HFM

High Field Magnets

High-Field Magnet Programme

FCC Week 2023, London, June 7, 2023

Andrzej Siemko and B. Auchmann (PSI/CERN)
for the HFM Programme Team

HFM
High Field Magnets

Outline

- Origin, Vision and Goals
- Participating Institues and Structure
- Focus Areas
  - Nb3Sn Conductors and Magnets
  - HTS Conductors and Magnets
- Cross-Cutting Activities
  - Examples
  - Fast-Turnaround R&D

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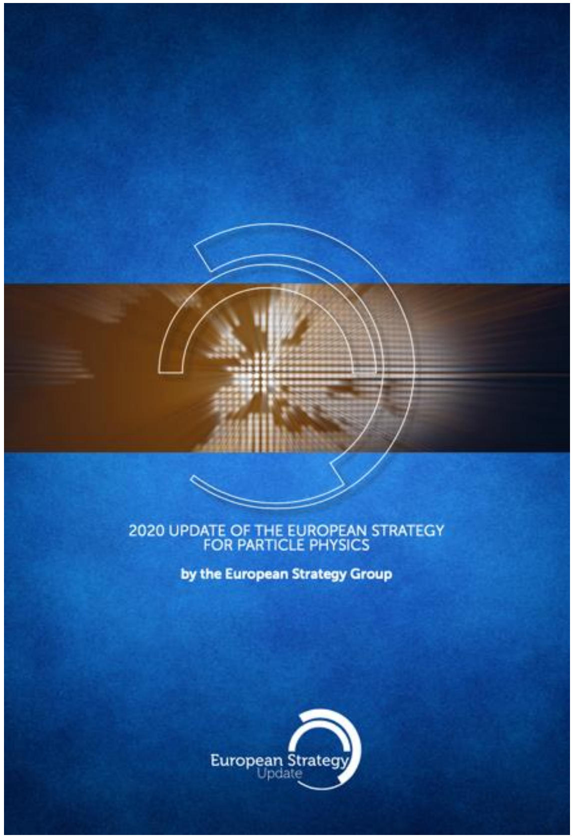
Origins of HFM

- ***"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV*** and with an electron-positron Higgs and electroweak factory as a possible first stage. "
- ***"The technologies under consideration include high-field magnets, high-temperature superconductors***, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. The European particle physics community must intensify accelerator R&D and sustain it with adequate resources.
- ***A roadmap should prioritise the technology,*** taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry.
- ***Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes."***



http://cds.cern.ch/record/2721370

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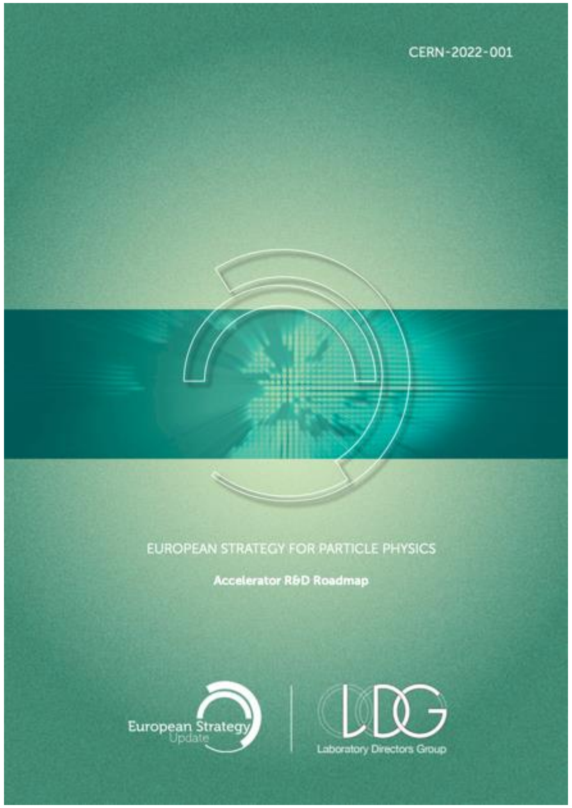

https://arxiv.org/abs/2201.07895

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High Field Magnets

https://cern.ch/hfm

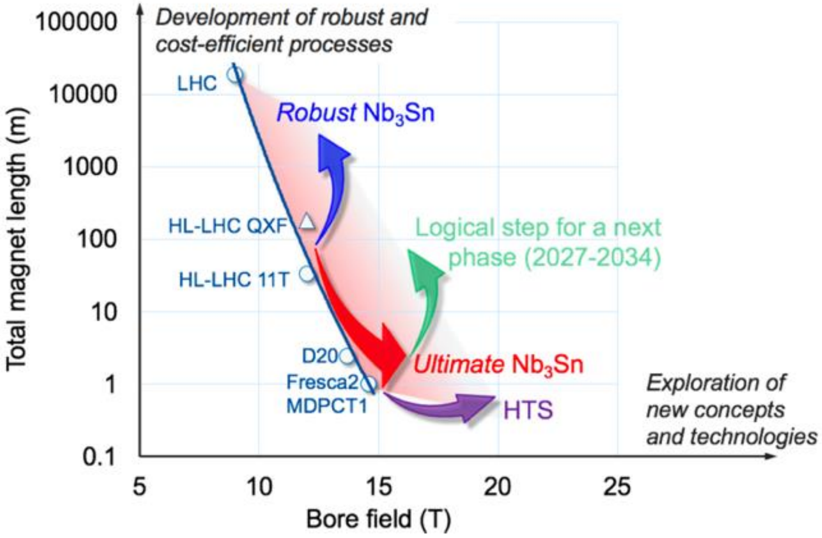
Vision of the HFM Programme

Create an innovative HFM research network that enables a future flagship HEP project in Europe.

- Fast-track pressing technology R&D.
- Invest in paradigm-shifting technologies.
- Provide timely feedback to ESPP via technology demonstrations and credible roadmaps.

Goals of HFM

1. Demonstrate Nb3Sn magnet technology for large scale deployment, pushing it to its limits in terms of maximum field and production scale.
   - The effort to quantify and demonstrate Nb3Sn ultimate field comprises the development of conductor and magnet technology towards the ultimate Nb3Sn performance.
   - Develop Nb3Sn magnet technology for collider-scale production, through robust design, industrial manufacturing and cost reduction.
2. Demonstrate the suitability of HTS for accelerator magnets, providing a proof-of-principle of HTS magnet technology beyond the reach of Nb3Sn.



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CERN | HFM High Field Magnets

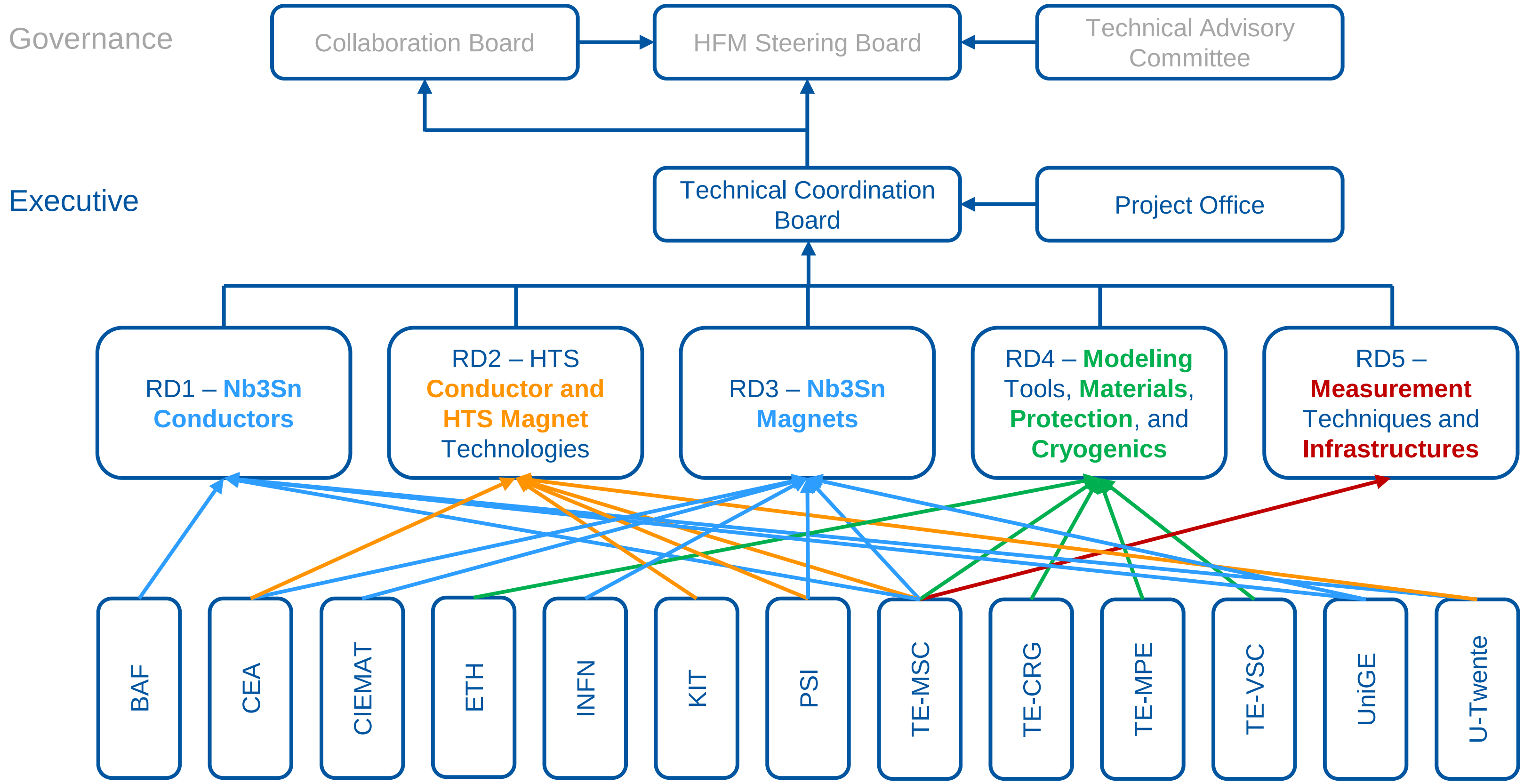
HFM Laboratories and Institutes

Magnets

Conductors

Enabling Technologies

HFM Programme Structure



HFM
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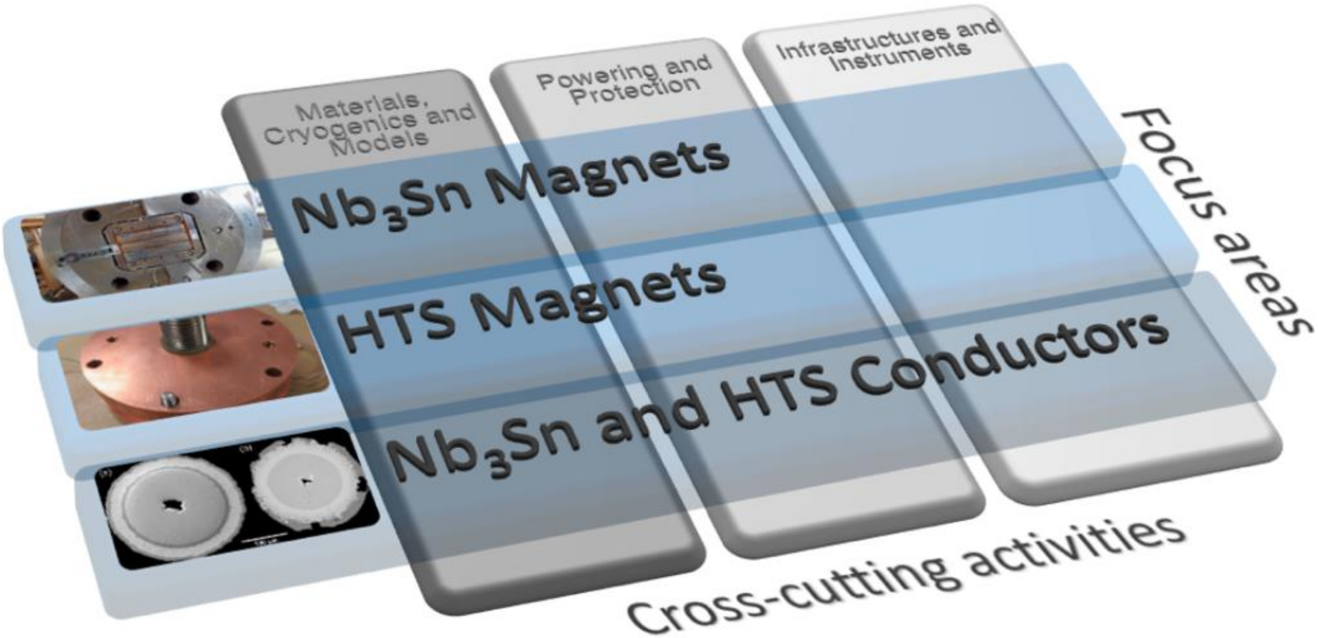
HFM Structure



"The R&D programme must be holistic in nature: a compatible selection of electromagnetic, mechanical and thermal design approaches, conductors, materials, and manufacturing processes needs to be integrated seamlessly with instrumentation and protection into a magnet solution responding to the required specification."

Conversely, work across R&D lines must be closely integrated.

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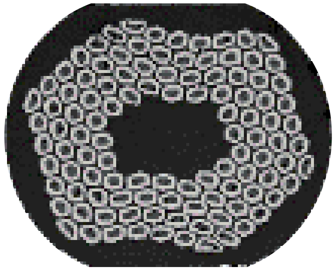
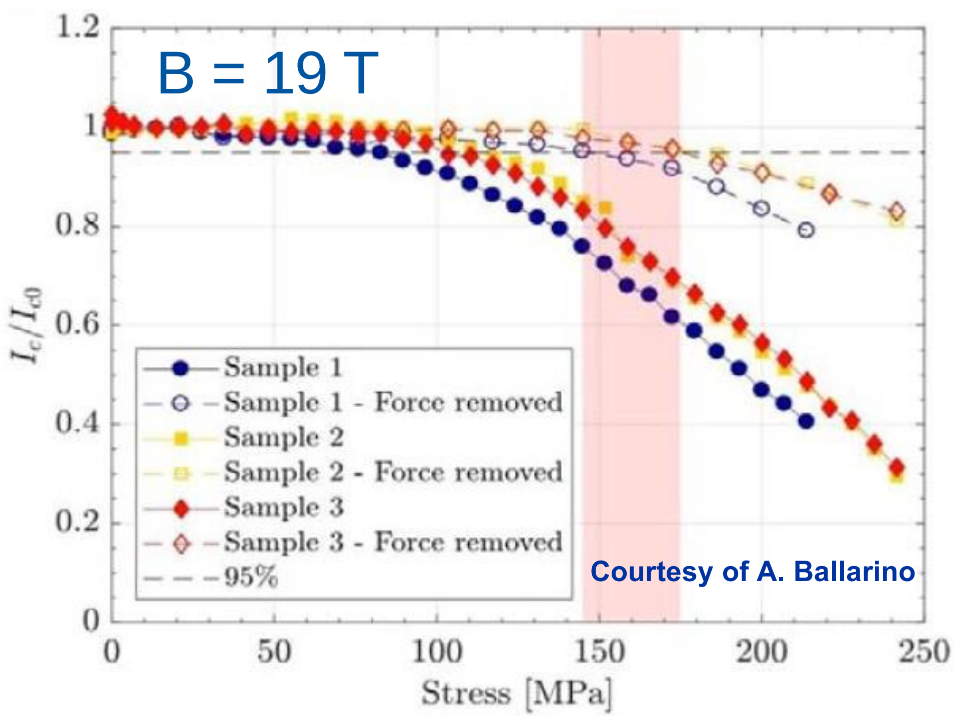
Nb_3Sn Conductor Challenge

- Nb3Sn critical current $I_c(B,T,\varepsilon)$ is strain dependent.
- Stresses above 150 MPa lead to:
  - copper plasticization that ’freezes’ strain permanently.
  - filment breakage that further degrades performance



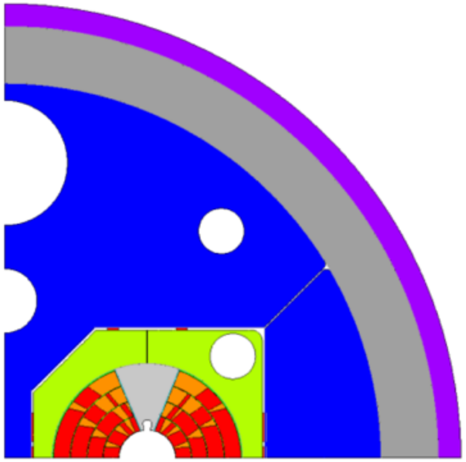


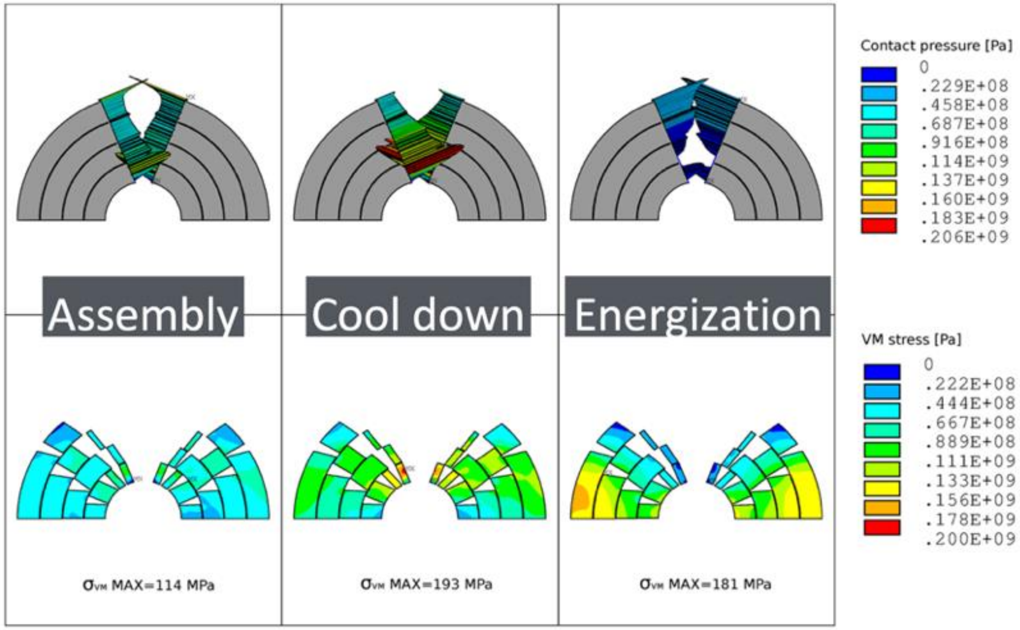
- σ_{irr} = 145–175 MPa
- I_c/I_{c0} @ 150 MPa
  → 16 % - 28 %

Nb_3Sn HFM Mechanics Challenge

Full pre-stress: a lesson learned from the Nb-Ti era:

- Keep coils under compression at all stages of operation → avoid stick-slip motion.
  - Forces scale quadratically with field. For 16 T dipole, forces equivalent of 1.5 kt/m pull coil-halves apart.
  - 10 µm abrupt movement is enough to cause quench.
- Need to limit stress on Nb_3Sn!





[S. Farinon et al., in M. Benedikt et al., *FCC Conceptual Design Report*, 2019.]

Focus Area 12 T Robust Nb_3Sn Dipole

- HL-LHC manufacturing processes are labor intensive.
- Fewer processing steps, shared tooling between steps, increased automation, etc. could improve manufacturability and yield and reduce cost.

- Integrate all lessons learned from HL-LHC and improve aspects of manufacturability (among others through collaboration with industry) and cost.
- Demonstrate maturity of Nb_3Sn technology up to full length.
- Explore maximum fields attainable with classical two-layer coils.

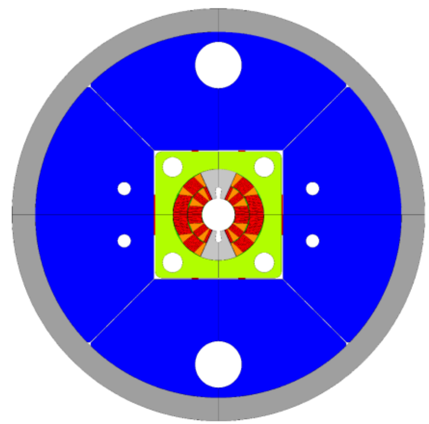
12 T Robust

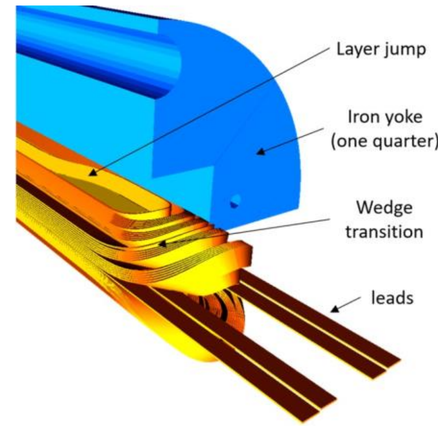
Ongoing projects:
12 T Robust Dipoles

Development of a single aperture “12 T Robust Dipole” in INFN, Genova

Main characteristics :

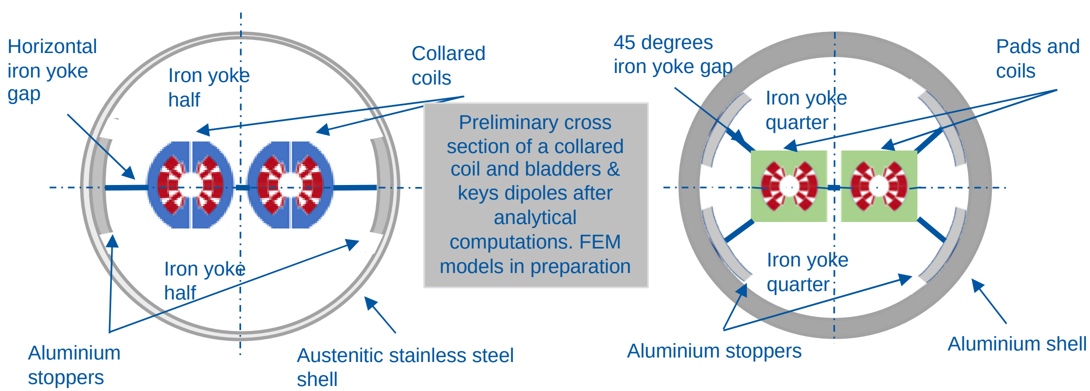
- 2 layers ; 50 mm bore
- Rutherford 40 strands (φ = 1 mm J_C(4.5 K, 16 T)=1200 A/mm^2)
- Nominal magnetic field: 12 T
- Ultimate (mechanical limit) field: 14 T
- Short sample limit : 15.7 T
- Mechanical structure: bladder & key
- Stress in conductors ≲150 MPa in all conditions
- Outer diameter: 640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





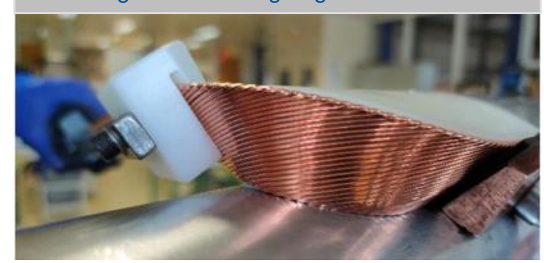
Courtesy of S. Farinon

Development of twin “12 T Robust Dipole” at CERN



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.

HFM High Field Magnets

Focus Area Nb_3Sn Conductors and Magnets

Reaching ultimate Nb_3Sn performance (towards 16 T) is aided by innovation and new approaches in:

Conductor Technology

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

Nb_3Sn Conductor R&D

Novel Design Concepts

Magnet Technology

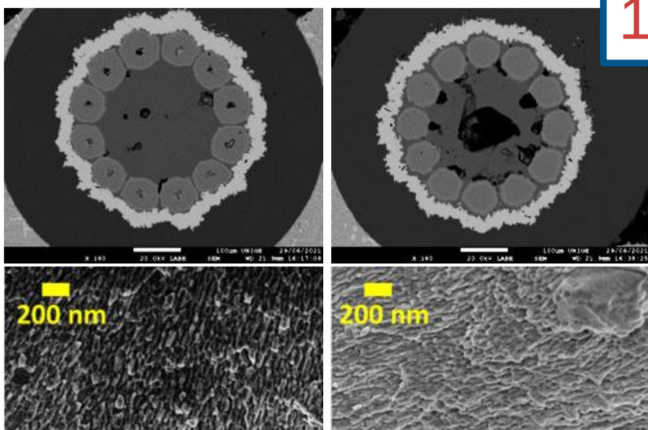
- Coil designs and structures with minimal stress in high-field regions.
- Low-prestress designs, allowing for some moderated movement.
- Reinforced coils; Stress-management eliminates pre-stress.

Ongoing projects:
Nb_3Sn Conductor

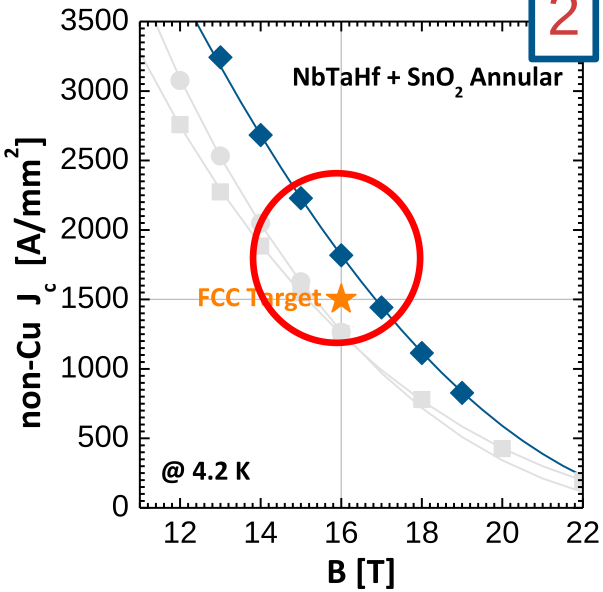
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

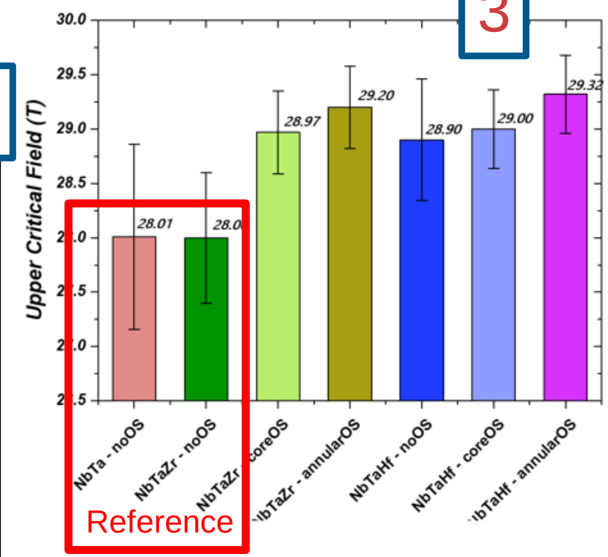
CHART
Swiss Accelerator Research and Technology

Internal Oxidation in prototype multifilamentary wires



Average grain size ~ 47 nm	Average grain size ~ 45 nm





Larger billets under development

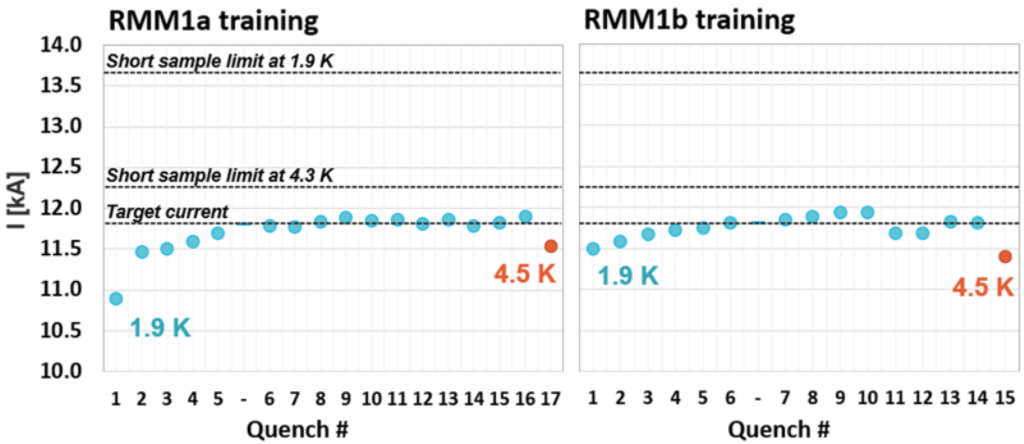
Pushing Nb_3Sn towards its ultimate performance

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

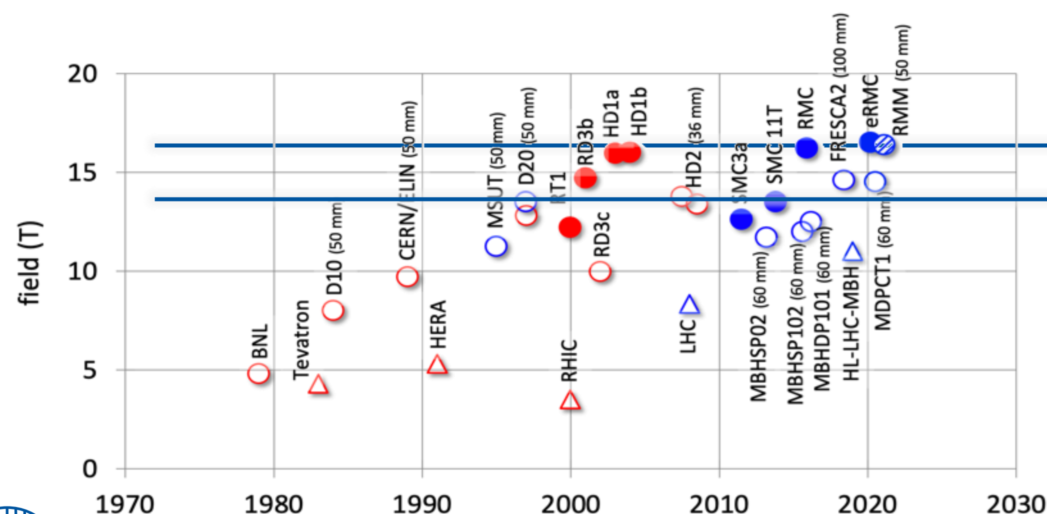
CERN | HFM High Field Magnets

Ongoing projects:
CERN RMM



Courtesy of J. C. Perez

RMM1c magnet has been assembled with increased pre-load and will be tested in few weeks.



Upper limit of today's Nb_3Sn technology (~16 T)

Present state-of-the-art (short models ~13-14.5 T)

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Ongoing projects:
Block-Coil 16-T Roadmap

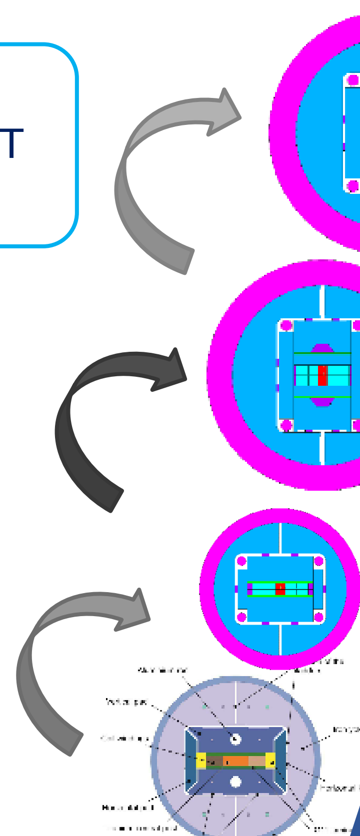
F2D2 Short model → **Planned**
Grading + Flared-ends + Aperture, 16 T
1.5 m, 50 mm bore **with aperture**

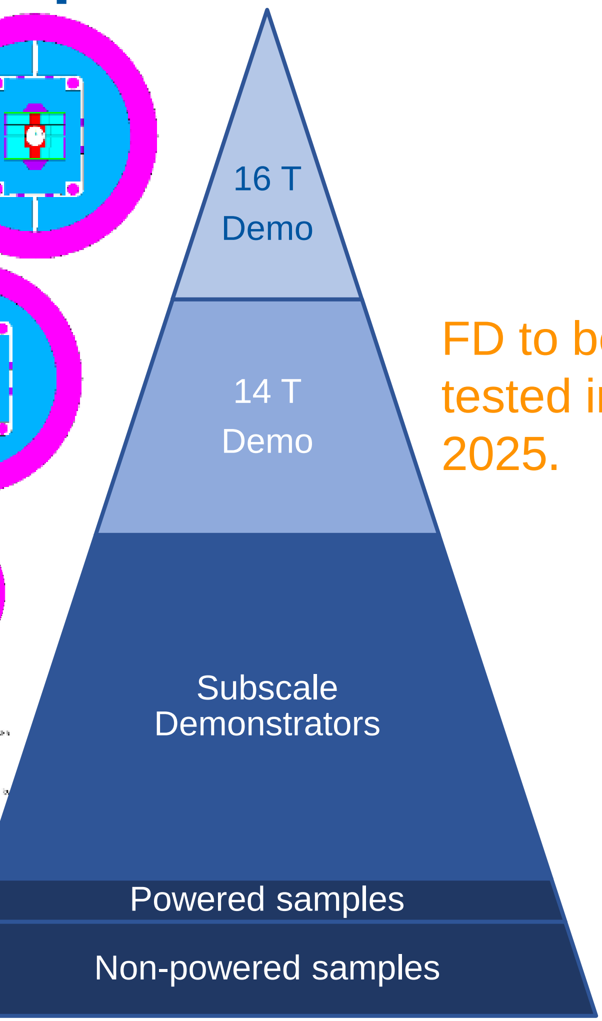
FD Demonstrator → **Planned**
Grading + flared-ends, 14 T
1.5 m, No bore **with flared ends**

CEA-CERN R2D2 → **Ongoing**
Demonstrate grading ≥ 12 T
1.5 m, No bor **with grading**

CEA-CERN SMC-11T coil ✓ **Done**
Demonstrate Nb_3Sn tech. ≥ 12 T





FD to be tested in 2025.

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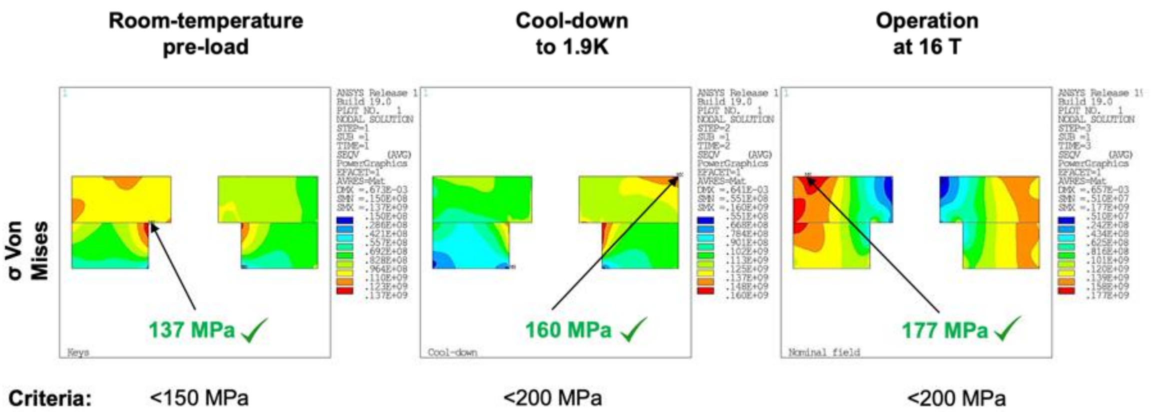
Courtesy of E. Rochepault

Ongoing projects:

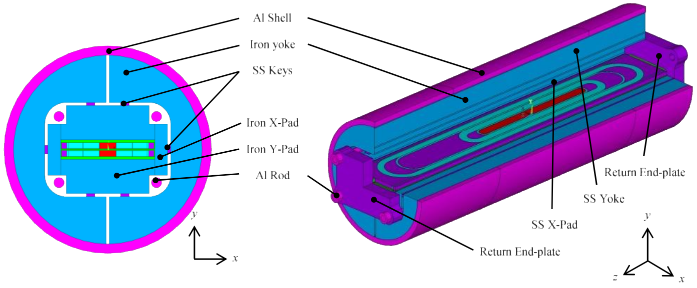
Block-Coil 16-T Roadmap

- Peak stress at cold and nominal in low-field, high-margin region.



- R2D2 graded flat-racetrack magnet fabrication started.

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

Courtesy of E. Rochepault

Nb_3Sn Magnet Projects Ramping Up

CERN

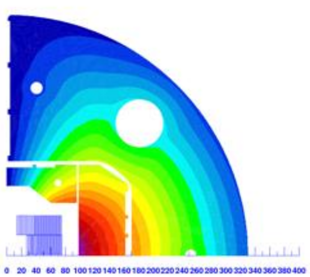
Development of technological steps towards 16-T block coil Nb_3Sn magnets with stress management: conceptual design has started.

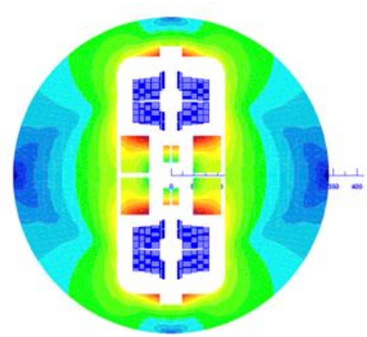
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

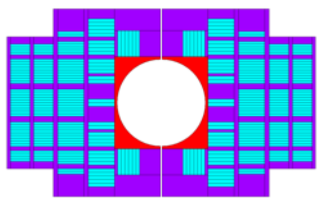
Collaboration agreement for the development of technological steps towards 16-T Nb_3Sn magnets with low-prestress common coil structure: preparation of workshops for the implementation phase.

CHART Swiss Accelerator Research and Technology
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 finalized. First test 14.5-15 T in 2025/26.







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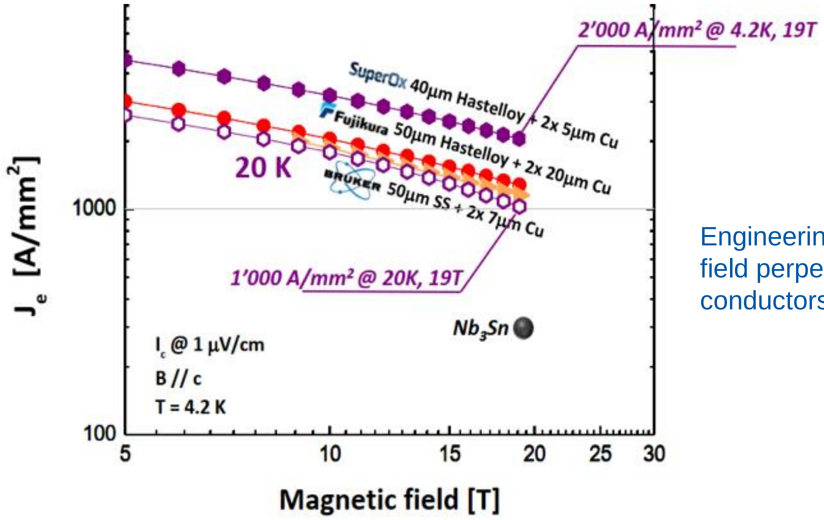
For implementation examples see talk by A. Ballarino (RD2).

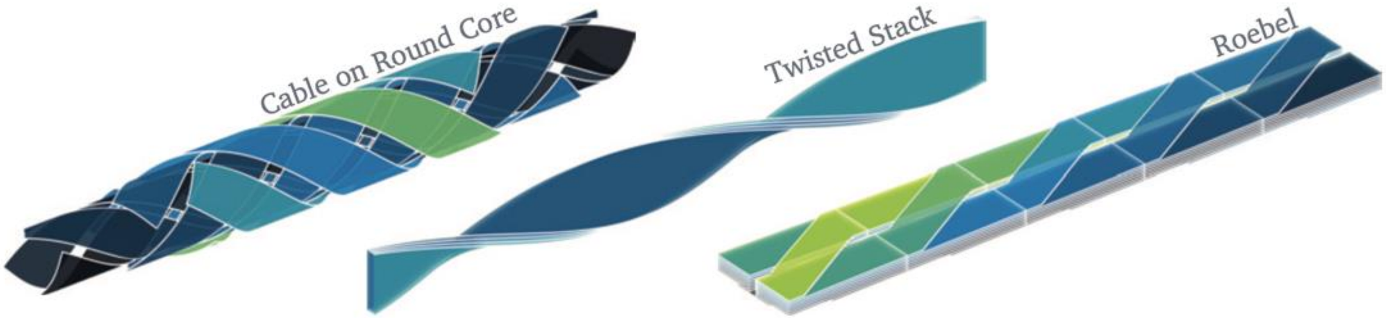
Focus Area HTS Conductors and HFMs

- In Europe, we focus mainly on ReBCO tape, due to its availability from multiple suppliers and excellent performance.
- Drawbacks are related to
  - limited shear-strength,
  - large magnetization effects that impact ramp losses and field quality,
  - large anisotropy,
  - unit lengths, uniformity, bending radius, etc.
- Other HTS-related challenges pertain to magnet protection (slow-rising voltage signal, large temperature margins).

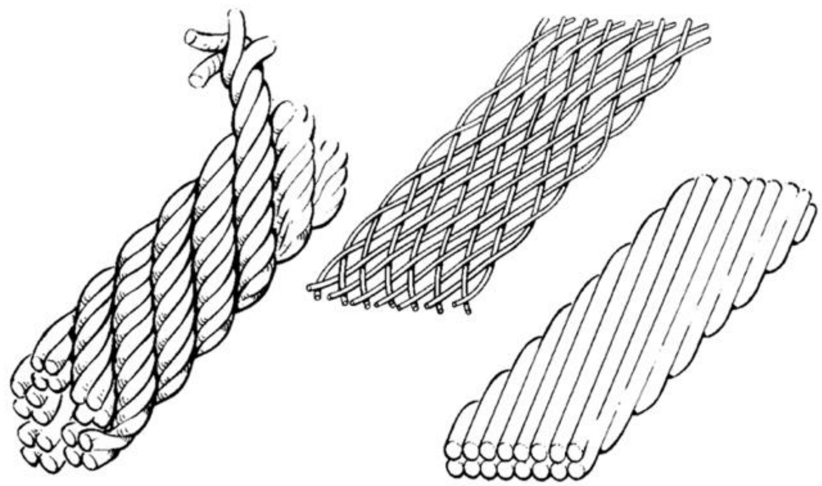


Engineering current density (J_e) in magnetic field perpendicular to substrate for selected conductors (C. Senatore, UNIGE)

Back to the Future …



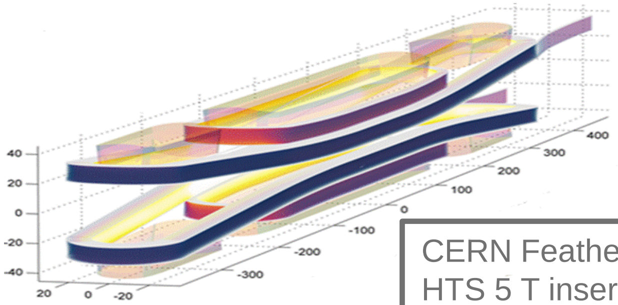
ReBCO magnet technology is at the stage of LTS in the 1970ies.



[J. v. Nugteren, High Temperature Superconductor Accelerator Magnets. UTwente, 2016.]
[M. Wilson, Pulsed Superconducting Magnets' CERN Academic Training May 2006]

Focus Area HTS Conductors and HFMs

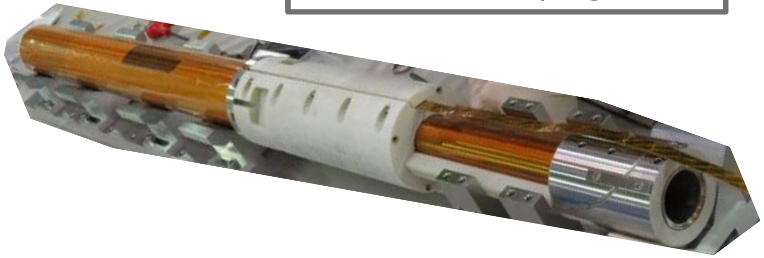
- EUCARD2 magnets at CERN and CEA represent the communities most targeted attempts to build accelerator magnets from ReBCO tape (here, Roebel bar cable).
- Both magnets were performance limited; Feather-M2 at CERN likely due to mechanical / thermo-mechanical effects; CEA's cos-theta coil due to over-heating of coils during manufacturing.



CERN Feather-M2
HTS 5 T insert magnet

Courtesy of G. Kirby,
J. Van Nugteren

CEA cos-theta magnet,
insulated and impregnated



Courtesy of T. Lecrevisse

Focus Area HTS Conductor and HFMs

- "Consideration of only engineering current density would suggest that magnetic fields in the range of 25 T could be generated by HTS"
- "… performance of HTS in the range 10 to 20K has reached values of Je well in excess of 500 to 800A/mm2, i.e., the level that is required for compact accelerator coils. […] it would open a pathway towards a reduction of cryogenic power, [and] a reduction of helium inventory (e.g., dry magnets)" [LDG Roadmap on High-Field Magnets, p. 33]
- We are building a new body of knowledge; today we do not know whether we can keep all of the above promises.
- Cryogenics, magnetics, mechanics, protection will be ever more tightly integrated – collaboration and communication, i.e., systems thinking and systems engineering will be mandatory.

For implementation examples, see talk by A. Ballarino

HTS Conductors

- Improvement of ReBCO for low magnetisation, mechanical robustness, and reduced anisotropy
- Development of practical HTS cables
- Development of alternative HTS superconductors such as IBS

HTS Magnets

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

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Cross-Cutting Activities

- Numerical models, materials, protection techniques, cryogenics, diagnostics, magnetic measurements, etc. are all challenging applications of their respective engineering sciences.

Disclaimer: The following examples are selected arbitrarily and do not give a complete overview of activities.

Cross-Cutting Activities

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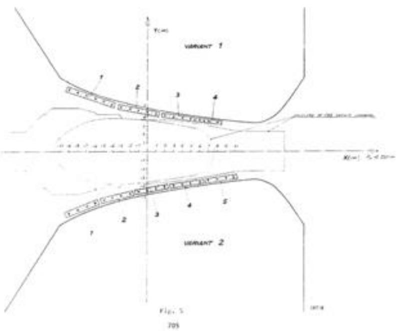
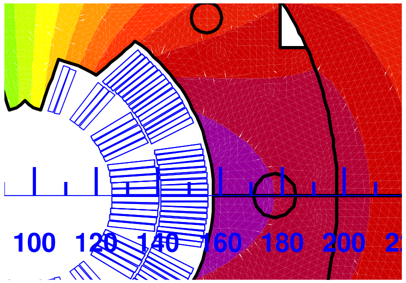
[A]





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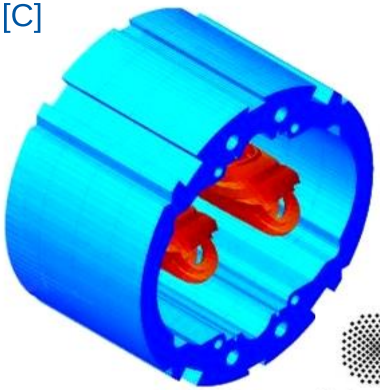
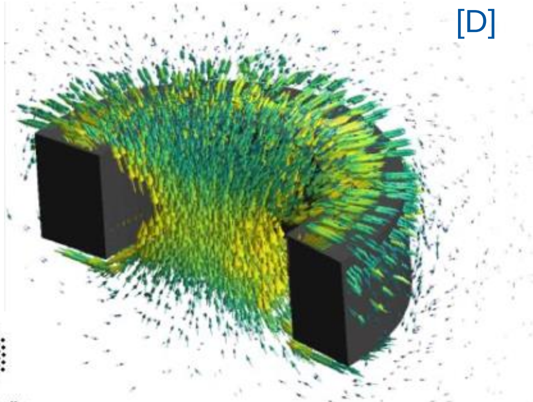


Universität Stuttgart

[D]



TECHNISCHE UNIVERSITÄT DARMSTADT

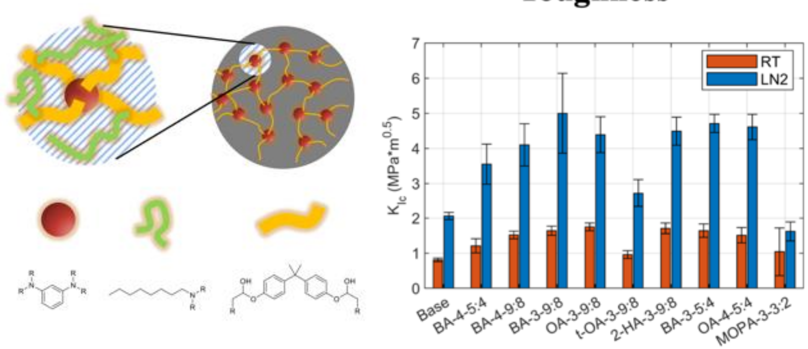
CERN

A. 1973: Asner, Holsinger, Iselin, MAGNET code.
B. 1983: Holsinger, Iselin, POISSON FEM code– still in use.
C. 1999: Kurs, Russenschuck, BEM-FEM in ROXIE, state of the art.
D. Today: Schaubelt, Vitrano, Verweij, Wozniak, FiQuS magnetic and thermal thin-film approximations for ReBCO, parallel in space and time FEA, under development

Cross-Cutting Activities

- Numerical models, materials, protection techniques, cryogenics, diagnostics, magnetic measurements, etc. are all challenging applications of their respective engineering sciences.

ETH zürich [A]



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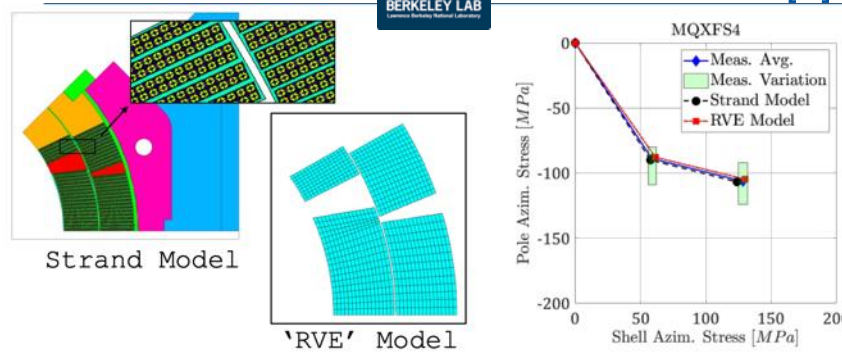

A. P. Studer, T. Tervoort: Best-in-class cryogenic fracture toughness in resins; ongoing.
B. G. Vallone et al.: Coil composite mechanical modeling, reference-volume technique; new state-of-the-art.

Cross-Cutting Activities

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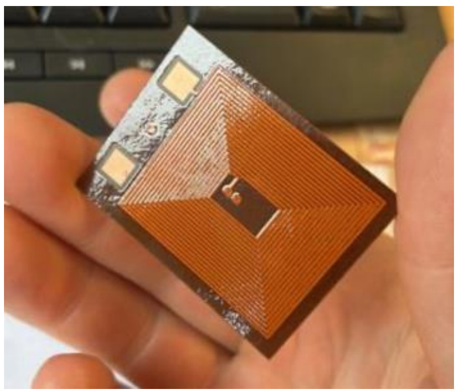
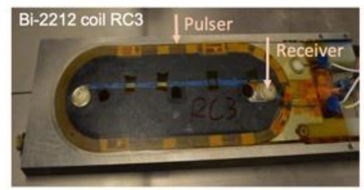
[A]

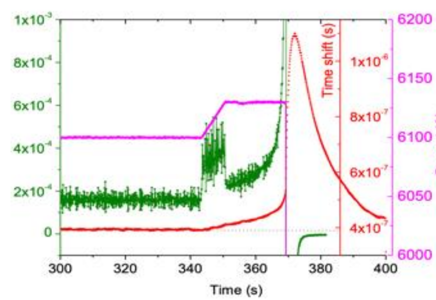


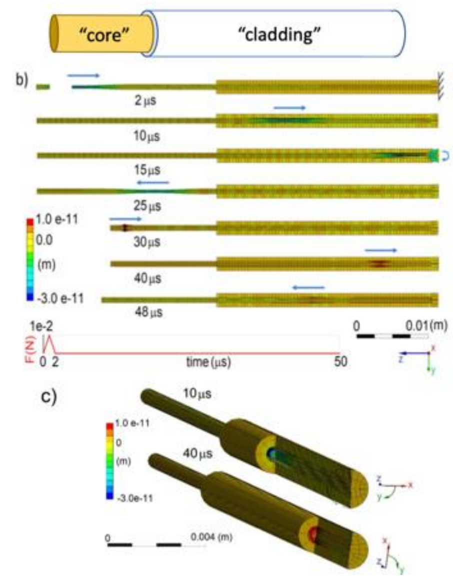
[B]



Coil design and test by T. Shen / K. Zhang

Experiment at 4.2 K. Current ramp stopped at 6100 A (stable) and then increased by 30 A (quenching)



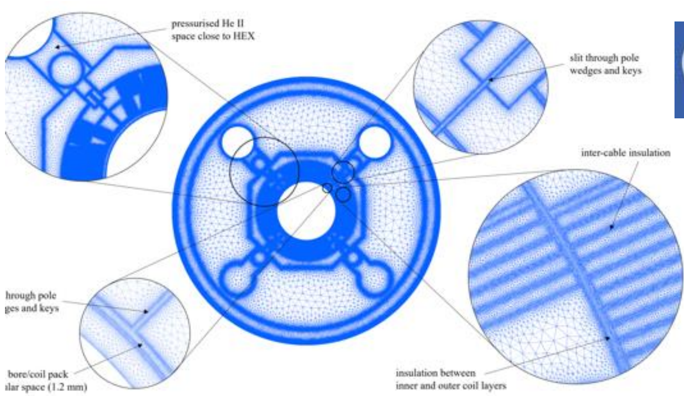


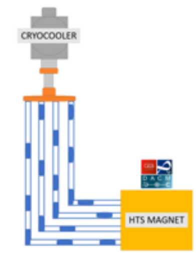
A. T. Mulder et al., eCLIQ, an induction heater for SC magnets, ongoing study.

B. M. Marchevsky et al. Active acoustic thermometry; Ultrasound reflectometry in acoustic waveguides.

Cross-Cutting Activities

- Numerical models, materials, protection techniques, cryogenics, diagnostics, magnetic measurements, etc. are all challenging applications of their respective engineering sciences.



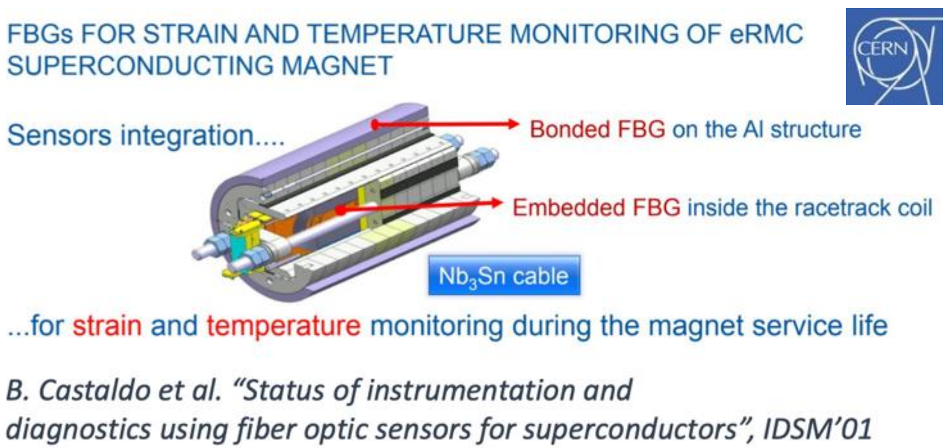


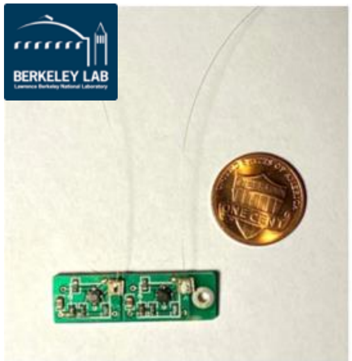
A. P. Borges de Sousa et al., Numerical framework to systematically assess the temperature distribution in complex He II-cooled magnet geometries using open-source software – applied for HL-LHC.

B. B. Baudouy et al. Pulsating Heat-Pipes for low thermal resistance, light-weight, fast thermal links – under development.

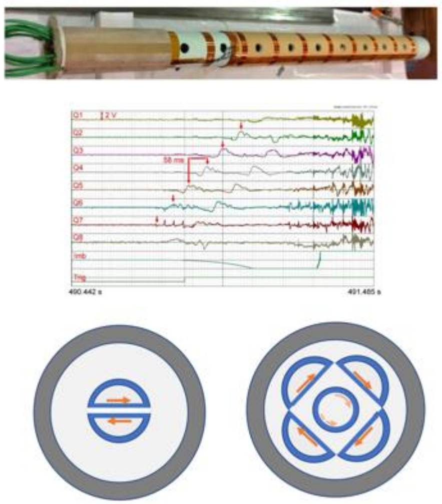
Cross-Cutting Activities

- Numerical models, materials, protection techniques, cryogenics, diagnostics, magnetic measurements, etc. are all challenging applications of their respective engineering sciences.





Waveguide acoustic sensors

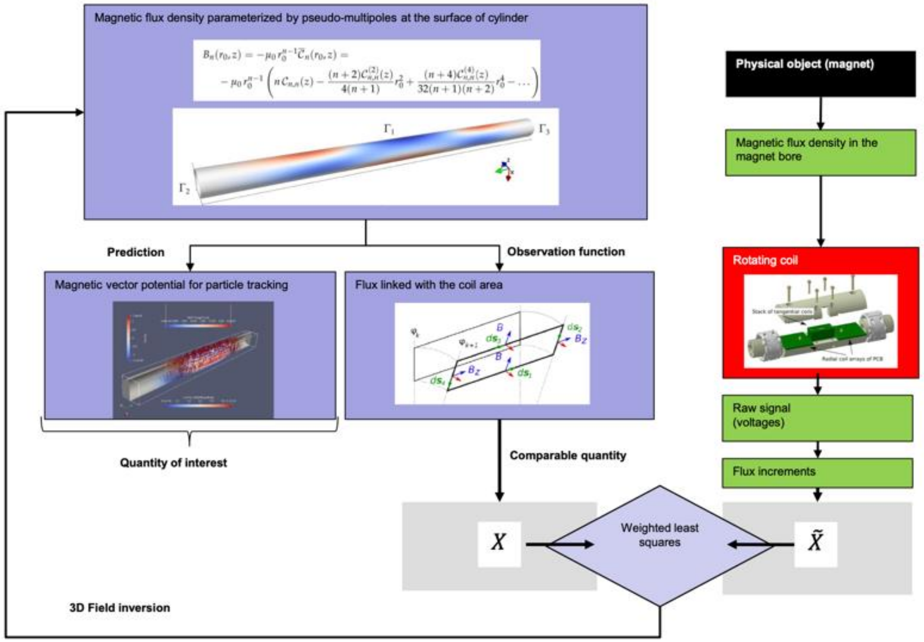

A "cloverleaf" axial antenna design (LBNL)

A. Fiber Bragg Grating sensors for distributed temperature and strain measuements

B. M. Marchvsky et al. Acoustic sensors and axial quench antennae.

Cross-Cutting Activities

- Numerical models, materials, protection techniques, cryogenics, diagnostics, magnetic measurements, etc. are all challenging applications of their respective engineering sciences.



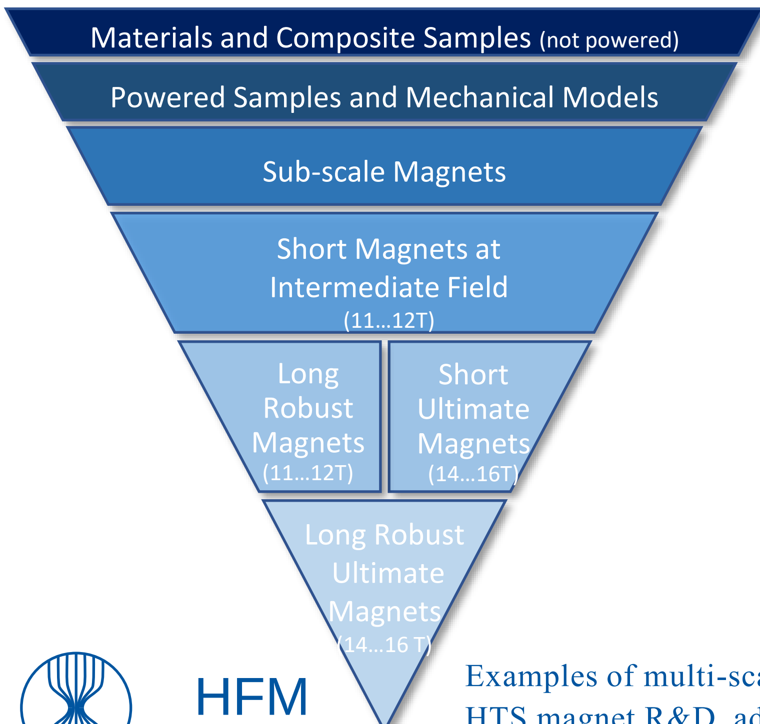
M. Liebsch, S. Russenschuck, Magnet avatar as numerical model augmented by magnetic measurements.

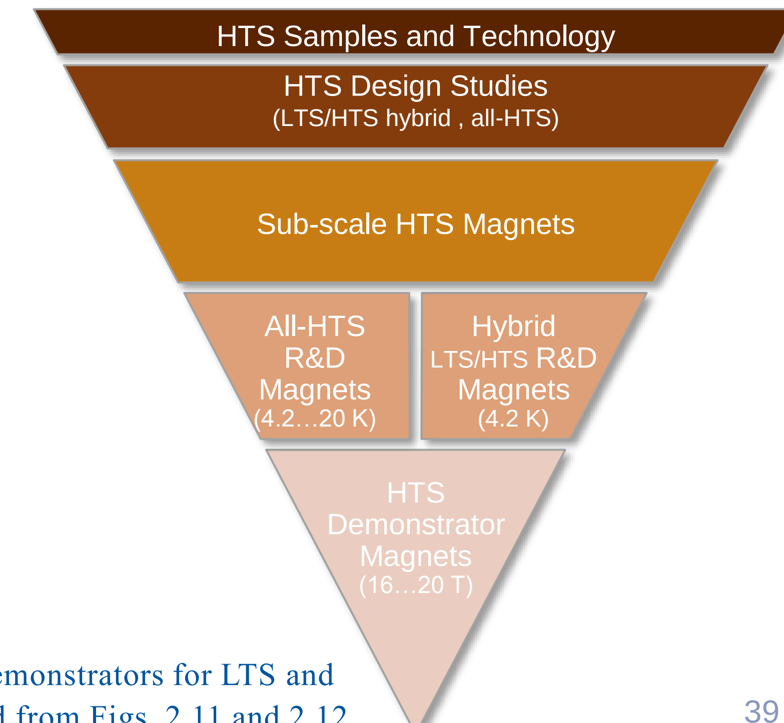
Cross-Cutting Activities

- Numerical models, materials, protection techniques, cryogenics, diagnostics, magnetic measurements, etc. are all challenging applications of their respective engineering sciences.
- Involving more labs as well as academic and industrial partners promises enhanced efforts, competency and cross-pollination.
- However, for cross-cutting R&D to effectively improve magnets, we need adequate management tools fostering systems thinking.
- Only a steady technical exchange can ensure that a magnet engineer's challenges motivate research into possible solutions, and that new developments inspire magnet designs.
- Open R&D Line Fora have started – now we must make HFM a dynamic research network!

Fast-Turnaround R&D as Innovation Funnel

- HFM R&D has suffered from slow turnaround and late feedback on technological choices.
- “We propose to structure the magnet R&D as a [~~succession~~ funnel] of meaningful fast-turnaround demonstrations, ranging from non-powered material […] samples […] towards ultimate specifications. In this way, new technologies can be tested under realistic conditions at the earliest possible stage, the smallest relevant scale and cost, and the fastest pace.“

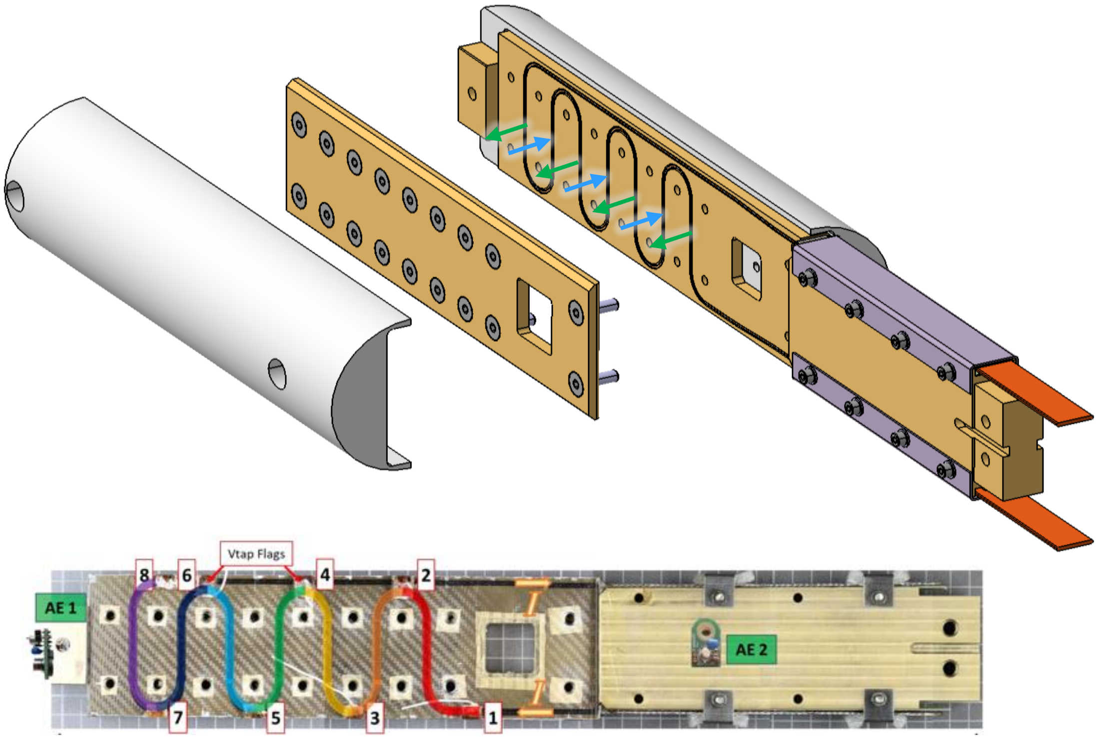




Examples of multi-scale demonstrators for LTS and HTS magnet R&D, adapted from Figs. 2.11 and 2.12.

HFM High Field Magnets

BOX Program

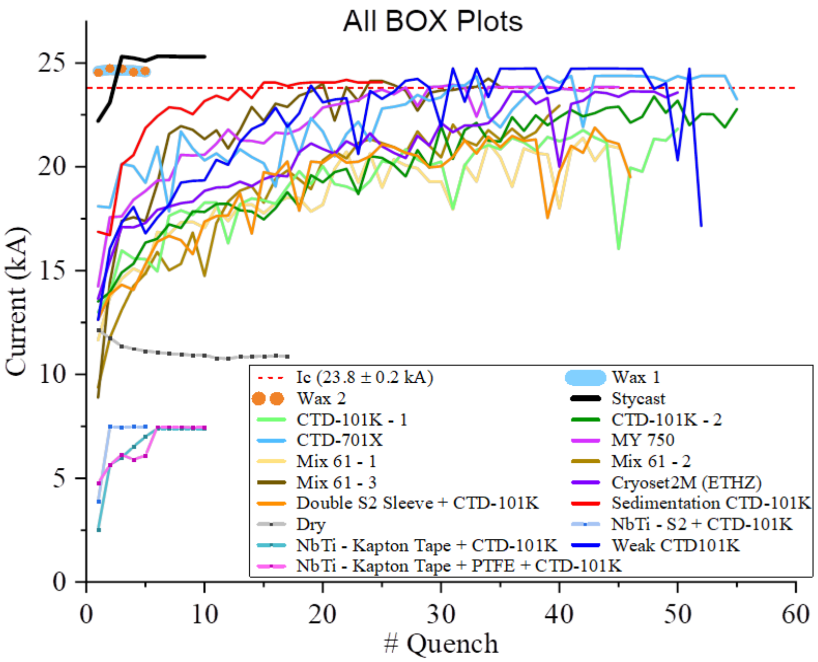


Pictures by M. Daly, S. Sidorov, S. Otten

SC Transformer

11-T solenoid

BOX Program



Pictures by M. Daly, S. Sidorov, S. Otten

BOX (BOnding eXperiment) program with uTwente has shown a wide variety of results, from complete conductor ***degradation (no impregnation)*** to substantial ***training (epoxy)*** to ***no-training (wax, Stycast),*** with ***18 BOX samples*** successfully manufactured and tested in 2 years.

BOX Program

A major factor in the design of large superconducting magnets is the problem of premature quenching, notably the 'training' effect, associated with the use of epoxy resin impregnants.

This paper draws attention to the existence of a simple but neglected solution to this problem. A review is given of a series of tests carried out in 1968–71 which showed that such effects were considerably reduced in the case of solenoid and quadrupole coils impregnated with wax or oil, allowing currents at least 85–90% of the critical value to be achieved consistently and reliably. The tests included a full scale prototype quadrupole (9 cm bore, 40 kG maximum field).

A discussion of the mechanical and thermal properties of such coils indicates no reason to doubt their long term reliability, and the adoption of this solution for operational magnets is recommended.

1975 review paper of 1968-71 results recommends wax or oil impregnation

Modern take on wax: combination with stress-management extends the validitity of the approach.

A solution to the 'training' problem in superconducting magnets

P. F. Smith and B. Colyer

BOX (BOnding eXperiment) program with uTwente has shown a wide variety of results, from complete conductor ***degradation (no impregnation)*** to substantial ***training (epoxy)*** to ***no-training (wax, Stycast),*** with ***18 BOX samples*** successfully manufactured and tested in two years.

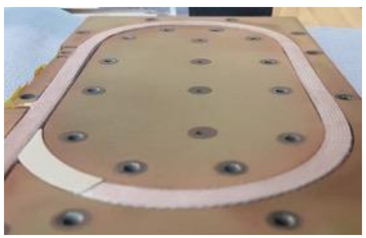
Feedback to Magnet Programs

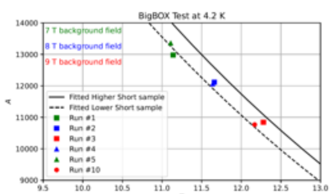
CHART Swiss Accelerator Research and Technology

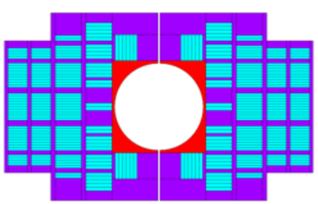
PAUL SCHERRER INSTITUT PSI

PSI's BigBOX: a 13-turn stress-managed racetrack.

- No training with 12.3 T coil field, 150 MPa coil stress at BNL's DCC17 facility.







[Courtesy D. Araujo et al]

LBNL's wax impregnated sub-scale (5 T) CCT.

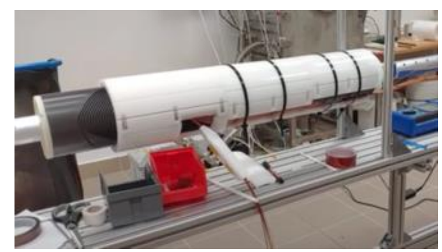
- First Nb_3Sn CCT without training.
- Follow-up magnet and test planned.

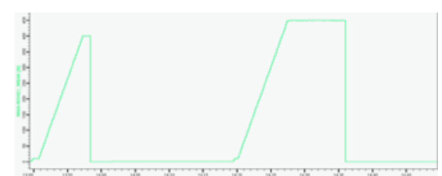
BERKELEY LAB

[Courtesy J.L. Rudeiros Fernandez, LBNL]

Wigner Inst. / CERN collaboration on SuShi septum for FCC-hh

- Wax impregnated CCT required no training to nominal current.





Wigner

[Courtesy D. Barna et al., Wigner Institute]

CERN | HFM High Field Magnets

Conclusion

The High-Field Magnet Programme, hosted at CERN, has begun to implement a strategic roadmap for High-Field Magnet R&D in Europe.

The programme shall:

- Fast-track pressing technology R&D.
- Invest in paradigm-shifting technologies.
- Provide timely feedback to ESPP via technology demonstrations and credible roadmaps.

To achieve this, we must

- foster communication, coordination, and cooperation among all actors
- provide (more) fast-turnaround R&D vehicles to reduce the feedback time on technology choices and encourage creative risk taking.

The challenges ahead are still considerable. Only as a TEAM can we produce the technological advances needed to achieve our goals and react swiftly as this complex research story unfolds.

For an implementation example see talk by S. Prestemon (US-MDP).