Thermal study of Nb3Sn magnets

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LARP CM16

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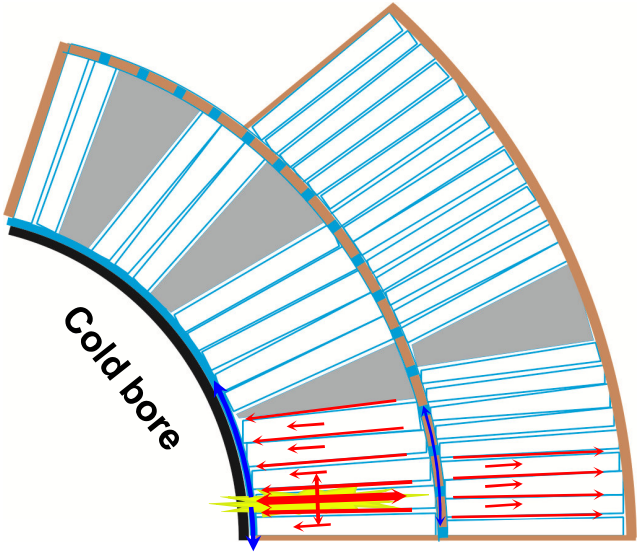
OUTLINE

- **Thermal analysis of superconducting magnets**
  - Motivation
  - Network Model construction
  - Thermal model of LARP Nb_3Sn quadrupole magnets
  - Model validation with TQC02b measurements
  - Thermal model of LARP HQ magnets
  - **HQ magnet study**
  - Conclusions
- **Study of Nb_3Sn conductor during heat treatment - shortly**
  - Motivation
  - Measurements
  - Results
- **Summary**

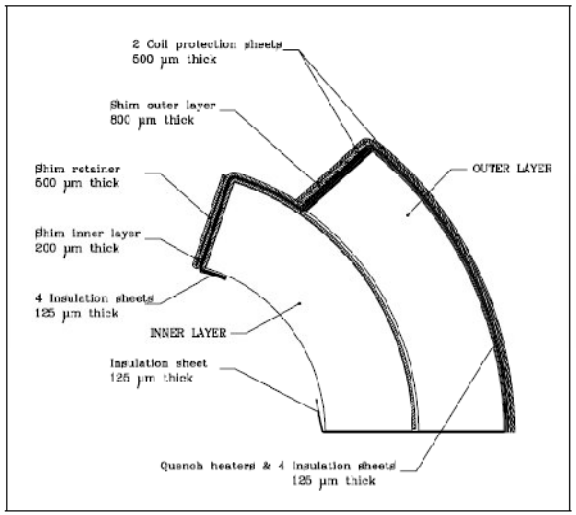
Thermal magnet study - Motivation

- Particles coming from proton-proton/ion-ion collision impact the LHC magnets
  - → energy deposition in the coils → possible magnet quench
  - → quench limits required for beam loss monitors → dump the beams before magnets quench
- Heat flow paths and heat flow barriers identification in the magnet
  - → quench limit of existing superconducting magnets (LHC)
  - → feedback to the future superconducting magnet designs
  - LARP Nb_3Sn quadrupole design
    - → impregnated coil → no helium link between the bath and the cable
  - New CERN quadrupole design
    - → enhanced insulation scheme → open helium paths between the bath and the cable

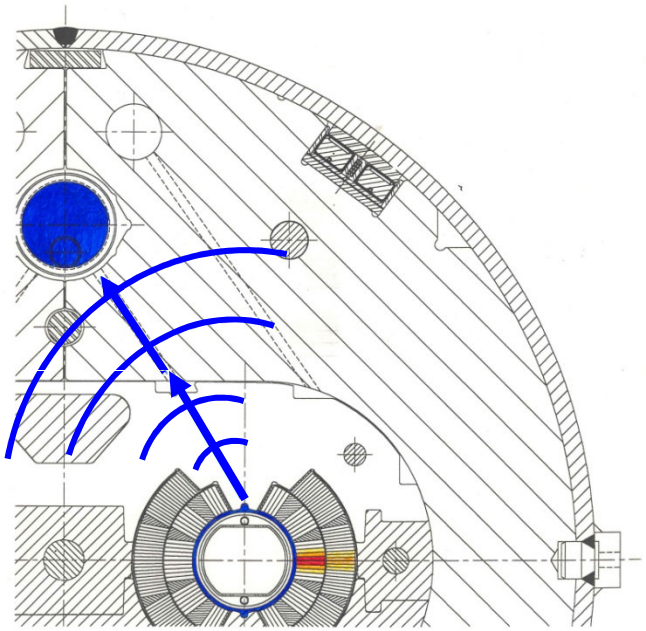
Heat transport in the magnet



inner layer outer layer

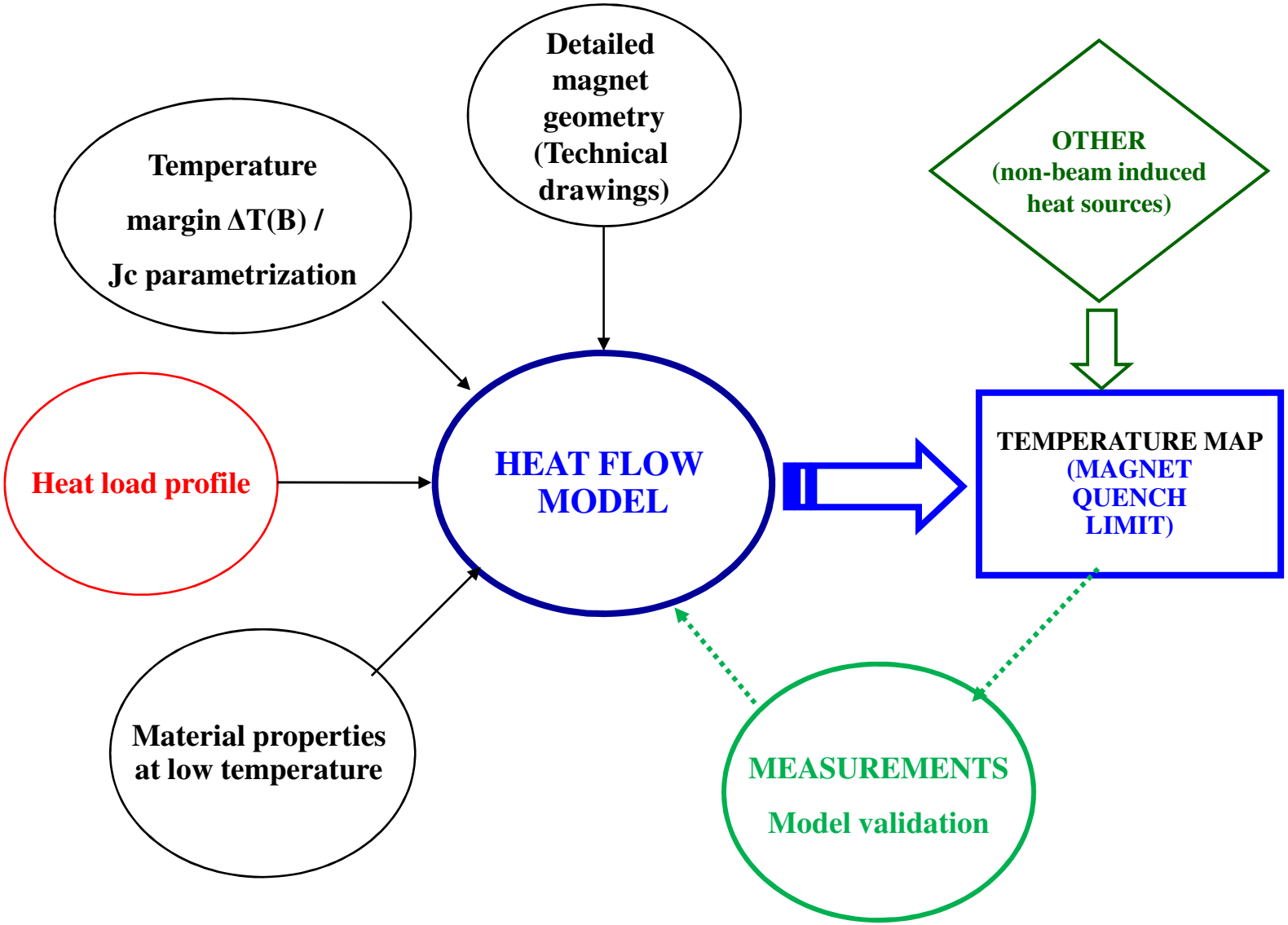


A heat transfer in the main dipole

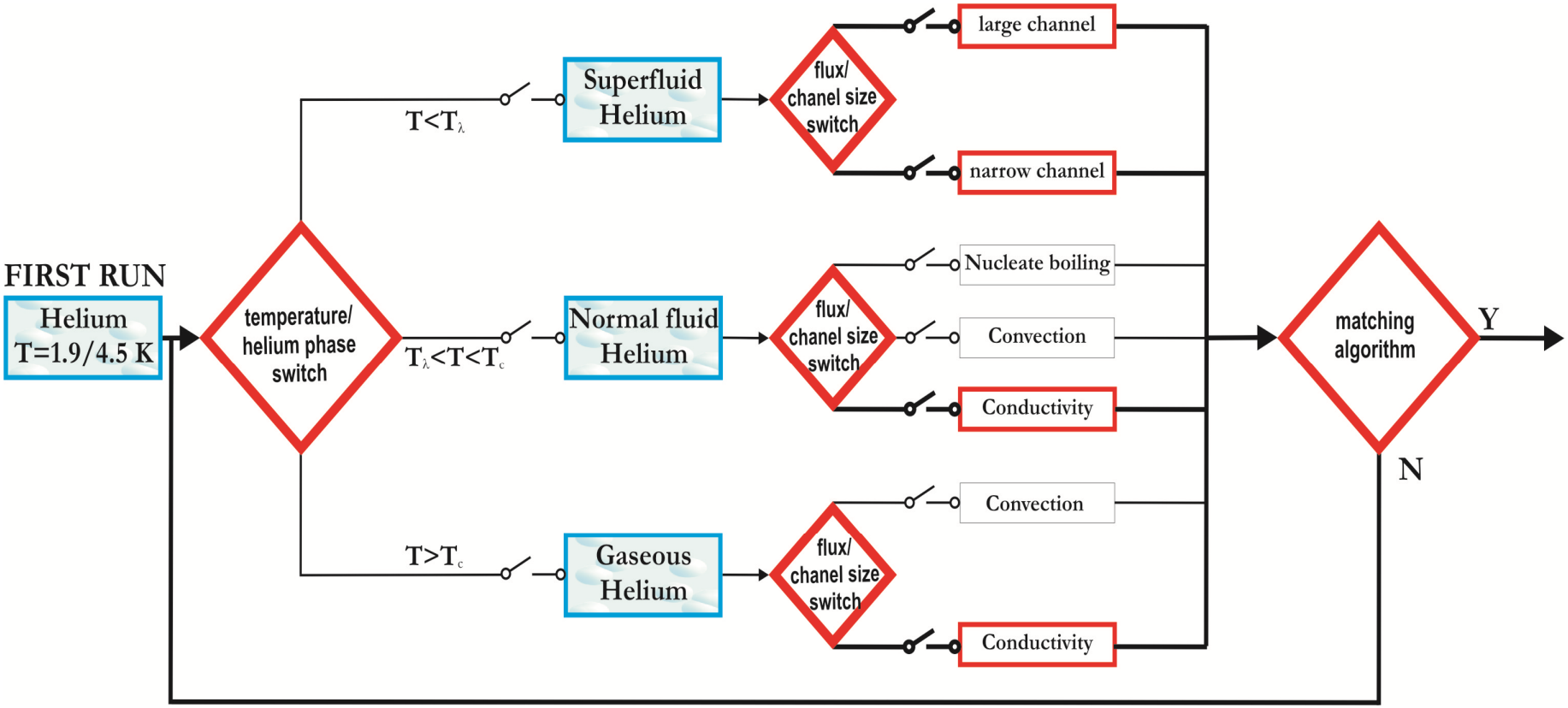


Cable insulation and helium channel around cold bore are the most critical parameters limiting heat flow from the magnet coil at steady state heat load

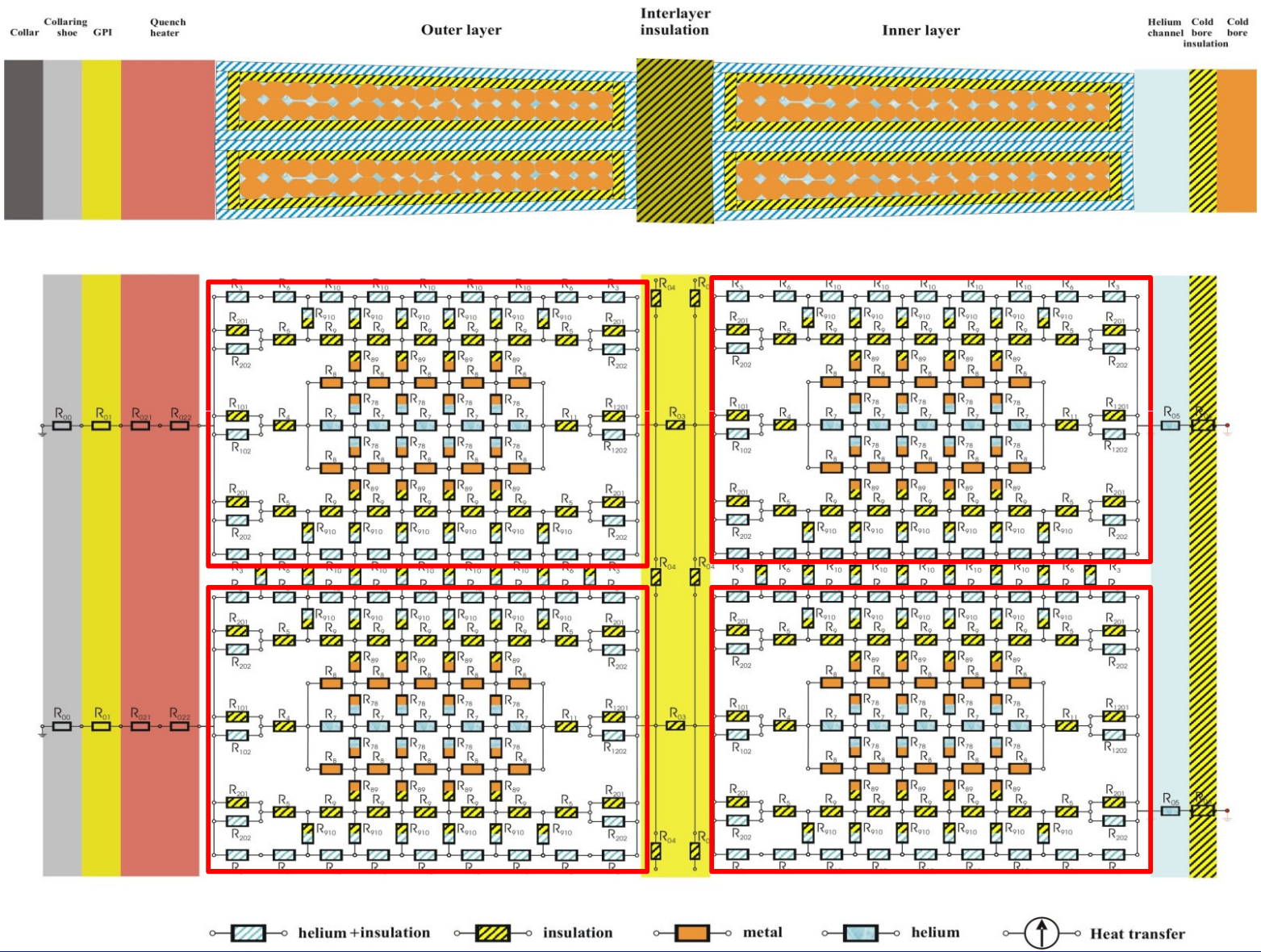
Network Model construction



Helium in the Network Model

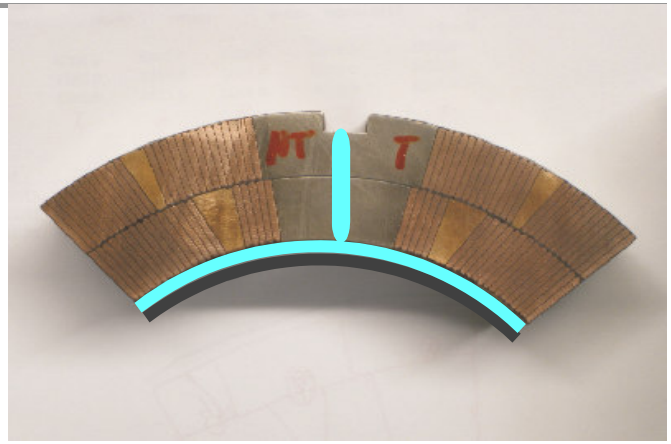


Network Model - coil modeling

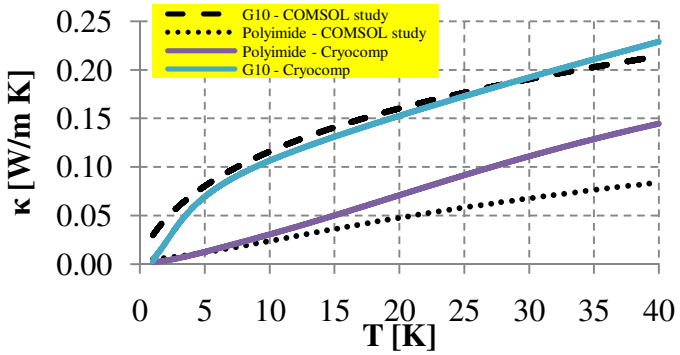


Modeling of Nb_3Sn magnets

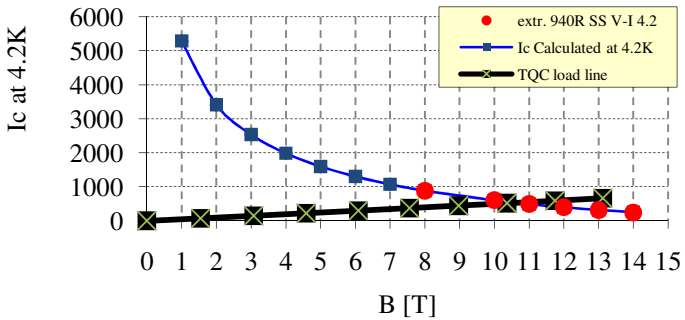
- LARP Nb_3Sn thermal modeling objectives:
  - → HQ coil insulation study → feedback to coil design
  - → size of the He channels in the HQ magnets
    - around cold bore
    - in the poles
  - → Optimization of heat extraction paths
  - → Magnets quench limit calculation ← MARS/FLUKA input
- Model parameters
  - Material properties at low temperatures
    - → Coil insulation (Polyimide, G10)
      →experimental data
  - Critical current parametrization
    - → critical current dependence on temperature
      → experimental data
- Model validation with measurements
  - → Measurements performed at Fermilab in 2008 with TQ
  - → New measurements with HQ?



Insulation



Critical current



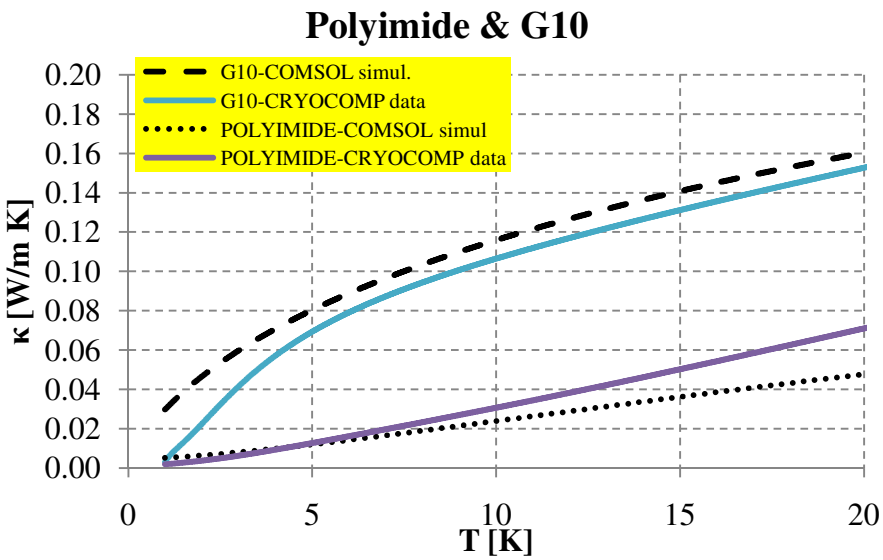
Model parameters - Material properties

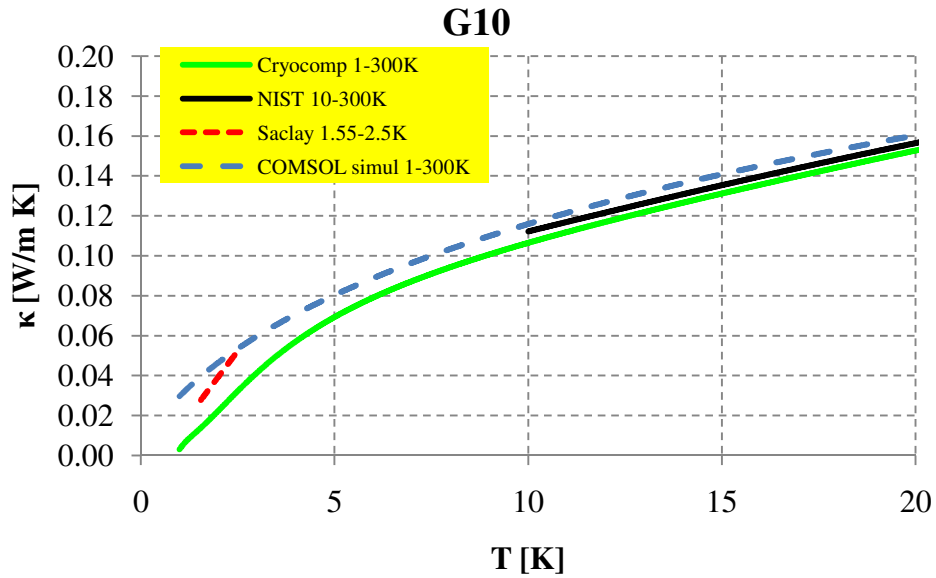
- Material properties at low temperatures

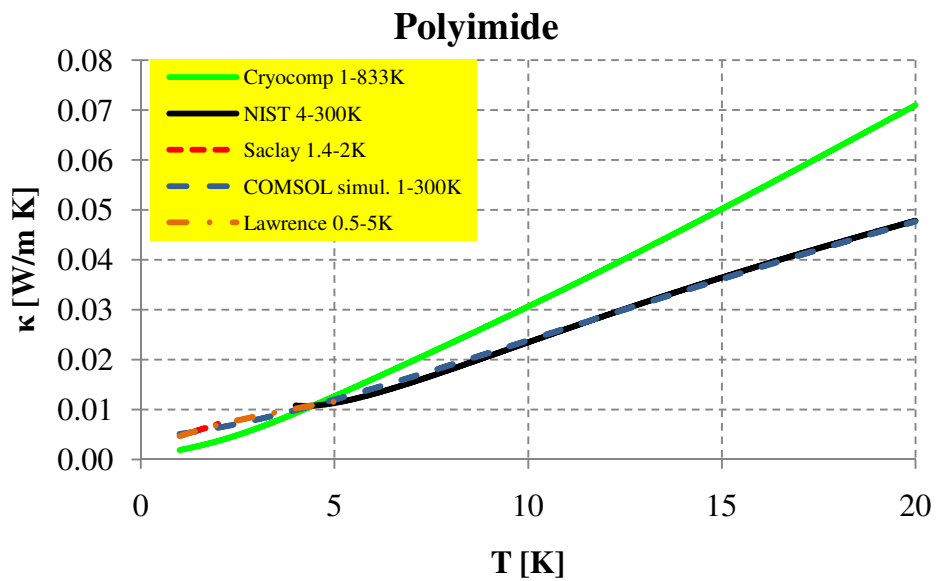
  → Coil insulation (Polyimide, G10)

  →experimental data available

Material data implemented in Network Model



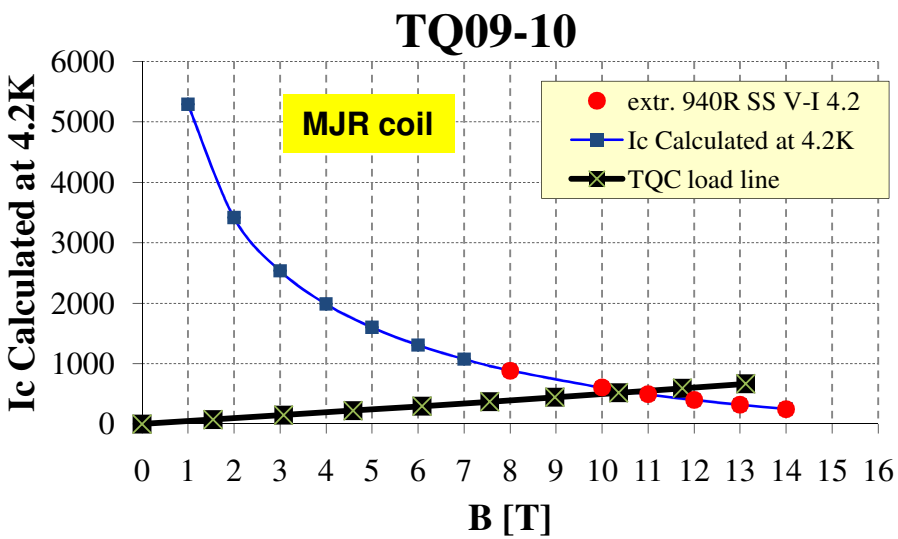


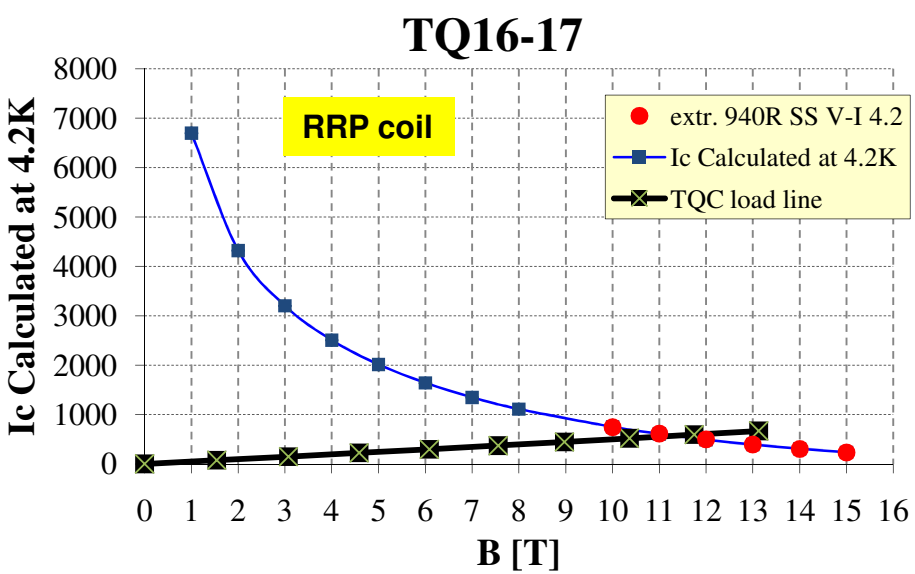


Bibliography:

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

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

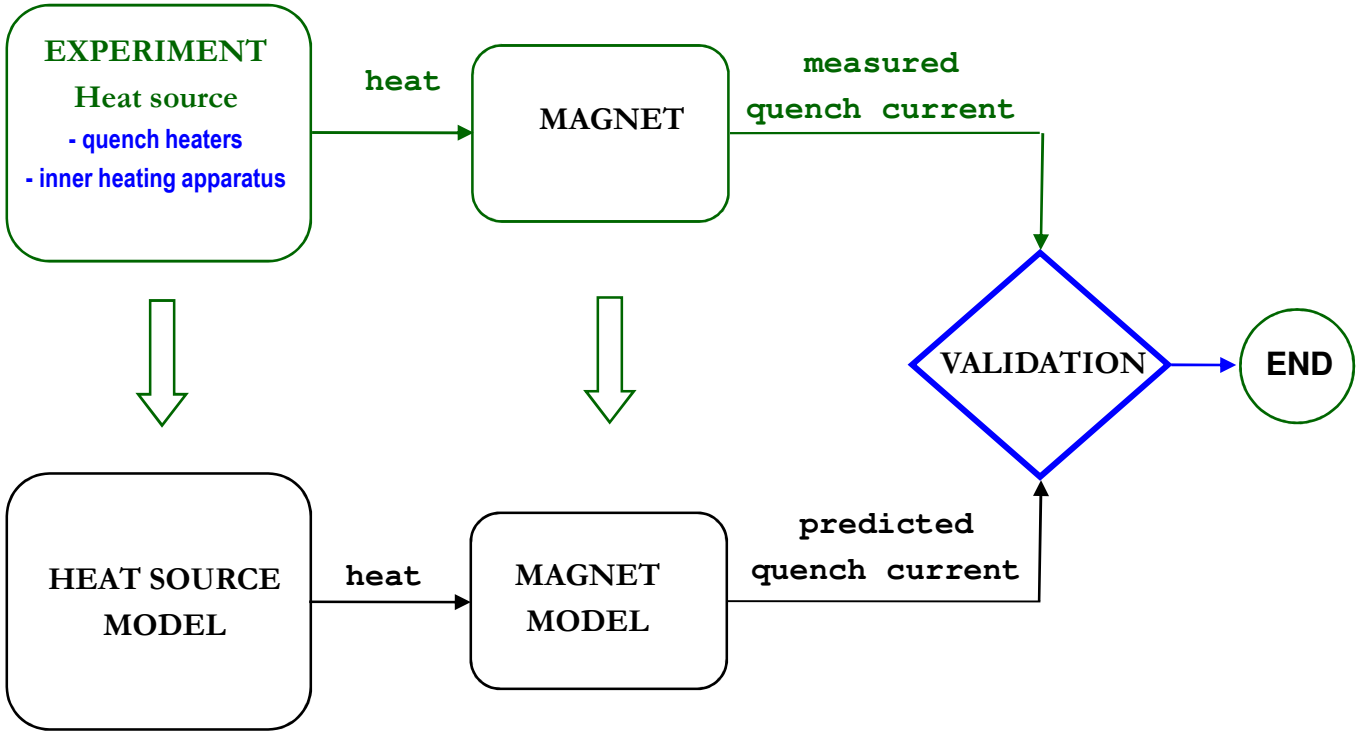
Tc0=17.2 K

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.**

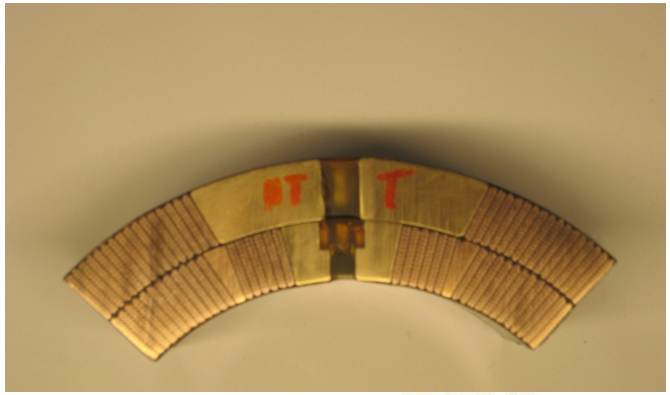
Network Model - Validation

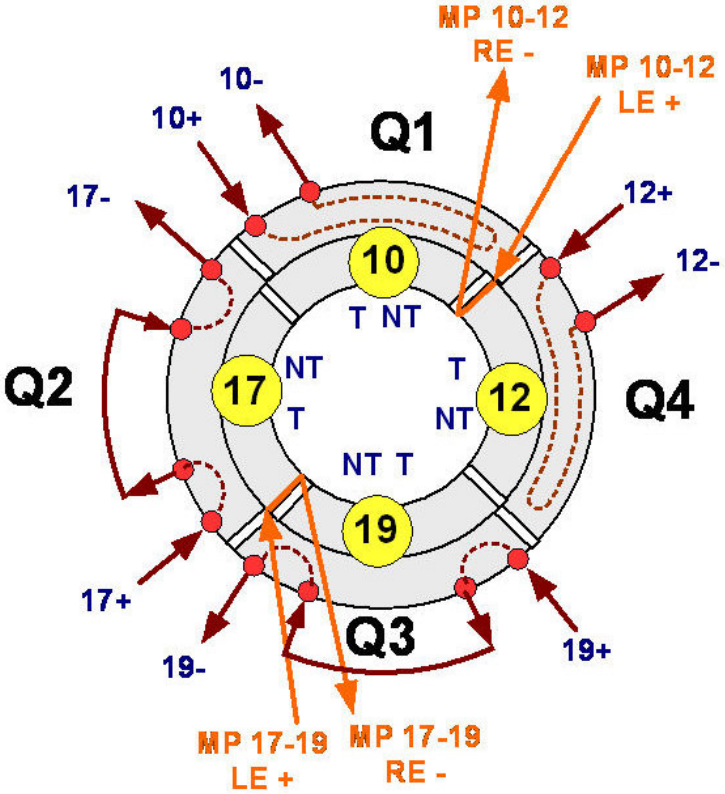


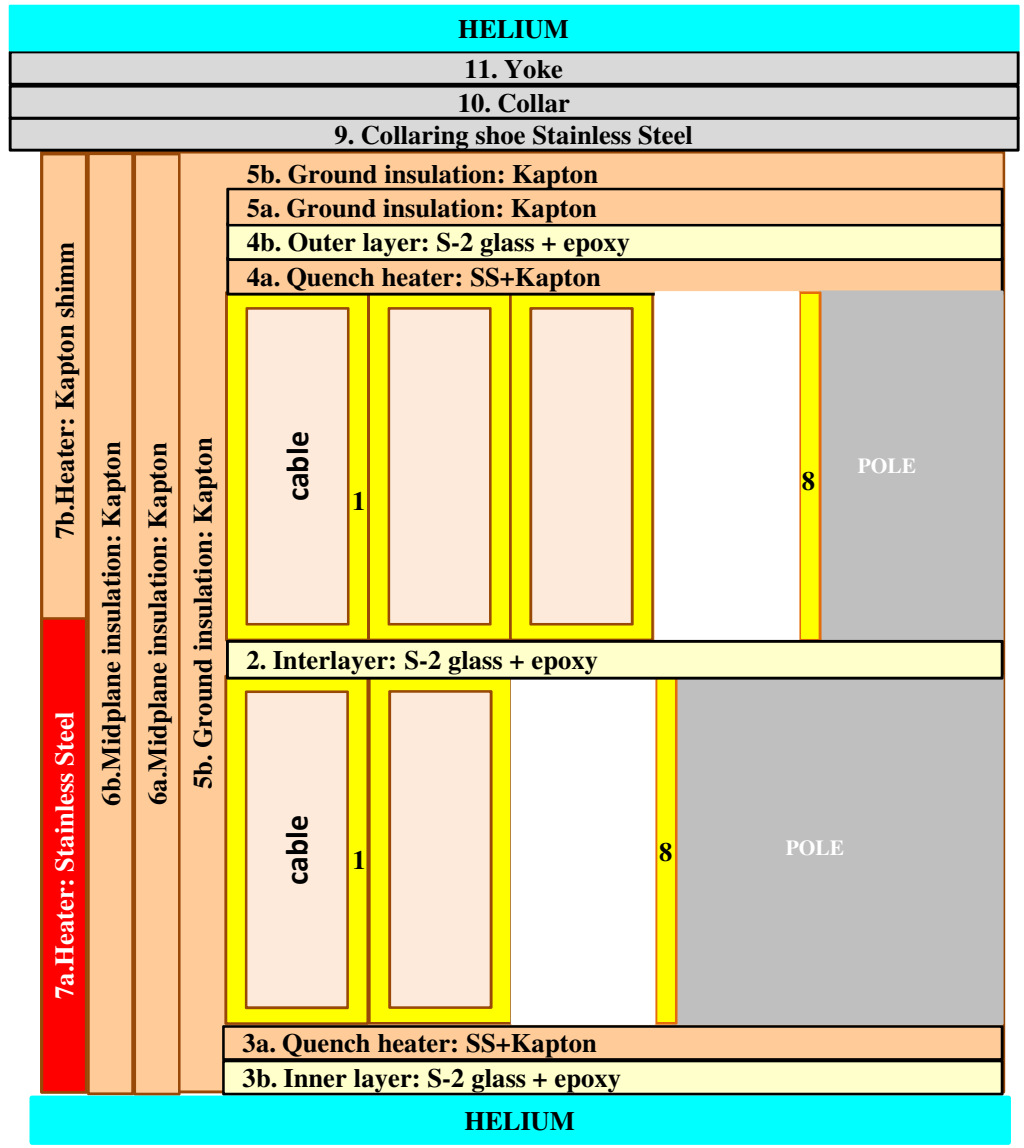
More details for NbTi magnets:
D. Bocian, B. Dehning, A. Siemko, *Modeling of Quench Limit for Steady State Heat Deposits in LHC Magnets*, IEEE Transactions on Applied Superconductivity, vol. 18, Issue 2, June 2008 Page(s):112 – 115;

D. Bocian, B. Dehning, A. Siemko, *Quench Limit Model and Measurements for Steady State Heat Deposits in LHC Magnets,* accepted for publication in IEEE Transactions on Applied Superconductivity, 2009

Model validation - TQ magnet

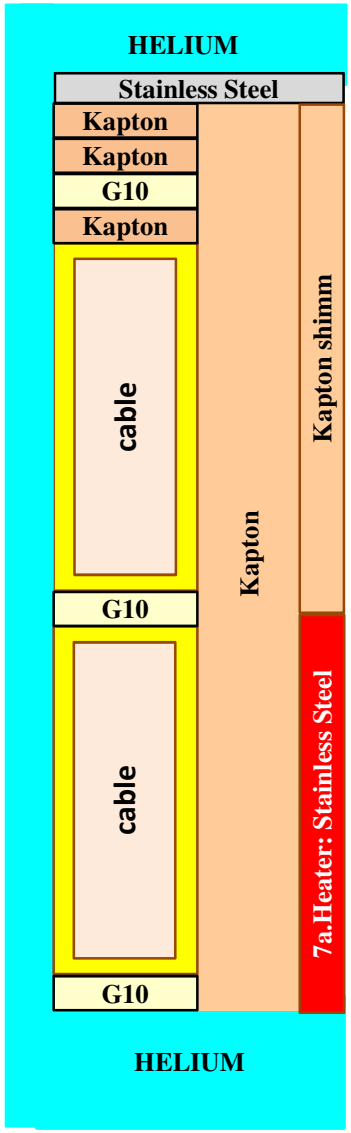






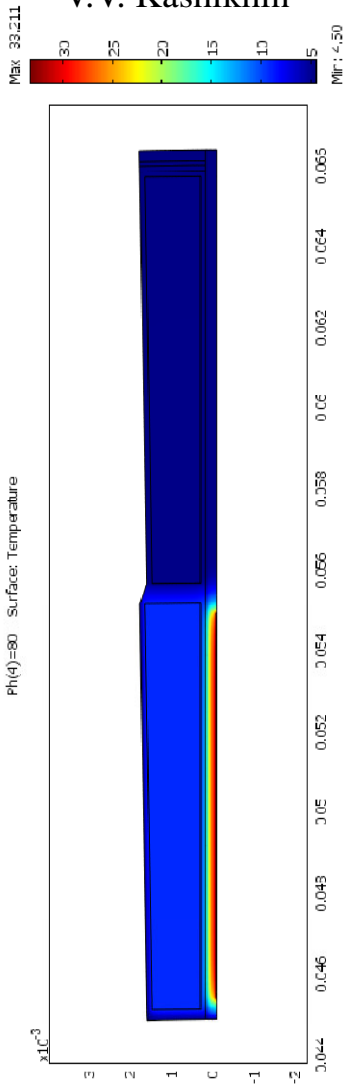
NM and COMSOL comparison

MODEL

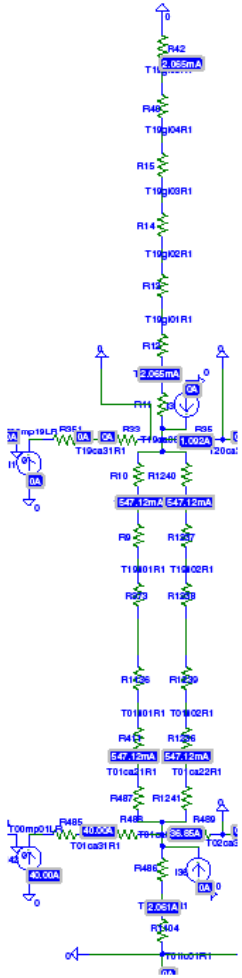


COMSOL

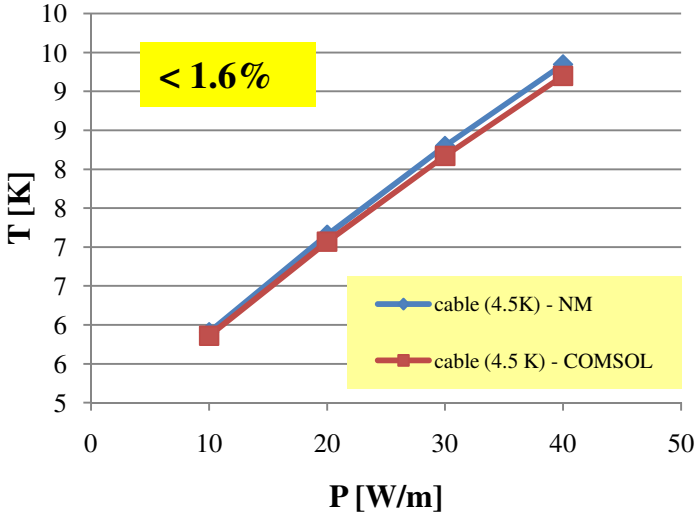
V.V. Kashikhin



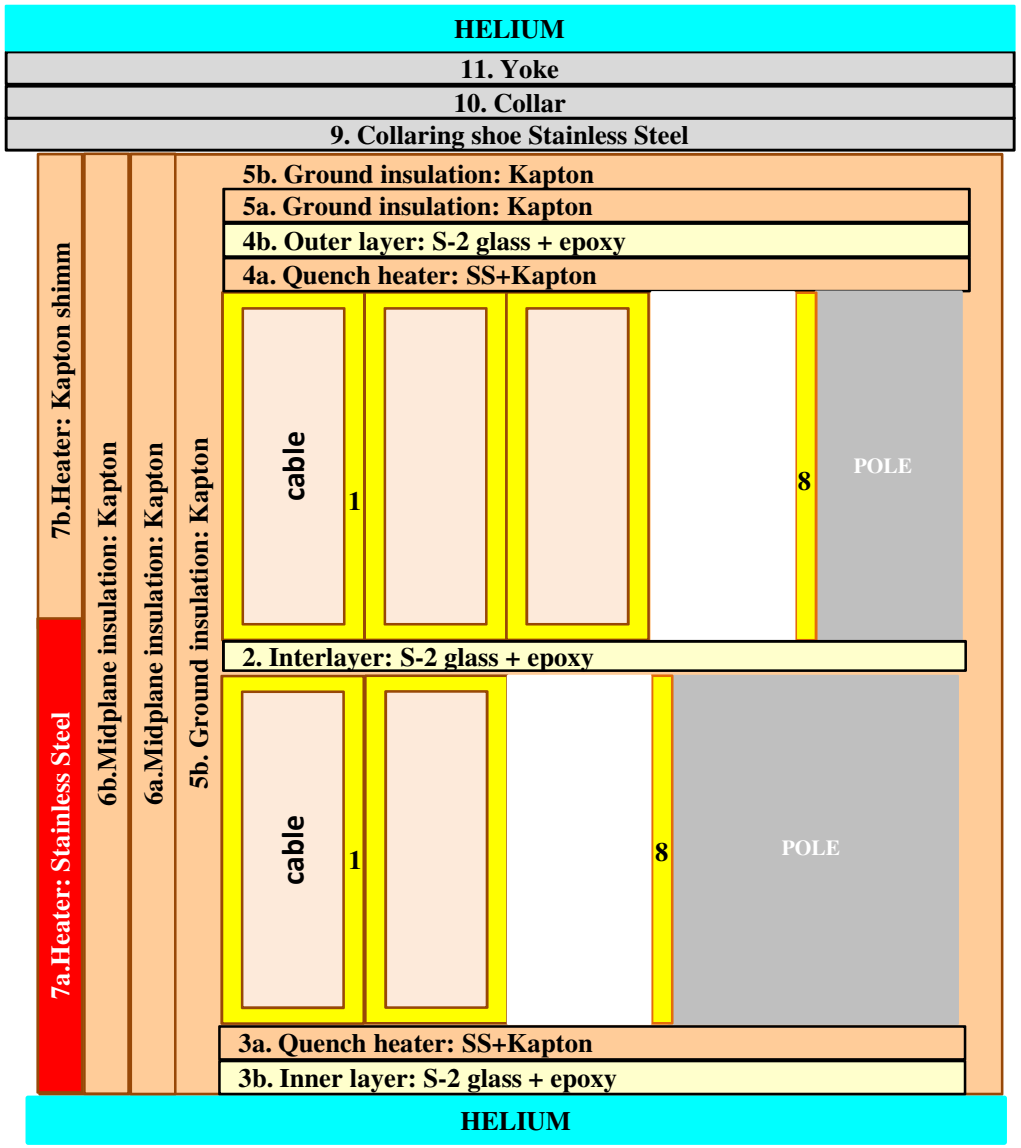
NETWORK MODEL



NM & COMSOL comparison



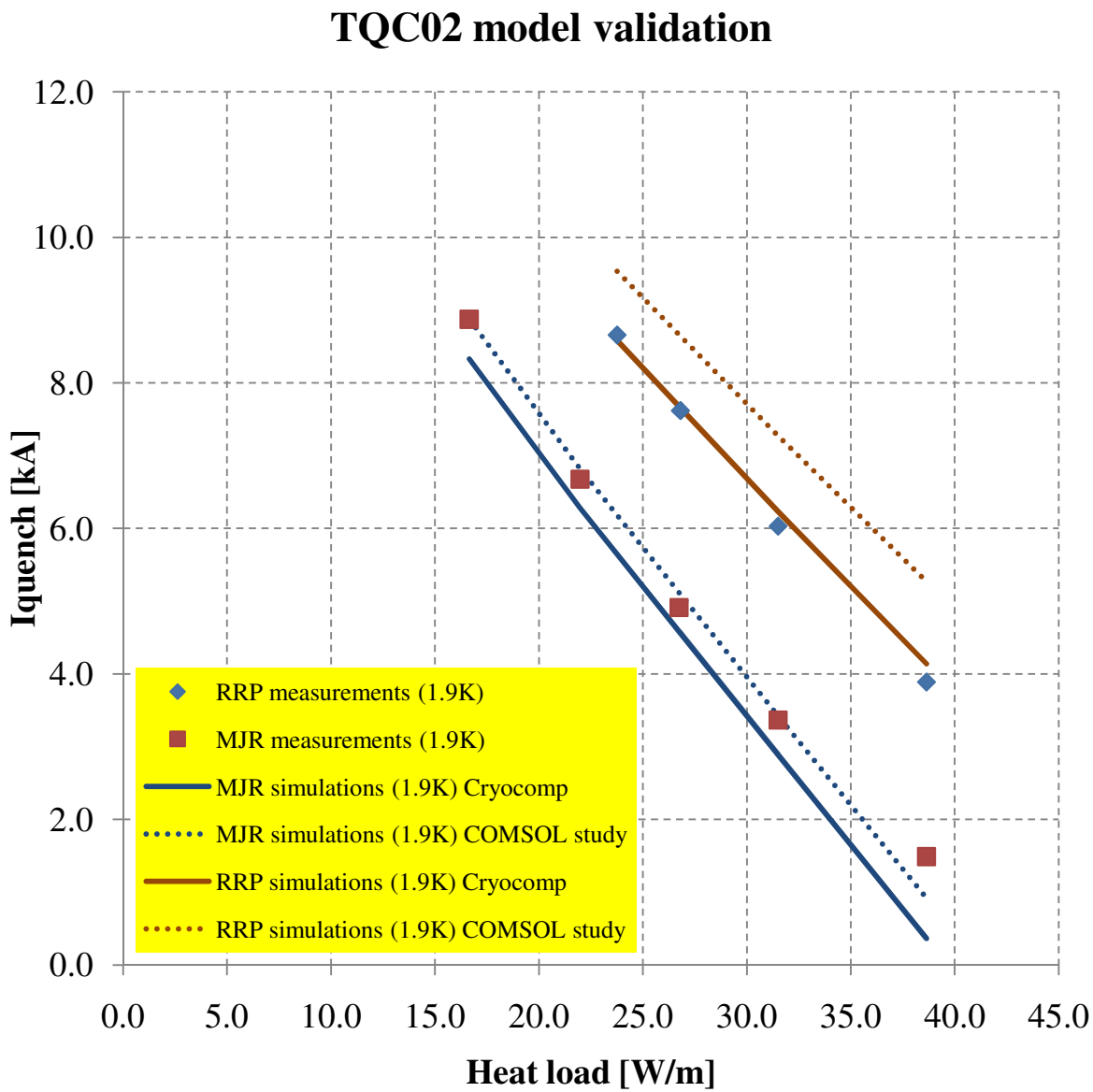
Thermal model of LARP TQ magnet

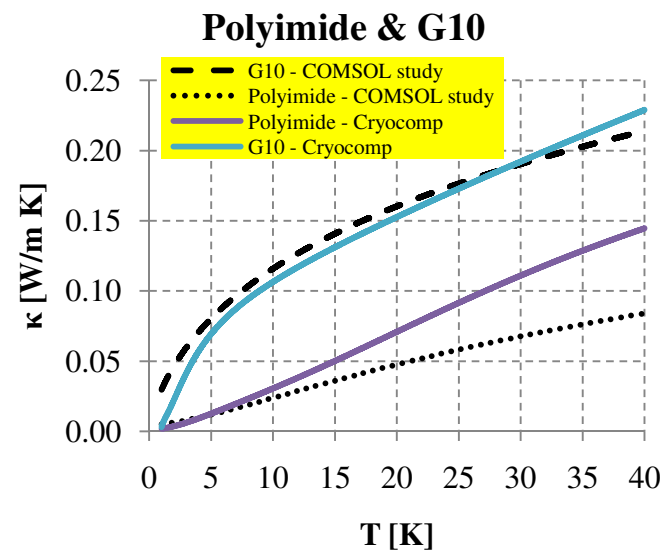


Data from measurements

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**

Thermal model of LARP TQ magnets



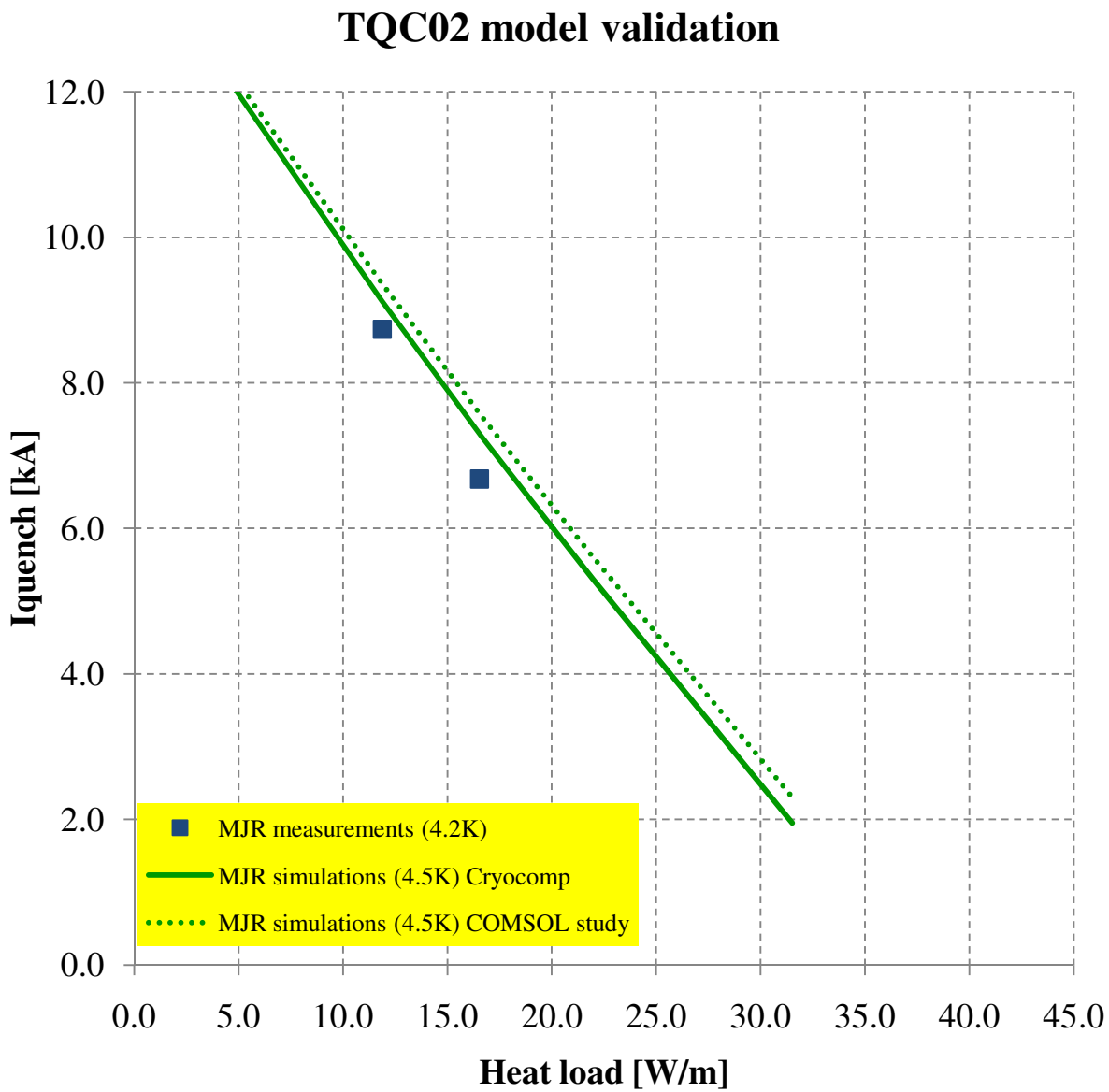


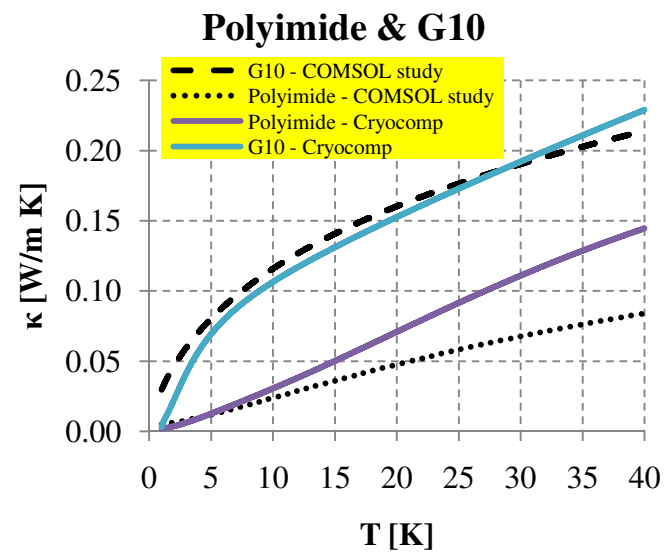
Citical current parametrization:
Bref=12T
Tref=4.2K

RRP:
Jcref=2404 A/mm2
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





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C0=40558

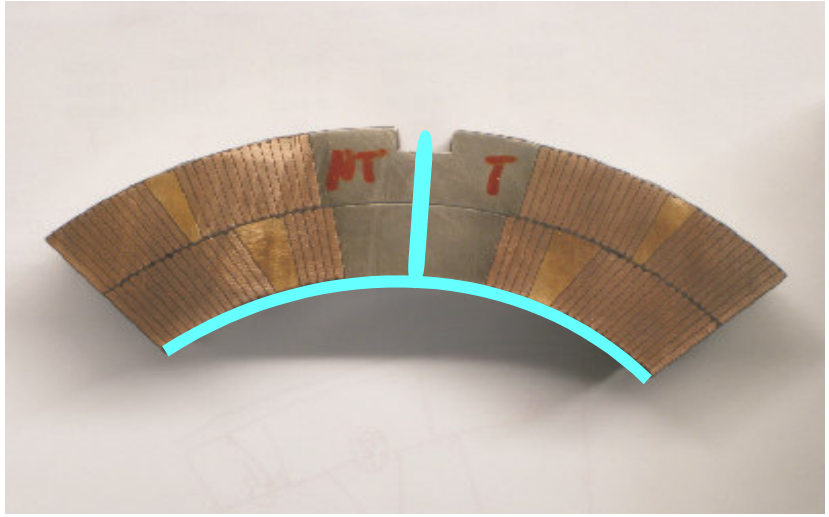
MJR:
Jcref=1954 A/mm2
Tc0= 17.6
Bc20= 26.6
C0=31848

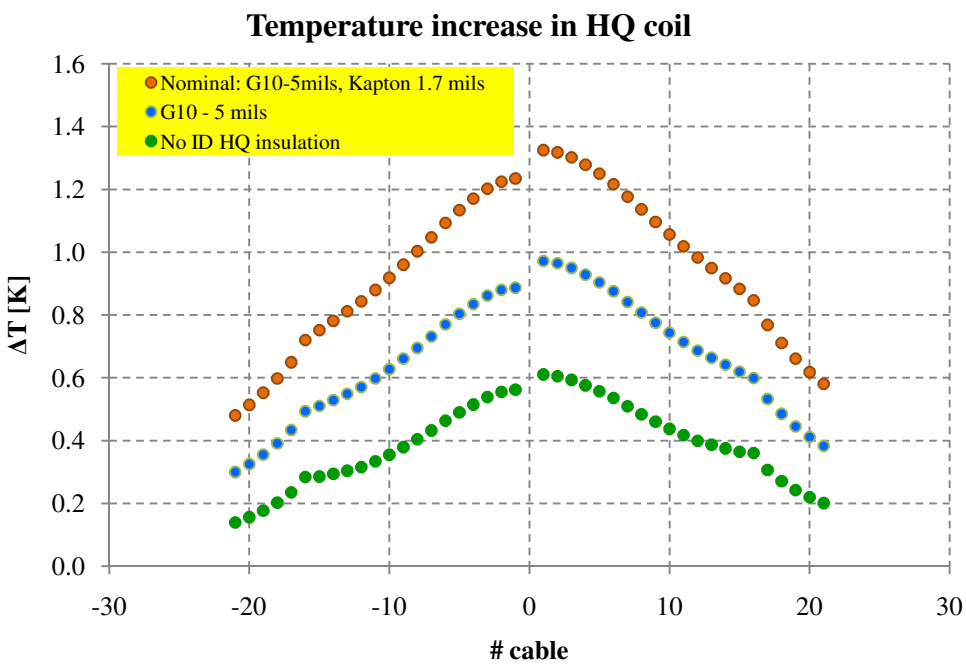
Thermal modeling – insulation thickness

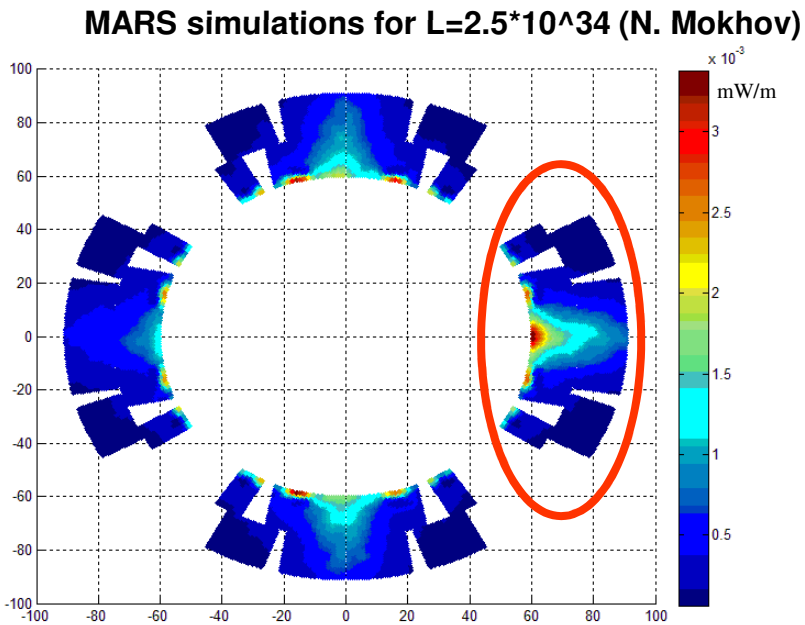
Nb3Sn coils parameters								
		TQ (RRP 54/61)		TQ (MJR)			HQ (RRP108/127)	
		NOMINAL	Network Model (TQ19 measurements)	NOMINAL	Network Model (TQ15)	COMSOL (previous study)	NOMINAL	MEASURED (HQ03)
layer	material	[mil]/[mm]	[mil]/[mm]	[mil]/[mm]	[mil]/[mm]	[mil]/[mm]	[mil]/[mm]	[mil]/[mm]
1	S-2+epoxy	**5 / 0.127**	**3.75 / 0.095**	**5 / 0.127**	**3.9/ 0.099**	**5 / 0.127**	**5 / 0.127**	**3.5 / 0.090**
2	S-2+epoxy	**10 / 0.254**	**6.5/ 0.165**	**10 / 0.254**	**12.9/ 0.327**	**10/ 0.254**	**10 / 0.254**	**8 / 0.203**
3a	Kapton	0	0	3 / 0.076	1.7/0.043	**0**	1.7 / 0.076	3/0.076
3b	S-2+epoxy	**5 / 0.127**	**8.2 / 0.208**	**7 / 0.178**	**11.8 / 0.299**	**5 / 0.127**	**5 / 0.127**	**24 / 0.610**
4a	Kapton	3 / 0.076	1.7/0.043	3 / 0.0762	1.7/0.043	**5 / 0.127**	1.7 / 0.076	3 / 0.076
4b	S-2 +epoxy	**7 / 0.178**	**6.5/ 0.165**	**7 / 0.178**	**10.77 / 0.273**	**5 / 0.127**	**15 / 0.381**	**5.5 / 0.140**
5a	Kapton	**5 / 0.127**	**5 / 0.127**	**5 / 0.127**	**5 / 0.127**	**5 / 0.127**	**5 / 0.127**	
5b	Kapton	**5 / 0.127**	**5 / 0.127**	**5 / 0.127**	**5 / 0.127**	**10 / 0.254**	**5 / 0.127**	
6a	Kapton	**5 / 0.127**	**3 / 0.076**	**5 / 0.127**	**3 / 0.076**		**5 / 0.127**	
6b	Kapton	**x**	**2 / 0.051**	**X**	**2 / 0.051**		**x**	
7a	Stainless steel	**x**	**1/0.0254 (9.5 mm width)**	**x**	**1/0.0254 (9.5 mm width)**	**1/0.0254 (9.5 mm width)**	**x**	
7b	Kapton	**x**	**1/0.0254**	**x**	**1/0.0254**	**1/0.0254**	**x**	
8	S-2+epoxy	**5 / 0.127**	**3 / 0.076**	**5 / 0.127**	**3 / 0.076**	**5 / 0.127**	**5 / 0.127**	
9	Stainless steel	**31/0.787**	**31/0.787**	**31/0.787**	**31/0.787**	**31/0.787**	**31/0.787**	

HQ heat load - MARS

- 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
  - → Optimization of heat extraction paths
  - → Magnets quench limit calculation ← MARS/FLUKA input

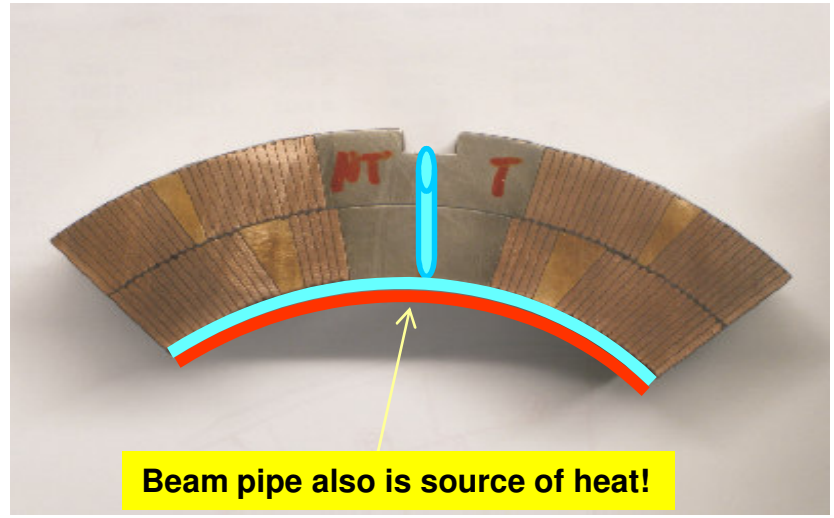


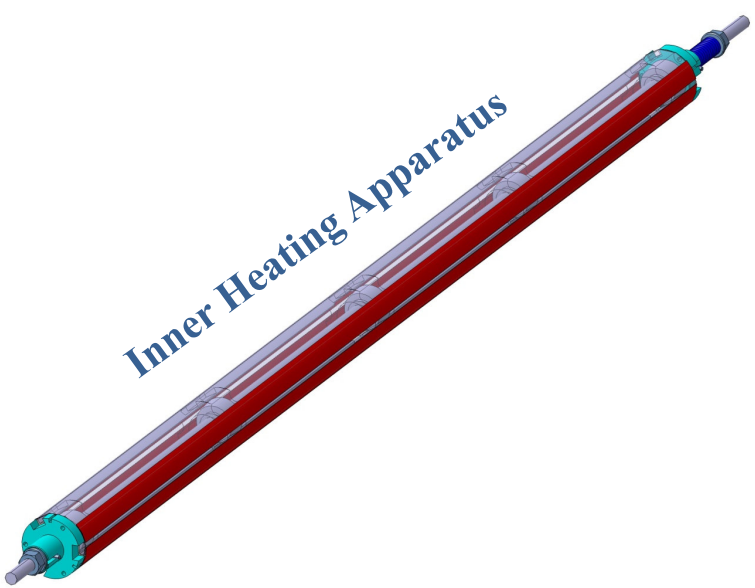




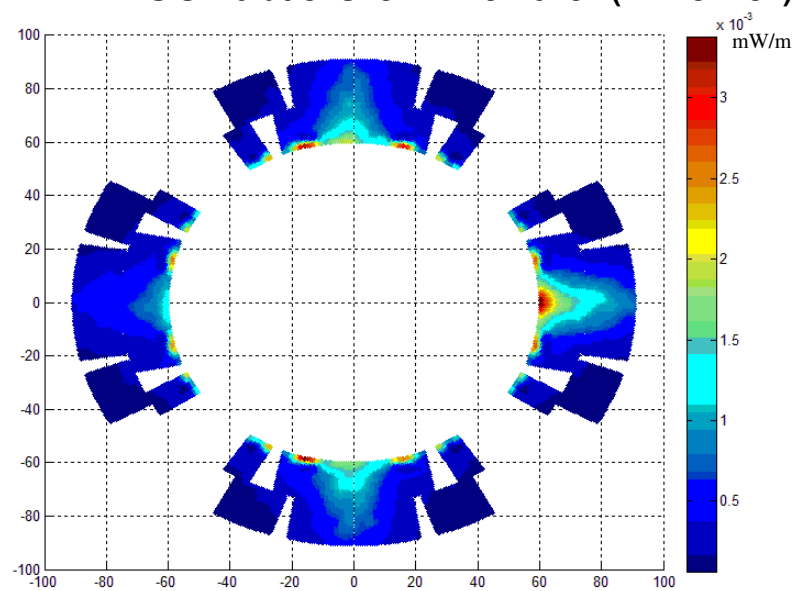
Future?

- In order to define He channels dimensions input from MARS/FLUKA is required
- Model validation with measurements (reproduce beam heat load)
  - → Heater in the midplane
  - → Heater inserted to cold bore





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



Conclusions

DONE:

- Reliable thermal models of Nb_3Sn superconducting magnets have been developed
- Model was validated with measurements performed at FNAL with TQ magnet
- Model was cross checked with COMSOL
- Model is used to study HQ coil insulation impact on magnet thermal performance (parameters analysis)

IN PROGRESS:

- Cooling channels dimensions in Nb3Sn magnets
  - require input from MARS/FLUKA teams
- Simulation error
  - material properties at low temperatures for materials used in LARP magnets
  - critical current dependence on temperature – on going

OUTLINE

- **Thermal analysis of superconducting magnets**
  - Motivation
  - Network Model
  - Thermal model of LARP Nb3Sn quadrupole magnets
  - Model validation with TQC02b measurements
  - Thermal model of LARP HQ magnets
  - **HQ magnet study**
  - Conclusions
- **Study of Nb_3Sn conductor during heat treatment - shortly**
  - Motivation
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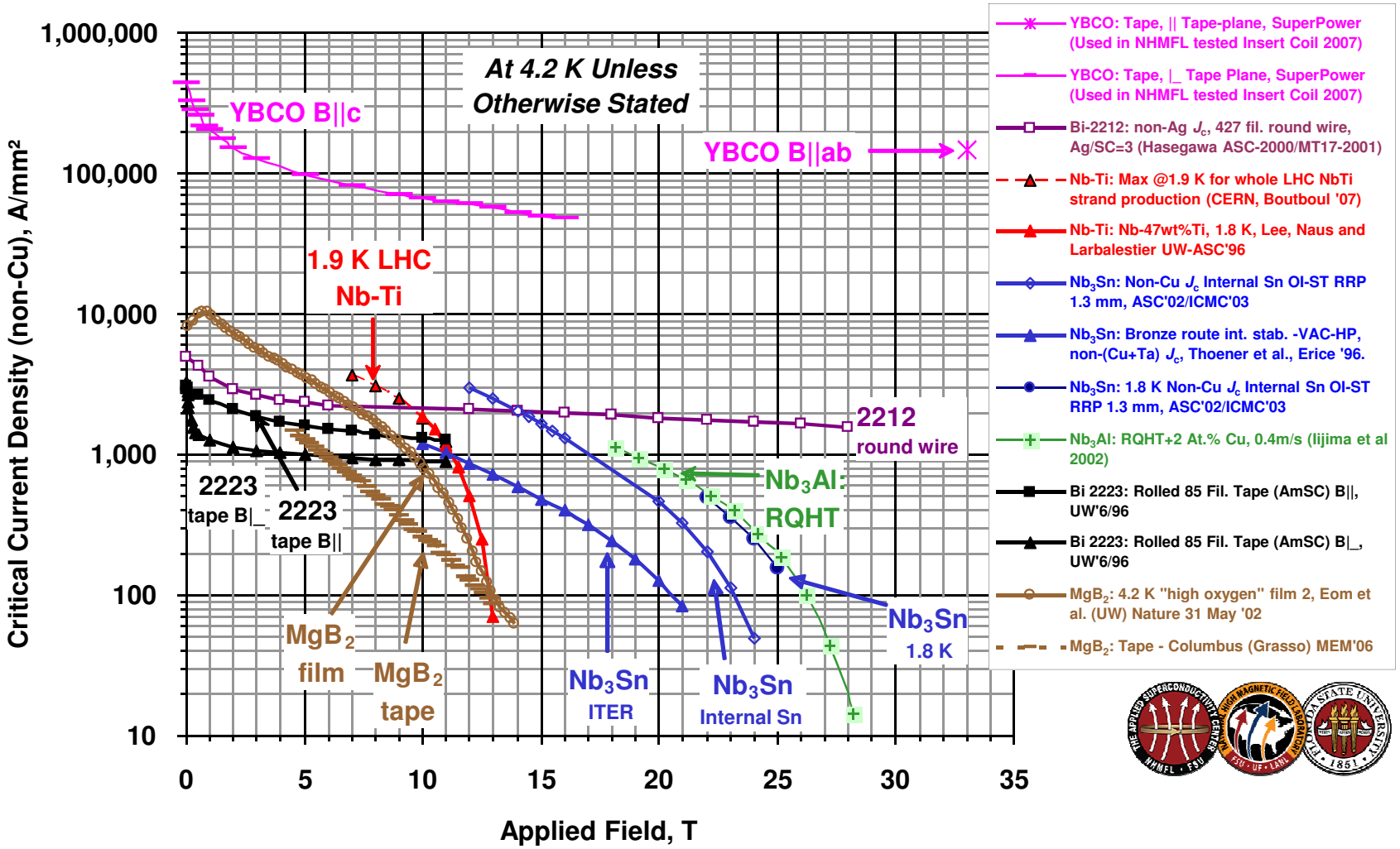
- **Summary**

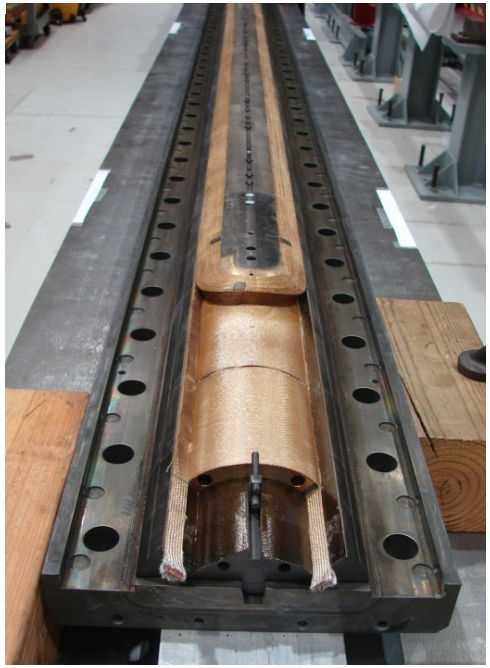
Motivation



http://www.magnet.fsu.edu/magnettechnology/research/asc/plots.html

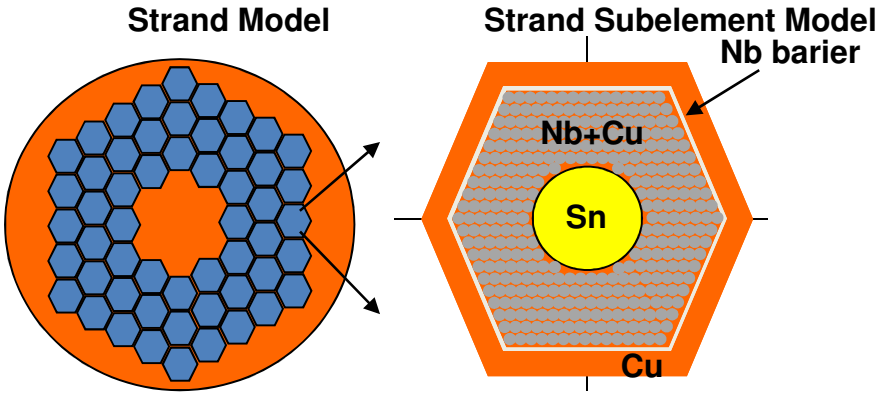
Motivation

- Nb_3Sn demonstrate better performance than NbTi
- Nb_3Sn formation require to 3 step reaction of components at high temperature (640-665 °C)
- Nb_3Sn is brittle material
- Material properties change during reaction
  - → strand / cable / coil dimension changes
  - → for proper study of coil mechanical behavior during reaction a material properties are required (E, ρ, CTE)



WORK PLAN

- Bibliography study and discussion with experts
  - Collection of the data and material properties for simulations (limited data available)
- **Experimental data collection**
  - **strand/cable sample measurement before/after heat treatment**
  - **dilatometer measurement at NHMFL**
- FEM simulation of the strand/cable/coil behavior during reaction
- Feedback to the coil fabrication technology



Simulation plan

Temperature 20 → 210°C
Linear/non-linear elongation

Temperature 210 → 400°C
Continuation of Sn diffusion to Cu
(Sn melts at 238°C)

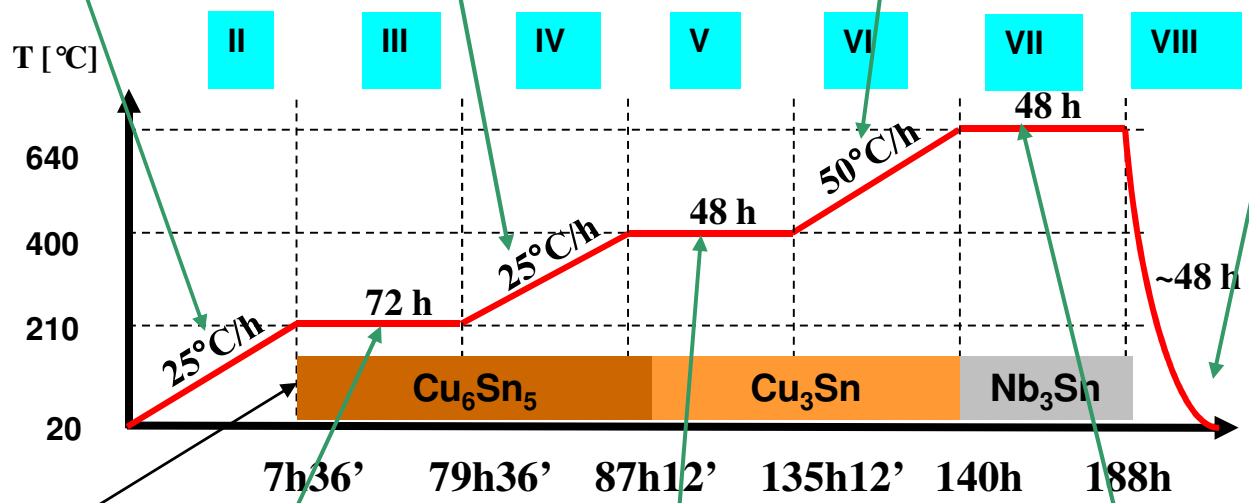
Temperature 400 → 640°C
Nb_3Sn formation start
(Sn diffusion into Nb)
Need Nb_3Sn properties
→ tuning of the model

Temperature 640 → 20°C
→ strand/cable shrinks

I

Preload on Nb (z-axis)
(Nb under tension,
Cu under compression)

Strand/cable annealing
(2 h at 200 °C)
Linear elongation,
Plastic deformation.



Ch. Scheuerlein *et al.*,
IEEE Trans. Appl. Supercond.
VOL.18, NO. 4, 2008,

Temperature=210°C
Sn diffusion to Cu
→ Cu_6Sn_5 formation
Strand/cable shrinkage
Need Cu_6Sn_5 properties
→ tuning of the model

Temperature=400°C
Further Sn diffusion to Cu
→ Cu_3Sn formation,
→ strand/cable shrinks,
→ all Sn reacted
Need Cu_3Sn properties
→ tuning of the model

Temperature = 640°C
→ Strand/cable expand,
→ Plastic deformation?
→ Larger strand cross-section?

E, ρ and CTE needed for each step

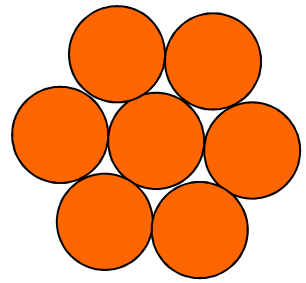
Strand sample measurement

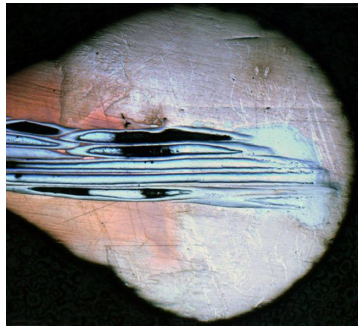
Sample preparation:

⇨ Sample length ~ 48 mm.

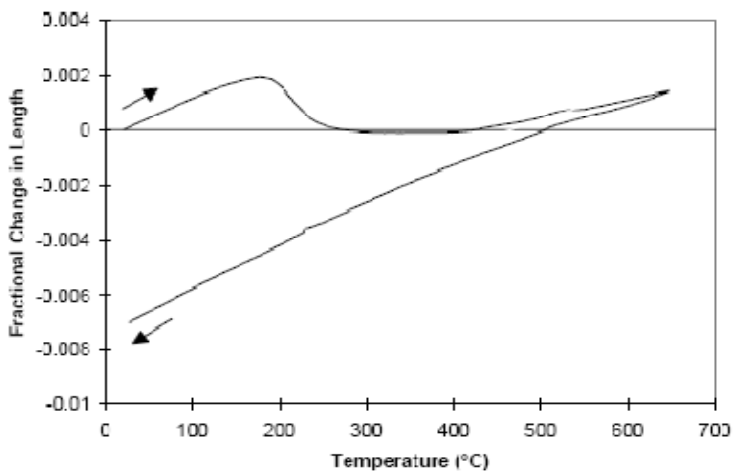
⇨group 7 strand sample together

⇨weld the ends of strands and file them.



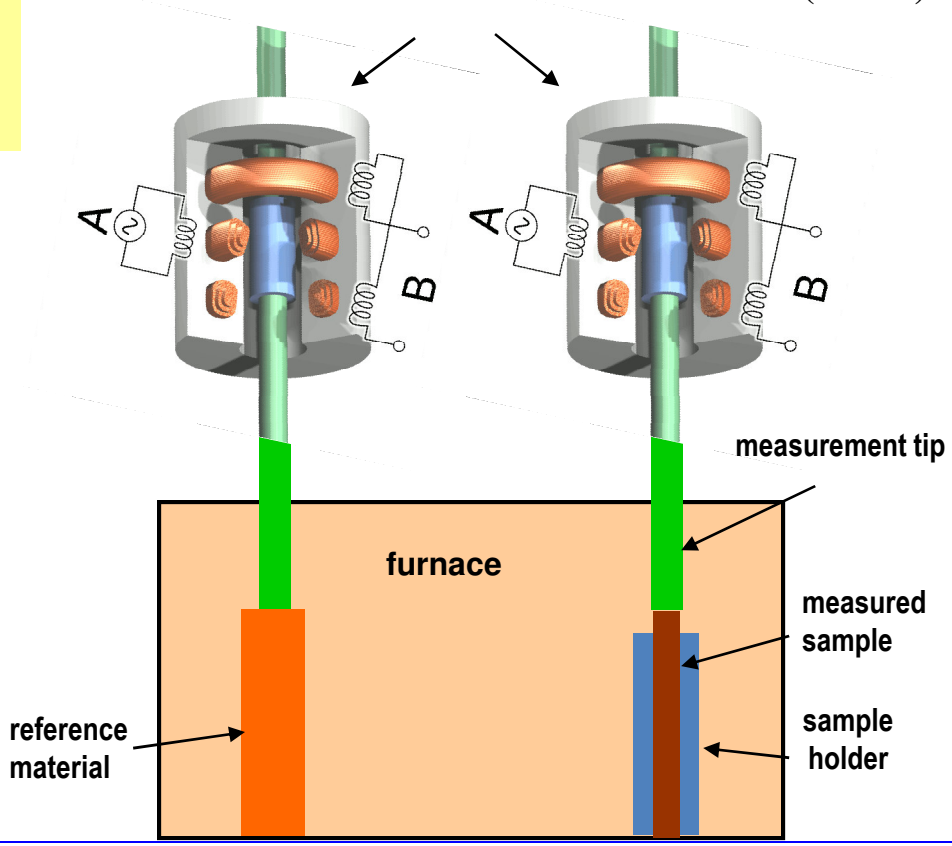


Continous ΔL/L measurement during full Heat Treatment at NHMFL

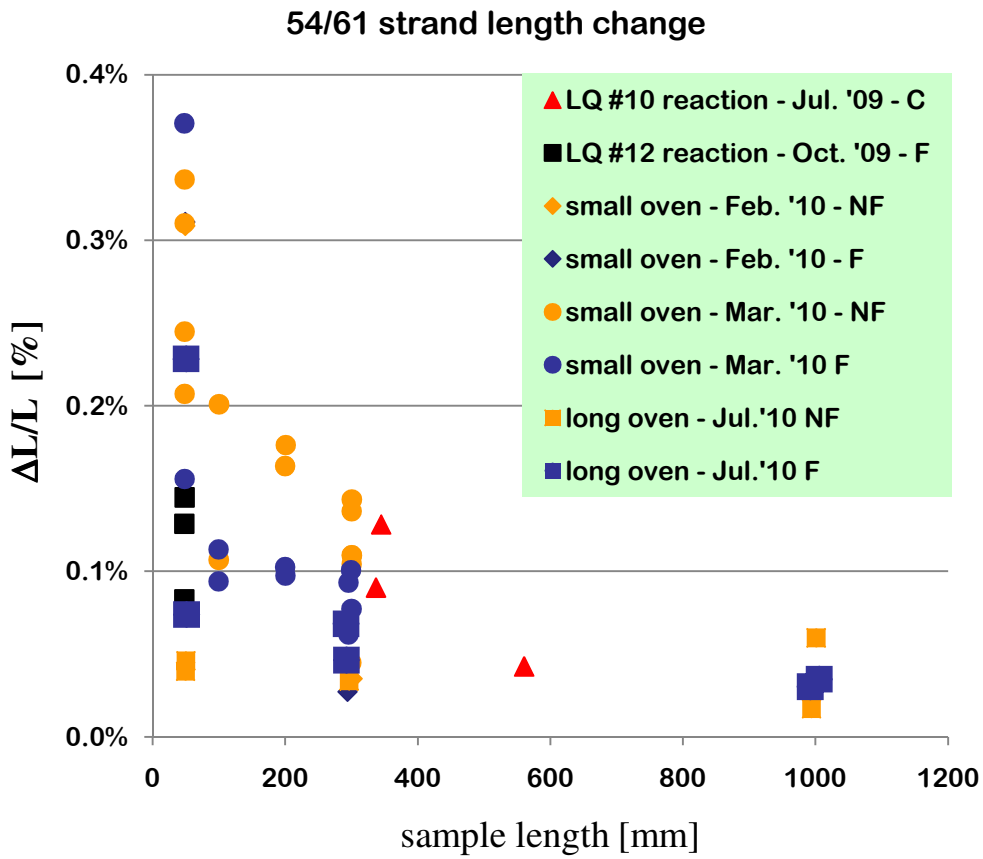


D. R. Dietderich *et al.*, *"Dimensional changes of Nb 3Sn. Nb3Al. and Bi2Sr2CaCu2O8 conductors during heat treatment and their implication for coil design."* Adv. Cryo. Eng., vol. 44b, 1013–1020,

Linear Variable Differential Transformers (LVDT)



54/61 strands measurement results



STRANDS ENDS: C – crimp, F – fused, NF – not fused (as cut)

After a few first measurements, following questions needed to be answered:

- Why strand sample elongate?

→ strand twist change contribution?

- Why is length dependence of ΔL/L?

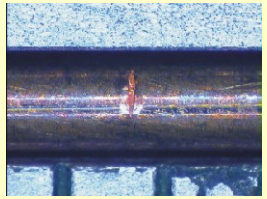
Before dilatometer measurements (l_{sample}<50 mm):

- Is there end effect?

Length dependence of ΔL/L

- The length changes were measured from scratch to scratch
- ΔL/L remains constant in the straight part of strands
- In the ends ΔL/L show large end effect.

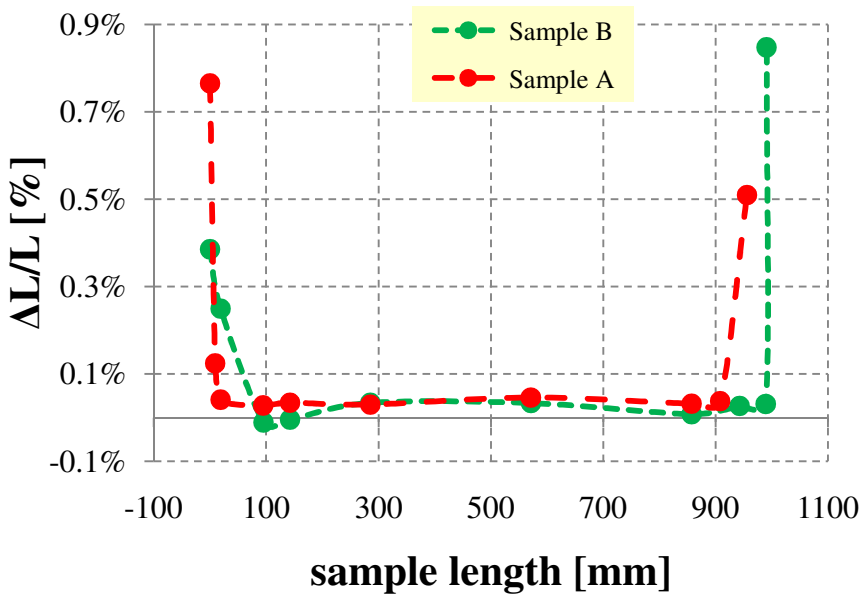
Sample measurement



Scratches on strand surface placed:

- 10 mm from strand ending
- 10 mm + N * 50 mm form strand end (N=3)
- Segmentation of rest strand length 300-500 mm.

RRP strands - 1 meter samples

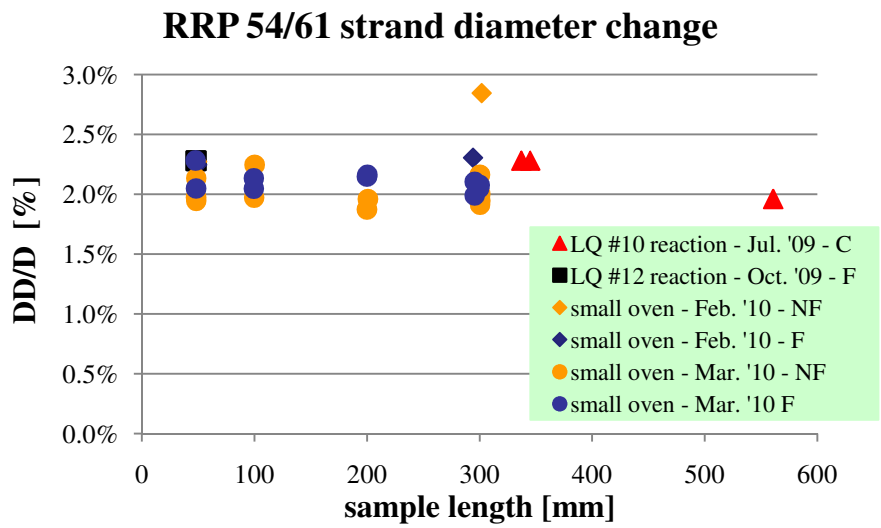


54/61 strands measurement summary

Measured strand samples demonstrate:

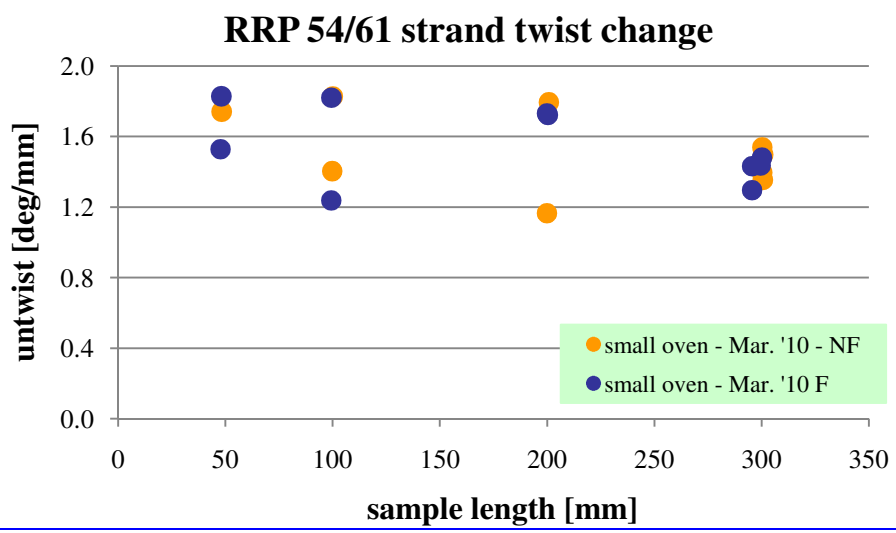
- Length increase by $\sim 0.035^{+0.025}_{-0.035}\ \%$,
- Diameter increase by $\sim 2.15^{+0.7}_{-0.25}\ \%$,
- Twist change by $\sim 1.6^{+0.2}_{-0.4}\ \frac{\text{deg}}{mm}$,

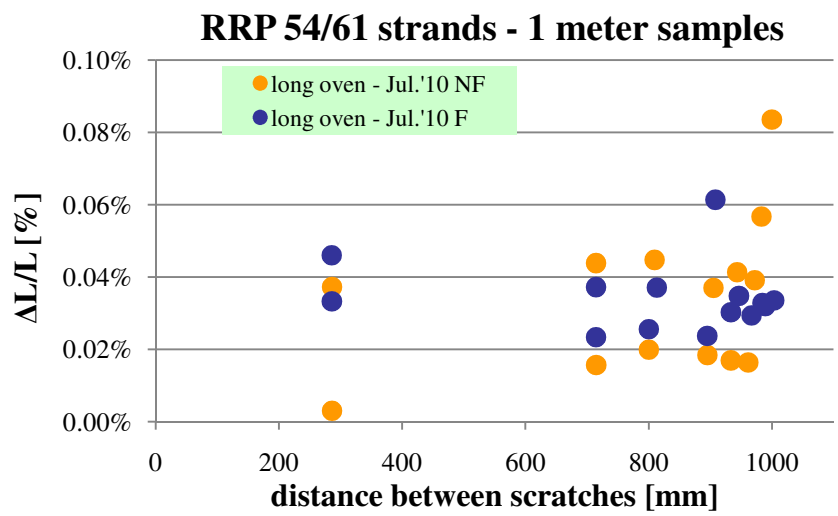
(~4% of nominal twist (nt), nt=13 mm)



Diameter increase show conformance with data in:
N. Andreev, E. Barzi, D.R. Chichili, S. Mattafirri, and A.V. Zlobin
„Volume expansion of Nb-Sn strands and cables during heat treatment"

STRANDS ENDS: C – crimp, F – fused, NF – not fused (as cut)

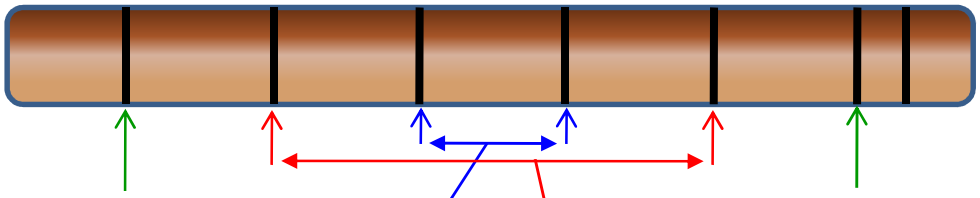


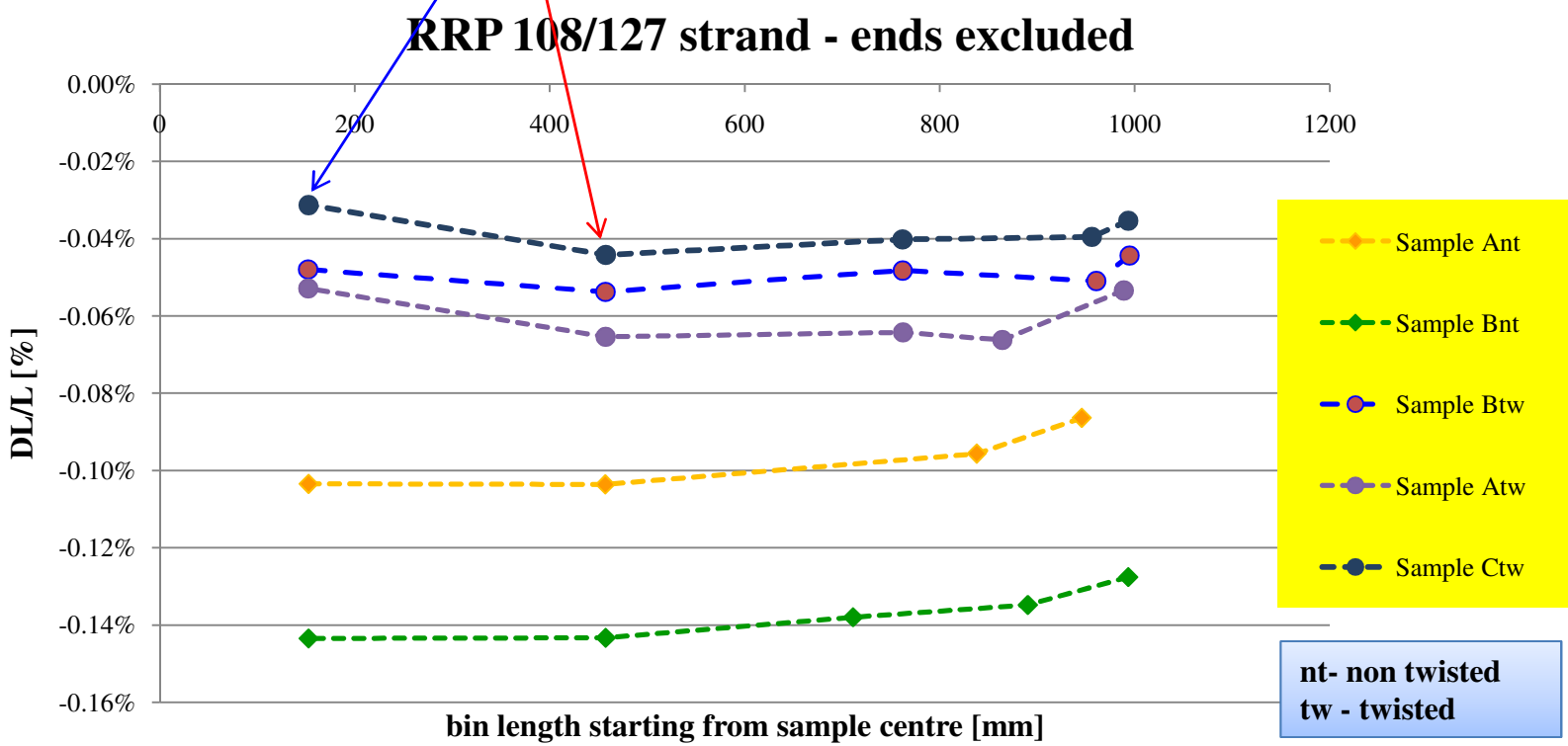


Twist change impact on ΔL/L

Measurement of108/127 strand (#12521)

- **Twisted samples elongate during the heat treatment**





STRAND measurement summary

- **Measured strand samples:**
  - **Strand OST RRP 108/127 (#12521), 54/61 (#9532)**
  - **strand diameter 0.7 mm – twisted and 0.84 mm – „non-twisted”,**
  - **Sample length: 1000 mm, sample ends: fused,**
- **Measured strand samples demonstrate:**

SAMPLE	Length change	Diameter change	Twist change
Strand 108/127 - twisted	$-0.045^{+0.025}_{-0.015}$ %	$+1.88^{+0.07}_{-0.04}$ %	$-1.3\ \frac{deg}{mm}$
Strand 108/127 - „non-twisted”	$-0.12^{+0.02}_{-0.03}$ %	$+1.71^{+0.06}_{-0.05}$ %	$-0.26\ \frac{deg}{mm}$
Strand 54/61 – twisted	$+0.035^{+0.025}_{-0.035}$ %	$+2.15^{+0.7}_{-0.25}$ %	$-1.6^{+0.2}_{-0.4}\ \frac{deg}{mm}$
Cable 54/61 – not constrained	$-0.13^{+0.09}_{-0.05}$ %	-	-

- **Strands are longer after reaction because they „untwist”**
  - **ΔL/L and twist change dependence confirmed by testing „non-twisted” strands**
  - ***„non-twisted” strands length change is the same order as measured cable length change BUT measurements has been performed on cables made from 54/61 strands***
    - → **Measurement of 108/127 cable and strand samples are on going**

Conclusions

- $\Delta L/L$ and twist change dependence confirmed by testing „non-twisted" strands

- Strand ends can introduce „noise" in measurements
  - Important for measurements of short sample (< 50 mm) with dilatometer
  - Careful preparation and measurements of short samples

- „non-twisted" strands are prefered in dilatometer measurements
  - twist change effect eliminated
  - behaves as confined strand in cable

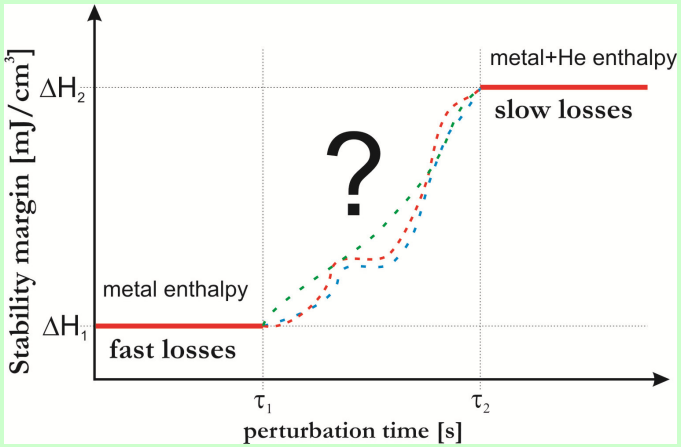
EXTRAS

Heat load in the LHC magnets

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

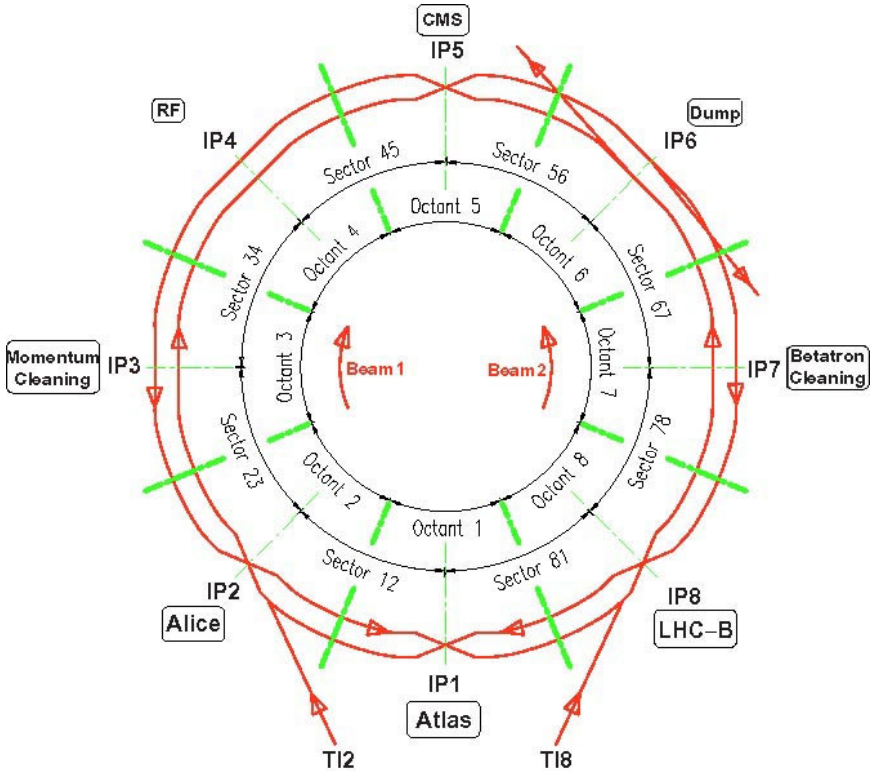
• Transient losses ~ns to ~ms

- 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



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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;

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*

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

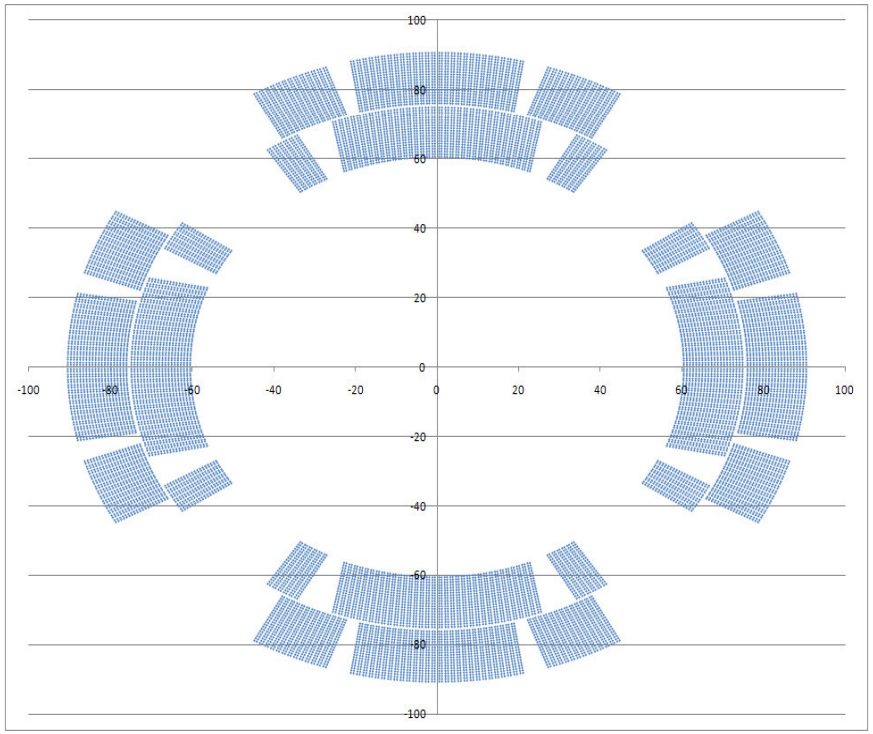
-transient condition *Heat diffusion* ⇔ *RC transmission line*

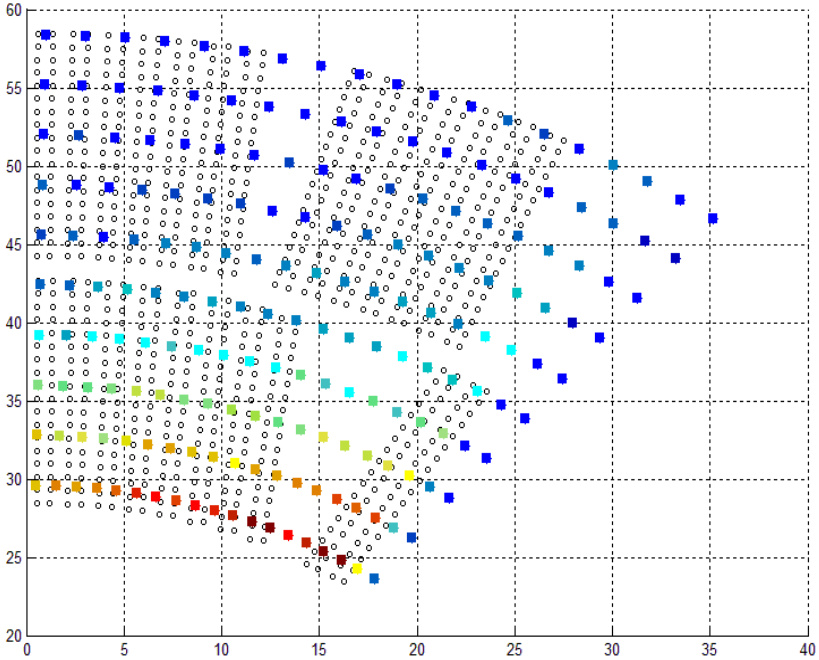
$$\nabla^2 T = R^{\Theta} C^{\Theta} \frac{\partial T}{\partial t} \quad \Leftrightarrow \quad \nabla^2 V = RC \frac{\partial V}{\partial t}$$

FLUKA/MARS Interpolation

- FLUKA & MARS are used to simulate energy deposits in the LHC magnets
- The coordinates of FLUKA/MARS bins often do not match coordinates for magnet conductors

  → need to interpolate





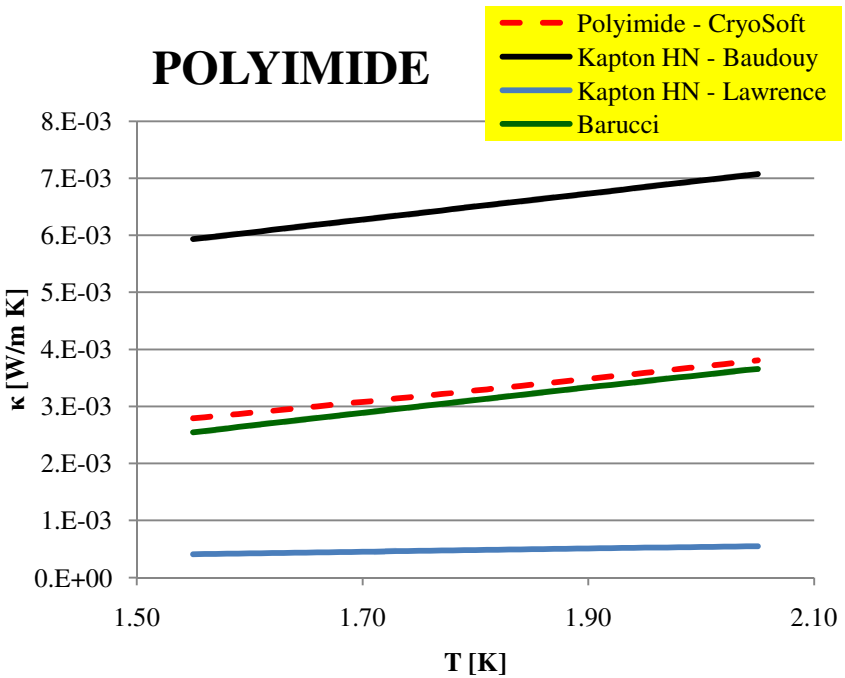
Insulation material properties

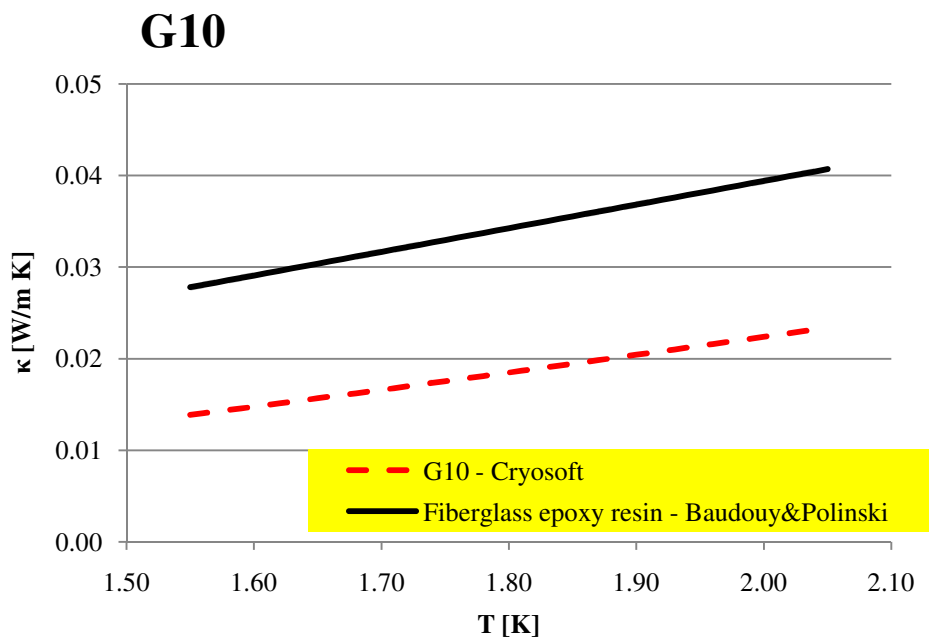
POLYIMIDE

κ = 2.4E-3*T+2.28E-3 1.4 < T < 2.0 K [1]
κ = 4.638E-3*$T^{0.5678}$ 0.5 < T < 5.0 K [2]
κ = 6.5E-3*T 0.2 < T < 5.0 K [3]

G10

κ = 25.8E-3*T-12.2E-3 1.55 < T < 2.5 K [4]





Bibliography:

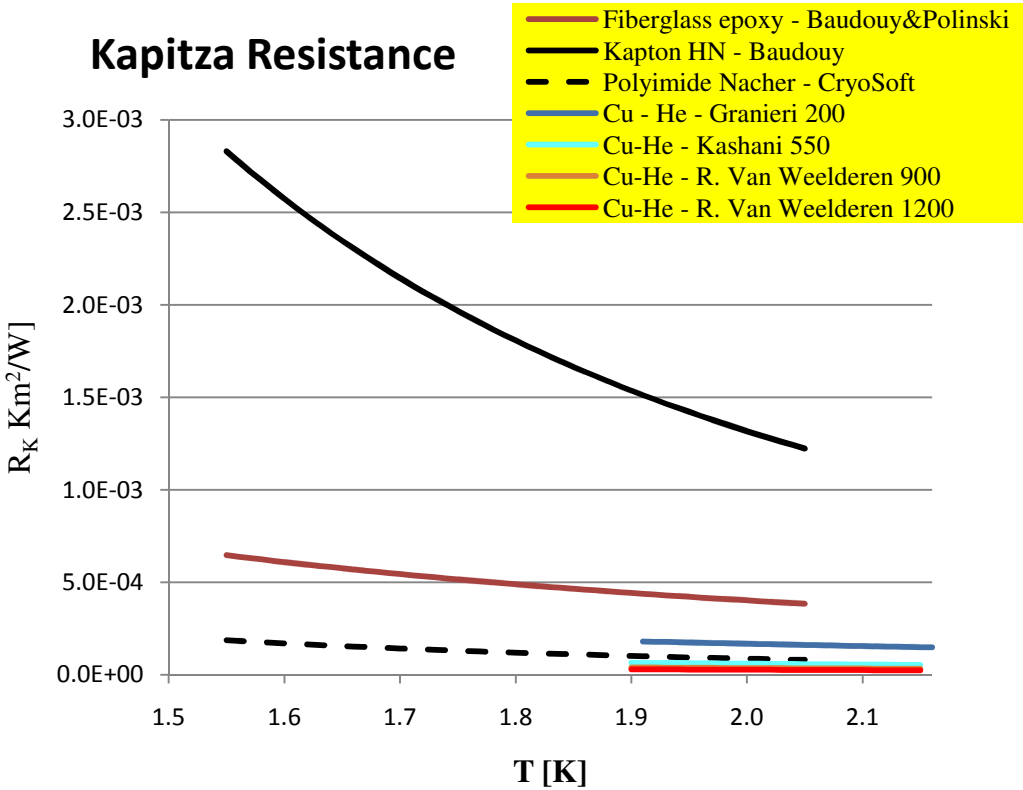
1. B. Baudouy, „*Kapitza resistance and thermal conductivity of Kapton in superfluid helium*", Cryogenics 43(2003), 667-672,
2. Lawrence et al., „ The thermal conductivity of Kapton HN between 0.5 and 5 K", Cryogenics 40 (2000), 203-207,
3. Barucci et al, „Low temperature thermal conductivity of Kapton and Upilex", Cryogenics 40 (2000), 145-147,
4. B. Baudouy, J. Polinski, „*Thermal conductivity and Kapitza resistance of epoxy resin fiberglass tape at superfluid helium temperature*", Cryogenics 49(2009), 138-143

Kapitza Resistance

Kapitza resistance reduces heat transfer in Kapton by 3÷6% and G10 by 5÷9%

For metal – He II:

$$h_K = \sigma_K \cdot (T_s^2 + T_f^2) \cdot (T_s + T_f)\,[Km^2W^{-1}]$$



Copper – He II

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

POLYIMIDE – He II

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 – He II

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.*

Helium properties

Superfluid helium

The He II thermal resistance is calculated as follow:

$$R_{HeII}^{\Theta} = \frac{\Delta T \cdot l}{w \cdot d \cdot q} \left[\frac{K}{W}\right]$$

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

$$q = \left[\frac{X(T_c) - X(T_h)}{l}\right]^{0.29} \quad [W]$$

and X(T) is an experimental results fitting

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

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.

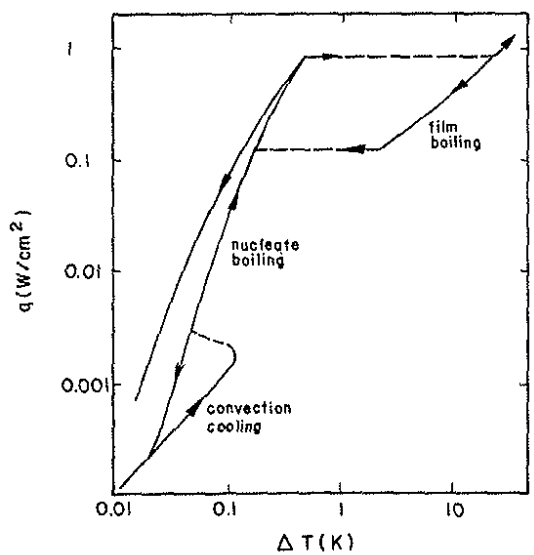


Fig. 6.2. Typical heat transfer relationship for pool boiling liquid.

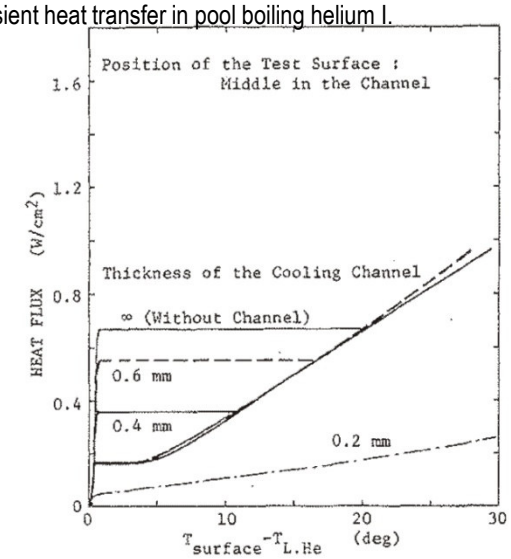
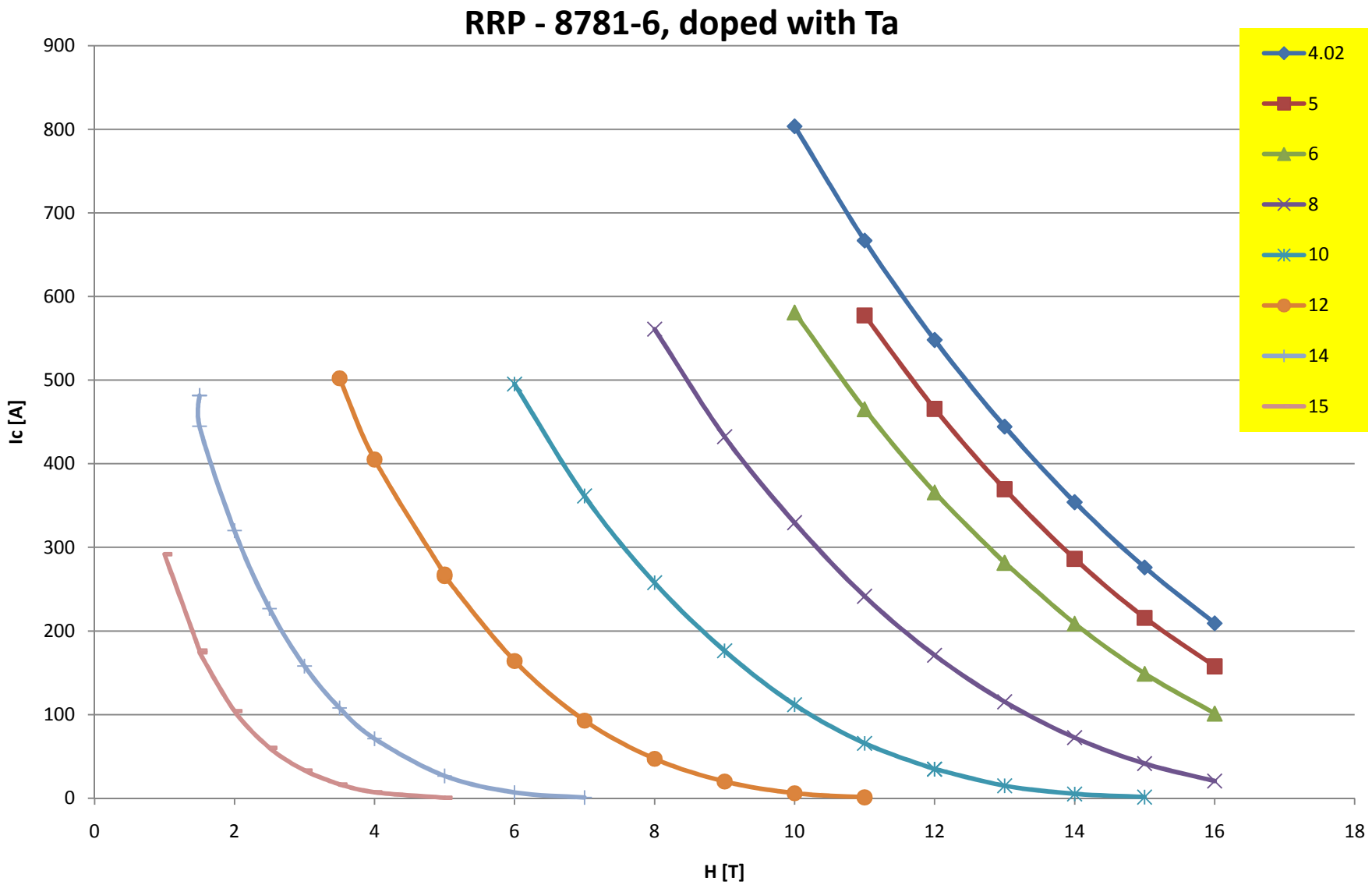


Fig.2 Steady state boiling helium heat transfer characteristics in narrow cooling channels

NIST data


RRP - 8781-6, doped with Ta
Ic [A]
H [T]
900
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
4.02
5
6
8
10
12
14
15