R&D Programme hosted at CERN for the Next Generation of High-Field Accelerator Magnets

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with inputs from:

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y Tecnológicas

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Istituto Nazionale di Fisica Nucleare

University of Twente
The Netherlands

ETH zürich

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

CERN

Outline

- Where do we stand on the LTS High Field Magnet development?
    - State-of-the-art LTS superconductors and magnet technology
    - Main challenges facing the development of LTS high-field magnets
    - R&D Strategy and Focus Areas for the LTS high-field magnets
    - Ongoing work and mid-term focus areas

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    - Ongoing work and mid-term focus areas

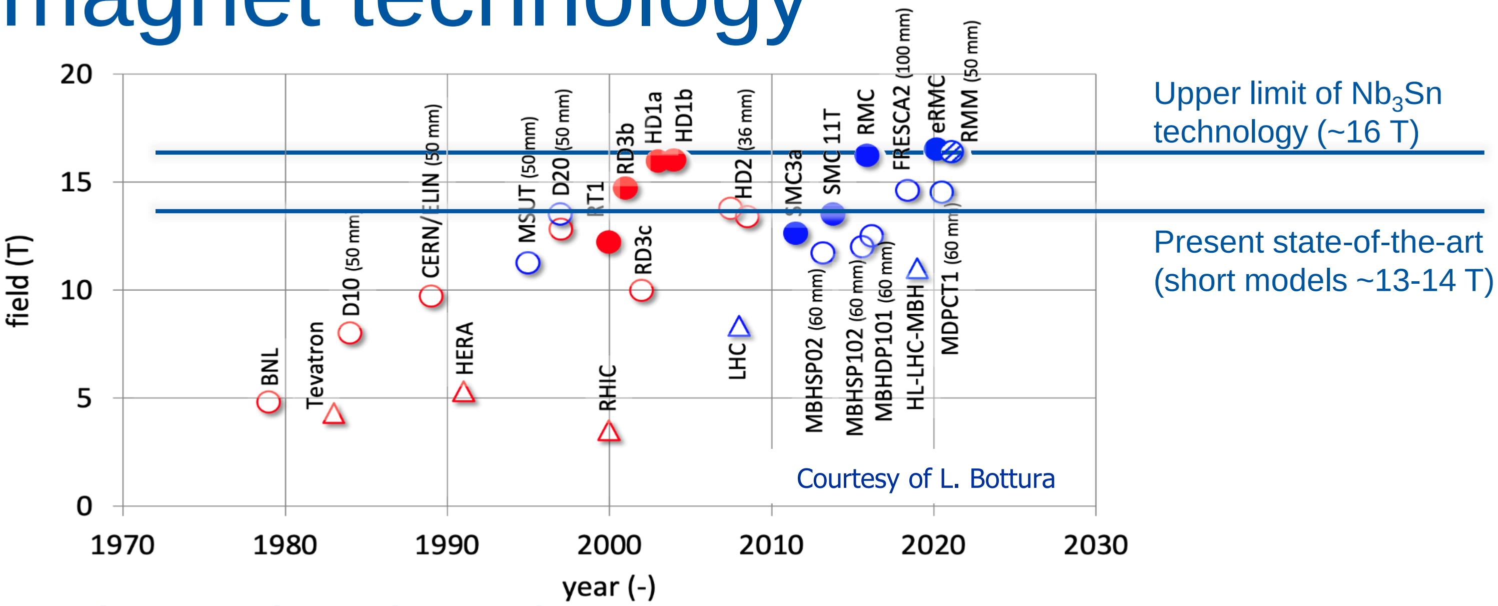
- Key mid-term deliverables until the next European Strategy update

- Short overview of the HFM R&D consortium

HFM Programme – broad goals

- The EU Accelerator R&D Roadmap identifies two main objectives for the High Field Magnet Programme:
  - The first is to demonstrate Nb_3Sn magnet technology for large-scale deployment. This will involve:
    - Striving 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 studied Future Circular Collider $FCC_{h\text{-}h}$)
  - The second objective is to explore and 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

State-of-the-art LTS superconductors and magnet technology



Upper limit of Nb_3Sn technology (~16 T)

Present state-of-the-art (short models ~13-14 T)

Courtesy of L. Bottura

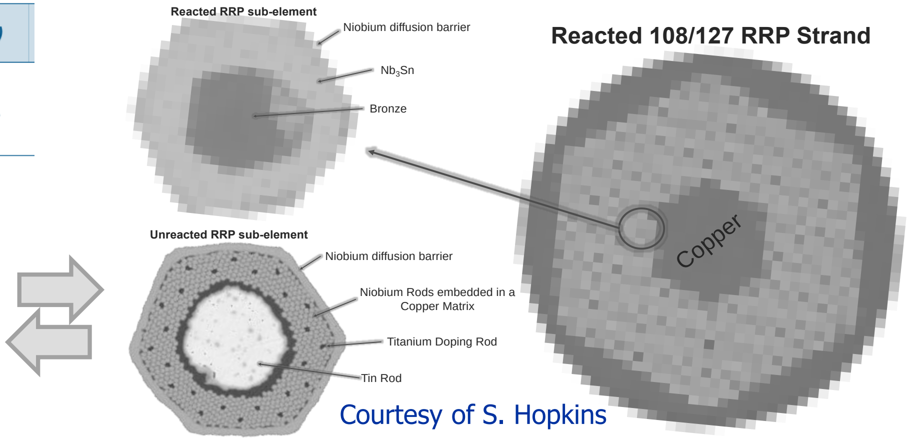
State-of-the-art Nb_3Sn conductor (HL-LHC)

	Technology	*# of subelements*	*Cu/non-Cu*	*Subelement size/shape*	*Diameter*	*I_c(16 T)*
	**RRP**	**108/127**	**1.2**	**~55 µm**	**0.85 mm**	**280 A**

Heat treatment

HT N: 535 Code: 3_665_B
Furnace: GERO_CERN163 Date: 13/09/2019

Plateau	T [°C]	Duration [h]	Ramp (up) rate [°C/h]
1	210	48	25
2	400	48	50
3	665	50	50



Courtesy of S. Hopkins

Demonstrator of state-of-the-art Nb_3Sn magnet technology – “12 Tesla Robust Dipole”

- So far, no full-size dipole magnet using Nb_3Sn technology has been built
- In order to demonstrate the maturity of the most advanced technologies today and to investigate the physical and technological effects related to the length of the magnets, an accelerator-size magnet demonstrator will be built towards a production scale through robust design, industrial manufacturing processes and cost reduction, taking HL-LHC magnets as a benchmark, i.e. 12 T

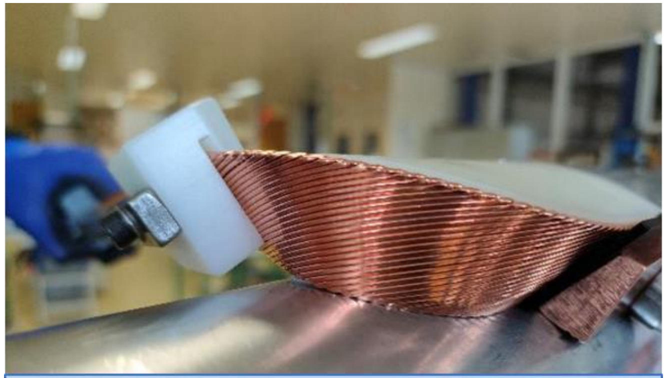
- **Full-size demonstrator of maturity of Nb_3Sn technologies, including improved manufacturability through collaboration with industrial partners**
- **Reaching 14+T with this robust technology will be aided by improved mechanical robustness of Nb_3Sn conductor**

12 Tesla

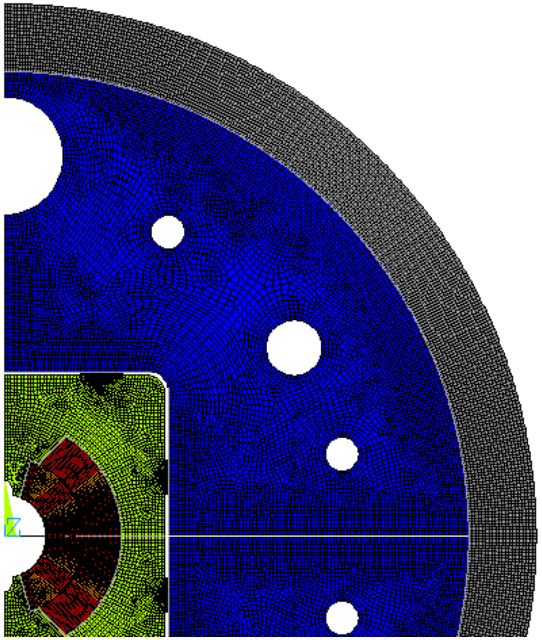
Robust

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
  - 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.



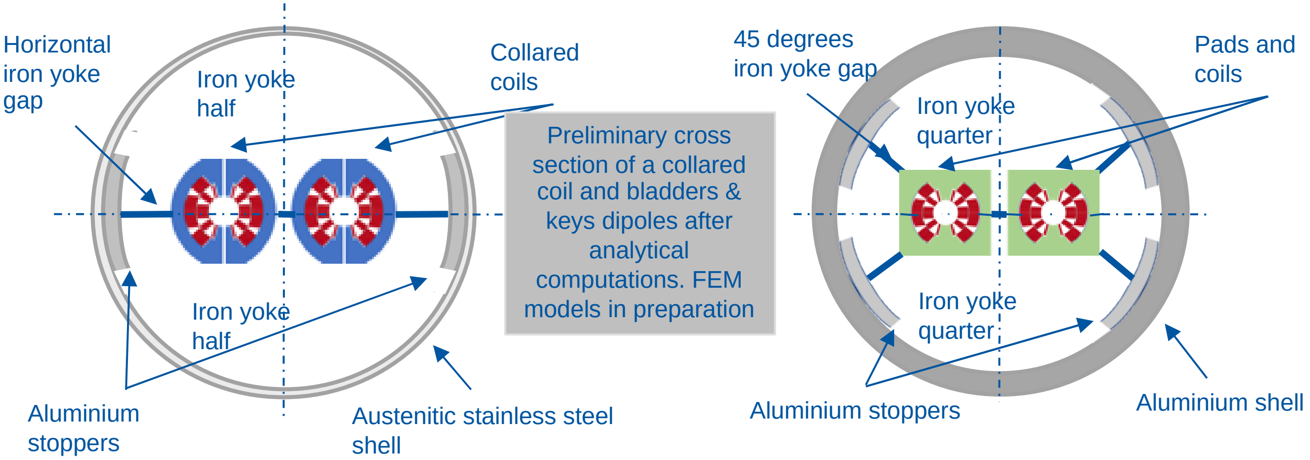
FEM model of the FalconD single aperture bladders and keys, 12 T dipole.

Courtesy of S. Farinon and D. Perini

Development of “12 T robust” dipole

Incorporates new ideas and lesson learned from HL-LHC magnets

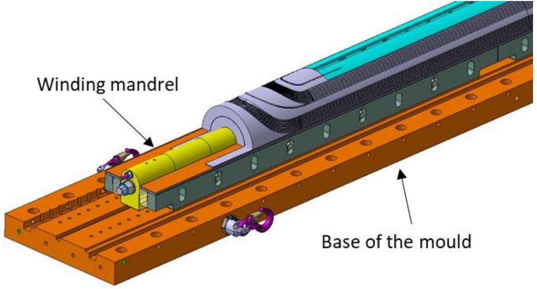
- Conceptual design with FEM computations in nominal condition and tolerance analysis with Monte Carlo methods



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

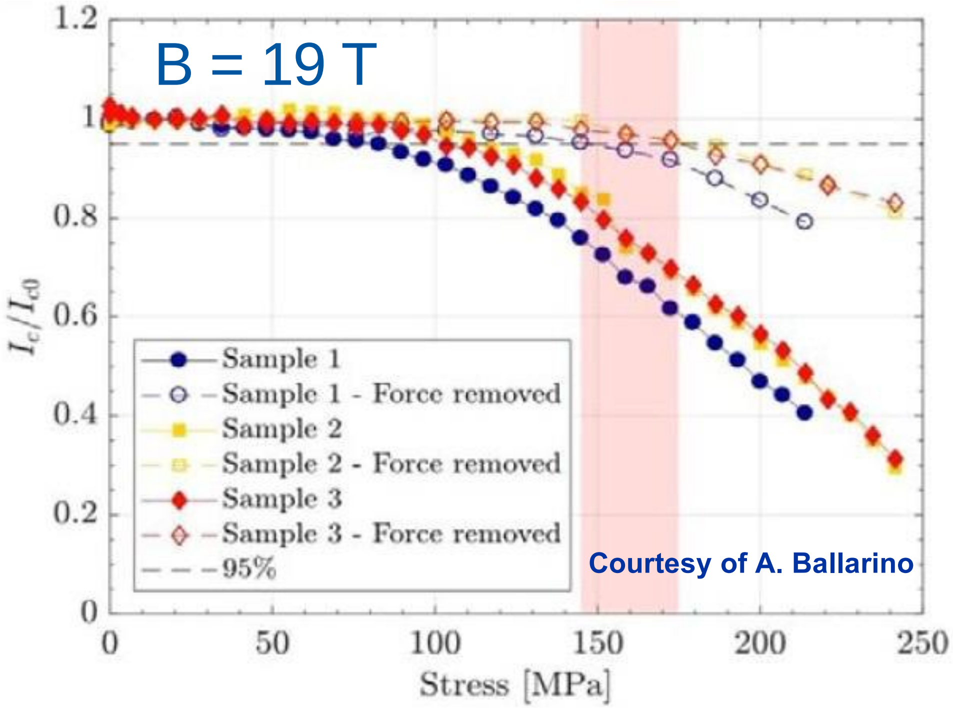


The winding mandrel as part of the heat treatment mould. CAD parametric model that can be adapted to different coil dimensions.

Main challenges facing the development of future 14+ Tesla LTS high-field magnets

Nb_3Sn Conductors

- Present limitations of Nb_3Sn technology are linked to:
    - conductor stress/strain sensitivity and degradation
    - thermomechanical behaviour and degradation of magnet performance



Courtesy of A. Ballarino

- σ_{irr} = 145–175 MPa
- I_c/I_{c0} @ 150 MPa
  → 16 % - 28 %

R&D Strategy and Focus Areas for the LTS high-field magnets

Nb_3Sn Conductors and magnets: pushing towards ultimate performance

- **Stress/strain sensitivity** and degradation of Nb_3Sn conductors **to be overcome** by one of the two development paths:

Nb_3Sn Conductor R&D

- New Nb_3Sn wire structures with improved mechanical robustness
- Higher Jc (increased margins)
- Industrialization of improved superconductor

Novel Magnet Structures

- Magnet structures need to be adapted through stress management to cope with performance limitations due to Nb_3Sn stress/strain sensitivity and thermomechanical behaviour

R&D Strategy and Focus Areas for the LTS high-field magnets

Nb_3Sn Magnets: 14+T Feasibility Studies

- Exploratory phase, 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 evolutionary to beyond state-od-the-art magnet structures

- 1st priority: performance and (sufficient) robustness.
- 2nd priority: maximum robustness and reduced cost.

- **Exploratory phase of magnet structure R&D**
  - cos theta (see 12 T Robust);
  - block coil;
  - common coil

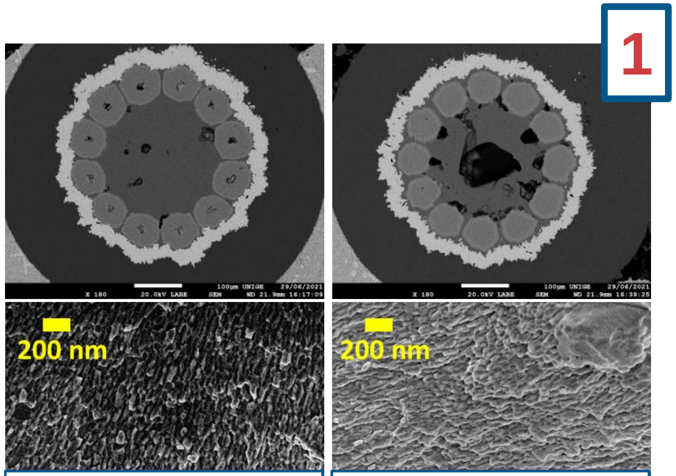
Evolutionary technology R&D

Beyond state-of-the-art

- **Magnet structures adapted to stress/strain sensitivity limitations**
  - stress managed version of either coil variant aimed at reduced coil stresses, at cost of lower efficiency

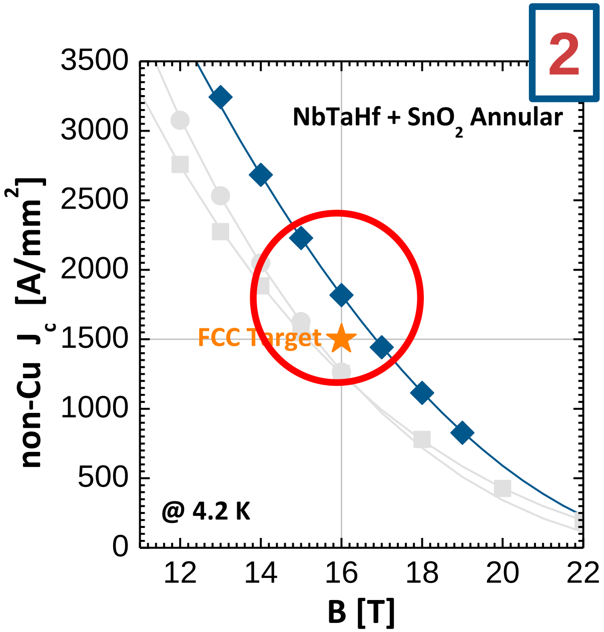
Ongoing work examples:
Nb_3Sn Wire Development at UniGE

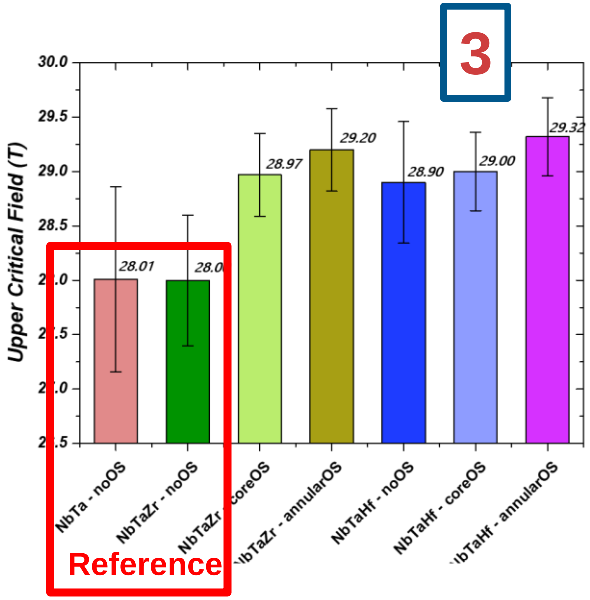
Internal Oxidation in prototype multifilamentary wires



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

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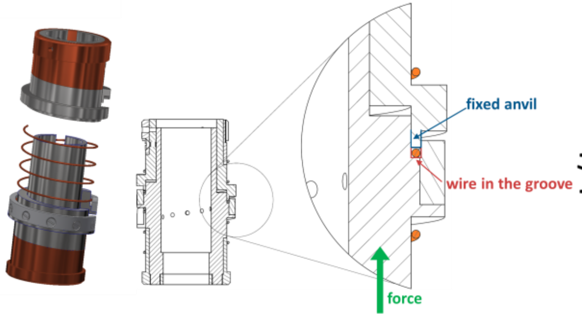
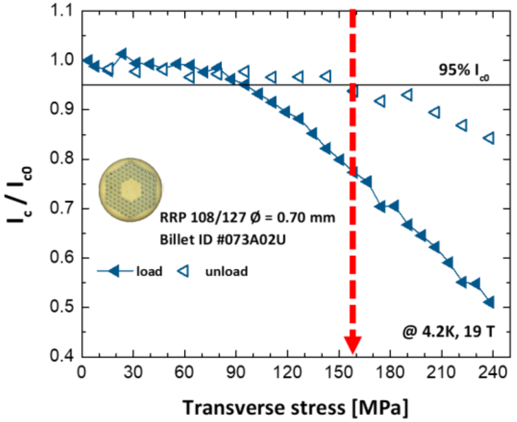
Advanced Characterizations of Technical Superconductors at UniGE

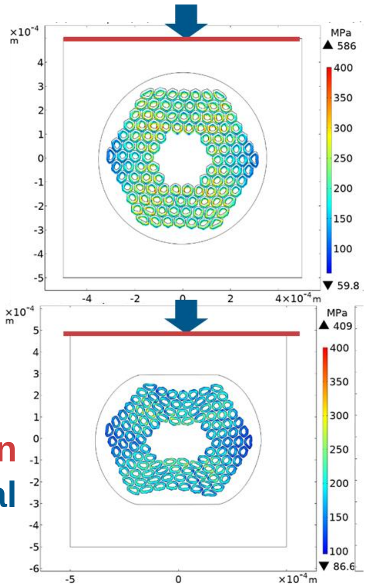
CHART
Swiss Accelerator Research and Technology

Assessing the mechanisms behind the permanent reduction of I_c

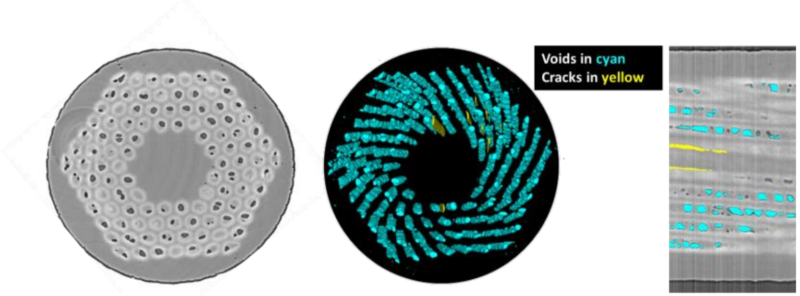




A comprehensive campaign of electromechanical tests on different wire types to gain knowledge on several practical aspects for magnet operations



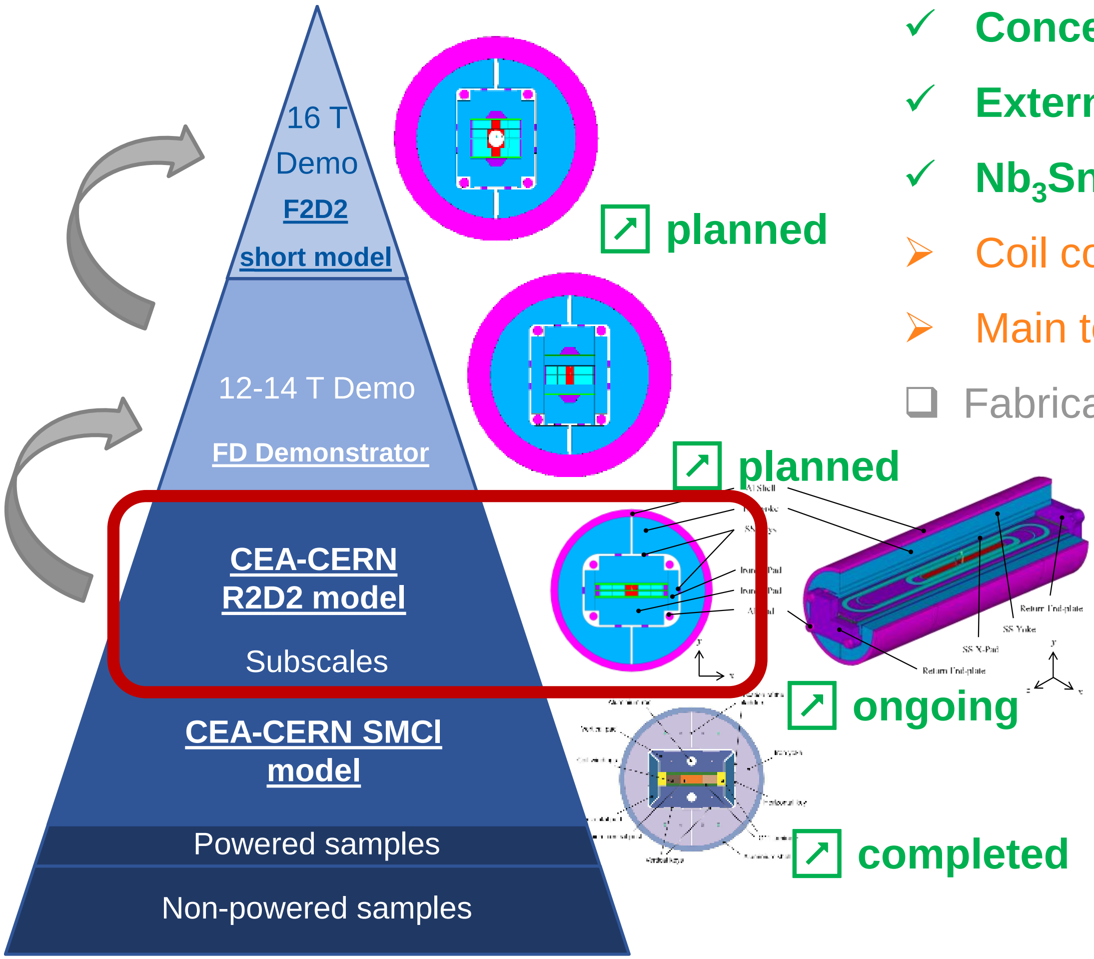
FE simulations to investigate the role of plastic deformation and residual stresses in the irreversible loss of critical current under transverse load, in collaboration with PSI



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

Status of R2D2 demonstrator of graded Nb$_3$Sn technology



- ✓ Conceptual design done and reviewed
- ✓ External joint procedure validated at CEA
- ✓ Nb$_3$Sn prototype cables validated at CERN
- ➢ Coil components ordered
- ➢ Main tooling ordered
- ❑ Fabrication planned to start early 2023 at CEA

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

Courtesy of E. Rochepault

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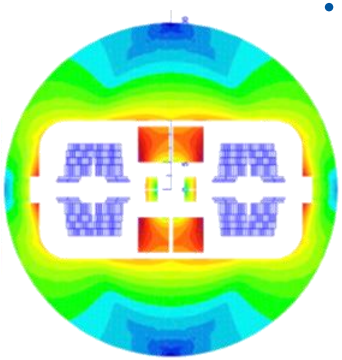
Preparation towards Nb3Sn common coil magnet development



- Conceptual design of the Spanish HFM dipole magnet with a common coil, featuring simplified mechanics and production, is pending development in the new CIEMAT magnet laboratory.
- The present collaboration agreement is in the process of re-scoping.

New magnet lab: the major renovation of Building 31 at CIEMAT will be completed before the end of the year

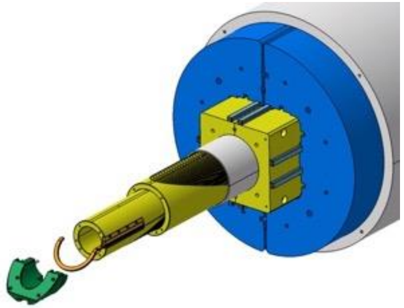
Main hall

Secondary hall

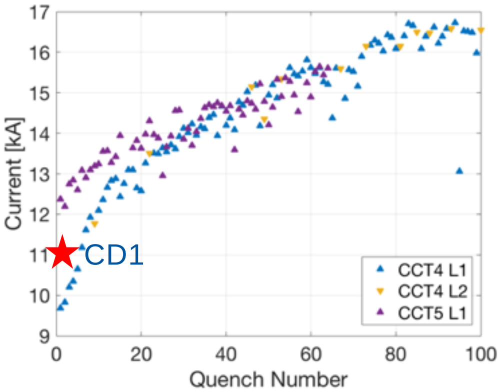
Courtesy of F. Torez

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.

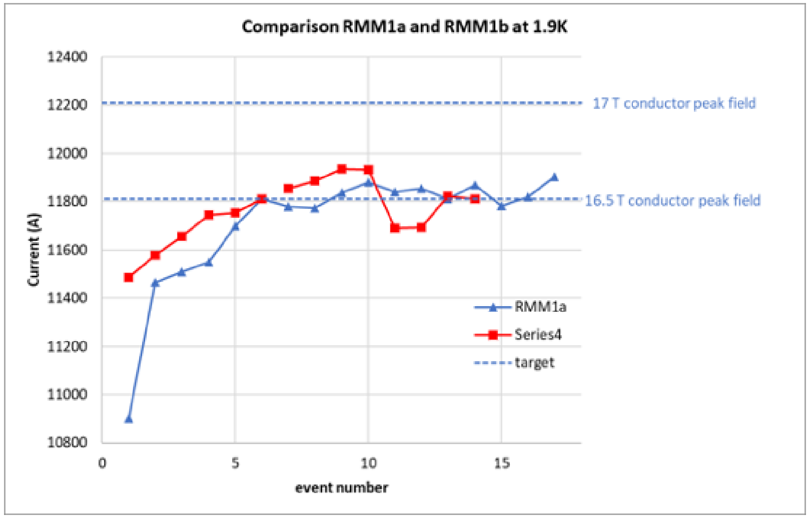


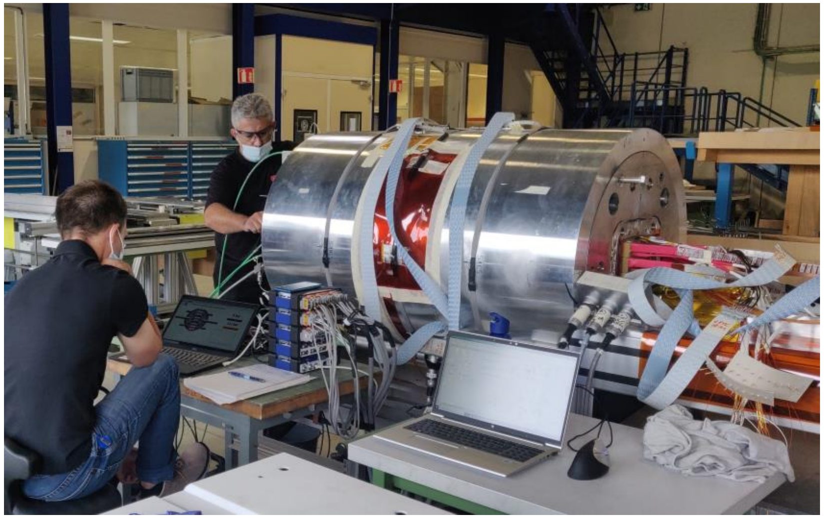
CD1 (Canted Dipole 1), design and manufacturing at PSI.



Courtesy of B. Auchmann

RMM1b test at CERN





- RMM1b test performed at CERN Aug/Sept 2022
- Maximum current reached in Q #9 & Q #10 of 11.94 kA corresponding to conductor peak field Bp of **16.7T and 16.5 T** in aperture cavity
- 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

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- Where do we stand on the LTS High Field Magnet development?
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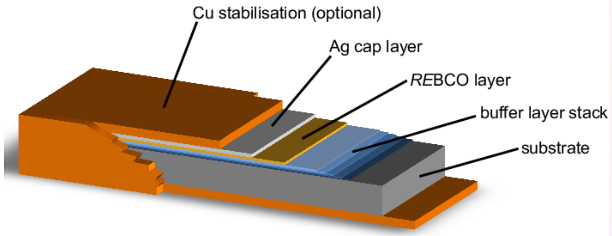
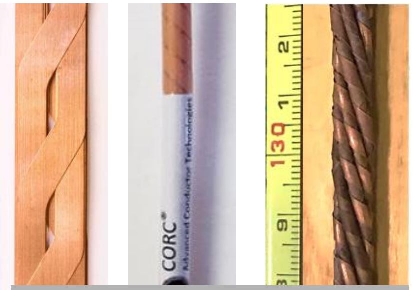
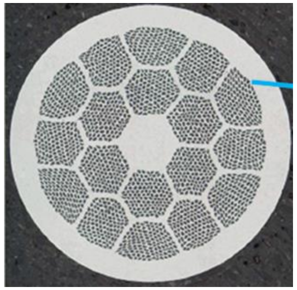
- Short overview of the HFM R&D consortium

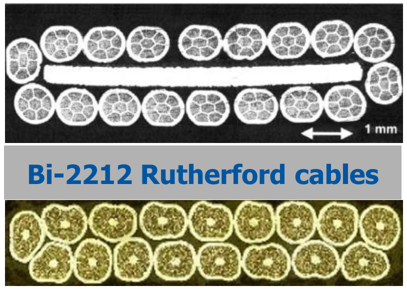
State-of-the-art HTS supercondutors: ReBCO vs Bi-2212





ReBCO cable design options





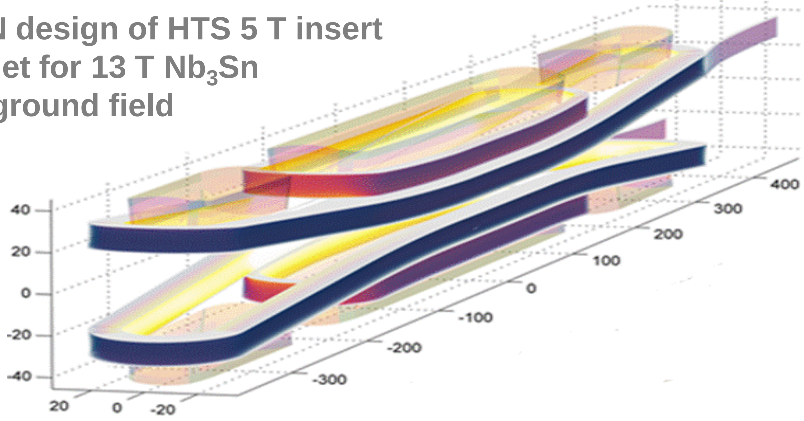
Bi-2212 Rutherford cables

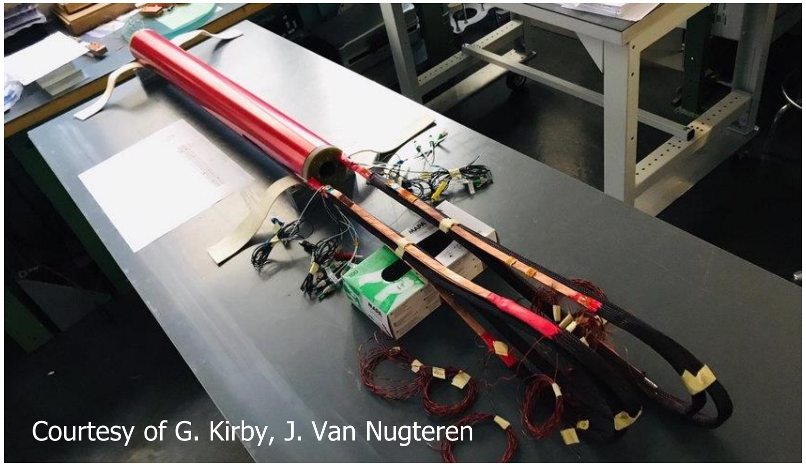
ReBCO	Characteristics	Bi-2212
High, steadily improving	**Critical current**	High, more stagnant
Roebel cable (waste), 50-200 m unit length available; CORC cable; STAR cable; Twisted stacked-tape cable	**Cabling methods**	Easy Rutherford cable, but need special H.T., very long length possible
Very bad (tape shape).	**Magnetization**	Worse than NbSn but manageable
Excellent vs. transversal stress, better than Nb_3Sn, very weak vs. shear stress	**Mechanical prop.**	Weak vs. transversal stress
Difficult bend in coil ends, joints not easy, good insulation and handling	**Coil technology**	Very complex HT under high-pressure, large-scale coils may be difficult. Easy joints
Various suppliers and projects everywhere	**Supply**	Limited number of suppliers

State-of-the-art HTS superconductors and magnet technology

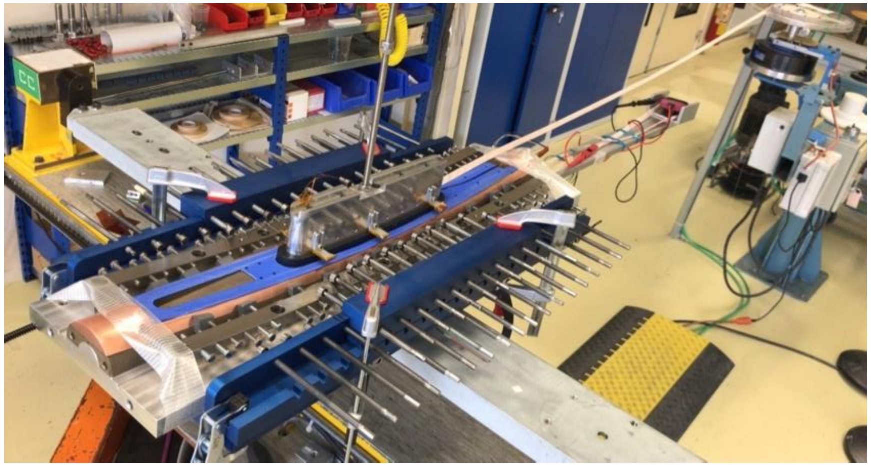
- So far only several accelerator magnet coils have been made with the ReBCO tapes and Bi-2212 cables
- Similarly, the first hybrid dipole demonstrators, such as 13+5 T at CERN and 12.3 T at BNL

CERN design of HTS 5 T insert magnet for 13 T Nb_3Sn background field





Courtesy of G. Kirby, J. Van Nugteren



Main challenges facing the development of future HTS high-field magnets

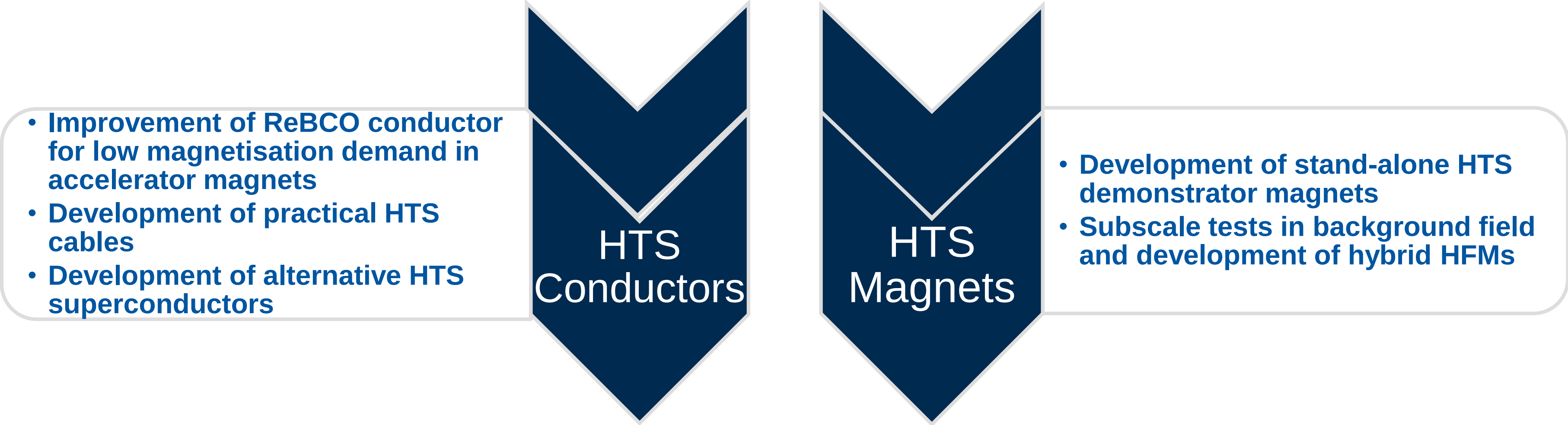
HTS Conductors

- Present main limitations of HTS technology are linked to:
  - ReBCO conductor shear stress sensitivity and degradation
  - Bi-2212 conductor stress/strain sensitivity and degradation
  - Large magnetization of ReBCO conductors. Tape conductor shape (rather than multifilamentary round wire) create field errors that may be too large for accelerator magnets
  - Quench protection of accelerator size magnets made with ReBCO and Bi-2212 HTS coils with high current and stored energy densities but low quench propagation velocity
  - Uniformity of ReBCO cables along the length and lot to lot
  - Limited length of ReBCO tapes and cables
  - Limited ability to bend at small radii of ReBCO conductors, forcing specific, not very effective structures of magnet coil ends allowing for large bend radii
  - Very complex Reaction Heat Treatment for Bi-2212 which must be performed under high-pressure in oxygen atmosphere what for large-scale coils may be difficult
  - …

R&D Strategy and Focus Areas for the HTS high-field magnets

HTS Conductors and Magnet Technology

- The broader HTS magnet technology, including cable design, coil design, joints, quench detection and magnet protection remains at an early stage of development
- Main focus area is demonstration of the suitability of state-of-the-art HTS conductors for accelerator magnets, providing a proof-of-principle of HTS magnet technology beyond the range of Nb_3Sn



- **Improvement of ReBCO conductor for low magnetisation demand in accelerator magnets**
- **Development of practical HTS cables**
- **Development of alternative HTS superconductors**

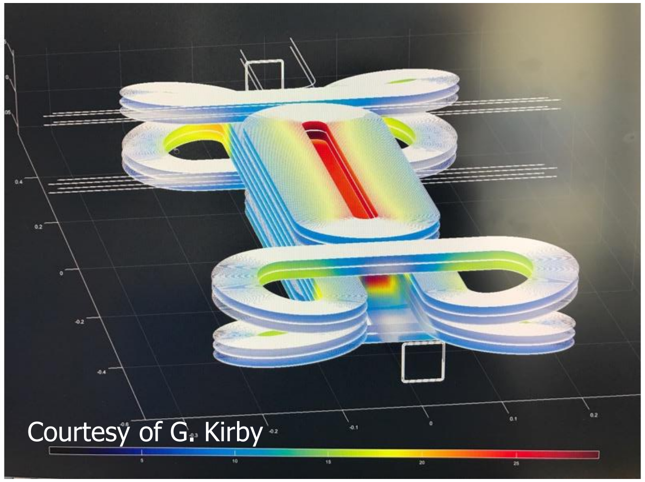
HTS Conductors

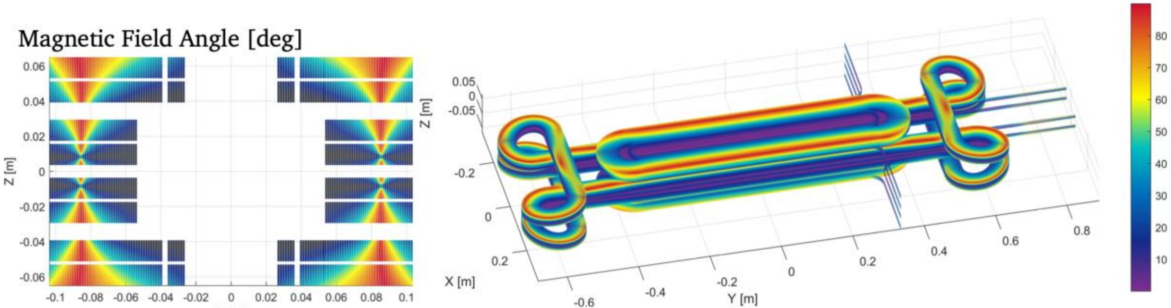
HTS Magnets

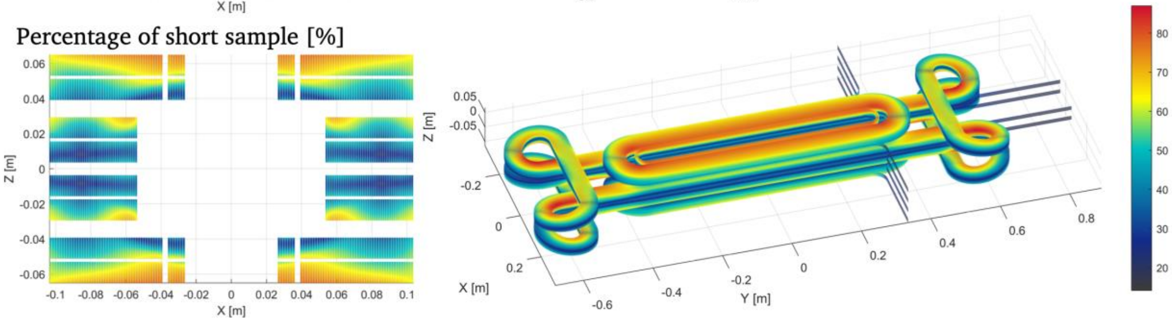
- **Development of stand-alone HTS demonstrator magnets**
- **Subscale tests in background field and development of hybrid HFMs**

HTS is the only path beyond 16 Tesla

- Using present HTS conductors now vs. waiting for better is under deliberation
- Conceptual design of HTS magnets using existing state-of-the-art conductors is ongoing


Courtesy of G. Kirby





Ongoing work examples: 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 November**

Courtesy of B. Holzapfel

R&D strategy in other areas of interest

Enabling Technology R&D

- Present limitations of state-of-the-art HFM are often linked to enabling technologies that need to be further developed and advanced

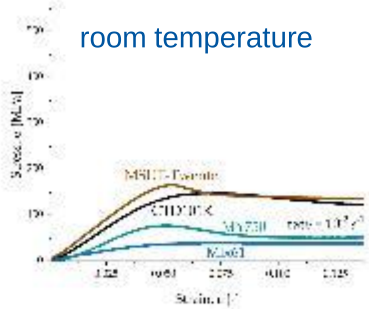
Enabling Technologies

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

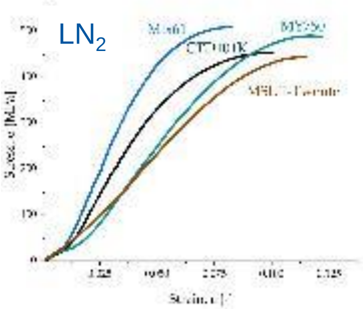
Resin Systems Development

- 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.

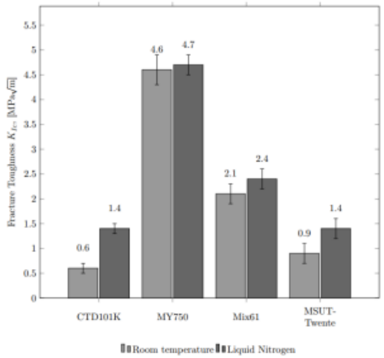
room temperature

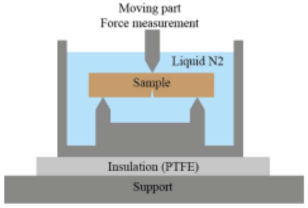


LN$_2$



~450 MPa





A. Brem, T. Tervoort, 2020.

Sample overview

Var. R

Var. f

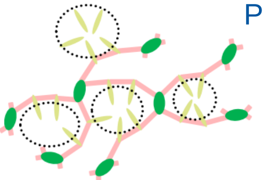
Var. sidechain

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.



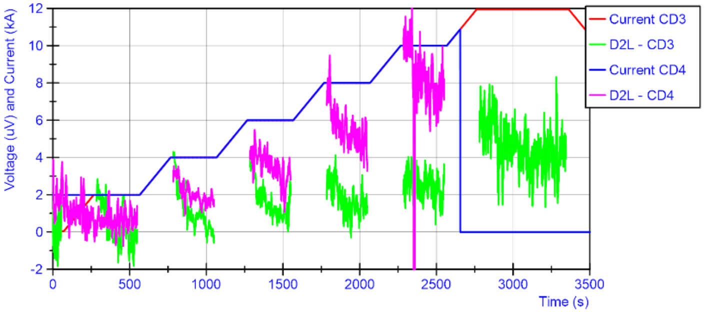
Are there nanodomains and are they responsible for improved properties?

Courtesy of T. Tervoort

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

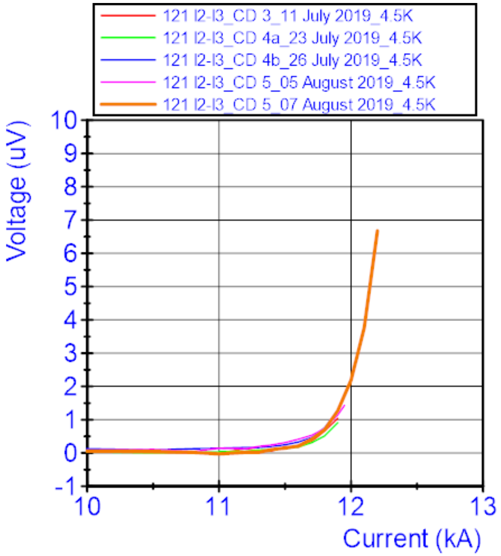
HL-LHC and HFM synergy: additional diagnostics developed within the HL-LHC Project will serve as well the HFM programme

- 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.



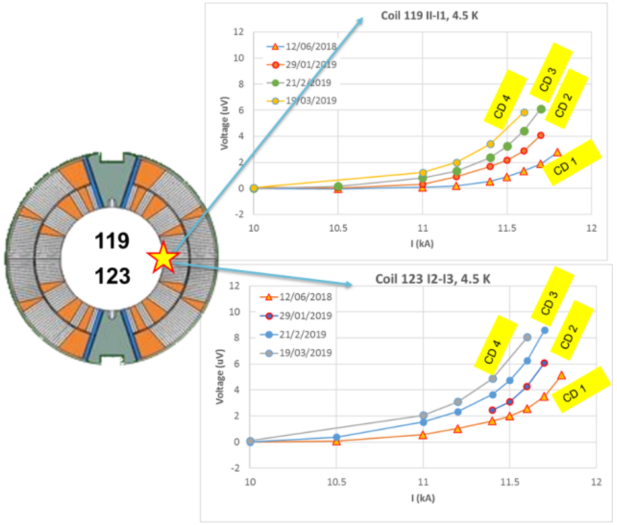
11T Series #2: Change in full coil voltage between cool down 3 and cool down 4; the method can show degradation and changes in degradation, even before the quench happens.

SP107



Stable Behavior

SP109

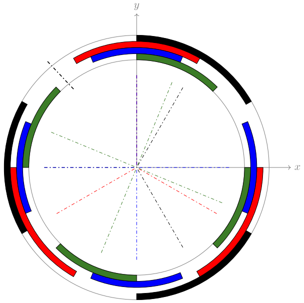


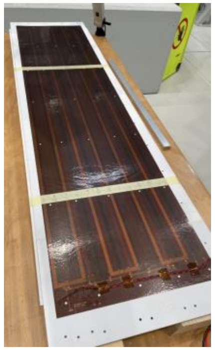
Degrading Behavior

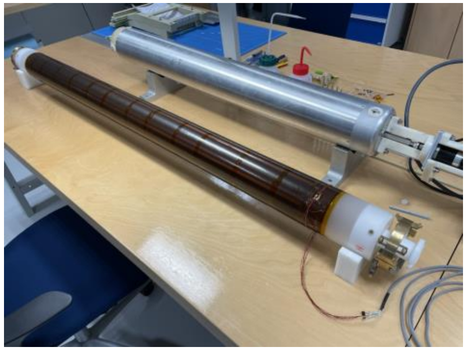
Courtesy of A. Devred

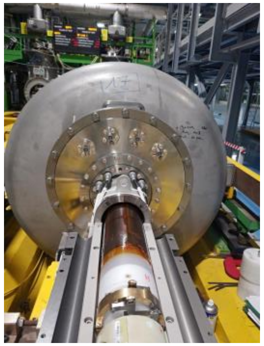
HL-LHC and HFM synergy
Multipole-Sensitive Quench Antenna

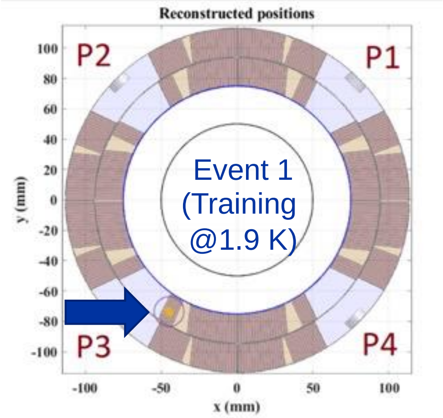
- Quench antenna configuration enabling accurate quench start localization, both longitudinally and azimuthally (concept initially proposed by T. Ogitsu, circa 1993)
- B3,A3,B4,A4 sensitive through coil design (analogue bucking -> Flex PCB design)
- Compromise between noise (PC, vibrations etc), resolution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

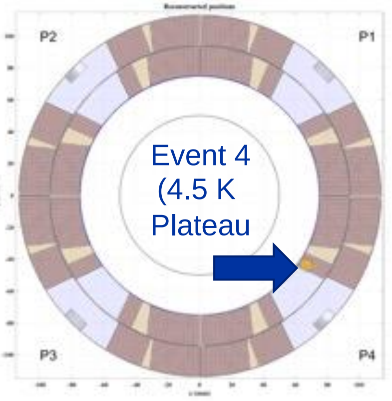


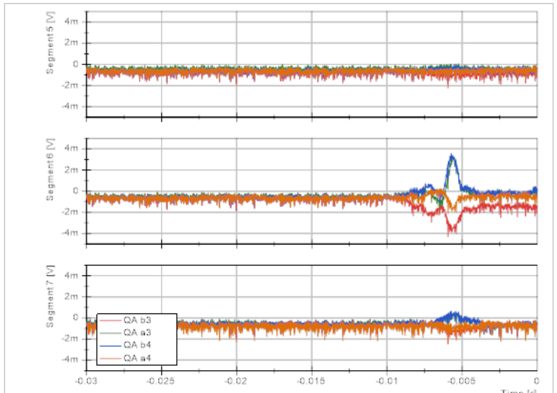






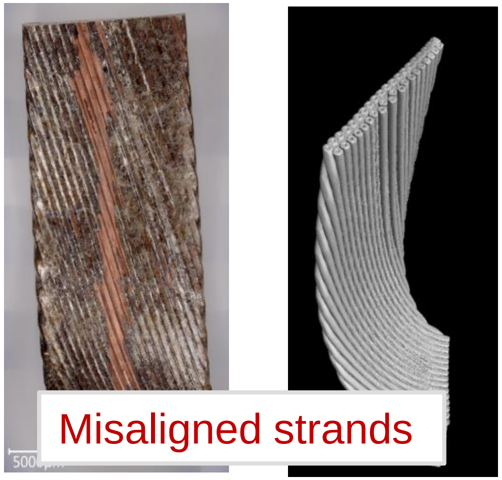


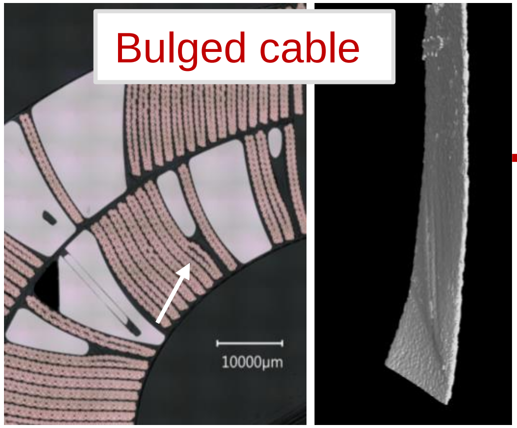


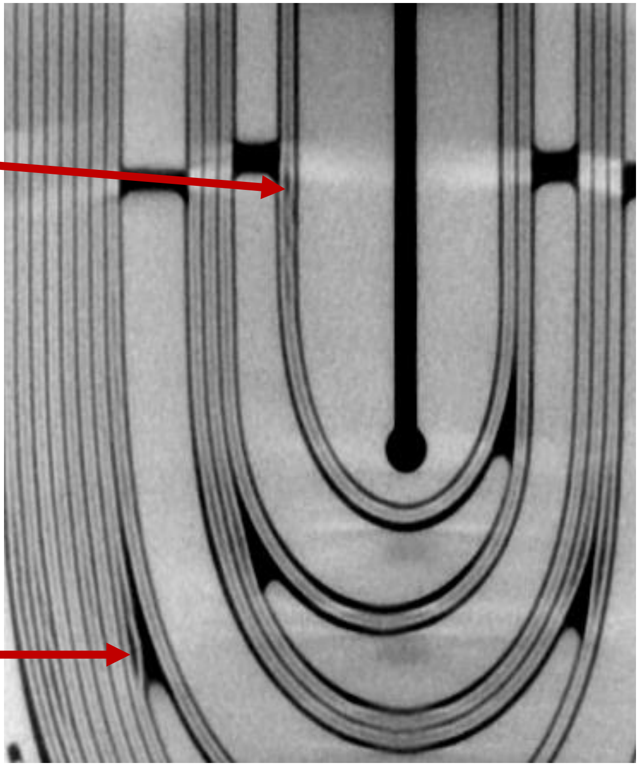


Courtesy of A. Devred

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

R&D strategy in other areas of interest

Infrastructures

- HFM R&D programme will require the development of new infrastructures related to both superconducting cables and magnets

- **Magnet test infrastructures for the HFM programme**
- **Infrastructure for conductors and characterisation**
- **Infrastructure for building demonstrators, short magnet models and full-scale prototypes**
- **Novel instrumentation, diagnostics and measurement equipment**

Infrastructures

Outline

- Where do we stand on the LTS High Field Magnet development?
  - State-of-the-art LTS superconductors and magnet technology
  - Main challenges facing the development of LTS high-field magnets
  - R&D Strategy and Focus Areas for the LTS high-field magnets
  - Ongoing work and mid-term focus areas

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  - R&D Strategy and Focus Areas for the HTS high-field magnets
  - Ongoing work and mid-term focus areas

- Key mid-term deliverables until the next European Strategy update
- Short overview of the HFM R&D consortium

Summary of main deliverables for 2022-2027 to be delivered as an input to the next Update of European Strategy for Particle Physics

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

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

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

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

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

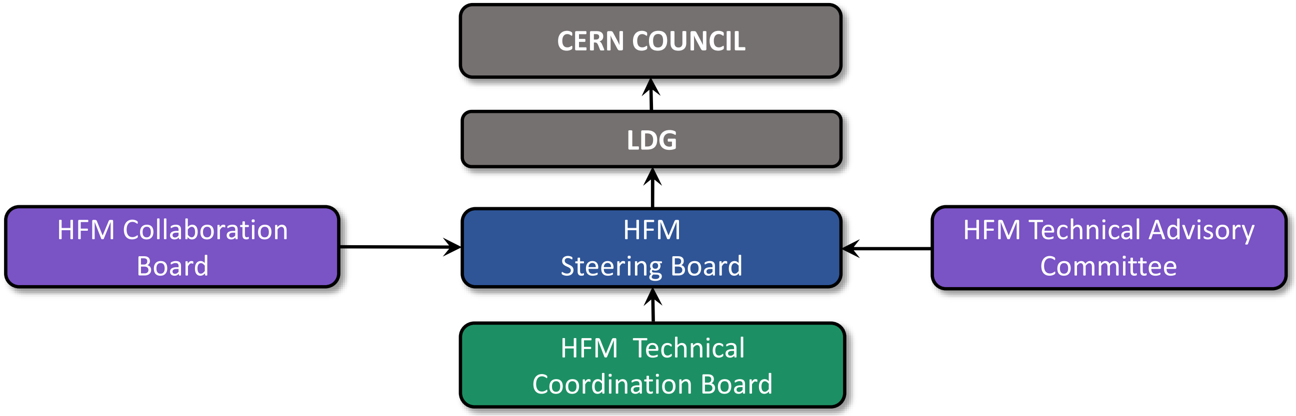
Short overview of the HFM R&D consortium Organisational structure

- 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
Carmine Senatore	**UniGE**	Collaboration Board Chair
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

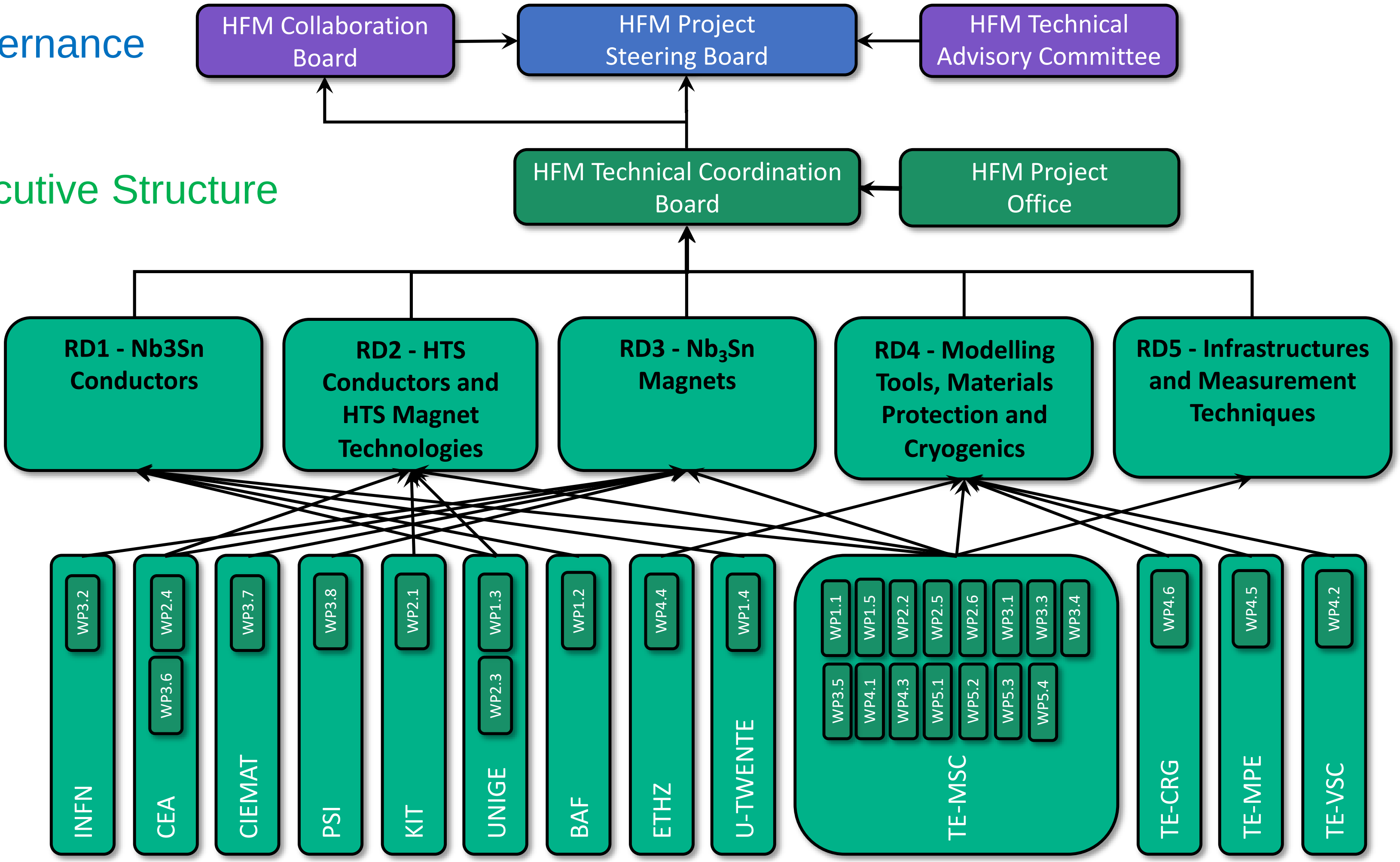
First kick-off meeting 25 August 2022

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

HFM Collaboration Board

HFM Project Steering Board

HFM Technical Advisory Committee

Executive Structure

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

HFM present active collaborations

Full Contract Number	Supplier Description	Country	Project scope
KE3782	CEA SACLAY DRF/IRFU	FR	Nb3Sn high-field magnet development with the design and construction of 14+ T block coil demonstrators
KE3920	CDTI MINIST.DE INDUS. Y ENERGIA (ILO SPAIN)	ES	Development of common coil 14+ T magnet demonstrators and models
KE4102	INFN - INSTITUTO NAZIONALE DI FISICA NUCLEARE	IT	Design and manufacturing of a single-aperture, 12 T robust design short model Nb3Sn dipole magnet
KE4612	UNIVERSITE DE GENEVE	CH	1. Characterization of the electrical and electromechanical properties of state-of-the-art and R&D Nb3Sn wires 2. Exploration of HTS-based technology for the next generation of particle accelerators
KE4663	UNIVERSITE DE GENEVE	CH	Development of methods for the fabrication of Nb3Sn multifilamentary wires with enhanced current carrying capabilities
KE4738	ETHZ (EIDGENOSSISCHE TECHNISCHE HOCHSCHULE ZURICH)	CH	Establish a body of knowledge and create a foundation for the improved performance of Nb3Sn impregnation systems in accelerator magnets
KE4808	PSI - PAUL SCHERRER INSTITUT	CH	Development of stress managed designs of superconducting accelerator magnet at PSI's facilities
KE5074	TECHNISCHE UNIVERSITAT BERGAKADEMIE FREIBERG	DE	Study thermodynamics and phase transformations in Cu-Nb-Sn, with alloying additions, to support the development of Nb3Sn wires
KE5276	UNIVERSITY OF TWENTE	NL	Characterization of Nb3Sn and HTS superconductor samples
KE5283	Karlsruhe Institute of Technology - KIT	DE	R&D Program for advanced ReBCO High Temperature Coated Conductors for high field magnets and energy applications

Two new collaboration agreements with CEA are in preparation

In conclusion

- **The CERN hosted HFM programme**, is a technology focussed R&D mission aimed at developing the next generation of accelerator magnets for future colliders

- 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. This will require a **high degree of innovation, and exploration of emerging technologies** such as the HTS-based magnets

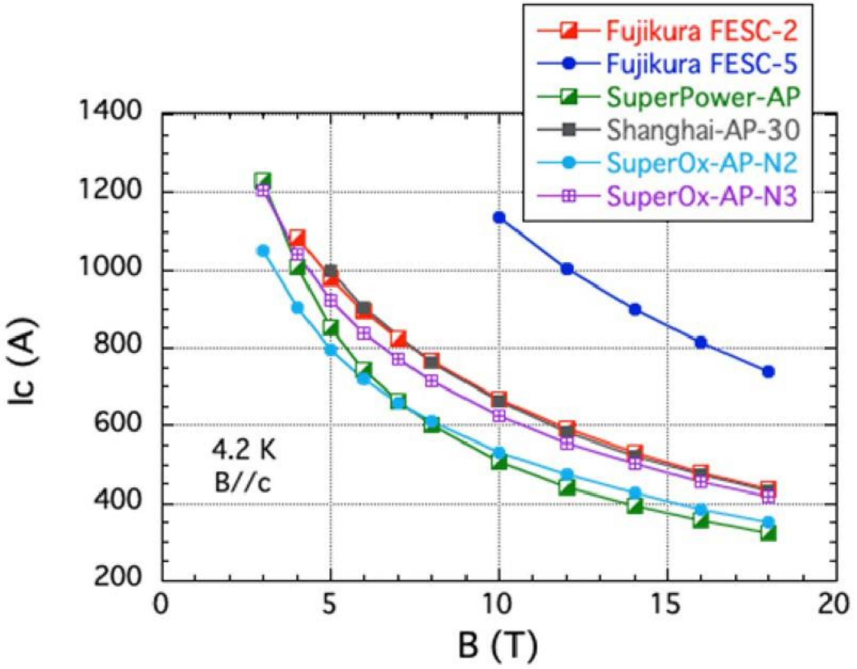
- Fostering and profiting from collaborations with **EU national laboratories** is an essential part of the HFM programme as well as linking to ongoing worldwide efforts, particularly in the **US and Japan**

- We intend to **accelerate the R&D effort** of the HFM programme, focusing on milestones to be achieved by the next ESPP update

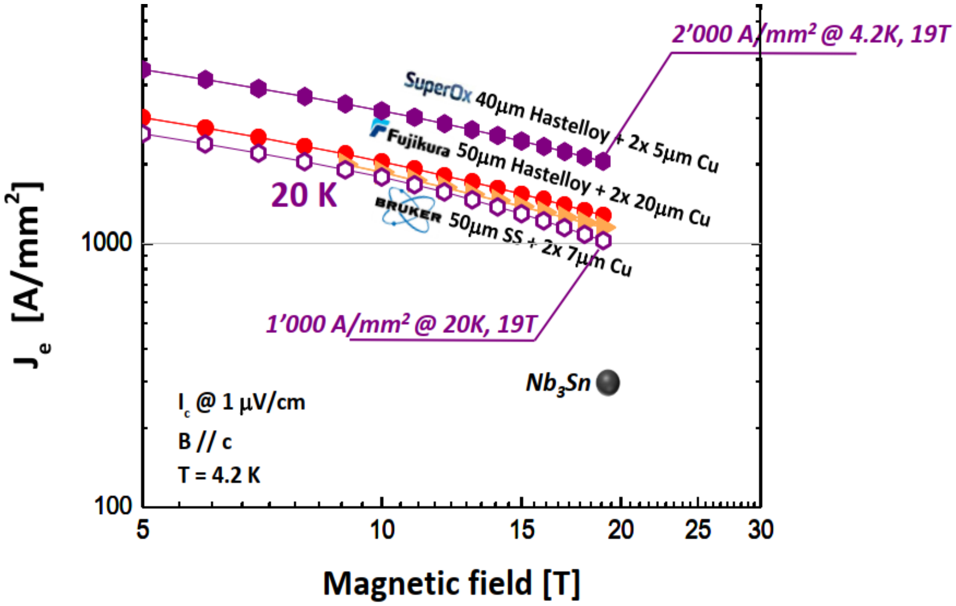
Spare slides

REBCO: State of the Art

- REBCO ($ReBa_2Cu_3O_{7-x}$, RE=rare earth) is a potential enabling technology for magnets beyond 16 T
- For REBCO coated conductor (‘tape’), core technology established, including APCs, but market not yet mature → distinct challenges from Nb_3Sn:



Critical current (I_c) in magnetic field (B) perpendicular to substrate at 4.2 K for selected commercial tapes
Tsuchiya et al., *Supercond. Sci. Technol.* **34** (2021) 105005



Engineering current density (J_e) in magnetic field perpendicular to substrate for selected conductors (C. Senatore, UNIGE)

Courtesy of S. Hopkins