HFM

High Field Magnets
Programme

HFM update: some news from the first semester 2024

E. Todesco, B. Auchmann,
G. Riddone and the program office

11 July 2024, HFM forum

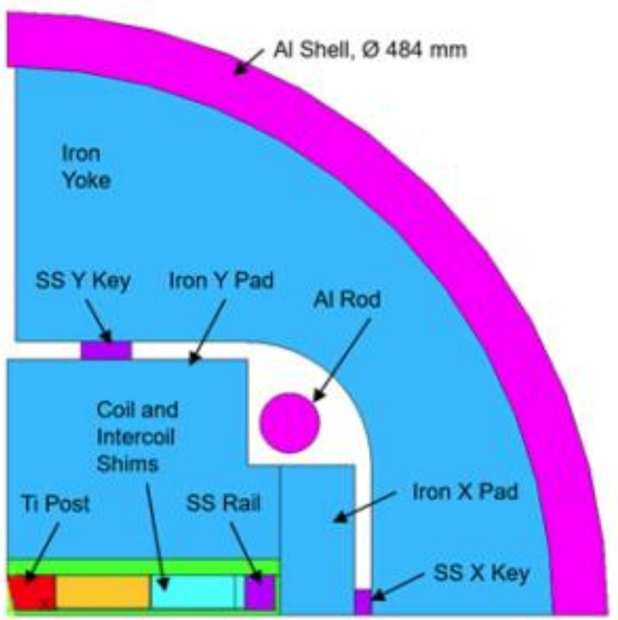
Some news: HTS

- Delivery of first REBCO tape made in KIT to CERN

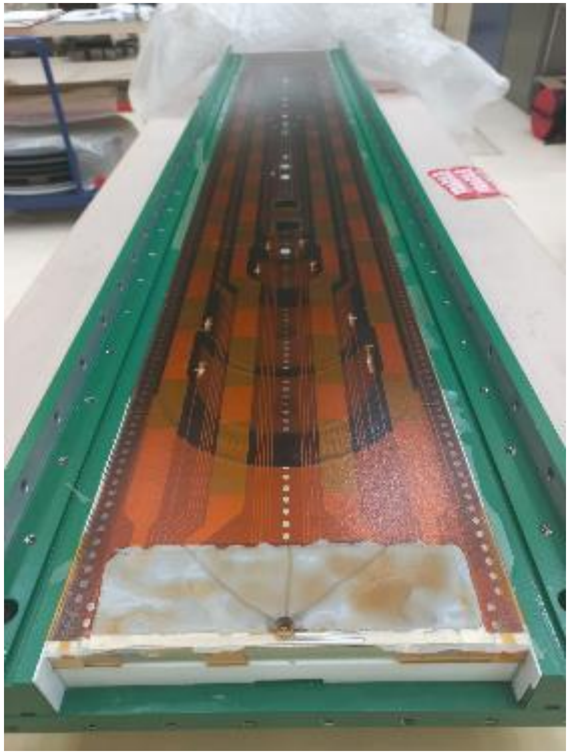
Bernhard Holzapfel (KIT) delivering the first REBCO tape to Amalia Ballarino (CERN)

Some news: Nb_3Sn magnets

- Winding of two R2D2 coils in CEA started
  - Assembly without free aperture, racetrack coils, first step towards a magnet with block coils and flared ends (F2D2) and grading



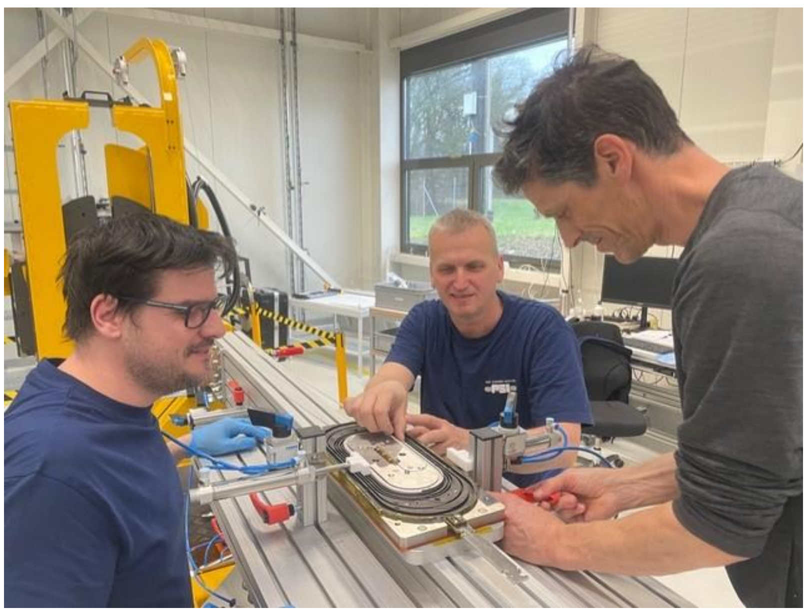
R2D2 cross-section and 3D model
[V. Calvelli, et al., IEEE TAS 31 (2021) 4002706]

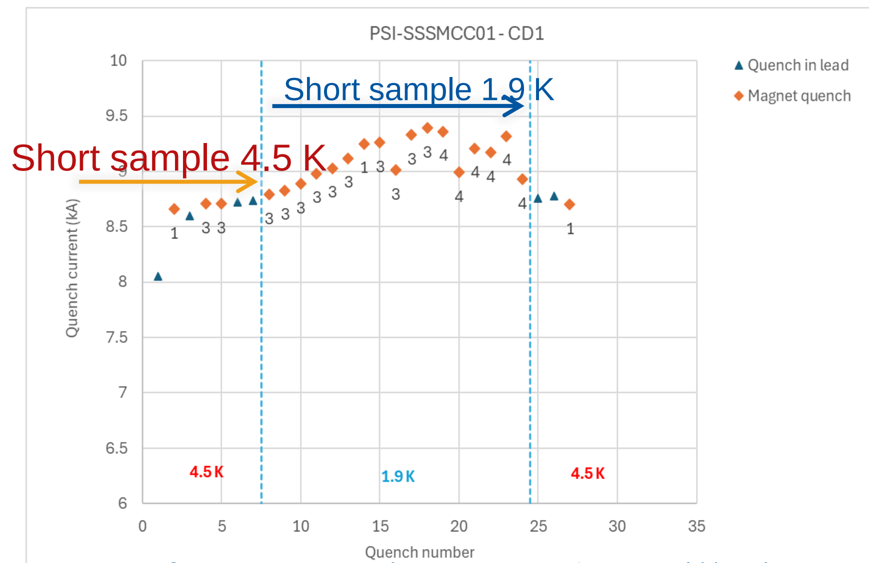


First R2D2 coil in CEA (E. Rochepault, et al.)

Some news: Nb_3Sn magnets

- Test of PSI subscale stress managed common coil (SSSMCC) at CERN – wax impregnated, reaction made at CERN – good paradigm for collaboration
- Magnet completed in May, test in June :-) at SM18 – Short sample at 4.5 K reached – test ongoing with thermal cycle in September
- Peak field in the coil of 6.5 T reached, >5 T in in the centre (June 2024)
- Talk next week in the forum



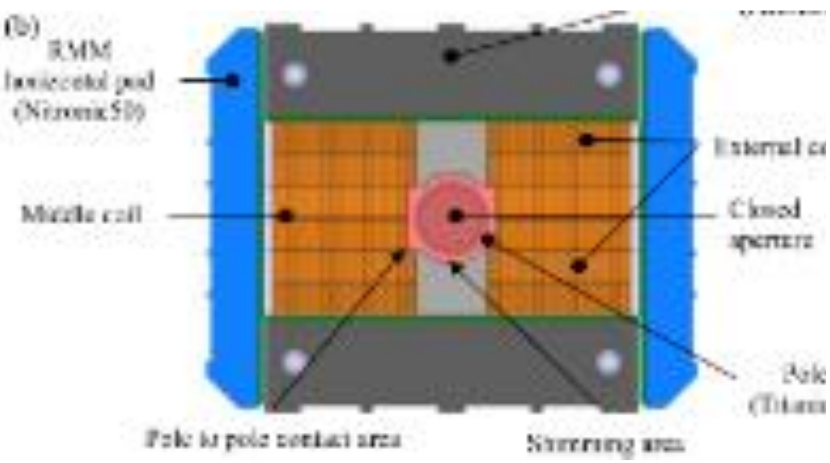


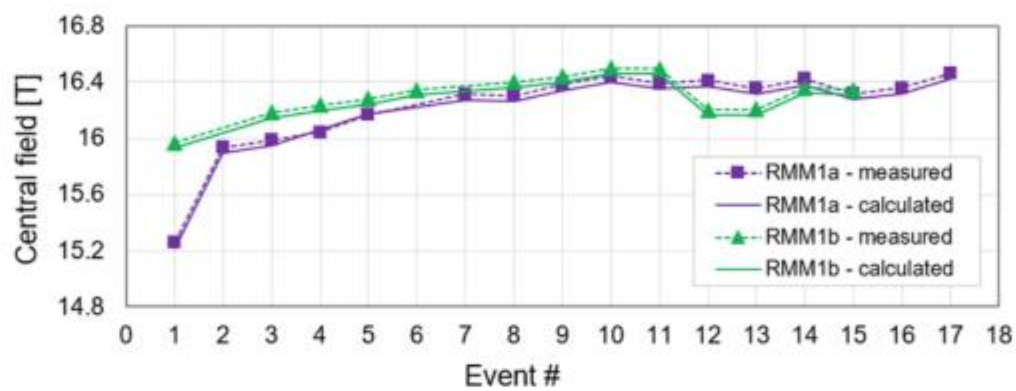
Test of SSSMCC in SM18 (G. Willering, et al.)

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

Some news: Nb_3Sn magnets

- Winding of second set of RMM coils started
- This is the technology demonstrator of EuroCirCol, that reached 16 T in 2022, proving margin to operate at 14 T (without the complexity of the ends, and with very low current density
- Reproducibility proof is important
- We will also reassemble RMM1 slightly increasing preload





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

Contents

- Program targets, mandate and energy reach
- Roadmap for Nb_3Sn
- Questions on adaptability of FCC-ee infrastructure to FCC-hh
- Relations to MDP, and hybrid magnets
- An overview on Nb_3Sn models
- Some notes about budget and organization

Program targets

- January 2024: revised mandate of HFM
  - 14 T is the operational field target for Nb_3Sn
    - Shall be reached at 80% of short sample at 1.9 K, with “improved HL-LHC conductor” j_c=1200 A/mm^2 at 4.2 K
    - Design (and mechanics, and protection …) shall be scalable to 15 m

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.

- Refine the roadmap to achieve the programme goals, in particular (i) establish the adequate operational margins for the ~14 T dipole magnet, (ii) select the ~14 T magnet design among the options presently pursued, (iii) scaling the selected design of Nb3Sn technology to long magnets and (iv) proving the viability of the HTS technology for accelerator dipoles, intensifying the R&D on HTS accelerator magnets to close the gap with LTS technology;

  - For HTS, we are not able to give today a target, but rather a 15-20 T range

Energy reach

- March 2024, steering board, energy reach
  - The European Strategy has set a target for FCC-hh of 100 TeV or larger
  - Even though it is well known that 100 TeV is not a hard threshold, all efforts should be done to approach this value as much as possible
  - Dipole field (and tunnel length) is not the only parameter: there is also the arc length, and the filling factor of the arcs (80% for the LHC)
    - The present optics, with cells three times longer than the LHC, allows to reduce the integrated quadrupole strength
- HFM should also focus on the global optimization of the system
- Setting target of 14 T operational field for FCC-hh Nb_3Sn option gives 85 TeV with present lattice (83% filling factor)
- Further optimization can provide 90 TeV (87% filling factor)

HTS correctors

- Correctors could be an ideal field for a first application of HTS to accelerator magnets, as a path towards further developments towards main magnets
    - A ultra-high gradient corrector sextupole (peak field >15 T) could save space in the lattice, increasing the filling factor, and gaining precious TeVs
- It would probably not need the complexity of following requirements on main magnets as
    - Transposed cables
    - Limitations due to hysteresis losses
    - Field quality constraints at injection
    - Geometry of coils: flat coils would be possible
- It would be an ideal testbed to check the models, protection, etc.

Energy reach and roadmap

- In February 2024 we had a request from top management of proposing an accelerated roadmap for Nb_3Sn option
  - Results were presented in steering board of March
- Main guidelines: (see next slides for details)
  - FCC-hh with 14 T Nb_3Sn dipoles could start operation in 2055
  - With further parallelization and involvement of the industry, and increased risk, as early as 2045-2050
  - The main element of this strategy is the selection of on (or max two) cross-sections by the beginning of the HL-LHC operation (2028)
  - The scaling in length will be applied to the final cross-section, at the horizon of end of RunIV
    - Activities on 15-m-long magnets will start after HL-LHC installation an applied to the final dipole cross-section (and not applied to MQXF coils as in previous baseline)

Roadmap: Present stage

- In the present stage, seven different types of magnets are being developed, and four designs for 14 T
  - Three cosθ: two one-layer by INFN and CERN, and one four layer by INFN
  - Two blocks: one two-layer by CERN and one four-layer by CEA with grading
  - Two common coils: one from CIEMAT and one with stress management from PSI, both with grading
- First magnet tests will not be before 2026
  - The coherence of these initiatives will be discussed in the next steering board
- Each program will produce 1-2 magnets of each type at the horizon of end of HL-LHC installation

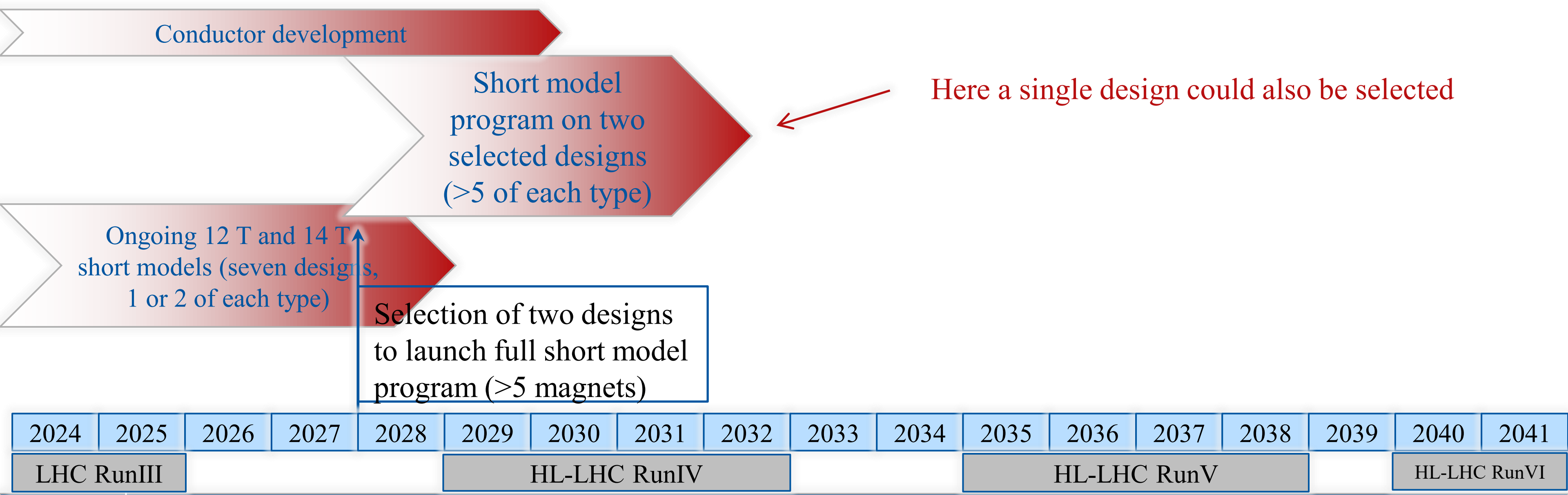
Ongoing 12 T and 14 T short models (seven designs, 1 or 2 of each type)

These are the activities in the 5-year plan of HFM 2024-2028

2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
LHC RunIII					HL-LHC RunIV						HL-LHC RunV					HL-LHC RunVI	

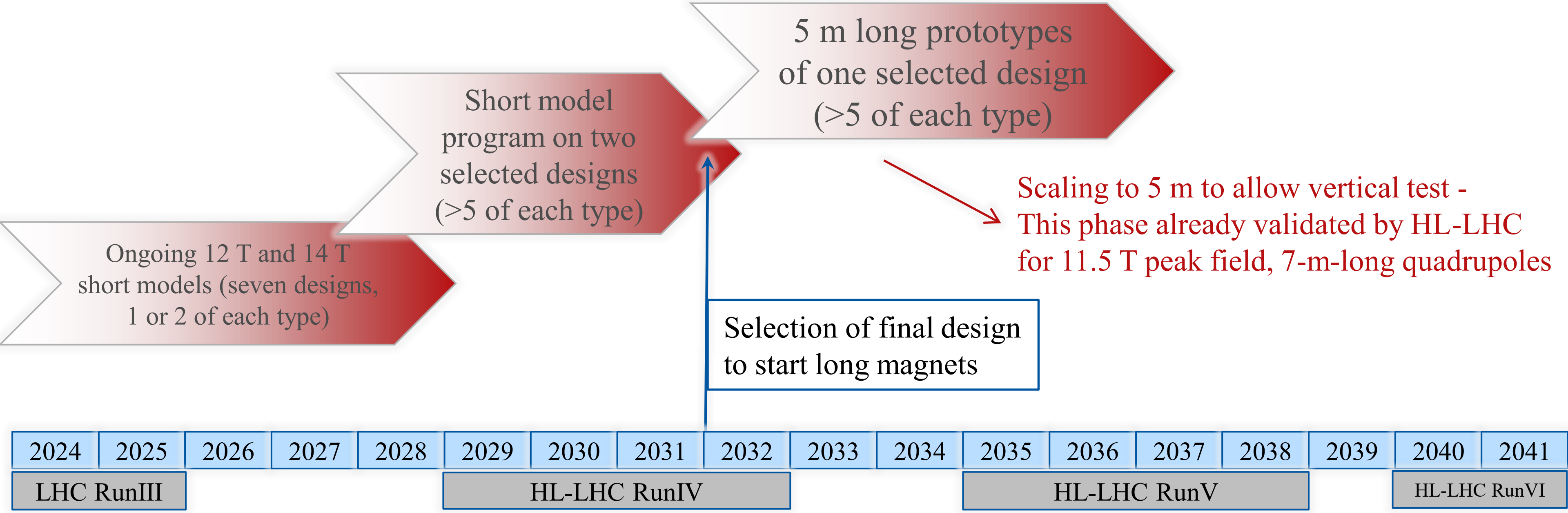
Short model program

- At the horizon of HL-LHC RunIV, we shall select one or two designs, and have a short model program (at least five) to explore performance reproducibility, dependence on assembly parameters
  - This should take about 4 years, and order of 15 M per program
  - ~2030 is the last moment for adopting improved conductor



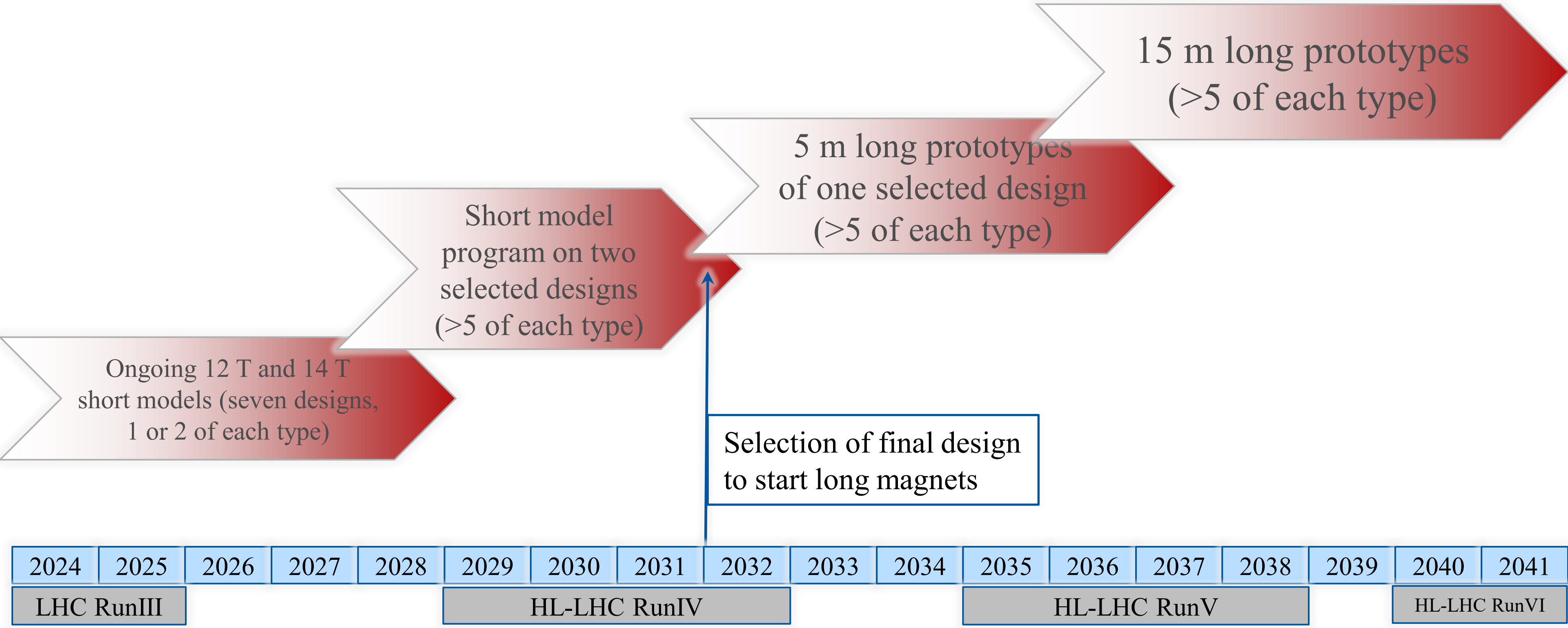
Scaling to 15 m

- At the horizon of the end of the first HL-LHC run (Run IV), we shall launch the scaling in length on the most promising option
  - Scaling should be split in two phases: first from 1.5 m to 5 m, then to 15 m
  - The intermediate scaling to 5 m shall allow vertical test



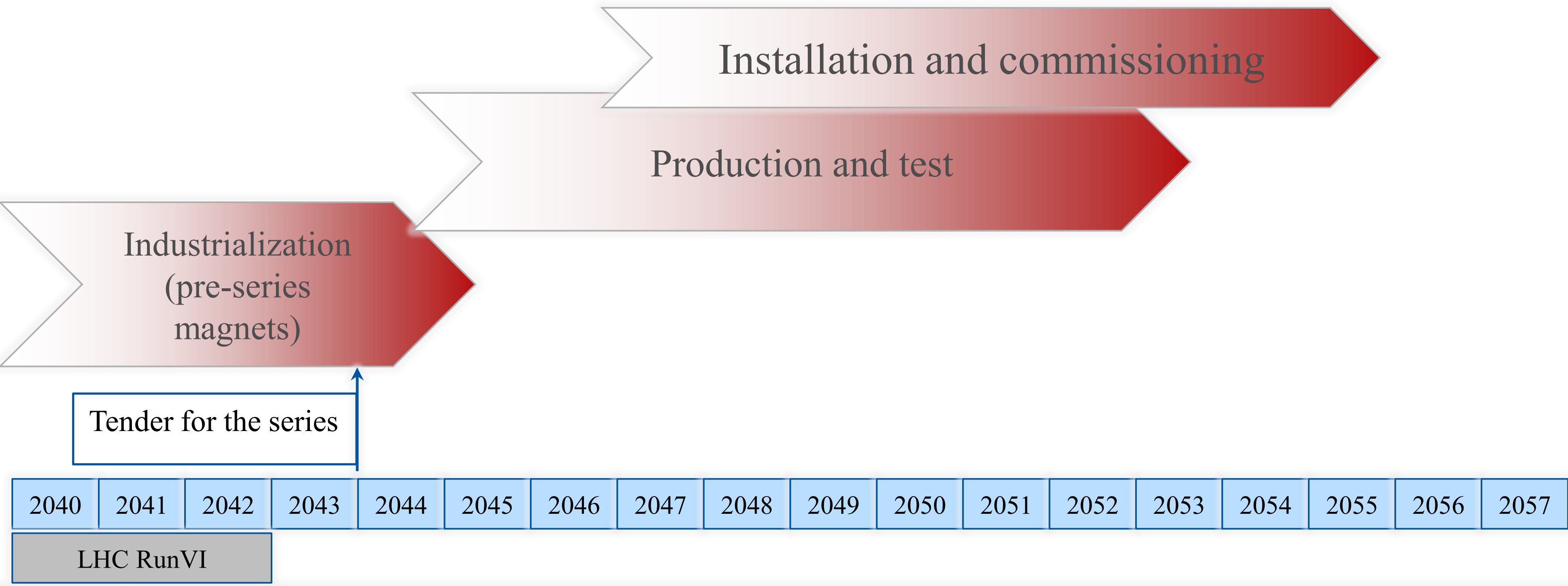
Scaling to 15 m

- During RunV, we shall launch the scaling to 15 m
  - To be completed at the end of the decade, where 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



Roadmap for HTS

- This is the roadmap defined in Summer 2023 – it is still the baseline for HTS

2025-2030: Canvassing

Intensification of HTS R&D to close TRL gap.

HTS dipoles have intermediate specifications.

Construction of 14 T short demonstrators and 15-16 T ultimate-field magnets

2030-2035: Scoping

LTS short and intermediate-length magnets with improved conductor.

HTS short magnets approach FCC-hh specs.

Systems engineering efforts (cryogenics, beam dynamics, powering, integration, etc.) intensify.

R&D on other magnet families ramps up.

2035-2040: Feasibility

Max. two candidate designs move forward to length-scaleup.

R&D increasingly focuses on system-wide performance and cost optimization

Roadmap presented to FCC (B. Auchmann, L. Bottura, A. Ballarino, S. Prestemon)

- In the coming year (mid 2024-mid 2025) we should clarify the steps in field, in length, if going to hybrid only for testing or also for magnet design, and how/when to face the challenges of protection, hysteresis losses, field quality

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Questions raised from SPC on FCC

- Scientific Policy Committee (SPC) raised the following questions after the presentation of the feasibility study:
  - Provide a roadmap / R&D plan.
  - Check tunnel integration up to 20 T
  - Address sustainability in a more integrated system approach
- Second questions addressed in TE workshop May 2024 https://indico.cern.ch/event/1411202/

	FCC-hh ACCELERATOR (High Field Magnet Programme… HFM)
P2	the current phase-gate R&D plan to establish the magnet feasibility between 2035 and 2040 is in tension with the overall FCC feasibility evaluation expected, in the current study, in 2025. In addition, the SPC is concerned that a decision on the technology by 2041 may turn out to be too early for a 100 TeV collider, which requires the availability of accelerator-quality magnets at fields much exceeding 14 T. The study indicates that there is some flexibility in the required date for this decision.
P1	**Preparing plausible benchmark roadmaps for target fields of up to 20 T** would be valuable. These should include a conservative Nb3Sn LTS scenario and an aggressive HTS and/or hybrid scenario, underscoring the significant challenges faced by each technology.
P1	Confirm that the current design diameter of 5.5 m of the **FCC tunnel can accommodate 20 T magnets.**
P2	Pursue with high priority the high-field magnet R&D programme, in particular the HTS option, to achieve the highest possible beam energy. The global effort should be vigorously supported and coordinated, across all stakeholders and in agreement with the Accelerator R&D roadmap (LDG) – within and beyond the Feasibility Study – to give the appropriate balance between the LTS (Nb3Sn) and HTS (ReBCO and IBS) technologies. Assessing the FCC-hh feasibility in the final report would be aided by having a concurrent status report on the global HFM efforts.
P1	a **well understood and appropriately prioritised R&D plan for high-field magnets should be a key goal** for the final report of the Feasibility Study. Assessing the FCC-hh feasibility in the final report would be aided by having a **concurrent status report on the global HFM efforts**.
P1	For **FCC-hh a full scope for the sustainability issues should be discussed** in the final report. The power consumption is driven by the cryogenic load of the superconducting magnet chain. Thus coil temperature, but also the intermediate temperature at which the significant synchrotron radiation load of 2.5MW/beam is absorbed, are key parameters for the cryogenic efficiency. The SPC **encourages a more integrated, system-wide approach to the SC Magnets and cryogenics developments**. And to include an estimate of energy consumption in the report
P1	SAC: Aim for an early decision on the FCC-hh injection energy which drives other choices in the collider design, including options for the injectors themselves. SPC recommends that a baseline injection scheme for the FCC-hh be proposed in the final report, based on all currently known constraints. The choice must not impose unreasonable constraints on the main machine dipoles.

Arc magnet dimensions historical

- In 2017, beam separation reduced to 204 mm, acceptable fringe field increased to 200 mT, and magnet diameter was reduced to 600 mm
  - This was done to have the same 16 T dipole for FCC-hh installable in the LHC tunnel for HE-LHC

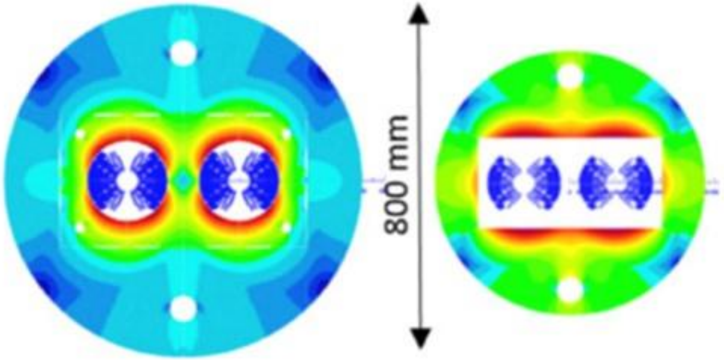


Fig. 1. Cosθ: electromagnetic cross section (left 2015, right 2017).

D. Tommasini, et al, IEEE TAS 28 (2018) 4001305

- In 2019, the parameters are fixed to 800 mm outer dimension, with a fringe field of 100 mT and a beam separation of 250 mm [D. Schoerling, et al, IEEE TAS 29 (2019) 4003109]
  - These are the numbers that are in the CDR [Europhys. J. 228 (2019), page 836]

Size of the tunnel

- The issue of transport for magnets over 40 tons is reviewed in the next talk today at the HFM forum (D. Lafarge)

Arc magnet dimensions: logistics

- There is an additional argument that should be taken into account: weight and logistics
  - Note that for a 800 mm diameter, a 14.5 m long cold mass weight is 55 tons, plus 6 of cryostat (see CDR, page 836 table 3.1)
  - A 55 tons cold mass is problematic in terms of transport – not clear to me how this is possible

    (FCC in the Netherlands?)
  - Having 10 m long dipole would fit the 40 tons, but would reduce the filling factor and the energy of the accelerator, and increase the manufacturing costs

S. Spielberg, et al, "Duel" Universal Television (1971)

PERMISSIBLE MAXIMUM WEIGHTS OF LORRIES IN EUROPE (in tonnes)

Country	Weight per non-drive axle	Weight per drive axle	Lorry 2 axles	Lorry 3 axles	Road Train 4 axles	Road Train 5 axles and +	Articulated Vehicle 5 axles and +
Albania	10	11.5 (1)	18	26 (2,3)	36	40	44
Armenia	10	10	18	22	36 (4)	36 (4)	36 (4)
Austria	10	11.5	18	26	36	40 (5)	40 (5)
Azerbaijan	10	10	18	24	36	42	44
Belarus	10	10 / 11.5	18 / 20	25	38 / 40	40 / 42	42 / 44
Belgium	10	12	19 (6)	26 (6)	39 (7,8,9)	44 (10,11,12,13,14)	44 (10,14,15)
Bosnia-Herzegovina	10	11.5	18	25 / 26	36 / 38	40 / 42	42 / 44 (16,17)
Bulgaria	10	11.5	18	26 (2)	36	40	40
Croatia	10	11.5	18	25 (18)	36	40	40 (5)
Czech Republic	10	11.5	18	26 (2)	32	48	48
Denmark (19)	10	11.5	18	24 (20)	38	44 (21)	44 (21)
Estonia	10	11.5	18	26 (2)	36 (22)	40 (23)	40 (23,24)
Finland (25)	10	11.5	18	28 (2)	36	44 (26)	44 (26)
France	12 (27)	12 (27)	19	26	38 (28)	40 / 44 (29)	40 / 44 (29)
Georgia	10	11.5	18	25 / 26 (30)	36	40	40 / 42 (16) (17)
Germany	10	11.5	18 (31)	26 (31)	36	40 (32)	40 (32)
Greece	7 / 10	13	19	26	38 (33,34)	40 / 42 (35)	40 / 42 (24)
Hungary	10 (36)	11.5 (36)	18 (37)	25 (38)	36 (39)	40	40 / 42 (16) (17)
Ireland	10	11.5 (40)	18	26 (41)	36 (42)	42 (2,43,44,45)	44 (45,46,47,48)
Italy	12	12	18	26 (2)	40	44	44
Latvia	10	11.5	18	25 / 26 (30)	36	40	40 (24,49)
Liechtenstein	10	11.5	18	26 (2)	36	40	40
Lithuania	10	11.5	18	25 (18,50,51)	36	40 (49)	40 (24)
Luxembourg	10	12 (52)	19	26	44	44	44
Malta	10	11.5	18	25	36	40	40 (53)
Moldova	10	11.5	18	25 (18)	36	40	40 (53)
Montenegro	10	11.5	18	26 (54)	36	40	40 (53)
Netherlands (19)	10	11.5	21.5	21.5-30.5 (55)	40	50	50
North Macedonia	10	11.5	18	25	36 (22)	40	40
Norway (19,56)	10	11.5	19	26 (57)	39	46-50 (58)	46-50 (59)
Poland	10	11.5	18	26 (2)	36	40	40
Portugal (19)	10 (60)	12	19	26	37 (61)	44 (60)	44 (62)
Romania	10	11.5	18	25 / 26 (30)	36	40	40 / 42 (16) (17)
Russia	10	10 (63)	18	25 (64)	36 (28)	40 (65)	40 (65)
Serbia	10	11.5	18 (66)	25 (18,67)	36 (68)	40	40 / 42 (16) (17)
Slovakia	10	11.5	18	26 (2)	40	40	40
Slovenia	10	11.5	18	25 (18,50)	36	40	40 / 44 (16,69)
Spain	10	11.5	18	25 (18)	36 (68)	40	42 (49) / 44 (24)
Sweden	10	11.5	18	25 / 28 (30)	38	40 (70)	44 (53)
Switzerland	10	11.5	18	26 (71)	36	40	40
Turkey	10	11.5	18	25 (72)	36 (28,73)	40	40 (74)
Ukraine	11	11	16 (75)	22 (76)	38 (77)	40 (77)	40 (77)
United Kingdom	10	11.5	18	26 (78)	36 (79)	40 / 44 (80)	40 / 44 (80)

HFM High Field Magnets Programme | May 2024 | E. Todesco | 5

Size of the tunnel

- Relying on previous studies for 16 T, 800 mm should be fine for 14 T but further studies for two-in-one magnets are strongly encouraged
  - All efforts to stay within 700 mm (weight<40 tons) are welcome
  - For HTS we are far from having a design, hard to make any statement

Arc magnet dimensions: the new targets for Nb_3Sn

- In the past four years, the indication of lowering the operational field of the FCC-hh dipole has become more and more evident
  - US-MDP considered 15 T as a target field for FNAL program
  - 12 T magnet was introduced in the HFM program
  - The last few tesla are very expensive in terms of conductor, see [D. Schoerling, et al, IEEE TAS 27 (2017) 4003105]
- Since 2024 the HFM mandate explicitly includes a target of 14 T for Nb_3Sn operational field (see https://indico.cern.ch/event/1377966/)
  - Since 800 mm diameter were proposed for the 16 T case, it will be fine 14 T (weight issue still to be clarified, maybe 700 mm would be more appropriate
  - For 800 mm diameter cold mass, 1220 mm diameter cryostat was proposed [FCC-hh CDR, Europhys. J. 228 (2019), page 835 Fig 3.1]

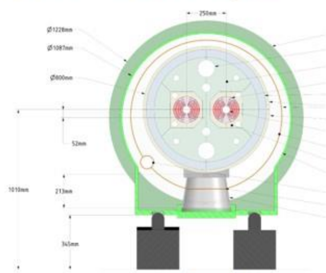


Fig. 3.1. Main dipole cross-section.

- On the other hand, I would exclude magnet diameters larger than 800 mm (and this is the information that is needed today)
  - The issue of the weight for 1000 mm diameter cold mass would become too challenging

Cooling

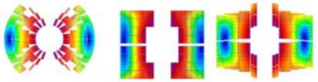
- For the cooling, with the new Nb_3Sn baseline thanks to the larger margin, and HL-LHC experience, we can have either 1.9 K or 4.5 K cooling
  - The heat load in the magnets is dominated by hysteresis losses
  - A factor two above targets of 10 kJ/m per cycle for the Nb_3Sn design, but could be significantly reduced by operating at 4.5 K
  - For HTS it could be a showstopper in case of tapes perpendicular (and not parallel) to field lines – this is a main point of design and modeling
  - Studies are ongoing (P. Tavares) and will be presented in September
  - We strongly encourage all activities on modeling hysteresis losses in HTS

Cooling targets for Nb_3Sn

- Targets for cooling considered operational temperature of 1.9 K, and are given in [D. Schoerling, et al, IEEE TAS 29 (2019) 4003109]
  - Static losses are estimated at 0.5 W/m at 1.9 K and 10 W/m at 50 K
  - A target has been set at 5 kJ/m per ramp (total 140 kJ per cycle for a 14 m long magnet) – source is [S. Izquierdo Bermudez, November 2017, presentation at EuroCirCol https://indico.cern.ch/event/679654/] – see following slides

Hysteresis losses for Nb_3Sn

- Hysteresis losses in the superconductor are the dominating source
  - 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)
  - To be compared to 0.5 kJ/m in the LHC dipoles
  - Hysteresis losses are found to weakly depend on magnet design



Coil geometry		Cos-theta	Block	Common Coil
Deff	µm	50	50	50
Xi	--	1	1	1
I1	Inom (50 TeV)	11060	10465	16100
I2	Ireset	100	100	100
I3	Iinj (3.3 TeV)	729.96	690.69	1062.6
I4	Inom (50 TeV)	11060	10465	16100
AC-loss (2 Ap)	J/m	18330	19603	23489
AC-loss/Asc	J/m$_3$	4728455	4633384	4776274

Talk given by S. Izquierdo Bermudez, November 2017, EuroCirCol meeting https://indico.cern.ch/event/679654/

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FCC week

- At the FCC week in June, we had a very interesting session about the FCC-hh magnets
  - P. Ferracin (for MQXF results and lessons)
  - E. Todesco (for HFM, Nb_3Sn)
  - B. Auchmann (for HFM, HTS)
  - S. Prestemon (for US-MDP)
  - E. Ravaioli (for protection)
  - L. Cooley (for conductor)
- see https://indico.cern.ch/event/1298458 (and ask for access if you do not have)

FCC week (June 2024): MDP and HFM

- May 2024: decision to open the HFM forum to MDP (in the invitation list, even though we keep the 9.30-11.00 slot) so they can follow offline the program advancement
- Special joint forum/seminars/WG are being organized in the EU afternoon
- We are also developing specific collaborations
  - Development of cable for 14 T block in LBNL (same as TDF)
  - Test of HD3 magnet, after 20 years, at 1.9 K (it was only tested at 4.5 K)
- There is a complementarity between MDP and HFM

Direct R&D (as LARP) ⟷ Basic R&D

HFM mandate

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.

- Refine the roadmap to achieve the programme goals, in particular (i) establish the adequate operational margins for the ~14 T dipole magnet, (ii) select the ~14 T magnet design among the options presently pursued, (iii) scaling the selected design of Nb3Sn technology to long magnets and (iv) proving the viability of the HTS technology for accelerator dipoles, intensifying the R&D on HTS accelerator magnets to close the gap with LTS technology;

- Establish new collaboration agreements and review the existing ones, ensuring the coherence of the efforts to achieve the program targets;
- Nurture the collaborative nature of the HFM Programme, encouraging active engagement among participating institutions, CERN groups, and the broader international community

MDP mandate

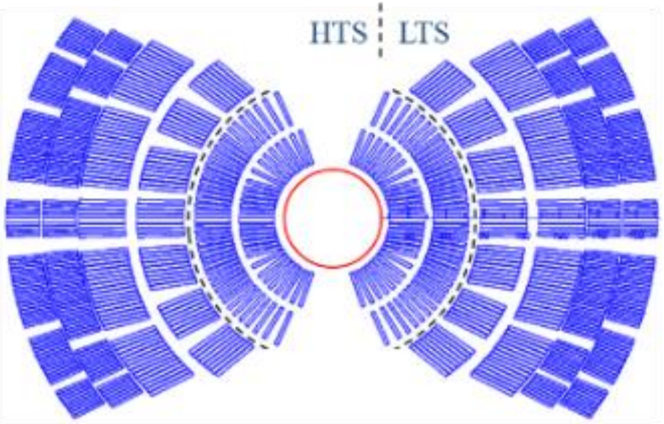
- Focus on the ***four primary goals*** identified in the the original MDP Plan
  - Explore the performance limits of Nb_3Sn accelerator magnets…
  - Develop and demonstrate an HTS accelerator magnet with a self-field of 5T or greater…
  - Investigate fundamental aspects of magnet design and technology…
  - Pursue Nb_3Sn and HTS conductor R&D …
- Further ***develop and integrate the teams*** across the partner laboratories and Universities for maximum value and effectiveness to the program
- Identify and ***nurture cross-cutting / synergistic activities*** with other programs to more rapidly advance progress towards our goals

FCC week (June 2024): hybrid magnets ?

- The topic of the hybrid magnets is highly debated in the community
- Hybrid was the initial proposal in the early 10s for 20 T, with the idea that HTS is much more expensive than Nb_3Sn - Today this is still the case for the 0-15 T range, but:
  - Difference in cost could be further reduced
  - Having an accelerator at 20 K could be interesting
  - Having LTS and HTS could take the worse of the two
- MDP has a research line relying on hybrid magnets, either CCT (LBNL) or stress-managed cos-theta
- HFM roadmap for the HTS has not yet clarified this design choice – we keep all options open
- MDP strategy for hybrid magnets

presented by P. Ferracin in HFM forum July 2024

https://indico.cern.ch/event/1434914/



P. Ferracin et al, IEEE TAS 33 (2023)
An example of 20 T cross-section using CCT, stress-managed cosθ and standard cosθ

Contents

- Program targets, mandate and energy reach
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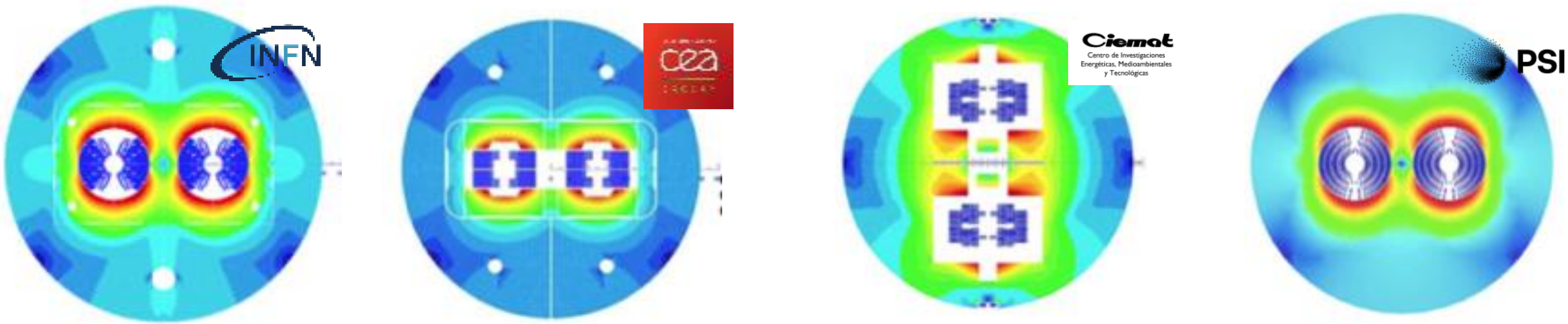
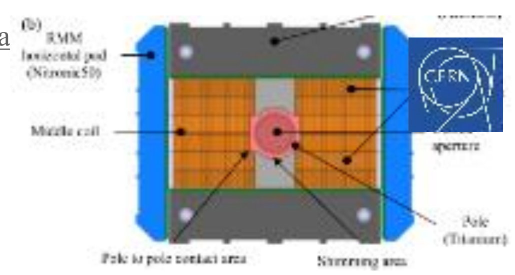
Historical on targets for Nb_3Sn magnets

- 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 HL-LHC
- 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)]

- PSI abandoned the CCT option in 2023 [B. Auchmann, et al., IEEE Trans. Appl. Supercond. 34 (2024) 4000906] and went for stress managed common coil [D. Araujo, et al., IEEE Tra similar to FNAL concept for cosθ
- In parallel, CERN launched a magnet technological program whose aim and built a 16 T demonstrator RMM



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

The 14 T plans

- Updated targets

	Units	EuroCirCol	HFM
Loadline fraction at 1.9 K	(adim)	0.86	0.80
Operational field	(T)	16	14
Critical current at 16 T, 4.22 K	(A/mm^2)	1500	1200

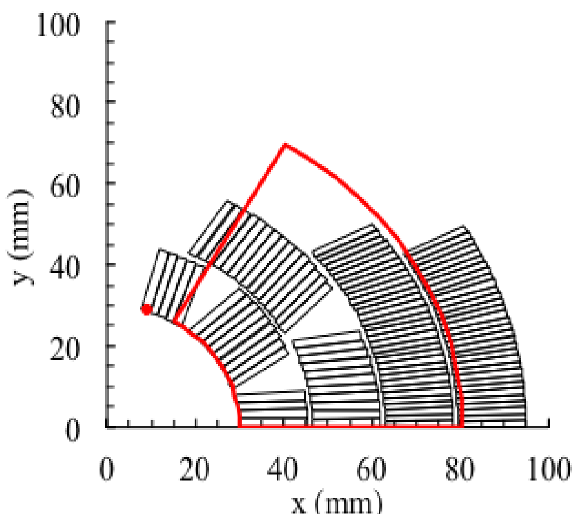
- Ongoing programs shall move towards these targets
  - Intermediate steps are welcome if well motivated
- Note that 14 T HFM magnets are very similar to the 16 T design developed for EuroCirCol, so all the design work in the 2015-2020 is not lost!
  - Note than since all EuroCirCol designs have been proved to satisfy (a bit at the limit) the <150 MPa at room temperature and the <200 MPa, the same design at 14 T will satisfy the stress limit <120 MPa at room temperature and the <150 MPa (more reasonable for a large production)

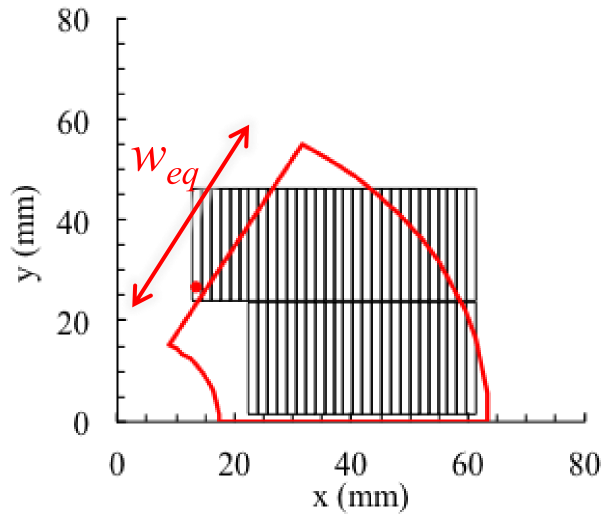
The 14 T plans

- Today 5 designs compatible with 14 T targets are being developed
  - Cos theta four layers (similar to MDPCT1) proposal from INFN → wide experience on cosθ
  - Block design two layers (similar to HD2) from CERN → world record is block (Fresca2)
  - Block design four layers with grading from CEA → also implements grading (but 4 coils)
  - Common coil from CIEMAT → similar design being developed in China
  - Common coil with stress management from PSI → most exotic design, fully stress managed
- When describing a magnet design the following quantities shall be given at nominal current
  - Overall current density (over insulated coil): in the range of 350 – 600 A/mm^2
  - Equivalent coil width: in the 50-55 mm range
  - Protection time margin: above 40 ms
  - Max stress at nominal current (but remember this quantity is not so well defined)

Equivalent coil width, equations for electrodipoles

- Equivalent coil width: width of a 60° sector coil with the same surface
  - This concept allow to compare different designs (block, cos theta, common coil …)



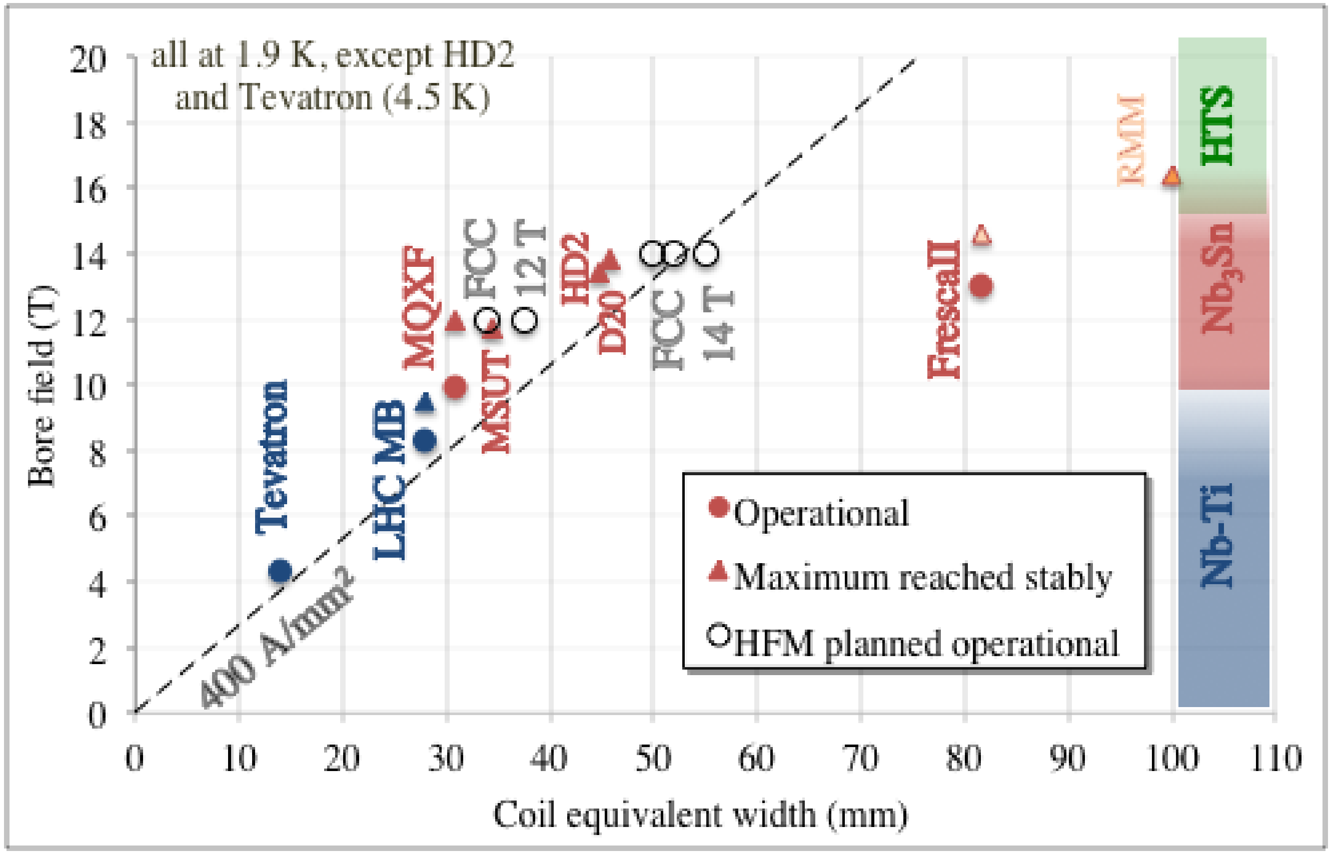


Equivalent coil width for MDPCT1 (left) and HD2 (right)

- Equations for a dipole, without iron: $B = \gamma_c w_{eq} j_o$
- γ_c order of $\mu_0/2$, ranging from 0.007 (most effective layouts) to 0.006 – for sector or block coils one has

$$B = \gamma_c w_{eq} j_o \approx 0.00066 \times w_{eq}[\mathrm{mm}]\, j_o[\mathrm{A/mm^2}]$$

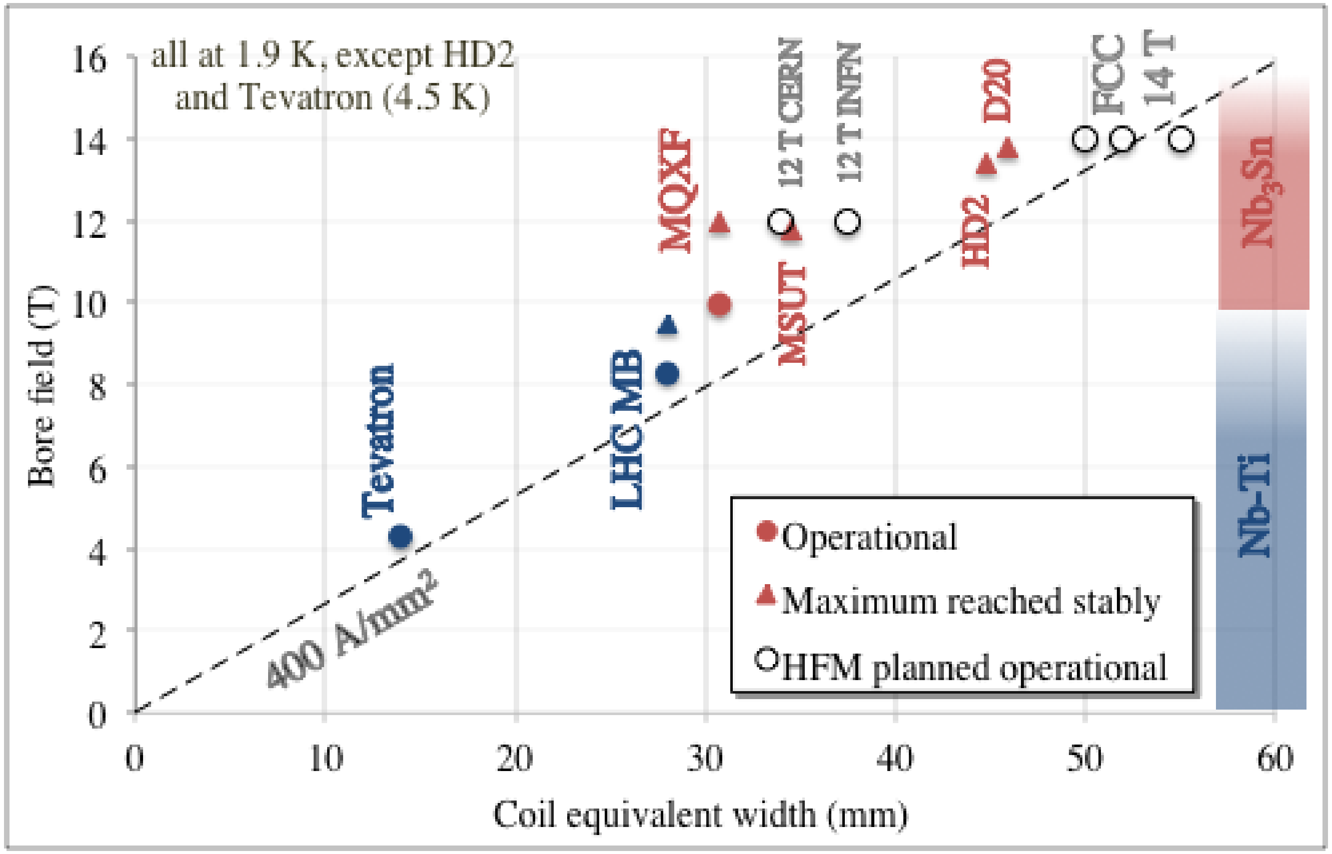
What are we building, in an historical perspective



*not including magnet that showed degradation

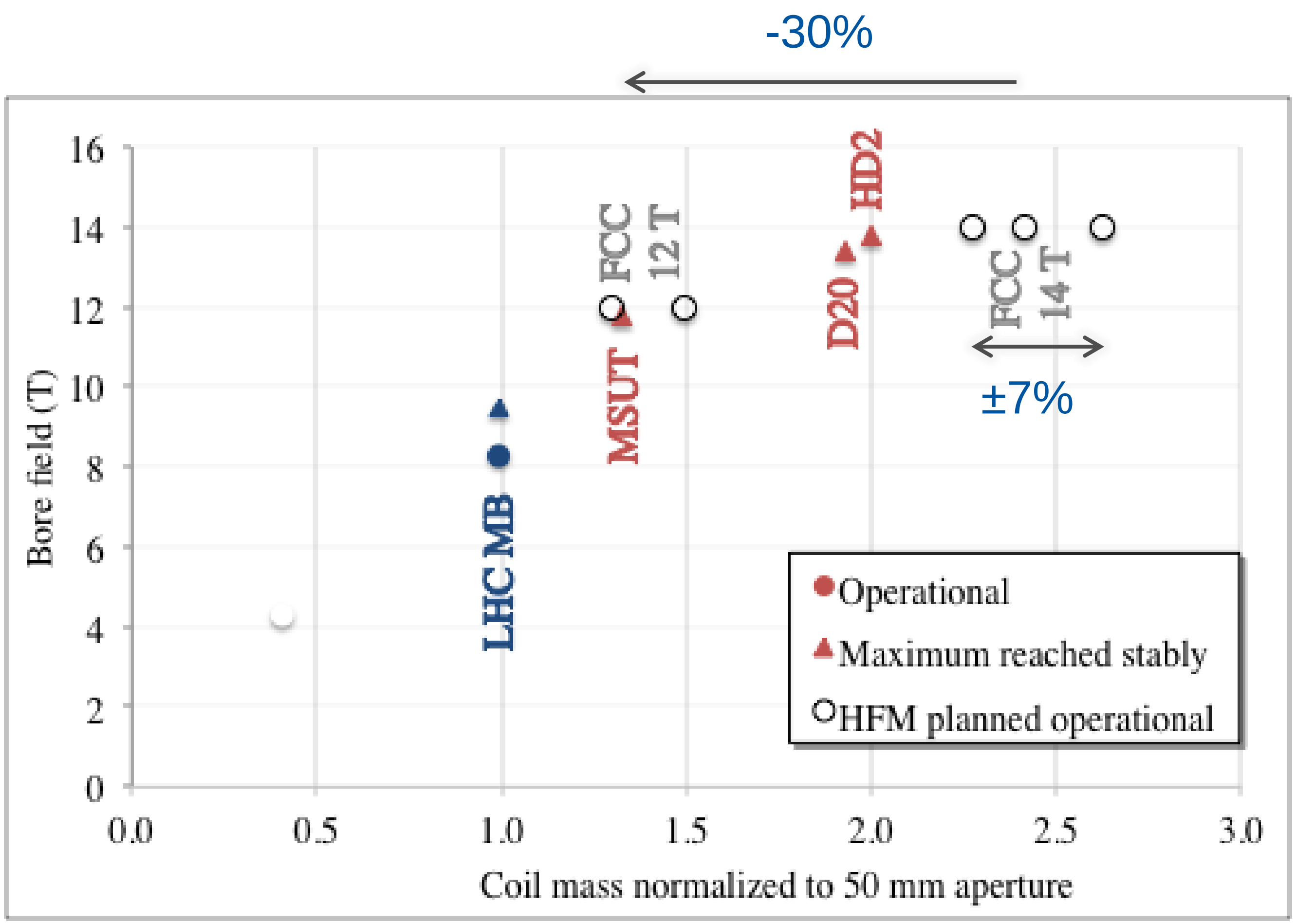
- Only 3 points are shown (CEA, CERN and INFN) for the 14 T
- Note the position of FrescaII and RMM (detaching from the 400 A/mm^2 line)
- Note: for MQXF we take as bore field G × r= 132.6 × 0.075= 10 T

What are we building, in an historical perspective



- Same plot as previous slide, but in the interesting range for Nb_3Sn FCC-hh
- The 14 T magnet will have 50 to 55 mm coil width
  - For the 12 T, 40 mm are needed (slightly more effective design, larger iron contribution)

What are we building, in a budget perspective



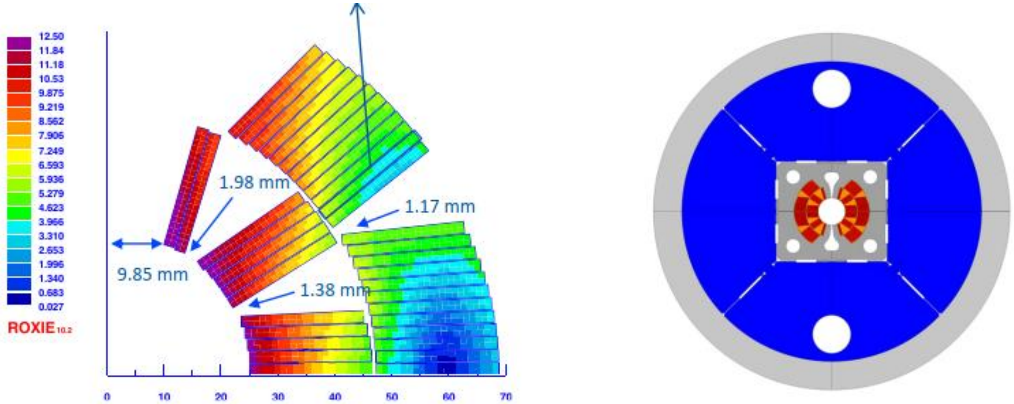
- The two additional tesla from 12 to 14 T need 50% more conductor quantity
- Use of grading gives a saving of the order of 10% (to be confirmed)

The 12 T option - INFN

- This is the most conservative magnet, based on two layer cosθ, with a 12 T operational field with a very low quantity of conductor (INFN Italy, manufacturing in ASG)
  - See last talk at HFM forum, March 2024 https://indico.cern.ch/event/1389304
  - 1.0 mm diameter strand, 40 strand cable, 0.9 Cu – protection not scalable to long magnets
  - 12 T is at 77% of loadline, in numerous papers 14 T is set as an ultimate current (at 90%), then in 2022 it was decided to go for a more conservative value of ultimate field of 13.5 T
- Winding starting this year, test in 2026 – addendum to agreement signed in Feb 2023

  (re-scoping of KE4102

  from 16 T to 12 T)



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

References:

R. Valente, et al., “Electromagnetic and Mechanical Study for the Nb3Sn Cos-Theta Dipole Model for the FCC,” IEEE Trans. Appl. Supercond. 30 (2020) 4001905

R. Valente, et al., “Study of Superconducting Magnetization Effects and 3D Electromagnetic Analysis of the Nb3Sn cosθ Short Model for FCC,” IEEE Trans. Appl. Supercond. 31 (2021) 4002205

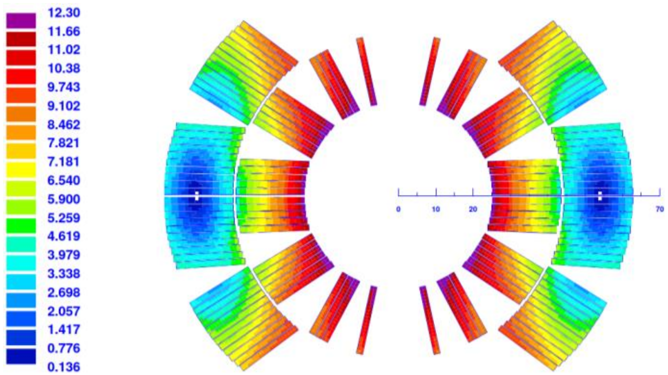
A. Pampaloni, et al., “Preliminary Design of the Nb3Sn cosθ Short Model for the FCC,” IEEE Trans. Appl. Supercond. 31 (2021) 4900905

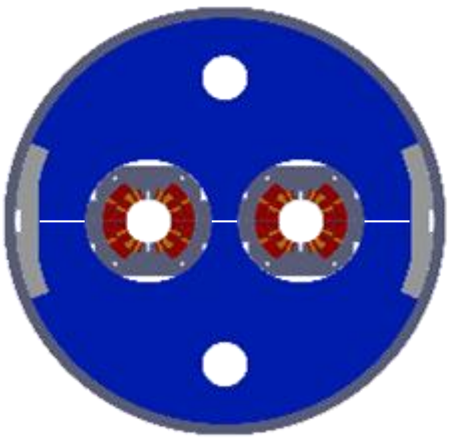
A. Pampaloni, et al., “Mechanical Design of FalconD, a Nb3Sn Cosθ Short Model Dipole for the FCC,” IEEE Trans. Appl. Supercond. 32 (2022) 4000605

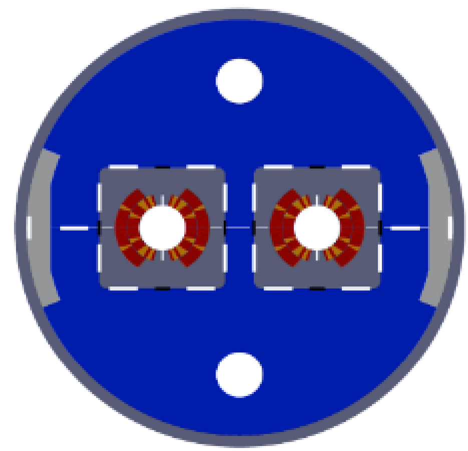
F. Levi, et al., “Updates on the Mechanical Design of FalconD, a Nb3Sn Cosθ Short Model Dipole for FCC-hh,” IEEE Trans. Appl. Supercond. 33 (2023) 4000805

The 12 T option - CERN

- CERN decided to build a similar magnet, with a well-known strand
  - It makes use of the 0.85 mm diameter strand, 40 strand cable
  - The copper ratio is 1.2, whereas it is 0.9 for the 1.0 mm (15% less of superconductor)
- Short sample field is 14.4 T rather than 15.6 T as in FalconD
- An interesting novel concept for the mechanical structure has been proposed, based on Al stoppers rather than Al rings







References:

CERN 12 T cross-section and coil [D. Perini, M. Masci, L. Fiscarelli, et al.

M. Masci, et al. “Mechanical design of the 12 T superconducting dipole, an accelerator fit Nb3Sn double apertur… IPAC 2024 (in press)

Some remarks on the 12 T program

- 12 T is far from the FCC targets (gives 77 TeV) …
  - At the moment there is a strong message (maybe too strong) from the community >100 TeV
- … but is a "cheap" option that we should keep in our pocket (see plot on slide 12)
- Moreover:
  - For INFN, a 12 T is propaedeutic to the 4 layer cosθ
  - In general, it is strategic to keep the knowledge and mastering of the cosθ technology for dipoles as a back-up if more exotic options are shown to be not suitable
- The 12 T INFN has 1.2 T a wider potential, whereas the 12 T CERN is more similar to the 11 T, which was already proved, with some successful short models
  - Splitting the efforts on two different coil design is less effective then working on the same geometry

Proposal on the 12 T program

- What was proposed and endorsed in the steering board of June 2024
- We opt for having the same coil to be built in INFN and at CERN – this brings the following advantages:
  - Synergy between the two programs, allowing to exchange experience on issues as done extensively for MQXF
  - CERN would compensate the lack of experience of ASG and INFN in Nb_3Sn coils for accelerator magnets (and the absence of a SMC to validate the manufacturing procedures)
- We would start with the 1.0 mm strand cable, and in case of evidence of major problems for winding, we would switch for 0.85 mm cable using the CERN design in both sites
- For the mechanical structure, we continue the studies and we will decide if having one or two

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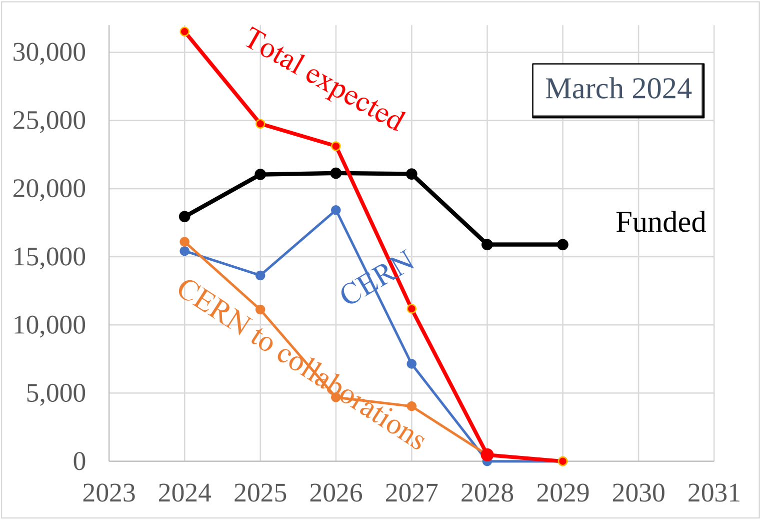
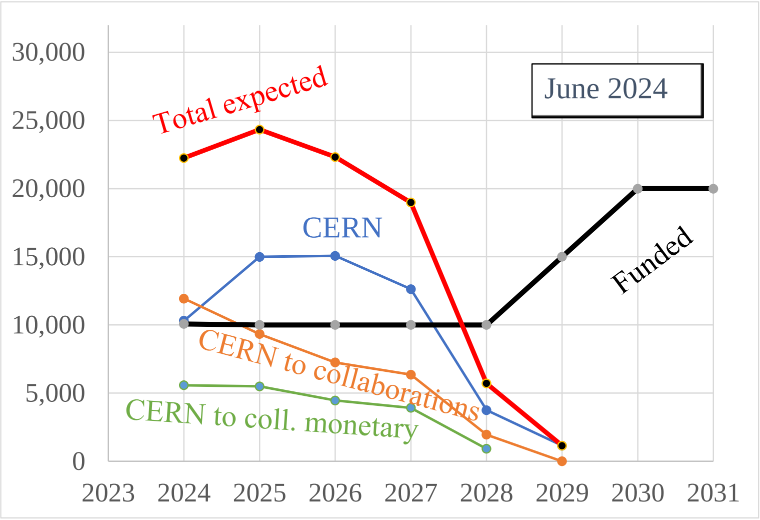
Budget

- The new baseline has a 10 MCHF / year until 2028, then increasing to 20 MCHF/year
- The profile looks more reasonable - if needed we can spend more
  - Note that today at CERN we have about 15 FTE on the program each year, that will increase to 30 at the end of HL-LHC
  - Note that to spend 20 MCHF per year you need order of 100 FTE





HFM budget (excluding staff and collaboration in kind)

Budget and schedule

- Role of WPL and CERN liason
  - The WPL will be the responsible of the budget code for CERN WPs
  - The CERN liason will be the responsible of the budget code for collaboration WPs
- Update of baseline
  - An update of baseline is natural in an R&D program – the technical content is essential
  - Discussion on update of budget shall go through PL (Ezio) and program office (Germana)
  - Discussions on update of timeline shall go through PCL (Bernhard) and program office (Germana)

Budget and schedule

- It is very important to have a credible spending profile
  - The definition of the timeline is the source of the spending profile – this is in your (WPLs) hands
- Contingency
  - WPs are supposed to have no contingency
  - Savings are given back to WP1 (management)
  - Extra cost are agreed and money is given from WP1 to WPs
- Program is structured in EVM, with tasks and milestones
  - Not easy to use EVM for an R&D program … we are learning this – please find a reasonable level of granularity (avoid to have too many deliverables)

Coming events

- HFM TE-day (TBD, fall 2024)
  - To present and discuss the updated HFM program at CERN
  - One day, focusing on the main CERN WPs
- Annual meeting (26-28 November 2024)
  - It will include a Collaboration Board
- Next steering board in October

HFM

High Field Magnets

Programme