



The Henryk Niewodniczanski  
Institute of Nuclear Physics  
Polish Academy of Sciences

# Superconducting accelerator magnets

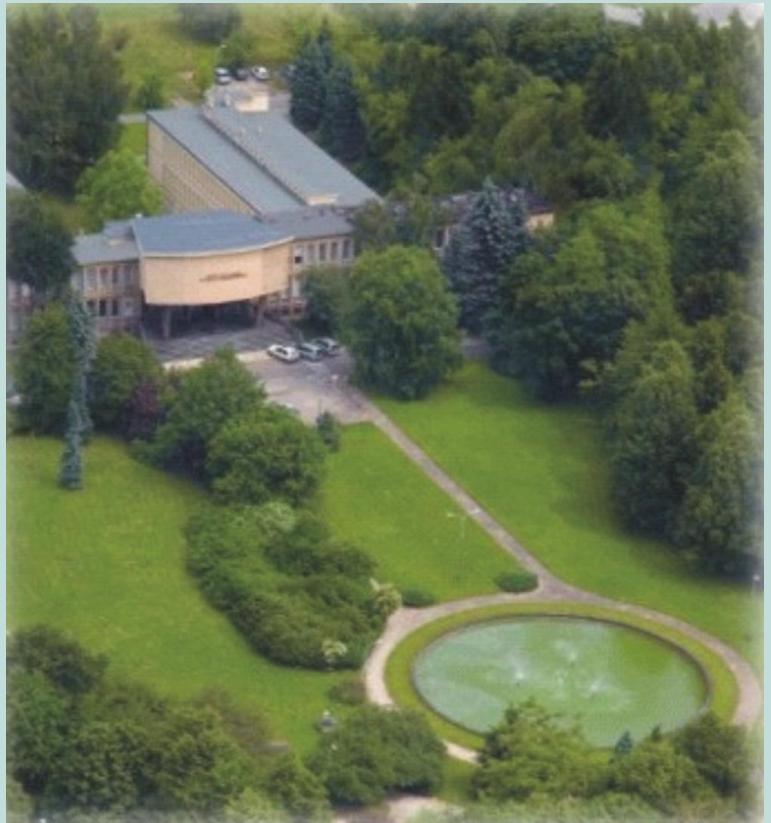
## A basic R&D on superconductors

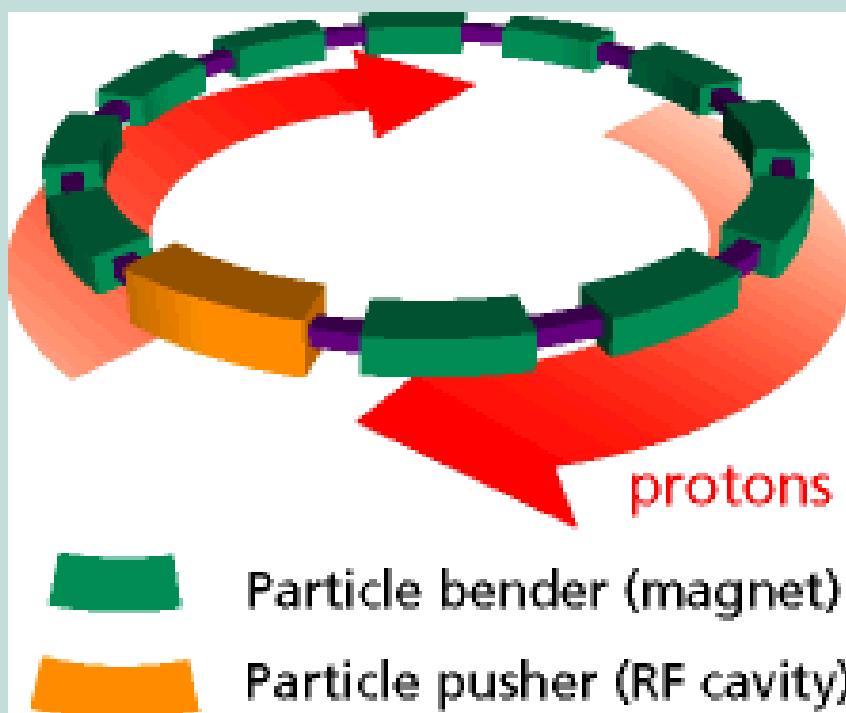
*Dariusz Bocian*

Division of Scientific Equipment and Infrastructure Construction (DAI)

**SPAS 2014, Kraków**

- **Motivation**
  - Accelerator magnets
  - Enhanced cable insulation
- **Network model**
  - 3D model construction
  - Electrical equivalent
- **Numerical calculations**
  - Comparison with measurements
  - Comparison with ANSYS model



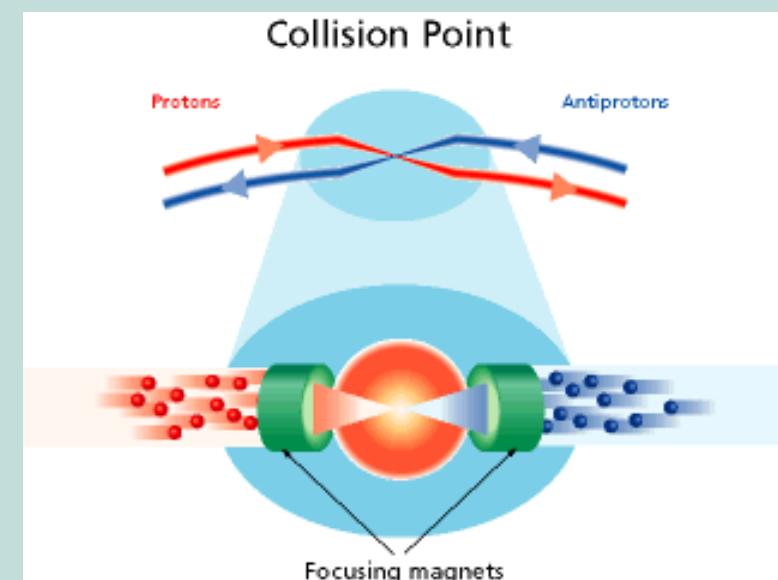
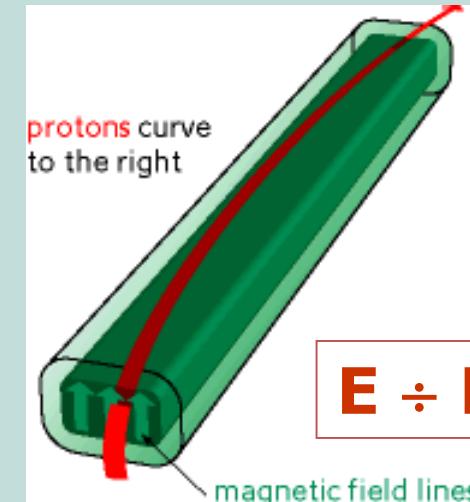


### → Lattice Quadrupoles

Quadrupole magnets to keep the particles in the beam

### → IR Quadrupoles

Quadrupole magnets to focus the beams  
in the Interaction Regions



- *Main dipoles* to bend the beam
  - Higher field → higher particles energy
- *Main quadrupoles* to keep the beam together
- *Corrector magnets* to preserve beam quality
- *Interaction Region quadrupoles* to focus the beam at interaction points
  - Higher gradients and aperture → higher luminosity

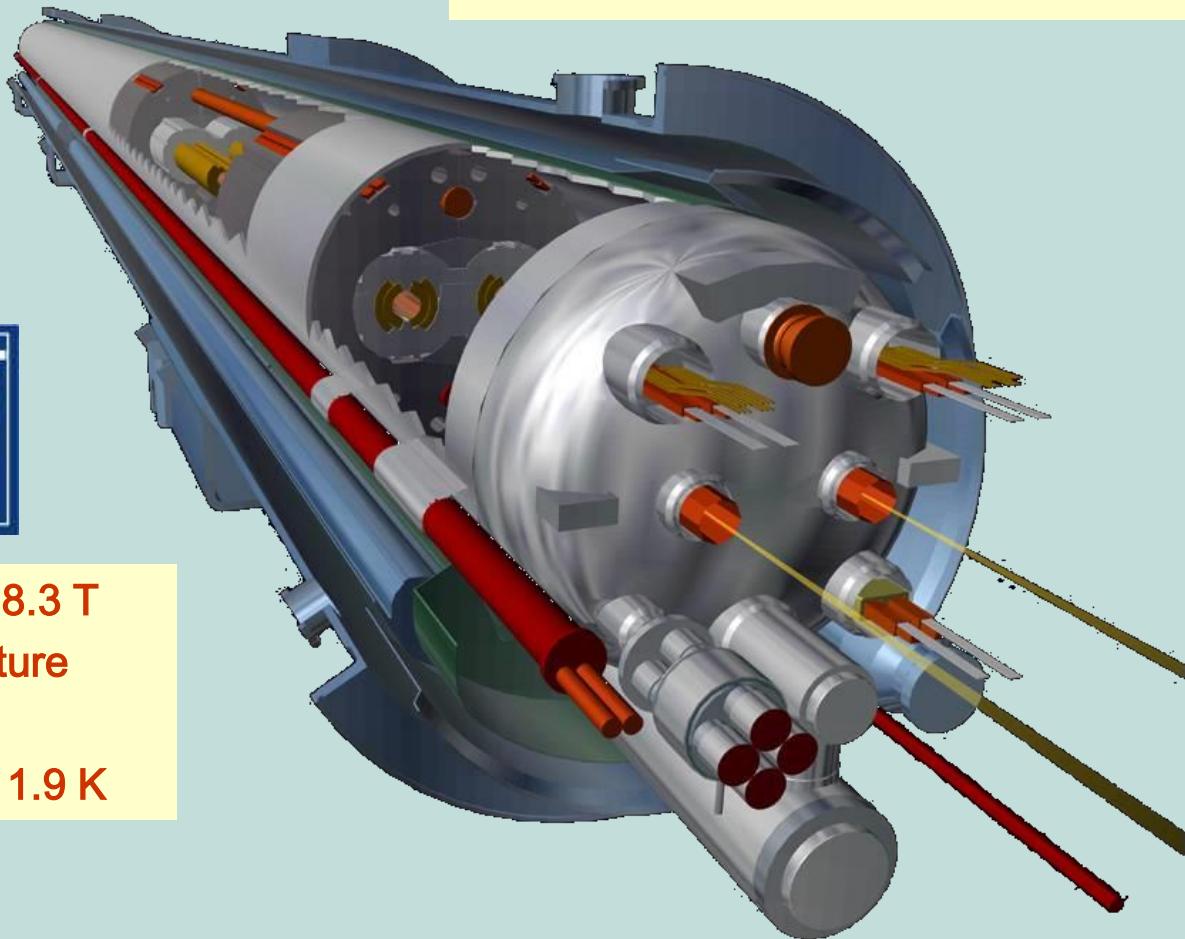
# Why superconducting magnets?

- Iron dominated magnets limited by iron saturation at 2 T
- Permanent magnets practically limited in the range 1-2 T
- Copper (or Al) dominated magnets 50-100 T but for ms !

Superconducting magnets are an enabling technology for high energy hadron colliders

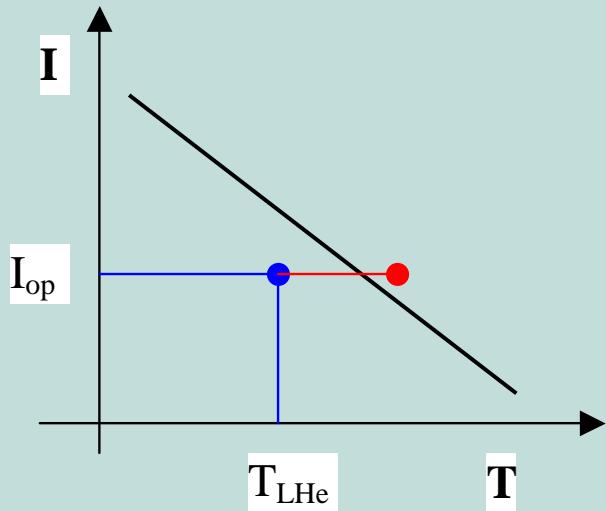


LHC dipoles: 8.3 T  
double aperture  
cold yoke  
operating at 1.9 K



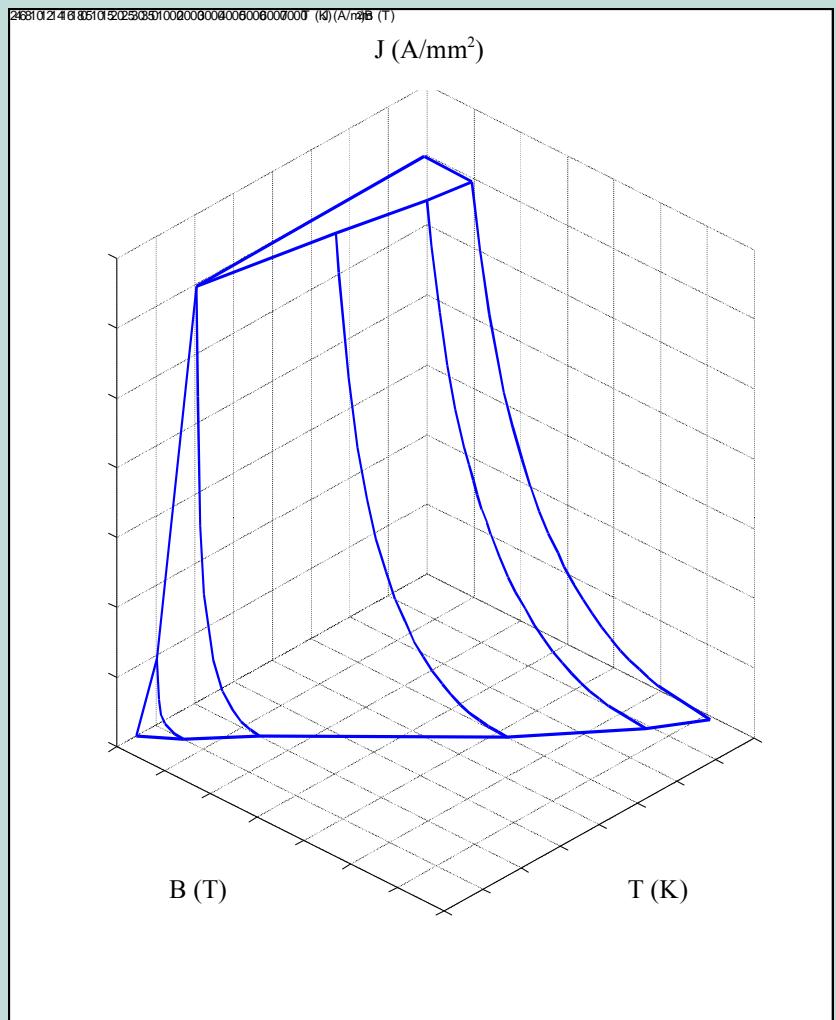
- Three parameters characterizing superconductor:
  - Critical current density
  - Critical magnetic field
  - Critical temperature

operating point of the magnet beyond critical surface  $\Rightarrow$  QUENCH

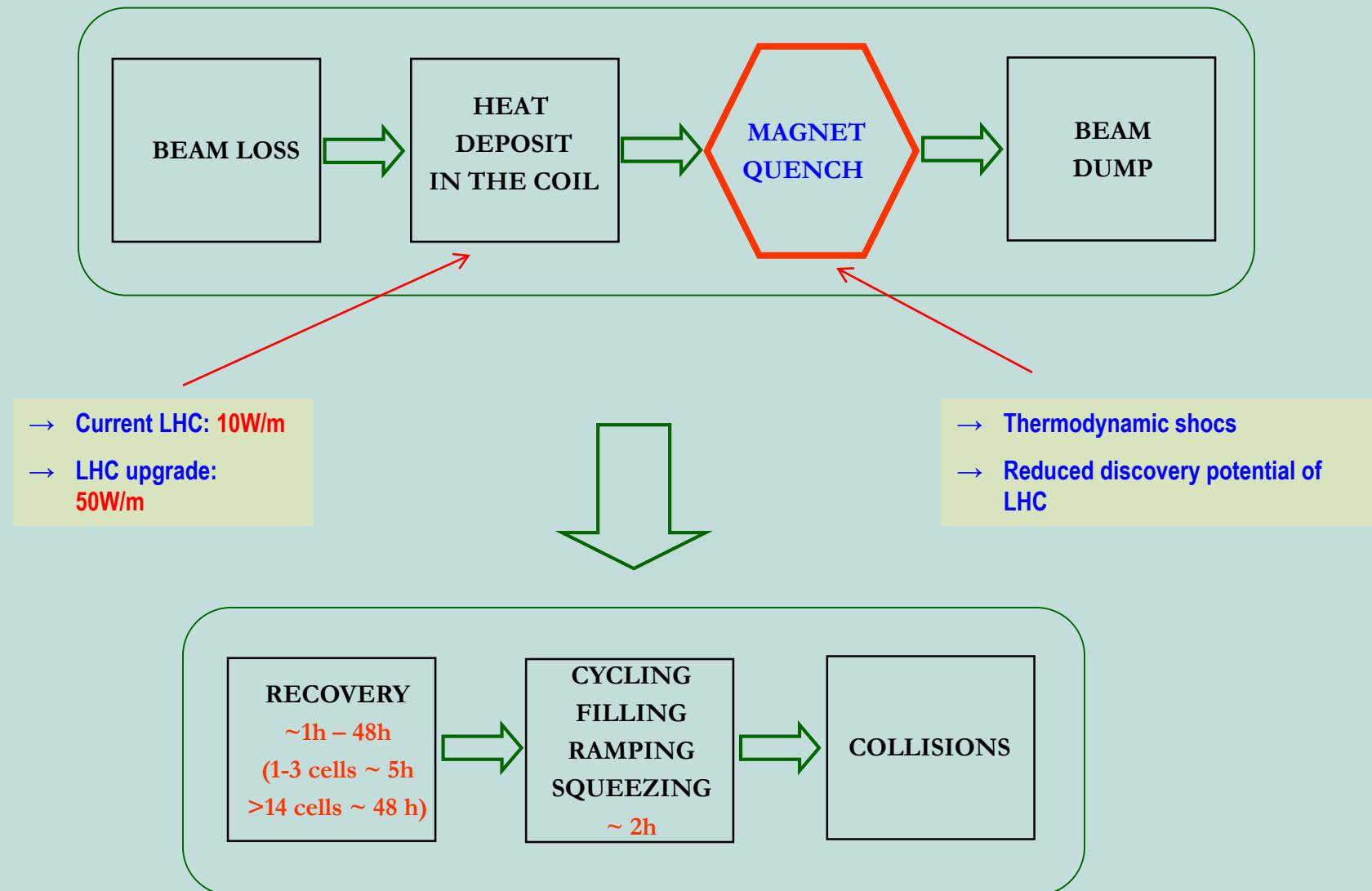


Accelerators: conductor temperature rise due to beam induced heat load  
 $\Rightarrow$  QUENCH

### Critical surface

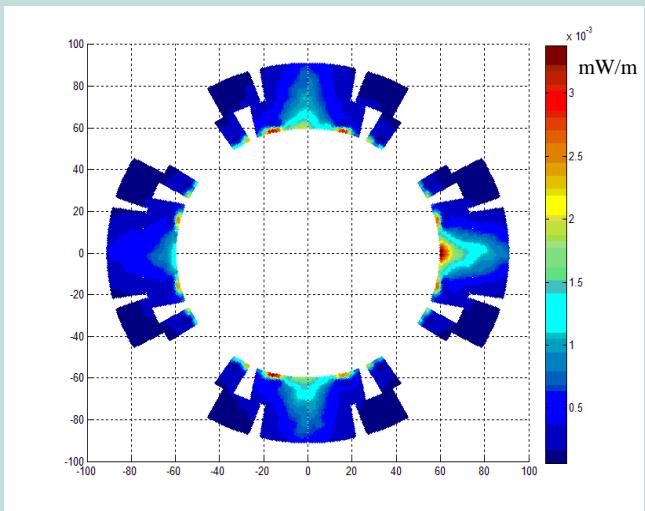


# Accelerator operation scheme

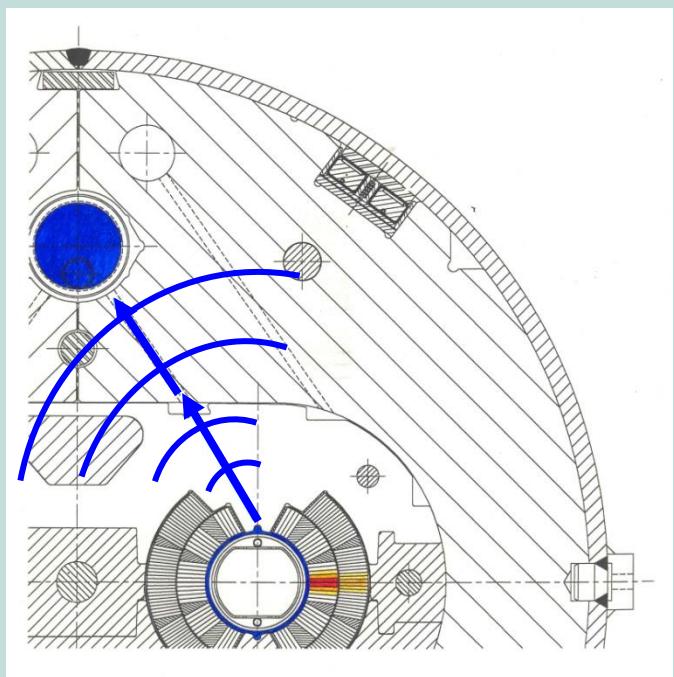


# Heat load in the LHC magnets

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



A heat transfer in the magnet

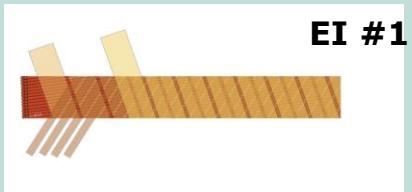
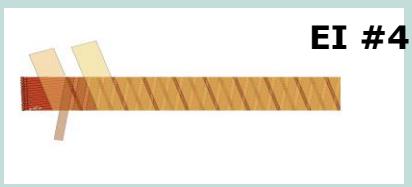


## References:

- 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;

# Enhanced cable insulation

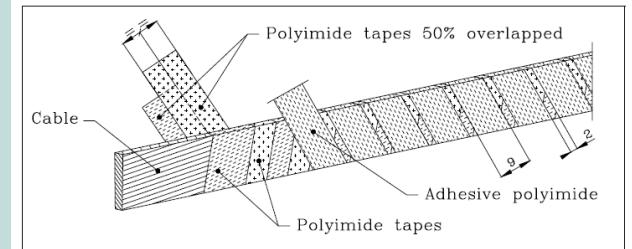
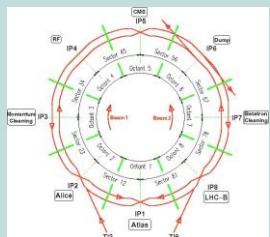
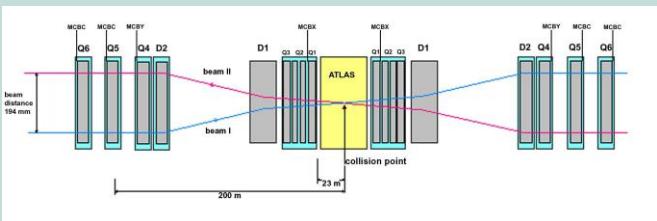
## Can we still exploit NbTi?


**EI #1**

**EI #4**

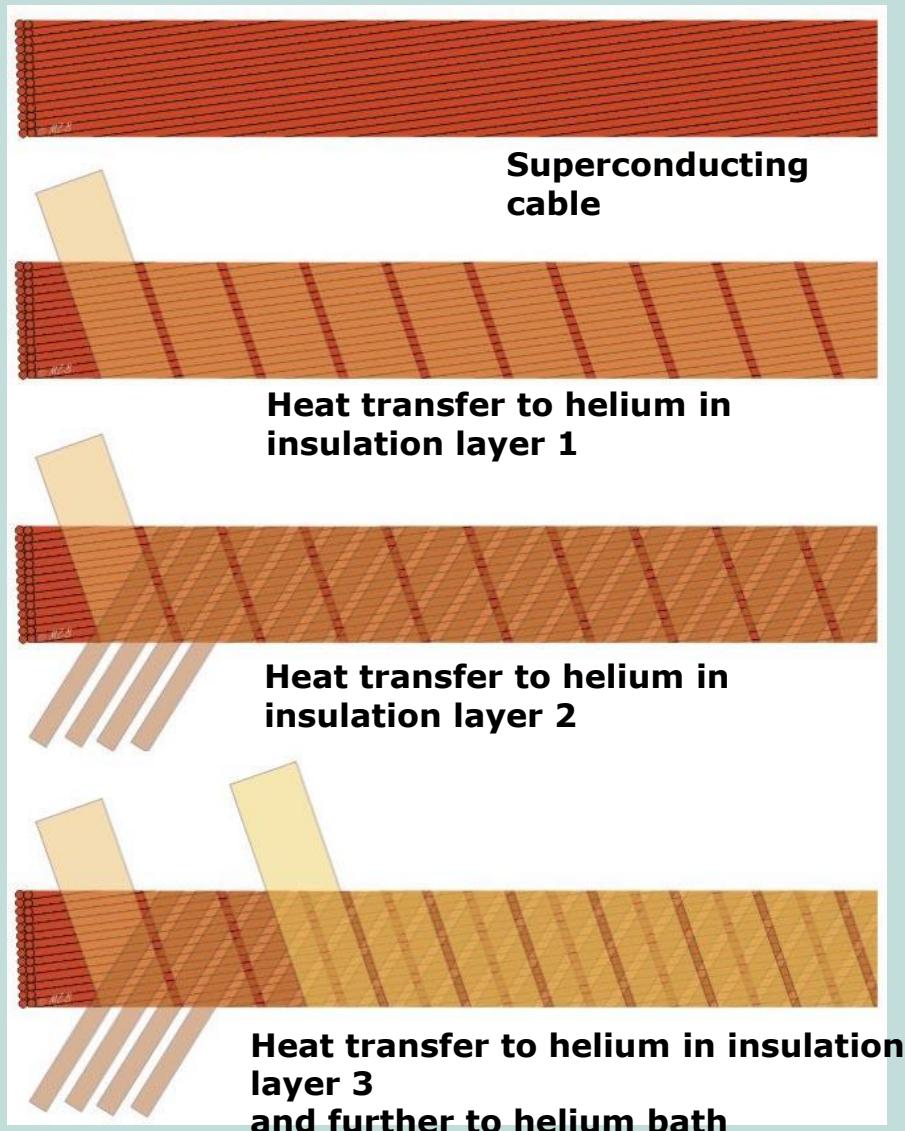
Strand diameter = 1.065 mm, cable width (bare)= 15.1 mm			
EI type	1st layer (polyimide)	2nd layer (polyimide)	3rd layer (polyimide with adhesive coating)
EI #1	9 mm wide, 1 mm gap 25.4 $\mu\text{m}$ thick wrap angle $\alpha_1 = 71.68$ deg	4 x(2.5 mm wide, 1.5 mm gap) 75 $\mu\text{m}$ thick, <u>cross wrapped with 1<sup>st</sup> and 3<sup>rd</sup> layers</u> wrap angle $\alpha_1 = 62.16$ deg	9 mm wide, 1 mm gap 55 $\mu\text{m}$ thick, <u>50% overlap with 1<sup>st</sup> layer</u> wrap angle $\alpha_1 = 71.90$ deg
EI #4	9 mm wide, 1 mm gap 50 $\mu\text{m}$ thick wrap angle $\alpha_1 = 71.68$ deg	1 x(3.0 mm wide, 1.5 mm gap) 75 $\mu\text{m}$ thick, <u>cross wrapped with 1<sup>st</sup> and 3<sup>rd</sup> layers</u> wrap angle $\alpha_1 = 81.6$ deg	9 mm wide, 1 mm gap 69 $\mu\text{m}$ thick, <u>50% overlap with 1<sup>st</sup> layer</u> wrap angle $\alpha_1 = 72.0$ deg

### Bibliography:

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).

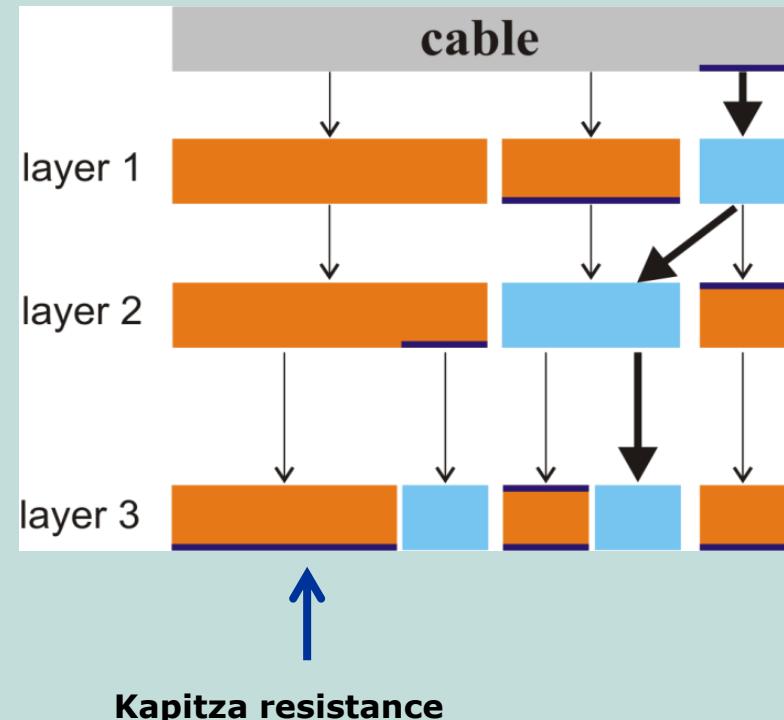


# Enhanced cable insulation

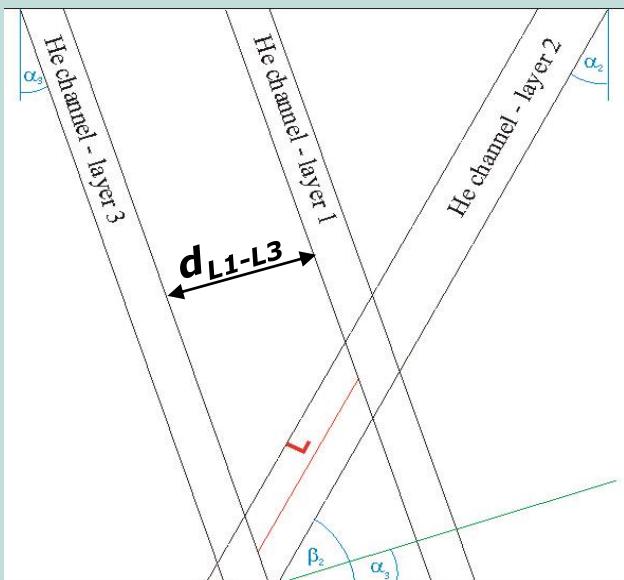


Heat is transferred to helium bath through:

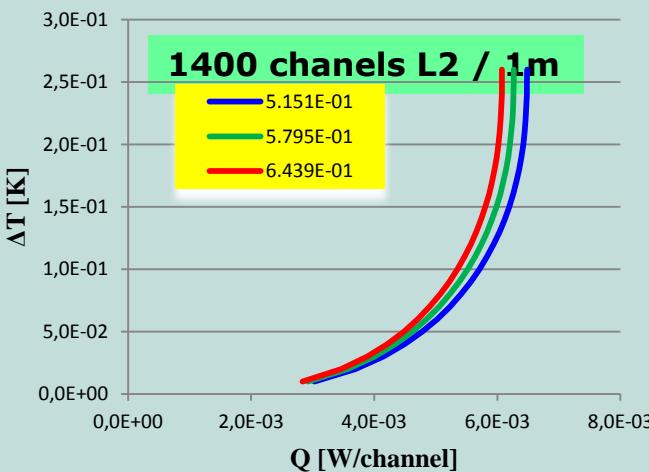
- superfluid helium
- cable insulation



# Layer 2 He channel length



Heat flow in He channel layer 2



$$L = \frac{d_{L1-L3}}{\cos(\frac{\pi}{2} - \alpha_{L2} - \alpha_{L3})}$$

$L$  – helium channel length in insulation layer 2,  
 $d_{L1-L3}$  – distance between the helium channel in layer 1 and 3,

$\alpha_{Li}$  – insulation wrapping angle of layer ( $i=1,2,3$ ),  
 $w_{ins}(L_i)$  – insulation layer width (insulation tape width + gap width)  
 $h_{ci}$  – cable width (15.1 mm + 2\*insulation thickness),

$$\alpha_{Li} = \arcsin\left(\frac{w_{ins}(L_i)}{2 \cdot h_{ci}}\right)$$

Calculated winding angle

$L1$	$L2$	$L3$
71.68	62.16	71.90

Helium channel length in insulation layer 2

	edge L1- edge L3	middle L1- edge L3	middle L1- middle L3
$d_{L1-L3} =$	4.0 mm	4.5 mm	5.0 mm
$L =$	5.15 mm	5.8 mm	6.44 mm

**He L2 channel cross-section:  $1.5E-3 \text{ m} \times 75E-6 \text{ m} = 1.125E-8 \text{ m}^2$**

Superfluid helium heat flux density calculation

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

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

$S$  is helium channel cross-section in [ $cm^2$ ],

$l$  is helium channel length in [cm],

$T_c$  is the temperatures of cold channel end in [K]

$T_h$  is the temperatures of hot channel end in [K]

# 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
$\kappa$	[W/Km]	Thermal Conductivity	$\sigma$	[1/Ωm]	Electrical Conductivity
$R^\Theta$	[K/W]	Thermal Resistance	$R$	[V/A]	Resistance
$C^\Theta$	[J/K]	Thermal Capacitance	$C$	[C/V]	Capacitance

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

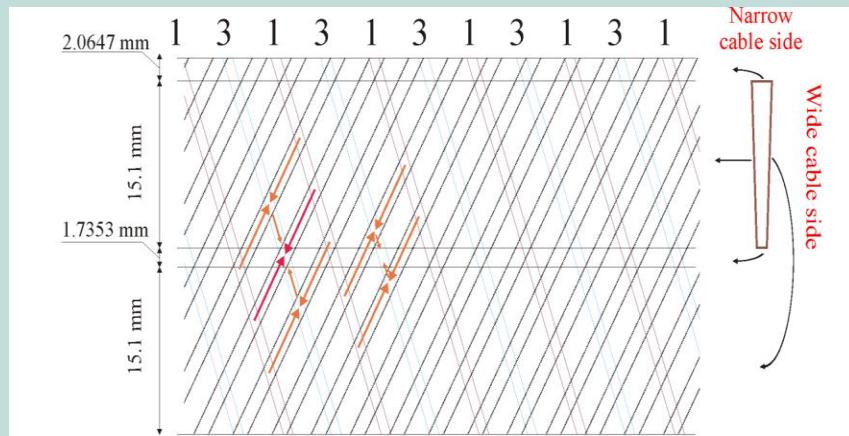
-steady-state condition      *Temperature rise*       $\Leftrightarrow$       *Voltage difference*

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

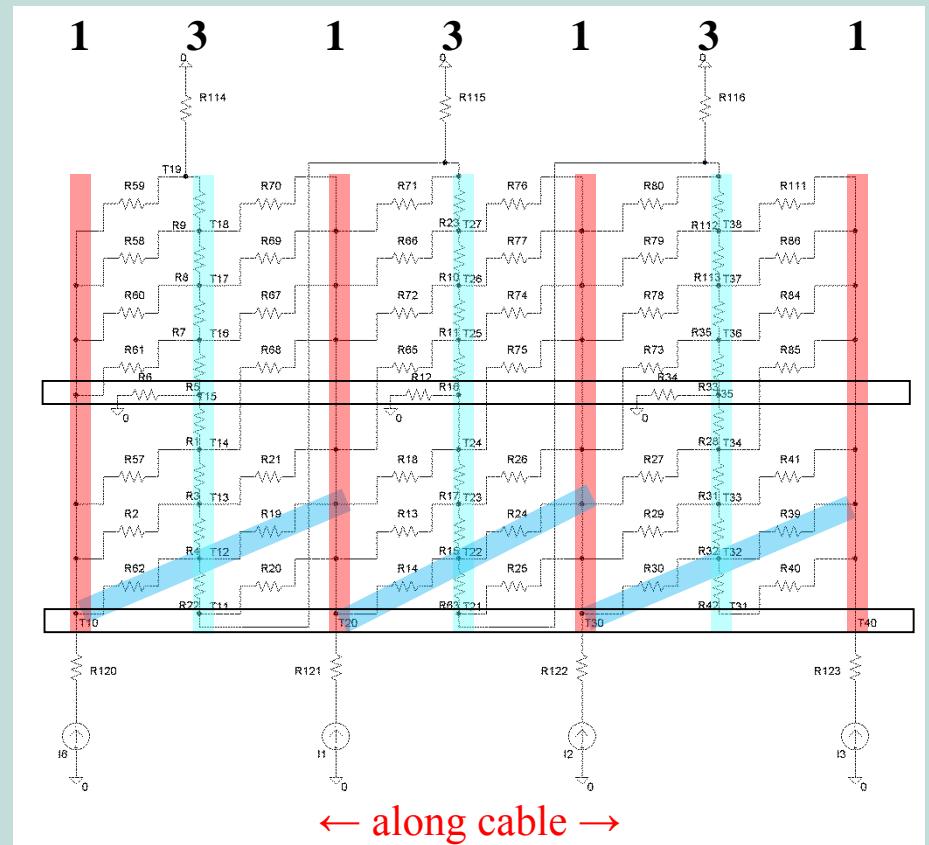
-transient condition      *Heat diffusion*       $\Leftrightarrow$       *RC transmission line*

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

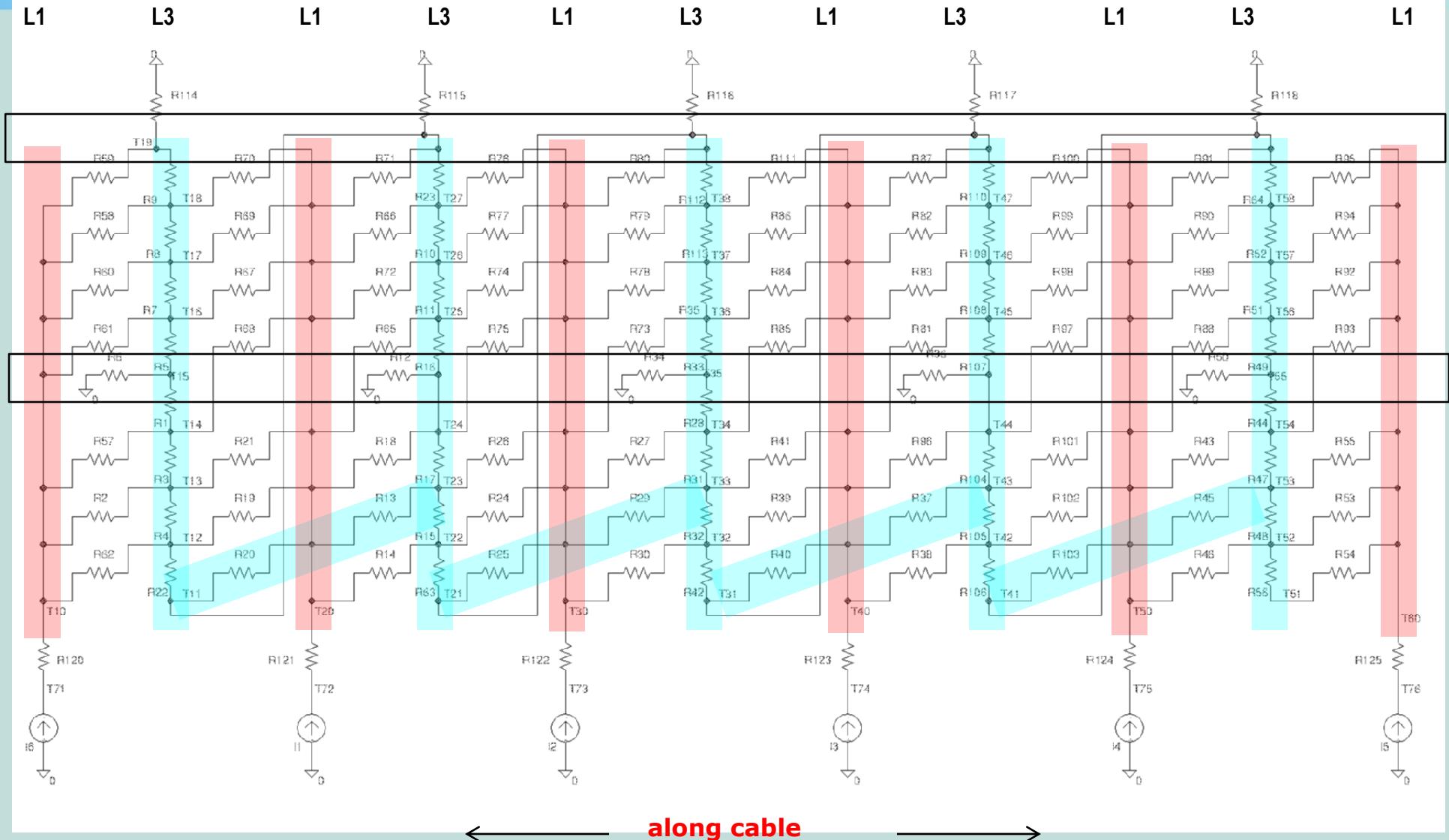
# Enhanced cable insulation



Helium channels network



# Simulations – Network Model construction



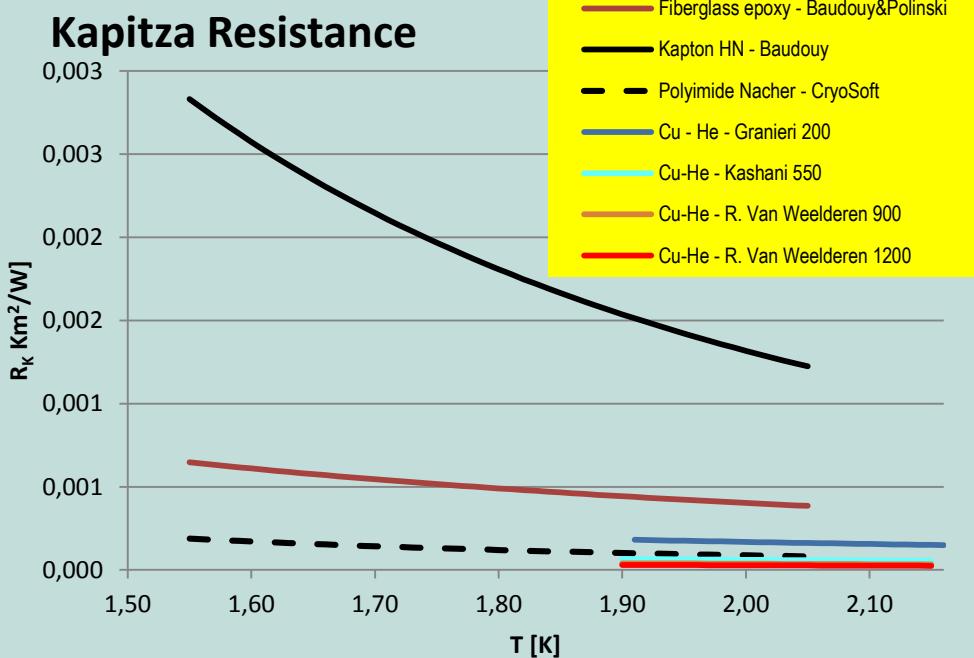
Kapitza resistance: A resistance to the flow of heat across the interface between liquid helium and a solid.

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

$T_s$  – solid temperature

$T_{He}$  – helium temperature

$\dot{Q}/A$  – heat flow per unit area



## Copper - HeII

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

## POLYIMIDE - HeII

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

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

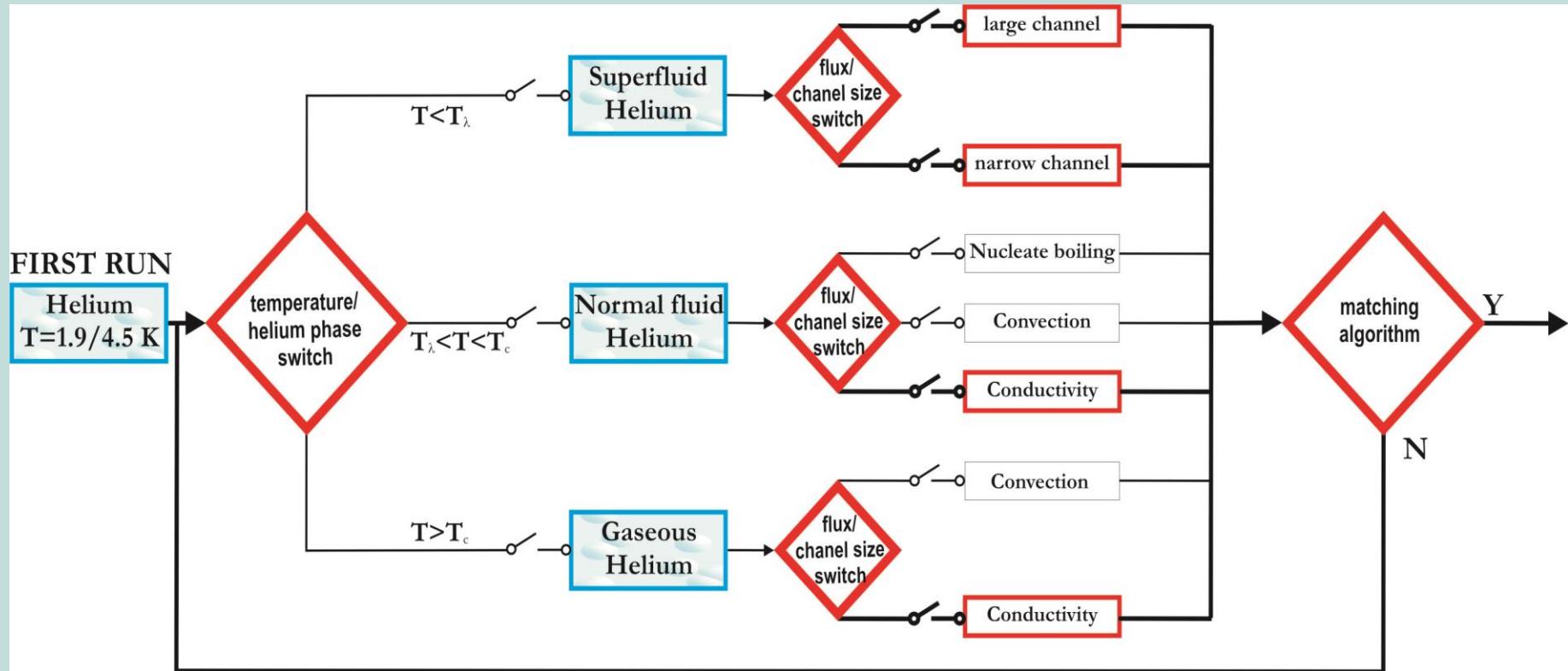
$$R_K = 0.7E-3 * T^3 \text{ Km}^2\text{W}^{-1} \quad [2]$$

## G10 - HeII

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

## 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.



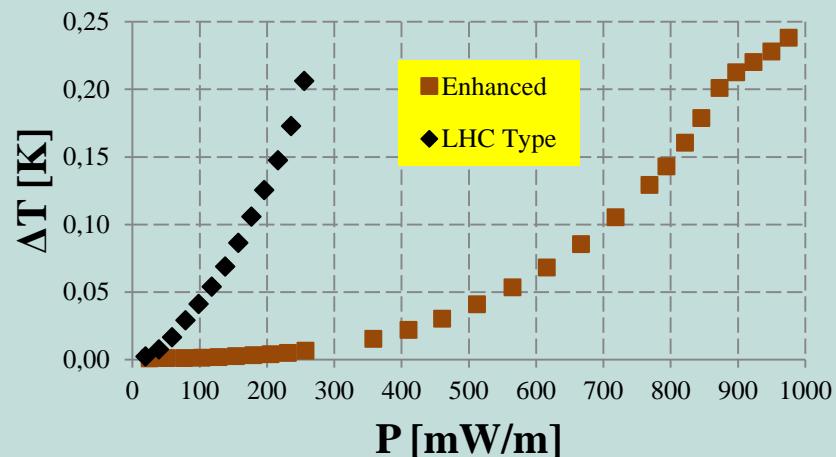
# Experimental setup

cable stack immersed in superfluid helium

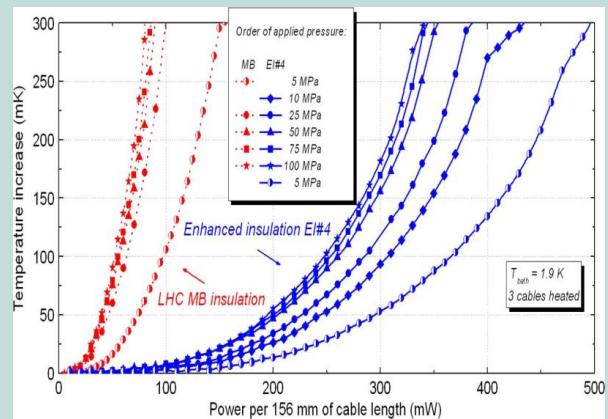
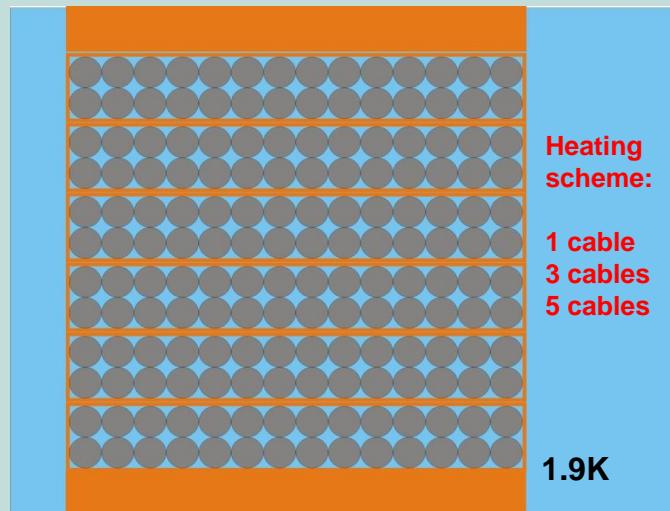
- 150 mm active part long
- 28 resistive CuNi<sub>10</sub> wt.% strands  
(with the same geometry as the LHC cable 1)
- Insulated according to EI#1 or EI#4
- Sample cured according LHC cycle (80 Mpa, 190 °C)

**Measurements performed under pressure**

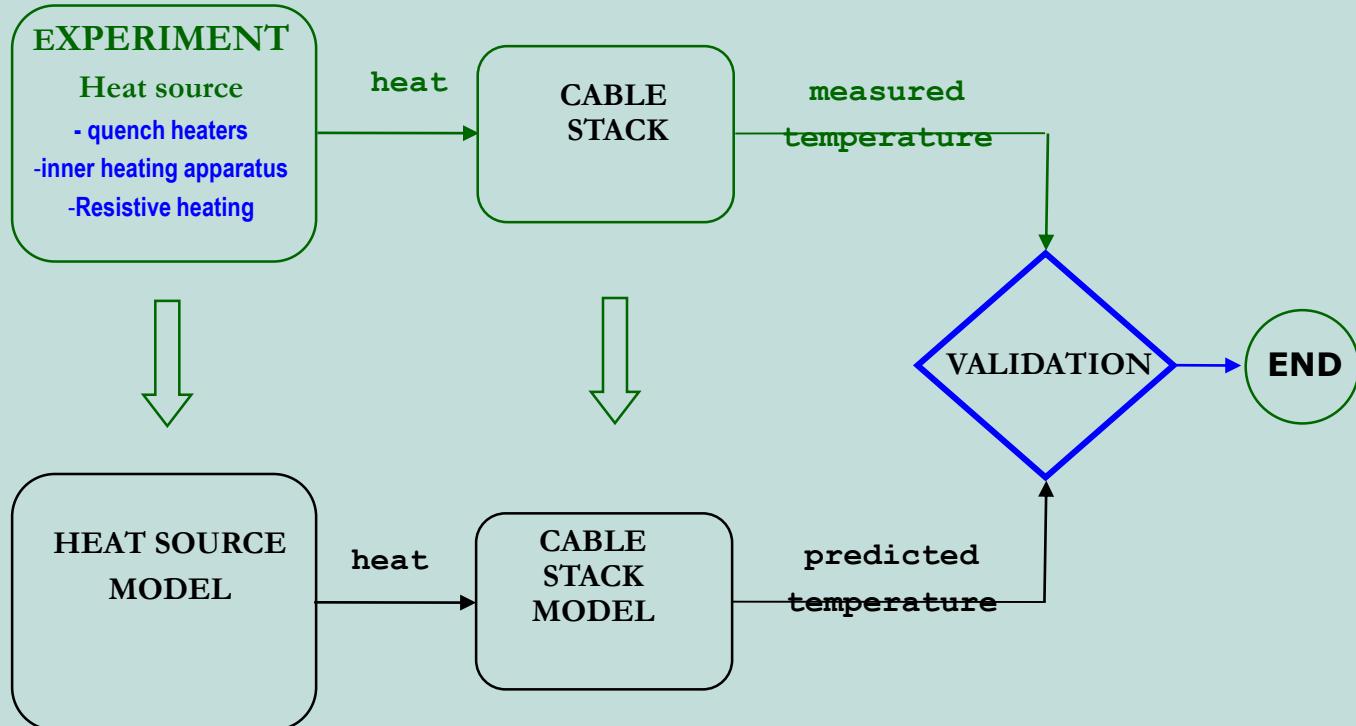
**30 MPa for EI#1 and 5 – 100 MPa for EI#4**

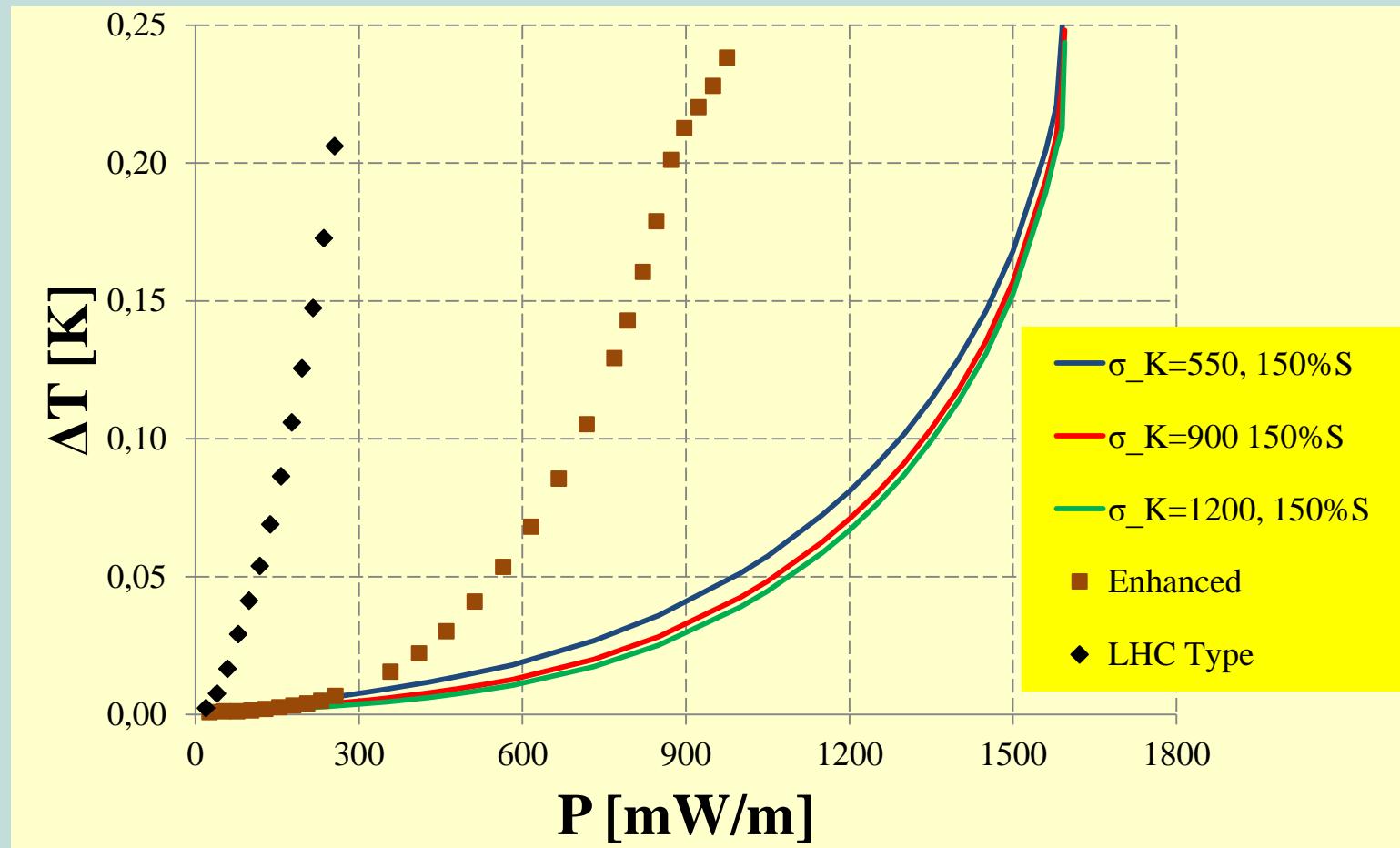


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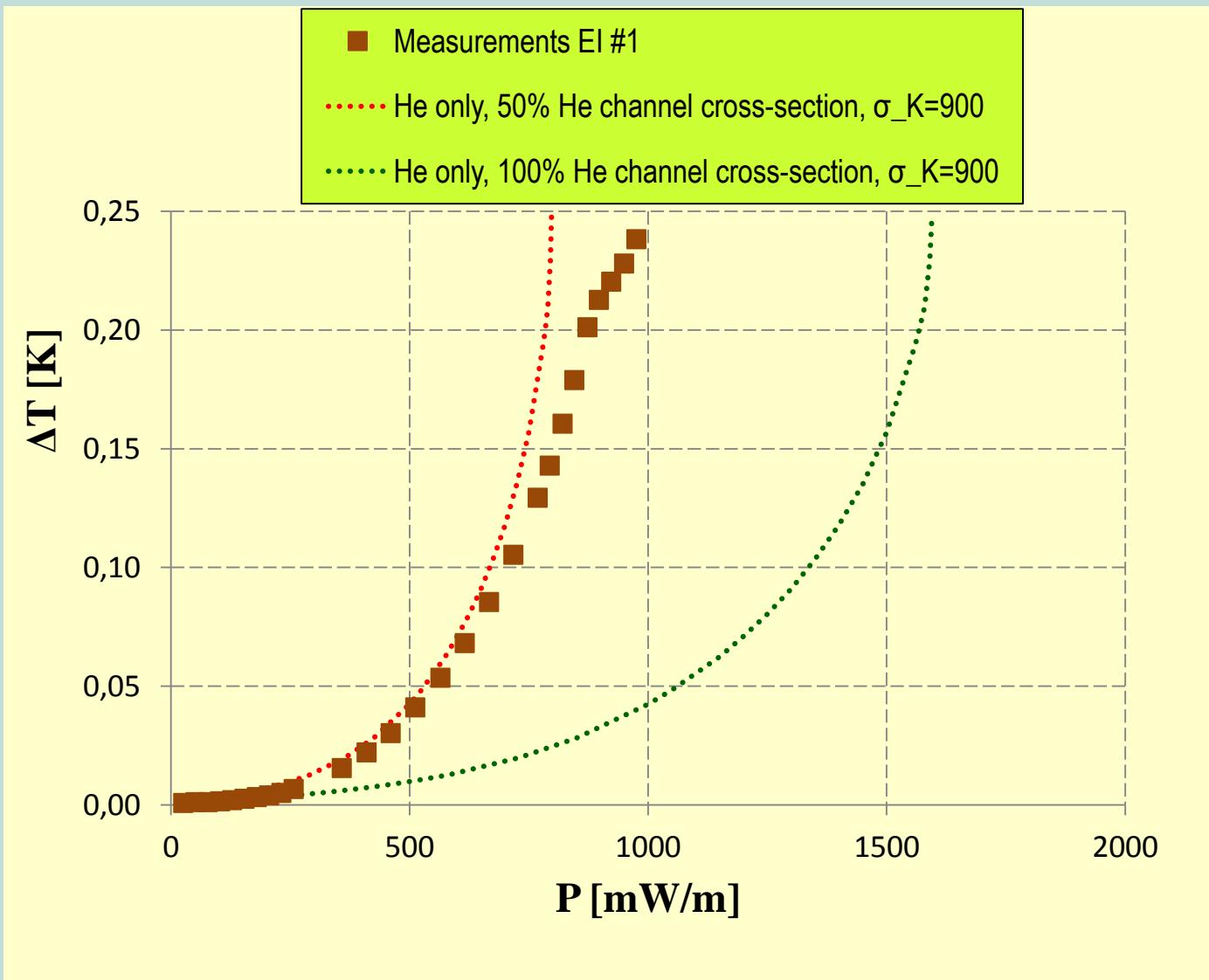
P. P. Granieri et al., "Heat transfer in an enhanced cable insulation scheme for the superconducting magnets of the LHC luminosity upgrade," IEEE Trans. Appl. Supercond., vol. 20, Issue 3, 2010



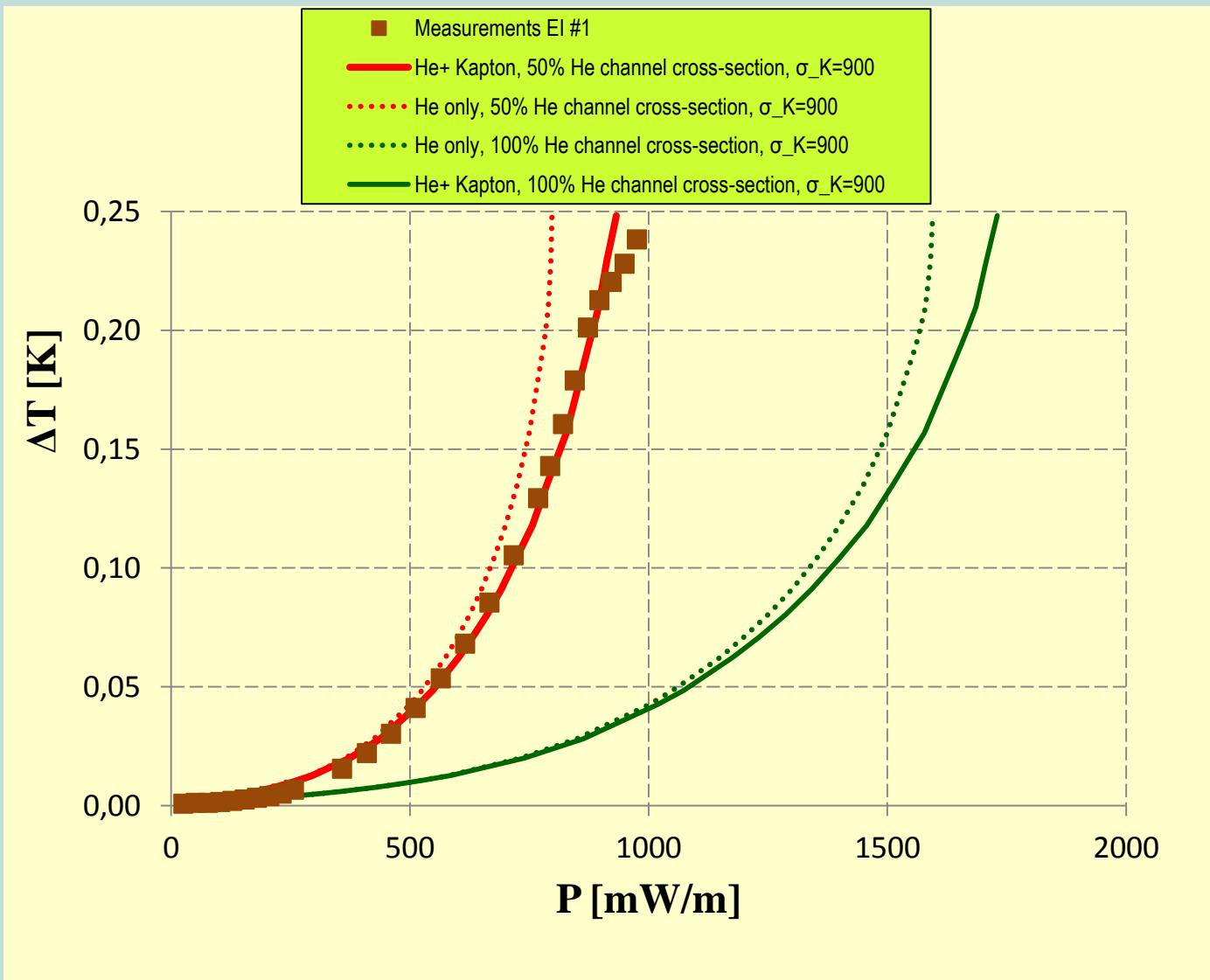


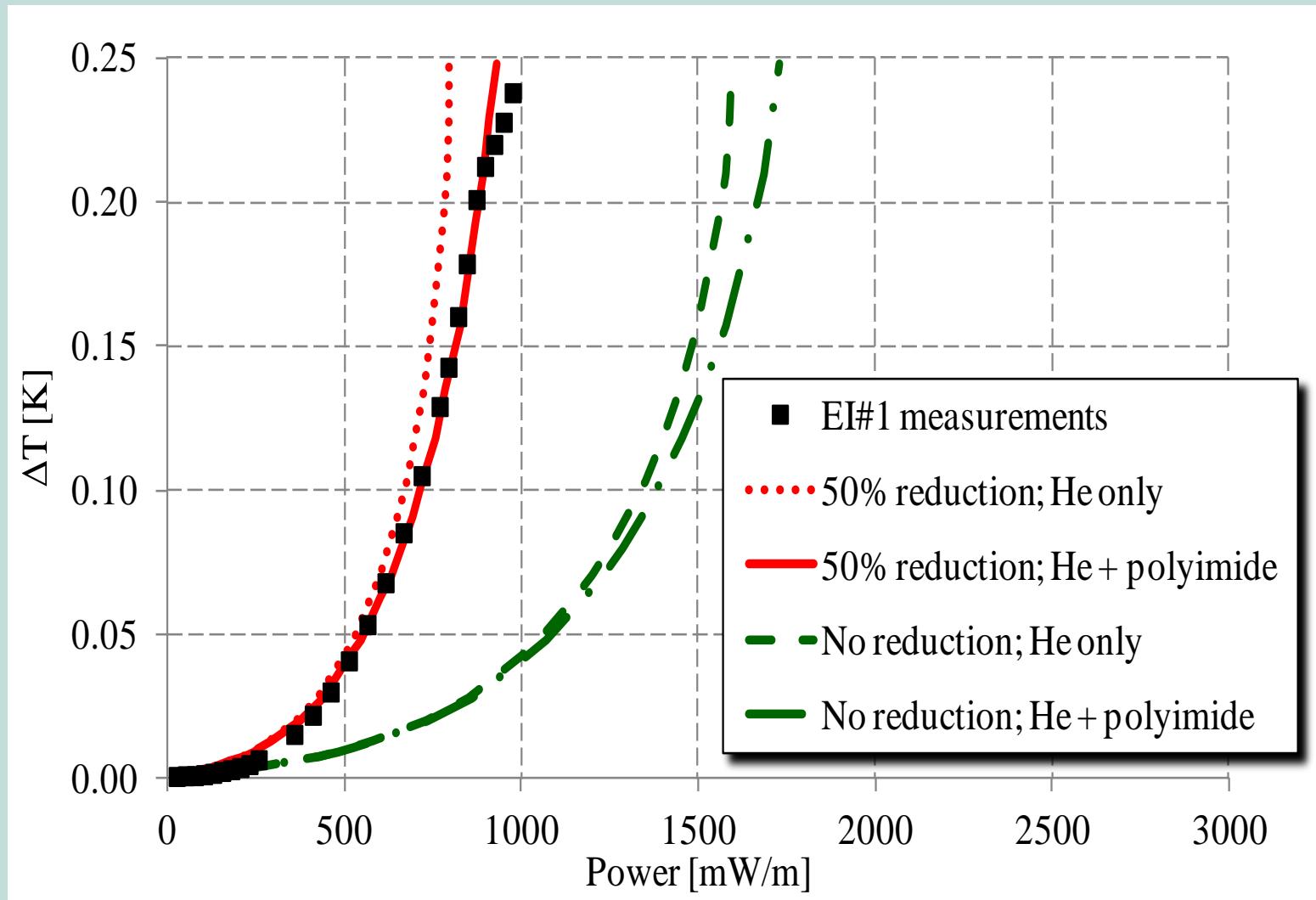
Cable should demonstrate better performance than measured!

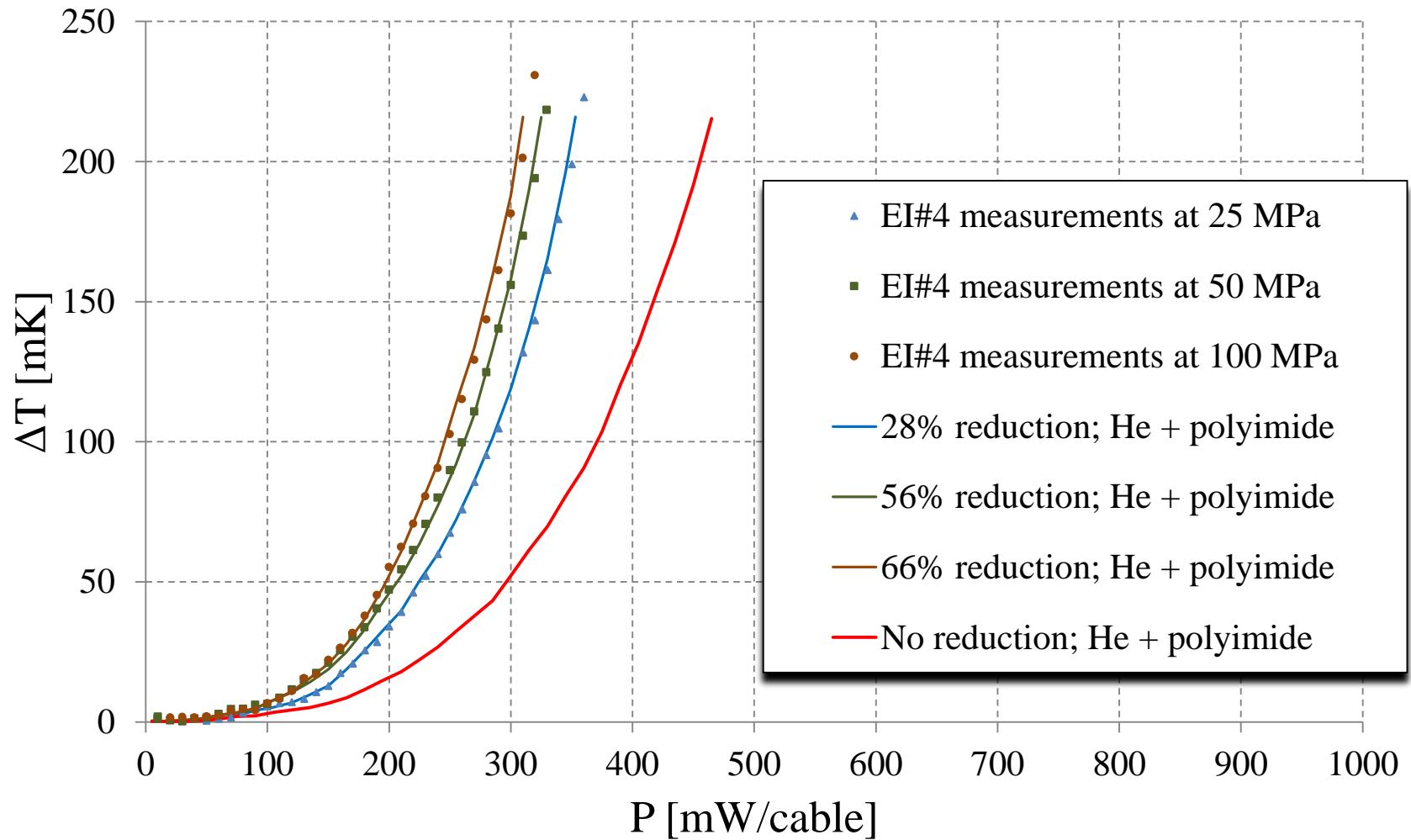
# Enhanced cable insulation

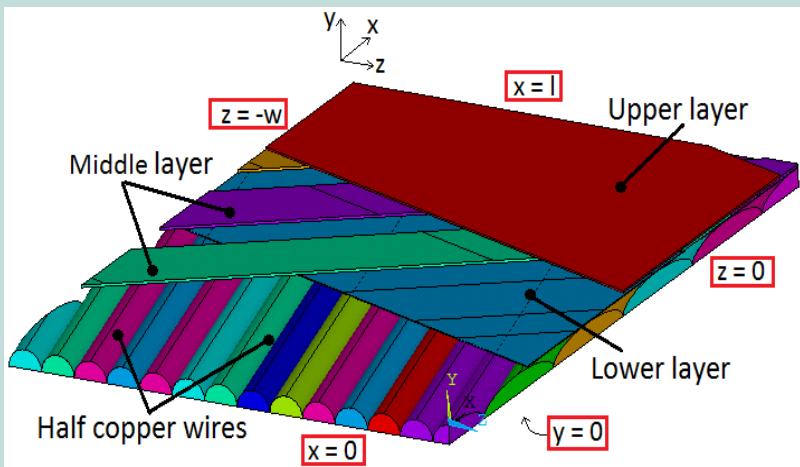


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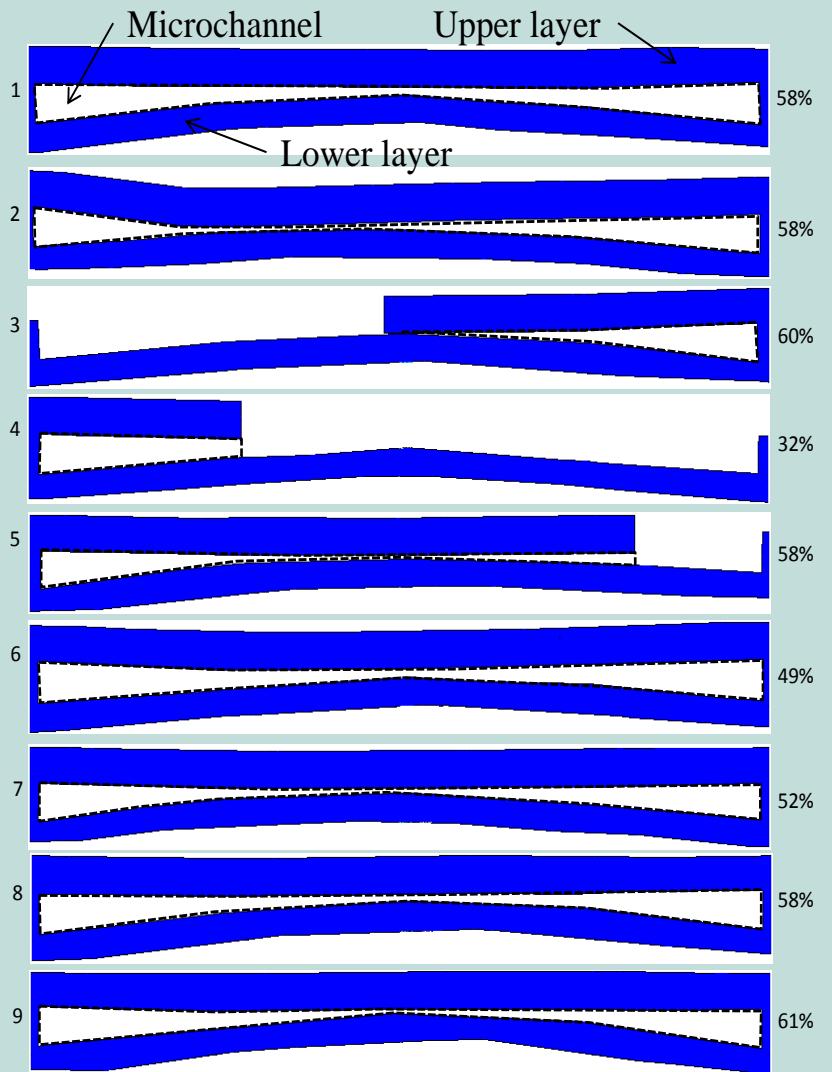




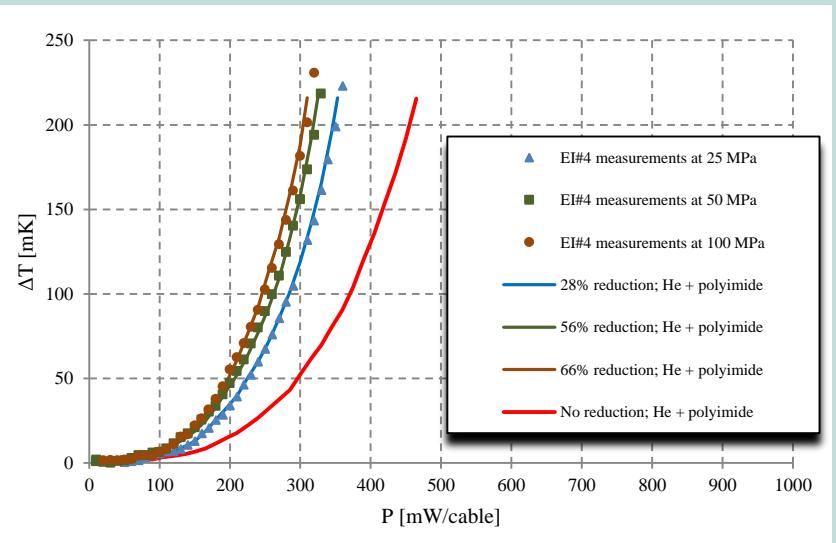
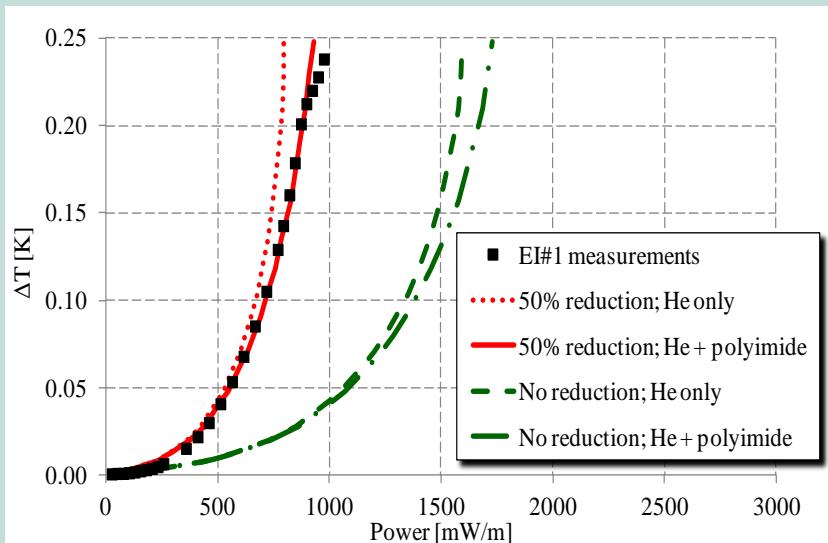




The ANSYS model shows that the cross-section of the channels is strongly reduced, i.e., by 20 to 60% depending on the applied pressure,

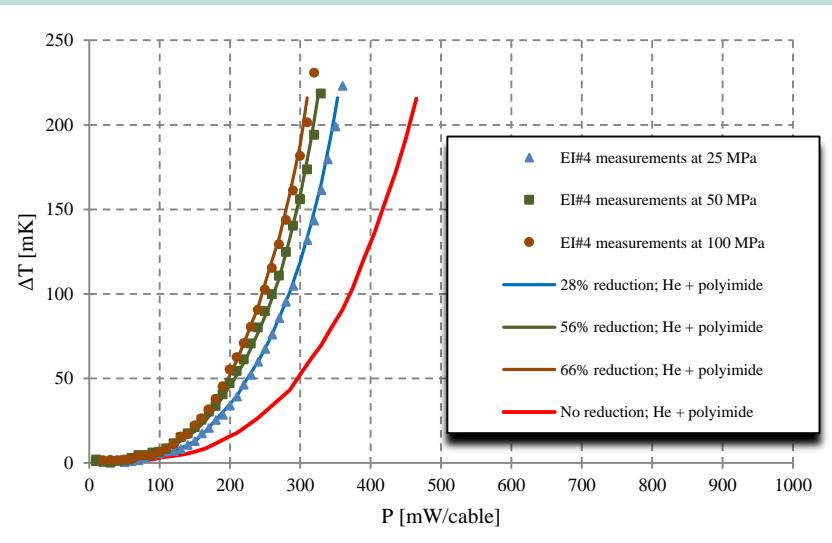
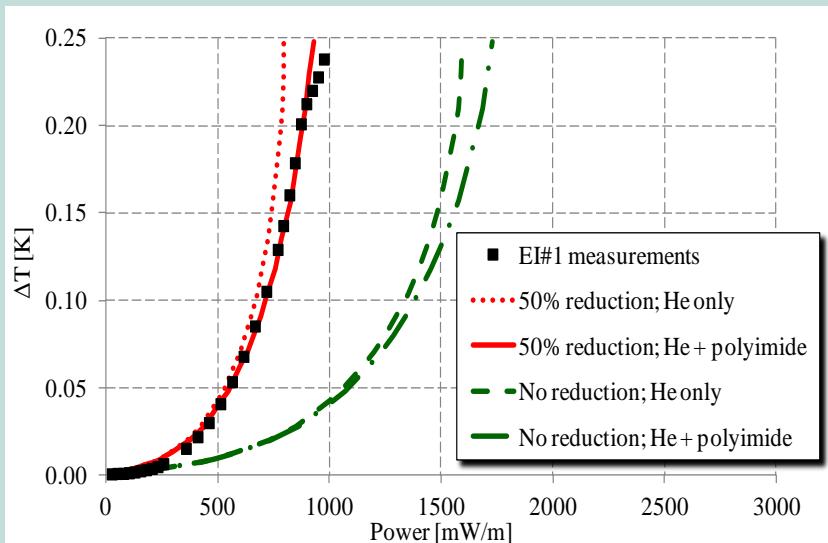


Insulation	EI#1			EI#4		
Load (MPa)	30	60	100	25	50	100
Average	22%	33%	42%	20%	39%	54%
Maximum	30%	61%	62%	25%	52%	61%
Network Model	50%	-	-	28%	56%	66%



- 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 simulations

# Conclusion



BUT

**Better heat transfer = quench protection problem**

**And this is a subject for another story**