High field magnets

F. Toral - CIEMAT

My deepest gratitude to D. Schoerling and D. Tommasini (CERN) for their unvaluable help to prepare this presentation

GOBIERNO DE ESPAÑA

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Ciemat

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Outline

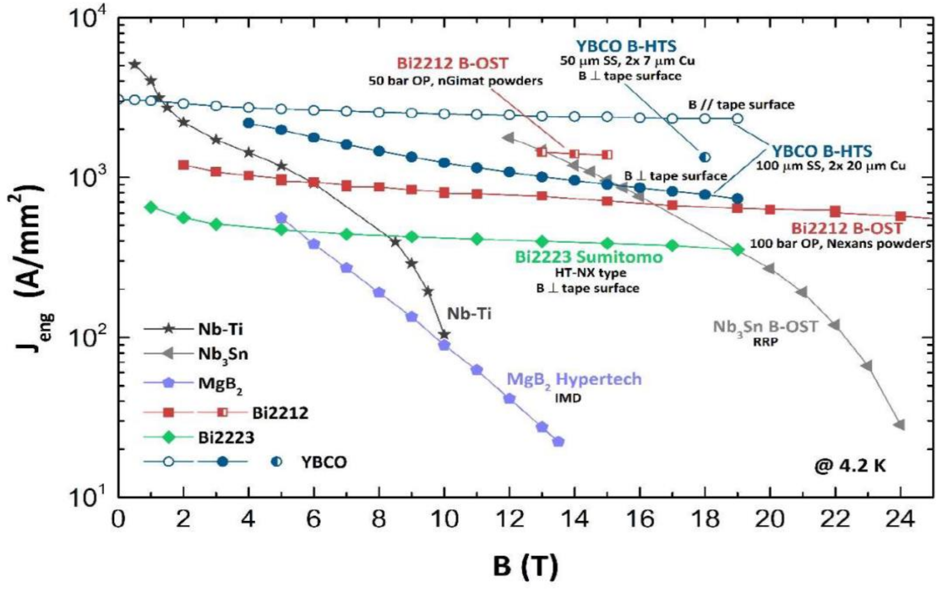
- Introduction
- Why is difficult to build a high field accelerator dipole?
- World wide efforts
- Conclusions

High field magnets: a key technology

- High field magnets are the key technology for a **future high energy circular collider**.

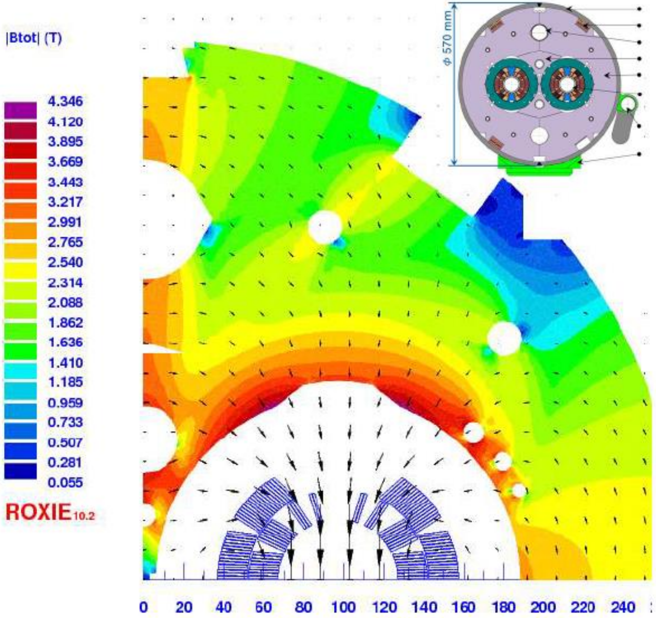
$$\vec{F} = q\vec{v} \times \vec{B} = \frac{d\vec{p}}{dt} = -m\frac{v_\theta^2}{\rho}\vec{u}_r \Rightarrow \frac{p_\theta}{q} = B_z\rho$$

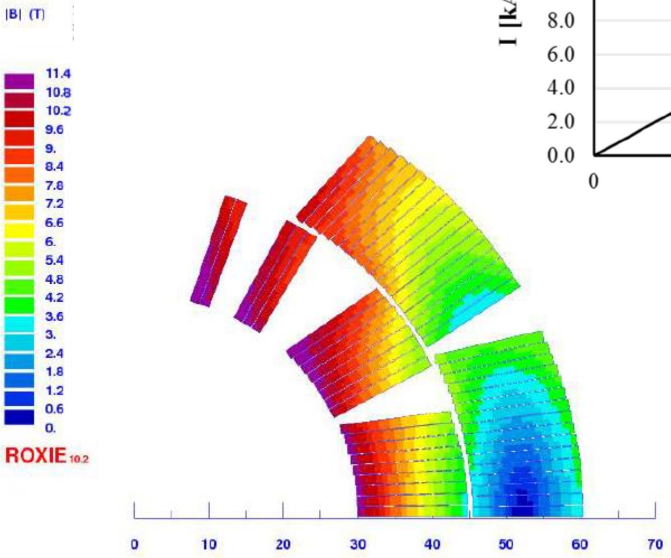
- LHC main dipole field is 8.3 T. They are based on **NbTi** coils.
- NbTi is an ideal material to produce cables, but it reached its limit at LHC dipoles.
- A different superconductor is needed for higher fields, but none of them can be easily produced as cables.
- Operating temperature is one of the main driving costs.

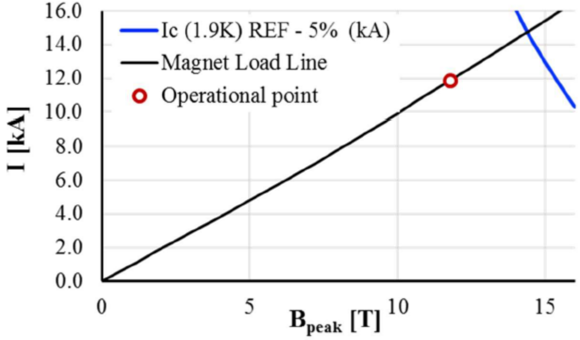


Increasing the field after LHC: HL-LHC

- **HL-LHC** highest dipole field is **11 T**. These magnets are based on Nb_3Sn coils.
- **Margin** on the load line is a key parameter for magnet design.

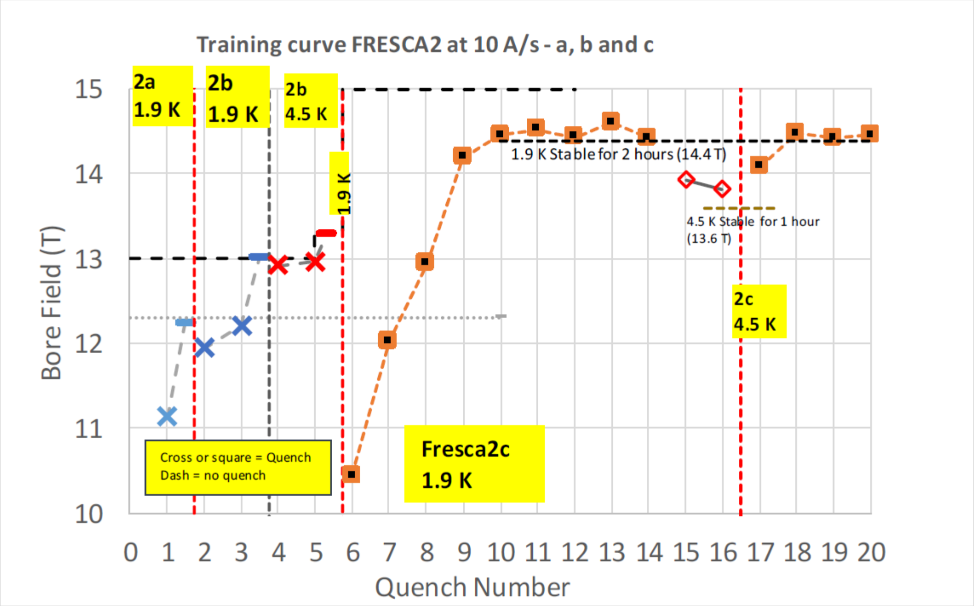






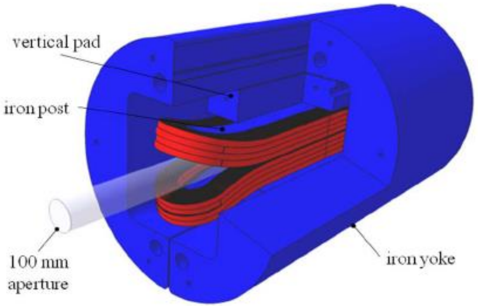
High field dipole world record: FRESCA2

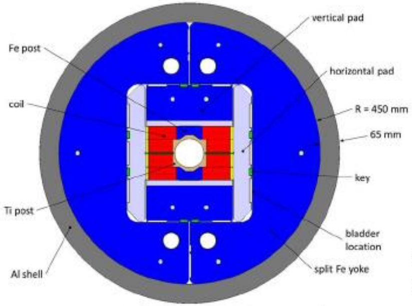
- The **present dipole field record** in a magnet with free aperture was established last April by FRESCA 2 magnet (CEA-CERN): 14.4 T.
- **Training** was very short for a high field magnet (moderately high working point on load line).

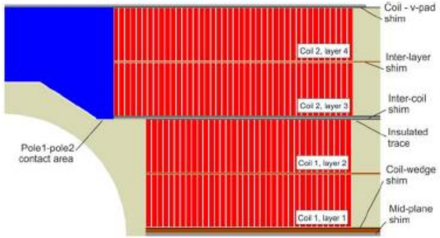


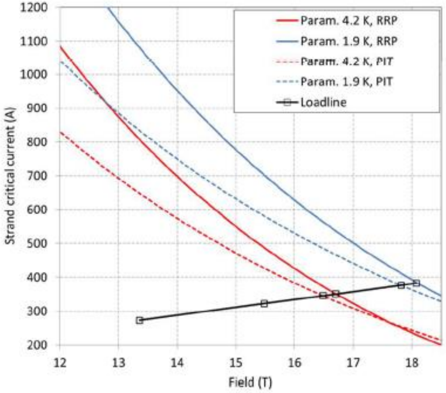
High field dipole world record: FRESCA 2

- Main challenge of a high field magnet is **mechanics**… it is even more difficult if accelerator field quality is necessary.







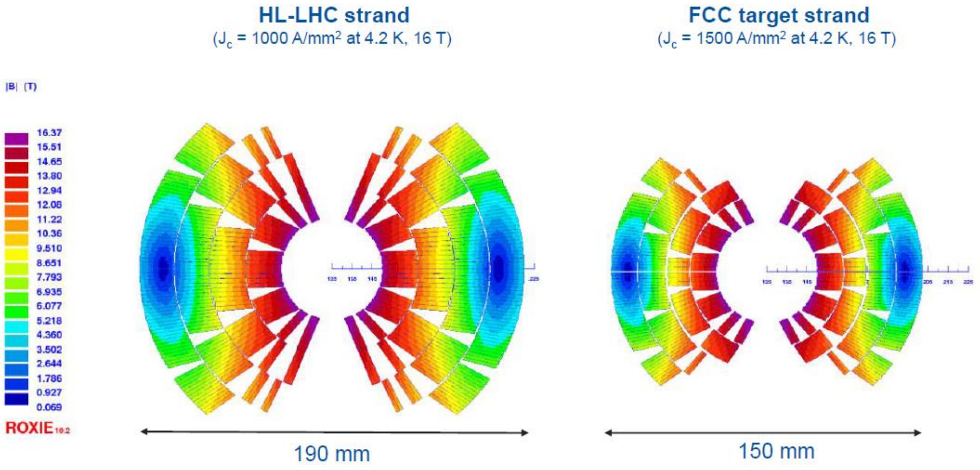


Why is difficult to build a high field magnet?

The Future Circular Collider (FCC), or an energy upgrade of the LHC (HE-LHC), will require bending magnets operating at up to 16 T.

Key critical aspects:

1. The improvement of the state of the art **conductor** performance towards 1500 A/mm^2 and a cost of 5 EUR/kA.m at 16 T and 4.2 K.
2. The **design** of cost-effective 16 T dipole magnets with adequate electromagnetic and structural designs.
3. The improvement of **training**.
4. Magnet **protection**.

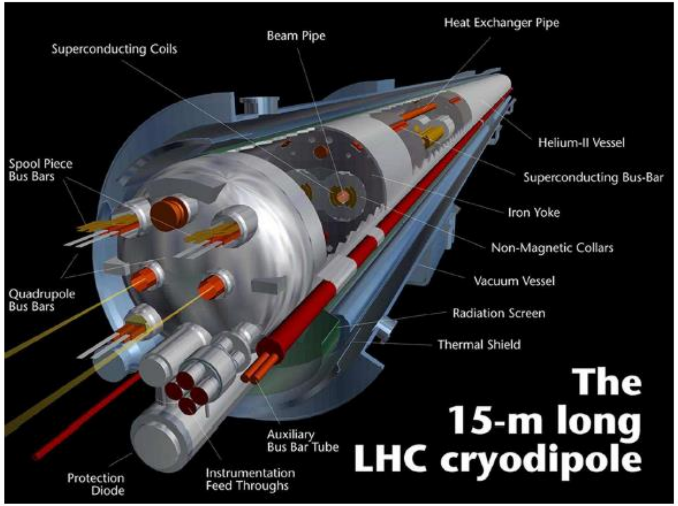


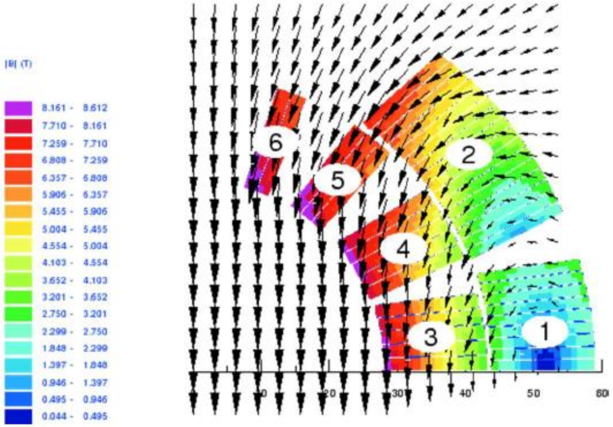
HL-LHC strand
(J_c = 1000 A/mm^2 at 4.2 K, 16 T)

FCC target strand
(J_c = 1500 A/mm^2 at 4.2 K, 16 T)

16 T dipole challenges: superconductor cost

- Nowadays, superconductor in a high field magnet is the **main driving cost**.
- Several strategies are being explored: improvement of the fabrication methods and the design strategy (mainly grading, which needs high field cable joints).



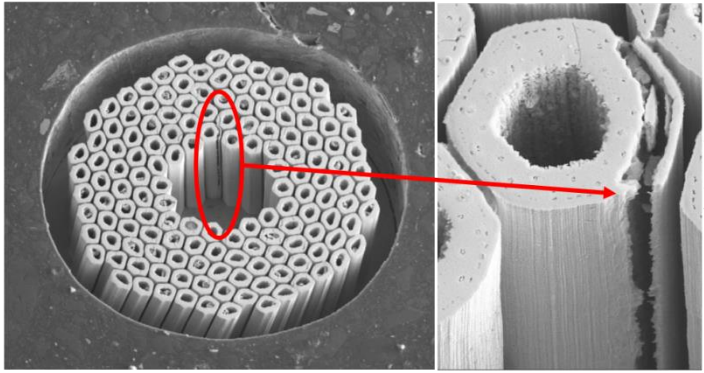


Courant nominal I=11850 A @ 8.3 T, avec 14% de marge sur la «load line»
Câble type 01 (couche interne) : 28 fils de diamètre 1.065 mm, largeur 15.1 mm, épaisseur moyenne 1.90 mm
Câble type 02 (couche externe) : 36 fils de diamètre 0.825 mm, largeur 15.1 mm, épaisseur moyenne 1.48 mm

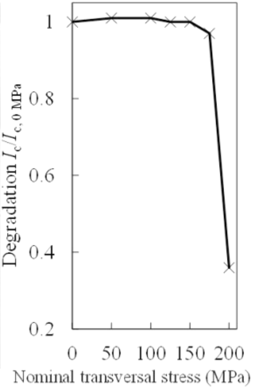
16 T dipole challenges: design

- Electromagnetic design is “always” feasible.
- Mechanics is more complex:
  - Large forces need a strong support structure
  - Coils are deformed by electromagnetic forces: pre-load
  - Nb3Sn coils degrade under large stresses

Scanning Electron Microscope (SEM) image after applying 200MPa transverse pressure on a cable

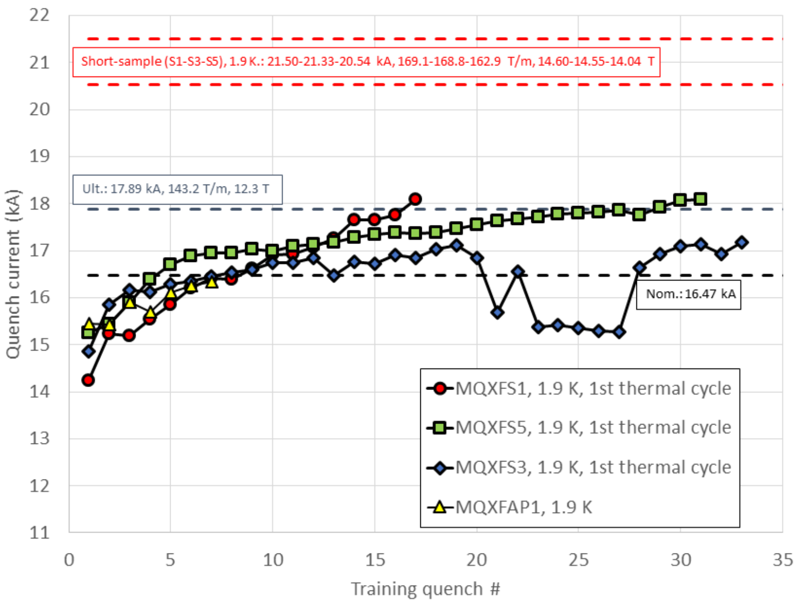


Irreversible degradation applied at warm and measured at 9.6 T and 4.2 K



16 T dipole challenges: training and protection

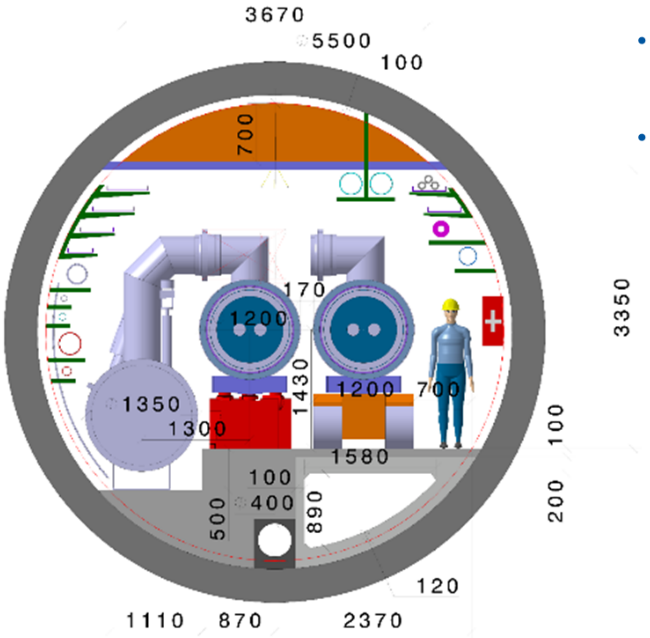
- Training is the learning curve of a magnet till it reaches the ultimate design current.
- It is directly linked to mechanical design: choice of support materials and resin.
- Large peak temperatures and voltages are associated to quench.
- Very fast and reliable protection systems are necessary: CLIQ and quench heaters.



Outline

- Introduction
- Steps towards 16 T dipole magnets
- World wide efforts
- Conclusions

16 T dipole target parameters



5.5 m diameter (FCC) and 3.7 m (HE-LHC)

- Magnets in accelerator quality for operation in a circuit (field quality, protection, alignment);
- To keep the magnet compact, a fringe field of up to 0.1 T is allowed in the tunnel, making the magnet size compatible with installation in both FCC and HE-LHC.

Item	**Unit**	**Value**
Number of units FCC/HE-LHC	-	4668/1232
Operating field	T	16
Coil physical aperture	mm	50
Operating current	A	<20 kA
Operating temperature	K	1.9
Magnetic length at 1.9 K	mm	14069

A program driven by collaborations

WP 5

EuroCirCol WP5 (CEA, CERN, CIEMAT, Geneva UNIV, KEK, INFN, Tampere UNIV, Twente UNIV)
Feed the FCC CDR with design and cost model of 16 T magnets

FCC 16 T Magnet Development, supporting:

- conductor development & procurement
- R&D magnets and associated development
- model magnets

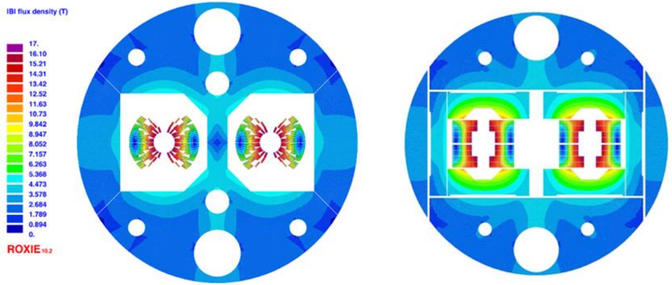
US Magnet Development Program (ASC/NHMFL, FNAL, LBNL)

- 14-15 T cosine-theta magnet (2017-2019)
- Design, manufacture, and test of a 2-layer 10 T CCT magnet
- Novel diagnostics and advanced modeling techniques

Conductor development and procurement

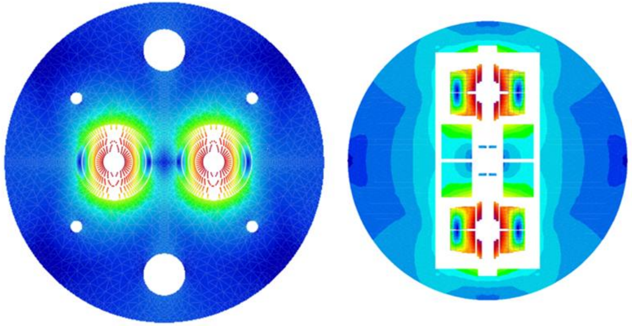
- Conductor program is key for succeeding in building cost-effective high field magnets. Around 500 km strand will be procured to sustain the magnet program until 2020
- The **CERN** managed program is developed in three phases
  - increase of the critical current by 50% with respect to HL-LHC (1500 A/mm^2 at 4.2 K and 16 T), while maintaining high RRR (150)
  - reduction of magnetization, in particular at low fields
  - preparation to industrialization, with focus on achieving long unit length (5 km) and competitive cost (5 EUR/kAm at 4.2 K and 16 T)
- The **US program** is synergic to the CERN program and is tackling similar targets focusing on
  - Increasing superconductor J_c at high fields by using Artificial Pinning Centres (APC)
  - Improving stability of composite Nb_3Sn wire with respect to external and internal perturbations by increasing its C_p

FCC magnet design



Cos-theta

Block (+3.7%)



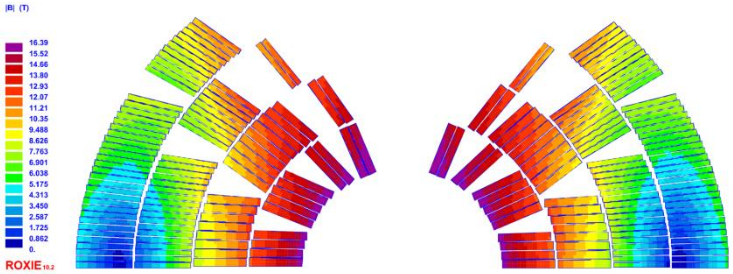
CCT (+27.7%)

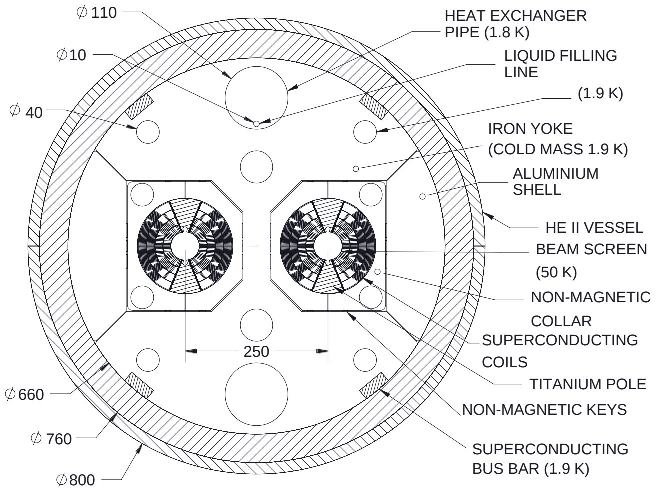
Common-coil (+25.4%)

Magnet design options (+strand mass wrt cos-theta)

- **Four different design options** have been developed under the same assumptions;
- It is planned to explore the different design options through model magnets;
- The cos-theta is the most efficient design in terms of **amount of conductor** used for a given integrated field strength, the same margin on the load-line and same protection strategy. It was the design choice of all so-far built colliders employing SC magnets.

FCC baseline magnet design

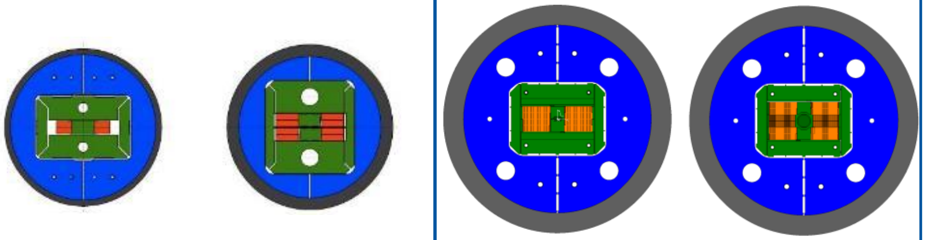




- **Baseline cold mass design:** key-and-bladder design, stress in conductor is below 150 MPa during assembly and below 200 MPa after cool-down and powering
- **Quench protection:** hot-spot temperature below 350 K and peak voltage to ground in the coil below 2.5 kV
- **Field quality:** slightly asymmetric coils for compensating the b_2 component,
- **Cost estimate:** We believe that the conductor cost is uncertain and opportunities exist for cost reduction through R&D programs and consider a cost range of 1.7-2 MEUR/magnet (~40% conductor, ~25% parts, ~35% assembly)

Overview of CERN small-scale R&D program

SMC	RMC	ERMC	RMM
OD = 530 mm	OD = 570 mm	OD = 800 mm	OD = 800 mm
L = 500 mm	L = 820 mm	L = 1.2-1.4 m	L = 1.2-1.4 m
No Ap.	No Ap.	No Ap.	50 mm cavity
B_{op}= n.a.	B_{op}= n.a.	B_{op}= 16 T	B_{op}= 16 T
B_{ult} = 14 T	B_{ult} = 16 T	B_{ult} = 18 T	B_{ult} = 18 T
Hi-Lumi & FCC R&D		FCC R&D	



SMC:
testing conductor variants, impregnation resins, sliding and separating surfaces and investigating their impact on training; and for high field internal splice technology.

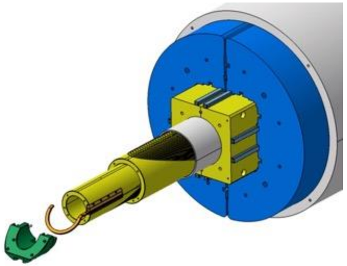
eRMC:
Reproducing full field and force conditions over a representative length, including transitions used to test: conductor grading, conductor interfaces to pole and end-spacers, layer jumps and splices, loading conditions, heat treatment and impregnation

RMM:
Testing and validating force and stress management, magnet loading in 3D, and field quality in 2D

Coil R&D: Status of different projects

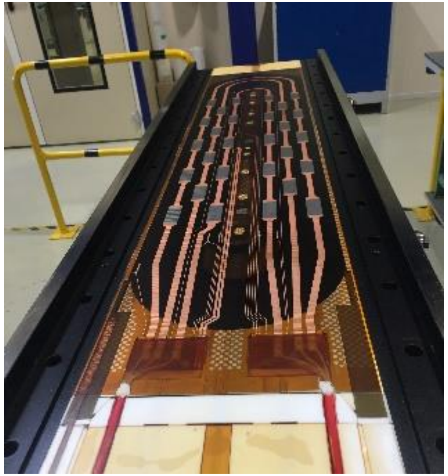
PAUL SCHERRER INSTITUT
PSI

CD1 (11.7 T design field)



CERN

ERMC (B_{ultimate} = 18 T)

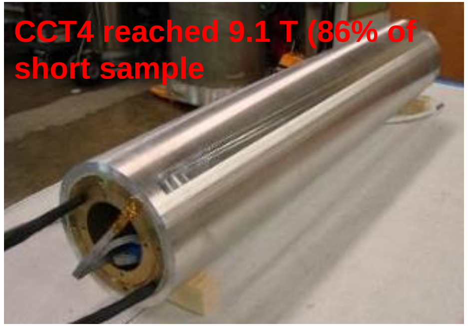


U.S. MAGNET DEVELOPMENT PROGRAM

BERKELEY LAB

REBCO (CORC) coil

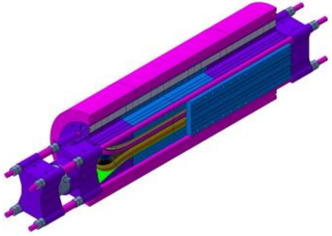
Bi-2212 coil



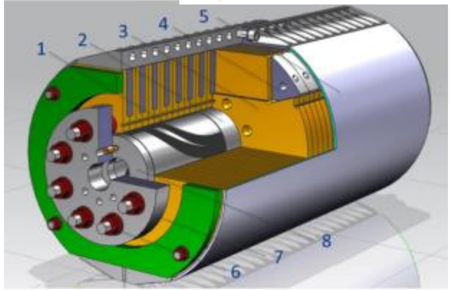
CCT4 reached 9.1 T (86% of short sample

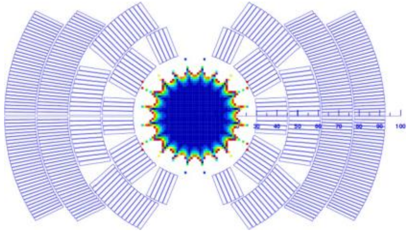
Model magnets

CEA: block-type, ~10 coils
INFN: cos-theta, ~6 coils
CIEMAT: common-coil, ~6 coils
PSI: CCT
BINP: different designs under study

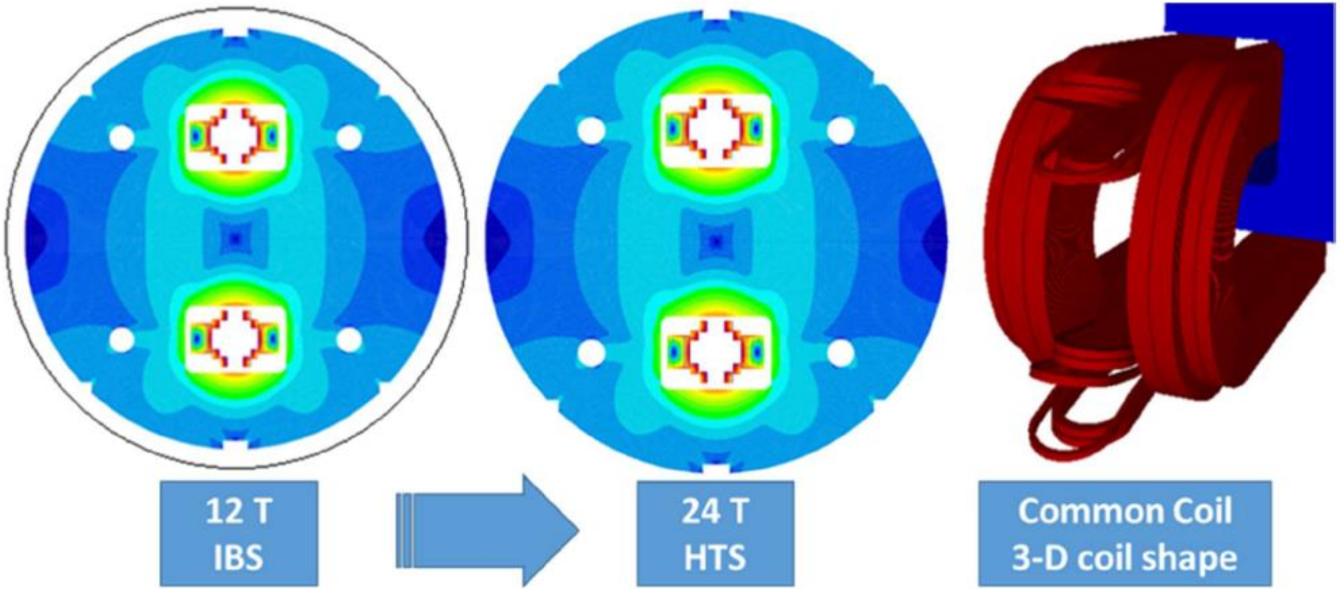


- 15 T dipole demonstrator
- 60 mm aperture
- 4-layer graded coil
- Test foreseen in early 2019





Chinese program towards SPPC



12 T
IBS

24 T
HTS

Common Coil
3-D coil shape

Qingjin Xu (IHEP, Beijing)

Conclusions

- Present accelerator high field dipoles provide 11 T.
- Future large circular colliders are based on dipole field of 16 T.
- Main challenges to develop a 16 T magnet are:
    - The properties and cost of the superconductor
    - The mechanical design of the support structure
    - The training curve and magnet protection
- World-wide effort based on collaborations to achieve a reliable 16 T dipole: Eurocircol, FCC, US-DMP, China.
- Other superconductors open the door towards dipole fields beyond 16 T, but technological challenges are even more formidable.

Papers on high field magnets at ASC’2018

- A. Ballarino et al., “The CERN FCC conductor development program: a world-wide effort for the future generation of high-field magnets”, 1MOr2B-01.
- X. Xu et al., “Recent progress with APC Nb3Sn conductors”,1MOr2B-05.
- F. Buta et al., “Properties and microstructure of binary and ternary Nb_3Sn superconductors with internally oxidized ZrO2 nanoparticles”, 1MPo2A-06.
- X. Xu et al., “Improvement of stability of Nb_3Sn conductors and magnets by increasing specific heat”, 1MPo2A-05.
- R. Valente et al. “Electromagnetic Design of a 16 T cos θ Bending Dipole for the Future Circular Collider”, 2LPo2K-03.
- C. Pes et al., “Magnetic and Mechanical Design of the Block-coil Dipole Option for the Future Circular Collider”, 2LPo1H-05.
- G. Montenero et al., “Production of the first 1-m long Canted-Cosine-Theta (CCT) model magnet at PSI”, 2LPo1H-01.
- T. Salmi et al., “Quench protection of the 16 T Nb_3Sn dipole mag-nets designed for the Future Circular Collider”, 3LPo2E-03.
- J.T. Troitino et al., “Critical Current Degradation of RRP Nb_3Sn Strands Under Applied Transversal Loads”, 1MPo2A-09.
- P. Gao et al., “Transverse pressure dependence of critical current in RRP and PIT type Nb_3Sn Rutherford cables for use in future accelerator magnets”, 3LPo1D-09
- C. Senatore et al., “Scaling behavior of the critical current under transverse stress in RRP and PIT Nb_3Sn wires”, 2MOr1A-02.
- F. Wolf et al., “Effect of epoxy volume fraction on the stiffness of Nb3Sn Ruther-ford cable stacks”, 1LPo2A-10.
- J.L.R. Fernandez et al., “Characterization of the mechanical proper-ties of impregnated Nb_3Sn coils”, LPo2G-04.
- F. Wolf et al., “Effect of applied compressive stress and impregnation material on internal strain and stress state in Nb_3Sn Rutherford cable stacks”, 2MPo2B-02.
- M. Kumar et al, "Nb_3Sn Rutherford cable splices for graded high field accelerator magnets", 1LOr1D-04.
- D. Arbelaez et al., “Design and test results of the Nb_3Sn Canted-Cosine-Theta dipole magnet CCT5”, 2LOr1B-04.
- H. Felice et al., “F2D2: a block-coil short-model dipole toward FCC “, 4LPo1F-01.
- A. Zlobin, et al., “Development of a 15 T Nb_3Sn Dipole Demonstrator by MDP”, 1LOr1D-02.
- E. Barzi et al., “Measurements and modelling of mechanical and superconducting properties of Nb_3Sn strands, cables and coils” ,1LPo2A-02
- I. Novitski et al., “Assembly and Tests of Mechanical Models of the 15 T Nb_3Sn Dipole Demonstrator”, 2LPo1H-04
- S. Stoynev et al., “Analysis of Nb_3Sn Accelerator Magnet Training”, 2LOr1B-03