HFM

High Field Magnets
Programme

HFM status, with focus on Nb_3Sn

E. Todesco, B. Auchmann

Thanks to S. Prestemon, P. Ferracin, A. Milanese, S. Izquierdo Bermudez, D. Schoerling, et al.

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A big thanks to our predecessors

Davide Tommasini, leading
EuroCirCol studies 2014-2020

Luca Bottura, leading
HFM program 2020-2021

Andrzej Siemko, leading
HFM program 2022-2023

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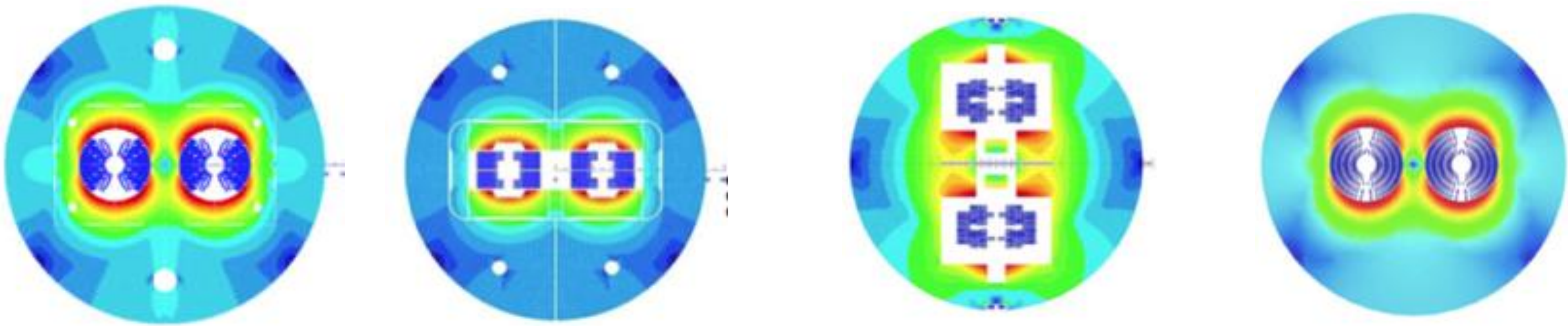
- Updated targets and integration in FCC-hh
- Planned magnets
- Updated roadmap
- Nb_3Sn conductor status and challenges

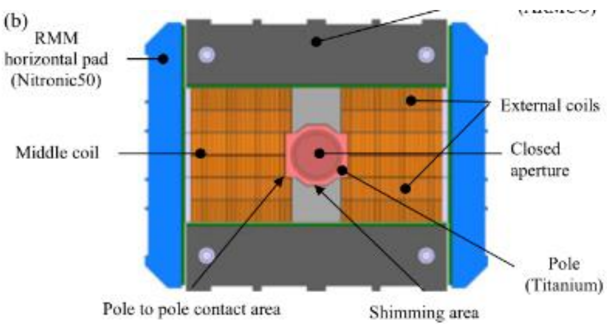
Historical on targets for Nb_3Sn magnets

- 2014: the target of EuroCirCol was a 16 T operational field magnet at 86% of loadline at 1.9 K, with a conductor 50% more performant than the available
- This led to proposing four different designs in 2018



Cross-sections of 16 T dipoles [D. Tommasini, et al., IEEE Trans. Appl. Supercond. 28 (2018)]

- In parallel, CERN launched a magnet technological program whose aim was to build a 16 T demonstrator RMM



Coil cross-sections of RMM [D. Tommasini, et al., IEEE Trans. Appl. Supercond. 28 (2018)]

HFM targets for Nb_3Sn magnets

- The proposal is to have 14 T operational field at 80% of the short sample of the existing conductor at 1.9 K today (the so-called improved hilumi Nb_3Sn conductor)
  - LHC magnets, in classical Nb-Ti, designed for 86% of short sample limit, all reaching this target during test, are operating today at 83% (6.8 TeV)
- Short model magnets should be able to reach an ultimate field of 1.0-1.5 T more (15 to 15.5 T), to prove the margin in mechanics according to the HL-LHC experience (see talk from P. Ferracin, and back up slides)
  - LHC short models achieved field levels of the order of 9.5 T
- Both short and long magnets shall be able to reach 14 T also at 4.5 K, to prove that half of the temperature margin is there
  - HL-LHC long magnets, working at 77%, systematically reached nominal gradient at 4.5 K

HFM targets for Nb_3Sn magnets

- With the present lattice 14 T gives 85 TeV c.o.m

	CDR	2024-I	2024-II
Dipole field (T)	16.0	14.0	14.0
Tunnel length (km)	100	90.7	90.7
Arc length (km)	82.0	76.9	76.9
Arc filling factor (adim)	0.80	0.83	0.87
Energy c.o.m (TeV)	100	85	90
Loadline margin	86%	80%	80%

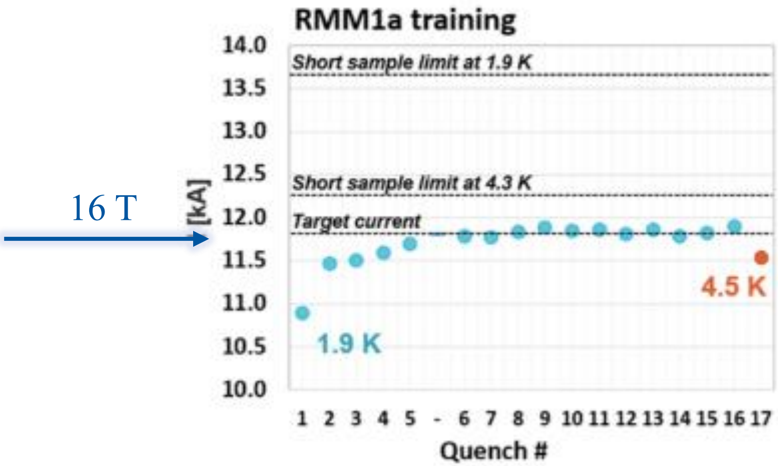
- A further optimization of the filling factor from 0.83 to 0.87 could be a viable option – 90 TeV can be achieved with 14 T, and work is ongoing in the optics team (see talk by G. P. Segurana)
  - Longer cells give less and less powerful quads, leaving more space to dipoles
  - We should consider correctors in HTS – ideal test bed for a first application

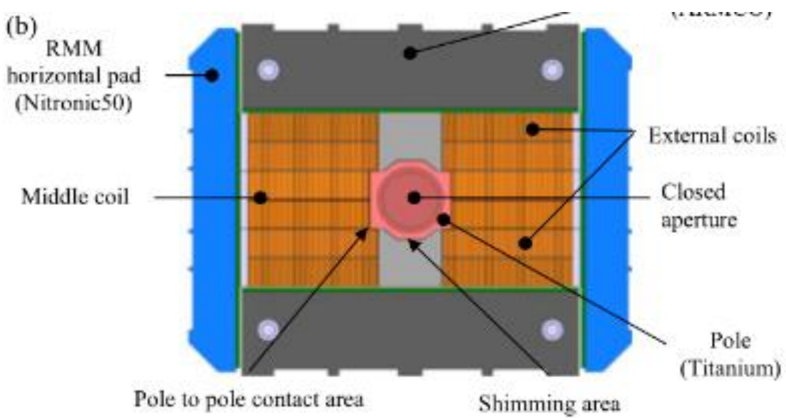
HFM targets for Nb_3Sn: conductor and stress

- Conductor:
  - If more performant conductor is developed and affordable (see the section about conductor), we will decide either to increase the operational field to get more TeV or to reduce the conductor mass to save $
- Stress limits:
  - In EuroCirCol studies, a limit of 150 MPa at room temperature and 200 MPa at 1.9 K have been given – all designs satisfied these requirements [D. Tommasini, et al. IEEE TAS 28 (2018) 4001305]
  - With the reduction of the operational field from 16 T to 14 T, all EuroCirCol design at 14 T will satisfy the limits 120 MPa at room temperature and 150 MPa at cryogenic conditions – looks a more consistent target for a large production
  - Stress management does not appear to be mandatory, but if effective will provide precious additional margin

Recent results for Nb_3Sn magnets: towards 16 T

- EuroCirCol launched a MTP (magnet technological program) with the construction and test of RMM (50 mm aperture)
  - Block coil, but no flared ends, targeting 16 T – This magnet operates with low current density and very large coil width (not affordable for FCC-hh)
  - It reached 16.4 T, proving that the singularity in the straight part of the block coil design is not a showstopper, and that there is a large margin for operation at 14 T on the mechanical side





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

  - We will reassemble with higher preload and we will manufacture a second set of coils to verify reproducibility (in 2024-2025)

Magnet cooling

- Hysteresis losses in the superconductor are the dominating source of energy dissipation in the magnet
  - For Nb_3Sn, they mainly depend on the filament size – with present HL-LHC technology (diameter of 50 μm) losses are order of 20 kJ/m per cycle (10 kJ/m per ramp, i.e. twice the target set for FCC-hh) – this is ten times larger compared to 0.5 kJ/m in the LHC dipoles
  - Hysteresis losses are found to weakly depend on magnet design
- The main dependence of hysteresis losses is on filament size
  - A reduction of D_{eff} from 50 μm to 20 μm can halve these losses – this is the reason for setting a target of 5 kJ/m for ramp
  - Pinning with internal oxidation also allows to reduce magnetization

Coil geometry		Cos-theta	Cos-theta	Cos-theta	Cos-theta	Cos-theta	Cos-theta
Deff	μm	50 (HF)	50 (HF)	50 (HF)/20 (LF)	50 (HF)/20 (LF)	20 (HF)/20 (LF)	20 (HF)/20 (LF)
Xi	--	1	0.5	1	0.5	1	0.5
I1	Inom (50 TeV)	11060	11060	11060	11060	11060	11060
I2	Ireset	100	100	100	100	100	100
I3	Iinj (3.3 TeV)	729.96	729.96	729.96	729.96	729.96	729.96
I4	Inom (50 TeV)	11060	11060	11060	11060	11060	11060
AC-loss (2 Ap)	J/m	18330	16685	14340	12980	8026	7127

Courtesy of S. Izquierdo Bermudez

- Operation at 4.5 K allows to use the present conductor and to fit the requirements
- Note that for HTS hysteresis losses with the conductor existing today could totally wipe out the advantage of operating at 20 K (see talk by B. Auchmann)

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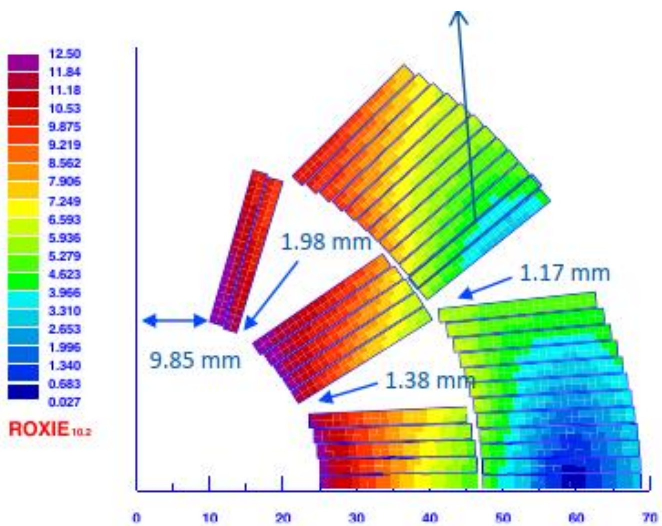
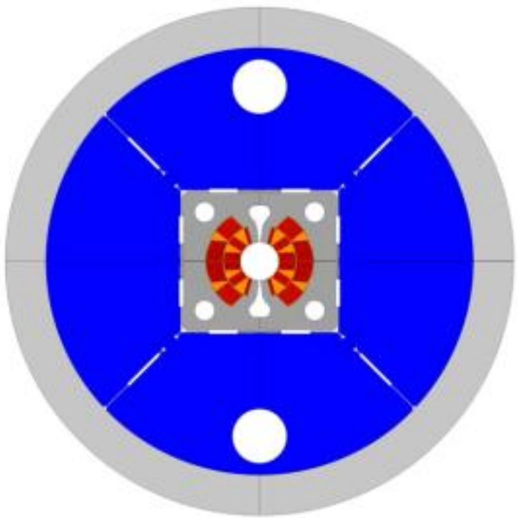
FalconD (cos θ, two layers)

- This is the most conservative magnet, based on two layer cosθ, with a 12 T operational field and possibility of reaching fields above 13 T with a very low quantity of conductor (INFN Italy, manufacturing in industry)
  - See talk on HFM forum, March https://indico.cern.ch/event/1389304
- Winding starting this year, test in 2026
- INFN is also proposing a 4 layer design aiming at 14 T

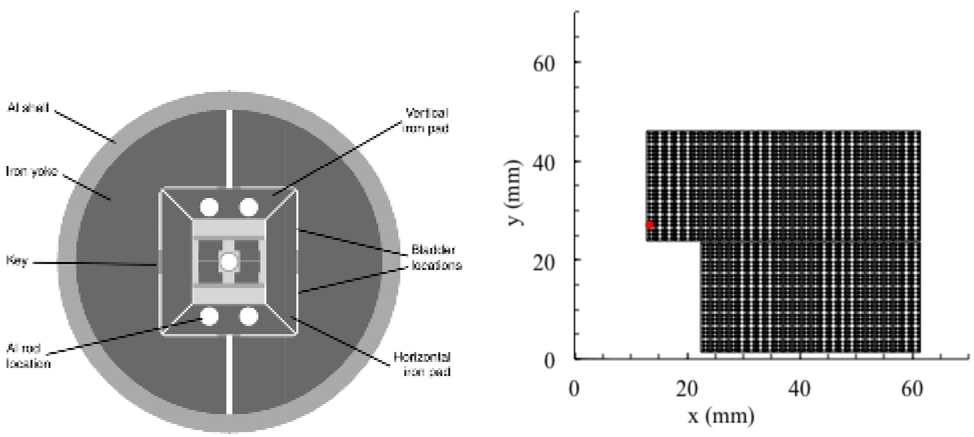




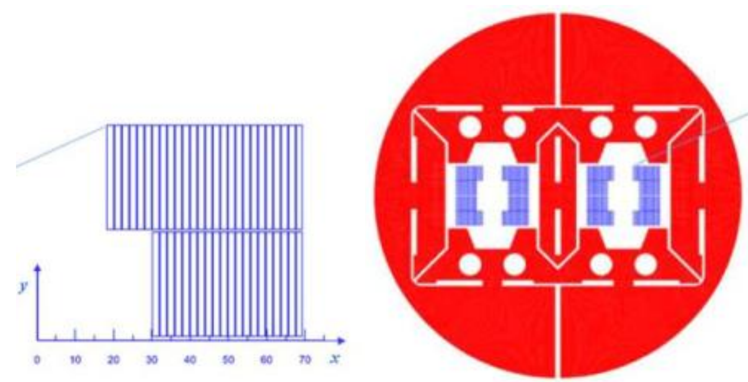
FalconD cross-section and coil [R. Valente, et al., IEEE TAS 30 (2020) 4001905]

14 T, block design, CERN

- Block coil
  - FrescalI, achieving 14.6 T, is based on block coil
  - Same coil design as HD2 reached 13.74 T at 4.5 K in 2005-2010
  - A simple design based on a two-layer coil, no grading is proposed
  - Design is ongoing, winding in 2025 and test in 2026
  - Support from the LBNL for the cable manufacturing (more than 40 strands, same of TFD)
  - See talk on 14 T meeting, February 2023 https://indico.cern.ch/event/1248907/



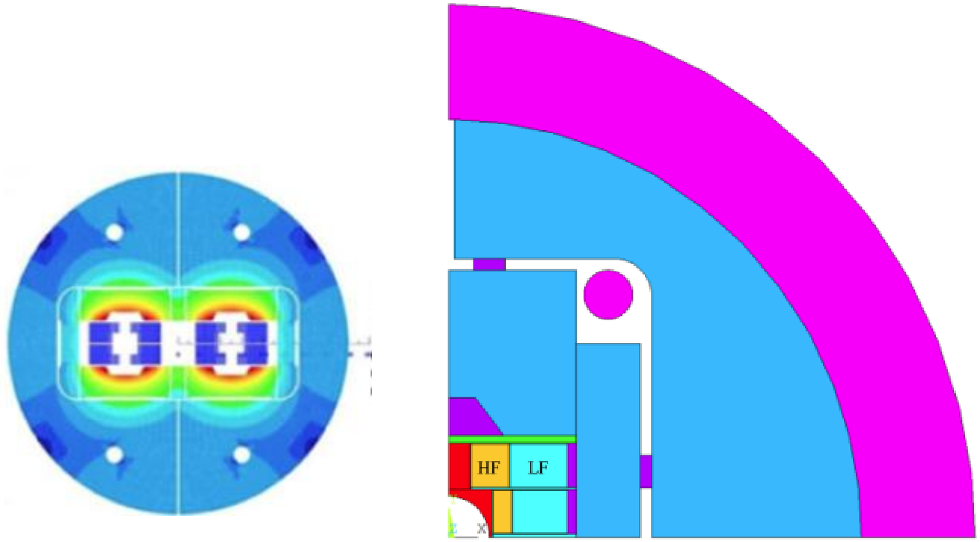
HD2 cross-section and coil [G. L. Sabbi, et al., IEEE TAS 15 (2005) 1128-1131, P. Ferracin, et al., IEEE TAS19 (2009) 1240-1243]



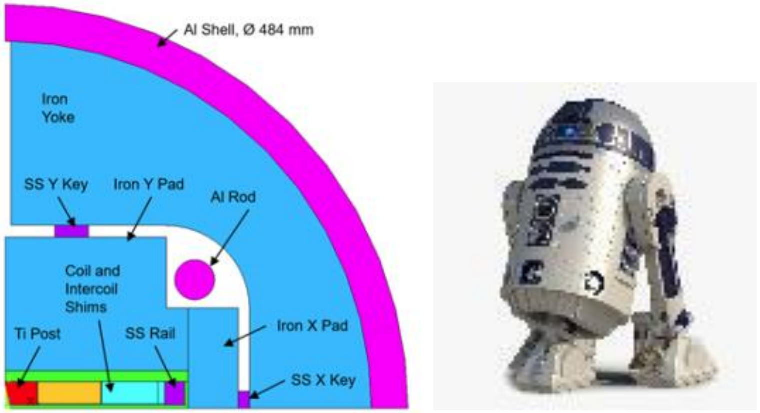
CERN 14 T cross-section and coil
(J. C. Perez, S. Izquierdo Bermudez, A. Haziot et al)

14 T, block design, CEA

- CEA is developing a more complex block design (F2D2), with grading and four layers coils
  - Winding and test will take place after 2025
  - Intermediate step: R2D2, to have two racetrack with two different cables - winding is ongoing and test in 2026, with target field of 11.5 T



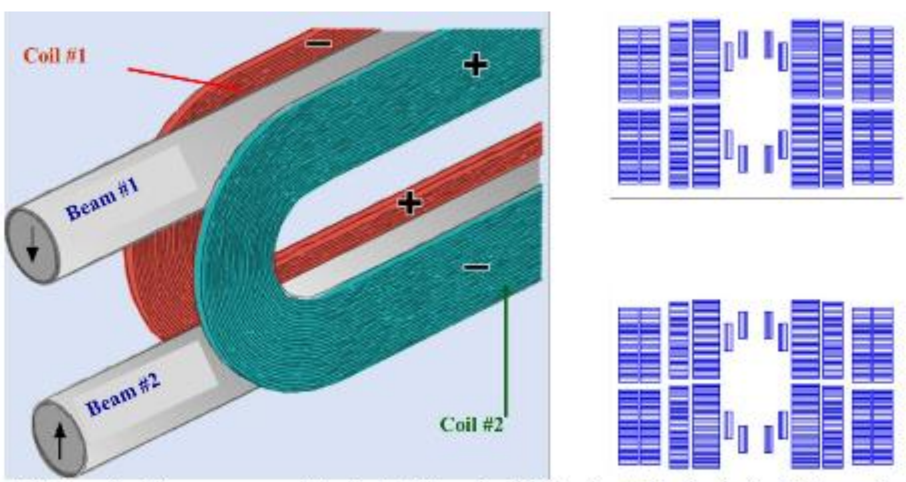
F2D2 cross-section and coil [H. Felice, et al., IEEE TAS 29 (2019) 4001807]



R2D2 cross-section and 3D model
[V. Calvelli, et al., IEEE TAS 31 (2021) 4002706]

14 T, common coil, CIEMAT

- Common coil design has been proposed since the last century
  - Advantage is to have flat coils (most of them)
  - Design is less effective (more conductor)
- CIEMAT is proposing to manufacture such magnet
  - Design is ongoing, test not before 2027
- Intermediate step: ISAAC magnet, with two racetrack coils from CERN
  - Target field above 12 T, it has a short sample of 14 T, test in 2025 (see also meeting on 21 March 2024, https://indico.cern.ch/event/1389304/)



ig. 1: Main coils of the common coil design (left), main coils (horizontally oriented) with the pole coi

Common coil concept (R. Gupta, et al.)

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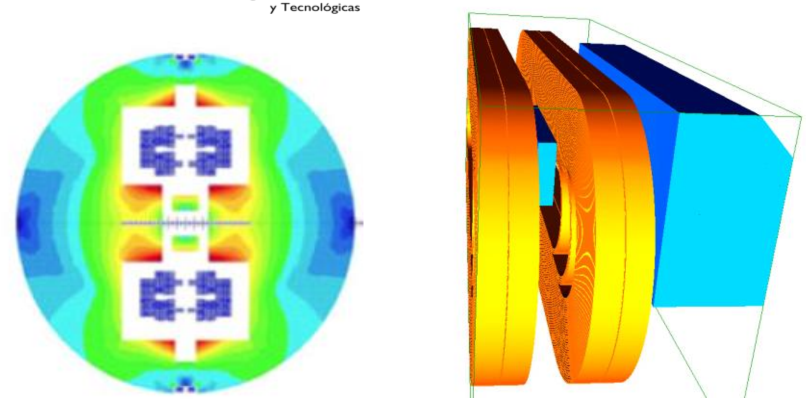
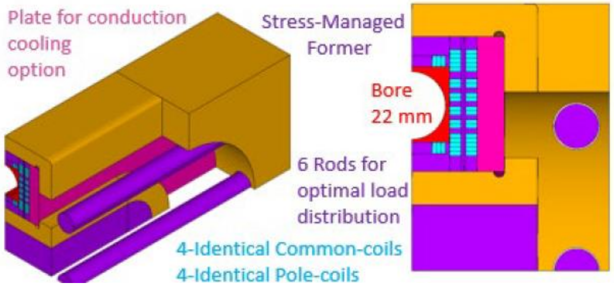
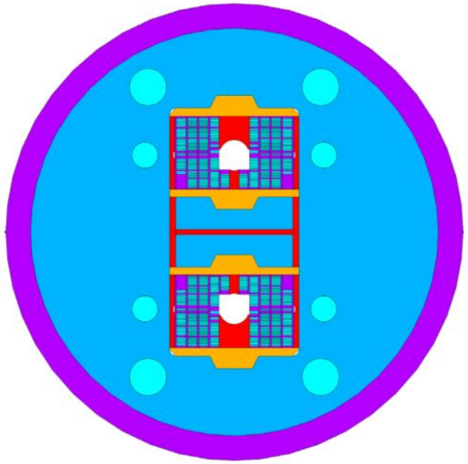


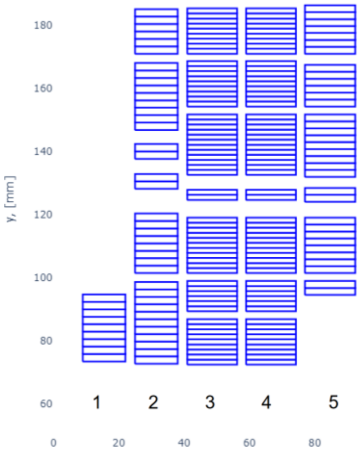
Common coil cross-section and 3D model
[F. Toral et al.]

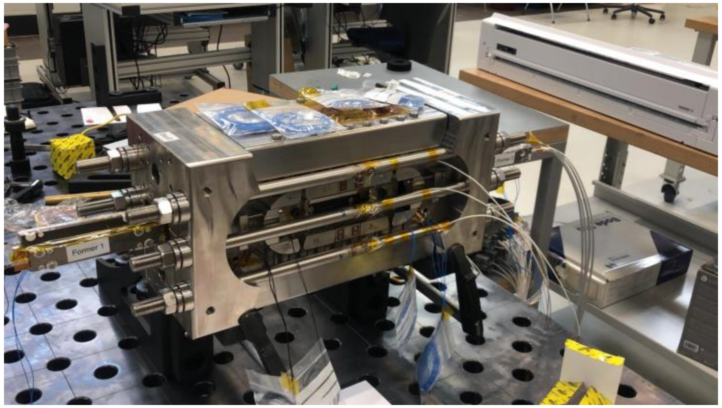
14 T, stress managed common coil, PSI

- PSI is proposing a fully stress-managed magnet, with grading
  - Stress management at 14 T is not required, but adds margin to a large production
  - Stress is managed both vertically and horizontally
  - The asymmetric coil design allows to have only flat coils
  - Test not before 2026
- Intermediate step: a small model proving the technology, to be tested in 2024









Stress managed common coil [D. Araujo,. B. Auchmann, et al.]

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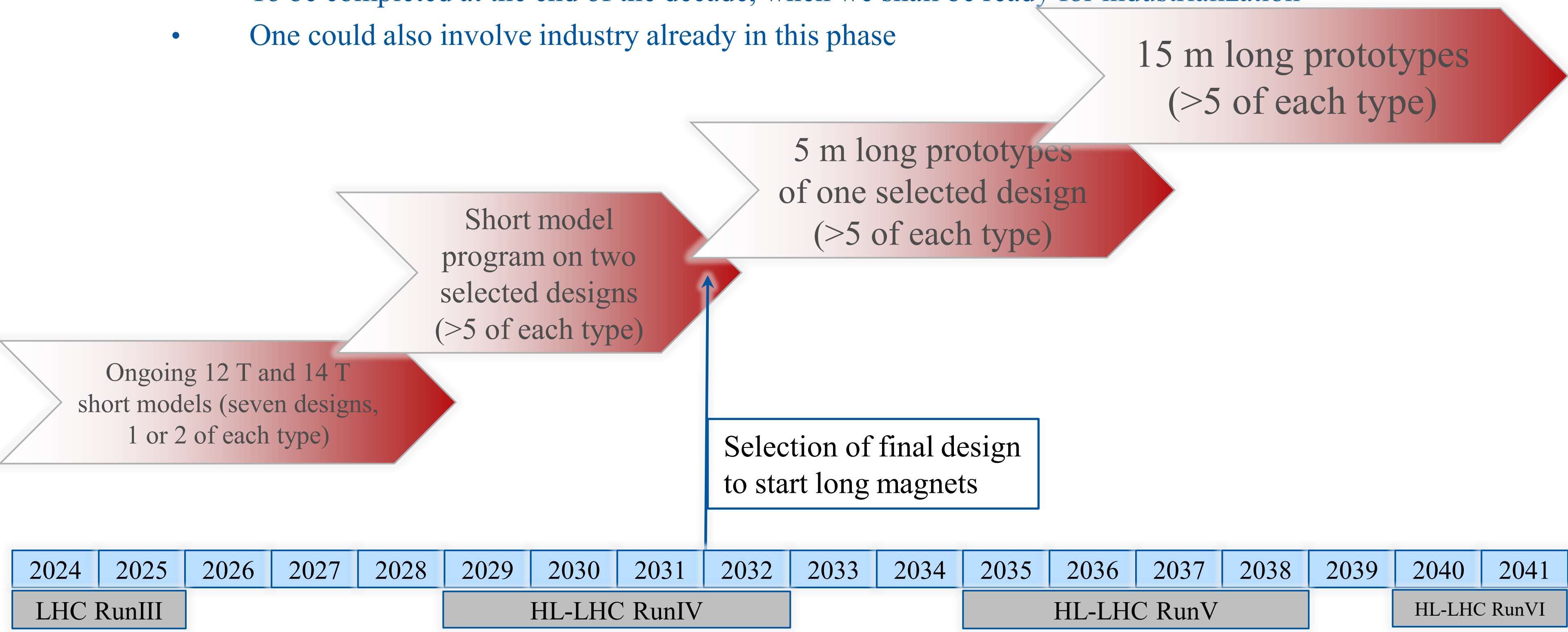
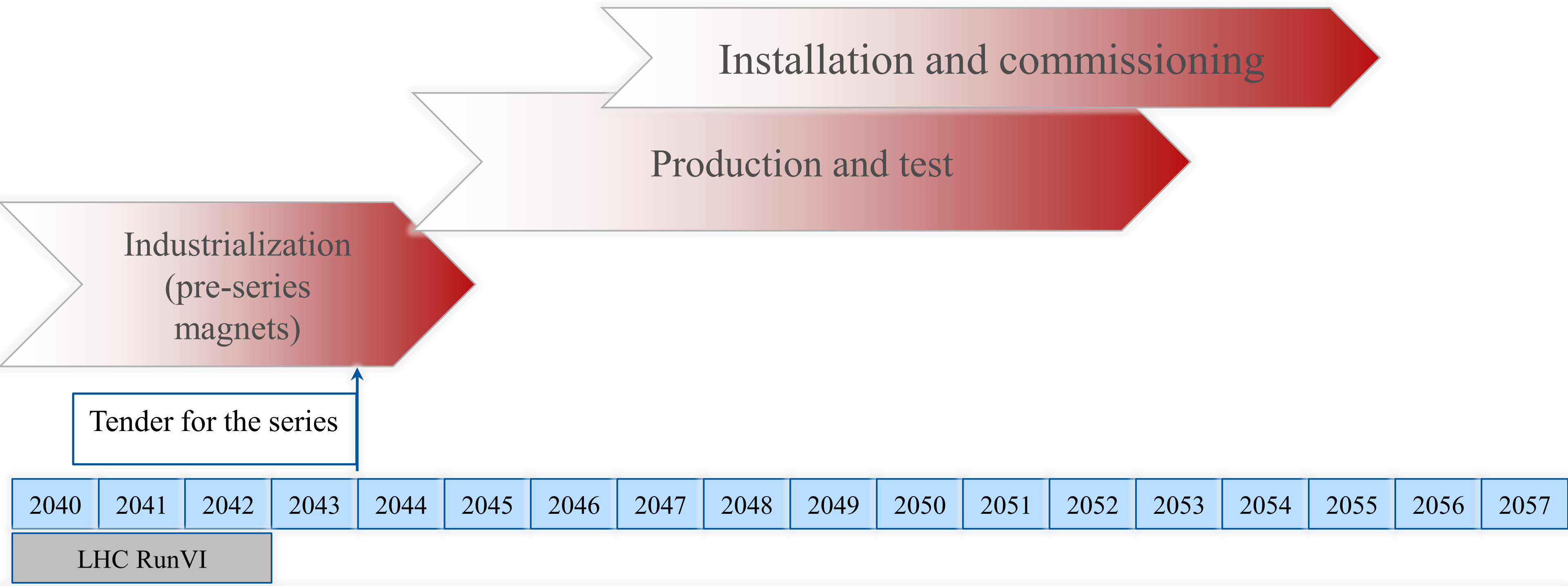
Roadmap to full scale prototypes

- At the horizon of HL-LHC RunIV, we shall select one or two designs, and have a short model program (at least five models) to explore performance reproducibility
  This should take about 4 years
- During RunV, we shall launch the scaling to 15 m
  - To be completed at the end of the decade, when we shall be ready for industrialization
  - One could also involve industry already in this phase



Industrialization, production, and commissioning

- At the end of HL-LHC, tender for the series
  - Production and test over nine years
  - Installation and commissioning in parallel



Can we go faster ?

- Can we have shorten the timeline by 10 years, so to fit the 2045 date for the FCC-hh right after HL-LHC?
  - Yes, but with some risks and additional cost
  - Go more in parallel between short models and prototpye
  - Go in parallel in the scaling to 5 m and to 15 m
  - Involve industry in prototypes (as done for LHC)
  - The present baseline assumes that scaling in length is not straightforward, as it has been for HL-LHC and that the HL-LHC experience does not apply
- The present priority is to get to a short model program for one (or max two) design asap

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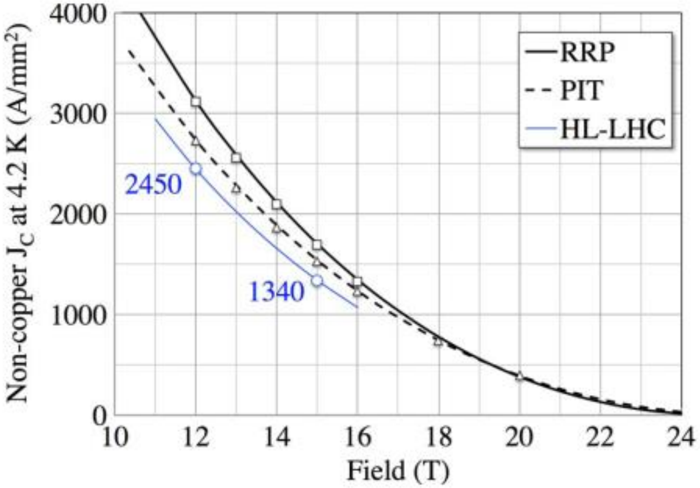
Conductor historical

- Targets for the conductor set in 2014:
  - Critical current of 1500 A/mm² at 16 T and 4.2 K (it is 1000 A/mm² in the HL LHC conductor requirements)
  - Filament size of 20 μm (it is 50 μm in HL-LHC)

TABLE I
TARGETS FOR FUTURE R&D ON Nb_3Sn FOR HEP APPLICATIONS

Strand diameter	(mm)	0.5 … 1
Non-Cu J_C (16 T, 4.2 K)	(A/mm²)	≥ 1500
$\mu_0 \Delta M$ (1 T, 4.2 K)	(mT)	≤ 150
$\sigma(\mu_0 \Delta M)$ (1 T, 4.2 K)	(%)	≤ 4.5
D_{eff}	(μm)	≤ 20
RRR	(-)	≥ 150
Unit Length	(km)	≥ 5

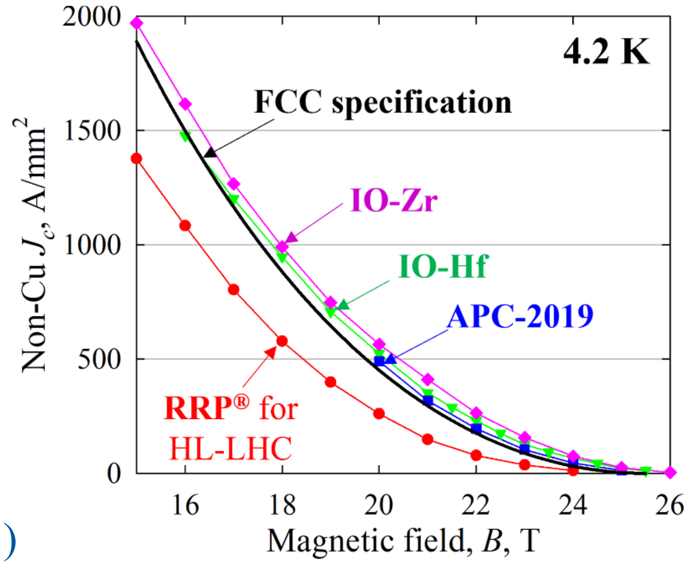
Nb_3Sn conductor targets of 2014
L. Bottura, A. Ballarino, IEEE TAS 25 (2015) 6000906



- Today (ten years later) we are at
  - Critical current of 1200 A/mm² at 16 T and 4.2 K → we have to lower the field from 16 T to 14 T if we want to keep affordable volume of conductor with proved margin
  - Filament size of 50 μm → impact on hysteresis losses, that with this filament are twice the target of FCC design, but this can be avoided working at 4.5 K – field quality can be mitigated by correctors ?

Conductor development

- Today we have only one provider of this type of strand: we should have more manufacturers able to produce this strand
  - Two more are being qualified
- Ongoing work on increase of critical current:
  - Activities in the HFM program at University of Geneva and at TU Bergakademie Freiberg (S. Hopkins, et al., talk on June 3 https://indico.cern.ch/event/1419912/)
  - Very promising, but not yet an industrialised wire technology validated for accelerator magnet applications
  - Still to be demonstrated:
    - Long lengths
    - Degradation on cabling
    - Magnetothermal stability



X. Xu *et al.*, *Supercond. Sci. Technol.* **36** 035012 (2023)

Conclusions

- In March 2024 we set the target of 14 T for the operational field of FCC-hh based on Nb_3Sn
  - This can provide up to 90 TeV c.o.m energy
  - Short models shall be able to reach 1-1.5 T more (15-15.5 T)
- Relevant progress in the field in the past few years
  - Scaling of length up to 7 m long accelerator quality quadrupoles
  - Reproducibility, margin in mechanics and in temperature
  - No degradation
  - Block based design, but with flared ends RMM reached 16.4 T
- 7 different magnets are being built by collaborations (too many?)
  - A selection of the final design shall be done at the horizon of HL LHC installation (2028)
- Work is ongoing on the conductor – if better will be available, shall be used to increase the field or decrease the conductor mass

HFM

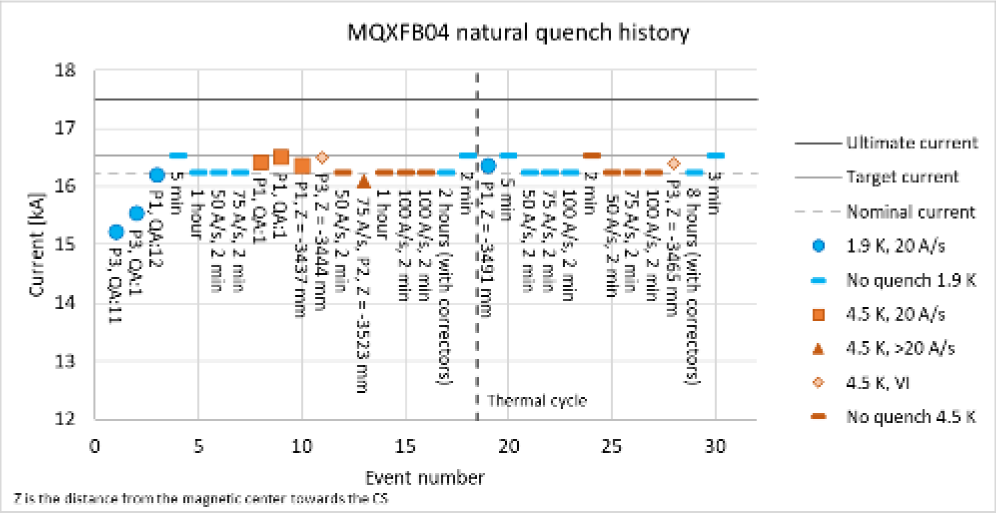
High Field Magnets

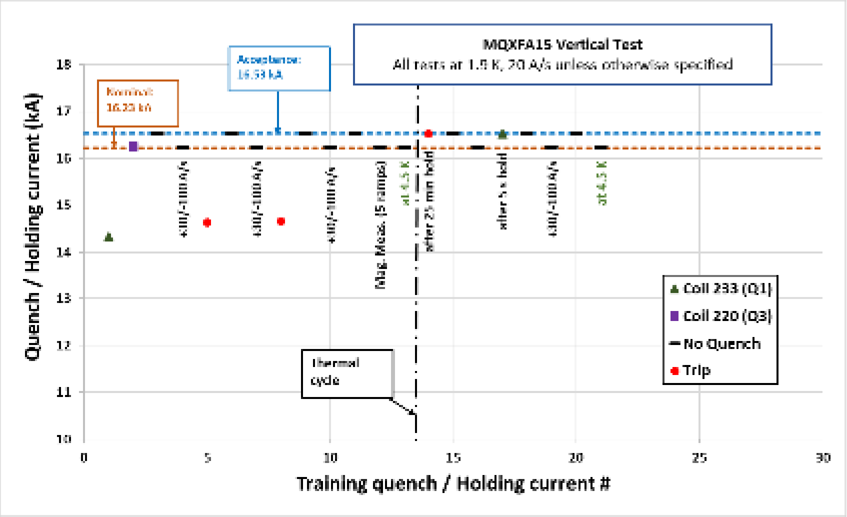
Programme

Recent results for Nb_3Sn magnets: margin and 4.5 K

- Experience on HL-LHC interaction region magnets, working at 77% of loadline fraction (23% margin) is showing that
  - This margin is being obtained with a good reproducibility
  - Scaling up to 7 m long has been completed successfully
  - Magnets are also working at 4.5 K

- Therefore with this target one can have also the possibility of working at 4.5 K





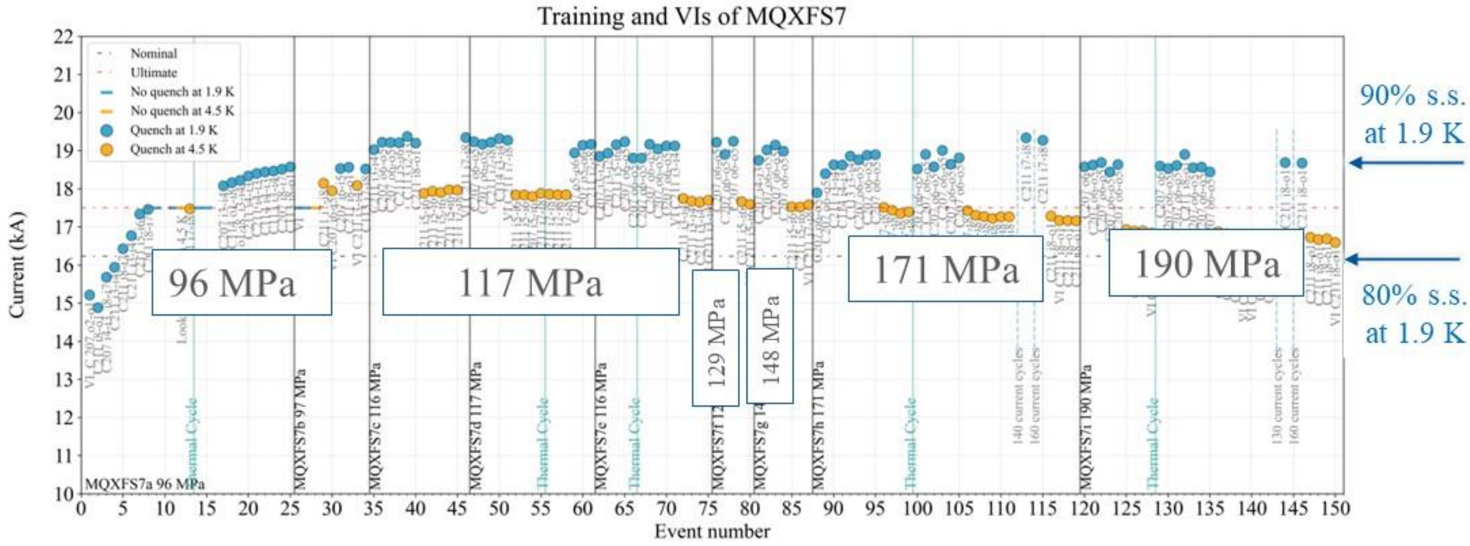
Recent results for Nb_3Sn magnets: production

- HL-LHC is the first experience with a Nb_3Sn magnet production:
  - Production of 3500 km of strand, 0.85 mm diameter, completed – both CERN and the US partners using same supplier
  - More than 100 coils built in the US, in two sites
  - More than 50 coils built at CERN
  - Magnet assembly in two sites (LBNL and CERN), more than 20 mangets assembled
  - Integration of the magnet, using Al shells and bladder and keys loading, in a cold mass compatible with integration in an accelerator has been proved both in the US and at CERN in 2022-2023

- A total of 30 magnets will be built and tested

Recent results for Nb_3Sn magnets: stress limits

- Similar to what done in TQ magnet, high preload are being explored (up to 200 MPa)
  - Test is ongoing, at 200 MPa nominal performance is still reachable, but signs of irreversible performance degradation in the range above 90% of short sample limit (but with a PIT conductor)



Preload experiment on MQXFS7, ongoing since 2023 (S. Izquierdo Bermudez, F. Mangiarotti, et al.)

- In EuroCirCol studies, a limit of 150 MPa at room temperature and 200 MPa at 1.9 K have been given – all designs satisfied these requirements [D. Tommasini, et al. IEEE TAS 28 (2018) 4001305]
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