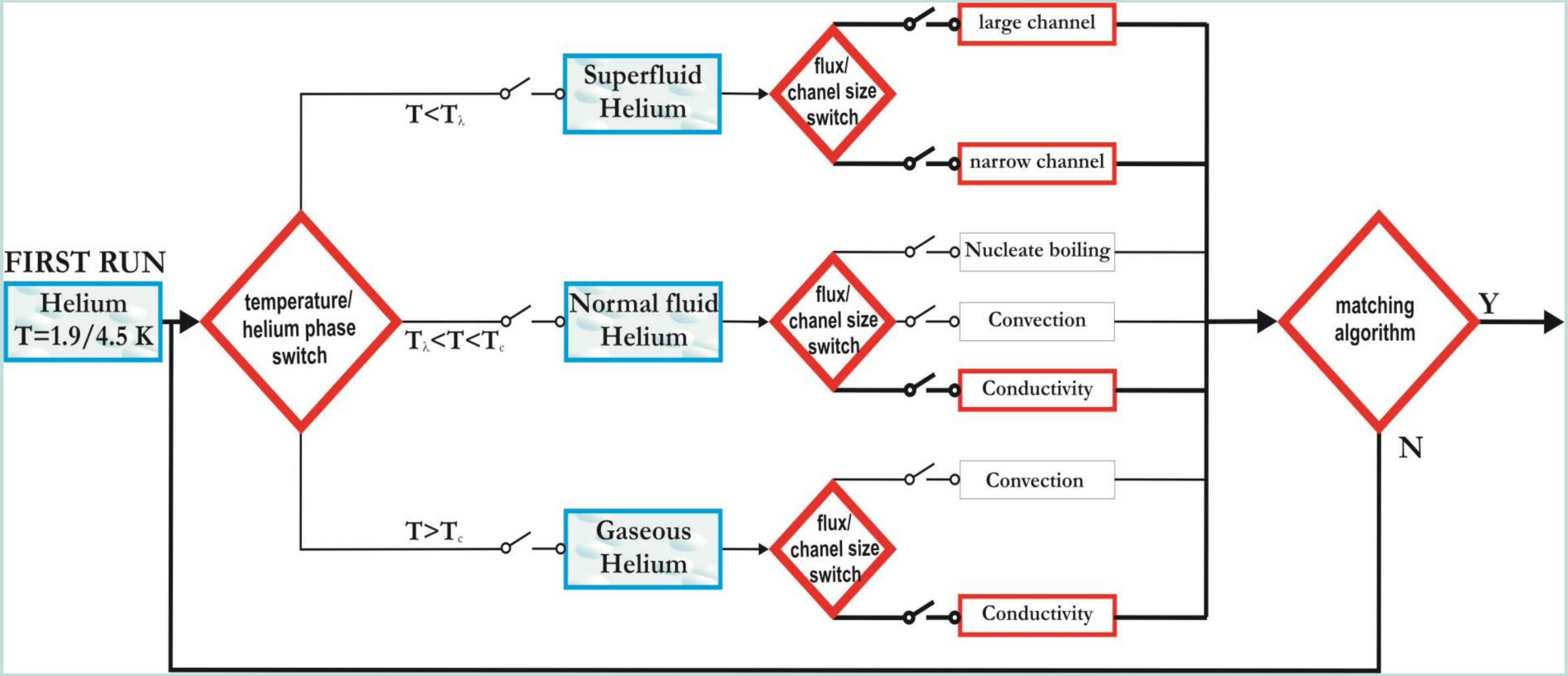
Thermal Model: cable modeling



μ-channel



Model parameters: Helium



Model parameters: Kapitza resistance

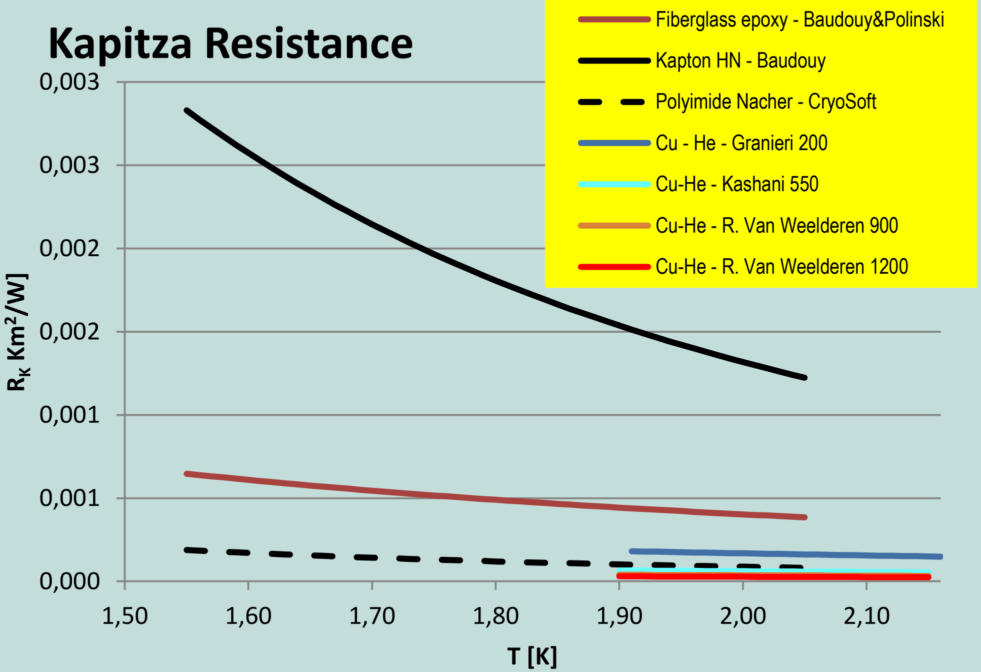
Kapitza resistance: A resistance to the flow of heat across the interface between liquid helium and a solid.

$$R_K = \frac{T_s - T_{He}}{\dot{Q}/A}$$

T_s – solid temperature

T_{He} – helium temperature

$\dot{Q}/A$ – heat flow per unit area



Copper - HeII

$R_K = 1/\sigma \cdot (T_s^2 + T_f^2) \cdot (T_s + T_f)\,[Km^2W^{-1}]$ [4-6]

POLYIMIDE - HeII

Theorerical: $R_K \sim T^{-2.57}$ Km^2W^{-1}, α=65.51 $Wm^{-2}K^{-3.57}$

R_K=10.54E-3T^{-3} Km^2W^{-1}, α=47.43 $Wm^{-2}K^{-4}$ [1]

R_K=0.7E-3*T^{-3} Km^2W^{-1} [2]

G10 - HeII

R_K=1462E-6$T^{-1.86}$ Km^2W^{-1}, h_K=239 $Wm^{-2}K^{-2.86}$ [3]

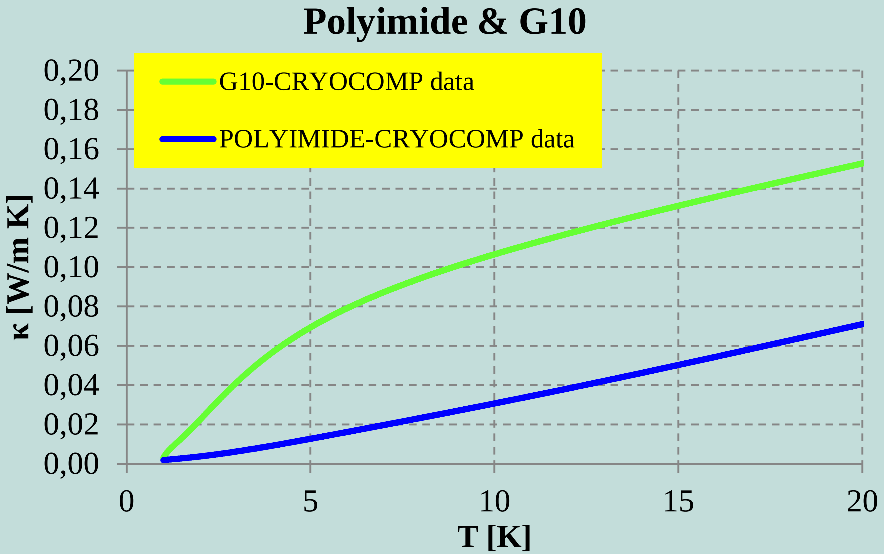
Bibliography:

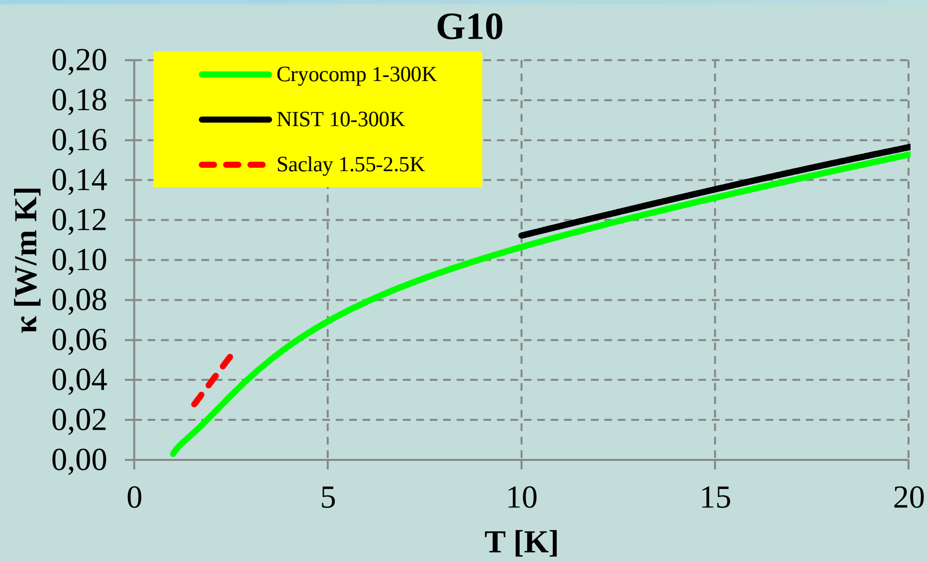
1. B. Baudouy, „*Kapitza resistance and thermal conductivity of Kapton in superfluid helium*", Cryogenics 43(2003) ,
2. Nacher PJ et al.," Heat exchange in liquid helium through thin plastic foils", Cryogenics 32 (1992),
3. B. Baudouy, J. Polinski, „*Thermal conductivity and Kapitza resistance of epoxy resin fiberglass tape at superfluid helium temperature*", Cryogenics 49(2009),
4. A. Kashani and S.w.Van Sciver, „*High heat flux Kapitza conductance of technical copper with several different surface preparations*", Cryogenics 25 (1985),
5. P.P. Granieri et al, „ *Stability analysis of the LHC cables for transient heat depositions*", IEEE Trans. Appl. Supercond., vol. 18, No. 2 (2008).
6. *D. Camacho et al.,"Thermal characterization of the HeII LHC heat exchanger tube", LHC Project Report 232, 1998.*

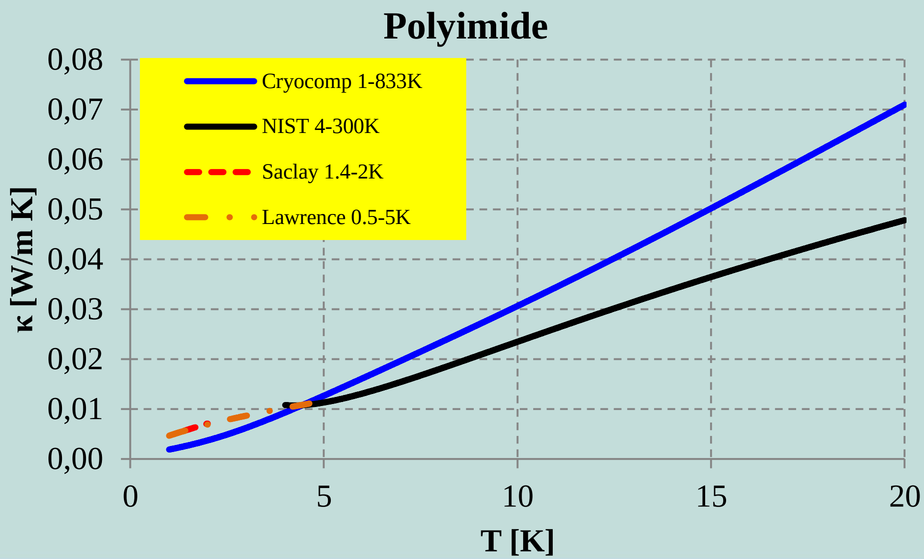
Model parameters: material properties

- Material properties at low temperatures
  - → Coil insulation (Polyimide, G10)
    - →**experimental data available**

Material data implemented in Network Model







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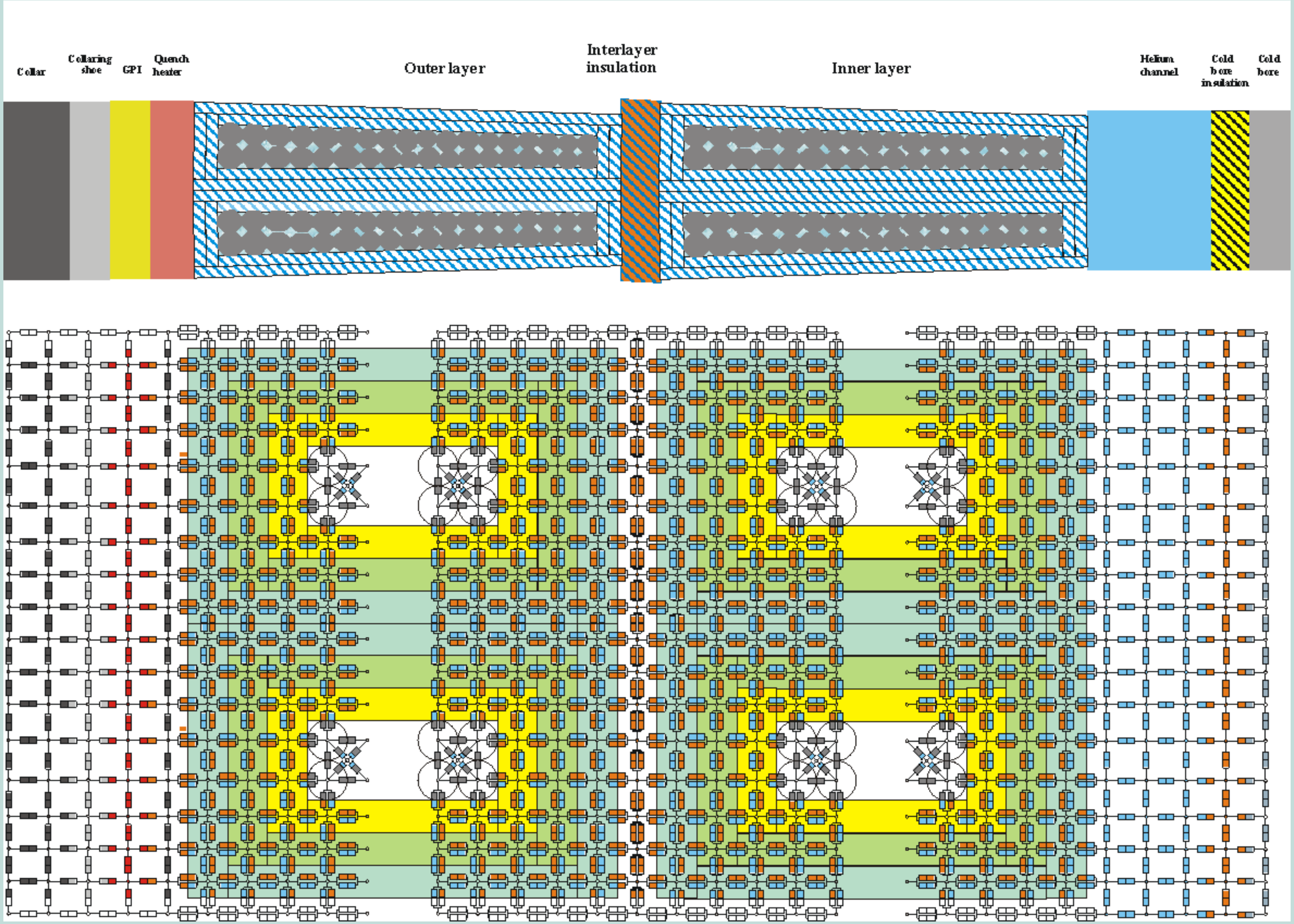
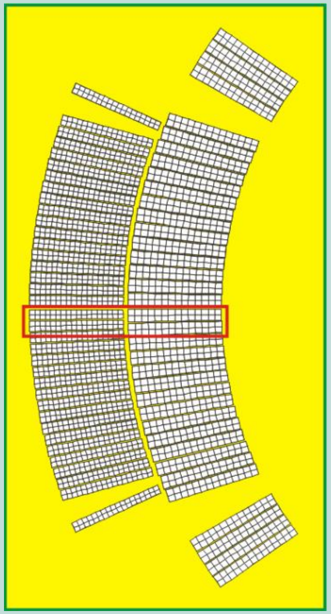
1. B. Baudouy, „*Kapitza resistance and thermal conductivity of Kapton in superfluid helium*", Cryogenics 43(2003), 667-672,
2. Lawrence et al., „ The thermal conductivity of Kapton HN between 0.5 and 5 K", Cryogenics 40 (2000), 203-207,
3. B. Baudouy, J. Polinski, „*Thermal conductivity and Kapitza resistance of epoxy resin fiberglass tape at superfluid helium temperature*", Cryogenics 49(2009), 138-143

Magnet thermal model





Which software?

Thermal – electrical analogy

Kirchhoff stated as early as 1845 that:

" Two different forms of energy behave identically when the basic differential equations which describe them have the same form and the initial and boundary conditions are identical".

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*

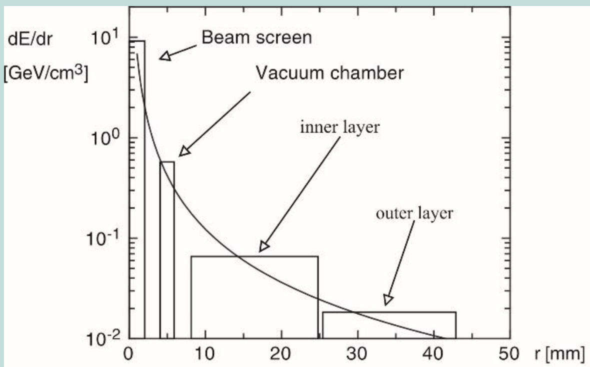
$$\Delta T = qR^{\Theta} \quad \Leftrightarrow \quad \Delta V = iR$$

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

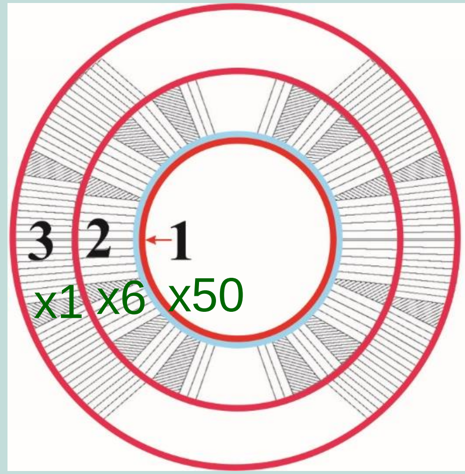
$$\nabla^2 T = R^{\Theta} C^{\Theta} \frac{\partial T}{\partial t} \quad \Leftrightarrow \quad \nabla^2 V = RC \frac{\partial V}{\partial t}$$

Quench limit simulations

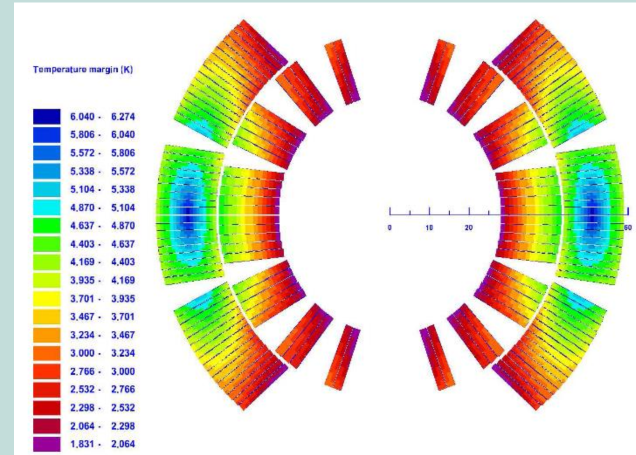
LHC Project Note 44
1 - cold bore - factor = 50
2 - inner layer - factor = 6
3 - outer layer - factor = 1



The maximum radial energy density along the most exposed azimuth



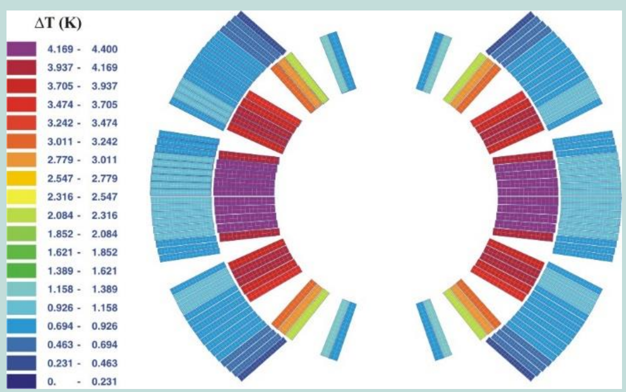
Concentric beam loss profile

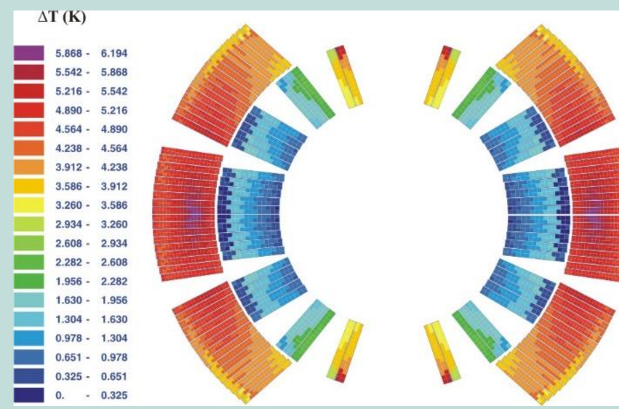


Temperature margin distriution, ΔT

Quench limit at 11850A
12 mW/cm^3

Quench limit at 12840A
10 mW/cm3

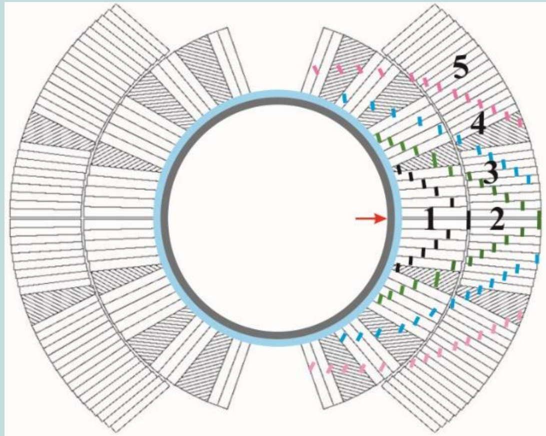




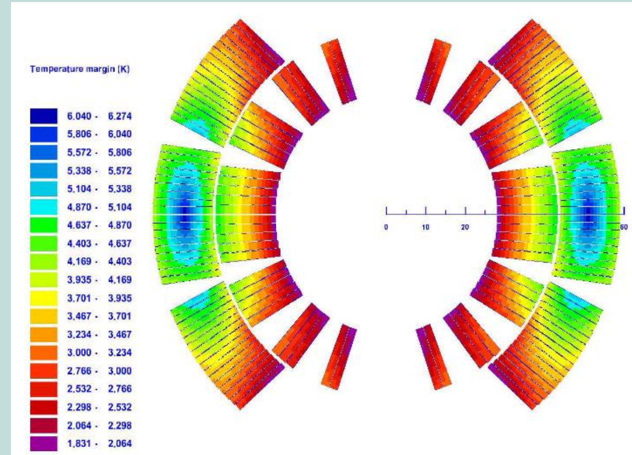
Quench limit simulations

FLUKA simulations

1 - factor = 1
2 - factor = 1.0/3.0
3 - factor = 0.4/3.0
4 - factor = 0.1/3.0
5 - factor = 0.03/3.0



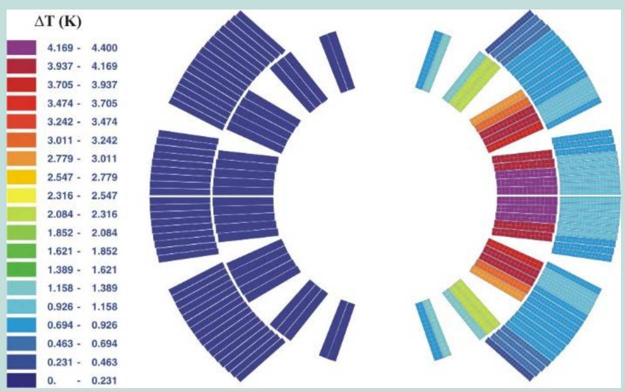
Gaussian beam loss profile



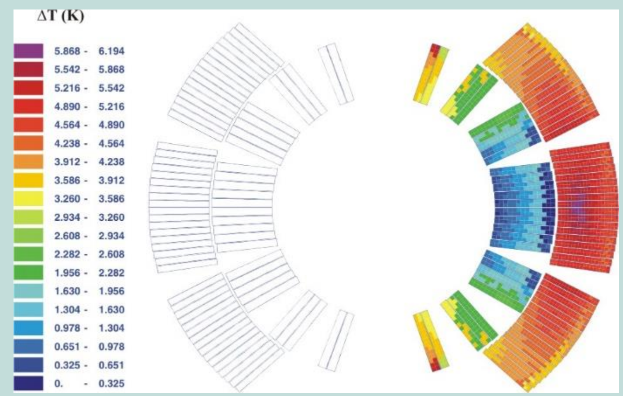
Temperature margin distriution, ΔT

Quench limit at 11850A
17 mW/cm^3

Quench limit at 12840A
14 mW/cm^3

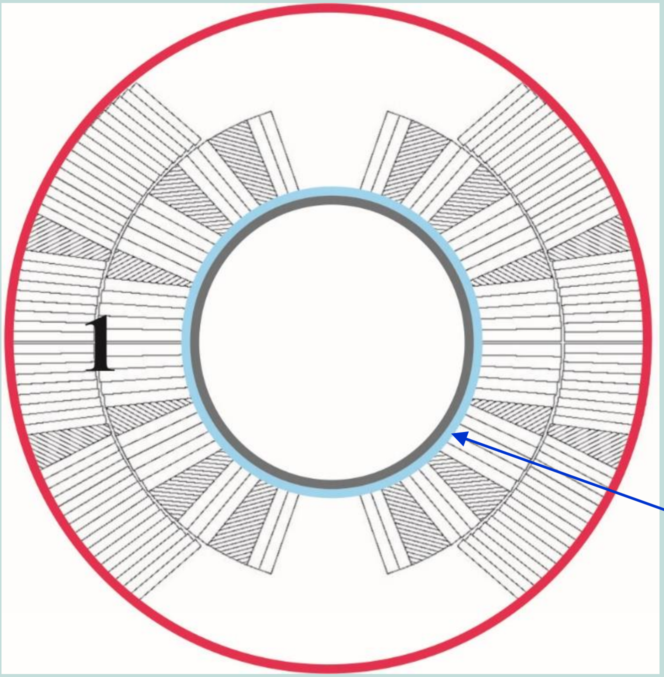


Temperature in the coil, $\Delta T_{simulation}$



Quench temperature map
$\Delta T-\Delta T_{simulation}$

Quench limit simulations



- Beam loss profile with homogenous heat deposition
- no heat load to the cold bore
  - 10500 A → Quench Limit ~ 150 mW/cm^3
  - 11850 A → Quench Limit ~ 100 mW/cm^3
  - 12100 A → Quench Limit ~ 72 mW/cm^3
- with heat load to the cold bore
  - 10500 A → Quench Limit ~ 20 mW/cm^3
  - 11850 A → Quench Limit ~ 14 mW/cm^3
  - 12840 A → Quench Limit ~ 9 mW/cm^3

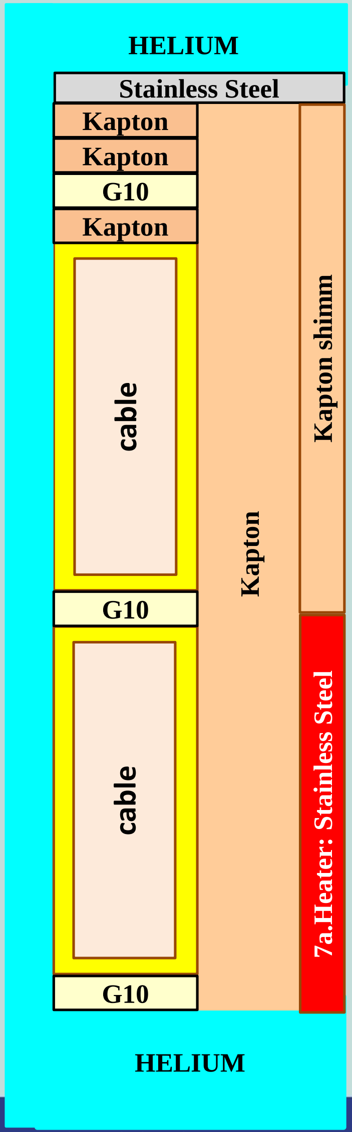
This is effect of Helium channel blocking, which is between cold bore and coil

Very important information for future design of accelerator superconducting magnets:

A better cooling of the cold bore is needed to increase quench level

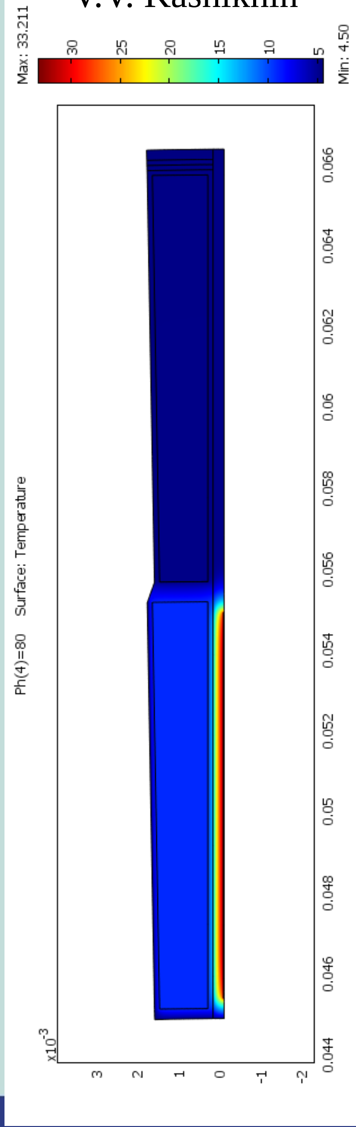
NM and COMSOL comparison

MODEL

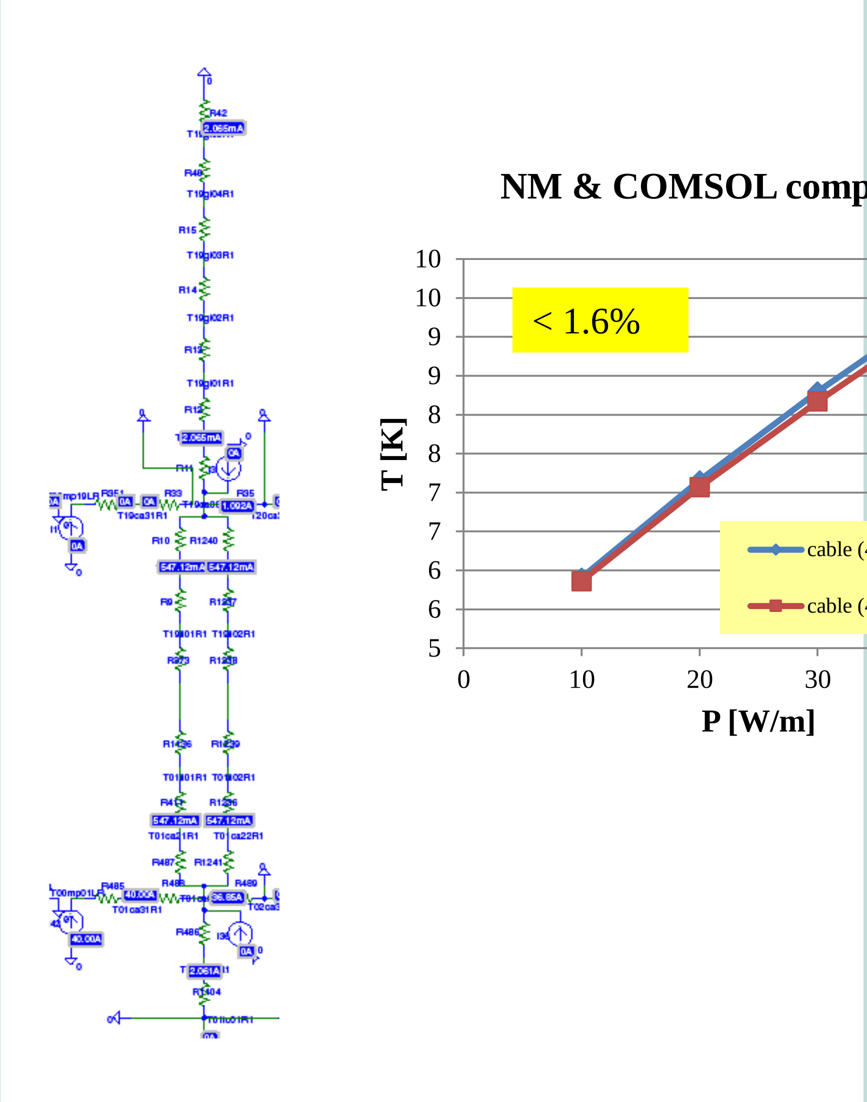


COMSOL

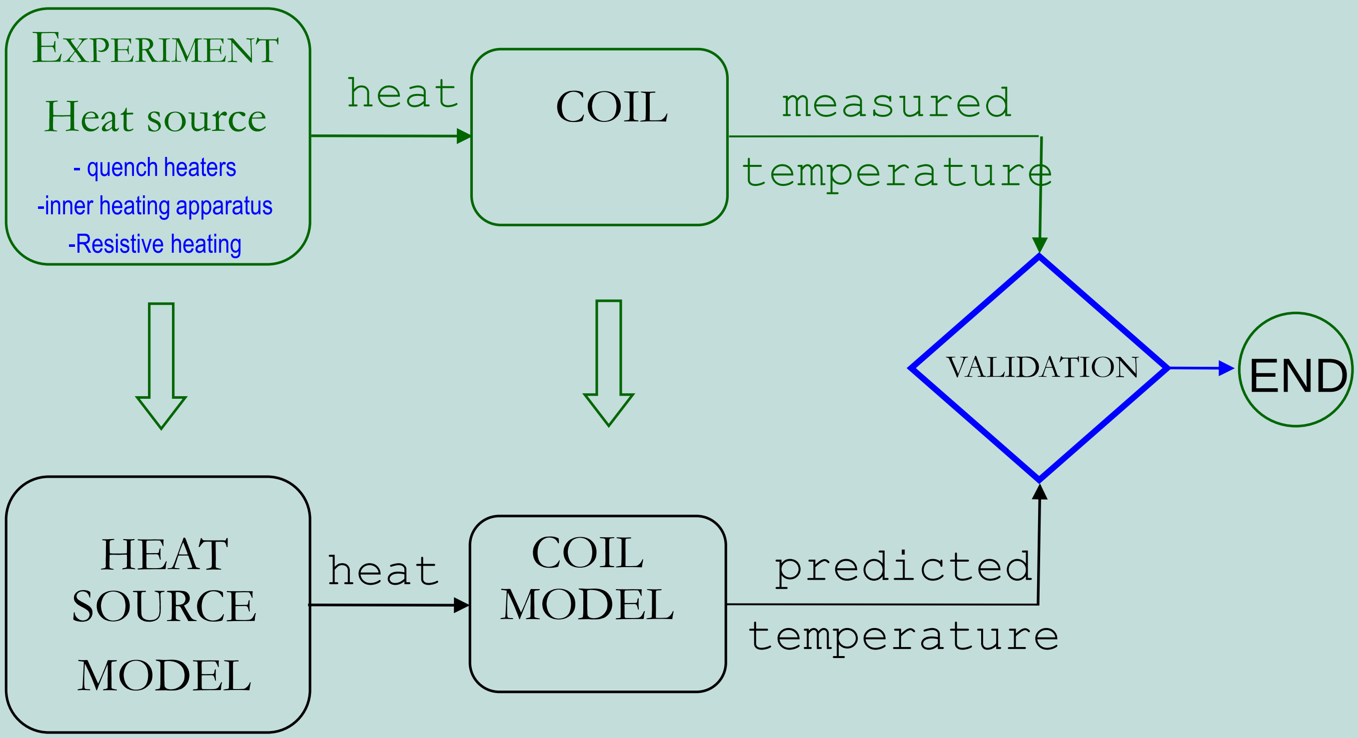
V.V. Kashikhin



NETWORK MODEL



Network Model - Validation



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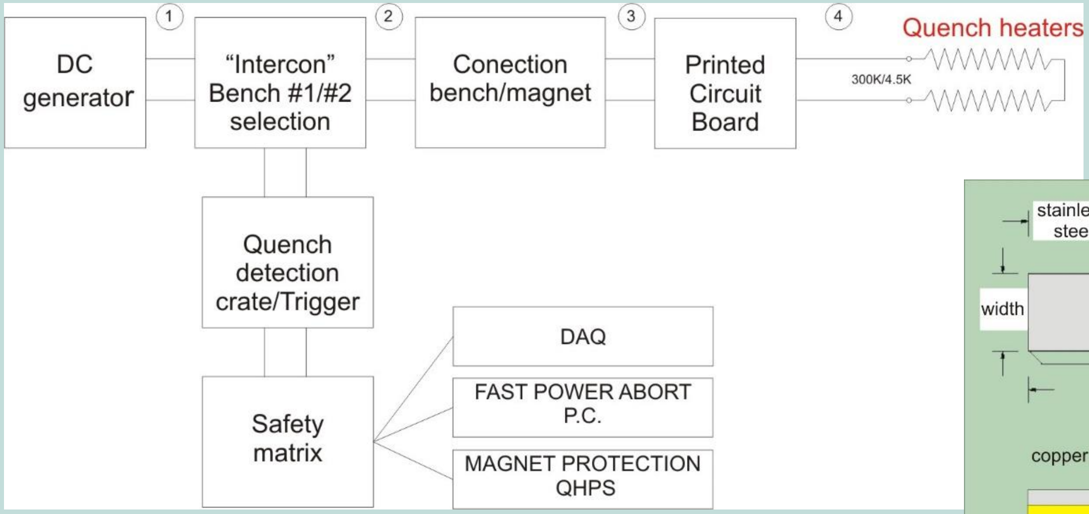
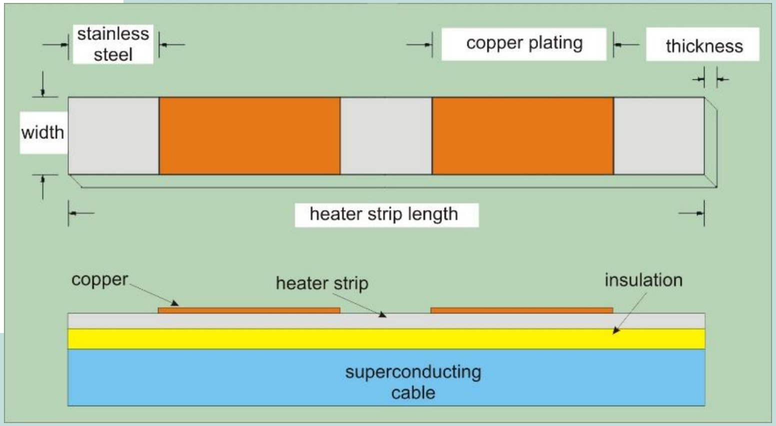
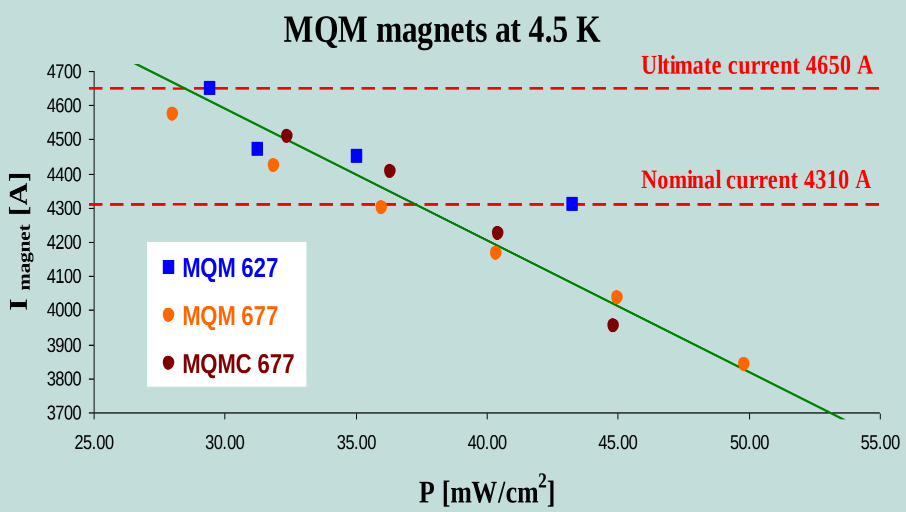
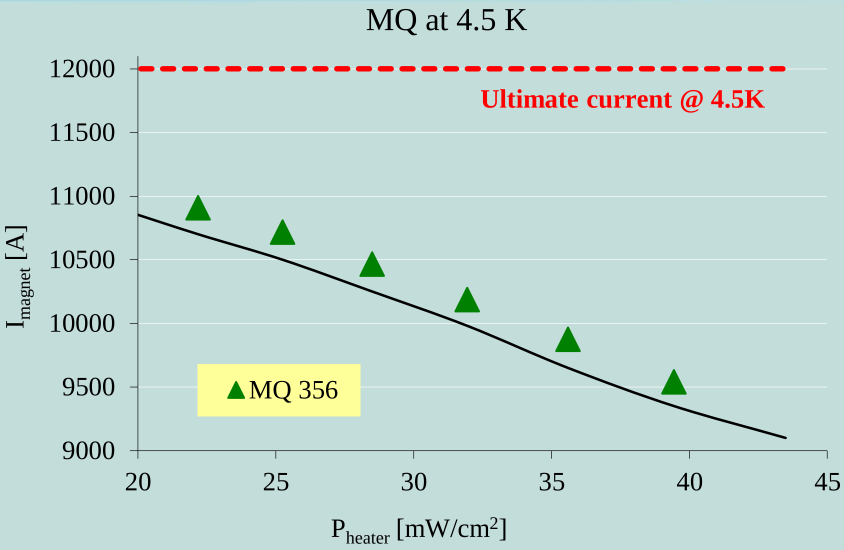


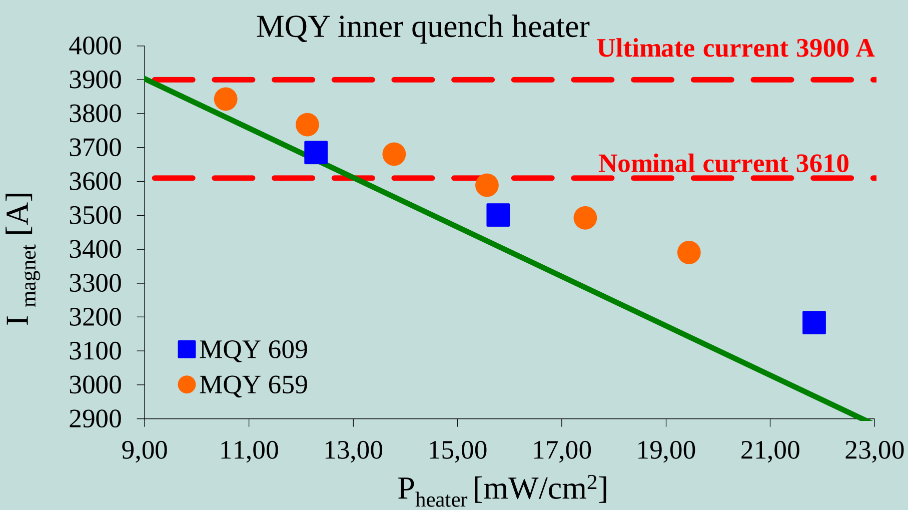


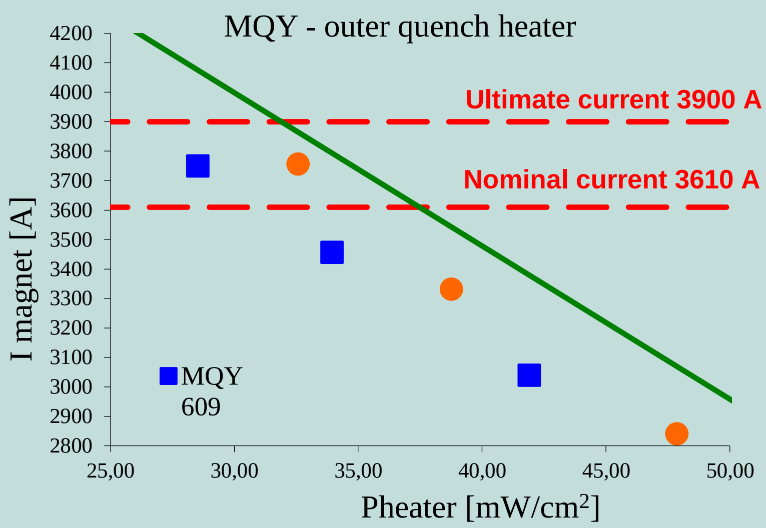
- Two methods of measurement
  - I_{coil} =const, increase of I_{QH} with a step of 0.1 A
  - I_{QH} =const, wait 300 second for steady state, then ramp of I_{coil}
- Second method is better for steady state heat transport
- 3 MQM, 2 MQY, MQ and MB have been tested at 4.5 K

Network Model - Validation









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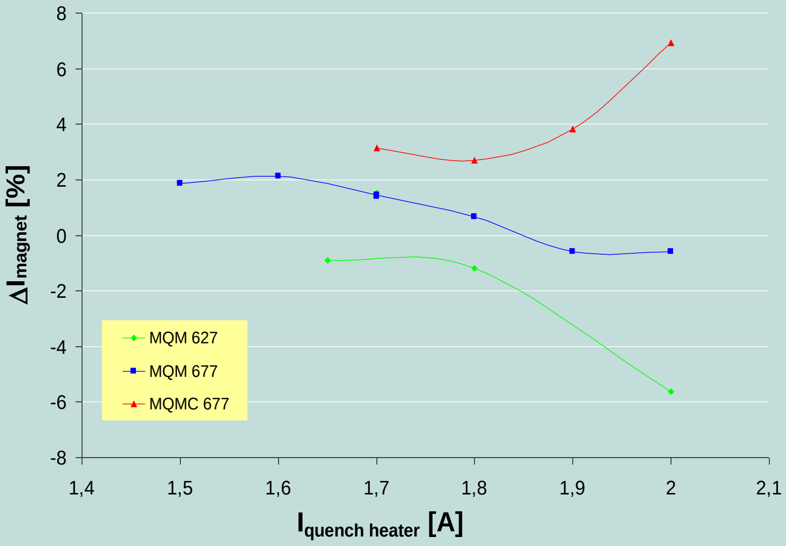
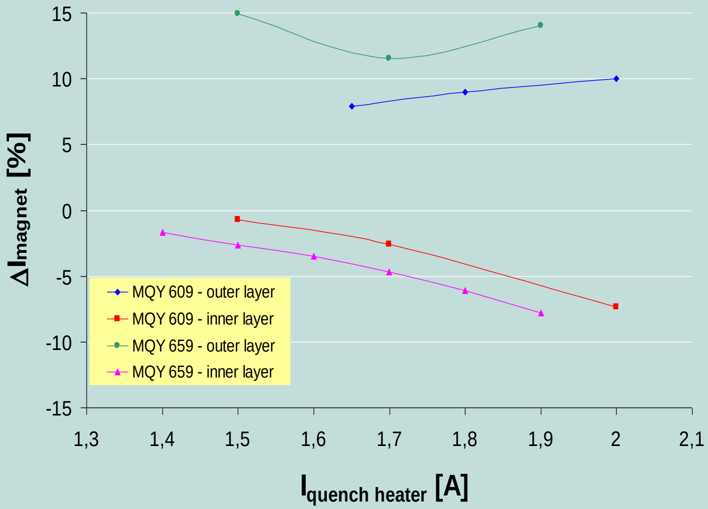
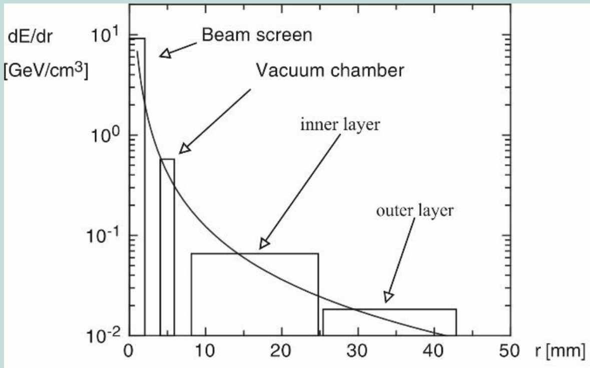


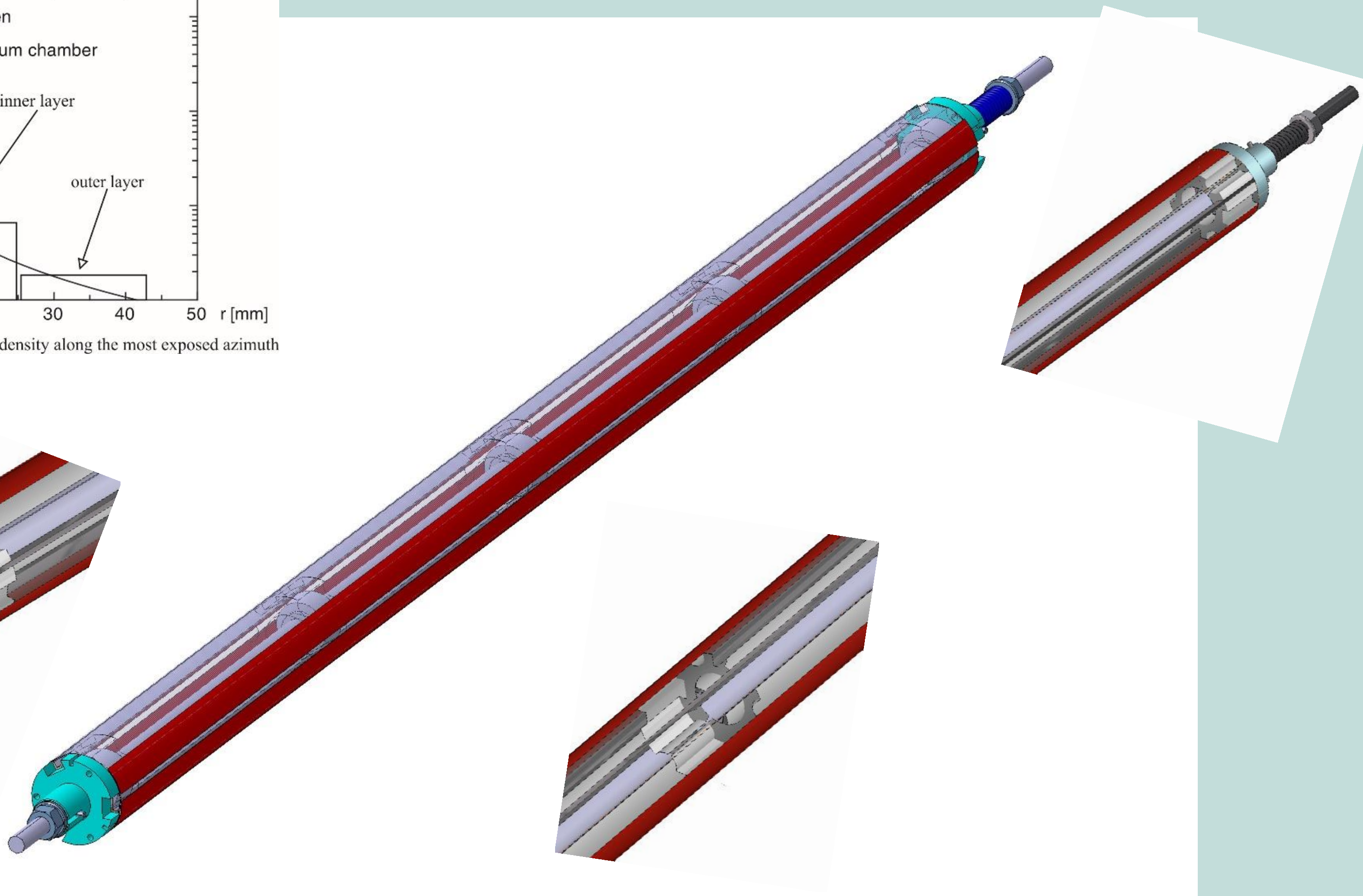


The relative difference between measured and calculated quench values are ranging from 0.6 to 15 % for all measured types of superconducting magnets at 4.5 K.

Network Model - Validation



The maximum radial energy density along the most exposed azimuth



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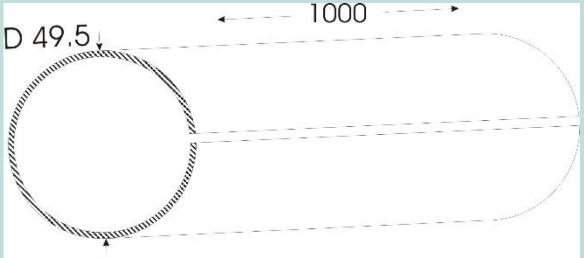

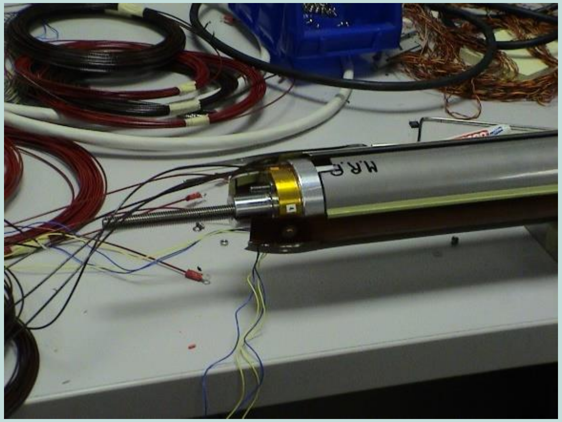

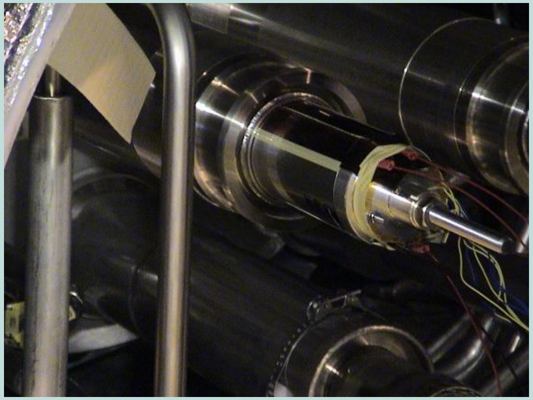

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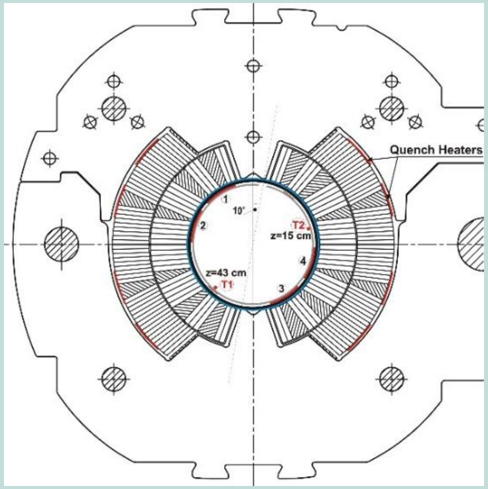
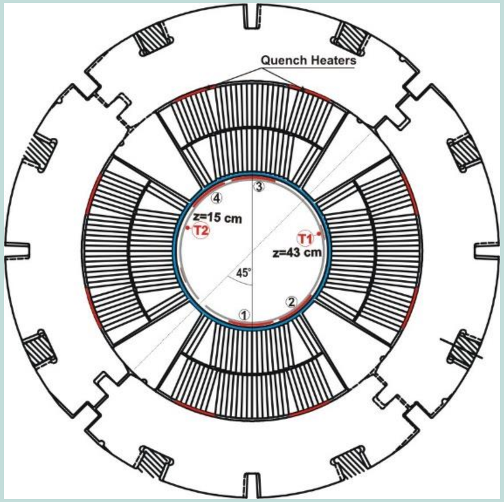
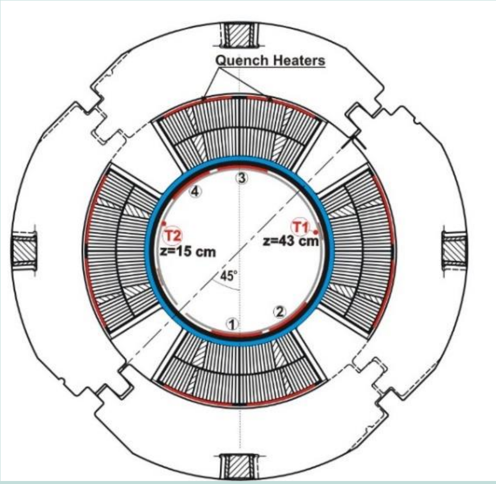


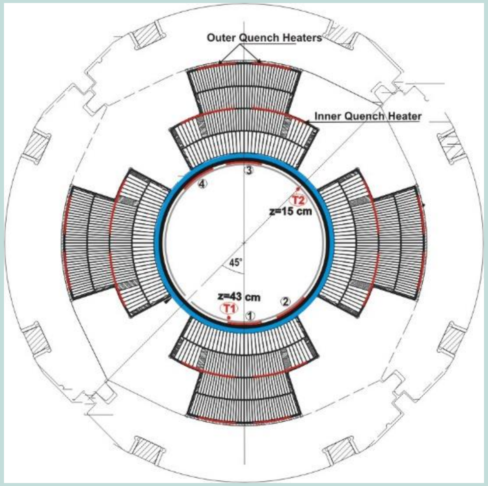
Main Dipole - MB



Main Quadrupole - MQ

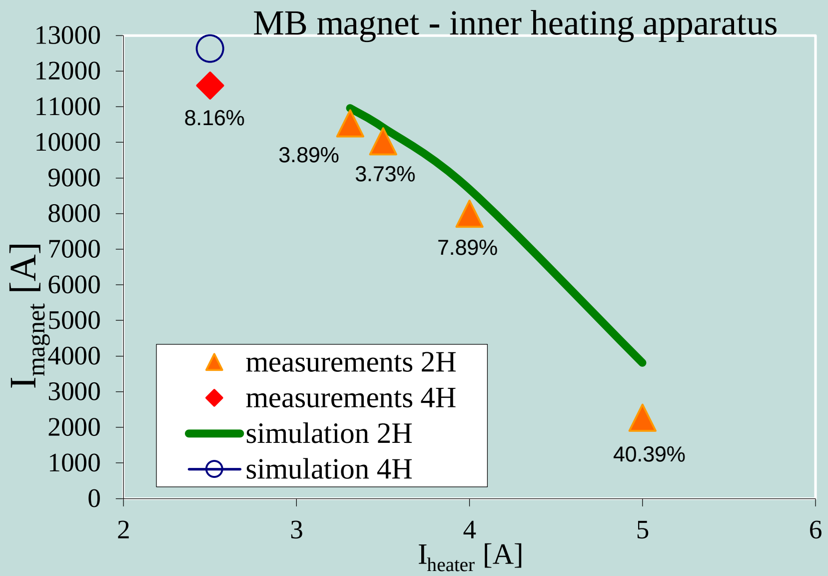


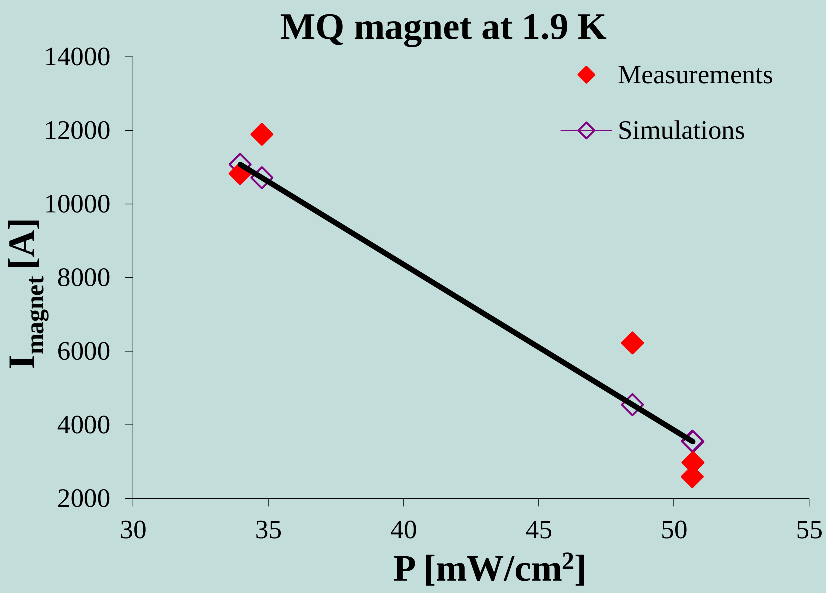
MQM

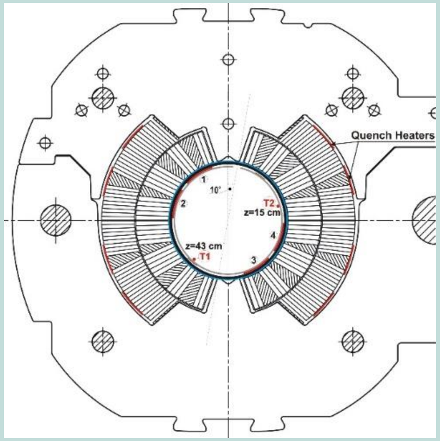


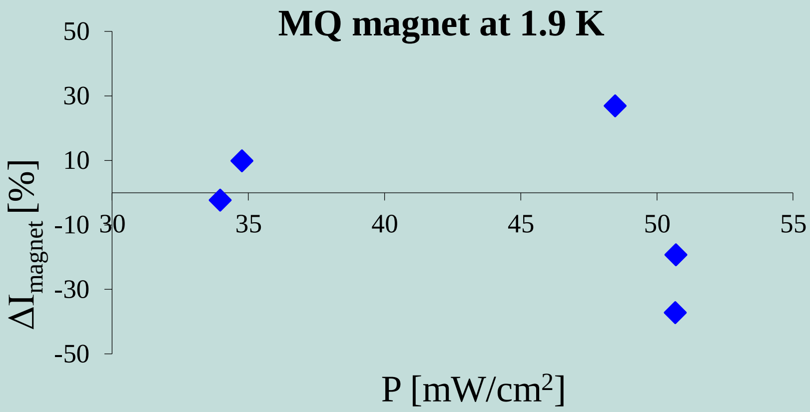
MQY

Network Model - Validation





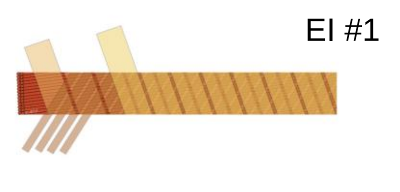


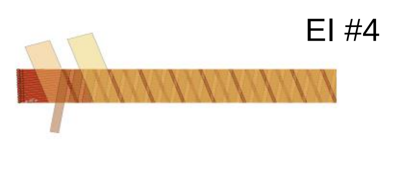


What next?

Enhanced cable insulation

Can we still exploit NbTi?





Strand diameter = 1.065 mm, cable width (bare)= 15.1 mm			
EI type	1st layer (polyimide)	2nd layer (polyimide)	3rd layer (polyimide with adhesive coating)
EI #1	9 mm wide,1 mm gap 25.4 µm thick wrap angle α_1 =71.68 deg	4 x(2.5 mm wide, 1.5 mm gap) 75 µm thick, cross wrapped with 1st and 3rd layers wrap angle α_1 =62.16 deg	9 mm wide, 1 mm gap 55 µm thick, 50% overlap with 1st layer wrap angle α_1 =71.90 deg
EI #4	9 mm wide, 1 mm gap 50µm thick wrap angle α_1 =71.68 deg	1 x(3.0 mm wide, 1.5 mm gap) 75 µm thick, cross wrapped with 1st and 3rd layers wrap angle α_1 =81.6 deg	9 mm wide, 1 mm gap 69 µm thick, 50% overlap with 1st layer wrap angle α_1 =72.0 deg

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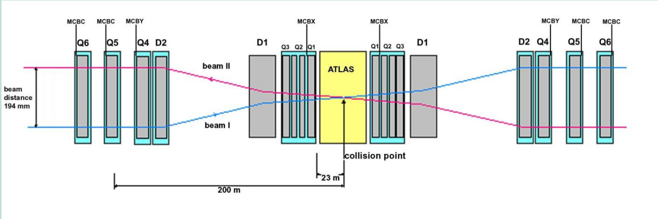
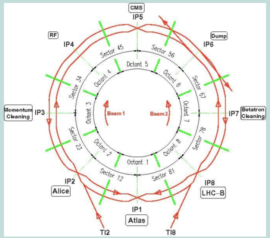
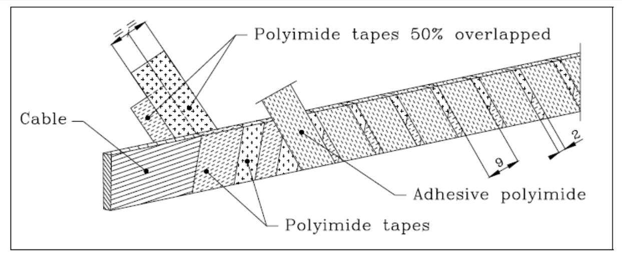
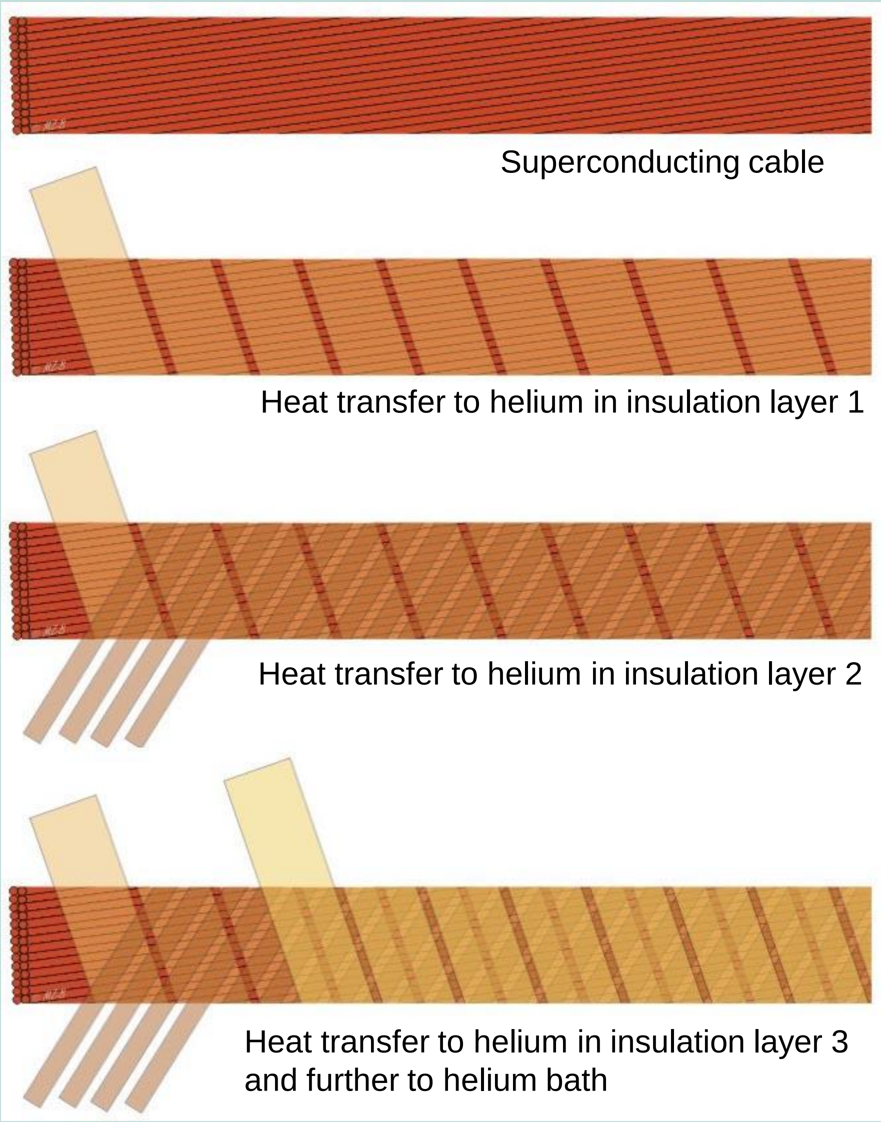
1. M. La China, D. Tommasini, "Cable insulation scheme to improve heat transfer to superfluid helium in Nb-Ti accelerator magnets", IEEE Trans.Appl.Supercond., Vol. 18, 2, (2008).
2. D. Tommasini, D. Richter, "A new cable insulation scheme improving heat transfer to superfluid helium in Nb-Ti superconducting accelerator magnets", proceedings of *EPAC08*, pp2467-2469, (2008).
3. P. P. Granieri, P. Fessia, D. Richter, D. Tommasini, "Heat transfer in an enhanced cable insulation scheme for the superconducting magnets of the LHC luminosity upgrade", IEEE Trans.Appl.Supercond., Vol. 20, 3, pp168-171, (2010).





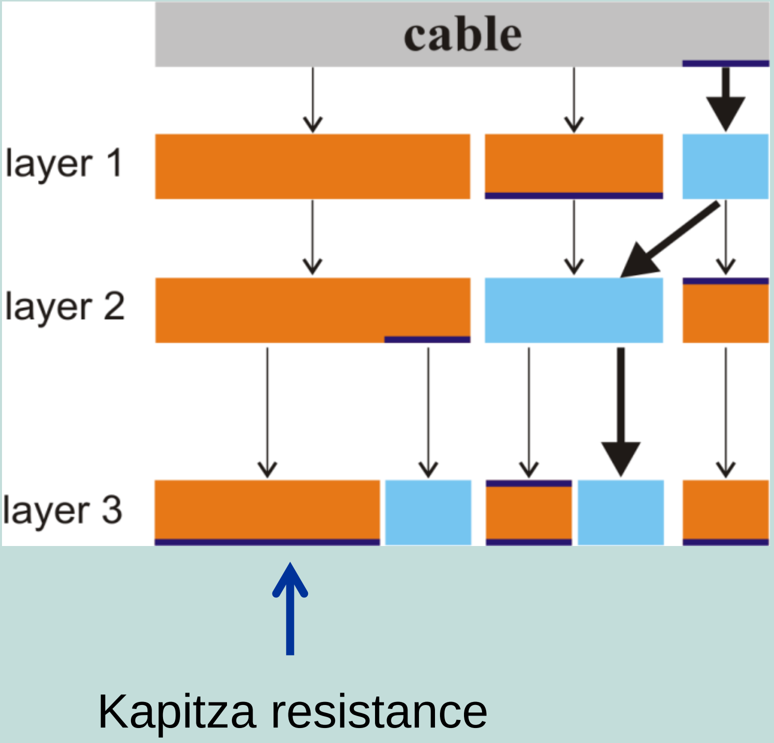


Enhanced cable insulation

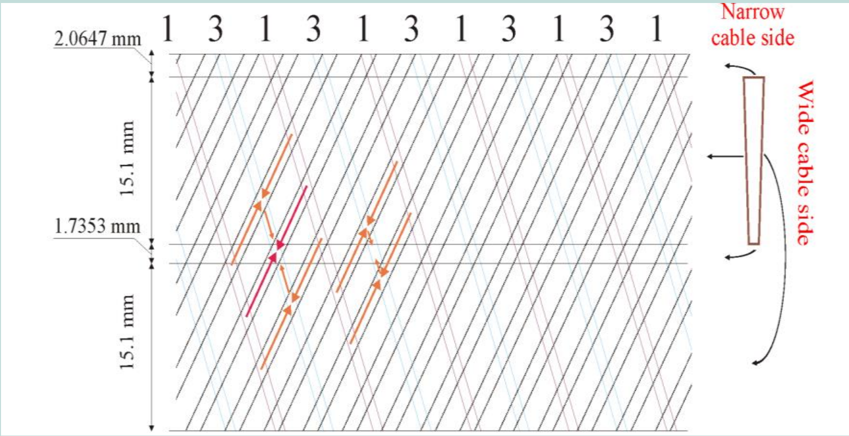


Heat is transferred to helium bath through:

- superfluid helium
- cable insulation

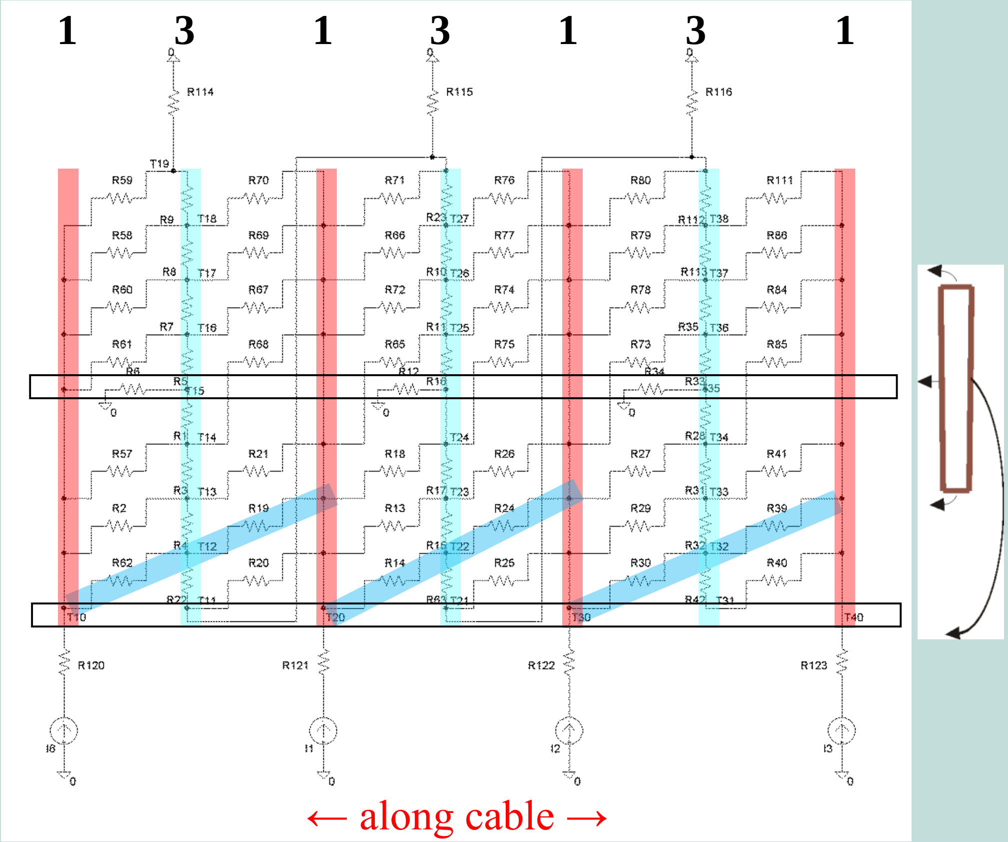


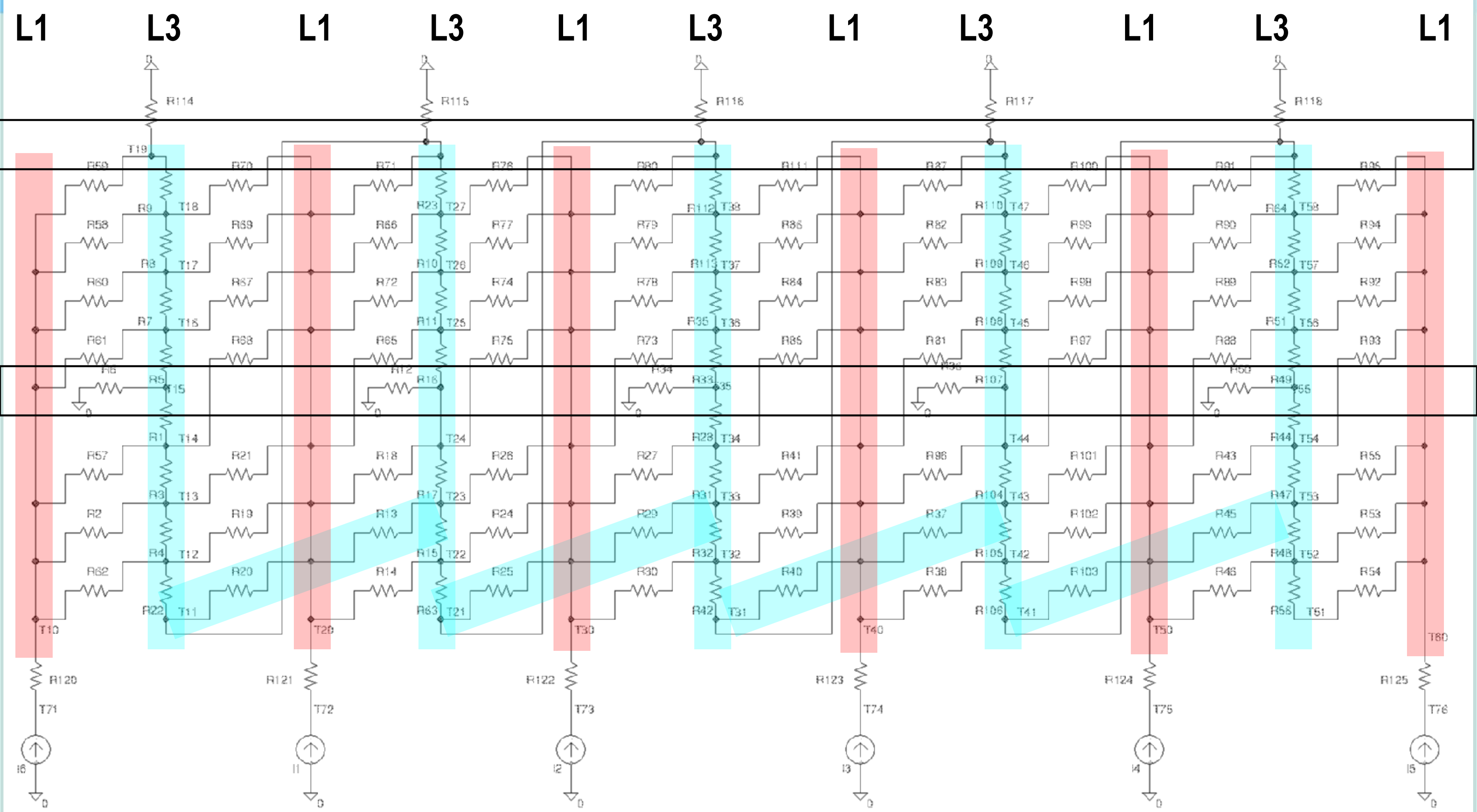
Enhanced cable insulation



Helium channels network

Thermal resistances equivalent





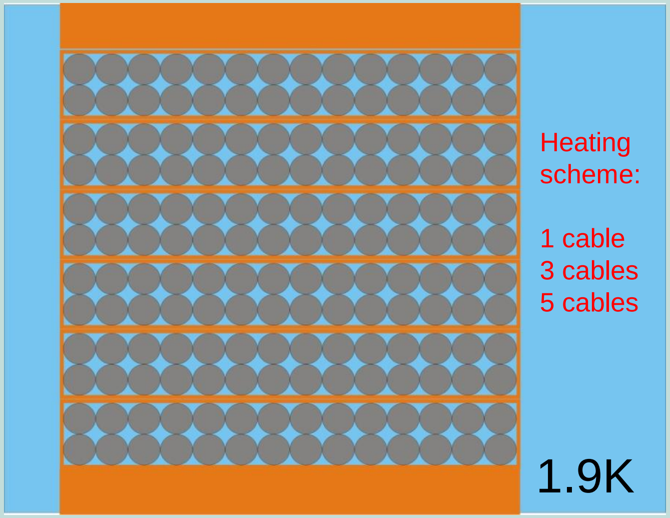
along cable

Experimental setup

cable stack immersed in superfluid helium

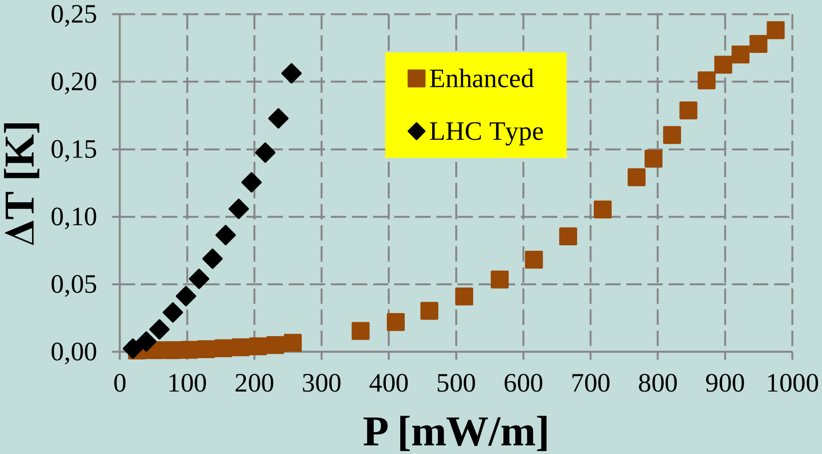
- 150 mm active part long
- 28 resistive $CuNi_{10\ wt.\%}$ strands

  (with the same geometry as the LHC cable 1)
- Insulated according to EI#1 or EI#4
- Sample cured according LHC cycle (80 Mpa, 190 ºC)

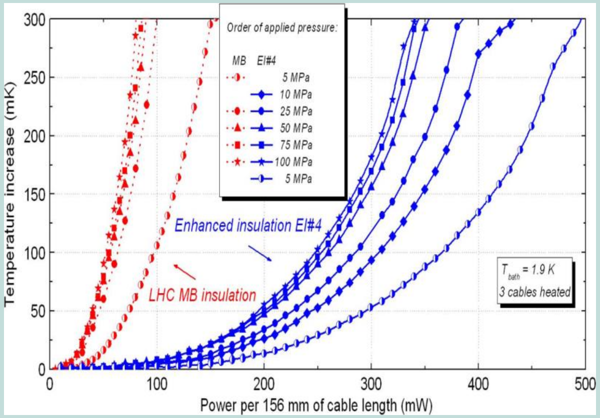


Measurements performed under pressure

30 MPa for EI#1 and 5 – 100 MPa for EI#4



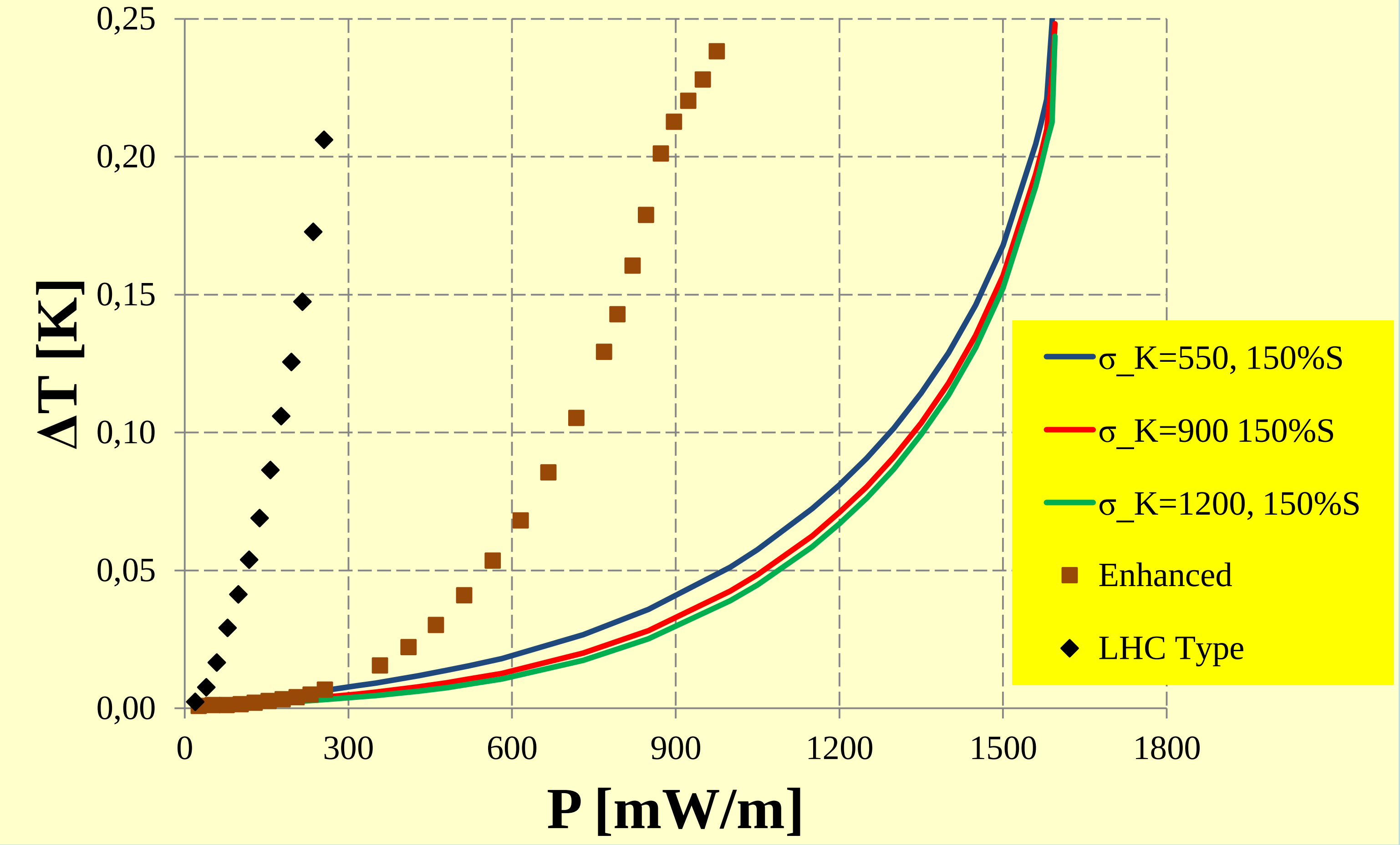
D. Tommasini, D. Richter, "A new cable insulation scheme improving heat transfer to superfluid helium in Nb-Ti superconducting accelerator magnets", proceedings of *EPAC08*, pp2467-2469, (2008)



P. P. Granieri *et al., "Heat transfer in an enhanced cable insulation* scheme for the superconducting magnets of the LHC luminosity upgrade," *IEEE Trans. Appl. Supercond., vol. 20, Issue 3, 2010*

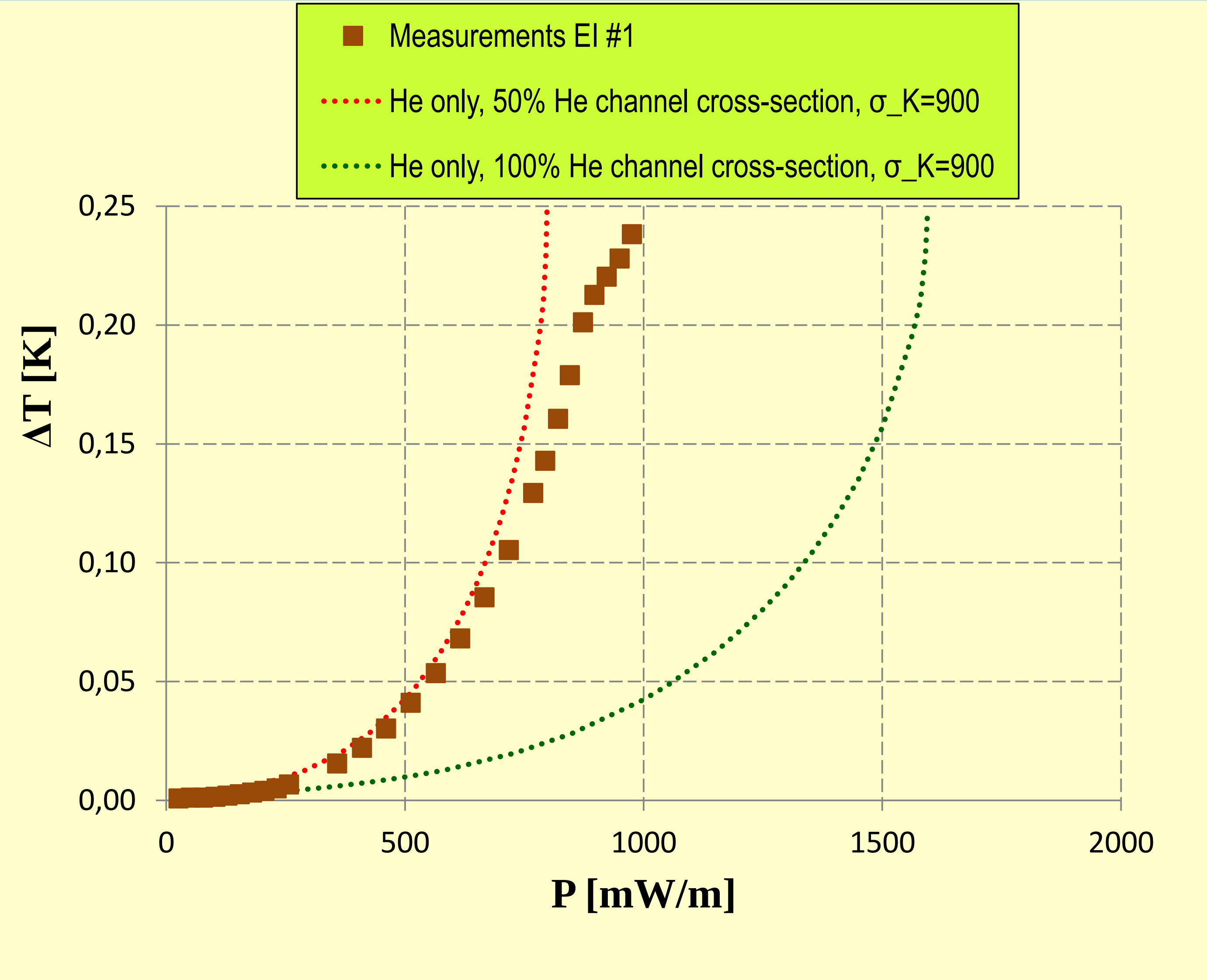
Enhanced cable insulation

Numerical calculations results

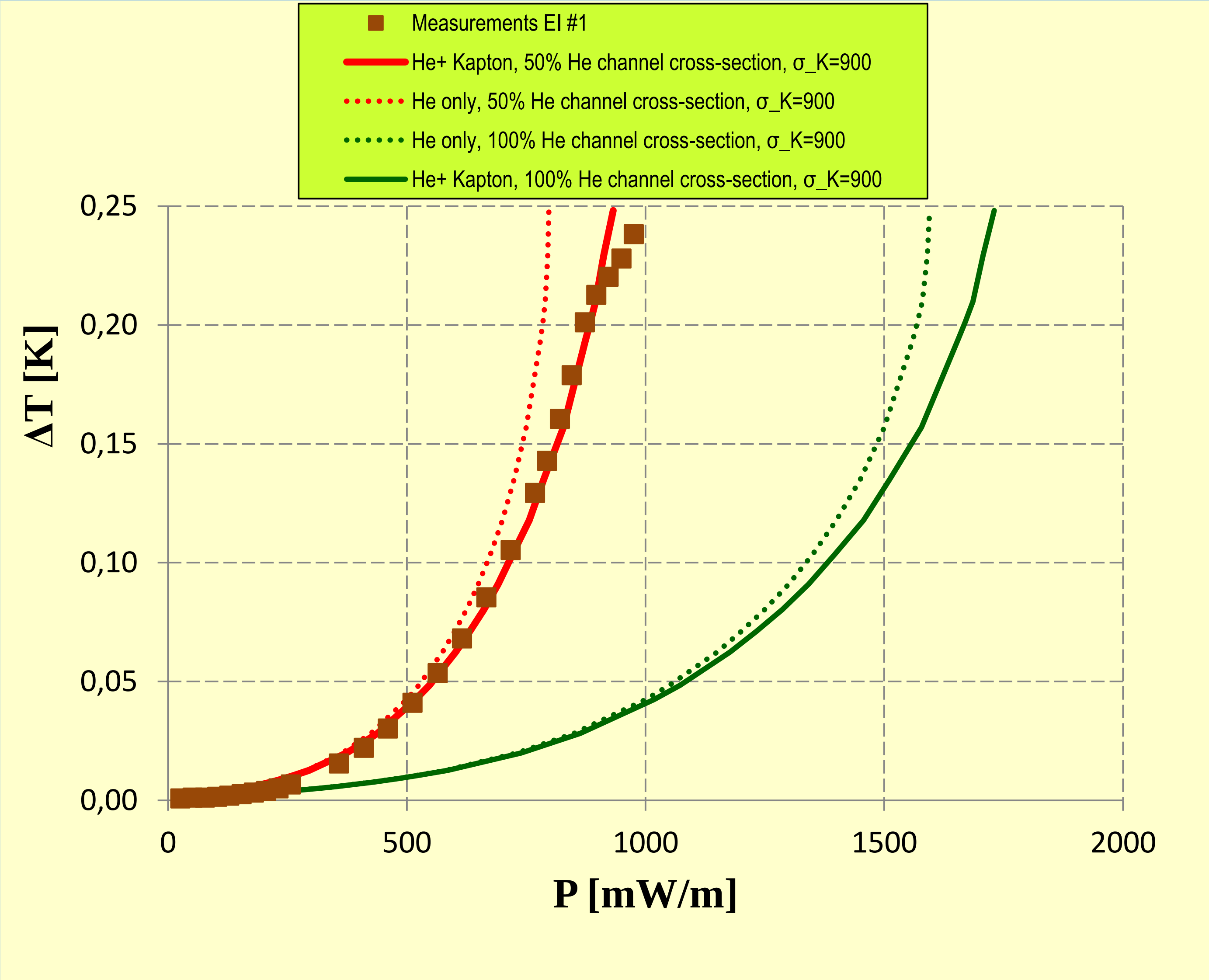


Cable should demonstrate better performance than measured!

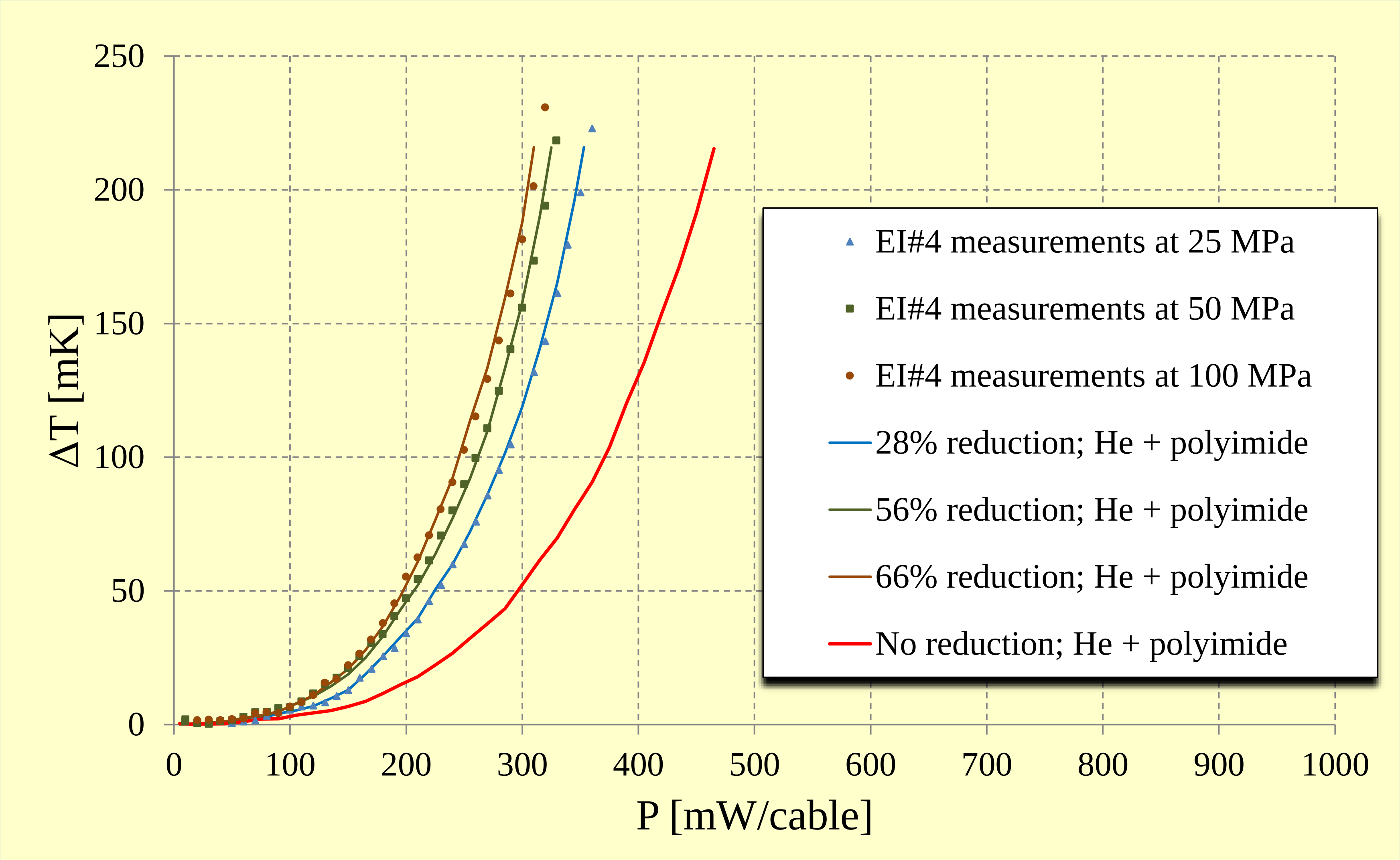
Enhanced cable insulation



Enhanced cable insulation

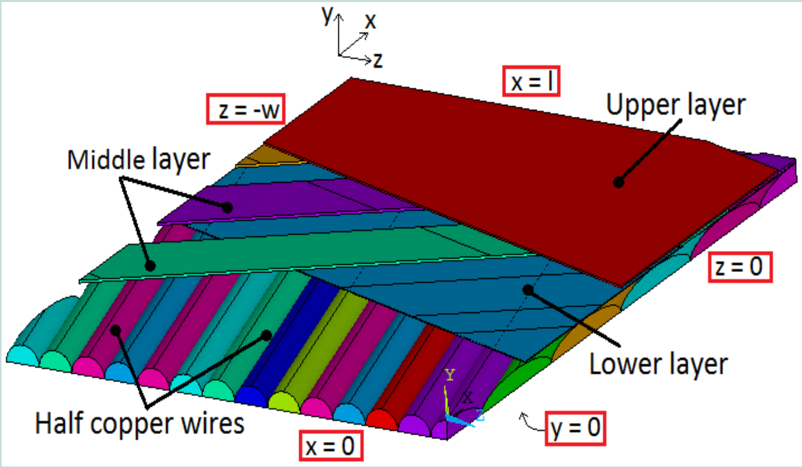


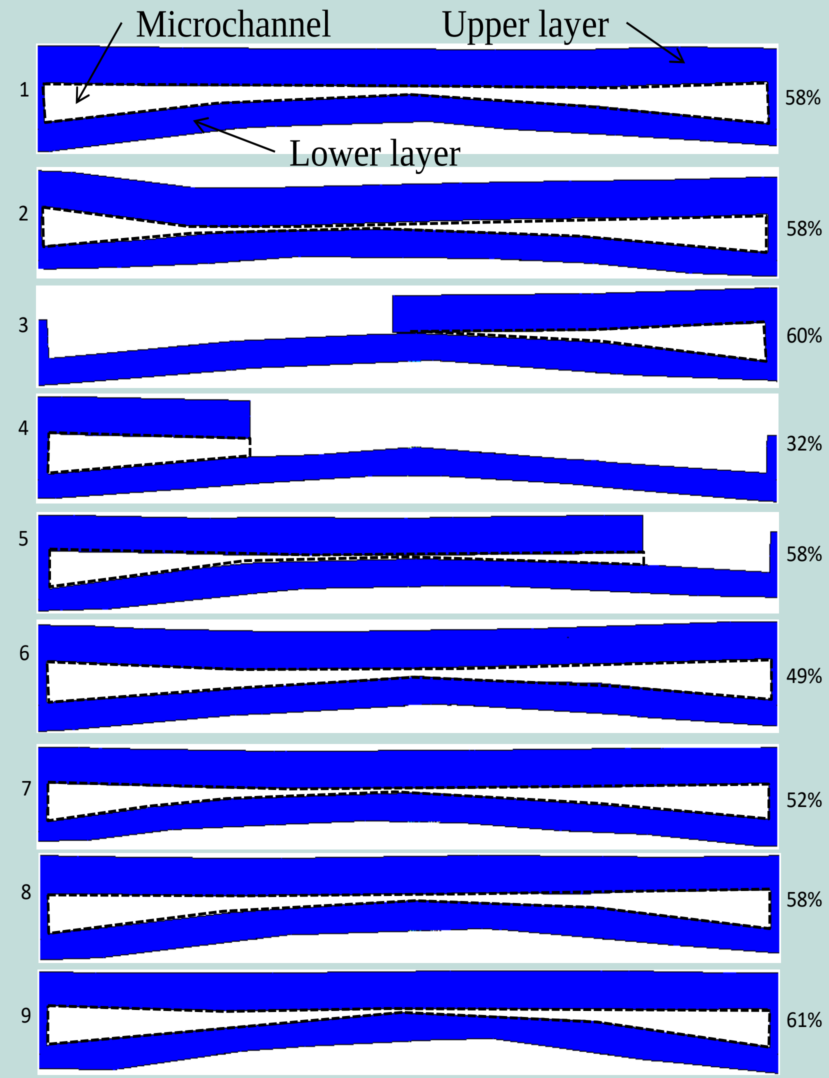
Enhanced cable insulation



Enhanced cable insulation

ANSYS model (C. Lorin)

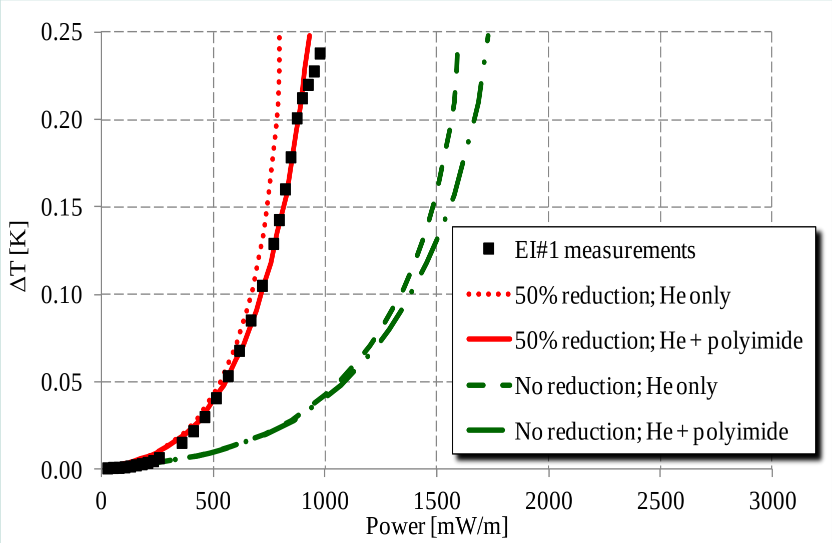


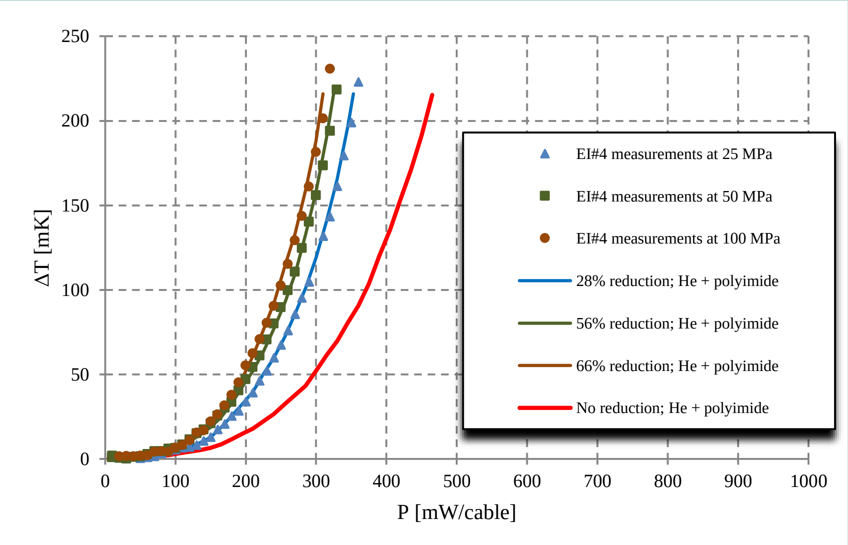


The ANSYS model shows that the cross-section of the channels is strongly reduced, i.e., by 20 to 60% depending on the applied pressure,

Insulation	EI#1			EI#4		
Load (MPa)	30	60	100	25	50	100
Average	22%	33%	42%	20%	39%	54%
Maximum	30%	61%	62%	25%	52%	61%
Network Model	50%	-	-	28%	56%	66%

Summary



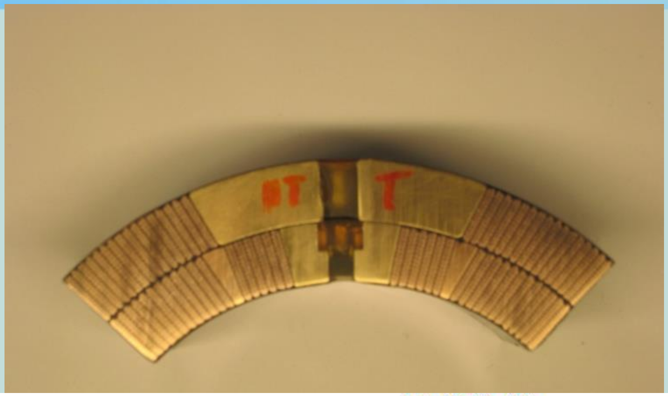


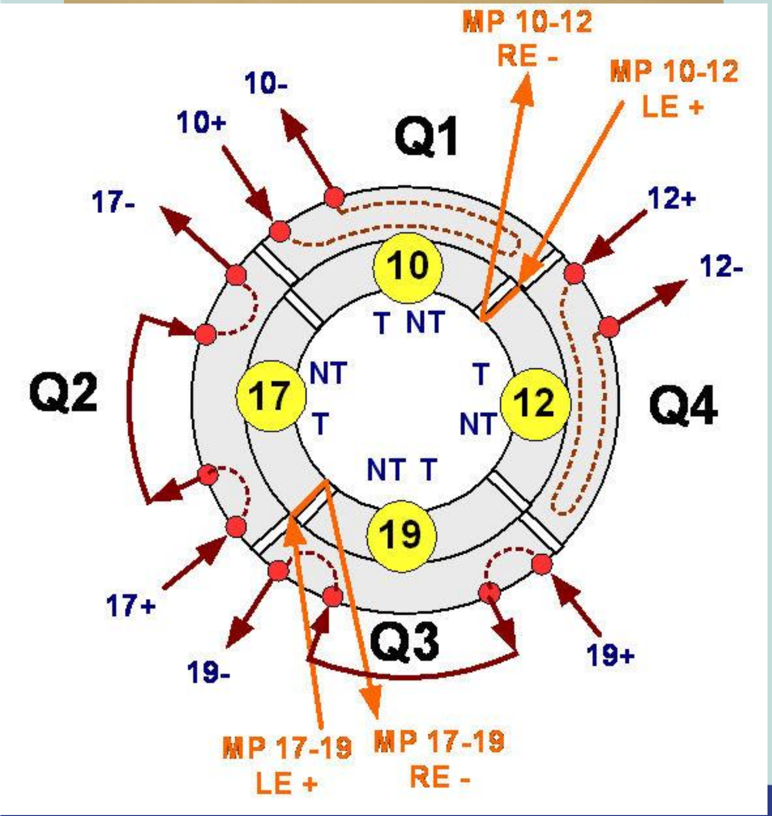
- Enhanced insulation studies completed
- Model validation performed
  - → One fitting parameter (channel geometry and cross-section)
  - → Agreement with measurements when He channel sizes reduce by 50%
  - → Model checked with ANSYS simulatons

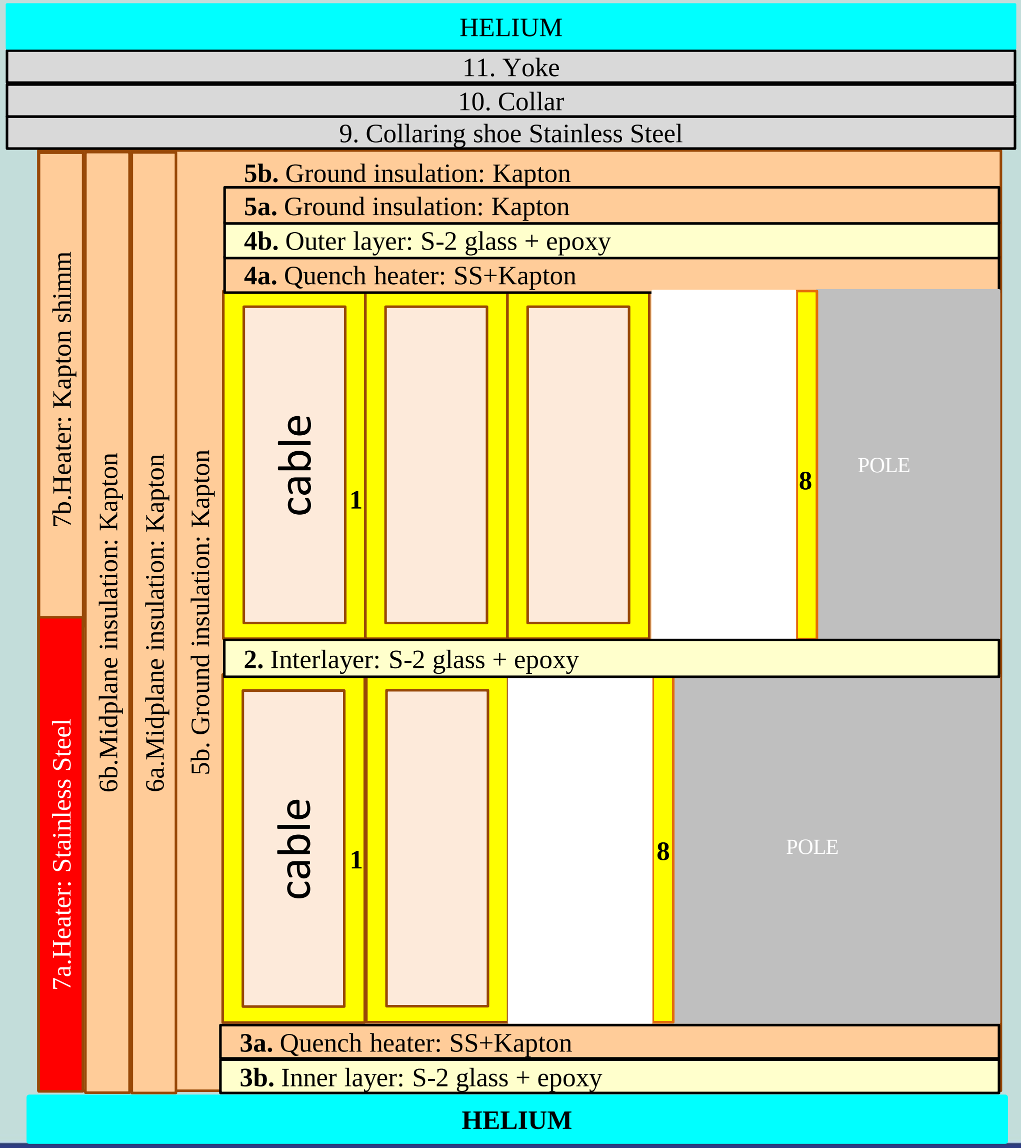
Network Model - Validation

What next?

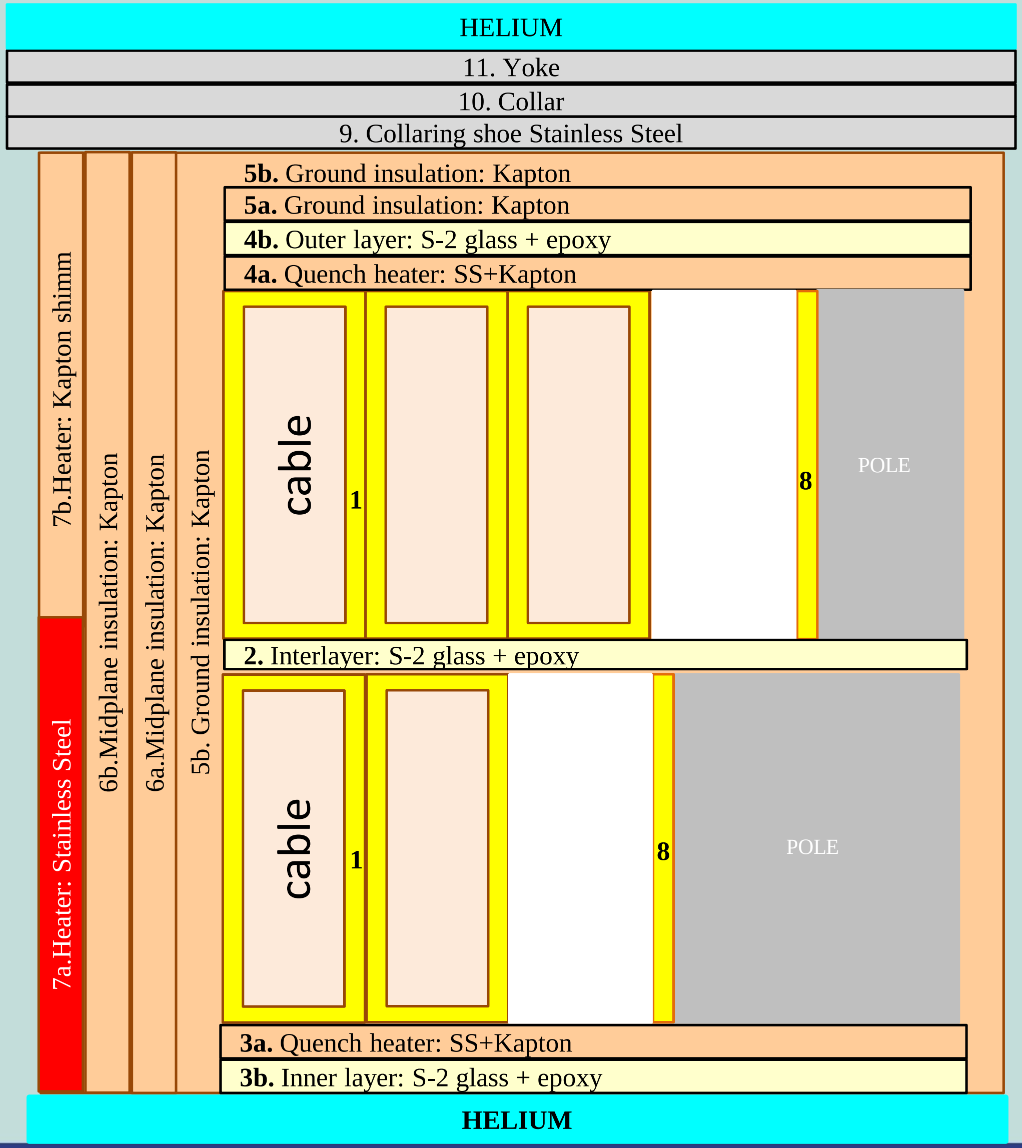
Model validation - TQ magnet







Model validation - TQ magnet



Data from measurements

TQC02a parameters			
layer	material	MJR	RRP
		[mil]/[mm]	[mil]/[mm]
1	S-2+epoxy	**3.9/ 0.099**	**3.75 / 0.095**
2	S-2+epoxy	**12.9/ 0.327**	**6.5/ 0.165**
3a	Kapton	1.7/0.043	0
3b	S-2+epoxy	**11.8 / 0.299**	**8.2 / 0.208**
4a	Kapton	1.7/0.043	1.7/0.043
4b	S-2 +epoxy	**10.77 / 0.273**	**6.5/ 0.165**
5a	Kapton	**5 / 0.127**	**5 / 0.127**
5b	Kapton	**5 / 0.127**	**5 / 0.127**
6a	Kapton	**3 / 0.0762**	**3 / 0.0762**
6b	Kapton	**2 / 0.0508**	**2 / 0.0508**
7a	Stainless steel	**1/0.0254 (9.5 mm width)**	**1/0.0254 (9.5 mm width)**
7b	Kapton	**1/0.0254**	**1/0.0254**
8	S-2+epoxy	**3 / 0.0762**	**3 / 0.0762**
9	Stainless steel	**31/0.7874**	**31/0.7874**

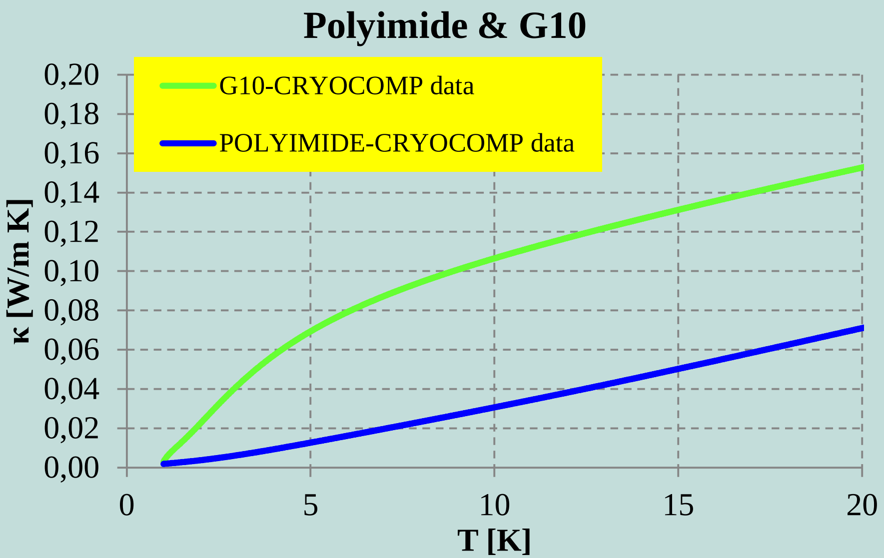
Model parameters - Material properties

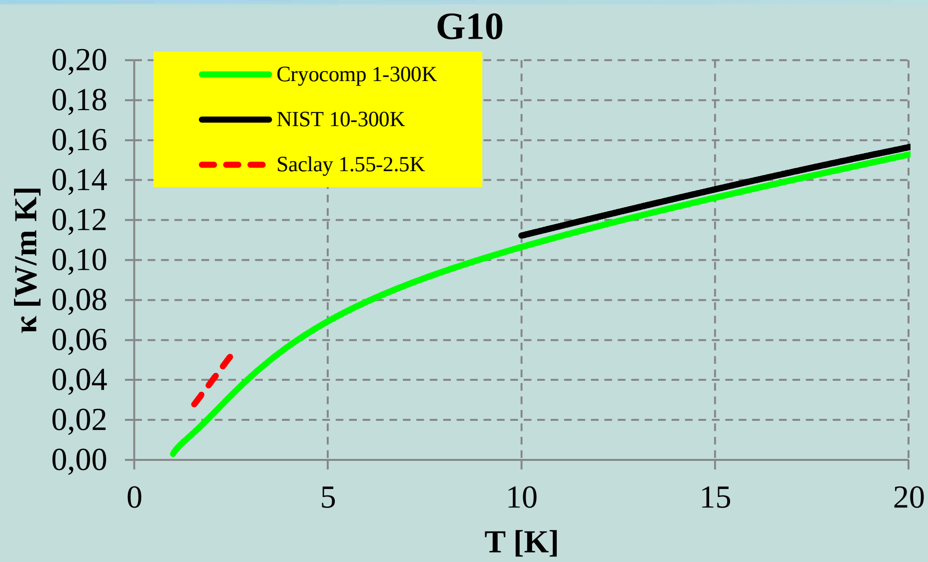
- Material properties at low temperatures

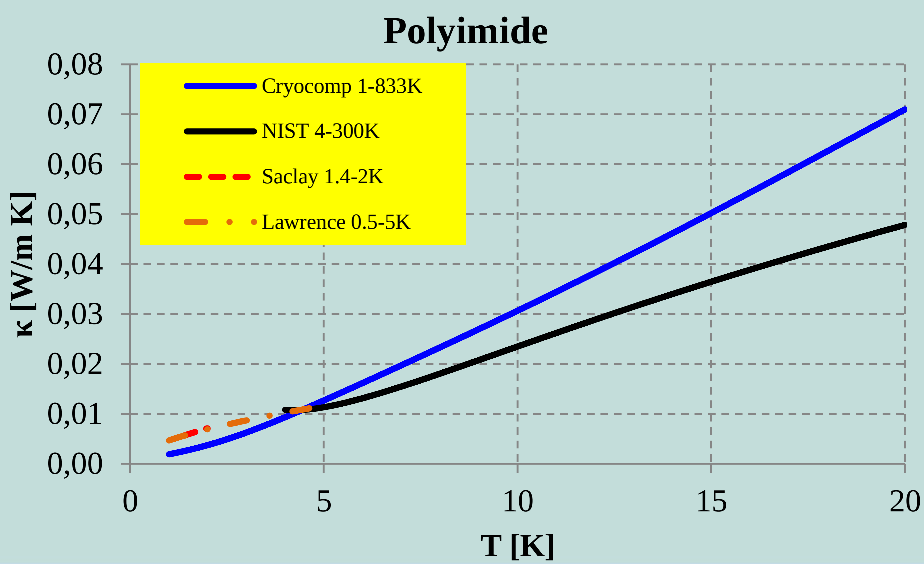
  → Coil insulation (Polyimide, G10)

  → **experimental data available**

Material data implemented in Network Model







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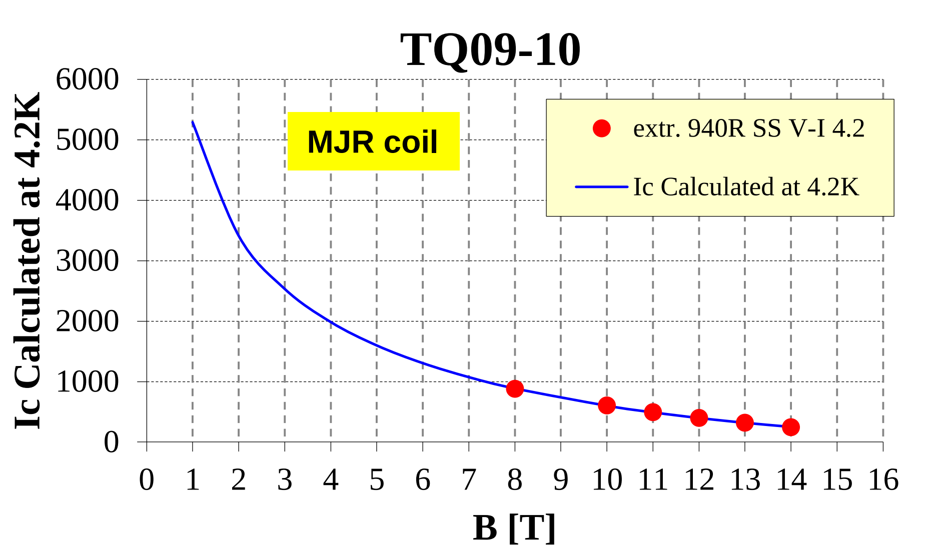
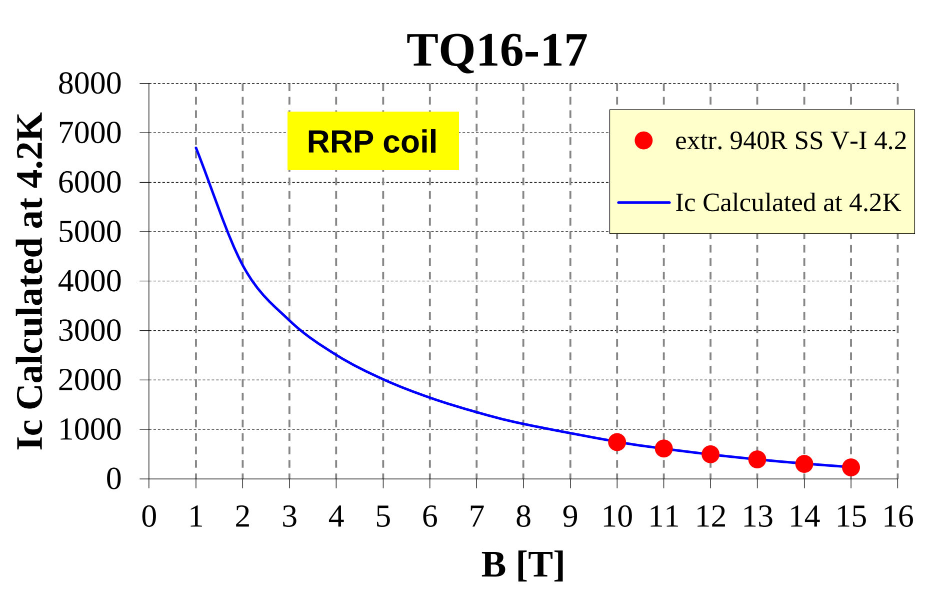
2. Lawrence et al., „ The thermal conductivity of Kapton HN between 0.5 and 5 K", Cryogenics 40 (2000), 203-207,
3. B. Baudouy, J. Polinski, „*Thermal conductivity and Kapitza resistance of epoxy resin fiberglass tape at superfluid helium temperature*", Cryogenics 49(2009), 138-143

Model parameters - Critical current parametrization





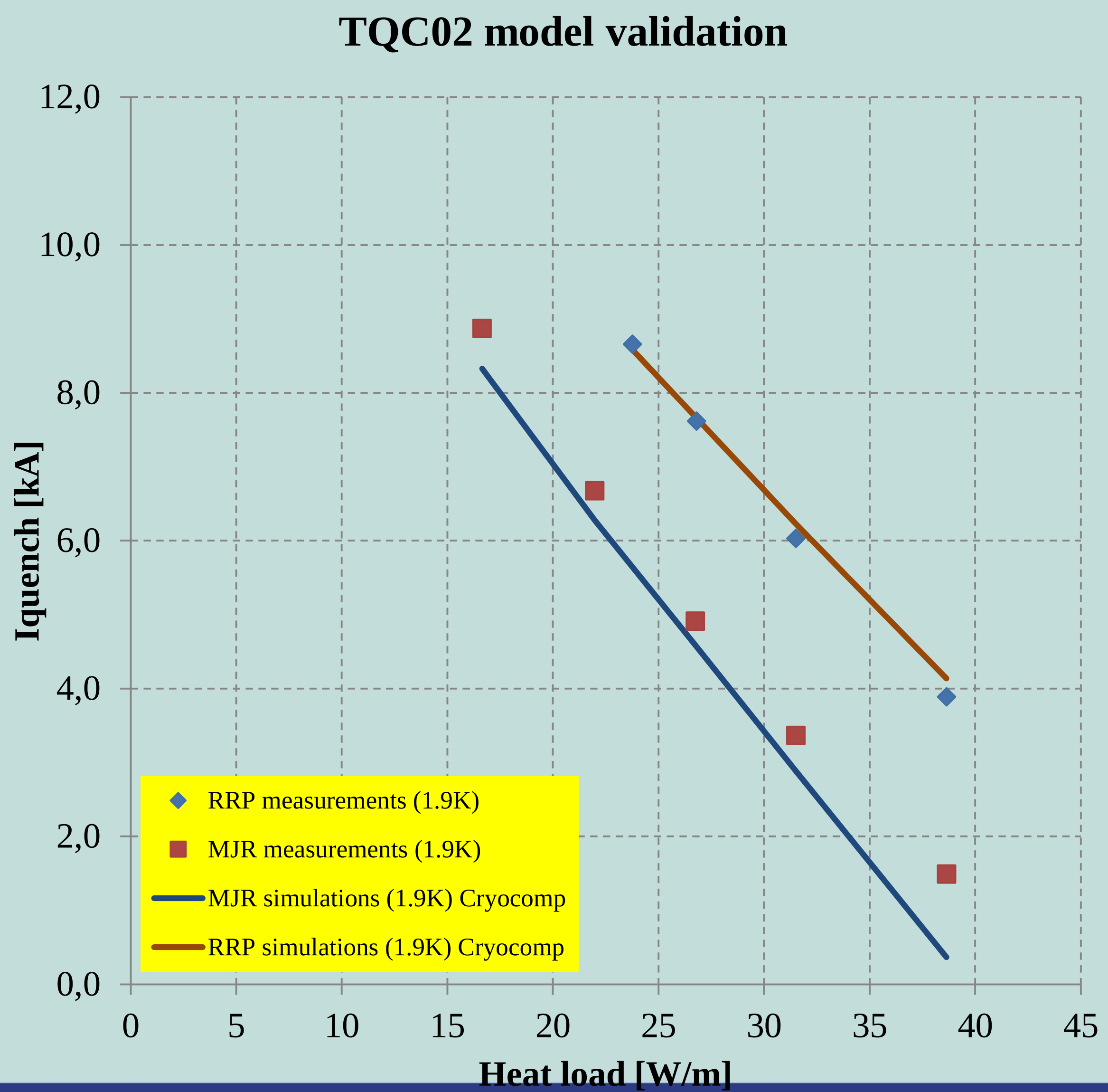
Critical current parametrization:
Bref=12T, Tref=4.2K

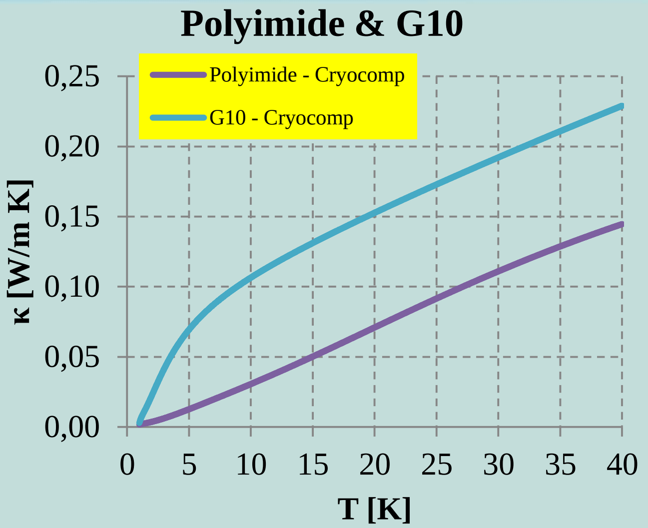
MJR:
Jcref=1954 A/mm2
Tc0= 17.6 K
Bc20= 26.6 T
C0=31848 A/mm^2 T$^{1/2}$

RRP:
Jcref=2404 A/mm2
Tc0=17.2 K
Bc20=26.3 T
C0=40558 A/mm^2 T$^{1/2}$

L.T. Summers, M.W. Guinan, J.R. Miller, P.A. Hahn, *A model for the prediction of Nb3Sn critical current as a function of field, temperature, strain and radiation damage*, *IEEE Trans. Magn.*, 27 (2): 2041-2044, 1991.

Thermal model of LARP TQ magnets





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Tref=4.2K

RRP:
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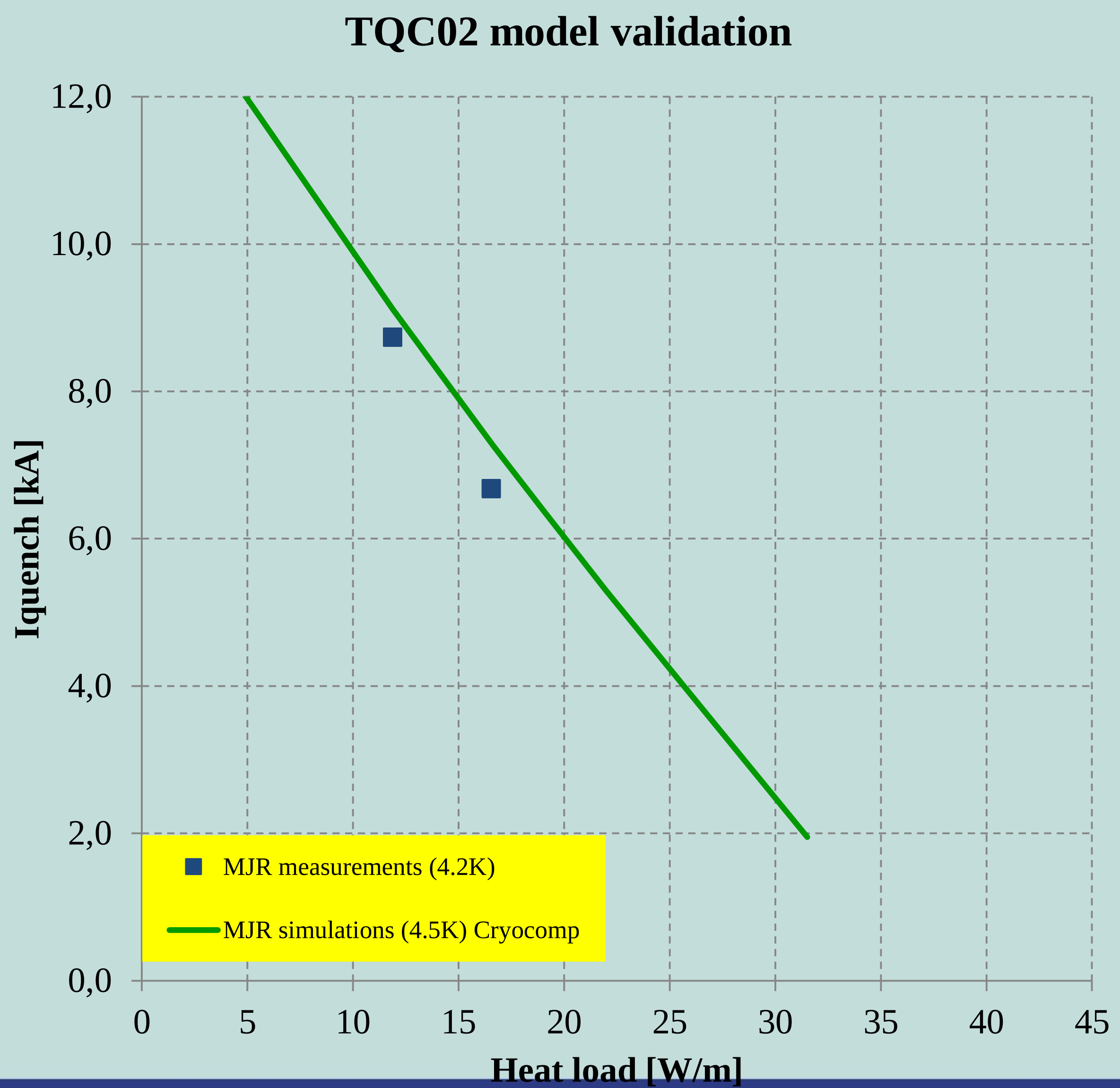
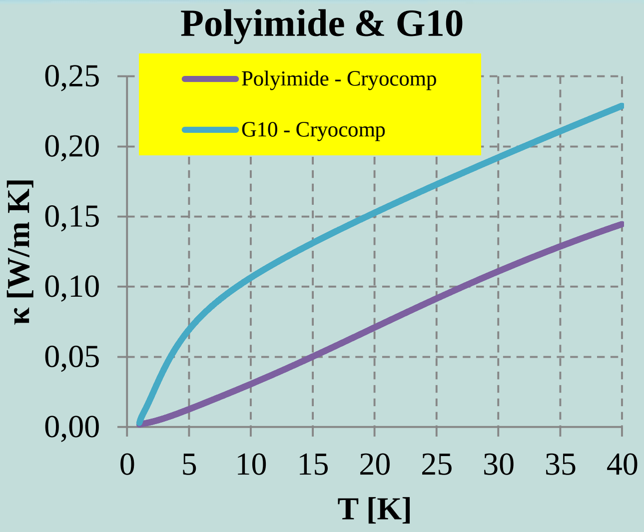
Tc0=17.2
Bc20=26.3
C0=40558

MJR:
Jcref=1954 A/mm2
Tc0= 17.6
Bc20= 26.6
C0=31848

Thermal model of LARP TQ magnets





Citical current parametrization:
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RRP:
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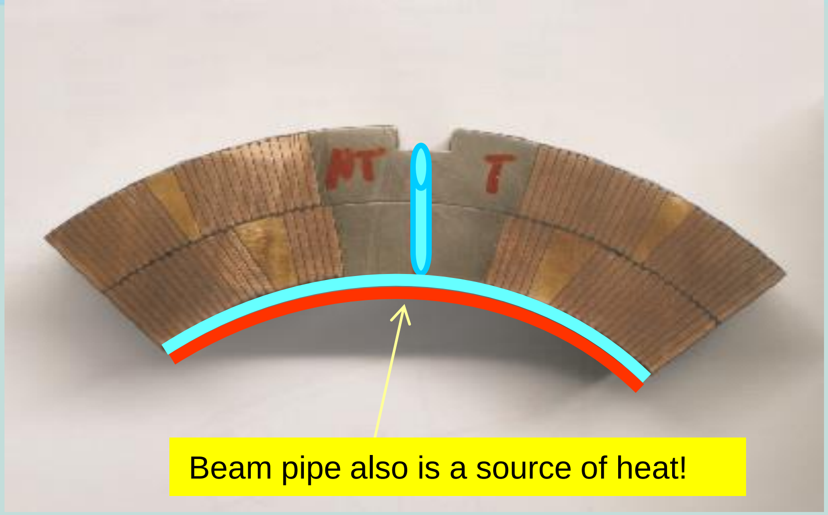
Tc0=17.2
Bc20=26.3
C0=40558

MJR:
Jcref=1954 A/mm2
Tc0= 17.6
Bc20= 26.6
C0=31848

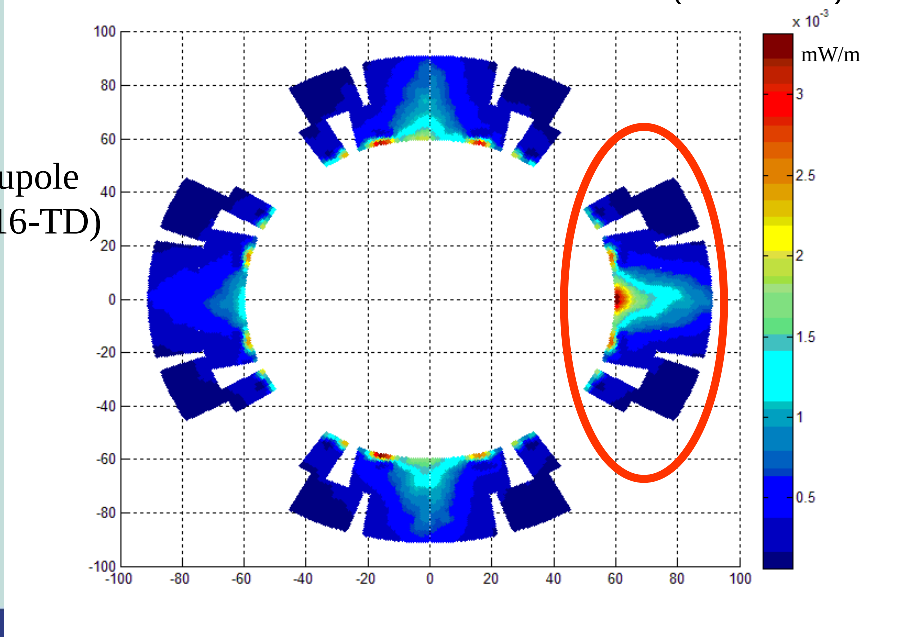
What next?

Nb_3Sn HQ magnets modeling

- LARP Nb_3Sn thermal modeling objectives:
  - → **HQ coil insulation study → feedback to coil design**
  - → size of the He channels in the HQ magnets
    - around cold bore
    - in the poles
  - → Magnets quench limit calculation
    - MARS/FLUKA input needed



MARS simulations for L=2.5*10^34 (N. Mokhov)

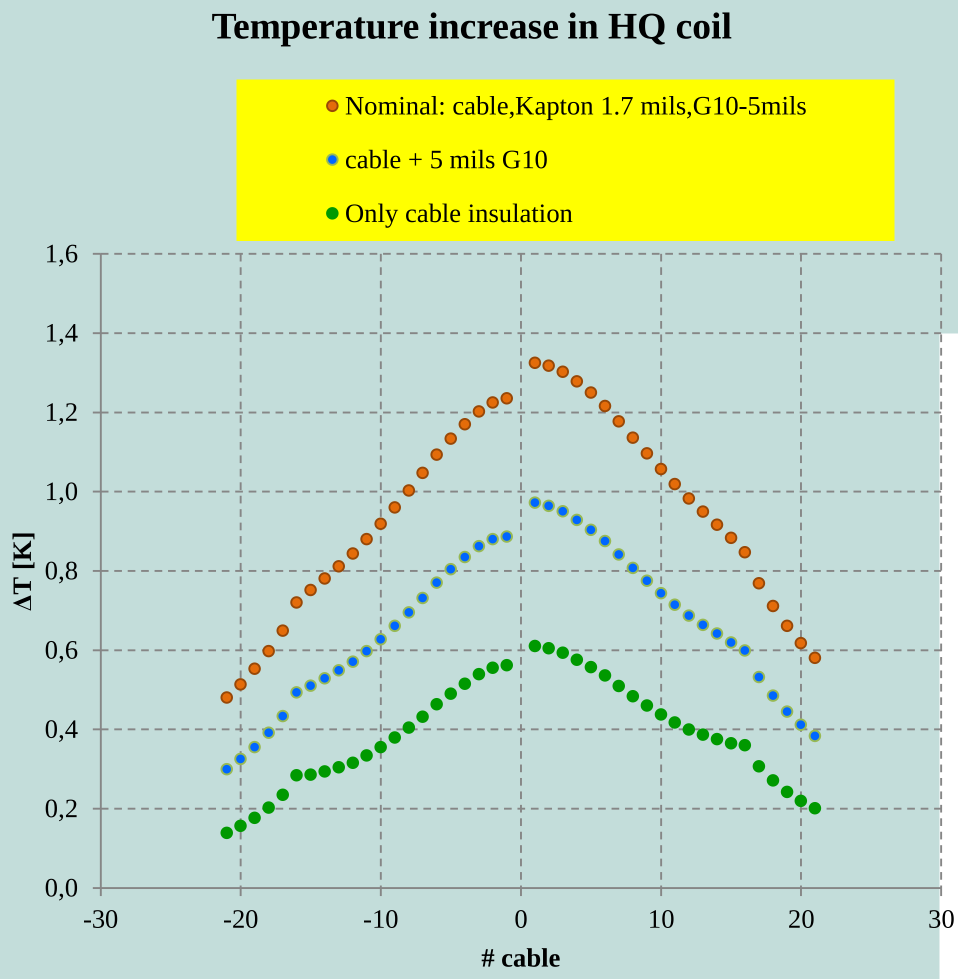


- Heat load simulations with MARS

(3 mm segmented tungsten absorber
Details: V.V. Kashikhin et al., „Performance of Nb_3Sn quadrupole magnet under localized thermal load"Fermilab-conf-09-316-TD)

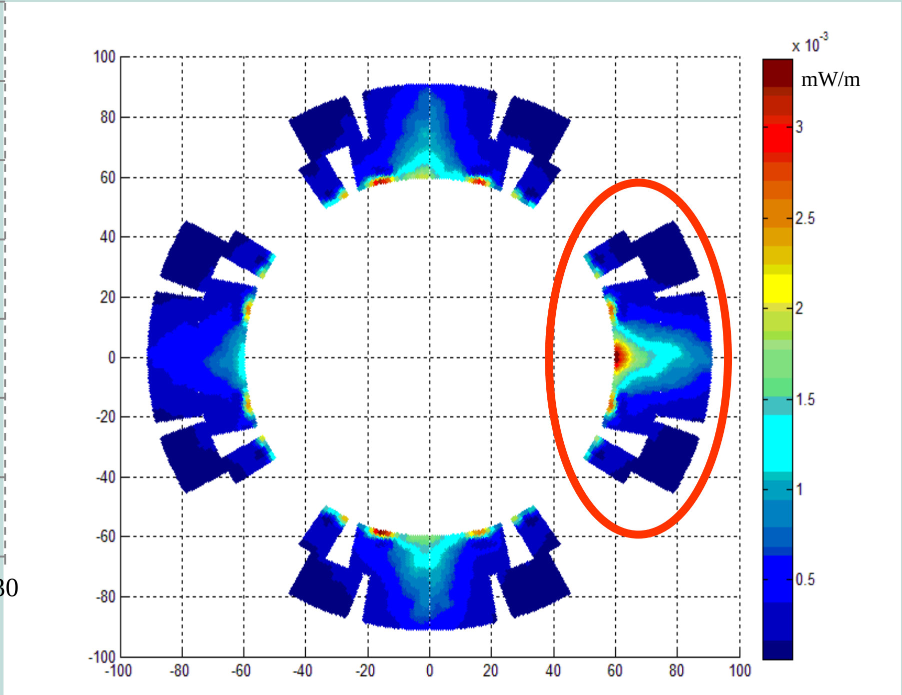
  - → Heat load interpolation algorithm implement (agree heat load map with conductor map)

Nb_3Sn HQ magnet modeling - results



LARP Nb_3Sn thermal modeling :

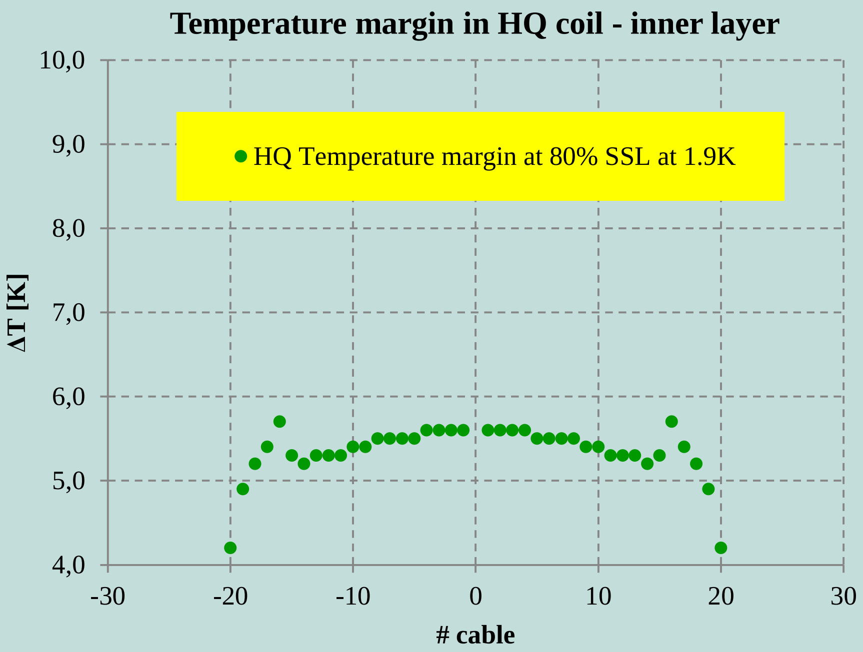
- → **Heat load (HL) = 2*MARS simulations (L=5*10^34)**
- → **HQ inner coil insulation impact**
- → size of the He channels in the HQ magnets
  - around cold bore ← set 1.29 mm
  - in the poles ← set d=5 mm every 10 cm
- → HL in the beam pipe = HL inner cable layer

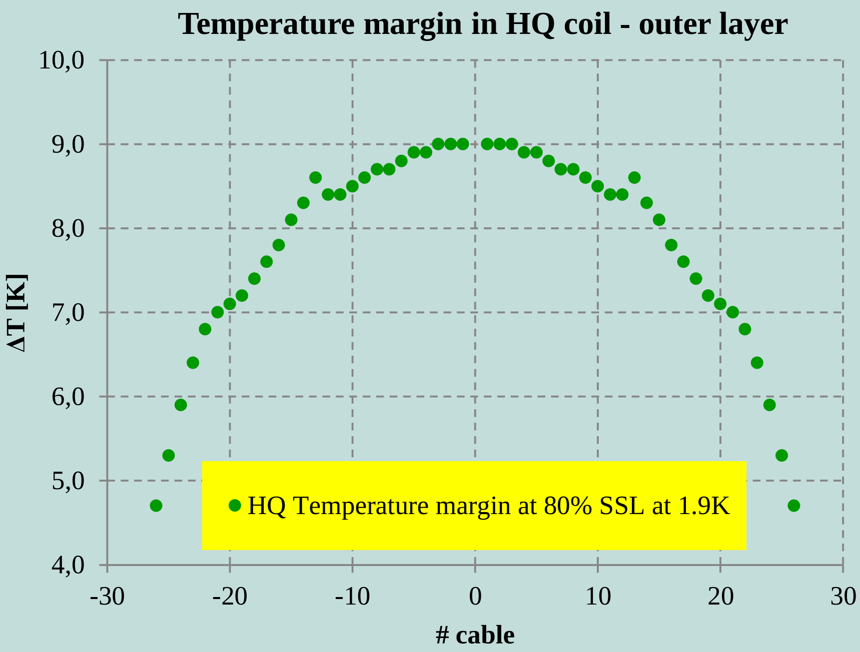


MARS simulations for L=2.5*10^34 (N. Mokhov)

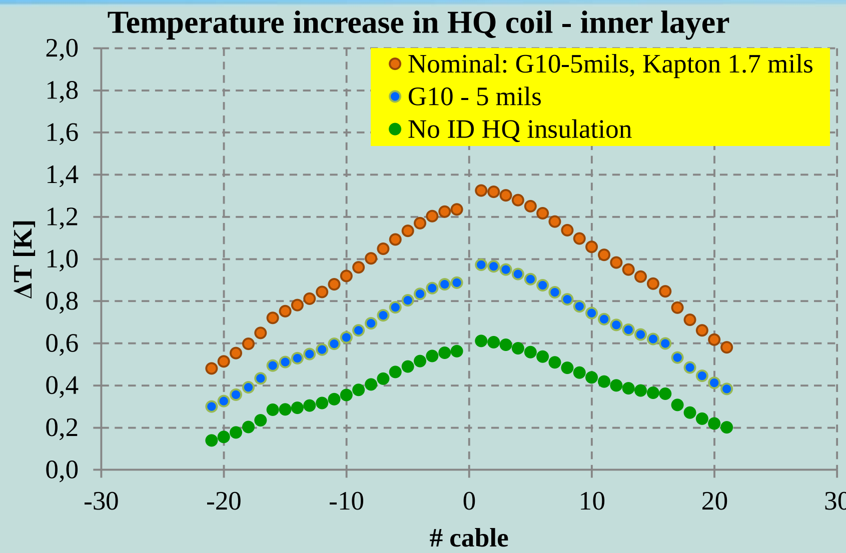
Nb_3Sn HQ magnet – Temperature margin

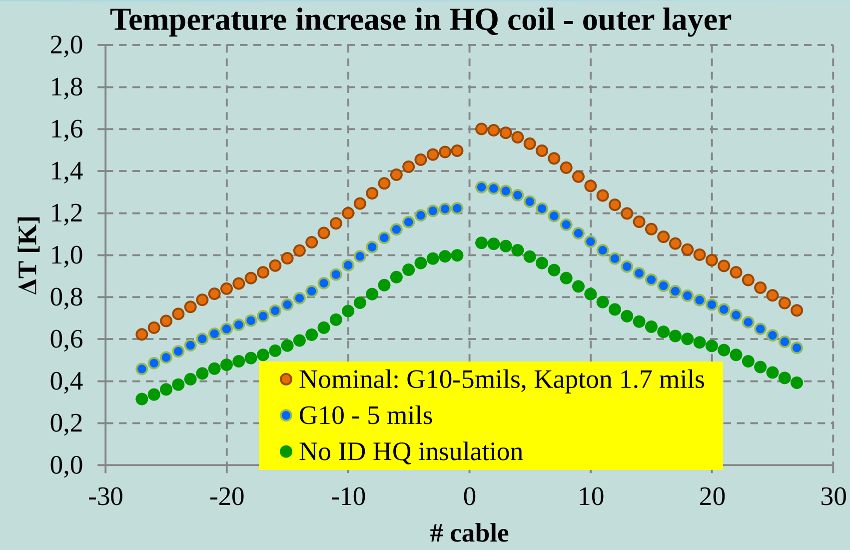
H. Felice – HQ ROXIE simulations

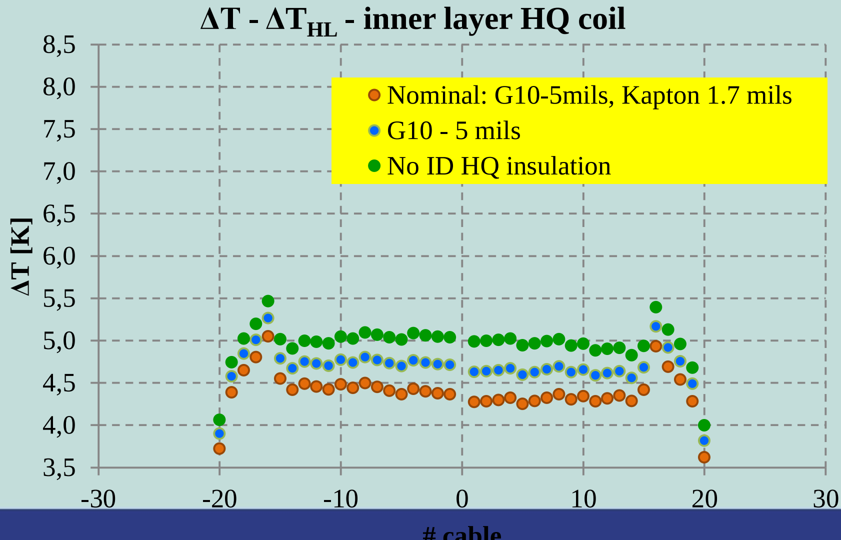




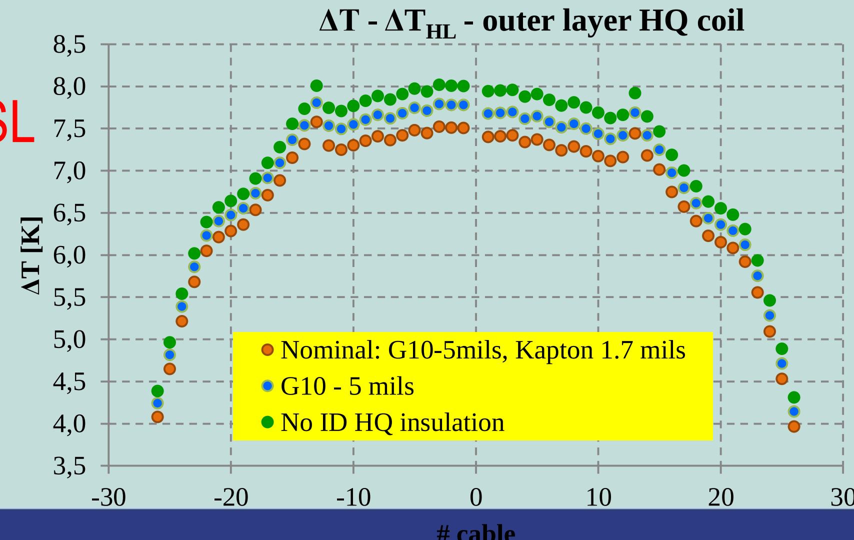
Nb_3Sn HQ modeling - results





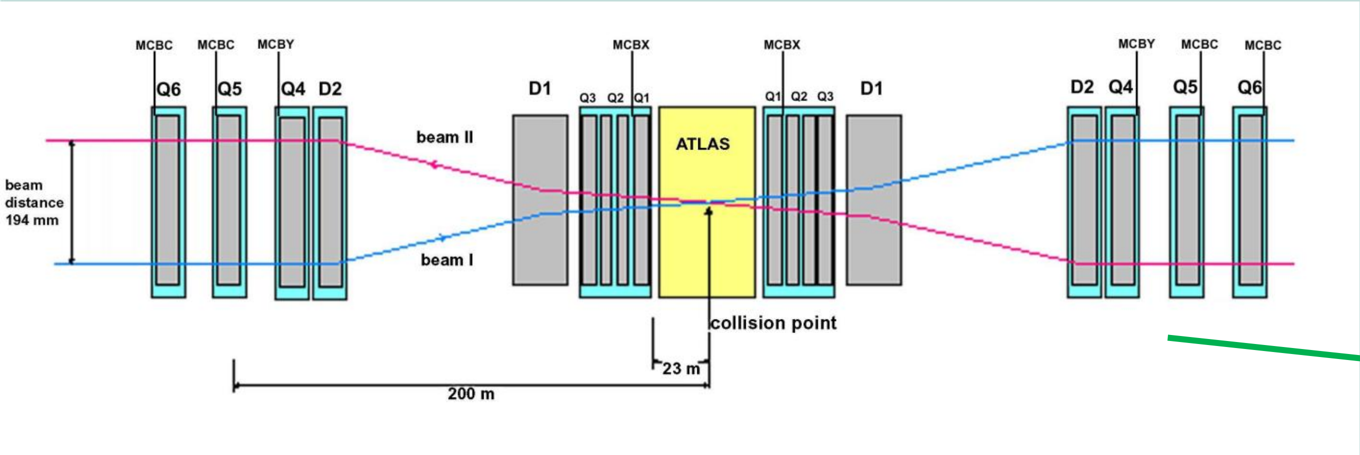


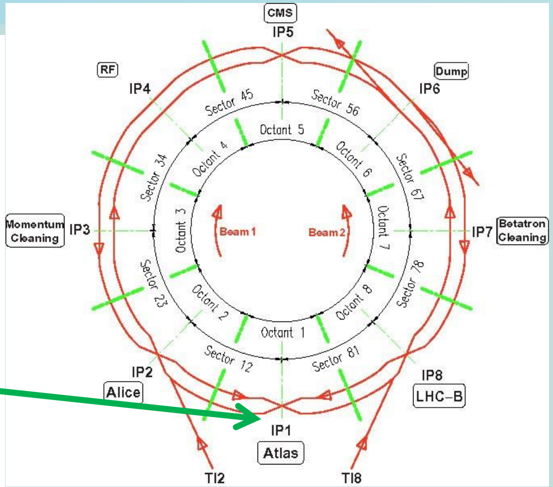
80% SSL
1.9K

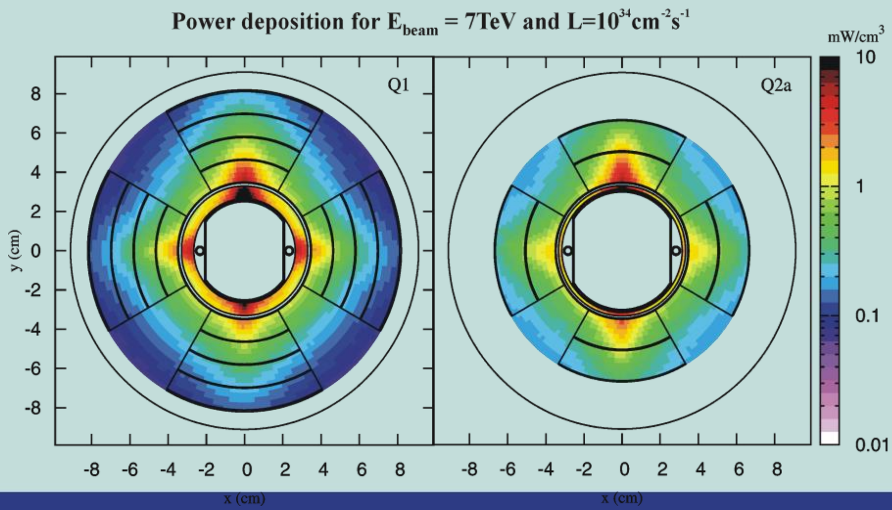


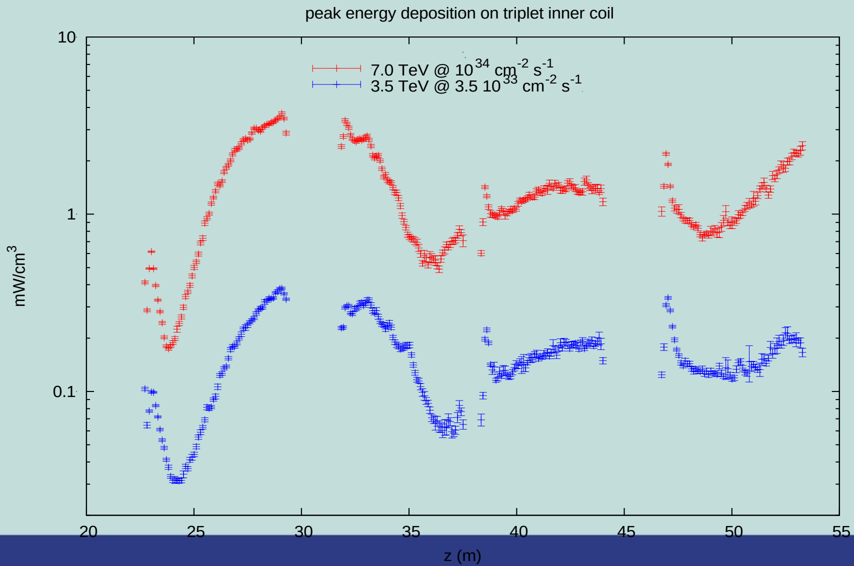
What next?

Quench limit calculation

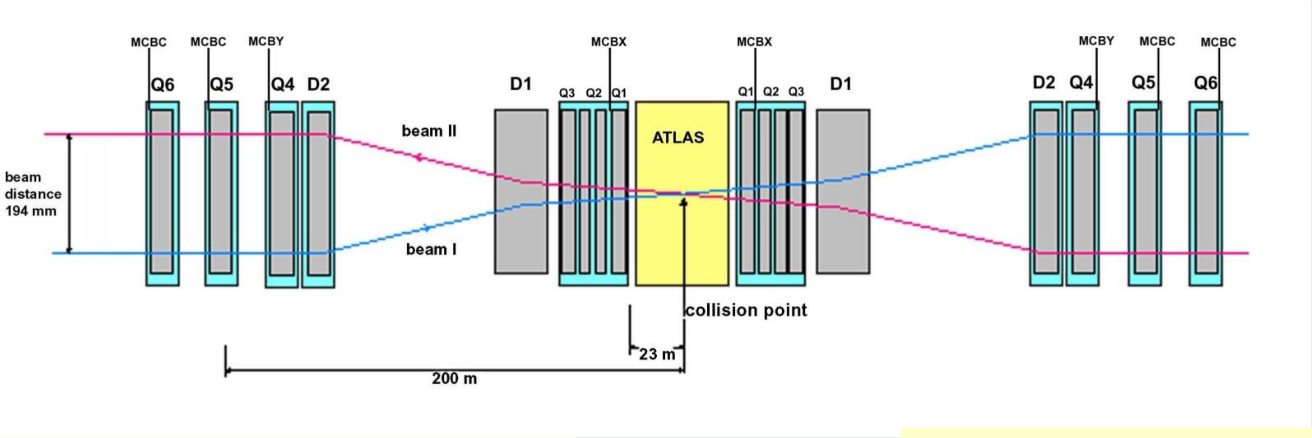


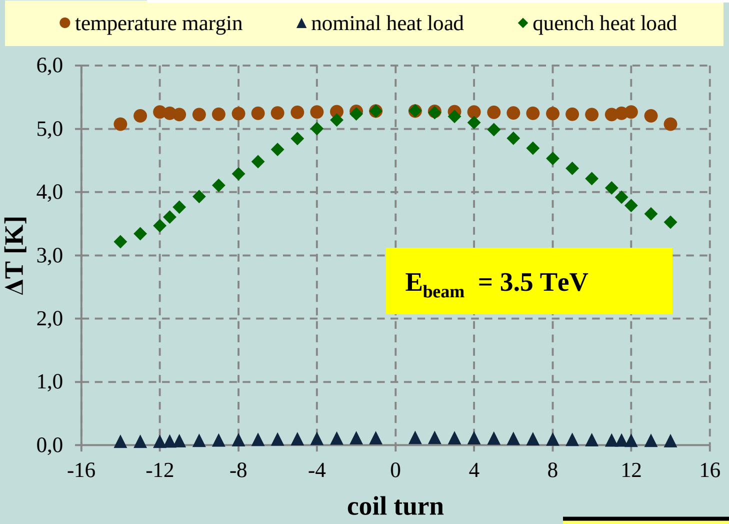


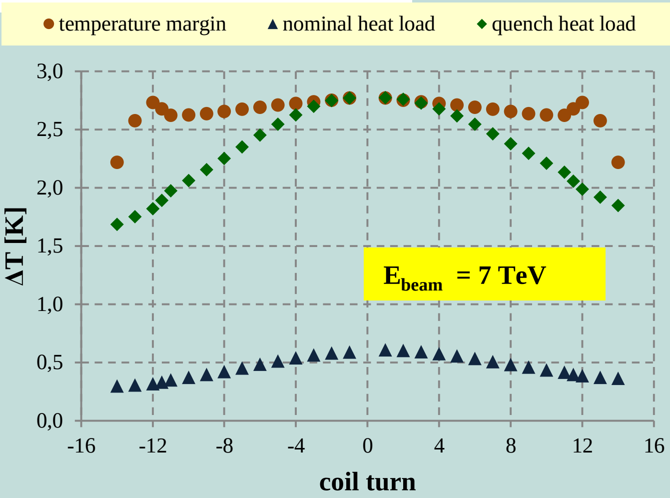




Quench limit calculation







Beam Energy (TeV)	Calculated Heat Load (mW/cm^3)	Quench Limit (mW/cm^3)
3.5	0.35	24*
7.0	3.5	9.1

Summary

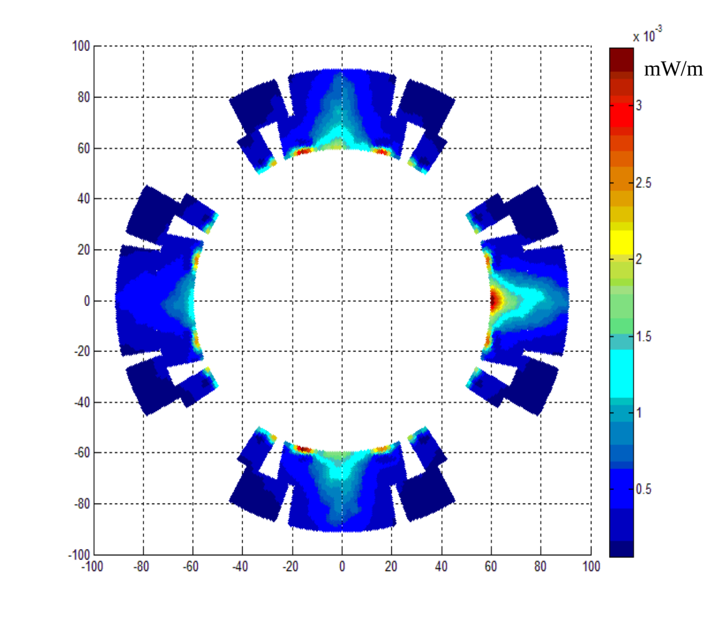
- Reliable thermal models of superconducting magnets have been developed
- Model was validated with measurements performed at CERN and FNAL
- Model was cross checked with COMSOL
- Model calculated LHC magnets quench limits at steady state conditions
- Model wass used to study the impact of new magnets design parameters on magnet thermal performance

D. Bocian, „Heat Transfer in High Field Superconducting Accelerator Magnets", monography: ISBN 978-83-63542-13-9

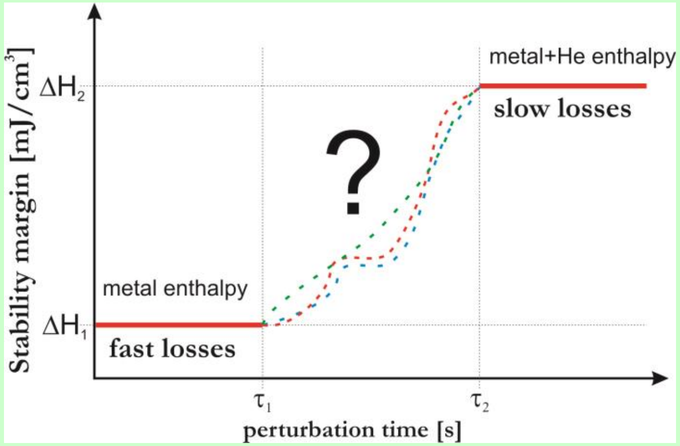
What next?

- Model to be implemented to transient cases?

Heat load in the LHC magnets



- Transient losses ~ns to ~ms
  - Enthalpy of the cable (metal only) (~ns)
  - Heat transfer to helium volume inside the cable (~μs)
  - Enthalpy of the cable (metal + He) (~ms)

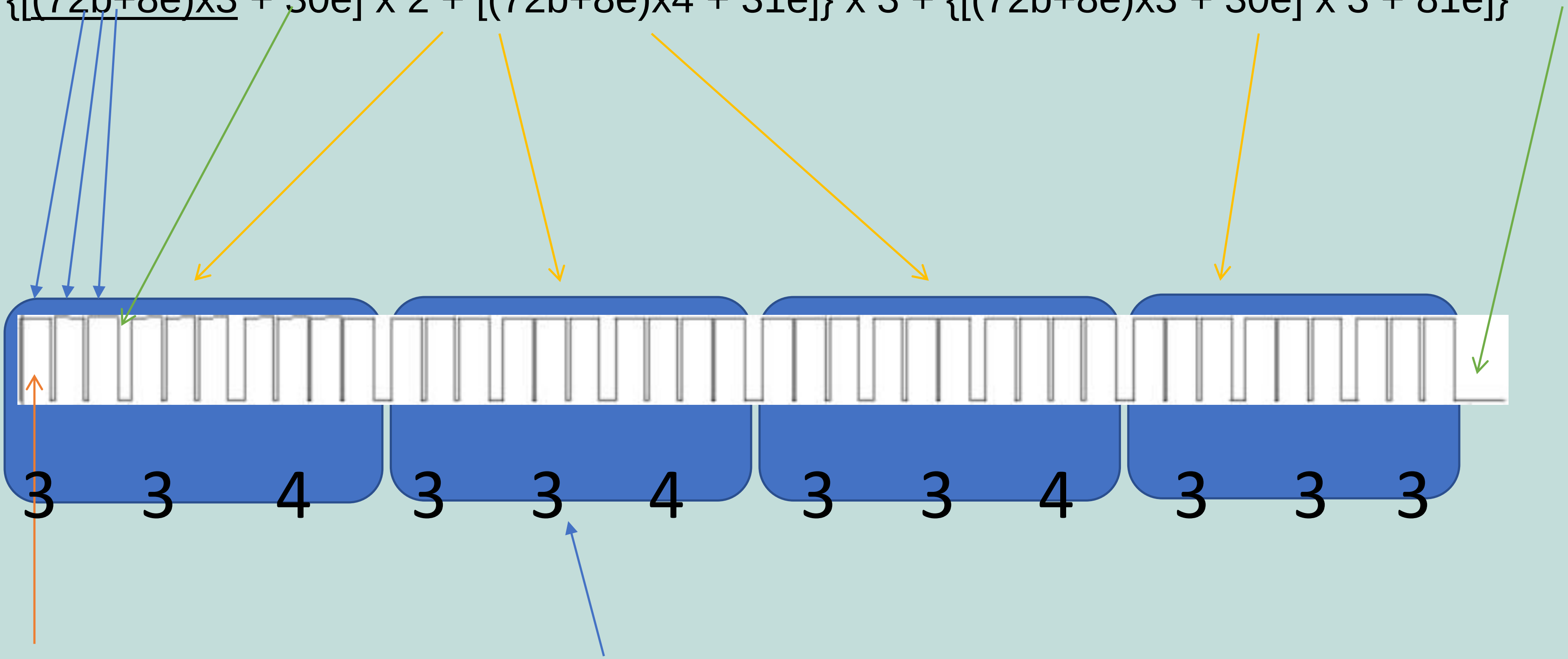


- Steady-state losses
  - Transfer of the heat from cable to the heat reservoir (~s)
  - Magnet structure and geometry of cooling channels

LHC beam structure

b – bunch; e – „empty” bunch

{[(72b+8e)x3 + 30e] x 2 + [(72b+8e)x4 + 31e]} x 3 + {[(72b+8e)x3 + 30e] x 3 + 81e]}



Carriage: 72 bunches

#carriages: 39

#time between bunches: 25 ns

What next?

Transient model!