High Field Magnet R&D Programme

Status of high-field magnet R&D for future colliders

Andrzej Siemko on behalf of HFM R&D Programme Team

Outline

- Current Consortium and main objectives of the HFM R&D Programme

- Focus areas for the LTS high-field magnets
  - Development of 12 T Nb_3Sn “robust dipole”
  - State-of-the-art LTS superconductors and magnet technology
  - R&D strategy and main focus areas

- Focus areas for the HTS high-field magnets
  - State-of-the-art HTS superconductors and magnet technology
  - R&D strategy and main focus areas

- 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)

PAUL SCHERRER INSTITUT
PSI

cea

CNR

SPIN

KIT
Karlsruher Institut für Technologie

Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

INFN
Istituto Nazionale di Fisica Nucleare

ETH zürich

University of Twente
The Netherlands

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

UNIVERSITÉ
DE GENÈVE
FACULTÉ DES SCIENCES

CERN

HFM Programme – broad goals

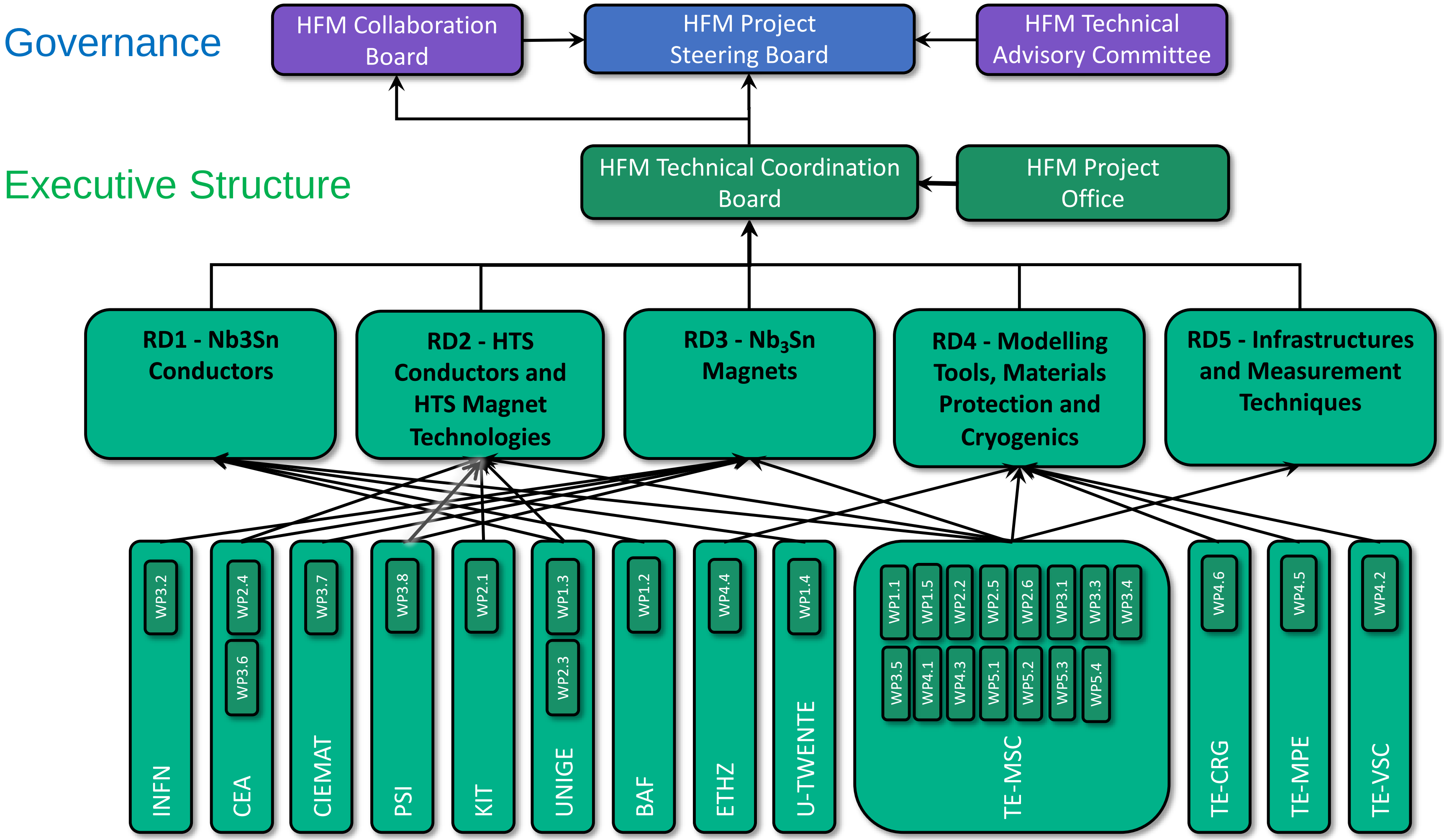
- **The EU Accelerator R&D Roadmap identifies main objectives for the High Field Magnet Programme:**
  - **OBJECTIVE 1:**

    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**

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

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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
- 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**
- **Achieving 14+T with this robust 12T technology will be possible due to the increase in Jc and enhancement of the mechanical properties of the Nb3Sn conductor**

12 Tesla

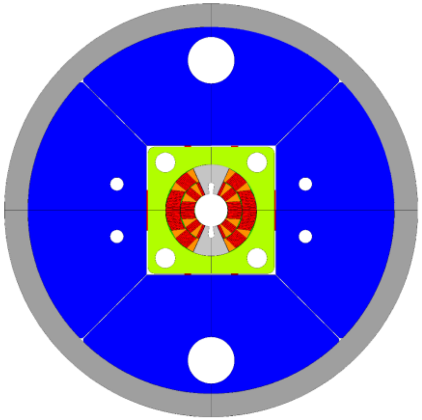
Robust

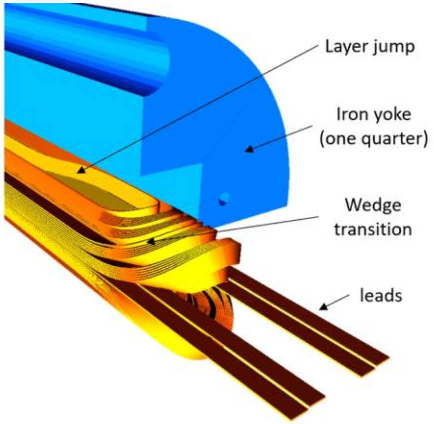
Ongoing work examples:
12 T robust dipole development

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

Main characteristics :

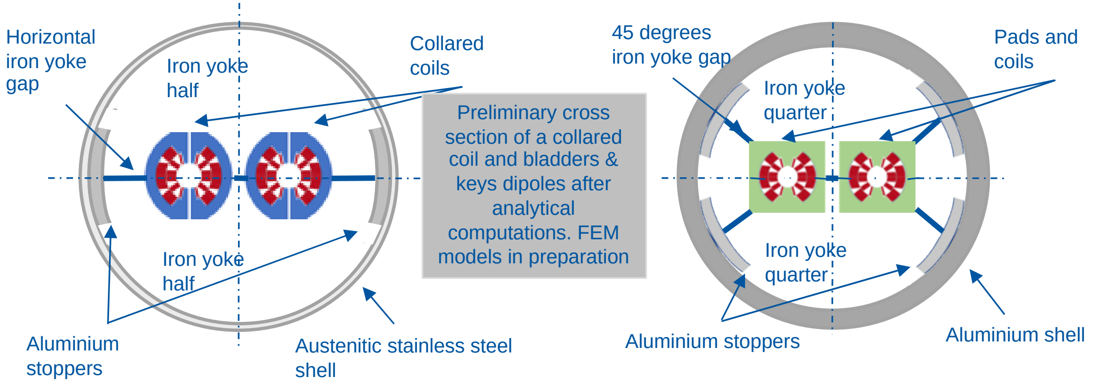
- 2 layers ; 50 mm bore
- Rutherford 40 strands (φ = 1 mm J_C(4.5 K, 16 T)=1200 A/mm^2)
- Nominal magnetic field: 12 T
- Ultimate (mechanical limit) field: 14 T
- Short sample limit : 15.7 T
- Mechanical structure: bladder & key
- Stress in conductors ≲150 MPa in all conditions
- Outer diameter: 640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





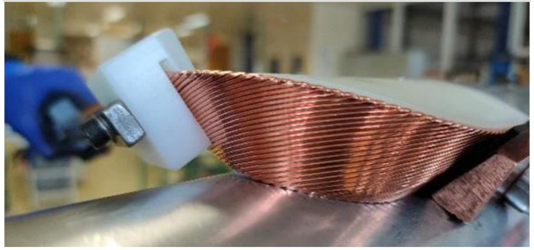
Courtesy of S. Farinon and D. Perini

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

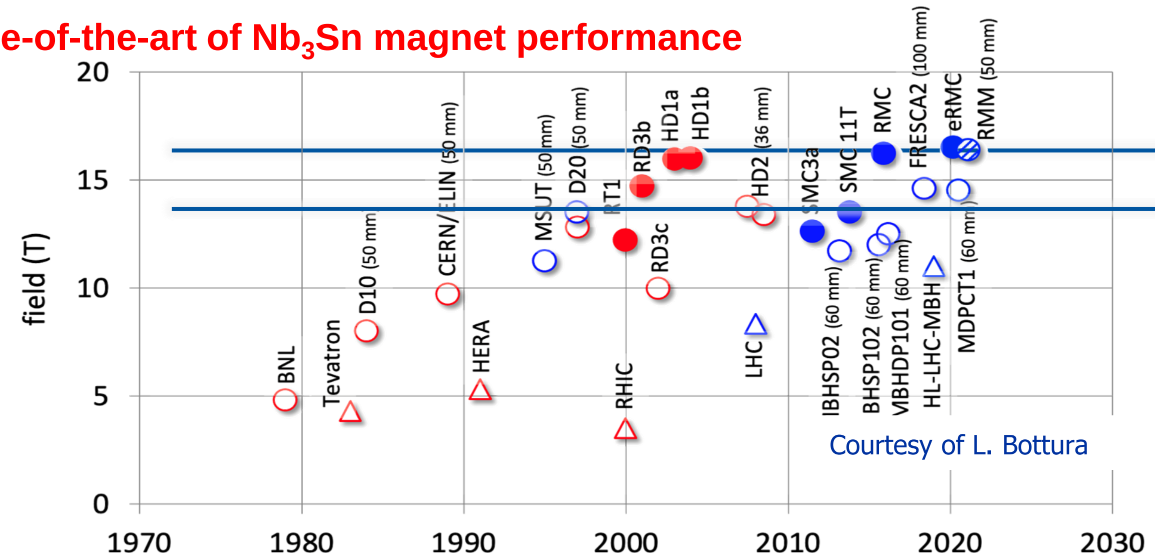
Winding tests are ongoing in INFN Genova



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

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

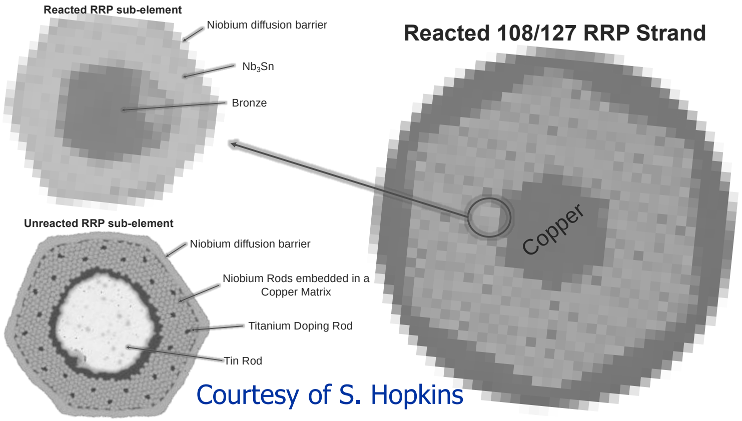
State-of-the-art Nb_3Sn conductor (HL-LHC)

	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

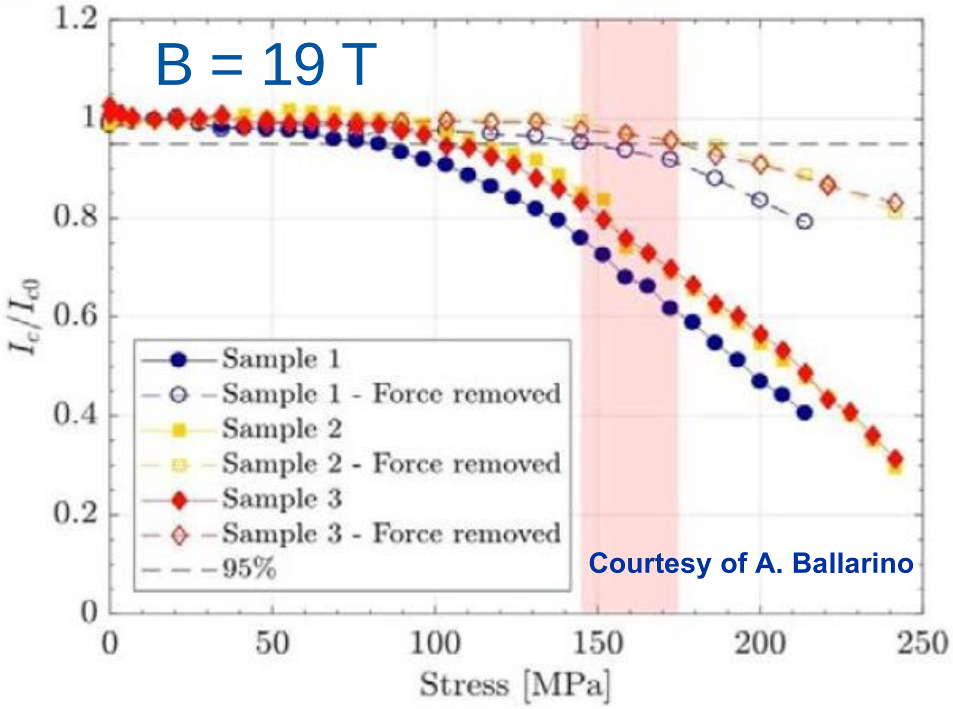


Courtesy of S. Hopkins

Main challenges facing the development of beyond state-of-the-art 14+ Tesla LTS 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 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:

Direct path

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

Nb_3Sn Conductor R&D

Novel Magnet Structures

Indirect path

- Magnet structures need to be adapted via 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

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

Evolutionary path based on the current state-of-the-art magnet structures

- **Evolution of LHC/LARP/HL-LHC technology and magnet structures**
  - cos theta (see 12 T Robust)
  - block coil
  - common coil

Achieving the 16 T target will basically require new Nb_3Sn wire structures with enhanced mechanical strength

Evolutionary technology R&D

Beyond state-of-the-art

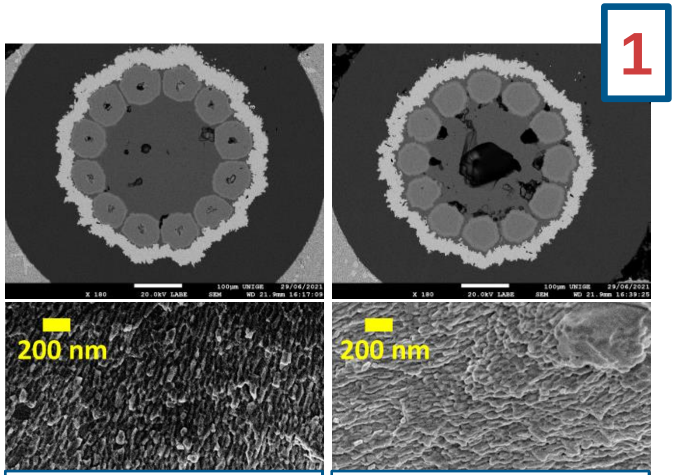
Innovative path that goes beyond current state-of-the-art magnet structures

- **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

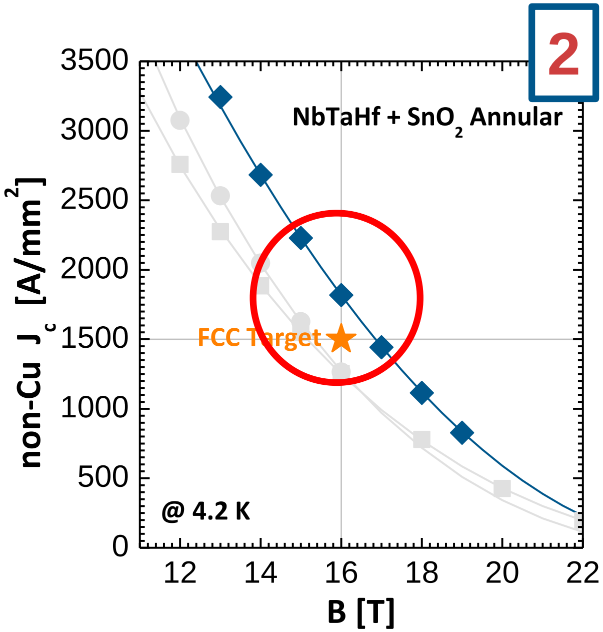
Achieving the 16 T target will not require new Nb_3Sn wire structures with enhanced mechanical strength

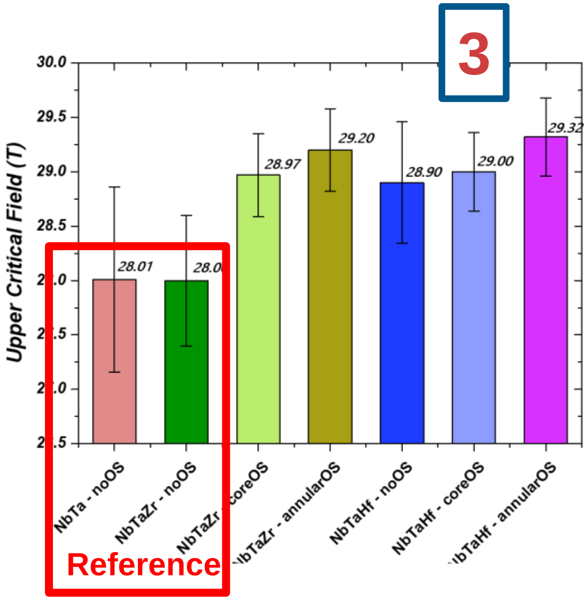
Ongoing work examples: Prototype Nb_3Sn Wire Development at UniGE

Internal Oxidation in prototype multifilamentary wires



Average grain size	Average grain size
~ 47 nm	~ 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

Ongoing work examples: Development Plan at CEA towards 16 T Nb_3Sn dipoles with block coil structure

F2D2 Short model → **Planned**

Grading + Flared-ends + Aperture, 16 T

1.5 m, 50 mm bore **with aperture**

FD Demonstrator → **Planned**

Grading + flared-ends, 14 T

1.5 m, No bore **with flared ends**

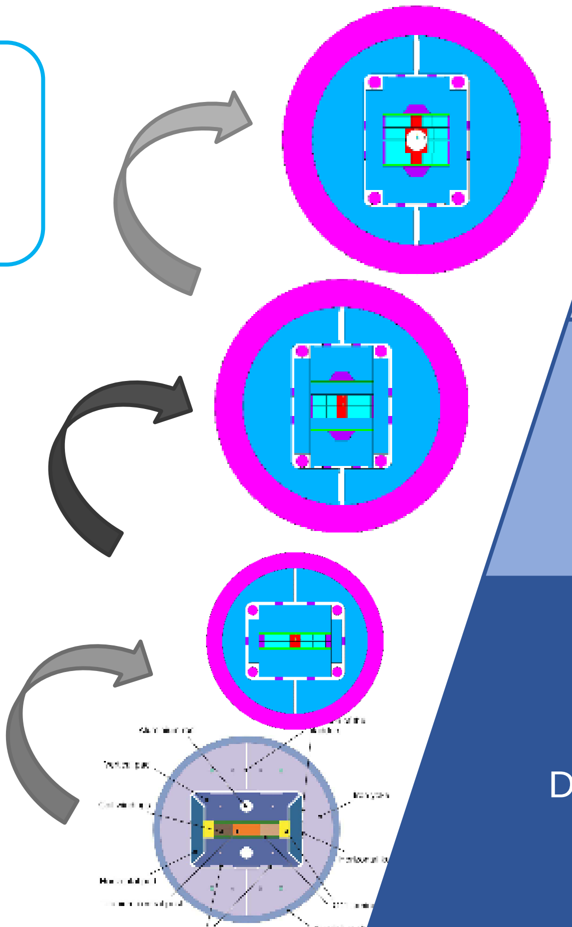
CEA-CERN R2D2 → **Ongoing**

Demonstrate grading ≥ 12 T

1.5 m, No bore **with grading**

CEA-CERN SMC-11T coil ✓**Done**

Demonstrate Nb_3Sn tech. ≥ 12 T



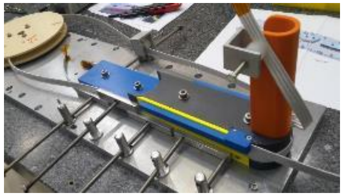
16 T Demo

14 T Demo

Subscale Demonstrators

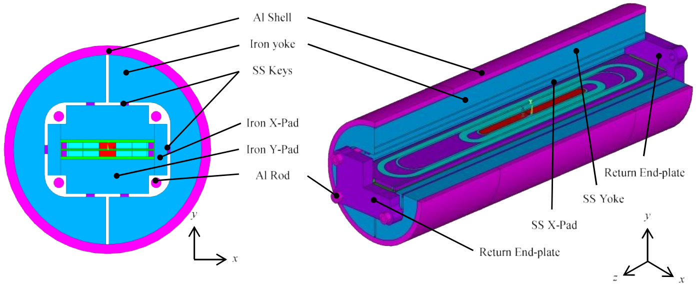
Powered samples

Non-powered samples

Status of R2D2 subscale demonstrator of graded Nb_3Sn block coil technology

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

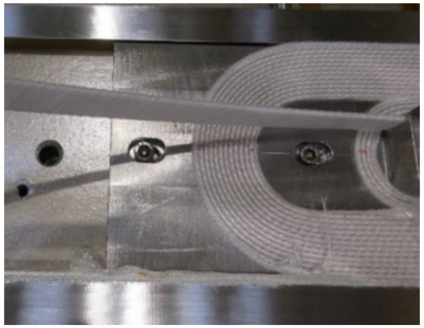


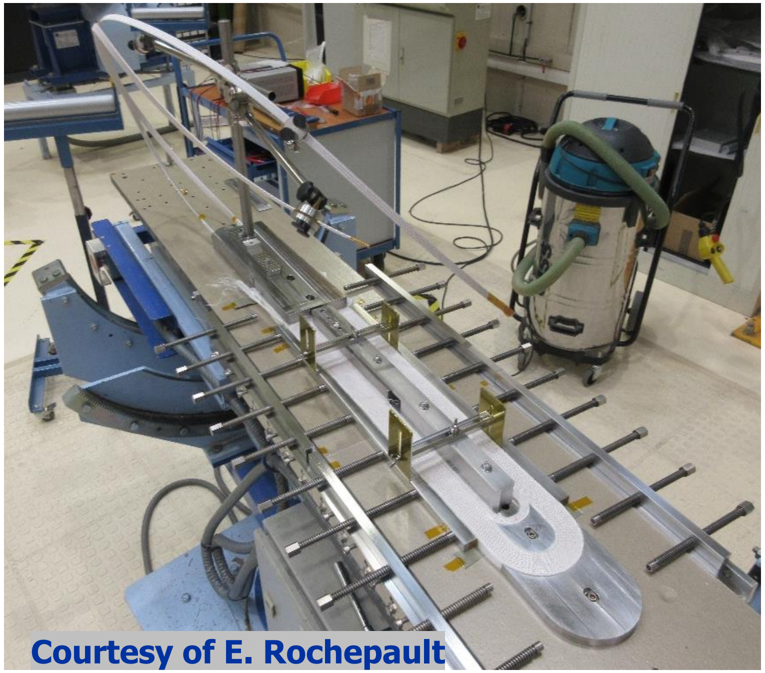
Aperture	None
Outer diameter	480 mm
Structure length	2.0 m
Nominal central field	11.1 T
Ultimate central field	12.0 T
Nominal peak field	12.7 T
Ultimate peak field	13.7 T

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**

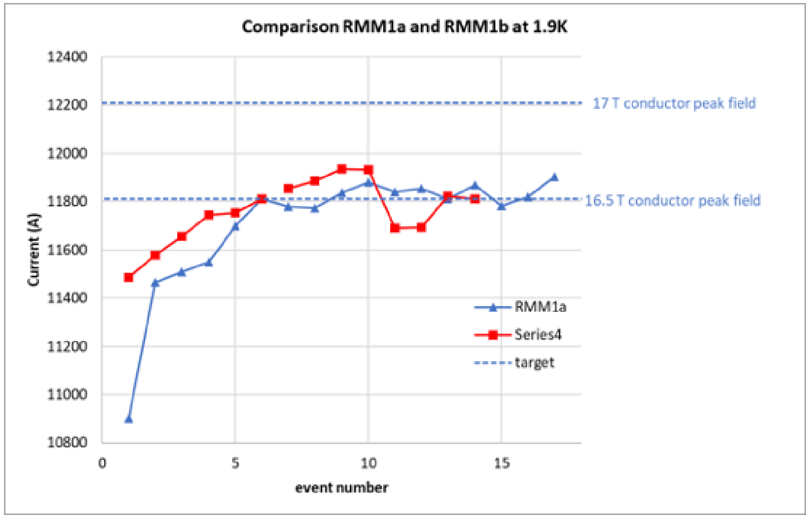
- ➢ Fabrication started at CEA

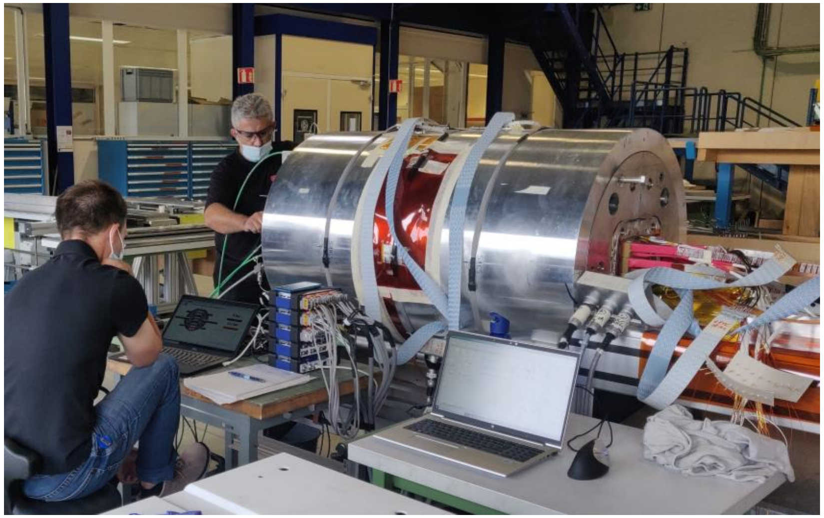




Courtesy of E. Rochepault

Ongoing work examples: 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

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- 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**

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PSI

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

CERN

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

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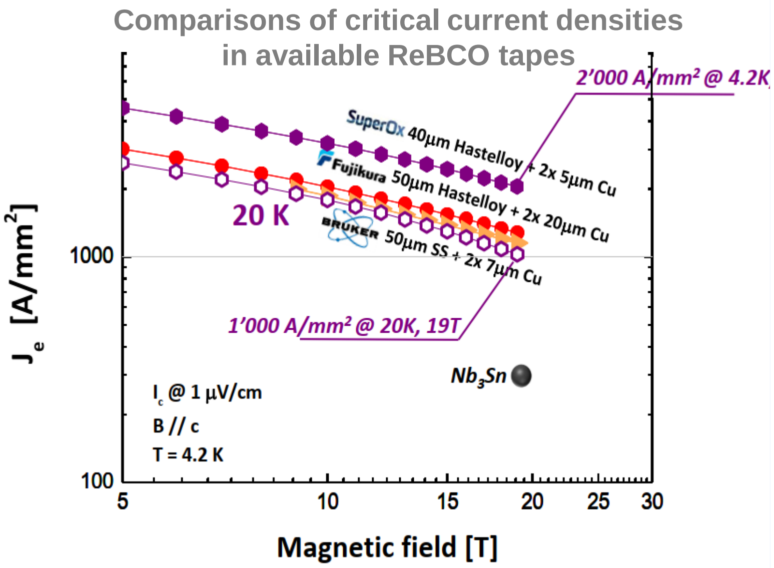
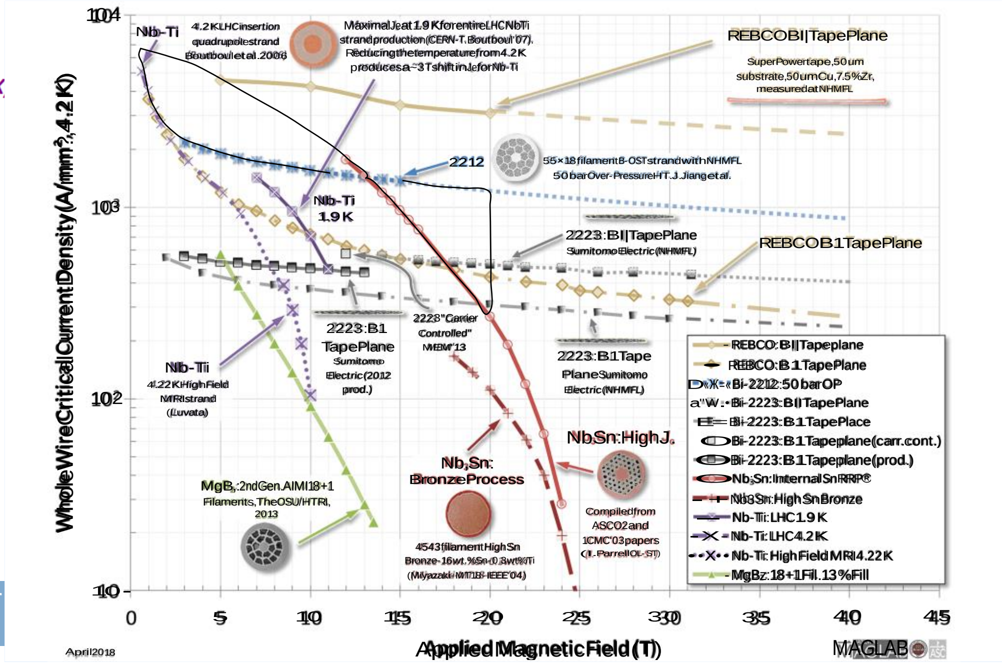
HTS REBCO and BSCCO: State of the Art

- 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 field, but under-perform at low field
  - Hybrid LTS/HTS magnets are most efficient



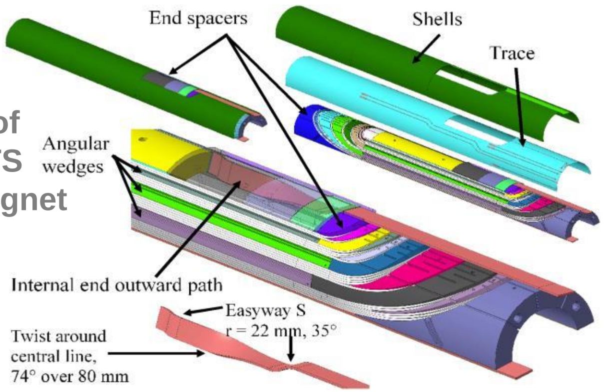
Engineering current density (J_e) in magnetic field perpendicular to substrate for selected conductors (C. Senatore, UNIGE)



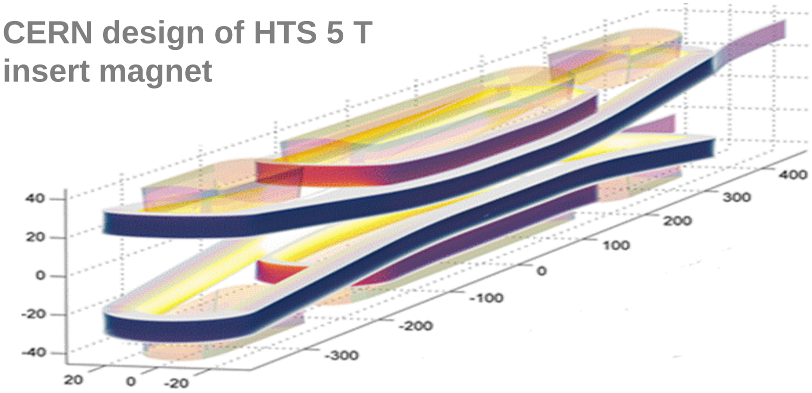
State-of-the-art of HTS magnet technology

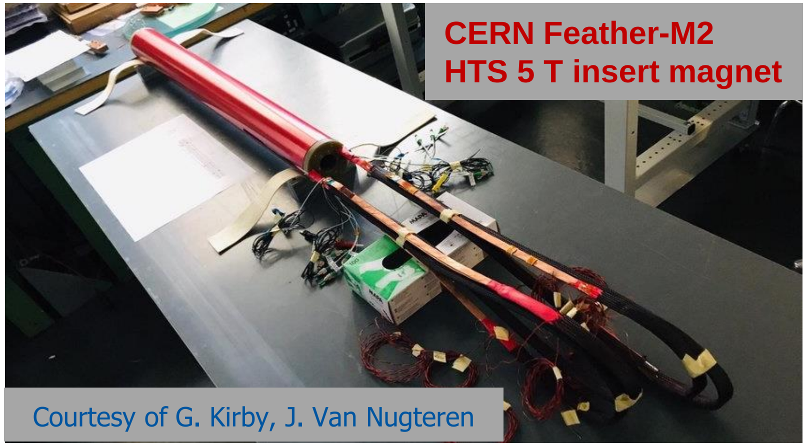
- So far, many small experimental solenoid magnets have been built, but only a few coils for accelerator dipole magnets made either of ReBCO tapes or Bi-2212 cables, and only the first HTS inserts for hybrid dipole demonstrators, such as 5 T inserts at CERN and CEA and 3 T at BNL
- **In practice, all insert coils built for hybrid LTS/HTS magnets had significant performance limitations**

CEA design of Cos-theta HTS 5 T insert magnet



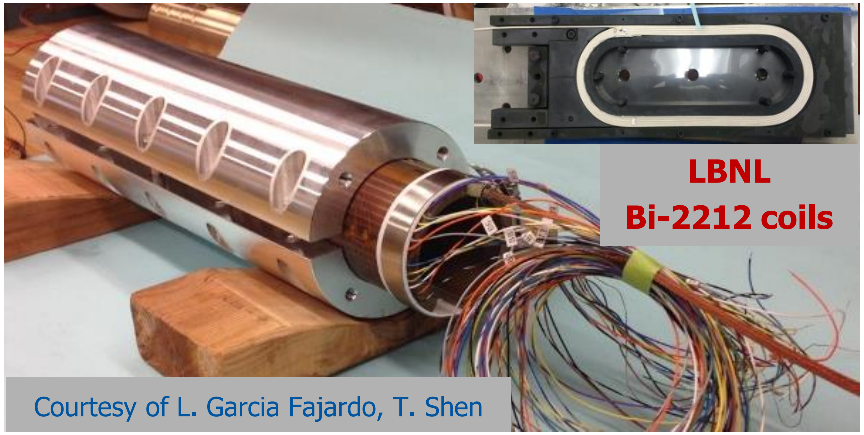
CERN design of HTS 5 T insert magnet





CERN Feather-M2 HTS 5 T insert magnet

Courtesy of G. Kirby, J. Van Nugteren



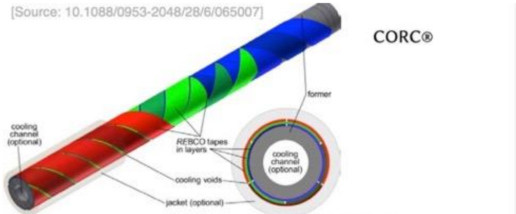
LBNL Bi-2212 coils

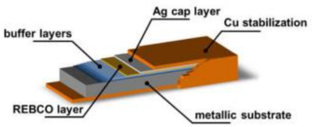
Courtesy of L. Garcia Fajardo, T. Shen

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

HTS Conductors

[Source: 10.1088/0953-2048/28/6/065007]





[Source: 10.1088/1361-6668/abb8c0]

Current main limitations of HTS conductors specific to accelerator magnets:

- ReBCO conductor shear stress sensitivity and degradation
- Large magnetization of ReBCO conductors. Tape conductor shape (rather than multifilamentary wire) creates field errors that may be too large for accelerator magnets
- Magnetic hysteresis, coupling currents and eddy currents (AC losses) are serious drawbacks of ReBCO tapes and cables. With a substantial modification of the tape architecture (filamentation) ReBCO tapes could comply with losses in Nb3Sn in high-fields (> 10 T)
- Limited ability to bend at small radii of ReBCO conductors, forcing specific structures of magnet coil ends
- Quench protection of accelerator size magnets due to low quench propagation velocity and high stored energy density in coils made of ReBCO as well as Bi-2212
- Uniformity of ReBCO 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
- …

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
- The 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 capability of LTS Nb_3Sn technology

- **Improvement of ReBCO conductor for low magnetisation demand and mechanical robustness**
- **Development of practical HTS cables**
- **Development of alternative HTS superconductors such as IBS**

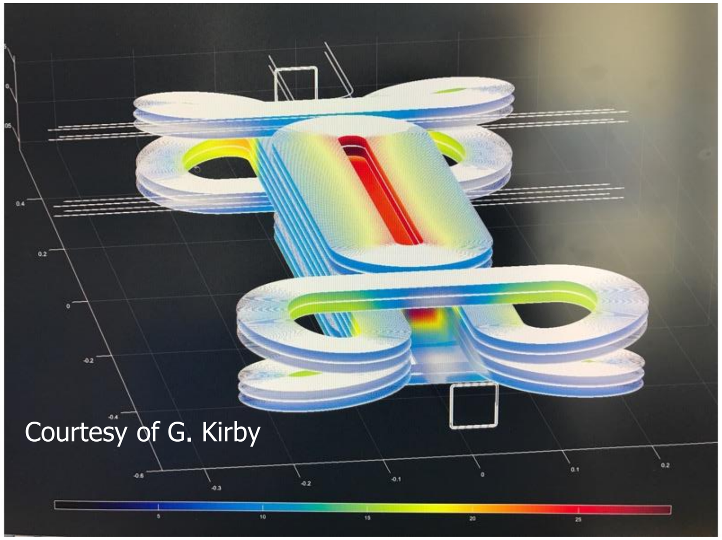
HTS Conductors

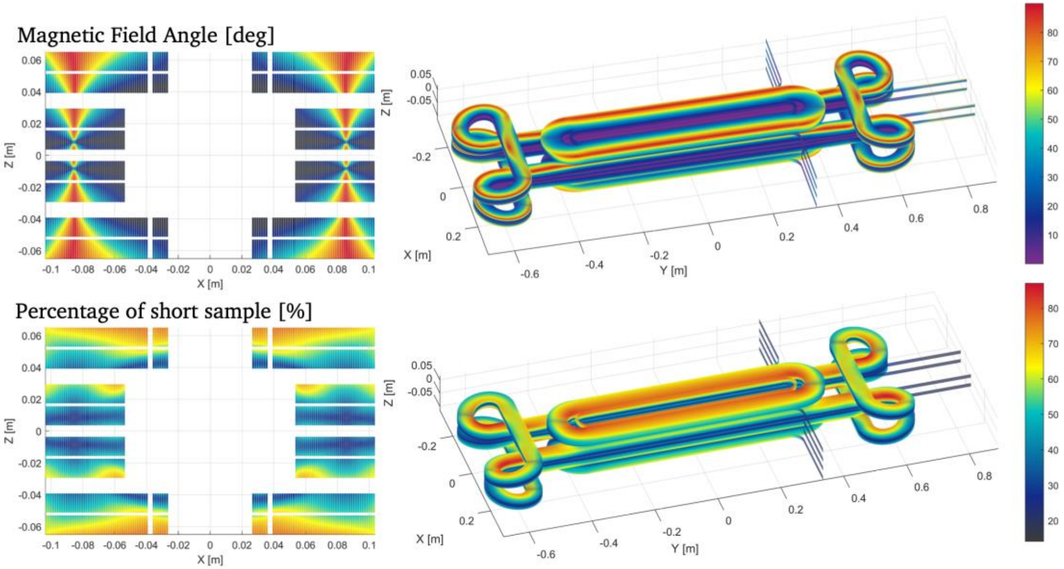
HTS Magnets

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

HTS is the only path beyond 16 Tesla

- Are we ready for the HTS revolution in accelerator magnets?
    - It seems that we still have a long way to go before all-HTS magnets replace LTS magnets
    - Hybrid LTS/HTS magnets seem to be the most promising in overcoming the 16 T barrier
    - In the coming years, the further development of practical HTS conductors will be the most important
- Using the available HTS conductors now rather than waiting for better once is under deliberation
    - As part of the HFM Programme, work is underway on the conceptual designs of HTS magnets using existing conductors and developing the magnet structures not as we would like, but as allowed by conductors


Courtesy of G. Kirby



Ongoing work examples: 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 **just started**

Courtesy of B. Holzapfel

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R&D strategy in other areas of interest

Enabling Technologies R&D

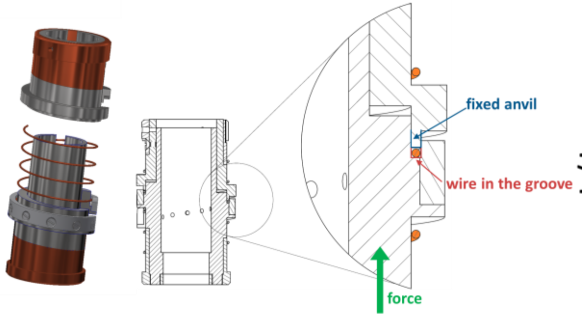
- Present limitations of state-of-the-art HFM are often linked to enabling technologies that need to be further developed and advanced

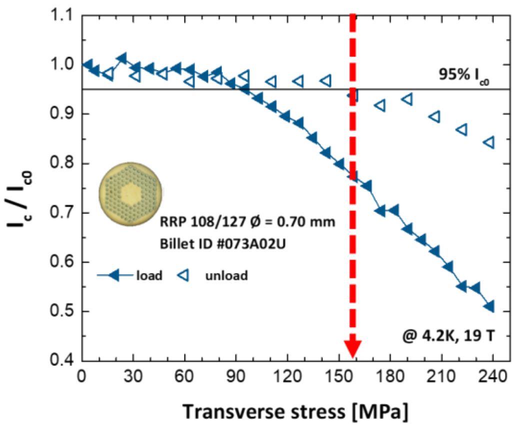
Enabling Technologies

- **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**

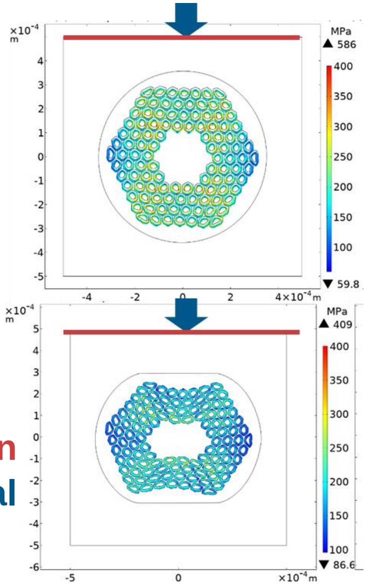
Ongoing work examples: Advanced Characterizations of Superconductors

Assessing the mechanisms behind the permanent reduction of I_c

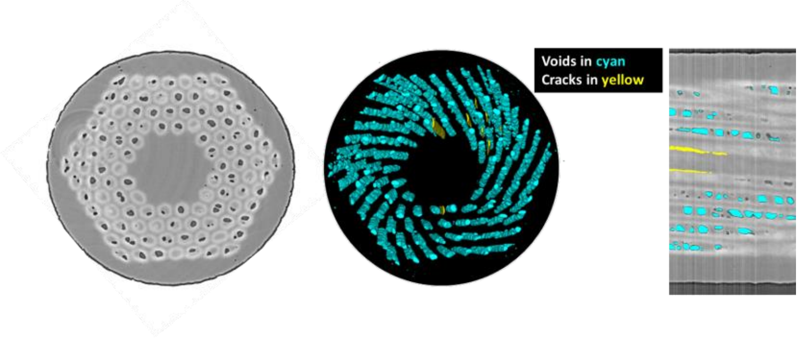




A comprehensive campaign of **electromechanical tests on different wire types** to gain knowledge on several practical aspects for magnet operations



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

HFM - Challenges and Plans for Test Infrastructures

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

Outline

- Current Consortium and main objectives of the HFM R&D Programme

- Focus areas for the LTS high-field magnets
  - Development of 12 T Nb_3Sn “robust dipole”
  - State-of-the-art LTS superconductors and magnet technology
  - R&D strategy and main focus areas

- Focus areas for the HTS high-field magnets
  - State-of-the-art HTS superconductors and magnet technology
  - R&D strategy and main focus areas

- Focus areas for other domains of interest

- Key mid-term deliverables until the next update of European Strategy for Particle Physics

- Final remarks

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 soldered tape-stack racetrack demonstrator with stress management.
  - CERN – development of dielectric-insulated racetrack coil demonstrator

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

Final Remarks

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

- The development of required LTS and HTS superconductors will require **innovations, and exploration of emerging technologies**, especially for the practical superconducting cable designs

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

Thank you for your attention!

Spare slides

Muon Collider

Magnet Challenges and R&D

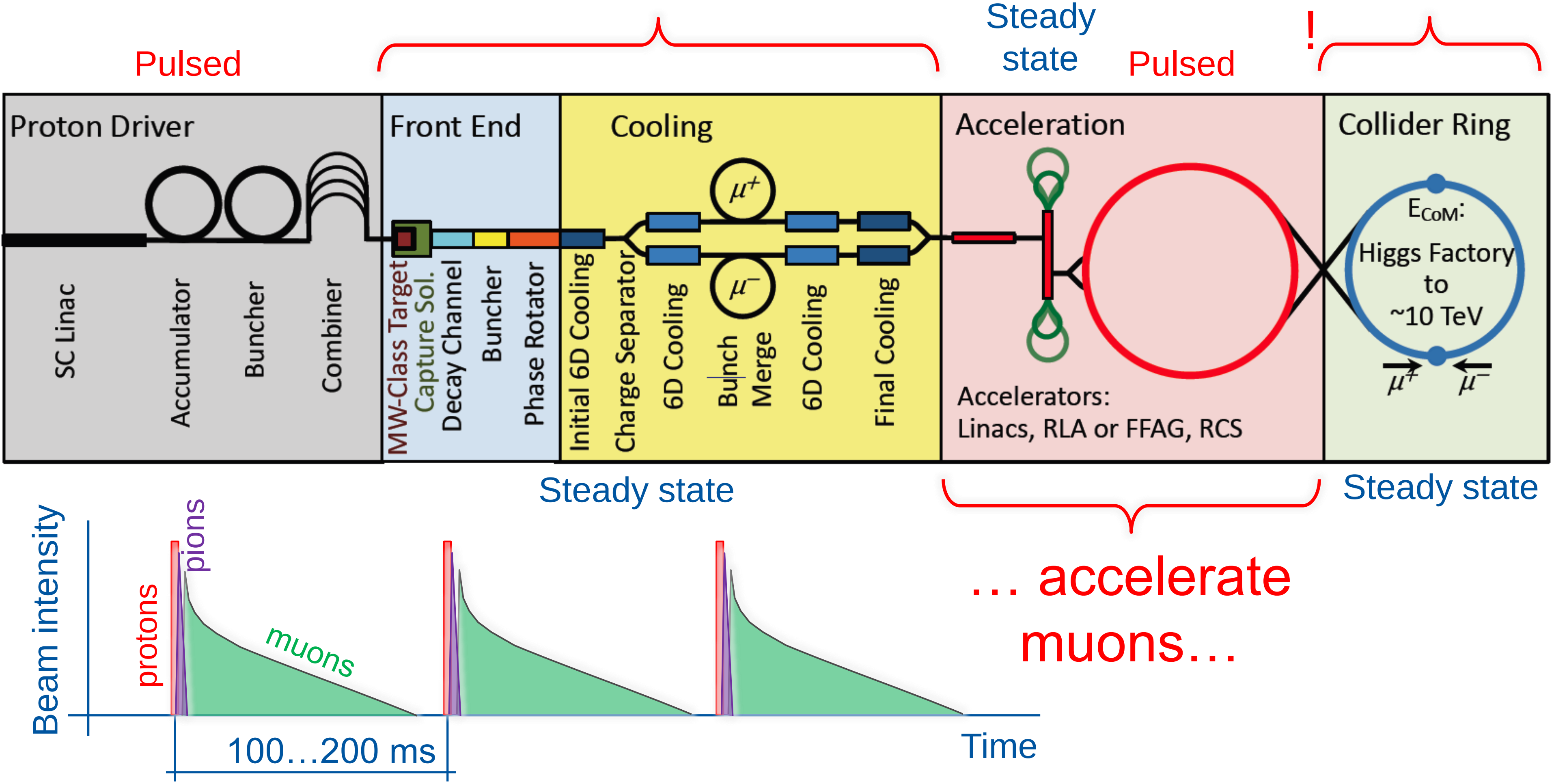
Summary by L. Bottura, CERN

for the Muon Magnets Working Group

HFM
High Field Magnets

Partly funded by the European Union under
Grant Agreement n. 101094300

Proton-driven Muon Collider Concept

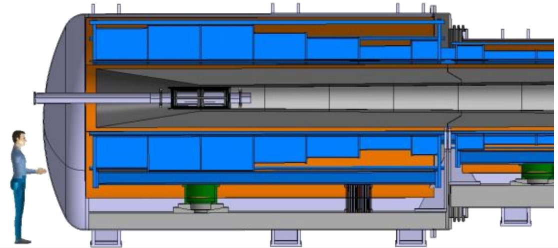


Muon Collider magnets

20 T, 200 mm **HTS !**

Radiation heat load ≈ 5…10 kW

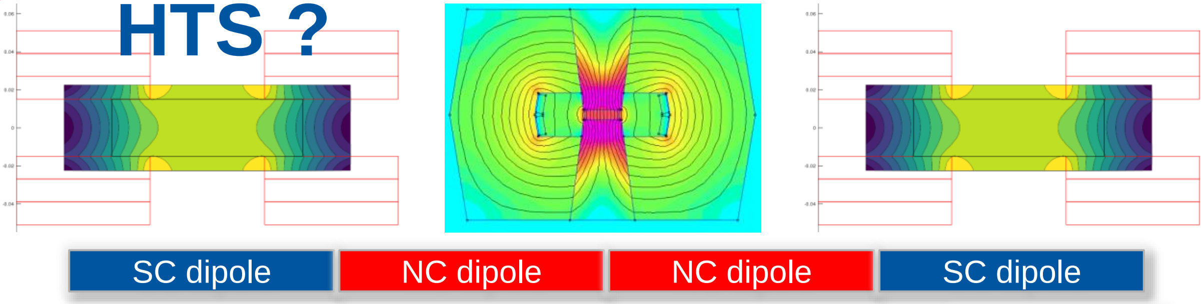
Radiation dose: 80 MGy

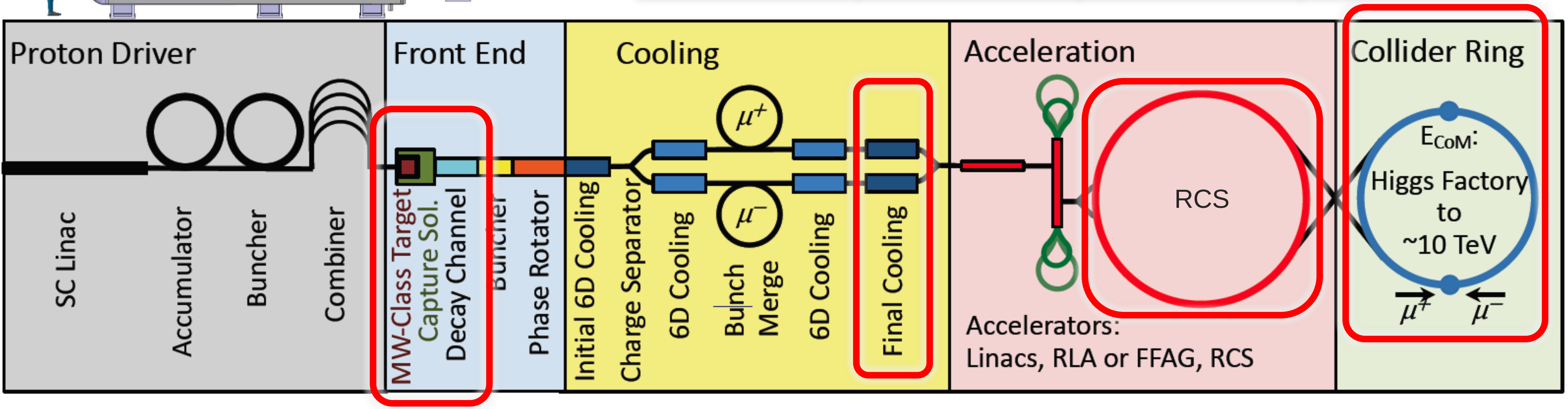


HTS ?

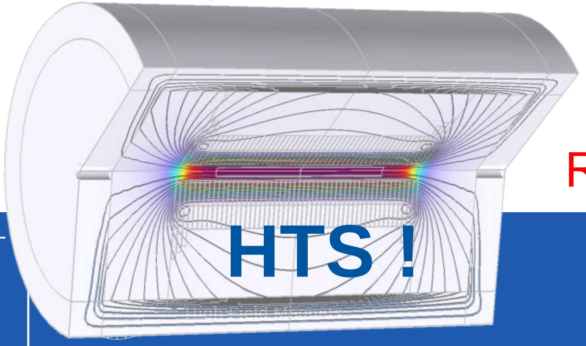
NC ±1.8 T, 400 Hz
100 mm x 30 mm

SC < 10T
100 mm x 30 mm





> 40 T, 60 mm

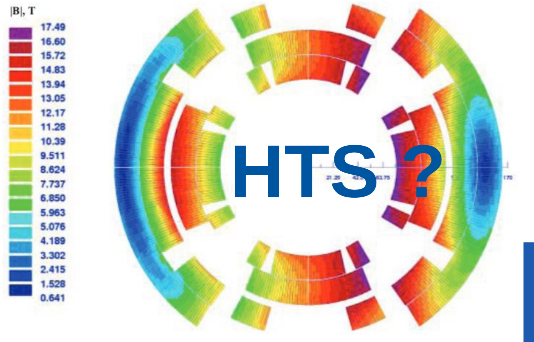


HTS !

16 T peak, 150 mm

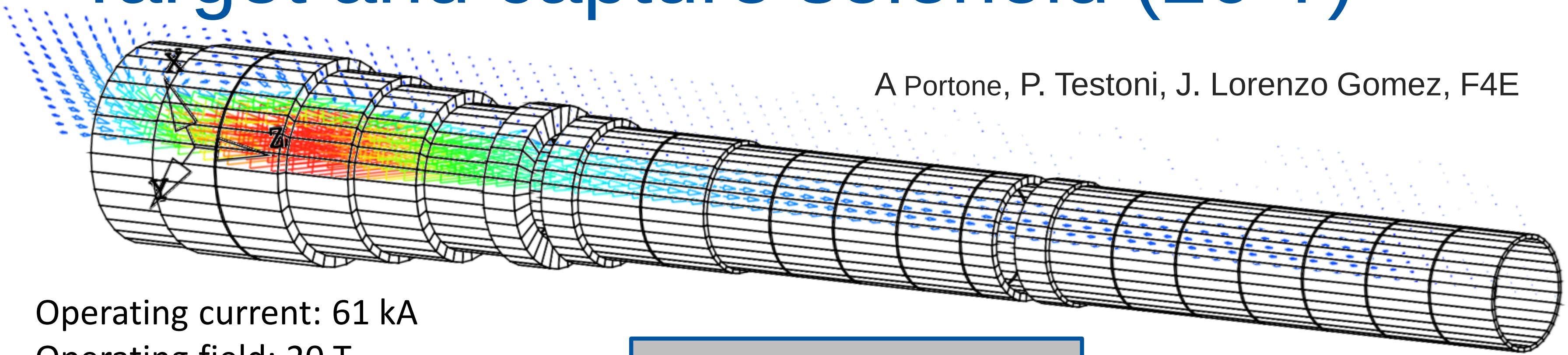
Radiation heat load ≈ 5 W/m

Radiation dose ≈ 20…40 MGy



HTS ?

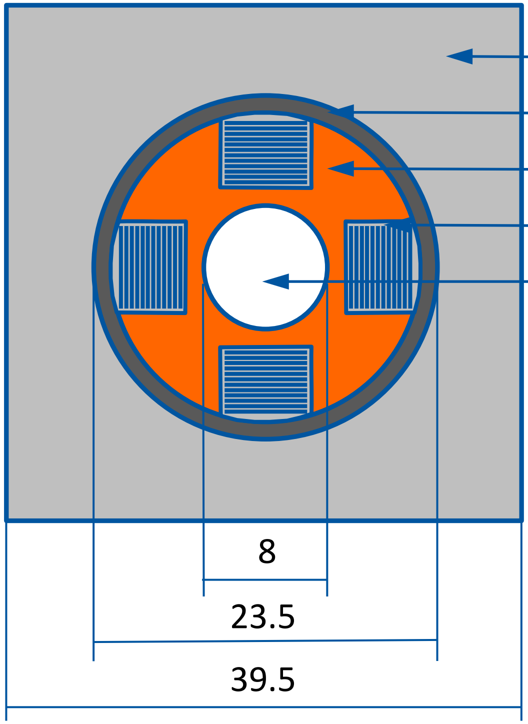
Target and capture solenoid (20 T)

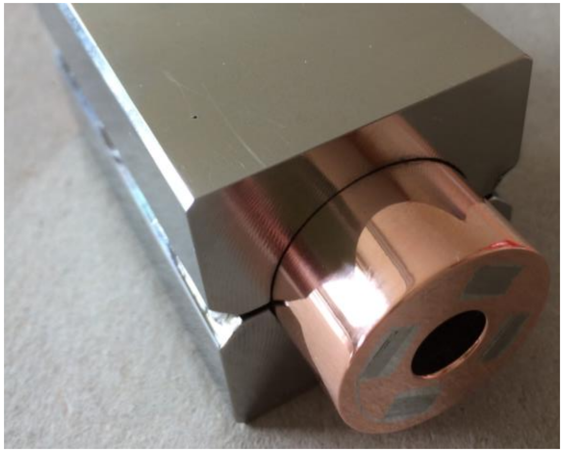


A Portone, P. Testoni, J. Lorenzo Gomez, F4E

Operating current: 61 kA
Operating field: 20 T
Operating temperature: 20 K


MIT “VIPER” conductor


SS JACKET
SS WRAP
COPPER FORMER
SOLDERED HTS STACK
COOLING CHANNEL



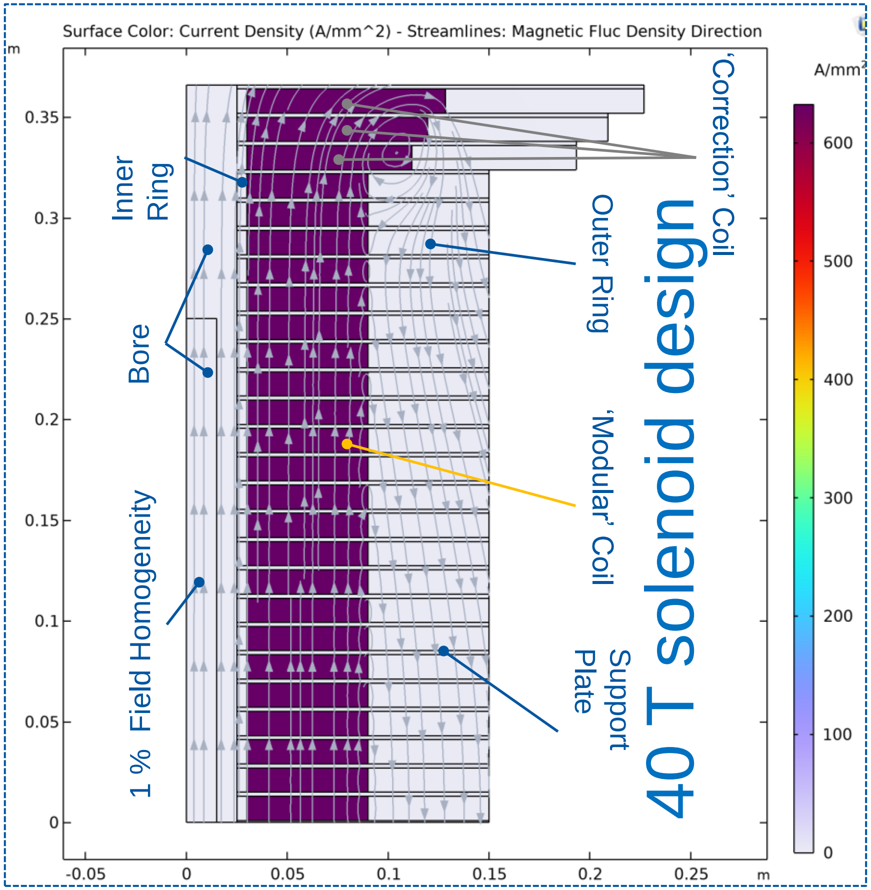
M. Takayasu et al., IEEE TAS, 21 (2011) 2340
Z. S. Hartwig et al., SUST, 33 (2020) 11LT01

Strong connection to HTS magnets for fusion

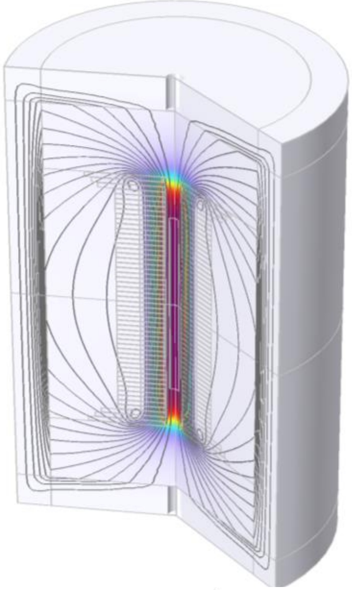
Final cooling (40 T)

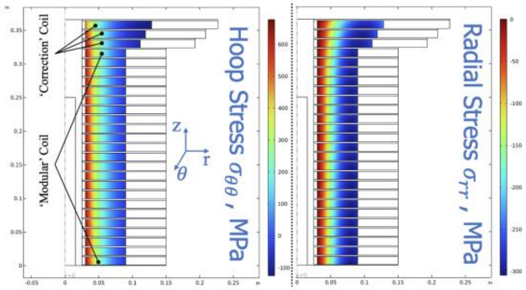
$$\mathbf{B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0}} \xrightarrow{\sigma_{max} = 600\ \mathrm{MPa}} \mathbf{B_{max} \approx 55\ T}$$

A. Dudarev, CERN

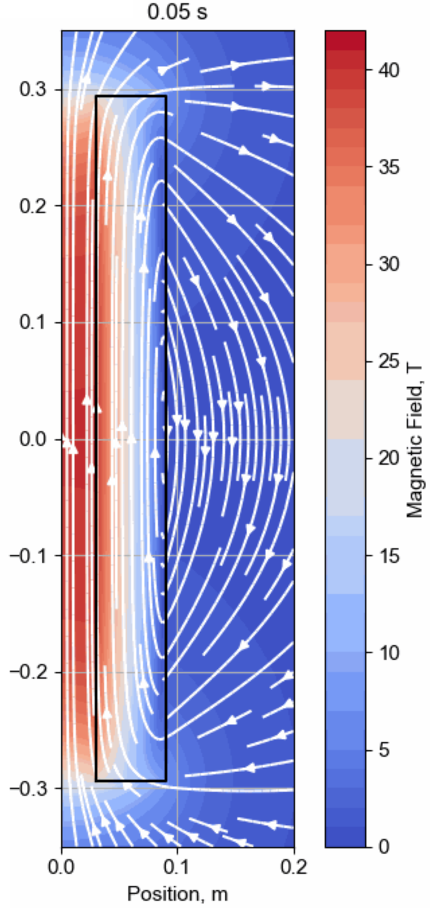


40 T solenoid design





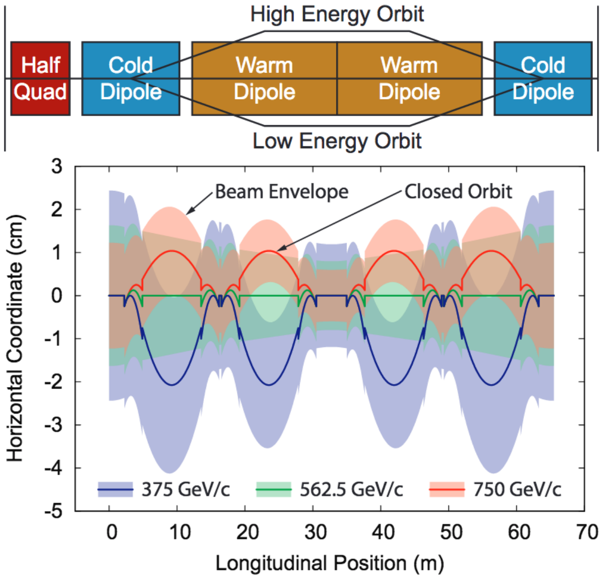
B. Bordini, CERN

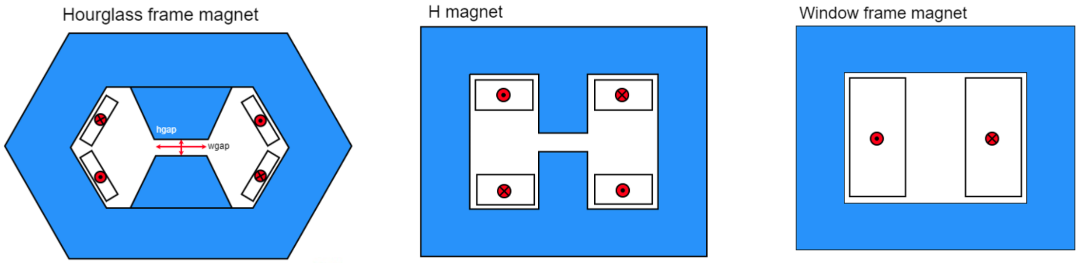


T. Mulder, CERN

Accelerator magnets (±1.8 T)

Warm dipoles are pulsed from -Bmax to +Bmax at high speed (0.35 to 6.37 ms) every 200 ms





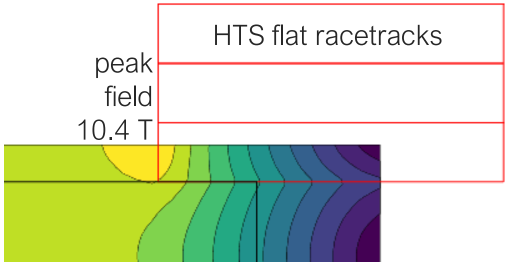
5.07 kJ/m 5.65…7.14 kJ/m 5.89 kJ/m

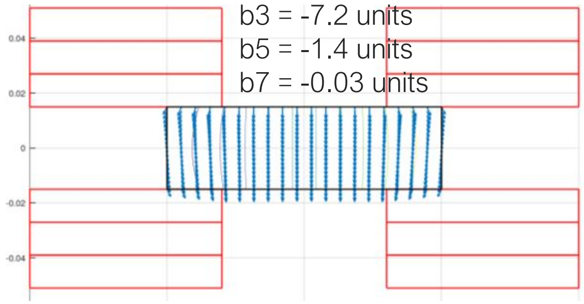
The main challenge is the management of the power in the resistive dipoles (several tens of GW):

- Minimum stored magnetic energy
- Highly efficient energy storage and recovery

A *simple* HTS racetrack dipole could match the beam requirements and aperture

Cold dipoles provide a steady baseline field of about 10 T

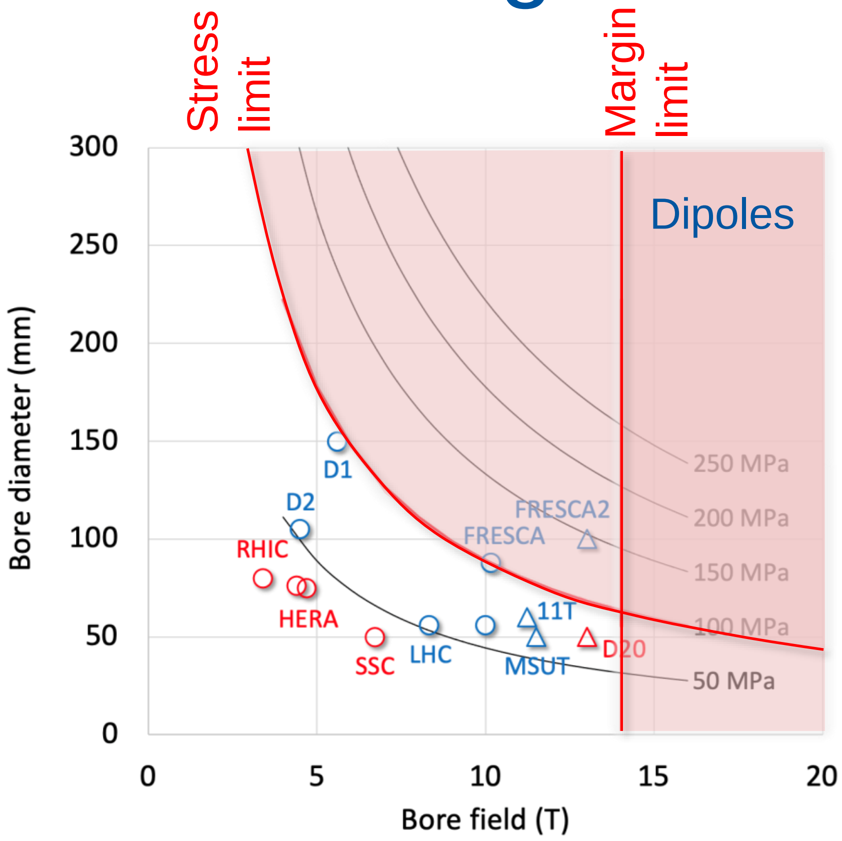


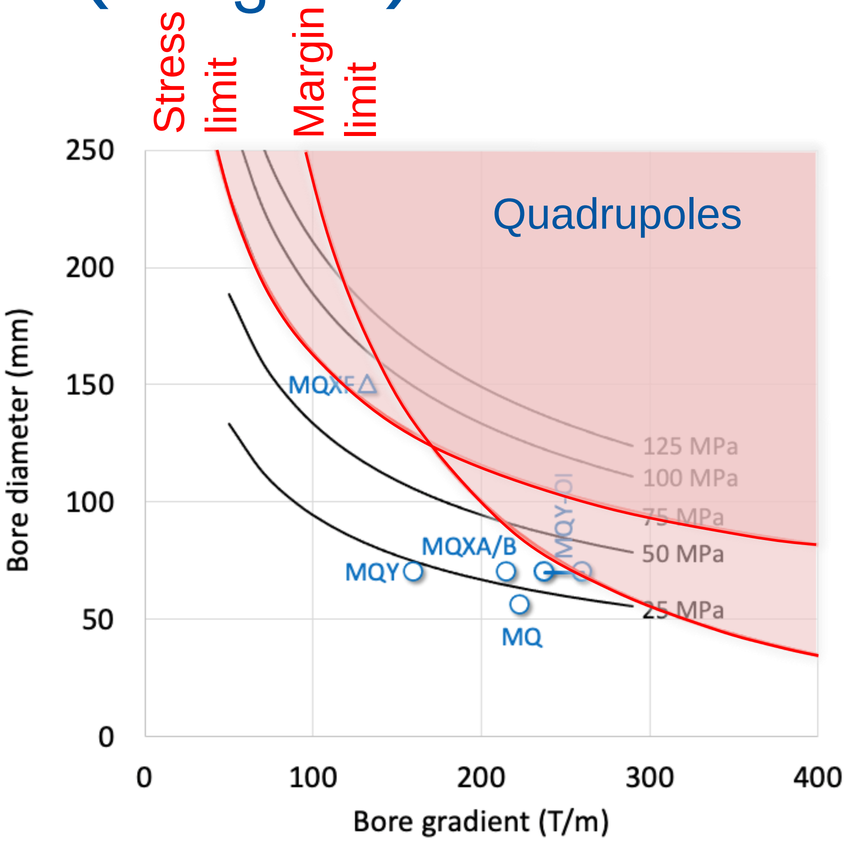


b3 = -7.2 units
b5 = -1.4 units
b7 = -0.03 units

Rectangular magnet bore 100 mm x 30 mm

Collider magnets limits (Nb_3Sn)

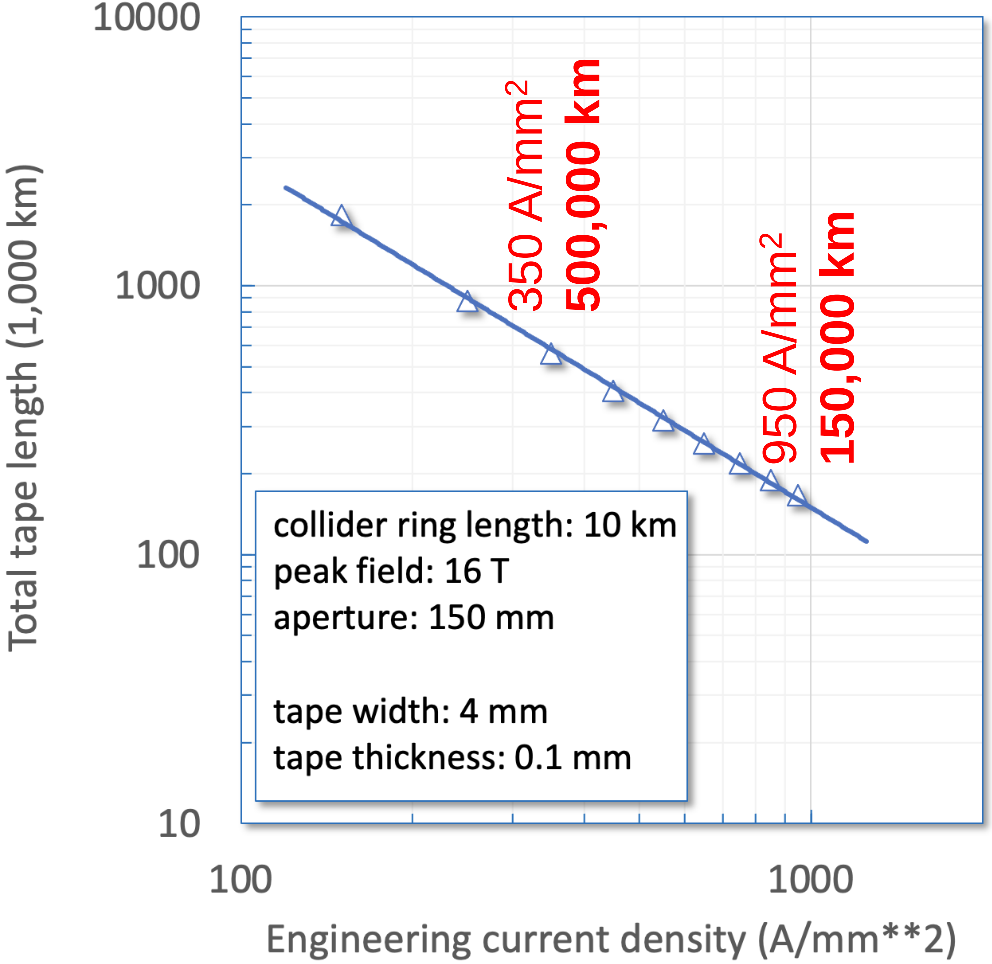




- Work in progress to provide analytical expression for the magnet design limits (including protection and cost)
    - Maximum field and gradient vs. magnet aperture in LTS and HTS
    - Combined function limits B+G and B/G
- **Proposal: take provisionally 9 T for NbTi and 14 T for Nb_3Sn**

Compact windings

Example of 16 T muon collider main dipole built with HTS



- We need to **increase the winding current density** to fall in a *reasonable* range of **conductor mass** (applies both to LTS and HTS)

- Unresolved issues:
  - Winding geometry for tapes and stacks (ends, alignment, transposition possibly superfluous ?)
  - Mechanics of coils under the exceptional electromagnetic loads (longitudinal stress in the range of 600 MPa, transverse stress in the range of 400 MPa)
  - Quench management at high current and energy density (above 100 MJ/m^3)
  - Radiation hardness of materials and coils (40…80 MGy and 10^{22} n/m^2)

The HEP push towards HTS

Reduce energy consumption
(FCC-ee 350 MW, FCC-hh 580 MW)

Risk with helium supply chain
(FCC-hh would require 900 tons of lHe)

Infrastructure (magnet) cost
(FCC-hh quoted at 9 BCHF)

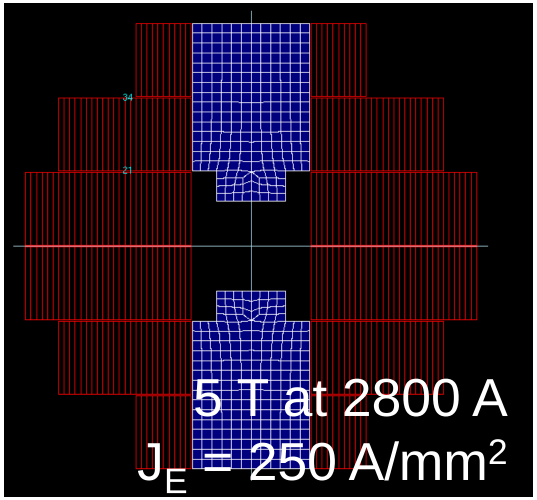
Operate SC magnets at *higher* cryogenic temperature (gas)

Increase energy efficiency
(COP at 1.9 K is about 1000)

Avoid large liquid helium bath and operate with gas (lower density)

Reduce SC cost per unit length and current

Increase coil current density to decrease conductor inventory

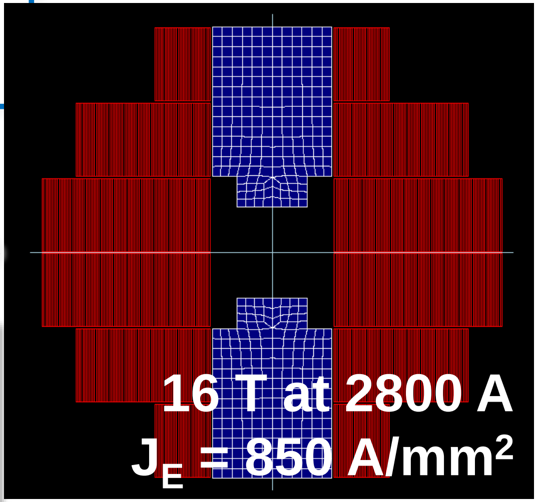


5 T at 2800 A
J_E = 250 A/mm²

Calculation example
(T. Lecrevisse, CEA)

Compact HTS windings
- **Target J_E 1000 A/mm²**

Operation in gaseous He
- **Range of 15…25 K**



16 T at 2800 A
J_E = 850 A/mm²

HTS for accelerators

		Specification	Target
Minimum $J_{non\text{-}Cu}$ (4.2 K, 20 T)	(A/mm^2)	1500	3000
Minimum $J_{non\text{-}Cu}$ (20 K, 20 T)	(A/mm^2)	600	1250
$\sigma(I_C)$	(%)	10	5
Minimum copper RRR	(-)		20
Minimum Unit Length (UL)	(m)	200	500
Minimum bending radius	(mm)	15	10
Allowable $\sigma_{longitudinal\ non\text{-}Cu}$	(MPa)	800	1000
Allowable compressive $\sigma_{transverse}$	(MPa)		400
Allowable tensile $\sigma_{transverse}$	(MPa)		25
Allowable shear $\tau_{transverse}$	(MPa)		20
Allowable peel σ_{peel}	(MPa)		TBD
Allowable cleavage $\sigma_{cleavage}$	(MPa)		TBD
Range of allowable $\varepsilon_{longitudinal}$	(%)	-0.1…0.4	-0.1…+0.5
Internal specific resistance $\rho_{transverse}$	($n\Omega/cm^2$)		20

Width: 4…12 mm
Substrate (non-magnetic alloy): 40…60 μm
Copper stabilizer (total): 20…40 μm
Total tape thickness: 60…100 μm