Development of the Cable Insulation for the LHC Triplet Upgrade Phase I

Pier Paolo Granieri

and many contributors

TE Magnet seminar, 3 July 2009

Contributors

- *Davide Tommasini, Paolo Fessia, TE-MSC*
- *David Richter, TE-MSC* *(Heat Transfer Tests)*
- *Sebastien Luzieux, TE-MSC* *(Samples Manufacture, Electrical Tests and Compression Tests @ 300 K)*
- *Michael Guinchard, EN-MME*
  Alexandre Gerardin, EN-MME
  Federico Regis, TE-MSC
  Stefano Sgobba, EN-MME *(Compression Tests @ 300 and 77 K, stress relaxation)*
- *Riccardo Musenich, INFN Genoa, Italy* *(Heat Transfer Tests in SHe)*
- *Jaroslaw Polinski, Michal Strychalski, WUT Wroclaw, Poland*
  Rob Van Weelderen, TE-CRG *(Heat Transfer Tests in He II btw 2 cables)*
- *Marco La China, Roberto Lopez, TE-MSC* *(preliminary tests)*

- *Many thanks to M. Casali, N. Elias, P. Ferracin, K. Saqi, E. Todesco*

Outline

- *Introduction*
- *Qualification Strategy of the Enhanced Insulation*
  - *- Samples Manufacture*
  - *- Heat Transfer Tests*
  - *- Electrical Tests*
  - *- Mechanical Tests*
- *Conclusions*

Introduction

- *An effective cooling of the magnet coils is essential in maintaining the superconducting (SC) state of the conductors against heat deposition / generation*

- *The next generation of SC accelerator magnets will deal with larger heat loads wrt the present applications (e.g. the interaction region magnets for the LHC luminosity upgrade)*

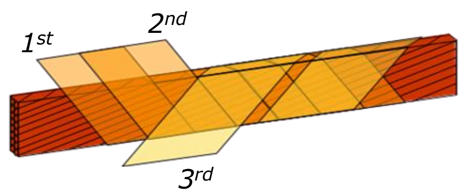
- *The main thermal barrier between cable and coolant is represented by the cable electrical insulation, but the potential of He superfluidity can be fully exploited with a helium permeable insulation*

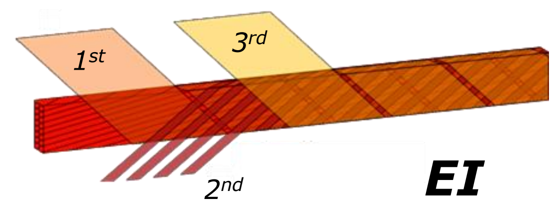
- *An enhanced cable insulation scheme (EI) is proposed aiming at increasing the heat exchange from Nb-Ti coils to He II bath, wrt the LHC standard insulation*

The concept of porous insulation

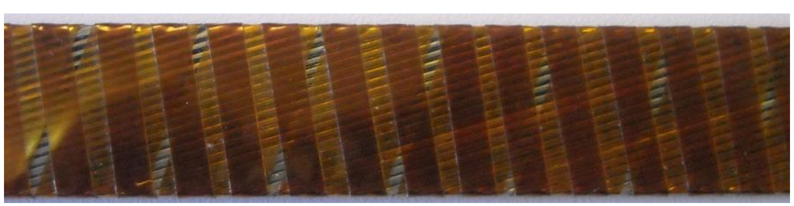
- *All-polyimide insulation scheme*

MB

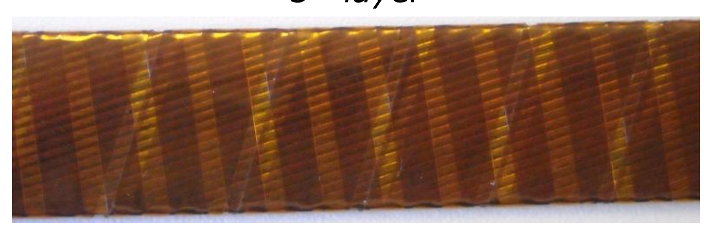




- *Electrical insulation provided by the combined effect of the 1^{st} ad 3^{rd} layer*
- *Increased size of the cooling μ-channels provided by:*
  - *- 2^{nd} layer made of thin strips wound counter-wise*
  - *- all layers wound with spacing*



1^{st} and 2^{nd} layer



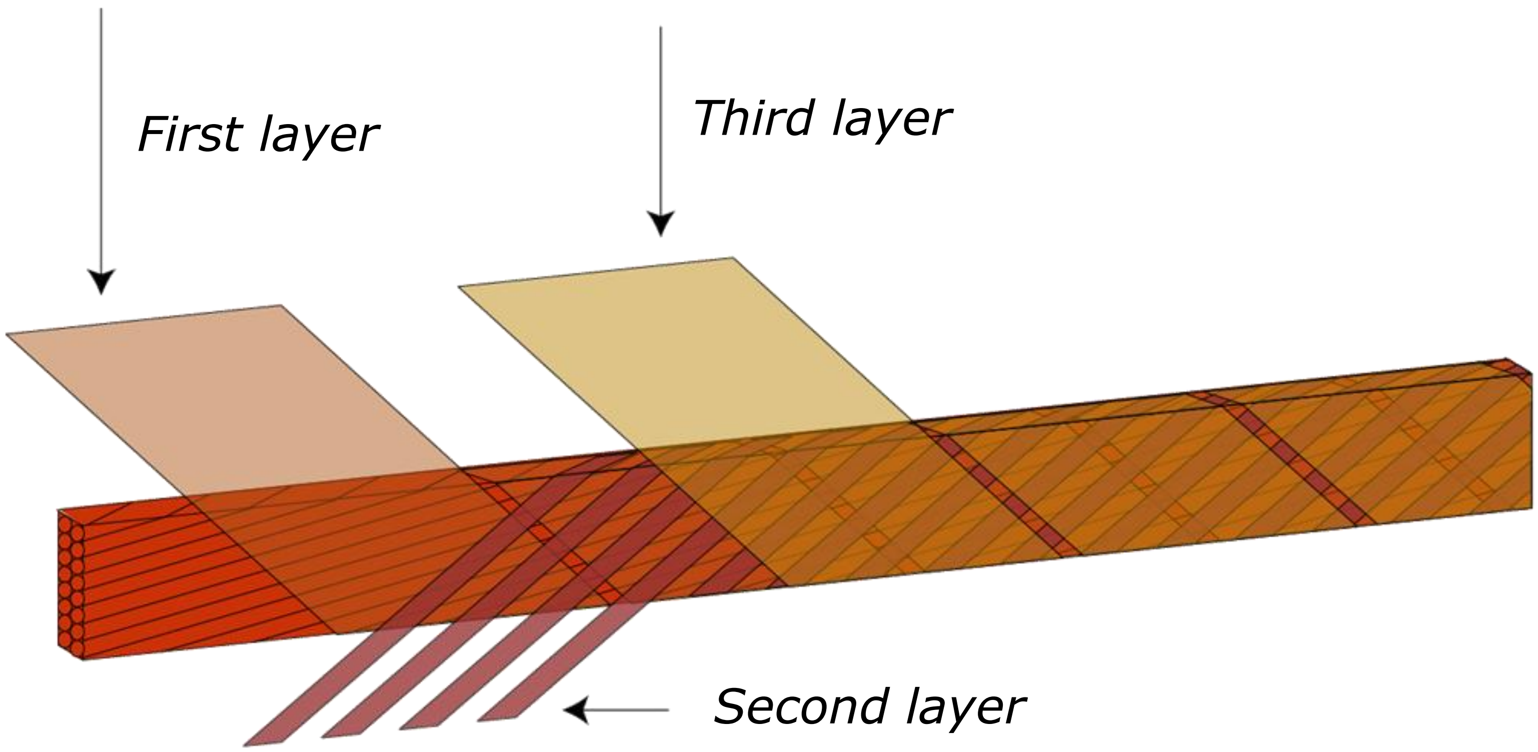
3^{rd} layer

Qualification of the Enhanced Insulation

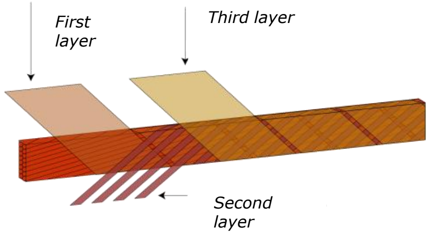
- *Definition of a layout enabling the use of commercially available tapes and the wrapping in a semi-industrial environment → Jeumont recovered insulating machine*

- *Thermal qualification:*
  - *heat transfer towards a 1.9 K helium bath* .... ongoing
- *Electrical qualification – Dielectric strength and leakage current:*
  - *on a 2-units stack* .... ongoing
  - *on a coil*
- *Mechanical qualification:*
  - *thickness, Young's modulus at 293 K* .... done
  - *thickness, Young's modulus at 77 K* .... ongoing
  - *stress relaxation* .... ongoing
  - *winding test*
  - *thermal contraction*

Samples Manufacture
Enhanced Insulation Schemes



Samples Manufacture
Enhanced Insulation Schemes

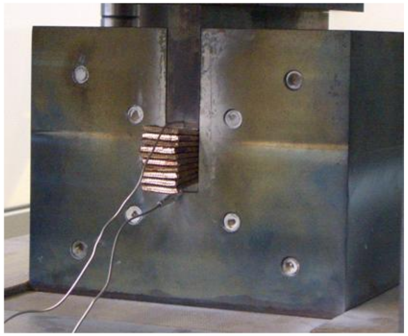


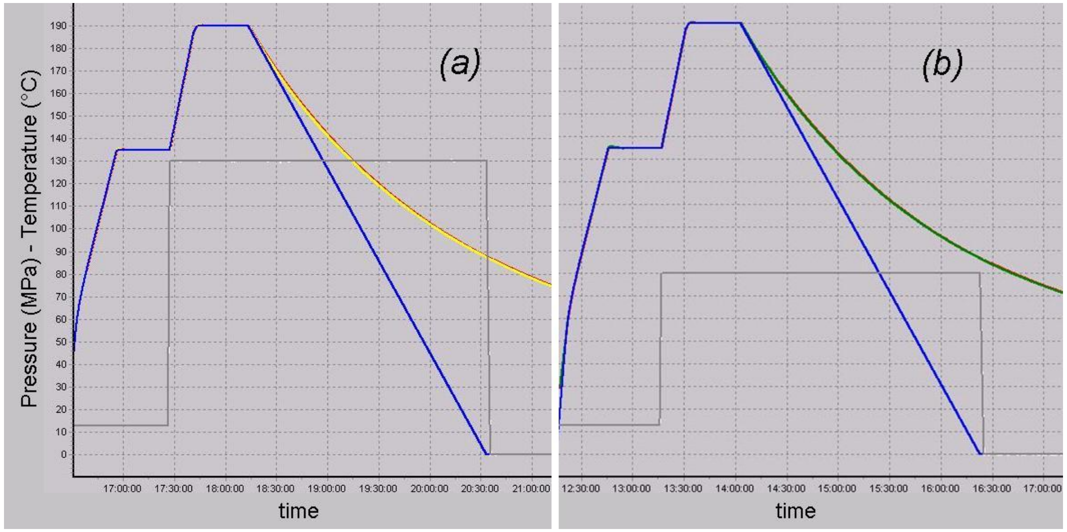
Insulation	1st layer (polyimide)	2nd layer (polyimide)	3rd layer (polyimide with adhesive coating)
MB	11 mm wide, no gap 50 μm thick	11 mm wide, no gap 50 μm thick, 50% overlap with the 1st layer	9 mm wide, 2 mm gap 69 μm thick, cross wrapped with the other layers
MQ	11 mm wide, no gap 50 μm thick	11 mm wide, no gap 37.5 μm thick, 50% overlap with the 1st layer	9 mm wide, 2 mm gap 55 μm thick, cross wrapped with the other layers
EI#1	9 mm wide, 1 mm gap 50 μm thick	3 mm wide, 1.5 mm gap 50 μm thick, cross wrapped with the other layers	9 mm wide, 1 mm gap 55 μm thick, 50% overlap with the 1st layer
EI#2	9 mm wide, 1 mm gap 50 μm thick	3 mm wide, 1.5 mm gap 75 μm thick, cross wrapped with the other layers	9 mm wide, 1 mm gap 55 μm thick, 50% overlap with the 1st layer
EI#3	9 mm wide, 1 mm gap 50 μm thick	3 mm wide, 1.5 mm gap 50 μm thick, cross wrapped with the other layers	9 mm wide, 1 mm gap 69 μm thick, 50% overlap with the 1st layer
EI#4	9 mm wide, 1 mm gap 50 μm thick	3 mm wide, 1.5 mm gap 75 μm thick, cross wrapped with the other layers	9 mm wide, 1 mm gap 69 μm thick, 50% overlap with the 1st layer

Samples Manufacture

- *The insulated cables have been superimposed alternatively to compensate the cable keystone, thus forming a rectangular stack:*

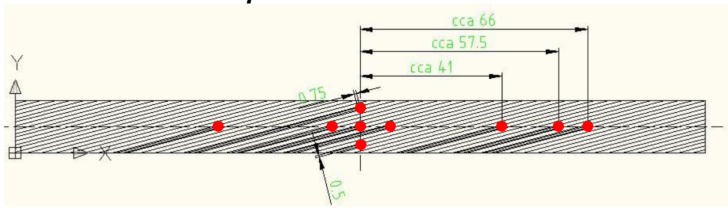
- *Curing over 170 mm according to two different bonding cycles: vertical pressure of either 130 MPa (a) or 80 MPa (b) at 190 °C:*

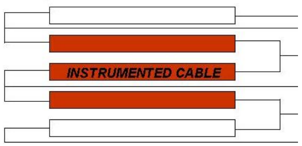


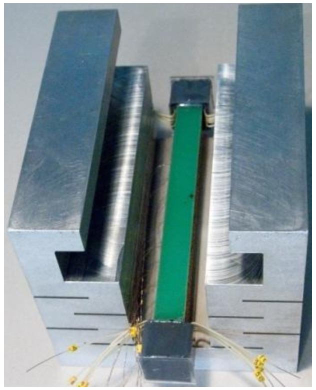


Heat Transfer Tests in 1.9 K bath Experimental Setup

- *6-units stacks made of LHC-type 01* ***CuNi cables****, wrapped with machine (but 3rd layer of EI#3,4),* ***curing*** *cycle:* ***130 MPa*** *at 190 °C*
- *Tested insulations: MB, EI#4*
- *grooves machined in one of the 2 central cables, to instrument it with 9 thermocouples:*

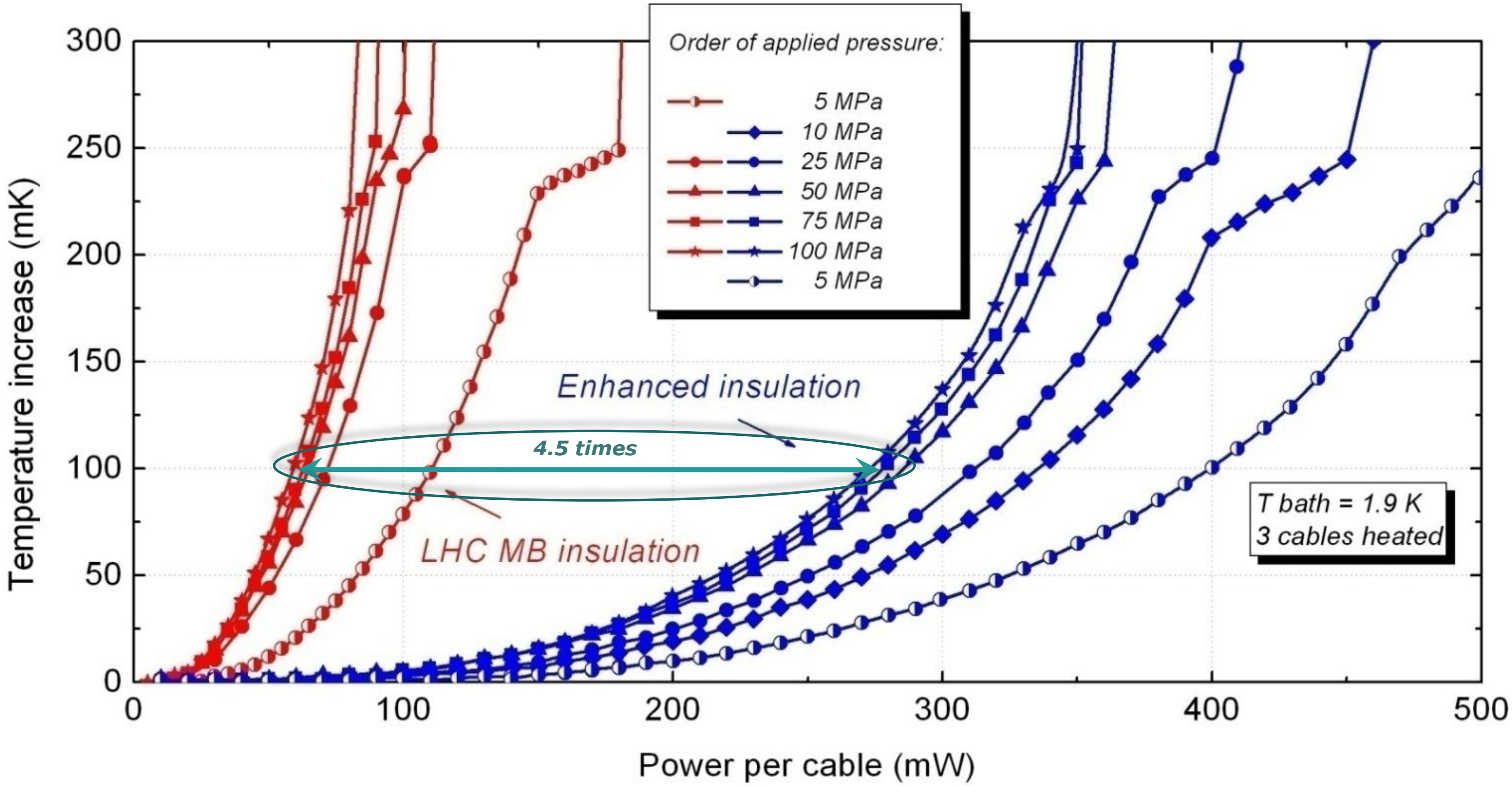




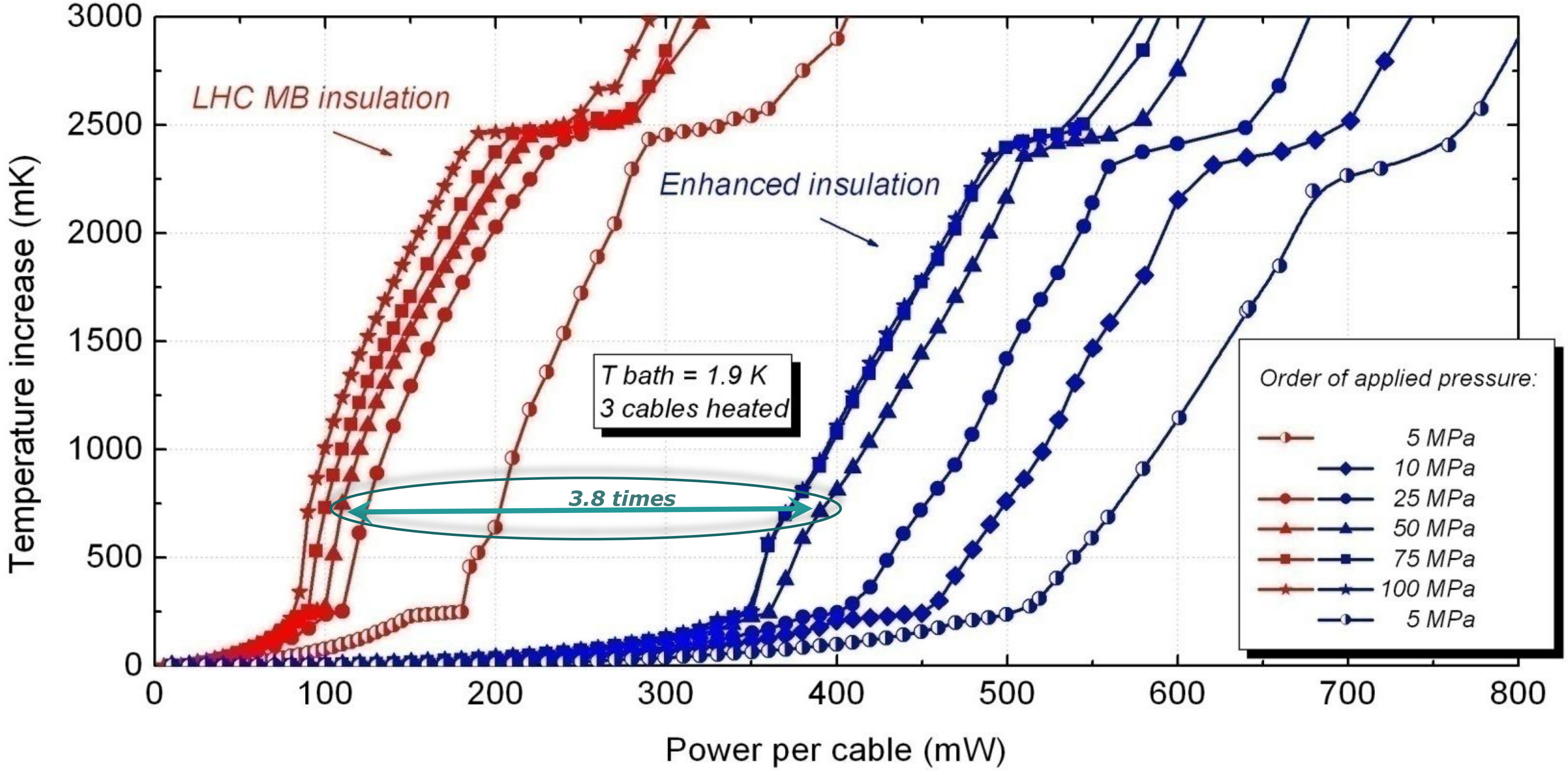


- *Goal: correlate the steady-state cable temperature increase with the power evacuated through the insulation*
- *Pressure applied at ambient temperature through the sample holder, then cooled at 1.9 K*

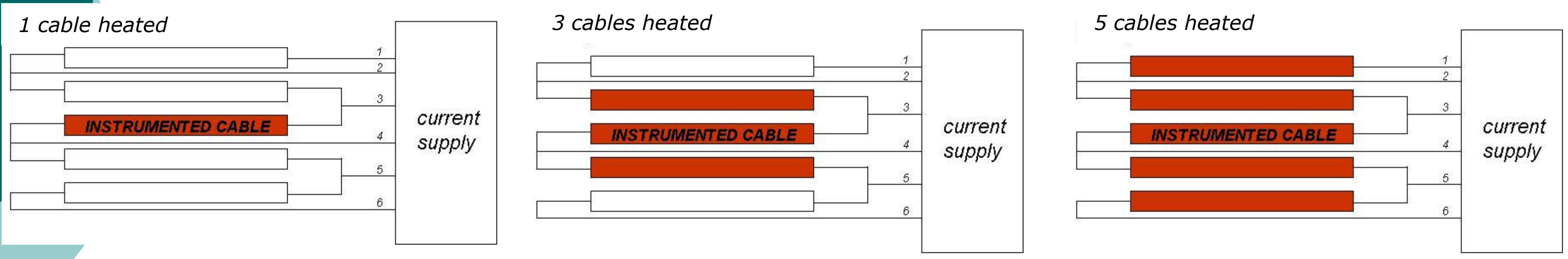
Heat Transfer Tests in 1.9 K bath Results

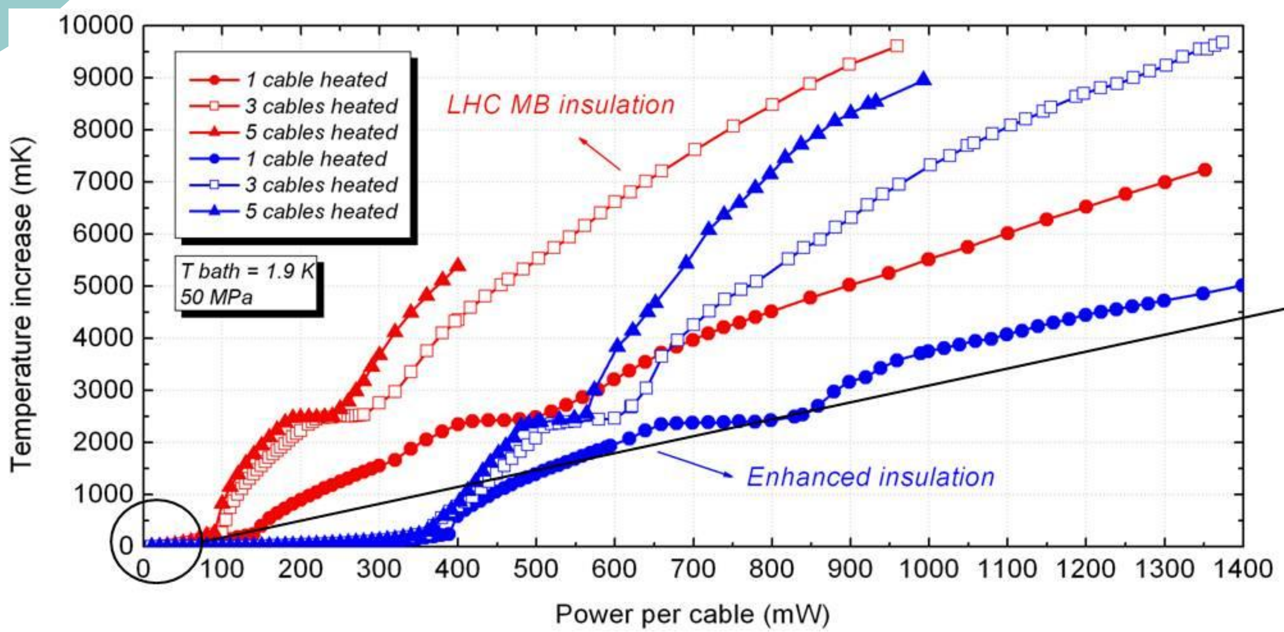


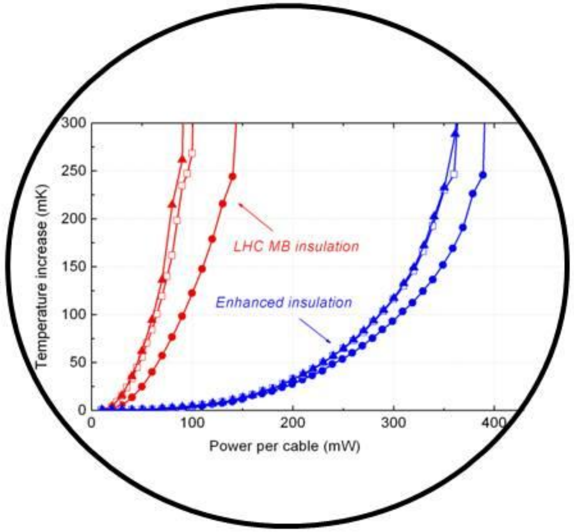
Heat Transfer Tests in 1.9 K bath Results



Heat Transfer Tests Results

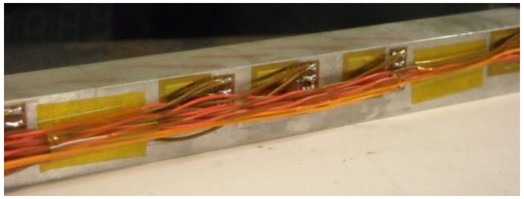


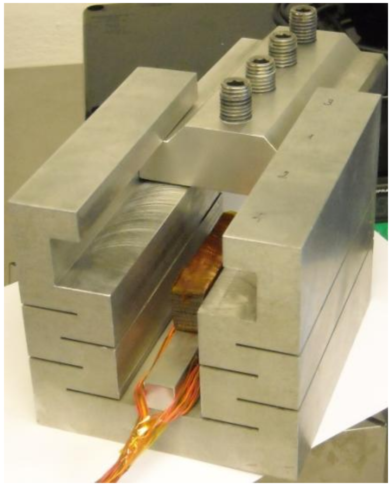




Heat Transfer Tests
Ongoing and Future Work

- *Assessment of the actual pressure at cryogenic temperatures:*





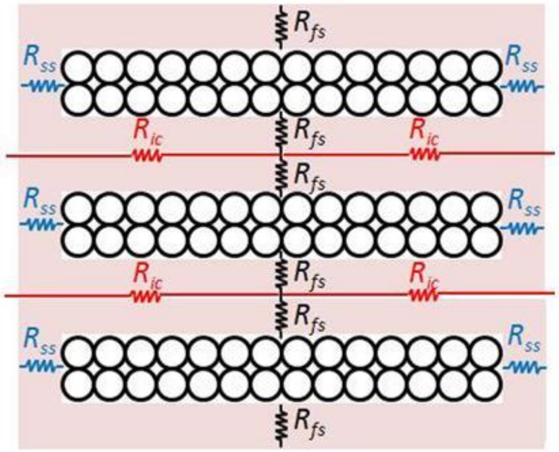
- *No impact of creep: EI#4 samples kept at 100 MPa during 2 weeks*

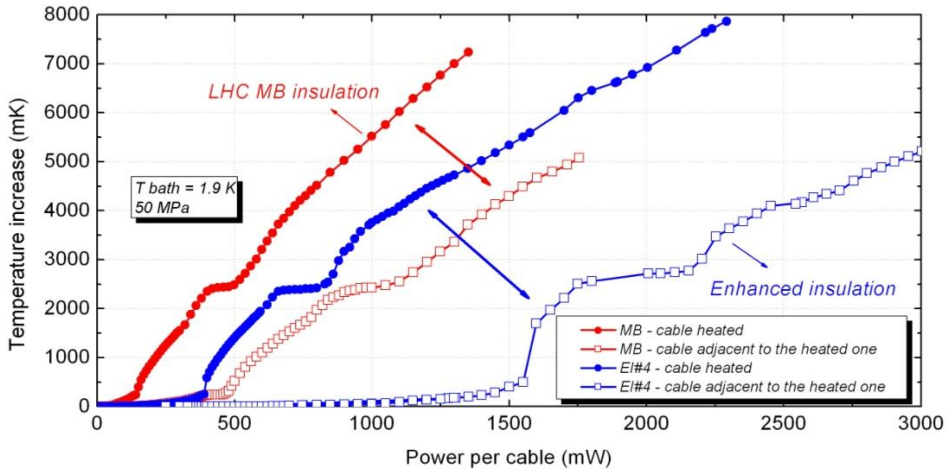
- *Impact of curing pressure: a sample cured with a bonding cycle at 80 MPa will be testes. Indeed, so far we are on the conservative side (130 MPa)!*

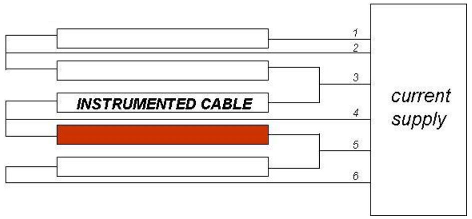
- *A new sample insulated with the EI#3 will be tested in the next months with the same applied pressure sequence than EI#4*

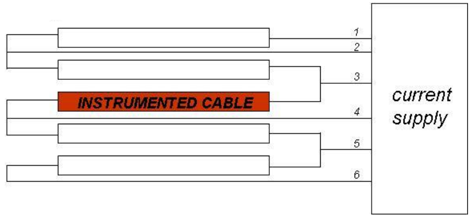
Heat Transfer Tests
Ongoing and Future Work

- *Ongoing modeling of the experimental results*
- *Starting from a phenomenological analysis (network of thermal resistances)*
- *The goodness of the enhanced insulation is confirmed by thermal independence between adjacents conductors (small R_{ss}) wrt the LHC insulation*



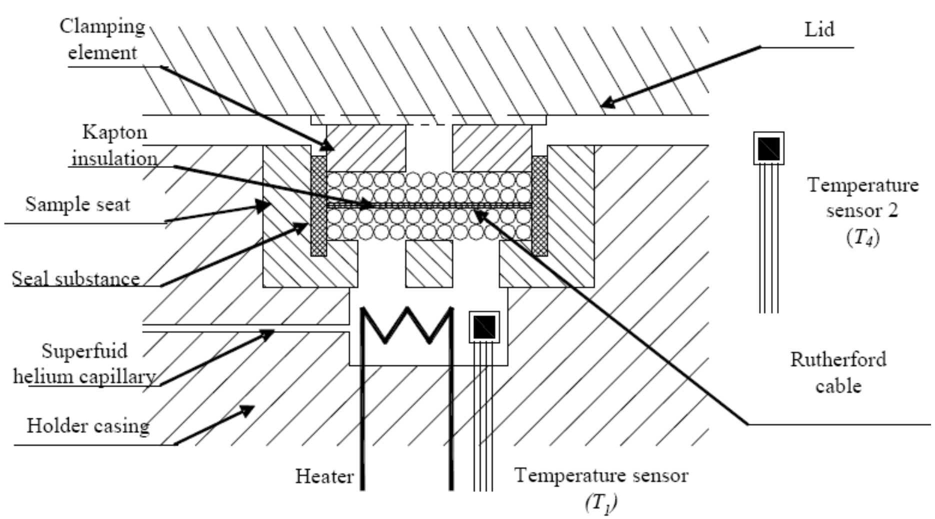


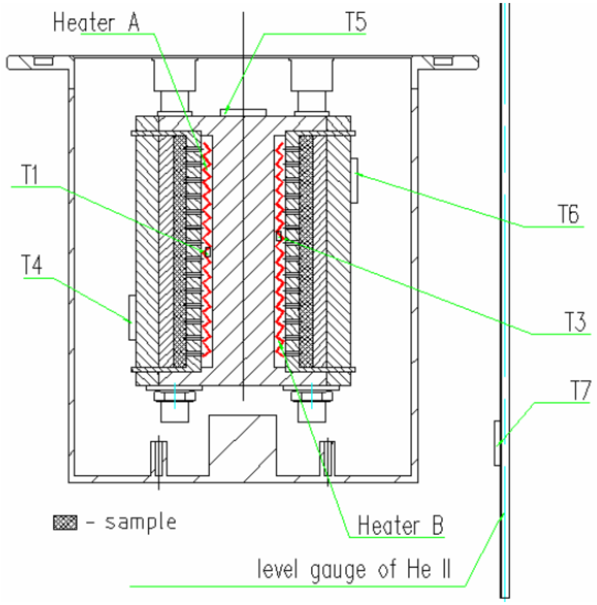




Heat Transfer Tests
Ongoing and Future Work

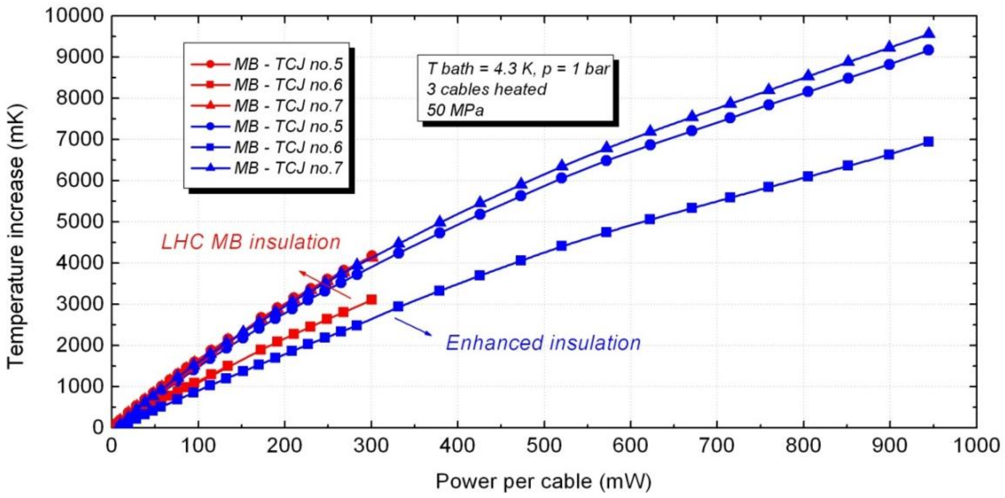
- *Investigation of the thermal coupling between two SC cables cooled at 1.9 K, in collaboration with the WUT Wroclaw, Poland*
- *Preliminary tests, T sensors and capillaries calibration carried out*
- *Heat transfer (and stress) measurements ongoing*



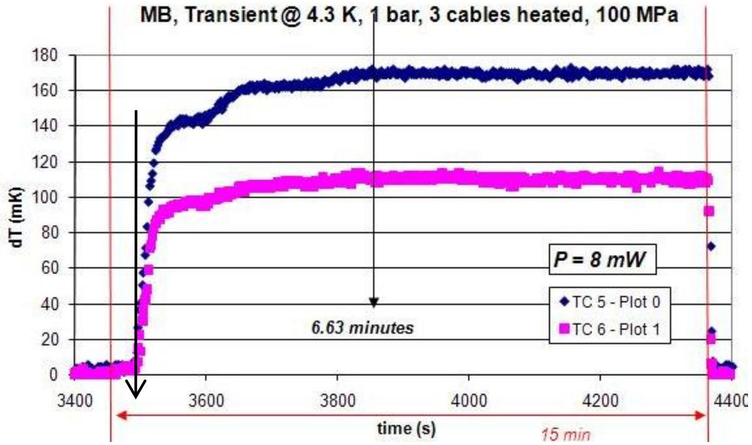


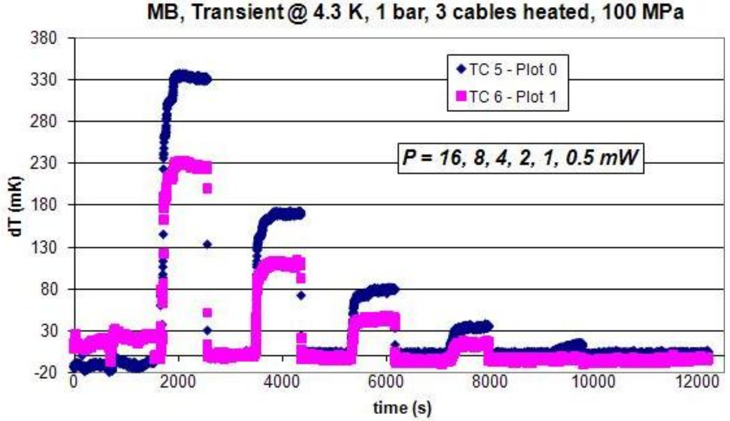
Heat Transfer Tests
Ongoing and Future Work

- *Steady-state heat transfer measurements in He I:*



- *Transient heat transfer measurements in He I :*
  (larger take-off time of the enhanced insulation)





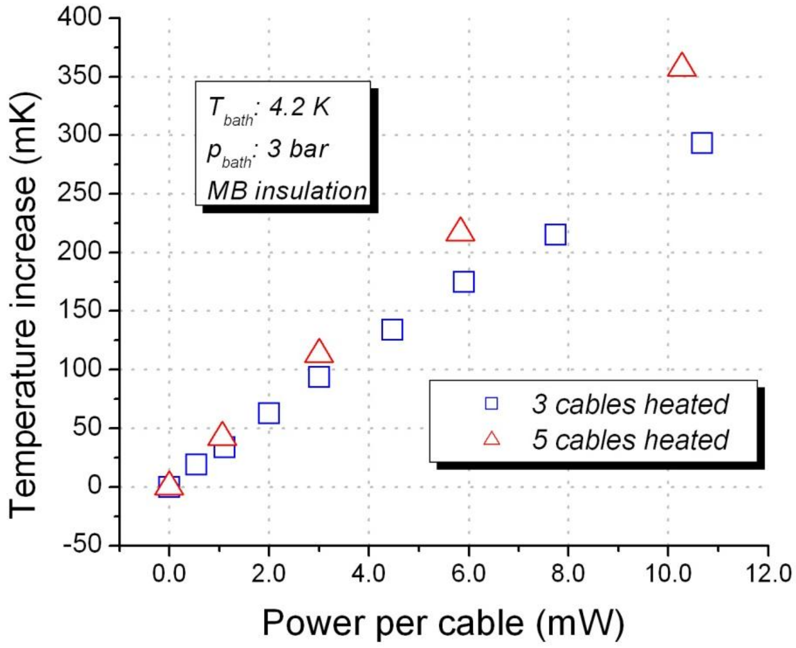
Heat Transfer Tests
Ongoing and Future Work

- *Thermal characterization of the cable insulation in supercritical helium*
- *In the framework of the R&D program DISCORAP for the synchrotron SIS 300 of the FAIR facility (GSI), in collaboration with INFN Genoa, Italy*

- *Operating conditions: 4.2 K, 3 bar*
- *Same samples previously tested at CERN*

Heat Transfer Tests
Ongoing and Future Work

- *Impact of compression stress: negligible*
- *First test: MB insulation*



- *EI#4 being tested*
- *DISCORAP cable insulation to be tested*

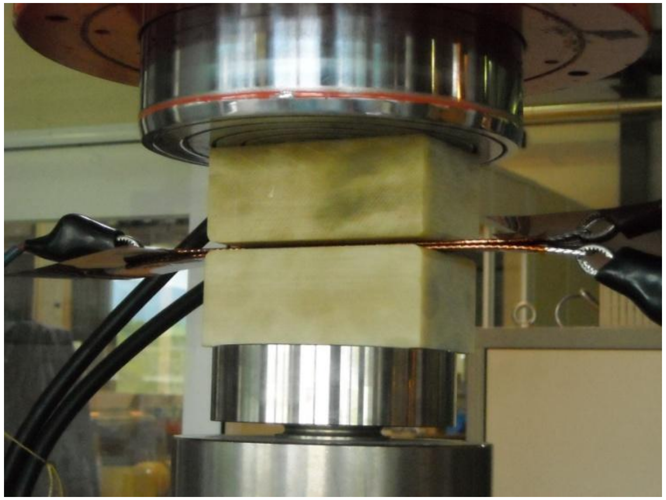
Electrical Tests
Experimental Procedure

- *Tests performed on 2-units stacks made of LHC-type 01 cable, cured at 130 MPa (conservative) at 190 ℃ over 170 mm, pressed over 113 mm*

  (RH: 23 - 30 %, T = 24.4 - 26.1 °C)

- *Tested insulation: MB, EI#4, EI#3*

- *Measurements of leakage current at:*
  - *1, 3 and 5 kV*
  - *50, 100 and 150 MPa*
  - *Each test repeated 5 times (3 so far)*
- *Measurements of dielectric strength:*
  - *80 MPa*
  - *Each test repeated 5 times (3 so far)*



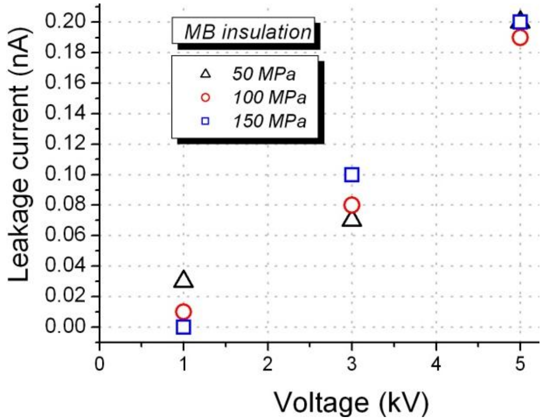
Electrical Tests
Dielectric strength

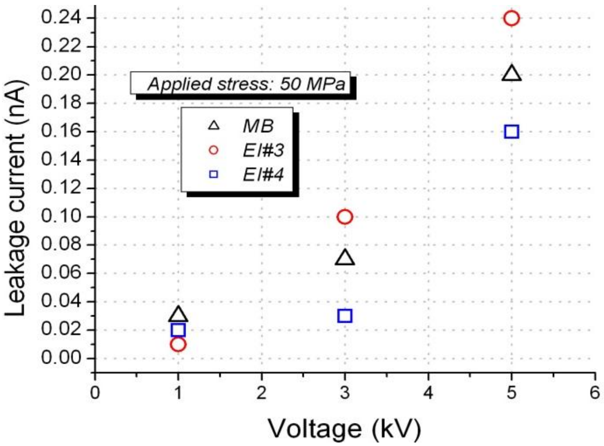
Insulation Scheme	Sample 1	Sample 2	Sample 3
LHC MB	*> 22-23 kV*	*18 kV*	*> 22 kV*
EI#4	*> 9 kV*	*> 12 kV*	*> 8 kV*
EI#3	*> 14 kV*	*12 kV*	*> 11 kV*

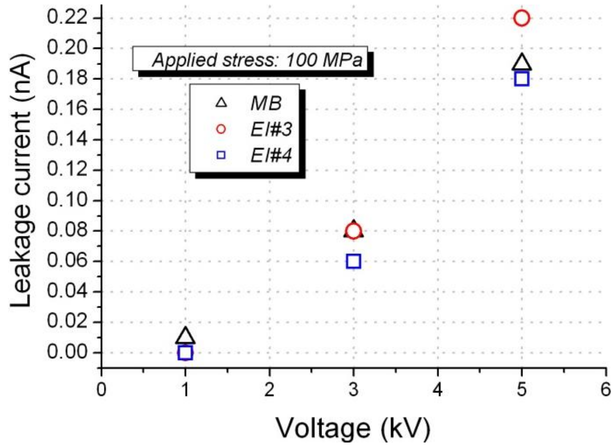
- *In agreement with the preliminary results: inter-turn breakdown voltage widely exceeds 5 kV in all cases*
- *The arcs often occur outside the pressed zone, in spite of the kapton foils*

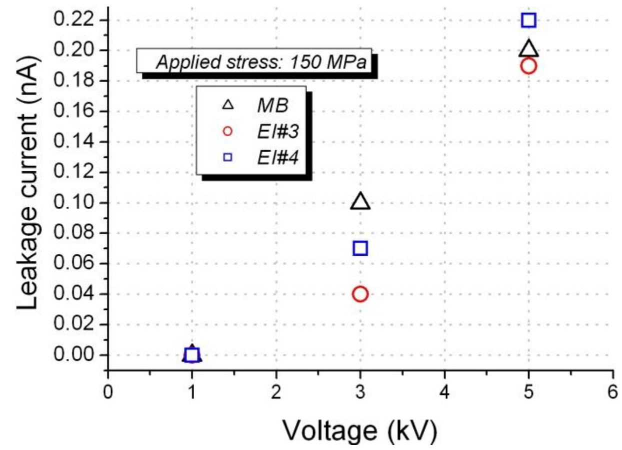
Electrical Tests
inter-turn leakage current

- *Measurement performed 2 minutes after the application of the voltage*
- *No influence of the applied stress*
- *The 3 cable insulation schemes feature the same behavior*



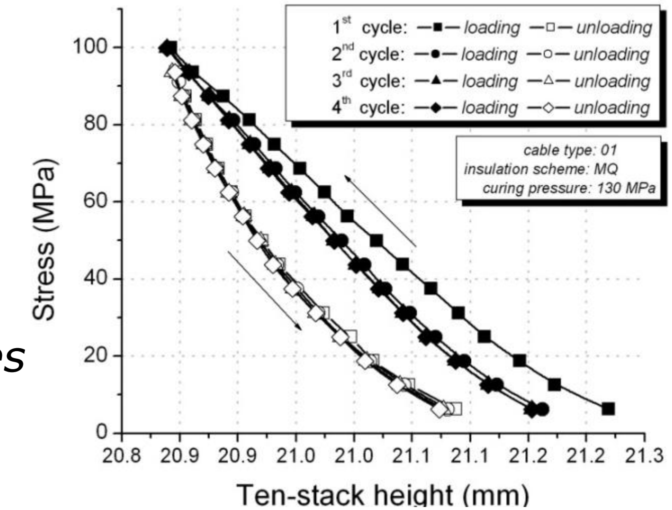






Mechanical Measurements at T_{amb} [6] Experimental Procedure

- *4 stacks have been prepared for each insulation scheme: wrapped around the **cables 01 and 02**, and cured with **the two bonding cycles***
- *+ 4 stacks made of bare cables*
  → total of <u>28 tested samples</u>
- *First loading on a virgin stack very different from the subsequent ones→ the results refer to at least the last of three cycles performed up to the same peak stress*

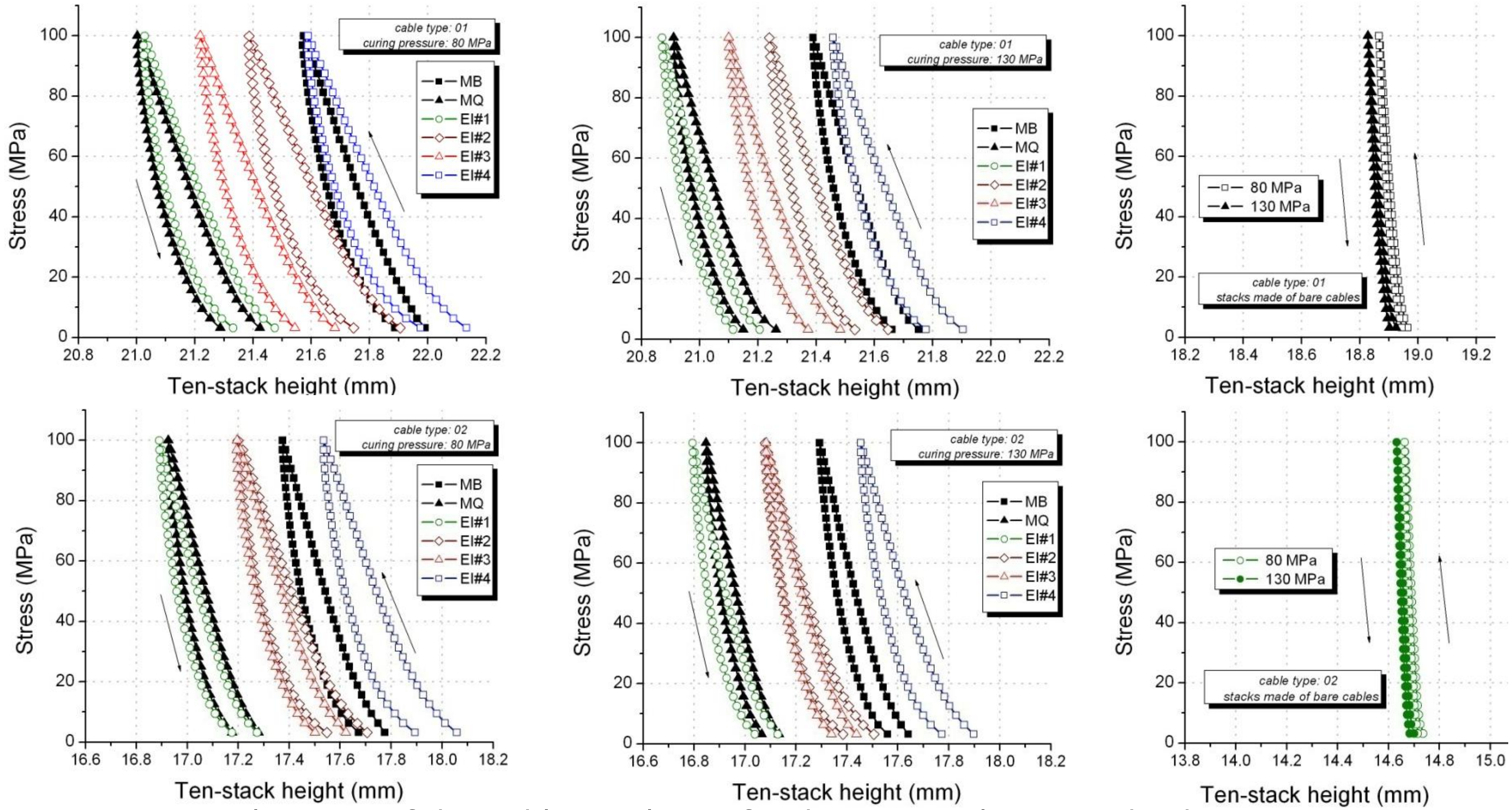


- *The raw measurements have been corrected taking into account the mold deformation, measured as a function of the applied stress, by compressing a reference steel bar of known Young's modulus*

[6] P.P. Granieri, "Mechanical Measurements at Ambient Temperature of an Enhanced Cable Insulation Scheme for the Superconducting Magnets of the LHC Luminosity Upgrade ", to be published as CERN TE Internal Report.

Mechanical Measurements at T_{amb}
Stack height (σ_{MAX} = 100 MPa)

- *All the samples have the same hysteretic behavior, being softer at low stress*
- *Height loss (0.6 MPa load-50 MPa unload): EI#4 → 480 µm (2.4 %)*
  MB & EI#3 → 400 µm (2 %)

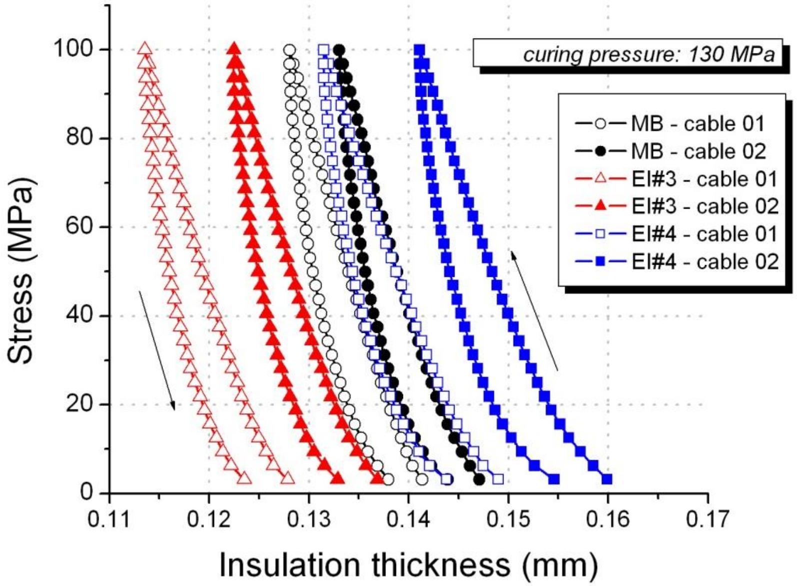


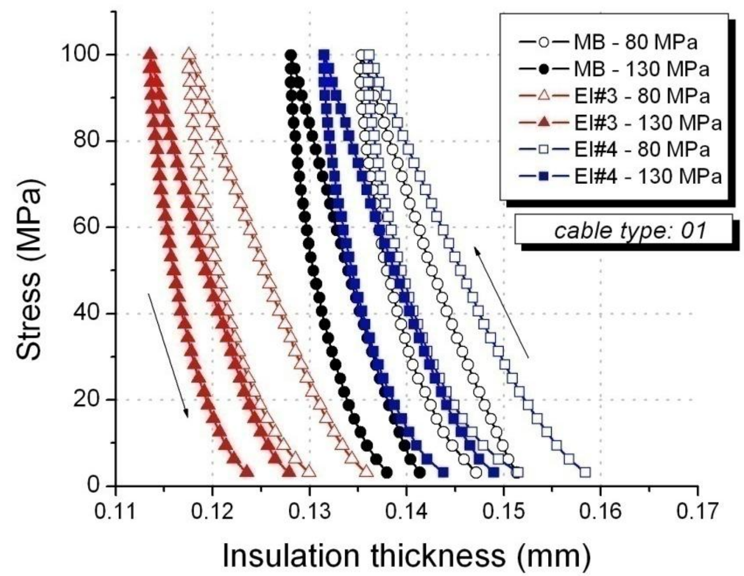
Mechanical Measurements at T_{amb} Insulation Thickness (σ_{MAX} = 100 MPa)

- *Ins. thickness varies mainly at low stress:*

		MB	EI#3	EI#4
3 MPa load - 50 MPa load :	*(µm)*	*8.4*	*9.5*	*12*
50 MPa load-100 MPa load:	*(µm)*	*6.5*	*6.7*	*8.2*

←→ *larger worsening of HT between 0 and 50 than between 50 and 100 MPa*





- *Influence of cable-type choice: up to 8 %*
- *Influence of curing pressure: 2 – 5 %*

Mechanical Measurements at T_{amb} Insulation Thickness (σ_{MAX} = 100 MPa)

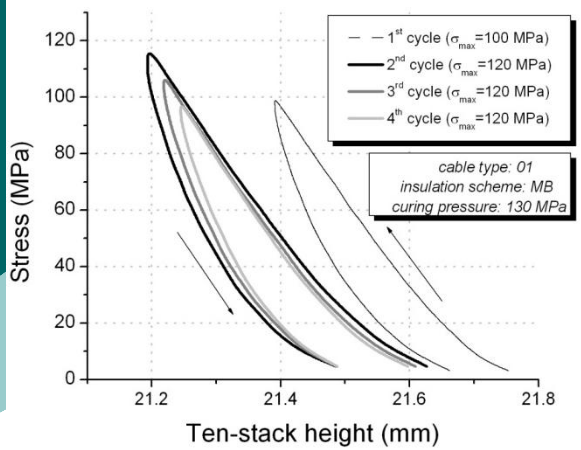
Insulation scheme	Cable	Curing pressure (MPa)	Sum of the insulation layers thickness (µm)	Insulation thickness at 50 MPa during unloading (µm)
MB	**01**	**80**	**169**	**138**
MB	**01**	**130**	**169**	**130.4**
MB	**02**	**80**	**169**	**138.4**
MB	**02**	**130**	**169**	**135.6**
MQ	01	80	142.5	109
MQ	01	130	142.5	106
MQ	02	80	142.5	115.5
MQ	02	130	142.5	112.8
EI#1	01	80	155	110.3
EI#1	01	130	155	104.2
EI#1	02	80	155	114
EI#1	02	130	155	110.3
EI#2	01	80	180	129
EI#2	01	130	180	123.2
EI#2	02	80	180	130
EI#2	02	130	180	125
EI#3	**01**	**80**	**169**	**120.5**
EI#3	**01**	**130**	**169**	**116**
EI#3	**02**	**80**	**169**	**129.4**
EI#3	**02**	**130**	**169**	**124.9**
EI#4	**01**	**80**	**194**	**139.5**
EI#4	**01**	**130**	**194**	**134.4**
EI#4	**02**	**80**	**194**	**147**
EI#4	**02**	**130**	**194**	**144.1**

loss of insulation thickness:

~ 21 % (MB, MQ)

~ 28 % (EI#1, EI#2, EI#3, EI#4)

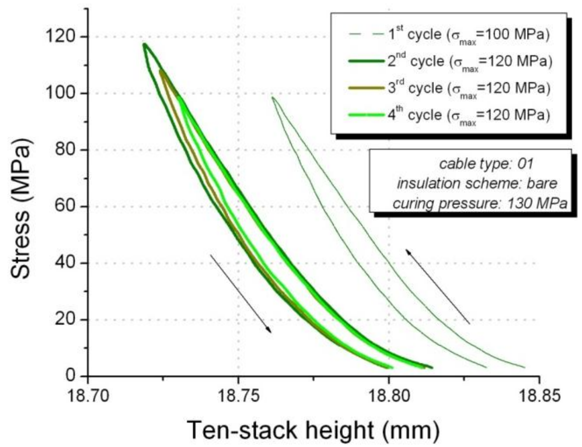
Mechanical Measurements at T_{amb} Impact of σ_{MAX} seen by the stack

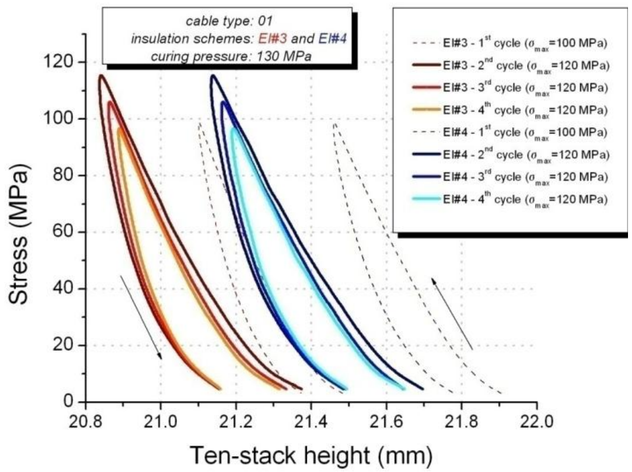


- *Impact of **σ_{MAX} seen by the stack**:*
  - *permanent deformation*
  - *still deforming after 5 cycles*
  - *Young's modulus*

  (1° and 2° cycles preceeded by 2 preliminary cycles at that σ_{MAX})

- *Unloading curves associated with different peak stresses (same σ_{MAX})*



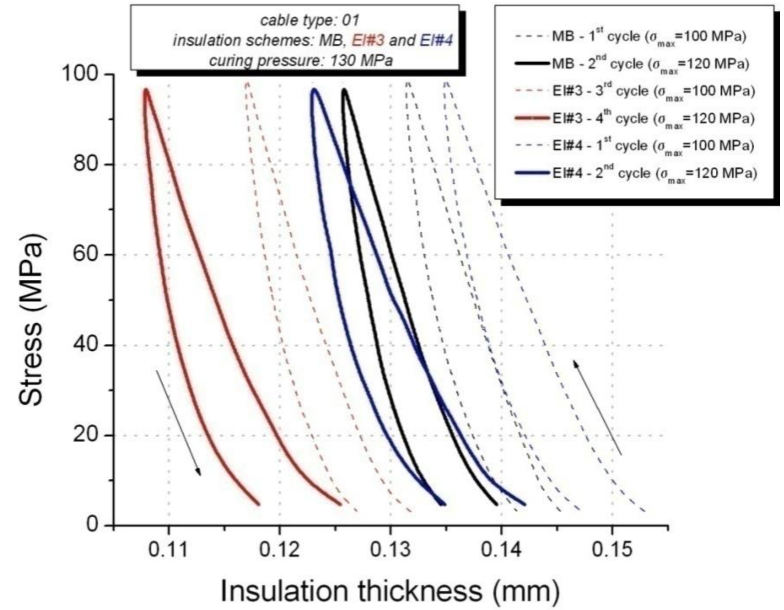


Insulation scheme	Cable	Curing pressure (MPa)	Ten-stack height for σ_{max} = 100 MPa (mm)	Ten-stack height for σ_{max} = 120 MPa (mm)	Difference (μm)
MB	01	130	21.460	21.309	**120.5**
MB	02	130	17.361	17.271	
EI#3	01	130	21.172	20.945	**198**
EI#3	02	130	17.147	16.978	
EI#4	01	130	21.540	21.255	**250**
EI#4	02	130	17.531	17.316	
bare	01	130	18.783	18.752	**31**

Mechanical Measurements at T_{amb} Impact of σ_{MAX} seen by the stack

- *Insulation thickness at 50 MPa during unloading, for a maximum stress σ_{max} seen by the stacks of 100 or 120 MPa*

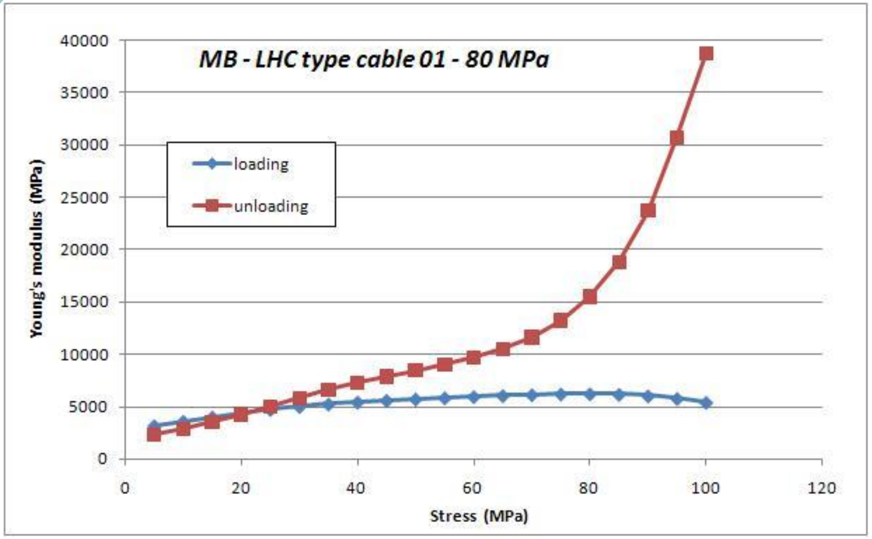
- *In this case the cable used to make the insulated cables-stacks is different from the cable used to make the bare cables-stack*

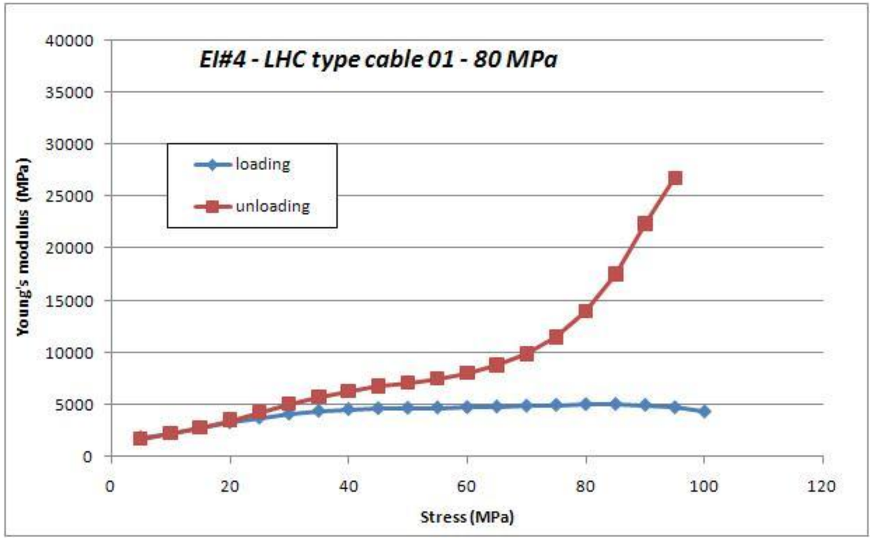


Insulation scheme	Cable	Curing pressure (MPa)	Insulation thickness for σ_{max} = 100 MPa (µm)	Insulation thickness for σ_{max} = 120 MPa (µm)	Difference (µm)
MB	01	130	133.8	127.9	**5.9**
EI#3	01	130	119.4	109.7	**9.7**
EI#4	01	130	137.8	125.2	**12.6**

Mechanical Measurements at T_{amb} Young's Modulus

- *The fit of the stress-strain curves allows to calculate analytically the Young's modulus at 293 K, during the loading and unloading part of the cycle*



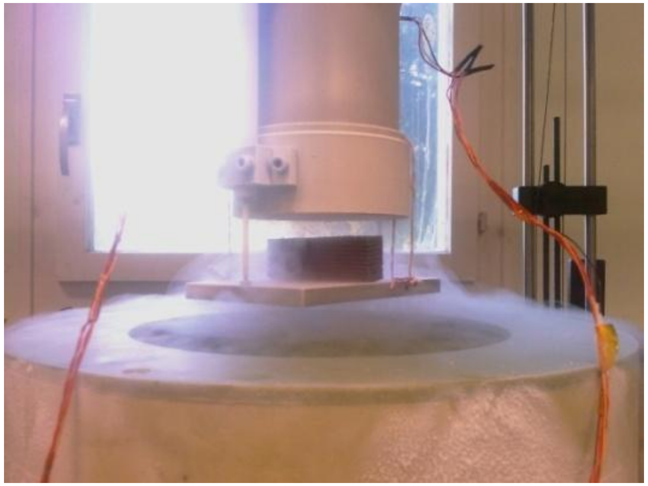


Mechanical Measurements at T_{amb} Future Investigations

- *An arch test is needed to measure the* <u>*insulation thickness in the coil configuration*</u>
- *σ_{MAX} to be taken into account*
- *The permanent deformation after a large number of stress cycles (σ_{min} - σ_{MAX}) could be determined, as a function of σ_{MAX}*
- *Analyze the influence of cycles, time, creep and σ_{MAX} on the Young's modulus*
- *Eventually perform compression stack tests of different parts of the coil (with relative stress cycle), to obtain local information of the cables mechanical behavior*

Mechanical Measurements at 77 K

- *Electromechanical apparatus*
- *Unloaded stack height at 293 K assumed for the strain calculation*
- *Increase of the elastic modulus and reduction of the hysteresis cycle wrt measurements at room temperature*

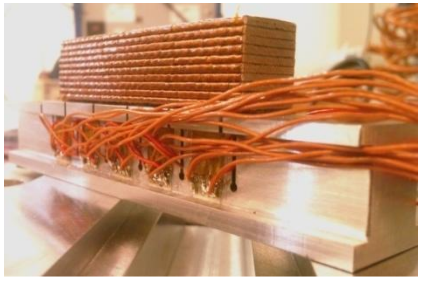


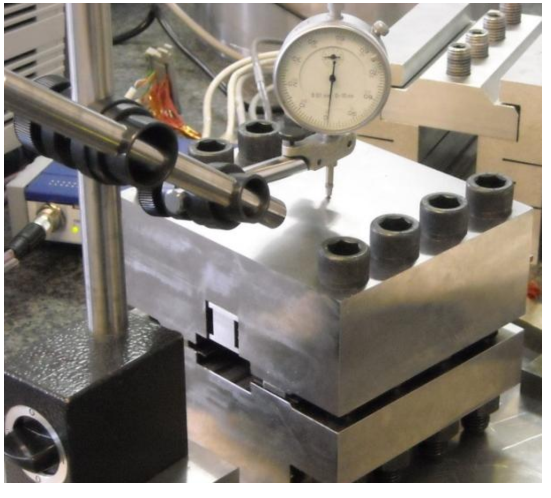
- *Measurements are ongoing (results in the table still preliminary)*

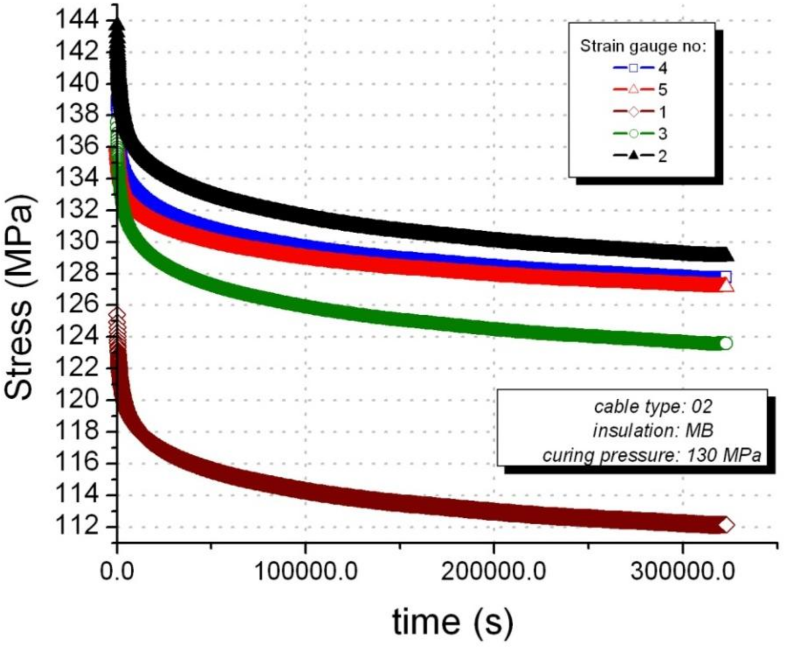
Insulation scheme	Cable	Curing pressure (MPa)	Young's modulus At 293 K (MPa) at 50 MPa during loading	Young's modulus At 77 K (MPa) at 50 MPa during loading
MB	01	130	6739	
MB	02	130	5870	8199
EI#3	01	130	6568	8323
EI#3	02	130	5689	7390
EI#4	01	130	5536	8239
EI#4	02	130	4834	

Mechanical Measurements
Stress Relaxation

- *Measurement of stress relaxation at ambient temperature, at a fixed volume of the cables-stack*
- *At 3 different values of initial stress: 70, 100 and 130 MPa*
- *First sample measured starting from 130 MPa: MB insulation, LHC-type cable 02, cured at 130 MPa*
- *It features a loss of stress of ~ 7-10 % during almost 4 days*





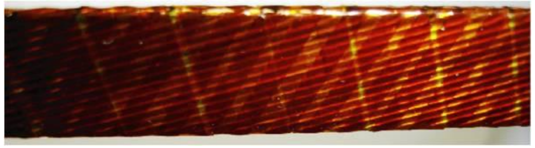


Conclusions

- *The proposed enhanced cable insulation is being characterized from a thermal, electrical and mechanical point of view:*
  - *The **increased heat transfer capacity** of the proposed insulation (4-5 times better than the LHC standard ones) has been confirmed by steady-state heat transfer measurements at 1.9 K, up to high pressure levels*
  - *The **electrical tests** on 2-units stacks have shown a satisfactory electrical robustness*
  - *The **mechanical measurements** aim at determining the conductor dimensions and Young's modulus at room and liquid nitrogen temperature as a function of the applied stress, as well as the cable stress relaxation and thermal contraction*
- *The proposed **enhanced insulation** is an **ideal candidate for the low-β SC quadrupoles for the phase-I of the LHC upgrade***

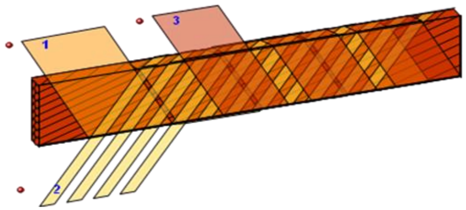
Back-up slides

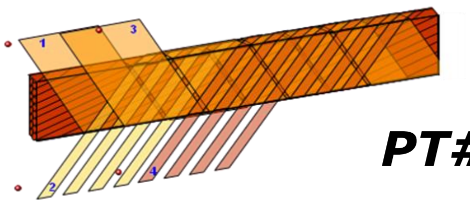
Preliminary tests
Porous Test (PT) Samples



- ***Manual wrapping*** *(and cut) of the tapes → imprecise dimension of the gaps, not uniform wrapping tension*

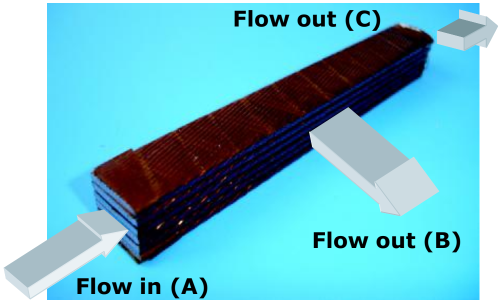
PT#1,2,4



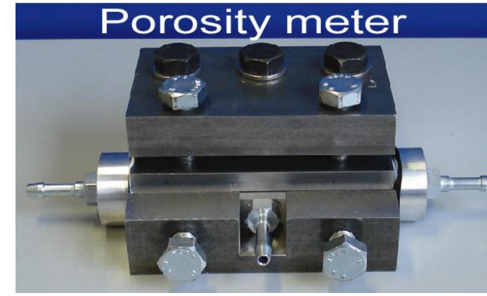


PT#3

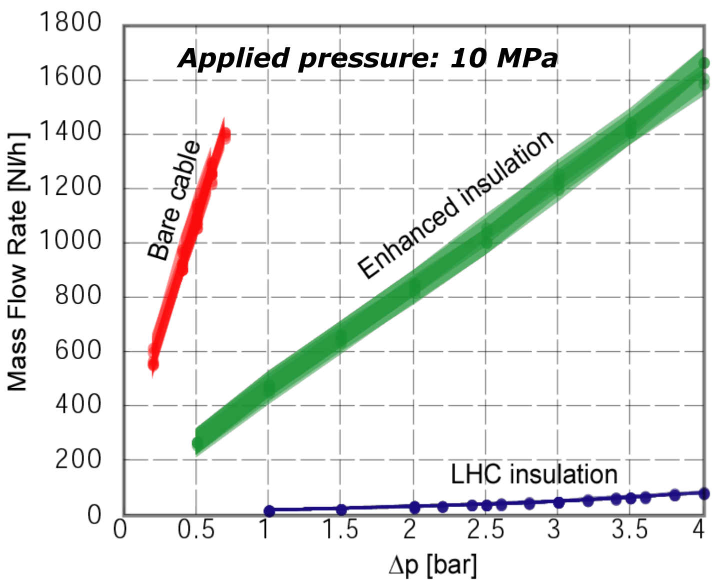
Sample	***1st layer***	***2nd layer***	***3rd layer***	***4th layer***
PT#1	***11*** *mm wide,* ***1*** *mm gap,* ***25*** *µm thick*	***2.5*** *mm wide,* ***1.5*** *mm gap,* ***75*** *µm thick, cross wrapped with the other layers*	***9*** *mm wide,* ***3*** *mm gap* ***55*** *µm thick (glue), 50% overlap with the 1st layer*	
PT#2	***11*** *mm wide,* ***1*** *mm gap,* ***50*** *µm thick*	***2.5*** *mm wide,* ***1.5*** *mm gap,* ***50*** *µm thick, cross wrapped with the other layers*	***9*** *mm wide,* ***3*** *mm gap* ***55*** *µm thick (glue), 50% overlap with the 1st layer*	
PT#3	***11*** *mm wide,* ***1*** *mm gap,* ***25*** *µm thick*	***2.5*** *mm wide,* ***1.5*** *mm gap,* ***50*** *µm thick, cross wrapped with the 1st and the 3rd layers*	***11*** *mm wide,* ***1*** *mm gap,* ***50*** *µm thick, 50% overlap with the 1st layer*	***2.5*** *mm wide,* ***1.5*** *mm gap,* ***55*** *µm thick (glue), 50% overlap with the 2nd layer*
PT#4	***8*** *mm wide,* ***2*** *mm gap,* ***25*** *µm thick*	***2.5*** *mm wide,* ***1.5*** *mm gap,* ***75*** *µm thick, cross wrapped with the other layers*	***9*** *mm wide,* ***1*** *mm gap* ***55*** *µm thick (glue), 50% overlap with the 1st layer*	

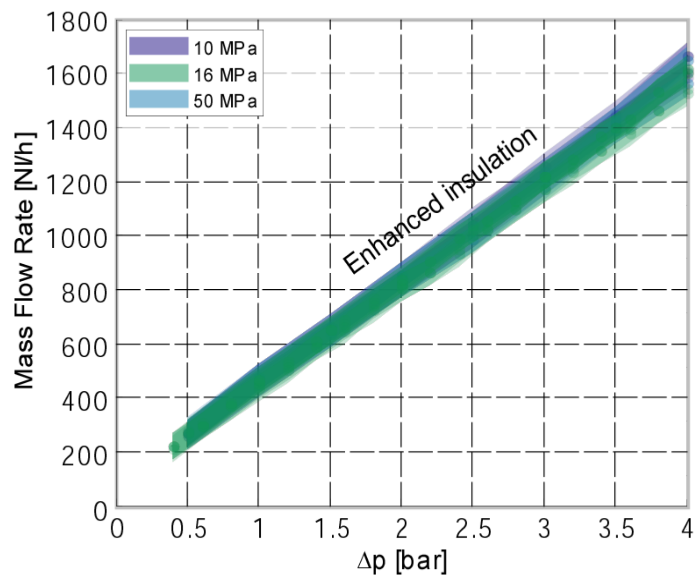


Preliminary tests: Porosity Test [1]



- *Radial porosity of the enhanced insulation to air at ambient temperature under 10 MPa: 10 times larger than LHC insulation, 10 times smaller than bare cables*
- *Ehanced porosity confirmed up to 50 MPa*





[1] M. La China, D. Tommasini, "A comparative study of heat transfer from Nb-Ti and Nb3Sn coils to He II", *Physical Review Special Topics - Accelerators and Beams 11, 082401 (2008)*.

Preliminary tests
Electrical Test (2)

- *Interturn breakdown voltage measured on stacks made of 2 cables (MB inner layer)*
- *Each test repeated twice*
- *Curing cycle: 80 MPa @ 190 °C*
- *Applied pressure: 50 MPa*

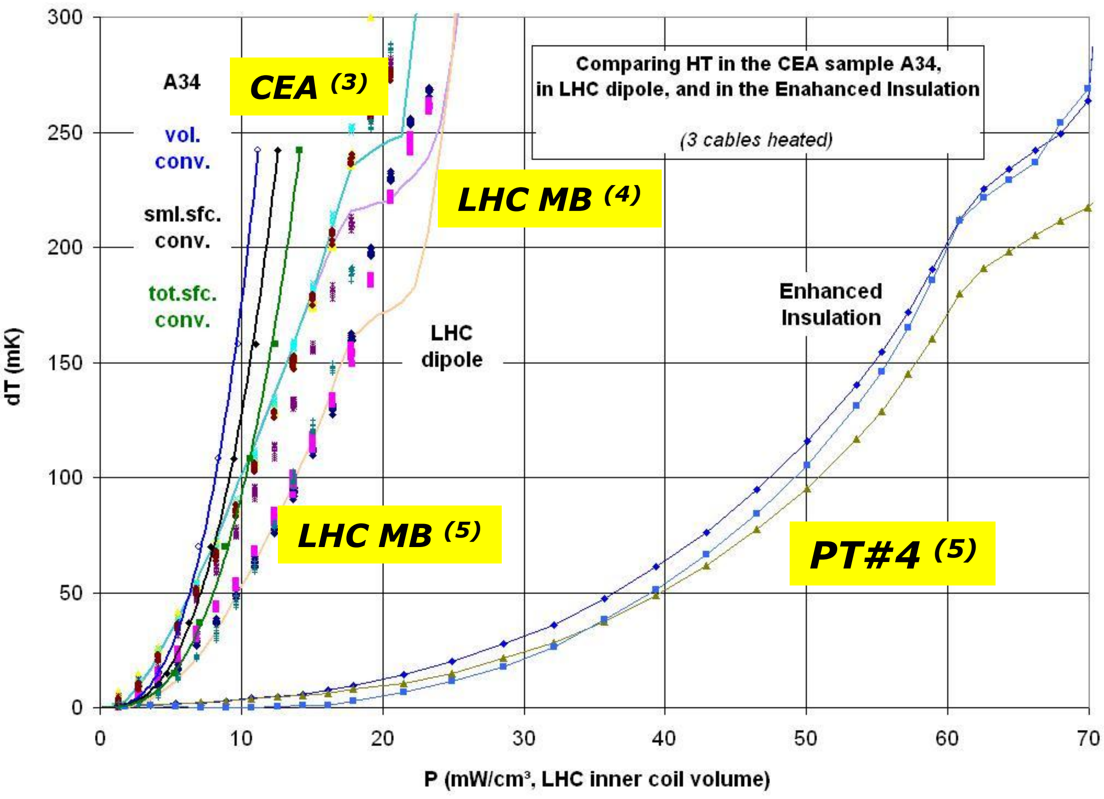
Insulation Scheme	***Sample 1***	***Sample 2***
LHC MB	*> 30 kV*	*> 25 kV*
LHC MQ	*> 18 kV*	*> 20 kV*
PT#1	*9 kV*	*8 kV*
PT#2	*> 15 kV*	*12 kV*
PT#3	*> 18-19 kV*	*12 kV*

- *The inter-turn breakdown voltage widely exceeds 5 kV in all cases*

(2) R. Lopez, "Dielectrical test on different kind of kapton wrapping", CERN AT-MCS NORMA Report, 2008.

Preliminary tests
Heat Transfer Test in 1.9 K bath

- *Reproducibility and reliability of the experimental method*
- *Major increase of extracted power in the PT#4 wrt LHC MB, although the applied pressure is only 30 MPa*



(3) C. Meuris et al., "Heat transfer in electrical insulation of LHC cables cooled with superfluid helium," *Cryogenics*, vol. 39, pp. 921–931, 1999.

(4) D. Richter et al., "Evaluation of the transfer of heat from the coil of the LHC dipole magnet to helium II", *IEEE Trans on Appl Sup*, vol. 17 no. 2, pp. 1263-1268, June 07.

(5) D. Tommasini, D. Richter, "A new cable insulation scheme improving heat transfer to superfluid helium in Nb-Ti superconducting accelerator magnets", Proceedings of EPAC-08,Genoa, Italy.

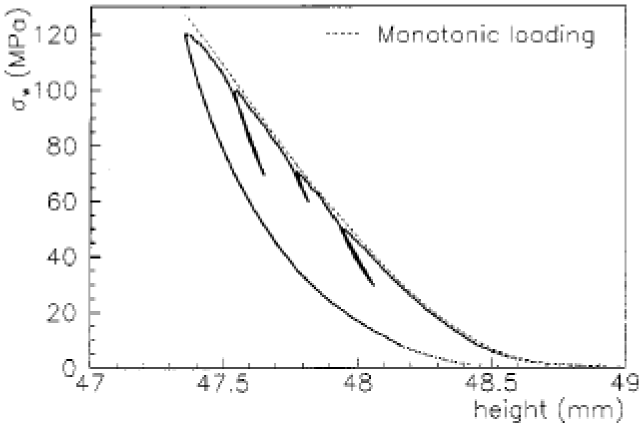


Fig. 15. Stress σ_w (MPa) at 293 K versus total height l_w (mm) for the outer layer conductor stack, loading with three steps: experimental data and comparison with the monotonic loading curve.

K. Coutourier, P. Ferracin, W. Scandale, E. Todesco, D. Tommasini, "Thermomechanical Properties of the Coil of the Superconducting Magnets for the Large Hadron Collider", *IEEE Transaction on Applied Superconductivity*, vol. 12, no. 2, 2002, pp. 1804-1812.