Status of High Field Magnet R&D Programme

Andrzej Siemko on behalf of HFM R&D Programme Team

HFM
High Field Magnets

Outline

- Current Consortium, organisation and main objectives of the HFM R&D Programme
- Strategy and focus areas for the LTS high-field magnets
- Strategy and focus areas for the HTS high-field magnets
- Focus areas for other domains of interest
- Key mid-term deliverables until the next update of European Strategy for Particle Physics
- Final remarks

HFM R&D Consortium (present main contributors)

Magnets

cea

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

INFN
Istituto Nazionale di Fisica Nucleare

PAUL SCHERRER INSTITUT
PSI

CERN

Conductors

KIT
Karlsruher Institut für Technologie

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

TU BERGAKADEMIE FREIBERG
TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG
Die Ressourcenuniversität. Seit 1765.

CNR SPIN

University of Southampton

University of Twente
The Netherlands

CERN

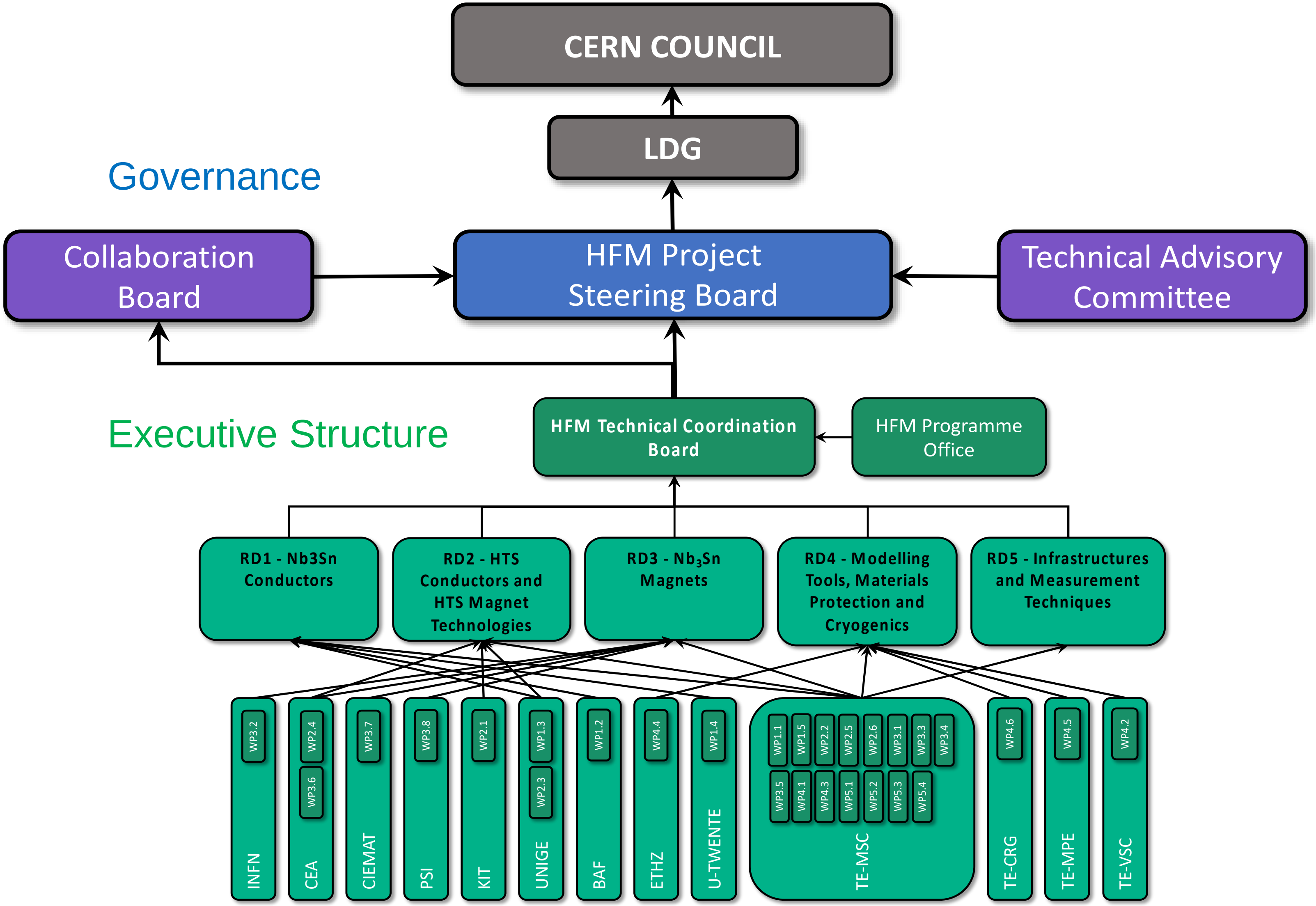
Enabling Technologies

ETH zürich

Tampere University

CERN

HFM R&D Programme Structure



Governance

CERN COUNCIL

LDG

Collaboration Board

HFM Project Steering Board

Technical Advisory Committee

Executive Structure

HFM Technical Coordination Board

HFM Programme Office

RD1 - Nb3Sn Conductors

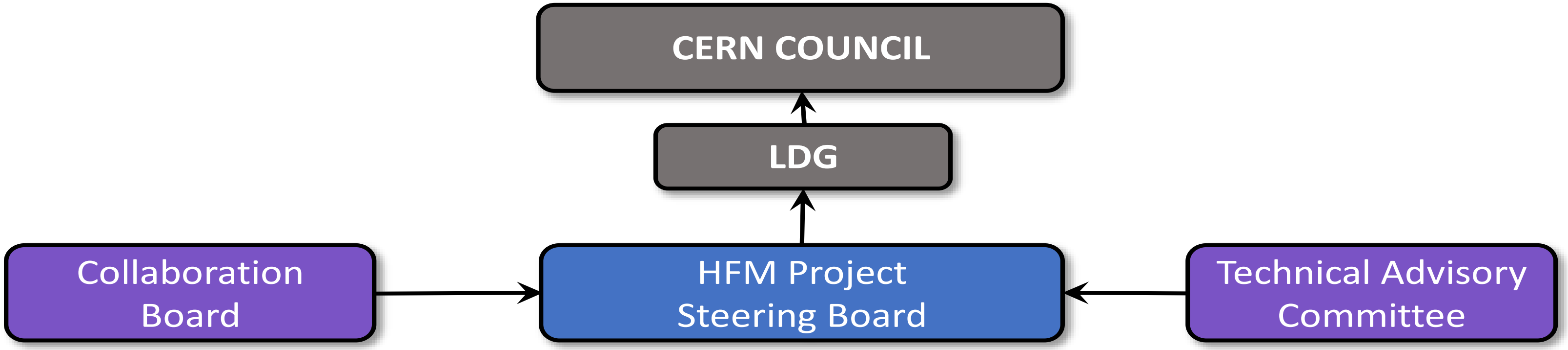
RD2 - HTS Conductors and HTS Magnet Technologies

RD3 - Nb_3Sn Magnets

RD4 - Modelling Tools, Materials Protection and Cryogenics

RD5 - Infrastructures and Measurement Techniques

HFM Governance



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

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**

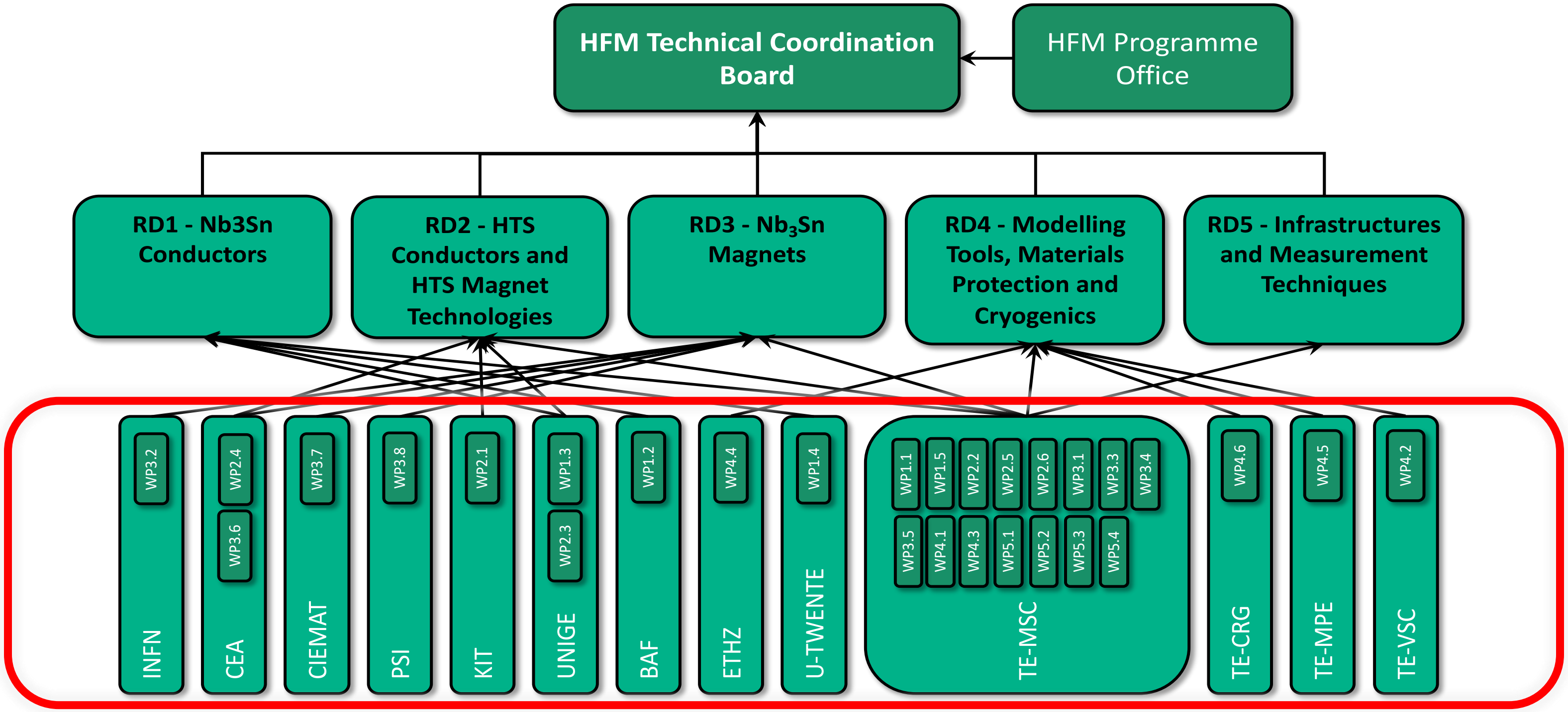
Advisory Committee to be defined, discussion in SB

HFM Executive Structure

- **Work Packages**

Work Packages refer to self-contained, focused units of work in the RD Line designed to achieve specific, measurable outcomes or deliverables within a predetermined timeframe and resources.

Work Packages are undertaken by collaborating institutions or CERN groups and outline the tasks, resources, dependencies, and milestones required to achieve tangible results. They are characterized by clear, focused deliverables, enabling monitoring and evaluation of progress towards the overall goals of the RD Line and HFM Programme



HFM Technical Coordination Board

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RD3 - Nb$_3$Sn Magnets

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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

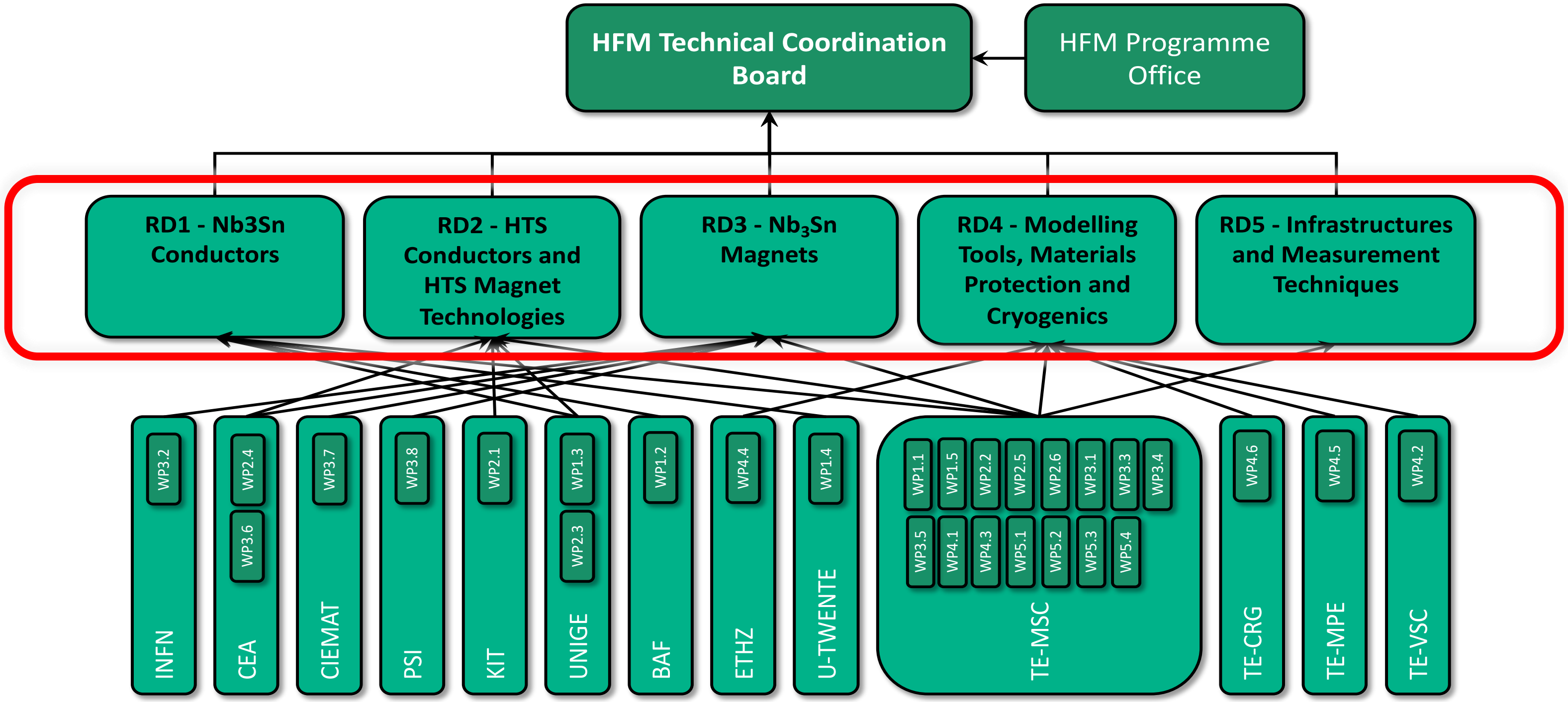
TE-VSC: WP4.2

HFM Executive Structure

- **RD Lines**

These are technical domains in the context of the LDG HFM Roadmap document, such as 'Nb3Sn magnets' or 'HTS conductors and HTS magnet technologies'. The RD Lines are conducting research in a collaborative, complementary, and, where appropriate, competitive spirit.

Each RD Line provides a community-wide forum for discussion and agreement on the technical aspects of the respective RD Line roadmap, including the formulation of new proposals.



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TE-CRG: WP4.6
TE-MPE: WP4.5
TE-VSC: WP4.2

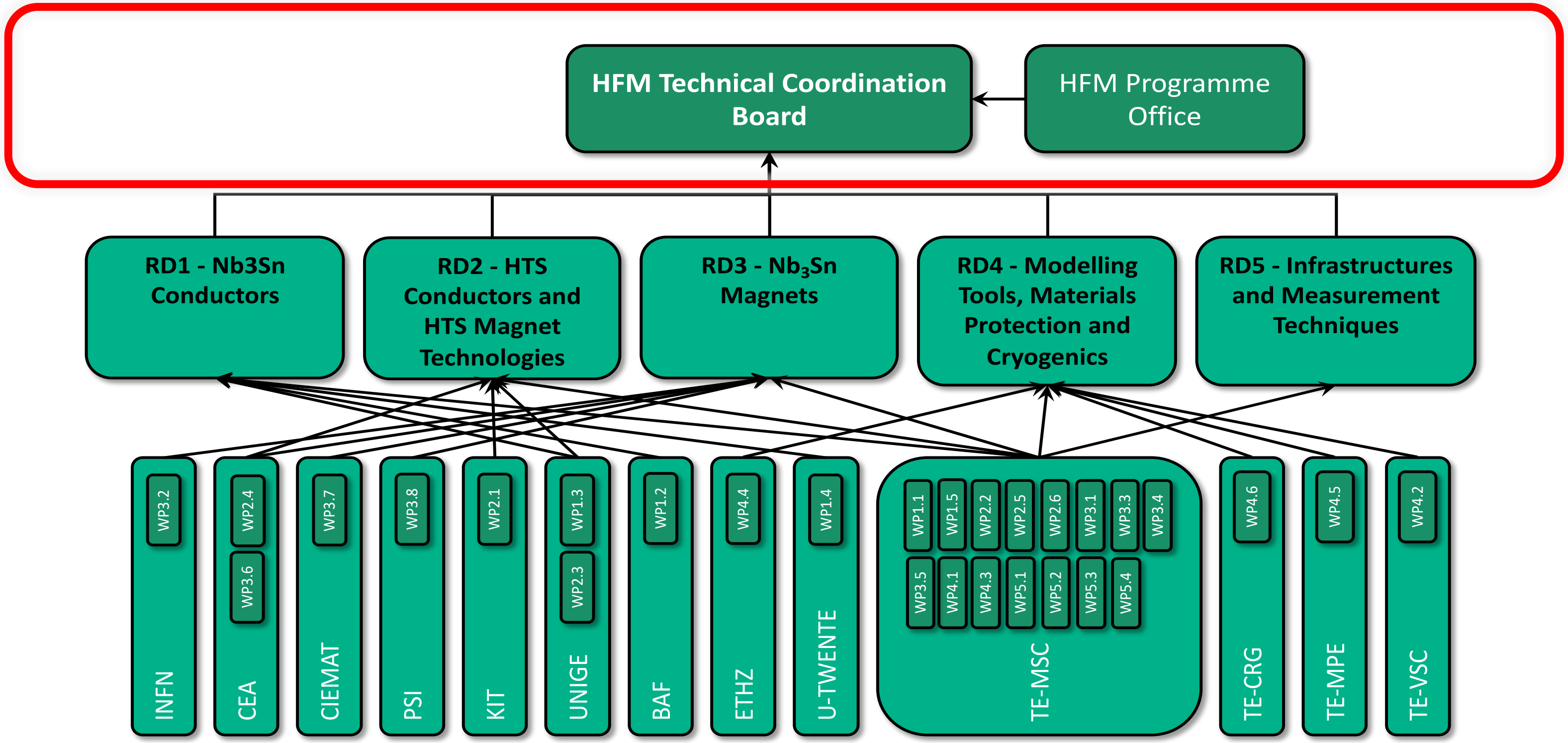
HFM Executive Structure

- ## Technical Coordination Board

Ensures and facilitates communication and coordination between Work Packages and RD Lines, the Steering Board, Collaboration Board, and the broader HFM community

- ## Programme Office

Manages all administrative aspects required by the HFM R&D Programme (WBS, budget structure, EVM, EDMS, master plan documentation) and assists in the tracking of resources and schedules



HFM Technical Coordination Board

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TE-CRG: WP4.6

TE-MPE: WP4.5

TE-VSC: WP4.2

HFM R&D Programme – broad goals

- **The EU Accelerator R&D Roadmap identifies main objectives for the High Field Magnet Programme:**
  - **OBJECTIVE 1:**

    Design and demonstrate a full-size Nb3Sn accelerator magnet to proof the maturity of the most advanced technologies today, based on the HL-LHC design, i.e., 12 T magnets, and applying all the lessons learned from the US LHC Accelerator Research programme (LARP), the US High-Luminosity LHC Accelerator Upgrade project (AUP) and the HL-LHC project
  - **OBJECTIVE 2:**

    Explore the limitations of the LTS state-of-the-art technology and push Nb3Sn magnet technology to its practical limits in terms of ultimate performance, towards the 16 T target targeted by the FCC-hh
  - **OBJECTIVE 3:**

    Explore the capabilities and limitations of state-of-the-art HTS and magnet technology based on these superconductors. Demonstrate the suitability of HTS
  - **Create a European Research Network involving CERN and National Labs**

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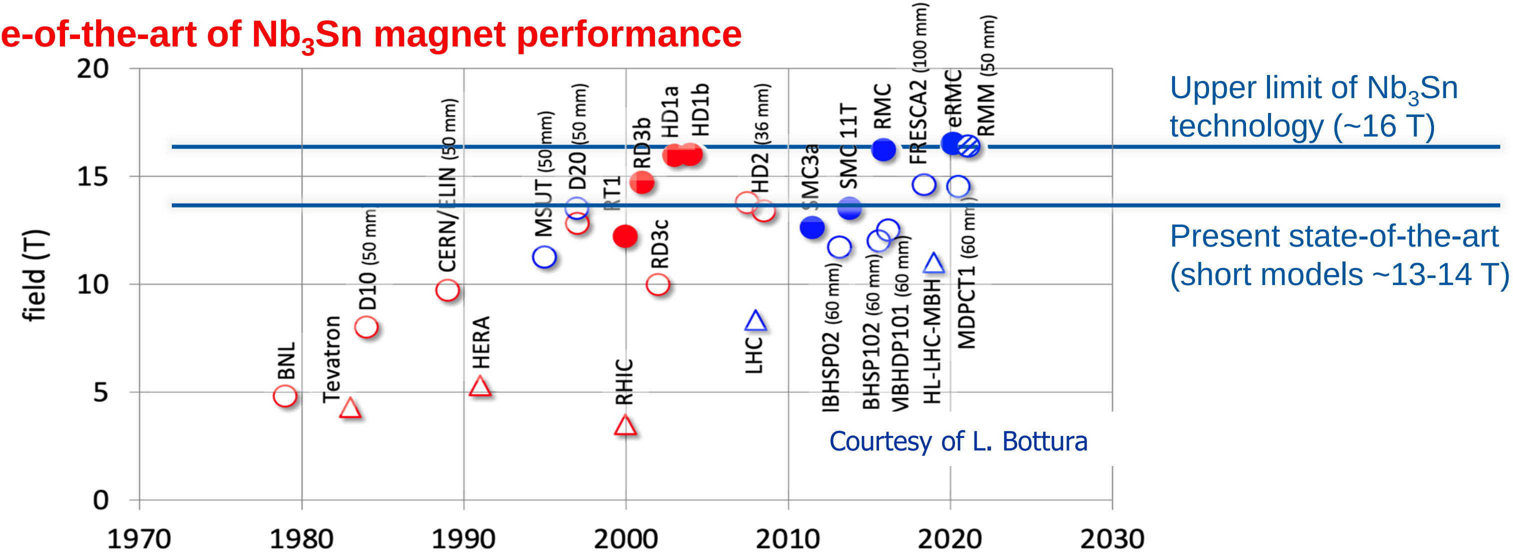
State-of-the-art LTS superconductors and magnet technology

State-of-the-art of Nb_3Sn magnet performance



Upper limit of Nb_3Sn technology (~16 T)

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

Courtesy of L. Bottura

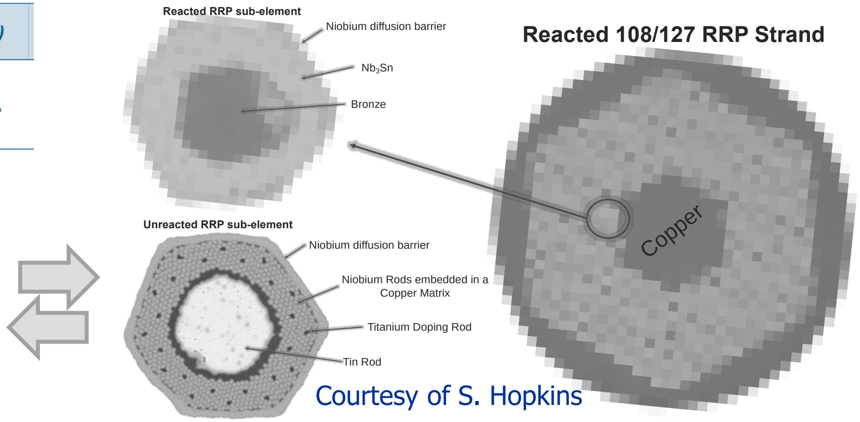
State-of-the-art Nb_3Sn conductor (HL-LHC)

	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

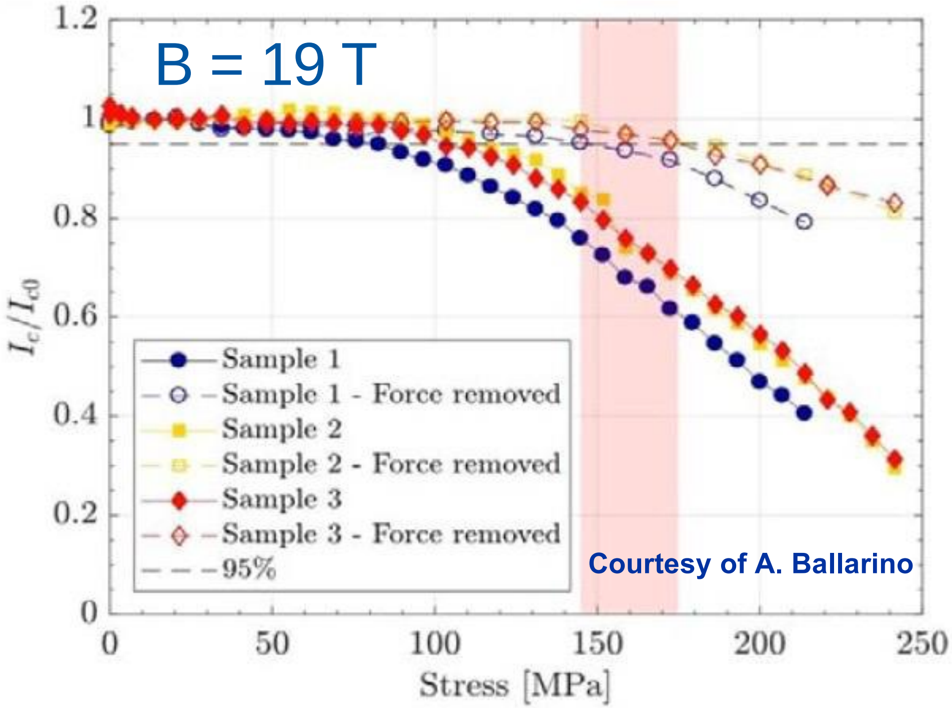


Courtesy of S. Hopkins

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 14+ T magnets

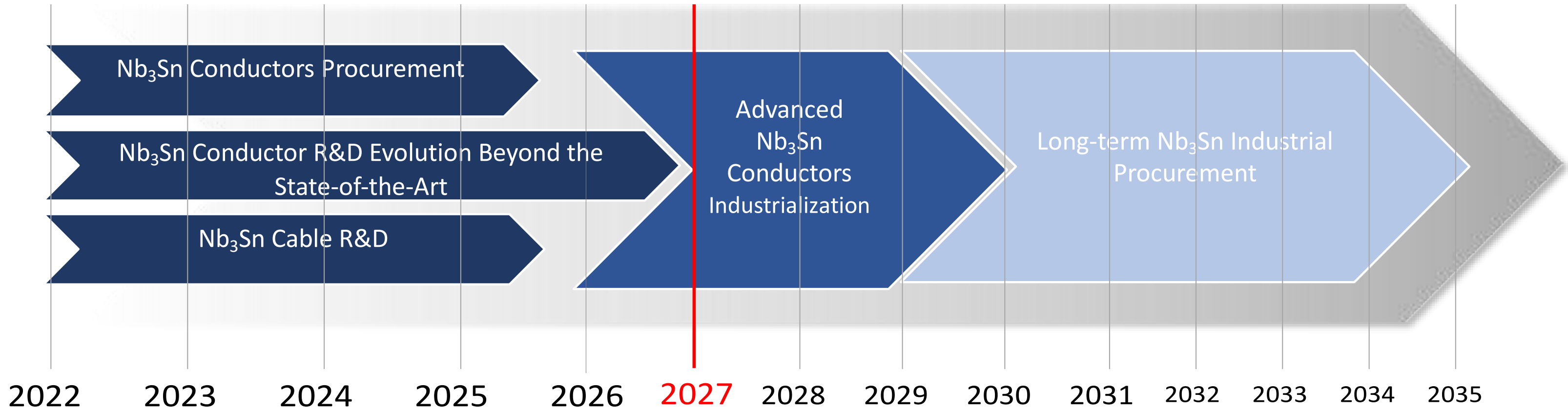
Nb_3Sn Conductors : pushing towards ultimate performance

- **Stress/strain sensitivity** and degradation of Nb_3Sn conductors **to be improved** by ~50% above the present state-of-the-art

- New Nb_3Sn wire structures with enhanced mechanical strength
- Higher Jc (increased margins)
- Industrialization of improved superconductors

Nb_3Sn Conductor R&D

RD1 - Nb_3Sn conductor development program



Nb_3Sn Conductors Procurement

Nb_3Sn Conductor R&D Evolution Beyond the State-of-the-Art

Nb_3Sn Cable R&D

Advanced Nb_3Sn Conductors Industrialization

Long-term Nb_3Sn Industrial Procurement

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

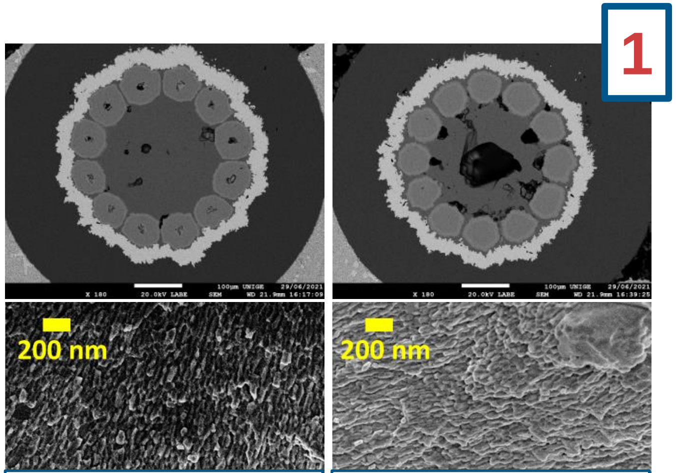
Ongoing work highlights : Prototype Nb_3Sn Wire Development at UniGE

CHART
Swiss Accelerator Research and Technology

Pushing Nb_3Sn towards its ultimate performance

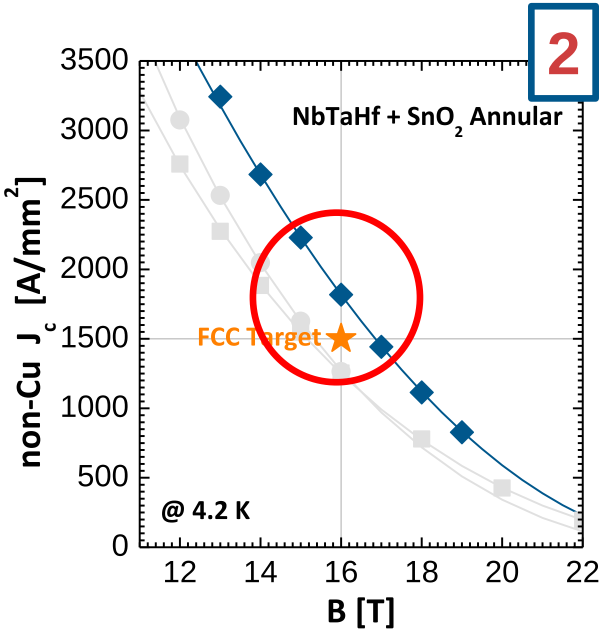
Internal Oxidation in prototype multifilamentary wires

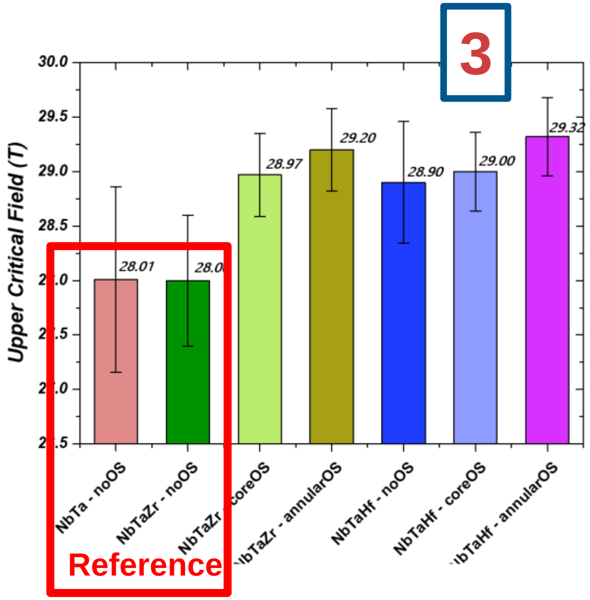
- 1 Refinement of the grain size: 100 nm → 50 nm
- 2 Large increase of the layer J_c → exceeding the FCC target
- 3 Enhancement of B_{c2} by > 1 T → improved in-field performance



Average grain size ~ 47 nm

Average grain size ~ 45 nm





Courtesy of C. Senatore

Focus areas for the LTS magnet technology

Demonstrator of the maturity of state-of-the-art Nb_3Sn technology

“12 Tesla Robust Dipole”

- So far, no full-size dipole magnet using Nb_3Sn technology has been built
- As stipulated by the Accelerator R&D Roadmap, in order to demonstrate the maturity of the most advanced technologies today applying all the lessons learnt so far, and to investigate the physical and technological effects related to the length of the magnets, an accelerator-size magnet demonstrator will be built, taking HL-LHC as a benchmark, i.e., 12 T

- **Accelerator-size demonstrator of maturity of Nb_3Sn technologies, including improved manufacturability through collaboration with industrial partners**
- **Reaching 14+T with this 12 T robust technology will be aided by increased J_c and enhanced mechanical properties of Nb_3Sn conductor**

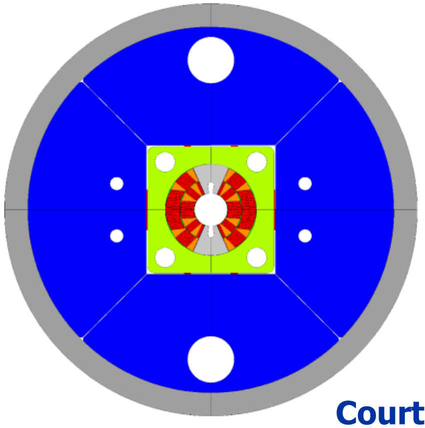
12 Tesla
Robust

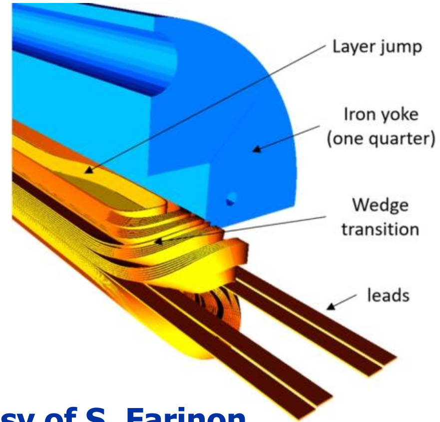
Ongoing work highlights:
12 T robust dipole development

Development of a single aperture 12 T “robust dipole” in INFN, Genova

Main characteristics :

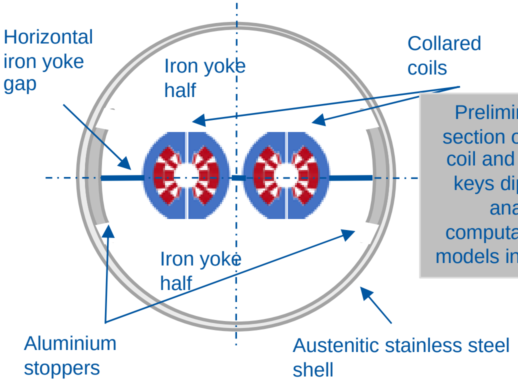
- 2 layers ; 50 mm bore
- Rutherford 40 strands (φ = 1 mm J_C(4.5 K, 16 T)=1200 A/mm^2)
- Nominal magnetic field: 12 T
- Ultimate (mechanical limit) field: 14 T
- Short sample limit : 15.7 T
- Mechanical structure: bladder & key
- Stress in conductors ≲150 MPa in all conditions
- Outer diameter: 640 mm (LASA test)



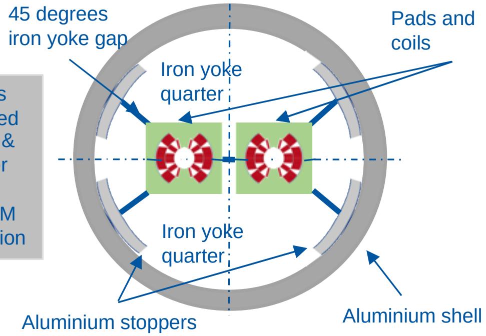


Courtesy of S. Farinon

Development of twin 12 T “robust dipole” at CERN

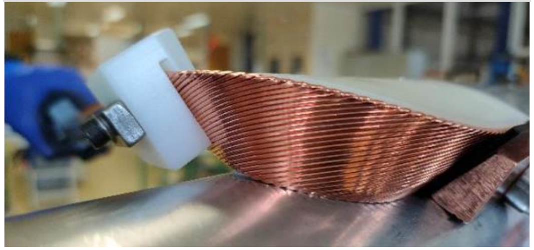


Preliminary cross section of a collared coil and bladders & keys dipoles after analytical computations. FEM models in preparation



Courtesy of D. Perini

Winding tests are ongoing in INFN Genova



Both the INFN and CERN 12 T short robust dipole models are expected to be ready in 2025

R&D Strategy for the LTS **14+ T** magnets

Nb_3Sn magnets: pushing towards ultimate performance

Classical Magnet Structures

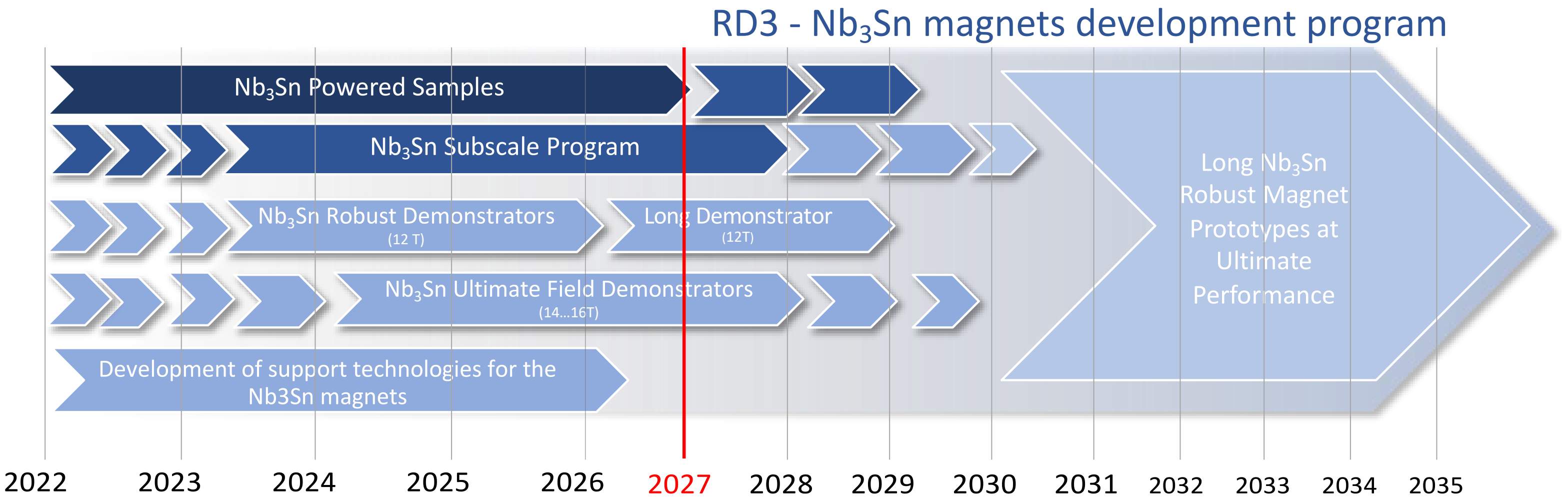
Direct path to overcome conductor stress/strain limitations

- New generation of Nb_3Sn wire structures with enhanced mechanical strength will allow to exploit classical magnet structures at required stress level for 14+ T field level

Novel Magnet Structures

Indirect path to overcome conductor stress/strain limitations

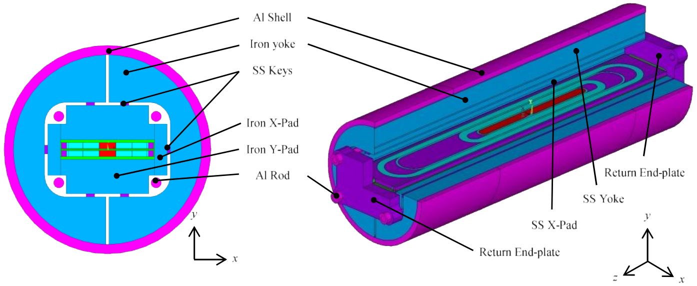
- Magnet structures need to be adapted via stress management to cope with performance limitations due to Nb_3Sn stress/strain sensitivity and thermomechanical behaviour



RD3 - Nb_3Sn magnets development program

Ongoing work highlights : R2D2 subscale demonstrator towards 16 T Nb_3Sn dipoles with block coil structure

R2D2 = **R**esearch **R**acetrack **D**ipole **D**emonstrator

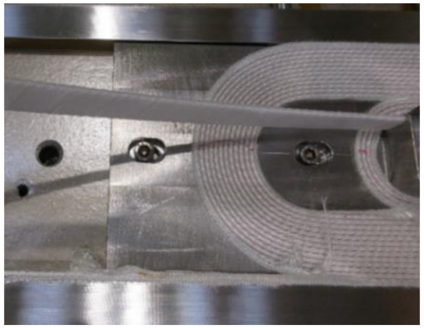


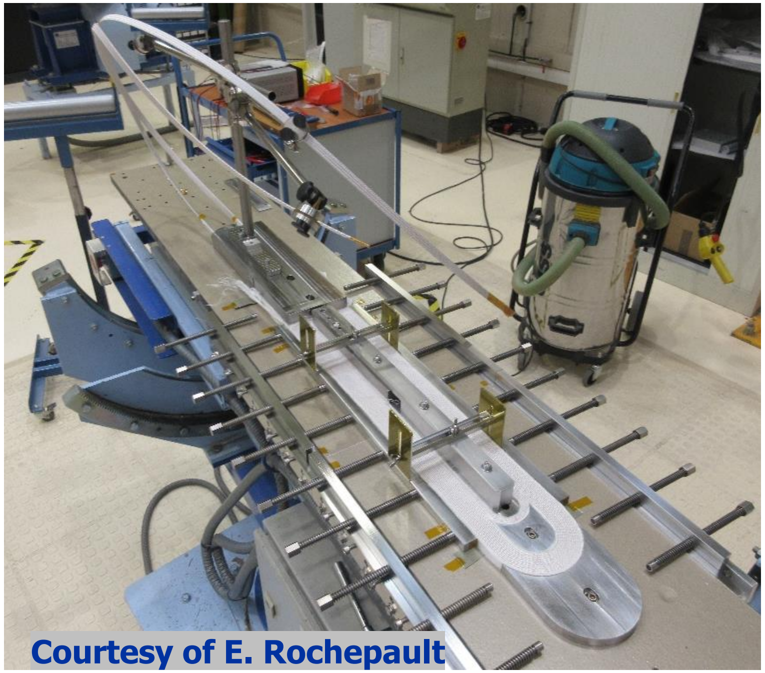
Aperture	None
Outer diameter	480 mm
Structure length	2.0 m
Nominal central field	11.1 T
Ultimate central field	12.0 T
Nominal peak field	12.7 T
Ultimate peak field	13.7 T

Parameter	Unit	HF cable	LF cable
Strand type		DEM-1.1	DEM-0.7
Strand layout		RRP® 162/169	RRP® 60/91
Strand diameter	mm	1.1	0.7
Number of strands		21	34
Cable mid-thickness	mm	1.969 ± 0.010	1.253 ± 0.010
Cable width	mm	12.579 ± 0.050	12.579 ± 0.050
Pitch	mm	84 ± 3	79 ± 3
Core		No core	No core

- ✓ **Conceptual design done and reviewed**
- ✓ **External joint procedure validated at CEA**
- ✓ **Nb_3Sn prototype cables validated at CERN**
- ✓ **Coil components and tooling received and qualified at Saclay**

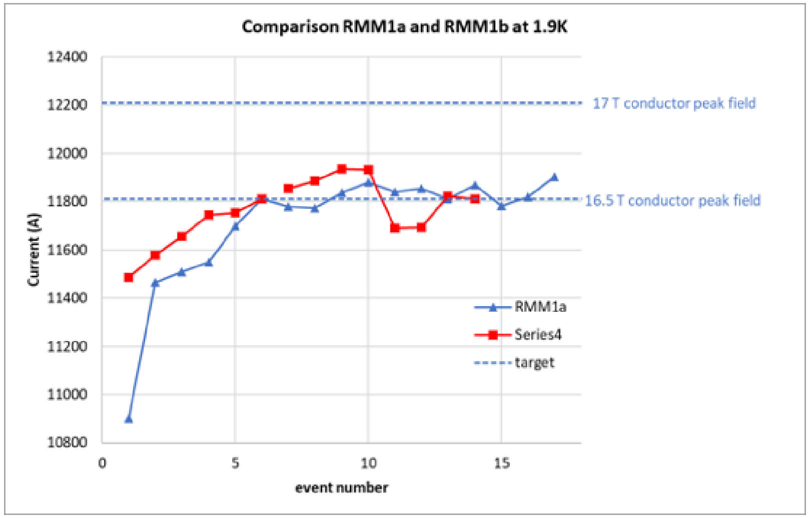
- ➢ Fabrication started at CEA

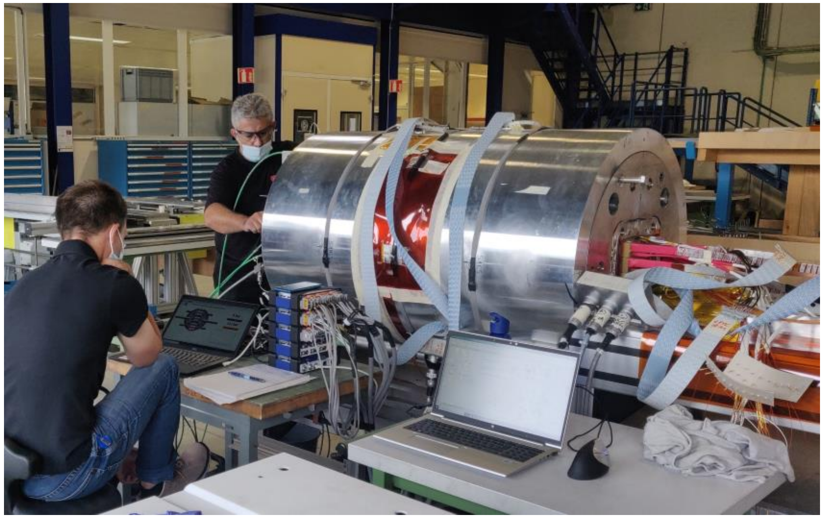




Courtesy of E. Rochepault

Ongoing work highlights : RMM1b demonstrator tests 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

State of development of other magnet structures within the LTS exploratory phase

Ciemat

Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

- Collaboration agreement for the development of technological steps towards 16 T Nb_3Sn magnets with common coil structure: **preparation of workshops for the implementation phase**

PAUL SCHERRER INSTITUT
PSI

- Collaboration agreement for the development of technological steps towards 16 T common coil Nb_3Sn magnets with stress management: **collaboration agreement is undergoing approval**

CERN

- Development of technological steps towards 16 T block coil Nb_3Sn magnets with stress management: **conceptual design has started**

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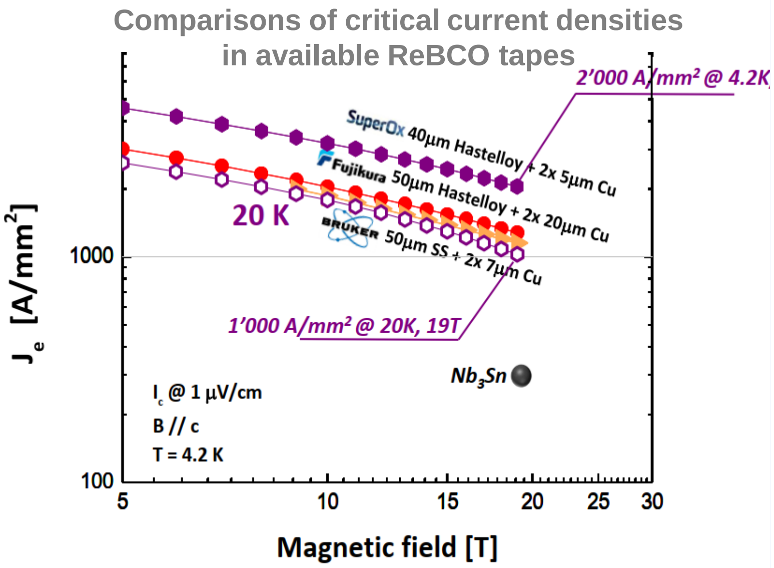
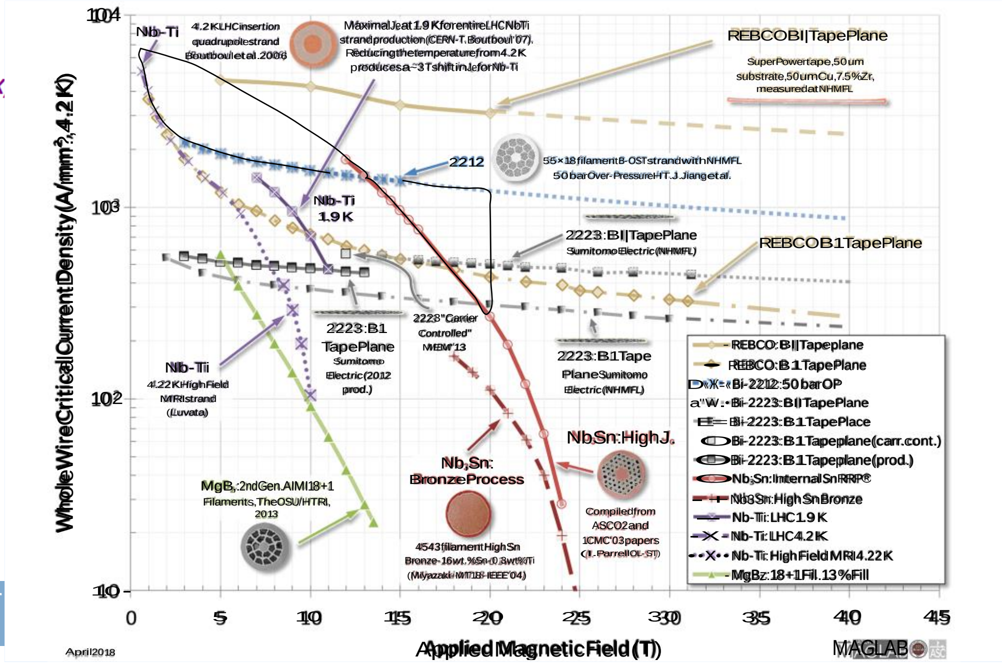
HTS REBCO and BSCCO conductors: State of the Art

- ReBCO ($ReBa_2Cu_3O_{7-x}$,) coated conductor is a potential enabling technology for **magnets beyond 16 T**
  - J_c is sufficient for most application requirements, J_e (4.2 K, 20 T) > 1000 A/mm^2
- HTS ReBCO and BSCCO materials outperform LTS Nb_3Sn at higher fields, but under-perform at low fields



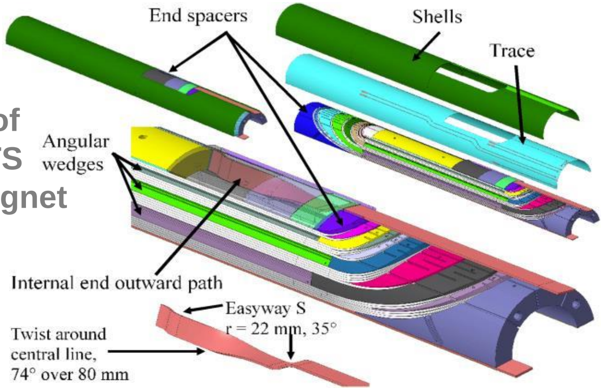
Engineering current density (J_e) in magnetic field perpendicular to substrate for selected conductors (C. Senatore, UNIGE)



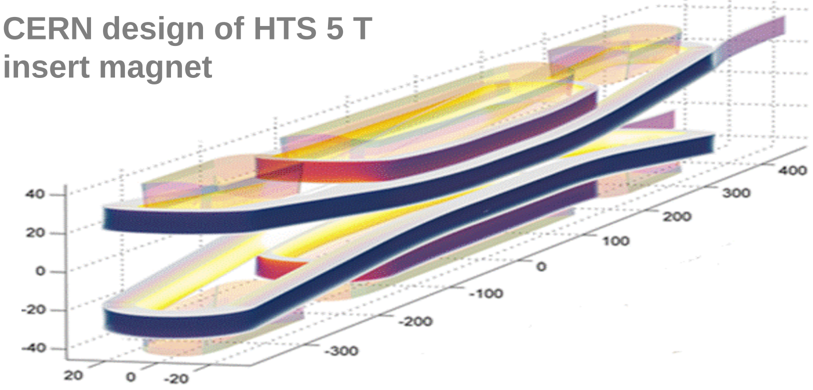
State-of-the-art of HTS magnet technology

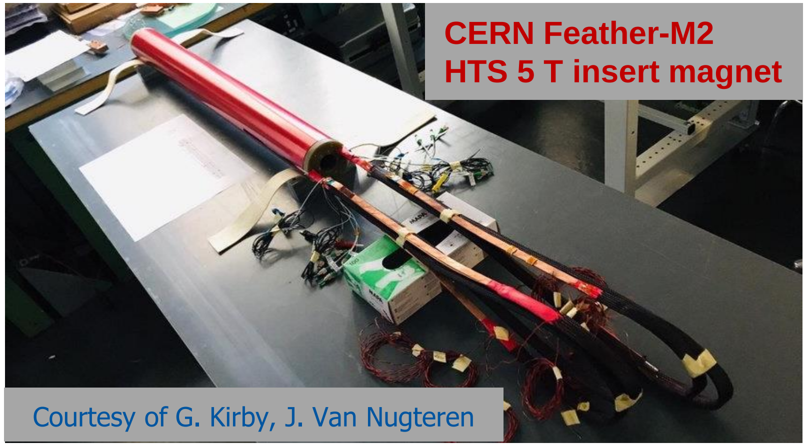
- The broader HTS magnet technology, including cable design, coil design, joints, quench detection and magnet protection remains at an early stage of development
- So far, many small experimental solenoid magnets have been built, but only a few coils for accelerator type dipole magnets made either of ReBCO tapes or Bi-2212 cables, such as the first HTS inserts for hybrid dipole demonstrators e.g., 5 T inserts at CERN and CEA and 3 T at BNL, but **all these insert coils had significant performance limitations**

CEA design of Cos-theta HTS 5 T insert magnet



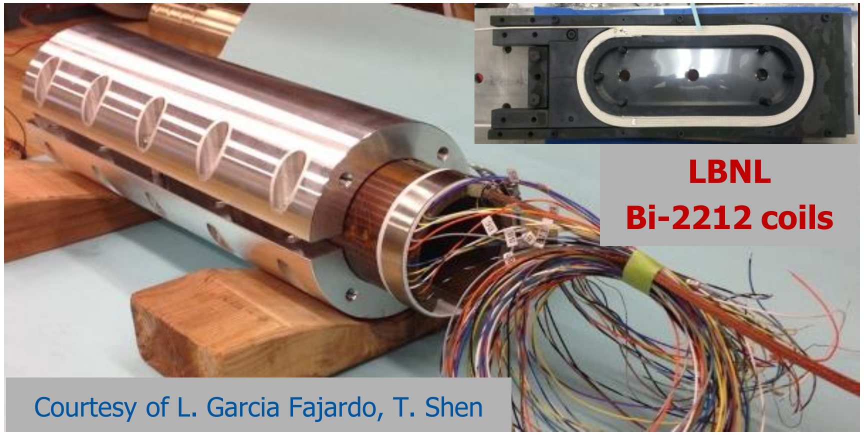
CERN design of HTS 5 T insert magnet





CERN Feather-M2 HTS 5 T insert magnet

Courtesy of G. Kirby, J. Van Nugteren

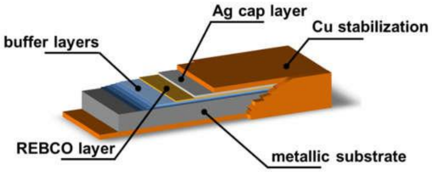


LBNL Bi-2212 coils

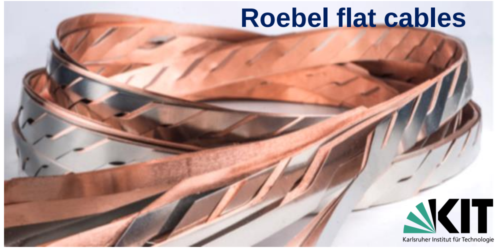
Courtesy of L. Garcia Fajardo, T. Shen

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

HTS Conductors



CORC® round cables



Are we ready for the HTS revolution in accelerator magnets now?

Current main **limitations of HTS conductors specific to accelerator magnets**:

- ReBCO conductor **shear stress sensitivity** and degradation caused by delamination
- **Large magnetisation** of ReBCO conductors (due to the tape shape) and resulting field errors
- **AC losses** (magnetic hysteresis, coupling and eddy currents) are major drawbacks of ReBCO. With significant “filamentation” the ReBCO losses could compare to Nb_3Sn (at > 10 T)
- **Limited ability to bend** at small radii of ReBCO tapes is forcing specific designs of coil ends
- **Quench protection** of accelerator size magnets due to **low quench propagation velocity**
- **Anisotropy** of ReBCO tapes properties, including mechanical properties. Uniformity of tapes and cables along the length and lot to lot, impacting on magnet protection

- **Bi-2212** conductor **stress/strain sensitivity and degradation**
- Very complex **Reaction Heat Treatment for Bi-2212**
- …

While these limitations are not currently showstoppers, they must be carefully addressed within the HFM Programme and resolved to ensure the long-term success of HTS in accelerator magnet applications

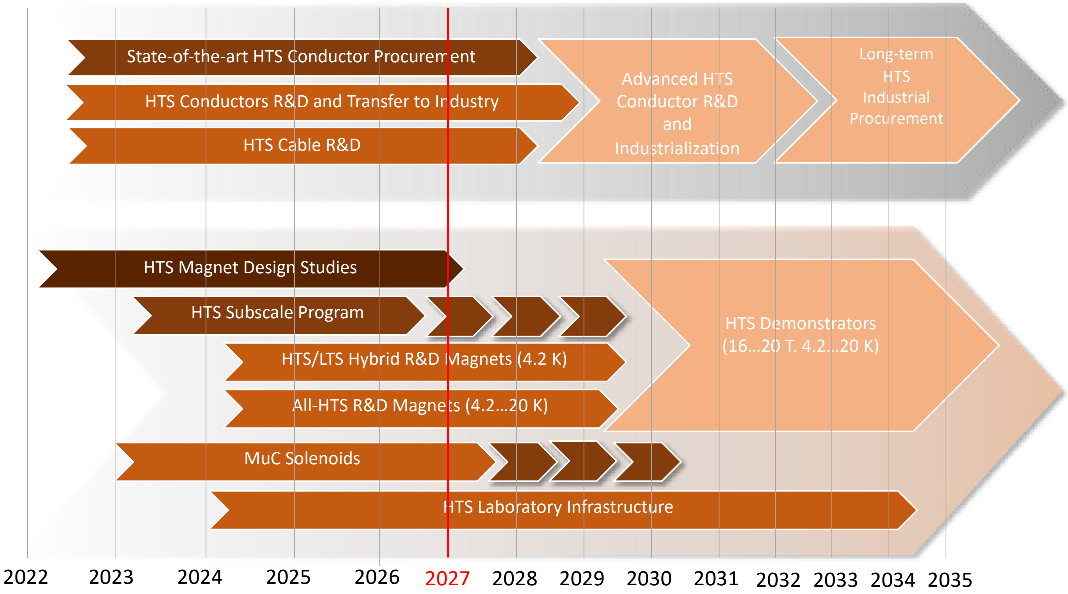
HFM Strategy and Focus Areas for the HTS Magnets

HTS Conductors

- **Development of ReBCO for low AC loss, magnetisation and delamination**
- **Development of novel practical HTS cables**
- **Development of alternative HTS such as IBS**

HTS Magnets

- **Development of subscale HTS insert coils for background field and development of hybrid LTS/HTS magnets**
- **Development of stand-alone all-HTS demonstrator magnets**


RD2 - HTS Conductor and HTS Magnet Technologies

- The primary objective is **to develop and demonstrate the suitability of state-of-the-art HTS conductors** for accelerator magnets, and provide a proof of principle for HTS magnet technology beyond the capabilities of LTS Nb_3Sn
- Exploring the potential of **hybrid LTS/HTS magnets** is a natural step at the present stage of R&D and the most promising way to go beyond 16 T by the end of this decade

Ongoing work highlights: KIT-CERN Collaboration on Coated Conductors

KC^4 mission

- **Development of tailored HTS-tapes for magnet and energy applications**
  - Company independent
  - Special tape architectures for R&D
  - Tape 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 **<u>just started</u>**

Courtesy of B. Holzapfel

Outline

- Current Consortium, organisation and main objectives of the HFM R&D Programme
- Strategy and focus areas for the LTS high-field magnets
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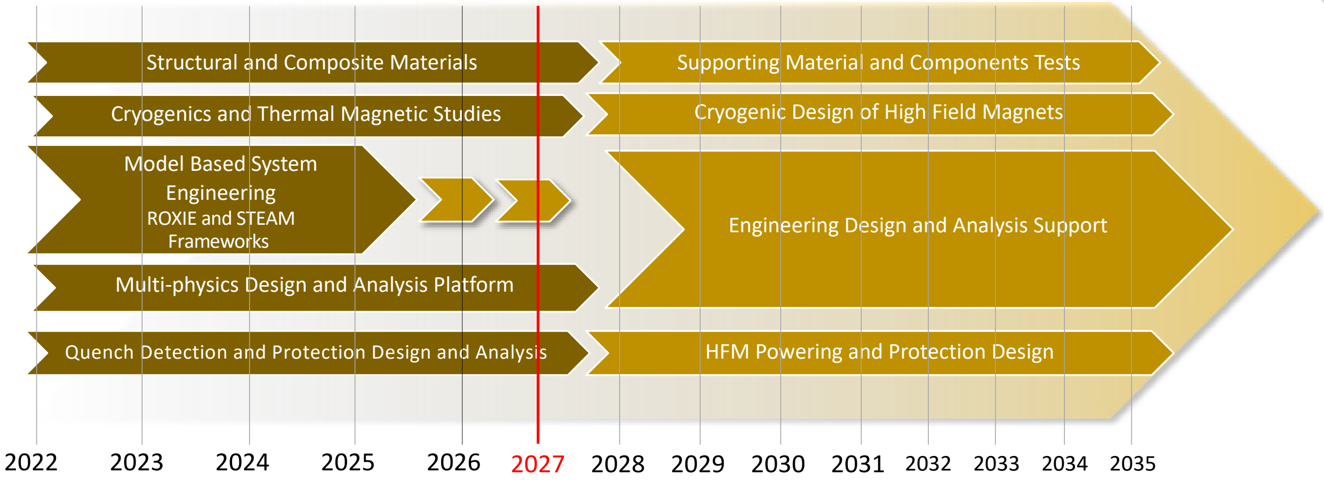
R&D strategy in other areas of interest

Enabling Technologies 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**
- **Enhanced insulation materials for HFM conductors and coils**
- **New structural materials for HFM magnets with enhanced functionality through additive manufacturing**
- **Common modelling and simulation tools for HFM magnets**
- **Novel quench detection and protection methods for both Nb3Sn and HTS high-field magnets**
- **Cryogenic and thermal management studies for HFM magnets**

Enabling Technologies



RD4 - Modelling Tools, Materials, Protection and Cryogenics

Structural and Composite Materials → Supporting Material and Components Tests

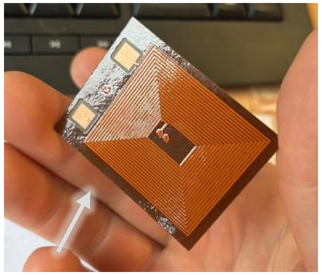
Cryogenics and Thermal Magnetic Studies → Cryogenic Design of High Field Magnets

Model Based System Engineering ROXIE and STEAM Frameworks → Engineering Design and Analysis Support

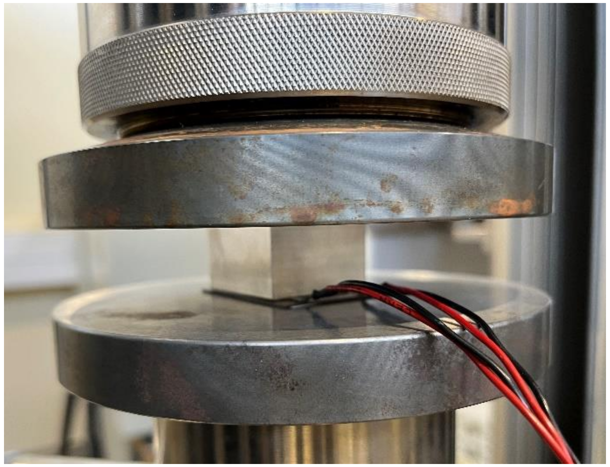
Multi-physics Design and Analysis Platform → Engineering Design and Analysis Support

Quench Detection and Protection Design and Analysis → HFM Powering and Protection Design

Ongoing work highlights:
Novel Magnet Protection Method
E-CLIQ: External Coil Coupled Loss Induced Quench



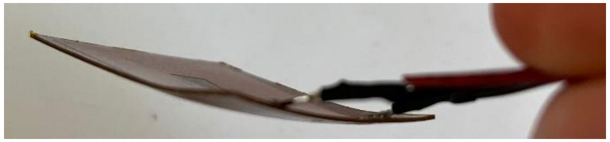
A set of very compact copper coils strategically positioned close to the primary coils, similar to resistive quench heaters, see Mulder et al. 2023



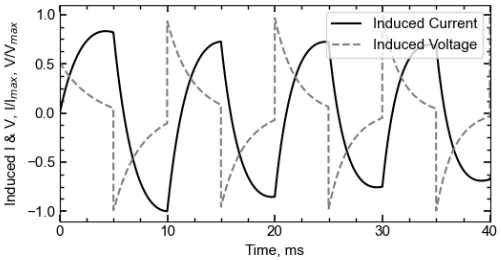
PCB E-CLIQ in development for **integration with an SMC**

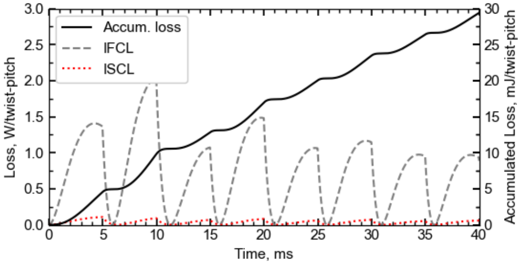
- Optimized for use with low-current amplifier
- Able to generate local dB/dt of > 100 T/s
- Compact envelope, width of a Nb_3Sn cable

The design is experimentally verified to withstand mechanical loads of over 200 MPa ✓



Thanks to I. Santillana and A. Terricabras (EN/MME) for effort during the mechanical tests





Modeling tools further matured

Challenges and Plans for Infrastructures and Novel Instrumentation

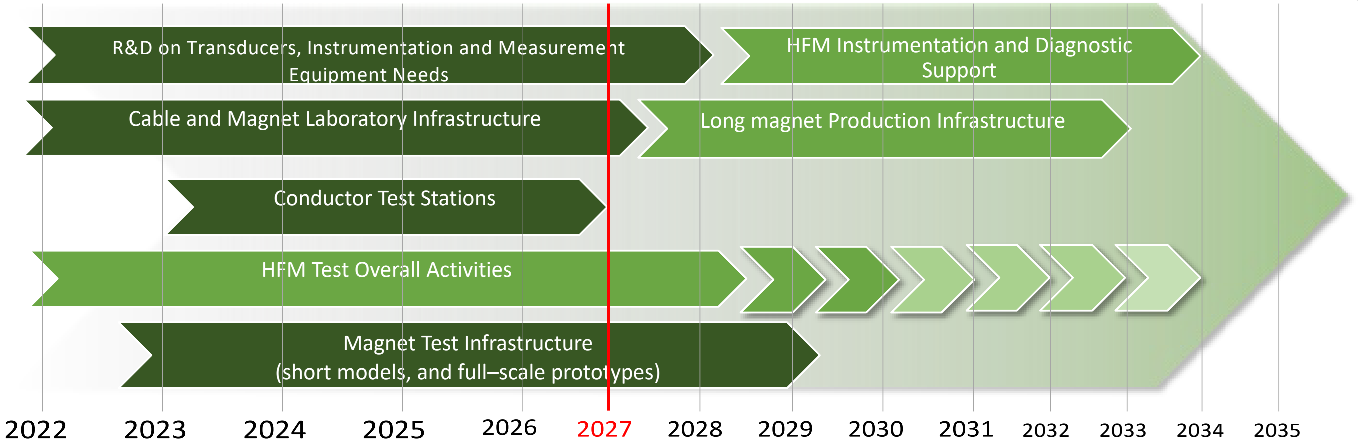
Main HFM Programme needs

- 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**
- **Infrastructures for conductors and characterisation**
- **Infrastructures for building demonstrators, short magnet models and full-scale prototypes**
- **Novel instrumentation, diagnostics and measurement equipment**

Infrastructures needs

RD5 – Infrastructure and Measurements Techniques



R&D on Transducers, Instrumentation and Measurement Equipment Needs

HFM Instrumentation and Diagnostic Support

Cable and Magnet Laboratory Infrastructure

Long magnet Production Infrastructure

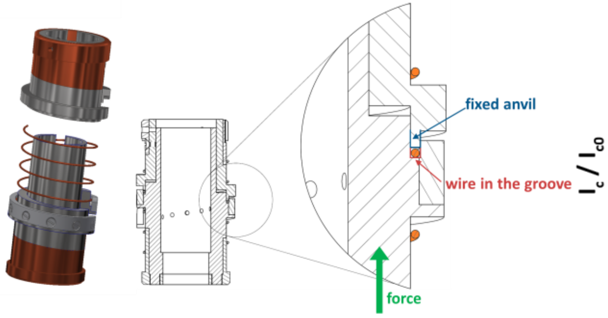
Conductor Test Stations

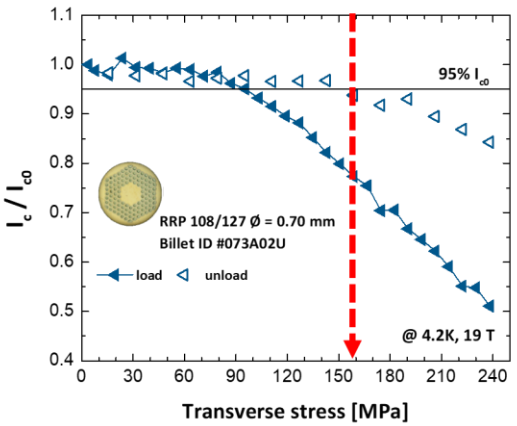
HFM Test Overall Activities

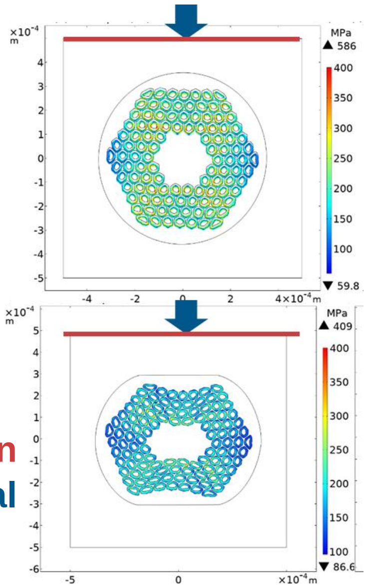
Magnet Test Infrastructure (short models, and full–scale prototypes)

Ongoing work highlights: Advanced Characterizations of Superconductors

Assessing the mechanisms behind the permanent reduction of I_c

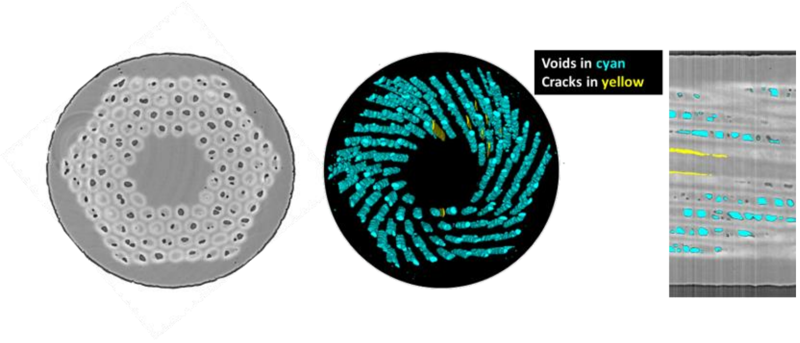






A comprehensive campaign of electromechanical tests on different wire types to gain knowledge on several practical aspects for magnet operations

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

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Summary of main deliverables during 2023-2026 as an input to the next update of ESPP (LTS)

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

- **Demonstration of the maturity of Nb_3Sn technology for collider-scale production through 12 T robust dipole magnet design**, including industrial processes and cost reduction:
  - INFN – 12 T FalconD single aperture short dipole model
  - CERN – 12 T Robust twin aperture short dipole model (either collared coils or bladder and key)

- **Demonstrators of the Nb_3Sn potential above 14 T:**
  - CEA – FD single aperture 14 T graded conductor block coil demonstrator (no aperture)
  - CERN – 14+T block coil demonstrator with coil stress management (targeting 16 T)
  - CIEMAT – 14+ T common coil demonstrator
  - PSI – 14+ T common coil demonstrator with coil stress management (targeting 16 T)

Summary of main deliverables during 2023-2026 as an input to the next update of ESPP (HTS)

- **Exploration and demonstration of suitability of state-of-the-art HTS conductors for building accelerator magnets**
  - KIT – accelerator magnet grade REBCO prototype tapes with optimized magnetization and mechanical properties
  - CERN – development of practical HTS cables
  - CEA – development of MI racetrack coil demonstrator
  - PSI – development of dielectric-insulated soldered tape-stack racetrack demonstrator with stress management.
  - CERN – development of dielectric-insulated racetrack coil demonstrator

Final Remarks

- The High-Field Magnet R&D Programme, hosted at CERN, has begun to implement a strategic roadmap in Europe with the aim to provide timely feedback to the ESPP update(s) via technology demonstrators and credible milestones

- Substantial acceleration of the HFM Program with first promising results were obtained over the past 12 month, but to accelerate further the progress, we must:
  - Shorten the development cycle of magnet demonstrators and models introducing new fast-turnaround R&D vehicles to reduce the feedback time on technology choices and encourage creative risk taking
  - Foster communication, coordination, and exchange of know-how among all actors

- The LTS and HTS magnet technology challenges faced by the HFM Programme are many and significant, in particular requiring a decisive advancement beyond the state-of-the-art in the development of required practical LTS and HTS superconductors and superconducting cable designs, but no showstoppers identified so far

- **The target objectives until 2027 are defined and challenges to reach them are shared with EU national labs**

Thank you for your attention!