The High-Field Magnet Programme: Magnet R&D for FCC-hh in Europe

B. Auchmann, A. Siemko, E. Todesco,

ICHEP 2024, July 18, 2024

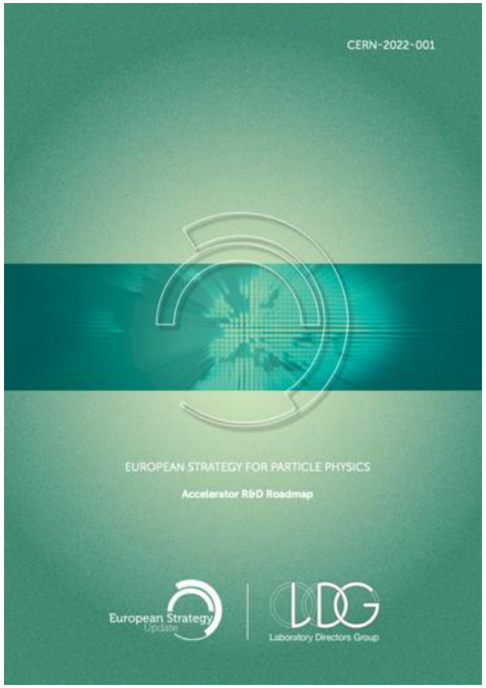
Overview

- The HFM Programme
- LTS R&D
- HTS R&D

HFM Programme

The High-Field Magnet Programme, hosted by CERN (http://cern.ch/hfm), was created in response to the 2020 ESPPU and the 2022 LDG R&D Roadmap.

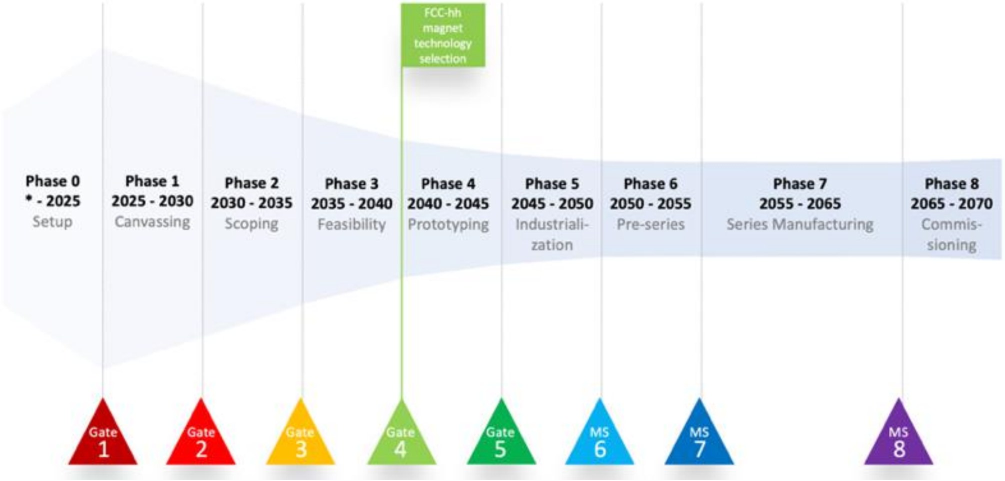
http://cds.cern.ch/record/2721370



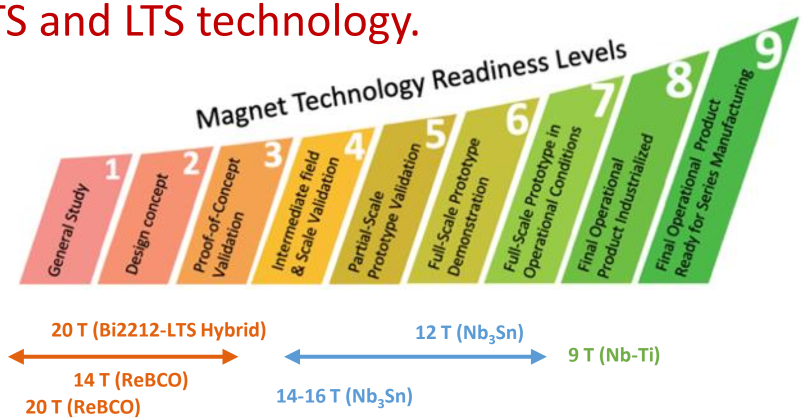
https://arxiv.org/abs/2201.07895

FCC-hh Magnet Development Roadmap

- 2024 FCC Feasibility Study midterm report places HFM activities in a long-term research roadmap and int'l context.
- Regular steering intervals serve to
  - steadily distill and solidify the technology options,
  - FCC-wide systems-engineering,
  - preparation of industrial involvement mostly from Phase 4 – "Prototyping".



- Need to close the significant TRL gap btw. HTS and LTS technology.
- Synergies – expected mostly from HTS technology – help to sustain the long-term effort.

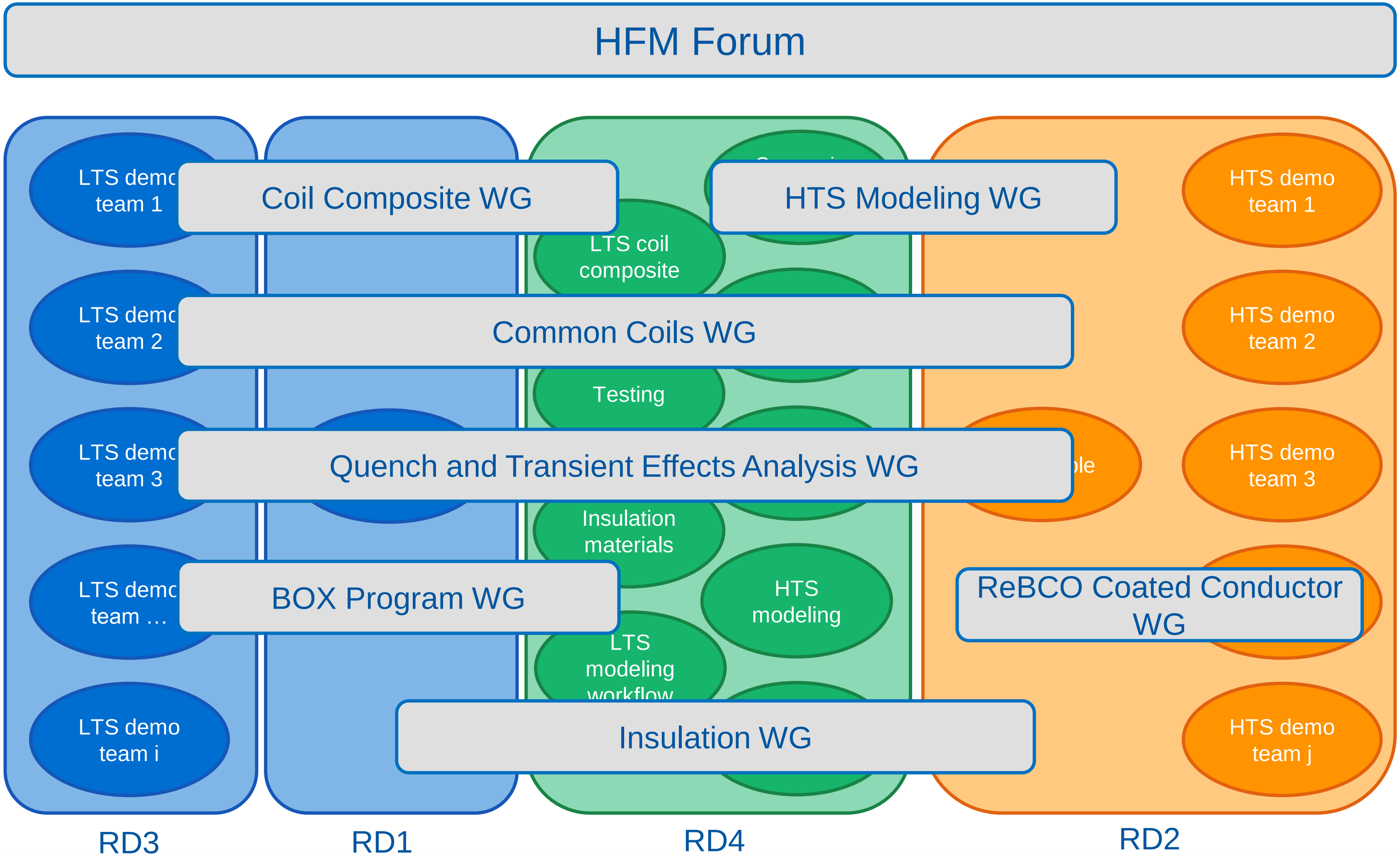


FCC Collaboration, Future Circular Collider (FCC) Feasibility Study Midterm Report, 2023.

HFM Partners

Today HFM comprises 13 European institutes.

HFM Organization

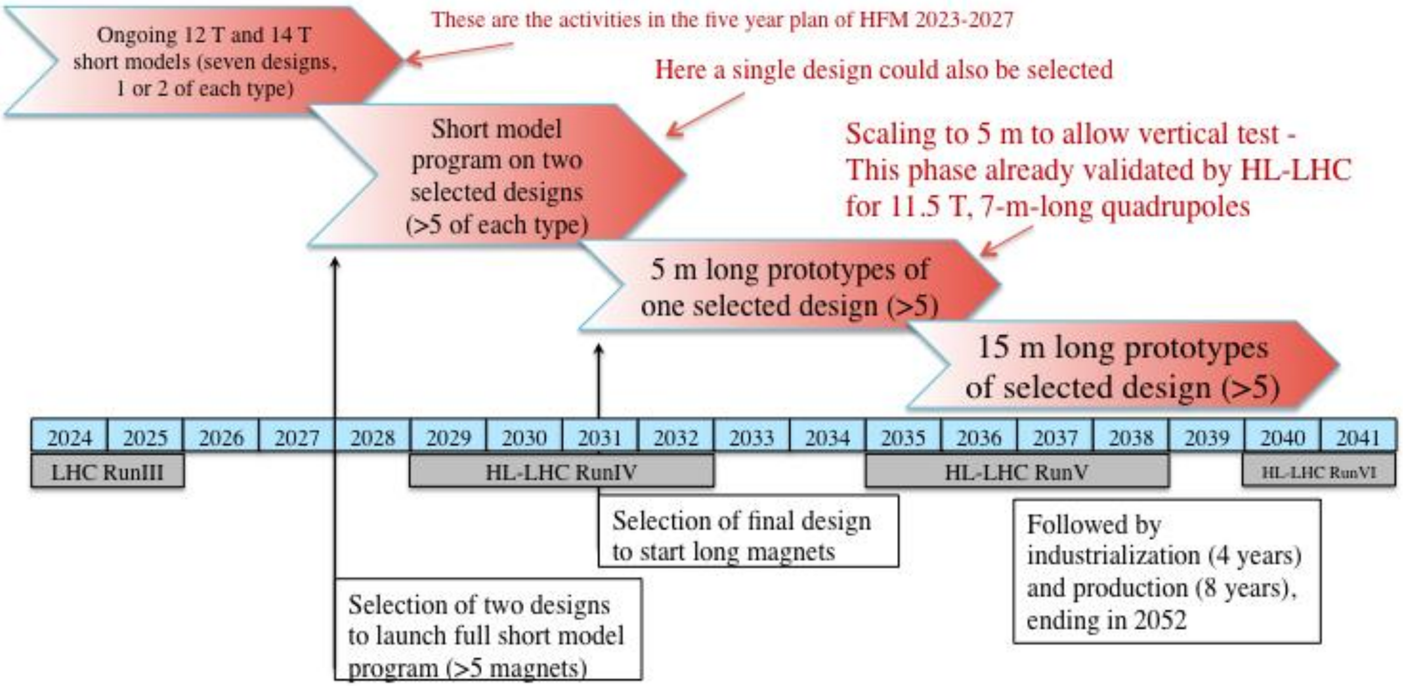


LTS – Nb_3Sn

Focus on FCC-hh Magnet Roadmap

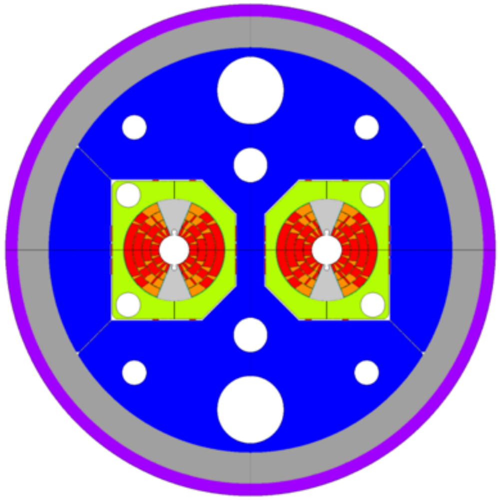
- R&D targets established for the FCC-hh
  - A 14 T Nb_3Sn magnet with 20% operational margin at 1.9 K (sufficient margin to produce 14 T also at 4.5 K)

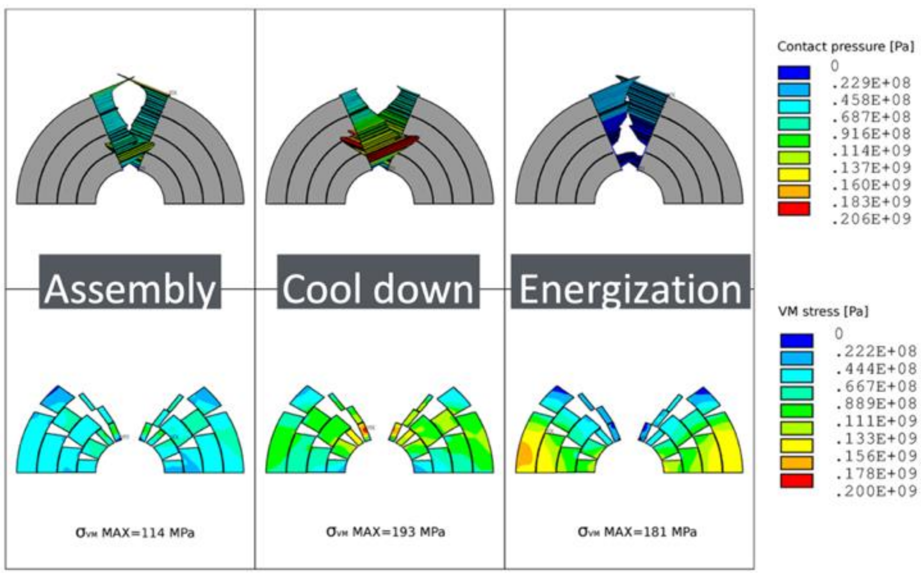
HFM LTS R&D Roadmap under discussion, courtesy E. Todesco

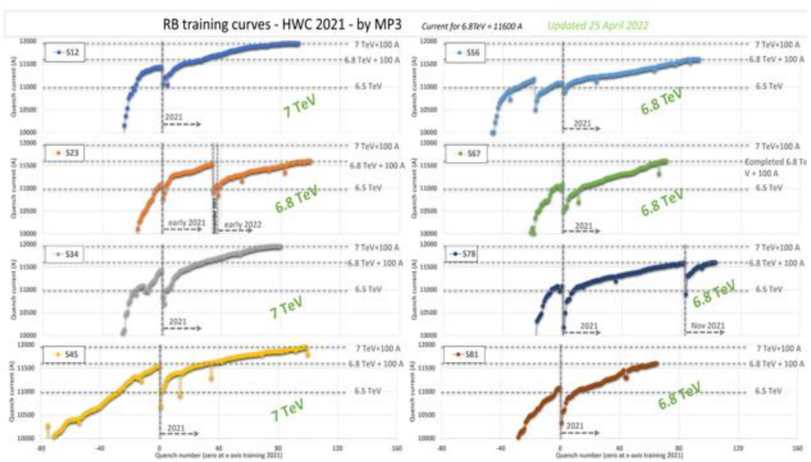


LTS Mechanics Challenge

- Avoid training and re-training → keep coils under compression at all stages of operation.
  - 14 T dipole experiences dipole forces equivalent to 1.2 kt/m.
  - 10 µm abrupt movement can cause quench.
- Nb_3Sn is brittle → limit stress to 150-200 MPa and reinforce with resin.
- Thermal-contraction mismatch and resin cracking compound the problem.





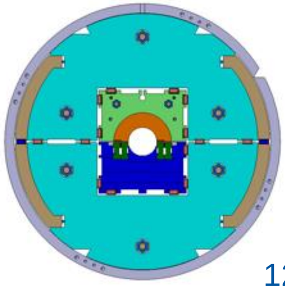


LHC Re-Training campaign to 6.8 TeV [http://cern.ch/mp3]

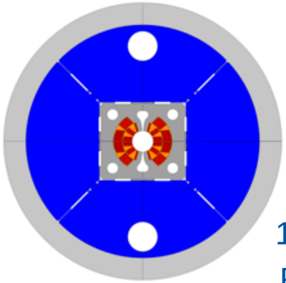
[S. Farinon et al., in M. Benedikt et al., *FCC Conceptual Design Report*, Vol. 3 – The Hadron Collider (FCC-hh), January 2019.]

HFM LTS Demonstrators

WPLs A. Foussat

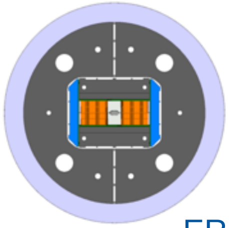


12 T CosTheta

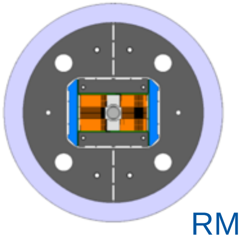


12 T CosTheta
FalconD

WPL S. Farinon, M. Sorbi

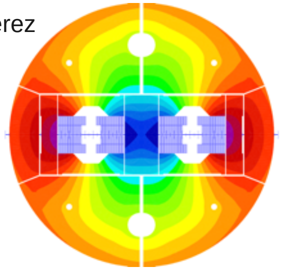


ERMC

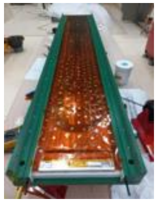


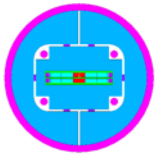
RMM

WPLJ. C. Perez

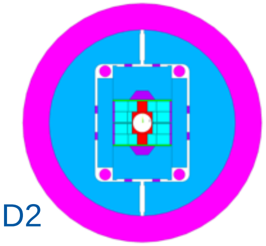


14 T no-grading
double-ap block coil





R2D2

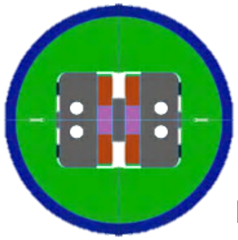


F2D2

14 T graded block coil

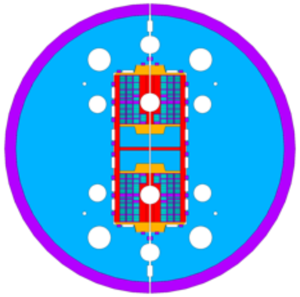
WPL E. Rochepault

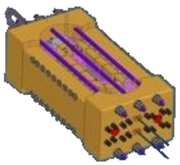
WPL F. Toral



ISAAC

14 T low-prestress common coil





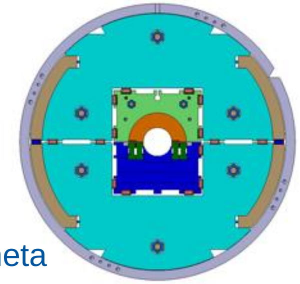
subSMCC

Stress Managed Asymmetric
Common Coil - SMACC

WPL D. M. Araujo

HFM LTS Demonstrators

WPLs A. Foussat



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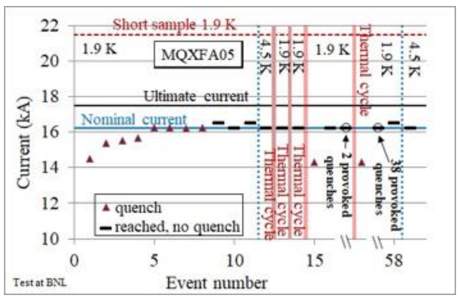
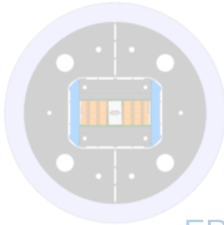
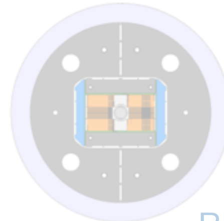


7-m-long CosTheta quadrupoles for HiLumi with brief training, no re-training, 11.3 T on conductor – Courtesy E. Todesco.



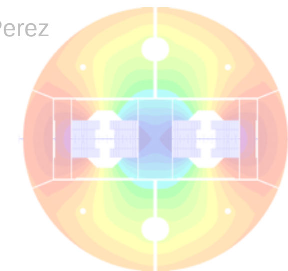
ERMC

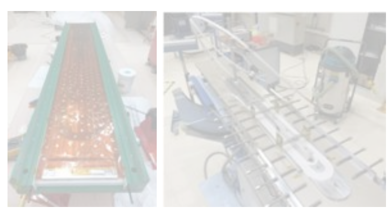


RMM

WPLJ. C. Perez

14 T no-grading double-ap block coil





R2D2

F2D2

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14 T graded block coil

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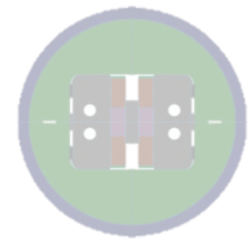

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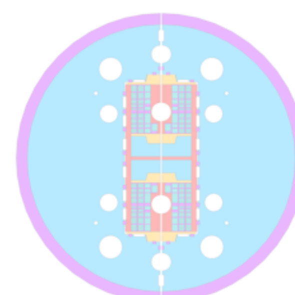

subSMCC

Stress Managed Asynmmetric Common Coil - SMACC

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HFM LTS Demonstrators

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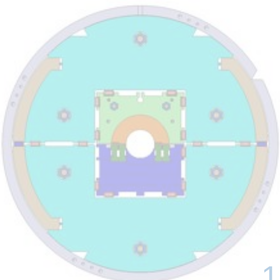

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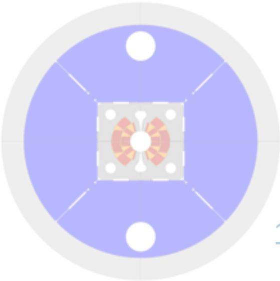
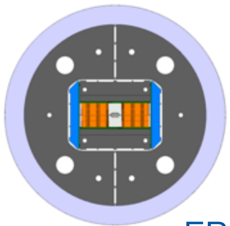
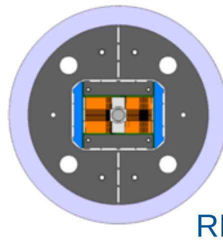


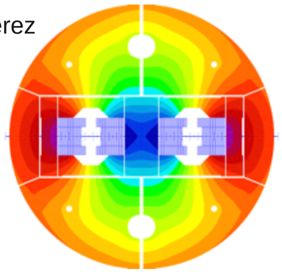
12 T CosTheta
FalconD

WPL S. Farinon, M. Sorbi

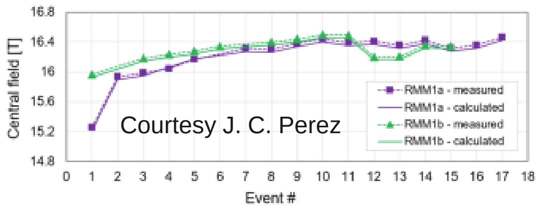


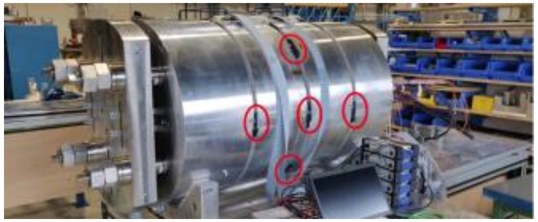


WPLJ. C. Perez



14 T no-grading
double-ap block coil

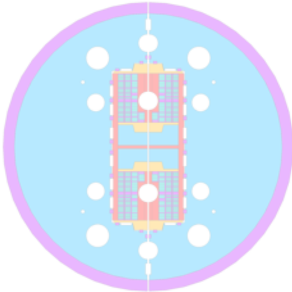


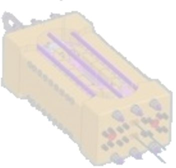


RMM1 flat-racetrack magnet during loading operation. The magnet achieved 16.4 T in the central cavity.

WPL F. Toral

14 T low-prestress common coil





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Common Coil - SMACC

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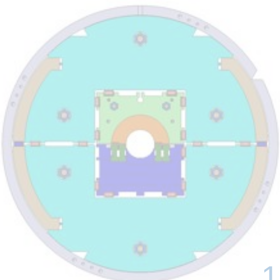
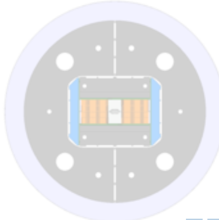
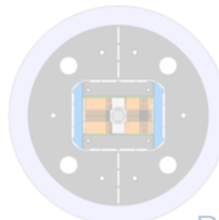


12 T CosTheta



ERMC



RMM

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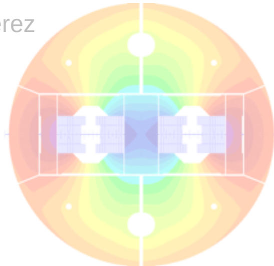
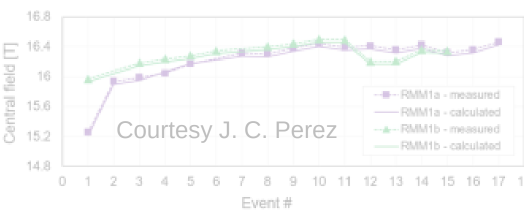
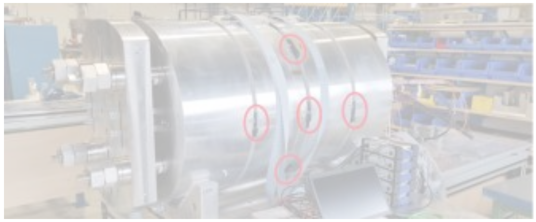
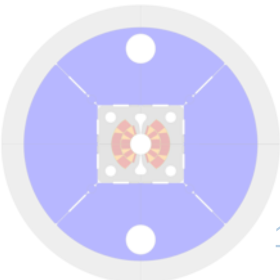




Courtesy J. C. Perez



RMM1 flat-racetrack magnet during loading operation. The magnet achieved 16.4 T in the central cavity.



12 T CosTheta
FalconD

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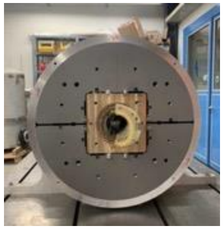
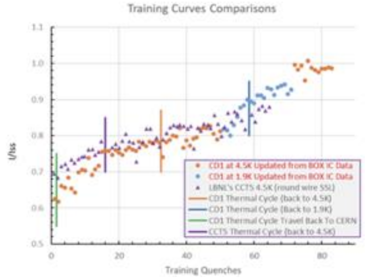
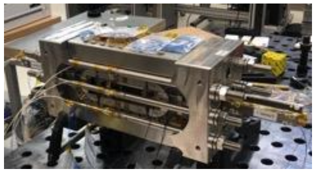
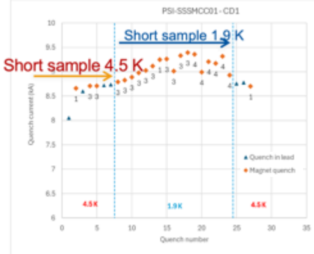




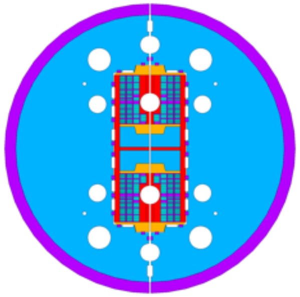
CD1 stress-managed magnet reaches 10 T and 100% of theoretical maximum performance.





5-T subSMCC magnet
reaching short sample without training at 4.5 K.

PSI CHART Swiss Accelerator Research and Technology



subSMCC

Stress Managed Asynmmetric
Common Coil - SMACC

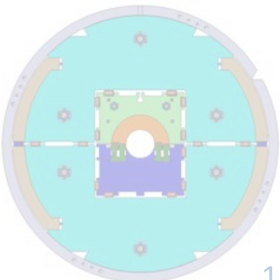
WPL D. M. Araujo

HFM High Field Magnets Programme

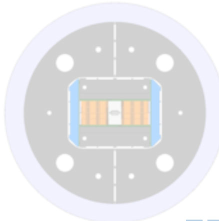
HFM LTS Demonstrators

Testing of FCC demo magnets will ramp up early 2026

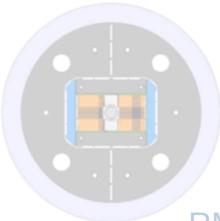
WPLs A. Foussat



12 T CosTheta



ERMC



RMM

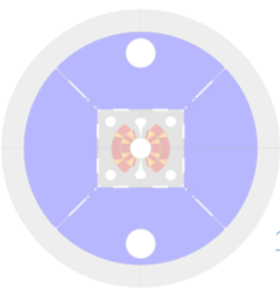
WPLJ. C. Perez

14 T no-grading double-ap block coil

WPL F. Toral

ISAAC

14 T low-prestress common coil



12 T CosTheta FalconD

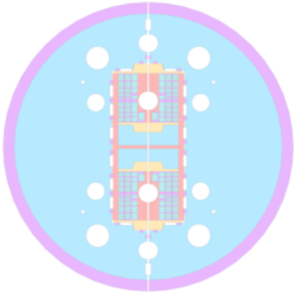
WPL S. Farinon, M. Sorbi

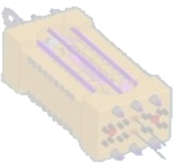
R2D2

F2D2

14 T graded block coil

WPL E. Rochepault





subSMCC

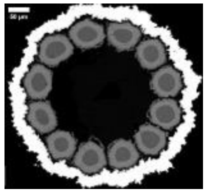
Stress Managed Asynmmetric Common Coil - SMACC

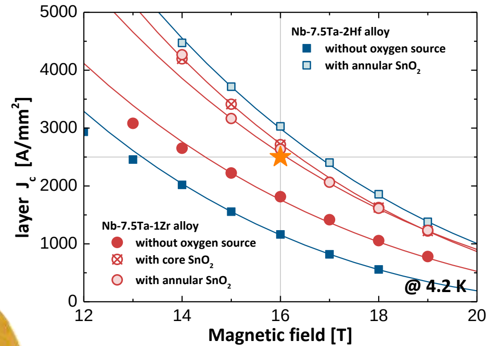
WPL D. M. Araujo

HFM LTS Conductor

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

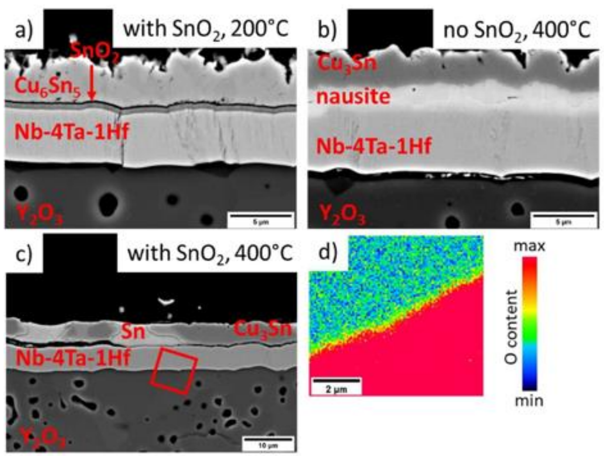
CHART
Swiss Accelerator Research and Technology





WPL C. Senatore

Exceed FCC specs via internal oxidation artificial pinning.

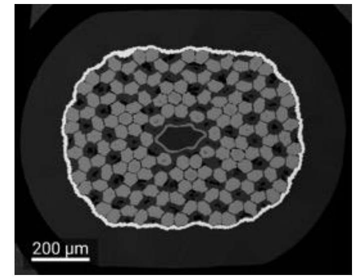


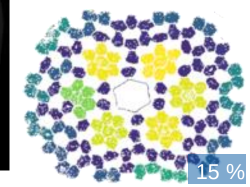
TU BERGAKADEMIE FREIBERG

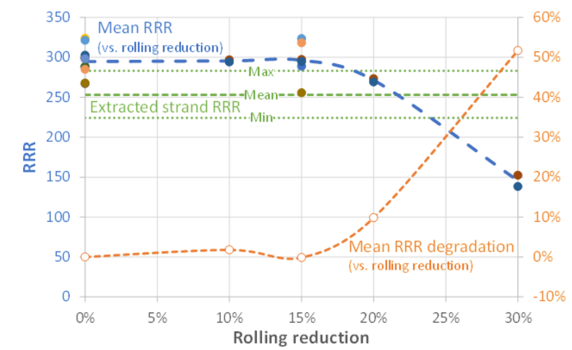
Understand internal oxidation artificial pinning at a microscopic level.

WPL T. Boutboul

CERN







Qualify new suppliers with alternative conductor technologies to diversify the supply base.

HTS – mostly ReBCO

HFM HTS Activities

WPL B. Holzapfel

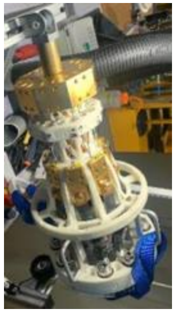
Karlsruhe Institute of Technology

KIT-CERN Collaboration on CC

Coated Conductor R&D Line Commissioned

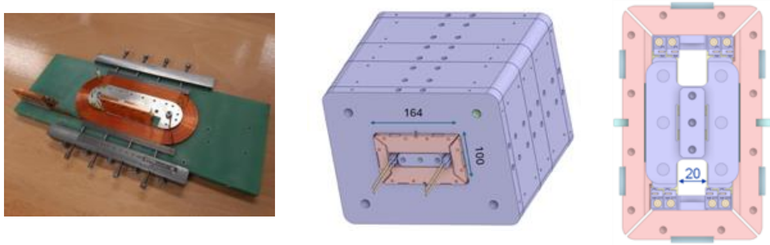
R&D on Iron-Based PIT conductor

WPL A. Malagoli



Tape characterization, Cabeling WPL A. Ballarino

WPL A. Ballarino

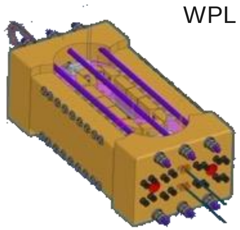


Insulated dry tape-stack racetrack and common coil configurations

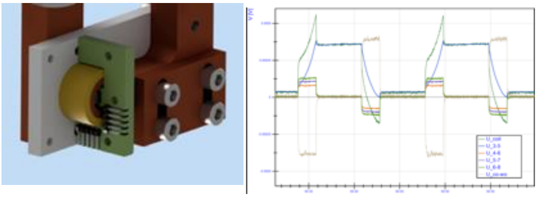
Metal-Insulated Racetrack Stack

WPL T. Lecrevisse

WPL D. M. Araujo



Hybrid subscale common coil

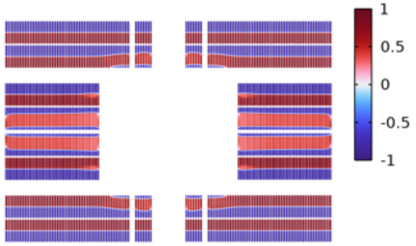


Insulated soldered tape-stack dynamic tests

Focus on FCC-hh Sustainability

Ramp-Induced Losses

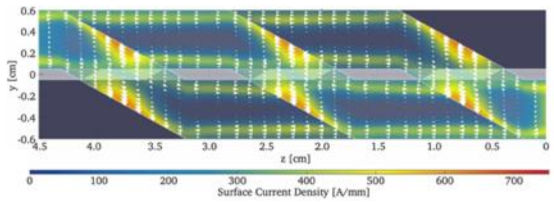
- Cable and coil design determine losses.
- Technology choices impose requirements on the cryo system for stable operating margins (and reproducible field quality?)
- Increased ramp losses may partly (or fully) cancel out the improved cryogenic efficiency at 20 K.
- But the full picture is more complex
  - main cryo load in FCC-hh is synchrotron radiation (SR) on the beam screen
  - SR scales ∝ B^4 (90, 100, 120 TeV → -35, 0, +100% SR)
  - beam screen baseline:
    - 60-80 K for both, LTS and HTS
    - 4.5-K cryo-pumping surface between beam screen and magnet cold bore needed – could increase coil ID



Estimation of screening-current induced losses in 20 T block-coil at 4.2 K with 12-mm tape-stack cable: 650 kJ/m (CDR target: 10 kJ/m)

[L. Bortot, priv. comm., April 2023]

Effective filament size: Nb-Ti 4-5 µm, Nb3Sn 20-50 µm, ReBCO **2-12 mm**



[J. v. Nugteren, High Temperature Superconductor Accelerator Magnets. PhD thesis, UTwente, 2016.]

Focus on FCC-hh Sustainability

Ramp-Induced Losses

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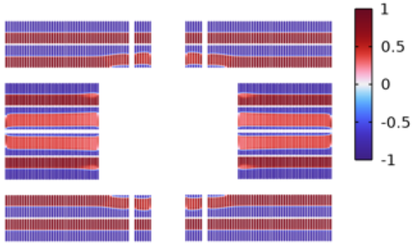
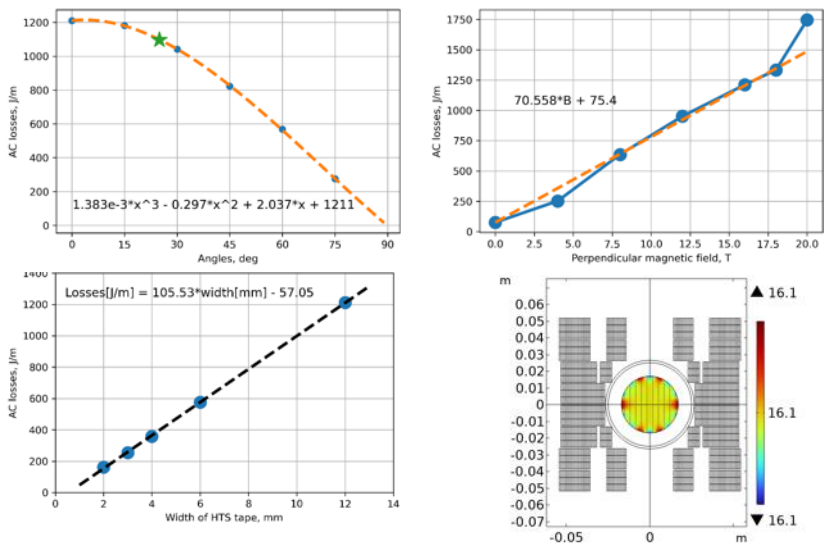


Estimation of screening-current induced losses in 20 T block-coil at 4.2 K with 12-mm tape-stack cable: 650 kJ/m (CDR target: 10 kJ/m)

[L. Bortot, priv. comm., April 2023]

[D. Sotnikov, priv. comm., April 2023]

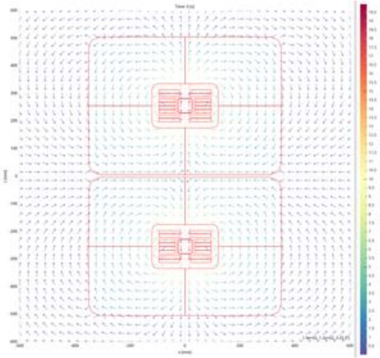


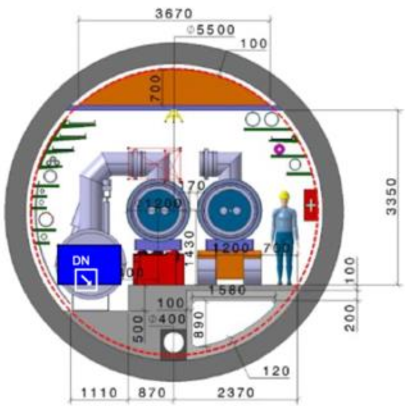
More studies, development of numerical tools, and rigorous model validation needed!

- Goal for FCC FS: derive a ramp loss target that is compatible with a plausible cryo concept and leads to equal or lower power consumption as LTS at the same beam energy.

Focus on FCC-hh Integration

- Physical dimensions of double-aperture HTS magnets up to 20 T are not known today.
- Integration requirements in the FCC-ee tunnel could potentially be met by vertical stacking of apertures.
- Cryogenics baseline for 20 K is high p high $\dot{m}$ He.
  - What is the achievable ΔT inlet/outlet along cryogenic sector given ReBCO ramp losses?
  - What are the implications on operating margins and field quality?
  - What are the size requirements?
  - US-MDP keeps an open mind towards a hydrogen cooling option.





Focus on HTS Roadmap

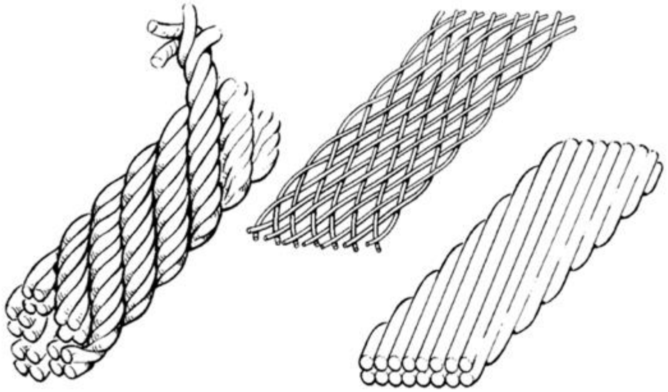
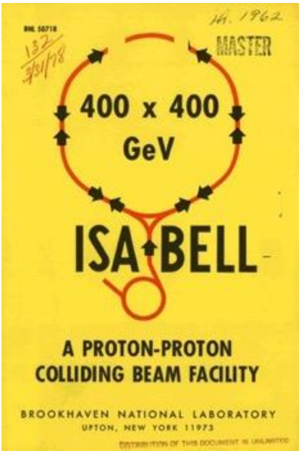


Figure 1.10. *Three different geometries for assembling a cable with ReBCO coated conductor. Also refer to Table 1.2.*

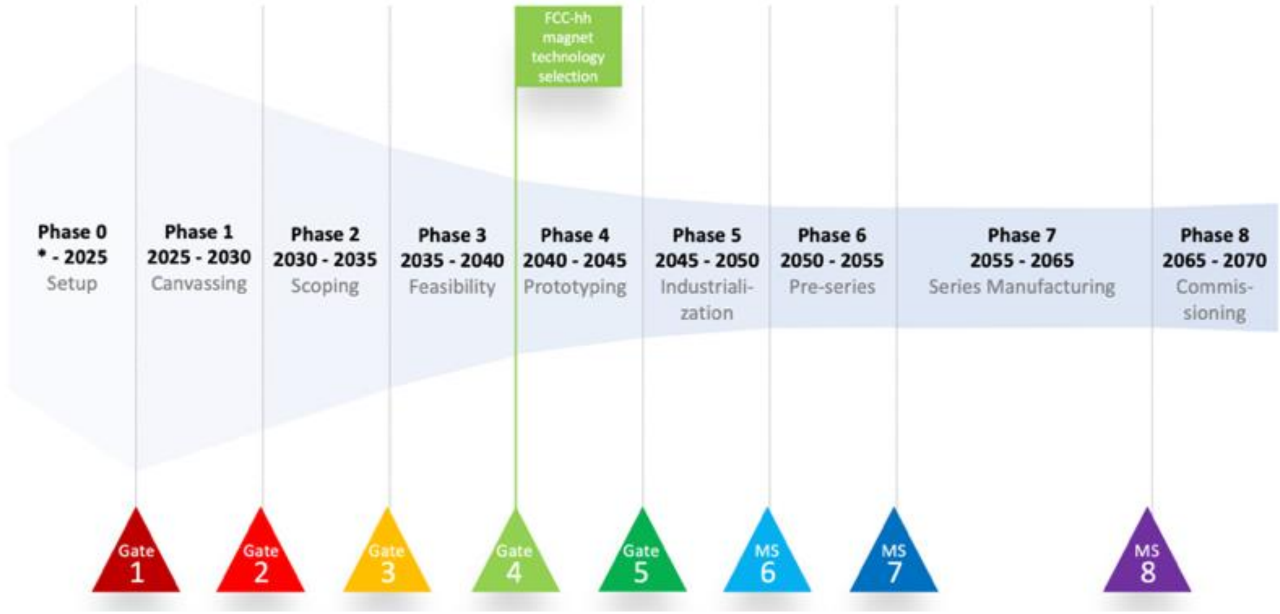
Early options of cables for main dipoles in Isabelle accelerator at BNL.

Braided cable failed in series manufacturing. Rutherford-cable development arrived too late, but underpins the LTS accelerator era: Tevatron (1983), Hera (1991), RHIC (2000), (SSC), LHC (2008), HL-LHC (2026)



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

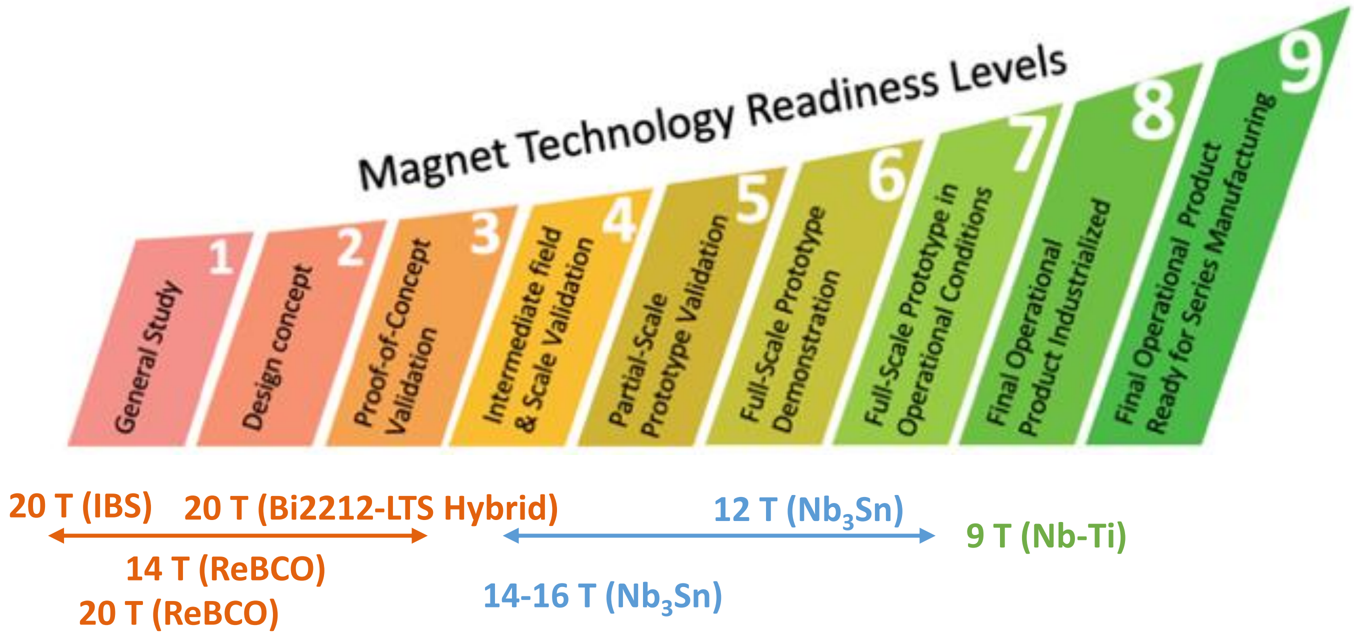
Towards an HTS Roadmap



B. Auchmann, A. Ballarino, L. Bottura, S. Prestemon in FCC Feasibility Study Midterm Report

- 2023-2025 … **setup** of manufacturing facilities, hiring in concerned labs
- 2025-2030 … **canvassing** candidate technologies
- 2030-2035 … **scoping** to achieve accelerator quality and target field in short magnets
- 2035-2040 … **feasibility** of length scale-up

Towards an HTS Roadmap

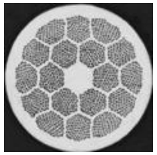


[B. Auchmann, A. Ballarino, L. Bottura, S. Prestemon in FCC Feasibility Study Midterm Report]

- ReBCO magnet technology for high-field accelerator magnets must close the TRL gap to LTS: Key technology questions must be solved over the next 5-10 years.
- A technical roadmap based on initial canvassing results will be developed over the coming year(s).
- We are entering uncharted territory. Breakthroughs and/or roadblocks may be encountered along the way.

Cooperation with US-MDP

U.S. MAGNET DEVELOPMENT PROGRAM




Complementarity of approaches mitigates risk factors:

- Bi-2212 as well as CORC/Star ReBCO wires in US-MDP,
- ReBCO anisotropic cables and IBS in HFM,
- High-risk high-reward topics (no-protection, hydrogen) covered in US-MDP.

Ongoing technical exchanges include the following topics:

- 20-T quench protection analysis,
- 20-T stress-managed common coils design,
- Stress-management material technologies,
- Bi-2212 cable characterization under transverse pressure,

Increased cooperation FCC/US-MDP/HFM is desirable, for example:

- Shared technical seminars,
- increased integration of each other's "working groups",
- testing and learning from each other's magnets,
- continued exchange on roadmaps and strategies,
- exchange of post-docs, etc.

HFM
High Field Magnets
Programme