HFM

High Field Magnets Programme

Report on High Field Magnet Programme

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A big thanks to our predecessors

D. Tommasini, leading
EuroCirCol studies 2014-2020

Luca Bottura, leading
HFM program 2020-2021

Andrzej Siemko, leading
HFM program 2022-2023

Contents

Guidelines since 2024

- Orient HFM more towards direct R&D for FCC-hh
- Injecting the experience we are getting from the HL-LHC project
- More synergies between the numerous WPs, and with other programs – in particular with US MDP

HFM as direct R&D

- Direct R&D: focused on a magnet for a specific use (in our case of accelerators, making TeV, i.e. T m)
  - Example: LARP mandate for the LHC IR upgrade was something like "build a 90 mm aperture quadrupole, with 200 T/m, …"
  - Note that target can evolve in time

LARP

- Generic R&D: focused on developing the technology, not directly related to a specific application (making T, not TeV)
  - Example: MDP mandate "explore the limits of Nb_3Sn technology, reduce training, …"

U.S. MAGNET DEVELOPMENT PROGRAM

HFM as direct R&D

- Our main mandate is to make a dipole for FCC-hh

The HFM Programme's principle goals are:

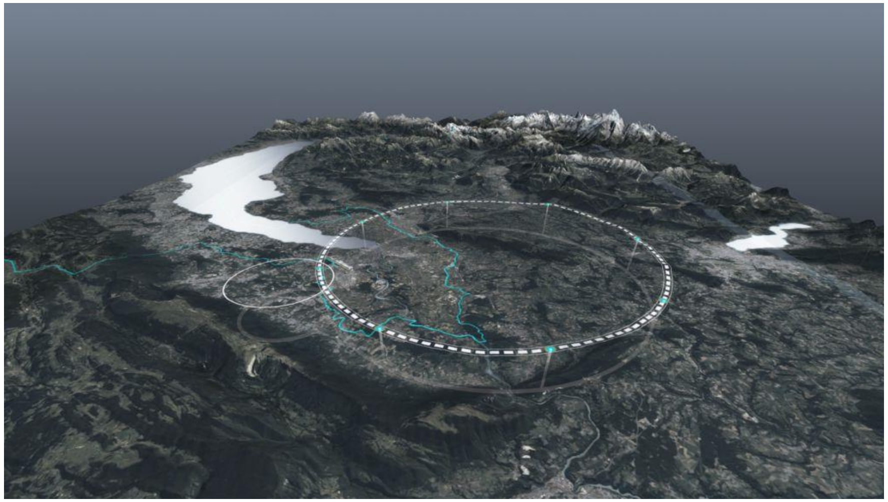
- Develop a Nb_3Sn accelerator dipole with ~14 T operational field, compatible with the FCC-hh minimum target of 80 TeV center of mass energy;
- Explore the use of HTS magnet technologies for an up to ~20 T operational field, compatible with FCC-hh target of order of 120 TeV center of mass; the dipole shall be either based on a Nb_3Sn-HTS hybrid coil, or on an HTS-only coil to open the possibility of operating at higher temperatures (above 10 K);
- Promote the required developments for the associated superconductors (both Nb_3Sn and HTS);
- Highlight the innovative nature of high-field magnets development and its implications for the broader scientific community and societal applications.

- For Nb_3Sn the target is 14 T operational field, giving a c.o.m. energy of 85-90 TeV
- For HTS the target is a range 16-20 T operational field, giving 100-120 TeV c.o.m. energy
- We keep one non-FCC WP: HTS solenoids for muon collider

FCC-hh targets

- The new targets for FCC-hh in Nb_3Sn allow reaching 90 TeV with 87% filling factor
  - The magnet is at 80% of short sample, and this gives more margin, allowing to consider operation at 4.5 K according to HL-LHC experience
  - 14 T operational field means that short sample shall systematically reach 15-15.5 T

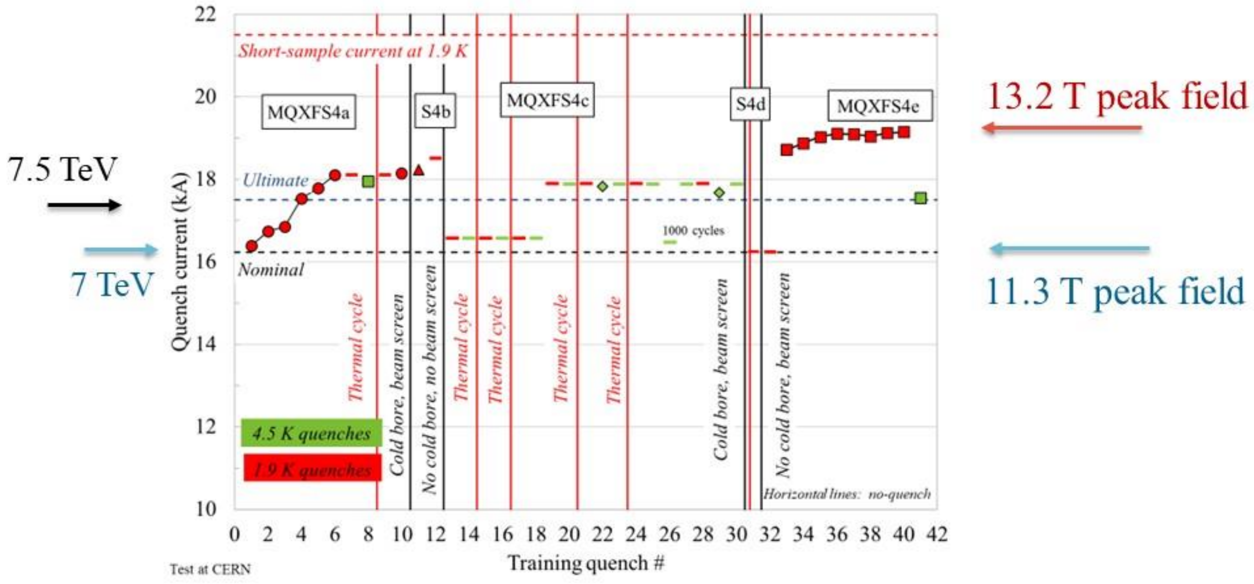
FCC-hh parameters	CDR 2019	2024-Nb_3Sn	2024-HTS
Dipole field (T)	16.0	14.0	16-20
Tunnel length (km)	100	90.7	90.7
Arc length (km)	82.0	76.9	76.9
Arc filling factor (adim)	0.80	0.87	0.85
Energy c.o.m (TeV)	100	90	100-125
Loadline margin	86%	80%	TBD



FCC layout and evolution of parameters

FCC targets and feedback from HL-LHC

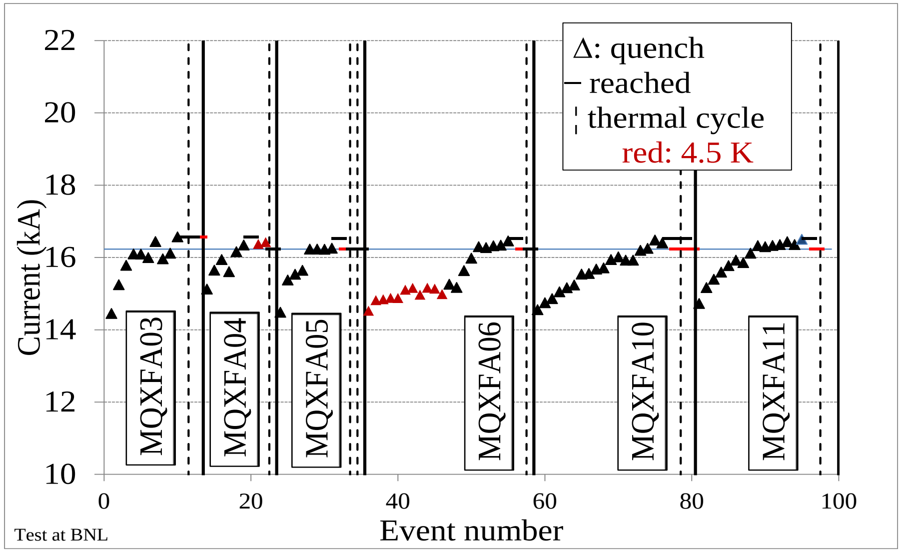
- 14 T operational field means that short models shall systematically reach 15-15.5 T
  - Do not make confusion between operational and achieved field: LHC dipoles reached 9.5 T, but they operate in the LHC slightly above 8.0 T
  - HL-LHC short models systematically reached >13 T, but they will operate at 11.3 T



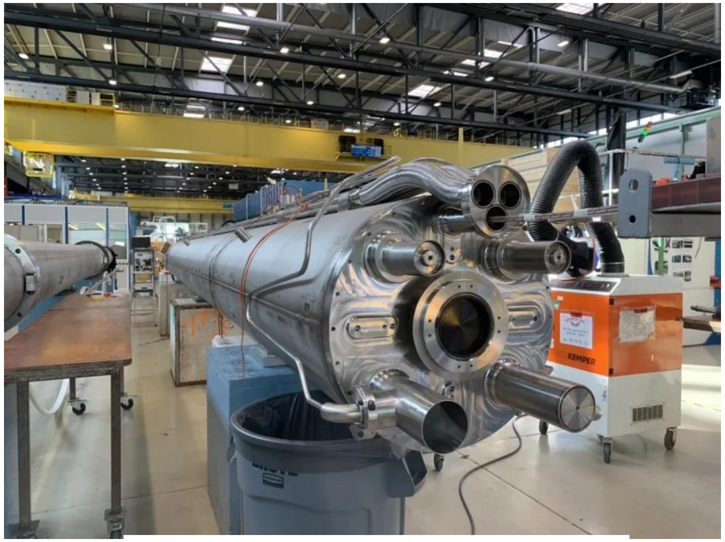
MQXFS4 test results [S. Izquierdo Bermudez, J. C. Perez, P. Ferracin, F. Mangiarotti, et al.]

FCC targets and feedback from HL-LHC

- Having the magnet at 80% of short sample at 1.9 K (instead of 86%), allows to consider operation at 4.5 K
  - HL-LHC MQXF experience shows that all magnets reaching operational field at 1.9 K are also able to operate at 4.5 K
  - With what margin ? We are exploring this aspect



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



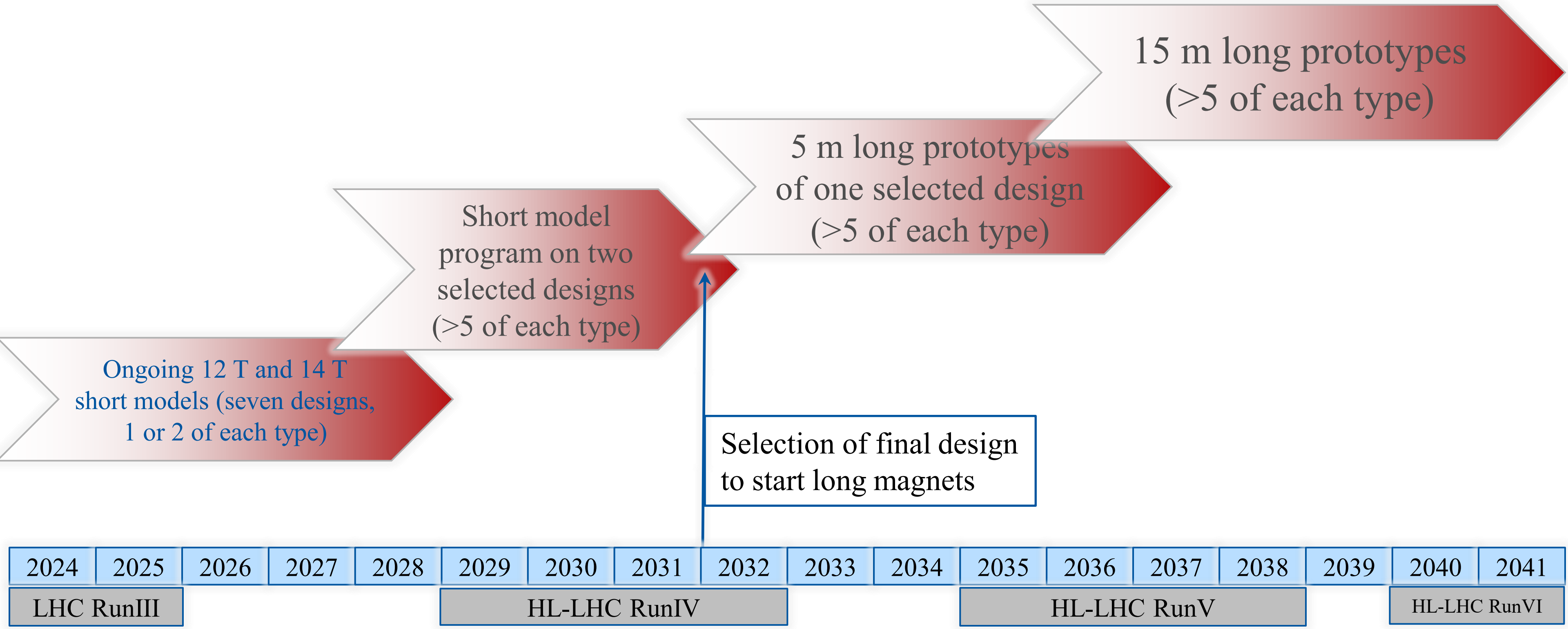
One of the first 7-m.long Nb_3Sn magnets

Integration in the FCC

- Two paths are given to reach a higher filling factor
  - Optimization of the lattice, together with the optics team
    - Longer cell--> less and less powerful quadrupoles → more space for dipoles
  - Work on high gradient correctors
    - Ideal test bench for HTS, and allows to get more TeV for the same field
    - For the moment scarce feedback on this proposal, please help
- Cooling
  - We are working on the 4.5 K option that has been opened by the HL-LHC results (WP4.6, P. Borges de Sousa and R. van Weelderen)
  - First preliminary results give a factor >3 of energy saving in going from 1.9 K to 4.5 K

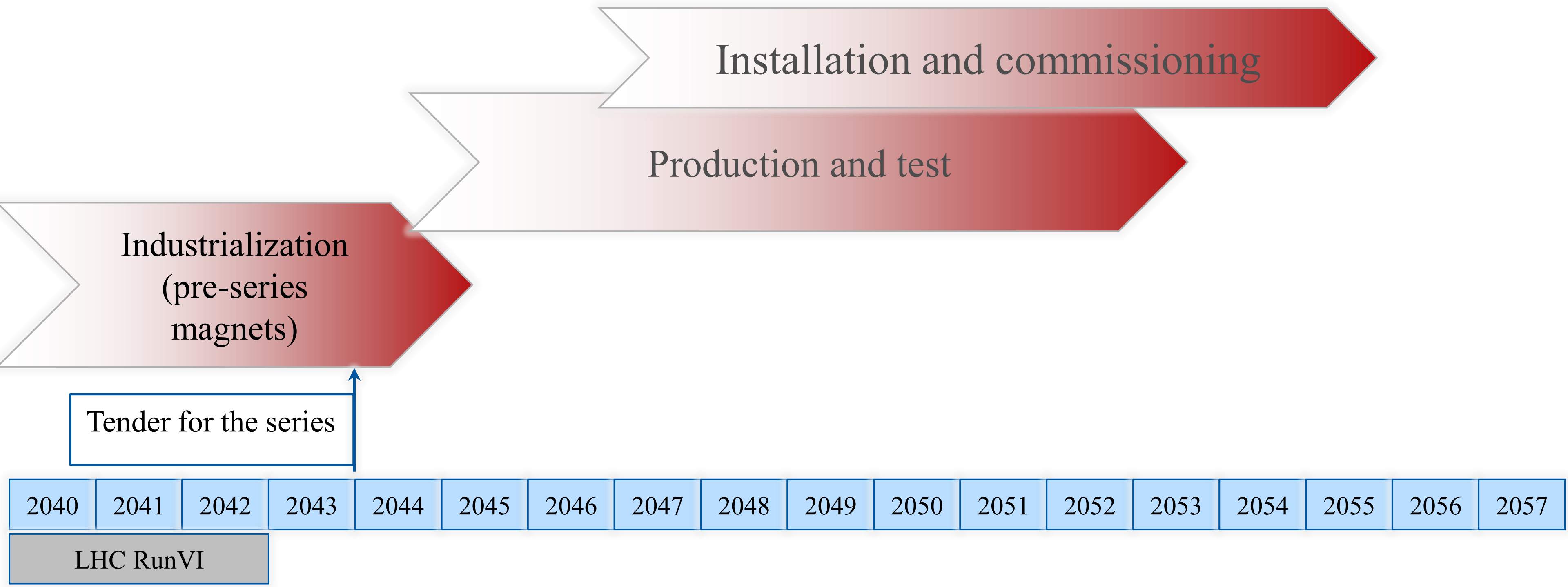
Roadmap for Nb_3Sn

- At the beginning of 2024 we were asked to present an accelerated roadmap FCC based on Nb_3Sn



Roadmap for Nb_3Sn

- This is rather a conservative roadmap, and could be shortened by 5-10 years (with more risk and cost) having less staggered phases and with earlier involvement of the industry



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- Guidelines for the program
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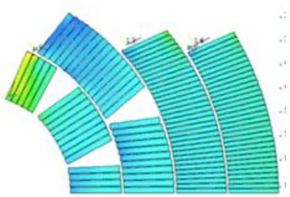
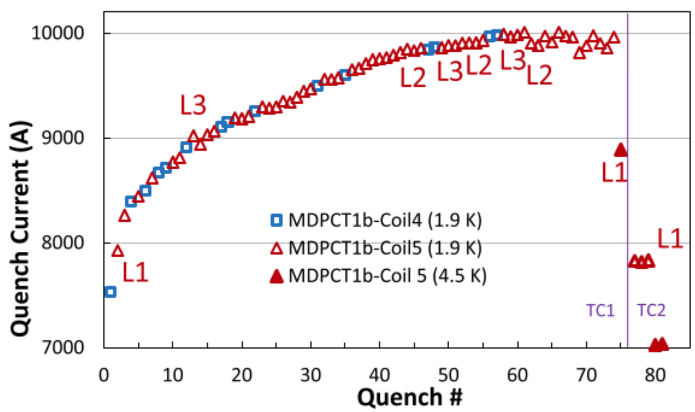
- Appendix: news from US and China

Nb_3Sn program for 14 T

- The cosθ option: the more classical path
  - MDPCT1: four layer cos theta made in FNAL reached 14.5 T at 4.2 K but degraded
    - This path was abandoned by MDP
  - INFN is proposing to have a 4 layer cosθ (endorsed by steering board, not yet approved)
    - Test in 2029-30 at earliest

Fermilab

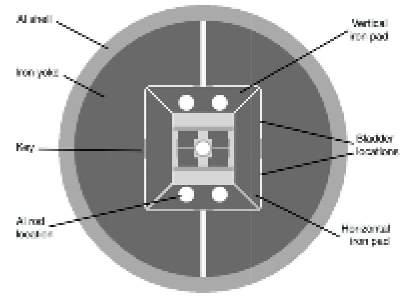




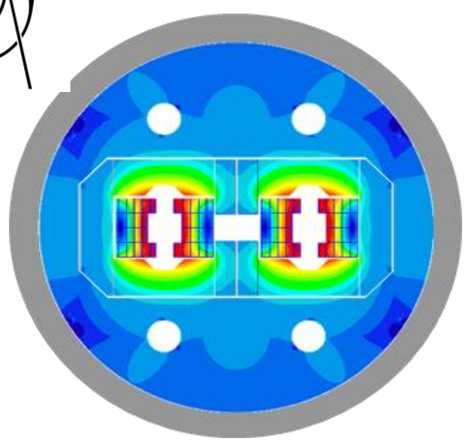
Power tests of MDPCT1 [S. Stoynev, et al. IEEE TAS 32 (2022) 4000705]

Nb_3Sn program for 14 T

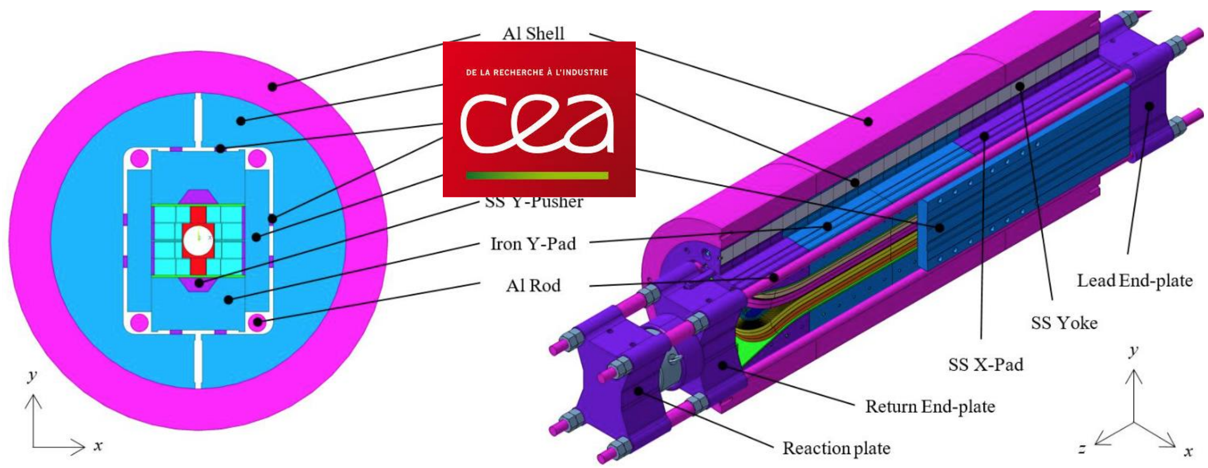
- The block option: this design has the world record
  - Advantage: no stress accumulation in the midplane
  - HD2 reached 13.8 T at 4.2 K
  - Two options:
    - CERN (no grading) – test in 2026
    - CEA (with grading) –test in 2027/8



[G. L. Sabbi, et al. IEEE TAS 15 (2005) 1128]



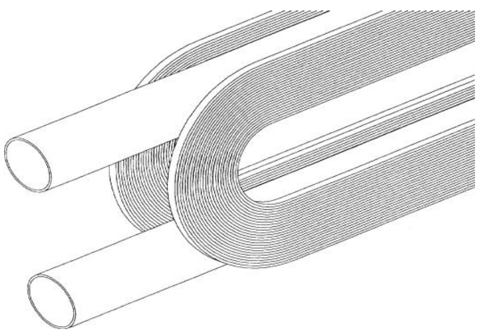
14 T block dipole (J. C. Perez, et al.)



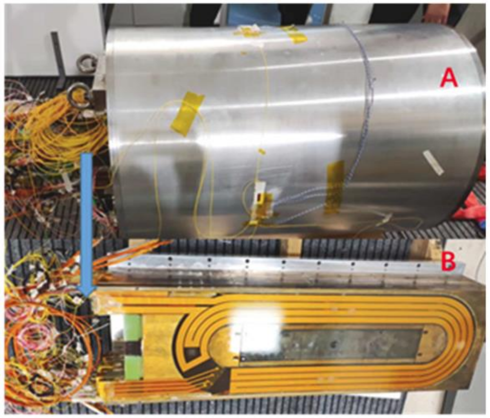
14 T block dipole F2D2 (E. Rochepault, et al.)

Nb_3Sn program for 14 T

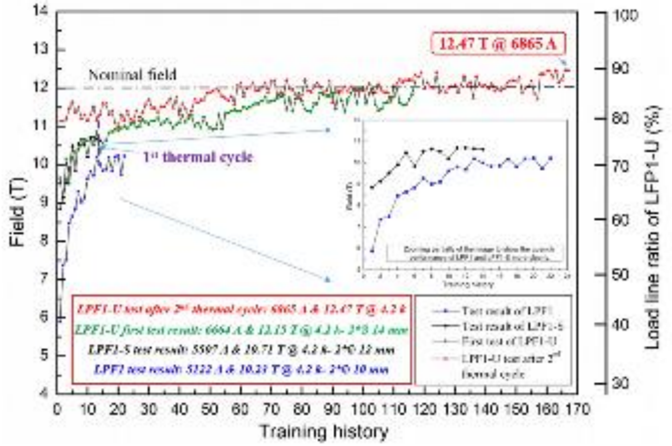
- The common coil design: a simpler path ?
  - Racetrack coils (but non planar coils needed for correcting field quality) – less efficiency
  - The IHEP program reached 12.5 T in Nb_3Sn, but with small aperture (14 mm and no field quality, see appendix)
  - CIEMAT is planning to build a common coil, test in 2027/8



Common coil design
[R. Gupta, IPAC 1997 3344]



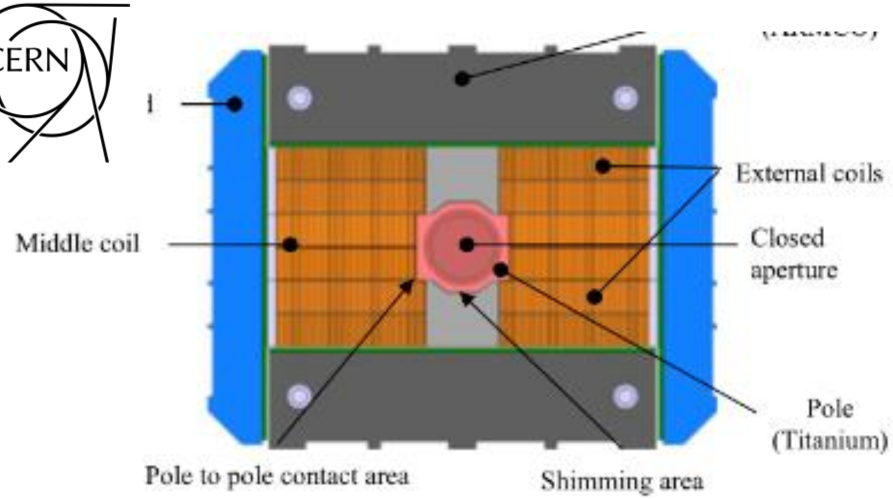
LFP3 magnet [J. Shi, Q. Xu, et al., IEEE TAS 34 (2024) 4701405]

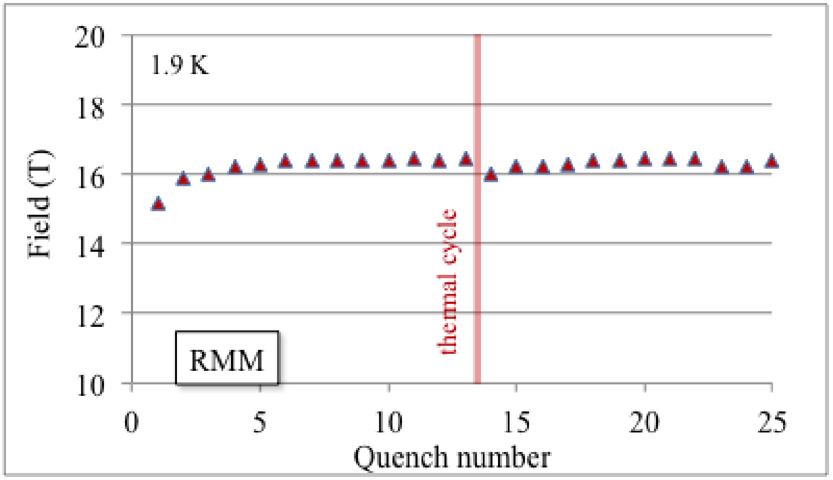


LPF1 training [C. Wang, et al., SUST 36 (2023) 065006]

Recent results: Nb_3Sn magnets

- All these design do not rely on stress management
  - RMM, based on a block coil, proved that 14 T can be achieved with a large margin without interception of stress
  - RMM reached 16.4 T in a 50 mm bore in 2022
- Test of reproducibility of the assembly coming in fall 2024
- Test of reproducibility of manufacturing (new set of coils) in 2025

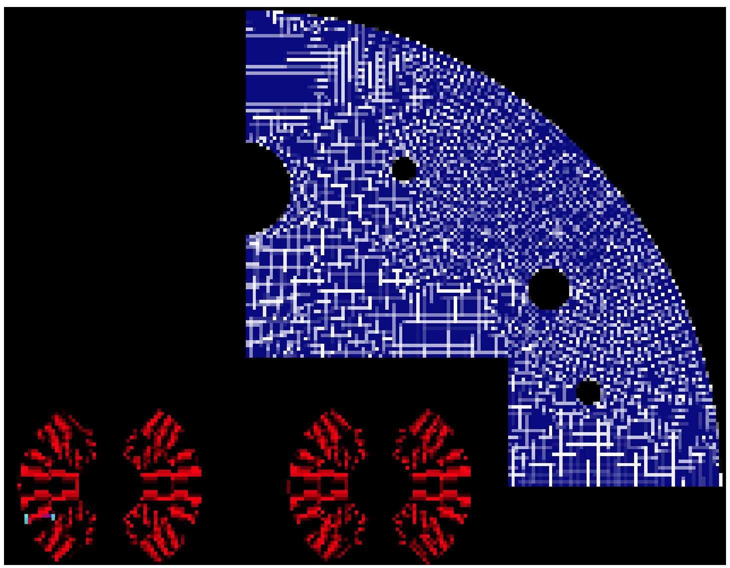


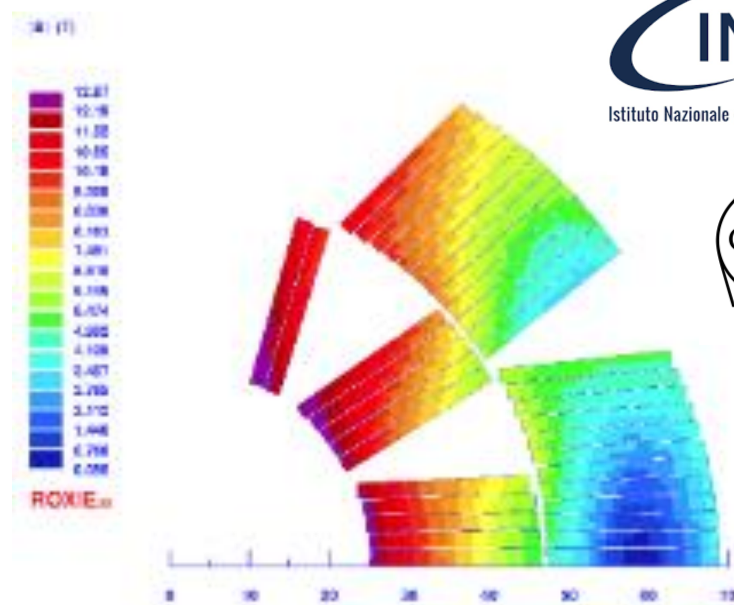


Cross-section and training of RMM [E. Gautheron, et al. IEEE TAS 33 (2023) 4004108]

Nb_3Sn program: the 12 T option

- A 12 T dipole based on cosθ geometry is in the HFM baseline since 2020
  - Why a 12 T ? Mainly because it can provide a cheaper magnet
    - It has about 30% less conductor



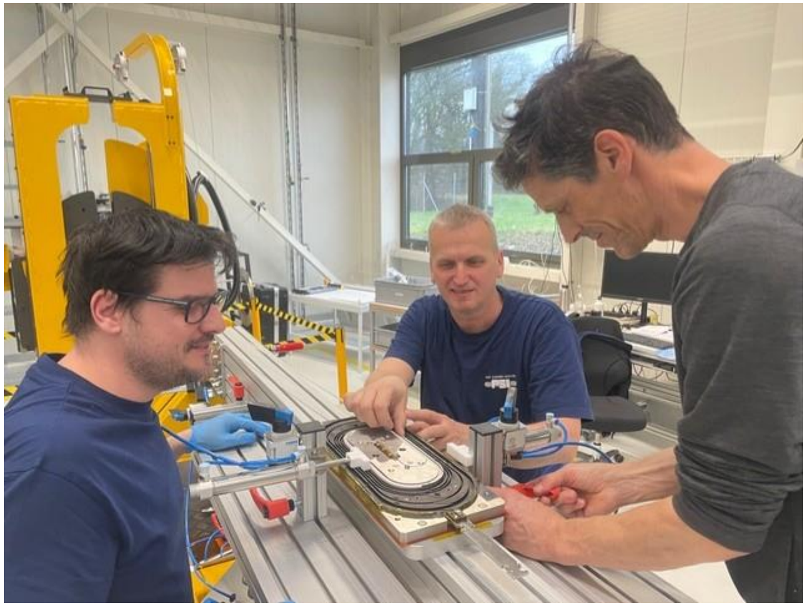


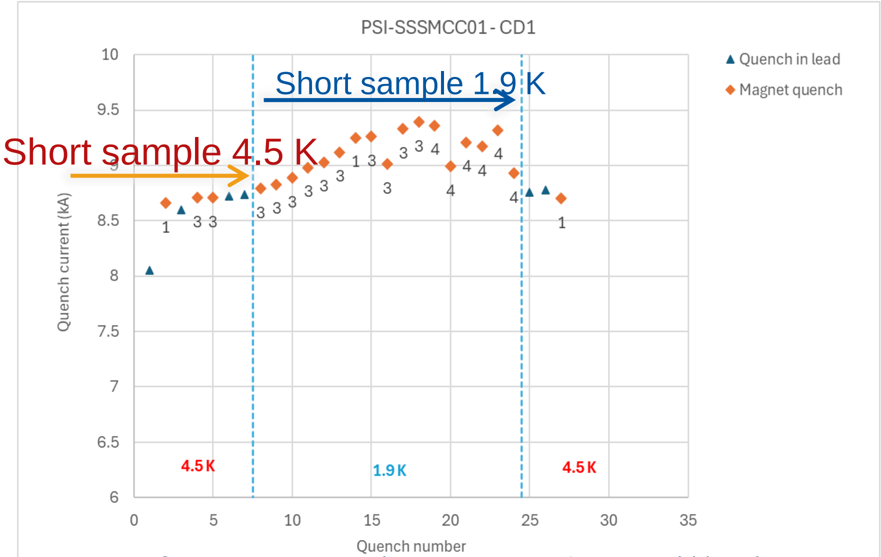
FalconD cross-section [S. Farinon, et al.]

Nb_3Sn program: stress management

- Even though stress management is mandatory only towards 20 T, it can provide precious margin at 14 T – PSI explores this option
  - Test of PSI subscale stress managed common coil (SSSMCC) at CERN – wax impregnated, reaction and test made at CERN
  - Peak field in the coil of 6.5 T reached, >5 T in in the centre (June 2024)

PSI

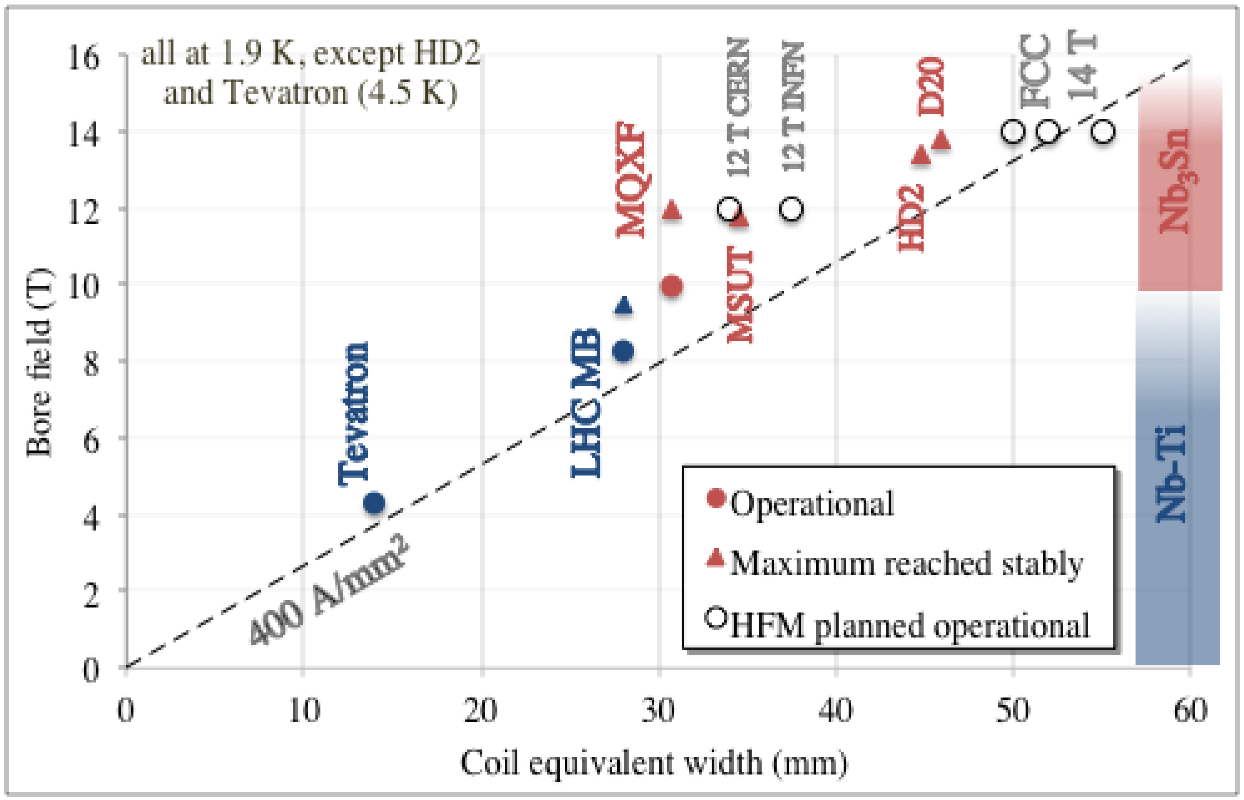


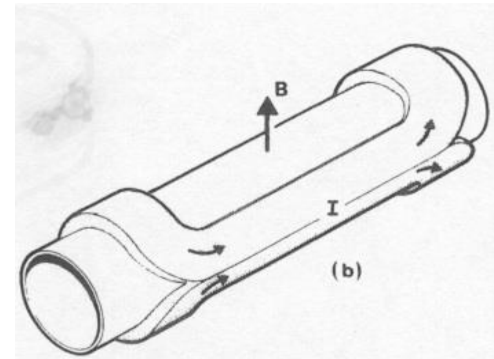


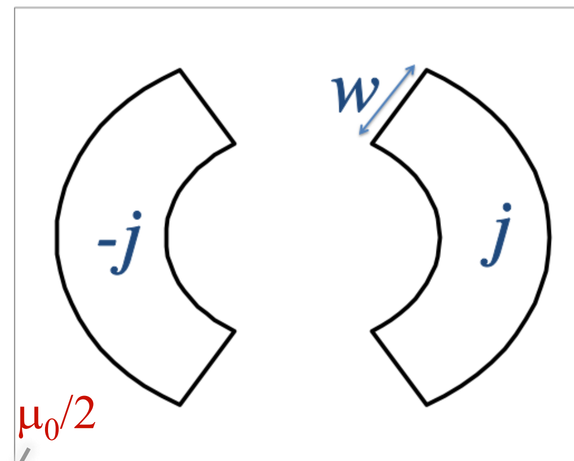
Test of SSSMCC in SM18 (G. Willering, et al.)

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

What are we building







$$B[\mathrm{T}] \approx 0.00063\, j\left[\mathrm{A/mm}^2\right] w[\mathrm{mm}]$$

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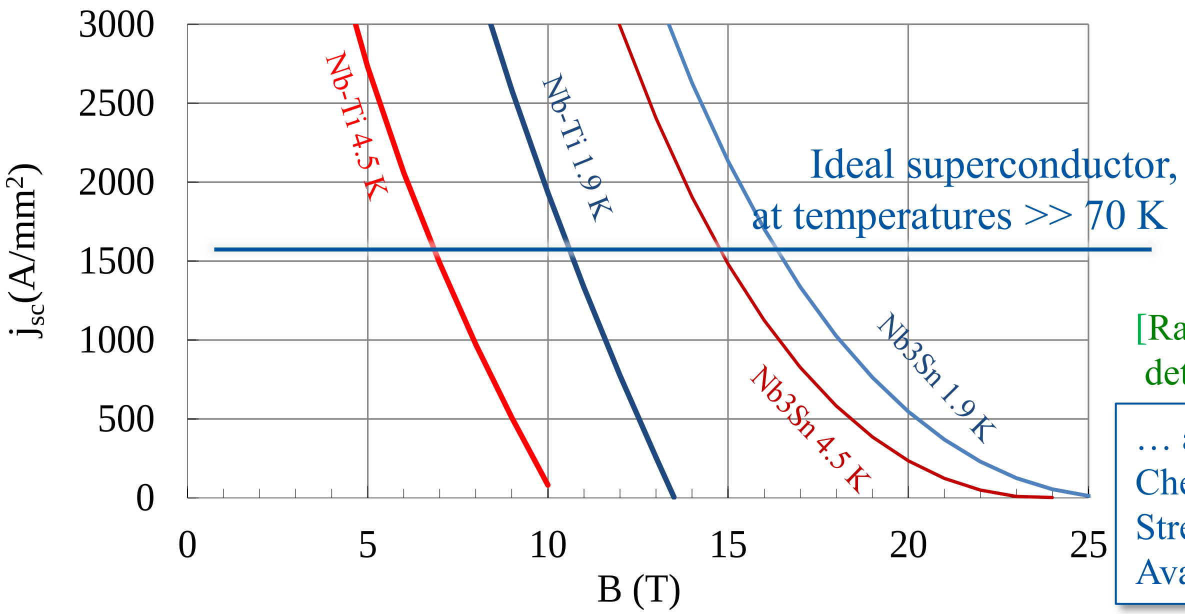
HTS: the ideal superconductor?

- … a critical current that does not decrease with field
- … a critical current that does not increase at lower fields (to reduce hysteresis, persistent currents)
- … 1500 A/mm^2 (just what is needed, nothing more) at high temperatures



[Raffaello et al., The School of Athens, detail, Musei Vaticani (1510)]

… and
Cheap: 5 $/(kA m)
Stress resistent at least up to 200 MPa
Available in long (km) lengths

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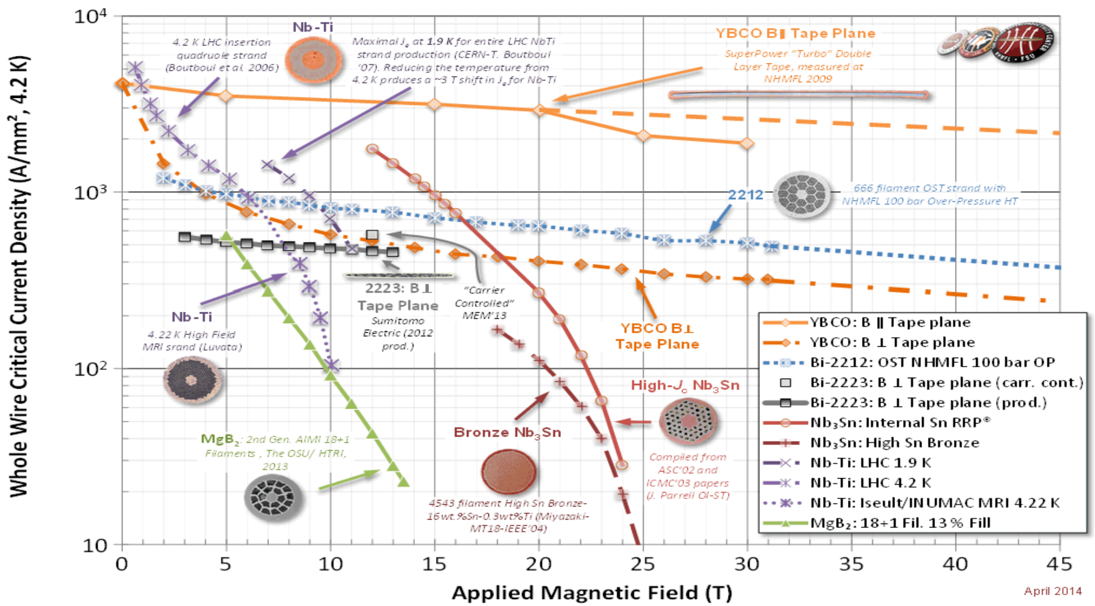


[Raffaello et al., The School of Athens, detail, Musei Vaticani (1510)]

… and
Cheap: 5 $/(kA m)
Stress resistent at least up to 200 MPa
Available in long (km) lengths

Three paths for HTS

- BSSCO 2212 (mainly developed in the USA)
  - Available in round strand, dipoles reaching 1.5 T have been done (LBNL)
  - Expensive, complicated manufacturing process (more than Nb_3Sn): reaction at 800 C in 100 bar of O_2
  - No activities foreseen in HFM
- REBCO (strong impluse from fusion investments of order of BCHF)
  - Recently, large reduction of cost, but still one 5-10 larger than what needed in the unfavorable direction, and with limited lengths
  - Available in tape, cable geometries being considered (Roebel, Corc®, Star ®)
  - Hysteresis losses can be a showstopper: the filament is the tape width
  - Workhorse for HFM
- IBS (strong impulse from China)
  - Critical current is improving (see appendix)
  - Potentially cheaper than REBCO
  - One WP in HFM

The challenge of hysteresis losses

- The larger temperature margin and lower *j* at low field, allows stability with very large filaments in one direction (up to 12 mm)
- Hysteretic losses, that are today critical for the FCC-hh (target of 5 kJ/m is given), can be a showstopper in this case

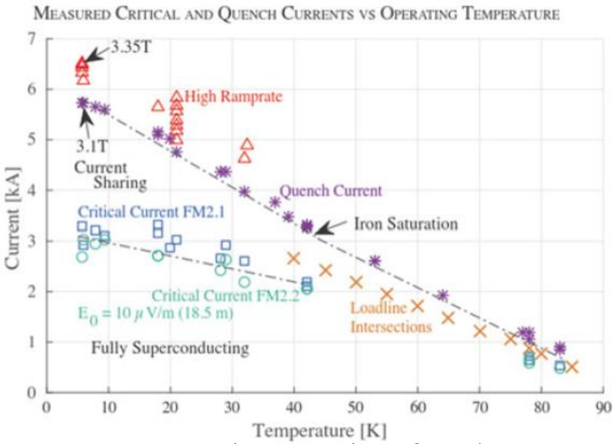
$$\frac{d}{2} < \frac{1}{j_c}\sqrt{\frac{3\gamma C_p\left(T_c - T\right)}{\mu_0}}$$

- In case of HTS insert, both common coil and cosθ have the cables perpendicular to the field: the ideal is the block, where they are parallel
- Feather magnet tested in 2017, REBCO,

block aligned: it reached 4.5 T, but did not prove all accelerator features

[L. Rossi, et al, Instruments 5 (2021)]

- Is REBCO tape a viable conductor for HEP main dipole magnets ? Question still open today

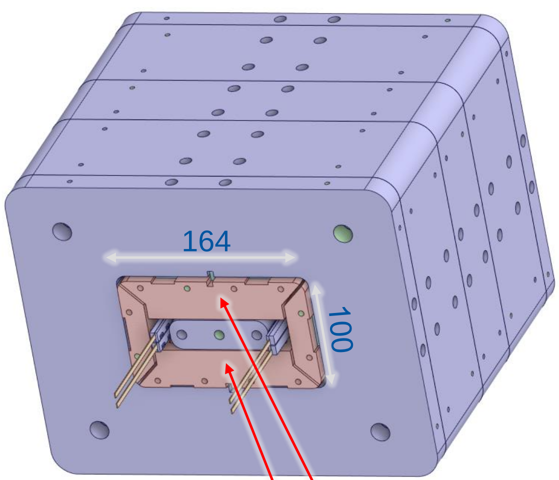


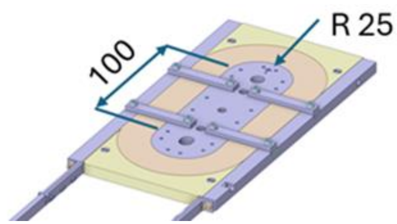
First powering of Feather

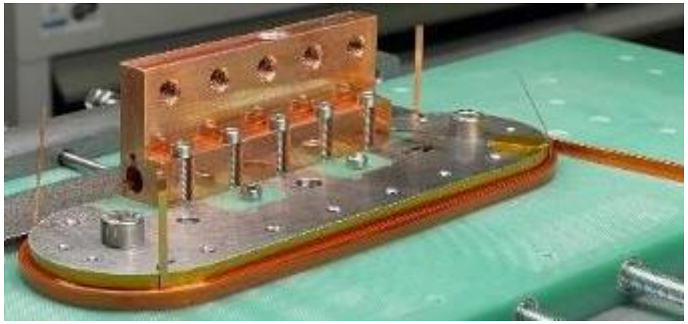
[L. Rossi, et al, IEEE TAS 28 (2018) 4001810]

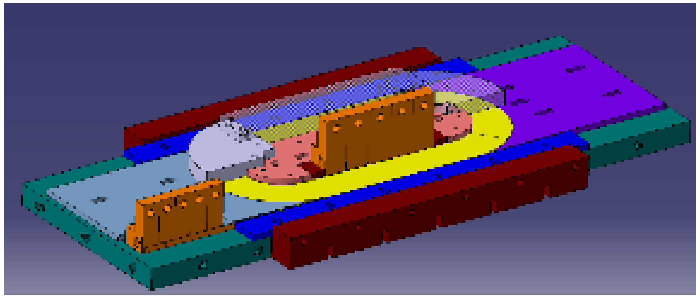
HTS news

- 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









Optimized for number of racetracks

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

Never forget the specificity of accelerator magnets

- First: An accelerator dipole is not a solenoid !!
  - Field is not parallel to the wire, forces are not perpendicular to the wire, stresses are 50% larger than magnet pressure
- Second: Overall current densities of ~500 A/mm^2 are a peculiar feature/challenge for accelerator magnets
  - One order of magnitude above HEP detector magnets or fusion magnets

	Overall current density (A/mm^2)	Superconductor current density (A/mm^2)	Ramp	Field in conductor (T)
Tevatron dipole	360	1550	slow	4.7
LHC dipole	360/440	1260/1820	slow	8.6
ATLAS BCT	30	950	very slow	3.9
ITER (TF & CS)	20 to 40	150	very fast	5 to 13
HL-LHC SC link	17	1450	slow	Self field (<1 T)

- Third: magnet operational range is not a single point, but a whole set of currents (from injection to high field)

HFM

High Field Magnets

Programme

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- HTS hopes and challenges
- News from US and China

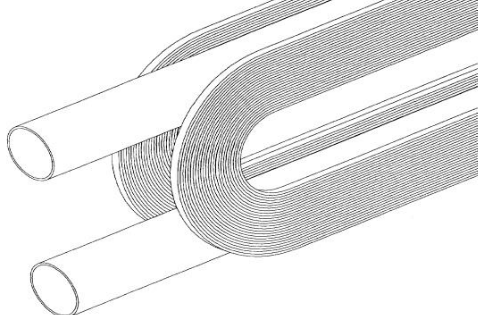
SPPC

- Comparison between FCC-hh and SPPC
  - As FCC-hh, SPPC went through a modification of parameters
  - Today it relies on 20 T magnet, with 100 km tunnel, and 125 TeV c.o.m.
  - The 20 T are given by 13 T in Nb_3Sn and 7 T in HTS

FCC-hh parameters	CDR 2019	2024-Nb_3Sn	2024-HTS
Dipole field (T)	16.0	14.0	16-20
Tunnel length (km)	100	90.7	90.7
Arc length (km)	82.0	76.9	76.9
Arc filling factor (adim)	0.80	0.87	0.85
Energy c.o.m (TeV)	100	90	100-125
Loadline margin	86%	80%	TBD

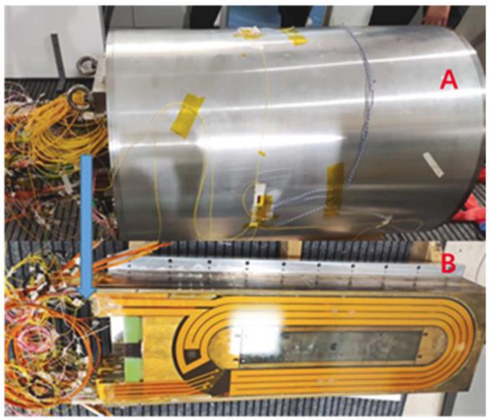
SPPC parameters	Nb_3Sn (2019)	HTS (2019)	Nb_3Sn/HTS (2023)
Dipole field (T)	12.0	20-24	20 (13+7)
Tunnel length (km)	100	100	100
Arc length (km)	81.8	81.8	81.8
Arc filling factor (adim)	0.79	0.79	0.79
Energy c.o.m (TeV)	75	125-150	125

SPPC magnets

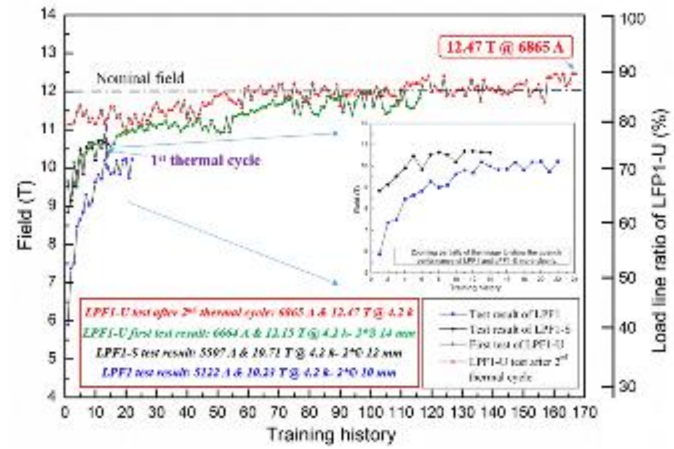


Common coil design
[R. Gupta, IPAC 1997 3344]

- IHEP has selected the common coil design
  - Steps aiming at 20 T increasing field and aperture
  - 2018-2023: LFP1 Nb_3Sn magnet reached 12.5 T in 14 mm aperture
    - Configuration based on flat racetrack, without field quality



LFP3 magnet [J. Shi, Q. Xu, et al., IEEE TAS 34 (2024) 4701405]

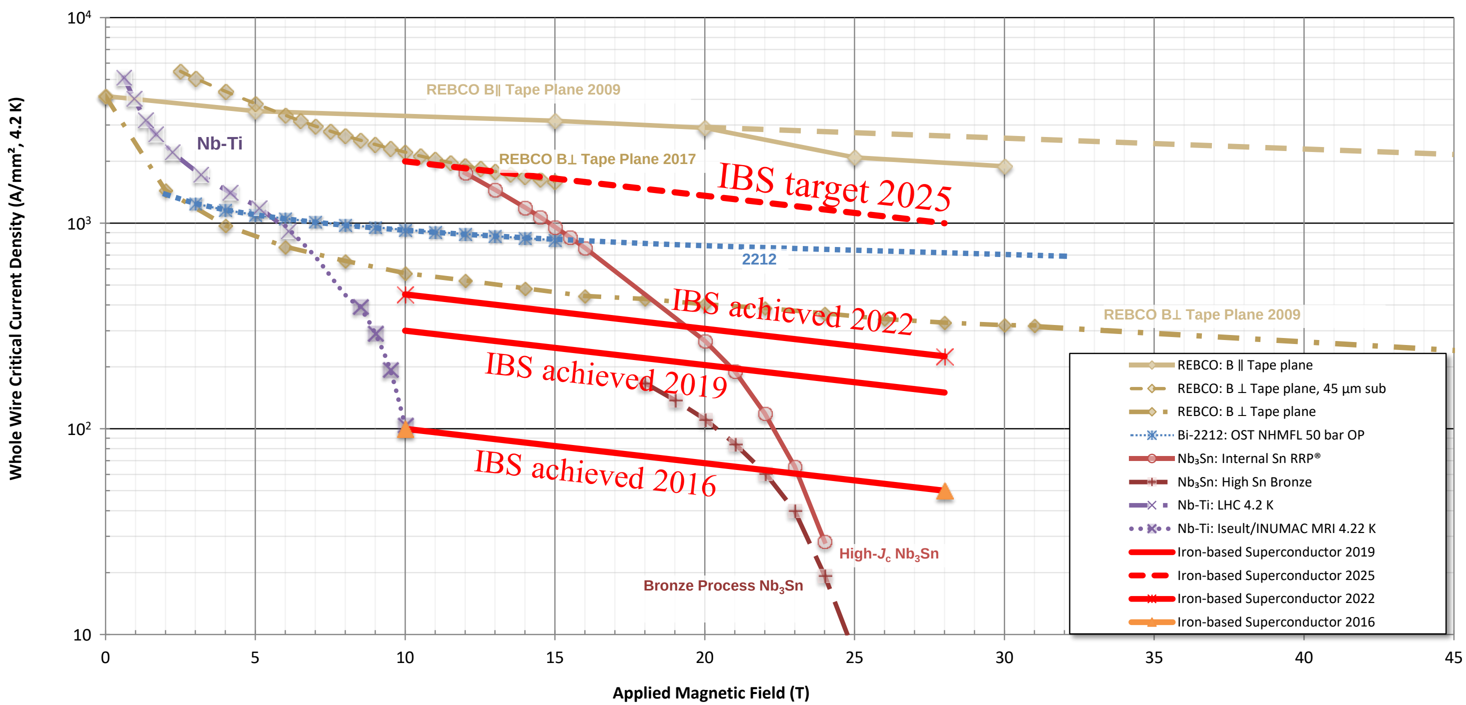


LPF1 training [C. Wang, et al., SUST 36 (2023) 065006]

- LFP3 construction ongoing since two years, aiming at 13 T with Nb_3Sn plus 3 T with HTS
  - Nb_3Sn coils limited at 11 T, HTS reached 3 T, then two coils lost during tests
  - New set of coils being manufactured, test at the end of 2024

SPPC magnets

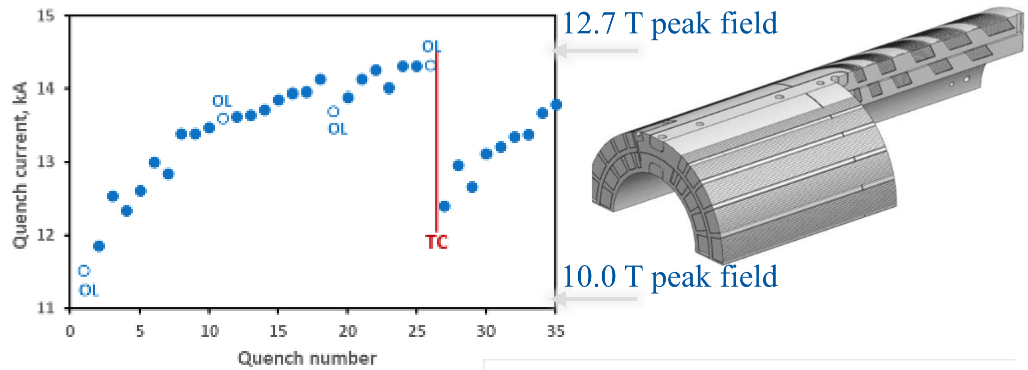
- The common coil shall contain a part (7 T) in HTS
  - China is investing on IBS since many years – solenoids successfully built
  - Considerable progress in the past years, but still far from target
  - HFM also has a WP on IBS development WP2.16, A. Malagoli from CNR SPIN)



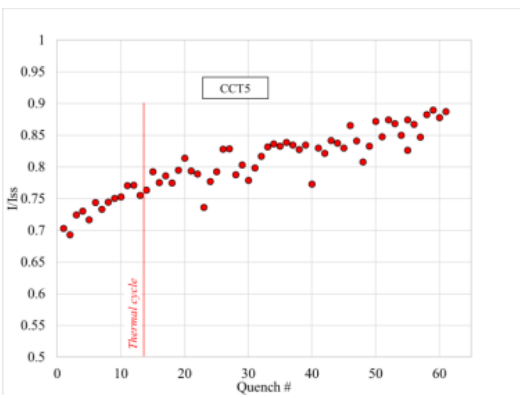
Improvement in IBS [see talk by Q. Xu, in Marseille, 2024 https://indico.in2p3.fr/event/20053/]

US magnet development program (MDP)

- MDP aims at reaching 20 T with an hybrid magnet
  - To reach 20 T the stress management is mandatory
  - Two paths: CCT and Cosθ



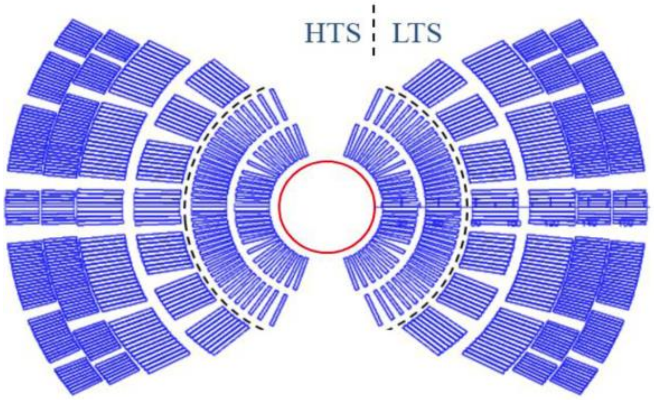
- Cosθ from FNAL: 12.7 T but in mirror
- CCT from LBNL: 8.5 T in 90 mm aperture



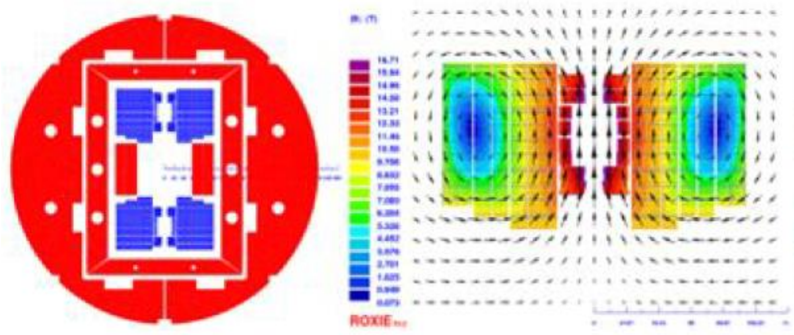
- PSI within the HFM: 10.1 T in 66 mm aperture
  - This path abandoned in favour of a stress managed common coil

Hybrid or all HTS ?

- All-HTS coil open the possibility of 20 K operation, which could consume less energy
  - Beware of drawing « easy » conclusions on sustainability … it is a very complex computation that is not intuitive
- «Hybrid» makes use of HTS in higher field regions, and of cheaper Nb_3Sn up to 13-15 T
  - This option is being developed in the US by MDP, and in China by IHEP
- HFM has not yet taken any decision on this



Hybrid design for 20 T magnet
[P. Ferracin, et al, IEEE TAS 33 (2023) 4002007 and 4LOr1B-01]



Hybrid design for 20 T magnet
[Q. Xu, et al, CEPC design report, pg 749]