Development and electrical test of high field and current splices between Nb_3Sn cables for particle accelerators magnets

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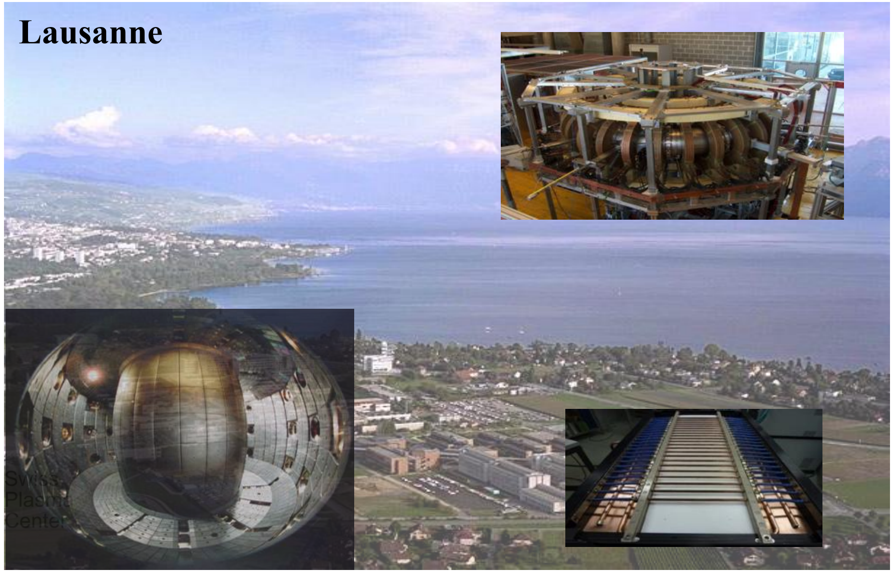
The superconductivity group

- Started in the 60' as a section of the Schweizerische Institut für Nuklearforschung (SIN, later PSI) for superconducting magnets and cryogenics
- Well known worldwide for the SULTAN test facility, built in the 80' under a EURATOM collaboration of CH-NL-I
- Joined the CRPP (now SPC) of Lausanne in 1993
- 23 people: 5 technicians, 3 operators, 4 PhD students, 10 professionals, 1 secretary

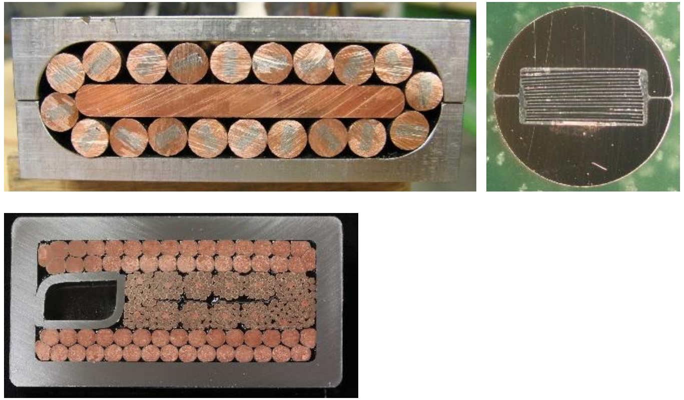


EPFL

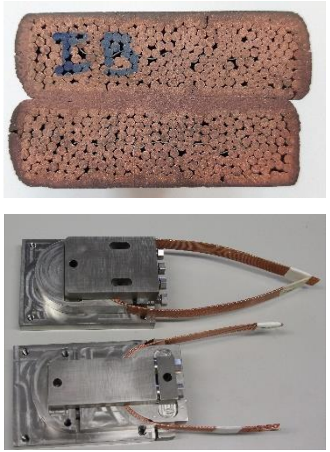
Group main expertise

- Test of cables, joints and small insert coils in DC and AC conditions
- Recently, SULTAN upgrade for test of HTS cables during quench (10 V maximum voltage at 18 kA)
- Development of Nb_3Sn and HTS conductors for fusion energy magnets
- Design and analysis of fusion energy magnets

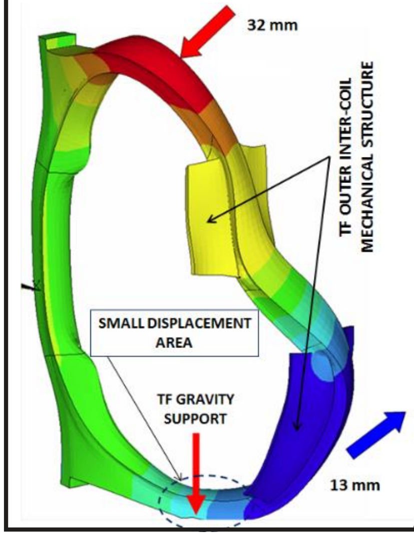
Fusion cables



Fusion & accelerator joints

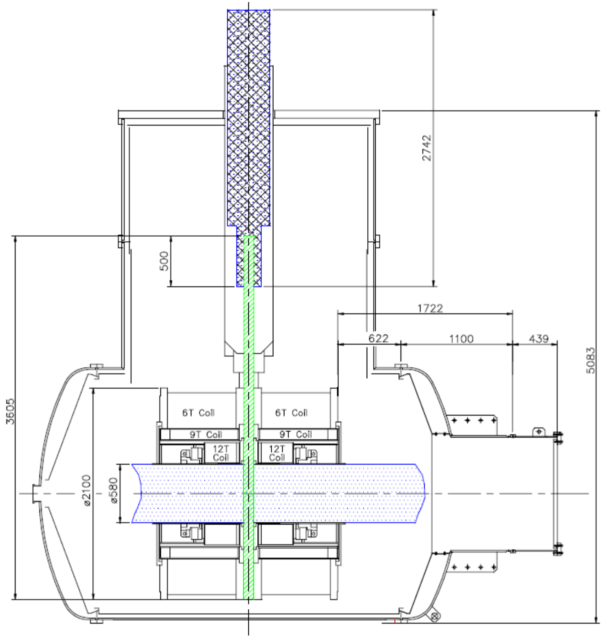


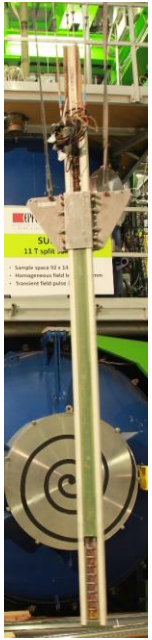
Fusion magnet design



SULTAN test facility

- Field generated by 3 pairs of concentric split solenoids:
  - B_{max} = 10.905 T in test well
  - Homogeneity (2%) along ~400 mm
  - Inserted through a vertical test well (144 mm × 94 mm rectangular pipe)
  - NbTi trafo supplies I_{sample} ≤ 100 kA





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Outline

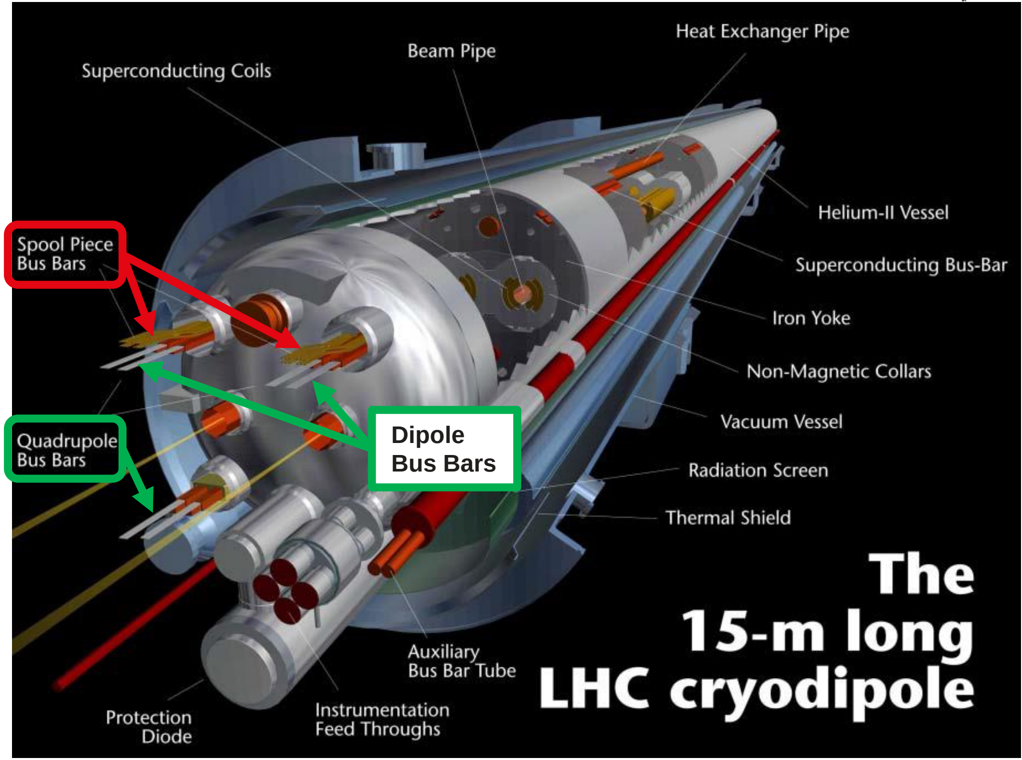
- Joints in superconducting magnets
- Background I: splices in LHC (NbTi - NbTi)
- Background II: splices in HL-LHC (Nb_3Sn - NbTi)
- Motivation: splices in FCC or HE-LHC, intergrade Nb_3Sn joints
- Internal Nb_3Sn splices
- Splicing techniques overview
- High field and current splices development at SPC
- Conclusions

Joints in superconducting magnets

- One of the most delicate parts. They introduce a disturbance:
  - Local heat deposition
  - Geometrical discontinuity
  - Mechanical discontinuity
- Reasons to built a joint in a magnet:
  - Feeding → connection to bus bars/power supply
  - Feasibility → cable too long for single winding
  - Economical → conductor grading

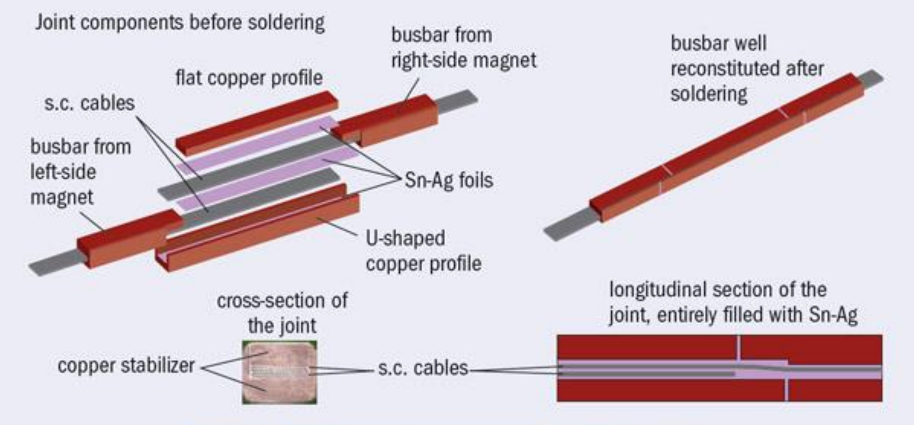
Background I: splices in LHC (NbTi)

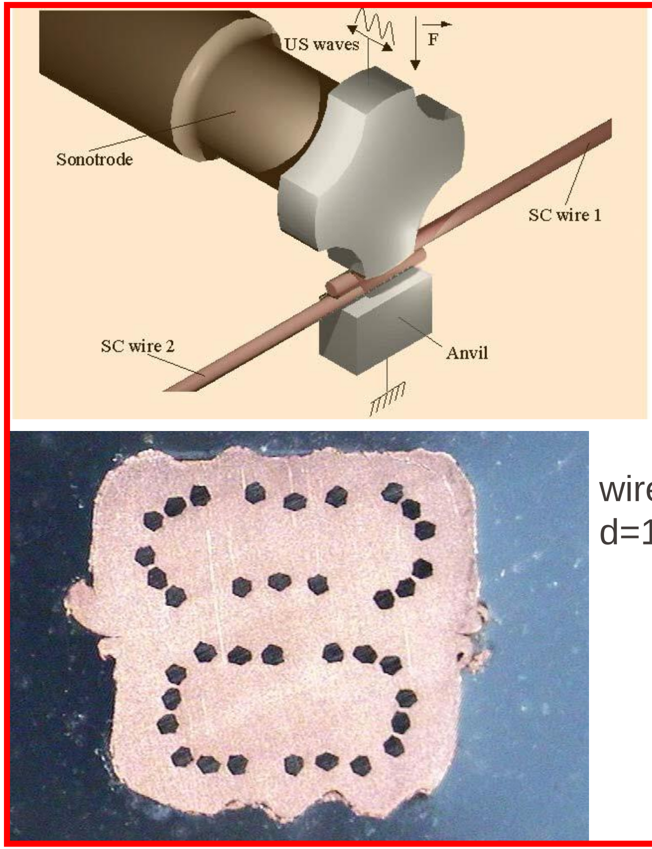
- Function of the splice: series connection of magnets
- When: splices are done once the magnets are in tunnel → limited space
- Two types of splices:
  - Between SC bus bars & dipoles, bus bars & quadrupoles (~10170 splices)
  - Between SC bus bars/correction coils (~50000 splices)
- Main splices characteristics:
  - Helium cooling capability → electrical resistance (<0.6 nΩ & <18 nΩ)
  - Mechanical strength
  - Enough stabilizer in case of quench



"Superconductivity: its role, its success and its setback in the large hadron collider (LHC) of CERN", Lucio Rossi, 2010

Background I: splices in LHC (NbTi - NbTi)





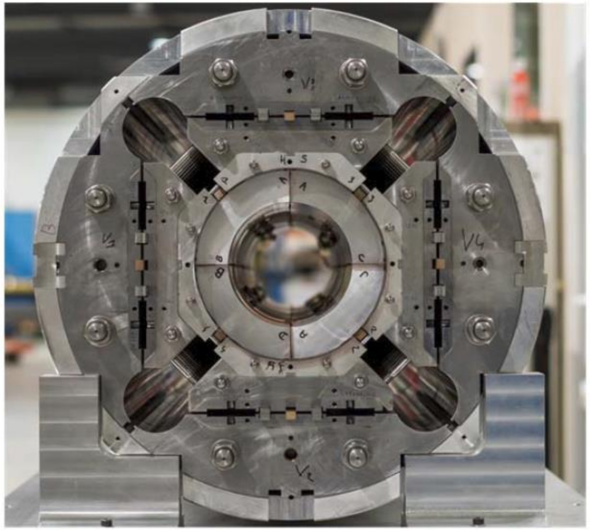
wire
d=1.6 mm

"Superconductivity: its role, its success and its setback in the large hadron collider (LHC) of CERN", Lucio Rossi, 2010

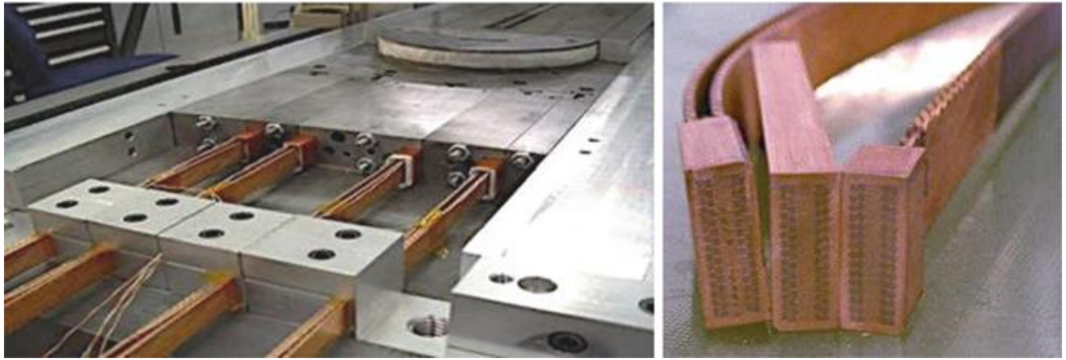
"Qualification and Start of Production of the Ultrasonic Welding Machines for the LHC Interconnections", A. Jacquemod et al., 2006

Background II: splices in HL-LHC (Nb_3Sn-NbTi)

- Nb_3Sn quadrupoles to increase the luminosity
- Nb_3Sn undergoes heat treatment to be formed
- Nb_3Sn leads of the quadrupoles soldered, after heat treatment, to flexible NbTi cables → external splice → accessibility
- Splice is out of the high field region

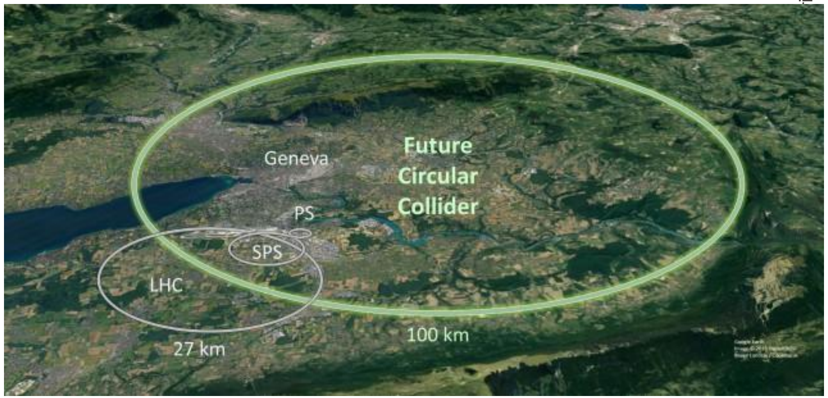


"The HL-LHC Low-β Quadrupole Magnet MQXF: From Short Models to Long Prototypes", P. Ferracin et al., 2019



"Nb_3Sn Accelerator Magnets", Editors: Daniel Schoerling, Alexander V. Zlobin

Splices in FCC or HE-LHC, motivation



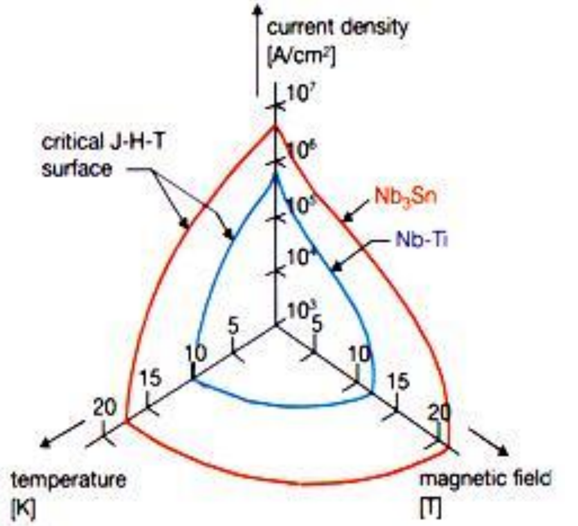
- In particle accelerators, the collision energy is

$$E\ [GeV] = 0.3 \cdot B[T] \cdot \rho[m]$$

Beam energy *Dipole field* *Bending radius*

- LHC:
  - E= 14 TeV
  - B=8.3 T, NbTi dipoles
  - 27 km long tunnel
- HE-LHC:
  - E=27 TeV
  - B=16 T, Nb_3Sn dipoles
- Future Circular Collider (FCC, ~2035)
  - E=100 TeV
  - B=16 T, Nb_3Sn dipoles
  - 100 km tunnel

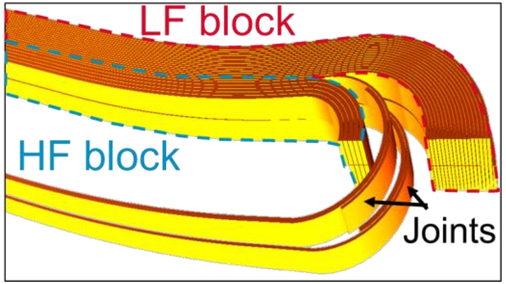
Conductor grading for affordable cost



Critical surface

Internal Nb_3Sn splices development

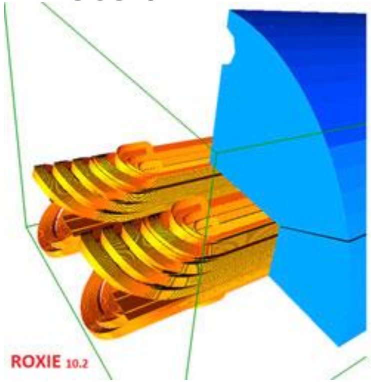
- 2017-2020 collaboration between CERN and Swiss Plasma Center → inter-grade internal splice solution, i.e. in the coil winding pack, for Wind-and-React (W&R) coils
- Requirements:
  - R≤1 nΩ at B≥10 T, $I/I_c \geq 1/3$, T=4.5 K
  - Integration at coil ends
- Boundary conditions: limited space, limited manipulation after heat treatment (Nb_3Sn brittleness), limited accessibility
- Use of the SULTAN facility for electrical tests



C. Lorin et al., IEEE, 2018

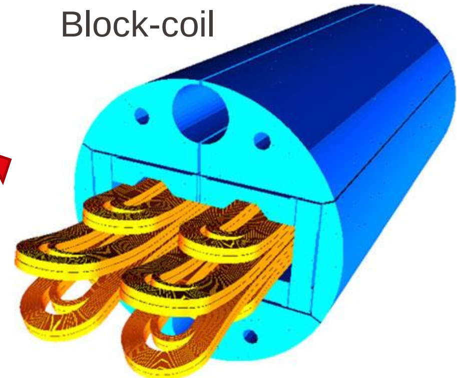
Dipole ends

Cos-θ

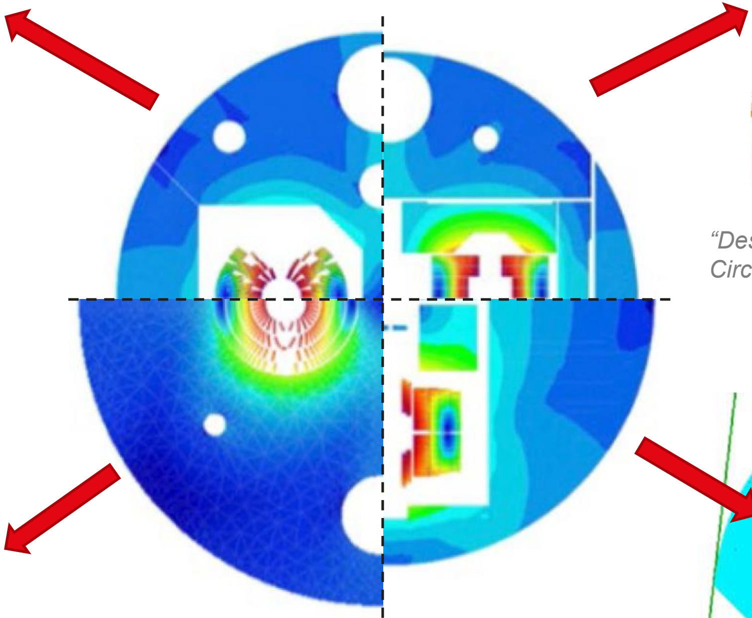


"Conceptual Design of a 16 T cos θ Bending Dipole for the Future Circular Collider", V. Marinozzi et al., 2018

Block-coil

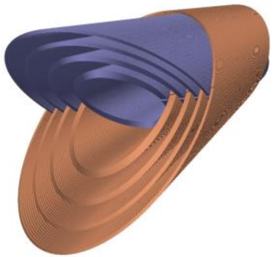


"Design of a Nb3Sn 16 T Block Dipole for the Future Circular Collider", C. Lorin et al., 2018



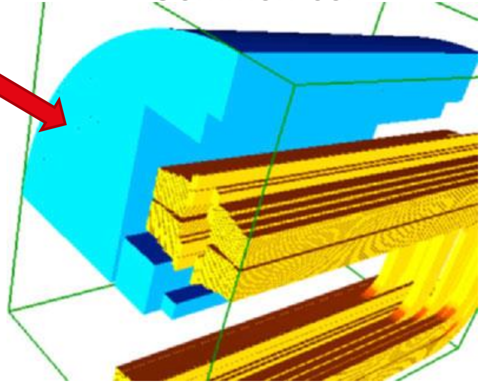
"The 16 T Dipole Development Program for FCC and HE-LHC", D. Schoerling et al., 2019

CCT



"Canted-Cosine-Theta Superconducting Accelerator Magnets for High Energy Physics and Ion Beam Cancer Therapy", Lucas Nathan Brouwer, PhD thesis, 2015

Common-coil



"Magnetic and Mechanical Design of a 16 T Common Coil Dipole for an FCC", F. Toral et al., 2018

Splicing techniques overview

Splicing techniques in Nb_3Sn magnets:

- When during coil manufacture?
- Dependence on magnet design?

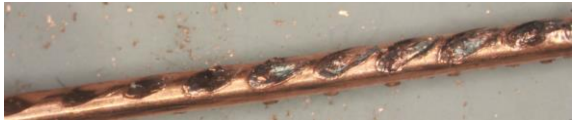
Identified potential techniques:

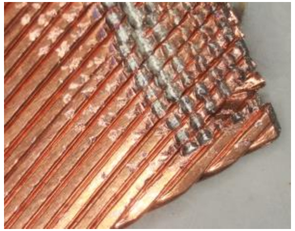
- Ultrasound welding, before Heat Treatment (HT)
- Copper diffusion bonding (DB), during HT
- Soldering, after HT

Splicing techniques overview : ultrasound welding

- It gave excellent results in welding NbTi wires in LHC
- Before HT
- Low dependence on magnet design
- Cable handling allowed, space available high.
- Trials with MQXF cable.
- Failed. Stabilizer peeled apart when trials bare strand/strand and cable/cable. Trial with reinforcing Cu coating but it failed the same.

After strand/strand trial





After cable/cable trial

Where joint was tried

Splicing techniques overview : diffusion bonding

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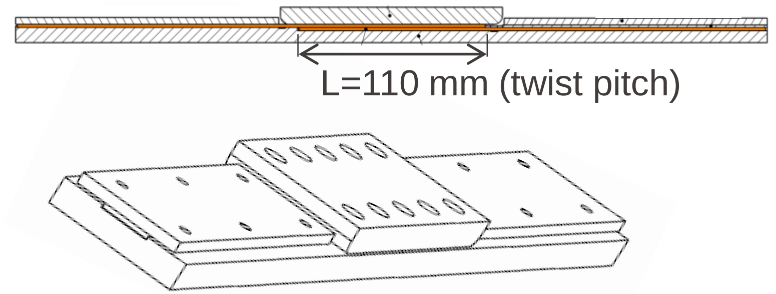
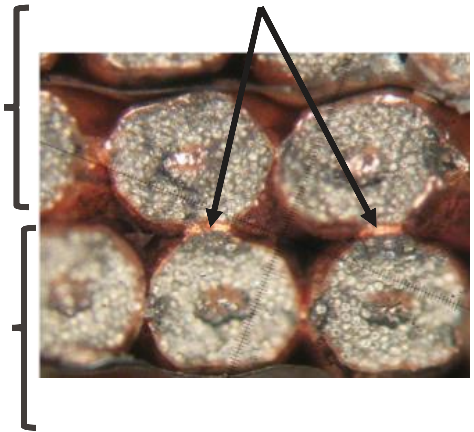
- Elegant solution, only bare cables without surface treatment
- During heat treatment
- Inter-diffusion between Cu surfaces need pressure at 600-700°C. Parametric study on pressure (5-30 MPa applied at room T).
- Pressure must be kept during heat treatment → the clamping fixture must be integrated into the winding pack → clamps design depends on magnet design
- The clamping fixture provides support for keeping tension during winding.





Splicing techniques overview : soldering

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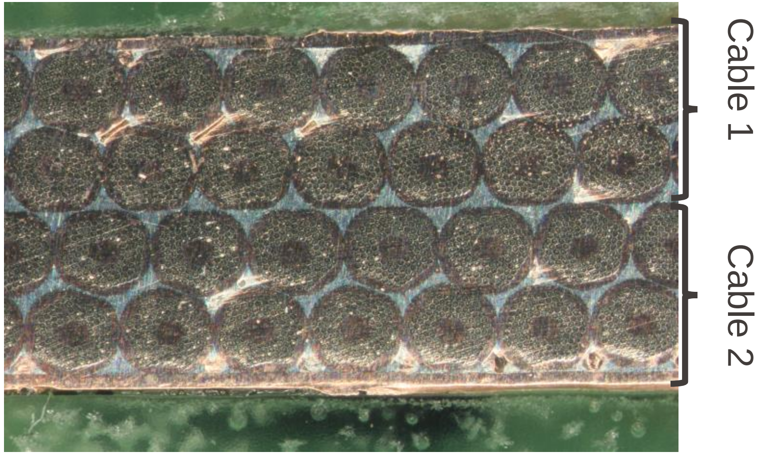
- Cables overlapped during magnet winding. Winding tension must be kept between not-joined cables
- Soldering after heat treatment → very limited cable handling
- Low melting point filler material, solder (Sn95Ag5), melts in contact area
- Space for heaters must already be allocated during winding. Spacers+fillers during heat treatment and after soldering



High field and current splices – samples heat treatment

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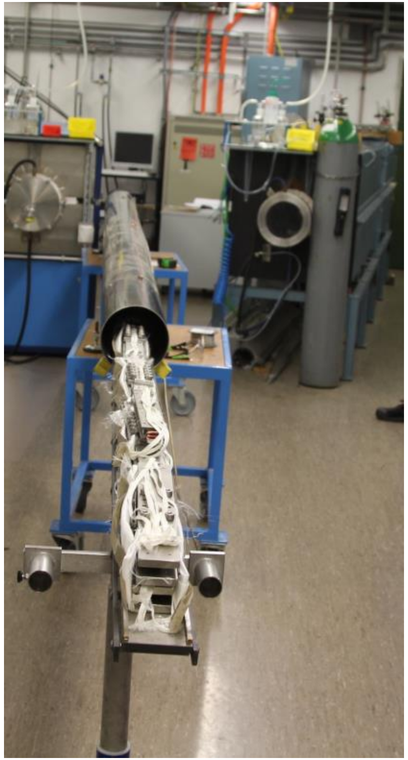
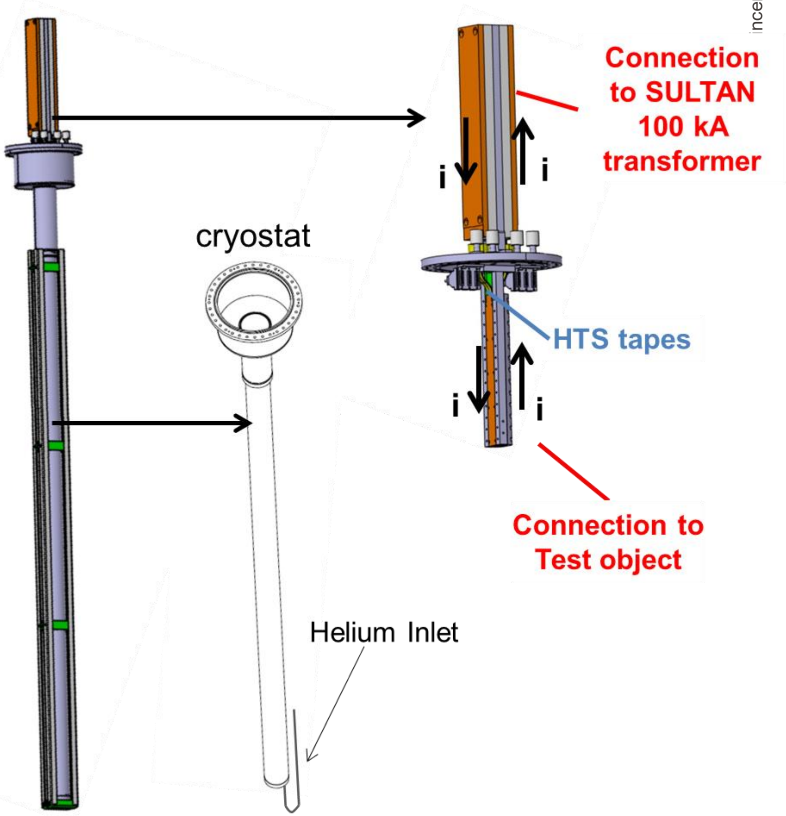
- Heat treatment is carried out in SPC-Villigen in a furnace with argon atmposphere
- We try to simulate the heat treatment environment of a magnet putting plenty of mica and fiberglass
- Soot covers the samples



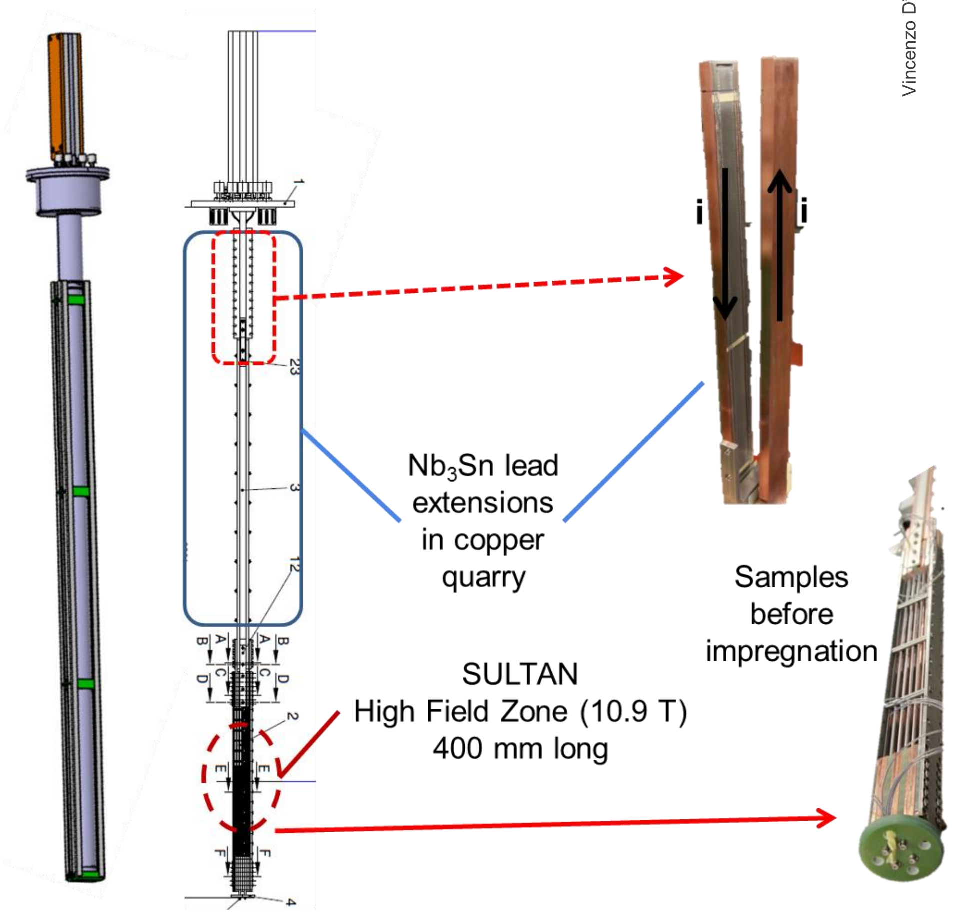
High field and current splices – experimental setup (I)

- HTS adapter as electrical connection between vacuum and test environment with He (p=10 bar)
- He almost stagnant in cryostat
- Temperature regulation 4.5-50 K



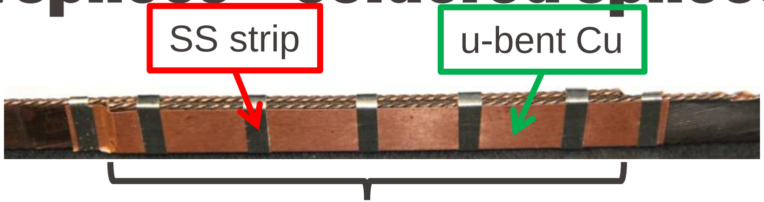
High field and current splices – experimental setup (II)

- Lead extensions connect the HTS adapter to the sample
- Lead extensions are two Nb_3Sn (MQXF) cables soldered in two copper slots
- Samples can be:
  - Stack of 6 splices
  - 1 bent splice
  - Insert coil



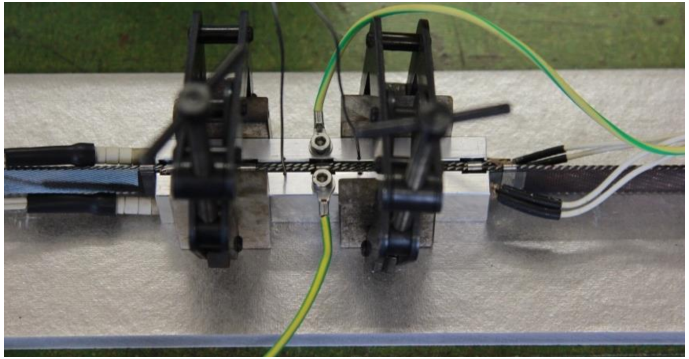
High field and current splices – soldered splices (I)

- Cable used for R&D is MQXF
  - Pitch 109 mm, mid thickness 1.53 mm, width 18.16 mm, keystone angle 0.376 °, 40 strands
  - Conductor I_c≈29 kA at B=10.9 T, T=5 K
- Samples preparation:
  1. Bare Cables Crimped in Copper foil envelop. Crimping strips pulled by hand + spot welding.
  2. Heat treatment
  3. Soldaflux K poured at room temperature (based on zinc chloride, ammonium chloride). Soldered with Sn95Ag5 wire, melted from top at 260 °C



Splice before heat treatment

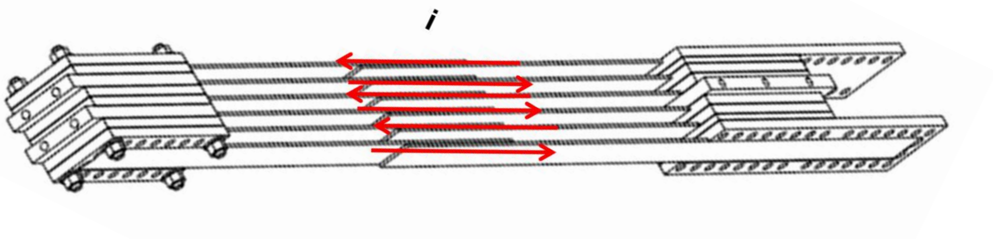
After heat treatment

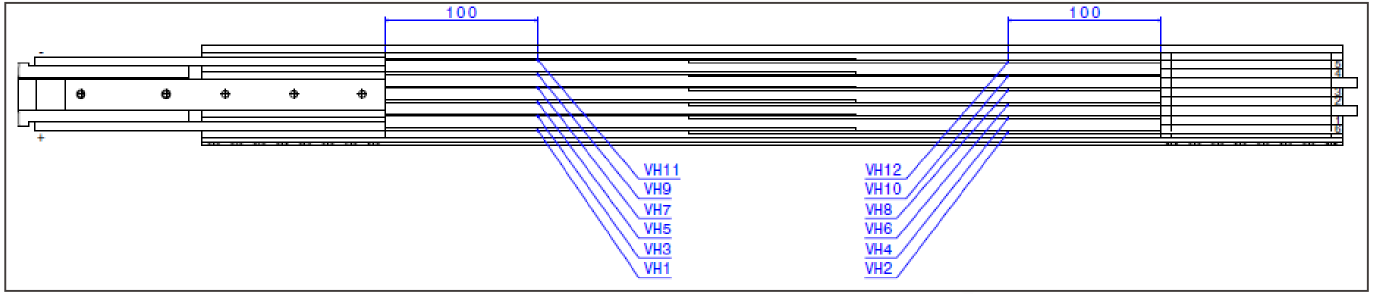


During soldering

High field and current splices – soldered splices (II)

- Two SULTAN campaigns, stack of 6 impregnated straight overlap splices per campaign.
  1. Study on R vs splice length, R vs steel core
  2. Study on reproducibility: 6 identical splices





Voltage drop measured for the 6 splices and 7 copper indium terminations

High field and current splices – soldered splices (III)

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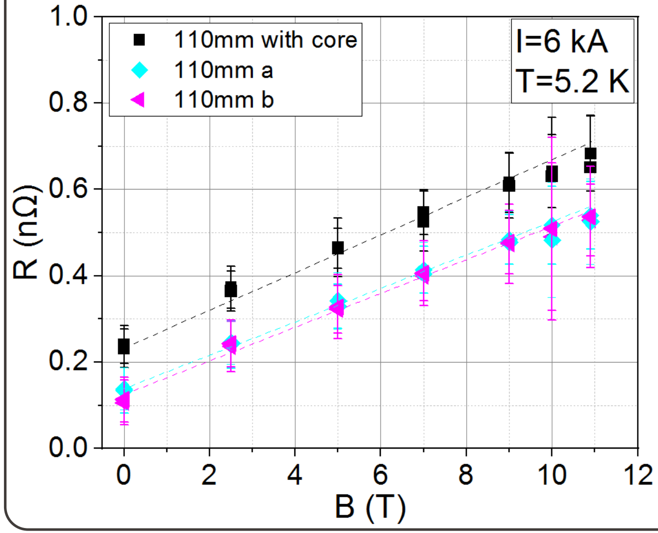
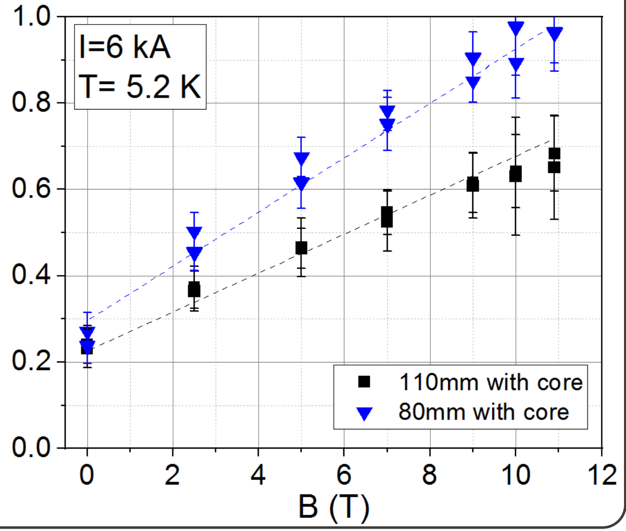
- R_{joint} vs SS core → no core has 0.77 resistance of samples with core
- R_{joint} vs joint length → inversely proportional in range studied
- Reproducibility → 0.5 nΩ ≤ R_{joint} ≤ 0.6 nΩ

R_{joint} vs SS core

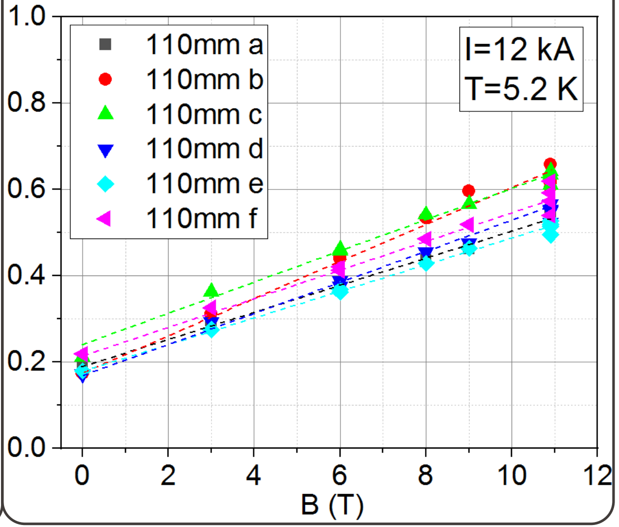


R_{joint} vs length



1st soldered SULTAN campaign

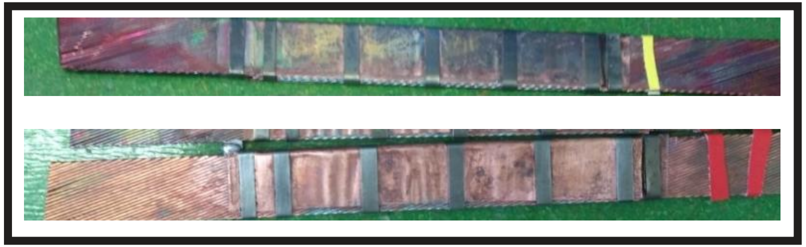
Reproducibility



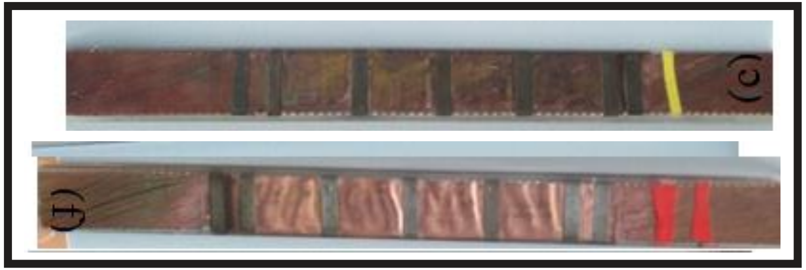
2nd soldered campaign

High field and current splices – soldered splices (IV)

- Solder penetration possible only with aggressive flux → solder flux residual may corrode the stabilizer → corrosion studies
- Soldering procedure repeated to different Cu dummy samples
- Green spots appear soon after soldering
- Samples are impregnated
- Samples monitored over one year: corrosion does not progress after impregnation



Samples after soldering



Samples after impregnation with araldite and after one year

High field and current splices – DB splices (I)

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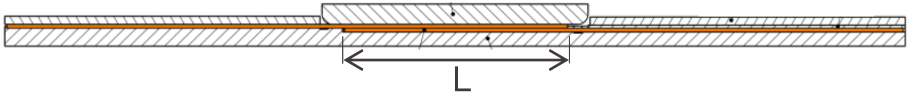
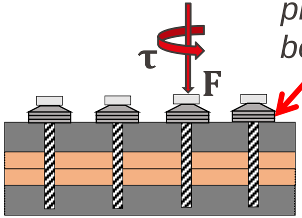
- Preliminary studies on straight joints:
  - Parametric analysis on pressure to apply at room temperature (5-14-35 MPa)
  - Same experimental set-up as for soldered splices
  - Splices between bare joints without steel core

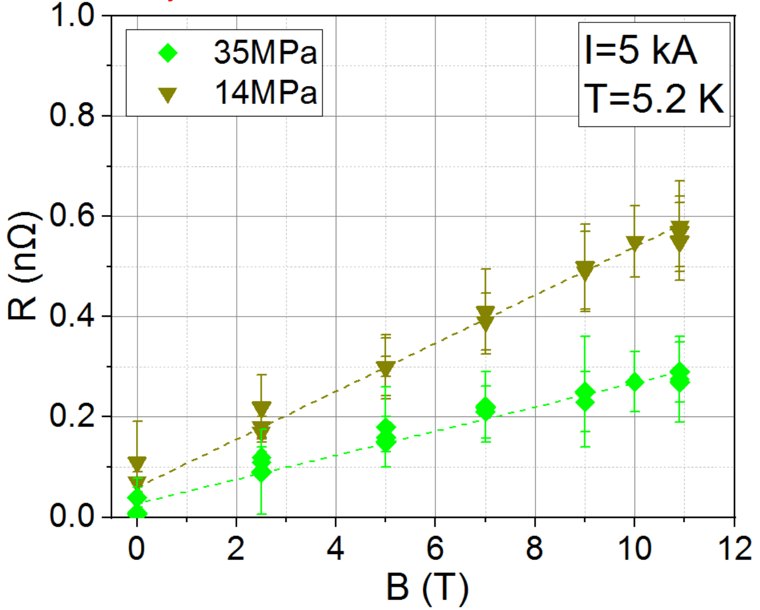




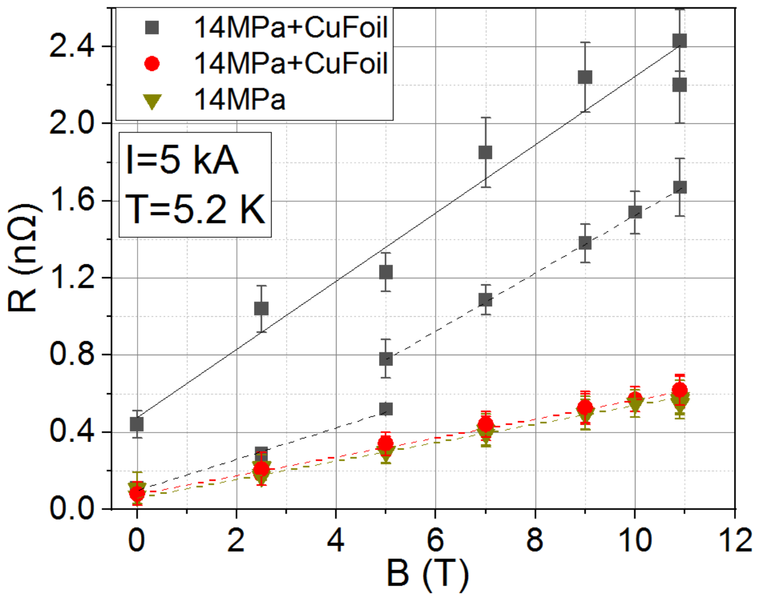
Conical disc springs for pressure relaxation between 20-650 °C

High field and current splices – DB splices (II)

R_{joint} vs pressure @ room T



Reproducibility

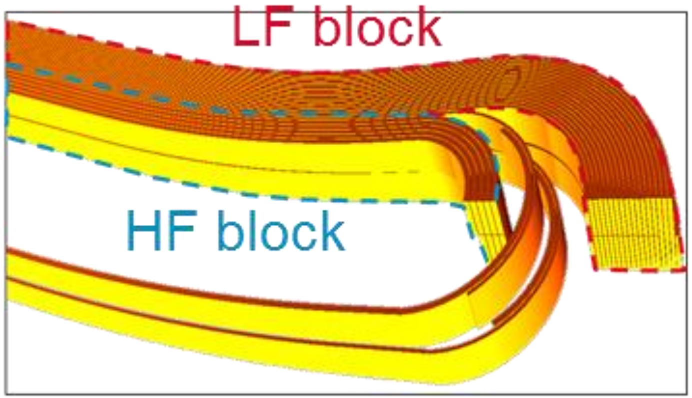


Conclusions:

- Target resistance achievable through DB
- No bonding if P<=5 MPa
- Reliable P≈30 MPa

High field and current splices – DB splices (III)

- U-bent splices
  - Geometry more relevant to dipoles (racetrack and block coils in particular)
  - Promising results with straight splices, without aggressive fluxes or any surface preparation → study of u-bent splices
  - R&D with cable SMC_11T:
    - strand diameter 0.7 mm
    - width 14.7 mm
    - thickness 1.26 mm
    - twist pitch 100 mm



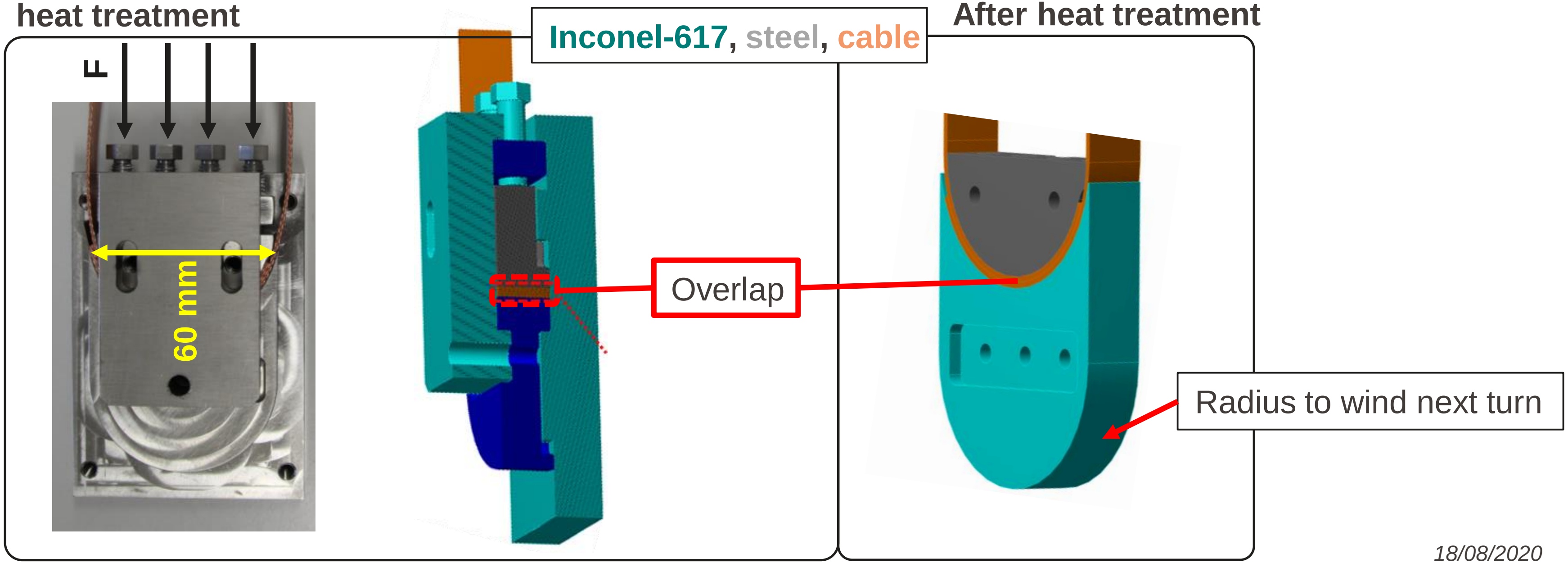
C. Lorin et al., IEEE, 2018

High field and current splices – DB bent splices (I)

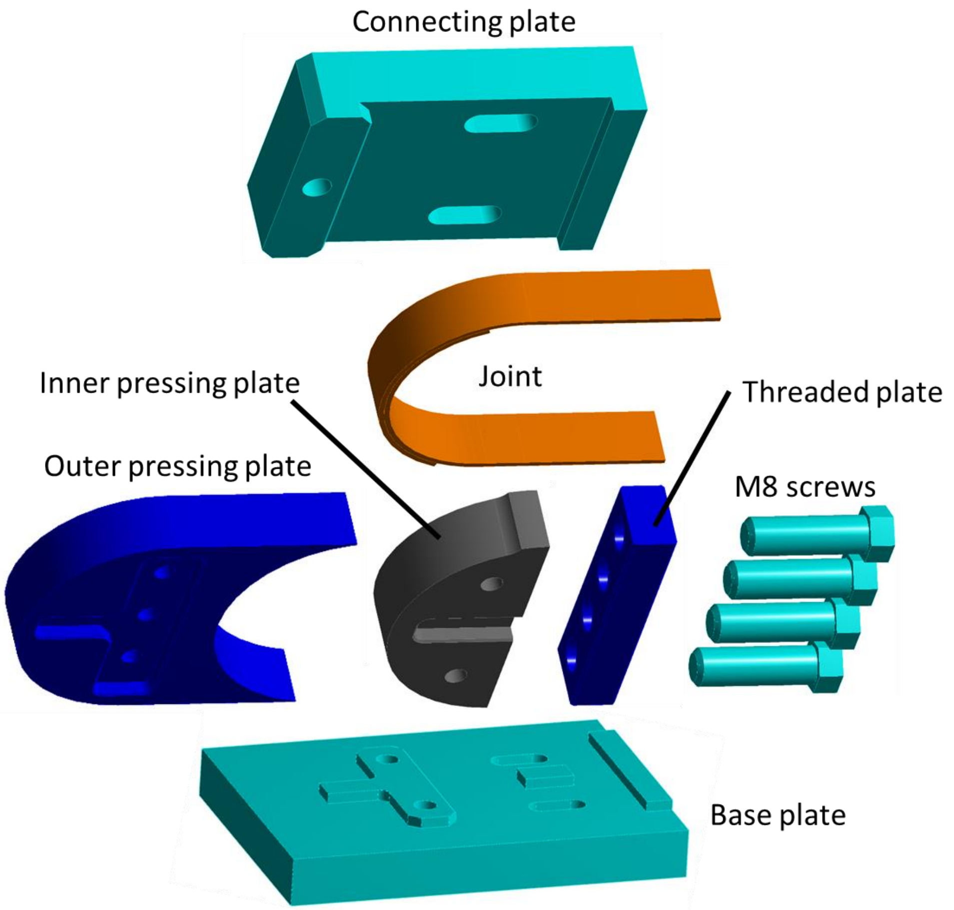
- Challenges:
  - Integration in the winding pack
  - Pressure uniformity: machining precision; combination of materials thermal expansion coefficient to increase P and uniformity with rising temperature
  - Accessibility after heat treatment for partial disassembly

During heat treatment

After heat treatment



High field and current splices – DB bent splices (II)



High field and current splices – DB bent splices (III)

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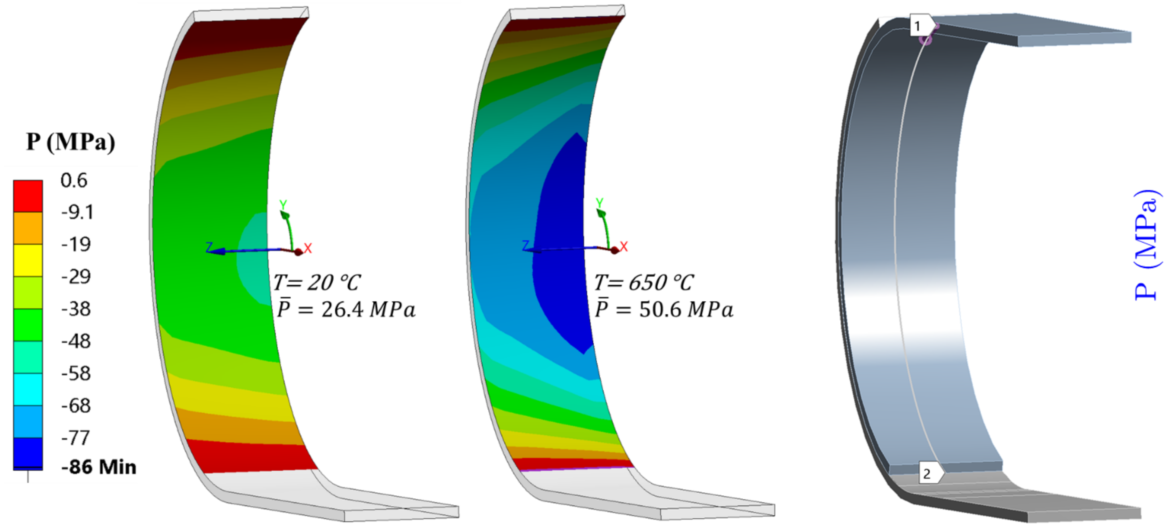
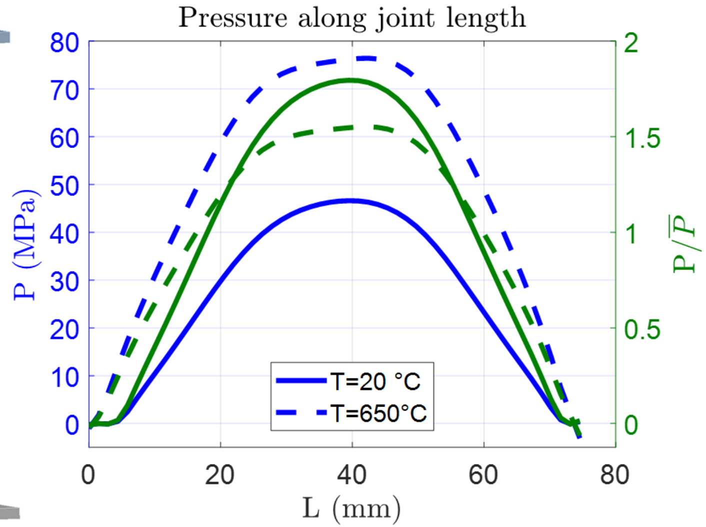
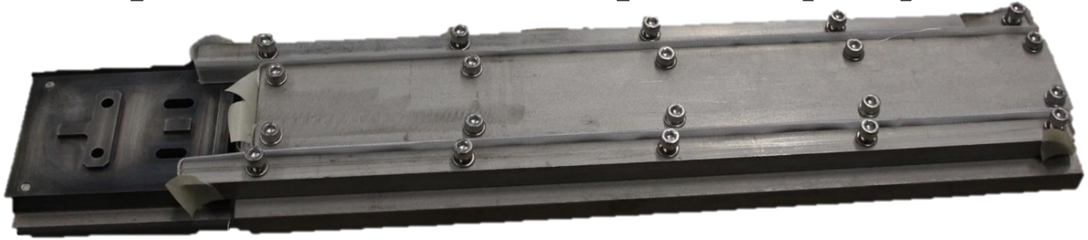
- Design based on pressure distribution
- Limitations:
  - Low pressure at the edges
  - Overlap length limited to 75% twist pitch for space limitations in cryostat

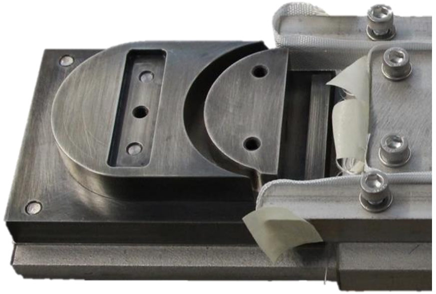


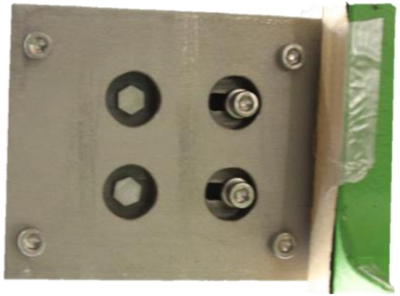


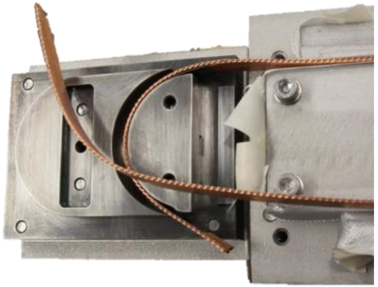
High field and current splices – DB bent splices (IV)

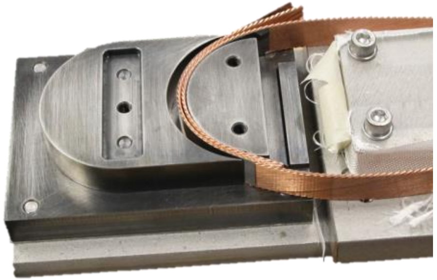
- Assembly for heat treatment

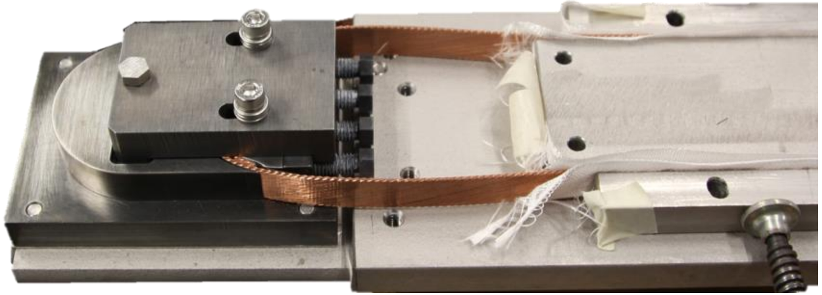






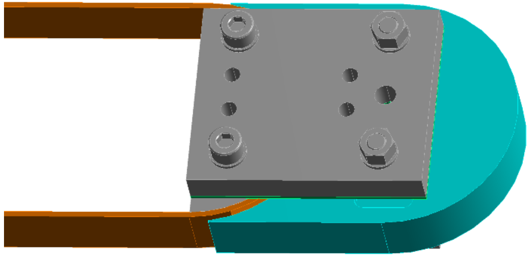


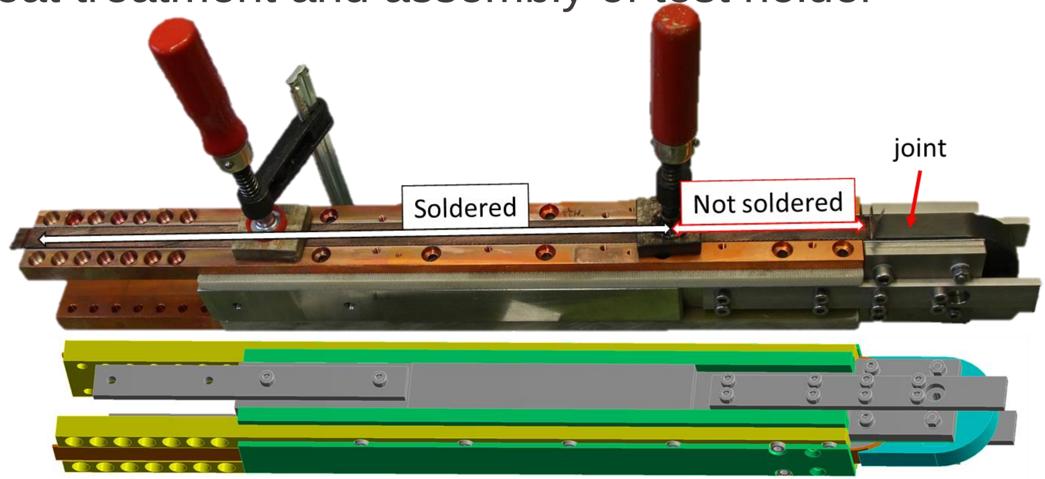


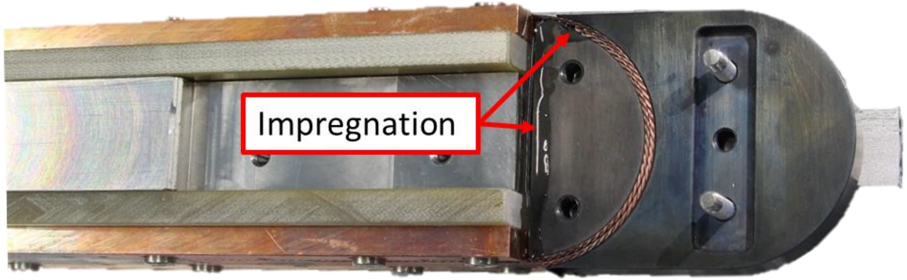


High field and current splices – DB bent splices (V)

- Partial disassembly after heat treatment and assembly of test holder

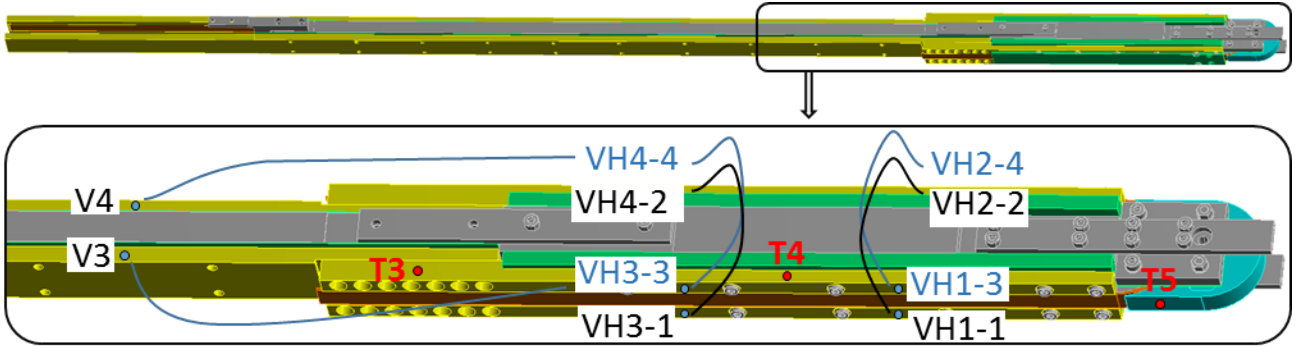


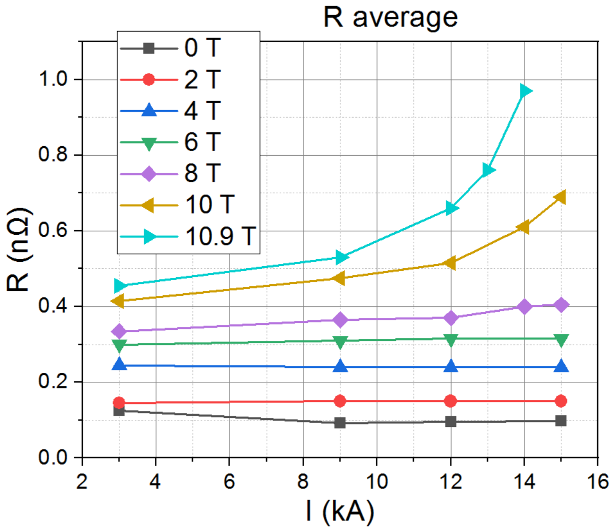


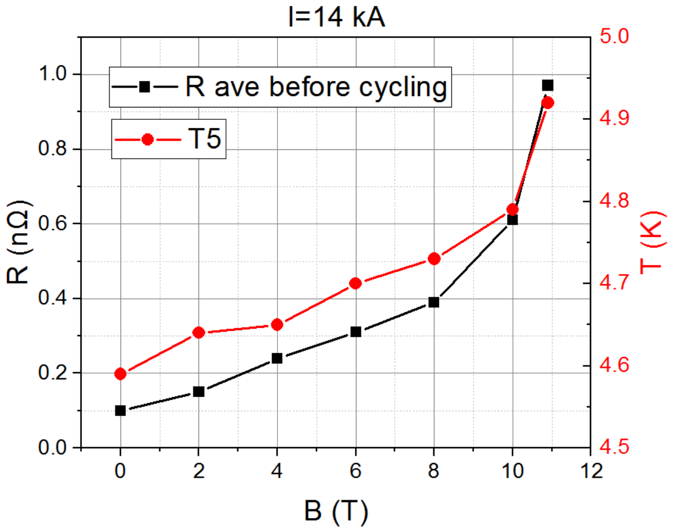


High field and current splices – DB bent splices (VI)

- Instrumentation and test
- $I/I_c \approx 61\%$



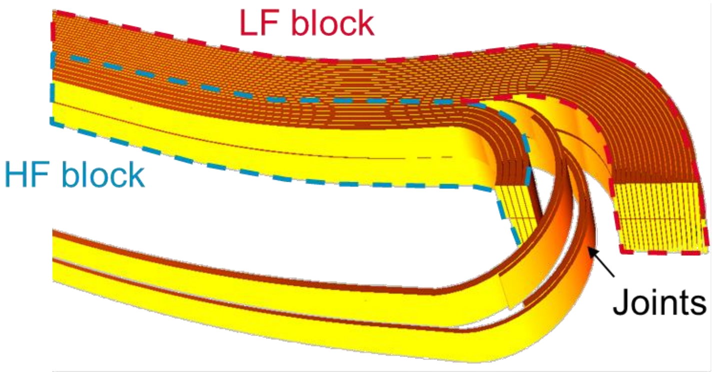




EPFL

DB bent splices, open questions

- The target resistance is reached also in bent geometry, but joint integration in a dipole is not demonstrated. Need to test a joint in a small insert coil
- Cable handling to make the overlap must be improved. Using spot-welded steel strips (as in soldered splices) could be an idea
- Joint insulation
- Integration in a real dipole means managing two joints with one clamp (in CEA block coil, High Field double pancake with two Low Field single pancakes)



Courtesy C. Lorin

Summary and conclusions

- The next generation of accelerator magnets foresees intensive use of Nb_3Sn as superconductor
- Disregarding the winding layout, the magnet must be graded to make the costs affordable
- An internal joint would allow to avoid lead extensions and limit mechanical discontinuity
- Three splicing techniques were investigated and the most promising, soldering and diffusion bonding, were electrically characterized at high field and current in the SULTAN test facility
- The developed test setup allows the test of stack of straight joints, single bent joints and small insert coil (also with internal joint)