HFM

High Field Magnets
Programme

WP 3.4
Nb_3Sn Magnet Technology Development Program (TDP)

Author: Ariel Haziot

Date: 19.09.2024

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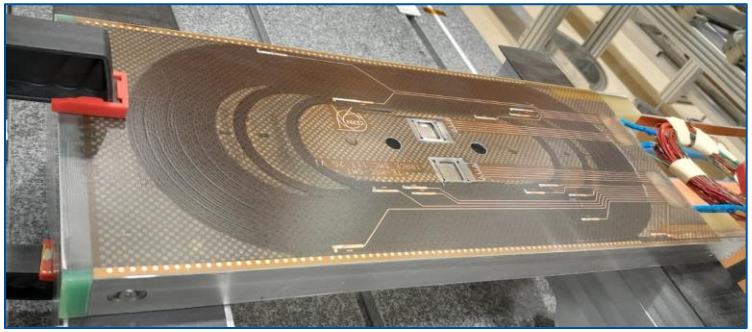
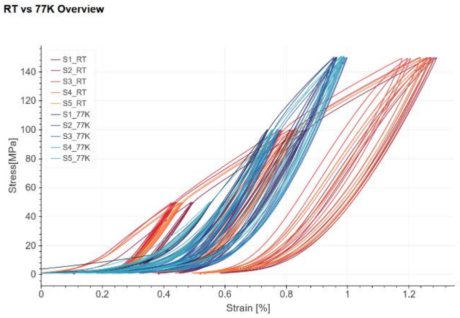
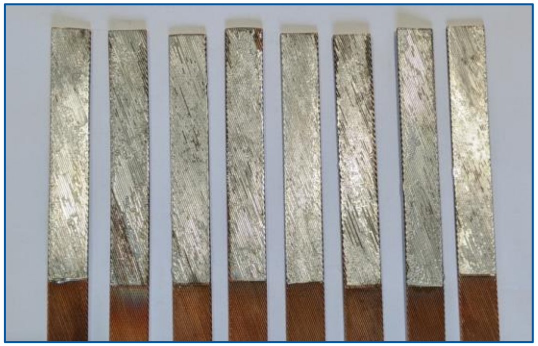


Quadrupole short model program (MQXFS)

Thermomechanical properties of coil composite material



Nb_3Sn/Nb_3Sn electrical connection - Splice



Racetrack magnets development program (SMC)

Racetrack magnets program (SMC)

Description of the scope

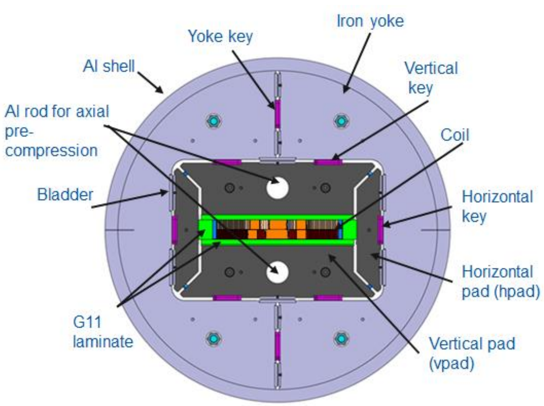
The Short Model Coil (SMC) assembly has been designed as a test bench for short racetrack coils wound with Nb_3Sn cable.

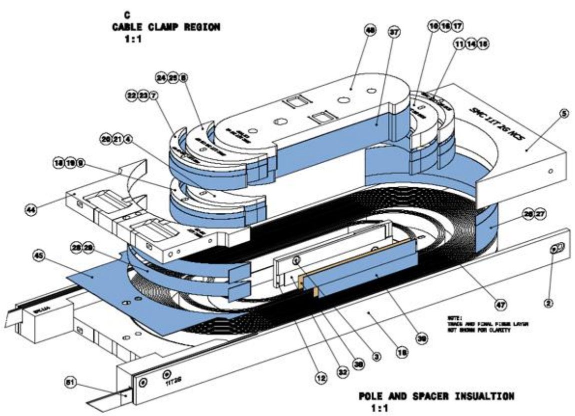
- A double pancake racetrack coil.
- An assembly relying on a bladder and key structure and hosting 1 coil.

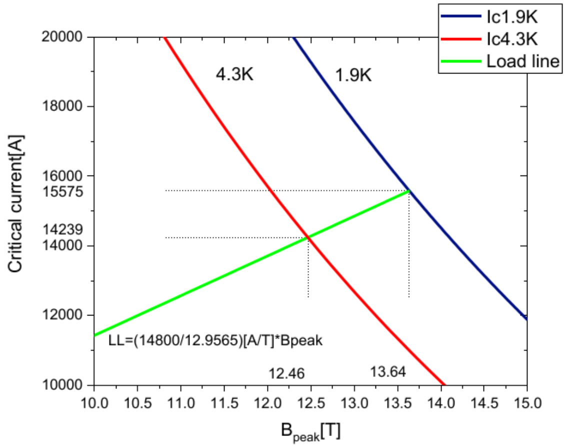
The SMC program led by J.C. Perez since 2009 now enters the TDP.

The SMC 11T 2nd Generation features:

- A conductor with 40x0.7 mm Nb_3Sn strands
- A layer jump in the straight section







Main persons involved:
J. Ferradas Troitino, J. Feuvrier, M. Guinchard, T. Mulders, J.C. Perez, E. Ravaioli, G. Willering, 927 and SM18 teams

Racetrack magnets program (SMC)

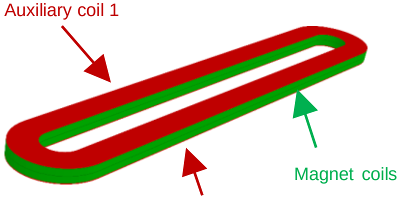
Goals of the program

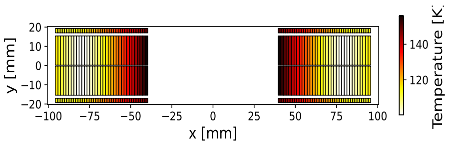
The main objective of the program is to explore the influence of different variables:

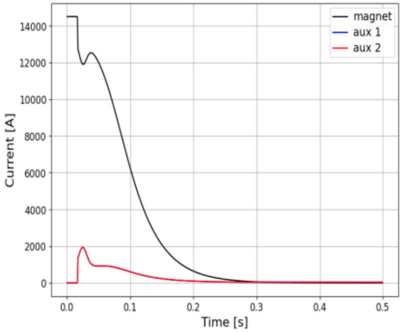
- the impregnation system
- the adhesion condition
- the conductor
- the electrical insulation

The SMC program is also used as a test bench for new magnet protection systems.
(in collaboration with WP4.5)

ESC (Energy Shift with Coupling)

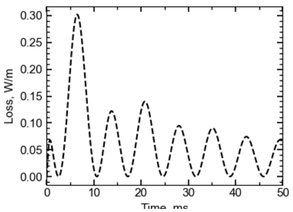


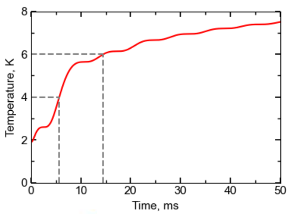


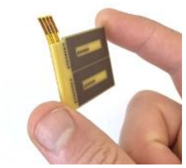


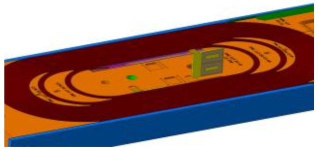
https://indico.cern.ch/event/1321217/
Courtesy to E. Ravaioli

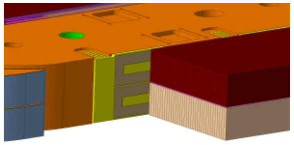
E-CLIQ











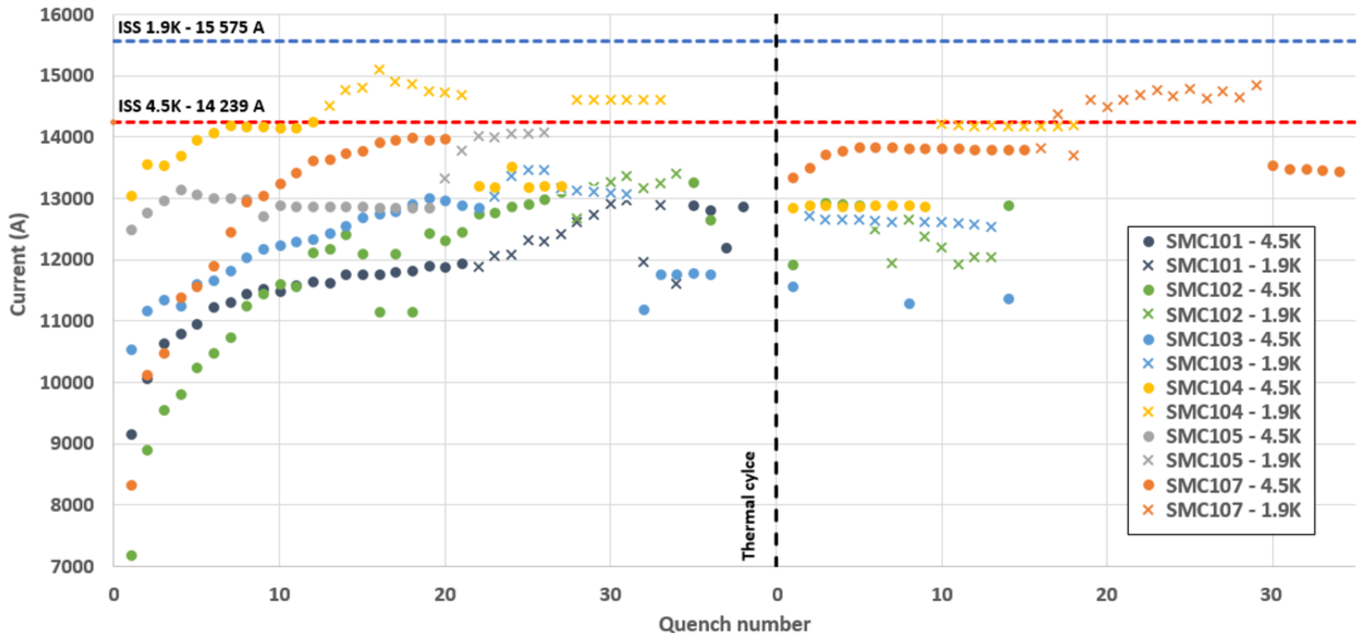
Courtesy of T. Mulder

Racetrack magnets program (SMC)

Overview of the results from SMC 11T 2nd Generation

- 6 SMC 11T 2G have been tested in 2 years.
- All coils exhibit a current limitation, and a weak point located in the layer jump.
- Tomography studies seems to confirm a degradation of the cable in the area.
- It is difficult then to pronounce any strong conclusion on the influence of the resin.
- The layer jump area has been modified since.

Name	Impregnation	Comment	Status
SMC2G-101	CTD-101K		Tested: 11.2022
SMC2G-102	MY750		Tested: 02.2023
SMC2G-103b	Mix61 (NHMFL)	Tomography	Tested: 07.2023
SMC2G-104	MY740 (MSU)		Tested: 10.2023
SMC2G-105	CTD-101K	Removable pole	Tested: 01.2024
SMC2G-106	(to be selected)	Removable pole	Not built yet
SMC2G-107	CTD-101K + DY040 (Polab)	CIEMAT training	Tested: 06.2024



Racetrack magnets program (SMC)

Coming next on SMC 11T 2nd Generation

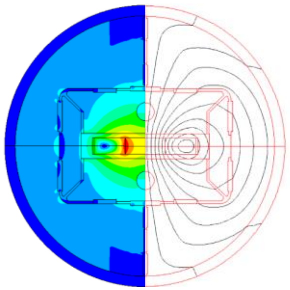
- Test of #107b (Q4 2024)
  - ESC coils
- Test of #108 and #109 (Q1 2025)
  - Modified layer jump
  - E-CLIQ
- Assembly of #110 (Q1 2025)
  - New layer jump geometry
  - Possibly impregnated with filled wax (collaboration with WP4.3)
- Assembly of #106 (Q2 2025)
  - New layer jump geometry
  - Best impregnation system
  - Removable pole
- Test of #110 and #106 (Q2 2025)

Name	Impregnation	Comment	Status
SMC2G-101	CTD-101K		Tested: 11.2022
SMC2G-102	MY750		Tested: 02.2023
SMC2G-103b	Mix61 (NHMFL)	Tomography	Tested: 07.2023
SMC2G-104	MY740 (MSU)		Tested: 10.2023
SMC2G-105	CTD-101K	Removable pole	Tested: 01.2024
SMC2G-106	(to be selected)	Removable pole	Not built yet
SMC2G-107	CTD-101K + DY040 (Polab)	CIEMAT training	Tested: 06.2024
SMC2G-107b	CTD-101K + DY040 (Polab)	ESC coils	Assembled: 10.2024
SMC2G-108	CTD-101K + DY040 (Polab)	E-CLIQ & Mod. layer Jump	Impregnated: 07.2024
SMC2G-109	CTD-101K + DY040 (Polab)	E-CLIQ & Mod. layer Jump	Impregnated: 08.2024
SMC2G-110	Possibly filled wax (WP4.3)	E-CLIQ & New layer Jump	Not build yet

No more 11T cable length are available for building more SMC 2nd generation after that.

Racetrack magnets program (SMC)

Coming soon: SMC_MQXF (3rd Generation)



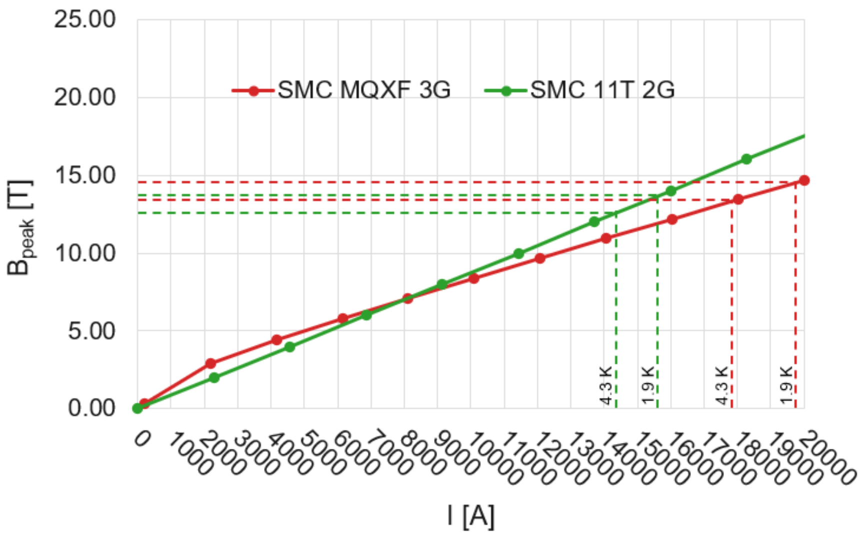
A new SMC coil using available MQXF strand has been proposed by J.C. Perez:

- It is compatible with the tooling we have today (used for SMC 11T 2G)
- It can be assembled in the 2 SMC structures we have

Cable		2nd Gen.	3rd Gen.
No. strand		40	32
Strand diam.	[mm]	0.700	0.850
Cu/NonCu		1.2	1.0
Bare cable thickness (R)	[mm]	1.31	1.59
Bare cable width (R)	[mm]	14.89	14.88

Coil		2nd Gen.	3rd Gen.
No. of turns per pole		35	31
Number of layer		2	2

Magnet		2nd Gen.	3rd Gen.
Short sample current (4.3K)	[kA]	14.24	17.84
Short sample current (1.9K)	[kA]	15.58	19.80
Short sample Field (4.3K)	[T]	12.46	13.30
Short sample Field (1.9K)	[T]	13.64	14.53



- Design completed in September 2024
- New parts procured for Q4 2024
- 1st coil for Q1/Q2 2025

The test program for this new SMC generation is under discussion.

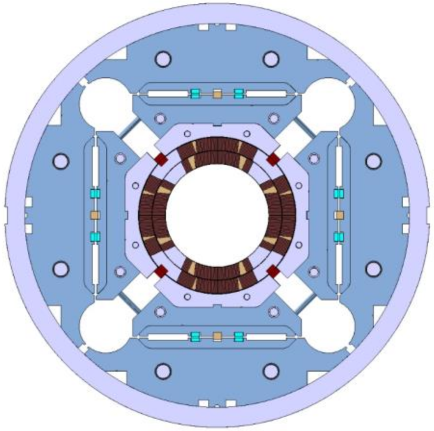
Quadrupole short model program (MQXFS)

Quadrupole short model program (MQXFS)

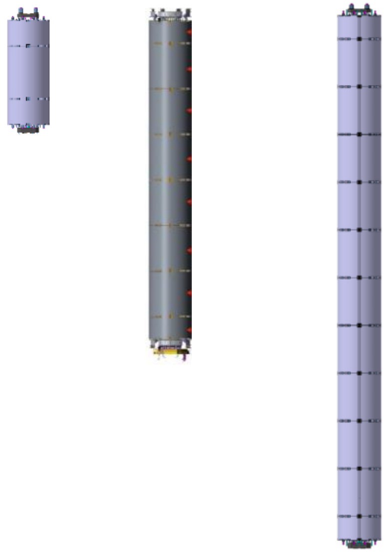
Description of the scope

The quadrupole short model (MQXFS) is a 1.2-m long magnet with the same design as MQXFA/MQXFB, and very similar manufacturing and assembly procedure.

- Initially, used for design and parameter validation
- Then, used as a tool to validate new measures implemented in full length magnets
- Now, used for technological studies



MQXFS (1.2 m) MQXFA (4.2 m) MQXFB (7.2 m)



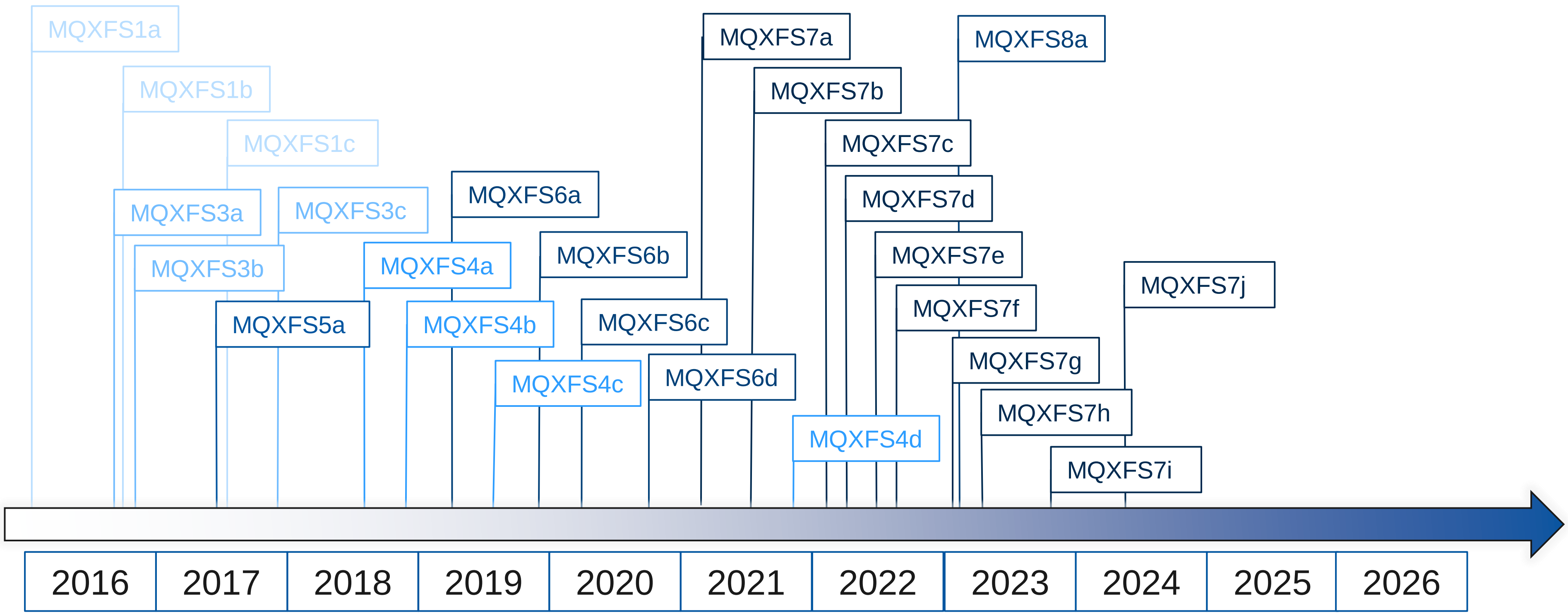
Main persons involved:
S. Izquierdo Bermudez, R. Diaz Vez, P. Ferracin, J. Ferradas Troitino, S. Ferradas Troitino, J. Feuvrier, L. Fiscarelli, M. Guinchard, F.J. Mangiarotti, J.C. Perez, P. Quassolo, E. Ravaioli, P. Rogacki, E. Todesco, G. Willering, M. Wozniak, 927 and SM18 teams

Quadrupole short model program (MQXFS)

Overview of MQXFS

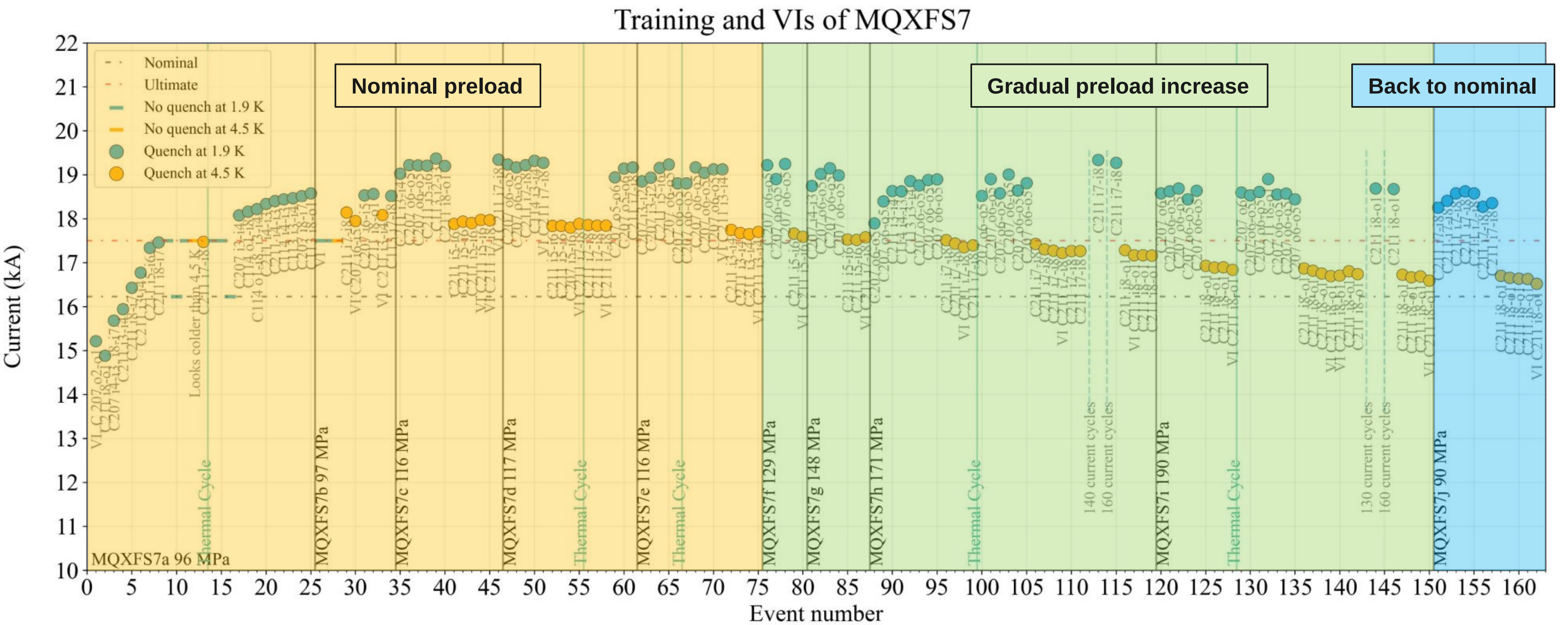
Since the first tests of MQXFS1 at Fermilab in 2016:

- 7 magnets fabricated and tested
- 27 coils tested
- 4 different conductors
- 11 pre-load configurations
- 2 test stations commissioned at CERN
- 2 beam screens tested
- 4 protection systems tested



Quadrupole short model program (MQXFS)

MQXFS7: 2 RRP coils and 2 PIT coils tested at stresses up to 190 MPa



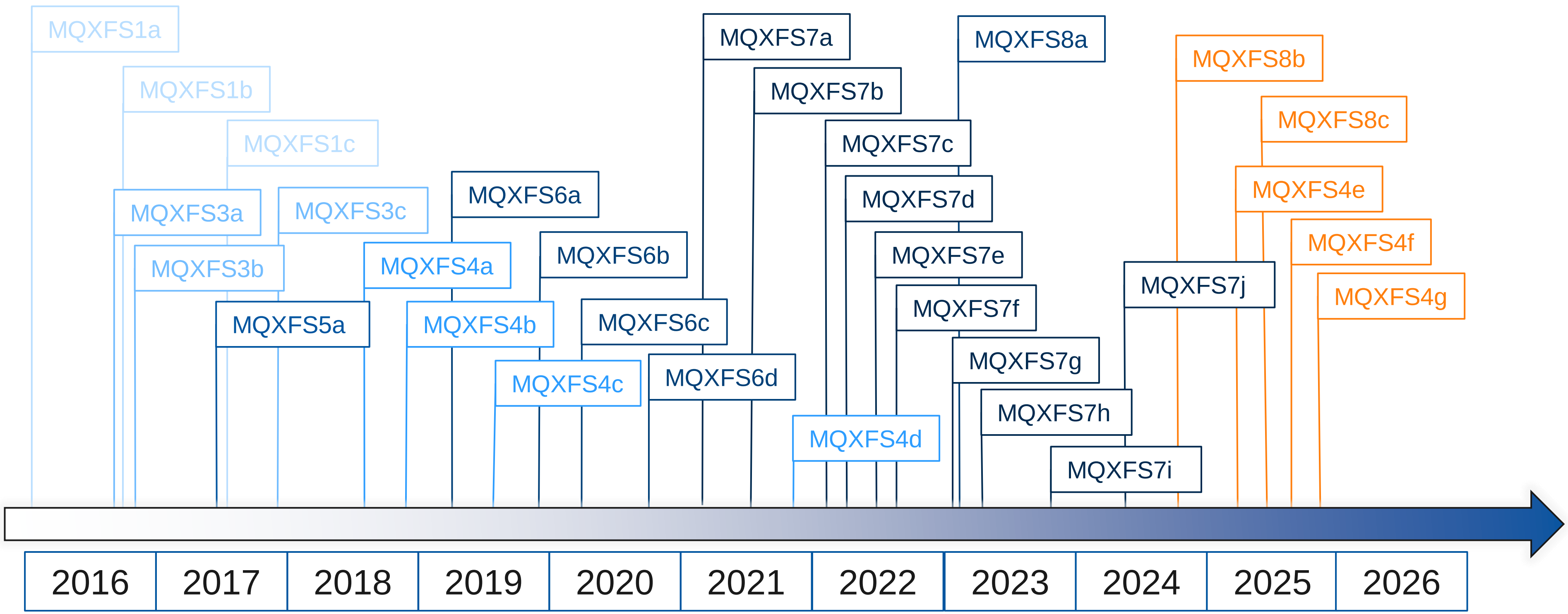
- No degradation observed in the RRP coils up to 190 MPa up to 85% of I_{ss}.
- The quench limitation was on the PIT coil with bundle barrier, and located in the pole turn (HF region).
- The induced degradation at 190 MPa is permanent.
- At high pre-stress levels (170-190 MPa), the performance of the magnet reduces after thermal cycles.

See presentation given at ASC-24 and article to be published by F.J. Mangiarotti *et al.*

Quadrupole short model program (MQXFS)

Coming next on MQXFS

- Re-assembly of MQXFS4 to test the stress limit on 4 RRP Nb_3Sn coils
  - Similar campaign as MQXFS7
  - Fast iteration using experience from MQXFS7
- Iterations on MQXFS8, toward lower axial pre-load and possibly azimuthal
  - Investigate the role of axial pre-load and the inter-play between axial and azimuthal
- Test of ESC (Energy Shift with Coupling) on MQXFS 4/8 depending on timeline
  - New collar sets will be procured, and secondary copper coils will be manufacture at 927



Thermomechanical properties of coil composite material

Properties of coil composite material

Description of the scope

Context: Degradation occurs in some Nb_3Sn magnets at computed stress below the "limit", some other work at computed stress higher than the "limit" (e.g. 11T can degrade at simulated 60 MPa, RMM can work at simulated 200 MPa).

Non exhaustive list of unsolved questions in a general context

- More accurate definition of the stress limit on conductor (3D)
- Model and experimental data are not in phase during cooldown and requires fine tuning (loss of prestress at cold)
- Local structural effect (peak stresses)
- Stress during reaction

Our objectives:

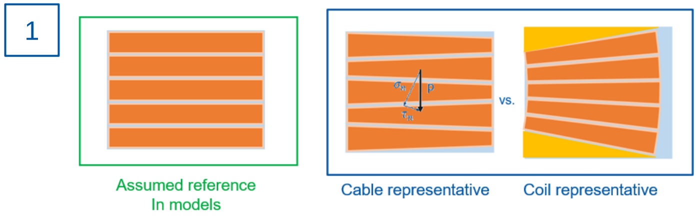
- Provide harmonized and model adapted experimental data for the coil pack (ID card for each coil)
- Explore and investigate the impact of different parameters:
  - Resin fraction and the use of new fiberglass layout (in collaboration with WP4.3)
  - Conditions during the reaction cycle (in collaboration with WP4.2)
  - …

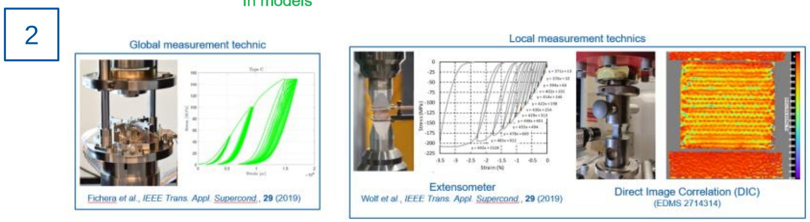
Main persons involved:
E. Fernandez Mora, O. Sacristian, 927 team

Properties of coil composite material

Thermomechanical properties measured on 10-stack samples

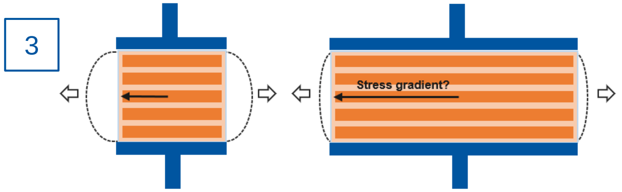
10-stack samples are used to extract mechanical properties. However, there exist no standard and no harmonized database.





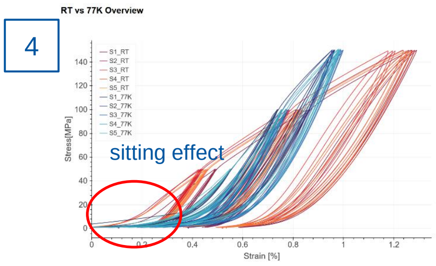
Phase 1: Solve questions towards standardization

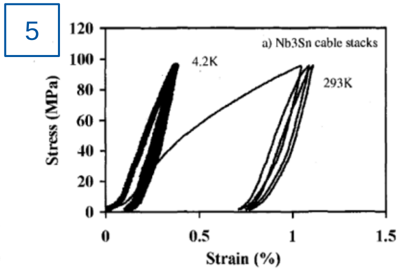
1. Relevant sample configuration?
2. Stress/strain measurements methods: global vs local?
3. Influence of sample's length?
4. Effect of contact surfaces?
5. Load effect on CTE?



Phase 2: Only then…

- Characterize and compare 10-stack samples of different cables
- Investigate impact of resin fraction, use of new fiber
- Investigate conditions during reaction
- …





M. Reytier *et al.*, *IEEE Trans. Appl. Supercond.*, **11** (2001)

Properties of coil composite material

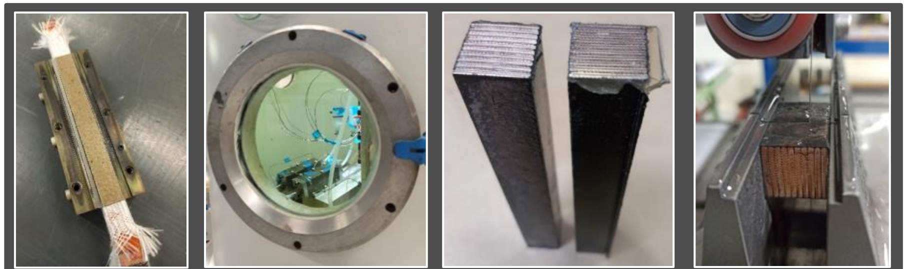
Thermomechanical properties measured on 10-stack samples

1st campaign

- Validate fabrication reproducibility
- Validate measurement reproducibility
- Start to answer some questions (local vs global, length,…)

Sample preparation

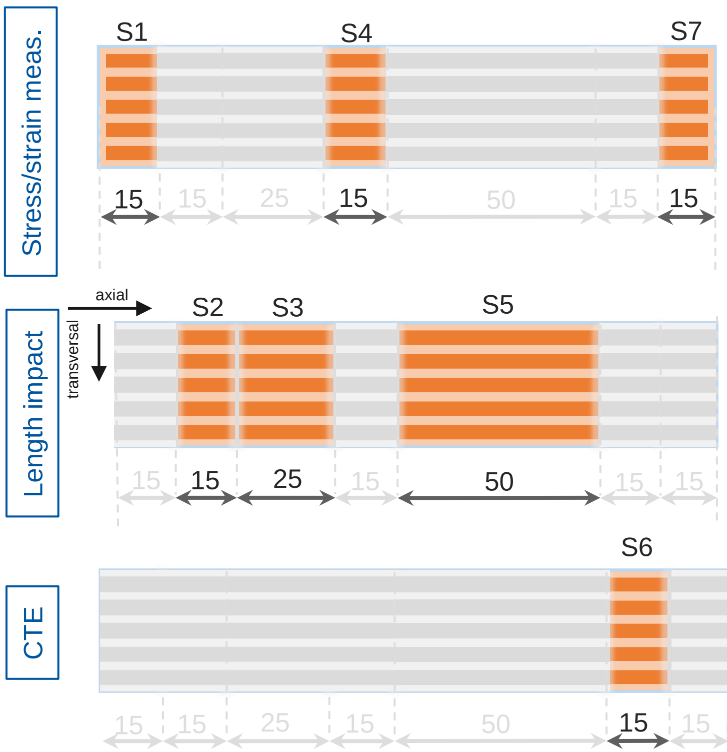
- Study case: Flat MQXF cable
- 3x 150 mm long samples were manufactured



HT preparation | Impregnation | Impregnated samples | Cutting samples

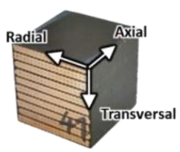
Tests ongoing. Results at the end of September 2024

Tests to be performed on each samples



Test plan for next year

- Measure samples with keystone (Q4 2024)
- Repeat measurements at 77K (newly commissioned optical cryostat) (Q1 2025)
- Study samples with different boundary conditions during reaction (Q2 2025)
- Study effect of contact surface, toward a coil representative stack (Q2 2025)

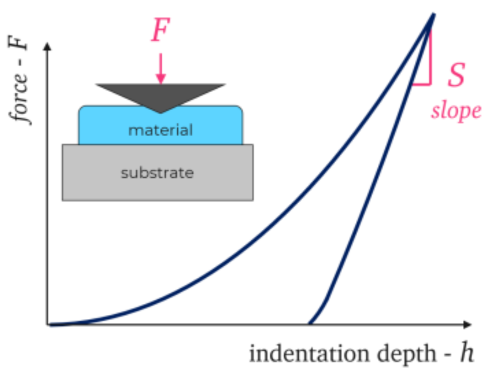


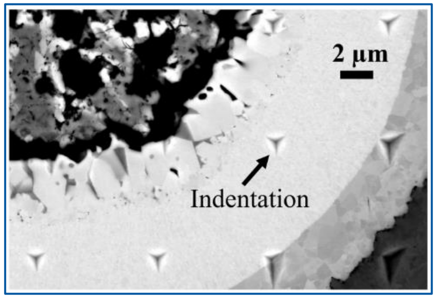
Properties of coil composite material

Perspective work: other methods of characterization

Use innovative characterization methods to extract independent mechanical properties of each material in the cable at the microscopical level.

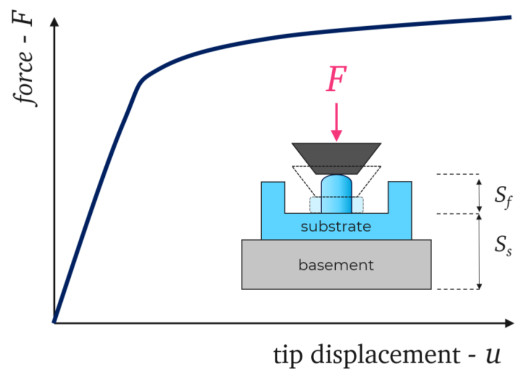
Nano indentation
Elastic modulus

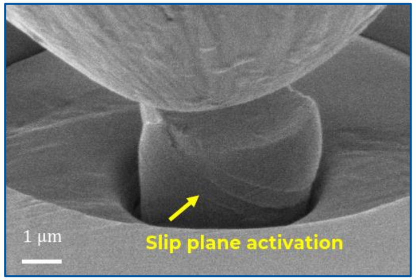




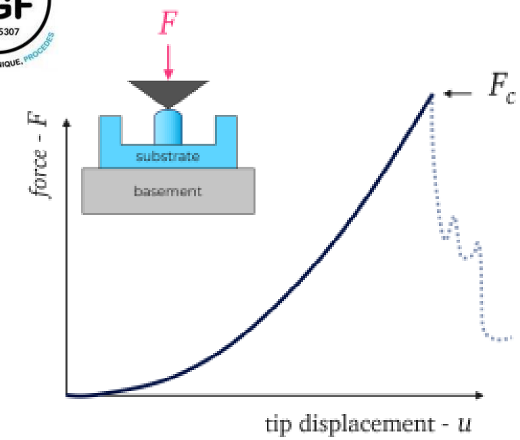
G. Lenoir et al., IEEE Trans. Appl. Supercond., **5** (2019)

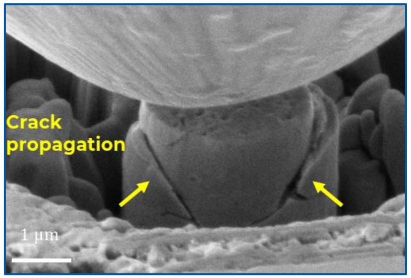
Micropillar compression
stress/strain curves

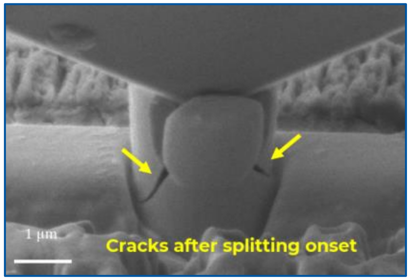




Micropillar splitting
fracture toughness







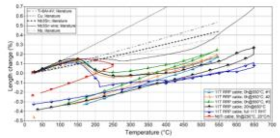
Courtesy of G. Vernassa, *ASC 2024*

Properties of coil composite material

A working group dedicated to the coil composite material study

Working group objectives:
- Connect people of different institutes within HFM
- Harmonized methods and data analysis
- Build a common database of references and data

https://hfm.web.cern.ch/hfm-working-groups

CERN / CEA
Mechanical characterization and model for heat treatment

UNIVERSITÉ DE GENÈVE

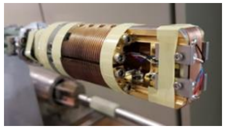
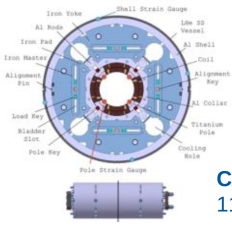
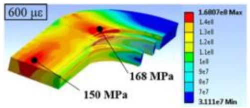


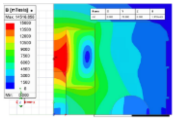
CHART WireChar
Mechanical limits of Nb_3Sn wires and Mechanisms behind critical current degradation

CERN Magnet programs
11T, MQXF, SMC

Ciemat

CIEMAT ISAAC program
Asses mechanical issues in Common coil



Coil composite loop: From strand to magnet

Predict/validate mechanical effects of **heat treatment**

Predict/validate **strand** performance under stress

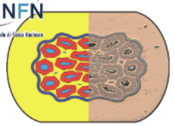
Predict/validate **cable** performance under stress

Predict/validate mechanical behavior of **cable stacks**

Implementation in 2D/3D **magnet models**

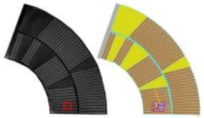
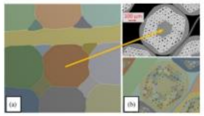
Validation on magnets

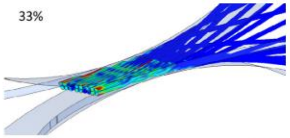
INFN



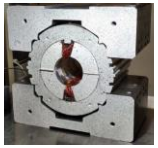
CERN / INFN / UNIGE
Model for strand deformation under stress

CERN - 11T / MQXF design

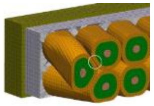





CERN / CEA / PSI
Cabling simulations



CERN
Methodology for testing and modelling

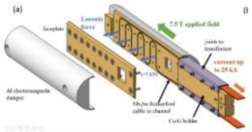


CEA Cocascope
Multiscale models

cea irfu

CERN
Thermomechanical characterization of 10-stacks

CHART MagComp
Mechanical Modelling and Failure identification of impregnated Nb3Sn Rutherford cable stacks



PAUL SCHERRER INSTITUT PSI

PSI – Box program
Assess degradation and training in cables

Nb_3Sn/Nb_3Sn electrical connection
- Splice -

Nb_3Sn/ Nb_3Sn electrical connection

Description of the scope

Development of the splice technology for Nb_3Sn cables, suitable for high field and integrating the constraints inherent to this superconductor technology.

Outcomes:

- Possibility of independent layers with internal connection
- Possibility of graded coils with internal splice

Challenges:

- Compliance with the manufacturing steps: heat treatment, impregnation,…
- Specialized tooling and tight spaces in the splicing area

A research plan in 3 phases:

1. Initial assessment of splicing process – On going
2. Process feasibility assessment and qualification – On going
3. Performance validation in high field - Coming

Main persons involved:
E. Fernandez Mora, V. Ilardi, K. Lazaridou, R. Piccin, 927 team

Nb_3Sn/ Nb_3Sn electrical connection

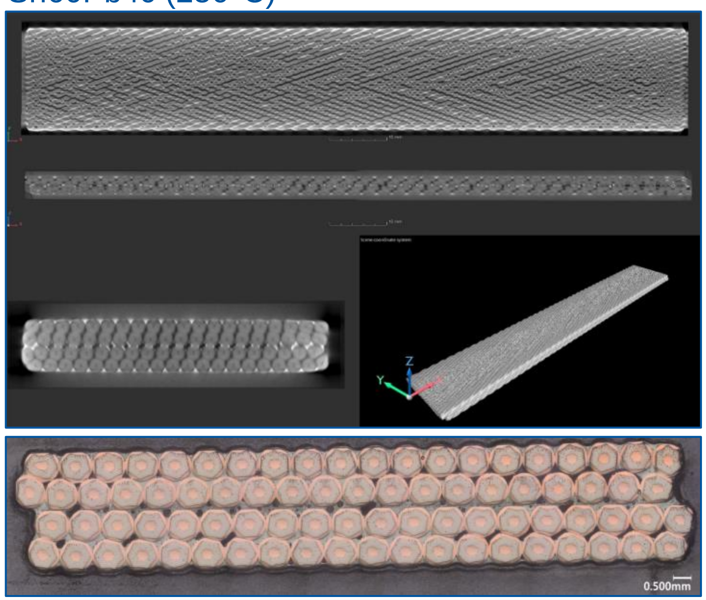
Phase 1: Initial assessment of splicing process – Solder analysis

Goal: Evaluate different soldering materials by assessing their wettability and melting temperature.

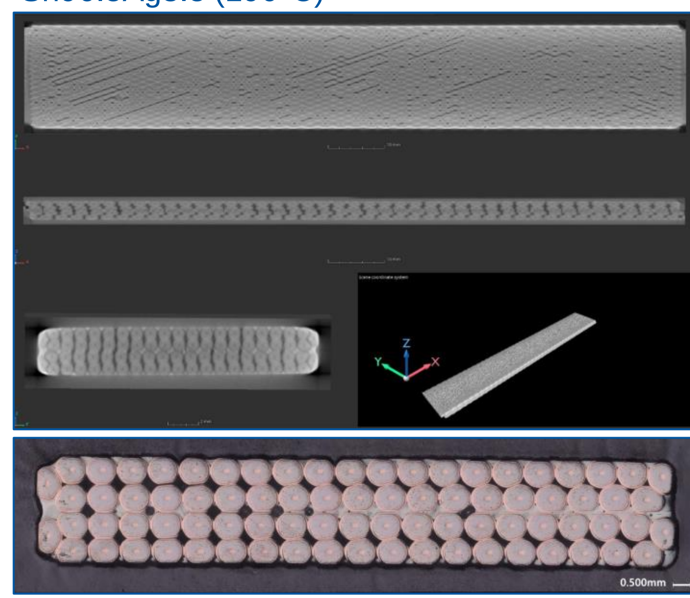
- Solder distribution analysis (tomography, metallography)

- Lead and silver based solders have been tested.
- Indium base solder to be explore further.

Sn60Pb40 (250°C)



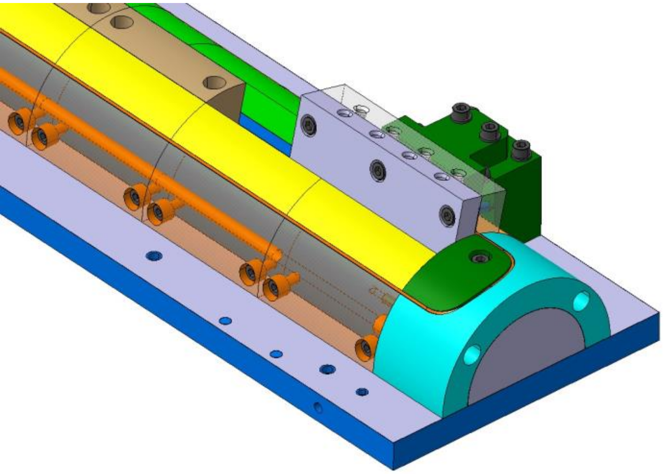
Sn96.5Ag3.5 (190°C)

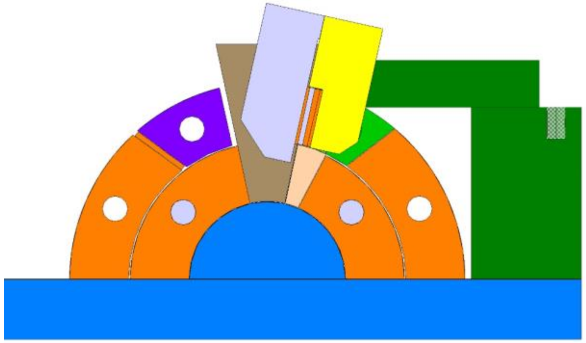


Nb_3Sn/ Nb_3Sn electrical connection

Phase 2: Process feasibility assessment and qualification – Mock-up of the splice area

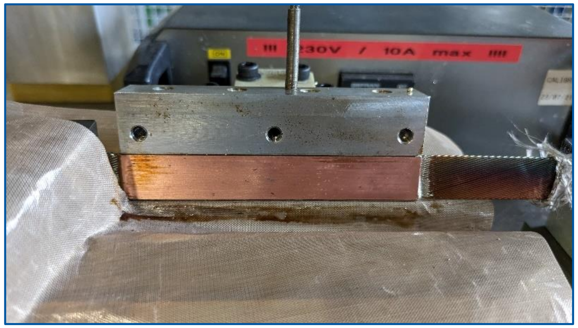
Goal: Develop specialized tooling and mock-ups to validate the feasibility of the splice in a particular environment specific to each project.





Courtesy of M. Canale

Mock-up developed in 2024 in the context of the 12T cos-theta magnet for internal splice between layers



Nb_3Sn/ Nb_3Sn electrical connection

Phase 3: Performance validation – Tests in FRESCA

Goal: Validate the splice performance by measuring the resistance at low temperature, and under high magnetic field.

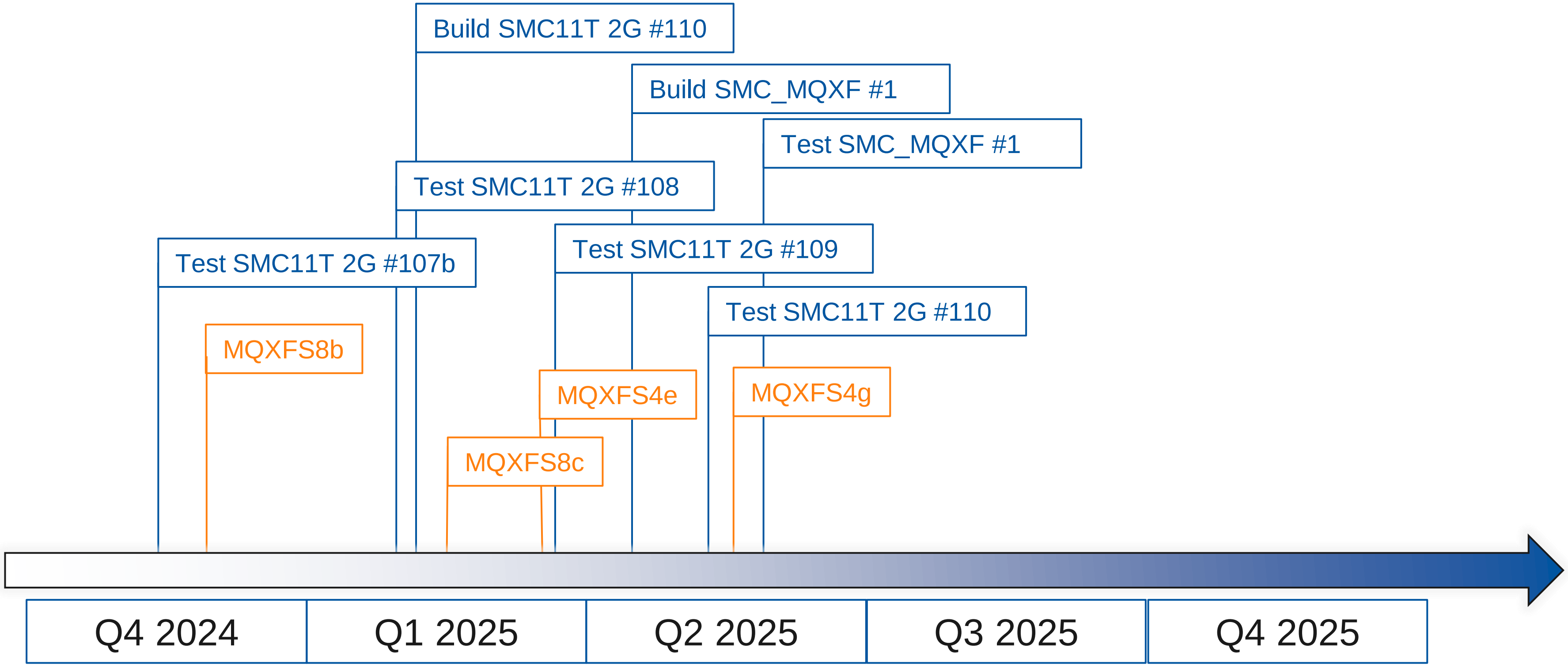
Tests to be carried in the FRESCA test station (and later FRESCA 2) at 9.7 T (or more):

- On a simpler praying hand configuration
  - Validate with experimental data the computed value
  - Test the impact of soldering length
  - Test the impact of reaction cycle
- Validate the quality of splices made with specific tooling representative of the manufacturing process

Firsts measurements to come in Q2 2025 after the commissioning of FRESCA 2.

HFM
High Field Magnets
Programme

Conclusion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Build SMC_MQXF #1
Test SMC_MQXF #1
Test SMC11T 2G #108
Test SMC11T 2G #109
Test SMC11T 2G #107b
Test SMC11T 2G #110
MQXFS8b
MQXFS4e
MQXFS4g
MQXFS8c
Q4 2024
Q1 2025
Q2 2025
Q3 2025
Q4 2025