HFM

High Field Magnets Programme

High Field Magnet Programme

E. Todesco, HFM programme leader
B. Auchmann, HFM programme co-leader
On behalf of HFM collaboration

With feedbacks from A. Milanese, A. Ballarino, S. Izquierdo Bermudez, G. Willering, D. Delikaris, M. Jimenez, M. Benedikt

30 January 2025, Chamonix

High Field Magnet Programme

E. Todesco (Leader), B. Auchmann (Co-leader)

HFM steering board
M. Lamont (chair)
P. Vedrine (co-chair)

HFM collaboration board
C. Senatore (chair)
TBD (deputy)

Programme office
G. Riddone

RD1: Nb_3Sn conductor

- 1.1 **Nb_3Sn wire and cable** – T. Boutboul (CERN)
- 1.3 **Internal oxidation wires** – C. Senatore (UniGe)
- 1.15 **Nb_3Sn development** – M. Sugano (KEK)
- 1.18 **Internal oxid. studies** – A. Leineweber (BAF)
- 1.19 **Nb_3Sn characterization** – C. Senatore (UniGe)

RD1 line coordinators:
T. Boutboul (CERN)
C. Senatore (UniGe)

RD2: HTS conductor+magnets

- 2.1 **REBCO development** – B. Holzapfel (KIT)
- 2.2 **REBCO conductor** – A. Ballarino (CERN)
- 2.5 **Demonstrator DI coils** – A. Ballarino (CERN)
- 2.6 **Solenoids and MuC** – L. Bottura (CERN)
- 2.11 **Demonstrator MI coil** – T. Lecrevisse (CEA)
- 2.15 **IBS development** – A. Malagoli (CNR-SPIN)
- 2.17 **REBCO development** – Y. Yang (SOTON)
- 2.18 **HTS 10 T dipole** – M. Statera (INFN)
- 2.19 **REBCO racetrack** – D. M. Araujo (PSI)
- 2.20 **REBCO characteriz.** – M. Eisterer (TUWien)

RD2 coord: A. Ballarino (CERN)

RD3: Nb_3Sn magnets

- 3.1 **12 T cosθ CERN** – A. Foussat (CERN)
- 3.2 **12 T cosθ INFN** – S. Farinon (INFN)
- 3.4 **Technology development** – A. Haziot (CERN)
- 3.5 **14 T Block dipole BOND** – J. C. Perez (CERN)
- 3.3 **5-m-long block** – S. Izquierdo Bermudez(CERN)
- 3.6, 3.12 **Block dipole F2D2** – E. Rochepault (CEA)
- 3.7 **Common coil DAISY** – F. Toral (CIEMAT)
- 3.11 **14 T Cosθ** – M. Sorbi (INFN)
- 3.14 **CC stress managed** – D. M. Araujo (PSI)

RD3 line coordinators:
F. Toral (CIEMAT)
A. Haziot, A. Foussat (CERN)

RD4: Integration, sustainability

- 4.3 **Insulation and HV** – R. Piccin (CERN)
- 4.5 **Quench D+P** – M. Wozniak (CERN)
- 4.6 **Cryogenics, thermal** – P. Borges de Sousa (CERN)

RD4 line coordinator:
P. Borges de Sousa (CERN)

RD5: Infrastructures

- 5.1 **Test** – F. Mangiarotti (CERN)
- 5.2 **Conductors, cables** – J. Fleiter (CERN)
- 5.4 **Manufacturing** – J. Axensalva (CERN)
- 5.5 **MM, modelling** – L. Fiscarelli (CERN)
- 5.7 **CIEMAT lab** – C. Martins (CIEMAT)
- 2.16 **HTS laboratory** – A. Ballarino (CERN)

6.1 **Societal impact** – E. Chesta (CERN)

Collaboration WPs

CERN WPs

Note: completed WP not shown

January 2025

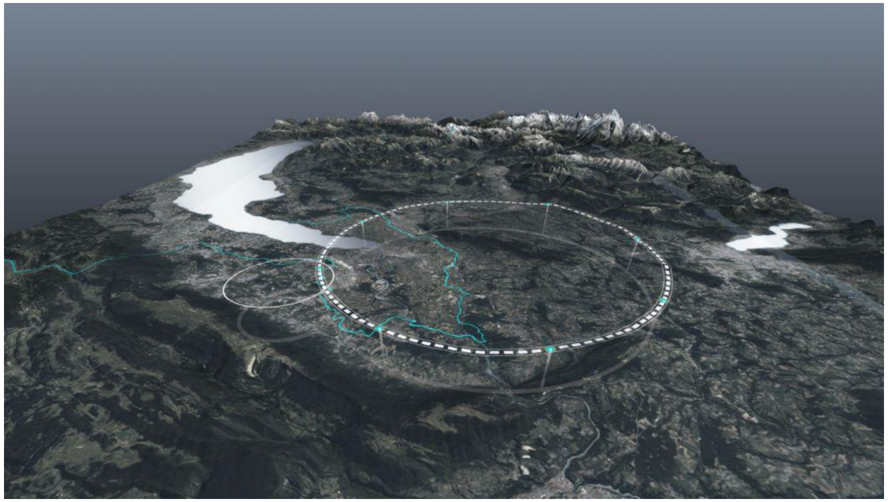
Contents

- Baseline for FCC, options and timeline
- Status of Nb_3Sn and recent results
- HTS hopes and challenges
- Appendix: news from US and China, magnet design, HFM organization

FCC-hh baseline

- The new targets for FCC-hh in Nb_3Sn allow reaching 85 TeV with 83% filling factor, and improved HL-LHC conductor
  - The magnet is at 80% of short sample, and this gives more margin, allowing ease several aspects (stress limits can be set at 150 MPa rather than 200 MPa, protection is less demanding, conductor is available today)
  - Further improvement of filling factor could allow 90 TeV c.o.m

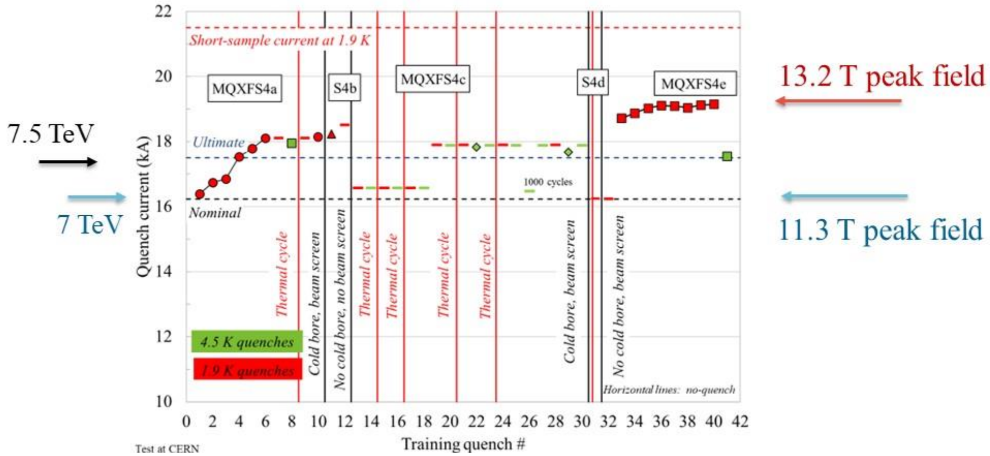
FCC-hh parameters	CDR 2019	2024-Nb_3Sn	2024-HTS
Dipole field (T)	**16.0**	**14.0**	**14-20**
Temperature (K)	1.9	1.9	4.5-20
Tunnel length (km)	100	90.7	90.7
Arc length (km)	82.0	76.9	76.9
Arc filling factor (adim)	0.80	0.83	0.83
Energy c.o.m (TeV)	100	85	85-120
Non Cu jc 16 T 4.2 K	1500	1200	TBD
Loadline margin	86%	80%	TBD



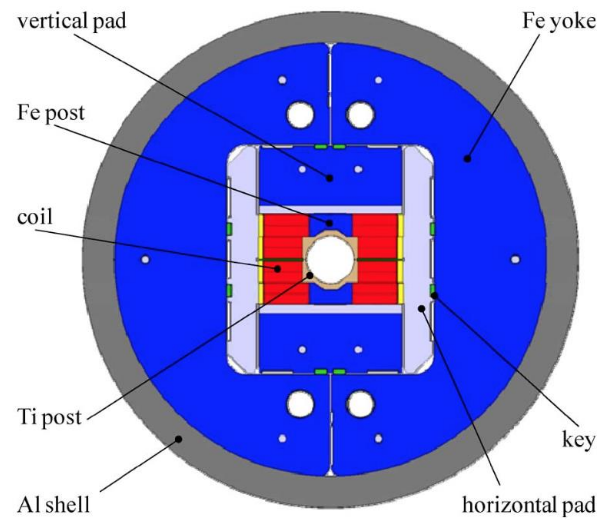
FCC layout and evolution of parameters

Feedback from HL-LHC

- 14 T operational field → short models shall 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
- 14 T shall be reached also at 4.5 K
  - In HL-LHC MQXF operational field is also achieved at 4.5 K, without retraining
  - Record of achieved field in accelerator dipoles
    - 13.8 T at 4.5 K (HD2, 2005)
    - 14.5 T at 1.9 K, 13.8 T at 4.5 K (Fresca2, 2019)
    - 14.1 T at 4.5 K (MDPCT1, 2020)



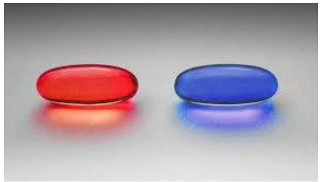
MQXFS4 test results [S. Izquierdo Bermudez, J. C. Perez, P. Ferracin, F. Mangiarotti, et al.]



Sketch of Fresca2 cross-section [A. Milanese, P. Ferracin, et al.]

Options to the FCC baseline

- We are exploring the following options
  - 12 T magnet and 77 TeV (15-20% cheaper magnet, for 10% less energy)
  - Operation at 4.5 K with the same magnet (significant reduction of power consumption of cryogenics)
  - Hybrid Nb_3Sn/Nb-Ti (large reduction in the mass of Nb_3Sn conductor, even more at 12 T, significant cost reduction)
  - 20-m-long magnets (25% less magnets to produce, plus a few more TeV or a bit more margin, an a bit cheaper magnet)
  - Combined function options was studied but for the moment is not pursued
- HTS long-term goal in the 14-20 T range, giving 85-120 TeV
- All this is in the FCC-FS, chapter on magnets (see talk today by M. Benedikt)
- Please don’t think that Nb_3Sn and HTS are in competition!
  - This is not a blue pill/red pill story …

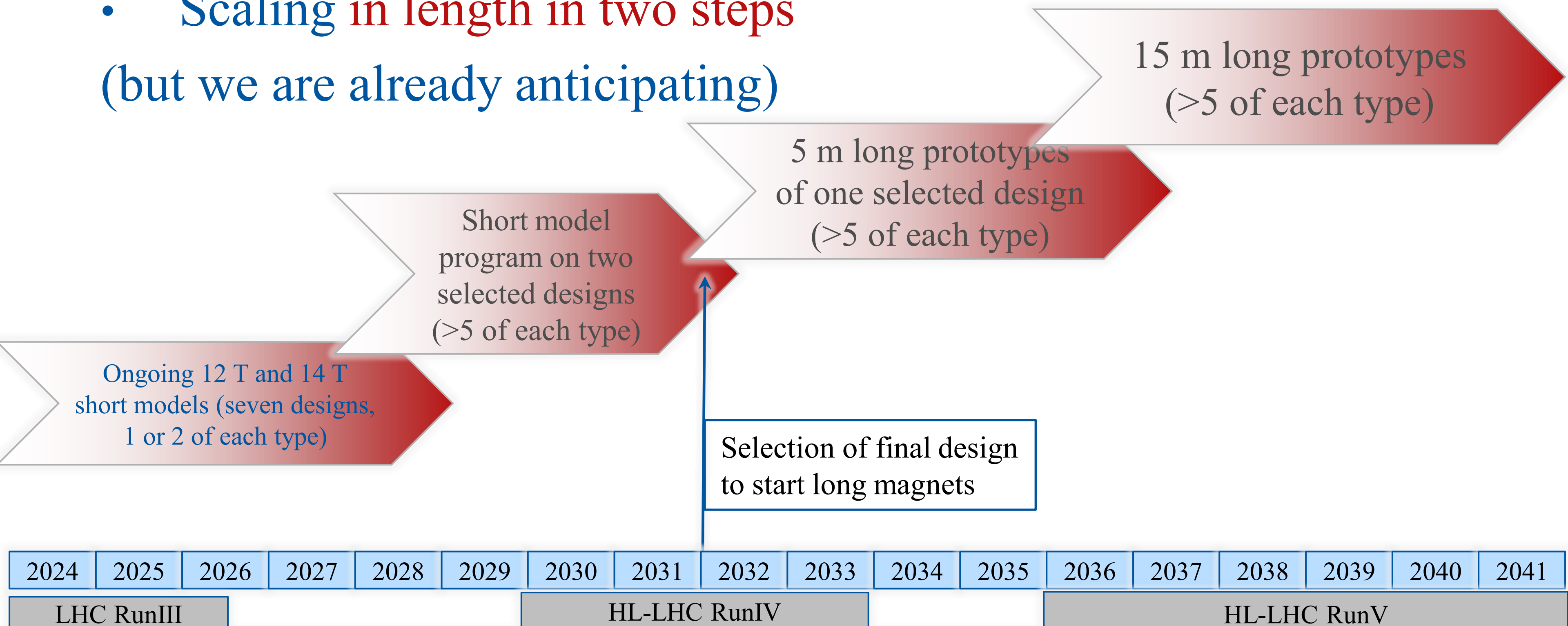


Wachowski broth., “Matrix” (1999, Warner Bros.)

Timeline for FCC-hh baseline

- Select the design by the end of LS3 (we should start having some indications from tests in 2026-2027)
- Have a full short model program as MQXF during RunIV
- Scaling in length in two steps

(but we are already anticipating)



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

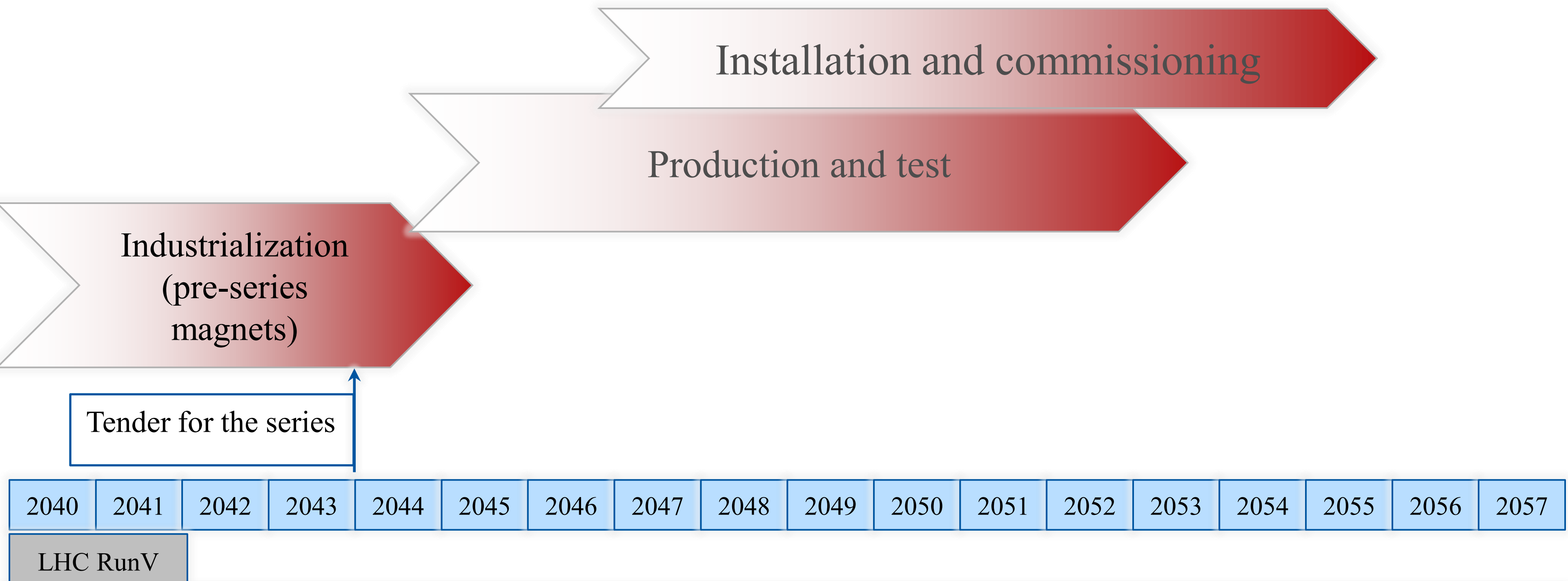


Table of contents

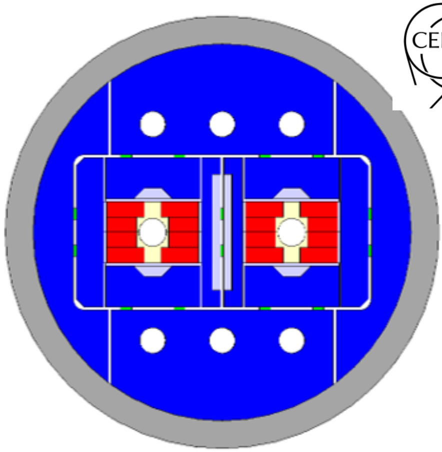
- Baseline for FCC, options and timeline
- Status and results of Nb_3Sn
- HTS hopes and challenges
- Appendix: news from US and China, magnet design, HFM organization

Conductor status and R&D

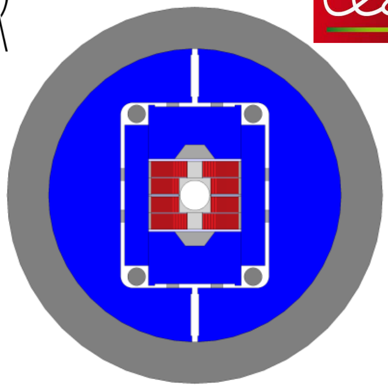
- Conductor development for Nb_3Sn follows two main guidelines
  - Have more providers (today there is only one fully qualifed industry)
  - Decrease the cost: this is only possible with prolonged investements on amid term plan as done in the US with CDP at the beginning of the 00's
- Plus
  - Increase the performance: FCC targets fixed in 2015 (50% more critical current at 16 T (L. Bottura, A. Ballarino, IEEE TAS) reached in laboratories, but not in industrial production – this would allow to have 30% reduction of conductor for the 14 T
  - Improve resilience to stress (efforts ongoing in KEK)
- APC (artificial pinning center) opportunities: more j_c, less hysteresis losses
  - Works in HFM on going in University of Geneva, BAF
  - Synergies with activities in FNAL (X. Xu et al, SUST)
- In fall 2024 we made an order to have a strategic reserve of Nb_3Sn conductor (1 ton) for the mid-term needs

Nb_3Sn magnet design

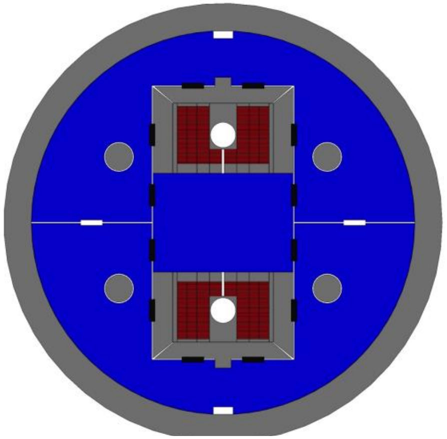
- The block option: this design has the world record
  - HD2 reached 13.8 T at 4.2 K, Fresca2 reached 14.6 T at 1.9 K
  - BOND (no grading) test in 2026, F2D2 (grading) test in 2028
- The common coil design: a simpler path ?
  - The IHEP program reached 12.5 T at 4.5 K (LFP1)
  - CIEMAT is planning to build a common coil, test in 2027/8
- Cosθ option: MDPCT1 reached 14 T at 4.5 K in the US, 11 T reached 12.5 T at 1.9 K
  - Two layer magnet in INFN and CERN, winding started, test in 2026



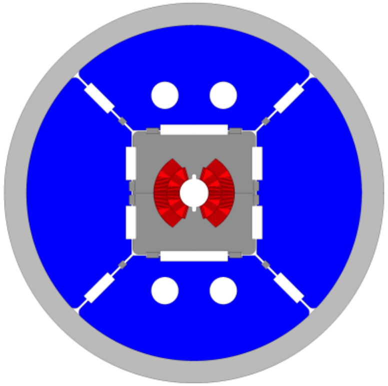
14 T block dipole
[J. C. Perez, et al.]



14 T block dipole F2D2
[E. Rochepault, et al.]



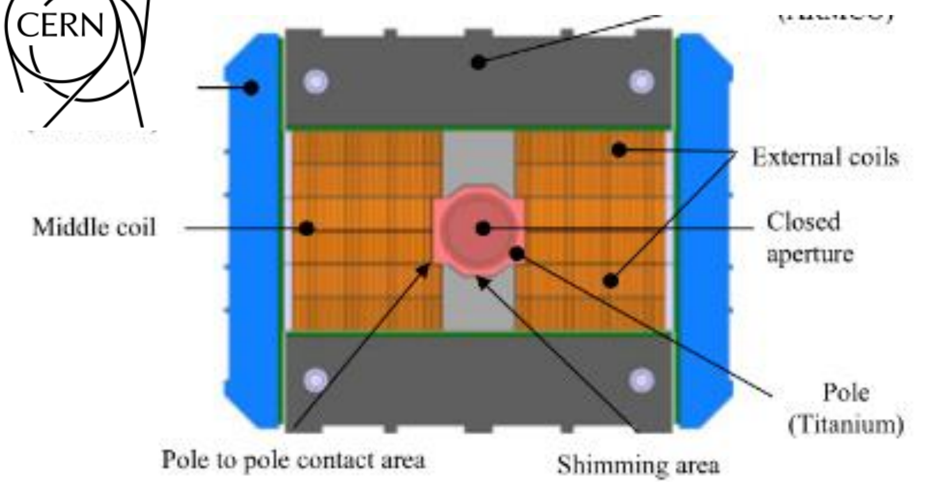
DAISY cross-section
[F. Toral, et al.]



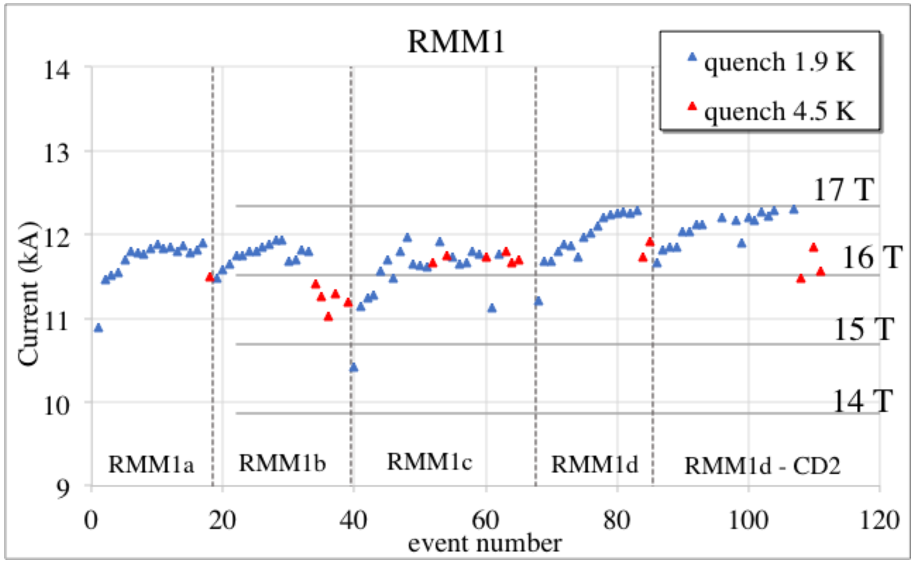
FalconD cross-section
[S. Farinon, M .Sorbi, A. Foussat et al.]

Recent results: Nb_3Sn magnets

- Demonstrator: RMM, large width block coil (100 mm) without flared ends launched by EuroCirCol
  - RMM reached 16.4 T in a 50 mm bore in 2022
  - Test of reproducibility of the assembly in 2024: 16.9 T achieved, and 15.7 T for long flattops
- Test of reproducibility of manufacturing (new set of coils) in 2025

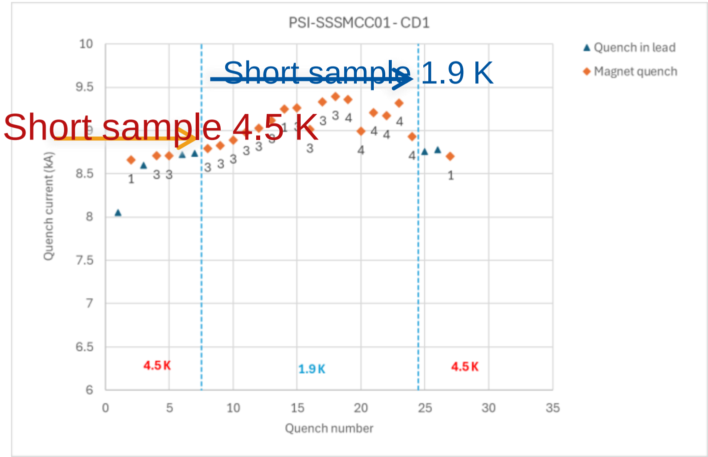


Cross-section of RMM [J. C. Perez, et al.]

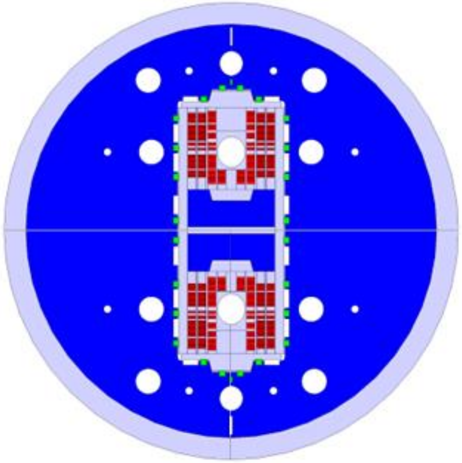


Nb_3Sn program: stress management

- Stress management consists in mixing the structure and the coil
  - Mandatory for 20 T, and MDP is investing only in this direction
    - CCT5: 8 T reached (LBNL), CD1: 10 T (PSI) reached with 17 mm width coil
- PSI manufactured a subscale stress managed common coil, with CERN support for parts of coil manufacturing and test
  - Peak field in the coil of 6.5 T reached >5 T in in the centre (June 2024)
- SMACC1 is a common coil stress managed, 12 T target, test in 2026



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

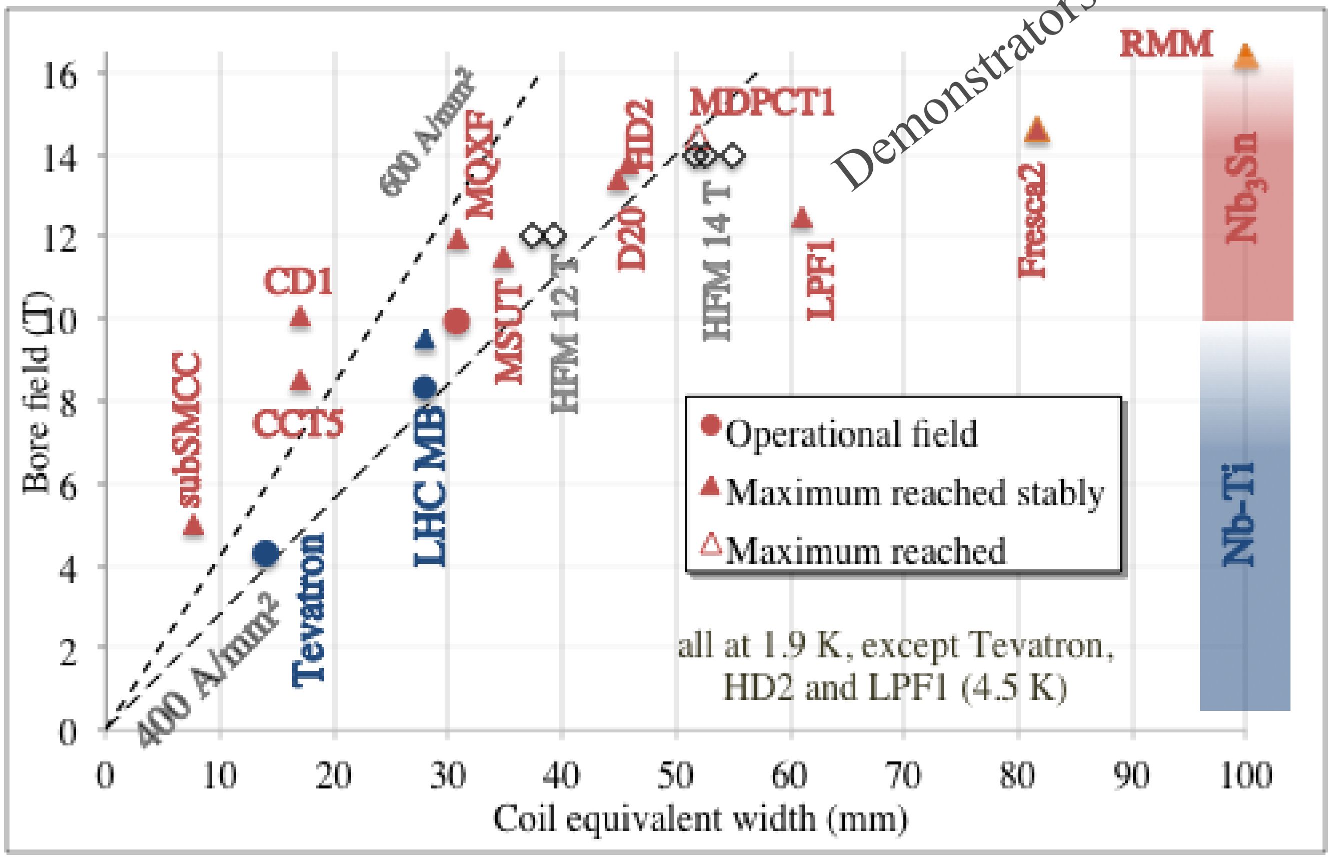


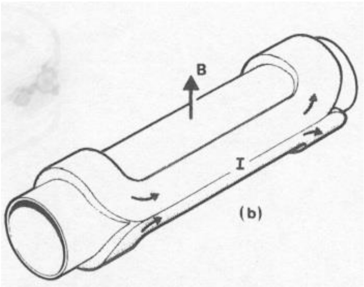
Design of 12 T SMACC1
(D. Araujo, B. Auchmann, et al.)

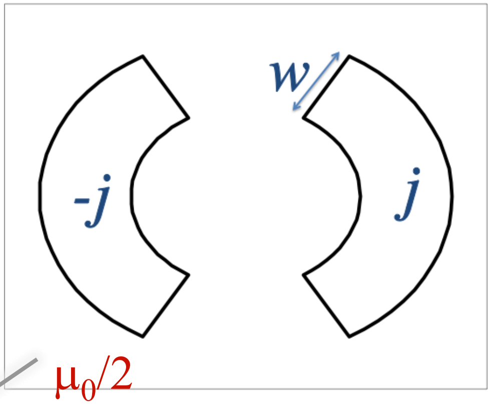
U.S. MAGNET DEVELOPMENT PROGRAM

PSI

What are we building

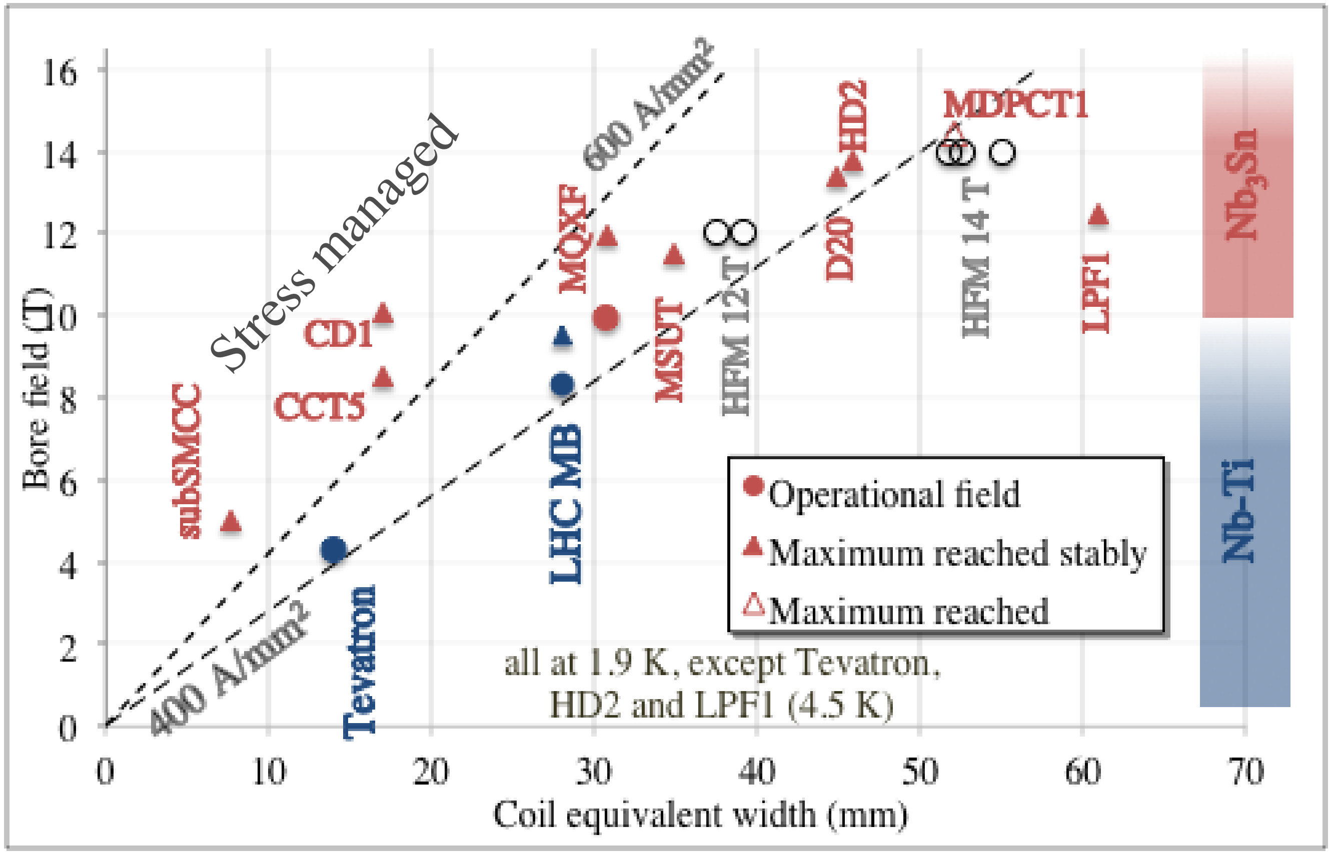


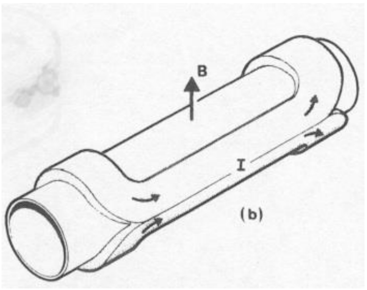


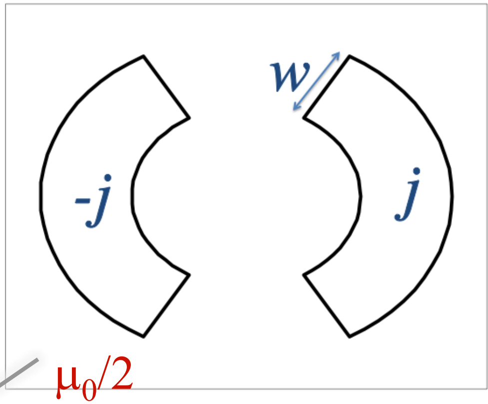


$$B[\mathrm{T}] \approx 0.00063\, j\,[\mathrm{A/mm^2}]\, w\,[\mathrm{mm}]$$

What are we building





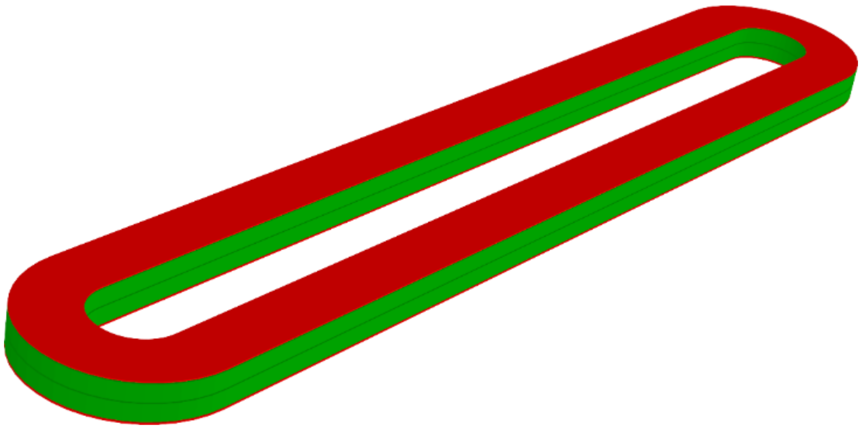


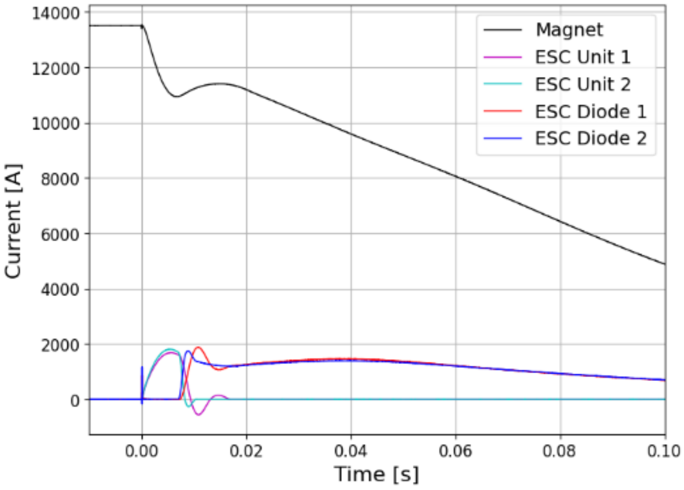
$\mu_0/2$

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

2024 results: novel protection schemes

- Larger current density → more compact and cheaper magnets
  - One of the limits to the design is the protection – all energy has to be dumped in the coil
  - Novel method proposed (E. Ravaioli et al.) and has been tested at CERN on a SMC to allow a part of energy extraction, and fast quenching
  - Second novel method (eCLIQ) is to be tested in the coming weeks



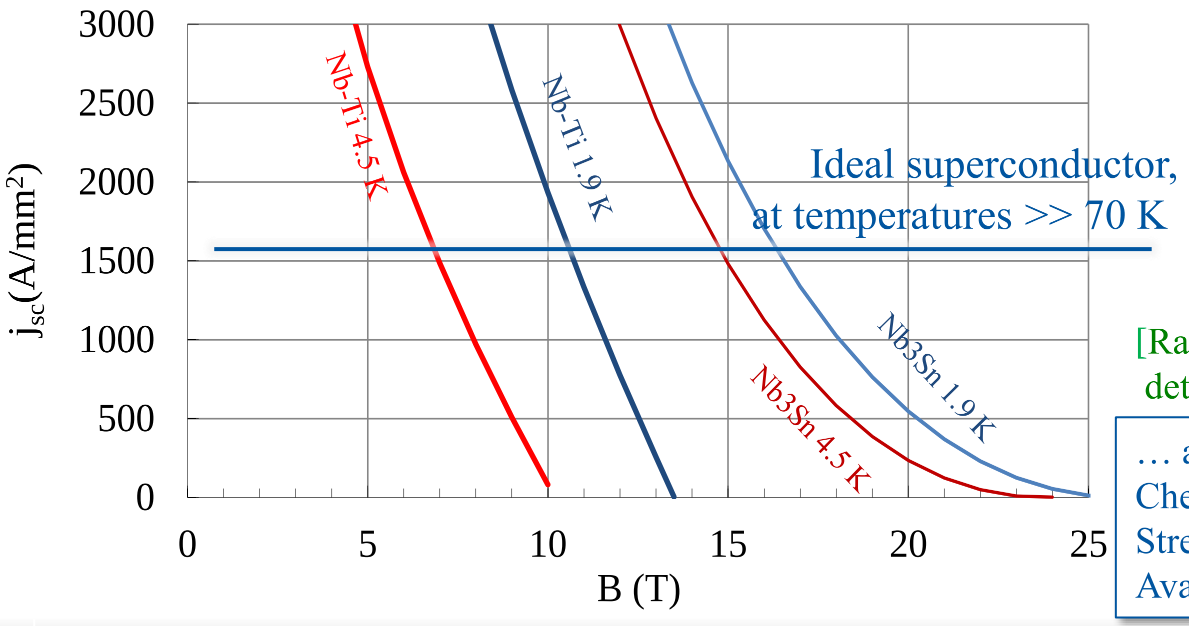


Copper coil and SC coil in ESC, and quench protection (E. Ravaioli, J. C. Perez, et al.)

Table of contents

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)
- … 10^3 to 10^4 A/mm^2 (just what is needed, nothing more) at 70 K



[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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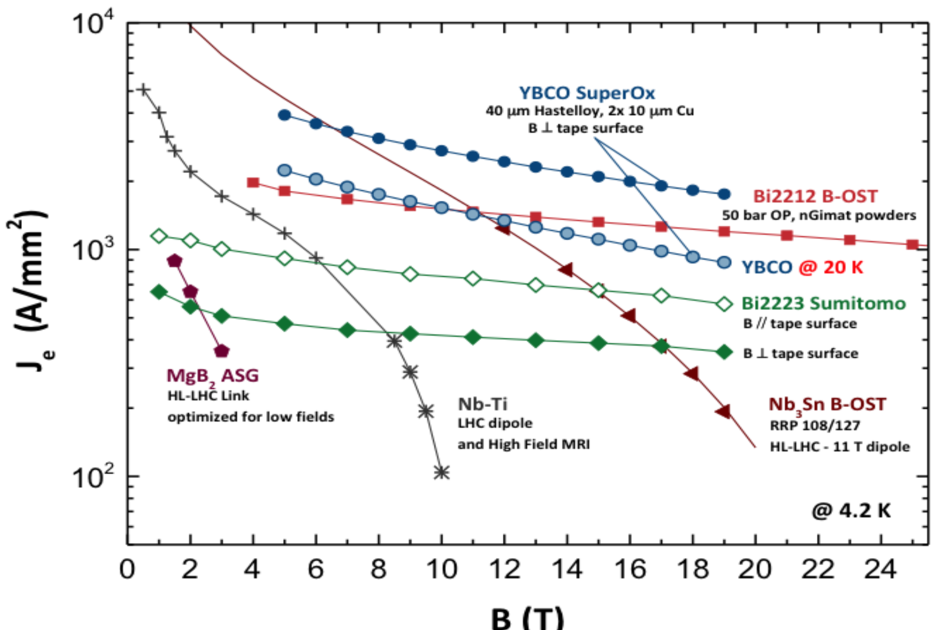


Jeng vs B, all at 4.2 K (courtesy of A. Ballarino)

[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

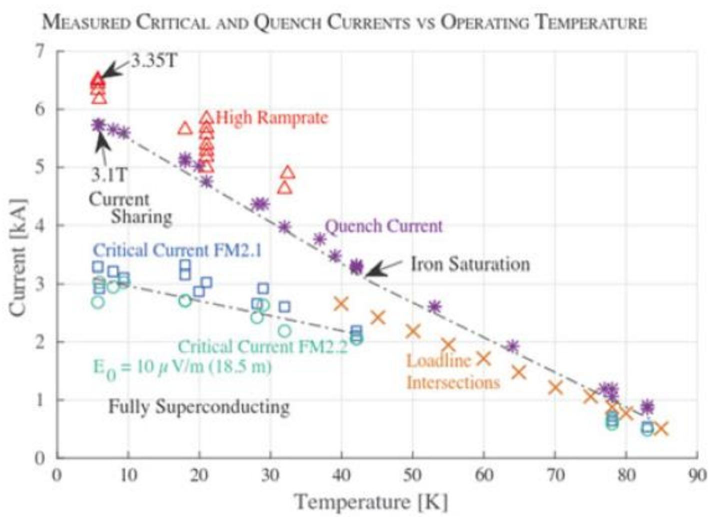
Three paths for HTS

- BSSCO (commercially available, mainly used in the US)
  - Available in round strand, dipoles reaching 1.5 T have been done (LBNL)
  - Expensive, complicated manufacturing process (more than Nb_3Sn)
  - No activities foreseen in HFM
- REBCO (commercially available, strong impluse from fusion investments of order of BCHF)
  - Recently, large reduction of cost, but still 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 – to be used, could be necessary renegotiating requirements
- IBS (not comercially available, strong impulse from China)
  - Critical current is improving, but not as expected (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 10 kJ/m per cycle is given), can be a showstopper in this case
  - 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

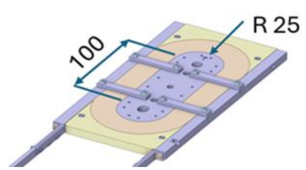
L. Rossi, et al, Instruments 5 (2021)]



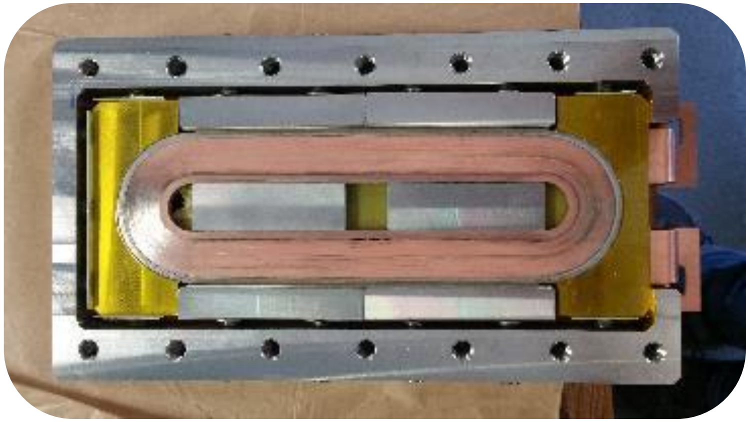
- Is the REBCO tape used in fusion a viable conductor for HEP main dipole magnets ? Question still open today

HTS results in 2024

- 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) – 2.7 T at 4.2 K reached in fall 2024 (but half of the field w.r.t. model !)
  - Remember that all magnets for fusion are NI (Non Insulated) – this design does not fit our requirements
  - Protection is still challenge far to be solved …. Many coil lost, in all fields



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



MI racetrack coil [T. Lecrevisse, et al.]

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)	Non-Cu current density (A/mm^2)	Ramp rate (mT/s)	Field in conductor (T)
Tevatron dipole	360	1550	~4	4.7
LHC dipole	360/440	1260/1820	~8	8.6
ATLAS BCT	30	950	~0.8	3.9
ITER (TF & CS)	20 to 40	150	~400	5 to 13
HL-LHC SC link	17	1450	~8	Self field (<1 T)

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

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

HFM

High Field Magnets

Programme

Appendix

- News from China
- News from the US
- HFM structure and organization

SPPC

中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

- 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
    - It will probably be lowered in the near future
  - Machine works at 4.5 K

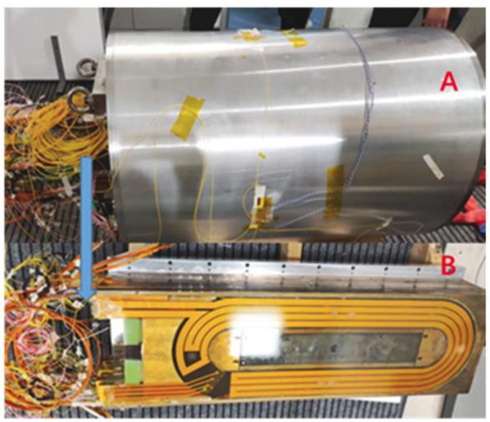
FCC-hh parameters	CDR 2019	2024-Nb_3Sn	2024-HTS
Dipole field (T)	16.0	14.0	14-20
Tunnel length (km)	100	90.7	90.7
Arc length (km)	82.0	76.9	76.9
Arc filling factor (adim)	0.80	0.83	0.83
Energy c.o.m (TeV)	100	85	85-120
Loadline margin	86%	80%	TBD

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

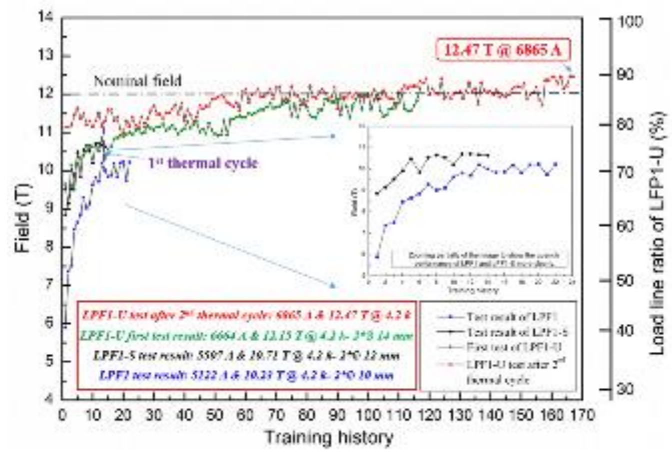
SPPC magnets

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

- 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 after very long training
    - Configuration based on flat racetrack, without field quality



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



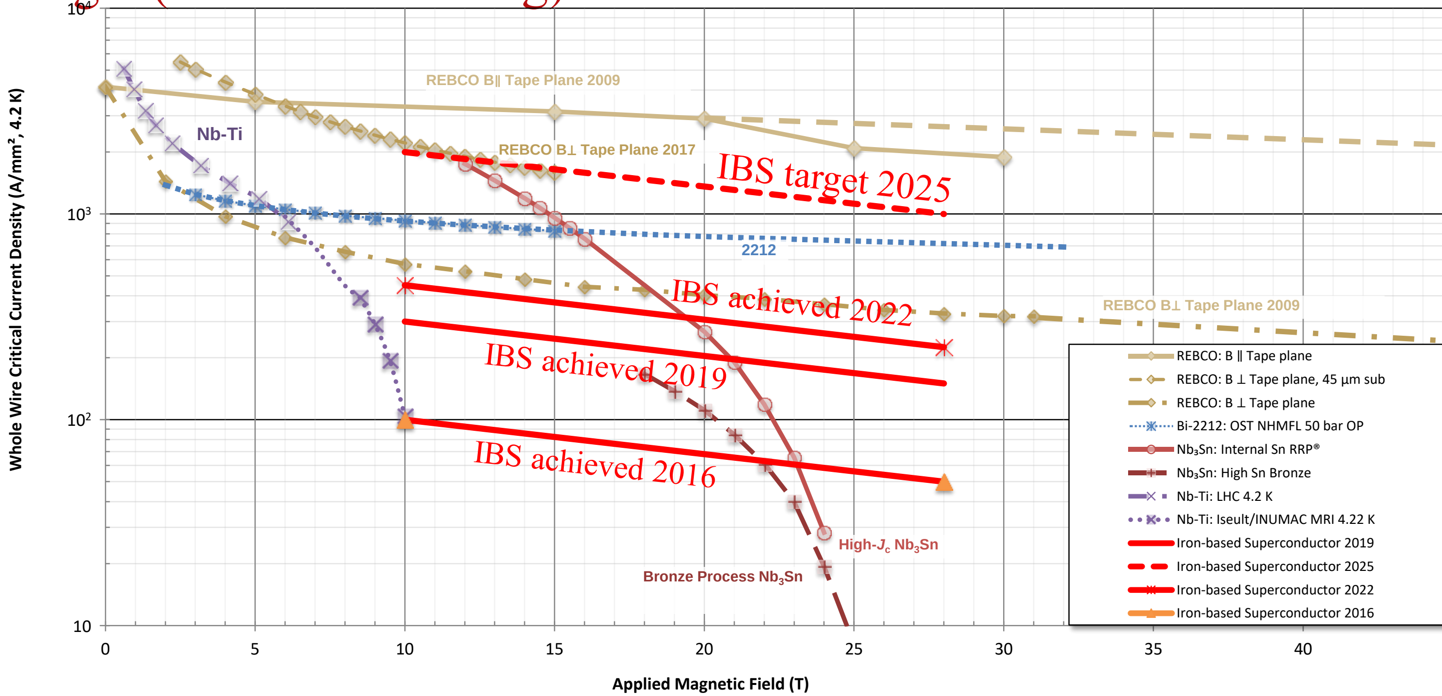
LPF1 training [C. Wang, et al., SUST 36 (2023) 065006]

- 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

IBS

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

- 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 critical current in the past years, but still far from target (a factor 4 missing)



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

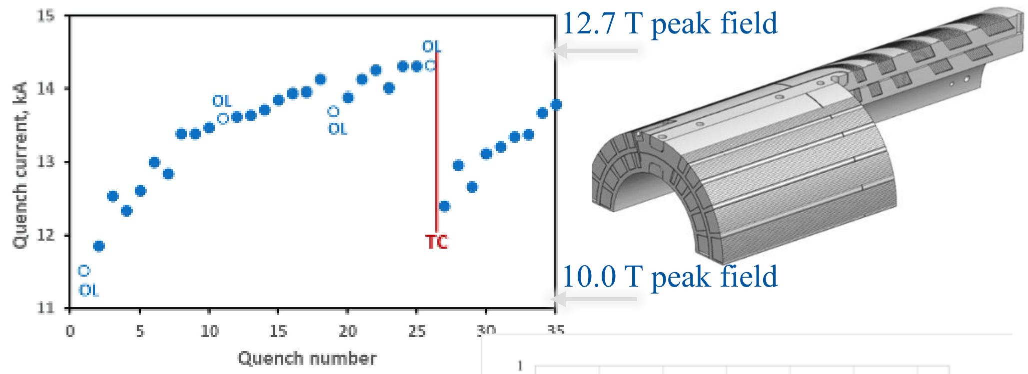
Appendix

- News from China
- News from the US
- HFM structure and organization

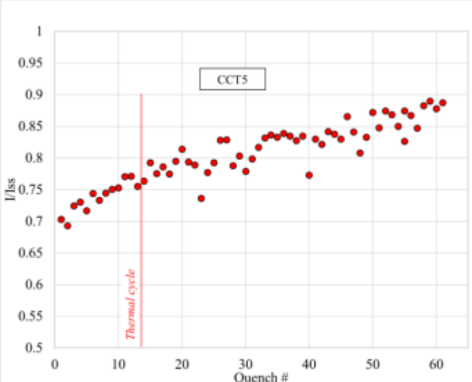
US magnet development program (MDP)

U.S. MAGNET DEVELOPMENT PROGRAM

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

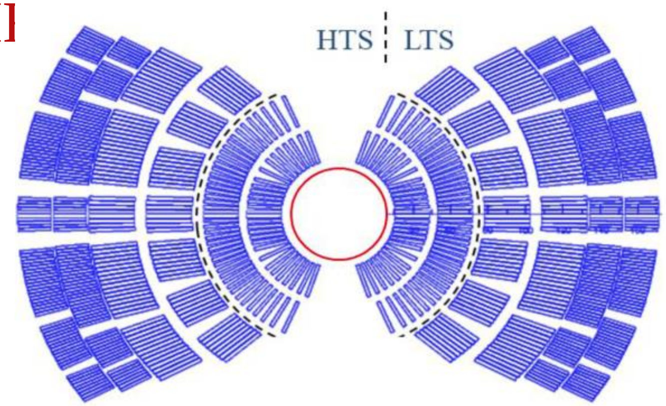


- Cosθ from FNAL: 12.7 T but in mirror
- CCT from LBNL: 8.5 T in 90 mm aperture
- HTS:
  - Bin5, made with BSSCO reached 1.6 T in 35 mm ape
  - CCT with REBCO corc® cable reached 2.9 T in 65 mm aperture
  - Record of 4.5 T still dates back to 6 years ago (Feather2)

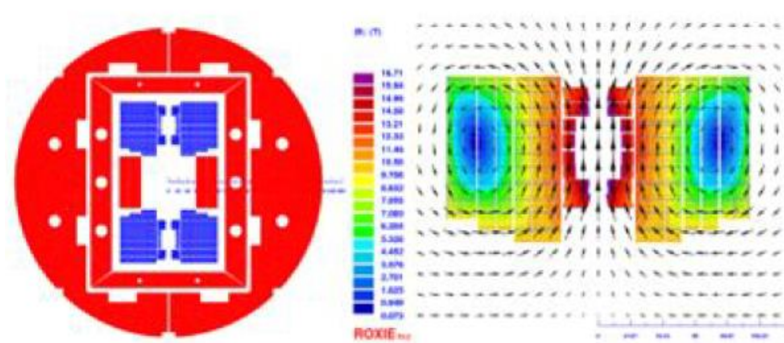


Hybrid or all HTS ?

- 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 – 20 K operation today requires 3 times conductor
- «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
- HI cision 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]

Appendix

- News from China
- News from the US
- HFM structure and organization

HFM structure and organization

- 33 WPs, 17 from CERN and 16 from collaborations
  - Since early 2024 reduction of WP number (20% less)
- Having a unique forum to share results
  - Since March 2024, 17 meetings, with average 50 colleagues
- MDP systematically invited to HFM forum, 4 joint meetings with the US in the afternoon
- 7 working groups established since 2024
  - Block coil – Common coil
  - BOX program - Composite WG - insulation
  - HTS modeling – Quench and transients
- More information on https://hfm.web.cern.ch/

HFM steering board
M. Lamont (chair)
P. Vedrine (co-chair)

High Field Magnet Programme

E. Todesco (Leader), B. Auchmann (Co-leader)

HFM collaboration board
C. Senatore (chair)
TBD (deputy)

Programme office
G. Riddone

RD1: Nb_3Sn conductor

- 1.1 **Nb_3Sn wire and cable** – T. Boutboul (CERN)
- 1.3 **Internal oxidation wires** – C. Senatore (UniGe)
- 1.15 **Nb_3Sn development** – M. Sugano (KEK)
- 1.18 **Internal oxid. studies** – A. Leineweber (BAF)
- 1.19 **Nb_3Sn characterization** – C. Senatore (UniGe)

RD1 line coordinators:
T. Boutboul (CERN)
C. Senatore (UniGe)

RD2:HTS conductor+magnets

- 2.1 **REBCO development** – B. Holzapfel (KIT)
- 2.2 **REBCO conductor** – A. Ballarino (CERN)
- 2.5 **Demonstrator DI coils** – A. Ballarino (CERN)
- 2.6 **Solenoids and MuC** – L. Bottura (CERN)
- 2.11 **Demonstrator MI coil** – T. Lecrevisse (CEA)
- 2.15 **IBS development** – A. Malagoli (CNR-SPIN)
- 2.17 **REBCO development** – Y. Yang (SOTON)
- 2.18 **HTS 10 T dipole** – M. Statera (INFN)
- 2.19 **REBCO racetrack** – D. M. Araujo (PSI)
- 2.20 **REBCO characteriz.** – M. Eisterer (TUWien)

RD2 coord: A. Ballarino (CERN)

RD3: Nb_3Sn magnets

- 3.1 **12 T cosθ CERN** – A. Foussat (CERN)
- 3.2 **12 T cosθ INFN** – S. Farinon (INFN)
- 3.4 **Technology development** – A. Haziot (CERN)
- 3.5 **14 T Block dipole BOND** – J. C. Perez (CERN)
- 3.3 **5-m-long block** – S. Izquierdo Bermudez(CERN)
- 3.6, 3.12 **Block dipole F2D2** – E. Rochepault (CEA)
- 3.7 **Common coil DAISY** – F. Toral (CIEMAT)
- 3.11 **14 T Cosθ** – M. Sorbi (INFN)
- 3.14 **CC stress managed** – D. M. Araujo (PSI)

RD3 line coordinators:
F. Toral (CIEMAT)
A. Haziot, A. Foussat (CERN)

RD4: Integration, sustainability

- 4.3 **Insulation and HV** – R. Piccin (CERN)
- 4.5 **Quench D+P** – M. Wozniak (CERN)
- 4.6 **Cryogenics, thermal** – P. Borges de Sousa (CERN)

RD4 line coordinator:
P. Borges de Sousa (CERN)

RD5: Infrastructures

- 5.1 **Test** – F. Mangiarotti (CERN)
- 5.2 **Conductors, cables** – J. Fleiter (CERN)
- 5.4 **Manufacturing** – J. Axensalva (CERN)
- 5.5 **MM, modelling** – L. Fiscarelli (CERN)
- 5.7 **CIEMAT lab** – C. Martins (CIEMAT)
- 2.16 **HTS laboratory** – A. Ballarino (CERN)

6.1 **Societal impact**
E. Chesta (CERN)

Collaboration WPs

CERN WPs

Note: completed WP not shown

January 2025

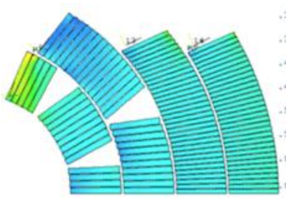
Appendix

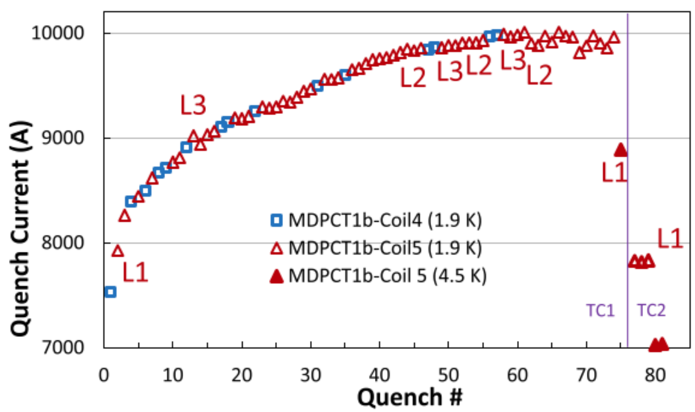
- News from China
- News from the US
- HFM structure and organization
- More about magnet design

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 (discussions on scope ongoing)
    - Test in 2029 at earliest

Fermilab

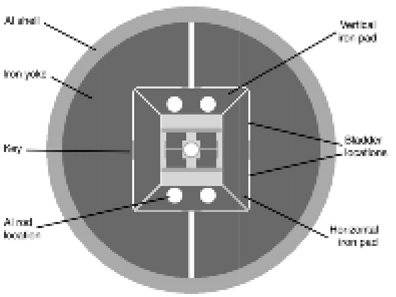




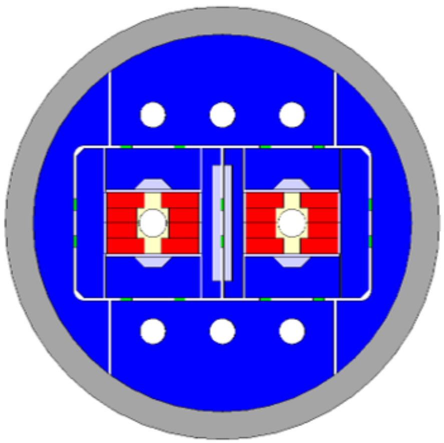
Power tests of MDPCT1 [S. Stoynev, et al. IEEE TAS 32 (2022) 4000705]

Nb_3Sn program for 14 T

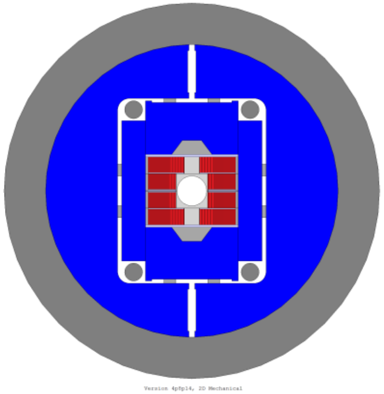
- The block option: this design has the world record
  - Advantage: no stress accumulation in the midplane
  - HD2 reached 13.8 T at 4.2 K
  - Two options:
    - CERN (no grading) – test in 2026
    - CEA (with grading) – test in 2028



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



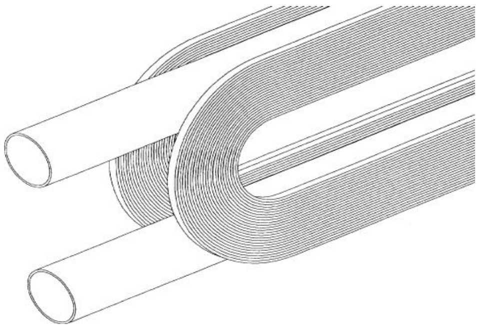
14 T block dipole (J. C. Perez, et al.)



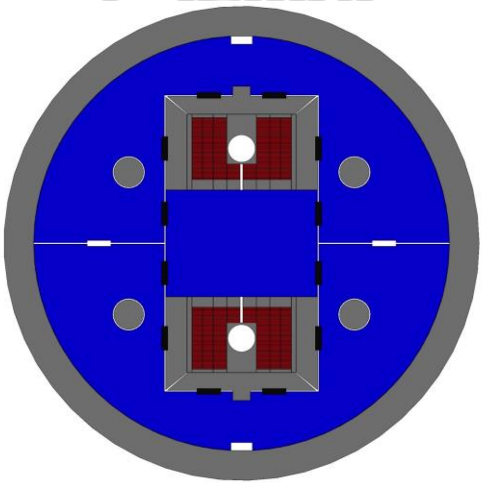
14 T block dipole F2D2 (E. Rochepault, et al.)

Nb_3Sn program for 14 T

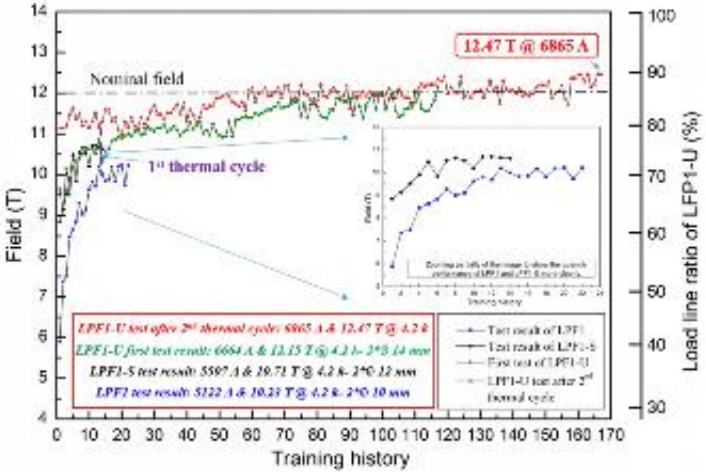
- The common coil design: a simpler path ?
  - Racetrack coils are easier to manufacture
  - The IHEP program reached 12.5 T with Nb_3Sn, but with small aperture (14 mm and no field quality, see appendix)
  - CIEMAT is planning to build a common coil, test in 2027/8



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



DAISY cross-section [F. Toral, et al.]



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