Status and perspectives in high field superconducting magnets for particle accelerators

E. Todesco, CERN

Applied Superconductivity Conference, September 4th 2024

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Plenary presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

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  - IHEP, IMP in China
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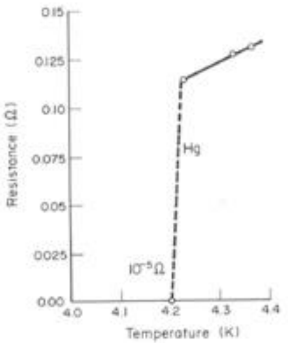
Foreword

- The history of superconductivity applied to magnets is a very interesting paradigm
  - Theory lags behind experimental results, arriving several decades later
  - Applications of superconductivity to build magnets above 1 T arrive 50 years after the Onnes discovery
  - The discovery is made possible by a technological achievement (making liquid He), explicitly mentioned in the attribution of the Nobel prize (whereas superconductivity itself is not mentioned)

”For his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium”



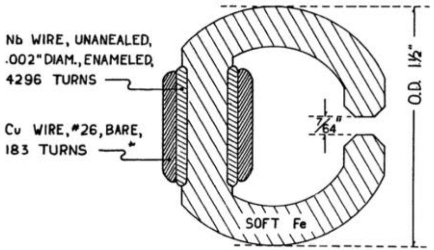
Heinke Kamerlingh Onnes
(18 July 1853 – 4 February 1928)
Nobel prize 1913

Onnes He liquefactor,
Boerhaave museum, Leiden

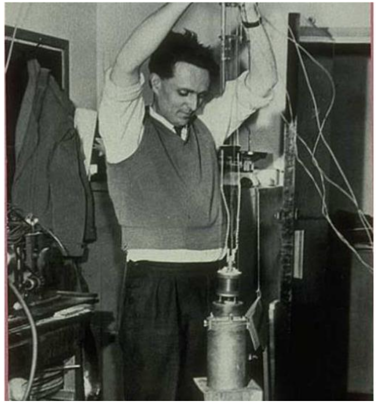
First superconducting magnets, 60’s

My name is Bond …

- 50 years after Nobel prize, the first superconducting solenoids well above 1 T
  - 1956: a Nb superconducting magnet reaching 0.7 T
  - 1962: a 4 T magnet (M. Wood, et al)
  - 1964: a 10 T Nb-Ti solenoid (H. T. Coffey and J. K. Hulm et al., J. Appl. Phys. 36 (1965) 128
    - See M. Wilson, IEEE TAS 22 (2012) 3800212 for an historical review
- Superconductivity rapidly enters the collective imagination !



G. Yntema, IEEE Trans. MAG-23, no. 2, p. 390, 1987



M. Wood with the first Oxford instruments magnet

The bad guy (C. Lee)

James Bond (R. Moore)

G. Hamilton, "A007 – The man with the golden gun" EON production (1974)

… a few years later, between France and Switzerland

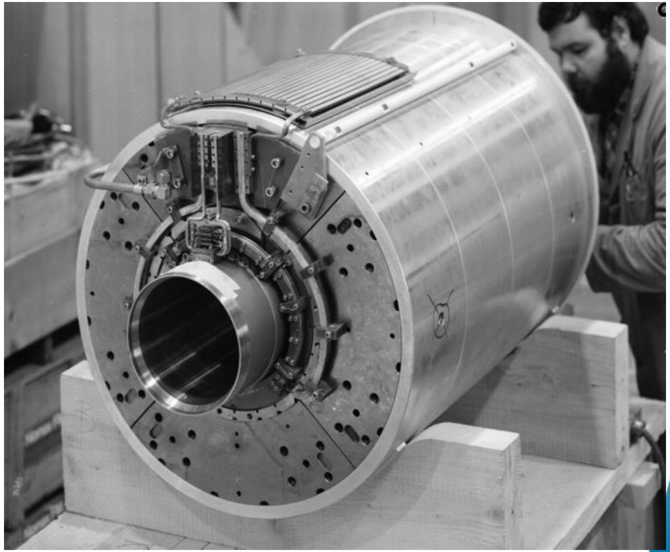
- First superconducting quadrupole magnets installed in a collider based on Nb-Ti
  - Eight quadrupoles for the ISR insertion region, 43 T/m in 173 mm bore –
  - Pole field 3.8 T, but peak field in the superconductor 5.8 T
  - Rectangular Nb-Ti wire with twisted filaments (no need of field quality along the ramp)
- Even though this design did not further evolve, we can start our history from here …

THE EIGHT SUPERCONDUCTING QUADRUPOLES FOR THE ISR HIGH-LUMINOSITY INSERTION

by

J. Billan, K.N. Henrichsen, H. Laeger, Ph. Lebrun, R. Perin, S. Pichler, P. Pugin, L. Resegotti, P. Rohmig, T. Tortschanoff, A. Verdier, L. Walckiers, R. Wolf

Presented at XIth International Conference on High Energy Accelerators, CERN, Geneva, July 7 - 11, 1980



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Features of superconducting magnets for accelerators

- Compact, highly optimizied, and cost-effective: the capsule hotels of applications of superconductivity ?

Nine Hours Narita Airport capsule hotel

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Features of superconducting magnets for accelerators

- Overall current densities of ~500 A/mm^2 are a peculiar feature/challenge for accelerator magnets (overall current density = current density over insulated coil)
  - One order of magnitude above applications as 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)

- This large current density is needed for compactness required in the transverse size:
  - ~10 cm for the active part (coil around the bore), ~1 m for the total size of the cryostat
- Other applications have other types of challenges as
  - Total size for HEP detector magnets, total size and pulsed field for ITER magnets
  - Coupling between circuits and different temperatures in the SC link

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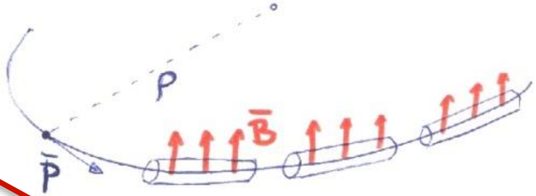
Field, collider size, and energy

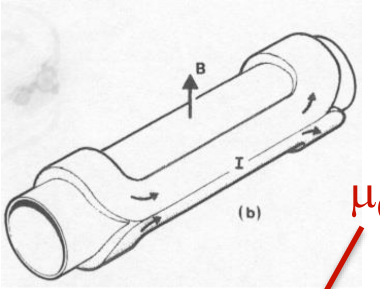
- Energy of a particle accelerator is given by magnetic field and accelerator size

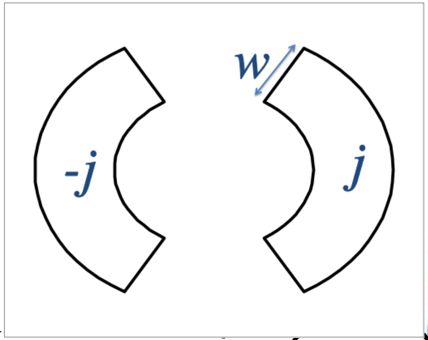
Speed of light

$$E[GeV] = 0.3 \times B[T] \times r[m]$$

Long accelerators ?

High fields ?

- Field of a magnet is given by current density and coil width





$\mu_0/2$

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

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Features of superconducting magnets for accelerators

- Resisitive magnets operate <5 A/mm^2, superconducting technology allows with 500 A/mm^2 a reduction of a factor 100 in the active part of the magnet
  - Zero resistance as an ecologic device (no consumption, but cryogenics), but compactness as well means sustainability
  - Small is beautiful … especially when you have to make thousands of them

A colleague in the structure for a large accelerator magnet

Requirements of superconducting magnets for accelerators

- Field quality:
  - <1 per mil relative error over two third of the aperture and over the operational range
  - Accelerators increase the energy of a factor 5 to 20, and even at “low field” and during the energy ramp the relative error has to be < 1 per mil
  - This needs fine filaments, twisting of filaments and twisting of strands in Rutherford cable
- Protection:
  - Energy extraction is not viable → energy has to be dumped in the coil
  - How? Once a quench is detected, rapidly (order of 10 ms) induce a global resistive transition
- Stress: locally, it is $j \times B$
  - The accumulation of high current density and high field induces a stress in the conductor of order of 100 MPa (unless it is intercepted)
  - 200 MPa is considered a limit that is better not to approach for a Nb_3Sn magnet to be produced in thousands units [F. Mangiarotti, 2LOr2E-02, experience on MQXF]

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1975 to 2008: Nb-Ti technology in accelerators

1960 1970 1980 1990 2000 2010 2020 2030 2040 2050

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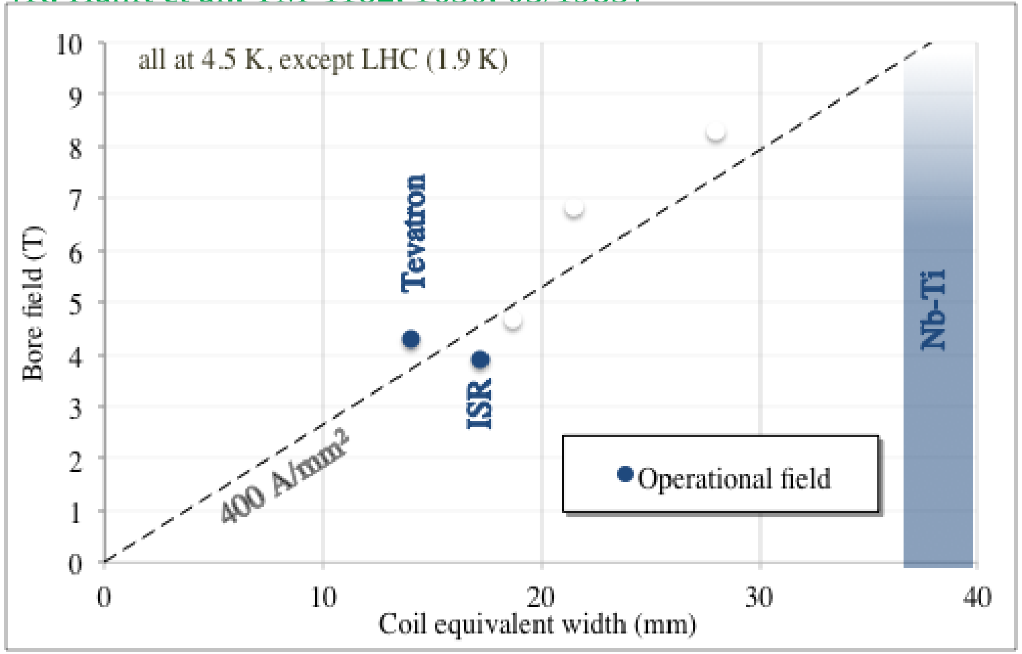
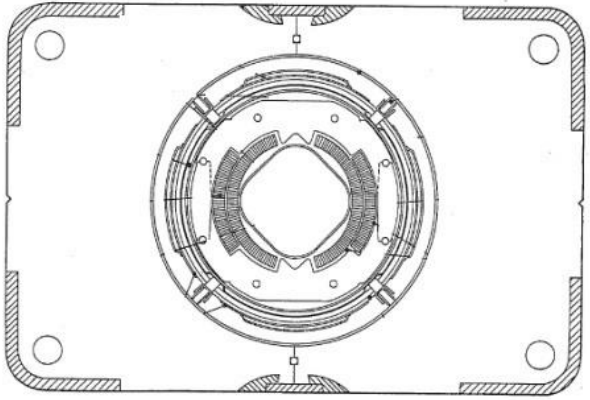
From ISR to LHC

- 1980-1986: Tevatron is the first collider using 4.3 T superconducting dipole magnets
  - First use of Rutherford cable, first use of collars
  - 774 dipoles, 6-m-long magnets, in house production in FNAL

[R. Hanft et al., TM-1182, 1630, 03/1983]





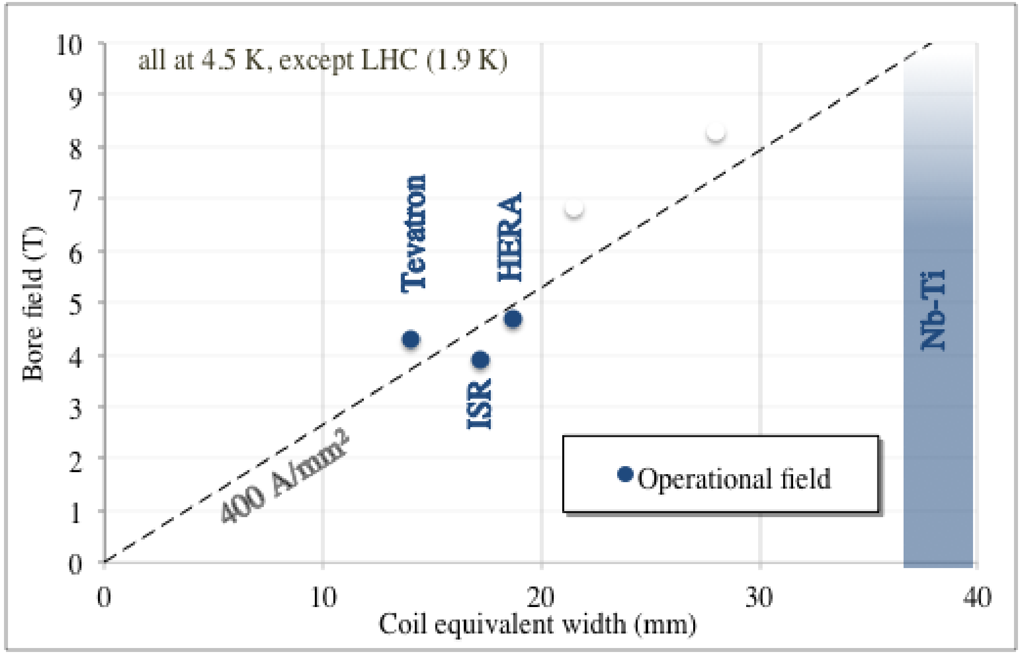
Tevatron dipole cross-section

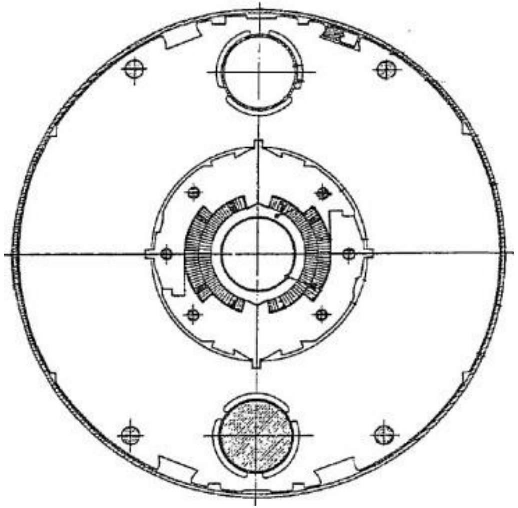
Note: for ISR quad, $G\,r$=3.8 T is used as bore field, but coil peak field is 5.8 T - for the coil width see appendix

From ISR to LHC

- 1985-1990: HERA dipoles break the 4.5 T operational field barrier
  - 454 dipoles, 9-m-long magnets, industrial production, Al collars

[R. Meinke, IEEE TAS 27, 1728 (1991)]



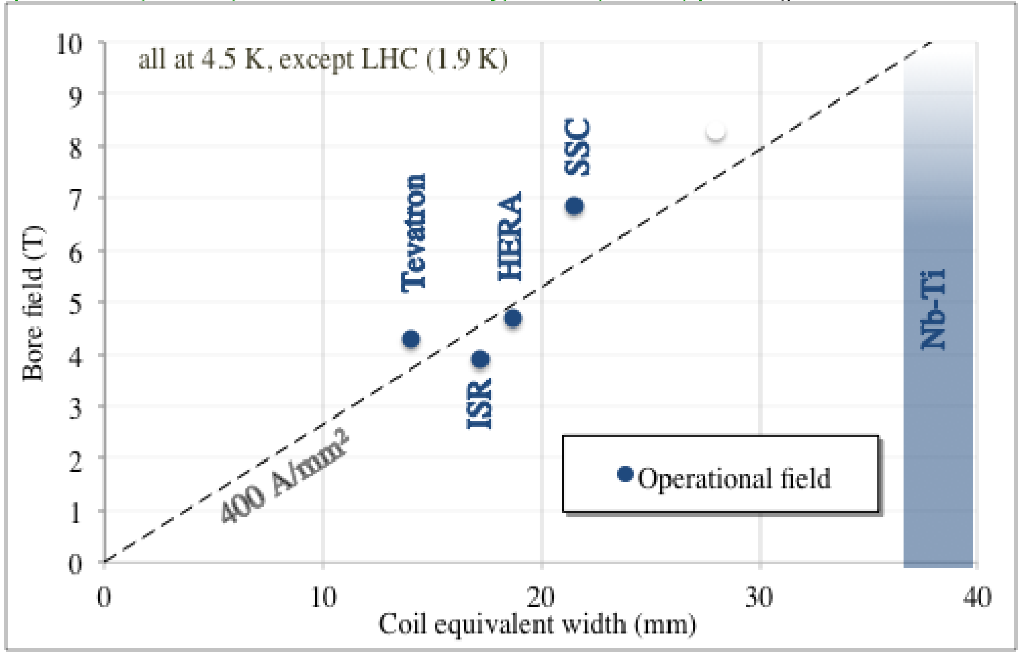


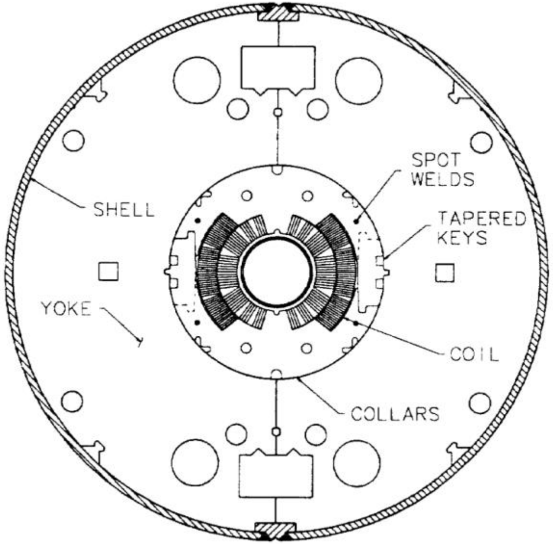
HERA dipole cross-section

From ISR to LHC

- 1984-1995: SSC protoypes break the 6.5 T barrier and double the length, above 15 m
  - 19 dipole prototypes, 17-m-long magnets with 50 mm aperture
  - 15 dipole prototypes, 15-m-long magnets with 40 mm aperture

[J. Strait, et al., IEEE Trans. Magn. 25 (1989)] Project canceled in 1993

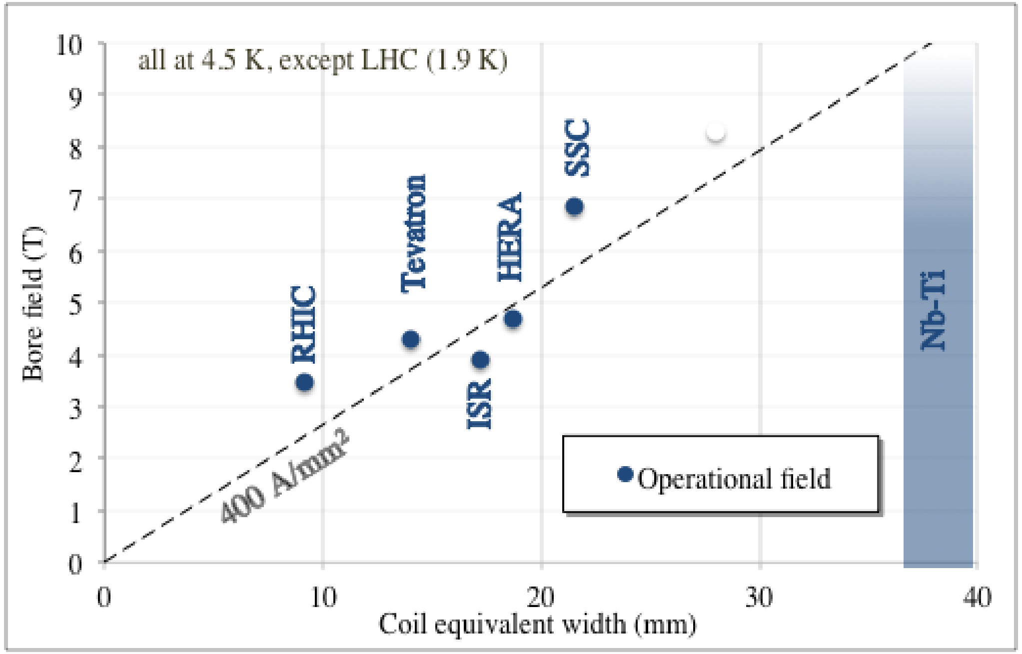


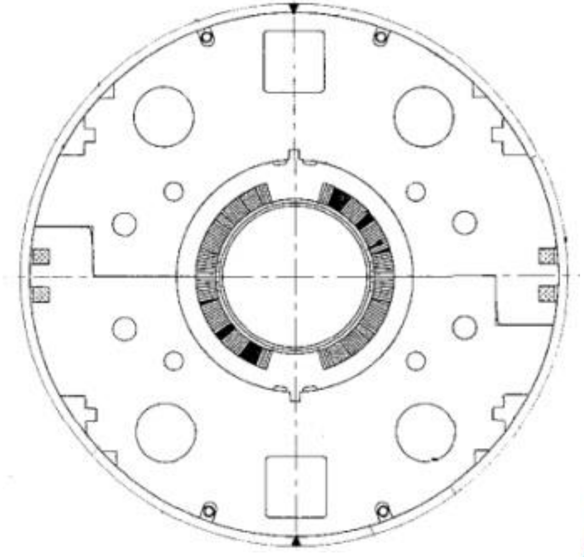


SSC dipole cross-section

From ISR to LHC

- 1994-1996: RHIC dipoles (3.5 T) explore the option of a low-cost magnet, with large margin, not requiring test before installation
  - 300 units, 9.45 m long [M. Anerella, et al., NIM 499 (2003) 280-315]





RHIC dipole cross-section

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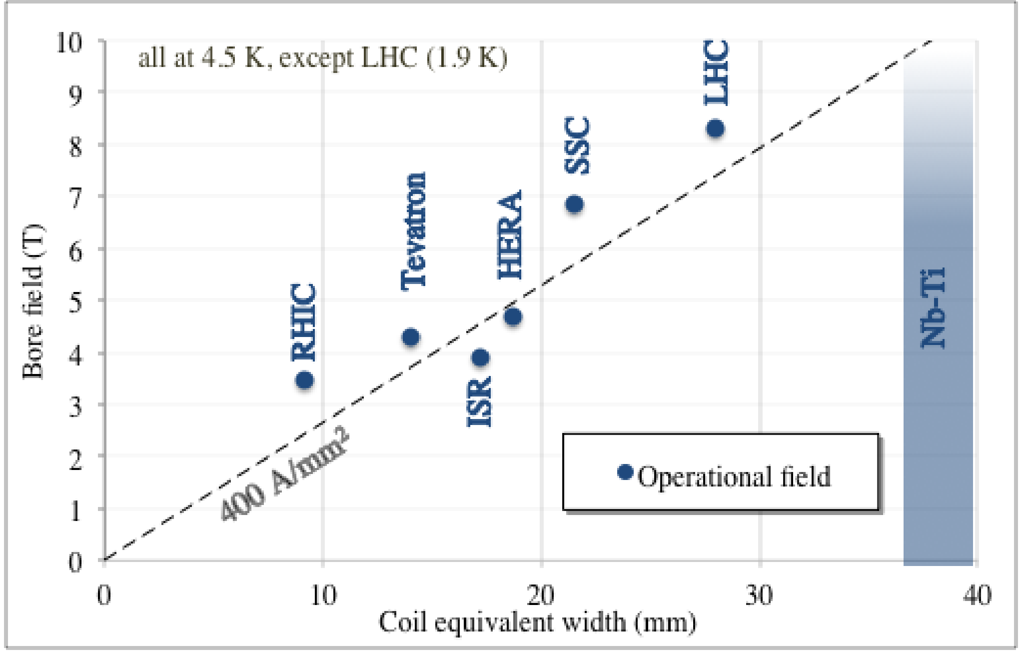
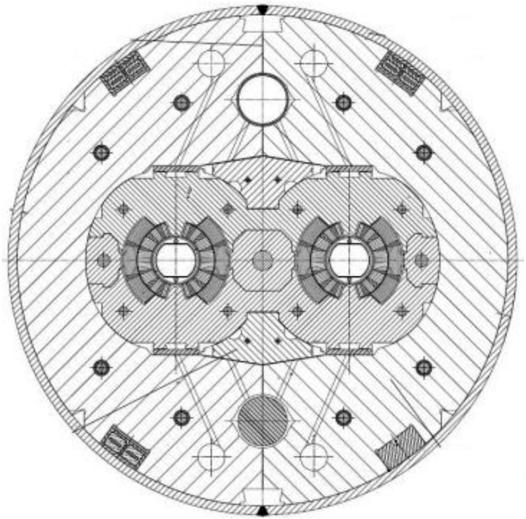
From ISR to LHC

- 2000-2005: LHC dipoles break the 8 T operational field barrier
  - 1278 dipoles, 14.3-m-long magnets, industrial production – towards the limit of Nb-Ti for main dipoles
  - First operation at 1.9 K following Tore Supra experience

[R. Perin, in Encyclopedia of Applied Superconductivity (IOP, London, 1998) 919–950 and L. Rossi, IEEE TAS 13, 1221





LHC dipole cross-section

Lessons to be taken

- Superconductivity allows not only zero consumption (except cryogenics), but for accelerator magnets gives a leap in the overall current density of two orders of magnitudes from ~5 to ~500 A/mm^2: enabling technology

- The history of Nb-Ti dipole magnets is a walk along the ~400 A/mm^2 line, increasing the coil width from ~15 mm (Tevatron) to ~30 mm (LHC dipoles) and the field from 4.3 T to 8.3 T

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Contents

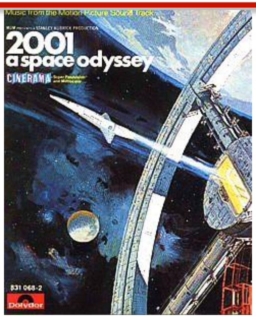
First solenoids

ISR

Tevatron

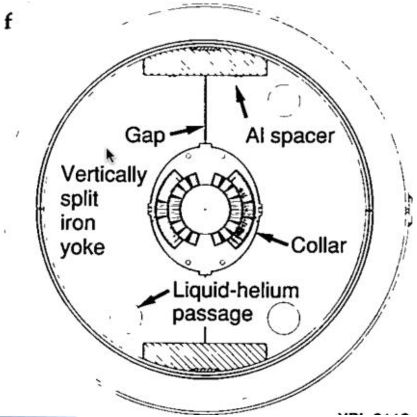
Nb_3Sn short model dipoles from 1987 to 2015

1960 1970 1980 1990 2000 2010 2020 2030 2040 2050



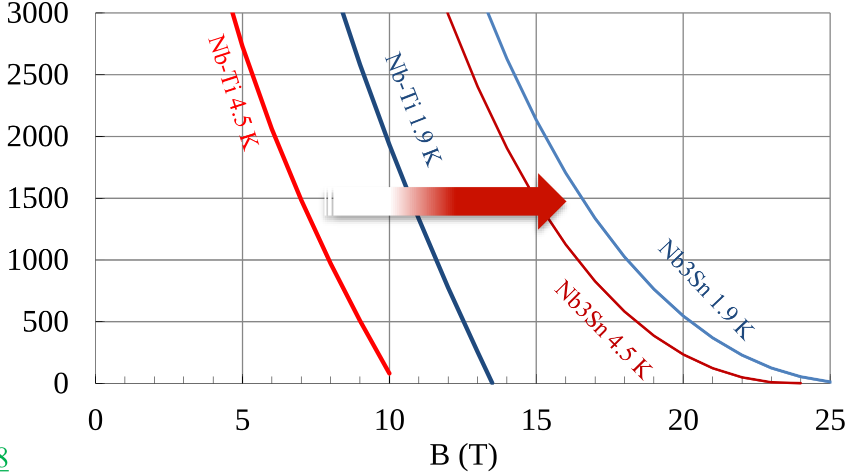
Above 10 T

- 10 T is the limit for Nb-Ti field in accelerator magnets (LBNL D19 went just above 10 T)
  - However operational field must be much lower
- Nb_3Sn, discovered before Nb-Ti, can tolerate higher field, at the price of a more complex process of coil manufacturing (reaction at 650 C, impregnation)
- In the next slides we will show that the paradigm of «More field ? More coil !» that we have seen for the Nb-Ti magnets is kept



LBNL D19 cross-section
[S. Caspi, et al,] mid 90's

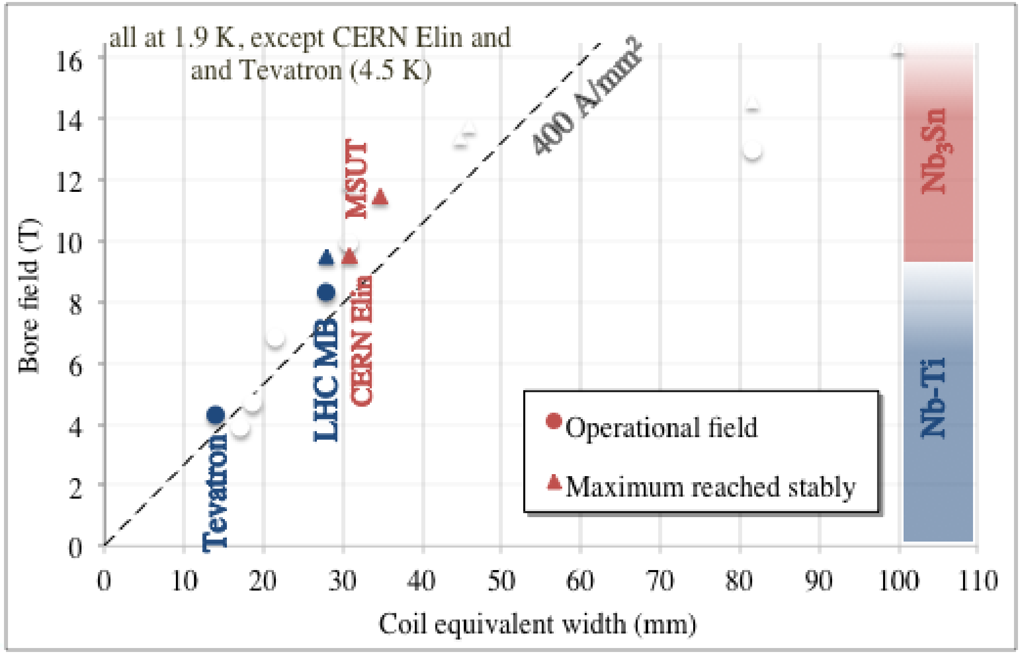
Iseult 11.7 T solenoid
P. Vedrine, et al. IEEE TAS **18** (2008) 868
L. Quettier, et al. *IEEE TAS* **30** (2020) 4400604

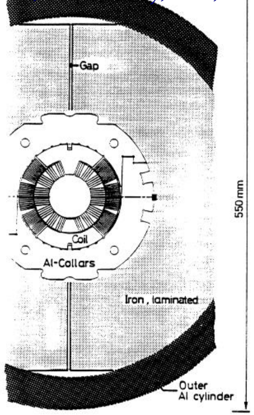


Nb-Ti and Nb_3Sn critical surfaces

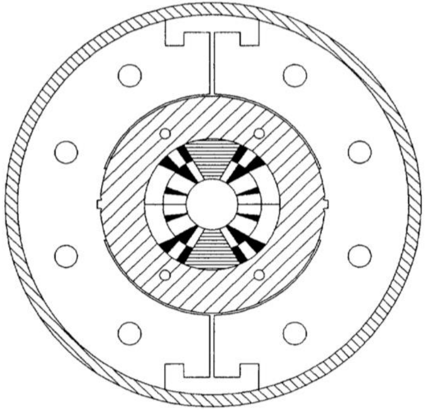
History of records in dipole field for Nb_3Sn

- 1989: CERN Elin reaches 9.5 T at 4.3 K (Nb_3Sn option for LHC)
- 1992-1997: MSUT reaches 11.3 T a 4.5 K, and >11.8 T a 1.9 K 25 years later
- Note the difference: now we talk about achieved field
  - The LHC has 8.3 T operational field but models, proto and series magnets >9.0, 9.5 T





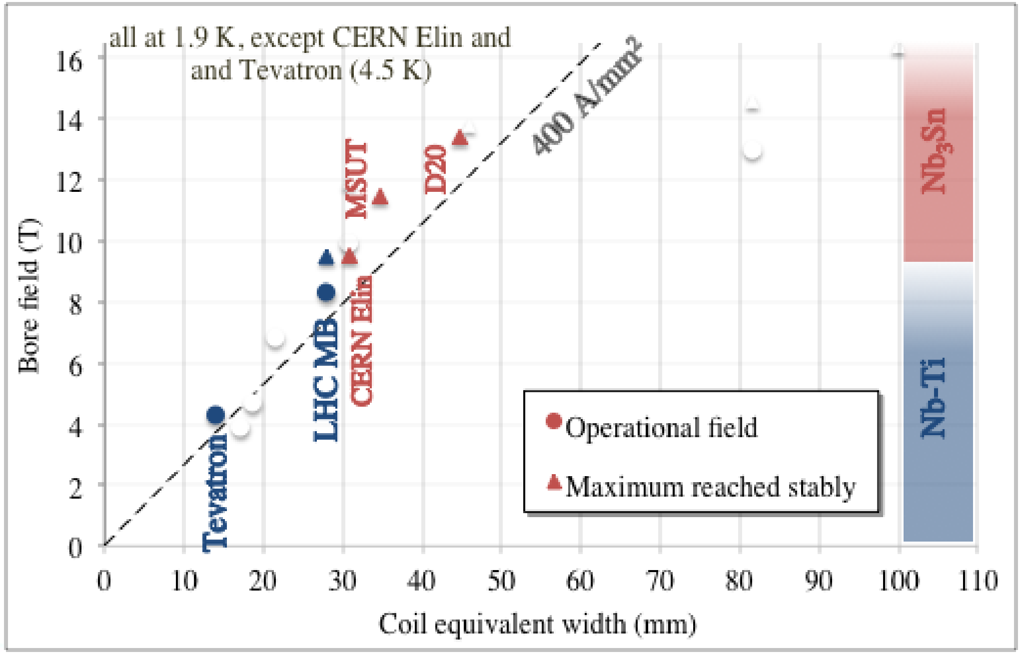
CERN-Elin dipole cross-section
[S. Wenger, et al., IEEE TAS 25 (1989)]

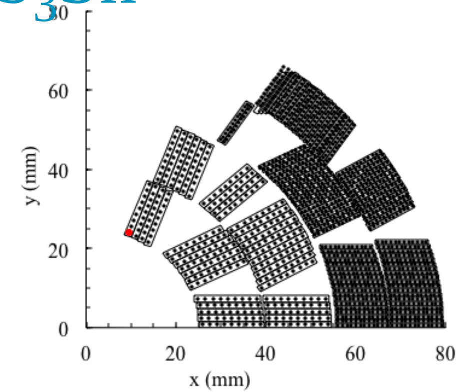


MSUT dipole cross-section
[A. Den Ouden, et al. IEEE TAS 7 (1997)]

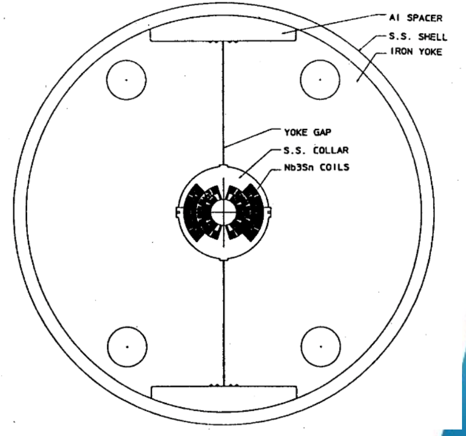
History of records in dipole field for Nb_3Sn

- 1993-1997: LBNL D20 reaches 13.4 T at 1.8 K
  - Complex coil, four layers [D. dall'Orco, et al. IEEE TAS 3 (1993)]
  - [A. McInturff, et al, Particle Acc. Conf. (1997)]





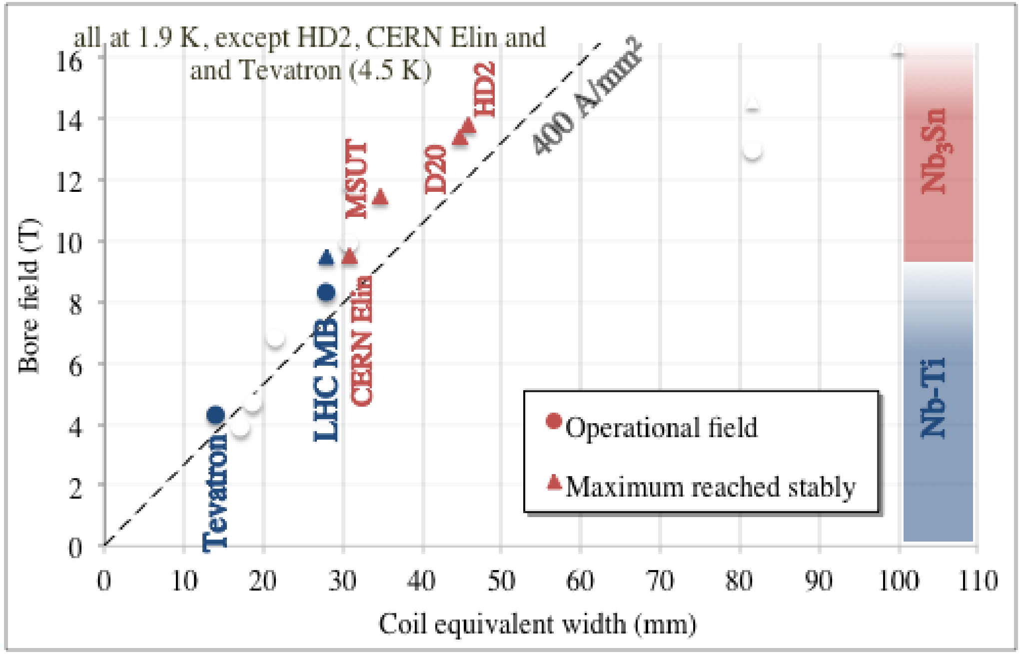
D20 dipole coil cross-section

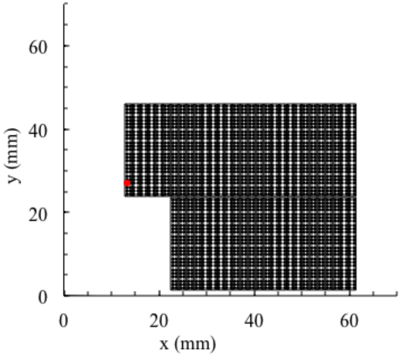


D20 dipole cross-section

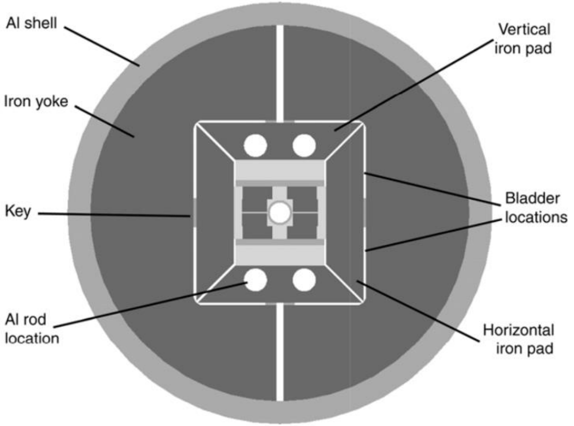
History of records in dipole field for Nb_3Sn

- 2005-2010: LBNL HD2 reaches 13.8 T at 4.5 K (never tested at 1.9 K)
  - Block coil, flared ends [G. L. Sabbi, et al. IEEE TAS 15 (2005) 1128]





HD2 dipole coil cross-section

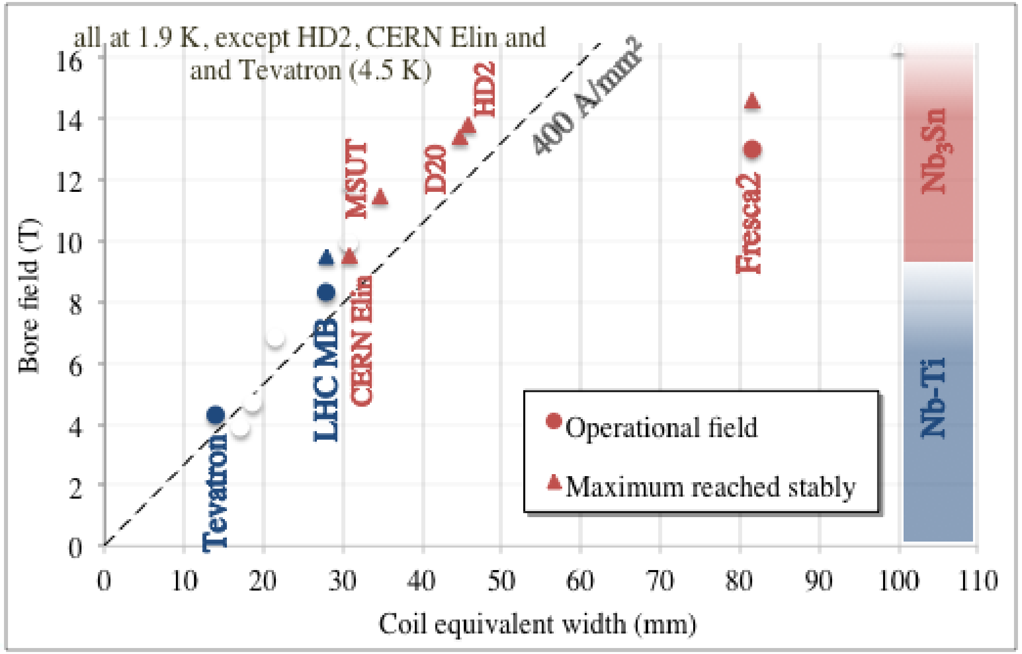


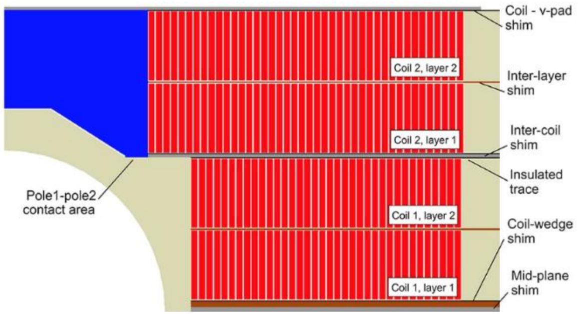
HD2 dipole cross-section

History of records in dipole field for Nb_3Sn

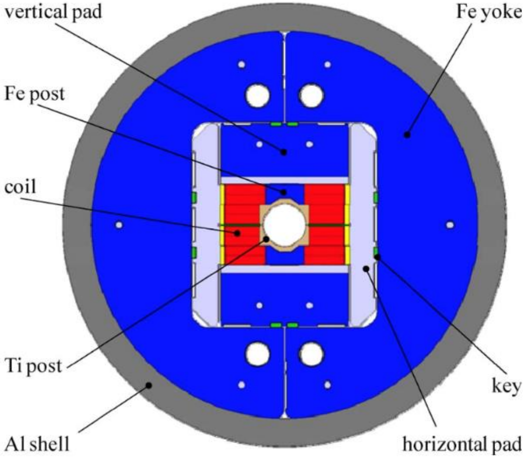
- 2012-2019: CERN-CEA Fresca2 reaches 14.5 T at 1.9 K
  - Block coil with 4 layers – Very large aperture (80 mm)
  - Large coil width, low current density
  - This is not a magnet for accelerator, but proves the technology

[A. Milanese, et al, IEEE TAS 22 (2012)] [G. Willering, et al, IEEE TAS 29 (2019)]





Fresca2 dipole coil cross-section



Fresca2 dipole cross-section

Lessons to be taken

- Nb-Ti solenoids up to 12 T have been built: nevertheless, 8-9 T is the limit for applications to main dipole accelerators
- Above 8-9 T operational field, one has to use Nb_3Sn, featuring a more complex manufacturing procedure
- There is a 1-2 T difference between operational field in several hundreds (thousands) magnets and maximum achievable field in one magnet or in a short model: our community should be more clear on this distinction
- As for Nb-Ti, for Nb_3Sn, the history of the short model dipoles walks around the 400 A/mm^2 line, exploring the 10 – 14 T range and coil widths from 30 to 50 mm, with the exception of Fresca2
    - Note that MDPCT1 reached more than 14 T, with a 50 mm coil width (see next sections)

Contents

8 T LHC Nb-Ti dipoles

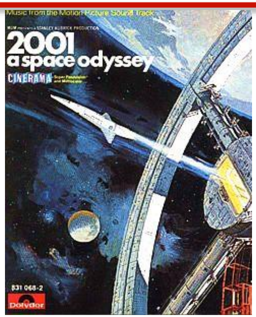
First solenoids

ISR

Tevatron 4.3 T Nb-Ti dipoles

2004 to 2028: LARP and HL-LHC towards long lengths and mini-series

1960 1970 1980 1990 2000 2010 2020 2030 2040 2050



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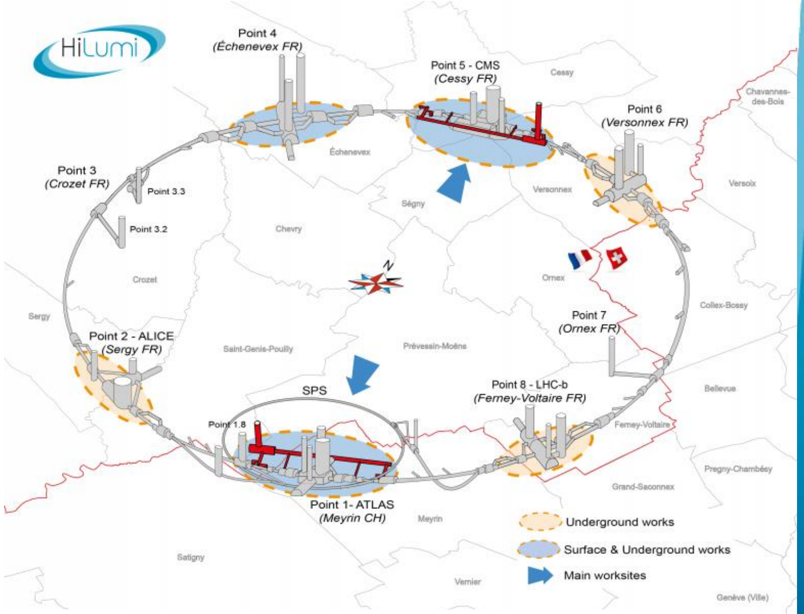
The high luminosity LHC (HL-LHC)

- Scope: LHC upgrade to reach 10 times more collisions data in the period 2030-2045
  - Same collision energy of 13.6 TeV center of mass
  - LHC will accumulate order of 30×10^{15} collisions in the years 2010-2025 (300 fb^{-1})
  - HL-LHC will accumulate 10 times more data (3000 fb^{-1})

  How ? [O. Bruning, L. Rossi, "The HL LHC" (2015) World Scientific]
  - More protons in the beam
  - Larger aperture magnets → More focussed beam
  - Better geometry of the collisions (crab cavities)
- Nb_3Sn technology will be used for the first time in the interaction region of a collider

[E. Todesco, et al., SUST 34 (2021) 053001]
  - As it was done 45 years ago in ISR with Nb-Ti
- A superconducting link in MgB_2 will be used
  - This will be another prima in applications of SC to HEP

  [A. Ballarino, J. P. Burnet, "The HL LHC" (2015) World Scientific Chapter



HL-LHC project [L.Rossi, O. Brüning et al]

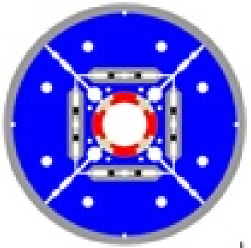
The US LHC accelerator R&D program

- In 2004, US-DOE launched the LARP to support the LHC luminosity upgrade – direct R&D program
- This program (2004-2015) paved the way to HL-LHC approval
  - Proof of performance achivement, peak fields of 10-11 T
  - Selection of the structure based on Al shell (so-called bladder and keys)

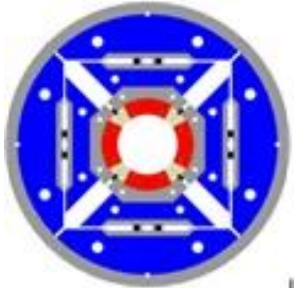
    [S. Caspi, et al. IEEE TAS 11 (2001) 2272]
  - LARP proved the first scaling in length for Nb_3Sn to 3.4 m on TQ

[S. Gourlay, et al. IEEE TAS 16 (2006) 324]

3.4 m long Nb_3Sn magnet [G. Ambrosio, et al. IEEE TAS 17 (2007) 1035]



TQS



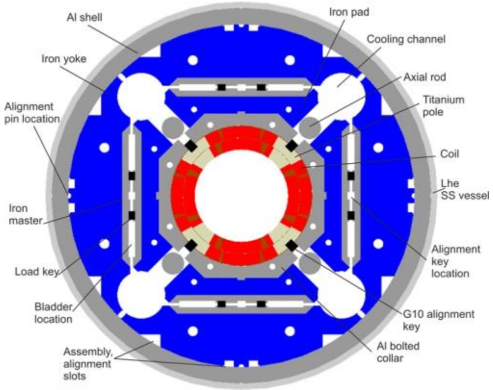
HQ

The Nb_3Sn triplet magnets MQXF

- Large aperture: 150 mm diameter
  - 110 MPa of accumulation of stress in the midplane due to e.m. forces
- US: 20 units of 4.2 m long quadrupoles
- CERN: 10 units of 7.15 m long quadrupoles
- Operational parameters (at 7 TeV)
  - 11.3 T peak field in the coil
  - 462 A/mm^2 overall j
  - Operates at 77% on the loadline
- Conductor: 40 strand cable, 0.85 mm strand
  - High j_c Nb_3Sn strand RRP B-OST, 1280 A/mm^2 at 15 T, 4.22 K
  - Production of more than 3000 km of 0.85 mm diameter strand, with cable unit lenghts of 500 m and 800 m

[J. Fleiter, et al. 2LOr2E-03]

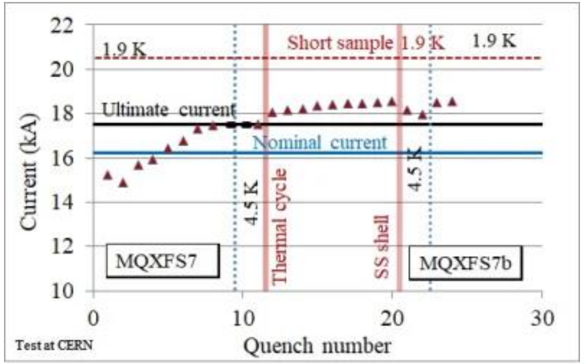
[L. Cooley, et al. FCC week (2024) https://indico.cern.ch/event/1298458]

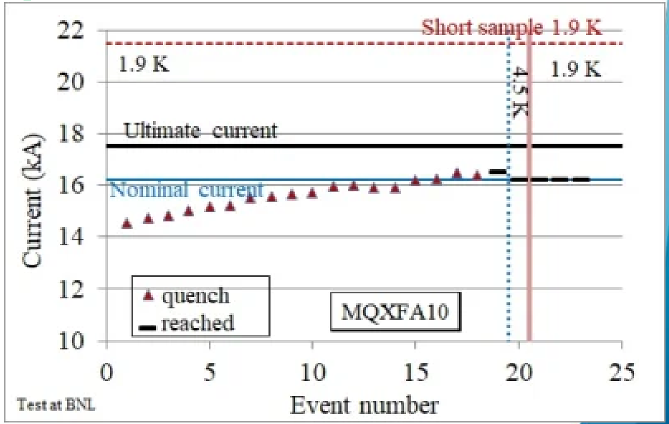


MQXF cross-section
(P. Ferracin, G. Ambrosio, et al. IEEE TAS 26 (2016))

Results: reproducibility

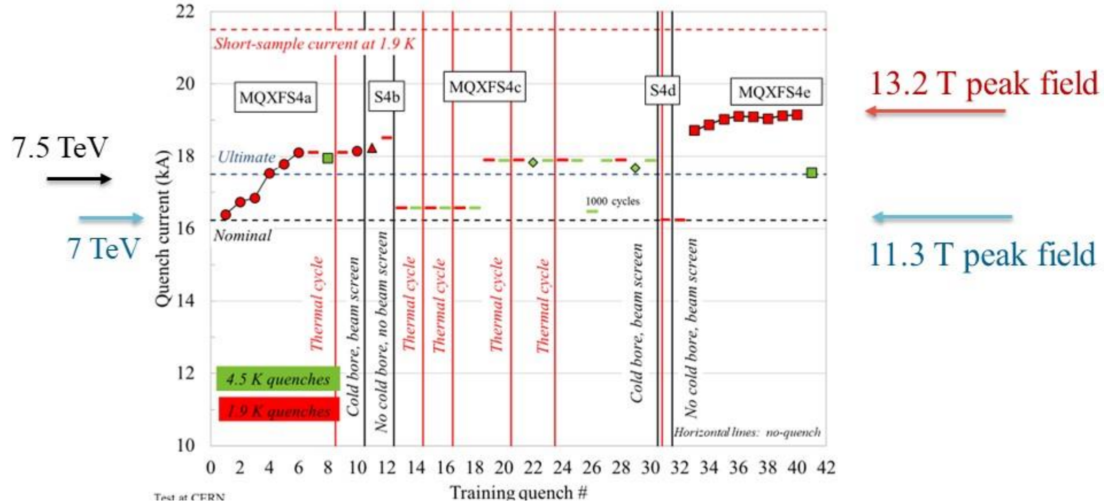
- 1-m-long models: 6 reaching performance out of 7
- 4.2-m-long magnets:
  - Two prototypes not reaching performance
  - 11 out of 12 series magnets reaching requirements
  - (3 magnets required a coil replacement, one to be done)
- 7.15-m-long magnets: [S. Izquierdo Bermudez et al. 2LOr2E-01]
  - Two prototypes not reaching performance,
  - 4 out of 4 series magnets reaching requirements
  - (issue with performance limitations has been solved)
- Full statistics and timeline in the appendix



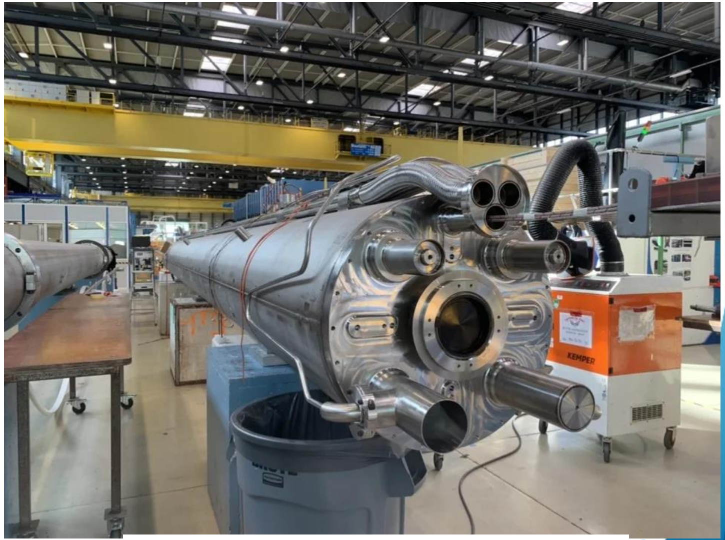


Results: operational margins

- Short models
  - Reached 1.5 – 2 T more than requirements (above 13 T) [F. Mangiarotti, et al. 2LOr2E-02]
  - Reached systematically operational field also at 4.5 K
- Long magnets are not powered above nominal
  - Reached systematically operational field also at 4.5 K (>2.5 K temperature margin)



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

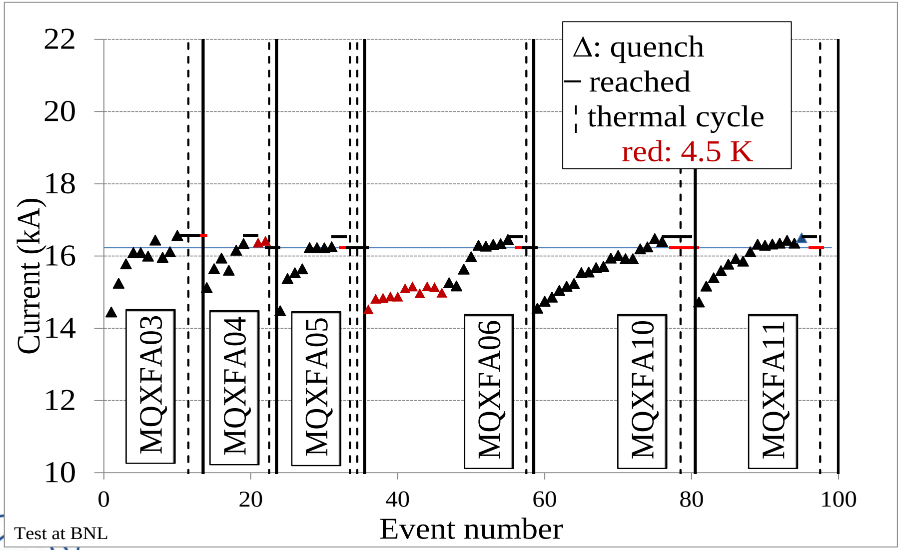


One of the first 7-m.long Nb_3Sn magnets

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Plenary presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Results: endurance and resiliance

- Endurance:
  - Several thermal cycles both on short and on long magnets, showing no degradation
- Resiliance
  - Accident during transport for MQXFA11, 10 g experienced, magnet reached performance

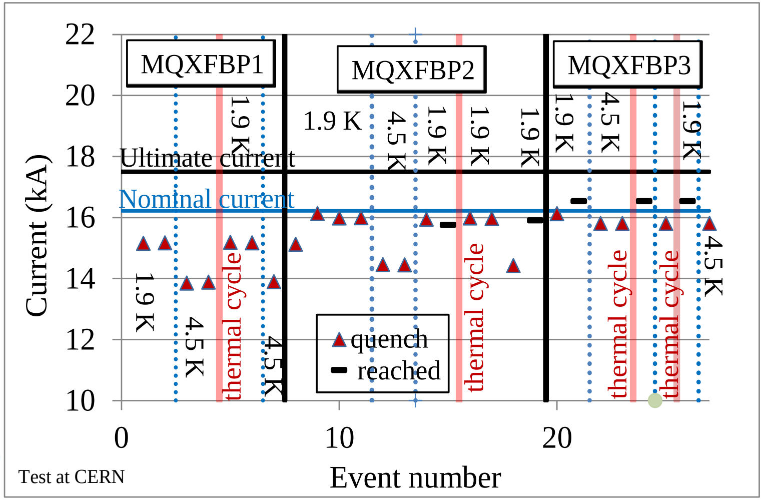


Powering test of first six conform MQXFA magnets
[J. Muratore, B. Ahia, S. Feher, G. Ambrosio et al.]

Non conform MQXFA11 transport

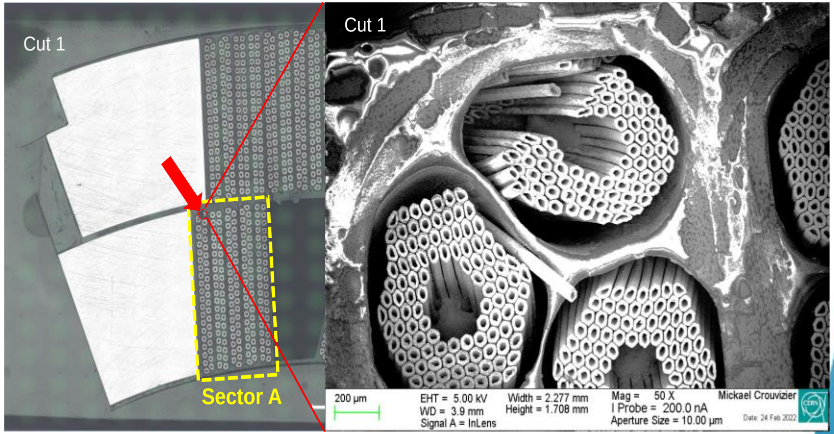
Results: overcoming limitations

- The first two 7-m-long prototypes did not reach requirements
  - The following two reached requirement, but still show performance limitations at 4.5 K
  - MQXFBP1 was disassembled, and longitudinally broken filaments were found in the limiting coil
  - The issue was removed by not having the binder in the outer layer of the coil (note that the US collaboration kept the original baseline, not seeing this issue)



MQXFB prototypes performance

[S. Izquierdo Bermudez, F. Mangiarotti, et al. IEEE TAS 33 (2023) 4001209]



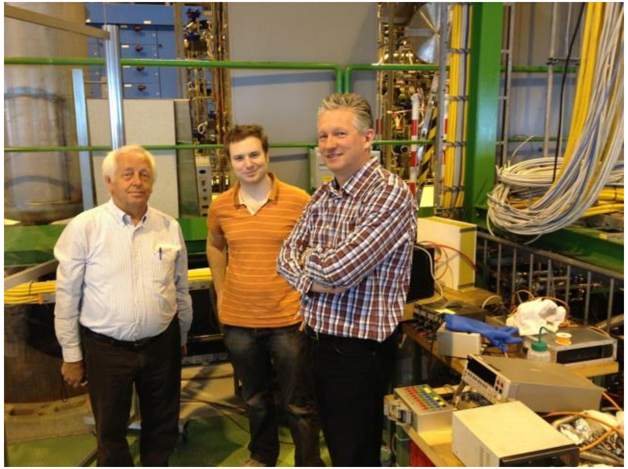
Broken filaments in coil 108, limiting MQXFBP1

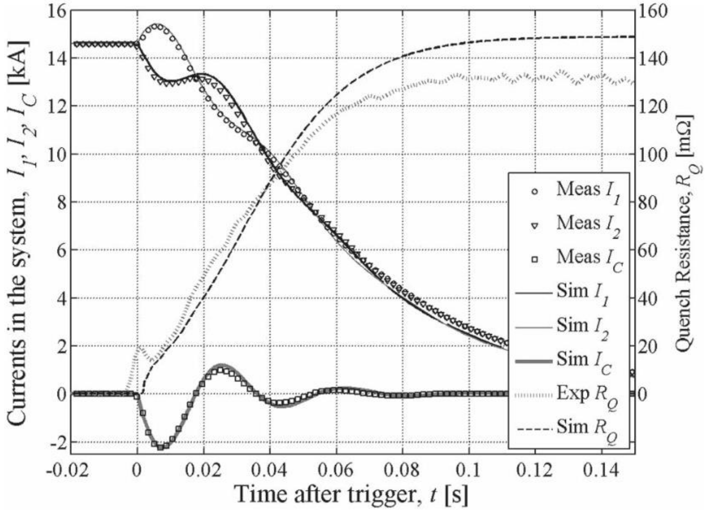
[A. Moros, S. Sgobba, et al. IEEE TAS 33 (2023) 4000208]

[I. Santillana, et al. SUST 37 (2024) 085007]

Results: new paradigm for protection

- HL-LHC uses CLIQ as a protection system, together with the standard technique of outer layer quench heaters
  - CLIQ units provoke a quench in the coils via the discharge of a capacitor and the ensuing current pulse
  - Developed at CERN by G. Kirby, V. Datskov, and E. Ravaioli in 2013-2018





CLIQ discharge in MQXF magnets [E. Ravaioli, et al, IEEE TAS 25 (2015) 4001305]

- This technique also used in China to protect short models magnets for SPPC

Lessons to be taken

- HL-LHC project is proving the viability of Nb_3Sn magnets with 11.5 T peak field and up to 7 m long
  - 30 full size magnets are being produced, with the same design, in US and at CERN: we are halfway
  - Magnets are compatible for operation in the HL-LHC in terms of performance, endurance, field quality, protection, etc ..
- Short models reached systematically >13 T peak field, i.e. 1.5 T more
  - For preload and limits in stress, see [F. Mangiarotti, et al., 2LOr2E-02 and G. Vallone, et al. 2LOr2E-05]
- Magnets built in three production lines (two in the US and one at CERN): this is the first requirement for industrialization
- Synergy betweeen US and CERN has been instrumental in the project success

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Plenary presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Contents

First solenoids

ISR

Tevatron 4.3 T Nb-Ti dipoles

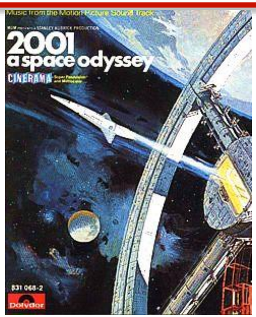
CERN Elin Nb_3Sn 9.5 T

8 T LHC Nb-Ti dipoles

2015 to 2050:

magnets for colliders towards 100 TeV

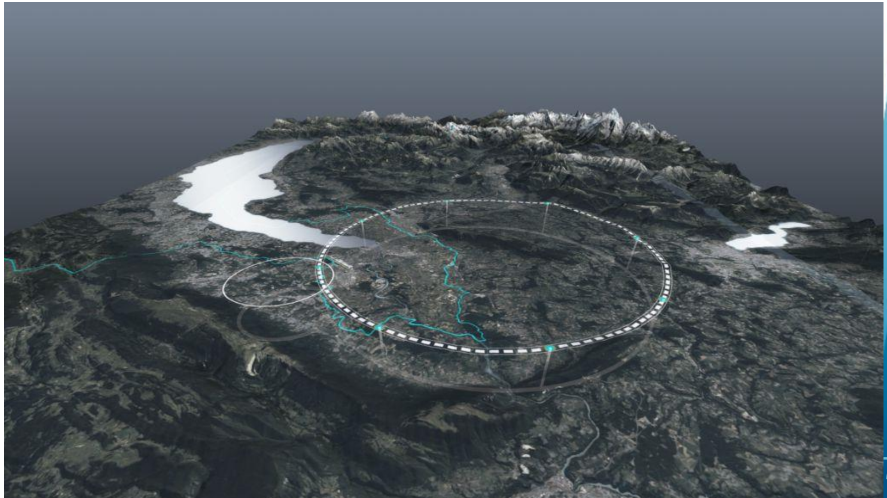
1960 1970 1980 1990 2000 2010 2020 2030 2040 2050



FCC-hh requirements: a 100 TeV collider at CERN

- First baseline: 16 T magnets, 100 km tunnel, 100 TeV [M. Benedikt, et al., FCC-hh CDR, EPJST 228 (2019)]
- Nb_3Sn option for FCC-hh: a proton-proton collider for 90 TeV c.o.m energy in a 91 km tunnel, based on 14 T operational field magnets
    - Note that to have 14 T operational field, the magnets should prove to be able to reach 15-15.5 T in standalone tests
- An 100-120 TeV option based on HTS is also proposed (see last part), with 16-20 T field

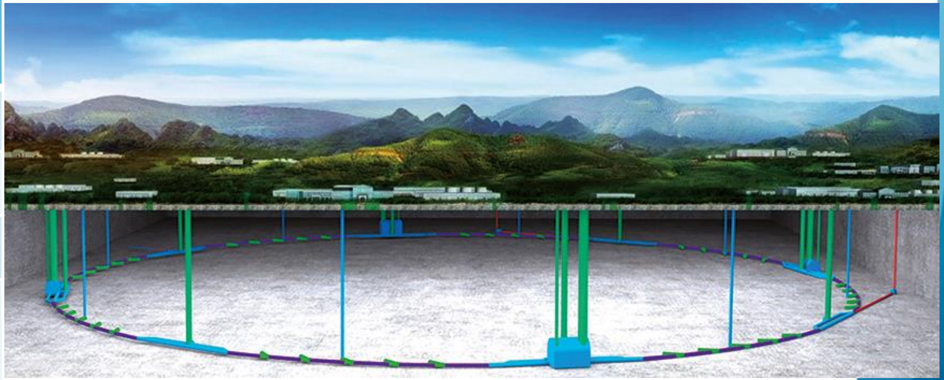
FCC-hh parameters	CDR 2019	2024-Nb_3Sn	2024-HTS
Dipole field (T)	16.0	14.0	16-20
Tunnel length (km)	100	90.7	90.7
Arc length (km)	82.0	76.9	76.9
Arc filling factor (adim)	0.80	0.87	0.85
Energy c.o.m (TeV)	100	90	100-125
Loadline margin	86%	80%	TBD



SPPC requirements: a 100 TeV collider in China

- A 100 km tunnel, initially with two options for the main dipoles [CDR of 2019]
  - A 12 T magnet based on Nb_3Sn (and common coil design)
  - A 20-24 T magnet based on HTS (IBS or REBCO conductor)
- Updated version of CDR: 100 TeV with a 20 T magnet based on Nb_3Sn and HTS, with a common coil geometry http://cepc.ihep.ac.cn/CEPC_tdr.pdf
  - 13 T given by Nb_3Sn
  - 7 T by HTS insert (REBCO or IBS)

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



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Superconductor needs

- Order of 0.5 to 1 TA m: half to one million of km of cable carrying 1 kA
  - Equivalent to 1 kA superconducting cable/wire connecting 1.5 to 3 times the distance of the Earth to the Moon

		Energy c.o.m.	Field	**Total**
		(TeV)	(T)	**(TA m)**
LHC	Nb-Ti	7.0	8.3	**0.067**
FCC-hh	Nb_3Sn	90	14	**~0.5**
FCC-hh	HTS	125	20	**~0.9**
SPPC	HTS	125	20	**~0.9**

Three programs

- MDP - US
  - Generic R&D for high field dipoles for HEP
  - 20 T target, stress management design, reduction of training, operating towards ss
  - Hybrid magnets HTS/Nb_3Sn
  - >14 T proved with Nb_3Sn, but followed by degradation
- EuroCirCol, followed by HFM programme - CERN
  - Direct R&D for 14 T Nb_3Sn dipoles for FCC-hh
  - Direct R&D for 16-20 T dipoles with HTS (hybrid or not)
  - Focus on sustainability, and cost
  - >16 T field proved in a magnet with 50 mm aperture but without flared ends
- IHEP programme - China
  - Direct R&D for 20 T dipoles for SPPC
  - 4.5 K operational temperature, hybrid Nb_3Sn/HTS, common coil
  - 12.5 T reached with 14 mm aperture diameter, common coil, racetracks

U.S. MAGNET DEVELOPMENT PROGRAM

HFM High Field Magnets Programme

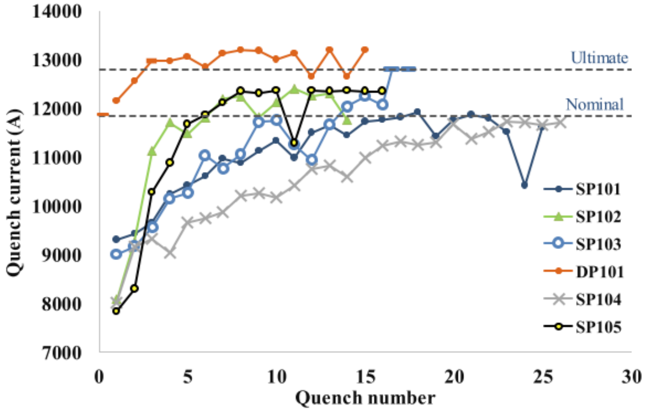
中国科学院高能物理研究所 Institute of High Energy Physics Chinese Academy of Sciences

Cosθ designs

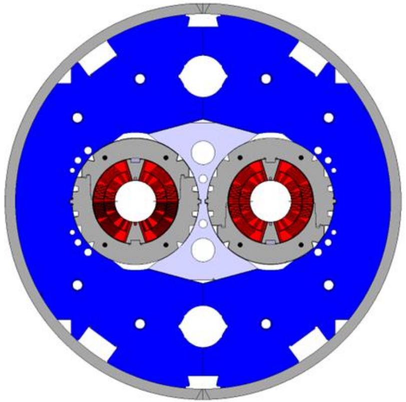
- 2011-2021: 11 T (CERN and FNAL)
  - Efficient magnet with 490 A/mm^2 overall current density
  - Some short models reached 12 T bore field, but with lack of reproducibility [see C. Abad Cabrera et al., 4LOr2E-06]
  - First two-in-one Nb_3Sn dipole
  - First Nb_3Sn dipole with all features for integration in an accelerator
  - CERN made first scaling to 5.5 m, reaching >11 T, but many magnets showed performance degradation

12.0 T

11.3 T



[G. Willering, et al. IEEE TAS 28 (2018) 4007205]

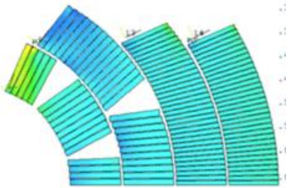


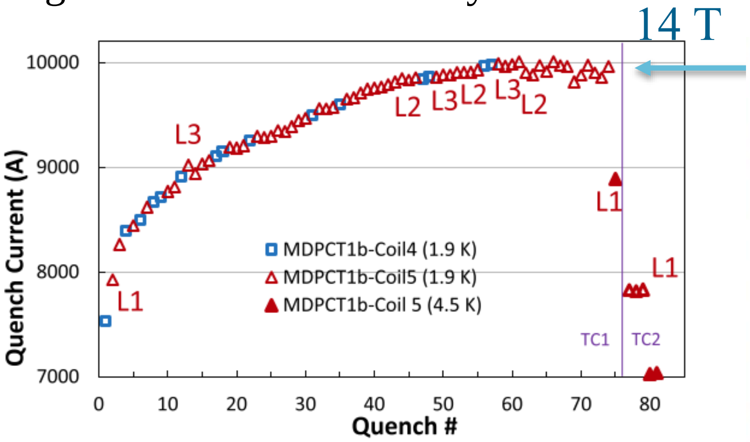
[M. Karppinen, et al. IEEE TAS 22 (2012) 4901504]
[S. Zolbin, et al. IEEE TAS 25 (2015) 4002209]

Cosθ designs

U.S. MAGNET DEVELOPMENT PROGRAM

- 2015-2020: MDPCT1 (FNAL) a four layer cosθ magnet
  - World record of 14.0 T at 4.5 K, level also reached at 1.9 K – first magnet above 14 T with « reasonable » coil width (50 mm)
  - Severe degradation after thermal cycle





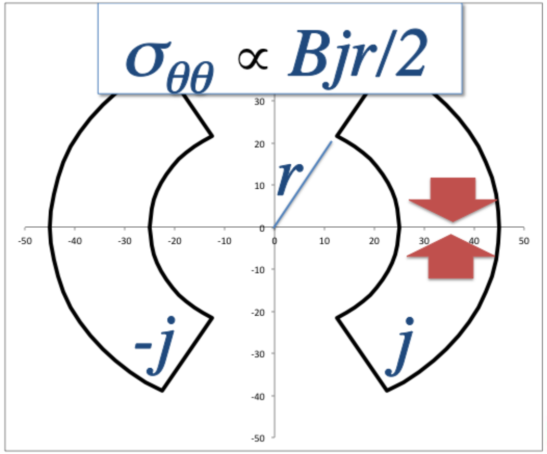
Power tests of MDPCT1 [S. Stoynev, et al. IEEE TAS 32 (2022) 4000705]

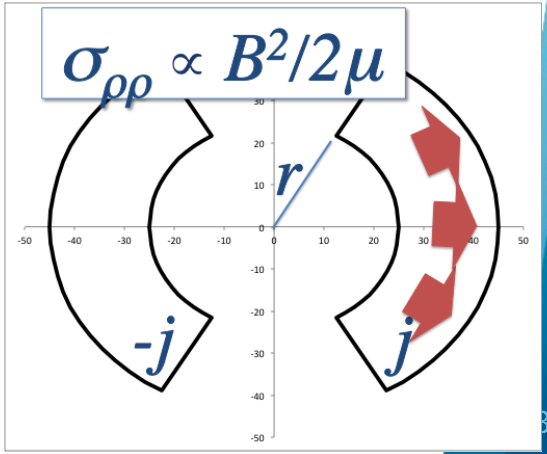
- FNAL abandoned this path, in EU this line is continued
  - A two layer cosθ magnet aiming at 12 T at INFN and CERN, test foreseen in 2026
  - A four layer cosθ magnet aiming at 14 T at INFN, test in 2029

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Plenary presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

How stress scales for sector coils

- There are two different types of stress in a sector coil
  - That have a totally different scaling on magnet parameters
- Accumulation of azimuthal stress in the midplane
  - Scales with *r* (aperture radius), *B* and *j*, times a shape factor
  - Higher fields B can be compensated by lower j
- Accumulation of radial stress
  - Scales with magnetic pressure $B^2/2\mu$, factor in front is about 1.5
  - At 14 T you get towards 150 MPa

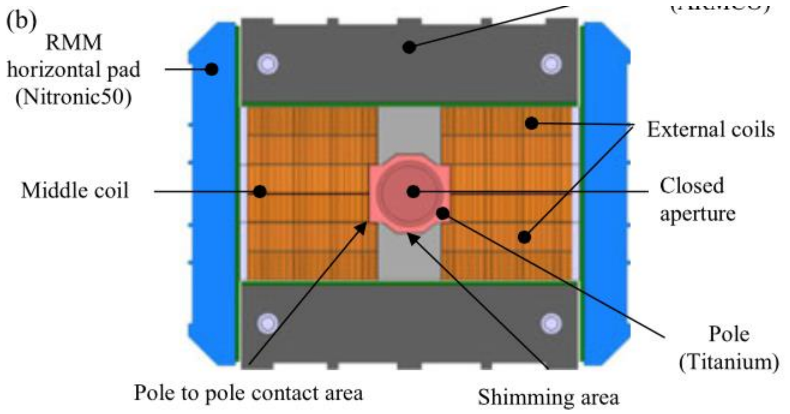




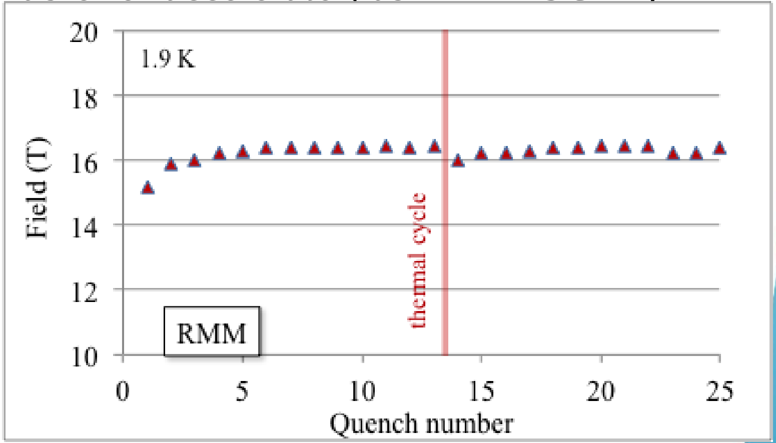
Some cases	Tevatron	LHC	14 T	20 T
Field (T)	4.4	8.3	14	20
Aperture radius (mm)	38.05	28	25	25
Overall j (A/mm^2)	360	400	400	400
$rBj/2$ (MPa)	31	46	70	100
$B^2/2\mu$ (MPa)	7	27	78	159

Block design

- Block design has also an internal structure allowing to avoid azimuthal stress accumulation – so only the radial stress is left
- 2015-2023: RMM is a block magnet, without flared ends, that reached 16.4 T bore field in 50 mm aperture (but the coil is huge, not afforable for accelerator, as in FRESCA2)



RMM cross-section [S. Izquierdo Bermudez, et al. IEEE TAS 27 (2017) 4002004]



RMM powering E. Gautheron, et al. IEEE TAS 33 (2023) 4004018]

- Planned magnets (test in >2025)
  - A double layer 14 T dipole «a la HD2» developed at CERN
  - A four layer 14 T dipole «a la Fresca2» developed at CEA, but with grading

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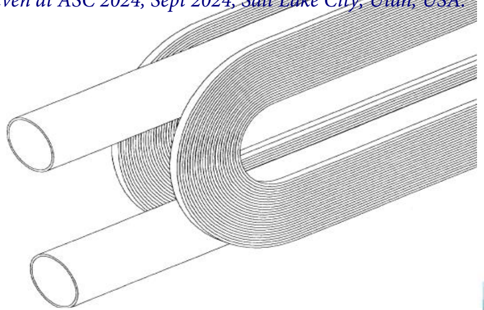
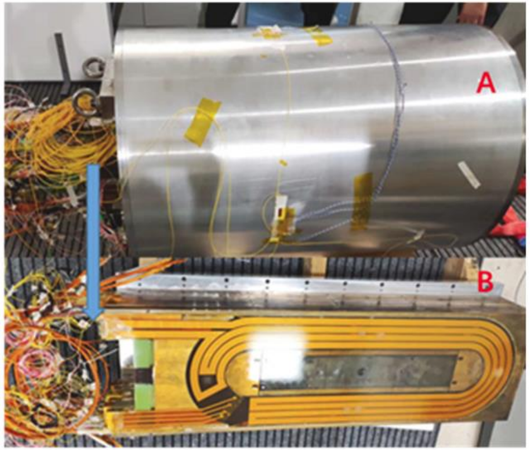
Common coil

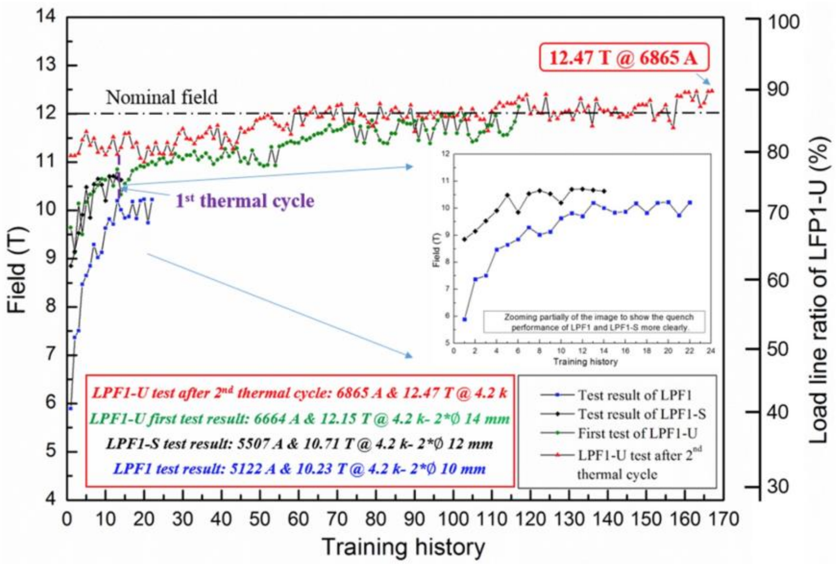


Common coil design [R. Gupta, IPAC 1997 3344]

- IHEP has chosen the common coil design
  - Steps aiming at final 20 T increasing field and aperture
  - 2018-2023 LFP1: 12.5 T reached within 14 mm aperture



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

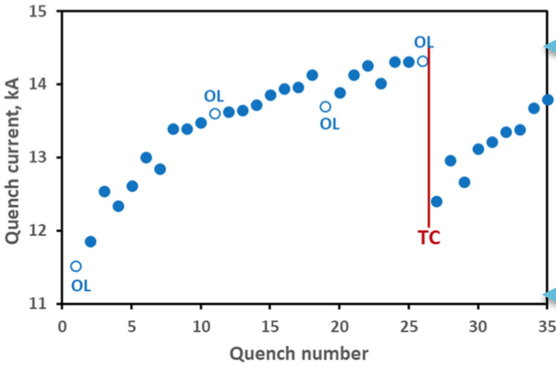


LPF1 training [C. Wang, et al., SUST 36 (2023) 065006]

- Ongoing or planned
  - IHEP is building LFP3 (13 T of LTS)
  - CIEMAT plans a 14 T common coil with Nb_3Sn only (see also C. Martins, 1LPO1G-08)

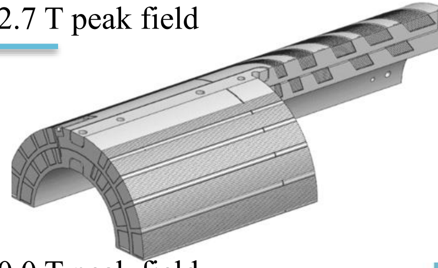
Stress management: cosθ and common coil

- Stress management consists in mixing the coil and the structure
  - Advantage: (i) Stress is intercepted at each block of conductors and (ii) the structure enthalpy can contribute to protection
  - Possible disadvantage: preload is not (or only partially)
- FNAL: SMCT (stress managed cos theta)
  - Cables blocks are wound in a former
  - Cos theta configuration with radial and azimuthal stress interception
  - Mirror reached 12.7 T peak field (87% ss))
- PSI: SMCC (stress managed common coil)
  - Racetracks wound in a former
  - Subscale reached 7 T peak field
  - Full scale magnet in 2025-2026

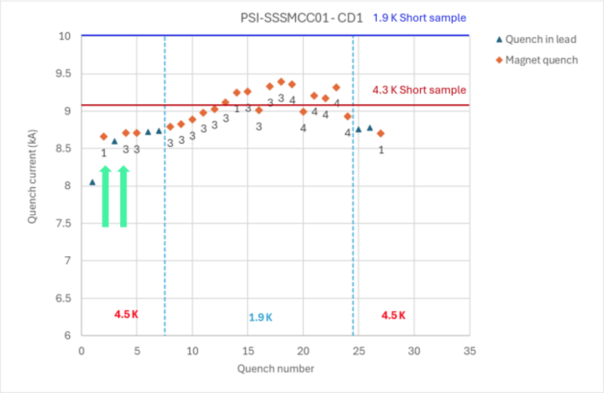


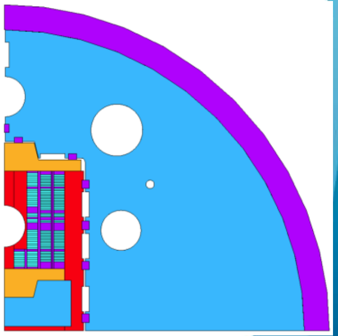
12.7 T peak field

10.0 T peak field



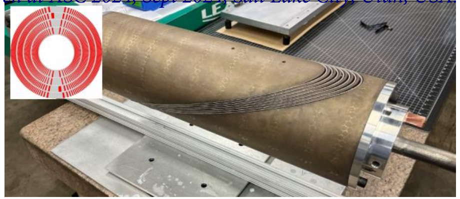
[A. Zlobin, 4LOr2E-01] I. Novitski, et al. IEEE TAS 34 (2024) 4001305]



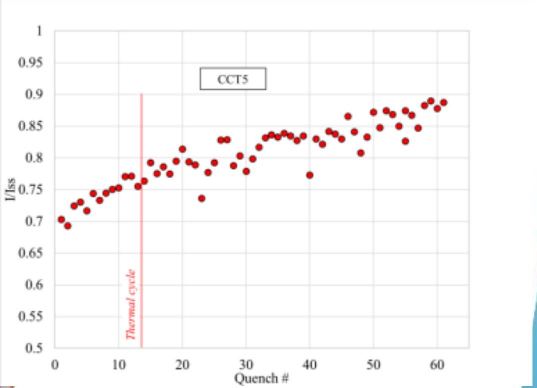


[D. Araujo, et al. ASC 2024]

Full stress management: CCT



- Canted cos theta is the extreme case of stress management
  - Winding on a former following the shape of a tilted solenoid: each cable turn is supportetd by the structure [D. Meyer, R. Flask, NIM (1970)] : less efficient use of conductor, but a modular design, allowing adding layers
- LBNL worked on this design since 2010
  - CCT5 in Nb_3Sn: 8.5 T in 90 mm aperture
  - [D. Arbealez, et al. IEEE TAS 32 (2022) 4003207]
- PSI reached 10.1 T in a 66 mm aperture
  - Using Nb_3Sn, design based on CCT5
  - [B. Auchmann, et al. IEEE TAS 34 (2024) 4000906]
- MDP is also building HTS magnets
  - 1.5 T reached with Bi2212 CCT in 31 mm ap.
  - 2.9 T with REBCO CCT in 65 mm ap. (LBNL)
  - 1.5 T with REBCO COMB (FNAL)
  - [P. Ferracin, et al. 4LOr1B-01]

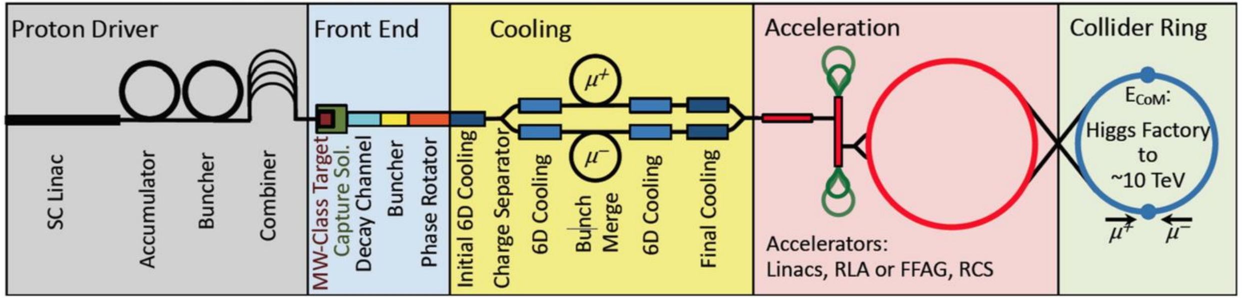


Lessons to be taken

- Stress managed structures are a new paradigm, mixing structure and coil : this allows avoiding stress accumulation and could ease protection since the structure could take part of the energy and increase the current density
  - However, you lose the possibility of preloading the coil → training can become an issue
  - Stress management can allow to use higher current densities, i.e go to more efficient magnets
  - At 20 T stress managed magnets are mandatory: US-MDP and PSI are investing on this option
- Up to 14 T operational field stress interception (management) is not mandatory, but can provide precious additional margin for a long production as for SPPC or FCC-hh
- The worldwide efforts are focussed on different designs
- Continuous (order of >10 years) and coherent efforts are the key to success

Muon collider requirements

- Muon collider is an idea that is in the community since at least 30 years: colliding muons
  - Muons have larger mass then electrons → much less synchrotron radiation
  - Muons are not composite particles as protons → (cleaner events)
  - Muons rapidly decay → they have to be accelerated very rapidly



- Many interesting magnets
  - High field solenoids (>>20 T)
  - High field magnets

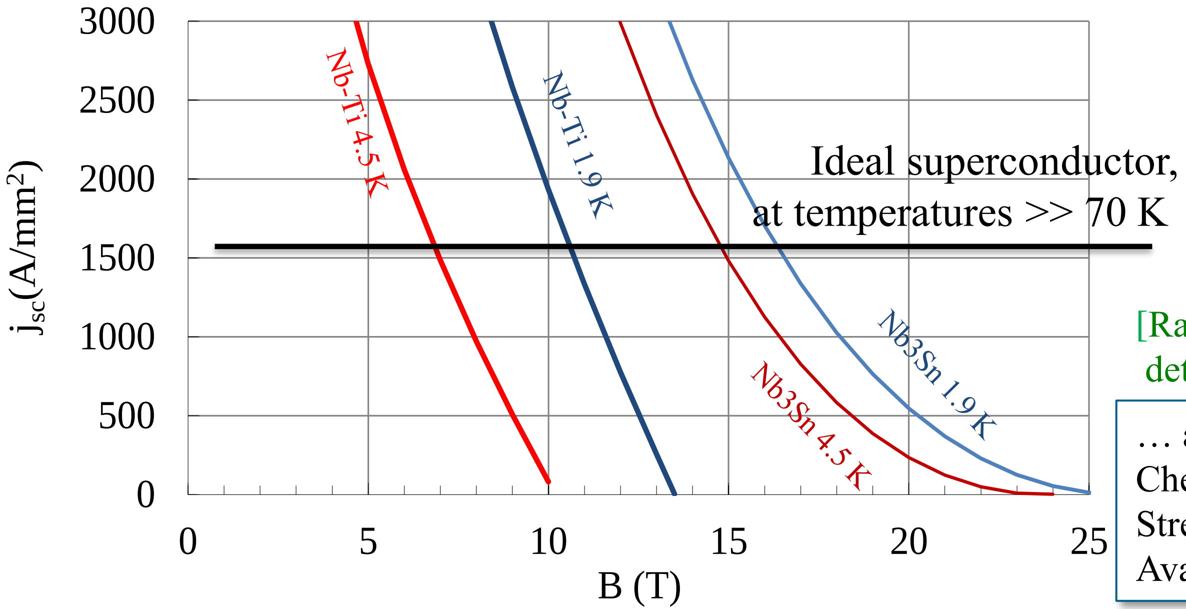
Complex	Magnet	Aperture (mm)	Length (m)	Field (T)
Target, decay and capture	Solenoid	1200	19	20
6D cooling	Solenoid	90…1500	0.08…0.5	4…15
Final cooling	Solenoid	50	0.5	> 40
Rapid cycling synchrotron	NC Dipole	30x100	5	± 1.8
	SC Dipole	30x100	1.5	10
Collider ring	Dipole	160…100	4…6	12…16

[L. Bottura et al. IEEE TAS 34 (2024) 4005708, 1LOr2E-01 – B. Caiffi, 1LOr2E-02]

Contents

The ideal superconductor would have …

- … 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

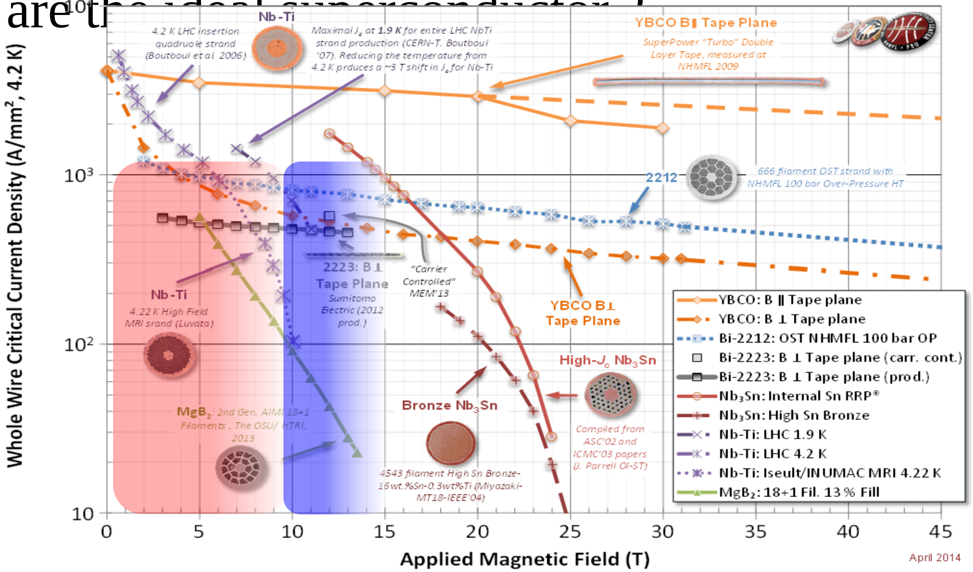


[Raffaello et al., The School of Athens, detail, Musei Vaticani (1510)]

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

The ideal superconductor for accelerator magnets

- … 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
- HTS are the ideal superconductor ?



[courtesy of P. Lee]

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

… and
Cheap: 5 \$/(kA m)
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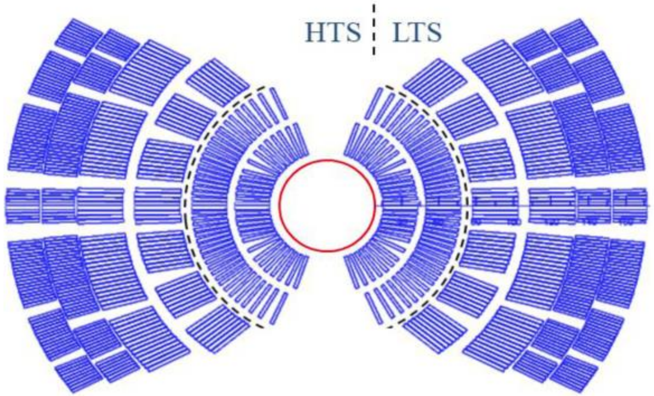
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Plenary presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Three conductors for HTS

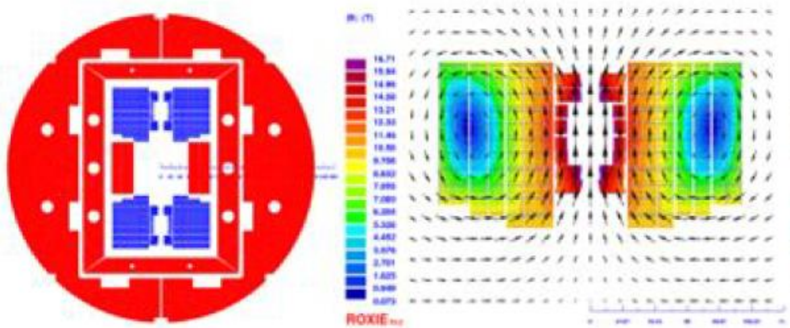
- BSSCO 2212 (mainly developed in the USA [T. Shen, 3MOr1A-01])
  - Available in round strand, dipole magnets reaching 1.5 T have been done in LBNL (1.5 T)
  - Expensive, complicated manufacturing process (more than Nb_3Sn): reaction at 800 C in 100 bar of O_2
- REBCO (a hope for a very fast track to fusion, [see plenary talk of D. Dunn])
  - Recently, large reduction of cost, but still one order of magnitude above what needed in the unfavorable direction, and with limited lengths
  - Available in tape, cable geometries are being considered (Roebel, Corc®, Star ®)
  - Hysteresis losses can be a showstopper: the filament is the tape width
- IBS (strong impulse from China) [see plenary talk of K. Iida]
  - Critical current is improving
  - Potentially cheaper than REBCO

Two options: hybrid or full 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 notalways not totally intuitive
- «Hybrid» makes use of HTS in higher field regions, and of cheaper Nb_3Sn up to 15 T
  - This option is being developed in the US by MDP, and in China by IHEP



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]

The challenge of hysteresis for tapes

- 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
- 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

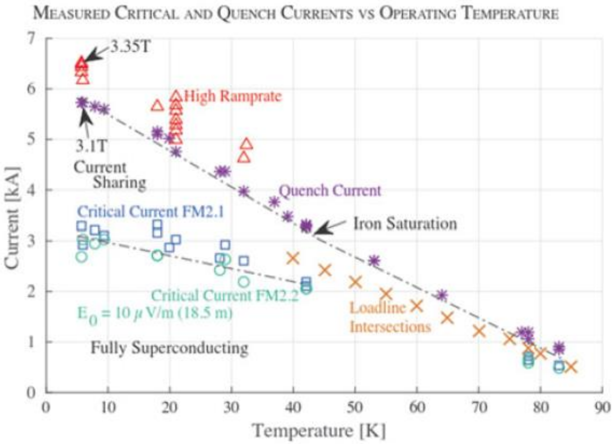
$$\frac{d}{2} < \frac{1}{j_c}\sqrt{\frac{3\gamma C_p\left(T_c - T\right)}{\mu_0}}$$

- Feather magnet tested in 2017

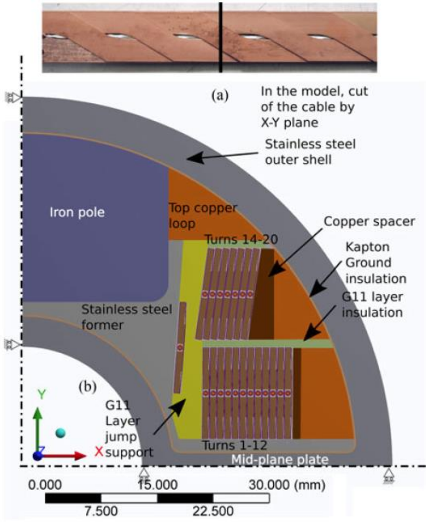
had block aligned: it reached 4.5 T

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

Is REBCO tape a viable conductor for HEP main dipole magnets ?



First powering of Feather
[L. Rossi, et al, IEEE TAS 28 (2018) 4001810]

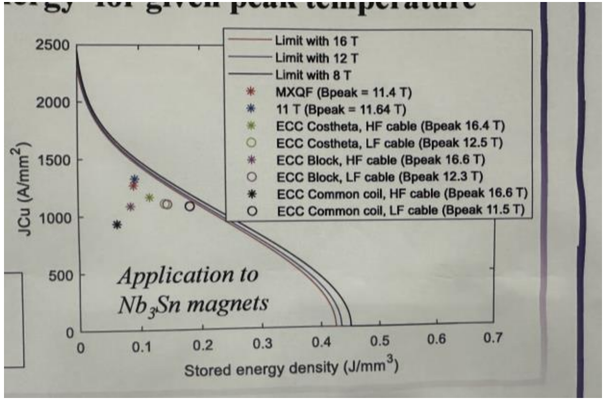


Aligned block design in Feather
[J. van Nugteren, G. Kirby, et al, IEEE TAS 25 (2015) 4000705]

The challenge of protection and detection

- Thanks to the larger temperature margin the quench velocity in HTS is very small – detecting the quench is troublesome and takes much more time than in LTS
- Moreover: magnetic pressure ⟷ energy density ⟷ enthalpy

Field	Pressure	Energy density
B (T)	$B^2/2\mu$ (MPa)	$B^2/2\mu$ (J/mm^3)
5	10	0.010
10	40	0.040
15	90	0.090
20	160	0.160



[see T. Salmi, et al, 1LPo1I-04]

- Three strategies
  - Have the structure participating to the removal of the heat (as in stress managed magnets?)
  - Invent a cheap extraction system for long magnets that can be applied to every magnet

[see ESC system, E. Raxaioli, et al, 1LPo1G-01]

  - Avoid quench

Lessons to be taken

- HTS opens a path towards operational fields higher than 15 T and higher operational temperatures
  - This could also open the possibility of simpler cryogenic systems, and be more economical – however the global optimization of the systen is not trivial
- Today the adaptability of present state of the art of HTS tapes to main magnets for HEP accelerators is not proven
  - A large current cable, windable, is needed – many efforts in the past years but a clear solution is not yet available
  - We are not sure that the conductor itself is viable for very special requirements needed by HEP applications – is the hysteresis due to large filaments a showstopper ?
  - Field quality still very far from requirements
  - Protection at 20 T requires new paradigms
- The 20 T target makes us enter in «new physics», requiring a well defined strategy to prove within 5-10 years if HTS is a viable technology for HEP

Some personal final remarks

- There is no free lunch: every tesla is gained with lot of effort, time, and technical advancements
- Since our research timelines are very long, collaboration in space and in time between different teams is needed – competition does not work, joining the efforts is much more effective
- To handle information between generations and between labs, journals (and conferences) are fundamental: (i) write, even about setbacks (ii) travel (iii) read, read, read … and forget, and then read again
- Long time ago, colleagues were building magnets without computer codes: analytical methods are an essential tool that can give a lot of insight

Thanks !

First Nb3Sn quadrupole made in the US after reception at CERN, December 2023

Appendix

- Timeline of HL-LHC
- Timeline for FCC-hh
- About preload and degradation with stress

MQXF short model timeline

- 2013-2023: 7 short models built, 6 conform

T_0: aperture and cable selection

MQXFS1: ≥12.9 T

MQXFS3: ~10.6 T

MQXFS5: ≥12.7 T

MQXFS4: ≥13.1 T

MQXFS6: ≥13.4 T

MQXFS7: ≥13.2 T

MQXFS8: ≥13.1 T

11.6 T peak field corresponds to the gradient requirement for 7 TeV operation (also called nominal)

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027

T_0+3

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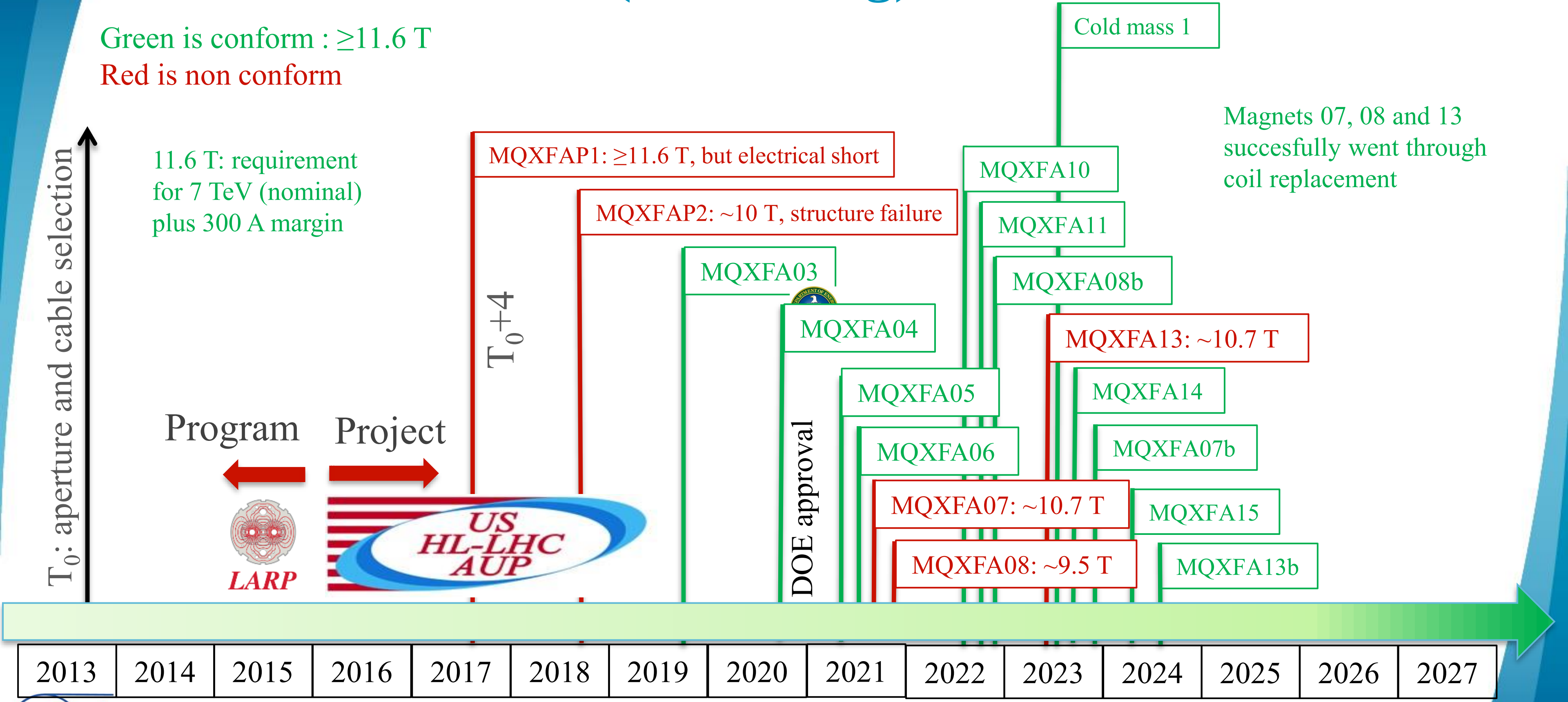
MQXFA (4.2 m long) timeline



11 magnet tested, 10 more new magnets to test (9,12,16-23)

MQXFB (7.15 m long) timeline

Green: conform ≥ 11.6 T
Red: non conform
Grey: to come

T_0: aperture and cable selection

MQXFBP1: ~10.5 T

MQXFBP2: ~11.2 T

MQXFBP3

MQXFB02*

MQXFB03

MQXFB04

This is the first Nb_3Sn magnet above 5.5 m lenght

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027

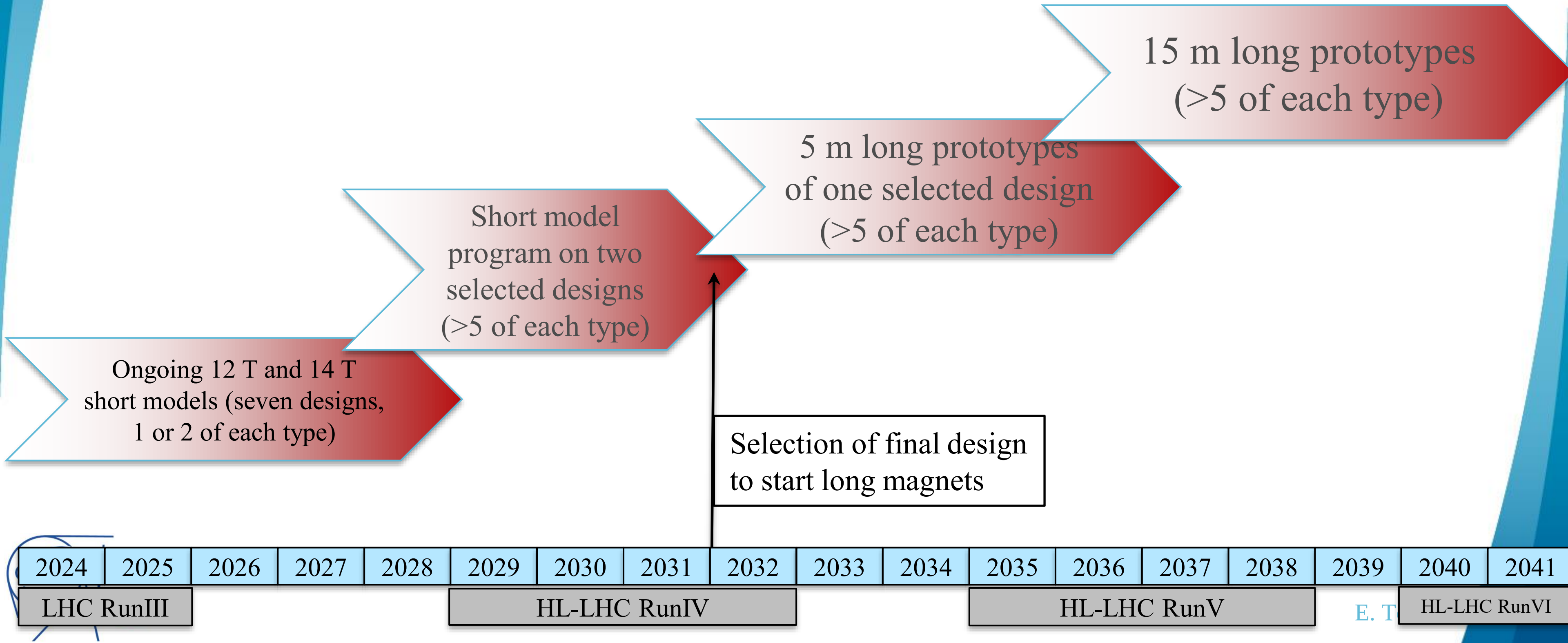
T_0+7

8 more magnets to test

* NC HV test, to be disassembled

Appendix

- A conservative timeline of FCC-hh for Nb_3Sn



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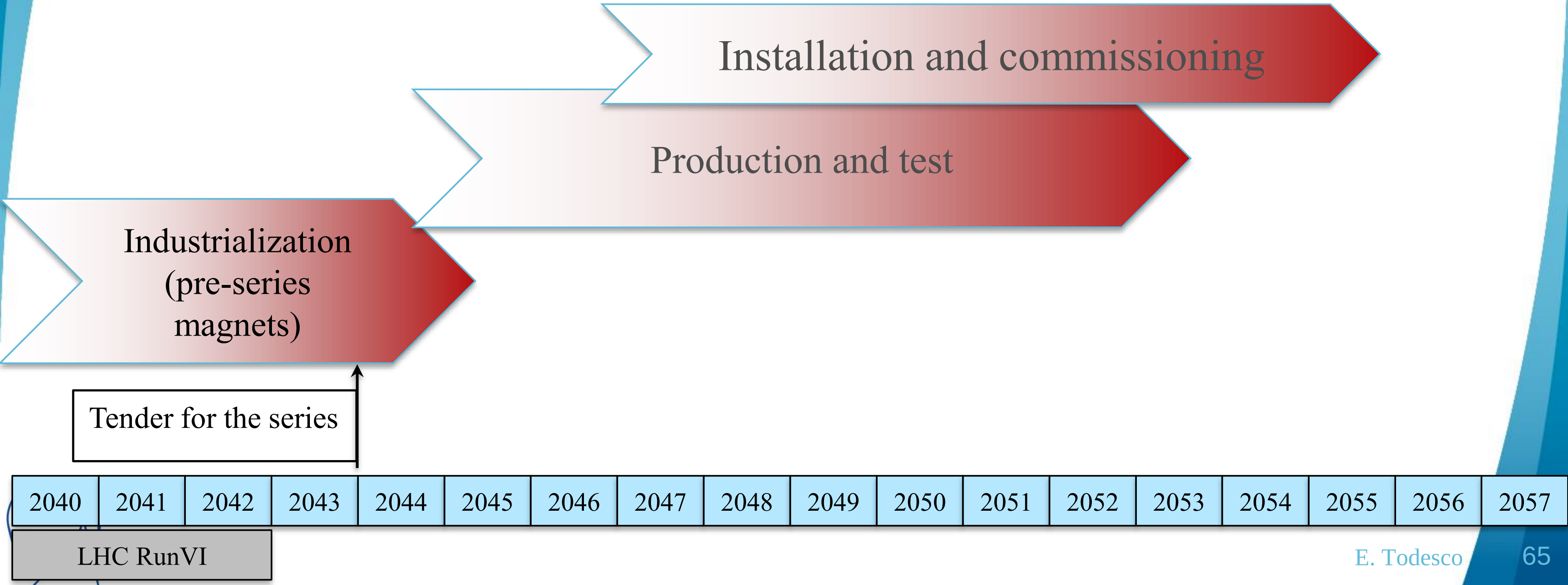
Appendix

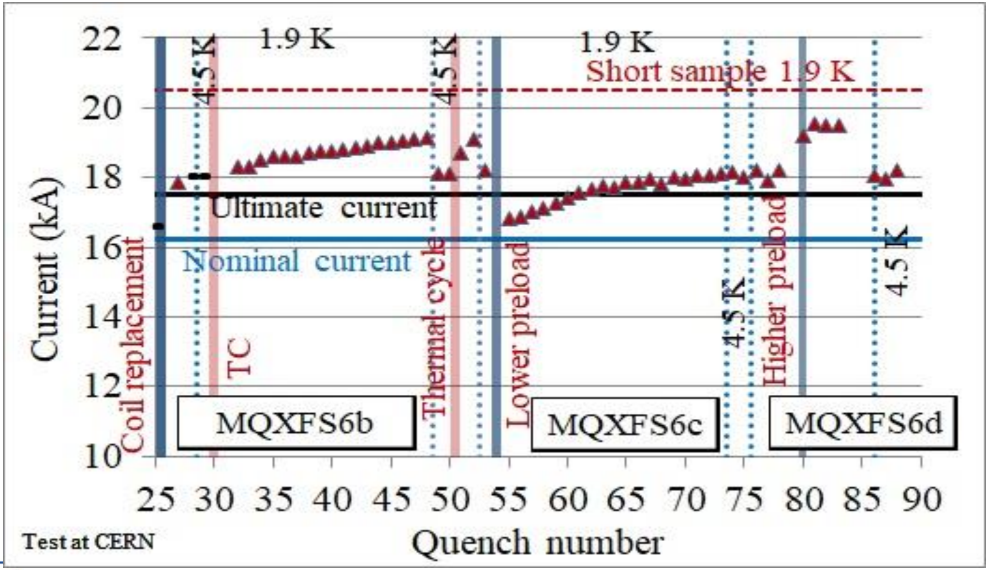
- A conservative timeline of FCC-hh for Nb_3Sn

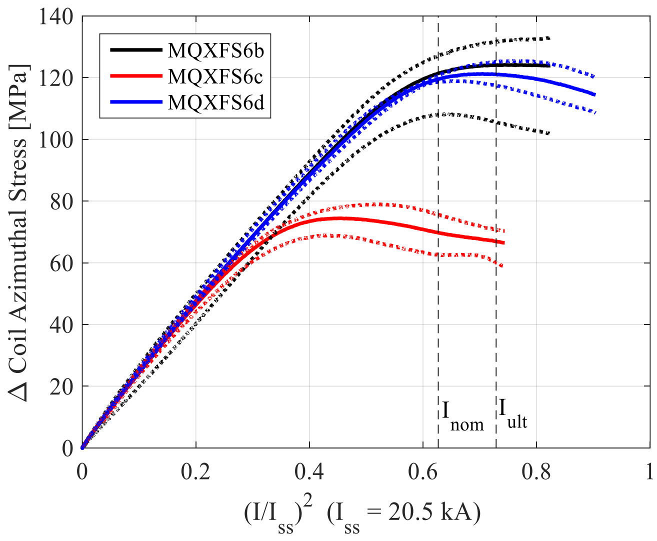


Preload matters (for cosθ)

- The structure based on Al shells aims at full preload just below nominal current
  - Very low preload has also been tested, corresponding to preload at 70% of nominal current: magnet was tsill able to operate at nominal current, but nearly 2 kA of maximum reachable current were lost

(S. I. Bermudez, et al., IEEE TAS 32 (2022) 4007106)





Preload experiment on MQXFS6 (S. Izquierdo Bermudez, F. Mangiarotti, et al.)

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Plenary presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Stress limits (for cosθ)

- Similar to what done in TQ magnet, higher preload were explored (up to 200 MPa)
  - Test is ongoing, at 200 MPa nominal performance is still reachable, but signs of performance degradation in the range above 90% of short sample limit – we are now going back to 120 MPa