Requirements for the protection of the SC links components¶

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Acknowledgements: R. Denz, J. Fleiter, J. Hurte

International Review of the Conceptual Design of the Cold Powering System for the HL-LHC Superconducting Magnets

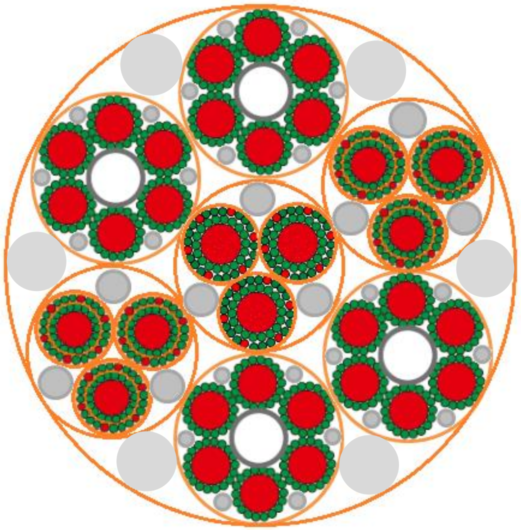
Outline

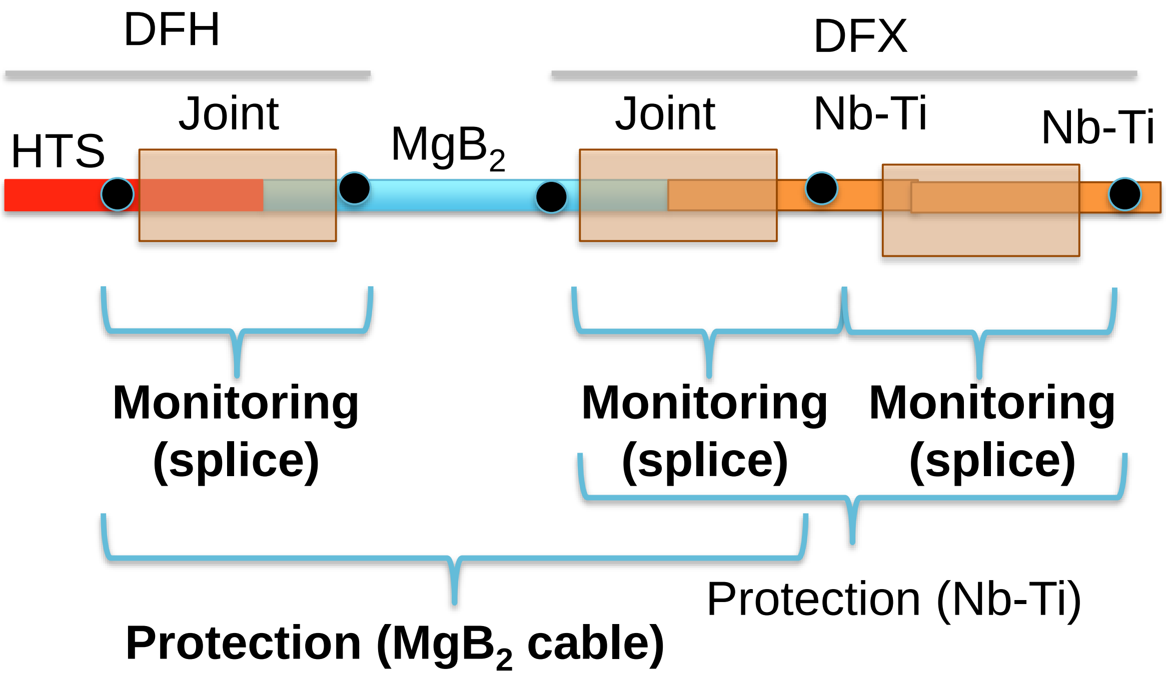
- Protection of components: strategy, protection thresholds, hard-wired and software interlocks
  - Current Leads
  - Superconducting Link
  - Electrical splices
- Transient analysis
  - Dimensioning of components vs circuit requirements
- Measurements
  - Quench of MgB_2 cables
  - Electrical splices
- Conclusions

Protection of Cold Powering System

- **Active protection** of superconducting components and current leads
  - Individually protected: **resistive part of each lead**, **superconducting part of each lead**, **MgB_2 and Nb-Ti cables**
- **Protection thresholds**
  - **Resistive part of each lead**: ~ 100 mV (as in LHC). Long integration times (few seconds) permitted
  - **HTS part of each lead**: 1 mV-5 mV (as in LHC). Electronics specifically developed for LHC HTS leads– successfully operational in the tunnel. Integration times of ~ 100 ms permitted
  - **MgB_2 cables**: 50 mV – 100 mV. Integration times ~ 100 ms permitted
- **Monitoring** of individual splices (MgB_2 to HTS, MgB_2 to Nb-Ti and Nb-Ti to Nb-Ti)

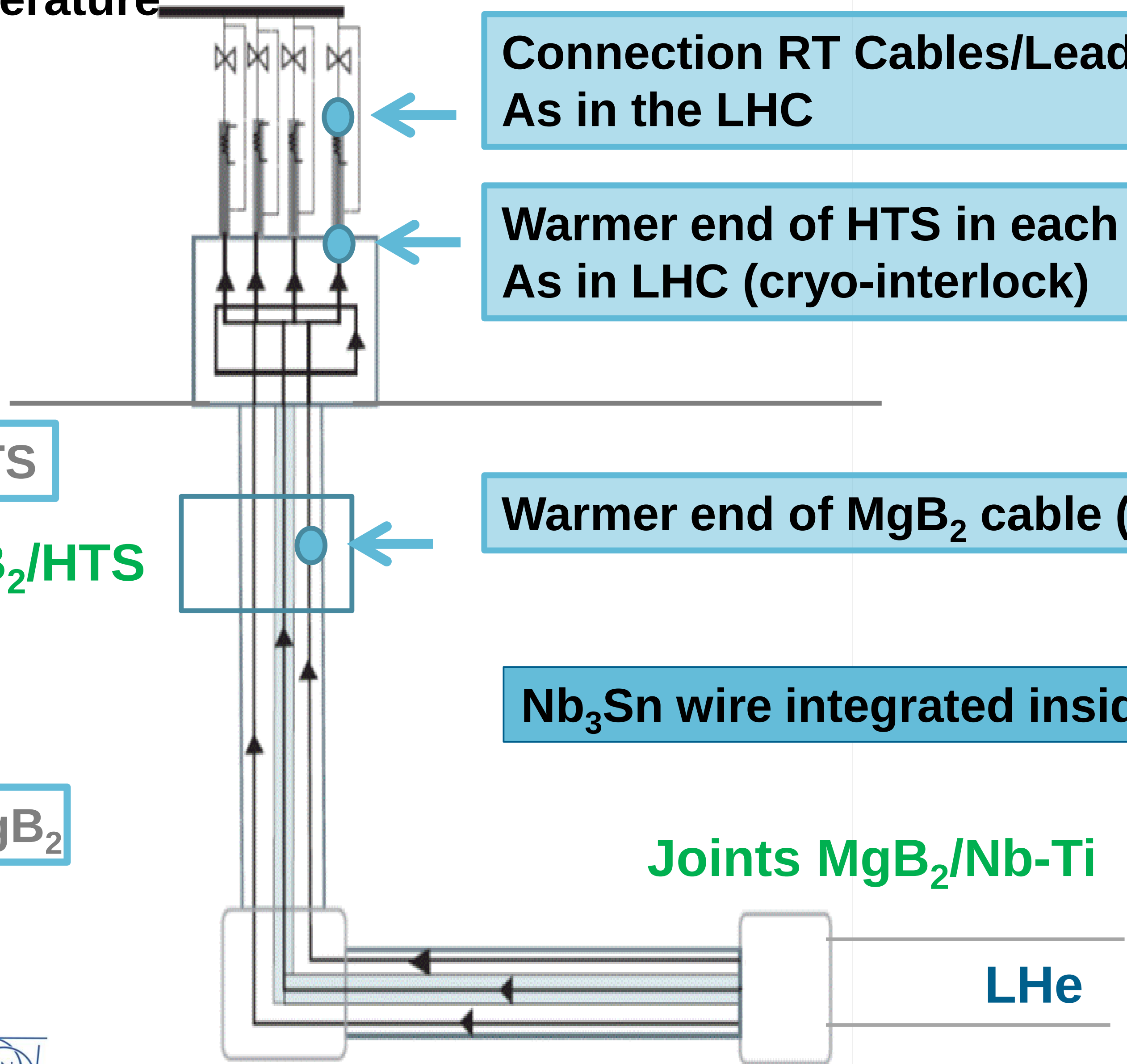
Protection of Cold Powering System





	Nb. of cables (HTS or MgB_2) protected	Nb. of leads protected (resistive part)
18 kA	6 (cable strands)×4 (cables)	4
7 kA	1 × 3	3
2 kA coaxial	2 × 6	12

Protection of Cold Powering System: interlocks



Connection RT Cables/Lead
As in the LHC

Warmer end of HTS in each Lead
As in LHC (cryo-interlock)

Warmer end of MgB_2 cable (cryo)

Nb_3Sn wire integrated inside the link

Temperature interlocks triggering a slow power abort

Nb_3Sn wire implementation

- Nb_3Sn strand selected for evaluation. Requirements:
  - High T_c (~18 K) with sharp transition (low ΔT_c)
  - Excellent strain tolerance
- Proposed solution:
  - Fully-reacted, fine-filament bronze route strand with diameter <1 mm
  - Well-characterised ITER TF conductors are suitable: particularly Bruker EAS or Hitachi
  - Heat treatment trials on Φ 300 mm spools (as used for MgB_2), and resistive T_c testing, are scheduled

Work on-going, S. Hopkins

Temperature interlock triggering a slow power abort

Protection strategy and transient analysis

- **Case 1**: **Quench of MQXF magnets**. Effect of MgB_2 cables due to over-currents in the circuit

  → **No quench of MgB_2 cables**

	Magnet	Cold Powering			
	I_{ult}(kA)	I_{peak}(kA)	I_{lead} (kA)	I_{cable}(kA)	N_{leads}/N_{cables}
MQXF	17.82	-	18	18	2
Trim Q1	2	2.4	2*	7	1
Q2a/Q2b	Protec.	5.6	2*	7	1
Trim Q3	2	6.8	2*	7	1

- SC Cables designed to transfer 7 kA in DC mode
- Leads designed to transfer the over-currents without overheating

Protection strategy and transient analysis

- **Case 2**: **Quench of SC Link**. This triggers the quench of the magnets
- Quench of 18 kA or 7 kA cables/leads → firing QPS of MQXF magnets (Quench heaters + CLIQ)
- Quench of 13 kA cables/leads of D1 → firing QPS of D1 (Quench heaters)
- Quench of 2 kA cables/leads→ Quench heaters or energy extraction

Circuits parameters

Rating (kA)	MIITs ($kA^2 \cdot s$)	τ_Q (quench of magnets) (s)	Equivalent time (s)
18	32	0.2	0.1
2	1	0.5	-
7	5	0.2	0.12

Quench of a SC link is a very rare event

Protection strategy and transient analysis

Quench of SC Link

Cu braid around each composite strand

T0=25 K

Rating (kA)	ACu (mm^2)	MIITs	Tmax
18*	200	15+32	57
2**	34	15+1	34
2 (7)***	36	15+5	35

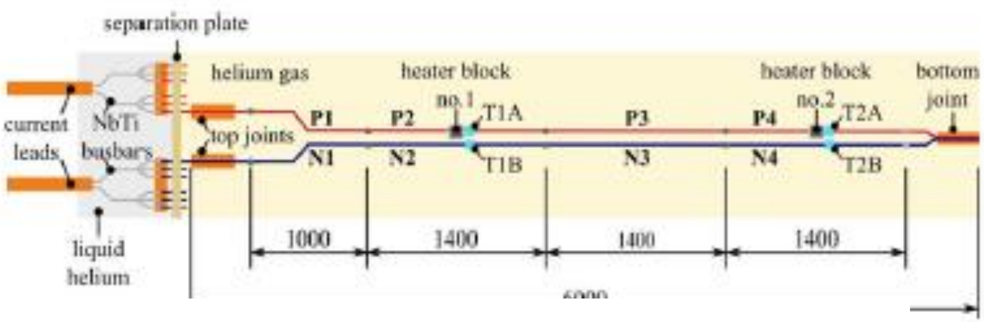
Cu RRR=100

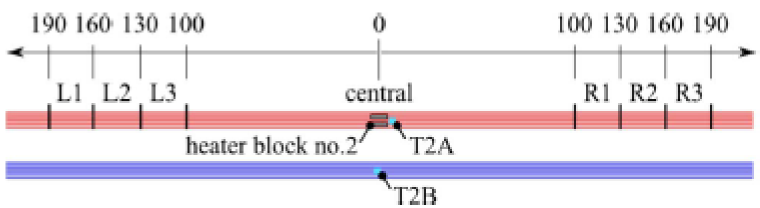
15 MIITs for reaching the100 mV detection threshold across a cable

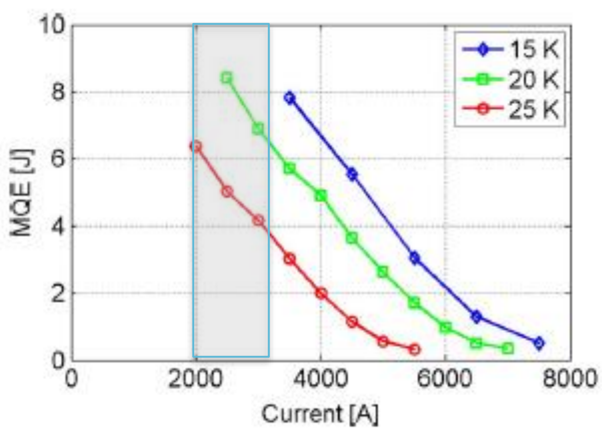
* It reaches 200 K with τ=30 s
** It reaches 42 K with τ_n=20 s
*** It reaches 67 K with τ_n=130 s (and I=2 kA)

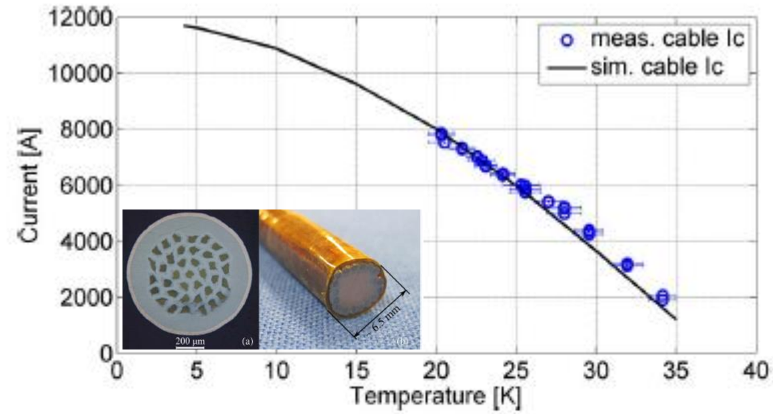
Protection of MgB_2 cables

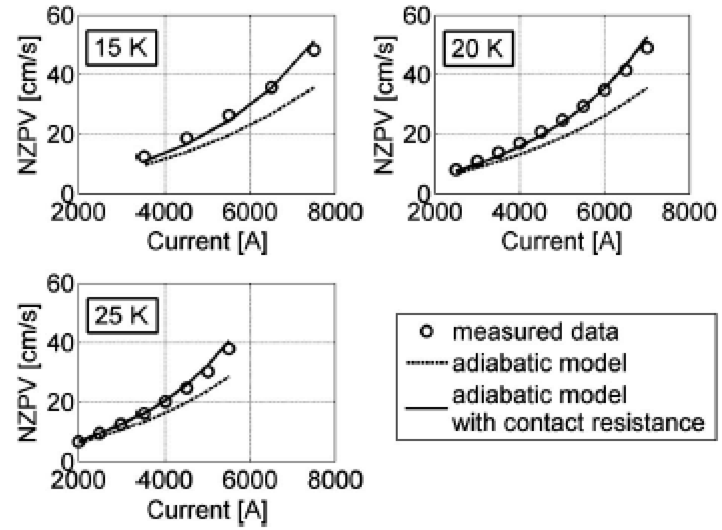
- Measurements in nominal conditions in the test station in the SM-18







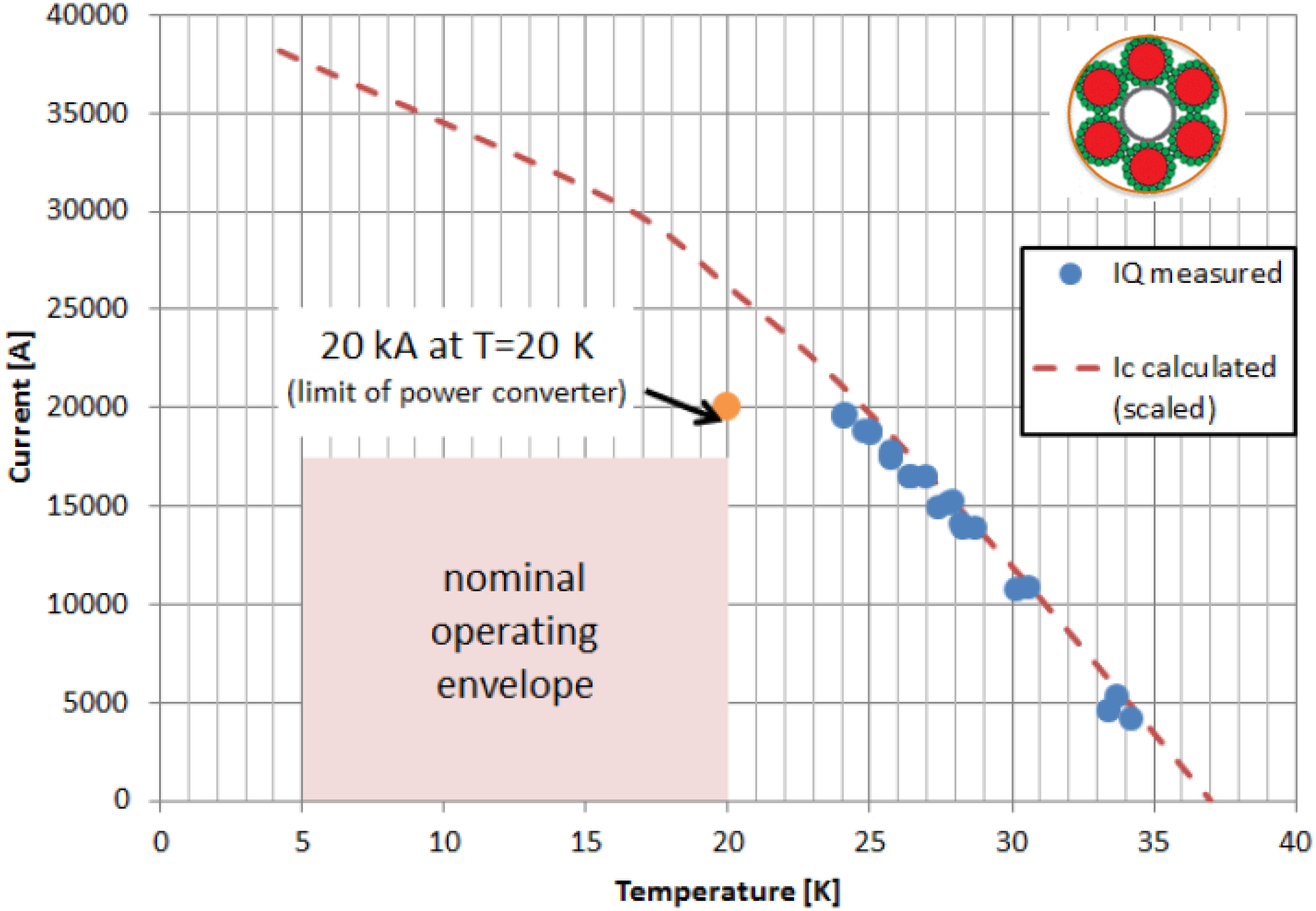




At 3 kA, NZP from 7.3 cm/s to 12.6 cm/s from 5 K to 20 K

GIANNELLI *et al.*: QUENCH PROPAGATION IN HELIUM-GAS-COOLED MgB_2 CABLES

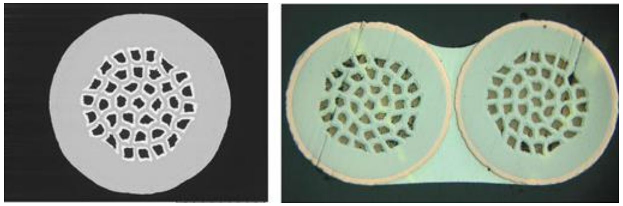
Protection of MgB_2 cables



Electrical splices

- Three types of splices will be used in the link:
  - MgB_2/HTS in the DFH
  - MgB_2/Nb-Ti in the DFX
- Splice resistances systematically addressed for:
  - Single MgB_2 wire
  - MgB_2 cable (to MgB_2 and to Nb-Ti)
  - HTS strands and cable

MgB_2 wire to MgB_2 wire



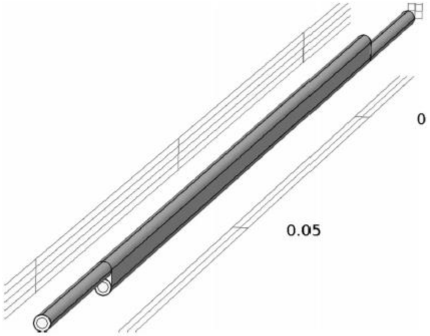
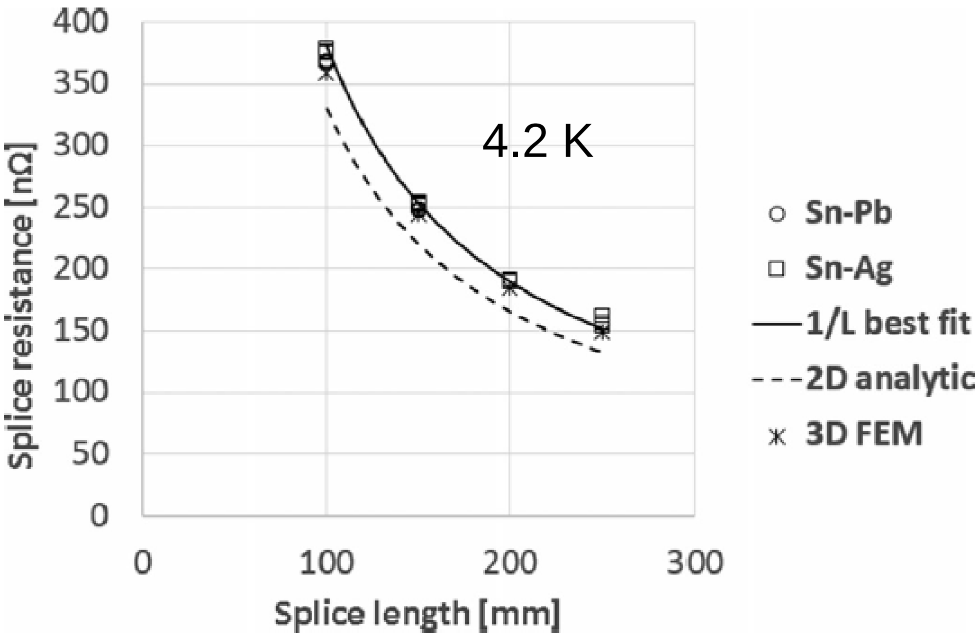


TABLE I
VALUES OF ELECTRICAL RESISTIVITIES AT DIFFERENT TEMPERATURES

Material	4.5 K	10 K	15 K	20 K	25 K
Nickel*	0.626	0.626	0.671	0.716	0.791
Nickel†	–	–	10.7	10.8	10.9
Copper RRR 30*	0.531	0.532	0.534	0.543	0.562
Copper RRR 100*	0.156	0.156	0.158	0.167	0.186
Niobium*	0.264	5.1	6.11	5.64	5.77
Monel*	278	278	278	278	278
Monel†	367	368	368	370	372

Values are reported in nΩ·m.
*Data from CryoComp v5.1. These data have been used in the models.
†Data from measurements at Columbus Superconductors.

Measured vs calculated



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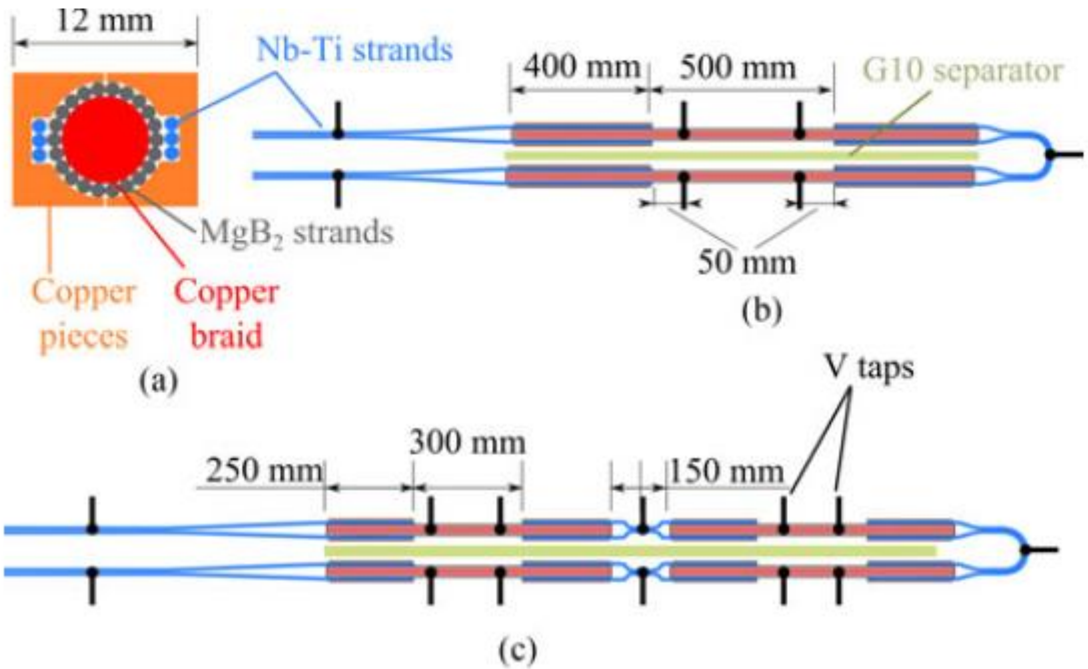
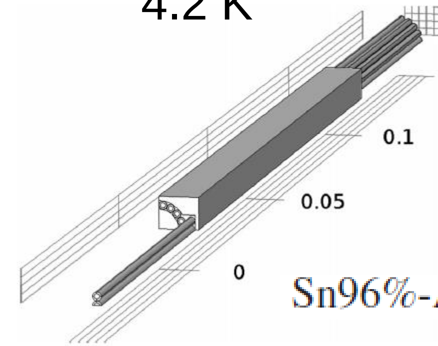
MgB_2 cable to Nb-Ti

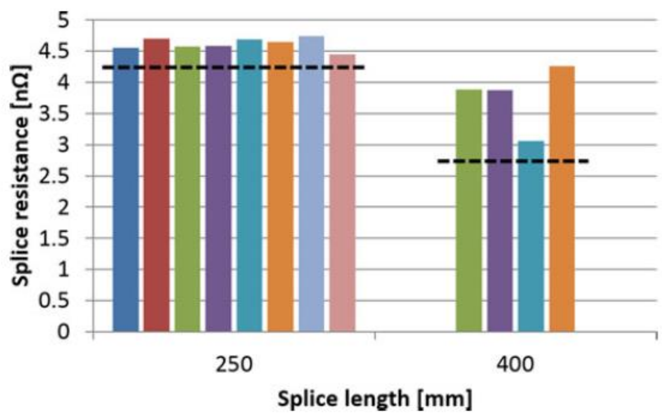


4.2 K



Sn96%-Ag4%.

Measured vs calculated



Measurements in Fresca test station, CERN

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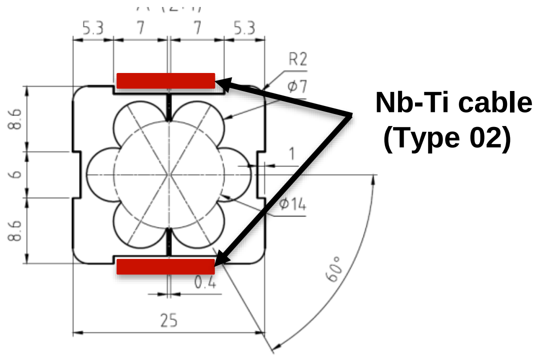
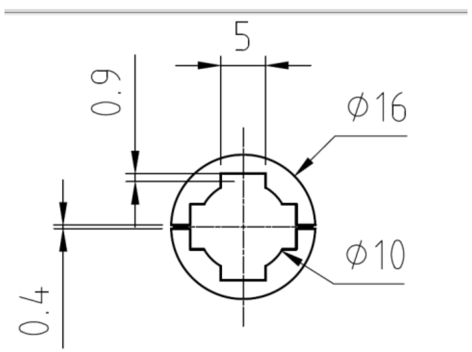
Electrical splices – MgB_2 cable to Nb-Ti cable

Measurements in Fresca test station, CERN



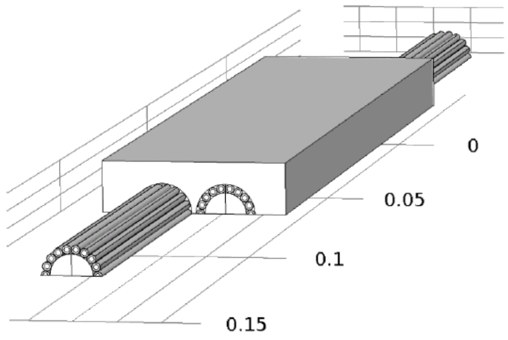
- **18 kA rope cable: 2- 4 nΩ (up to 26 kA) (<1 nΩ achievable)**
  - **200 mm long splice**
  - **Two half shell made of copper**
  - **Two Nb-Ti Type 02 LHC cable (15.1x1.48 mm)**

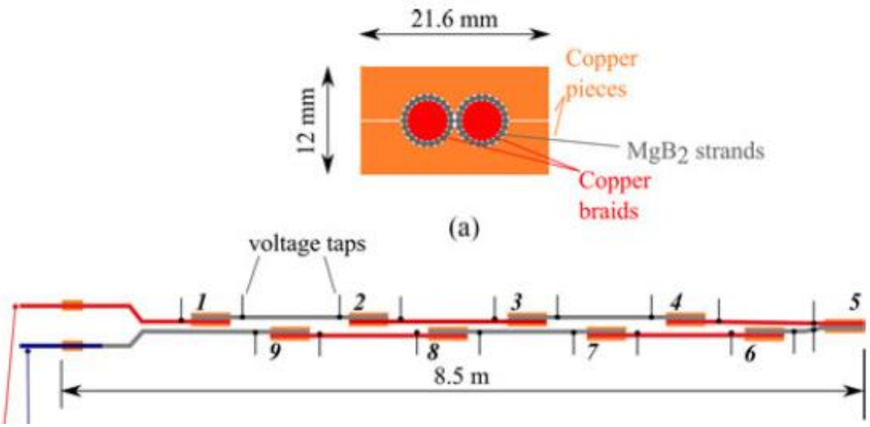


- **2 kA coaxial cable: ≤ 5 nΩ (up to 13 kA)**
  - **200 mm long splice**
  - **Two half shell made of copper**
  - **Nb-Ti Type 02 LHC strands**

J. Fleiter and J. Hurte, Internal Note on measurement in Fresca test station

MgB_2 cable to MgB_2 cable in He gas





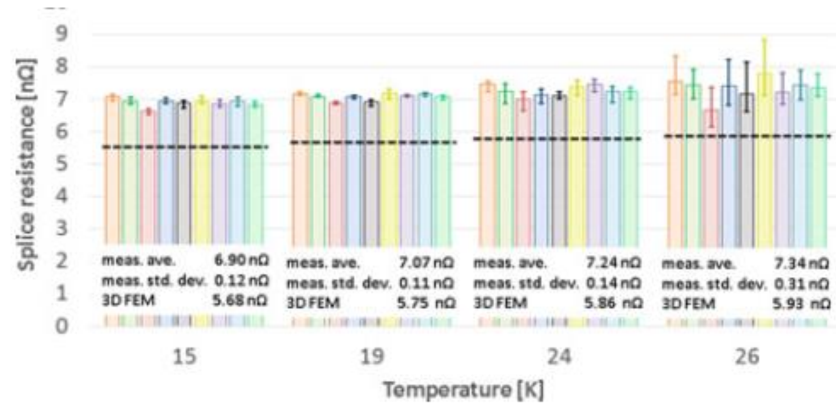


Fig. 10. Comparison of measured and calculated resistance data of 400 mm long MgB_2-MgB_2 cable splices.

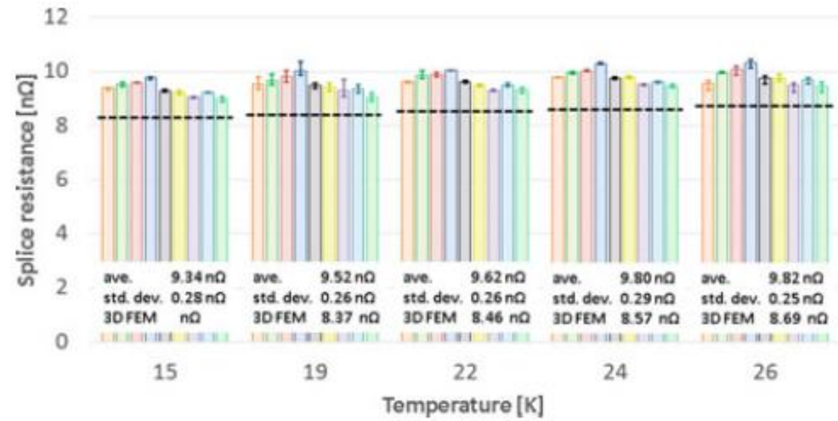


Fig. 11. Comparison of measured and calculated resistance data of 250 mm long MgB_2-MgB_2 cable splices.

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S. Giannelli, G. Montenero, and A. Ballarino

Conclusions

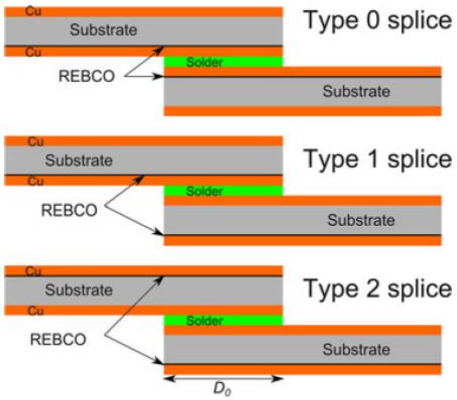
- Strategy for quench protection of each element of the Cold Powering System has been defined
- Experience from LHC design/operation of components has been used for the for definition of protection requirements
- Discussions with quench protection team confirm feasibility of proposed solutions (see next talk of R. Denz)
- The thresholds selected for protection are the results of modelling and measurements performed in nominal conditions (cryogenic and electrical)
- The test program that aims at the validation of a system demonstrator and a prototype system includes validation of quench protection strategy and hardware (dedicated electronics)

Thanks for your attention !

Additional slides

Electrical splices – MgB_2/HTS

- **Three topologies of splices for REBCO tapes**
  - Type 0: no substrate interleaved
  - Type 1: 1 substrate interleaved
  - Type 2: 2 substrates interleaved.
- Measured at 4 K and in field up to 12 T
- Measured at 77 K in self field

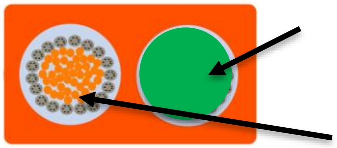


=>Type 0 *splices*: Lowest resistance - constant versus field and temperature

- ~**40** nΩ·cm^2 at 4 K (≤ 1 T)

=> Type 1 splices: higher resistance dependent on copper RRR

- ~**300** nΩ.cm^2 at 4 K (≤ 1T)



R≤ 10 nΩ at 20 K
250 mm long splice

J. Fleiter et al., **In-Field Electrical Resistance at 4.2 K of REBCO Splices**, IEEE trans. on Appl. Supercond., Vol. 27, No. 4, June 2017