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High Field Magnets for Future Accelerators

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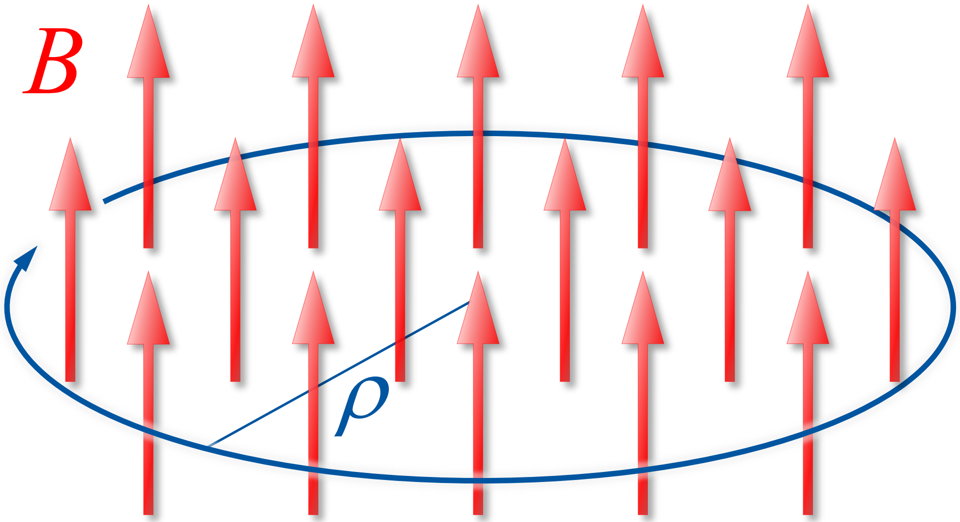
Virtual CCA-2021
October 11-15, 2021
EDMS 2645714

Outline

- Motivation for high fields
- State of the art and challenges
- High Field Magnet R&D
- Summary

Motivation for high fields – 1/2



Beam energy

Bending radius

$$E[GeV] = 0.3\, B[T]\, \rho[m]$$

Dipole field

	LHC	FCC
E_{beam} (GeV)	7000	50000
B (T)	8.33	16
ρ (km)	2.8	10.4

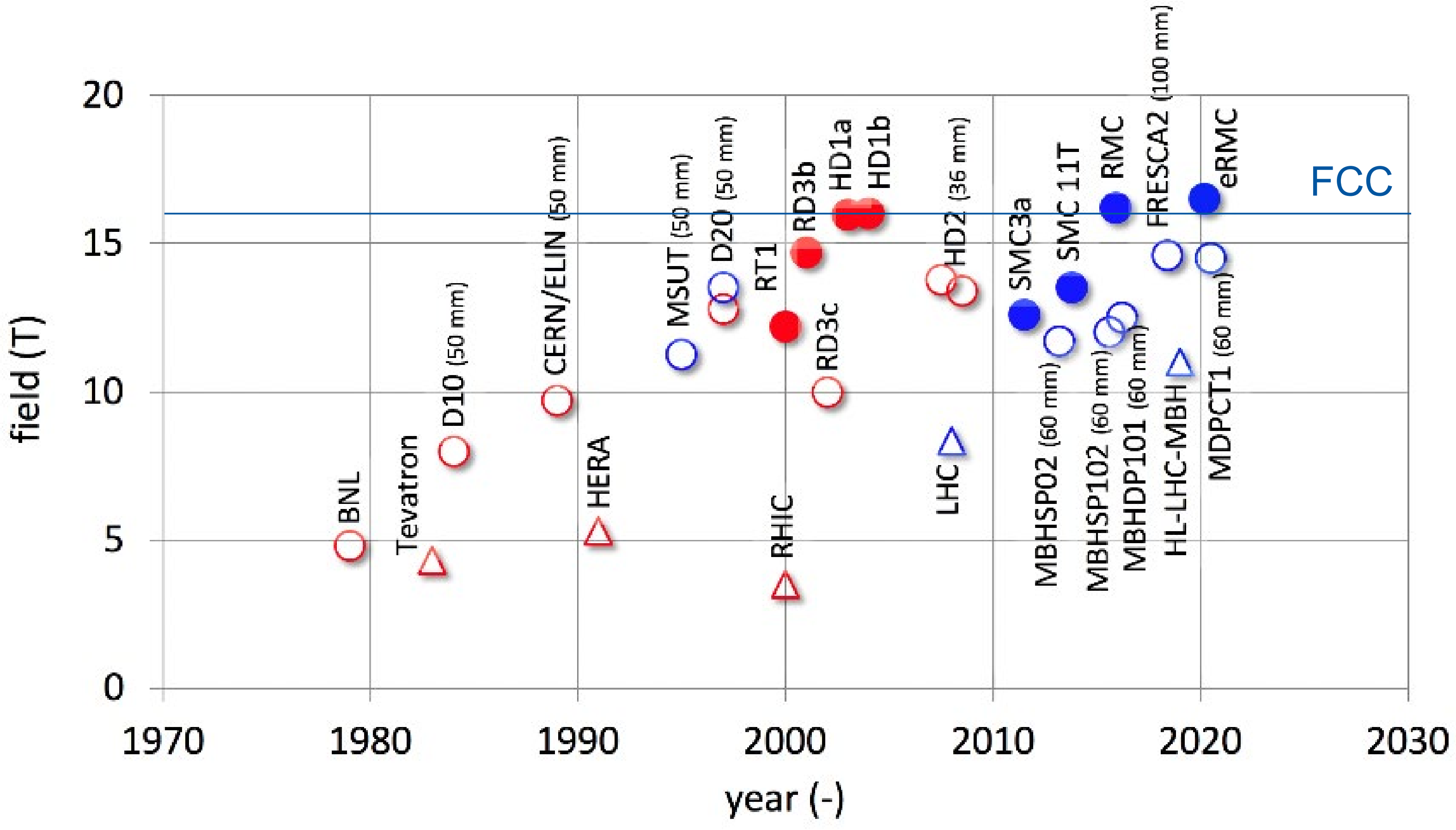
Motivation for high fields – 2/2

F. Gianotti (CERN DG), asked at ASC-2020 about "*What is the highest conceivable energy reach of a next generation collider*", replied to the audience: "*It depends on you*"

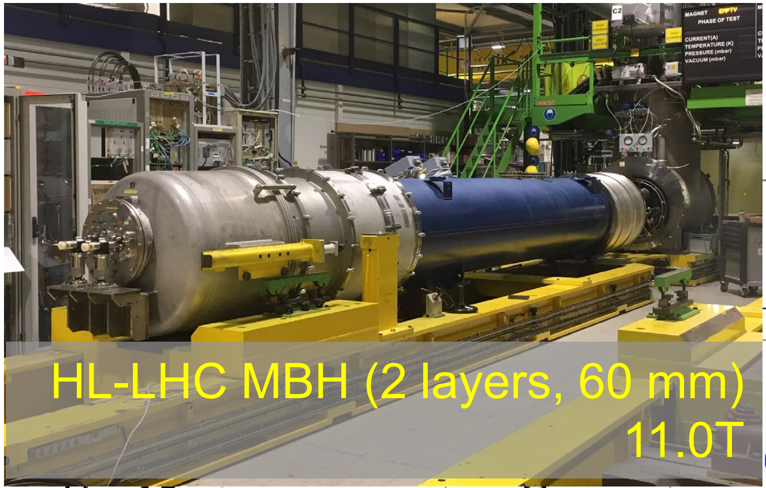
Magnets are the **limiting factor** to the energy reach of a circular collider

The development of high-field magnets is **crucial to the future of HEP**

State of the art – Nb_3Sn history

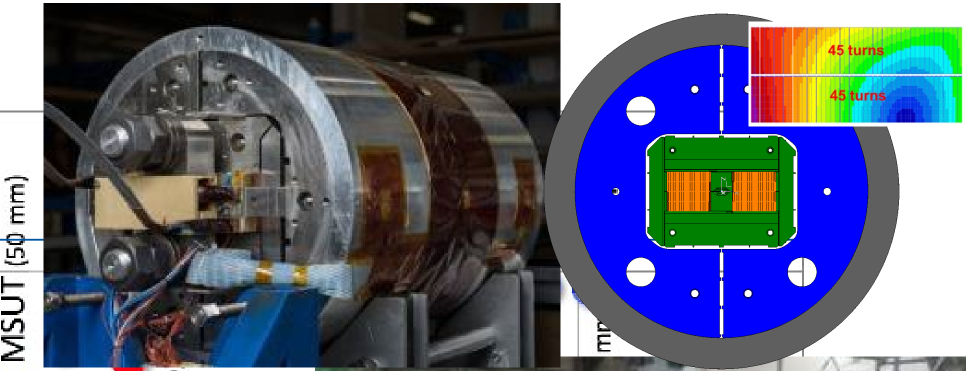


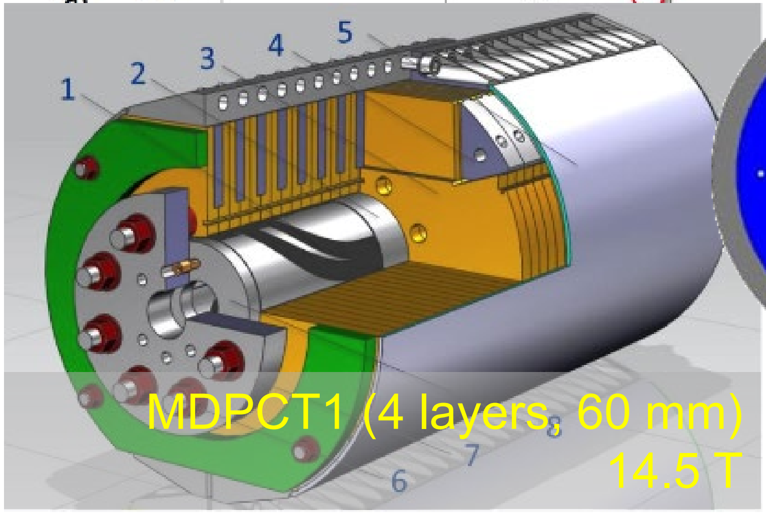
State of the art – Nb$_3$Sn history



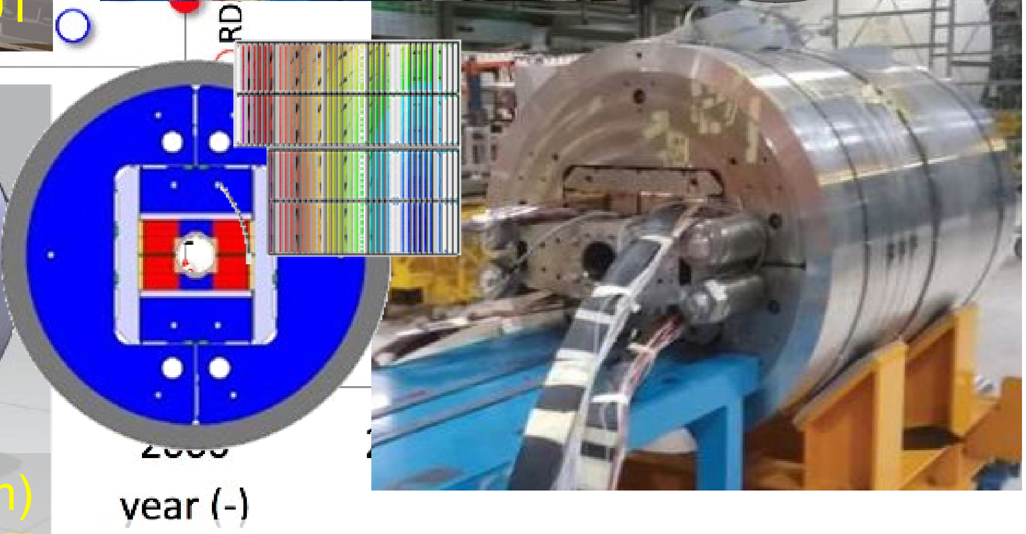
HL-LHC MBH (2 layers, 60 mm) 11.0T

RMC/eRMC (2-decks, no aperture), 16.5 T





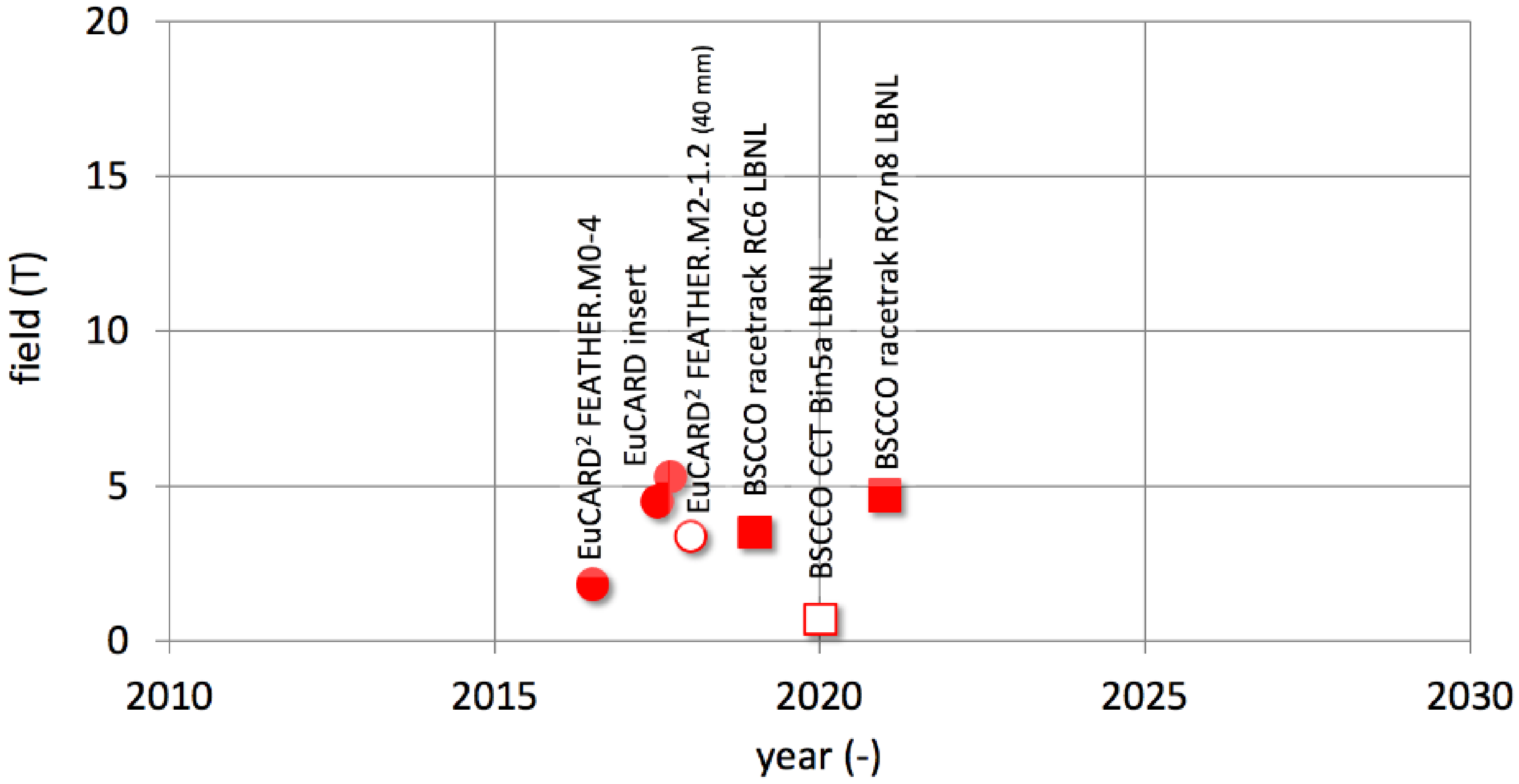
MDPCT1 (4 layers, 60 mm) 14.5 T



FRESCA2 (4-decks, 100 mm), 14.6 T

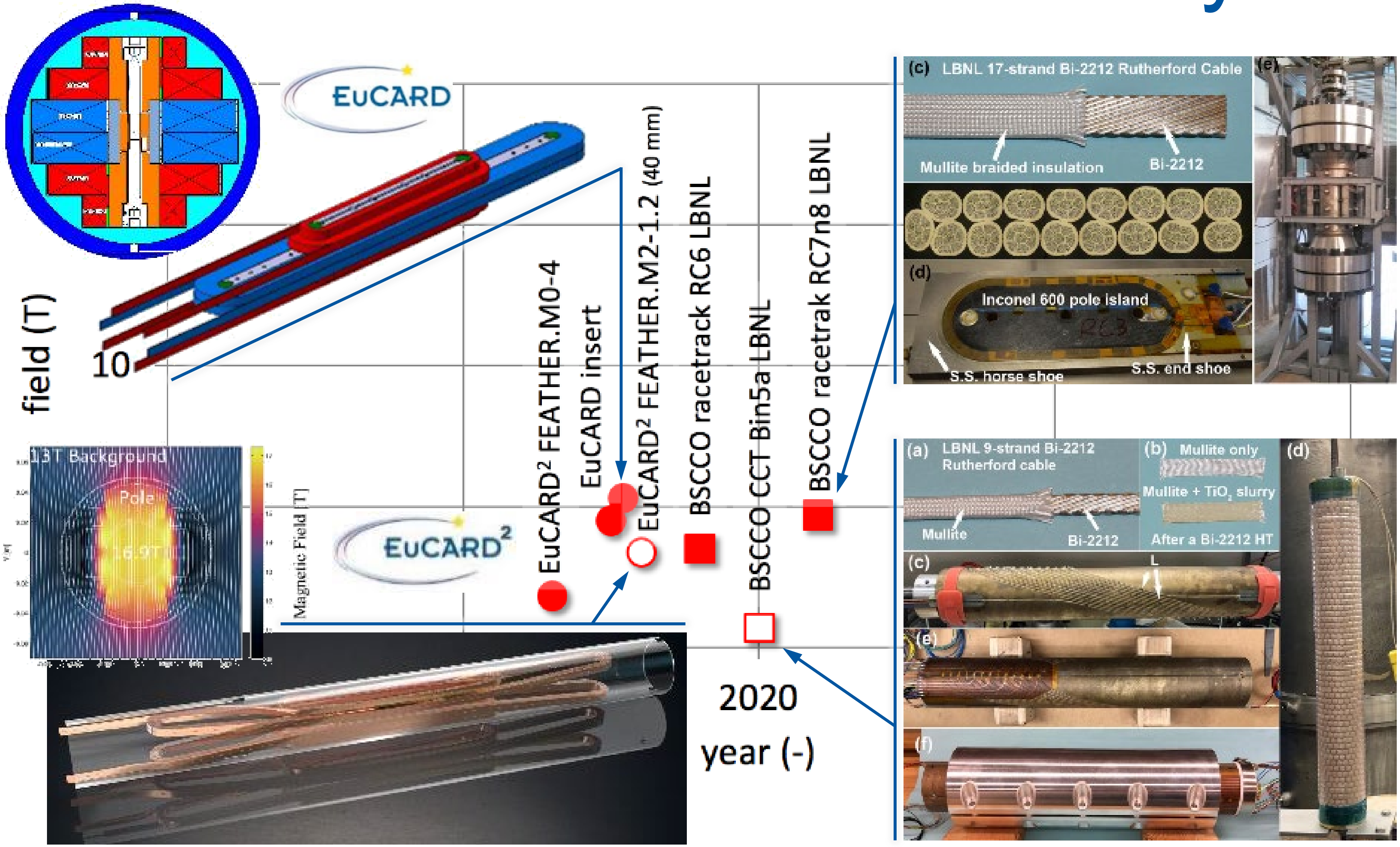
A long history of development

State of the art – HTS history



A relatively young field of research

State of the art – HTS history



A relatively young field of research

Challenges of high fields (LTS and HTS)

In much simplified terms…

1. Engineering current density
   - A high current density is necessary to **make compact magnets**, reduce their volume, mass, foot-print and cost
2. Mechanics
   - **Forces, stresses and deformations increase** as the field increases. In addition, **all high-field superconductors are brittle**
3. Quench management
   - **The stored energy and energy density of the magnet increase** as the field increases. Quench detection and dump times must be reduced

1. Current density

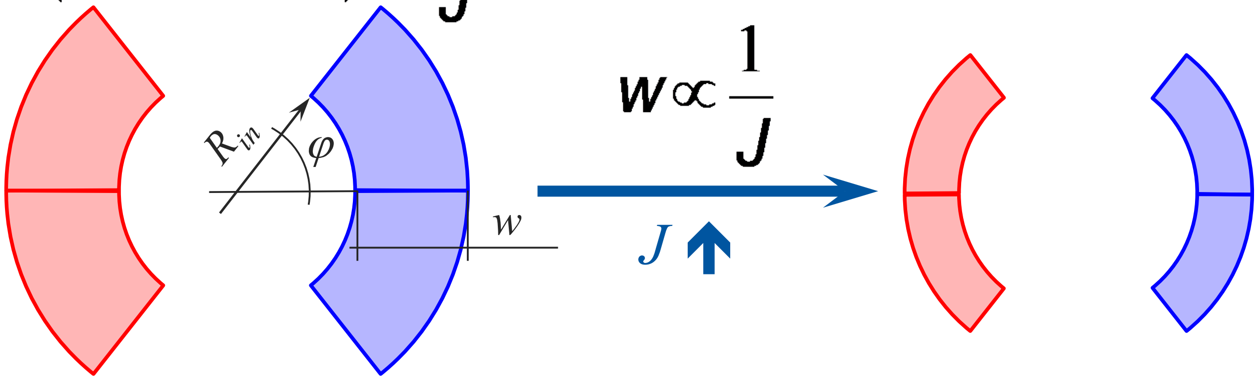
Dipole field generated by a current distribution with constant current density J over a sector of inner radius R_{in}, outer radius R_{out}, coil width $w = R_{out} - R_{in}$ and opening angle φ

$$B = \frac{2\mu_0}{\pi} J w \sin(\varphi)$$

$$A_{coil} = 2\varphi\left(w^2 + 2R_{in}w\right) \propto \frac{1}{J^n}$$

$n \approx 1 \ldots 2$

In the range of typical magnet designs considered $n \approx 1.5$



$$w \propto \frac{1}{J}$$

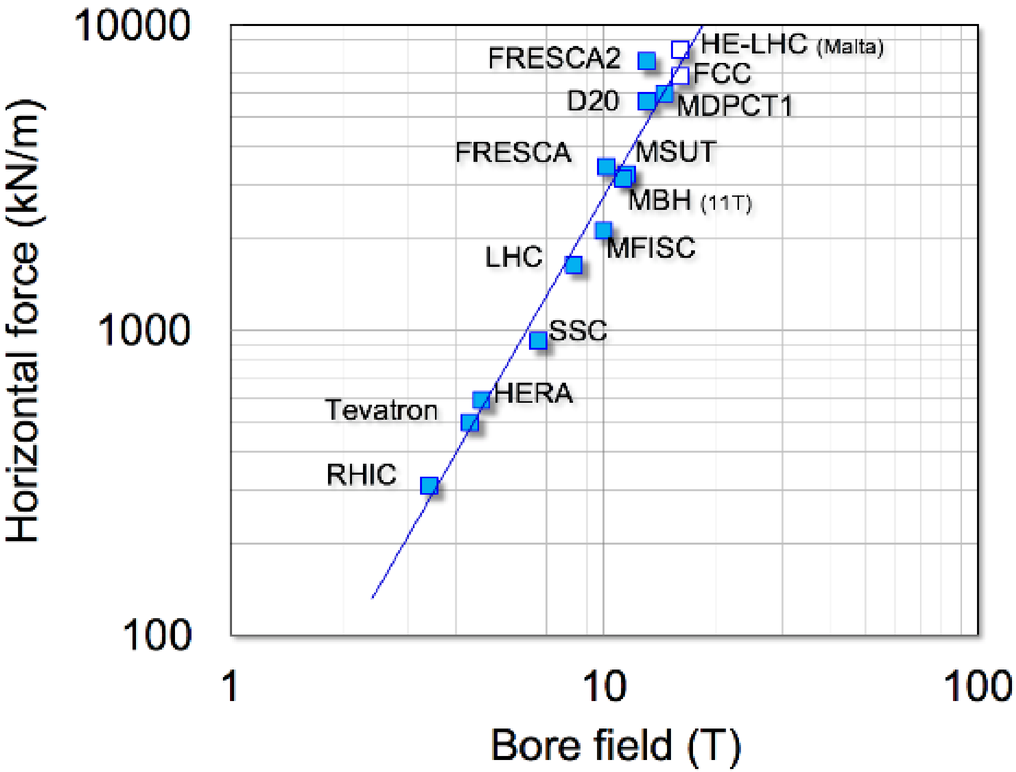
B	(T)	16	16	
J	(A/mm²)	300	600	Factor 2
w	(mm)	76	38	
A_{coil}	(mm²)	20,000	7000	Factor 3

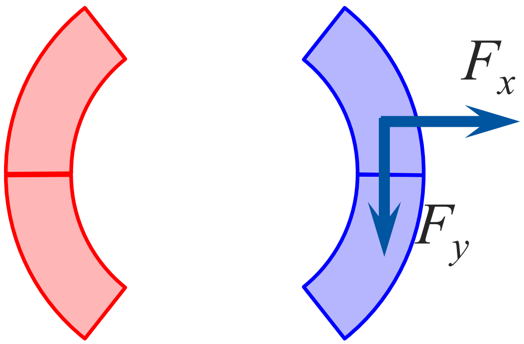
$$A_{coil} \propto M_{coil} \propto COST$$

2. Mechanics

Lorentz forces in the plane of a thin coil of radius R_{in} generating a dipole field B (thin shell approximation), referred to a coil quarter

$$F_x = -F_y \approx \frac{4}{3}\frac{B^2}{2\mu_0}R_{in}$$

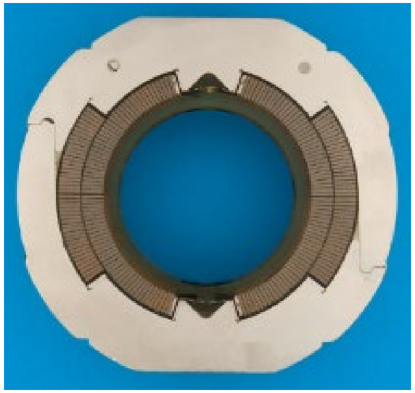




Progression of F_x:
LHC MB(8.33T) ≈ 1.7 MN/m
LHC MBH(11T) ≈ 3.2 MN/m
FRESCA2(13T) ≈ 7.6 MN/m

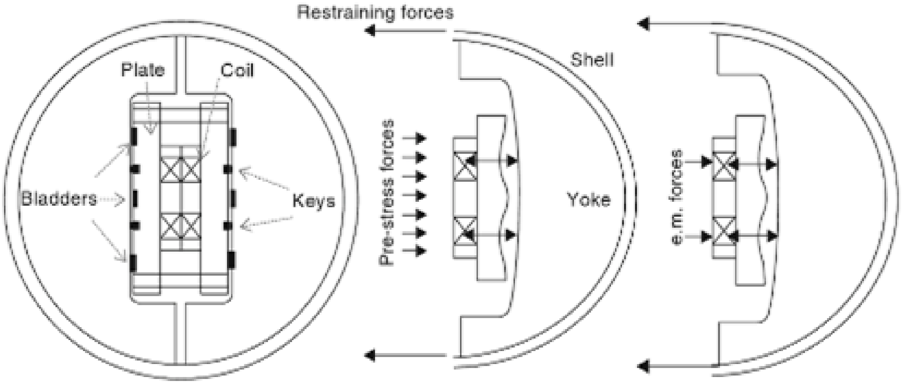
FCC MB(16T) ≈ 8 MN/m
HE-LHC MB(20T) ≈ 10 MN/m

New support structures



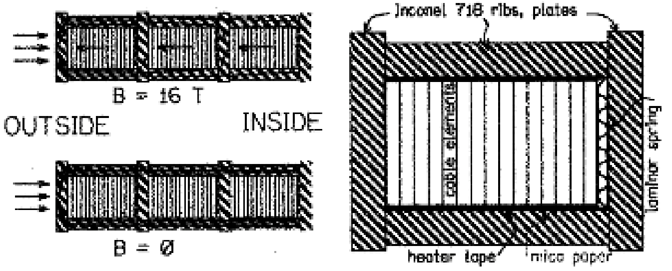
mid 1970's, FNAL: Collared coils

A. Tollestrup, Proc. Int Conf. on the History of Original Ideas and Basic Discoveries in Particle Physics, Erice (1994).



2002, LBNL: Bladder and keys

R.R. Hafalia, et al., IEEE TAS, 12(1) (2002), pp. 47-50.

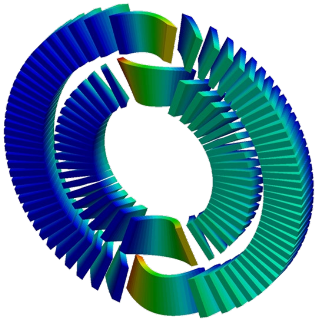


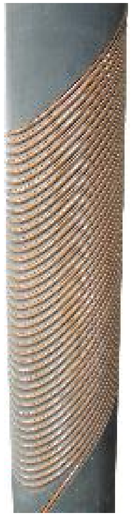
1998, TAMU: Stress management

N. Diaczenko, et al., Proc. PAC, Vancouver (1997), pp.3443-3345.

2014, LBNL: CCT

S. Caspi, et al., IEEE TAS (2014), p. 4001804.

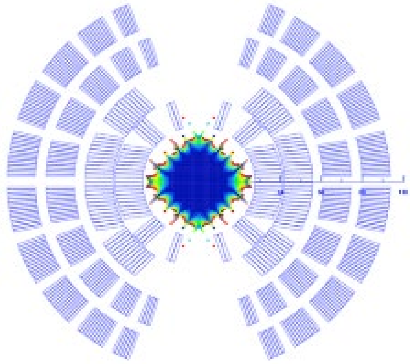




HTS version (CORC cable)

2017, FNAL: SM cos(θ)

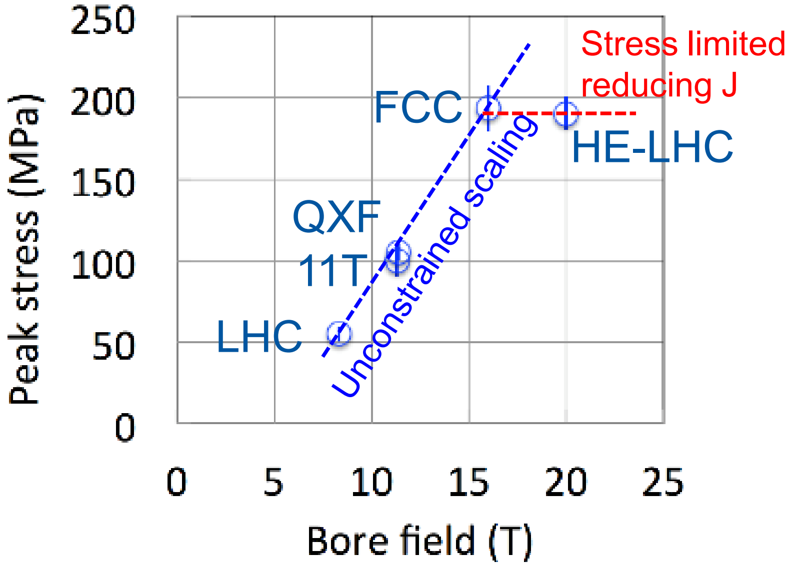
V. Kashikin, et al., Proc. IPAC, Copenhagen (2017), pp. 3597-3599.



NOTE: the pre-load concept needs to be revised !

Stress in high field magnets

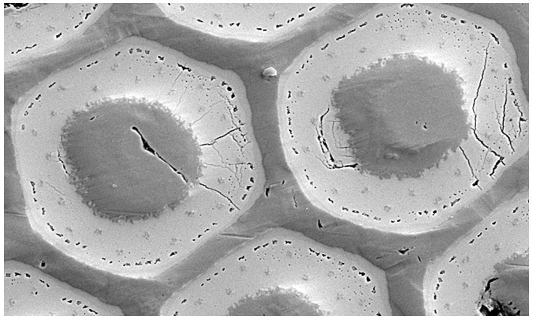
$$\left.\begin{aligned} F &\propto B^2 \\ w &\propto \frac{B}{J} \end{aligned}\right\} \longrightarrow \sigma \approx \frac{F}{w} \propto JB$$



Natural cable irregularities lead to stress concentration

Cracking and resin adhesion issues (metallic components, strands)

Filament fracture



This is the true challenge of Nb_3Sn today !!!

3. Quench management

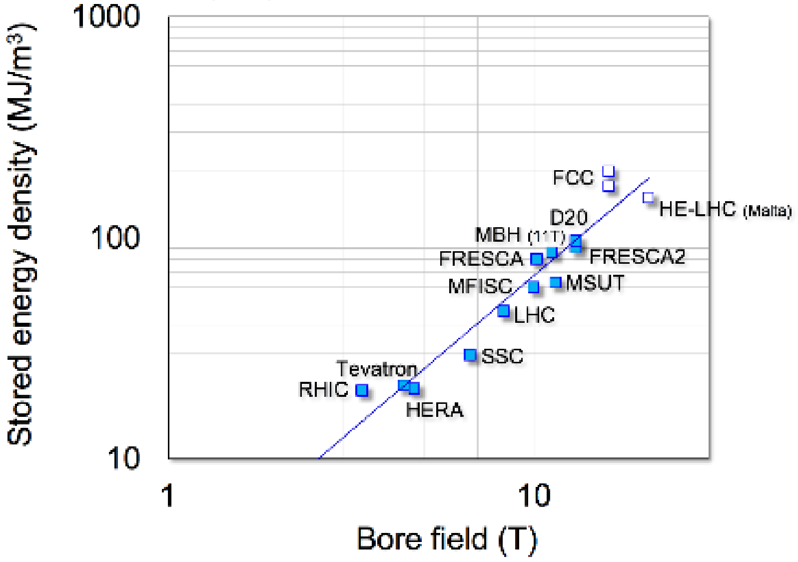
Energy per unit length in a sector coil of inner radius R_{in}, outer radius R_{out}, coil width $w = R_{out}-R_{in}$ producing a dipole field B

$$E/l = \frac{\pi B^2 R_{in}^2}{\mu_0}\left[1+\frac{2}{3}\frac{w}{R_{in}}+\frac{1}{6}\left(\frac{w}{R_{in}}\right)^2\right]$$

$$A_{coil} \propto \left(\frac{B}{J}\right)^n$$

In the range of typical magnet designs considered $n \approx 1.5$

$$\longrightarrow e \approx \frac{E/l}{A_{coil}} \propto J^n B^{2-n}$$



Progression of energy densities e:

LHC MB(8.33T) ≈ 50 MJ/m^3

LHC MBH(11T) ≈ 85 MJ/m^3

FRESCA2(13T) ≈ 100 MJ/m^3

FCC MB(16T) ≈ 200 MJ/m^3

HE-LHC MB(20T) ≈ 150 MJ/m^3

Needs advanced diagnostics and powering strategy

Models

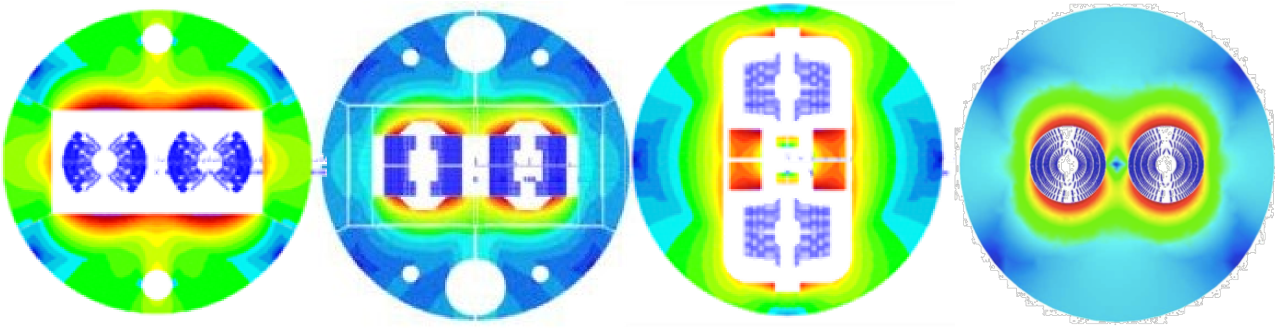
INFN Istituto Nazionale di Fisica Nucleare

cea

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

PAUL SCHERRER INSTITUT PSI

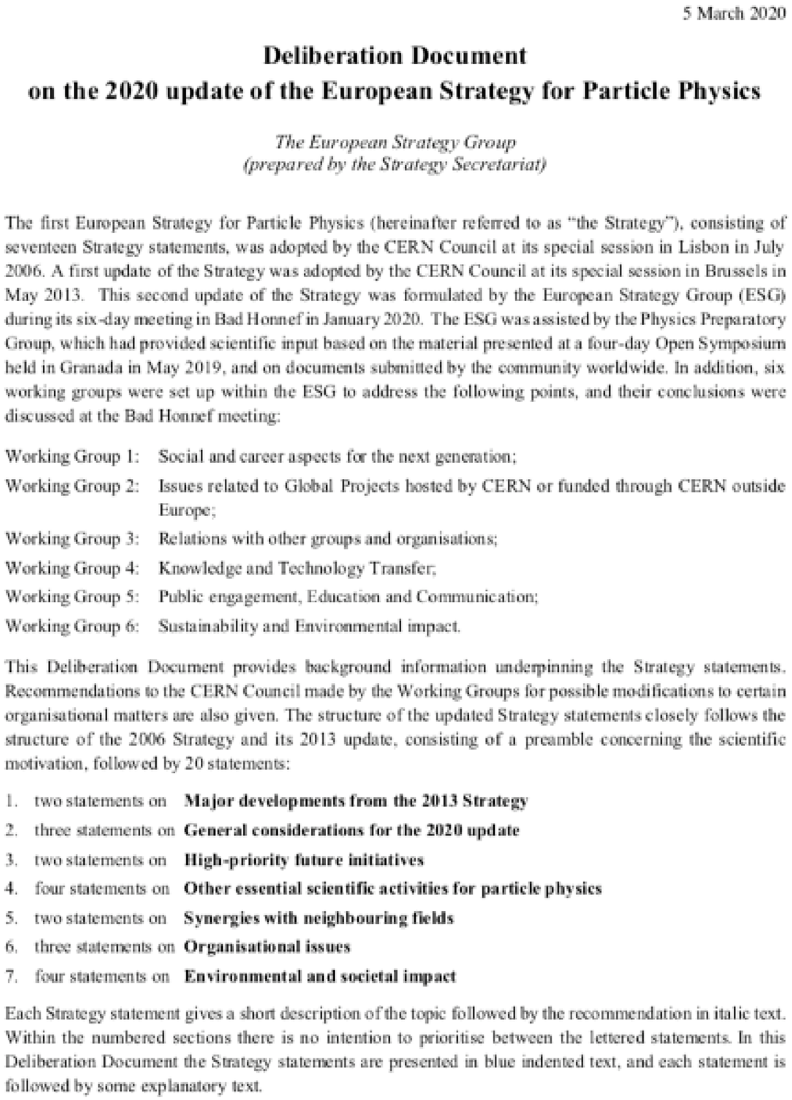
OD = 600 mm
L = 2 m
50 mm aperture
$B_{ultimate}$ = 16 T



		cos(θ)	blocks	common coil	CCT
Current	(A)	10000	11230	16100	18055
Inductance	(mH/m)	50	40	19.2	19.2
Stored energy	(kJ/m)	2500	2520	2490	3200
Coil mass	(tons)	7400	7400	9200	9770

Broad scoping study of coil and structure options

CERN-ESU-014



5 March 2020

Deliberation Document on the 2020 update of the European Strategy for Particle Physics

The European Strategy Group
(prepared by the Strategy Secretariat)

The first European Strategy for Particle Physics (hereinafter referred to as "the Strategy"), consisting of seventeen Strategy statements, was adopted by the CERN Council at its special session in Lisbon in July 2006. A first update of the Strategy was adopted by the CERN Council at its special session in Brussels in May 2013. This second update of the Strategy was formulated by the European Strategy Group (ESG) during its six-day meeting in Bad Honnef in January 2020. The ESG was assisted by the Physics Preparatory Group, which had provided scientific input based on the material presented at a four-day Open Symposium held in Granada in May 2019, and on documents submitted by the community worldwide. In addition, six working groups were set up within the ESG to address the following points, and their conclusions were discussed at the Bad Honnef meeting:

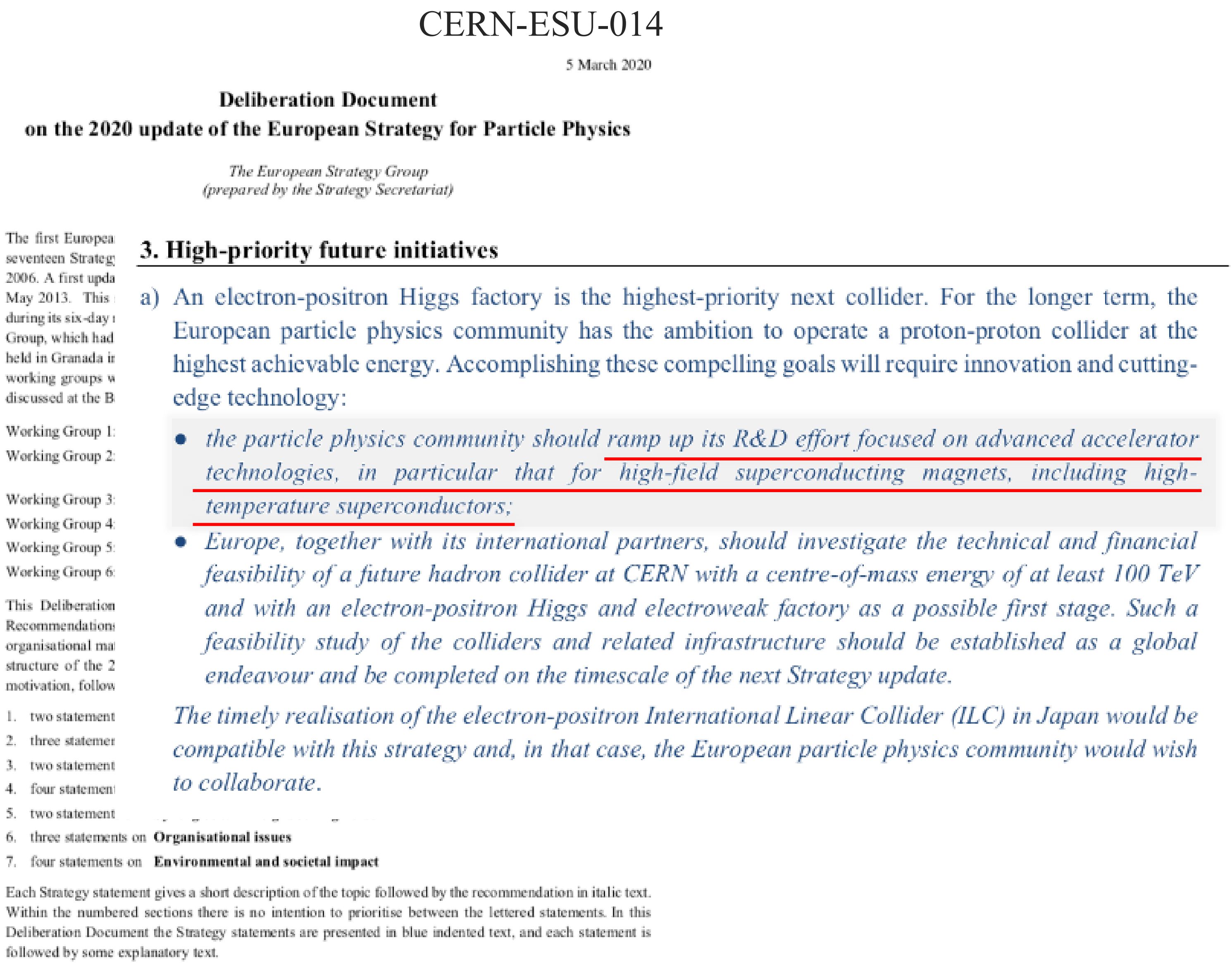
Working Group 1:	Social and career aspects for the next generation;
Working Group 2:	Issues related to Global Projects hosted by CERN or funded through CERN outside Europe;
Working Group 3:	Relations with other groups and organisations;
Working Group 4:	Knowledge and Technology Transfer;
Working Group 5:	Public engagement, Education and Communication;
Working Group 6:	Sustainability and Environmental impact.

This Deliberation Document provides background information underpinning the Strategy statements. Recommendations to the CERN Council made by the Working Groups for possible modifications to certain organisational matters are also given. The structure of the updated Strategy statements closely follows the structure of the 2006 Strategy and its 2013 update, consisting of a preamble concerning the scientific motivation, followed by 20 statements:

1. two statements on **Major developments from the 2013 Strategy**
2. three statements on **General considerations for the 2020 update**
3. two statements on **High-priority future initiatives**
4. four statements on **Other essential scientific activities for particle physics**
5. two statements on **Synergies with neighbouring fields**
6. three statements on **Organisational issues**
7. four statements on **Environmental and societal impact**

Each Strategy statement gives a short description of the topic followed by the recommendation in italic text. Within the numbered sections there is no intention to prioritise between the lettered statements. In this Deliberation Document the Strategy statements are presented in blue indented text, and each statement is followed by some explanatory text.

Available at https://cds.cern.ch/record/2720131/files/CERN-ESU-014.pdf



CERN-ESU-014

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3. High-priority future initiatives

a) An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*
- *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

Available at https://cds.cern.ch/record/2720131/files/CERN-ESU-014.pdf

CERN response (excerpts from talk of CERN DG on 8 October 2020)

[…] reinforced, comprehensive R&D programme for superconducting high-field magnets, as key technology for future accelerators (hadron colliders, muon colliders, neutrino beams, etc.) and detectors, with great potential for wider societal applications.

[…] All magnet R&D activities at CERN (including FCC and others) now under one roof and budget line to maximise synergies.

Main R&D activities:
- ☐ materials: LTS (Nb_3Sn) and HTS (including iron-based) → goal: 16 T for LTS, at least 20 T for HTS inserts
- ☐ magnet technology: engineering, mechanical robustness, insulating materials, field quality
- ☐ production of models and prototypes to demonstrate material, design and engineering choices, industrialisation and costs
- ☐ infrastructure and test stations for tests up to ~ 20 T and 20-50 kA

Strong partnership with industry […]

[…] Goals (ambitious) for next ESPP (~ 2026):
- ☐ Nb_3Sn: demonstrate technology for large-scale accelerator deployment
- ☐ HTS: demonstrate suitability for accelerator magnet applications

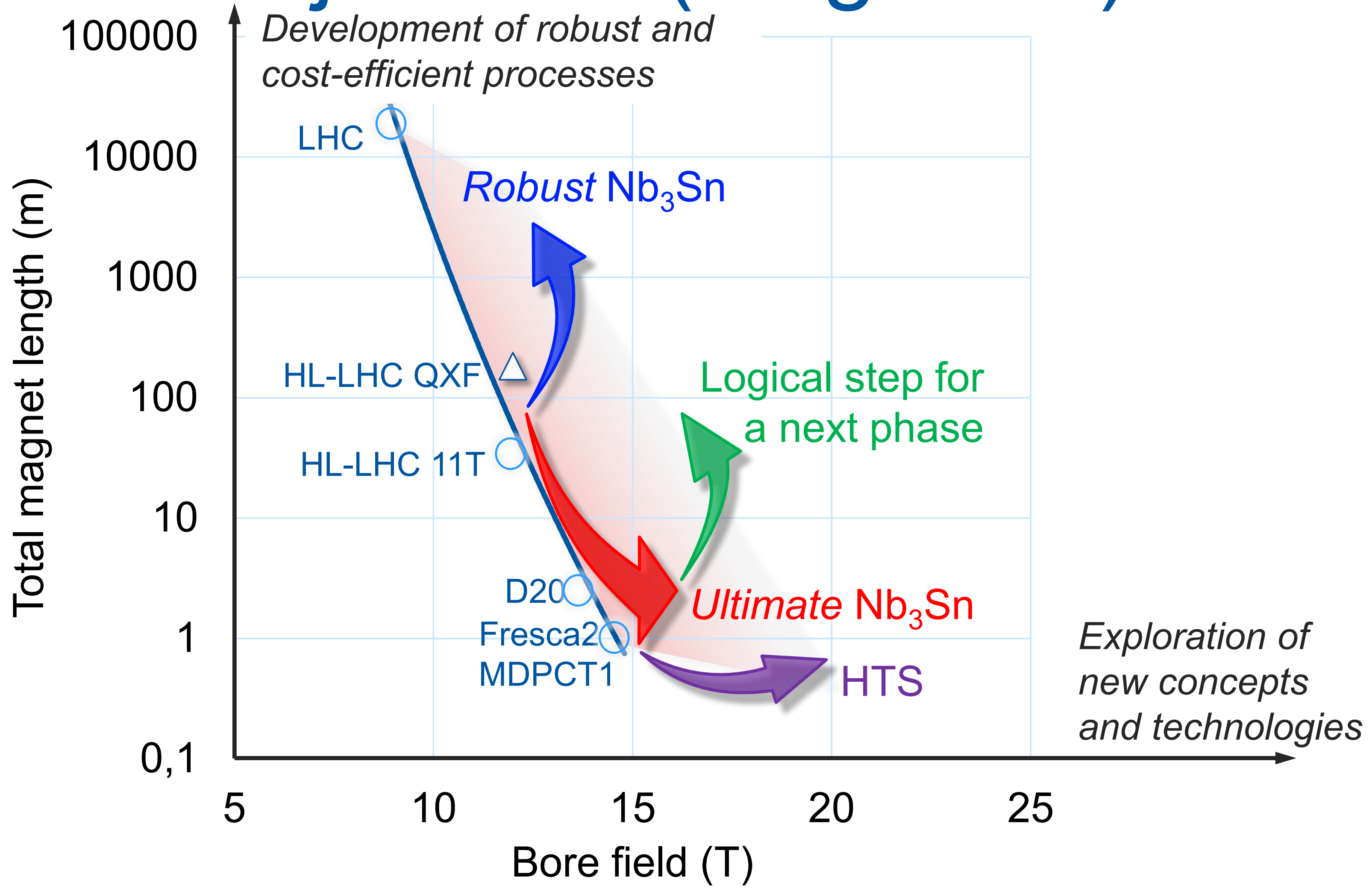
HFM High Field Magnets

Courtesy of F. Gianotti, CERN

HFM Goals (long term)

- Demonstrate Nb_3Sn magnet technology for large scale deployment, pushing it to its practical limits, both in terms of maximum performance as well as production scale
  - I **Demonstrate Nb_3Sn full potential** in terms of ultimate performance (target 16 T)
  - Develop Nb_3Sn magnet technology for **collider-scale production**, through robust design, industrial manufacturing processes and cost reduction (benchmark 12 T) II
- II Demonstrate suitability of HTS for accelerator magnet applications, **providing a proof-of-principle of HTS magnet** technology beyond the reach of Nb_3Sn (target in excess of 20 T)

HFM objectives (long term)



LDG HFM Expert Panel

European Strategy Update

- A *High Field Magnets Expert Panel (HFM-EP)* is mandated by the European Large National Laboratories Directors Group (LDG) to create a **prioritized R&D roadmap**
- The proceedings of the HFM-EP, planned to be endorsed by the CERN council in December 2021, will document:
  - The **scientific drivers** for High Field Magnets R&D, and the progress needed to enable this technology for future facilities
  - The current **state-of-the-art**, and the further steps to be taken over the next decade
  - Potential **deliverables and demonstrators** for the next decade
  - A **prioritized work plan**, considering the capabilities and interests of stakeholders
  - A range of **scenarios for engagement**

- “HFM State-of-the-Art” (**SoftA workshop**) took place April 14-16, 2021: https://indico.cern.ch/event/1012691/
- “HFM Roadmap Preparation” (**RoaP workshop**) took place June 1-3, 2021: https://indico.cern.ch/event/1032199/
- Now formalizing the roadmap and final report to LDG, due for presentation and endorsement at the December session of the CERN Council

Summary – Challenges

1. There is good progress on superconductor performance
   - Nb_3Sn **has the potential to meet the FCC targets**, the challenge will be to do this on a large-scale production at competitive cost
   - HTS has exceptional performance at high field, and requires **R&D to make it an accelerator-grade material** (mechanical and electrical material characteristics other than J_C, high-current cable, coil winding, production)
2. **Mechanics is the real challenge** of high-field accelerator magnets. This requires:
   - At macroscopic scale: R&D and demonstration of practical coils and structures, sustaining the exceptional electro- and thermo-mechanical loads
   - At microscopic scale: improvement of conductor and coil composite mechanics, providing adequate support to the fragile SC phase
3. Quench management will require modern technology for Nb_3Sn and substantial innovation for HTS
   - Fast and reliable detection and dump for Nb_3Sn magnets in the 12…16 T range (evolutionary change)
   - Use of alternative detection methods and protection strategies for HTS generating fields in excess of 20 T (**revolutionary change**)

Summary – Program

- CERN has initiated the HFM R&D programme, a **focussed technology R&D mission**:
  - In a **spirit of continuity** with the on-going work, and in particular the FCC-hh program, but also
  - In a **spirit of innovation**, intentionally **fostering and profiting from collaborations**
  - Intended to **provide a seed to the EU-wide HFM R&D** and connect to the on-going global HFM effort, with the required **flexibility** to accommodate for the result of the LDG Roadmap process (end 2021)
- On the horizon of the next Strategy Upgrade (2025-2027) we plan to provide crucial results that respond to the *mission statement* as set out by the ESPP:
  - **Nb_3Sn: demonstrate technology for large-scale accelerator deployment**
  - **HTS: demonstrate suitability for accelerator magnet applications**

HFM

High Field Magnets