HFM

High Field Magnets

HFM R&D at CERN - Plans and Achievements, Relevance to the Muon Collider

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with inputs from:

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cea

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CERN

UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES

Outline

- Organisational structure of HFM programme
- HFM R&D strategy and focus areas
- Selected latest developments from current work
- Key mid-term deliverables
- Summary

HFM programme foundations

- HFM programme builds on the past programmes, in particular vibrant bilateral collaborations established for the preparation of **conceptual designs of FCC-hh magnets** and within **EuroCirCol** (2015 – 2020)

- HFM programme is incorporating all ongoing collaborations related to the magnet technologies that were initiated as part of the FCC-hh study

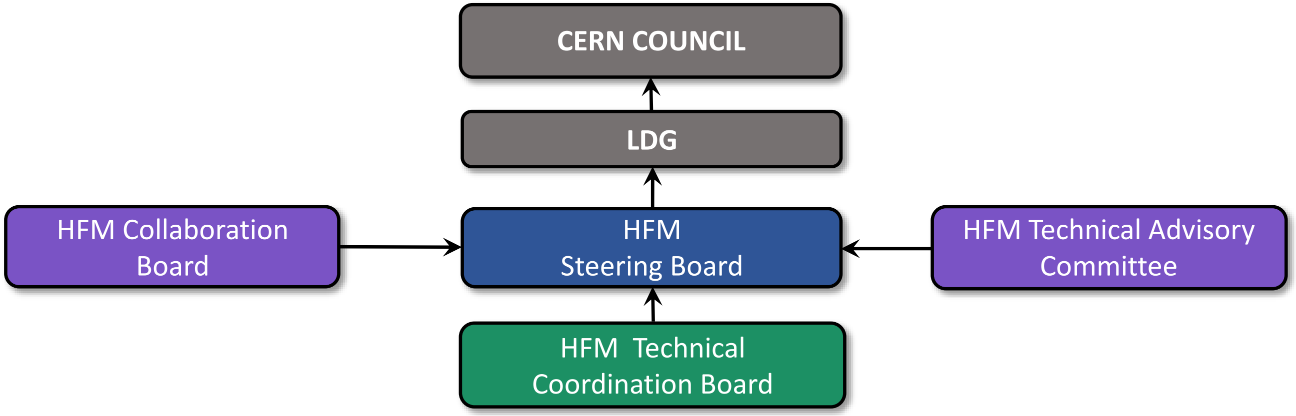
- Fostering and profiting from collaborations with **EU partners will be an essential part of the HFM programme** as well as linking to ongoing worldwide efforts, particularly in the **US and Japan**

- HFM programme is now being adapted to the **LDG roadmap** (arXiv:2201.07895v3 [physics.acc-ph])

Organisational structure

- The organizational structure comprises the following bodies:
  - HFM Programme **Governance**
    - HFM Steering Board
    - Collaboration Board
    - HFM Technical Advisory Committee
  - HFM Programme **Executive Structure**
    - HFM Technical Coordination Board
    - Project Office
    - Structure of R&D Lines with Work Package breakdown

HFM Governance Structure



Steering Board Members

Following input from LDG

Mike Lamont	**CERN**	Co-chair
Pierre Védrine	**CEA**	Co-chair
Chair of the Collaboration Board (to be elected)		
Bernhard Auchmann	**PSI**	
Bernhard Holzapfel	**KIT**	
Jose Manuel Perez	**CIEMAT**	
Lucio Rossi	**INFN**	
Jose Miguel Jimenez	**CERN**	TE DH
Michael Benedikt	**CERN**	FCC
Andrzej Siemko	**CERN**	Programme Leader

First kick-off meeting 25 August 2022

Collaboration Board Members

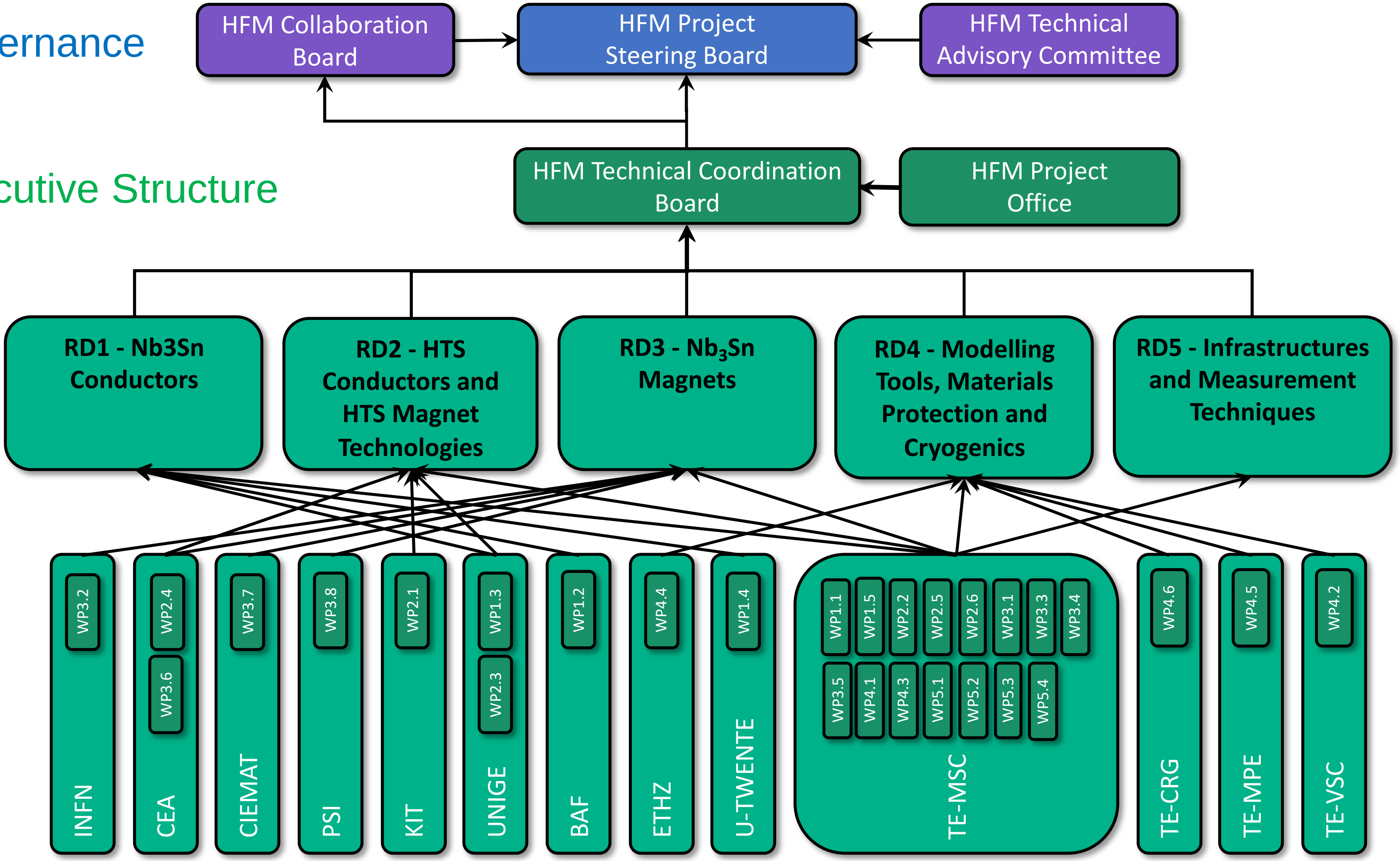
Bernhard Auchmann	**PSI**
Pierluigi Campana	**INFN**
Bernhard Holzapfel	**KIT**
Anna Kario	**U-Twente**
Jose Miguel Jimenez	**CERN**
Jonas Lachmann	**TU-Freiberg**
Jose Manuel Perez	**CIEMAT**
Philippe Rebourgeard	**CEA**
Carmine Senatore	**UNIGE**
Theo Tervoort	**ETHZ**
Andrzej Siemko	**CERN**

First kick-off meeting 13 Sept. 2022

HFM Programme Executive Structure

Governance

Executive Structure



HFM Collaboration Board

HFM Project Steering Board

HFM Technical Advisory Committee

HFM Technical Coordination Board

HFM Project Office

RD1 - Nb3Sn Conductors

RD2 - HTS Conductors and HTS Magnet Technologies

RD3 - Nb_3Sn Magnets

RD4 - Modelling Tools, Materials Protection and Cryogenics

RD5 - Infrastructures and Measurement Techniques

INFN: WP3.2

CEA: WP2.4, WP3.6

CIEMAT: WP3.7

PSI: WP3.8

KIT: WP2.1

UNIGE: WP1.3, WP2.3

BAF: WP1.2

ETHZ: WP4.4

U-TWENTE: WP1.4

TE-MSC: WP1.1, WP1.5, WP2.2, WP2.5, WP2.6, WP3.1, WP3.3, WP3.4, WP3.5, WP4.1, WP4.3, WP5.1, WP5.2, WP5.3, WP5.4

TE-CRG: WP4.6

TE-MPE: WP4.5

TE-VSC: WP4.2

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HFM Programme – broad goals

- The Accelerator LDG R&D Roadmap identifies two main objectives for the HFM programme:
  - The first is to demonstrate Nb_3Sn magnet technology for large-scale deployment. This will involve:
    - moving towards production scale through robust design, industrial manufacturing processes and cost reduction, taking as a reference the HL-LHC magnets, i.e., 12 T).
    - pushing the Nb_3Sn magnet technology to its practical limits in terms of ultimate performance (towards the 16 T target required by $FCC_{h\text{-}h}$)
  - The second objective is to demonstrate the suitability of high temperature superconductors (HTS) for accelerator magnet applications, providing a proof-of-principle of HTS magnet technology beyond the range of Nb_3Sn, with a target in excess of 20 T.

R&D Strategy and Focus Areas 1/3

R&D Line 1 Nb3Sn Conductor

- Present limitations linked to stress/strain sensitivity and degradation, to be overcome by
  - improved mechanical robustness
  - higher Jc (thus, increased margins)
- Industrialization of improved superconductors
- Otherwise, magnet structures must be adapted to deal with performance limitations in more realistic ways than FCC-hh CDR.

R&D Line 2: HTS Conductor and Magnet Technology

- Improve ReBCO conductor in view of accelerator requirements.
- Development of alternative HTS superconductors.
- Stand-alone demonstrator magnets.
- Subscale tests in background field and hybrid HFMs.

R&D Strategy and Focus Areas 2/3

R&D Line 3: Nb_3Sn Magnets

- 12 T Robust Nb_3Sn Magnets
  - Implement all lessons learned from LARP + HL-LHC
  - Demonstrate maturity of Nb3Sn technologies, including improved manufacturability and collaboration with industrial partners.
  - Reaching 14+T with this robust technology will be aided by improved mechanical robustness of conductor (see R&D Line 1)

- 14+T Feasibility Studies
  - Exploratory, multiple magnet-development of various magnet structures at CERN and national laboratories.
  - Approaches range from evolutionary, based on LARP/HL-LHC technology to departures from state-of-the-art.
  - From evolutionary to revolutionary:
    - cos theta (see 12 T Robust); block coil (reduced high-field coil stress); common coil (simplification of coil-manufacturing); stress managed version of either coil variant (drastically reduced coil stresses, at cost of lower efficiency)
  - 1st priority: performance and (sufficient) robustness.
  - 2nd priority: maximum robustness and reduced cost.

R&D Strategy and Focus Areas 3/3

R&D Line 4: Enabling Technology R&D

- Common modelling and simulation tools for HFM magnets and conductors
- Structural materials for HFM magnets
- Insulation materials for HFM magnet coils and conductors
- Enhanced impregnation materials for HFM magnet coils
- Quench detection and protection methods for Nb3Sn and HTS high-field magnets
- Cryogenic and thermal management studies for HFM magnets

R&D Line 5: Infrastructures

- Test infrastructure needs for the HFM R&D programme
- Infrastructure needs for conductors
- Infrastructure needs for demonstrators, short magnet models and full-scale prototypes
- Novel instrumentation and measurement equipment needs

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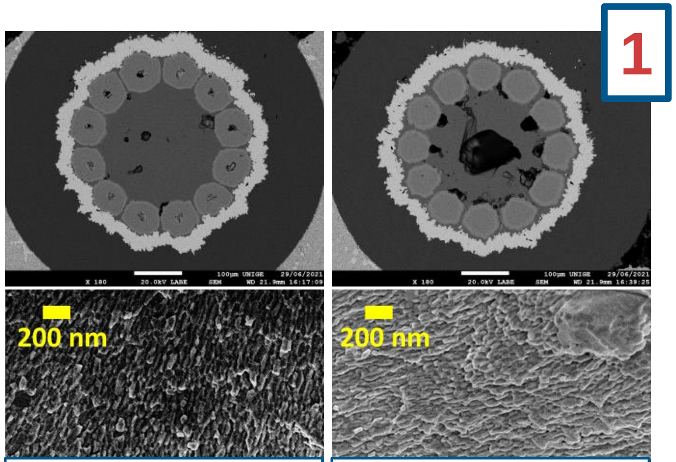
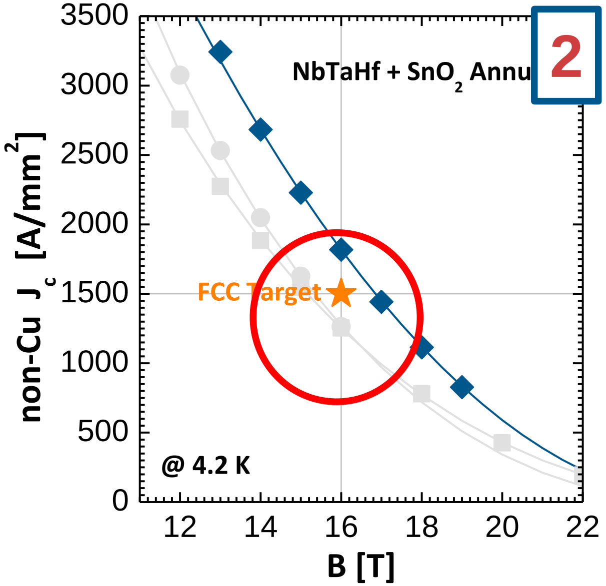
Wire Development at UniGE

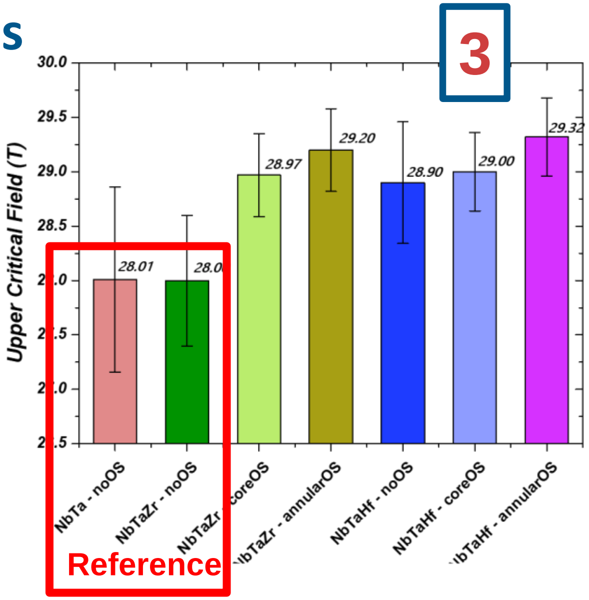
Internal Oxidation in prototype multifilamentary wires



Average grain size
~ 47 nm

Average grain size
~ 45 nm





Larger billets under development

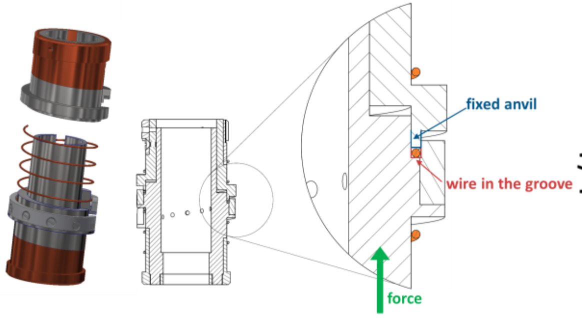
Pushing Nb_3Sn towards its ultimate performance

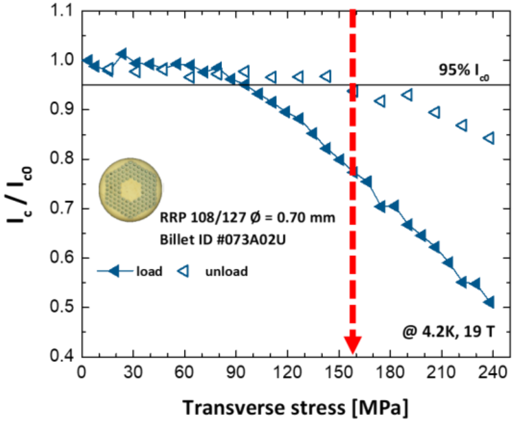
1	Refinement of the grain size: 100 nm → 50 nm
2	Large increase of the layer J_c → exceeding the FCC target
3	Enhancement of B_{c2} by > 1 T → improved in-field performance

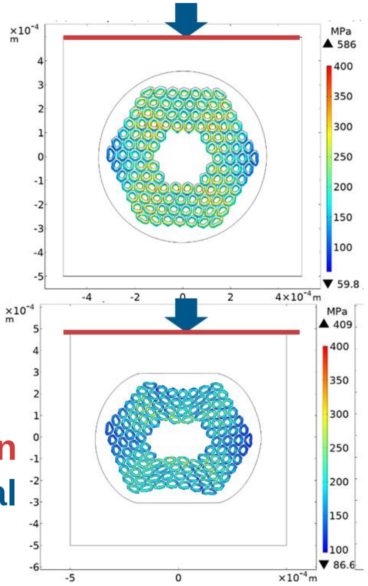
Courtesy of C. Senatore

Advanced Characterizations of Technical Superconductors at UniGE

Assessing the mechanisms behind the permanent reduction of I_c

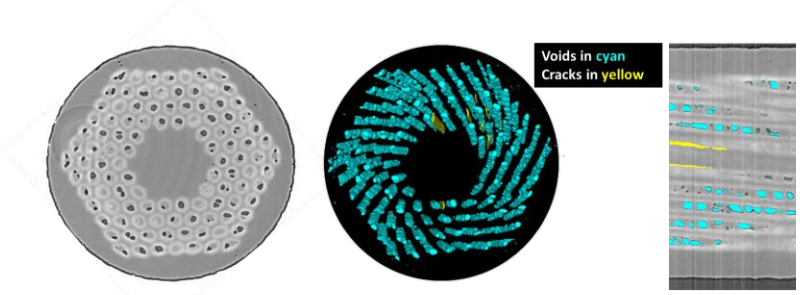






FE simulations to investigate the role of plastic deformation and residual stresses in the irreversible loss of critical current under transverse load, in collaboration with PSI

A comprehensive campaign of electromechanical tests on different wire types to gain knowledge on several practical aspects for magnet operations



Machine learning applied to X-ray tomography as a new tool to analyze crack formation and propagation in Nb_3Sn wires, in collaboration with ESRF

Courtesy of C. Senatore

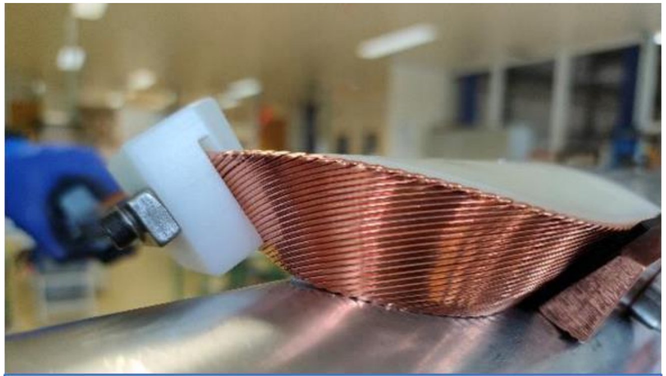
FalconD: single aperture, dipole model as part of the 12 T robust dipole development

- The collaboration between INFN and CERN for the design and constructions of a single aperture high field dipole has been rescoped to become part of the HFM “12 T robust dipole” development program.

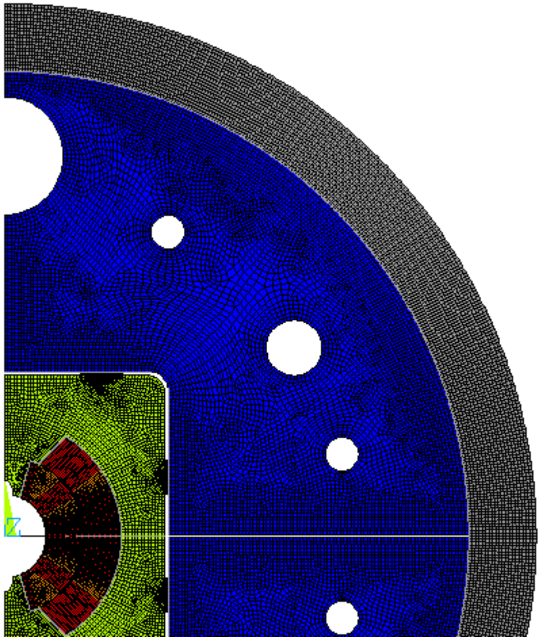
- Systematic winding tests have started.

- Three generations of FalconD end spacers were developed in a few months.

- The Preliminary Design Review was successfully completed in August 2022.



FalconD winding test, End spacers iteration 2. In some of the winding tests the cable is not insulated to have a better visibility of the strand position and deformation. The white plastic element is part of the tool that help to keep the strand in position during the bend.



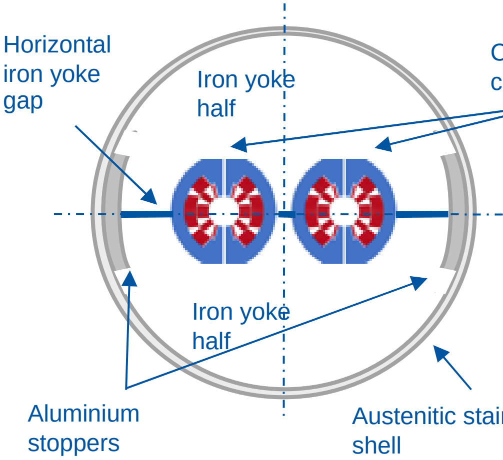
FEM model of the FalconD single aperture bladders and keys, 12 T dipole.

Courtesy of S. Farinon and D. Perini

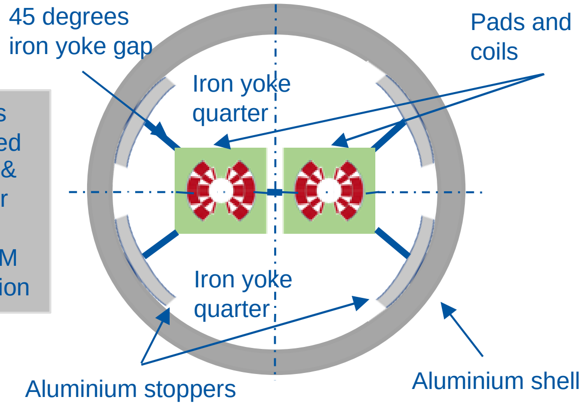
Development of “12 T robust” dipole

Incorporates new ideas and lesson learned from HL-LHC magnets

- Conceptual design with FEM computations in nominal condition and tolerance analysis with Monte Carlo methods

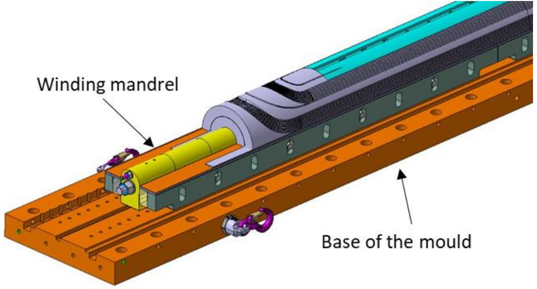


Preliminary cross section of a collared coil and bladders & keys dipoles after analytical computations. FEM models in preparation



- Applied features and assumptions
  - Optimization of the end spacers with additive manufacturing techniques.
  - Separation of the inner layer from the outer layer for better control of coil prestress and easier manufacturing.
  - Winding mandrel becomes part of the heat treatment mould.
  - Test campaign with mock-ups to understand and control the coil stress distribution during the different assembly phases.

Courtesy of D. Perini



The winding mandrel as part of the heat treatment mould. CAD parametric model that can be adapted to different coil dimensions.

“Block coil” path toward 16T dipoles

F2D2 Short model → Future agreement

Grading + Flared-ends + Aperture = 16 T

1.5 m, 50 mm bore **+Aperture**

FD Demonstrator → Future agreement

Grading + Flared-ends ≥ 14 T

1.5 m, No bore **+Flared ends**

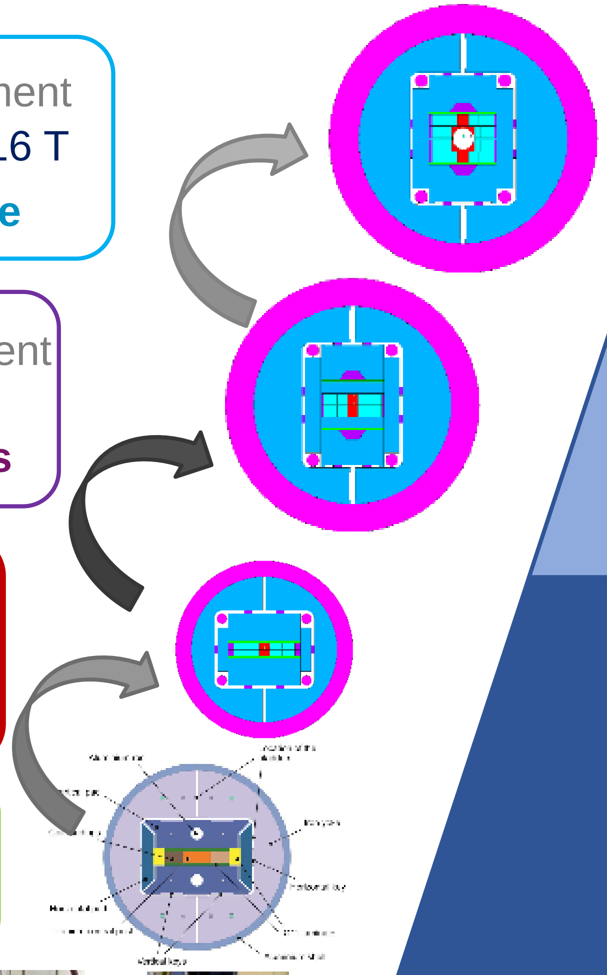
CEA-CERN R2D2 ↗ **ongoing**

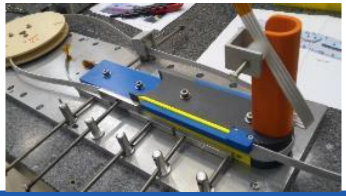
Demonstrate Grading ≥ 12 T

1.5 m, No bore **+Grading**

CEA-CERN SMC-11T coil ✓done

Demonstrate Nb_3Sn tech. ≥ 12 T





16 T Demo

12-14 T Demo

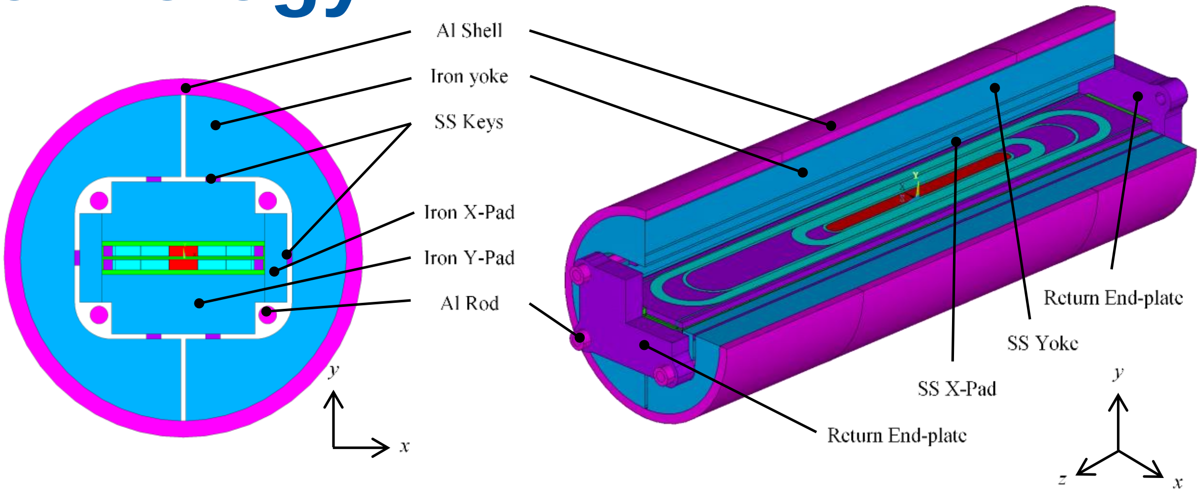
Subscales

Powered samples

Non-powered samples

Status of R2D2 demonstrator of Nb_3Sn grading technology

Aperture	None
Outer diameter	480 mm
Structure length	1.5 m
Nominal central field	11.1 T
Ultimate central field	12.0 T
Nominal peak field	12.7 T
Ultimate peak field	13.7 T

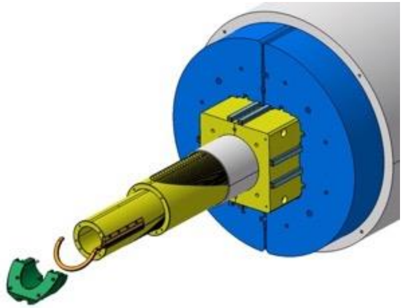


- ✓ **Conceptual design done by CEA and reviewed by an external panel**
- ✓ **External joint procedure validated at CEA with mockups**
- ✓ **Nb_3Sn prototype cables validated at CERN**
- ➢ Coil components ordered; delivery expected in September
- ➢ Main tooling ordered, delivery expected between November and December
- ☐ Fabrication planned to start early 2023 at CEA
- ☐ Cold and powering tests at CERN

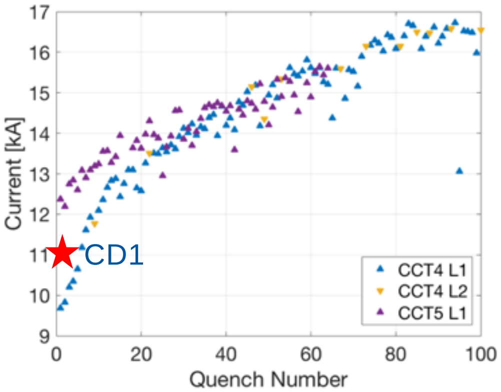
Courtesy of E. Rochepault

Innovative Canted Dipole (CD1)

- CHART MagDev @ PSI explores stress-management concepts to reduce the stress on Nb_3Sn conductor.
    - Research and development in close collaboration with US-MDP (LBNL) and CERN led to the design and construction 2016-2019 of the CD1 magnet at PSI.
    - CD1 testing is ongoing at CERN. CCT4 and CCT5 test results have meanwhile become available at LBNL.
- Debonding on the coil-structure interface and resin cracks caused long training.
- Analysis of manufacturing requirements led to a decision against CCT technology for FCC-hh on the part of PSI.

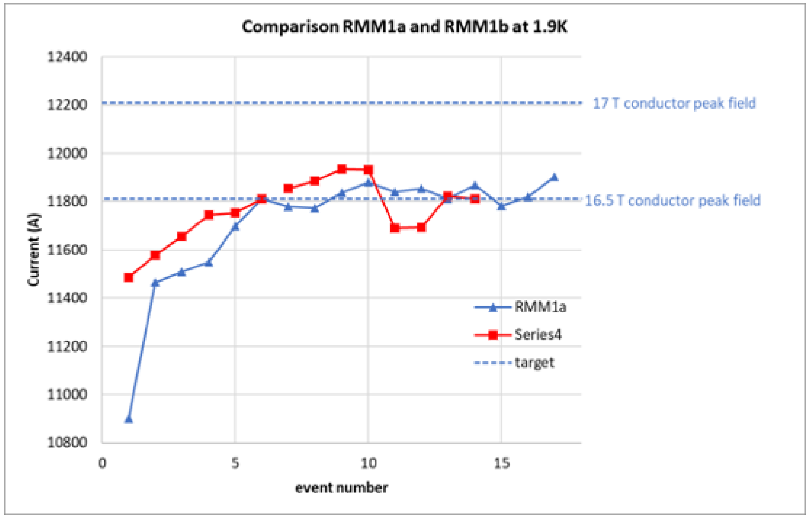


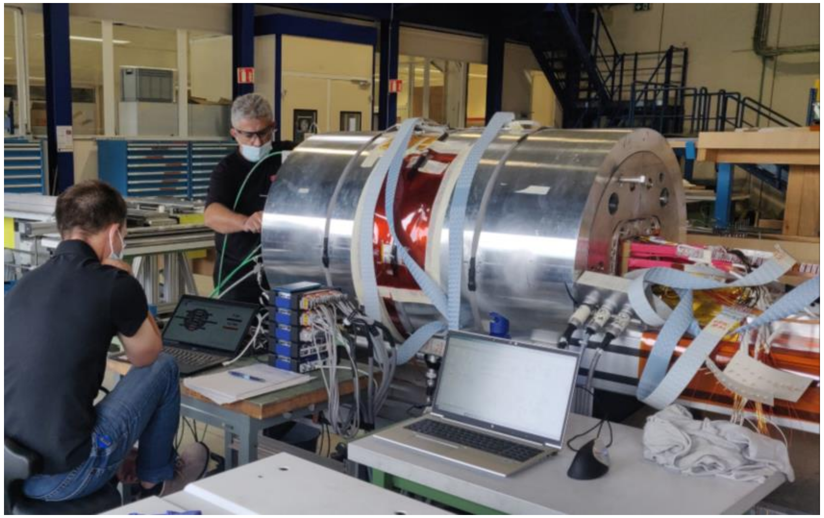
CD1 (Canted Dipole 1), design and manufacturing at PSI.



Courtesy of B. Auchmann

RMM1b test at CERN



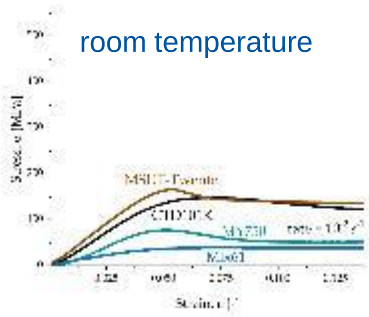


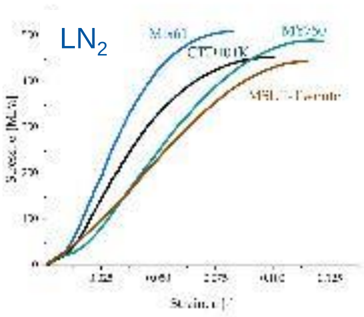
- RMM1b test performed in SM18 Aug/Sept 2022
- Maximum current reached in Q #9 & Q #10 of 11.94 kA corresponding to conductor peak field Bp of **16.7T**
- Small detraining is attributed to insufficient prestress in the coils
- Magnet was warmed up and will be assembled with higher prestress in the coils

Courtesy of J. C. Perez

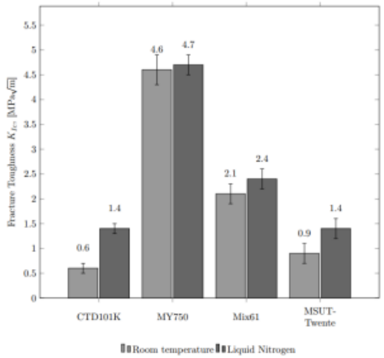
Resin Systems Development

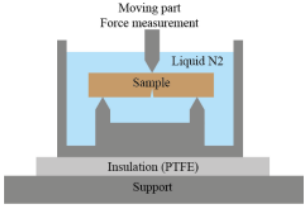
- Initial characterization of state-of-the-art systems, followed by research on improved fracture toughness at cryogenic temperatures.
- New CryoSet II shows best-of-class K1c mixed from readily available components.
- Tests in BOX facility indicate that low glass-transition and curing temperatures may be equally important.





~450 MPa





A. Brem, T. Tervoort, 2020.

Sample overview

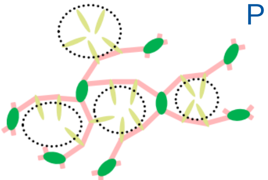
Var. R
Var. f
Var. sidechain

System	ID	R	f	KIC (RT)	KIC (LN2)	Tg (max tand)	Density
DGEBA, MPD	Base	1:0	4	0.8 ± 0.1	2.0 ± 0.1	160.1	1.217
DGEBA, BA, MPD	BA-4-5:4	5:4	4	1.2 ± 0.2	3.5 ± 0.6	68.3	1.153
DGEBA, BA, MPD	BA-4-9:8	9:8	4	1.5 ± 0.1	4.1 ± 0.6	61.4	1.145
DGEBA, BA, MPD	BA-2-9:8	9:8	2	1.9 ± 0.2	5.3 ± 0.4	n.a.	1.145
DGEBA, BA, MPD	BA-3-9:8	9:8	3	1.6 ± 0.1	5.0 ± 1.1	73.0	1.147
DGEBA, OA, MPD	OA-3-9:8	9:8	3	1.8 ± 0.1	4.4 ± 0.5	54.4	1.109
DGEBA, t-OA, MPD	tOA-3-9:8	9:8	3	1.0 ± 0.1	2.7 ± 0.4	100.7	1.108
DGEBA, 2-HA, MPD	2HA-3-9:8	9:8	3	1.8 ± 0.1	4.7 ± 0.3	72.4	1.115
DGEBA, BA, MPD	BA-3-5:4	5:4	3	1.6 ± 0.2	4.7 ± 0.3	n.a.	1.153
DGEBA, OA, MPD	OA-4-5:4	5:4	4	1.5 ± 0.2	4.6 ± 0.4	n.a.	1.115

- ➢ Addition of Butylamine, Octylamine or 2-Heptylamine → **Improved toughness at 77 K!**

1st hypothesis: Nanodomains

P. Studer, T. Tervoort, 2022.



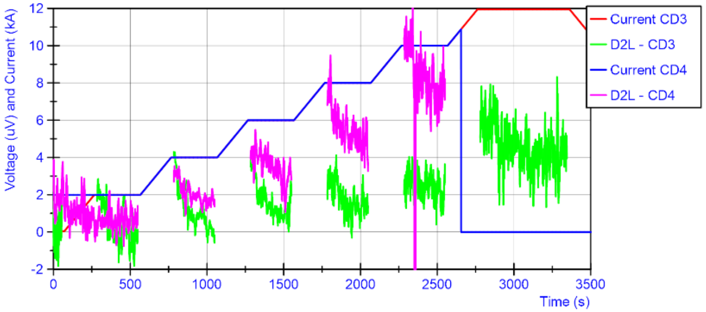
Are there nanodomains and are they responsible for improved properties?

Courtesy of T. Tervoort

HL-LHC and HFM synergy
Novel Diagnostics: *V*-*I* Measurements

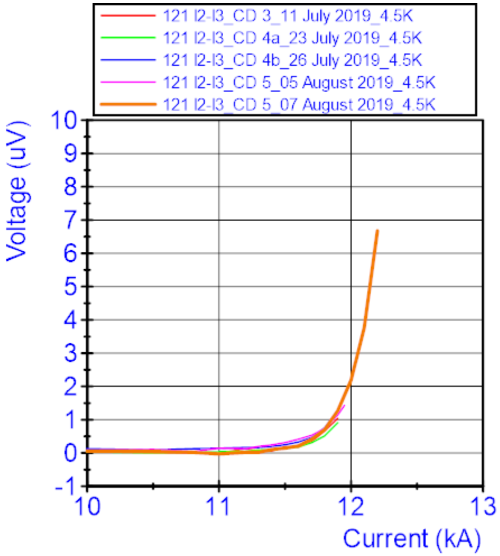
HL-LHC and HFM synergy: additional diagnostics developed within the HL-LHC Project will serve as well the HFM programme

- Sensitive voltage measurements can be carried out on during magnet testing, enabling early detection of resistive transitions and monitoring of their evolutions after EM and thermal cycling.
- Can confirm the presence or not of Nb_3Sn conductor degradation.



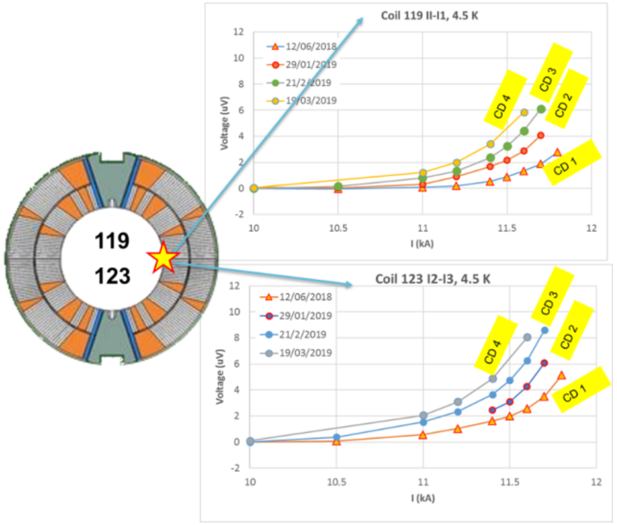
11T Series #2: Change in full coil voltage between cool down 3 and cool down 4; the method can show degradation and changes in degradation, even before the quench happens.

SP107



Stable Behavior

SP109

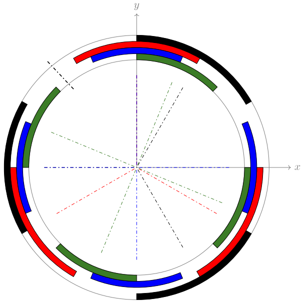


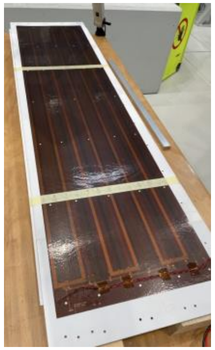
Degrading Behavior

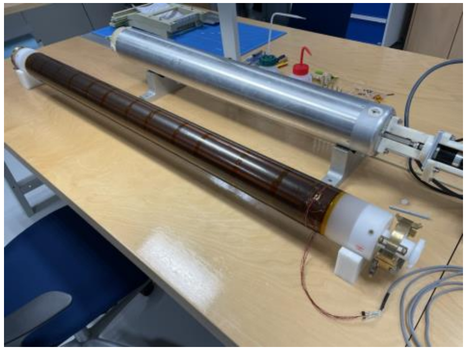
Courtesy of A. Devred

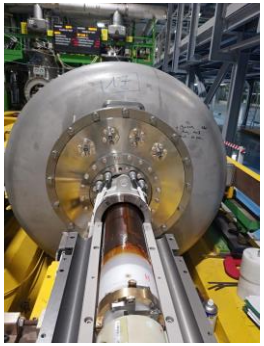
HL-LHC and HFM synergy
Multipole-Sensitive Quench Antenna

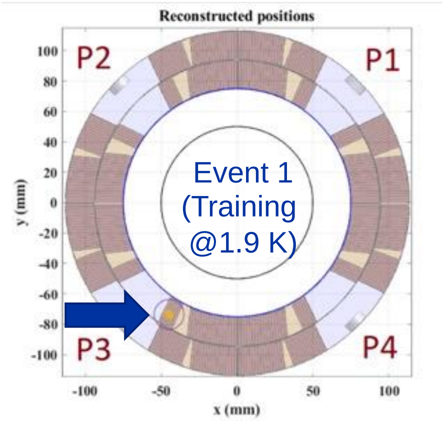
- Quench antenna configuration enabling accurate quench start localization, both longitudinally and azimuthally (concept initially proposed by T. Ogitsu, circa 1993)
- B3,A3,B4,A4 sensitive through coil design (analogue bucking -> Flex PCB design)
- Compromise between noise (PC, vibrations etc), resolution in radial direction, and signal strength.

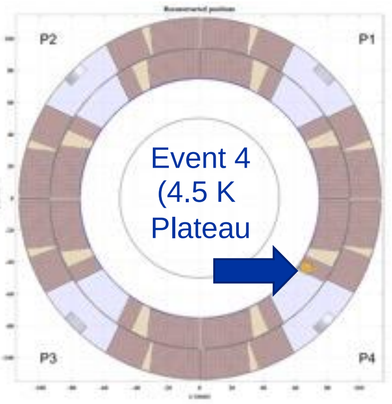


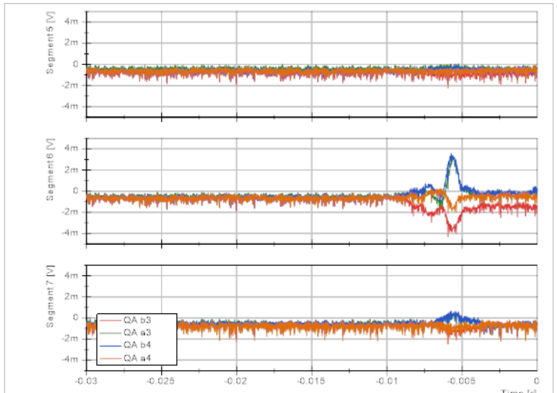






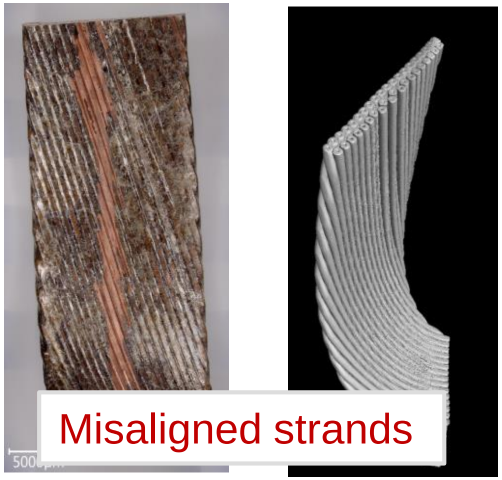


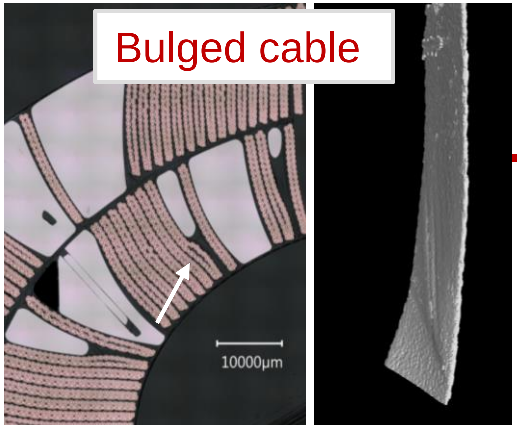


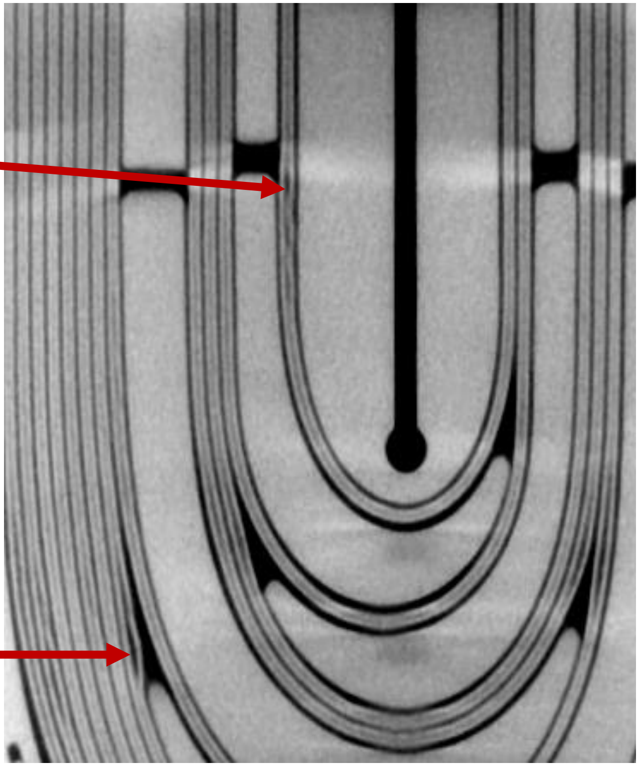


Courtesy of A. Devred

HL-LHC and HFM synergy
Linac X-Ray Computerized Tomography





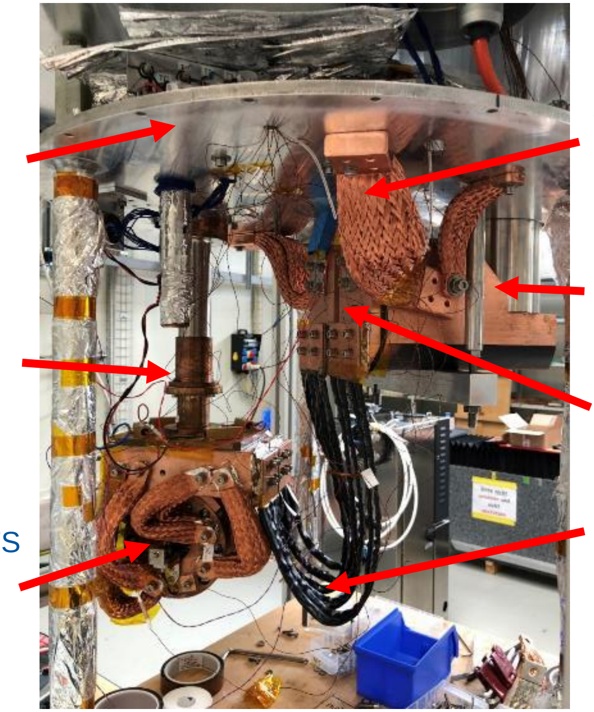


- CT examination of the series **11 T coils** revealed **several unexpected events.**
- The presence of events such as strand pop-out and bulging, which occur at the same location for all the coils inspected.
- Cracks and shrinkage cavities have been observed in the composite structure and resin system.
- Metallurgical analyses revealed microcracks in the superconductor (sign of excessive strain, due to internal or external causes).

Courtesy of A. Devred and F. Savary

PSI ReBCO Technology Solenoid Program

- Successful test in cryogen-free test station of 4-pancake HTS NI solenoid, built in-house at PSI and using licensed Tokamak Energy Ltd technology.
- Coil reached **18.2 T** in the center, **20.3 T** on the conductor at the maximum current of the power converter of 2 kA and 12 K coil temperature.



radiation shield top plate

1st cryocooler 4K coldhead

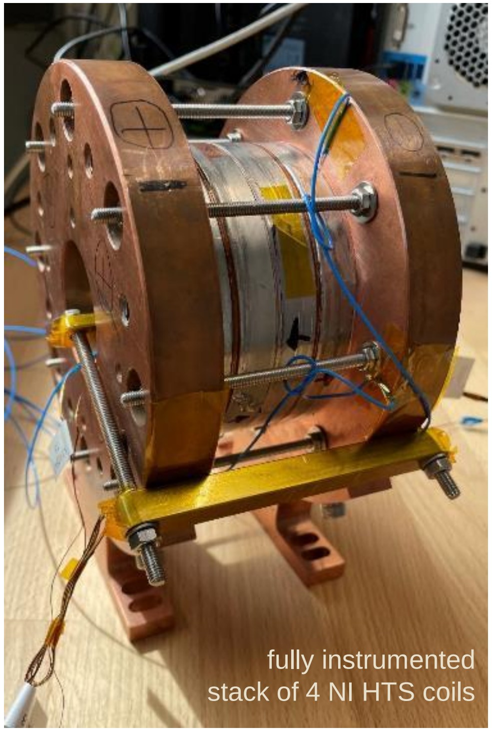
stack of 4 NI HTS coils with thermal/current connectors

thermal connectors

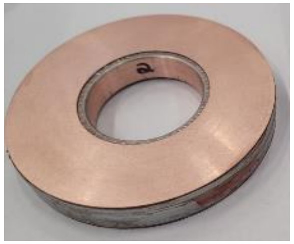
2nd cryocooler 20K coldhead

Cu leads

HTS leads



fully instrumented stack of 4 NI HTS coils



Diameter: 100 mm
Aperture: 50 mm

SC type: ReBCO
tapes: 2
turns: 2 x 170
SC length: 2 x 49 m

Courtesy of B. Auchmann

KC^4 - KIT-CERN Collaboration on Coated Conductors

KC^4 mission

- **Development of tailored HTS-wires for magnet and energy applications**
    - Company independent
    - Special wire architectures for R&D
    - Wire length up to 100m to meet demonstrator needs
- **Commissioning of CC deposition equipment**
    - PLD setup adapted to local lab requirements
    - Short sample (10m batches) synthesis **planned to start in October/November**

Courtesy of B. Holzapfel

Outline

- Foundations and organisational structure of HFM programme
- R&D strategy and focus areas
- Selected latest developments from current work
- Key mid-term deliverables
- Summary

Summary of main deliverables for 2022-2027: what will be delivered in time as an input to the next ESPPU

- Development of new **HFM grade Nb_3Sn conductor** with increased mechanical properties and target Jc 1500 A/mm2 @ 16 T

- Procurement of the present state-of-the-art Nb3Sn conductors for short and long 12 T Robust Dipole and 12-14 T demonstrators

- **Development and demonstration of the Nb_3Sn magnet technology for collider-scale production through robust design**, industrial processes and cost reduction (12 T short models)

- **Demonstrator of the Nb_3Sn potential above 14T.** Feasibility of building short magnet models on time for the ESPPU will require shortening the present development cycle

- **Exploration and demonstration of suitability of HTS conductors for building accelerator magnets**

- **The target objectives are defined and challenges to reach them are shared with national institutions**

In conclusion

- **The CERN hosted HFM programme**, is a technology-focussed R&D mission aimed at developing the next generation of accelerator magnets for possible future colliders and therefore the relevance of this program to the MuC collider is by definition beyond question, despite the fact that MuC magnets have unique requirements

- For the current scope of the programme and its budget, the MuC collider magnets were not explicitly included

- The conductor and magnet technology challenges faced by HFM will be many and significant, in particular requiring a **decisive advancement beyond the state of the art** to make the next generation magnets possible

- Fostering and profiting from collaborations with **EU partners** is an essential part of the HFM programme as well as linking to ongoing worldwide efforts, particularly in the **US and Japan**