

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

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with inputs from:



HFM
High Field Magnets

ECFA
Plenary
Meeting
18.11.2022

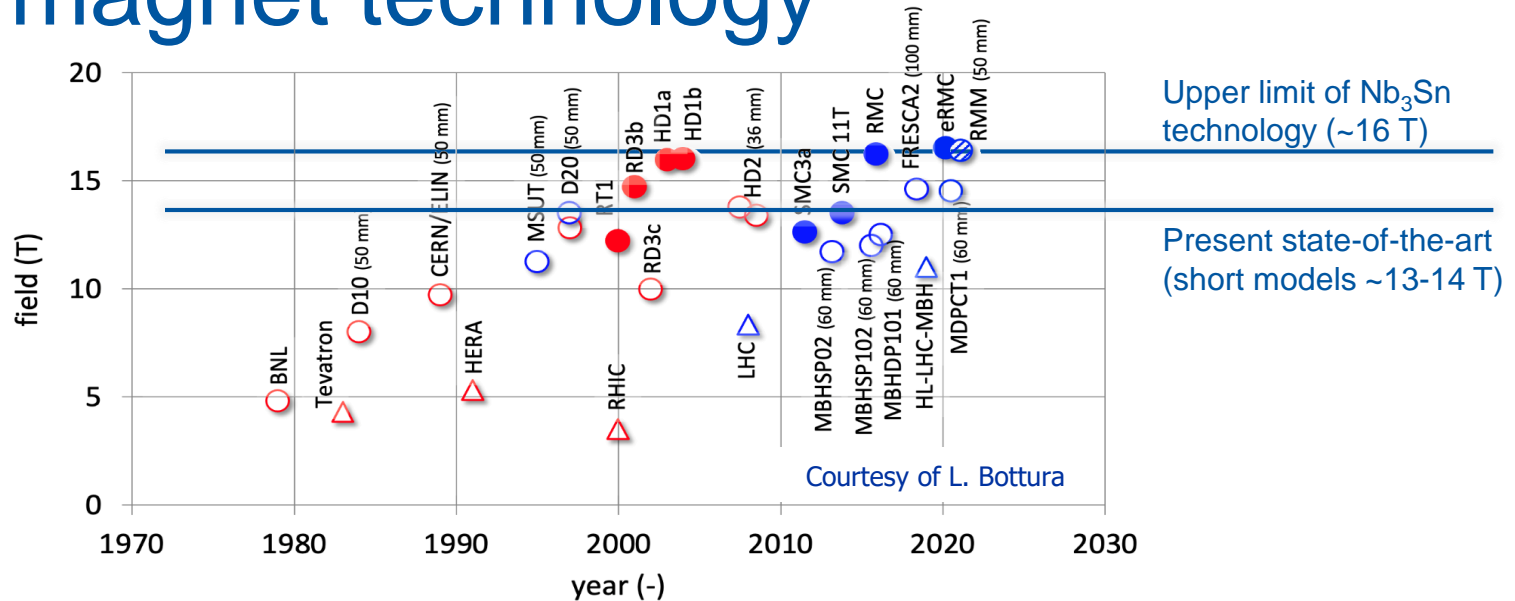
Outline

- 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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- 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 Nb₃Sn 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 Nb₃Sn magnet technology to its practical limits in terms of ultimate performance (towards the 16 T target required by studied Future Circular Collider FCC_{h-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 Nb₃Sn, with a target in excess of 20 T

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



State-of-the-art Nb₃Sn conductor (HL-LHC)

Technology	# of subelements	Cu/non-Cu	Subelement size/shape	Diameter	I _c (16 T)
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RRP

108/127

1.2

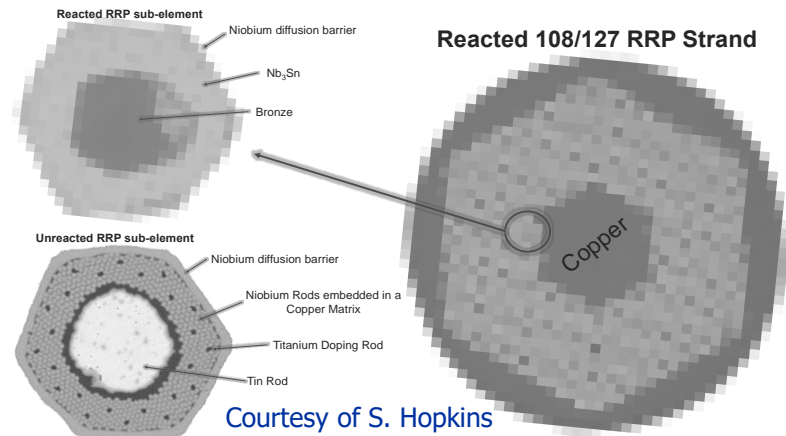
~55 μ m

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



Demonstrator of state-of-the-art Nb₃Sn magnet technology – “12 Tesla Robust Dipole”

- So far, no full-size dipole magnet using Nb₃Sn 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

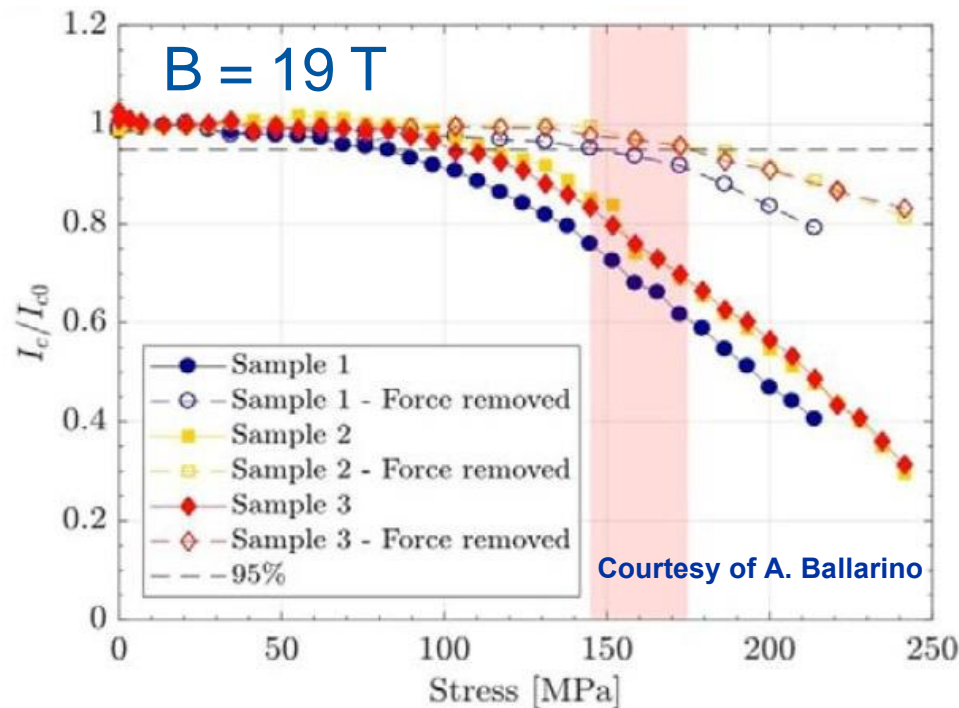
- **Full-size demonstrator of maturity of Nb₃Sn technologies, including improved manufacturability through collaboration with industrial partners**
- **Reaching 14+T with this robust technology will be aided by improved mechanical robustness of Nb₃Sn conductor**

12
Tesla
Robust

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

Nb₃Sn Conductors

- Present limitations of Nb₃Sn technology are linked to:
 - conductor stress/strain sensitivity and degradation
 - thermomechanical behaviour and degradation of magnet performance



- $\sigma_{irr} = 145\text{--}175 \text{ MPa}$

- $I_c/I_{c0} @ 150 \text{ MPa}$
 $\rightarrow 16 \% - 28 \%$

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

Nb₃Sn Conductors and magnets: pushing towards ultimate performance

- **Stress/strain sensitivity** and degradation of Nb₃Sn conductors **to be overcome** by one of the two development paths:

- New Nb₃Sn wire structures with improved mechanical robustness
- Higher J_c (increased margins)
- Industrialization of improved superconductor

Nb₃Sn
Conductor
R&D

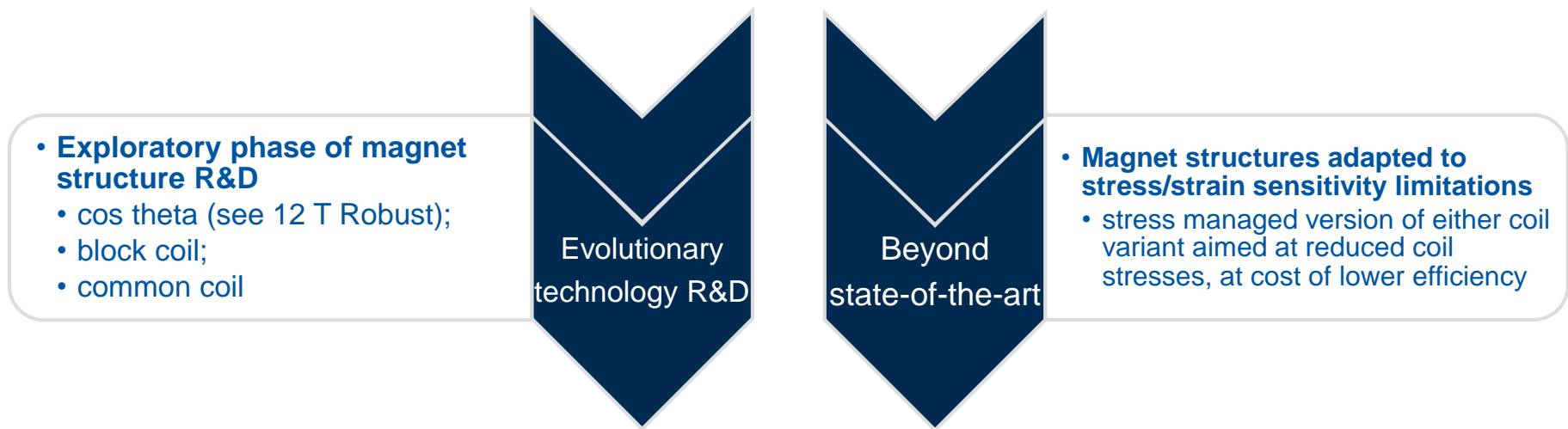
Novel
Magnet
Structures

- Magnet structures need to be adapted through stress management to cope with performance limitations due to Nb₃Sn stress/strain sensitivity and thermomechanical behaviour

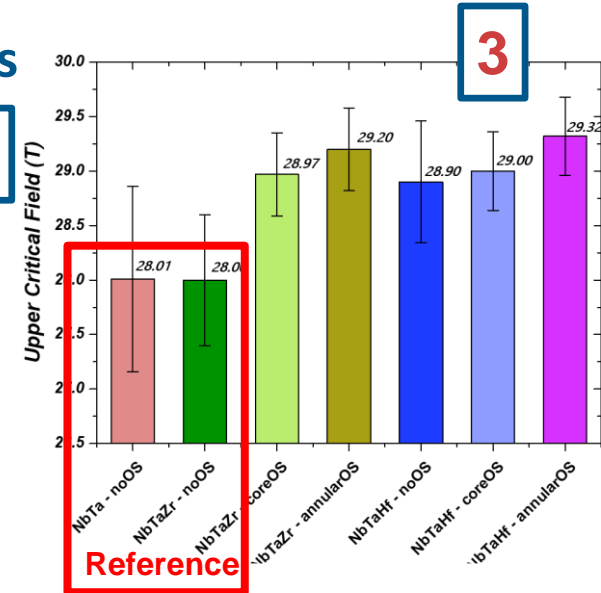
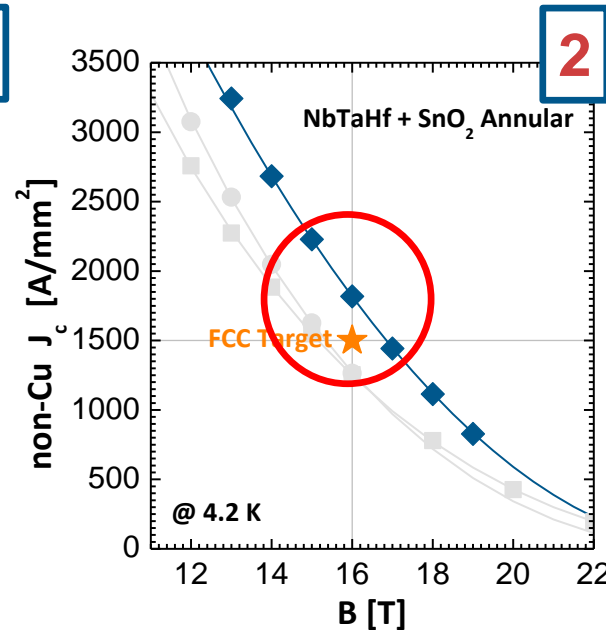
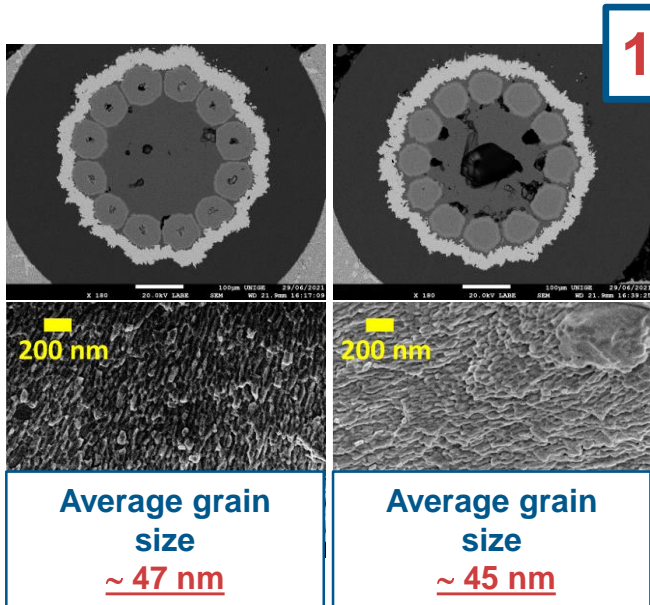
R&D Strategy and Focus Areas for the LTS high-field magnets

Nb₃Sn 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-of-the-art magnet structures
- 1st priority: performance and (sufficient) robustness.
- 2nd priority: maximum robustness and reduced cost.



Internal Oxidation in prototype multifilamentary wires



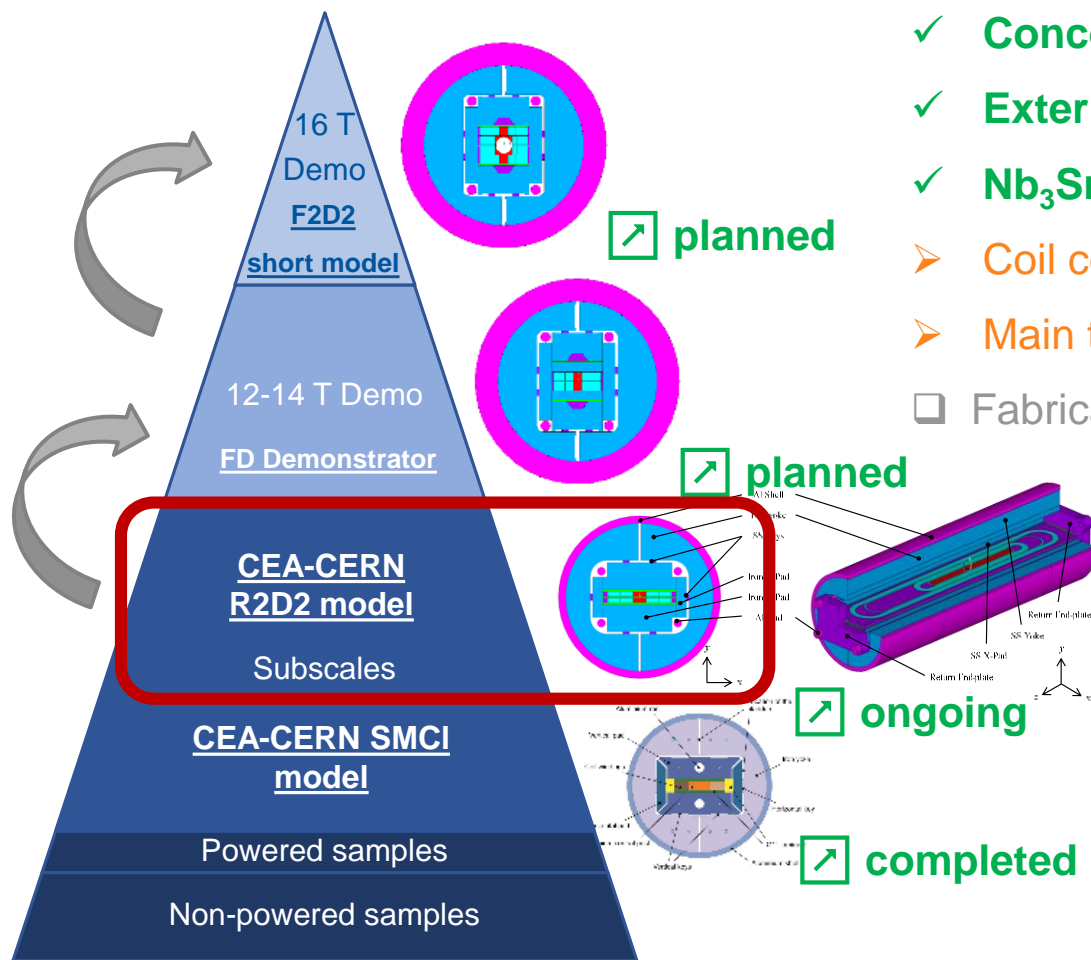
Pushing Nb₃Sn towards its ultimate performance

- 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

Status of R2D2 demonstrator of graded Nb₃Sn technology

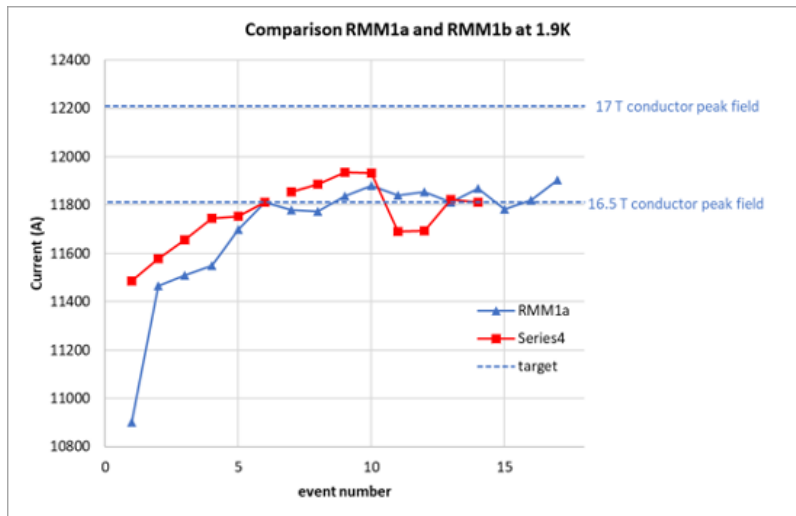


- ✓ Conceptual design done and reviewed
- ✓ External joint procedure validated at CEA
- ✓ Nb₃Sn prototype cables validated at CERN
- Coil components ordered
- Main tooling ordered
- ❑ Fabrication planned to start early 2023 at CEA

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

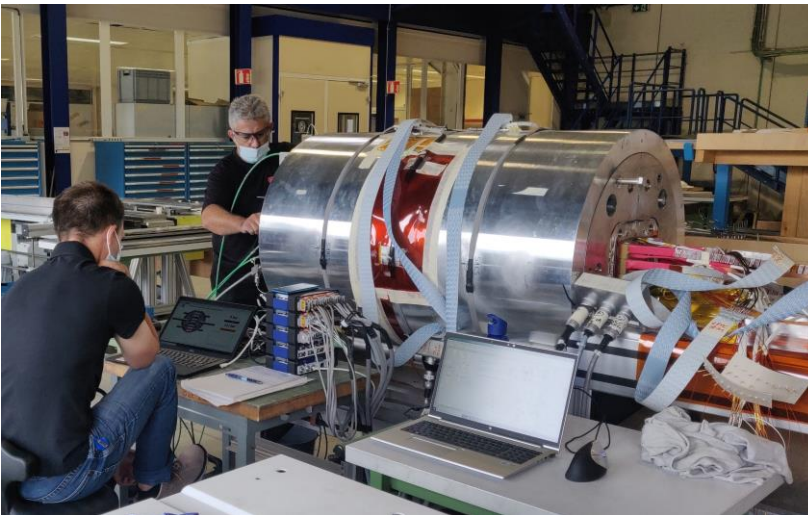
Courtesy of E. Rochepault

RMM1b test at CERN



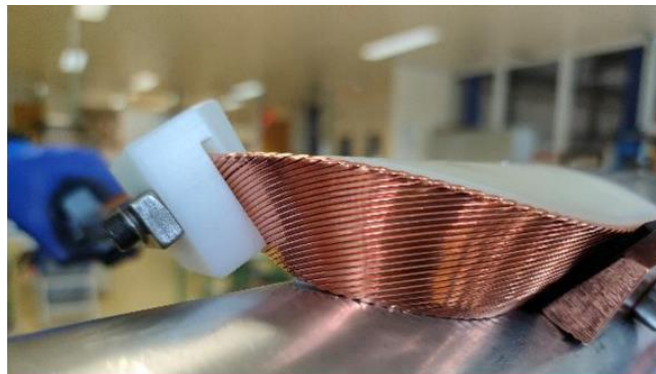
- RMM1b test performed at CERN Aug/Sept 2022
- Maximum current reached in Q #9 & Q #10 of 11.94 kA corresponding to conductor peak field B_p of **16.7T and 16.5 T** in aperture cavity
- Small detrainning is attributed to insufficient prestress in the coils
- Magnet was warmed up and will be assembled with higher prestress in the coils

Courtesy of J. C. Perez

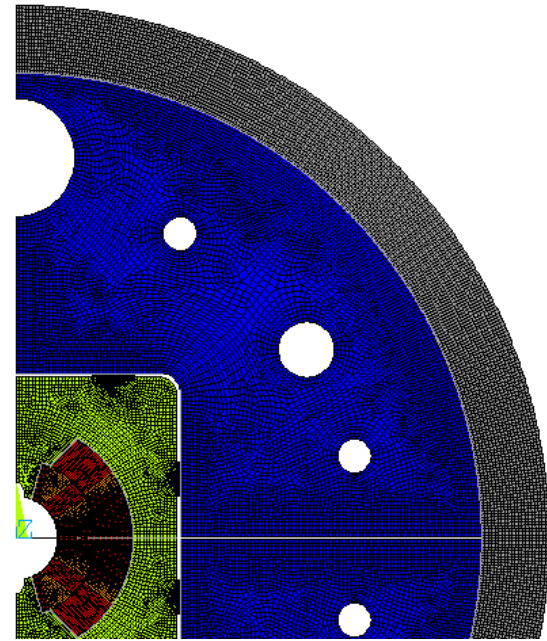


FalconD: single aperture, dipole model as part of the 12 T robust dipole development

- 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.



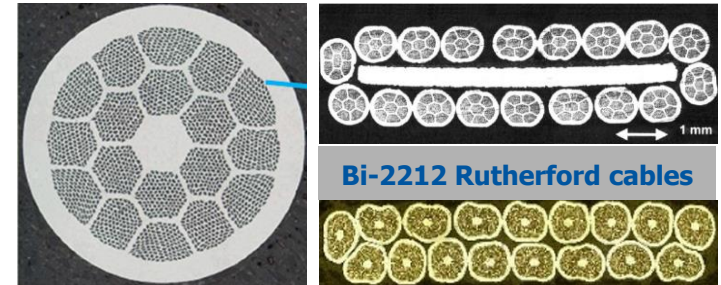
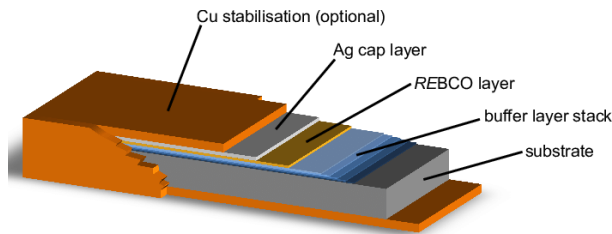
FEM model of the FalconD single aperture bladders and keys, 12 T dipole.

Courtesy of S. Farinon and D. Perini

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



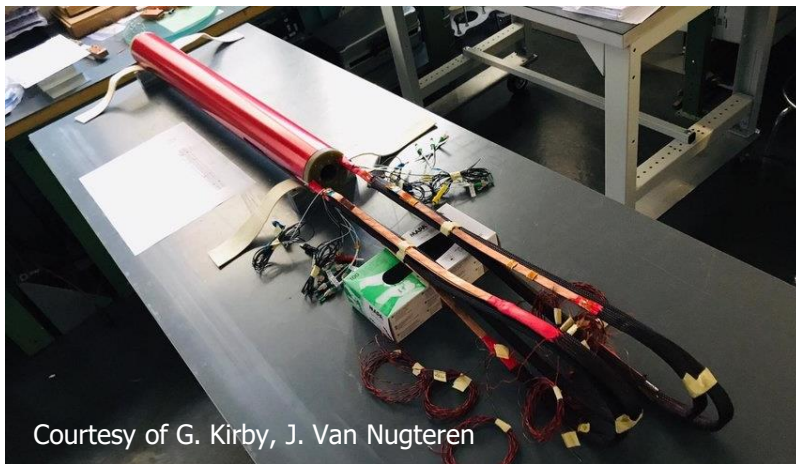
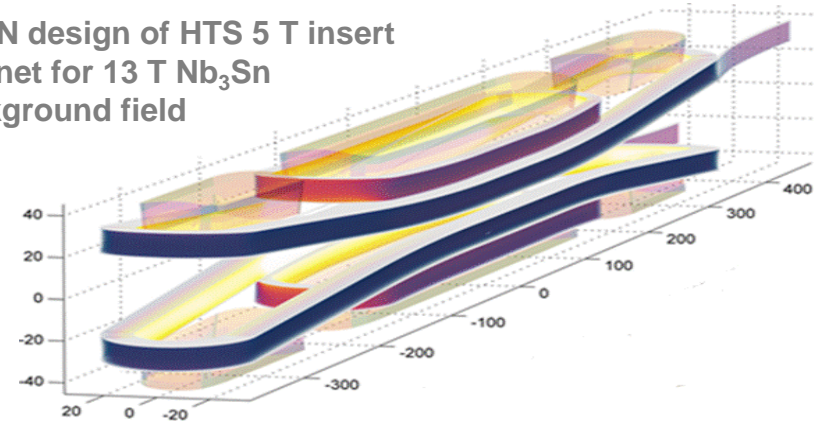
ReBCO	Characteristics	Bi-2212
High, steadily improving	Critical current	High, more stagnant
Roebel cable (waste), 50-200 m unit length available; CORC cable; STAR cable; Twisted stacked-tape cable	Cabling methods	Easy Rutherford cable, but need special H.T., very long length possible
Very bad (tape shape).	Magnetization	Worse than NbSn but manageable
Excellent vs. transversal stress, better than Nb ₃ Sn, 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



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 Nb₃Sn

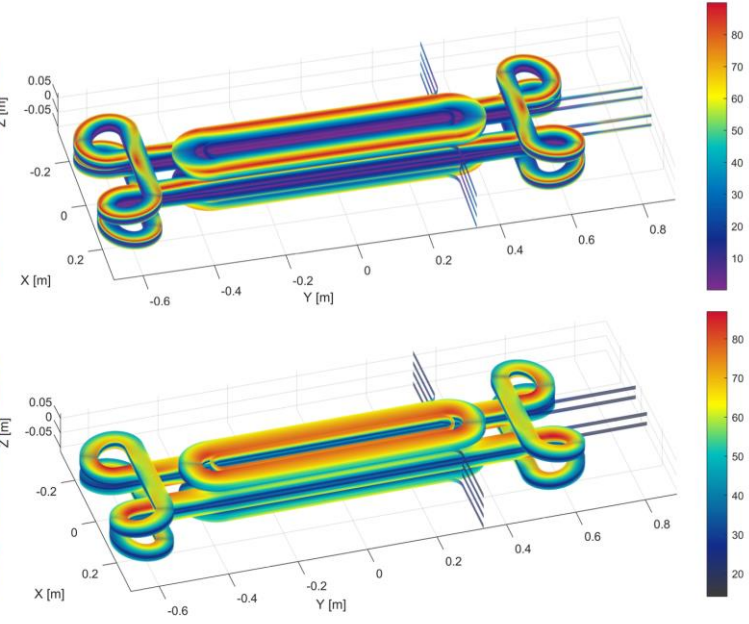
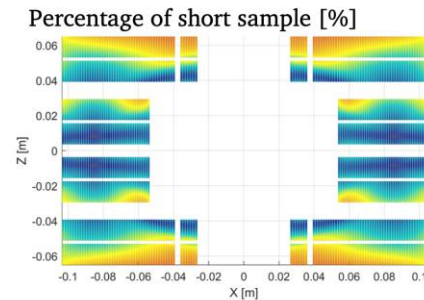
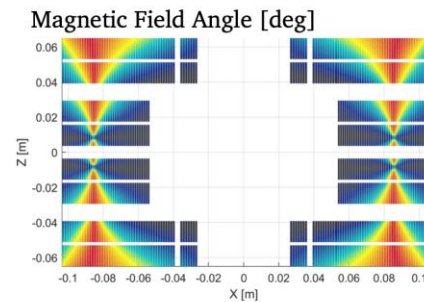
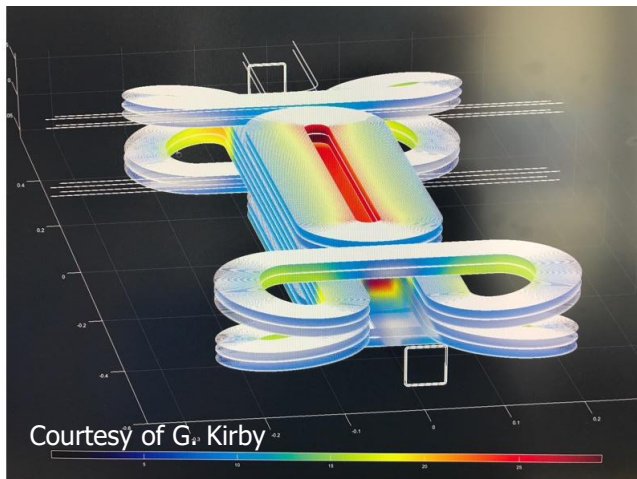
- Improvement of ReBCO conductor for low magnetisation demand in accelerator magnets
- Development of practical HTS cables
- Development of alternative HTS superconductors



- 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

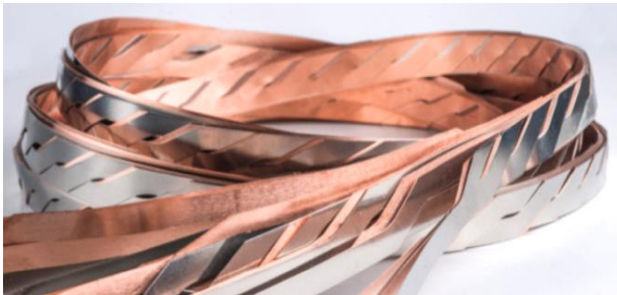
- Using present HTS conductors now vs. waiting for better is under deliberation
- Conceptual design of HTS magnets using existing state-of-the-art conductors is ongoing



Ongoing work examples: KIT-CERN Collaboration on Coated Conductors

KC⁴ 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

- 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



Enabling
Technologies

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

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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 Nb₃Sn conductor** with increased mechanical properties and target Jc 1500 A/mm² @ 16 T
- **Development and demonstration of the Nb₃Sn magnet technology for collider-scale production through robust design**, industrial processes and cost reduction (12 T robust short models)
- **Demonstrator of the Nb₃Sn 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

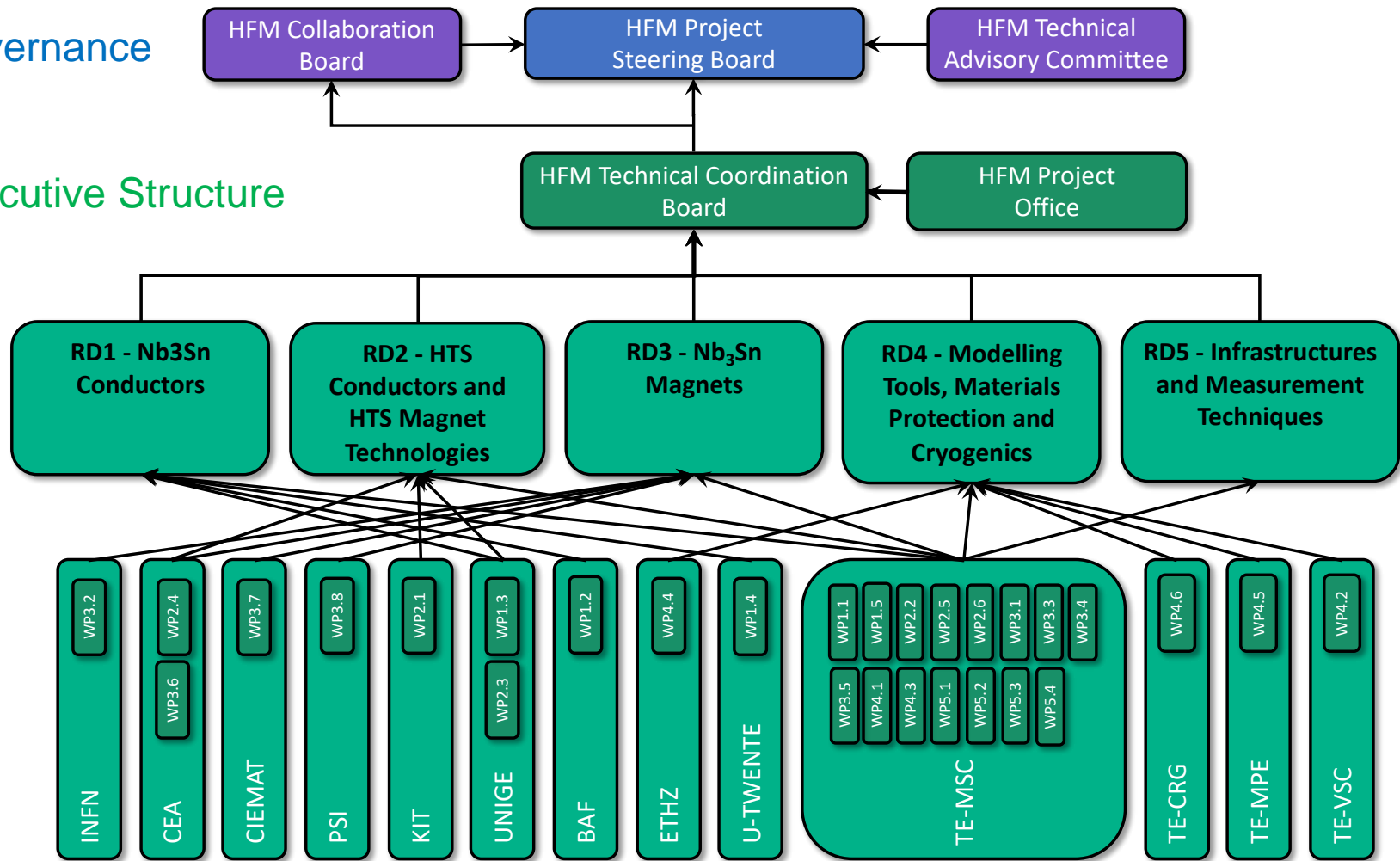
Organisational structure

- 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 Programme Executive Structure

Governance

Executive Structure



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



HFM
High Field Magnets

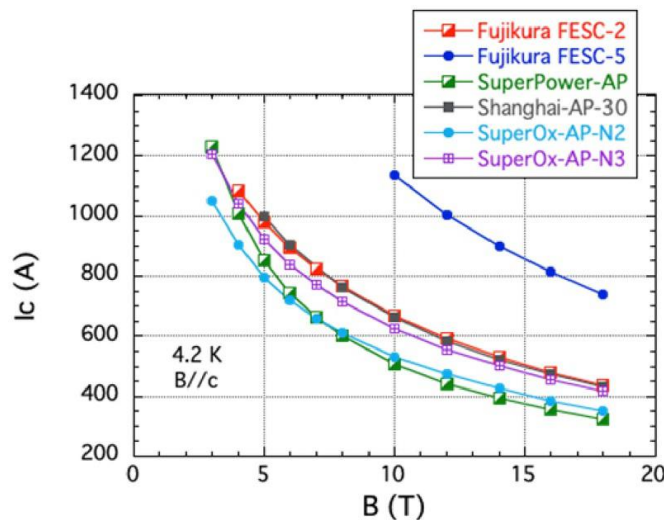
HFM present active collaborations

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 - ISTITUTO 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

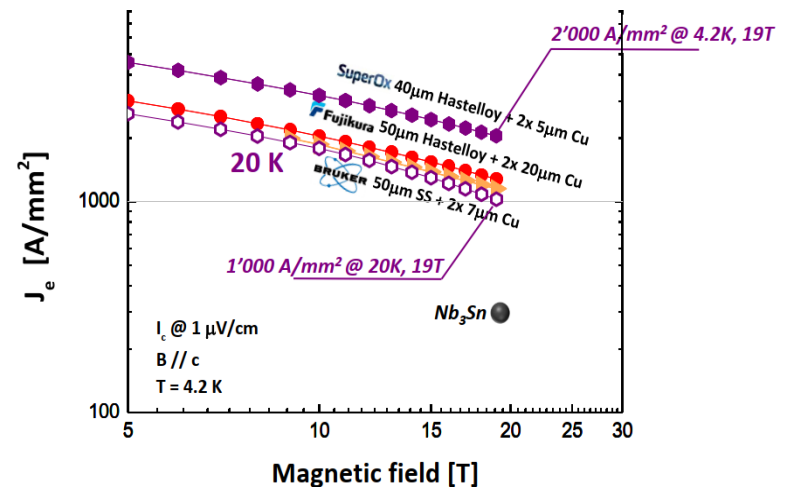
Two new collaboration agreements with CEA are in preparation

REBCO: State of the Art

- REBCO ($\text{ReBa}_2\text{Cu}_3\text{O}_{7-x}$, 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 :
 - J_c is sufficient for most application requirements, J_e (4.2 K, 20 T) > 1000 A/mm², but **anisotropic**, and $J_c(B, T, \theta)$ is strongly **supplier-dependent**, according to technology, composition and APCs.
 - Production yield and piece lengths (< 1 km) still relatively low, contributing to high cost
 - Long-length uniformity of performance, geometry, electrical resistances etc. requires further development



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