MgB_2 cables: design, manufacturing and assessment

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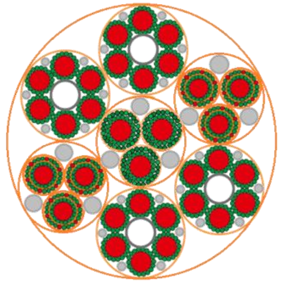
Outline

- Introduction
- Design parameters
- Experimental R&D assessment
  - Cabling at CERN
  - Tests and results
- Industrial cabling process
- Conclusions

Introduction: Problem statement

Design, for the first time, of a MgB_2 multi-cable assembly by using an *ex-situ* superconducting wire:



- **Different sub-cables carrying currents up to 18 kA.**
- **Made with 1 mm MgB_2 reacted wire.**
- **Definition of the main cabling parameters: tensile load, twist pitch and bending radius.**
- **Complexity of the cabling process due to the electro-mechanical performance of the MgB_2 wire.**

Introduction: Problem statement

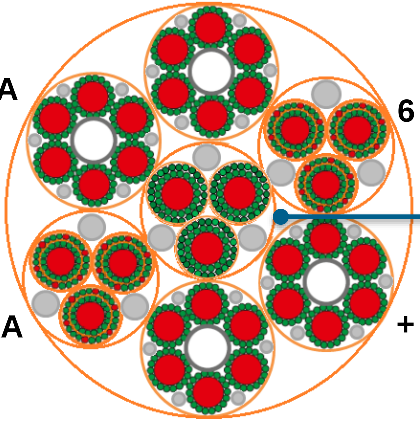
MgB_2 multi-cable assembly

- 18 kA

+ 18 kA

6 x 2 kA

3 x 7 kA



6 x 2 kA

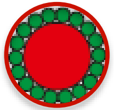
+ 18 kA

- 18 kA

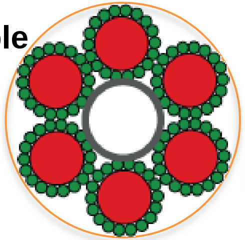
Φ ~ 75 mm

4 main sub-cables

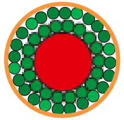
Composite strand



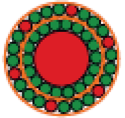
18 kA rope cable



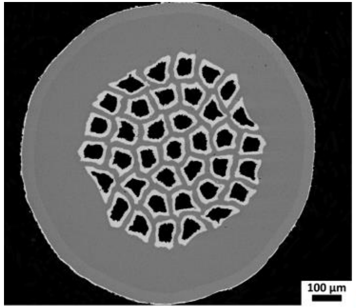
7 kA cable



2 kA coaxial cable



MgB_2 wire

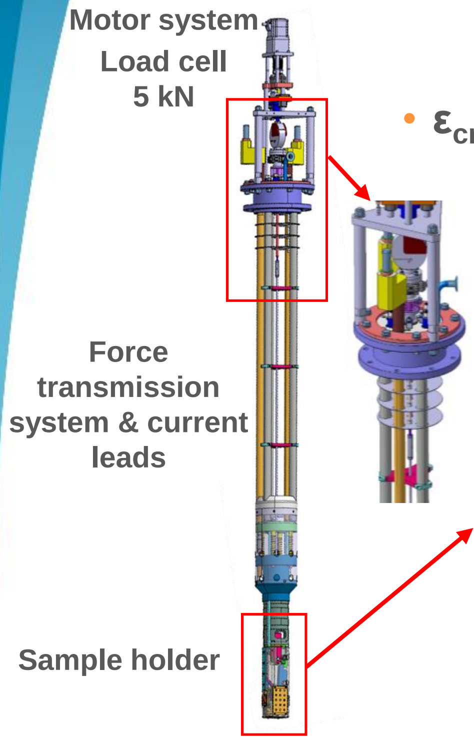


Φ ~ 1 mm

Introduction: Performed activities

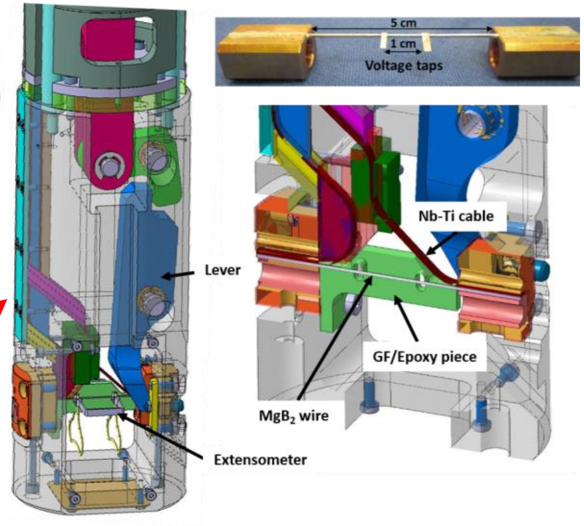
- Electro-mechanical characterization of the 1 mm MgB_2 wire at RT and 4.2 K.
- Definition and evaluation of the main cabling parameters.
- Cable manufacturing and experimental validation.
- Overseeing of the industrial manufacturing.

Design parameters: MgB_2 wire critical strain



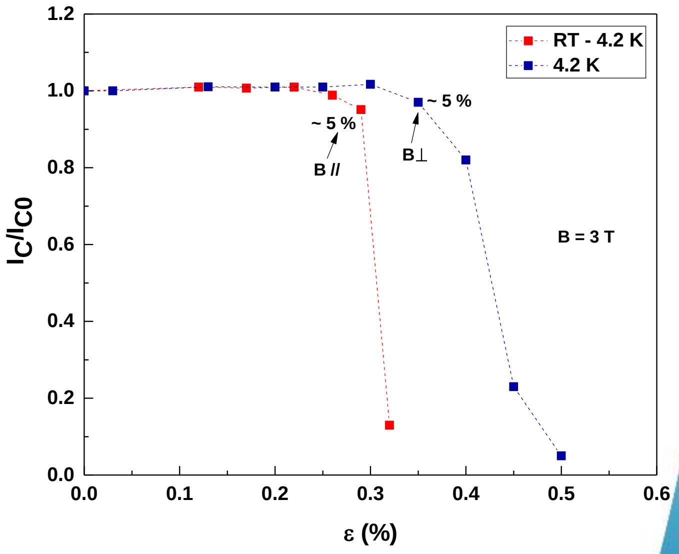
- Purpose-built device
- ε_{crit} determination: no I_C degradation*

* No or negligible I_C degradation (<5%)



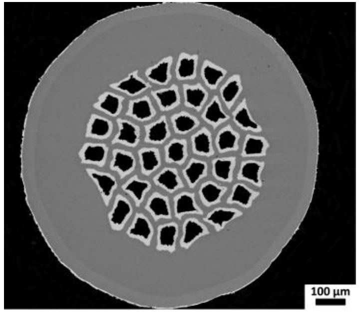
Tensile tests

ε_{crit} (%) at RT	ε_{crit} (%) at 4.2 K
0.26 ± 0.01	0.30 ± 0.01



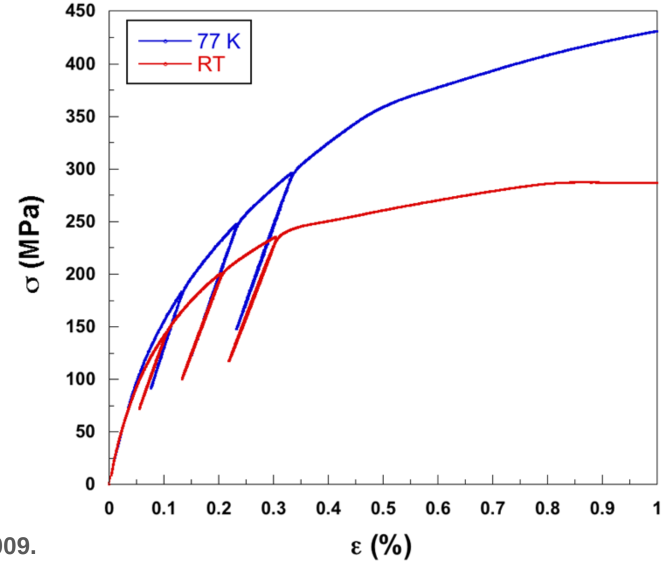
K. Konstantopoulou *et al*. 2016 Supercond. Sci. Technol. 29 084005.

Mechanical characterization of the MgB_2 wire



1 mm wire	E (GPa)	$\sigma_{y,\ 0.2\%}$ (MPa)
RT	151 ± 2	244 ± 3
77 K	162 ± 1	323 ± 3

- Tensile tests at RT and at 77 K
- Single bending tests
- Triple bending tests
- Nanoindentation measurements

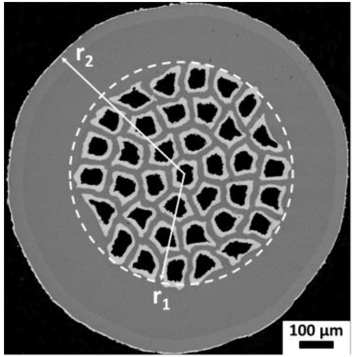


	MgB_2	Nb	Ni	Nb-Ni	Monel	Cu
E (GPa)	97	103	207	230	179	118

Sugano M. *et al*. 2016 Supercond. Sci. Technol. 29 025009.

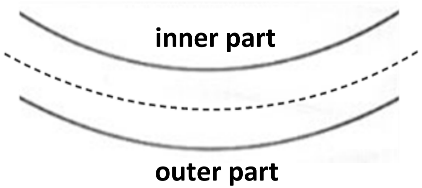
Konstantopoulou K. *et al*. 2016 Supercond. Sci. Technol. 29 084005.

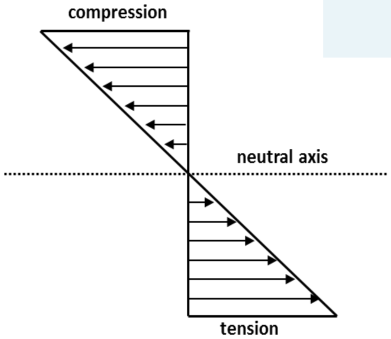
Design parameters: MgB_2 wire bending radius



ε_t (%)	$\varepsilon_t / \varepsilon_{crit,RT}$	$R_{b,\ wire}$ (mm)
0.05	0.19	656
0.10	0.38	328
0.15	0.58	218
0.20	0.77	164
0.25	0.96	131
0.30	1.15	109

symmetric cross section



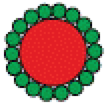


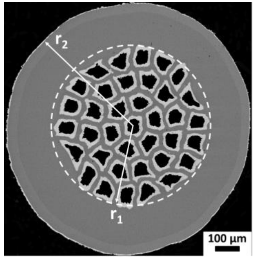
Strain distribution

ε_t : tensile strain in the outer MgB_2 filaments.

$R_{b,wire}$: bending radius of the MgB_2 wire.

Konstantopoulou K. *et al*. 2016 Supercond. Sci. Technol. 29 084005.

Design parameters: MgB_2 wire on "Composite strand" cable 



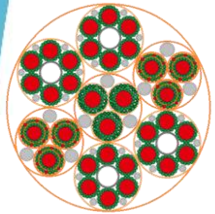
ε_t (%)	ε_t / $\varepsilon_{crit,RT}$	$R_{b,\ wire}$ (mm)	$T_{p,\ wire}$ (mm)
0.05	0.19	656	276
0.10	0.38	328	195
0.15	0.58	218	158
0.20	0.77	164	137
0.25	0.96	131	122
0.30	1.15	109	111

ε_t : tensile strain in the outer MgB_2 filaments.

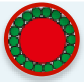
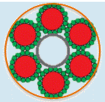
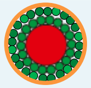
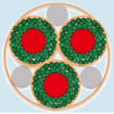
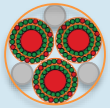
$R_{b,wire}$: bending radius of the MgB_2 wire.

$T_{p,\ wire}$: twist pitch of the MgB_2 wire in the "Composite strand" cable.

Design parameters: proposed for sub-cables



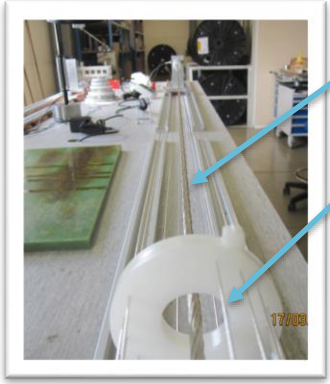
Φ **spool ≈ 3.5 m**

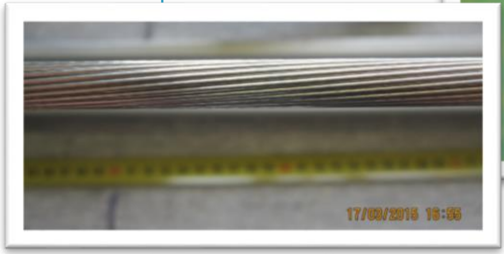
	Wire/Cable	Φ (mm)	R_b (mm)	T_p (mm)	Tensile load (kg)
	MgB_2 wire	~1.0	100	180 200	1.5 ± 0.5
	Composite strand	~7.5	300	600 – 800 - 1000	5 - 10
	18 kA rope cable	~24.0	550	1300	15 - 20
	7 kA cable	~10.5	400	600	10 - 15
	Triplet 7 kA coaxial cable	~23.5	550	-	15 - 20
	2 kA coaxial cable	~11.5	400	600	10 - 15
	Triplet 2 kA cable	~25.0	550	1300	15 - 20

The tolerance of the design parameters for the sub-cables is to be defined.

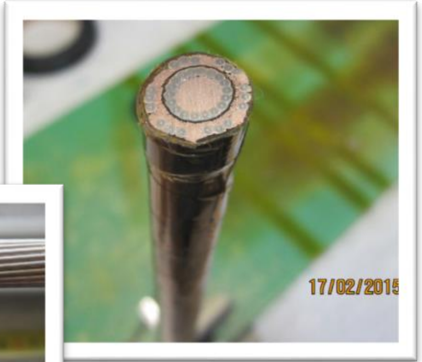
Experimental R&D assessment: cabling at CERN

- 25 configurations of “Composite strand” MgB_2 cables have been prepared at CERN to validate the cabling parameters. Twist pitch = 160 – 400 mm.
- 1 configuration of “2 kA coaxial cable” has been prepared at CERN and tested in FRESCA test station.
- 4 samples of “18 kA rope cable” have been prepared at CERN and measured at SM18.





“Composite strand” MgB_2 cable



“2 kA coaxial cable”

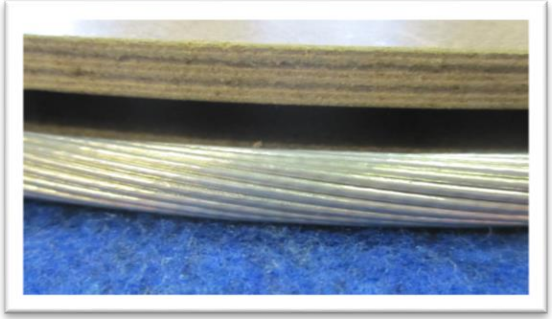
T_p = 200 mm

Experimental R&D assessment: tests and results

- 1 m long "Composite strand" MgB_2 cables were bent around a spool of 400 mm diameter, without additional applied load (single and double bending).
- 3 m long "Composite strand" MgB_2 cables were bent around a spool of 600 mm diameter by applying tensile load of 10 kg per cable.

Spool diameter = 600 mm

Spool diameter = 400 mm

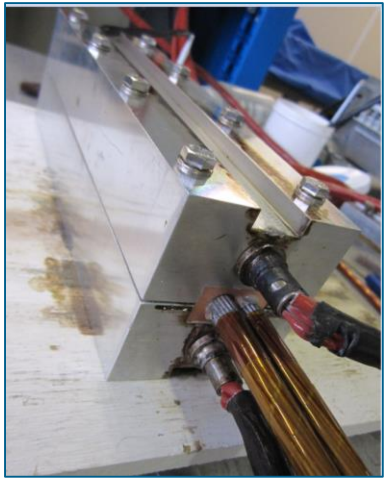


Experimental R&D assessment: tests and results

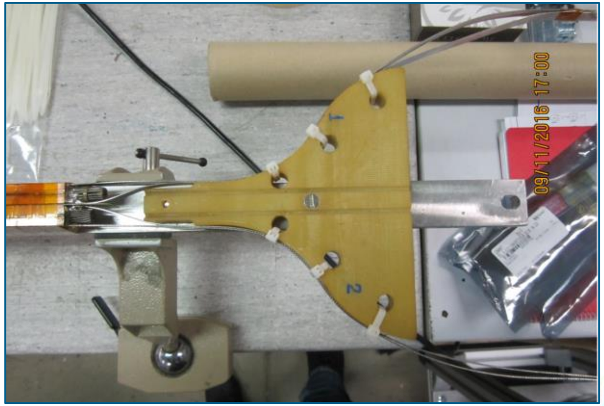
I_C measurement of “Composite strand” MgB_2 cable at FRESCA test station

Top splice

Bottom splice



Support

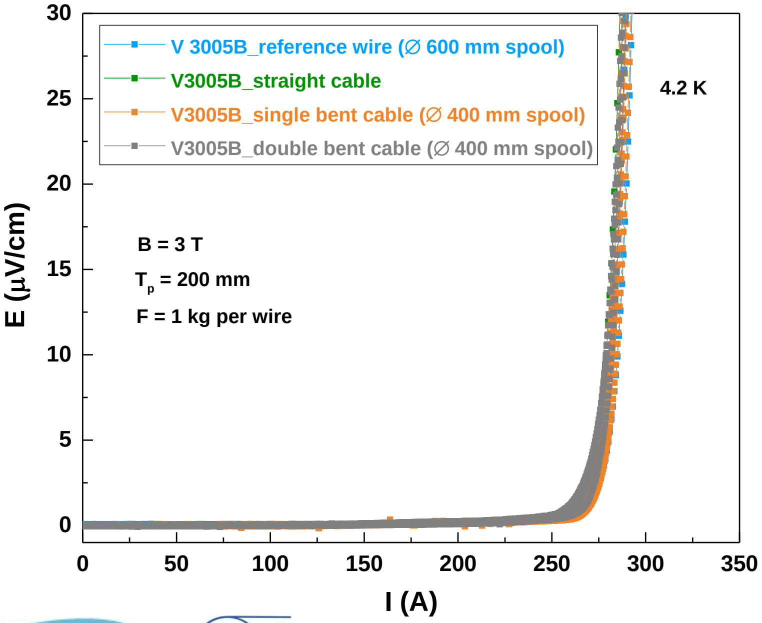


Images by courtesy of S. Giannelli (CERN).

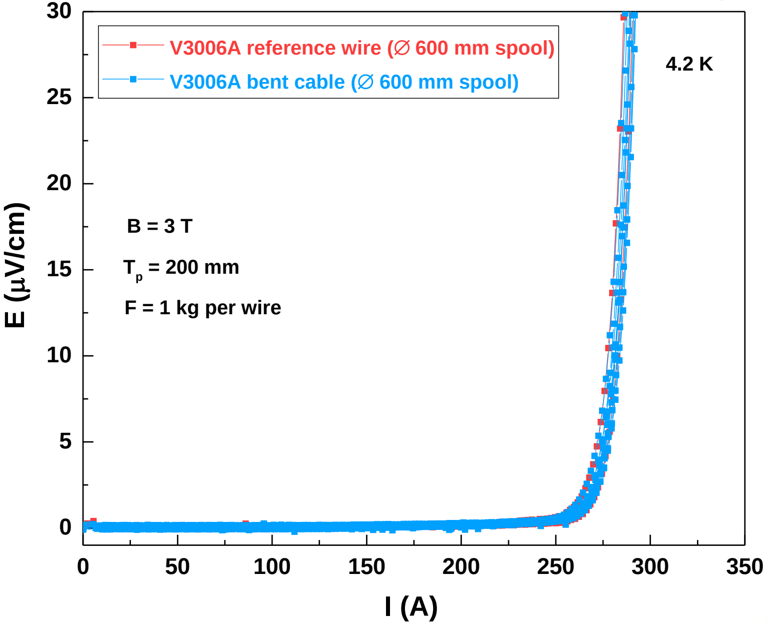
Experimental R&D assessment: tests and results

I_C measurement of extracted strands at 4.2 K and in 3 T parallel field.
No or negligible (<5%) I_C degradation was observed.

- The cable was bent without additional load.



- The tensile load on the cable was 10 kg.

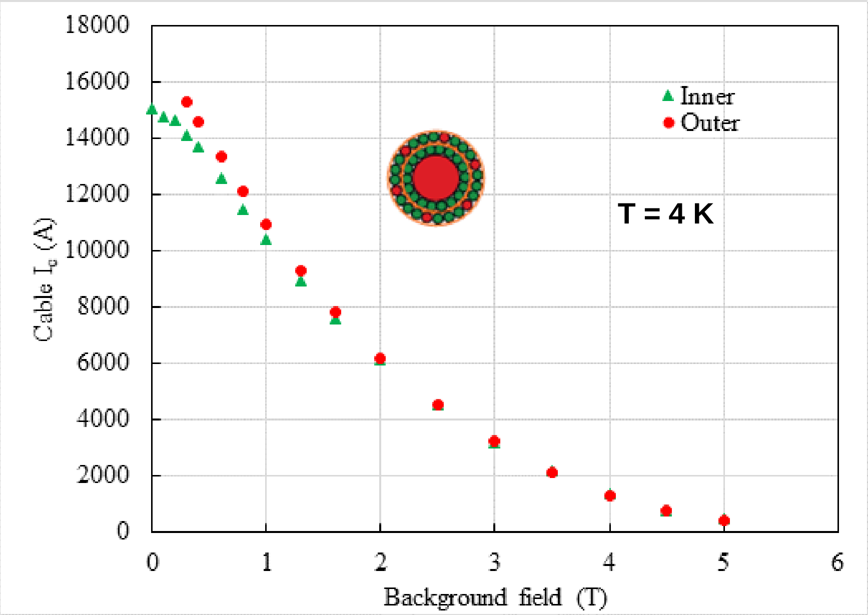


Konstantopoulou K. *et al*. 2017 Internal Note 2017-01, EDMS Nr. 1752117.

Experimental R&D assessment: tests and results

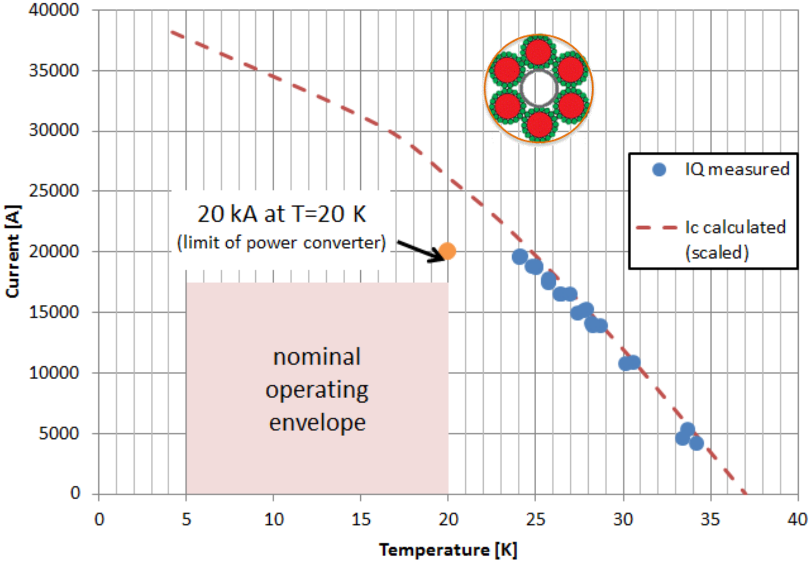
I_C measurement of MgB_2 cables at FRESCA test station and at SM18

"2 kA coaxial cable"



Data by courtesy of J. Fleiter (CERN).

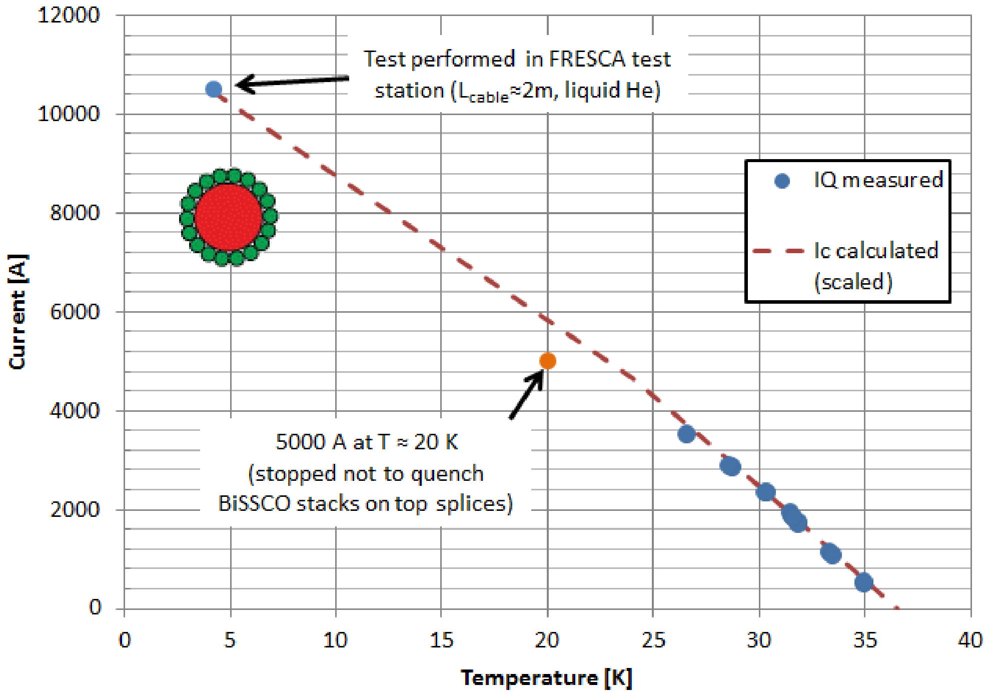
"18 kA rope cable"



Giannelli S. *et al*. 2015 Internal Note 2015-03, EDMS Nr. 1476839.

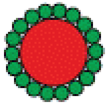
Experimental R&D assessment: tests and results

I_C measurement of MgB_2 cables at FRESCA test station and at SM18



Giannelli S. *et al*. 2015 Internal Note 2015-03, EDMS Nr. 1476839.

Industrial cabling process: "Composite strand" MgB_2 cable



- The industrial manufacturing of "Composite strand" MgB_2 cables were carried out by TRATOS Cavi SpA (Italy), industrial partner and charter member of ICAS.

- 1st contract phase: 12 samples "Composite strand" MgB_2 cables (6 straight and 6 bent) for the validation of the cabling process. The total length of the cables is 5 m.

All the bent cables were spooled on 450 mm diameter spools.

"Composite strand" MgB_2 cable	Tensile load per wire (kg)	T_p (mm)	ε_t (%)
SC sample #1	1.5	200	~ 0.09 < 0.2
SC sample #2	1.5	170	~ 0.14 < 0.2
SC sample #3	1.5	150	~ 0.18 < 0.2
SC sample #4	2.5	200	~ 0.11 < 0.2
SC sample #5	4.0	170	~ 0.16 < 0.2
SC sample #6	2.5	170	~ 0.15 < 0.2

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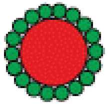
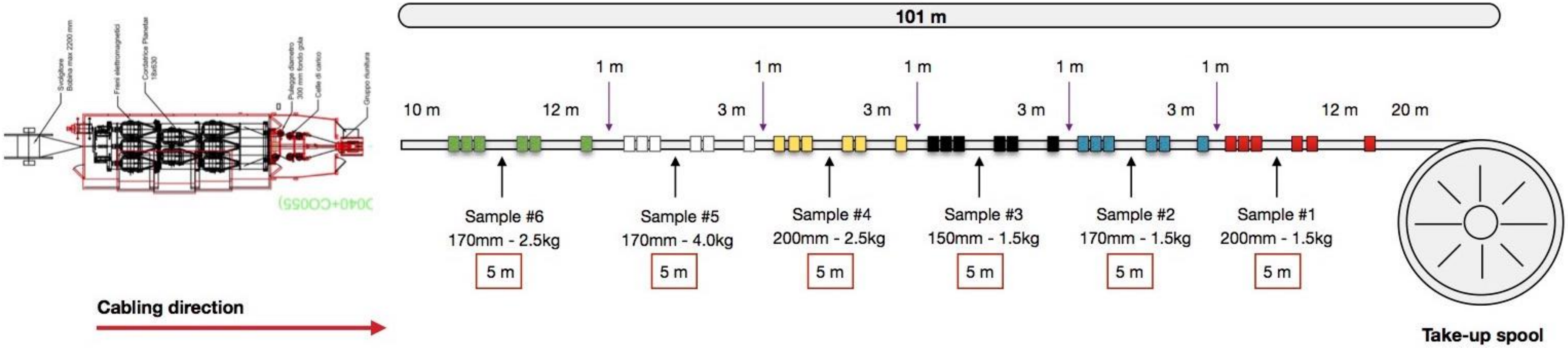
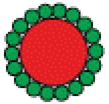
Industrial cabling process: “Composite strand” MgB_2 cable



Cabling machine layout at TRATOS Cavi SpA.

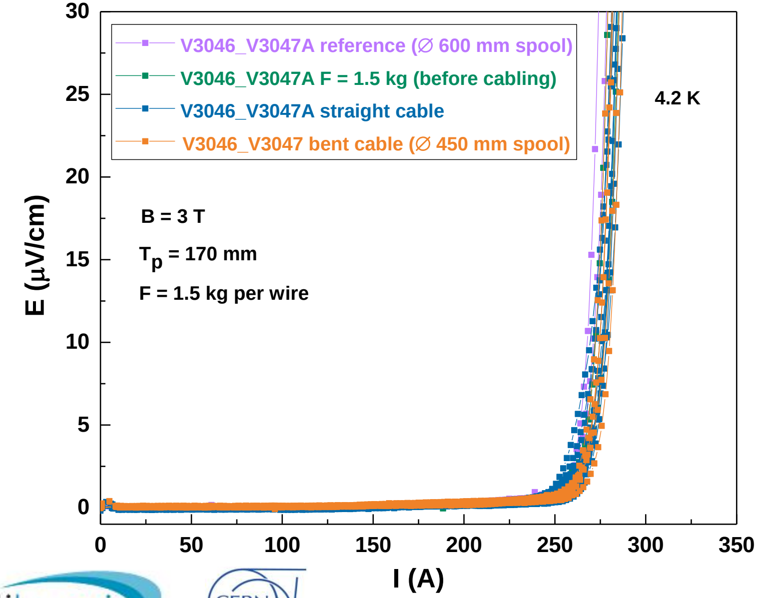


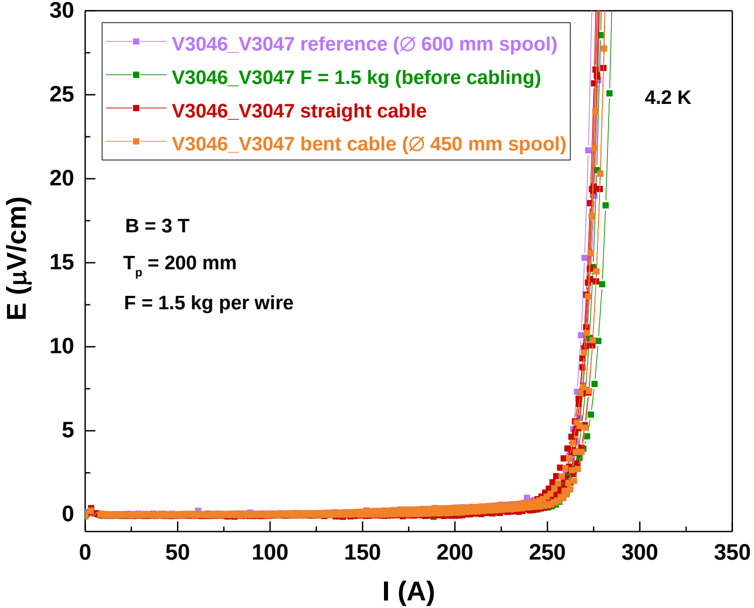
Industrial cabling process: “Composite strand” MgB_2 cable



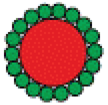
Experimental assessment at CERN

- The I_C of 135 extracted strands, from the received cables, was measured at 4.2 K and in parallel field up to 3 T.
- No or negligible (<5%) I_C degradation was observed when the tensile load per wire was 1.5 kg and twist pitch of 200 mm.

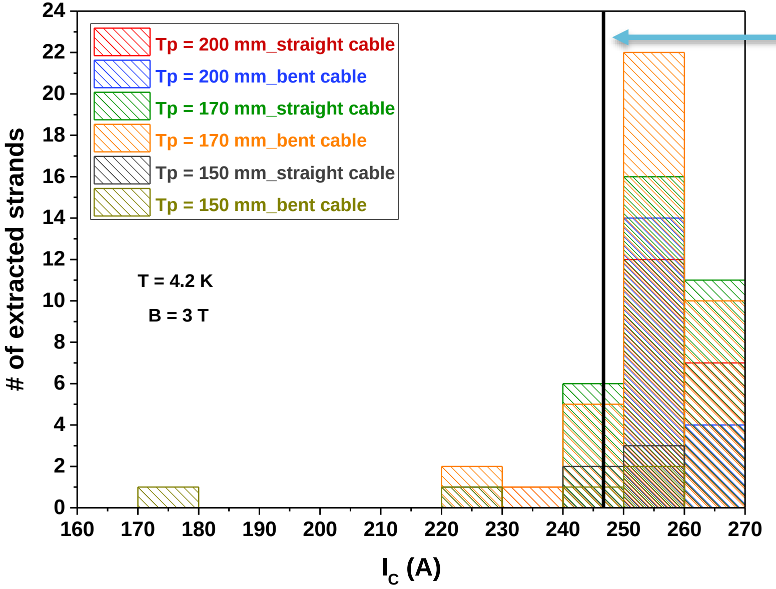




Experimental assessment at CERN

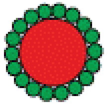


SC sample #1
SC sample #2
SC sample #3

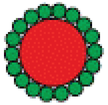


I_C degradation < 5%

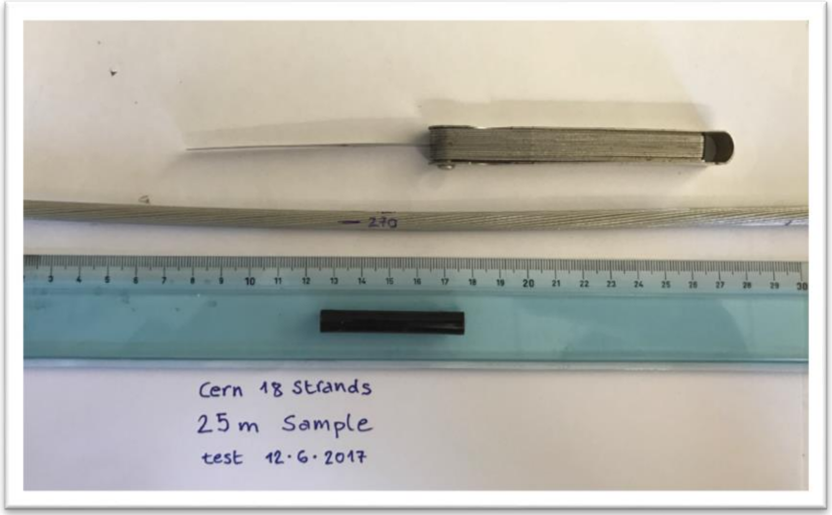
"Composite strand" MgB_2 cable	Tensile load per wire (kg)	$T_{p, wire}$ (mm)	ε_t (%)	$R_{b, cable}$ (mm)
25 m long	1.5	180	0.12 < 0.2	300

Industrial cabling process: 25 m long "Composite strand" MgB_2 cable 

- 2st contract phase: One 25 m long "Composite strand" MgB_2 cable for the qualification of the long cabling process. The cabling parameters are: twist pitch of 180 mm, bending radius of 300 mm and tensile load per wire 1.5 kg.
- Single and double bending of a "Composite strand" MgB_2 cable on a 600 mm diameter spool.

Industrial cabling process: 25 m long "Composite strand" MgB_2 cable 

- Shape recovery of a "Composite strand" MgB_2 cable after single and double bending.
  - No additional force was applied during the bending.



Industrial cabling process: upgraded machine

Cabling machine for "Composite strand"

Cabling machine for the bigger sub-cables.

Image: Confidential information

Conclusions (1/2)

- A thorough electro-mechanical characterization of 1 mm MgB_2 wire has been carried out at CERN for the determination of the adequate cabling parameters.

- Short length samples of "Composite strand" cables, "18 kA rope cable" and "2 kA coaxial cable" have been prepared and experimentally validated at CERN. I_C measurements of cables and extracted strands.

- The minimum *bending radius*, minimum *twist pitch* and maximum *tensile load* of the MgB_2 wire and cables have been proposed considering the geometry of each sub-cable and the mechanical performance of the MgB_2 wire at RT.

Conclusions (2/2)

- Twelve samples (straight and bent) of "Composite strand" MgB_2 cables have been manufactured by TRATOS Cavi SpA. and measured at CERN for the assessment of the cabling parameters and the industrial cabling process.
- A 25 m long "Composite strand" MgB_2 cable with *twist pitch* of 180 mm, *tensile load per wire* of 1.5 kg and *bending radius* of 300 mm has been manufactured and shipped at CERN, by TRATOS Cavi SpA.
- Experimental assessment at CERN of the 25 m long "Composite strand" MgB_2 cable.
- Specification for the "18 kA rope cable" and the "2 kA coaxial cable".

Thank you for your attention

Acknowledgements: Many thanks to Sebastiano Giannelli, Jerome Fleiter, Jean-Eudes Maurice Duvauchelle, Alban Stimac, Jean-Sebastien Denis, Gerard Perrier Gros Claude, Pierre-Francois Jacquot, Anne Eychenne, Francis Beauvais and Bernardo Bordini.