HFM

High Field Magnets Programme

Report on High Field Magnet Programme

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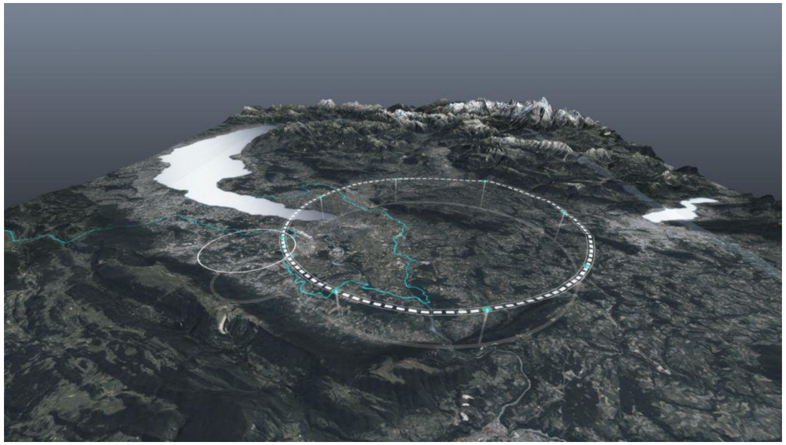
- FCC-hh parameters and options
- Roadmap
- HFM directions and recent results
- HTS outlook

FCC-hh targets (Nb_3Sn)

- As discussed in previous years, FCC-hh dipole operational field moved from 16 T to 14 T, for 85 TeV c.o.m energy
  - 14 T is reached with 0.80 loadline fraction rather than 0.86 (more reasonable margin)
  - 14 T is reached with conductor available today (20% more critical current than HL-LHC) rather than with FCC targets
  - 14 T allows rather than 16 T to significantly reduce the stresses in the coil (below 150 MPa), thus giving required margin for such a large production
    - A maximum of 90 TeV could be reached with further improvements of filling factor

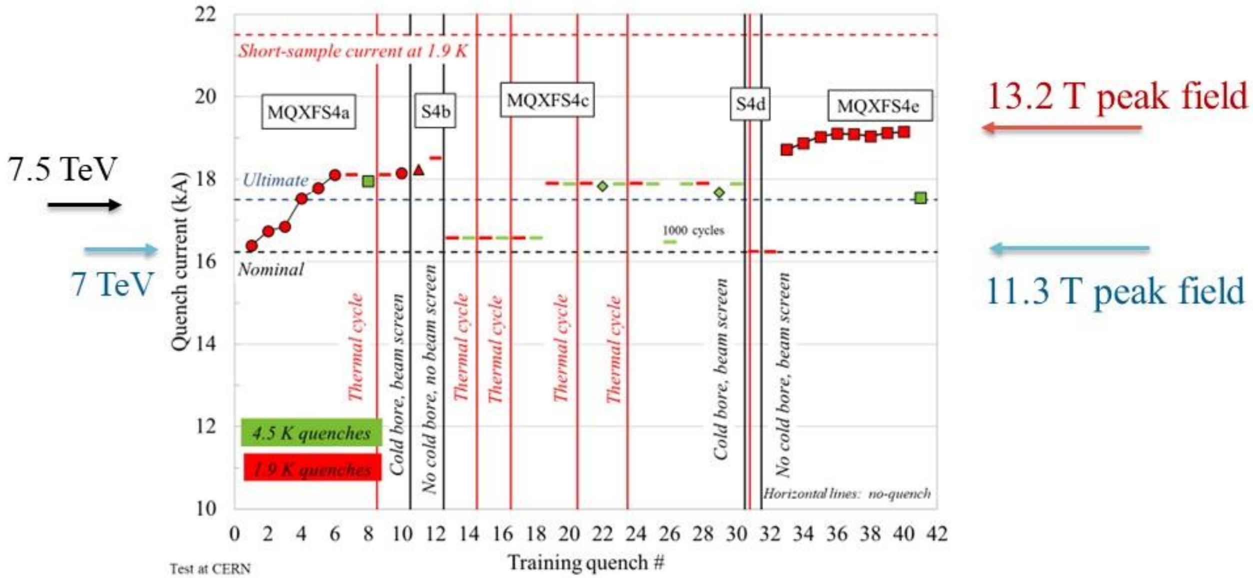
		CDR 2019	2024-Nb_3Sn
Dipole field	(T)	16.0	14.0
Dipole aperture	(mm)	50	50
Dipole magnetic length	(m)	14.3	14.3
Operational temperature	(K)	1.9	1.9
Tunnel length	(km)	100	90.7
Arc length	(km)	82.0	76.9
Arc filling factor	(adim)	0.80	0.83
Energy c.o.m.	(TeV)	50+50	42.5+42.5
Loadline fraction	(adim)	0.86	0.80
j_c at 16 T and 4.2 K	(A/mm^2)	1500	1200
Number of dipoles	(adim)	4587	4440
Number of quadrupoles	(adim)	760	520



FCC layout and evolution of parameters

Margins

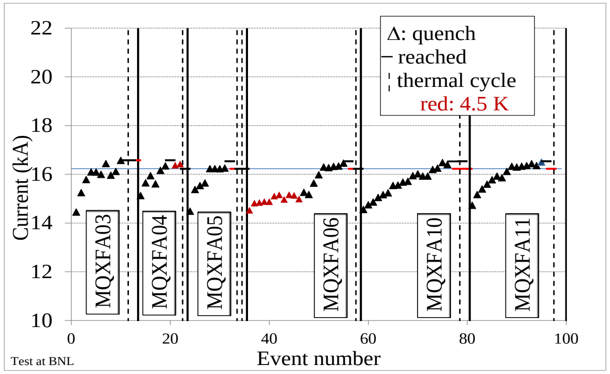
- 14 T operational field means that FCC-hh short models shall aim at reaching systematically 15-15.5 T
  - We should avoid confusion between operational and achieved field: LHC dipoles reached 9.5 T, but they operate in the LHC slightly above 8.0 T
  - HL-LHC experience: short models systematically reached >13 T, but they will operate at 11.3 T



MQXFS4 test results [S. Izquierdo Bermudez, J. C. Perez, P. Ferracin, F. Mangiarotti, et al.]

Options

- 4.5 K operation [P. Borges, R v. Weelderen et al.]
  - HL-LHC MQXF experience shows that all magnets reaching operational field at 1.9 K are also able to operate at 4.5 K
  - It is a very daring reduction of margins, that should be fully proved on models
  - Advantage: simpler cooling, and cheaper costs
- 20 m long magnets
  - Advantage: reduction of production from 4440 to 3330 units, minor decrease of cost (6%) or increase in energy (3%)
- 12 T dipoles giving 73 TeV c.o.m.
  - Advantage: 30% less conductor, 15-20% less cost per dipole



Powering test of first six conform MQXFA magnets [J. Muratore, B. Ahia, S. Feher, G. Ambrosio et al.]

One of the first 7-m.long Nb_3Sn magnets

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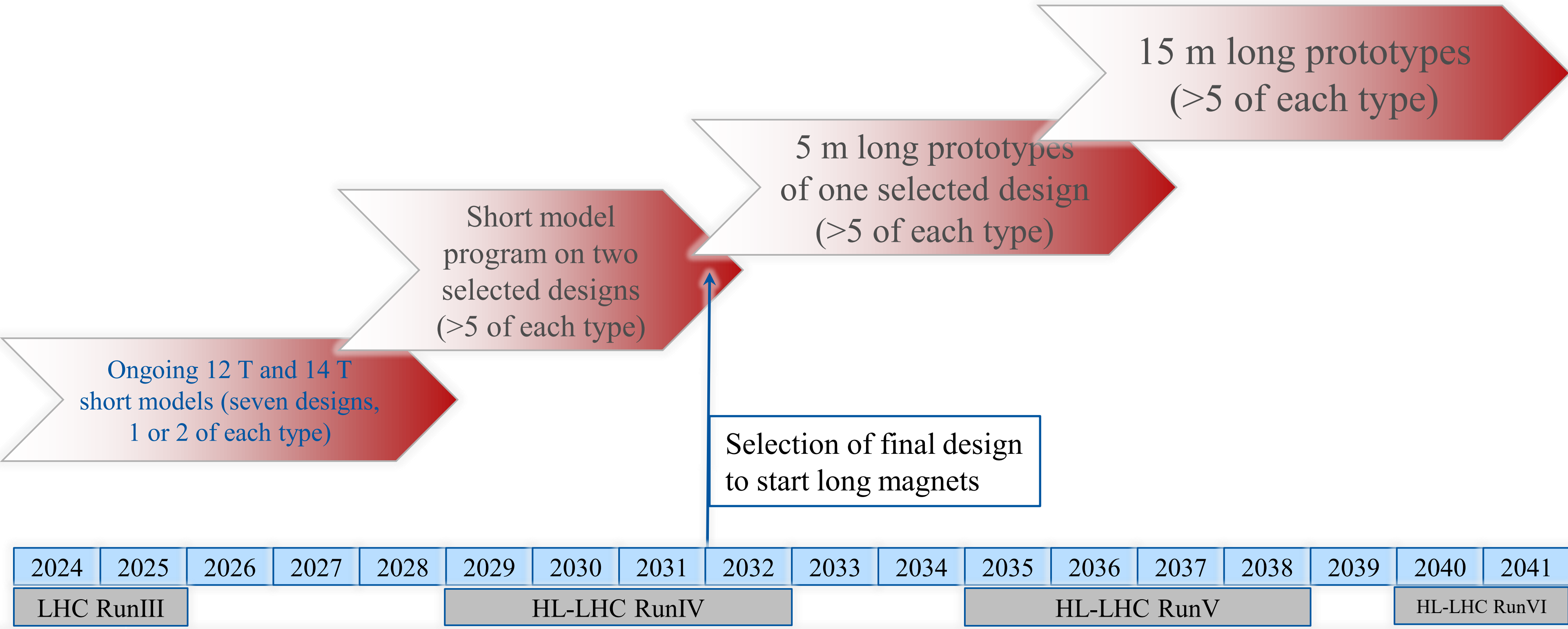
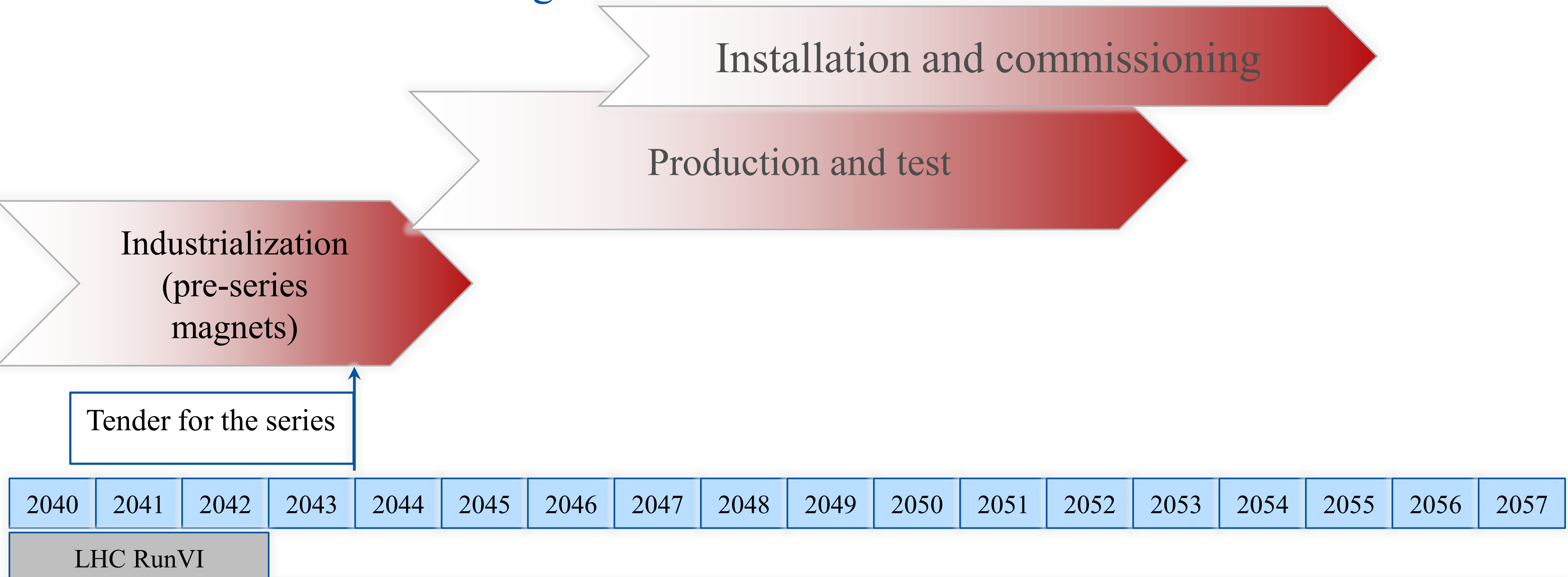
Roadmap for Nb_3Sn

- At the beginning of 2024 we updated the roadmap for FCC based on the new parameters for Nb_3Sn dipoles
  - This is a quite conservative roadmap, giving 10 years to make the scaling in length in two steps (first 5 m, then 15 m)



Roadmap for Nb_3Sn

- This gives 2055 as possible start for FCC-hh at 90 TeV
  - 5-10 years can be gained by anticipation of some phases, more parallelization and early involvement of industry
  - We are already planning anticipating the scaling in length to 5 m in 2025-2030 using HL-LHC conductor



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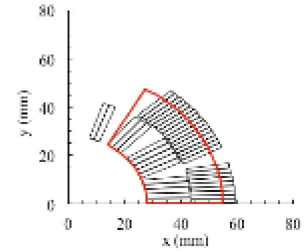
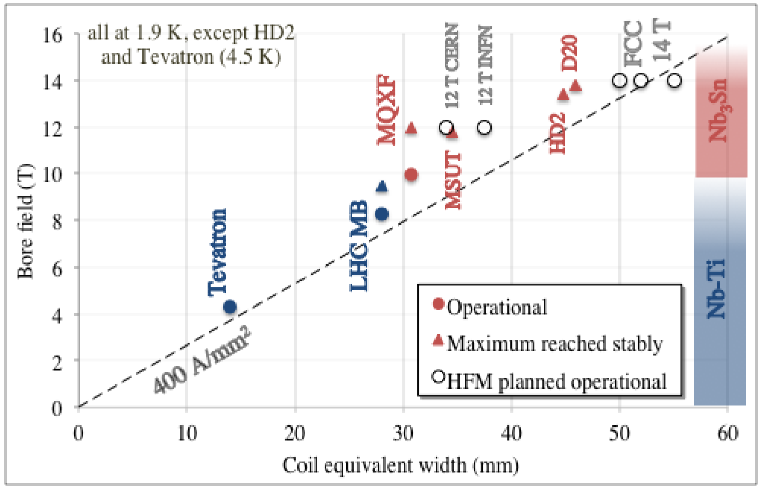
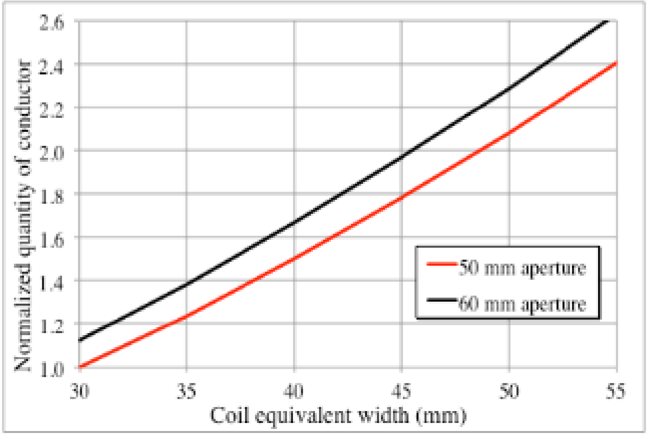
Where are we going ?



- Maximum fields close to 14 T were achieved in short models
- Equation for the field in a dipole $B[\mathrm{T}] \approx 0.00070\, j[\mathrm{A/mm^2}]\, w_{eq}[\mathrm{mm}]$
    - j: overall (over insulated coil) current density w_{eq}: equivalent width of the coil
  - We set targets of 14 T with three different designs: block (CERN and CEA), and common coil (CIEMAT): each design has advantages, we will see in the coming years the most promising
- This is based on having a conservative value a 400 A/mm^2 overall current density as in the past, giving 50-55 mm coil width (it was 30 mm in LHC dipole)
    - We will need 2 to 2.5 more conductor than in the LHC dipoles

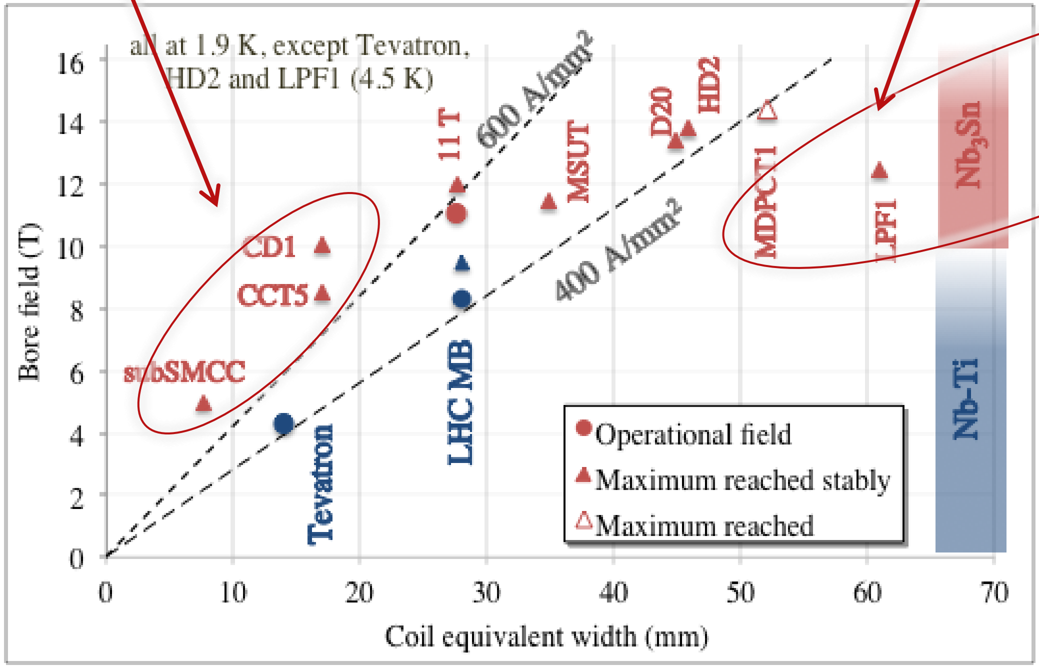




Where are we going ? Two more directions

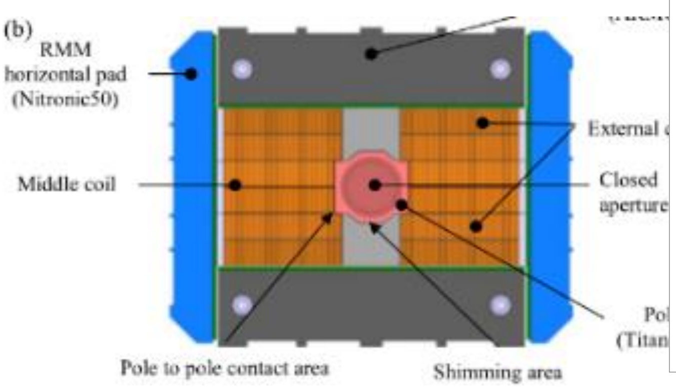
- Stress managed: mixing structure and coil, aiming at more efficient (and possibly cheaper) magnets – US MDP and PSI are working on this: only path above 15 T for HTS

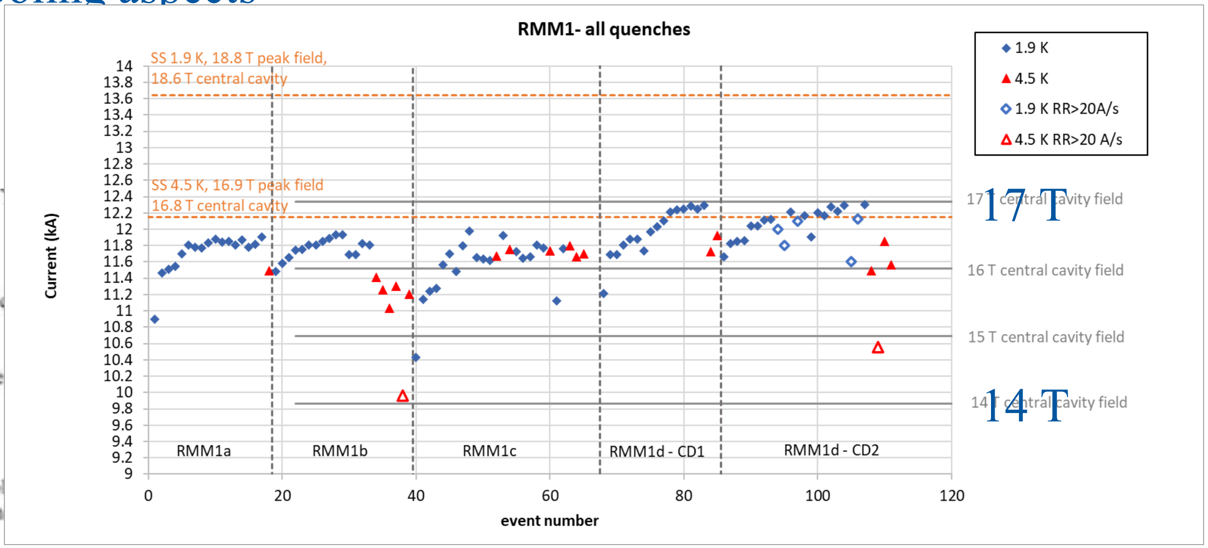
- Technology demonstrators: magnets with design parameters not compatible with accelerator, to explore the technology – CERN and IHEP are working on this



Recent results: Nb_3Sn magnets

- RMM is a technology demonstrator launched by EuroCirCol
  - This means a magnet to prove technology but not with a design compatible with accelerator (in this case too much conductor, and no flared ends)
  - RMM reached 16.4 T in a 50 mm bore in 2022 – proves adequate margin for 14 T
  - Second assembly reached 17 T (November 2024) no degradation
  - The demonstrator can keep 15.75 T for 4 h) https://indico.cern.ch/event/1464833/
  - We are working on cooling aspects

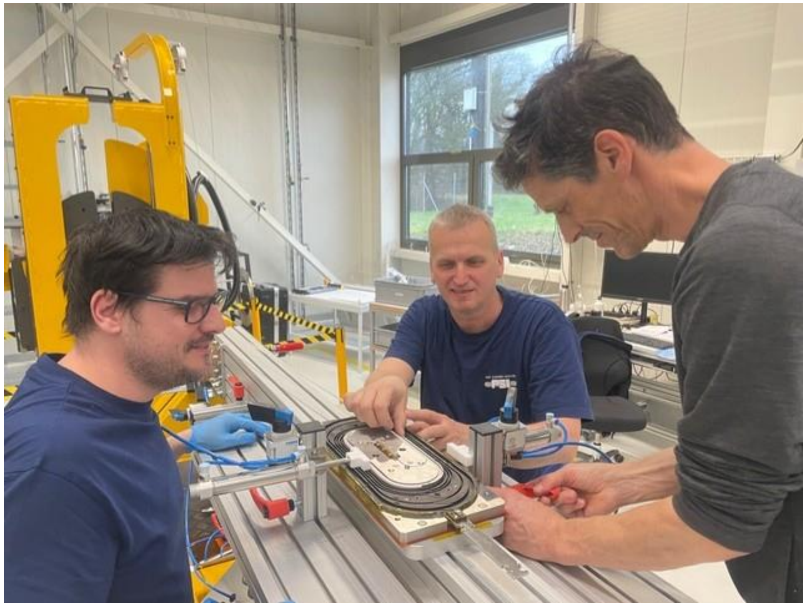


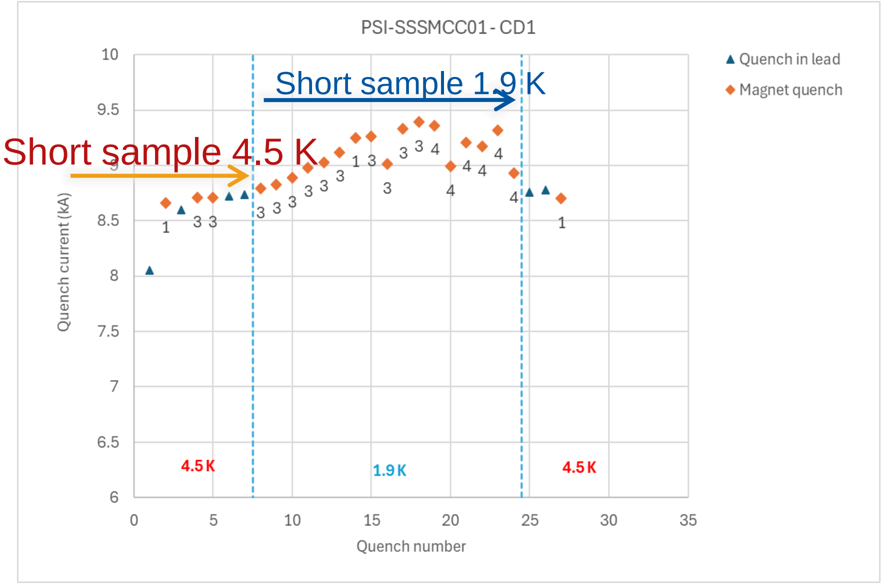


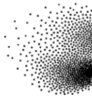
Cross-section and training of RMM [E. Gautheron, et al. IEEE TAS 33 (2023) 4004108, and G. Willering]

Recent results: Nb_3Sn magnets

- SubSMCC is a small scale magnet based on stress management
  - This is a new paradigm that could allow having more efficient magnets with higher current density - Similar path is pursued by the US MDP
  - Peak field in the coil of 6.5 T reached, >5 T in in the centre (June 2024)



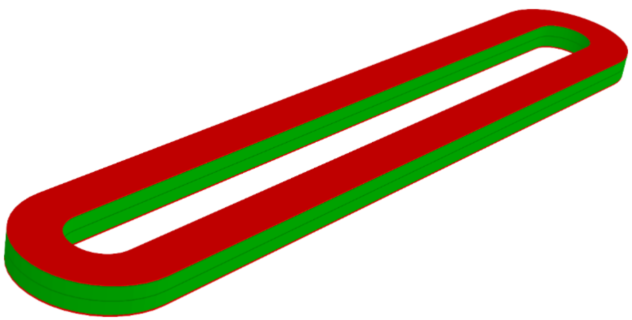


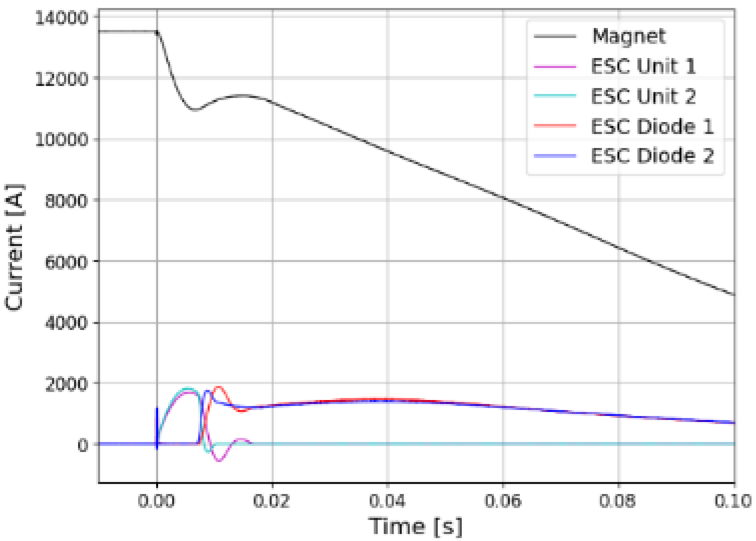


Manufacturing of SubSMCC in PSI (D. Araujo, B Auchmann, et al.)

Recent results: improved protection

- Larger current density → more compact and cheaper magnets
  - One of the limits to large current densities is the protection – all energy has to be dumped in the coil
  - Novel method proposed (E. Ravaioli et al.) and being tested at CERN (October 2024) to allow a part of energy extraction, and fast quenching





Copper coil and SC coil in ESC, and quench protection (E. Ravaioli, et al.)

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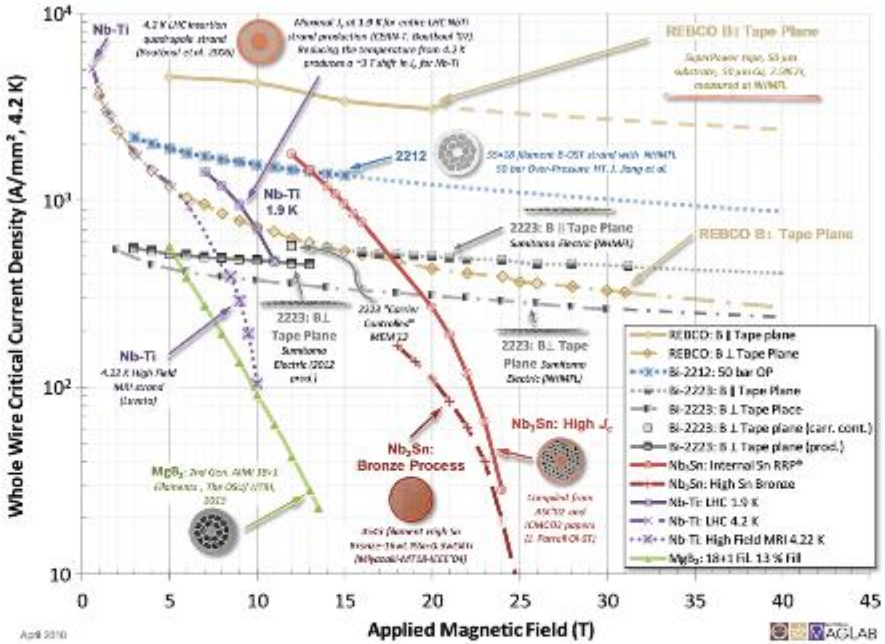
HTS opening ways above 14 T

- HTS is a game changer in accelerator physics, since it could allow
  - Operational fields well above 14 T due to the weak dependence of the critical current on the field
  - Cooling at higher temperatures (possibly 20 K), giving less consumption and simpler cryogenics



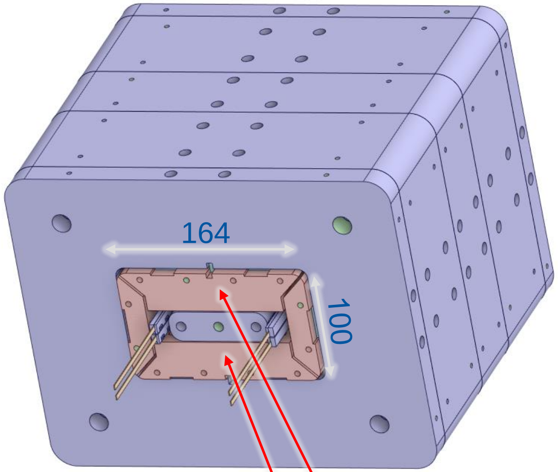
Critical current versus field (please note semilog scale) [Courtesy of P. Lee]

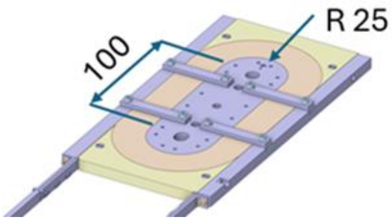
HTS opening ways above 14 T

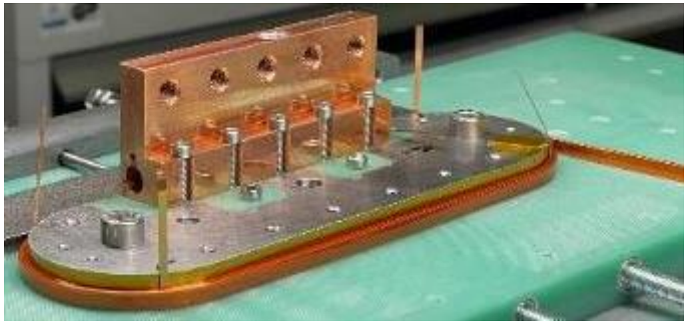
- Three conductors on the market: are they good for our needs?
  - BSSCO 2212 (mainly developed in the USA)
  - REBCO (strong impulse from fusion investments of order of BCHF)
  - IBS (Iron Based Superconductor, strong impulse from China)
- Our requirements are very special:
  - Field quality over a vast field range and reproducibility of 10 ppm of max field – very different from fusion magnets or solenoids
  - Limited energy consumption, and cost
- Dipoles up to 4 T were built (Eucard2), but without full proof that HTS technology can be used for accelerator main magnets
  - A possible roadmap: prove viability within 2030 for short models and possibility of scaling in length by 2035
- Some points are particularly tricky
  - Hysteresis losses are large due to filament size
  - Reproducibility and stability of transfer function (current redistribution)

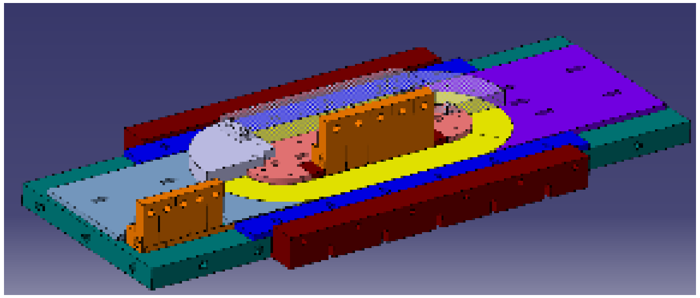
HTS news

- Production line in KIT commissioned (B. Holzapfel et al.) in March 2024
- At CERN, racetrack wound with dielectric insulated (DI) REBCO and went through preliminary tested at 77 K
  - A research line of MI (metal insulated) is also active in HFM (CEA)
  - Remember that all magnets for fusion are NI (non insulated) – not good for us
- Then a test at 4.5 K – 20 K will be done









[A. Ballarino, et al., HFM TE day https://indico.cern.ch/event/1425262/]

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Programme