HIAT 2022 | Darmstadt

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Superconducting magnets challenges for the future

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Università degli Studi di Milano – Dipartimento di Fisica

& INFN – Milano – LASA Laboratory

(@CERN 2001-2020 – leading LHC SC magnets & High Luminosity-LHC project)

Talk @ 15th Int. Conf. on Heavy Ion Accelerator Technology – Darmstadt 27 June 2022

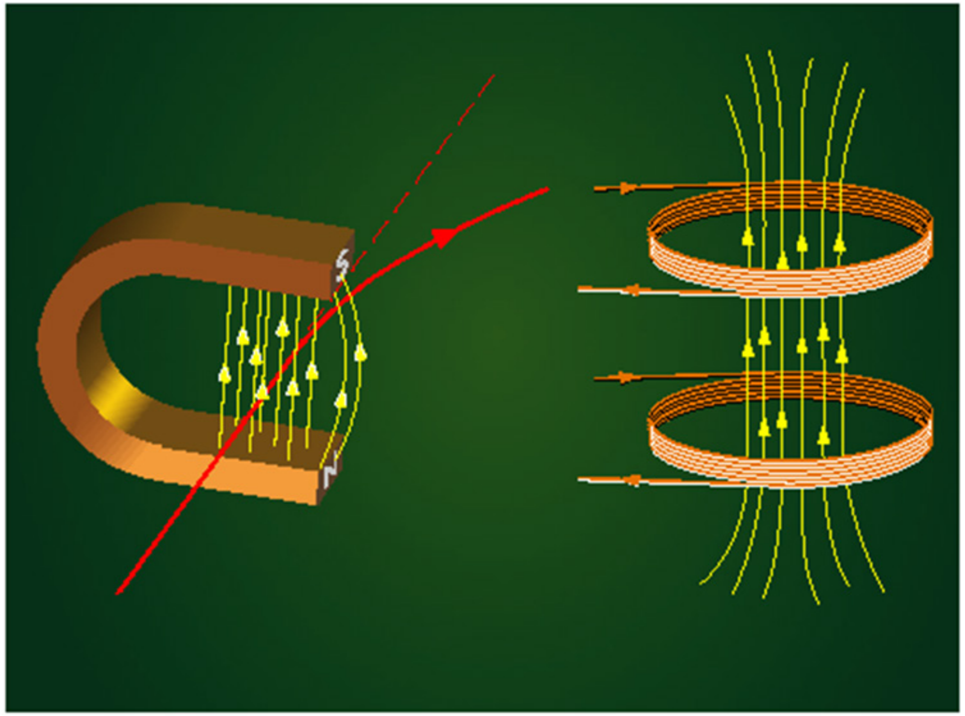
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

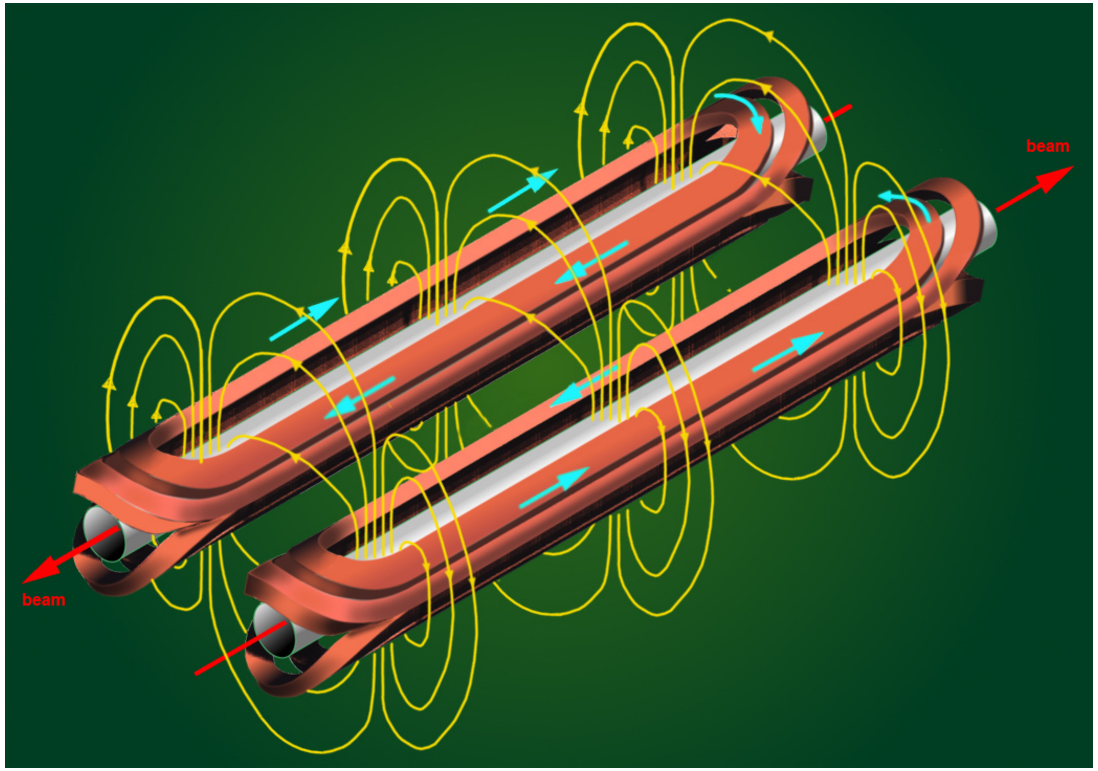
HITRI plus Heavy Ion Therapy Research Integration

iFAST

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

Basic shape ; circular coils for cyclotrons vs HEP slim long coils





Canada (Chalk River) and K500 and K1200 at NSCL-MSU and K800 Milan→Catania; 1976-1989

Main feature

- Circular split coil in iron yoke
- Field about 5 T (with iron pole)
- I_{op} about 1-2 kA
- $J_{overall}$ about 20-40 A/mm^2
- Cables with large amount of copper and LHe direct cooling (wet coils)
- Hoop stress containment system
- Issue:
  - split coils (friction on midplane)
  - Subdivision of the coil into two sections with (also) opposite excitation)

Scheme of SC cyclotron of Chalk River

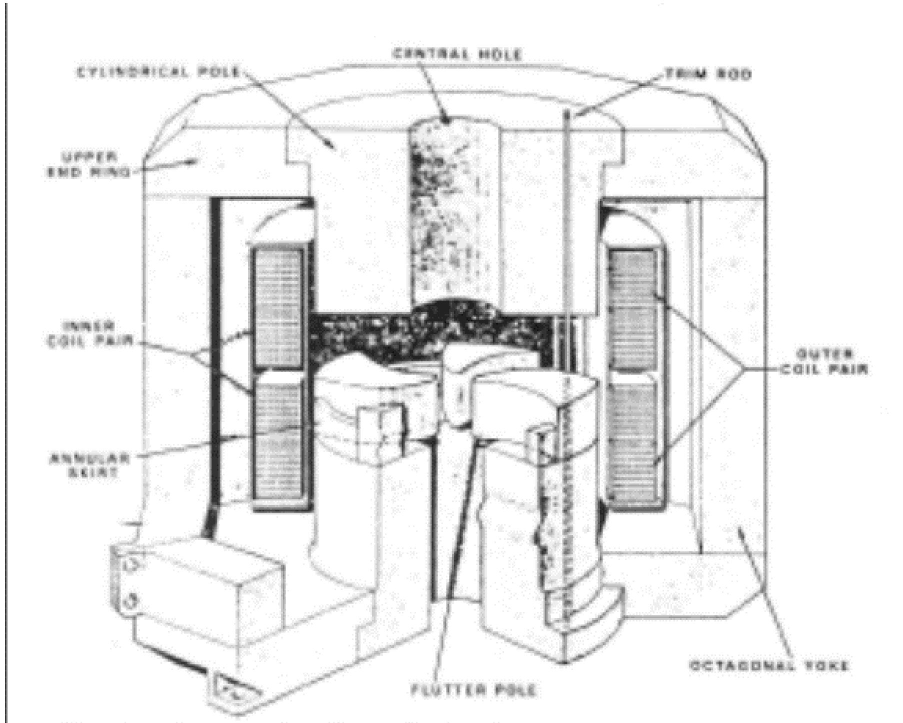
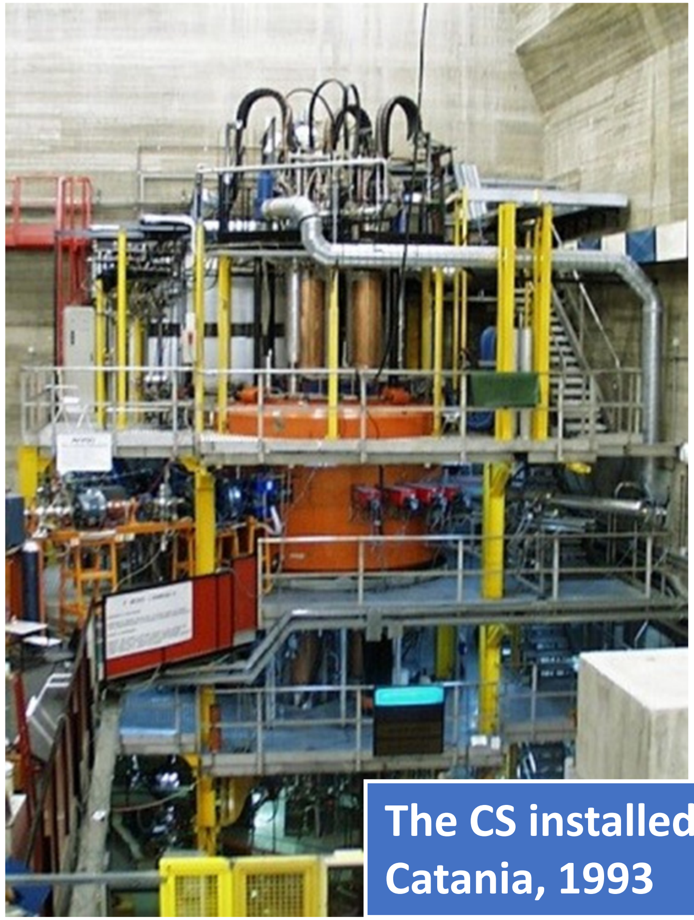


Fig. 5: Schematic view of the Chalk River K510 magnet as actually constructed.[10)]

CS (Sup. Cyclotron) designed and built by INFN-Milan, assembled (1991-93) and operated in INFN-LNS Catania

SC coils of the CS-INFN-Milano
c/o Ansaldo, Genova 1983



The CS installed in INFN-LNS ,
Catania, 1993

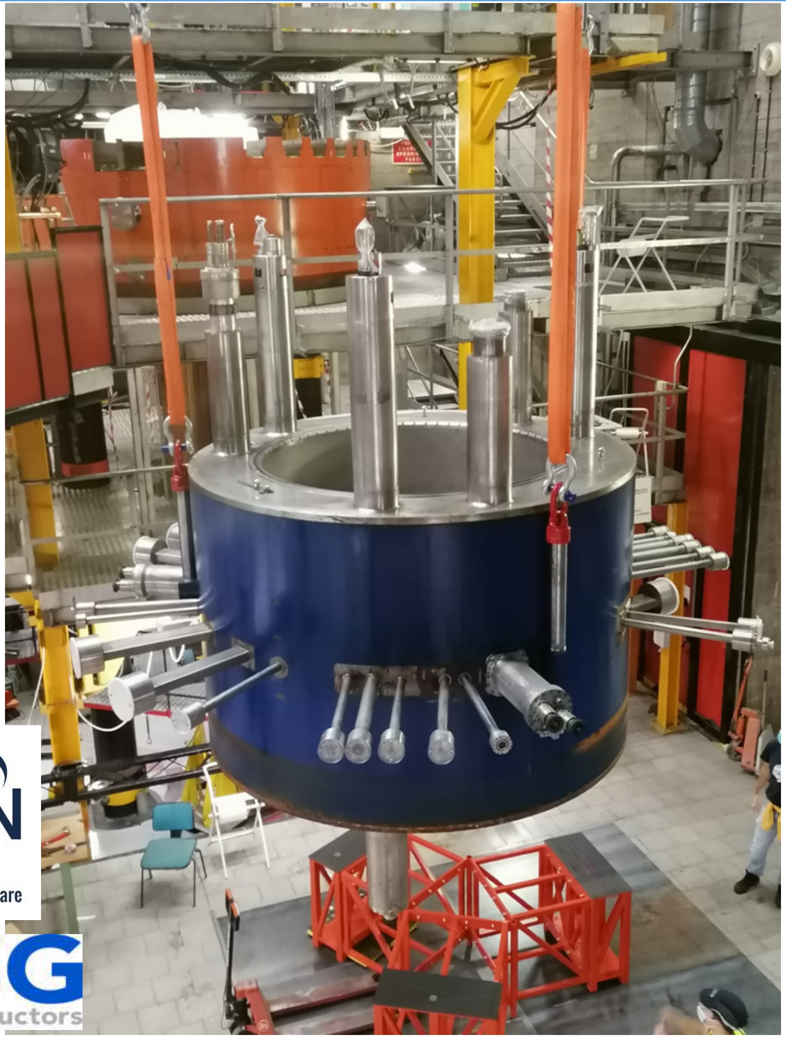
Second Generation SC Cyclotrons with impregnated coils and reduced stabilizing copper

Synchrocyclotron of Henry Blosser at NSCL-MSU

The Orsay-KVI Groningen Superc. Cyclotron – operated 1996

The SC magnet during power test at ANSALDO (now ASG) Genova, 1992

Last generation under construction
CATANA- CS upgrade@INFN-LNS



INFN
Istituto Nazionale di Fisica Nucleare

ASG
Superconductors

SC cyclotrons with closed loop cryogenics

AMIT @ CIEMAT Technology dept. (Madrid)

Energies < 15 MeV Short-lived PET isotope production:

^{18}F, 11C, ^{13}N, ^{15}O. For on-site production (hospital)

First SC coil (4 T , high current density)

And coil-yoke assembly

GOBIERNO DE ESPAÑA

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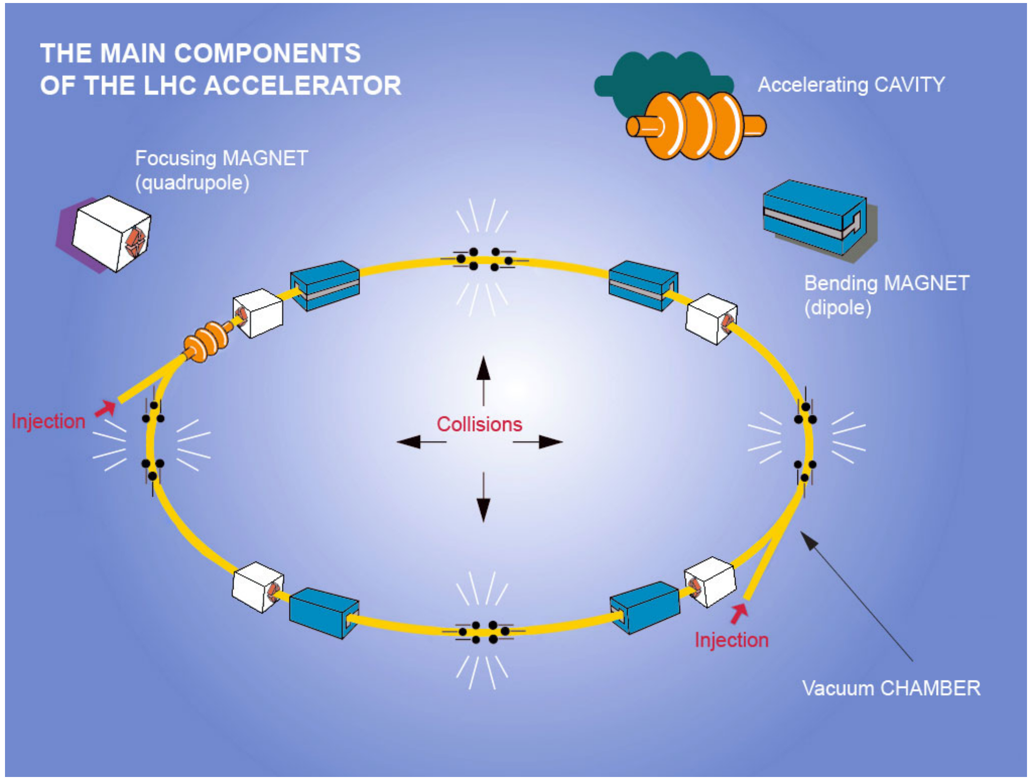
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

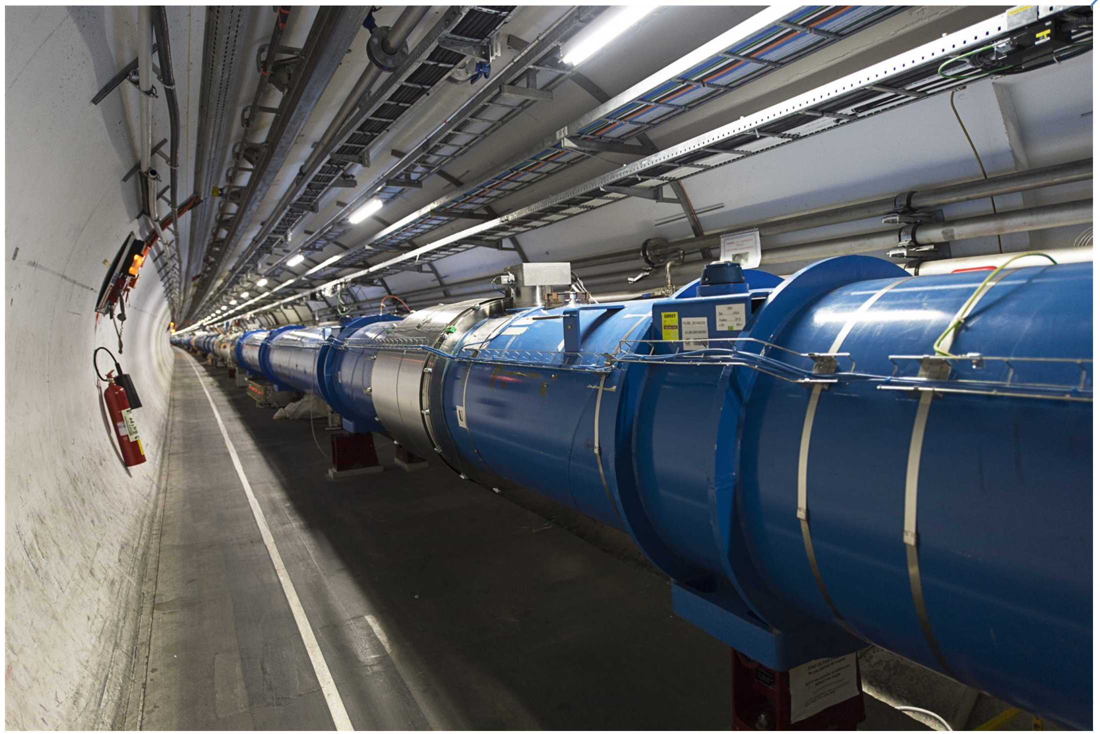
SC Magnet technology for large (long) accelerators – Colliders for HEP

Magnets cover about 85% of the length

Dipoles field covers 65%: $E_{beam} = 0.3 \cdot B \cdot R_{bend}$ (TeV, T, km)



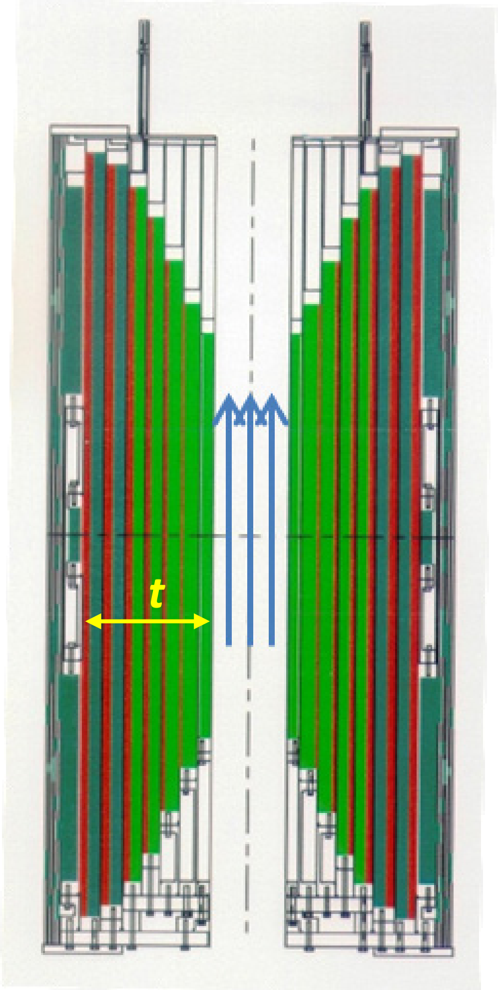
Main dipoles (blue tubes) sequence in the LHC tunnel



Transverse field coils generate half filed than solenoid (with same coil thickness)

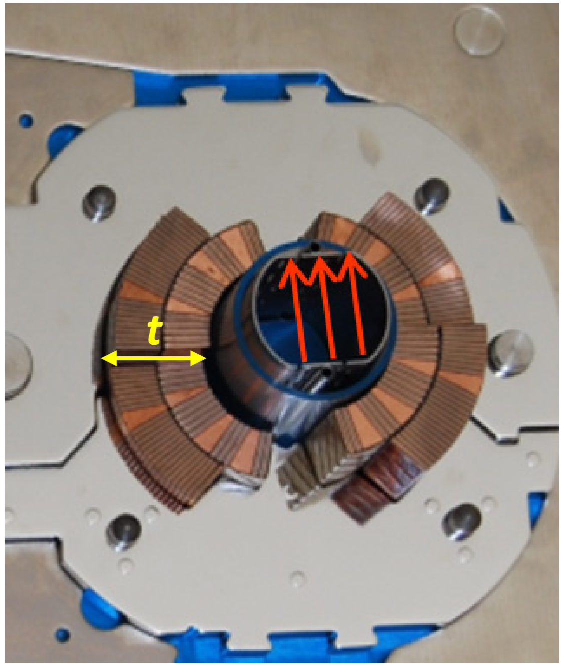
Solenoids gives

- $B_{sol} = \mu_0 J \cdot t$



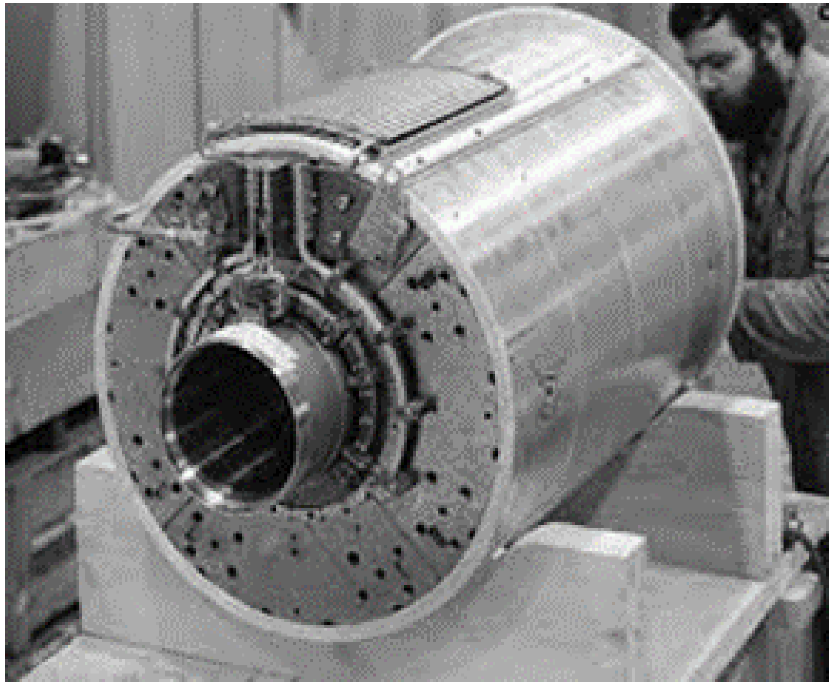
In dipole and long magnets , force are not self contained

- $B_{dip} = \frac{\mu_0}{2} J \cdot t$



First HEP accelerators using Superconductivity 4 T Colliders → slow ramp up and then steady state

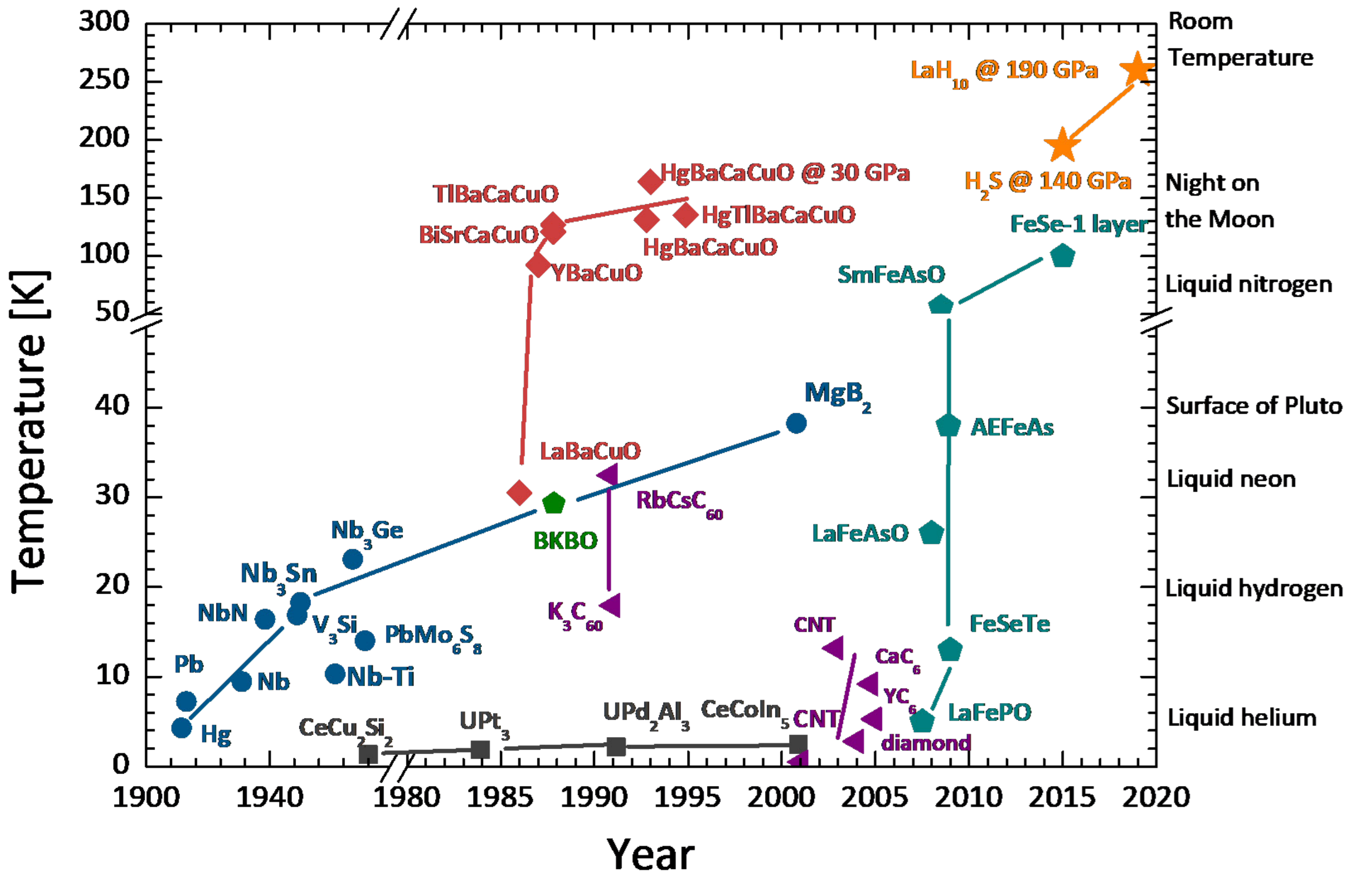
CERN ISR quadrupoles (1981-83)



Tevatron (1984): winning technologies

Use of large cables (~ 5 kA), collars…

Superconductivity: > 100 y of progress…



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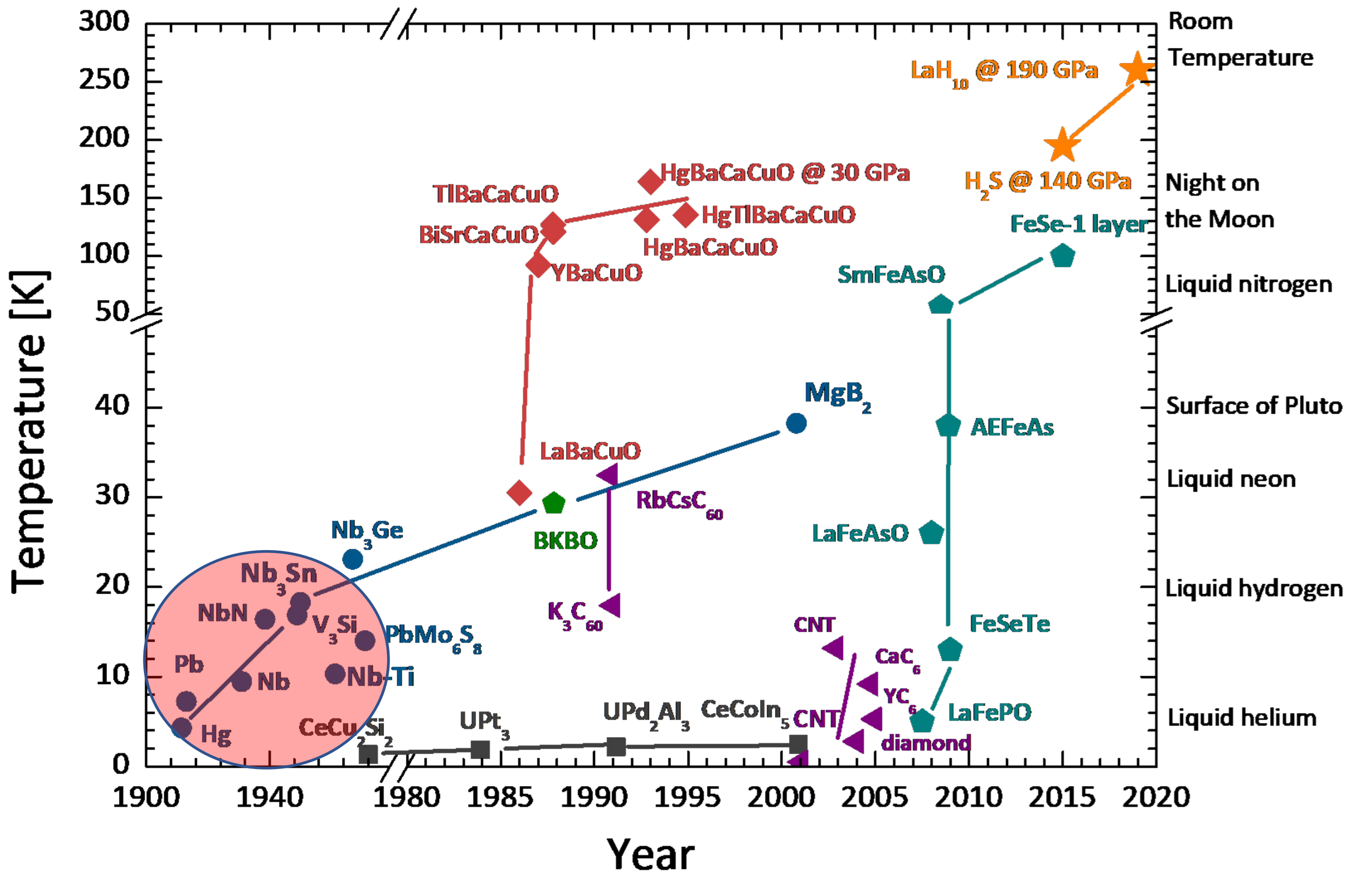

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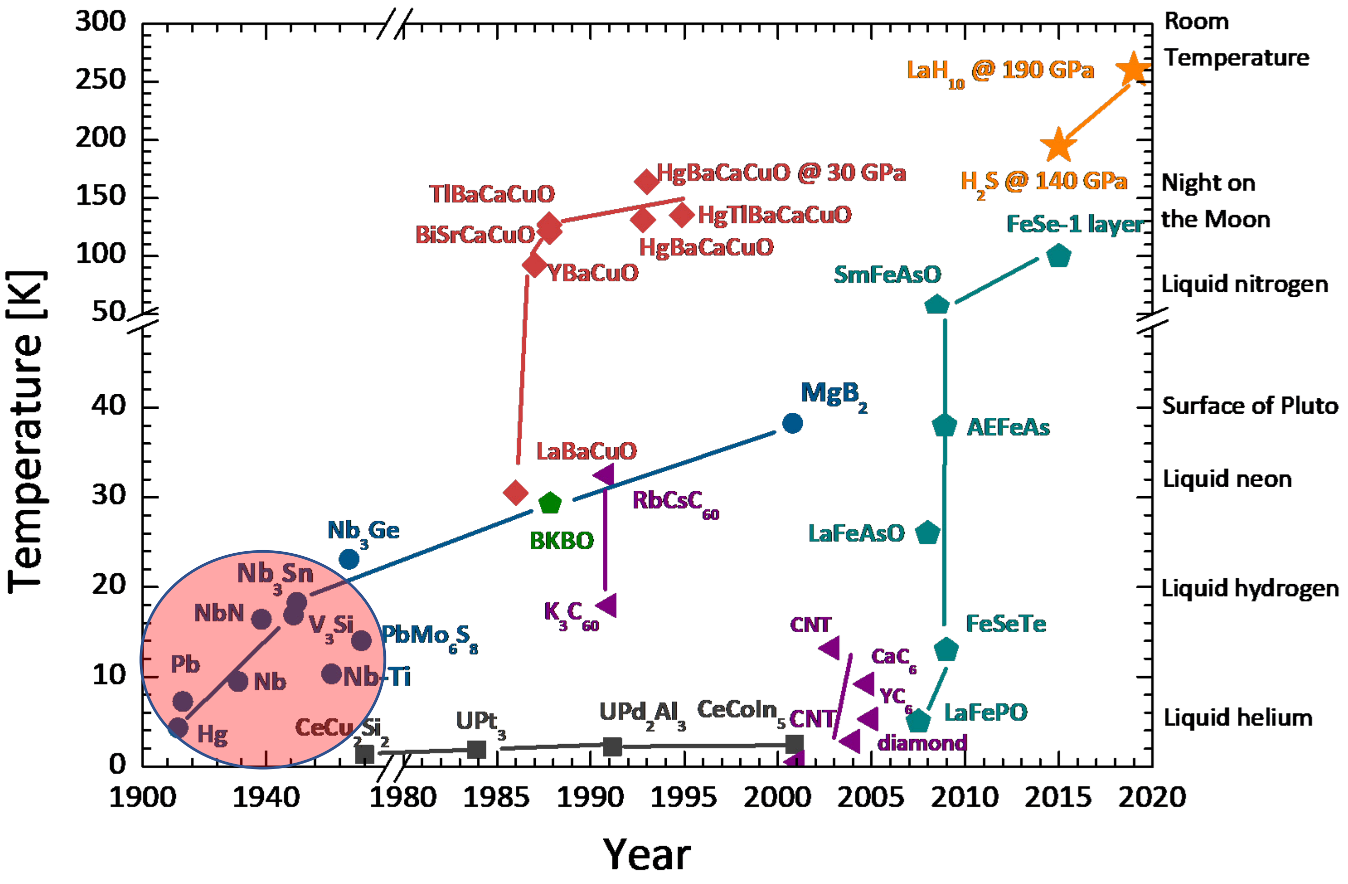

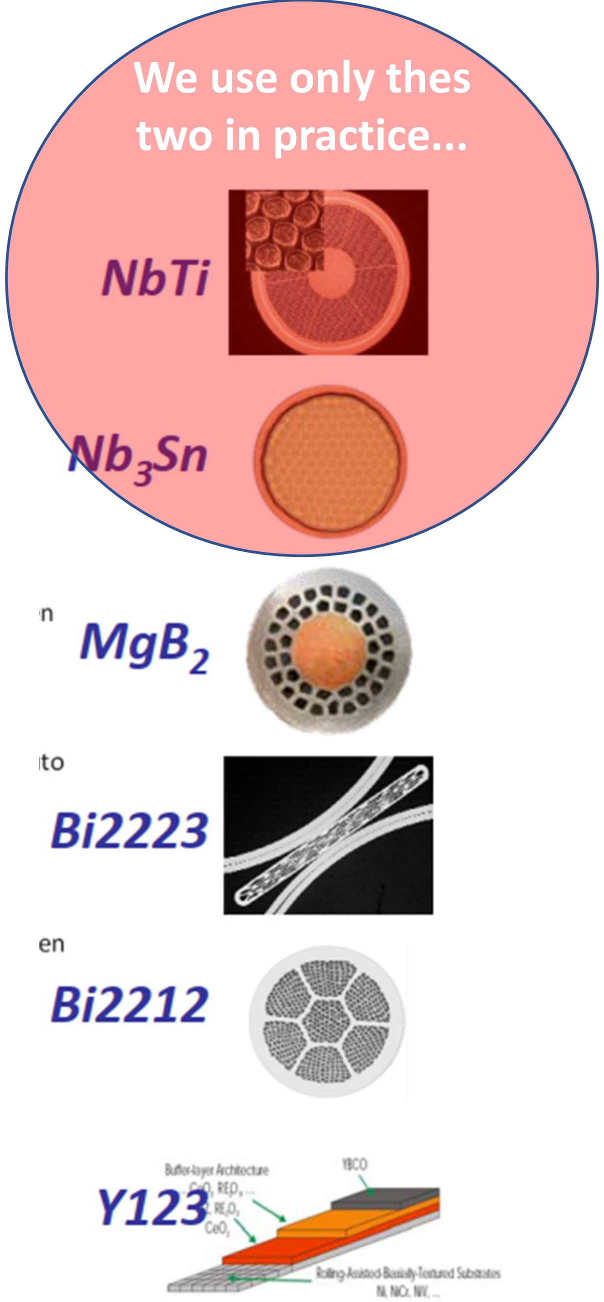

Why we need superconductivity

Superconducting LHC

- Tunnel: 27 km
- Field : 8.3 T
- Cryoplant power at the plug: 40 MW: **always on**
- ~ 70 MW for LHC. 150 MW for the accelerator complex
- 180 MW for the whole CERN complex

Normalconducting LHC

- Tunnel 120 km
- Field : 1.8 T
- Dissipated power at collision: ~ 2,200 MW
- Average power (0.4 coefficient): 900 MW only for accelerator

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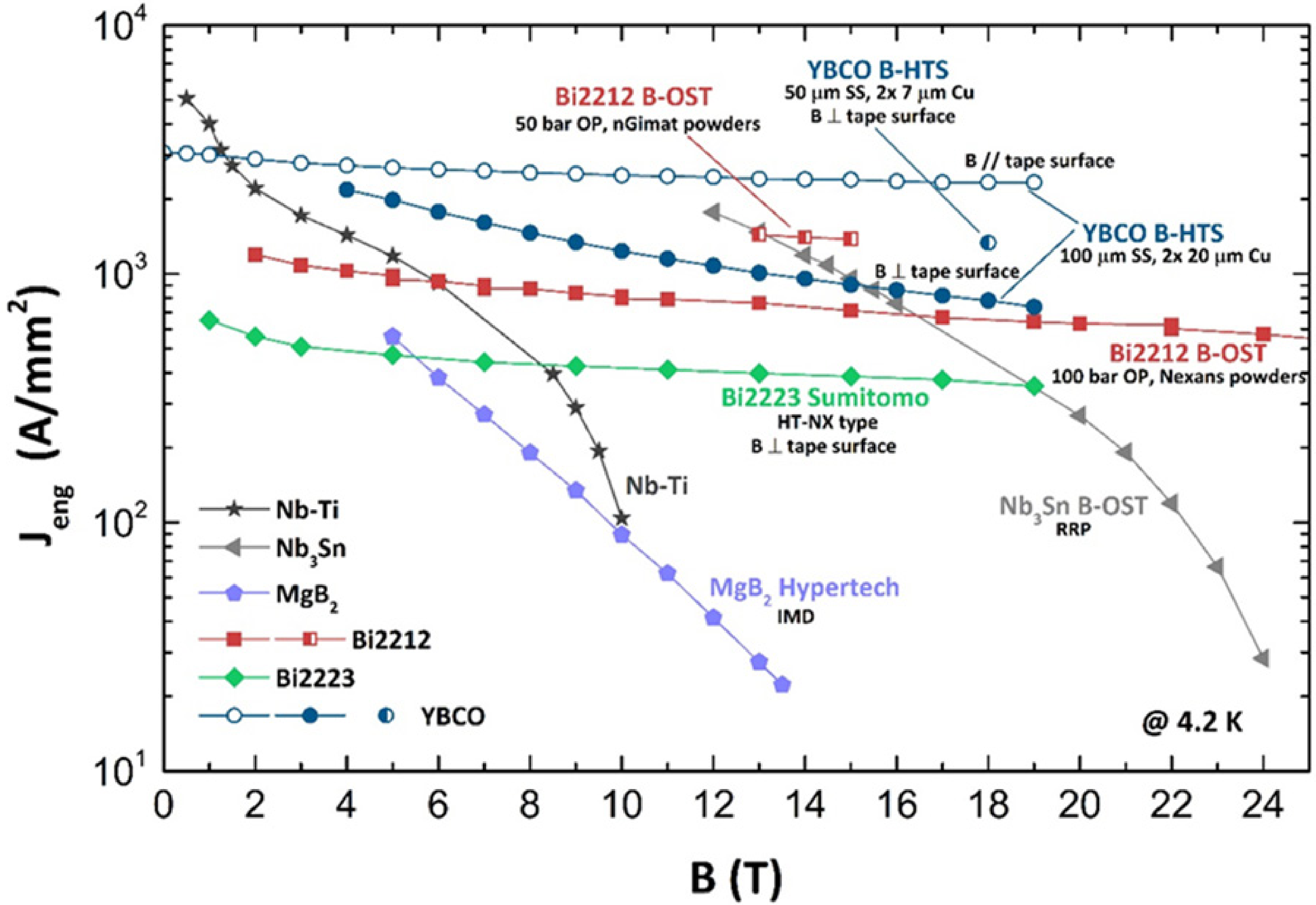
However, power is required only when operating while power in SC magnets is needed to keep it cold… a factor 2 favorable in energy for NC

The unfair advantage of Superconductivity: J_{coil}



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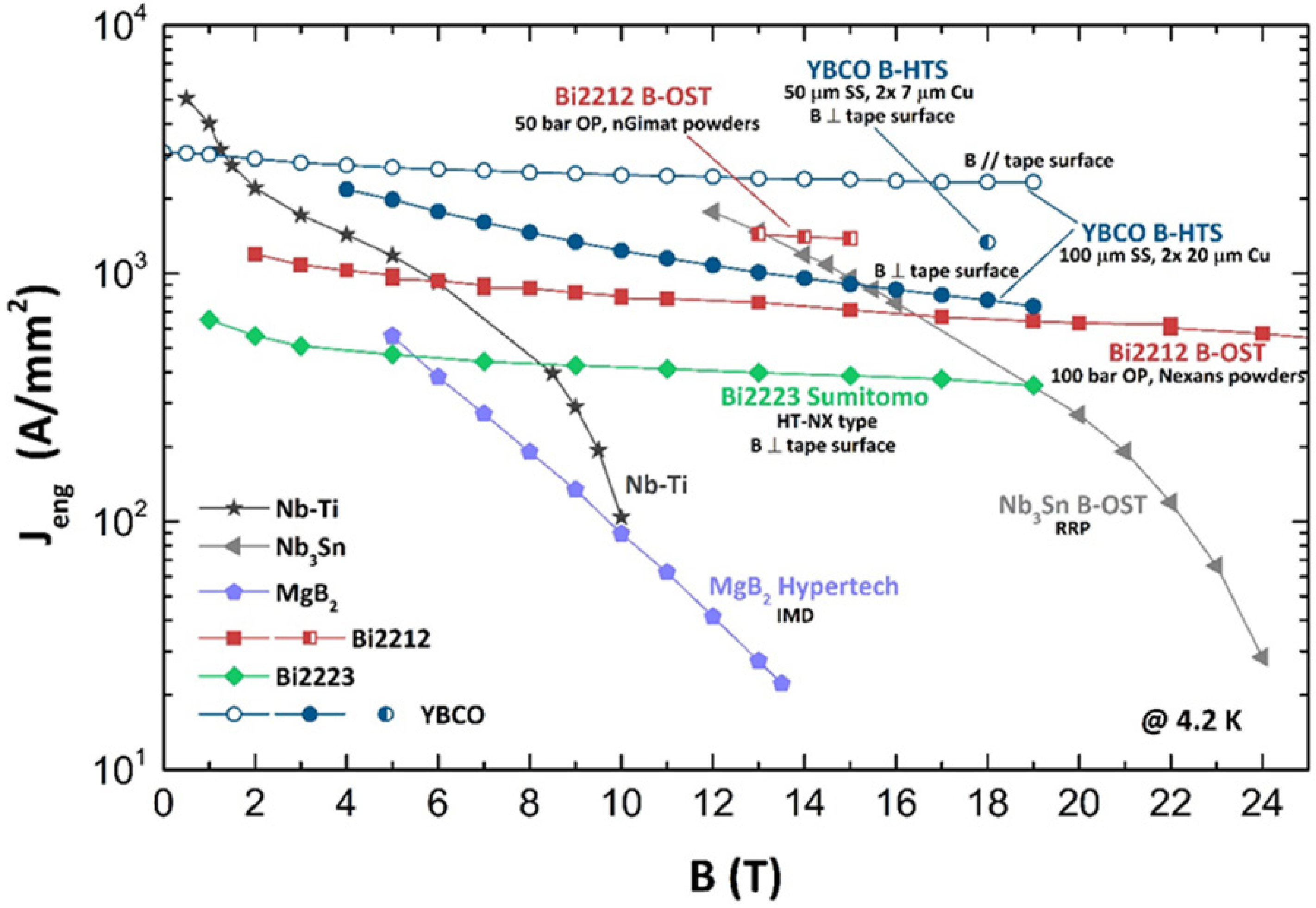

ITER
Det. Magnets

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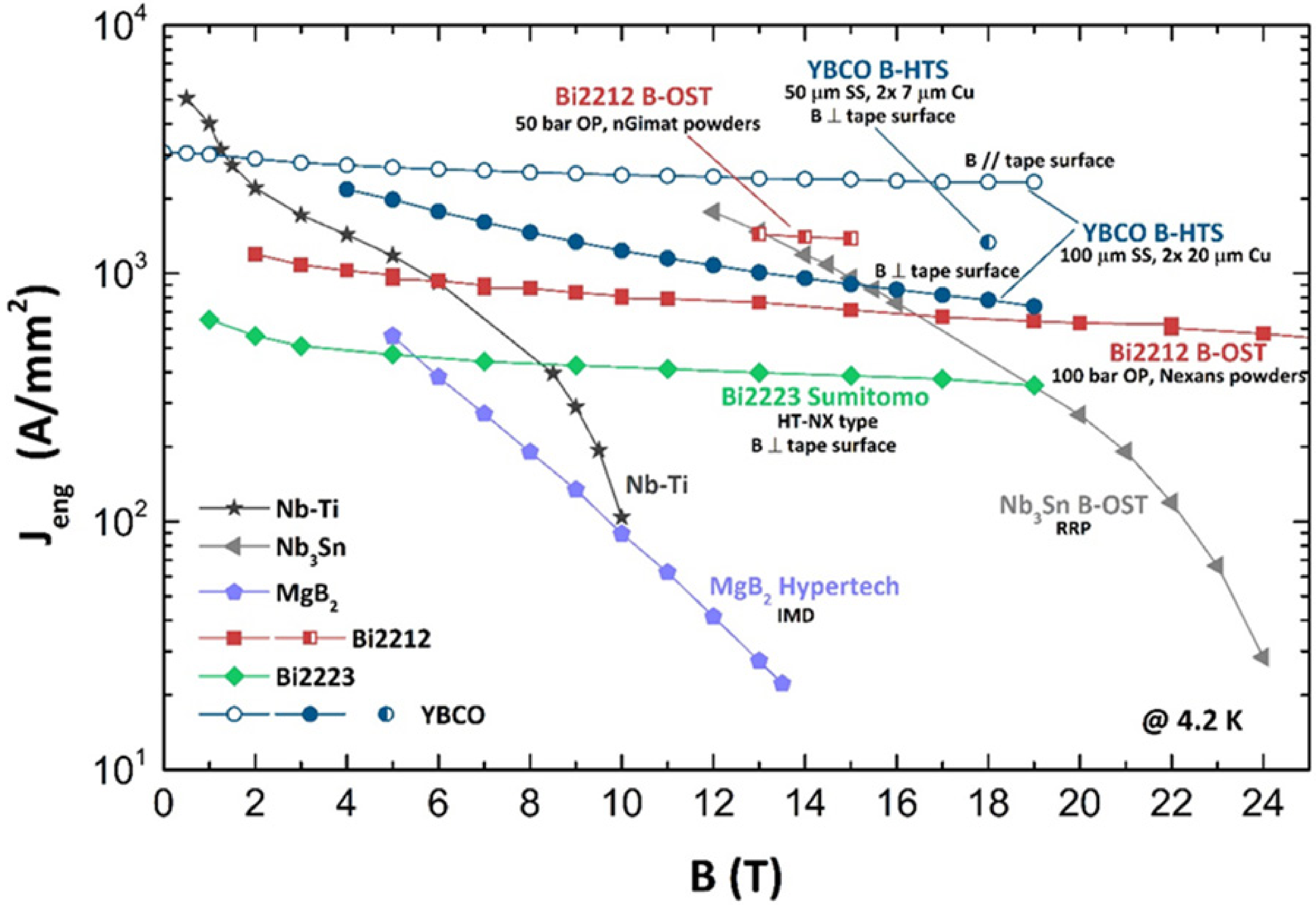

Small solenoids

ITER Det. Magnets

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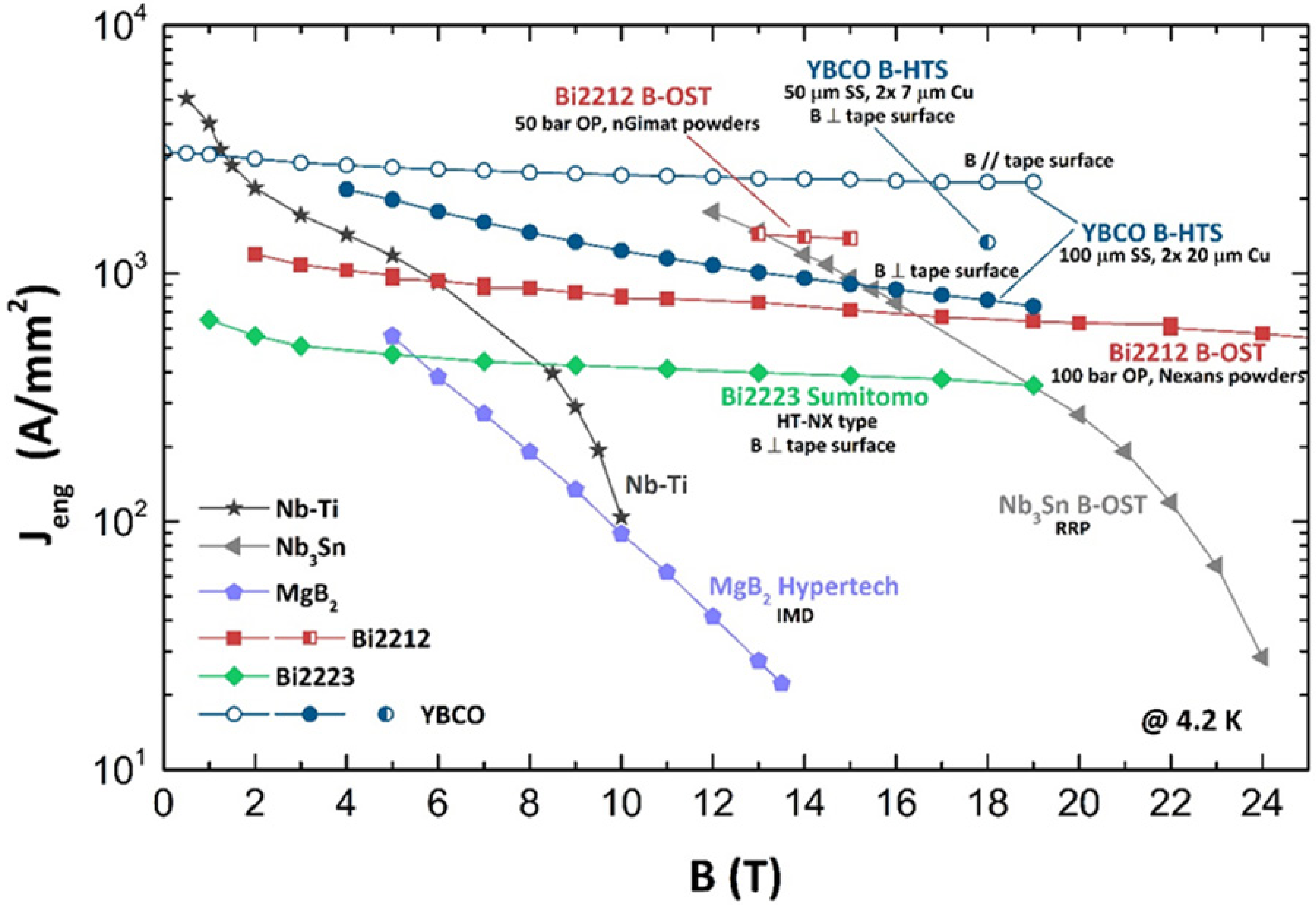

Transverse fields

Small solenoids

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Det. Magnets

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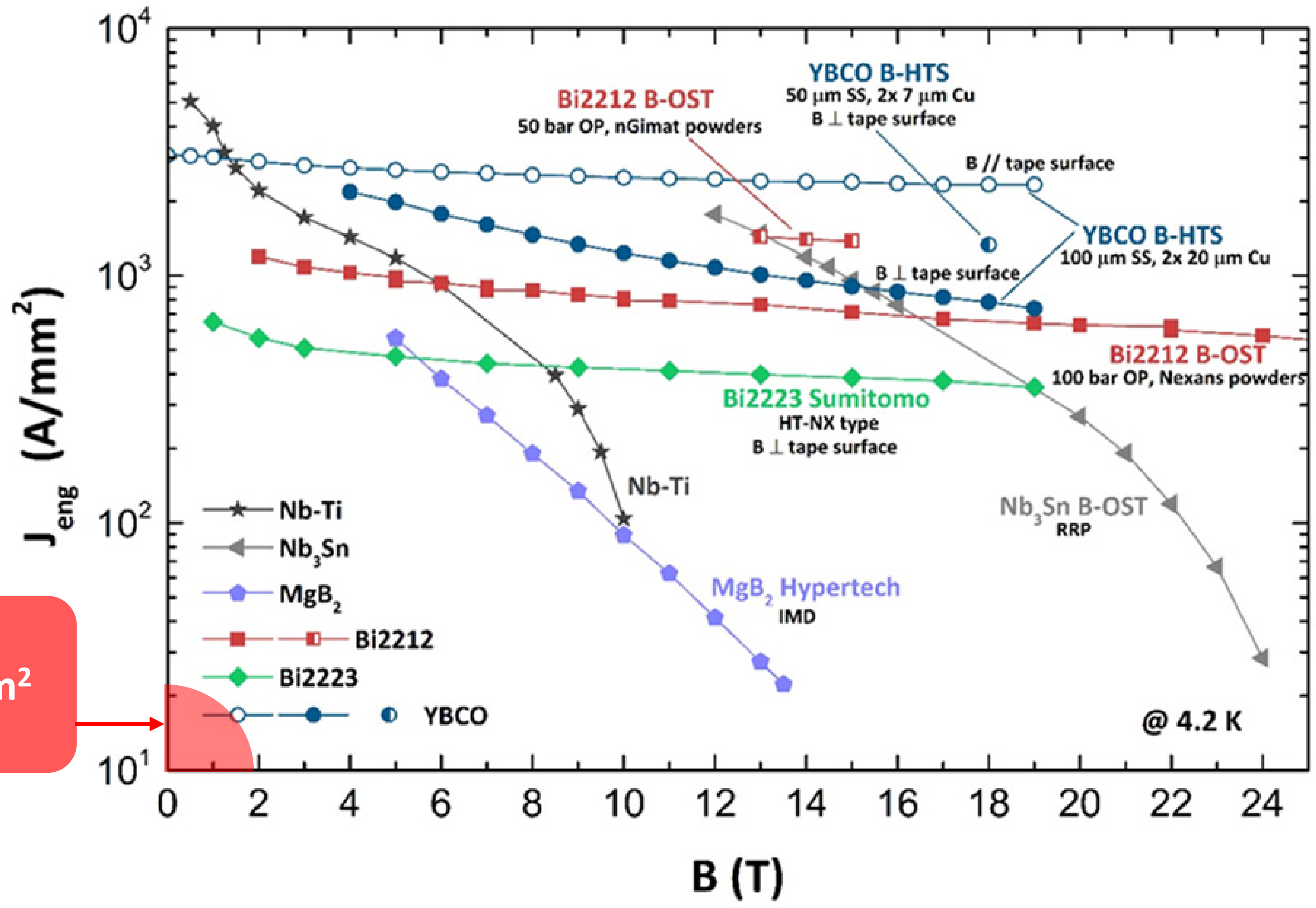


Electromagnets
$J_{overall}$ ~ 5 -20 A/mm^2
B < 1.5 - 2 T

Transverse fields

Small solenoids

ITER
Det. Magnets

jump

Graphics by courtesy of M.N. Wilson

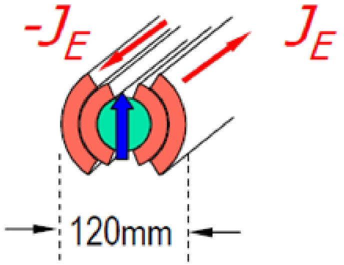
The advantage of high current density

- The field produced by an ideal dipole is:

$$B \approx 1/\pi \ \mu_0 J_E t$$

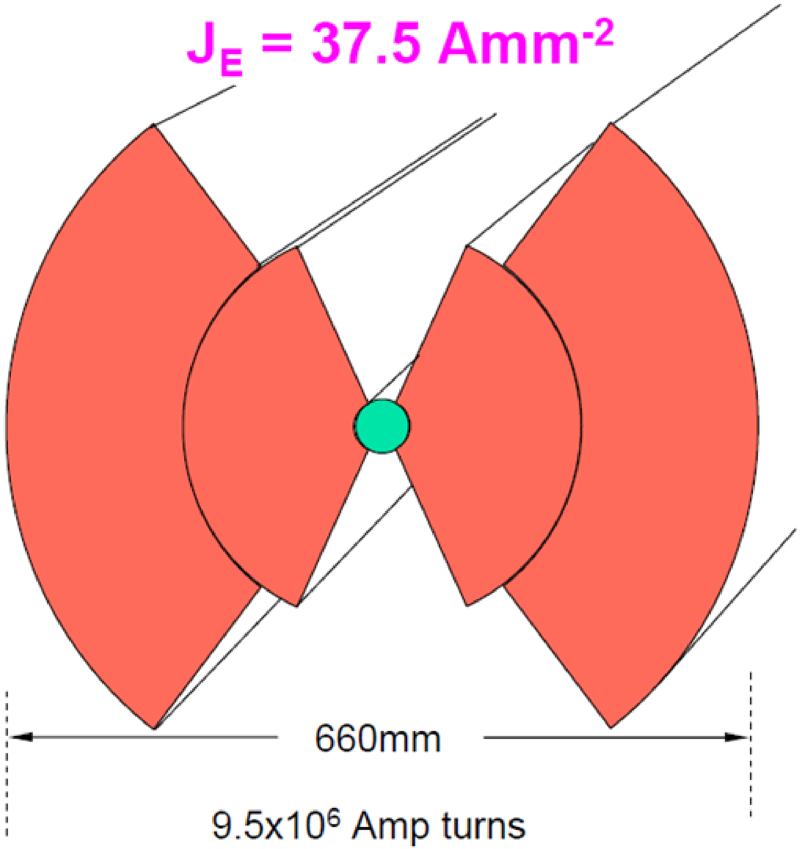
J_E = 375 Amm^{-2}

LHC dipole



9.5x10^5 Amp turns
=1.9x10^6 A.m per m

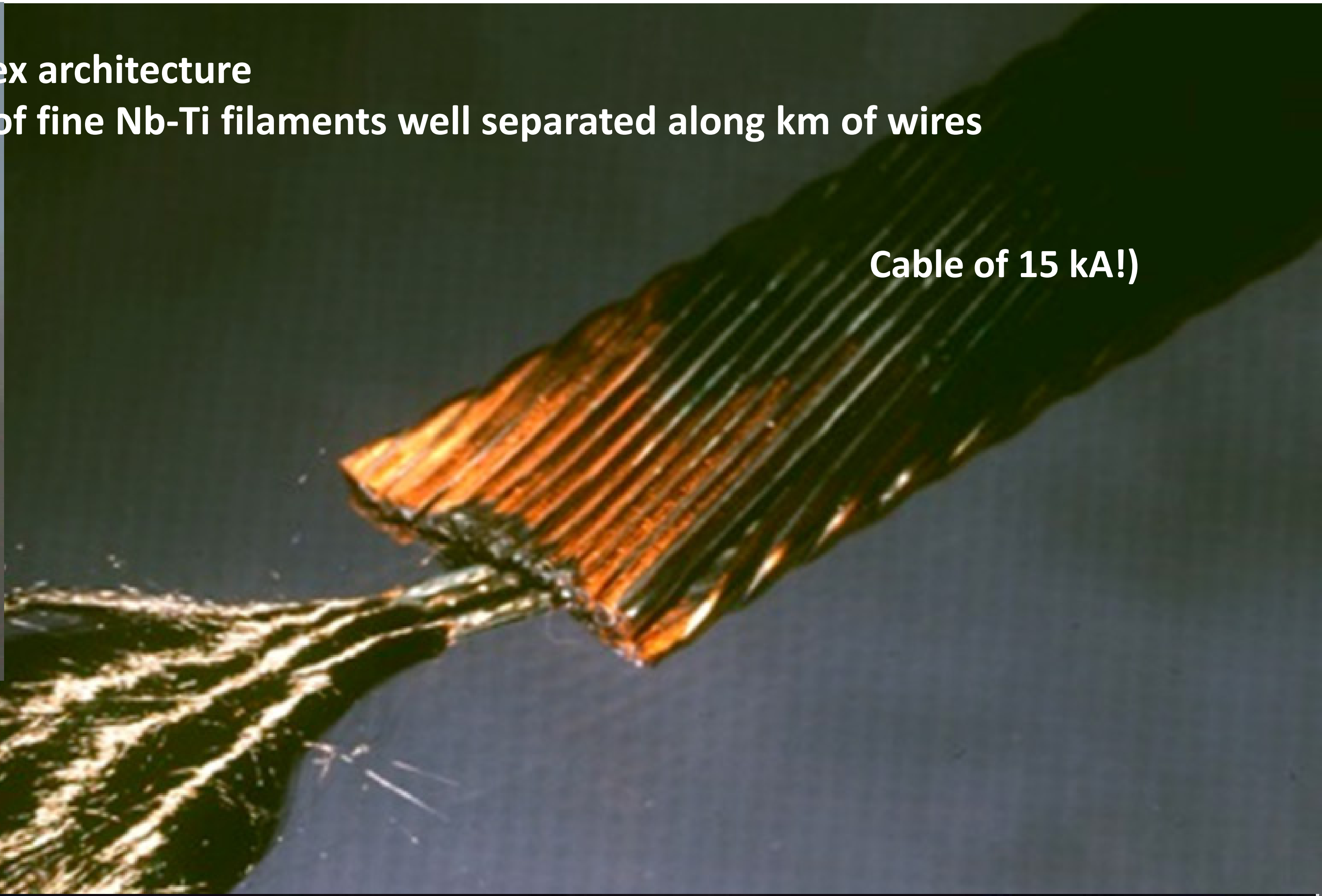
J_E = 37.5 Amm^{-2}



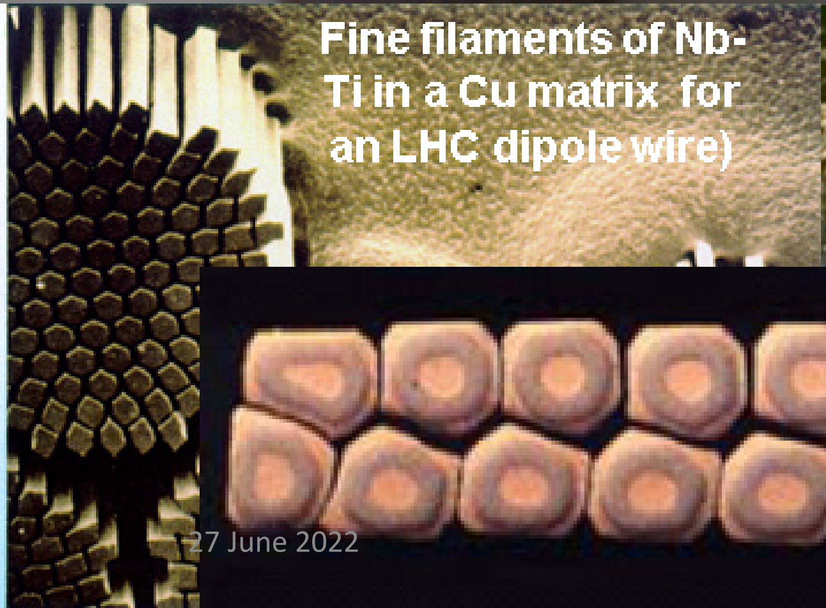
9.5x10^6 Amp turns
=1.9x10^7 A.m per m

Very complex architecture

Thousands of fine Nb-Ti filaments well separated along km of wires



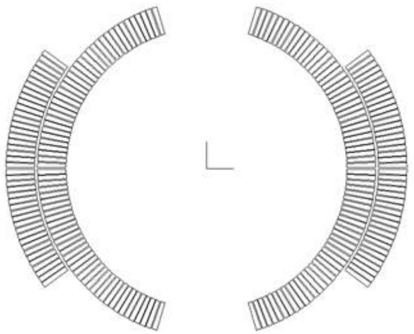
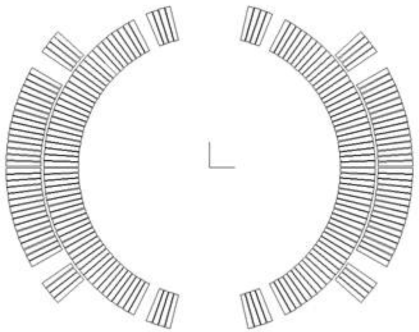
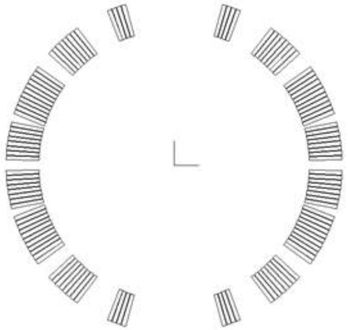
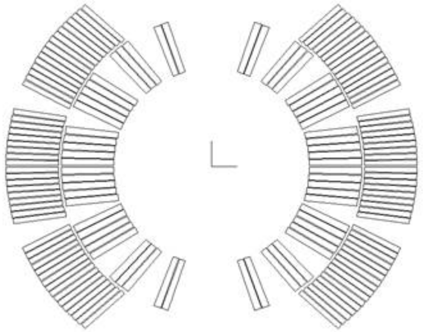
Cable of 15 kA!)

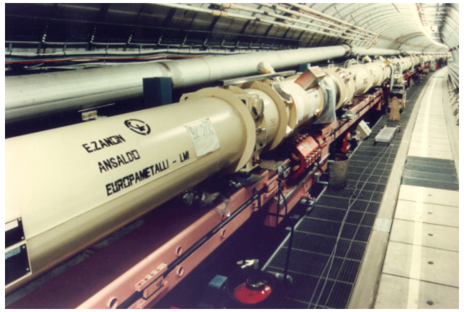


Fine filaments of Nb-Ti in a Cu matrix for an LHC dipole wire)

Coil cross section of main dipoles for colliders

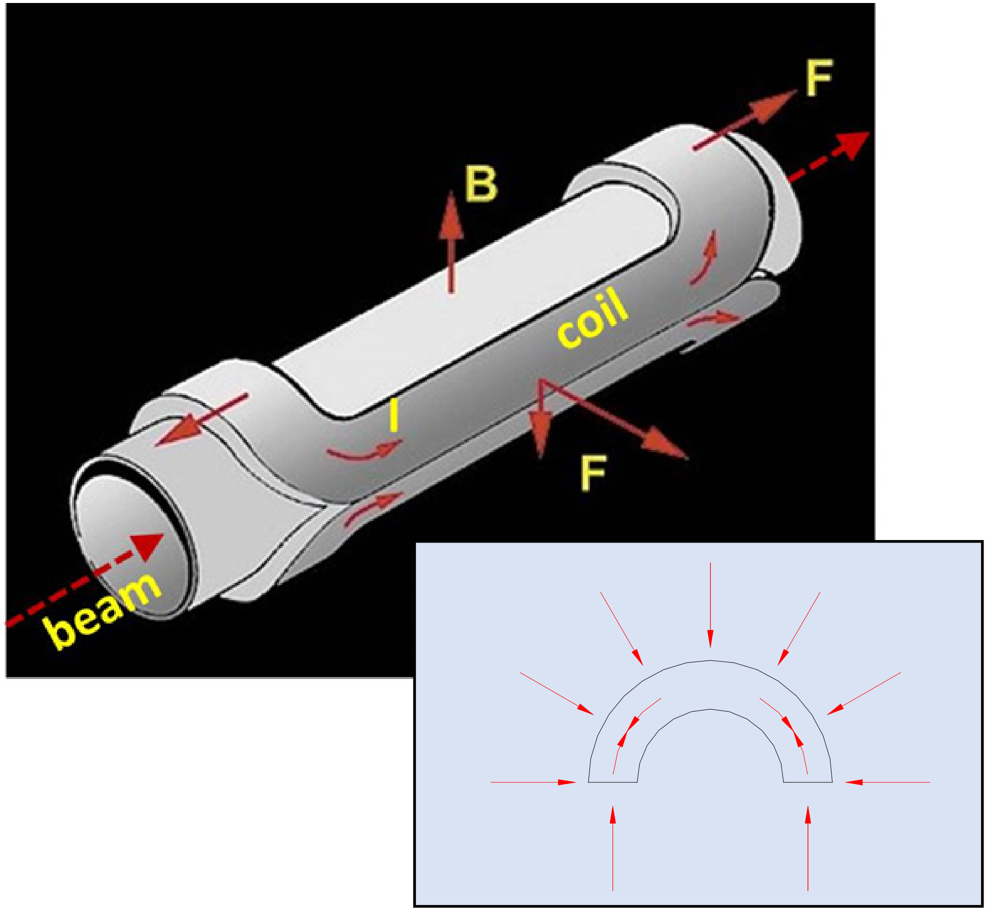
Main dipoles of various colliders put in operation

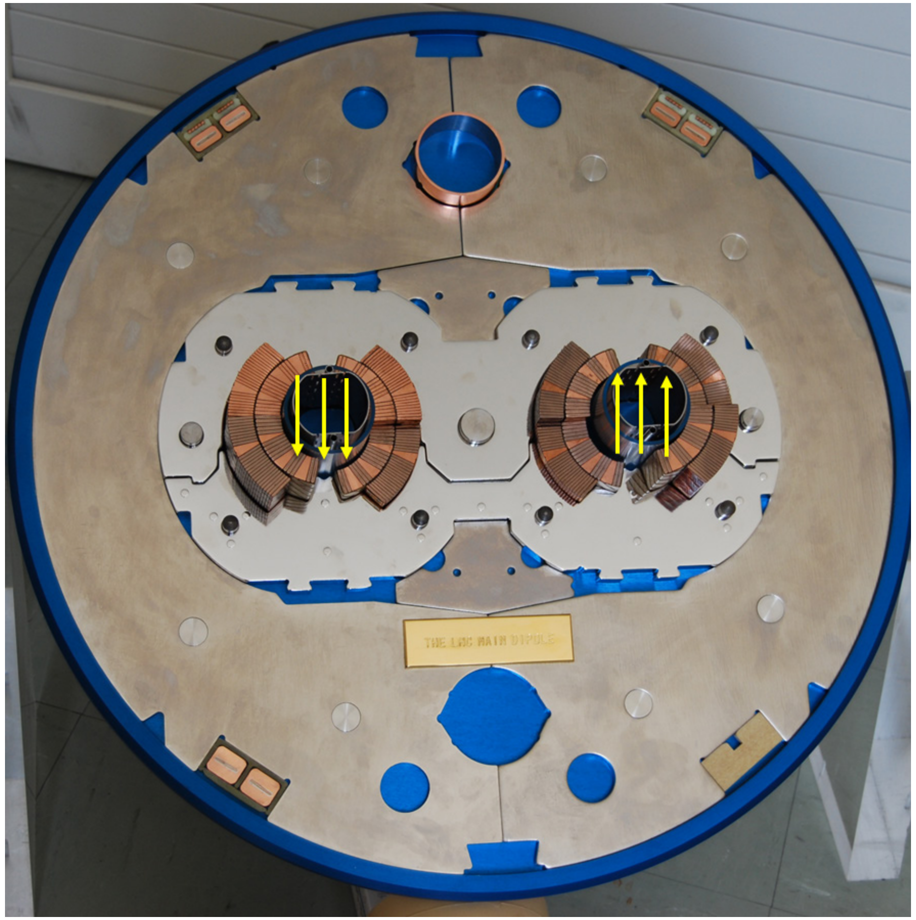





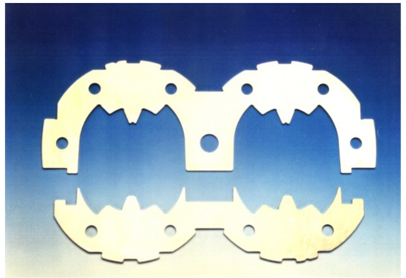

Tevatron **HERA** **RHIC** **LHC**

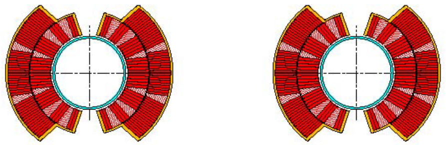
LHC magnets: cold mass contain two dipoles… Two-in-One or Twin dipoles

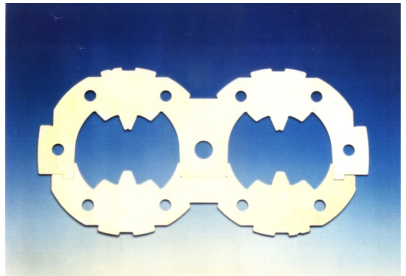


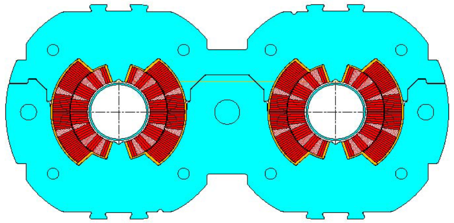


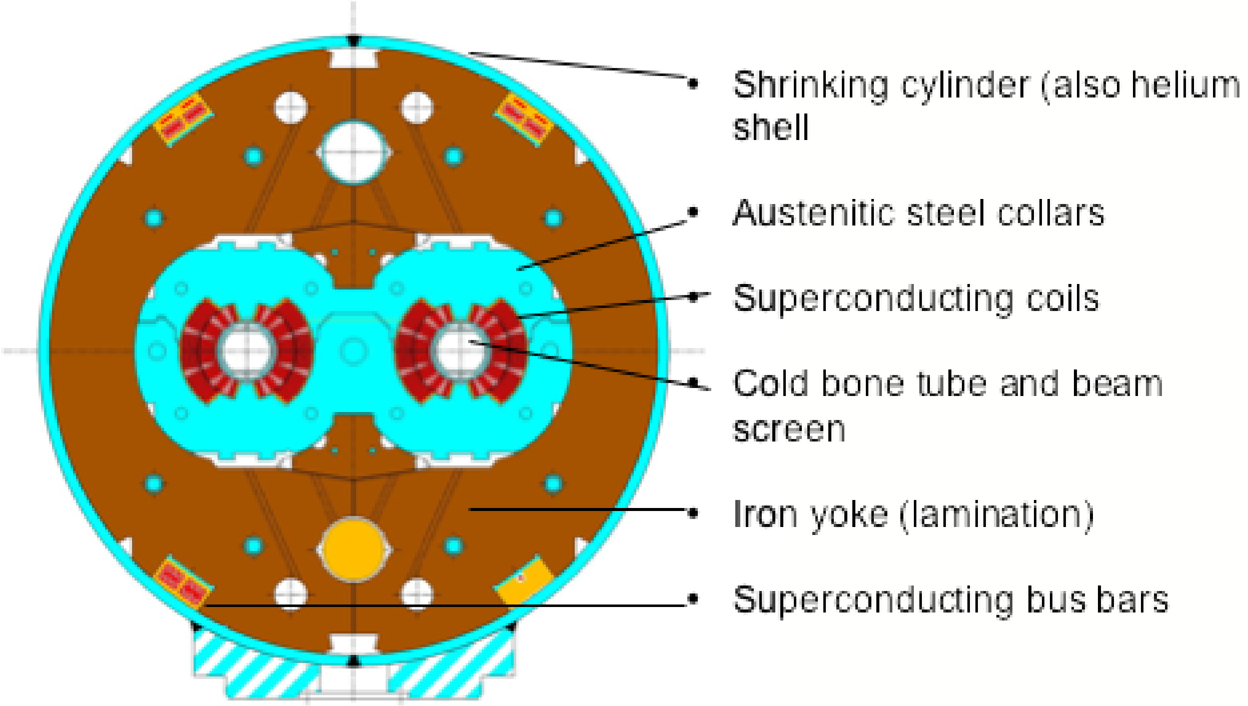
Austenitic collars counteract magnetic forces



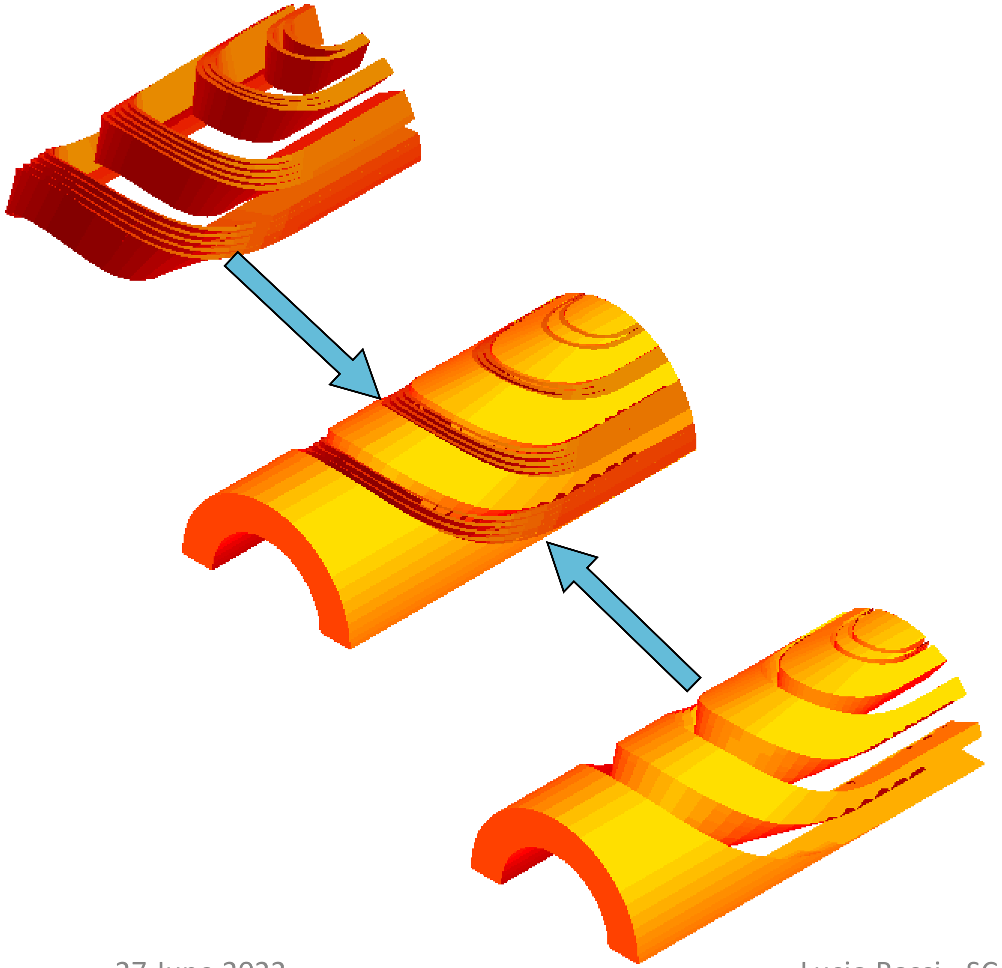








Zones with issues… coil saddle shape ends and magnet connection/end



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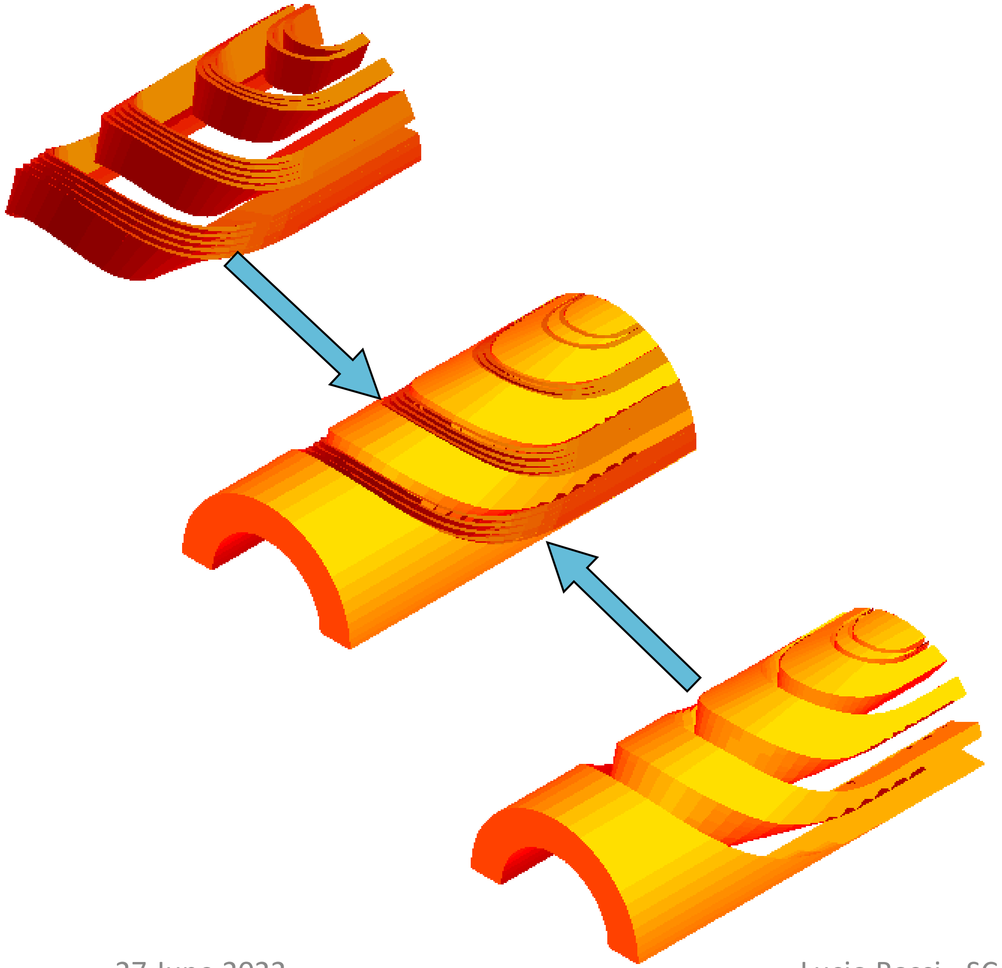

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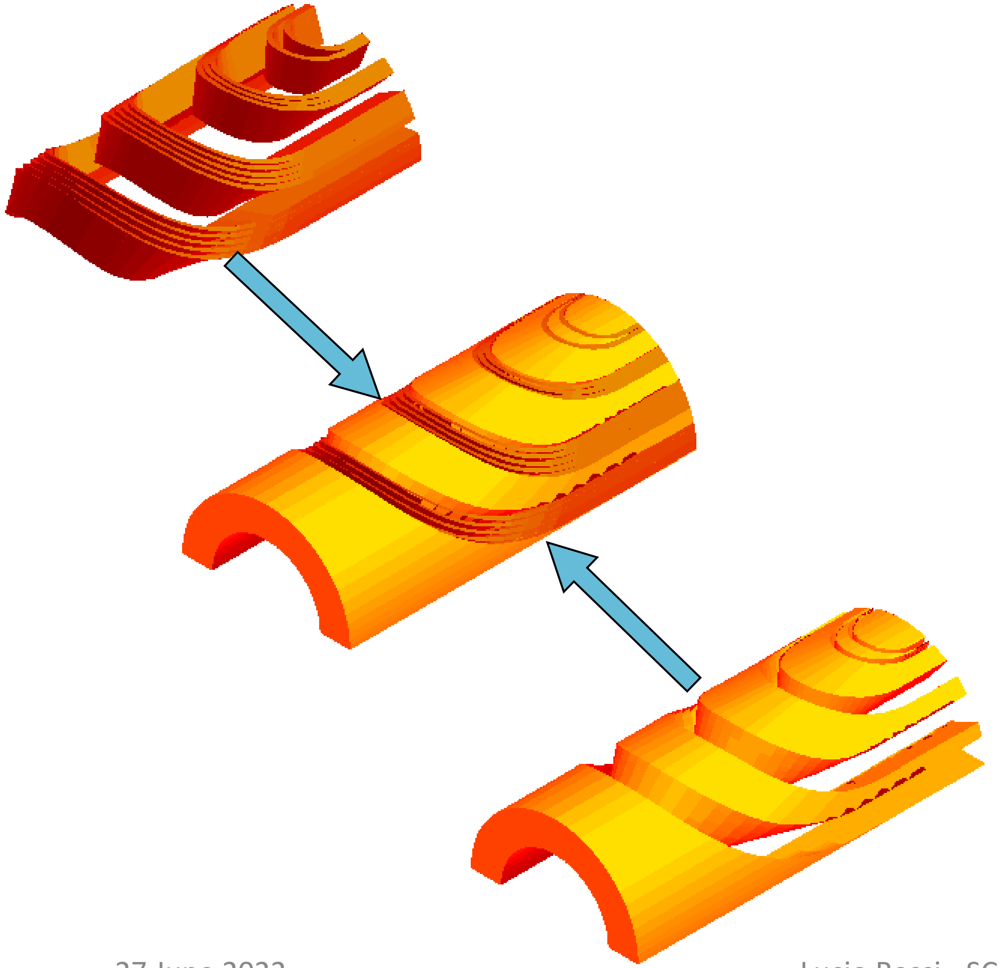

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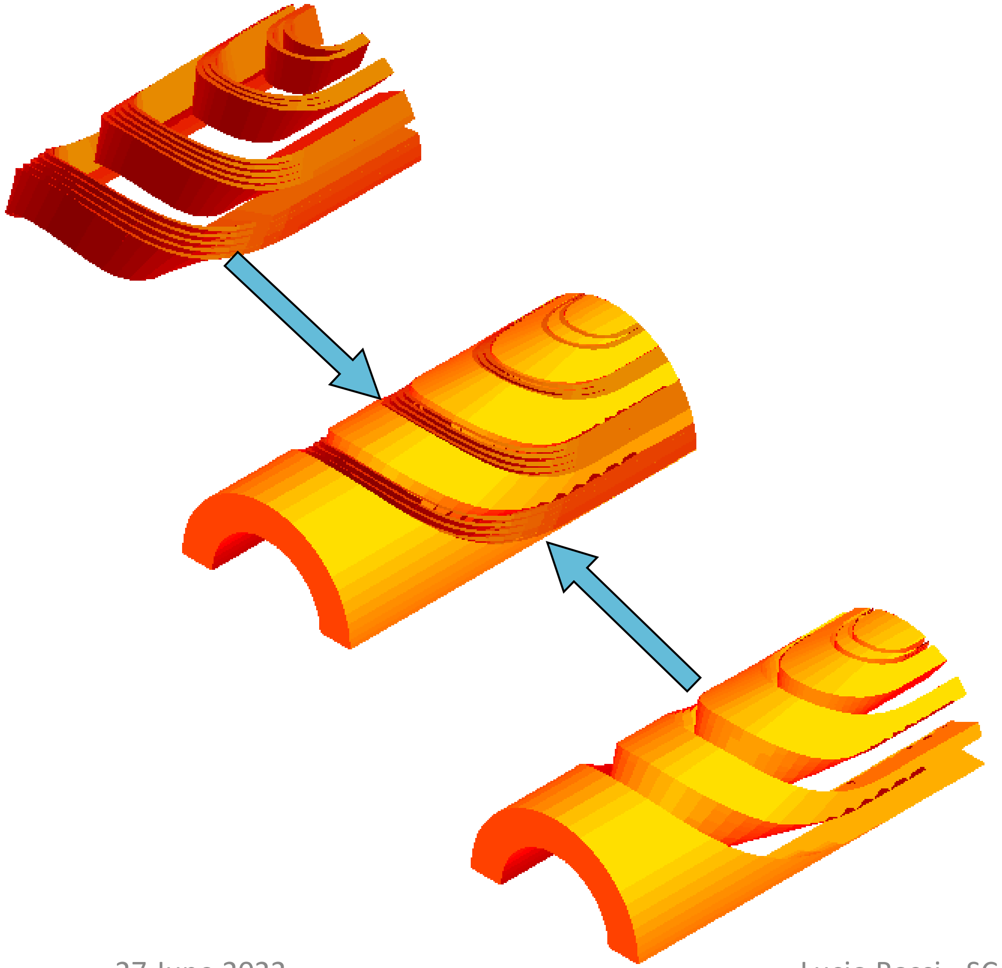
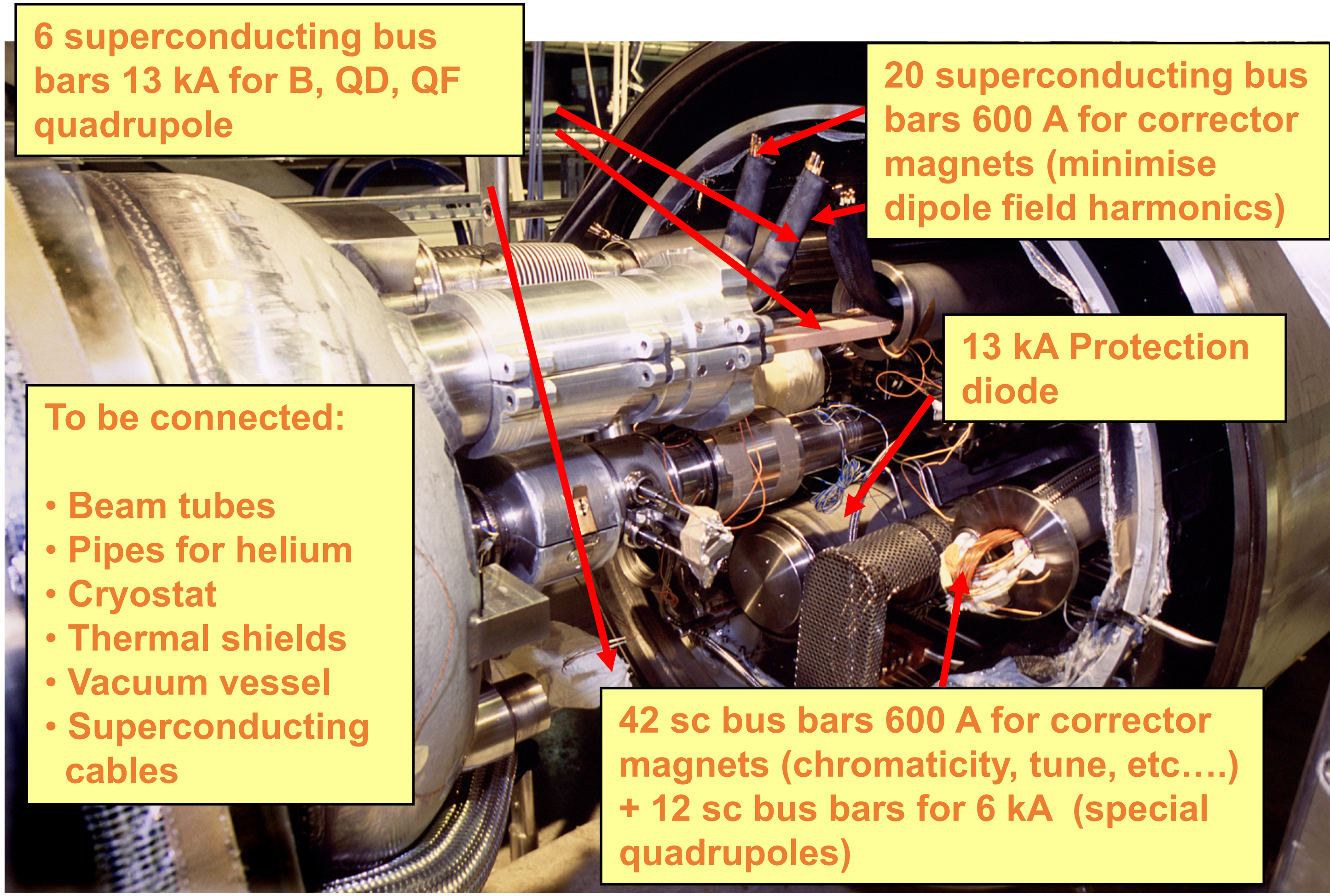
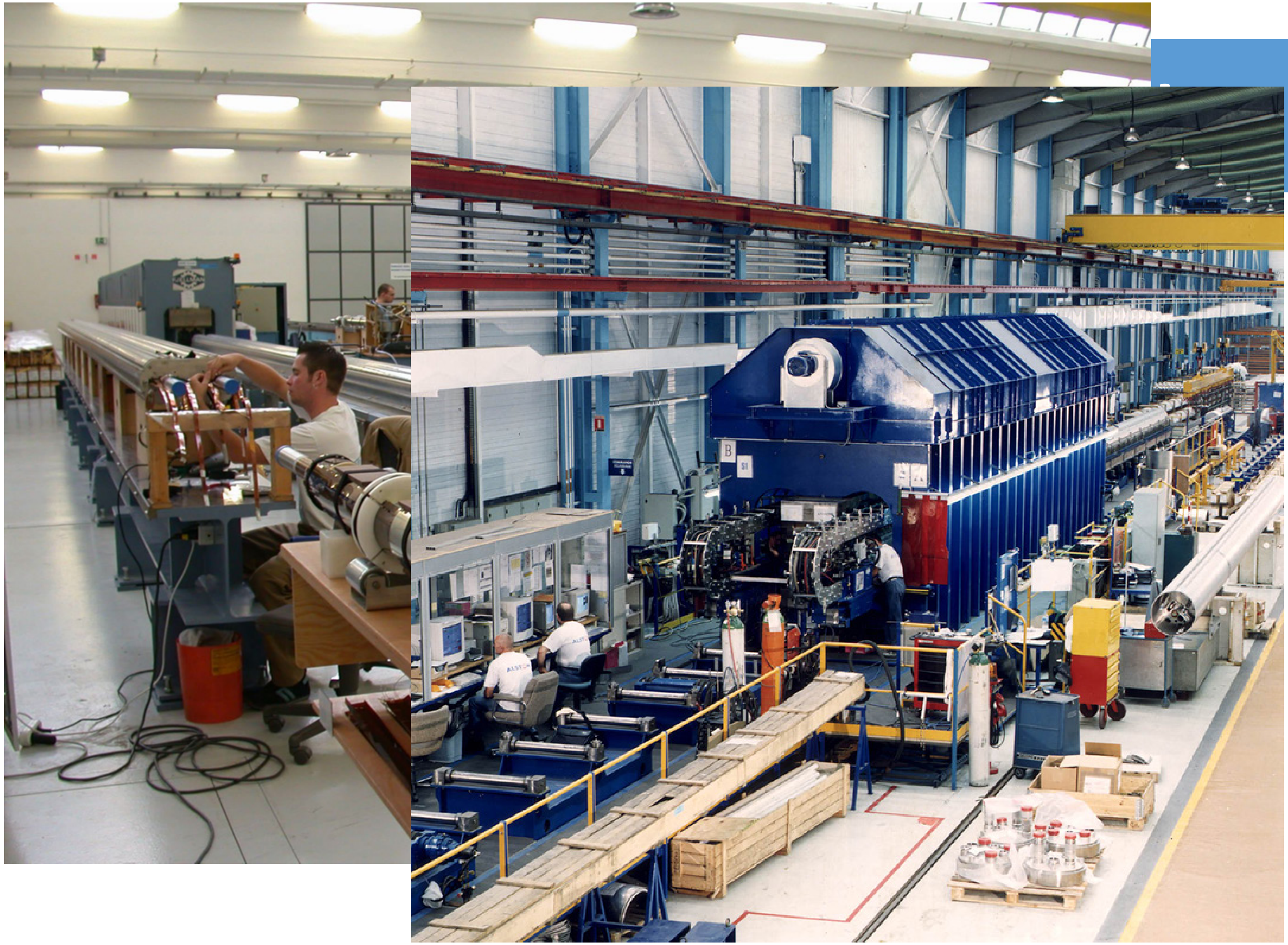




But Industry can make it… when there is a series…

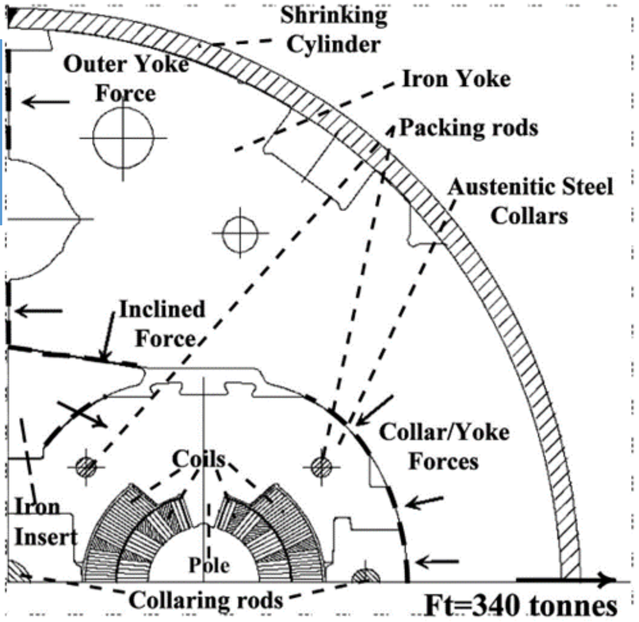
hen there is a series…

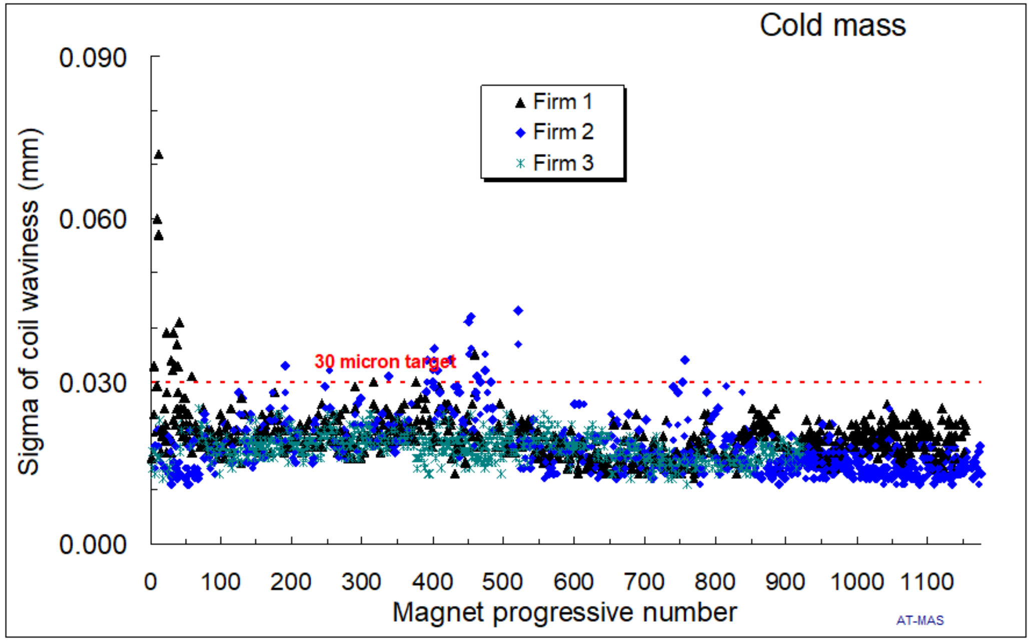
there is a series…

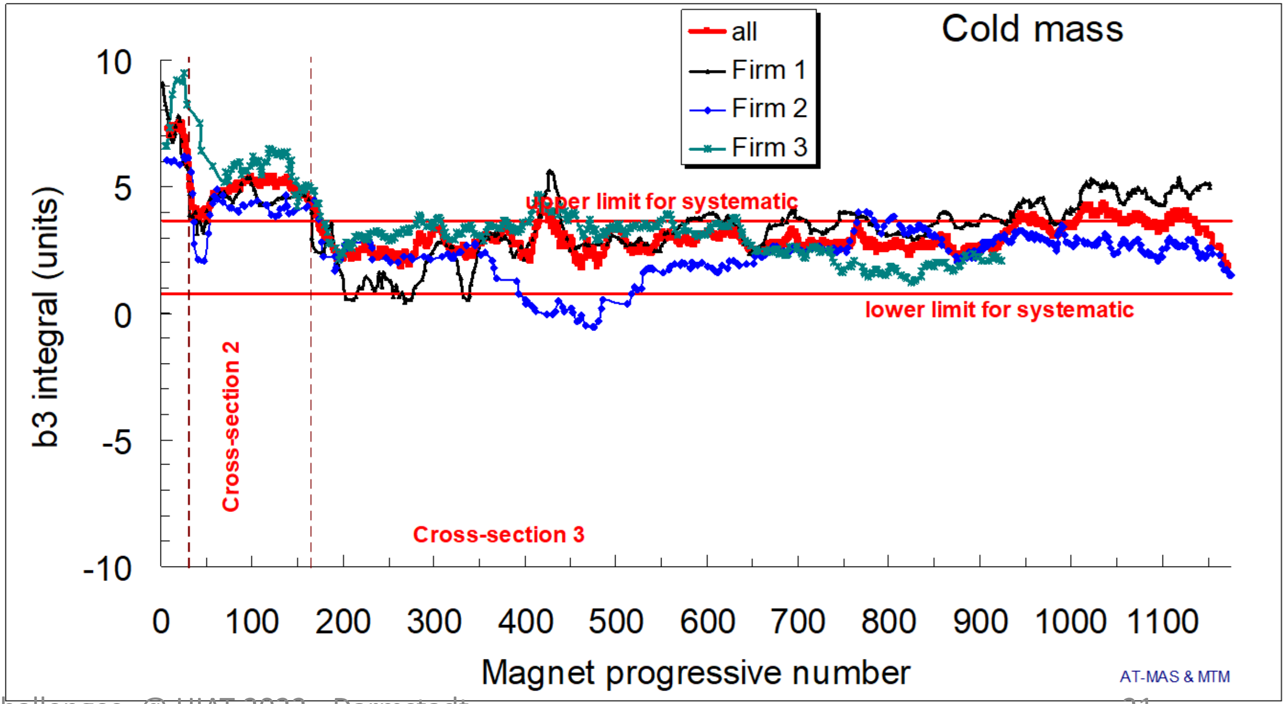


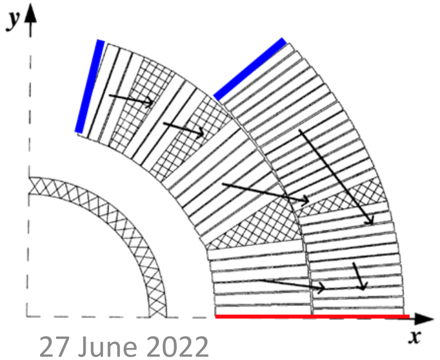
there is a series…

Accuracy : order of 20-30 μm for Field Quality and for mechanics

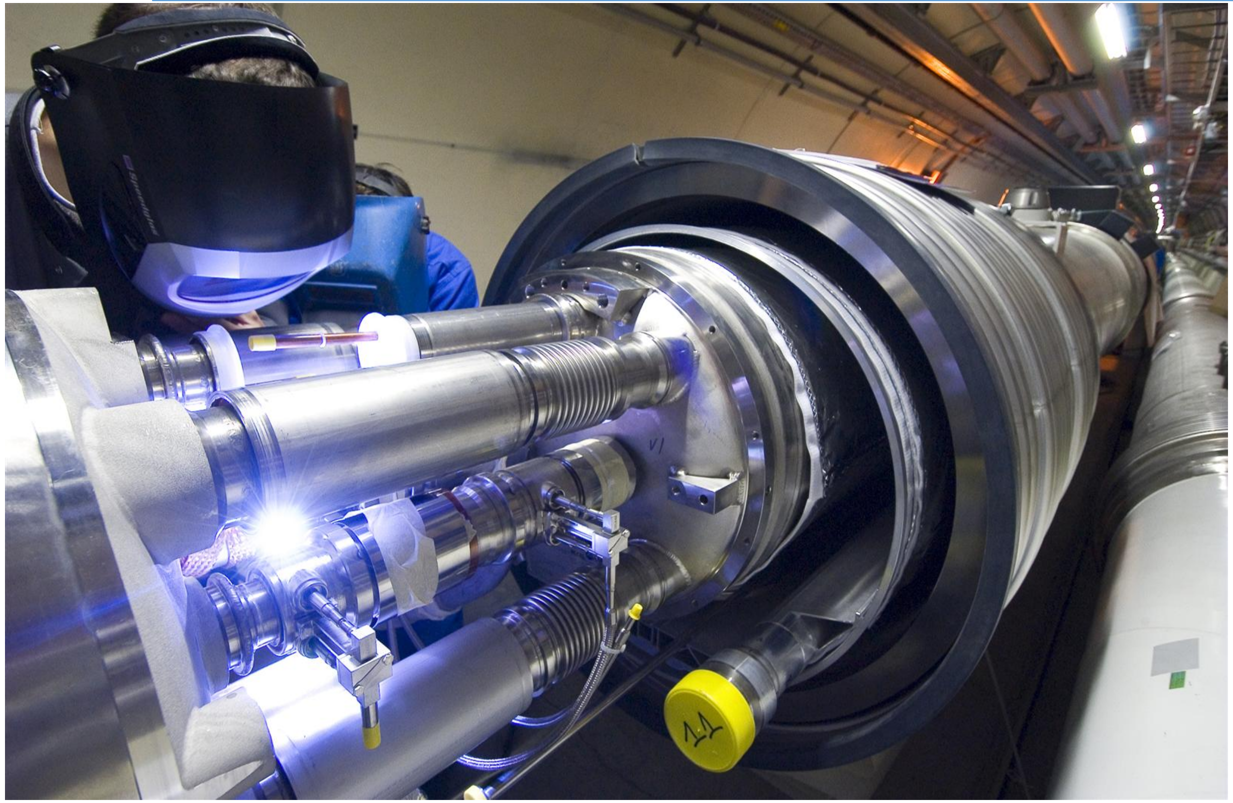








Installation – Incident – recovery and successful operation from 2010



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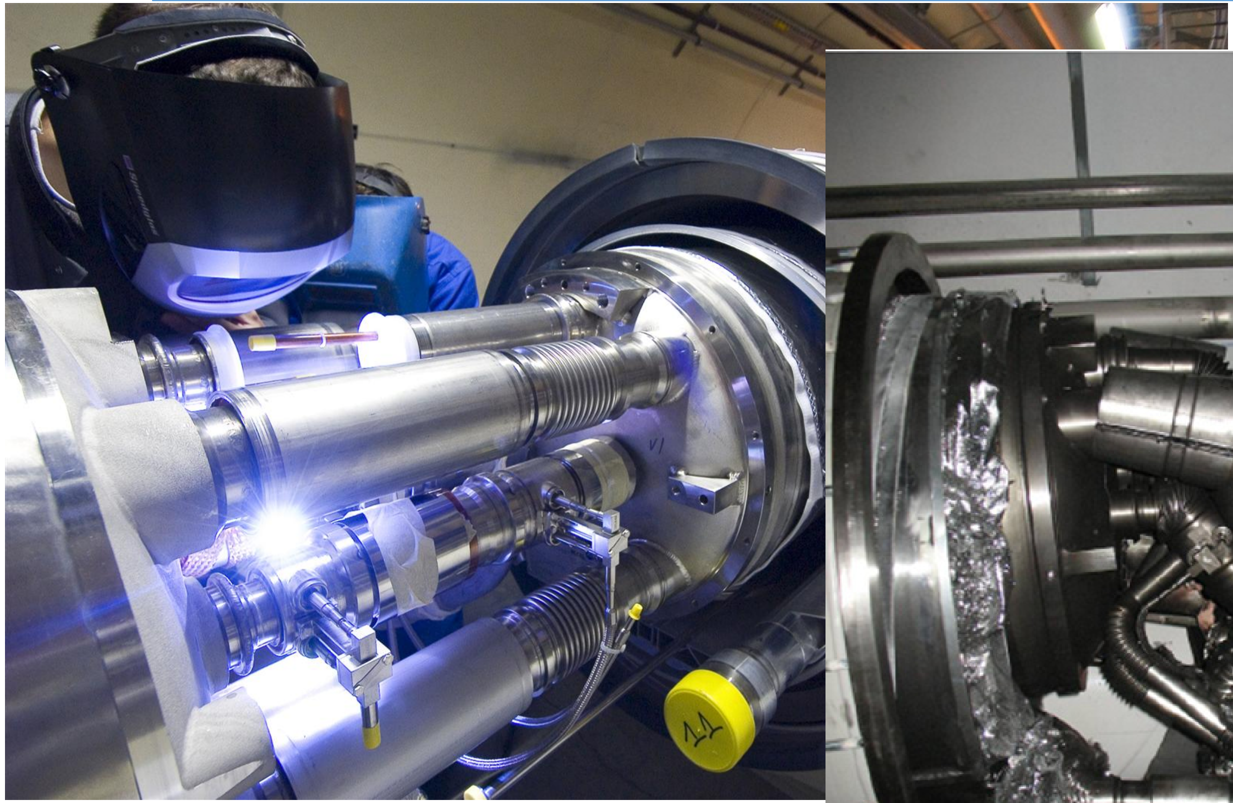

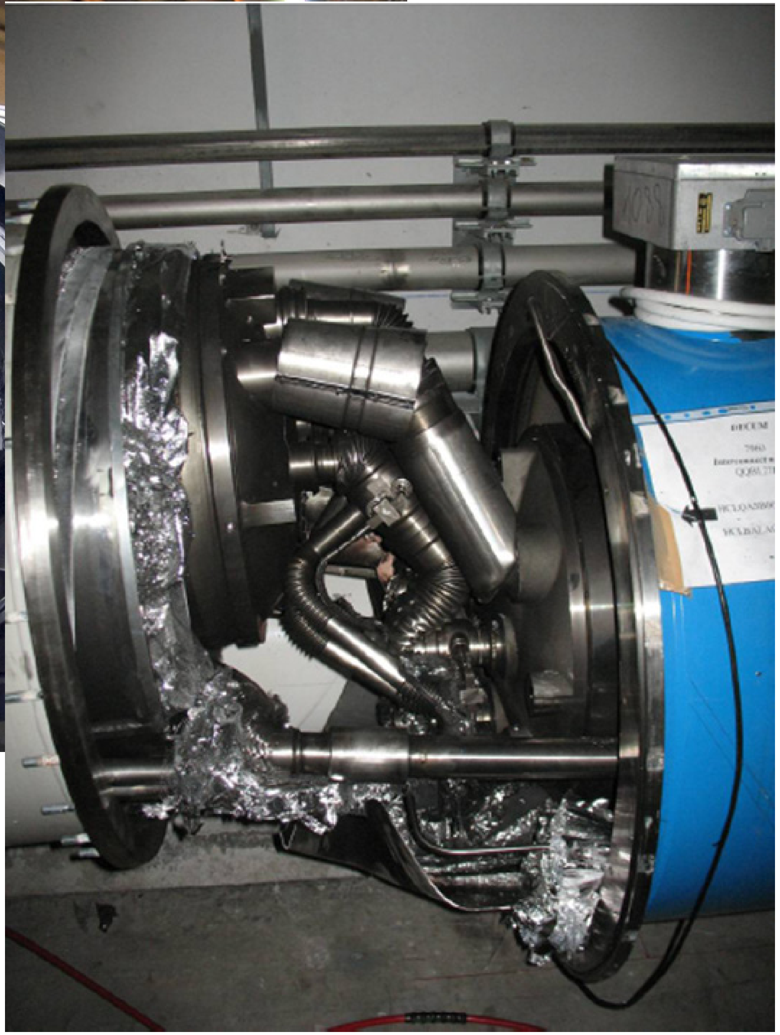

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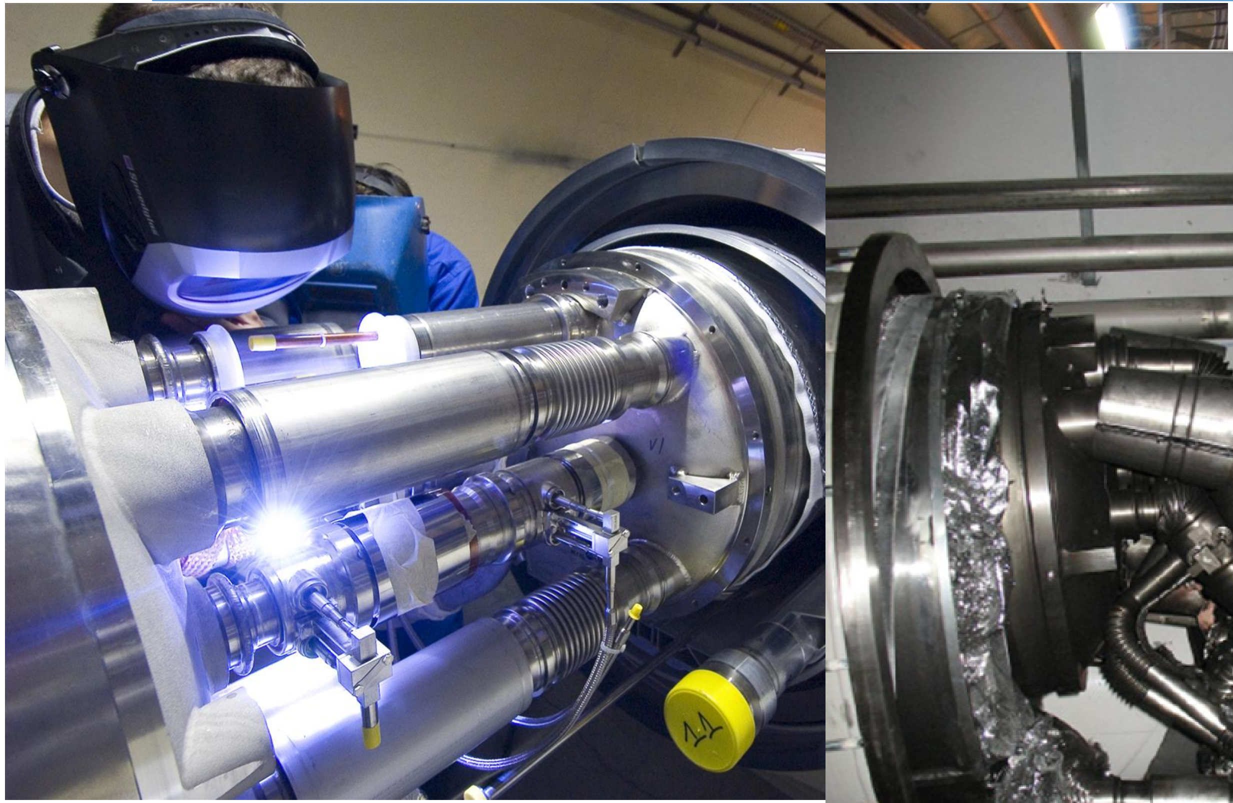

And discovery of Higgs boson… 4 July 2022

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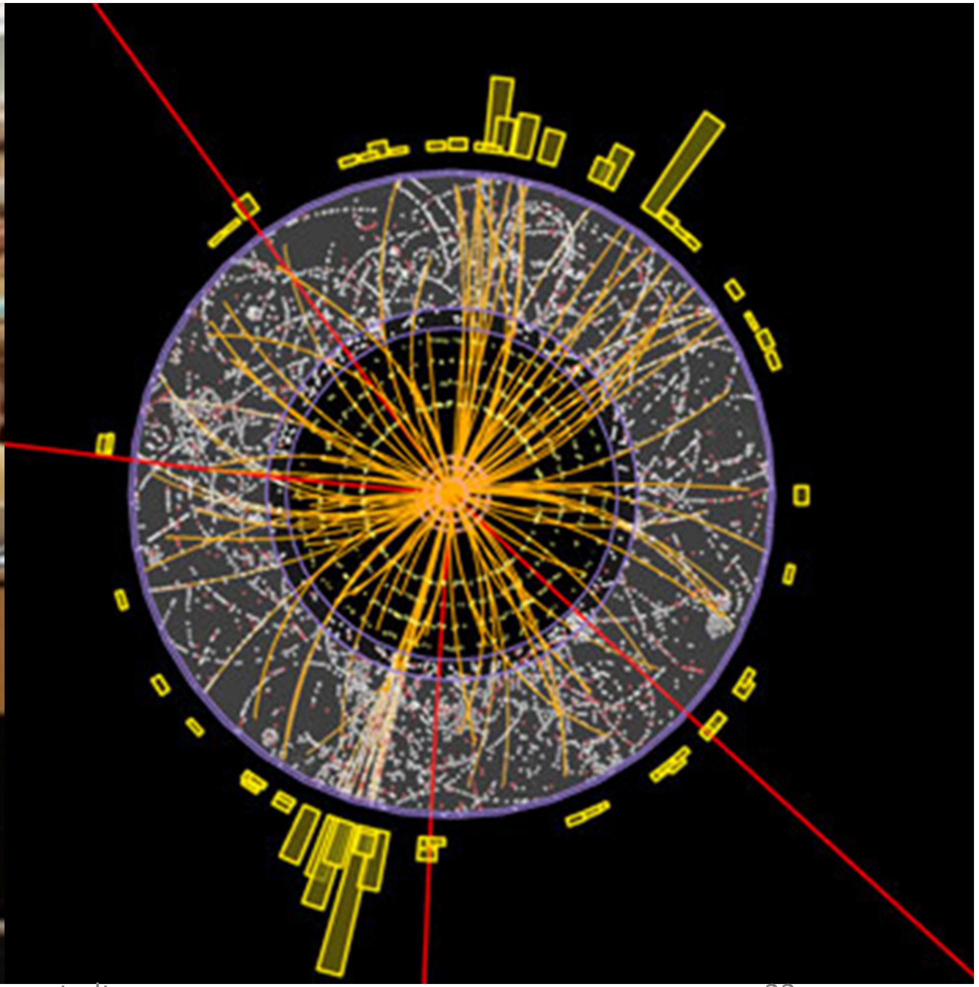

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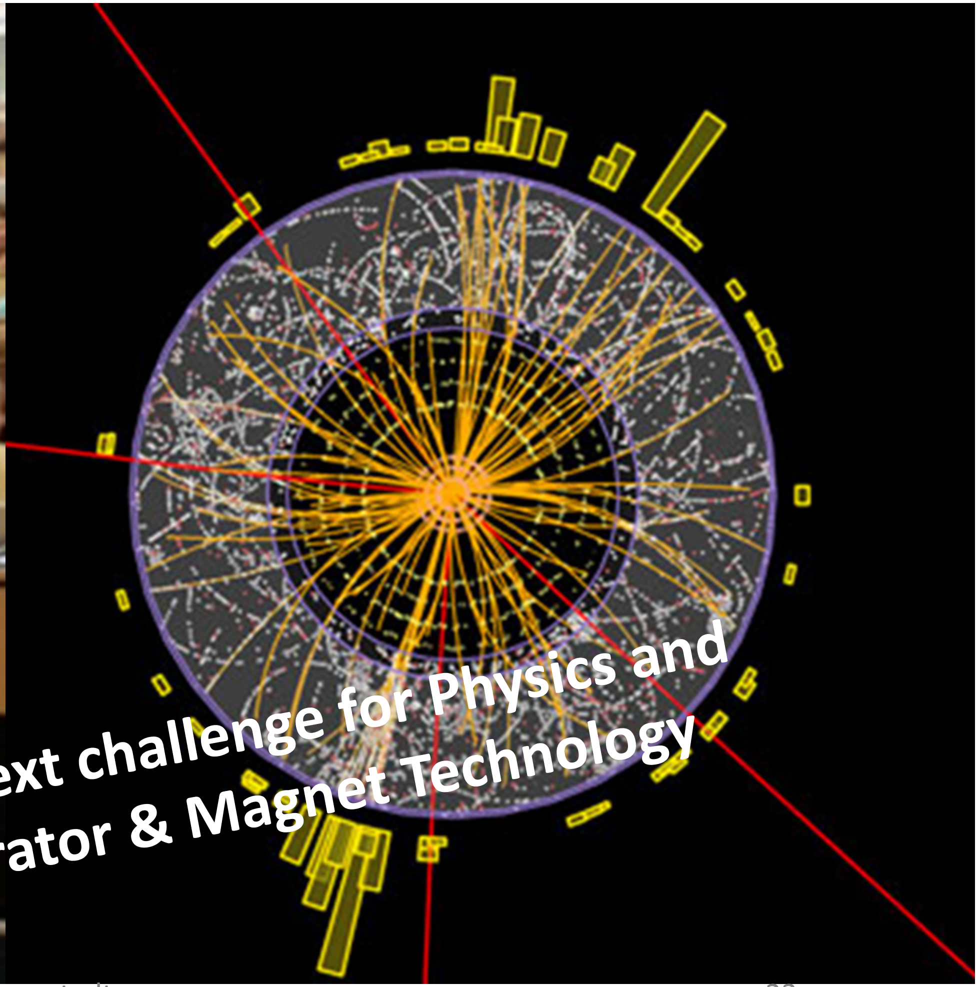

Actually the next step started in 2010…**The High Luminosity LHC project** aims at increase the luminosity by 10 time

Technology landmarks

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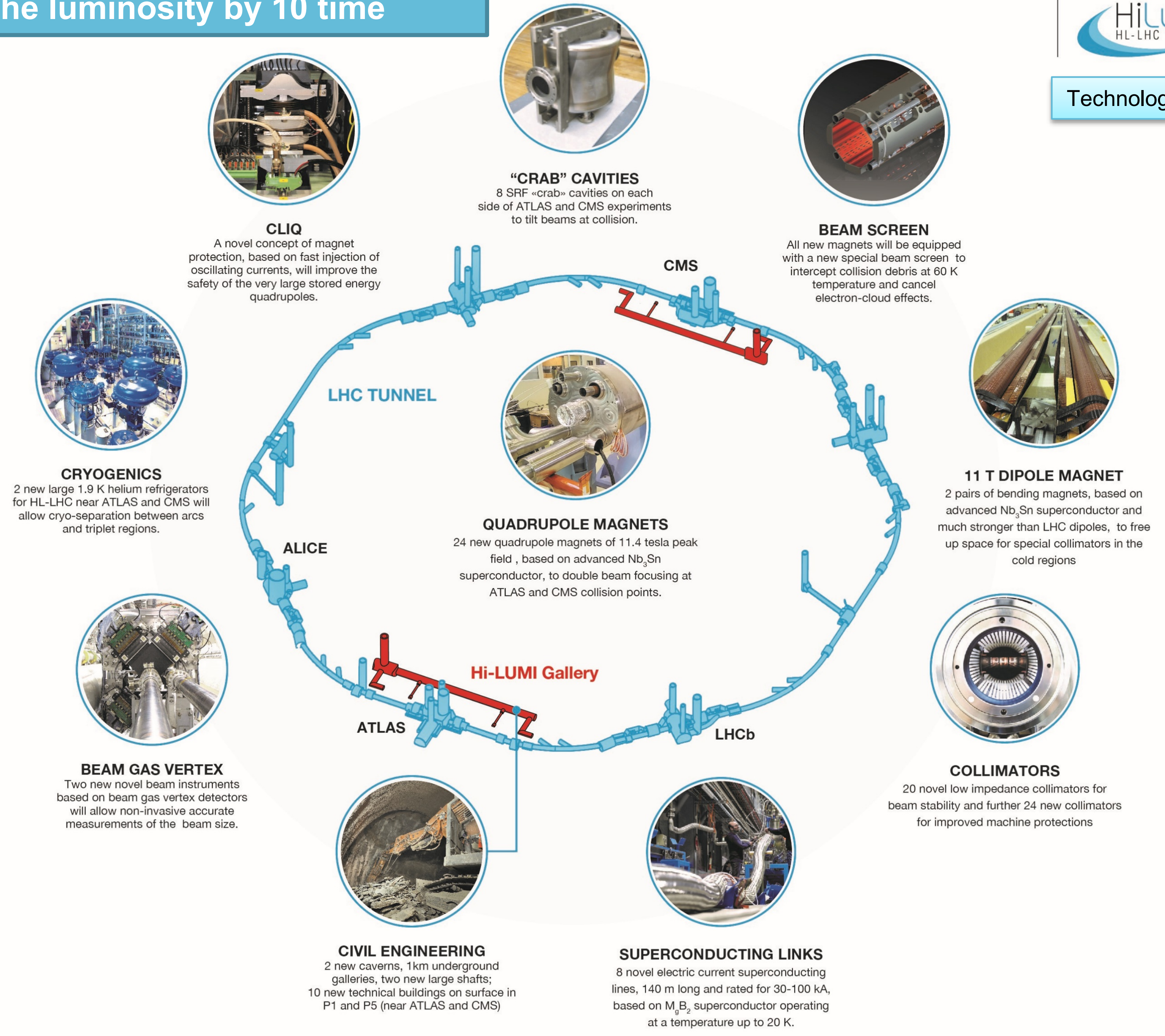
CERN 2019

Technology landmarks

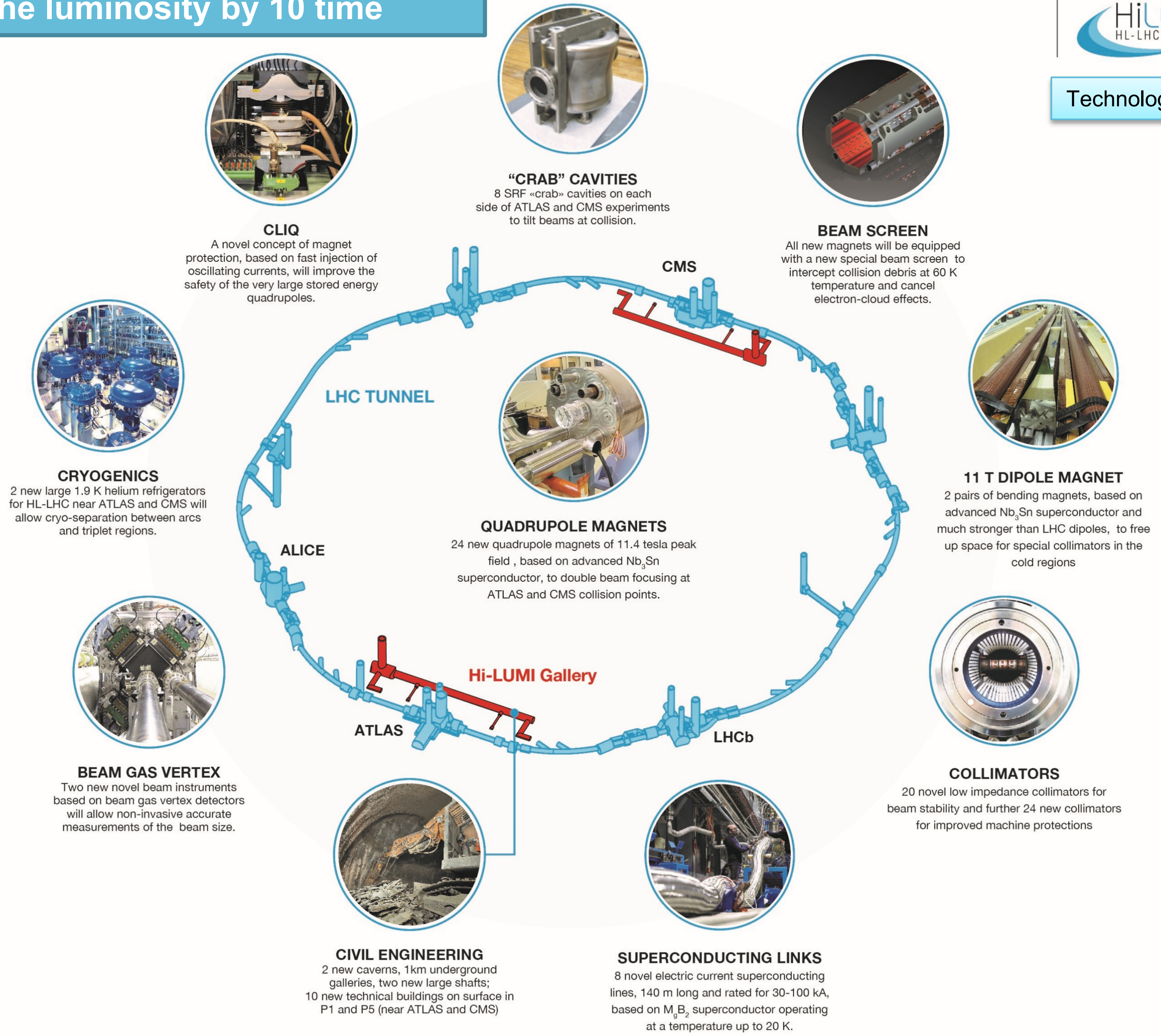


Actually the next step started in 2010…**The High Luminosity LHC project** aims at increase the luminosity by 10 time

Technology landmarks

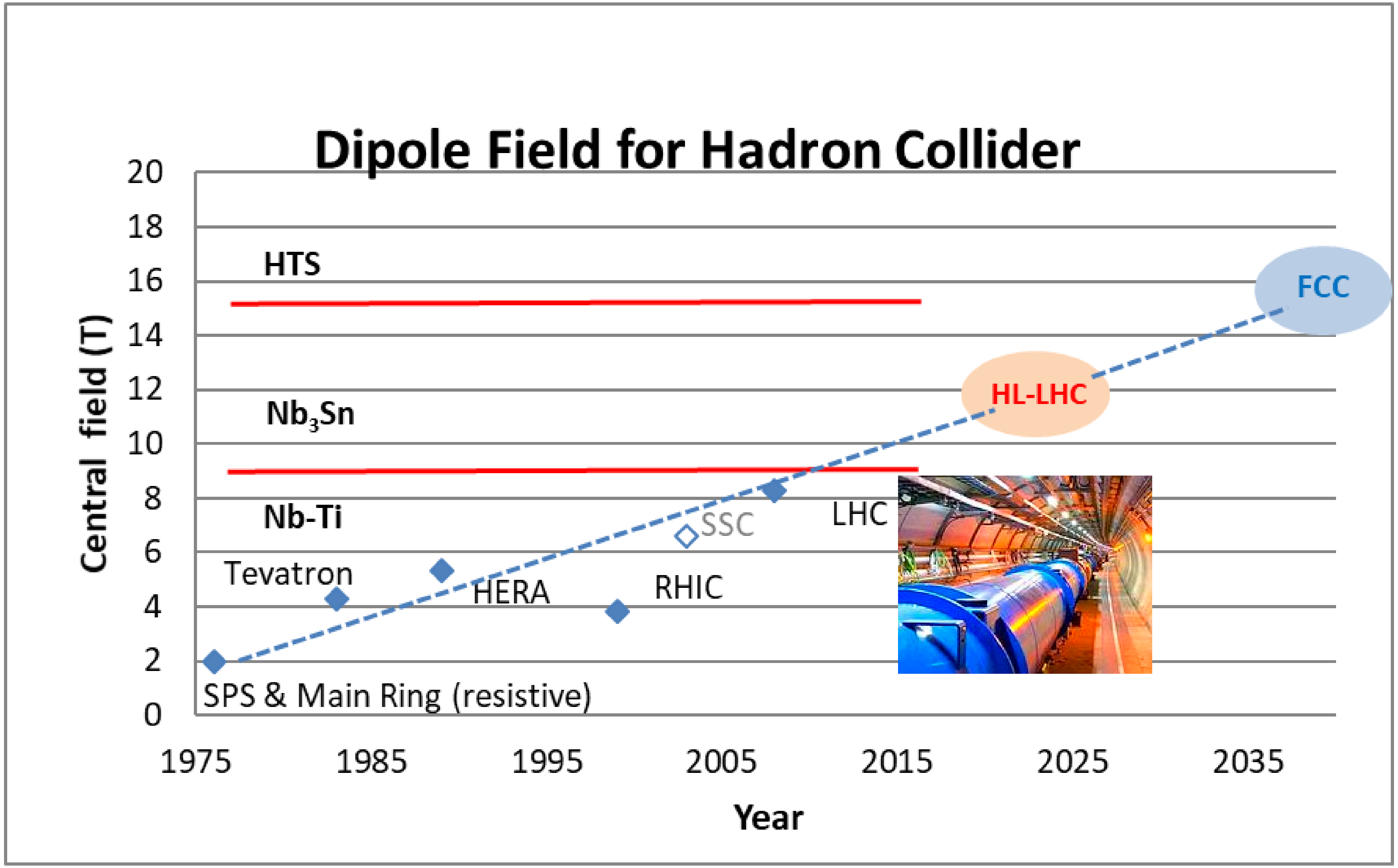
LHC is already highly optimized… an upgrade need a broad spectrum of new technologies, especially (not only) for magnets…

HL-LHC is a technology intensive project!



CERN 2019

With HiLumi we prepare the new technology for a future leap in hadron colliders…



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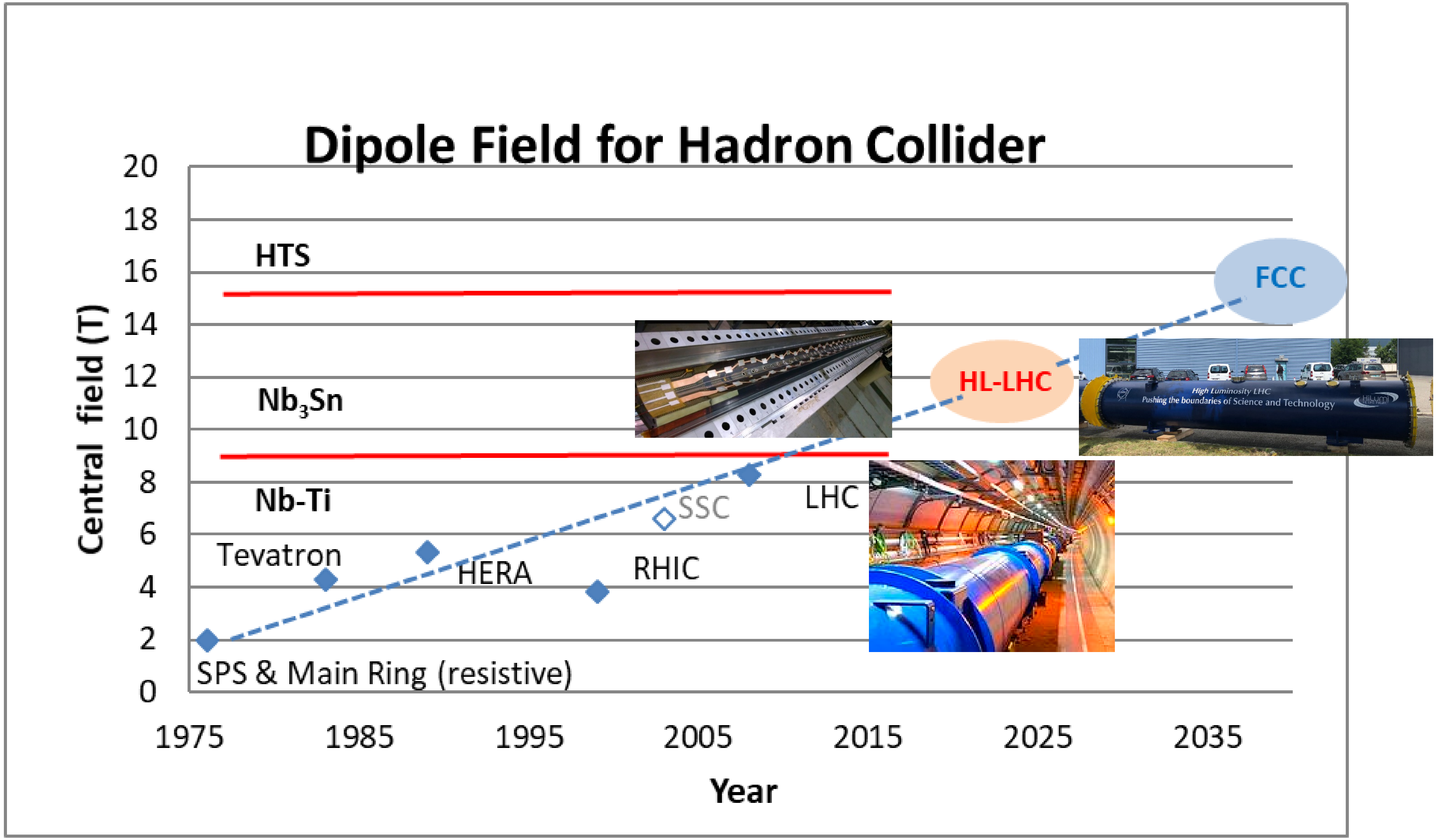
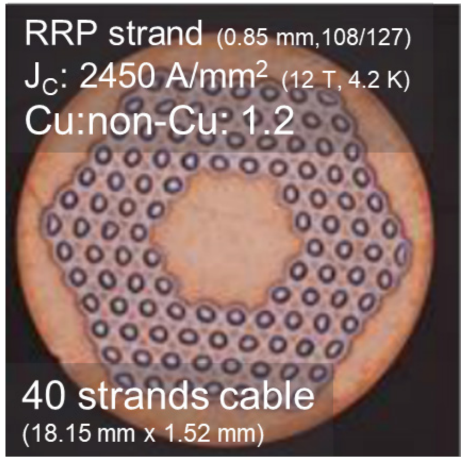
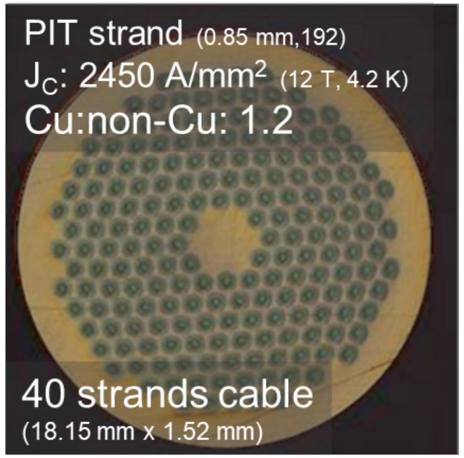
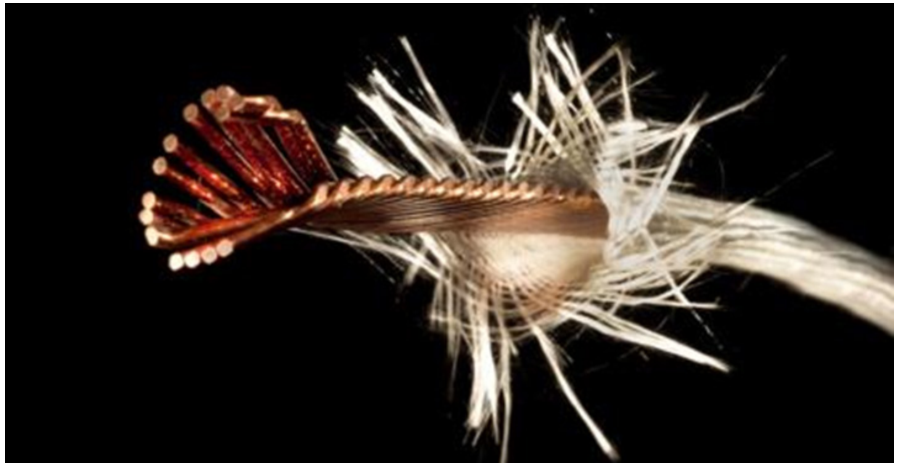
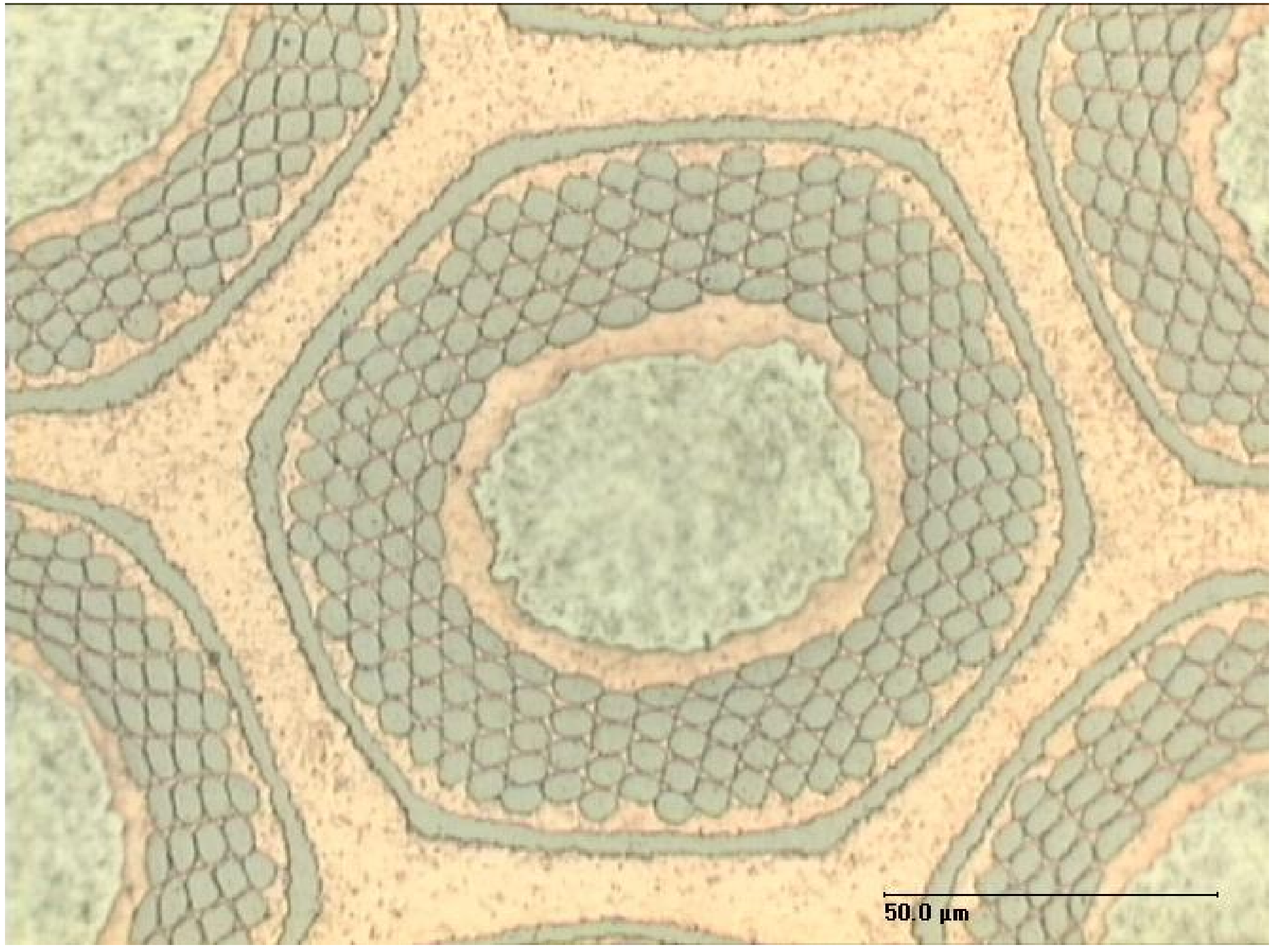


Nb_3Sn : high Je also at 12- 16 T but it is brittle and needs thermal treatment of whole coil @ 700 °C !



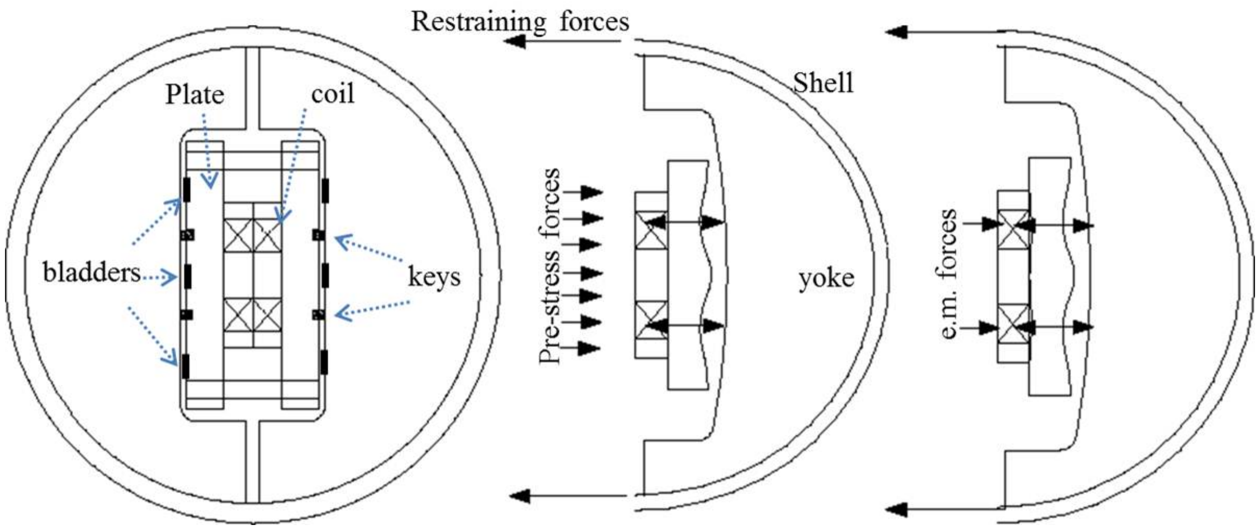




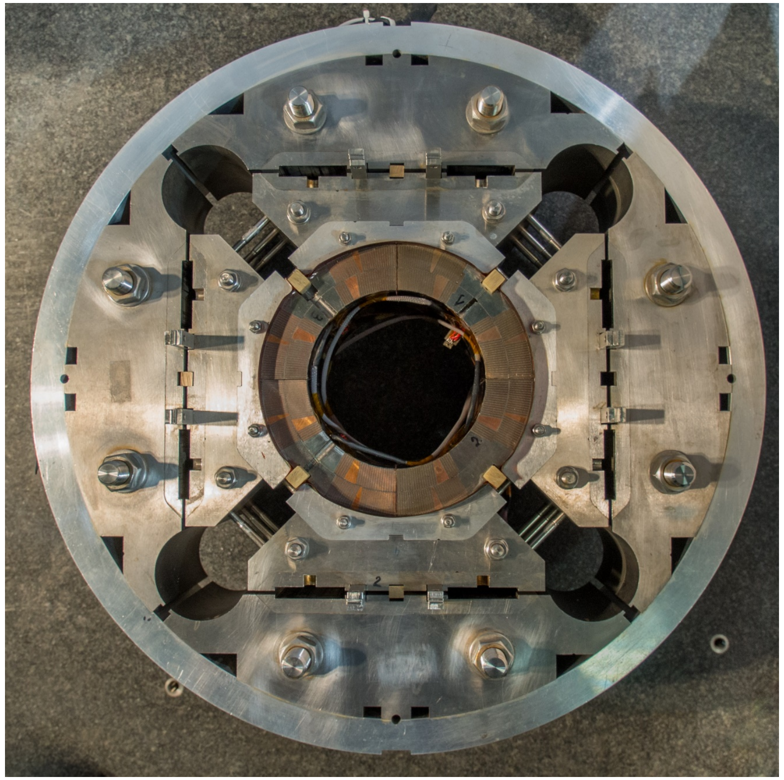


New way to keep the stress : HiLumi paves the way to reach a controlled precompression of ~130 MPa

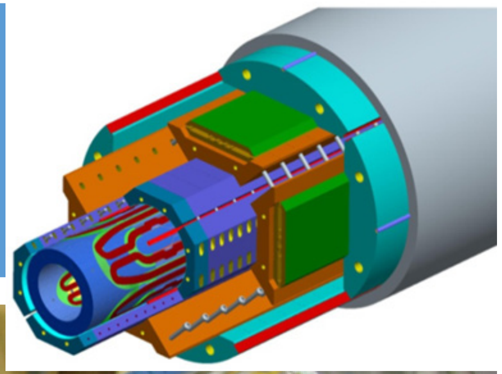
New concept: bladders and keys

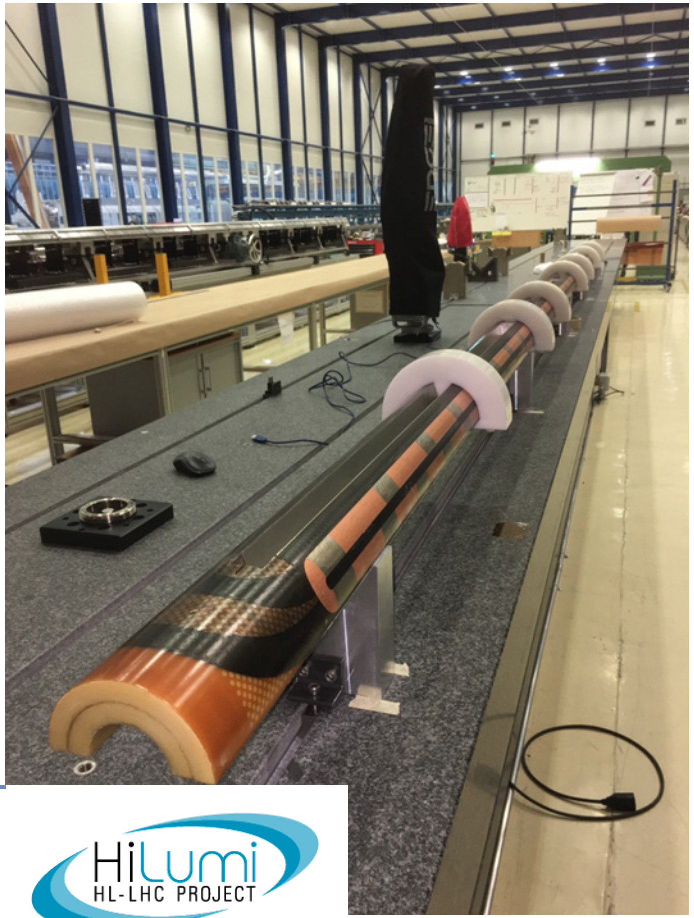


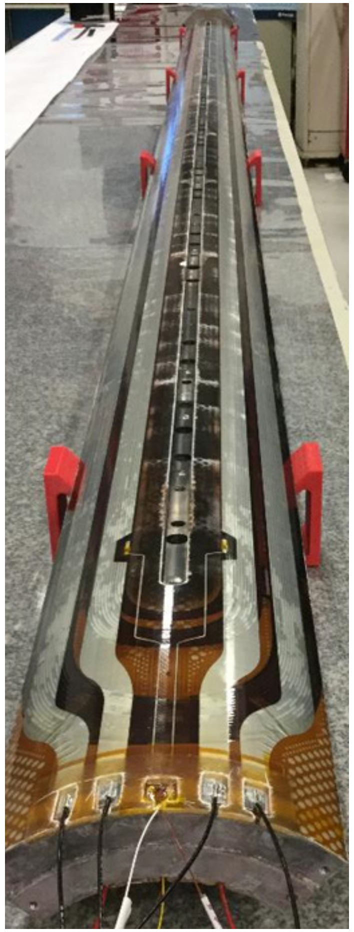
Cross section of the Quad for HiLumi

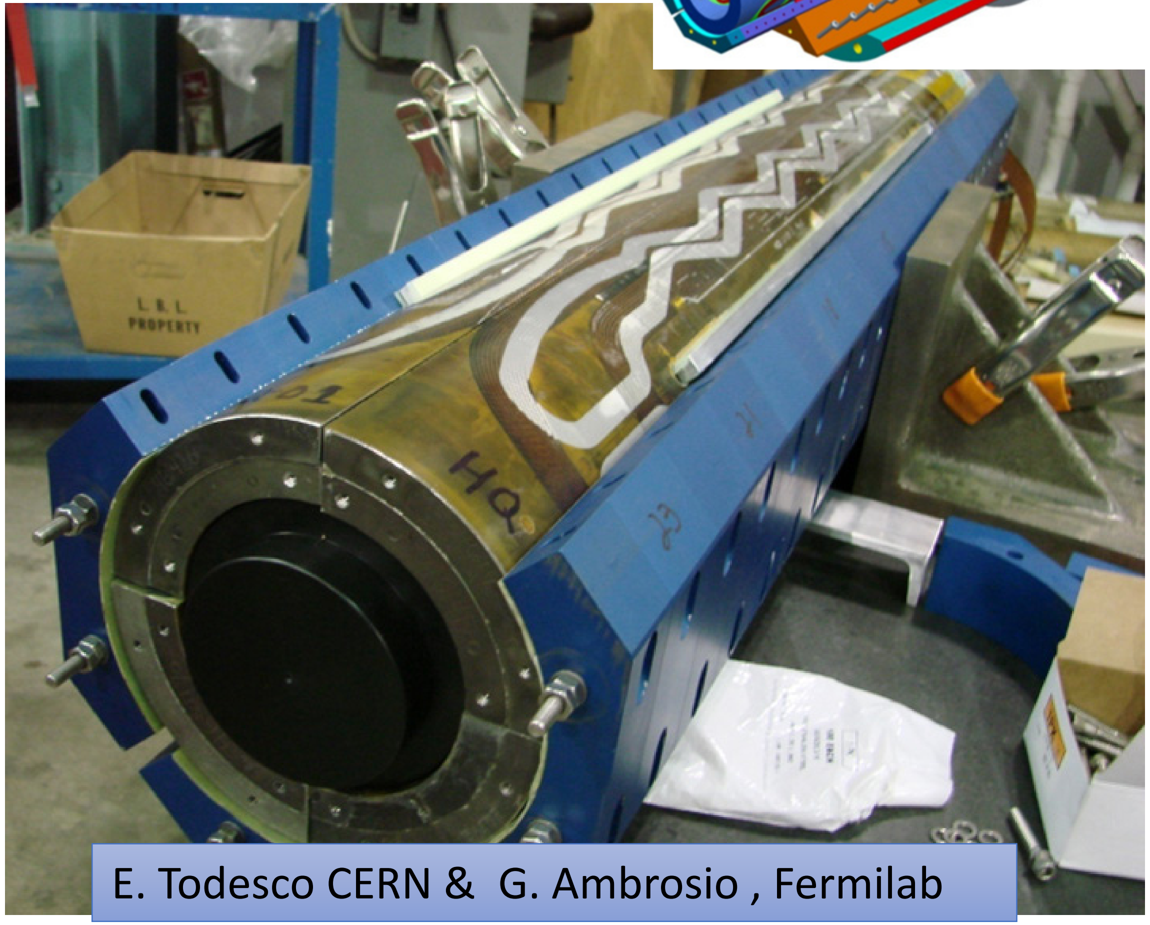


The HiLumi Quad: 12 T in ∅=150 mm
<u>~ equivalent to a dipole 15 T-∅50 mm</u>



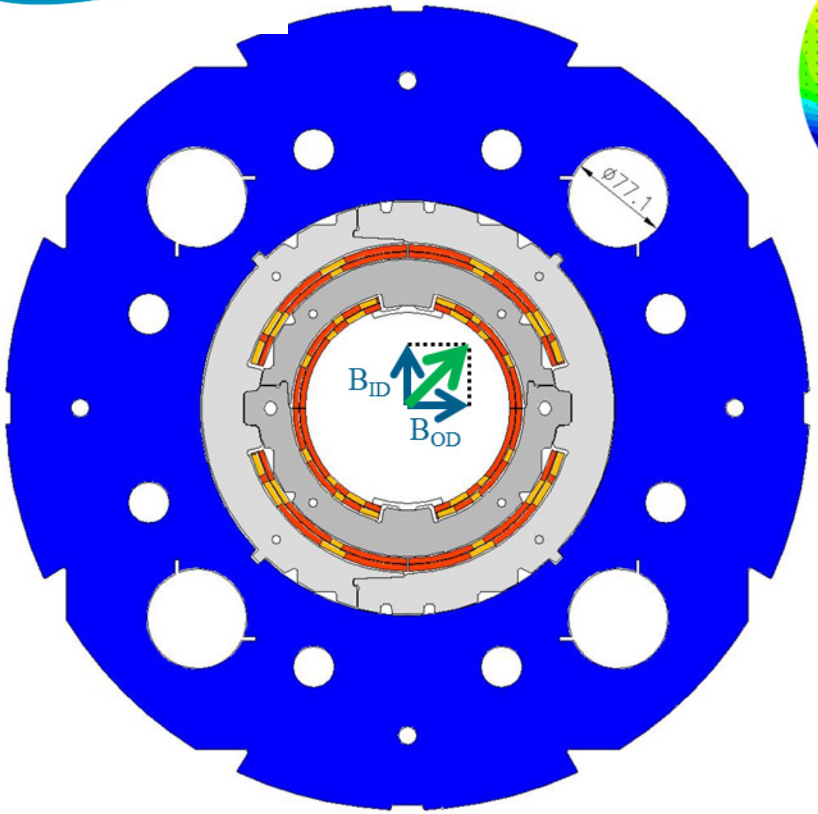


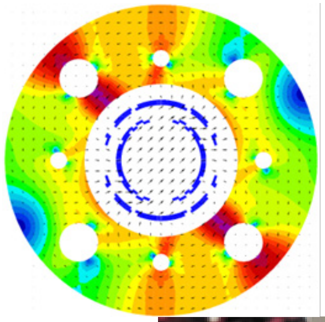


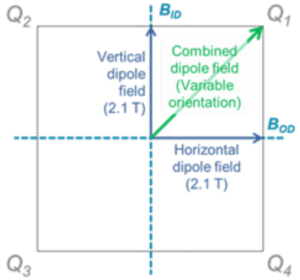


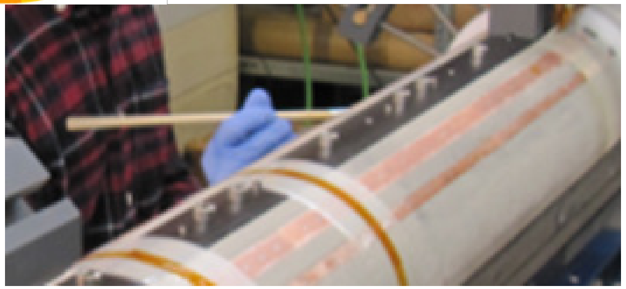
E. Todesco CERN & G. Ambrosio , Fermilab

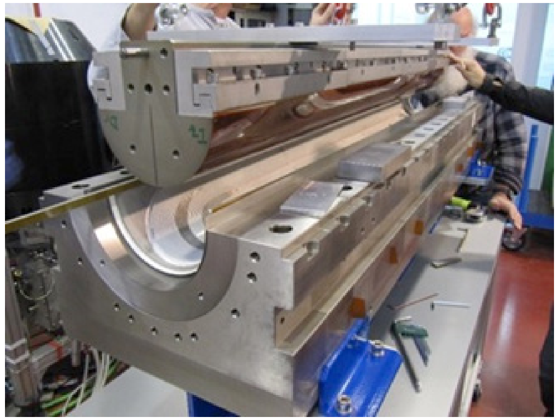
Other development with classical Nb-Ti: nested X-Y dipole Steering – Bending with compact magnet, space is precious…

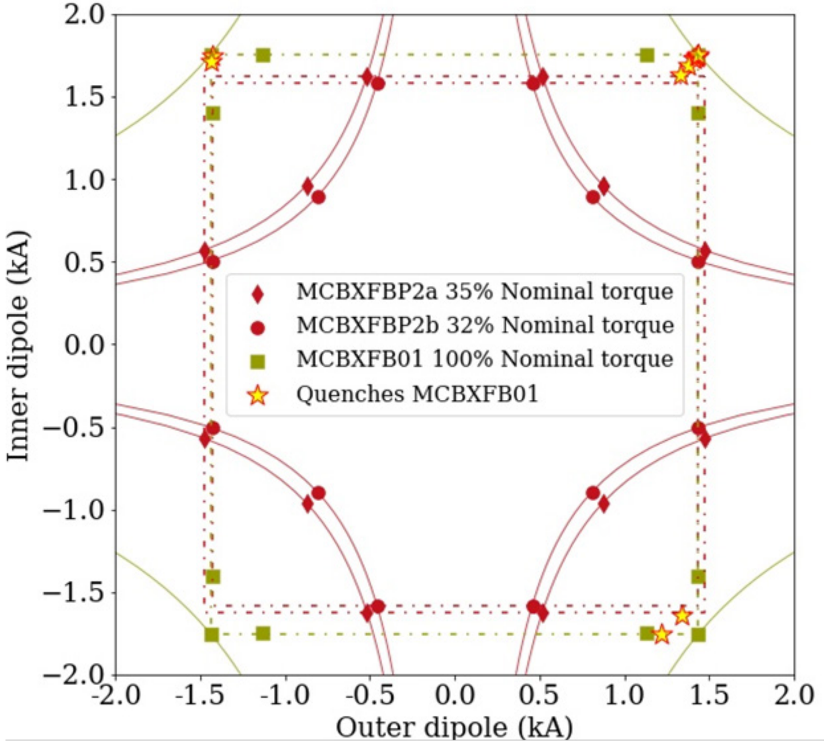












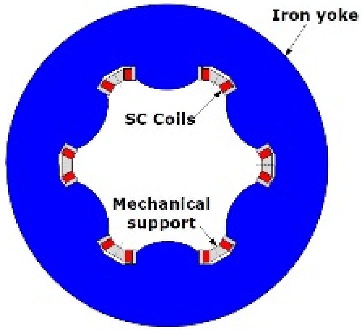
Courtesy S.Ferradas (CERN)

Thanks to F. Toral, Ciemat

Superferric magnet technology: 2-3 T iron drive by SC coils very convenient in terms of performance/cost

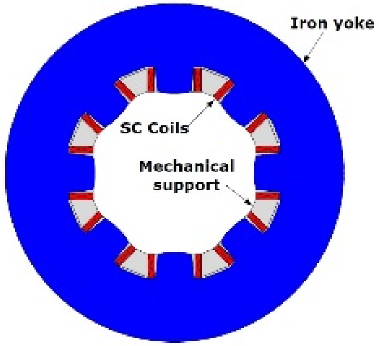
Thanks to M. Statera, INFN-LASA

OD=320 mm



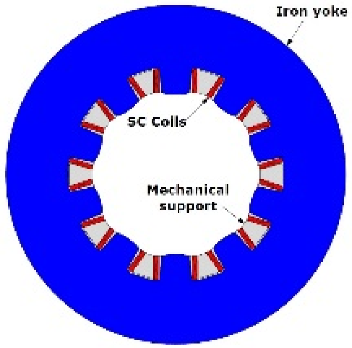
Sextupole

OD=320 mm



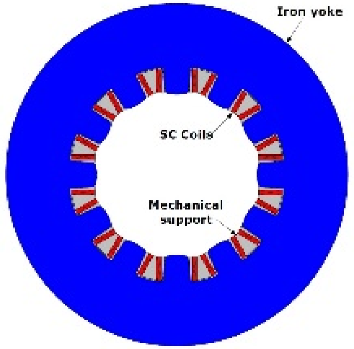
Octupole

OD=320 mm



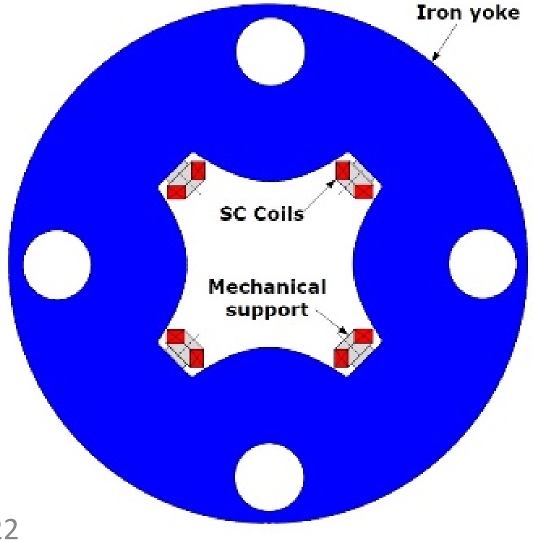
Decapole

OD=320 mm



Dodecapole

OD=460 mm



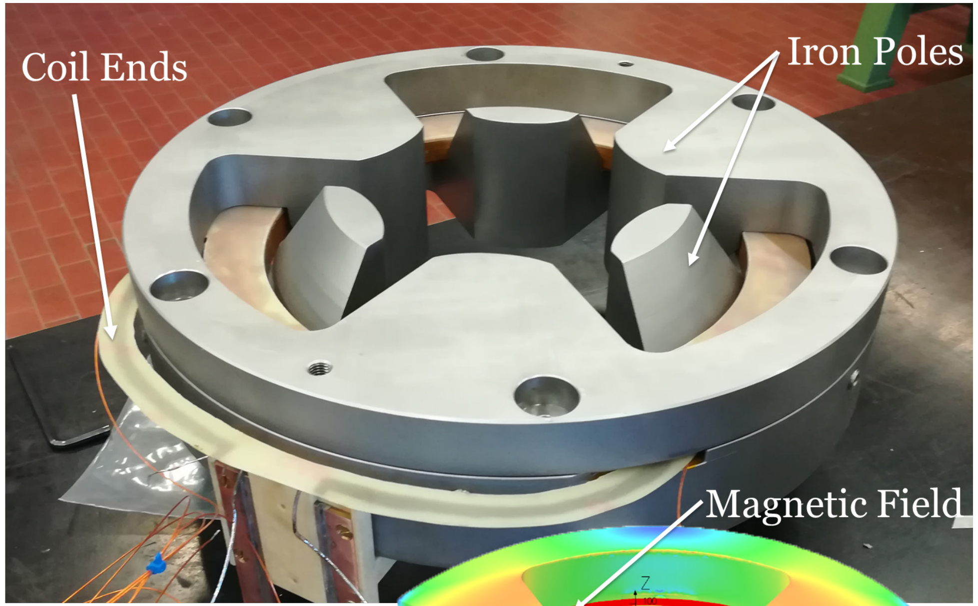
Skew quad

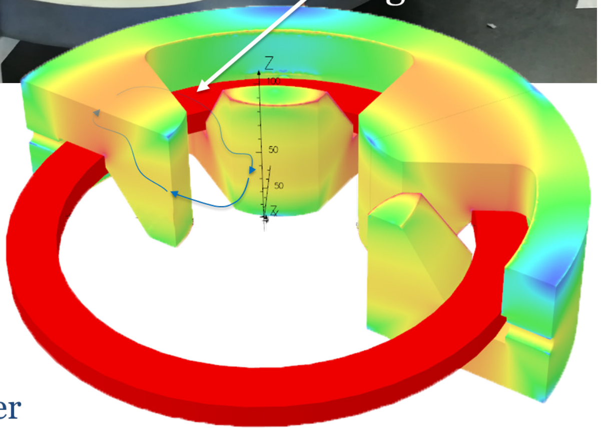
Physical lenght:
- 90-120 mm from 6-pole to 10-pole
- 430 mm 12-pole normal
- 840 mm 4-pole skew

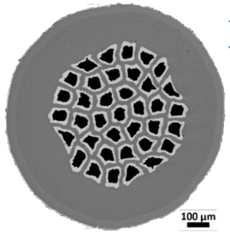
Conductor type: NbTi
Peak field on cond.: 2-3 T
Operating current: 120-180 A
Margin on load line: 40%

Next step for superferric: going cryogen-free HTS or RCSM design with MgB_2

S. Mariotto and R. Valente
INFN-Mi-LASA

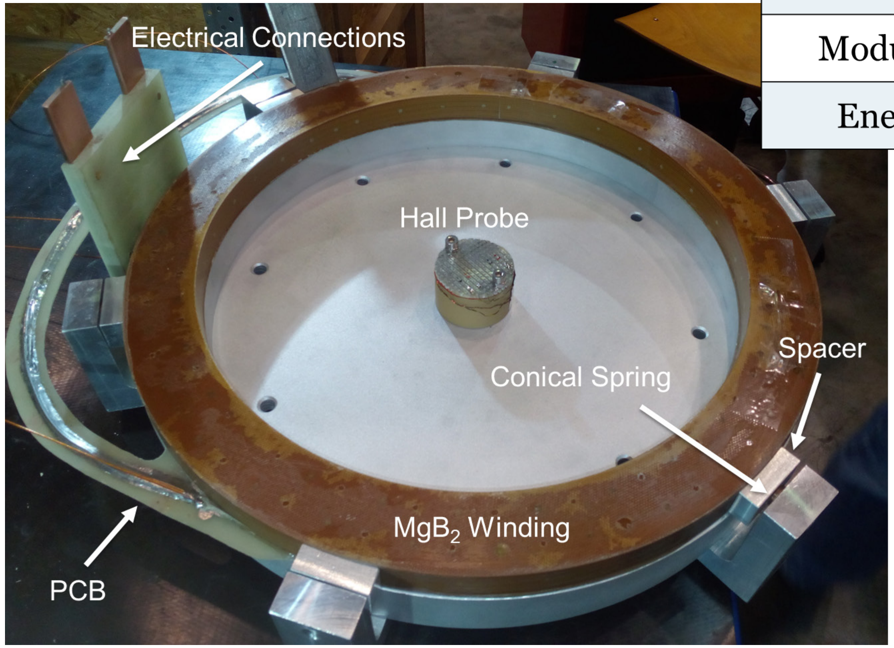






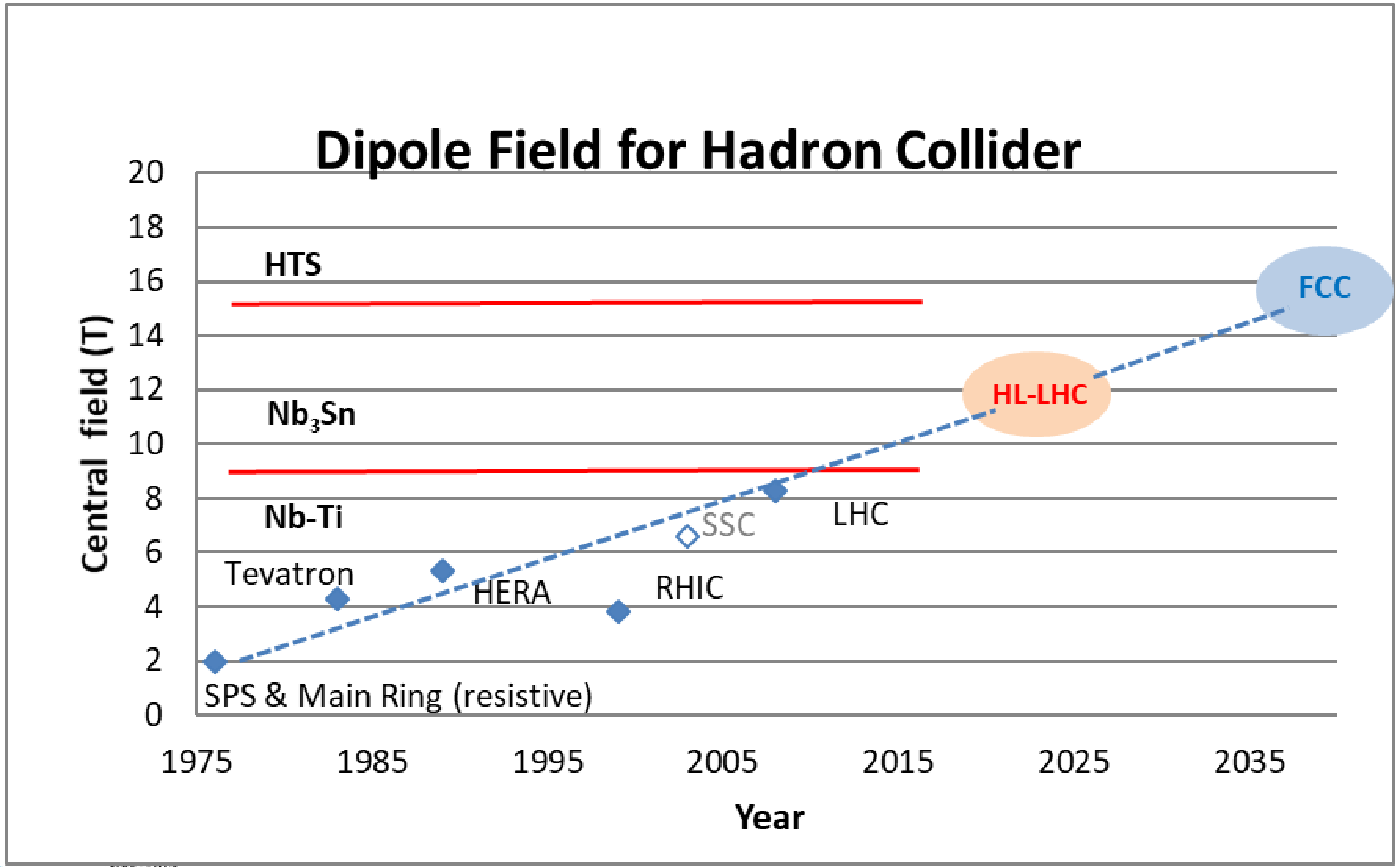
MgB_2

No S_2-fiber glass Insulation with Polyester



	Value
Integrated Field @ R=50 mm	70.06
B_{max} on SC @ I_{op}	1.37 T
B_{max} on Iron @ I_{op}	3.52 T
Module Lenght	384 mm
Energy @ I_{op}	3754 J

Can we extrapolate linearly from the past beyond HiLumi: 16-20 T FCC? ⇒ ELN?



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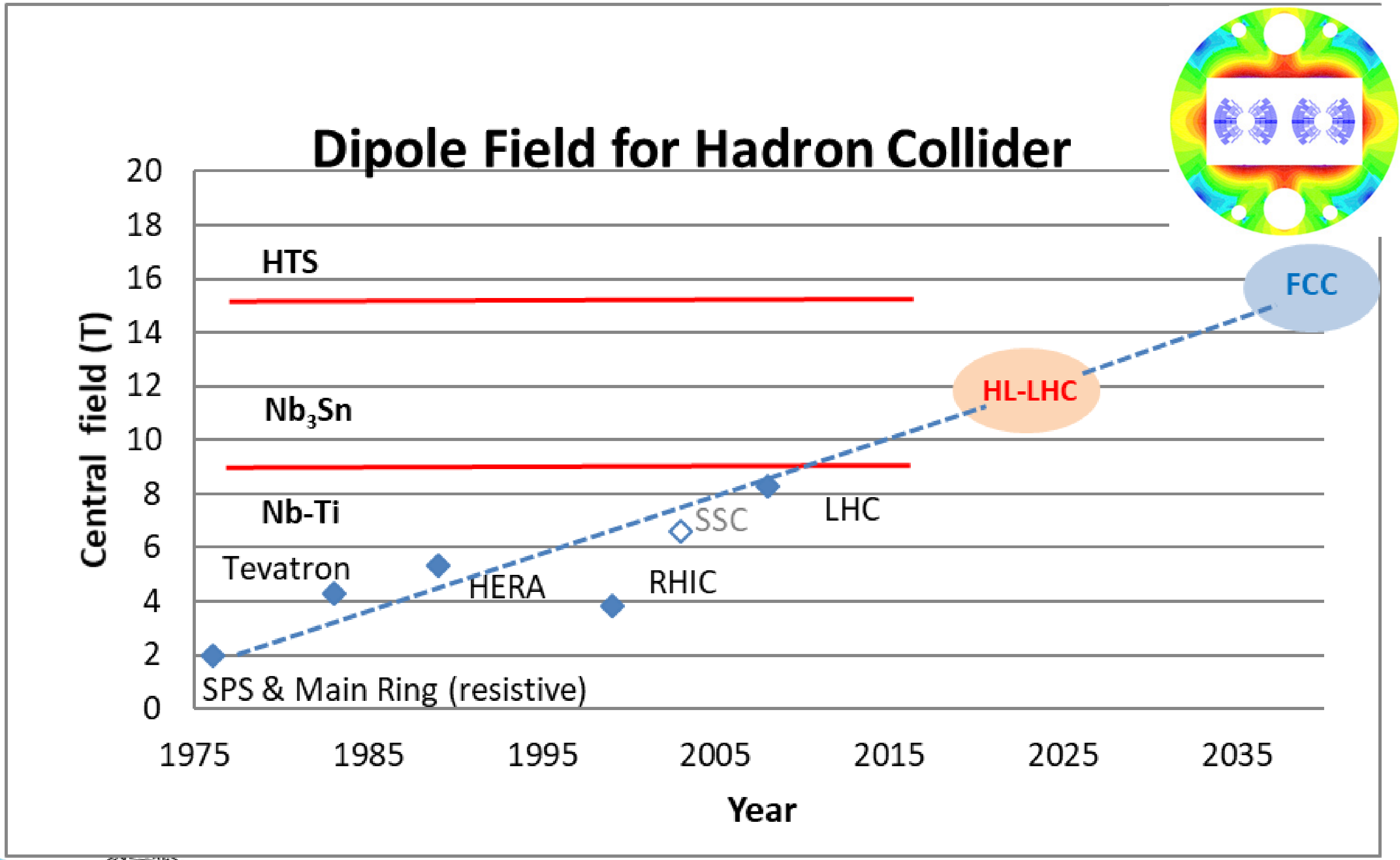

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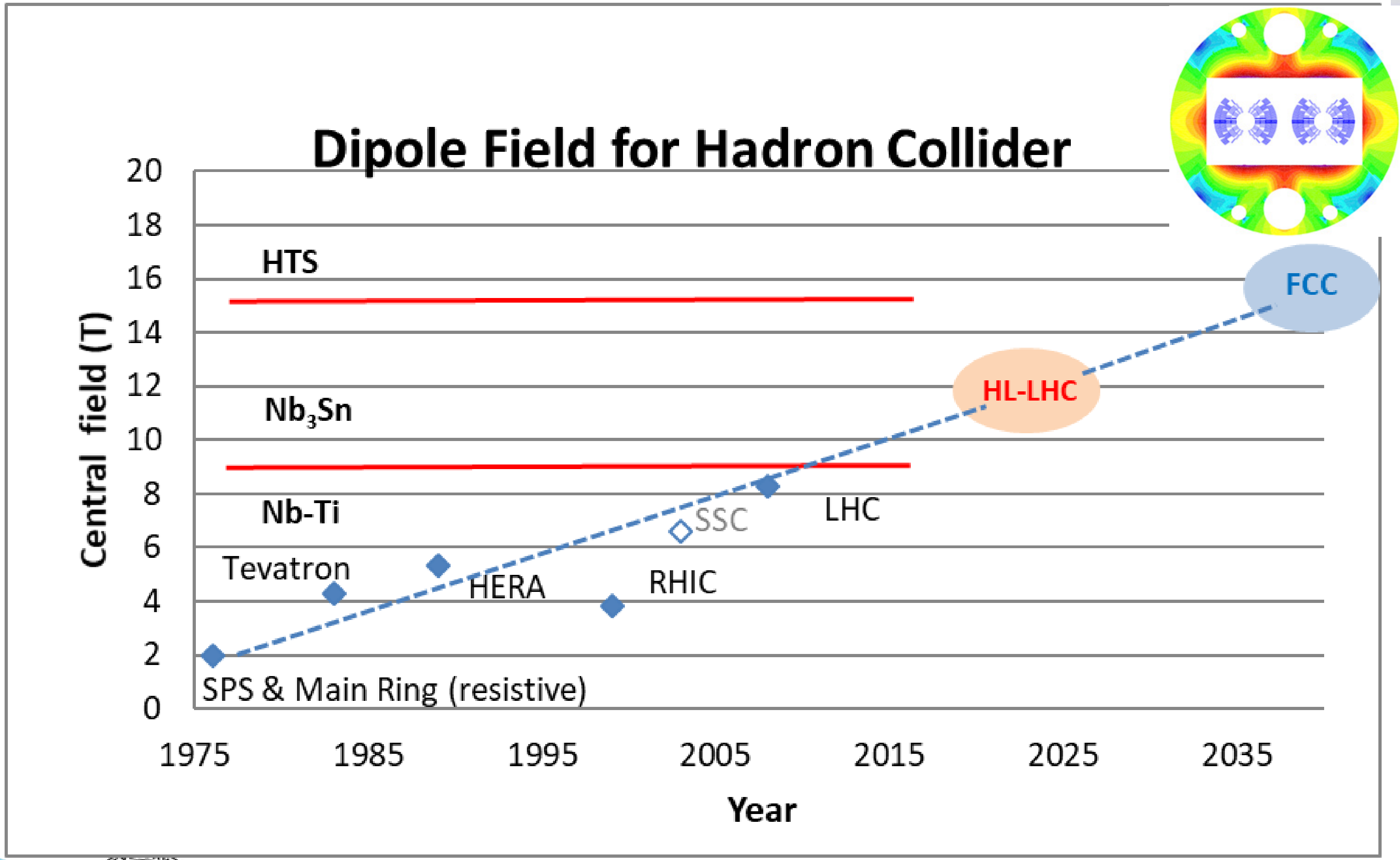
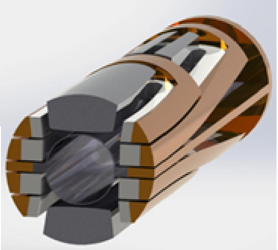
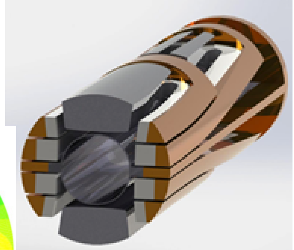




EuCARD²

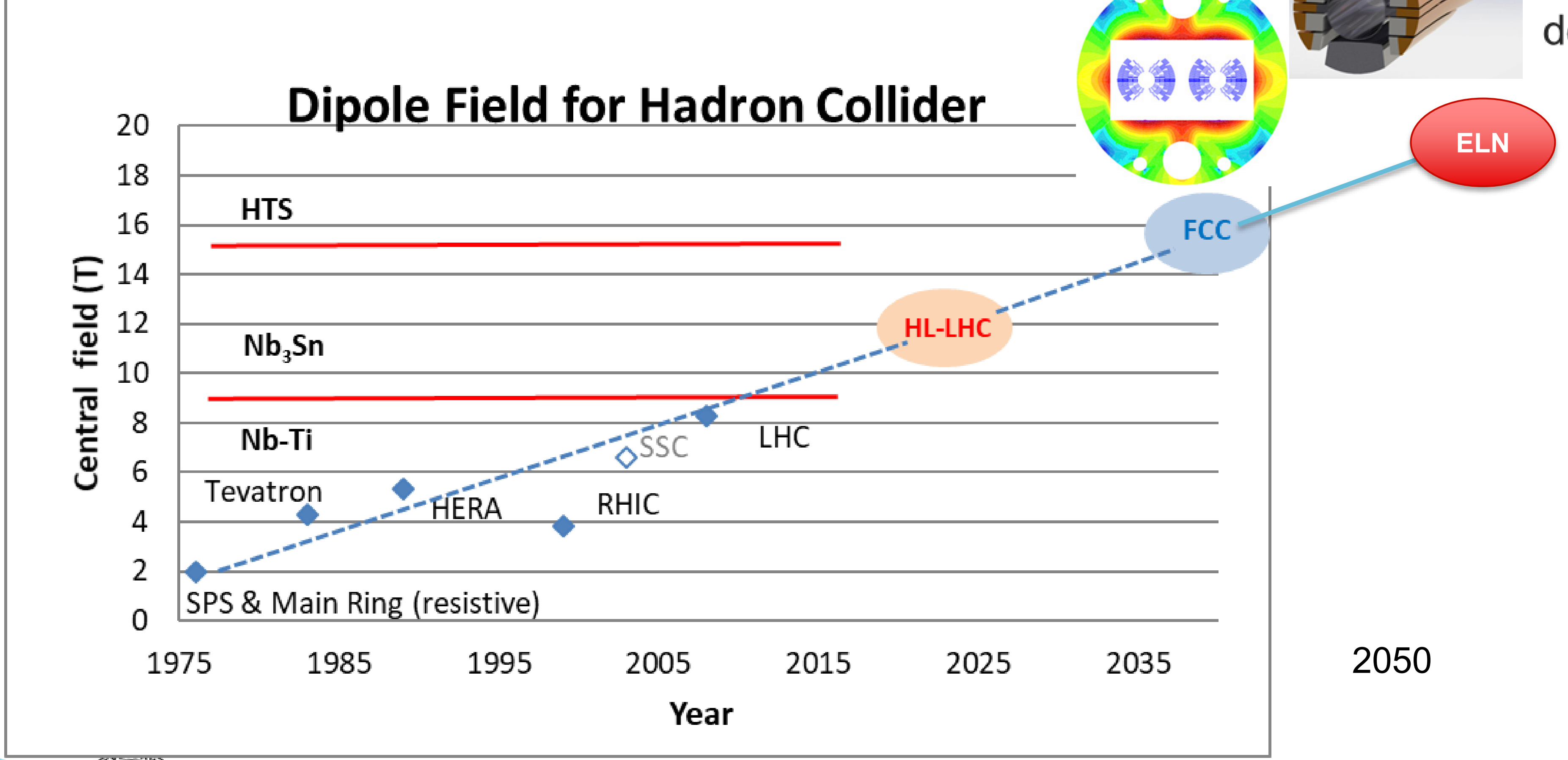
5T HTS demos

Can we extrapolate linearly from the past beyond HiLumi: 16-20 T FCC? ⇒ ELN?

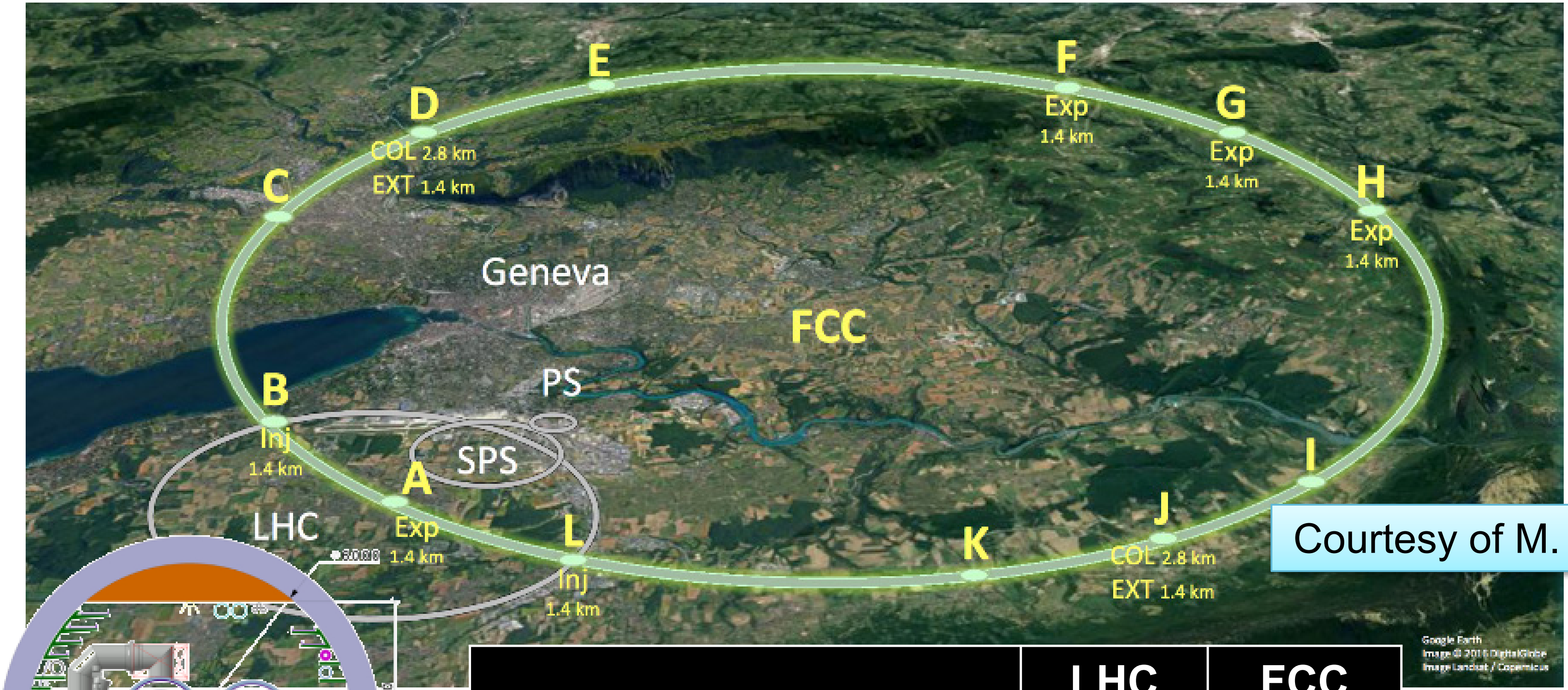


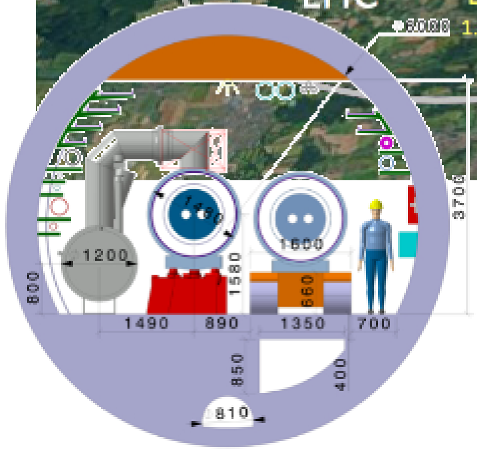
EuCARD²

5T HTS demos



Future Circular Collider





Courtesy of M. Benedikt, FCC

	LHC	FCC
Circumference (km)	26.7	97.5
Dipole field (T)	8.33	16
C.o.M. energy (TeV)	14	100

2020 Update of the ESPP

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.

2020 Update of the ESPP

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)

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7. four stat

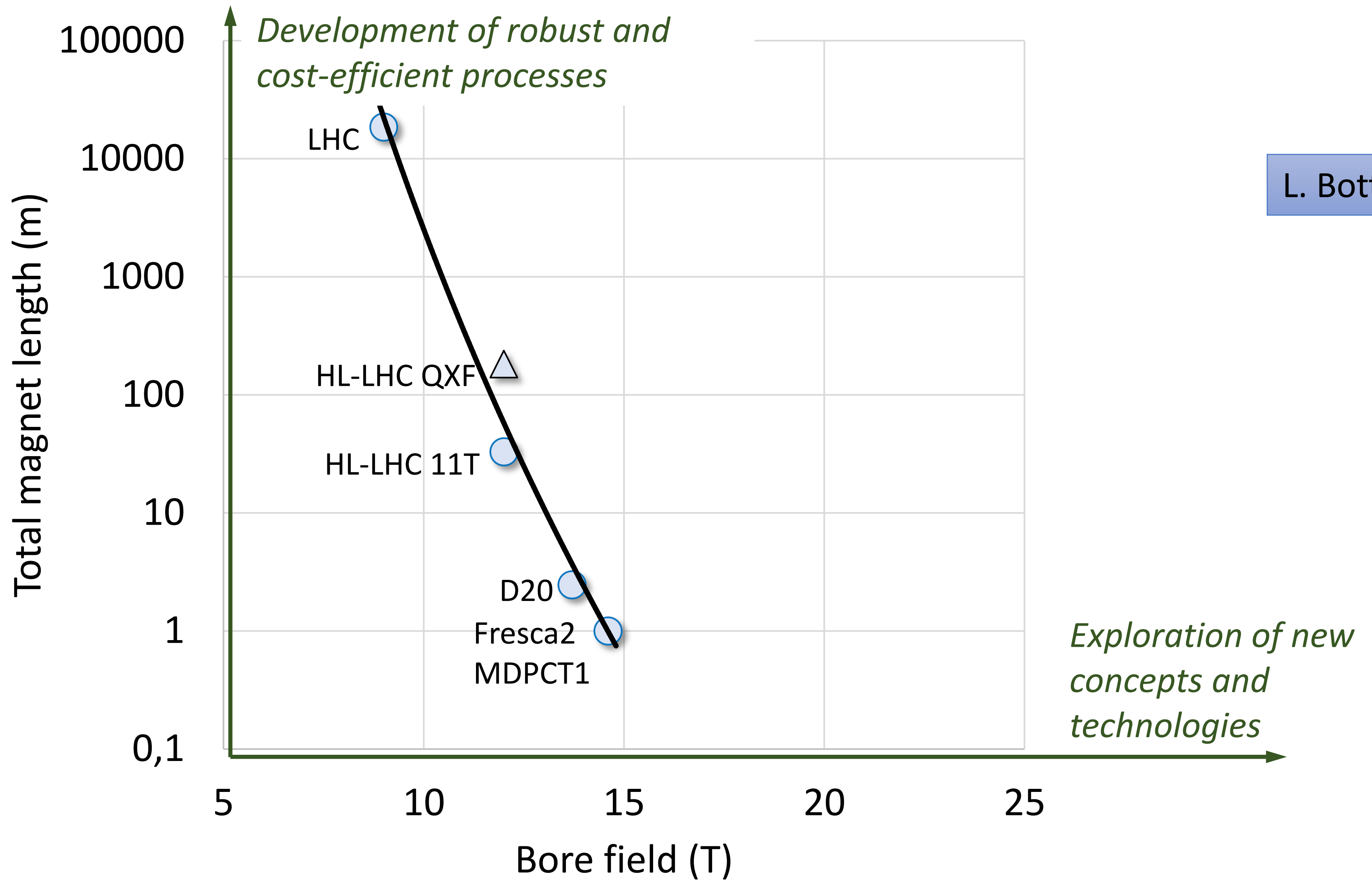
Each Strateg
Within the
Deliberation Document the Strategy statements are presented in blue indented text, and each statement is
followed by some explanatory text.

3. High-priority future initiatives

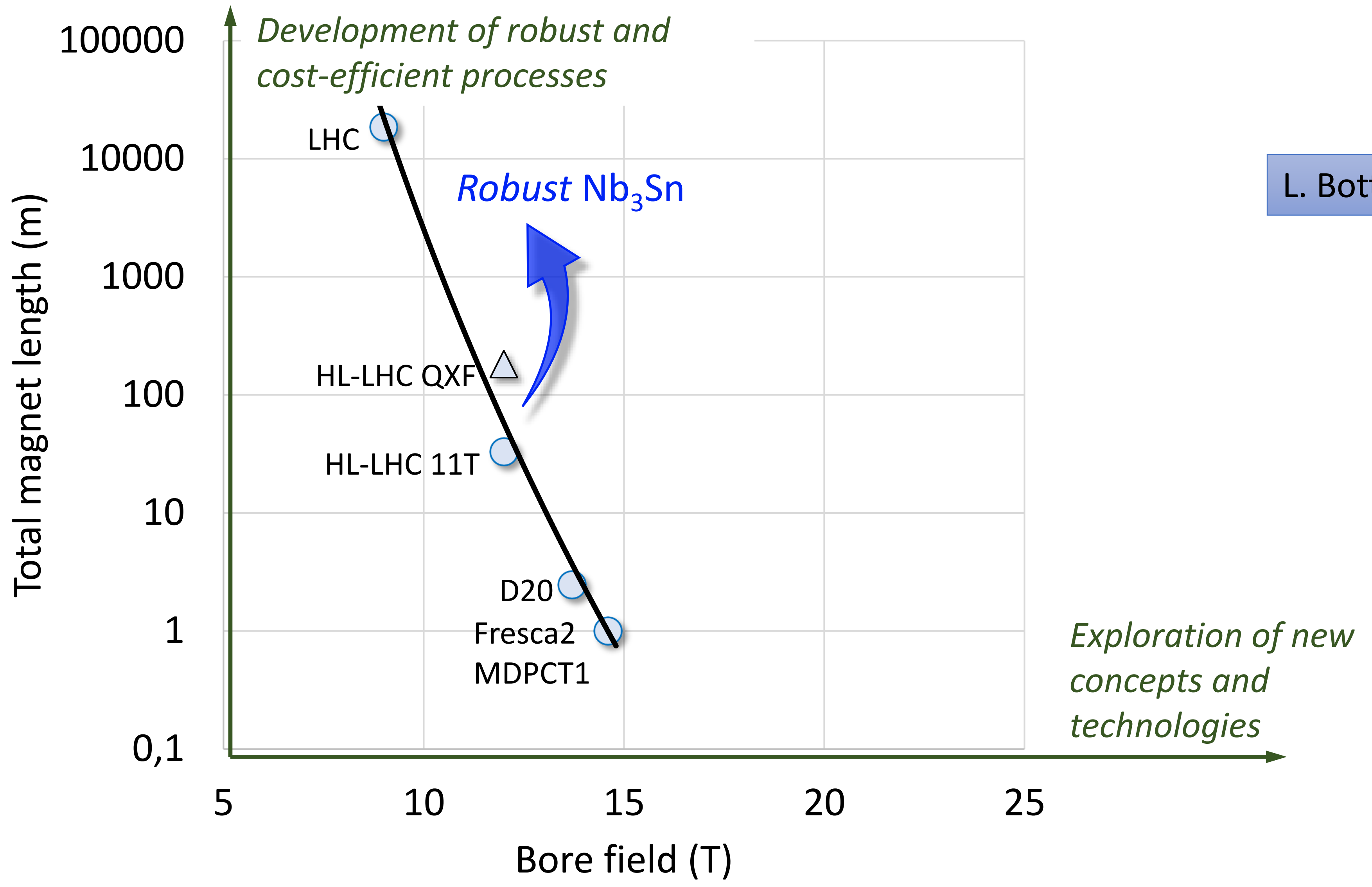
a) An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge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



L. Bottura, CERN



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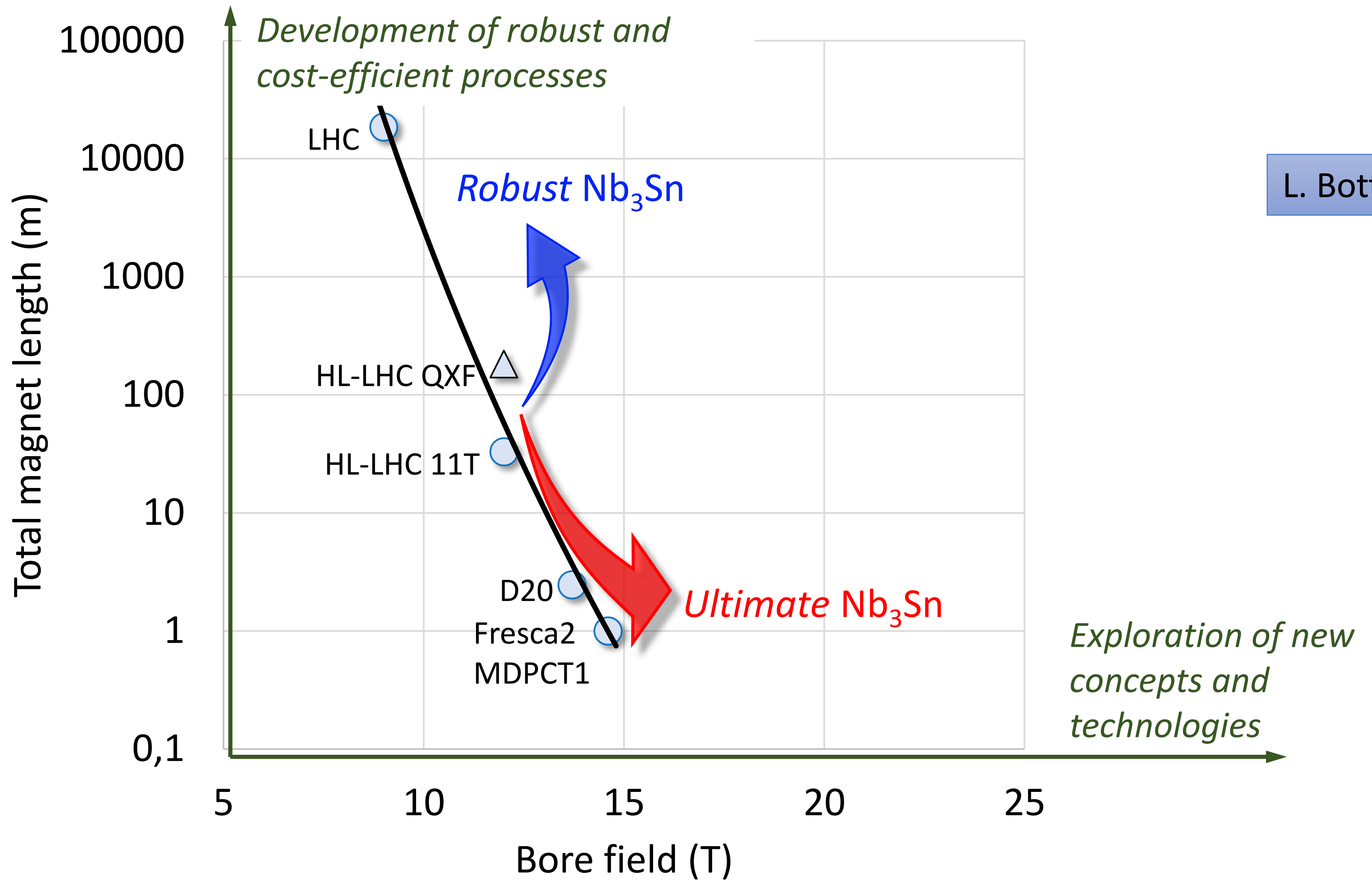

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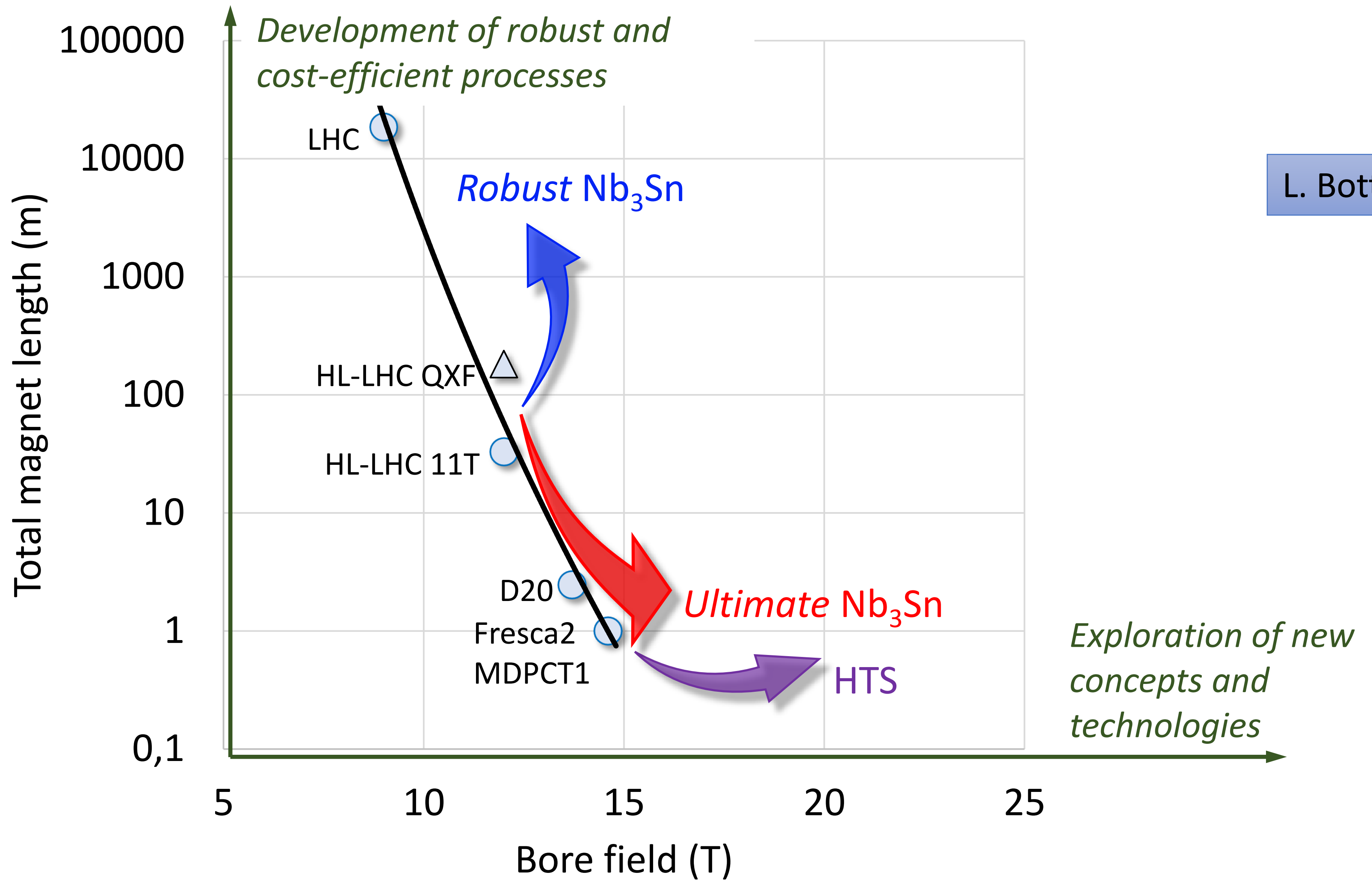

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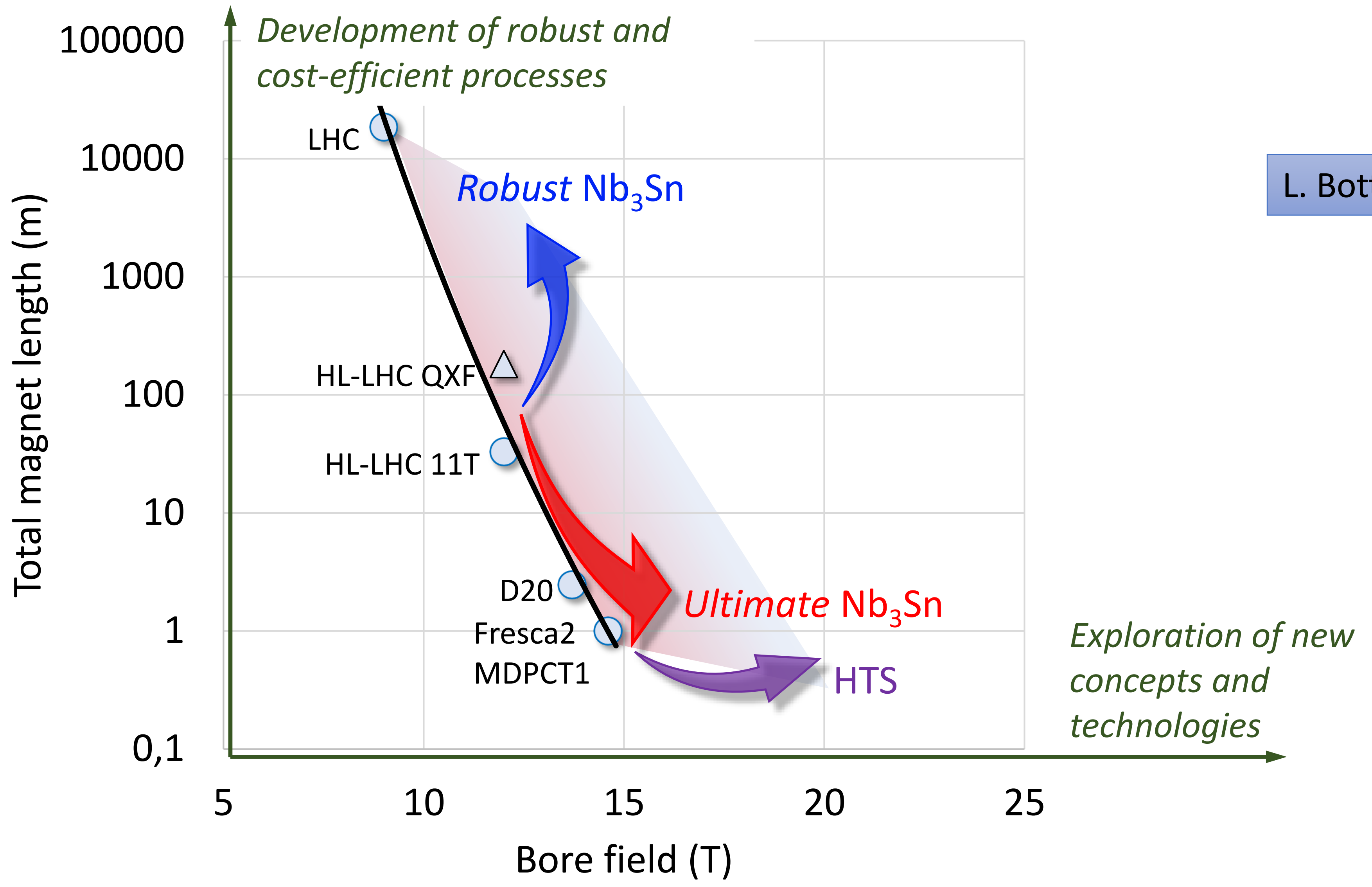

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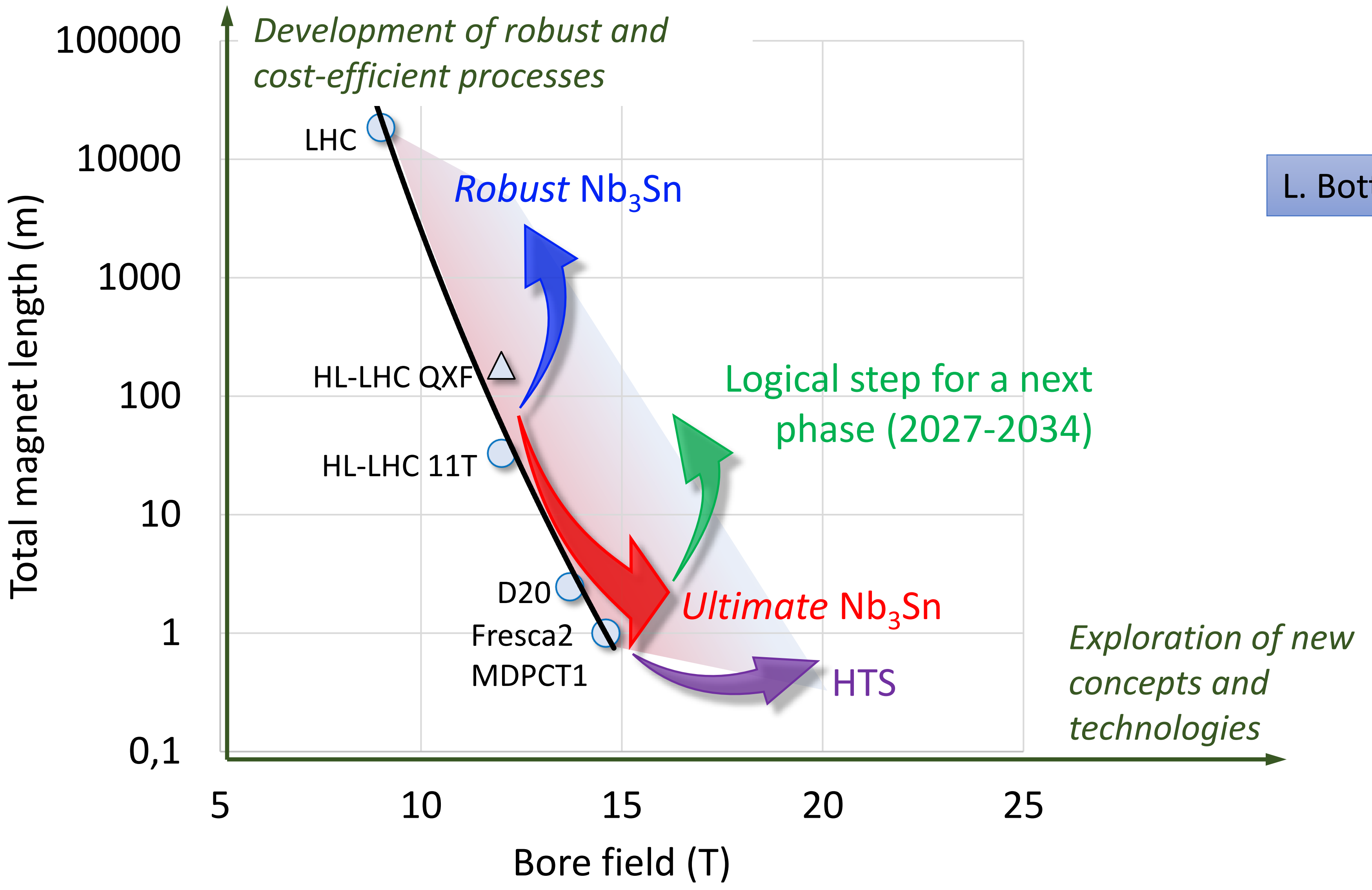
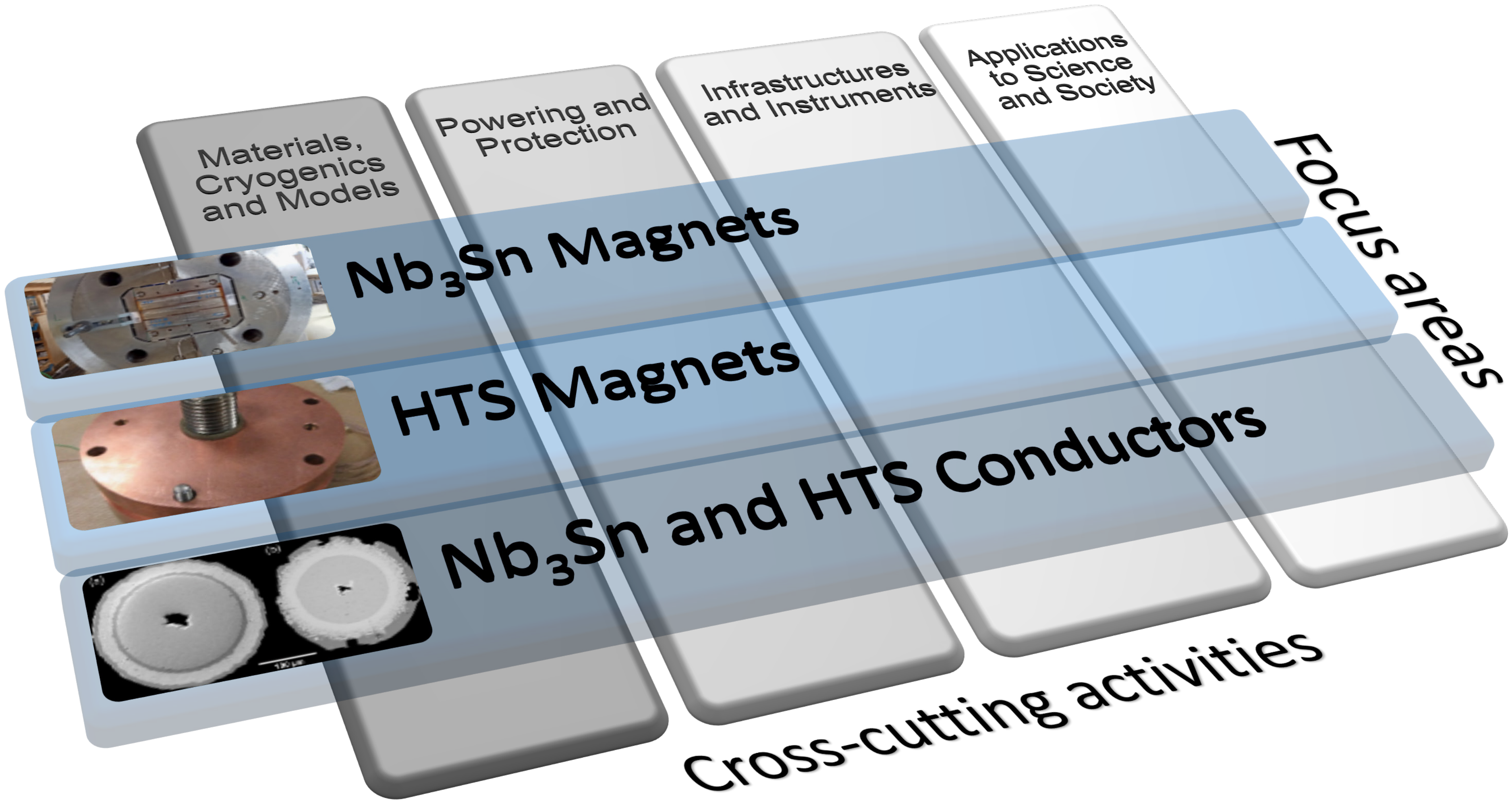


L. Bottura, CERN

Activities – Topics matrix



Towards the ultimate performance of Nb_3Sn

Performance target for FCC-hh J_c(4.2K,16 T) = 1'500 A/mm^2

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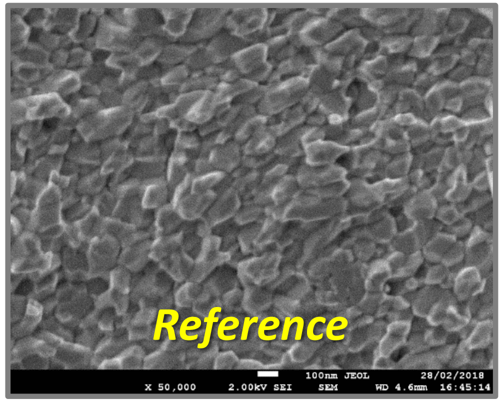
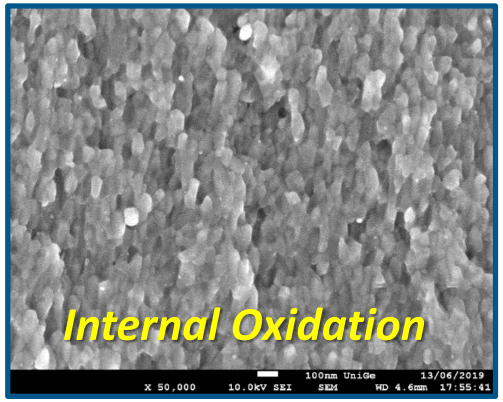
FACULTÉ DES SCIENCES
DQMP
http://supra.unige.ch



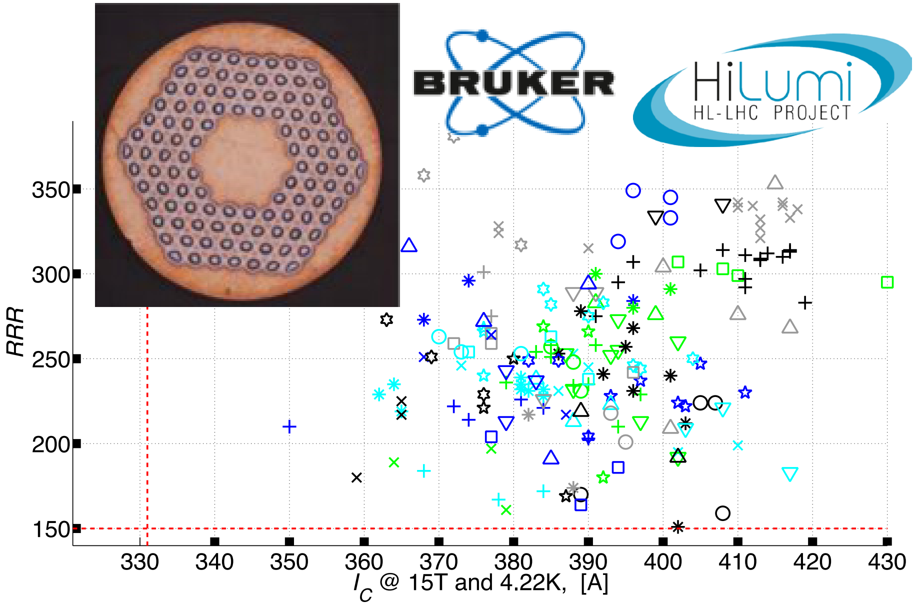


<u>Grain refinement</u> from 120 nm (left) to 60 nm (right)

Enhanced grain boundary pinning

BRUKER

HiLumi HL-LHC PROJECT



1750 A/mm^2 @ 15T, 4.2K

≈ 1400 A/mm^2 @ 16T, 4.2K

FCC-GOV-CC-0112 (KE3545/ATS)

FNSNF FONDS NATIONAL SUISSE DE LA RECHERCHE SCIENTIFIQUE Grant No. 200021_184940

Towards the ultimate performance of Nb_3Sn

Performance target for FCC-hh J_c(4.2K,16 T) = 1'500 A/mm²

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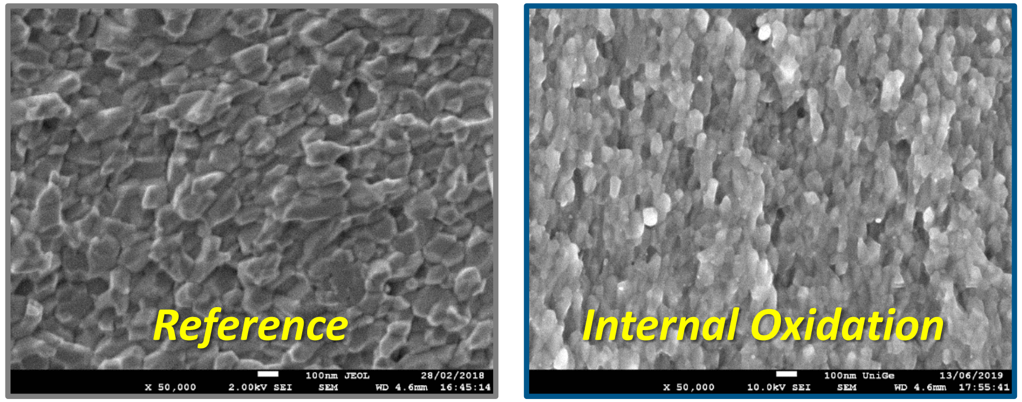

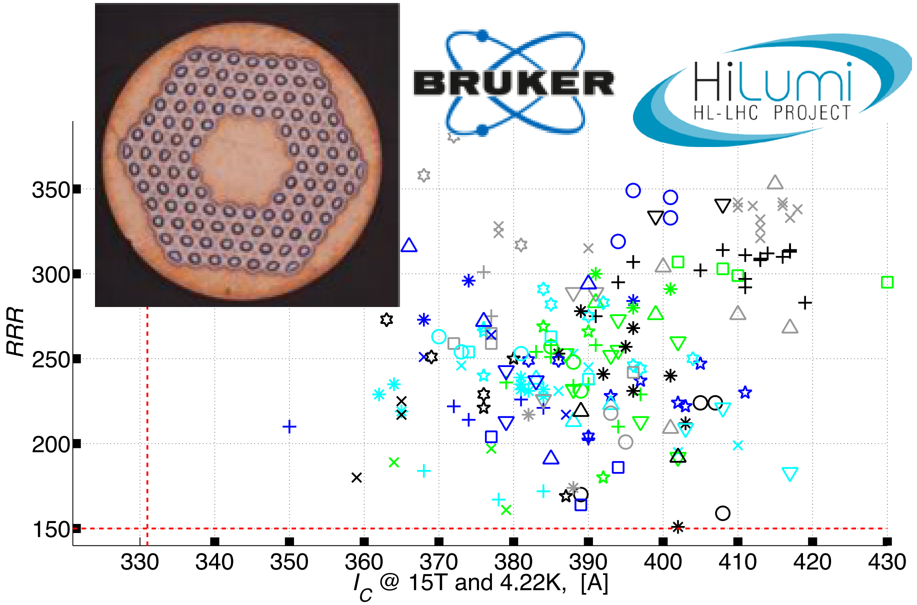

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Enhanced grain boundary pinning

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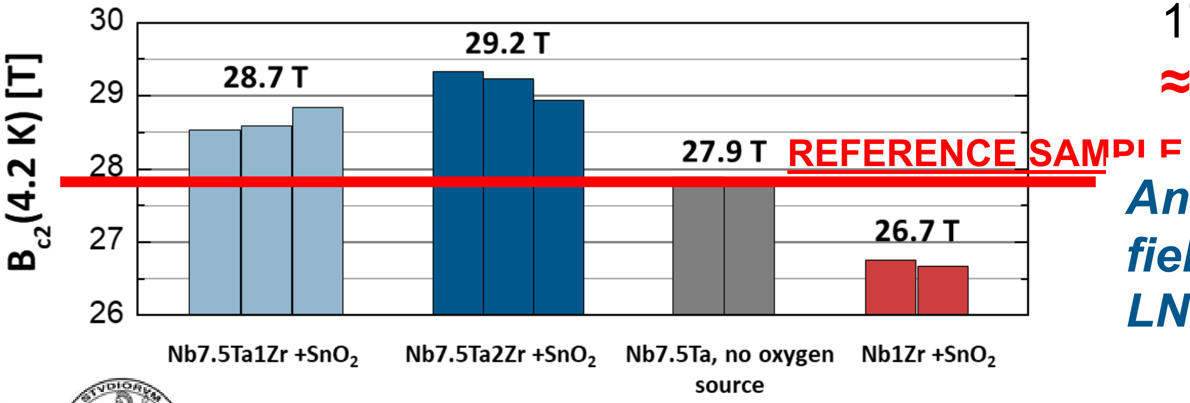

And record-high upper critical field !!
LNCMI-Grenoble

Towards the ultimate performance of Nb_3Sn

Performance target for FCC-hh J_c(4.2K,16 T) = 1'500 A/mm²

UNIVERSITÉ DE GENÈVE
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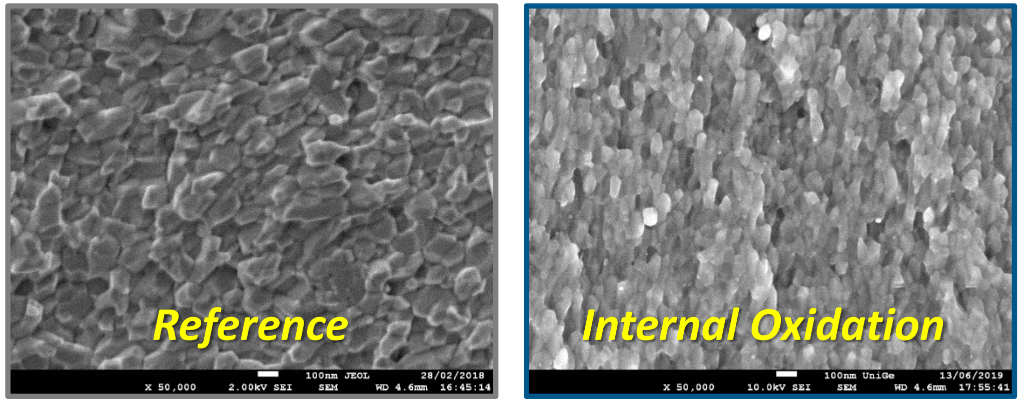

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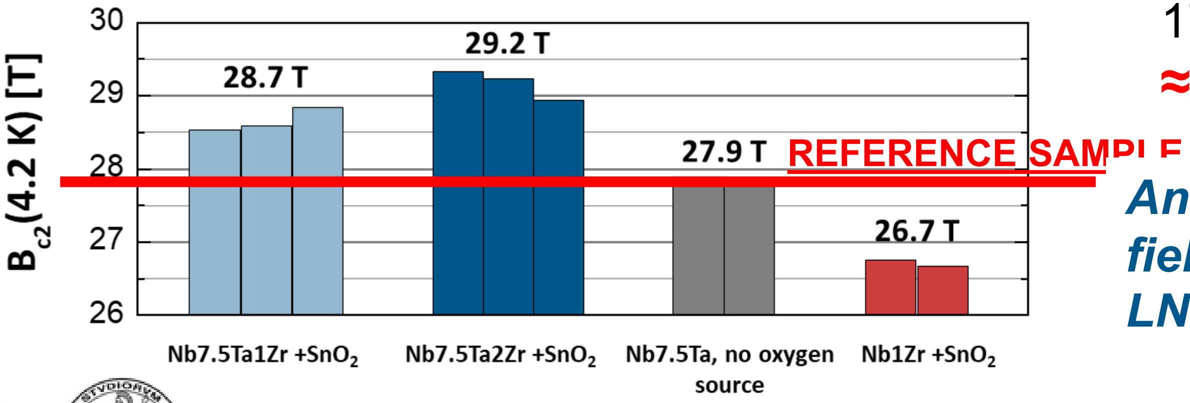
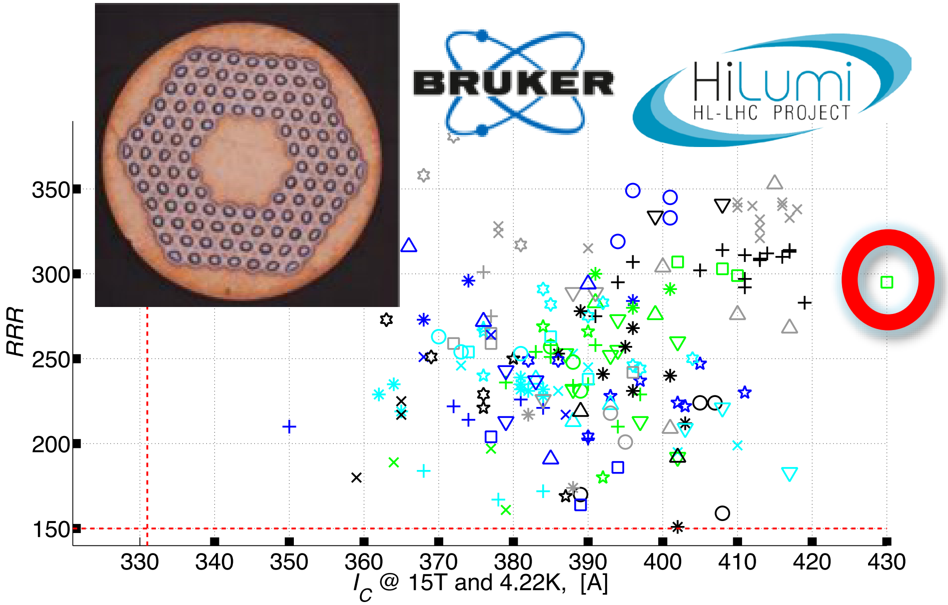
Enhanced grain boundary pinning





1750 A/mm² @ 15T, 4.2K

≈ 1400 A/mm² @ 16T, 4.2K

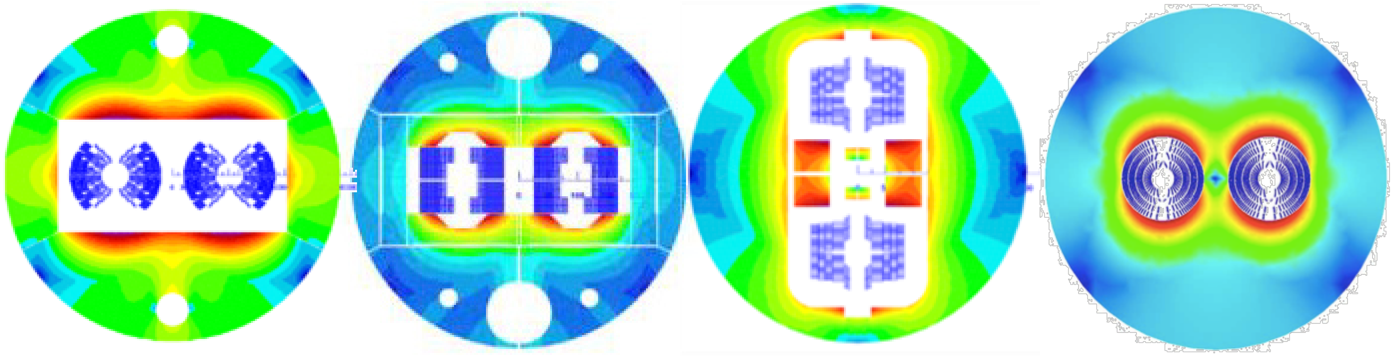
And record-high upper critical field !!
LNCMI-Grenoble

FCC-GOV-CC-0112 (KE3545/ATS)

FNSNF FONDS NATIONAL SUISSE DE LA RECHERCHE SCIENTIFIQUE Grant No. 200021_184940

If advanced superconductors are there, magnets come

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

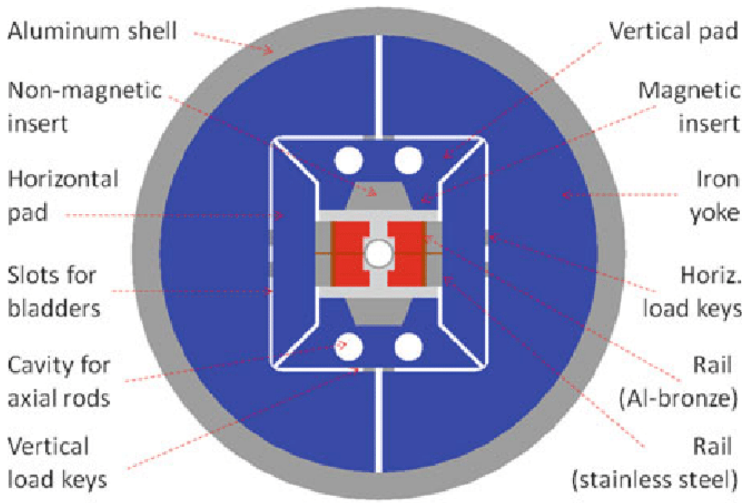


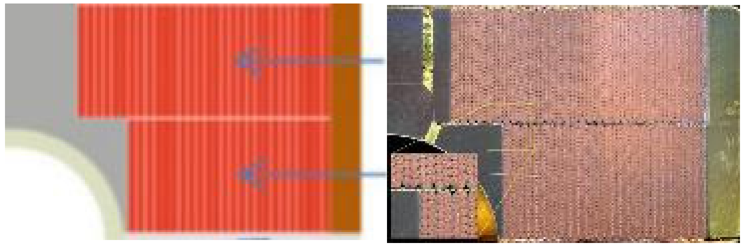
		cos(θ)	blocks	common coil	CCT
Current	(A)	10000	11230	16100	18055
Inductance	(mH/m)	50	40	19.2	19.2
Stored energy	(kJ/m)	2500	2520	2490	3200
Coil mass	(tons)	7400	7400	9200	9770

Exploring new coil lay-out (again with bladder-key system)

L. Bottura, CERN

Exploring new coil lay-out (again with bladder-key system)

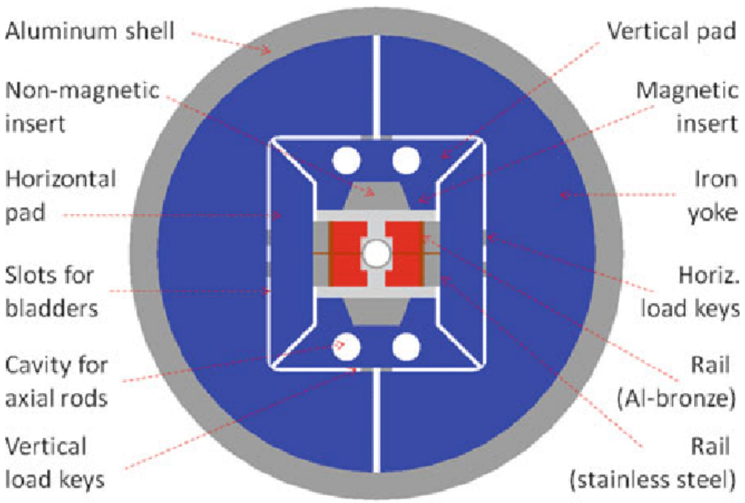


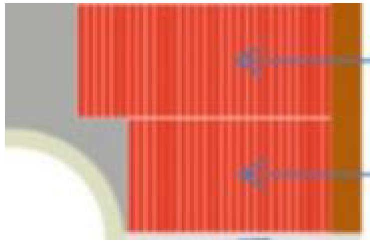


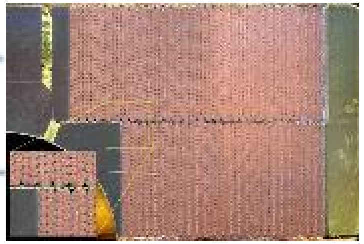
HD2 (2-decks, 36 mm), 13.8 T

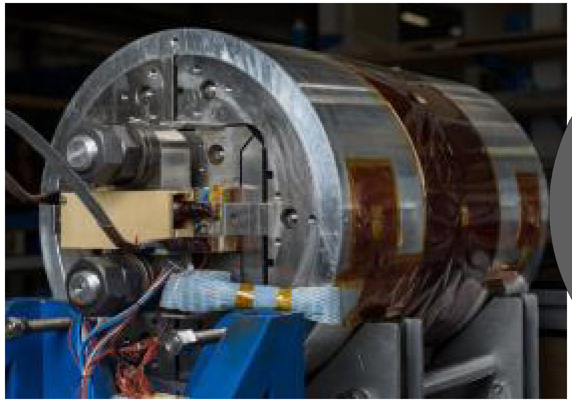
L. Bottura, CERN

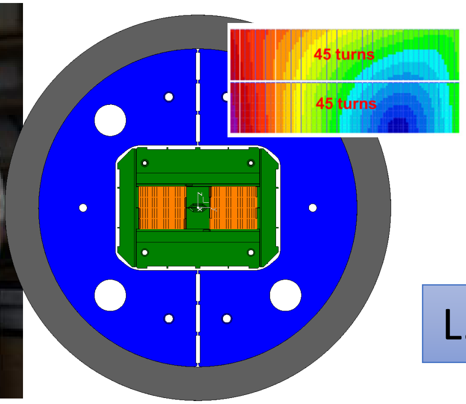
Exploring new coil lay-out (again with bladder-key system)







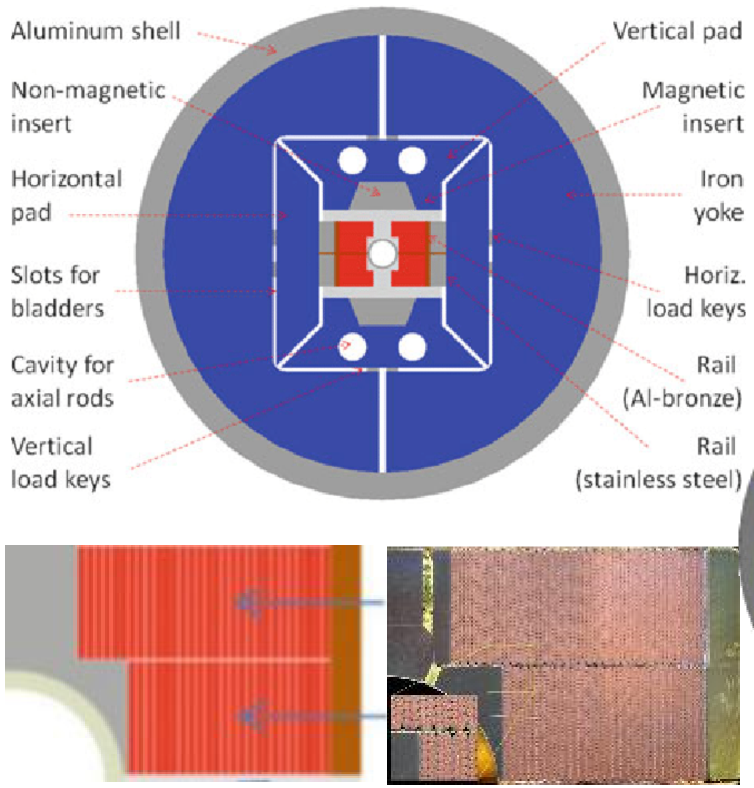


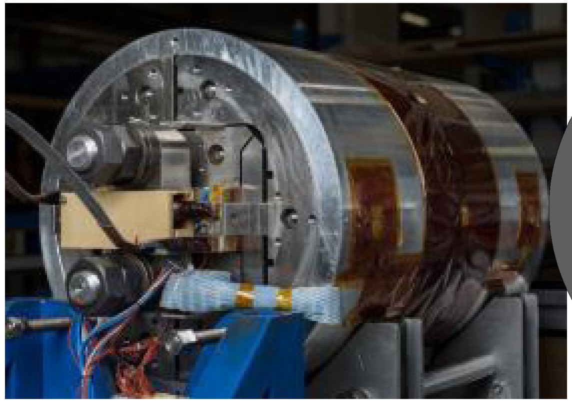


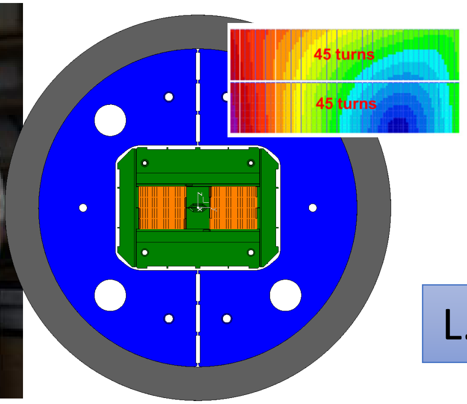
L. Bottura, CERN

HD2 (2-decks, 36 mm), 13.8 T

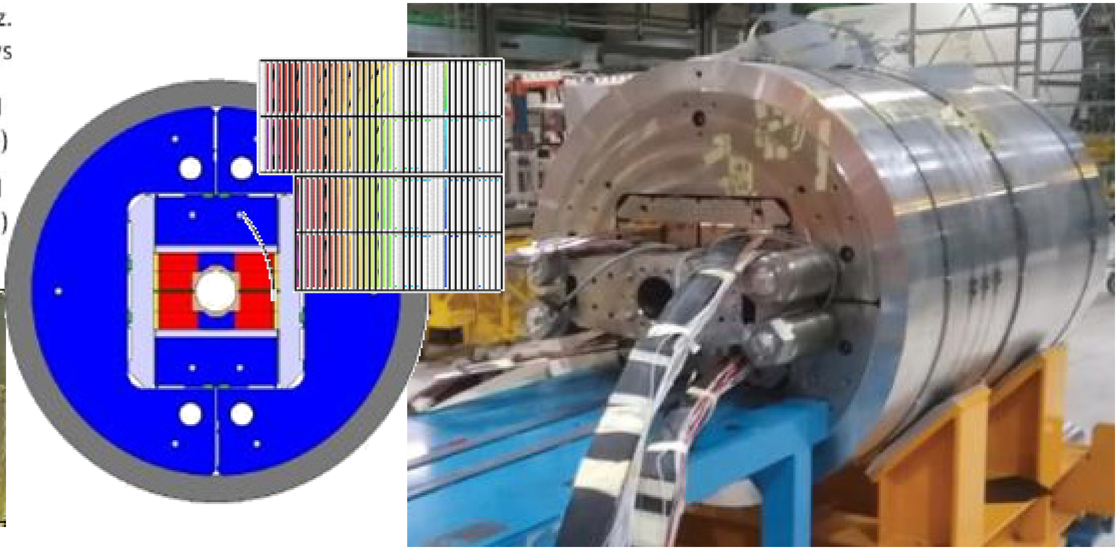
Exploring new coil lay-out (again with bladder-key system)







L. Bottura, CERN

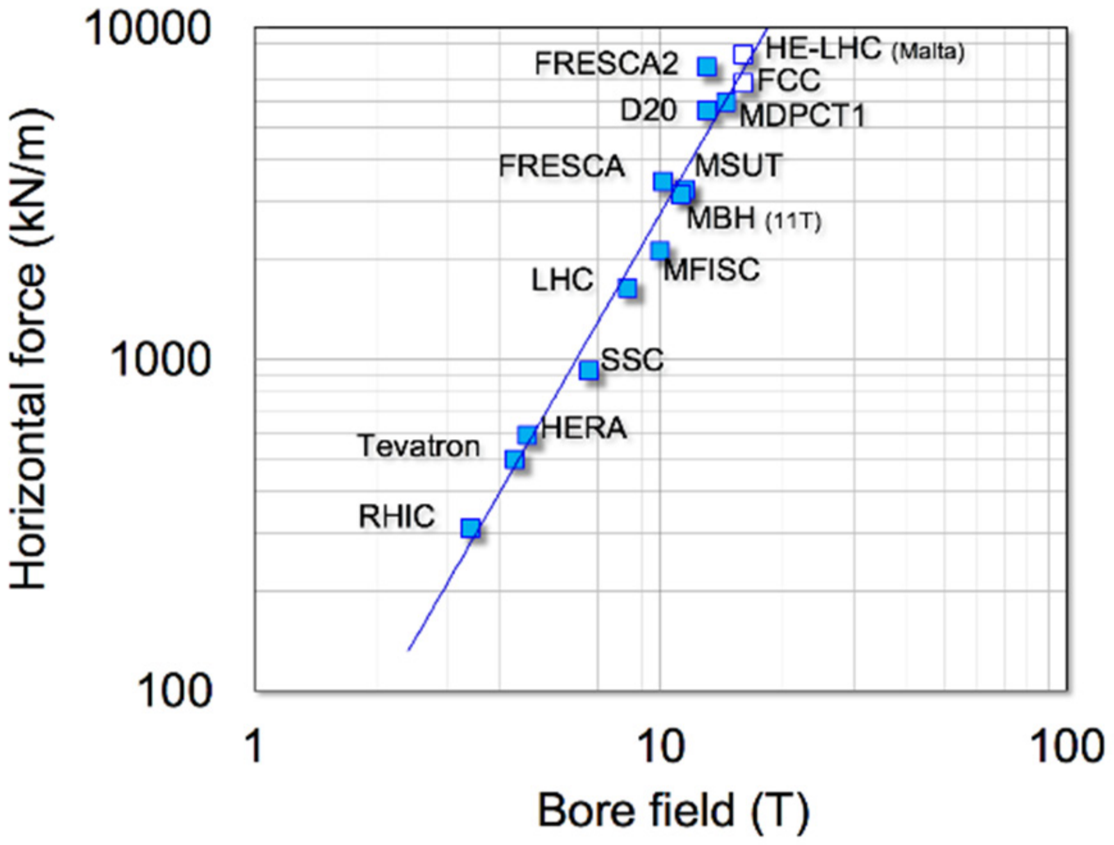


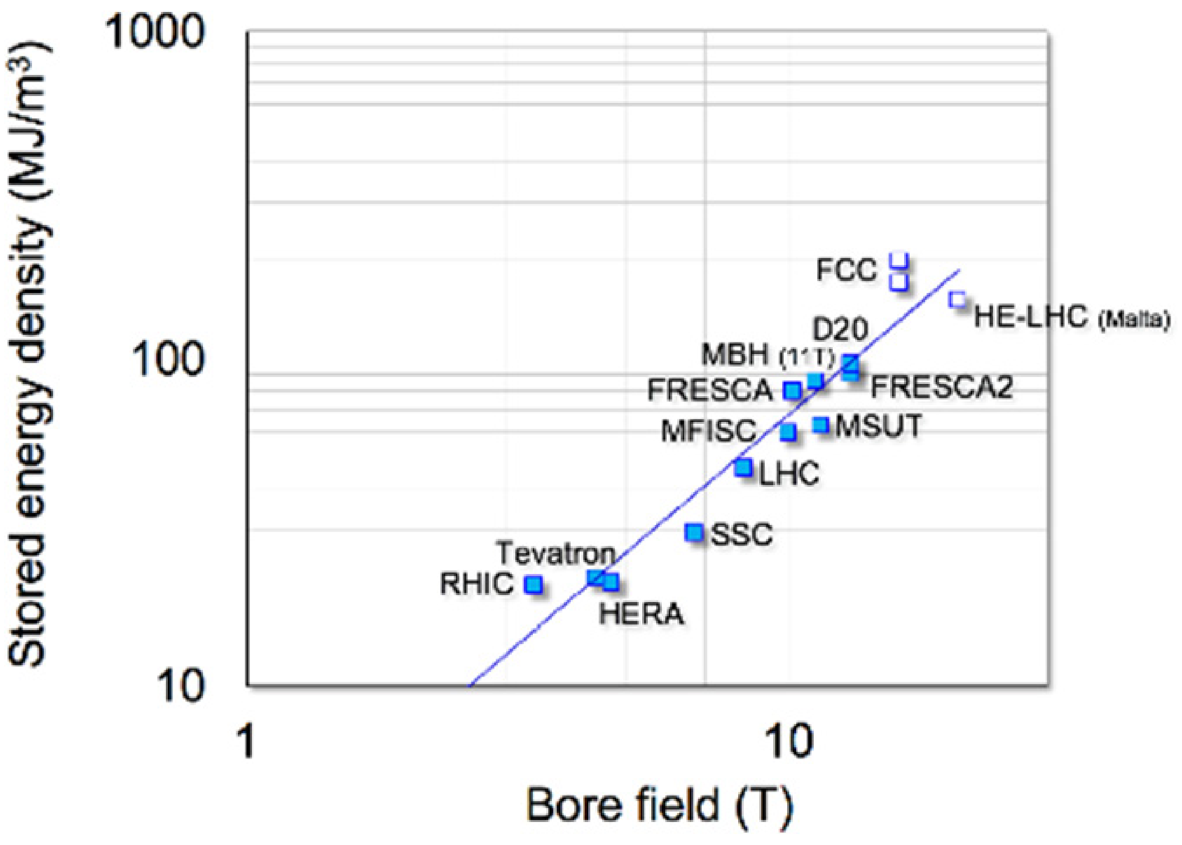
HD2 (2-decks, 36 mm), 13.8 T

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

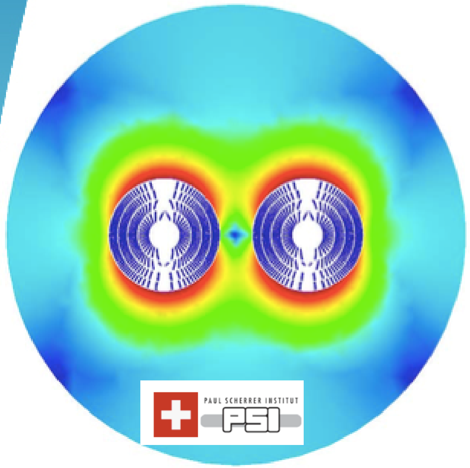
New structure to support forces/stresses
Effort in making magnets with huge energy safe

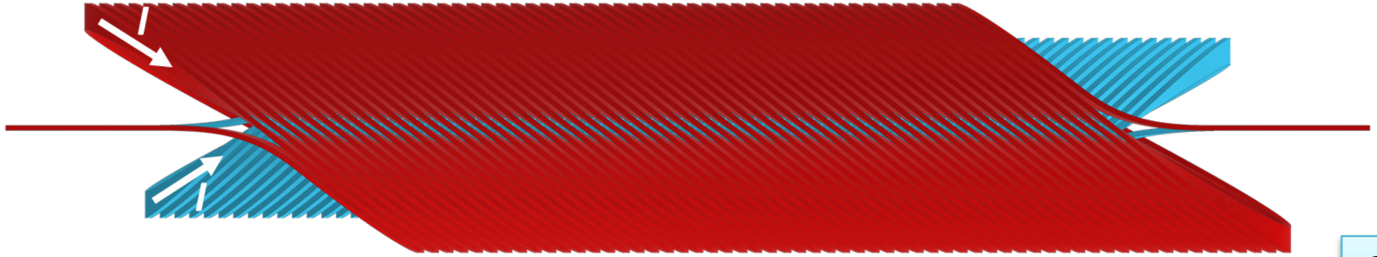
L. Bottura, CERN





CCT Canted CosTheta design : from FCC → Hadron Therapy





G. Ceruti & E. DeMatteis, INFN-Mi-LASA

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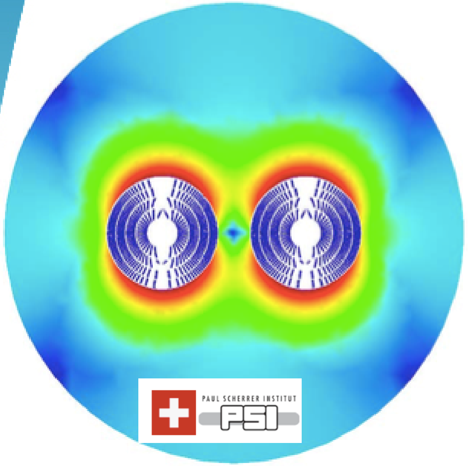

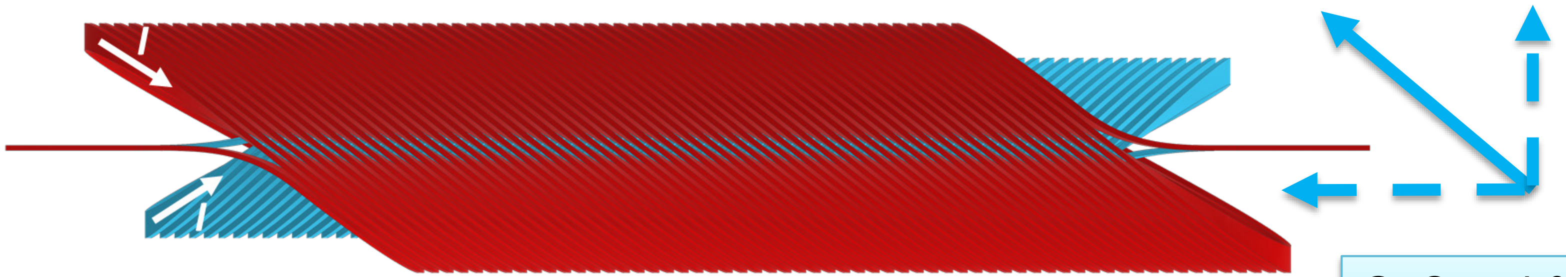

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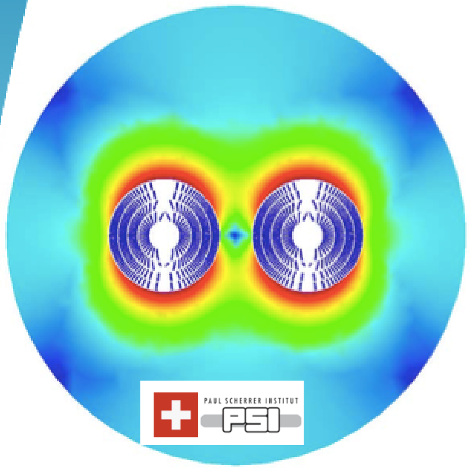

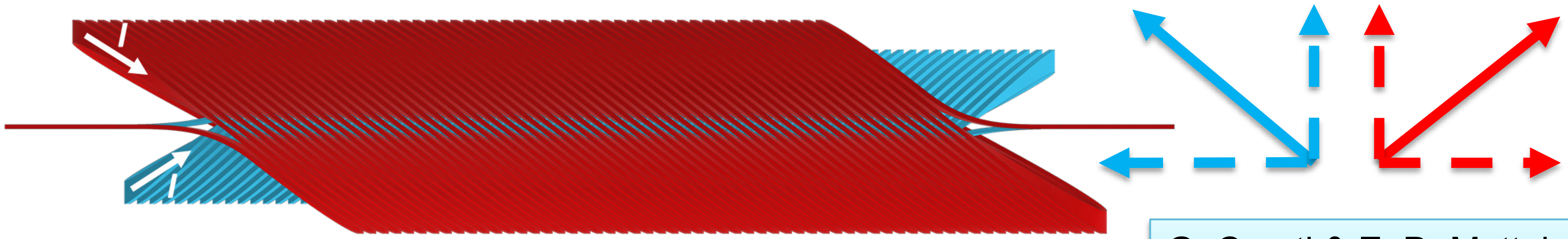

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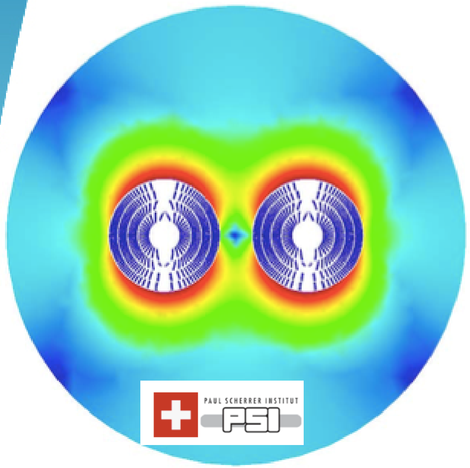

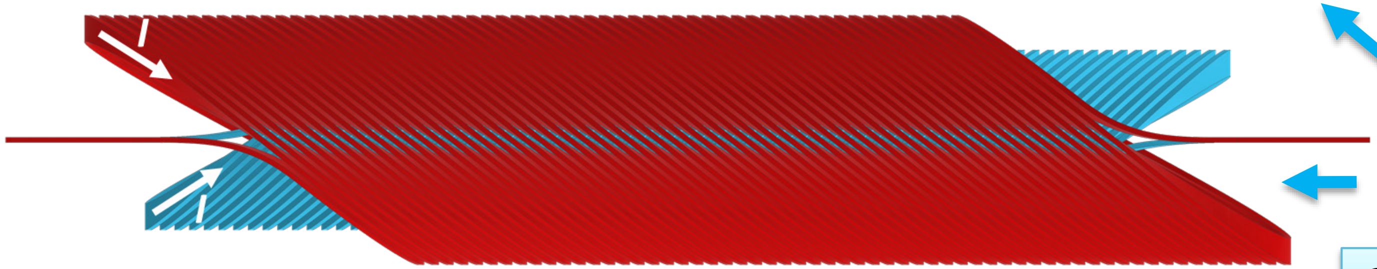

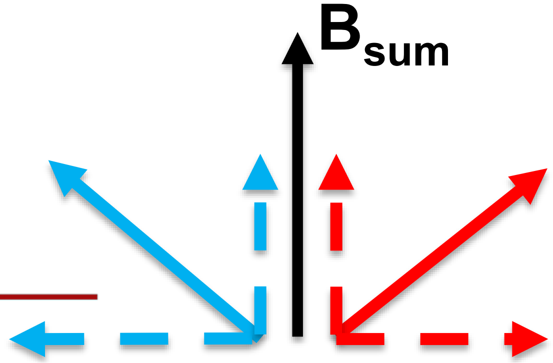

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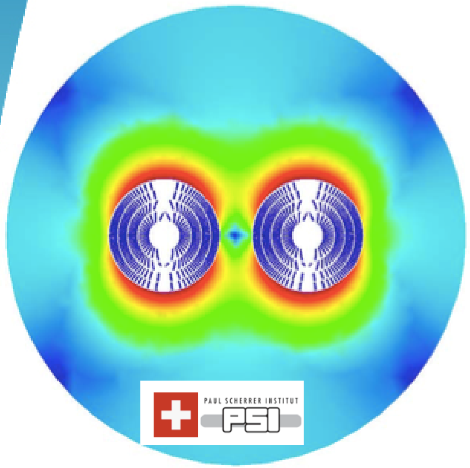

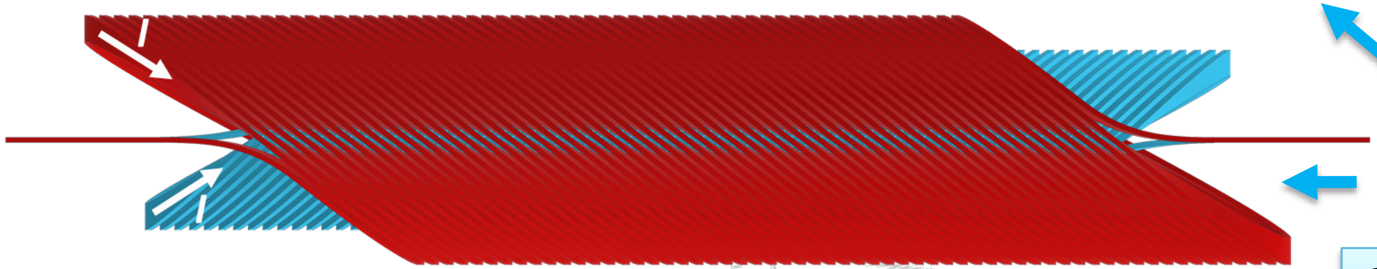

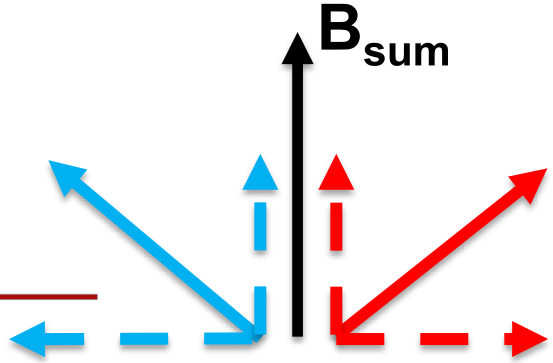

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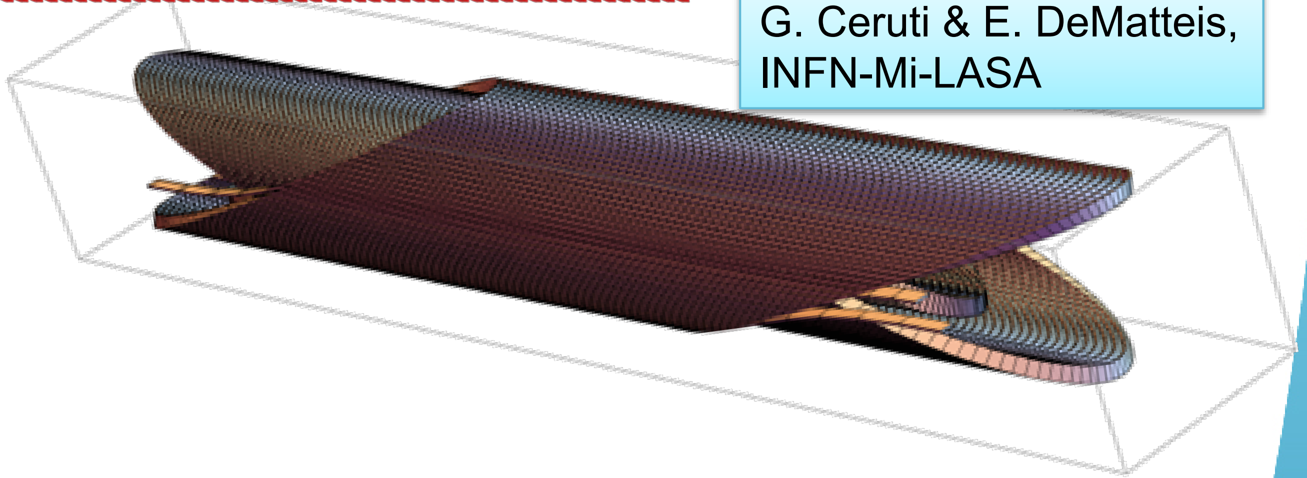

HITRI plus
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HiLumi HL-LHC PROJECT

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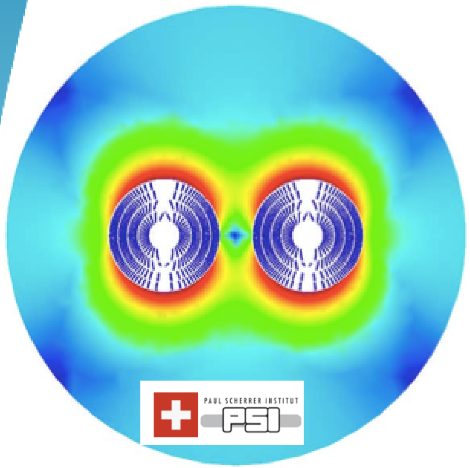

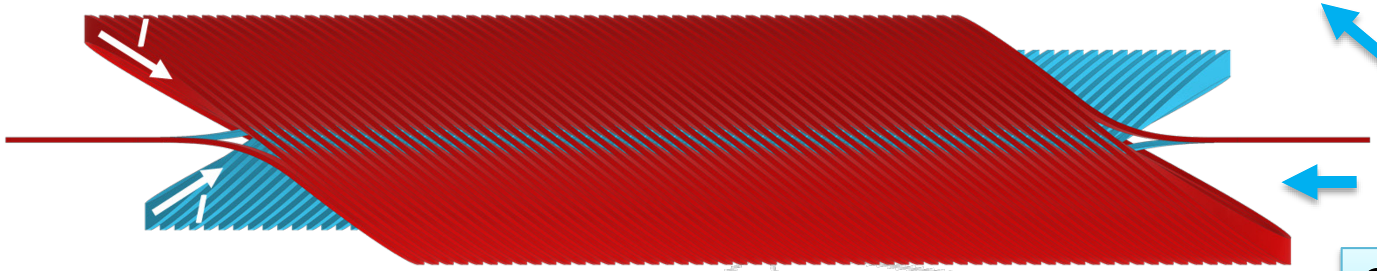

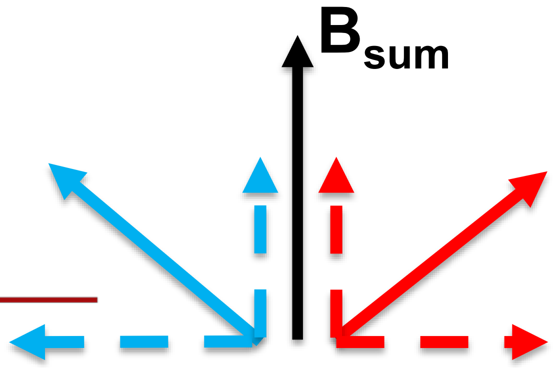

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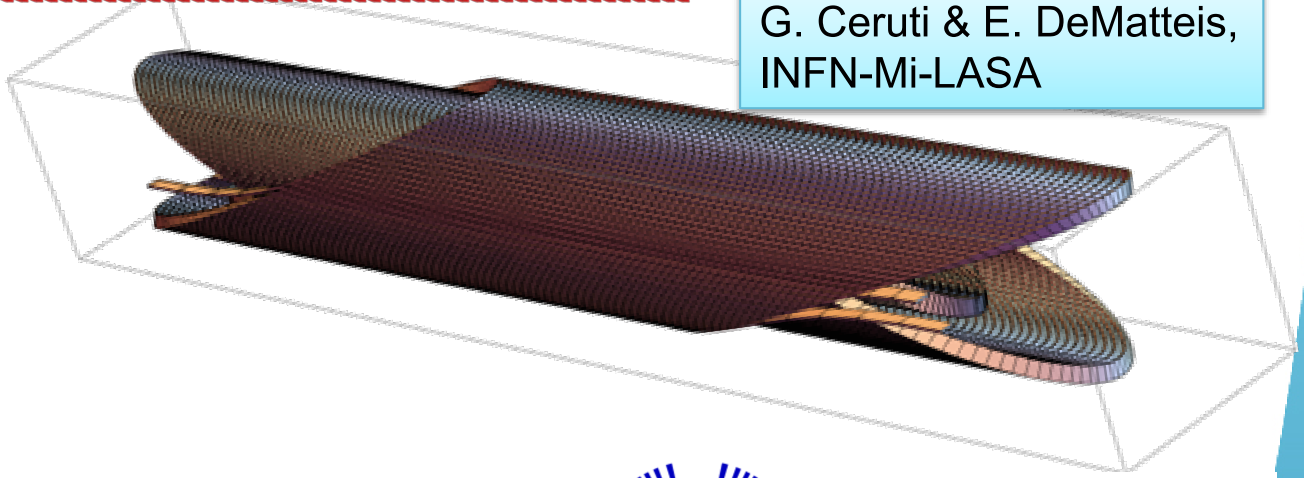

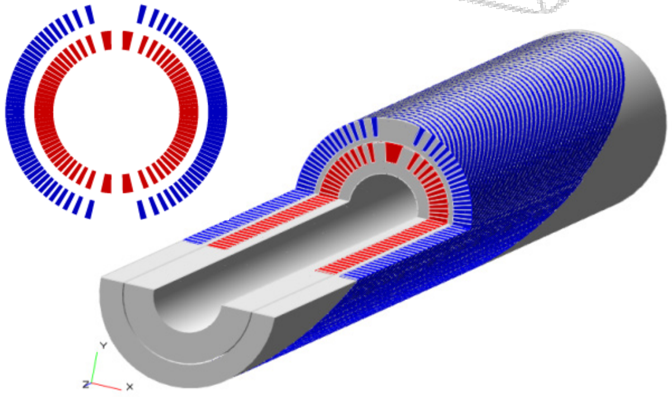

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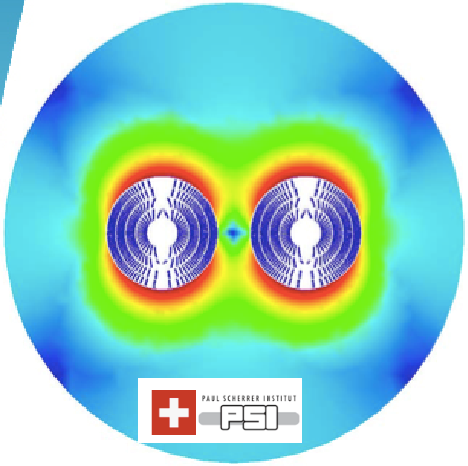

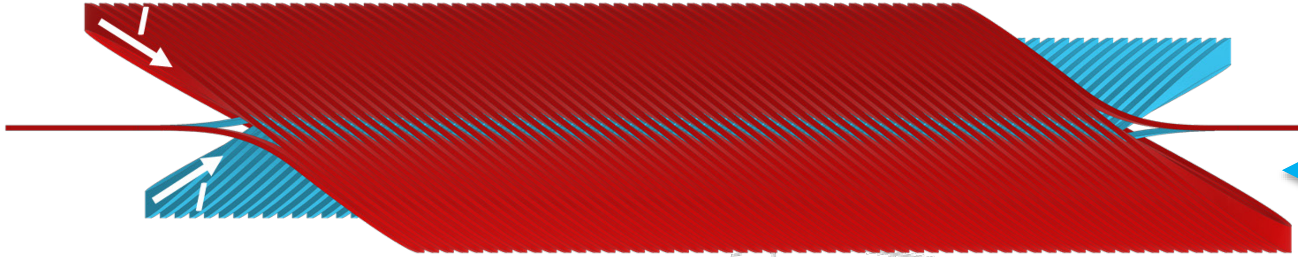

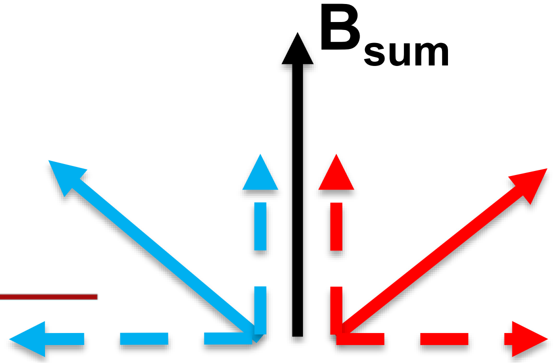

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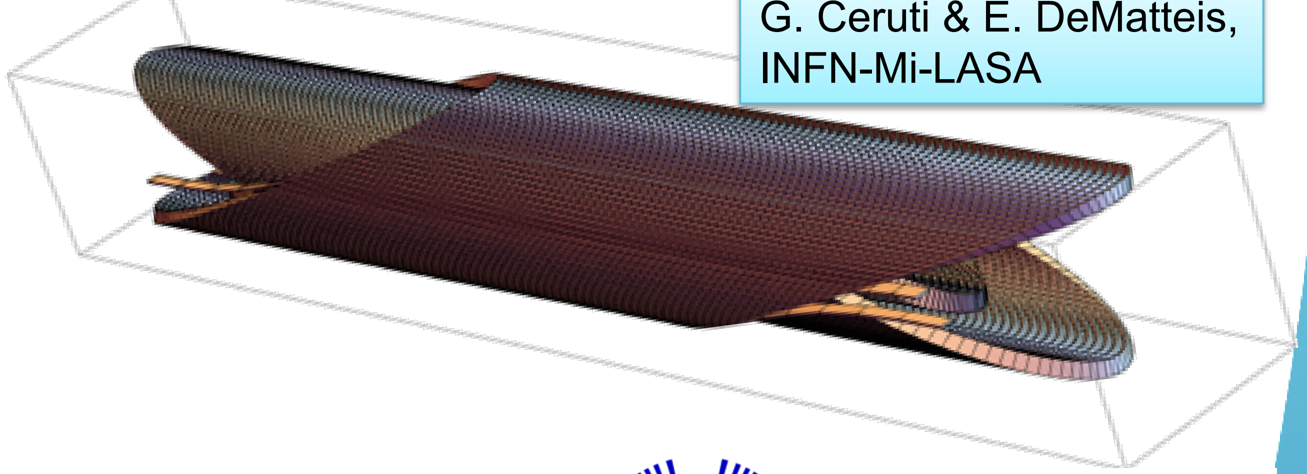

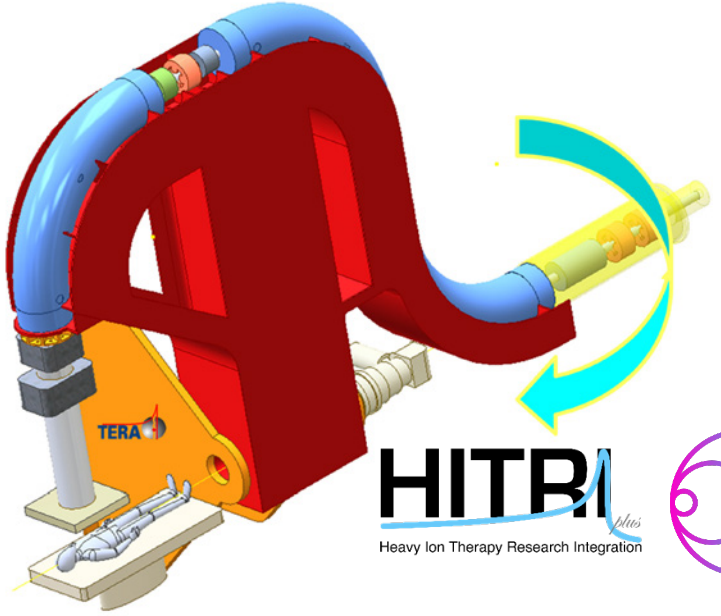

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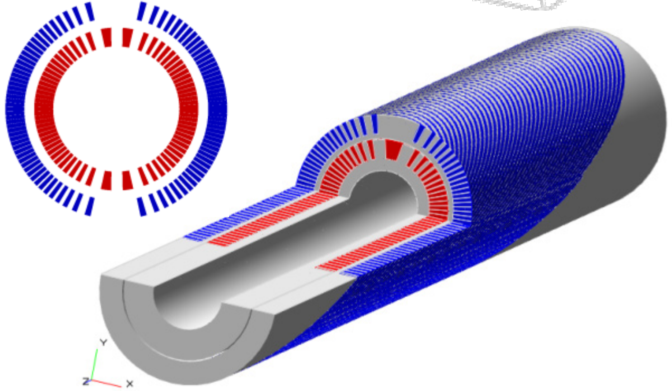

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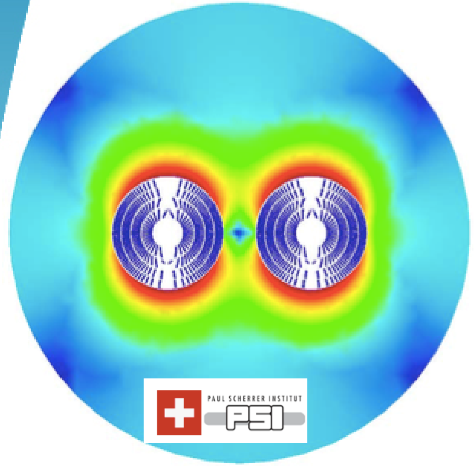
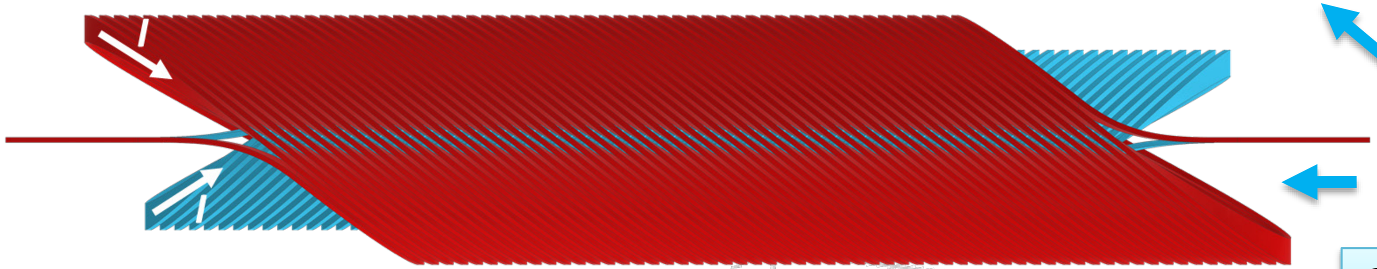
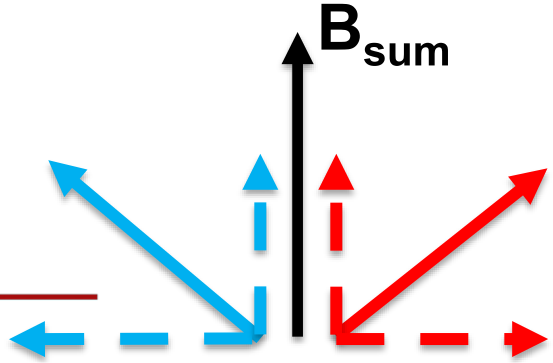
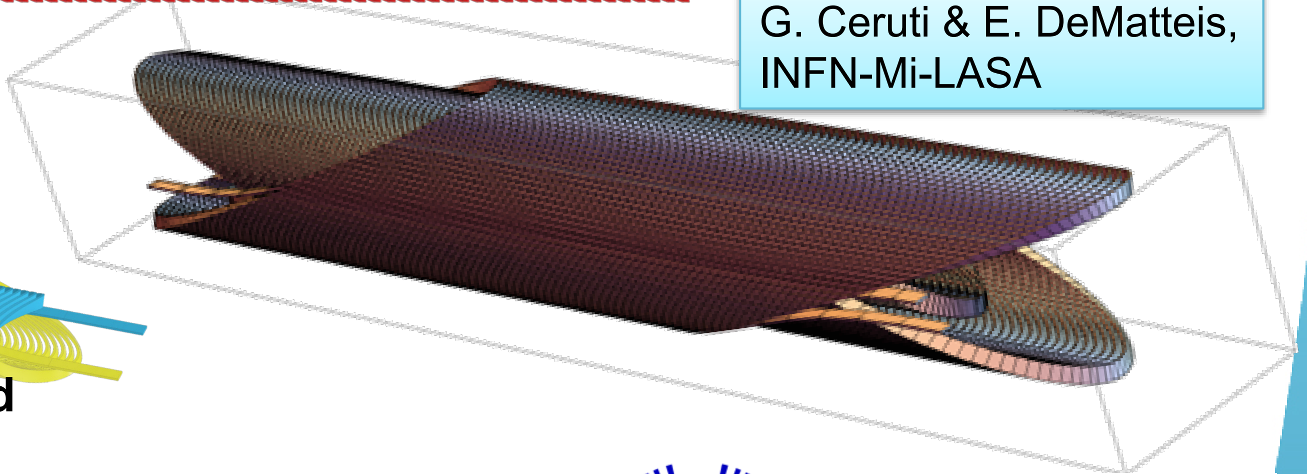


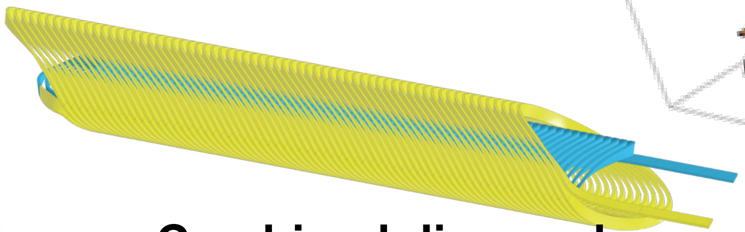


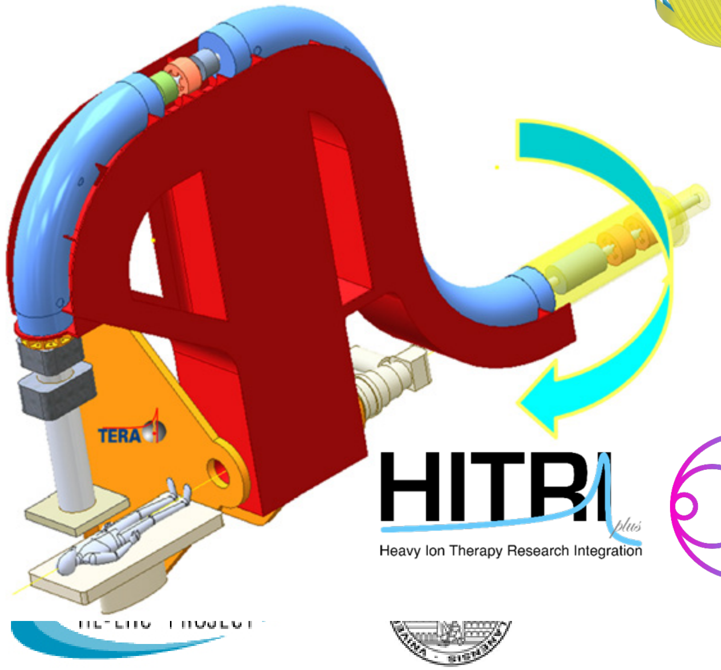


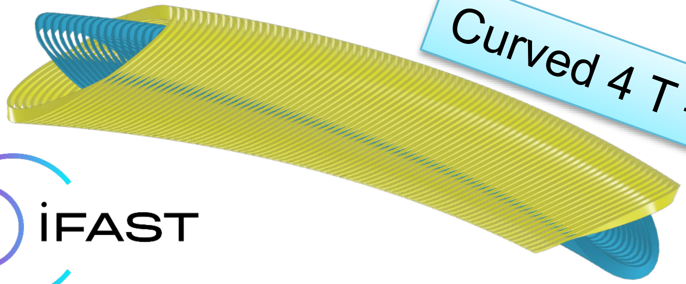
G. Ceruti & E. DeMatteis,
INFN-Mi-LASA



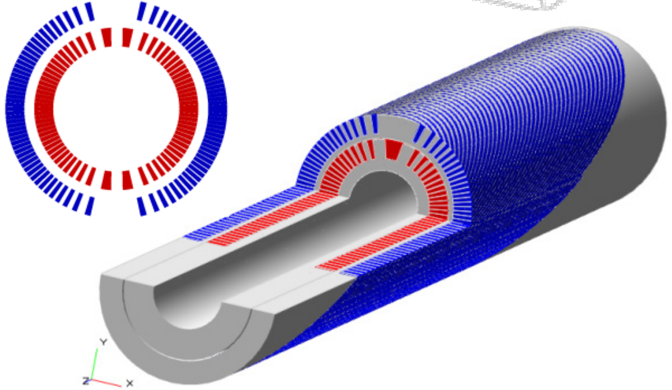
Combined dip-quad







Curved 4 T – 0.4T/s



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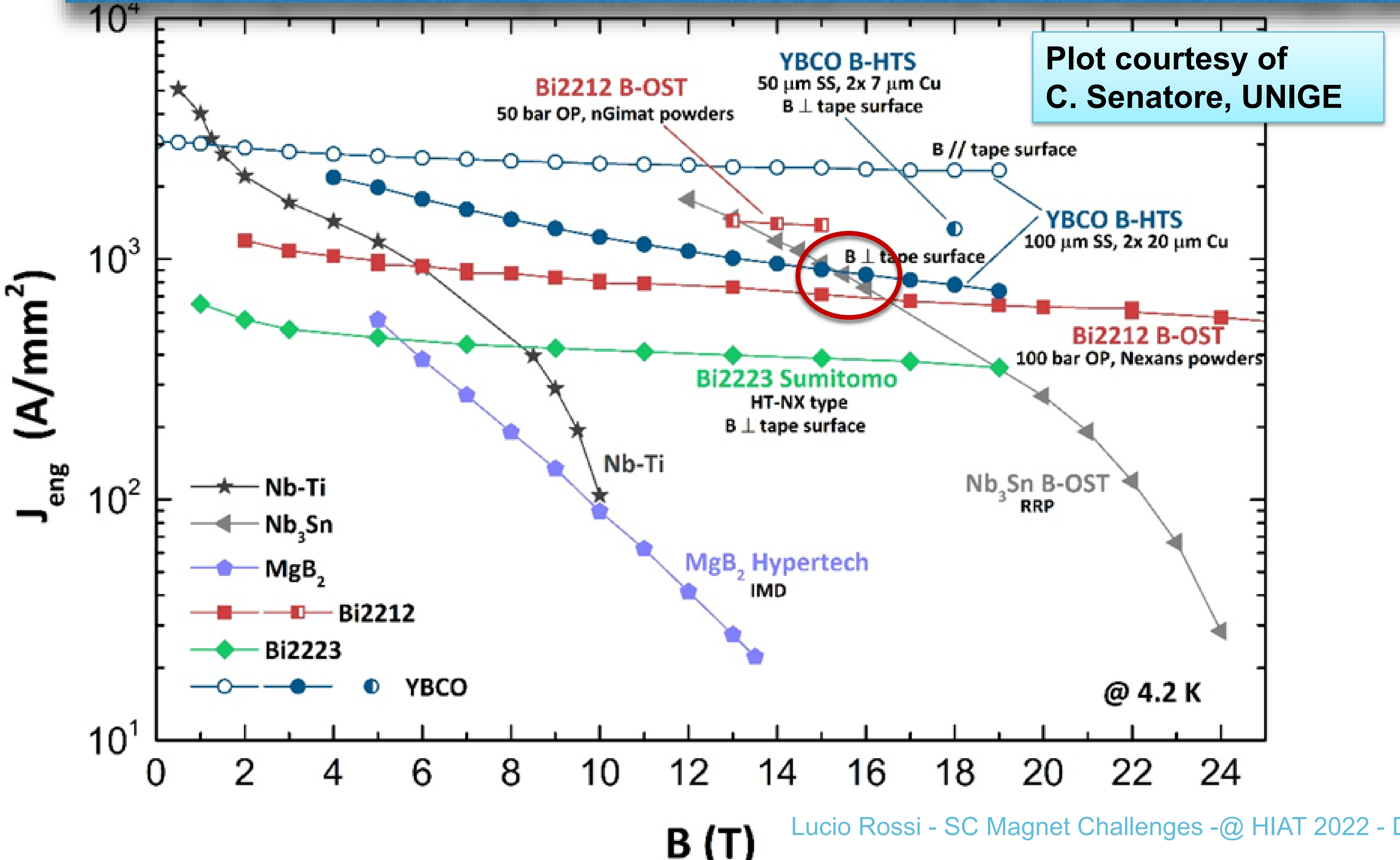
High Temperature Superconductors – HTS: next technology step



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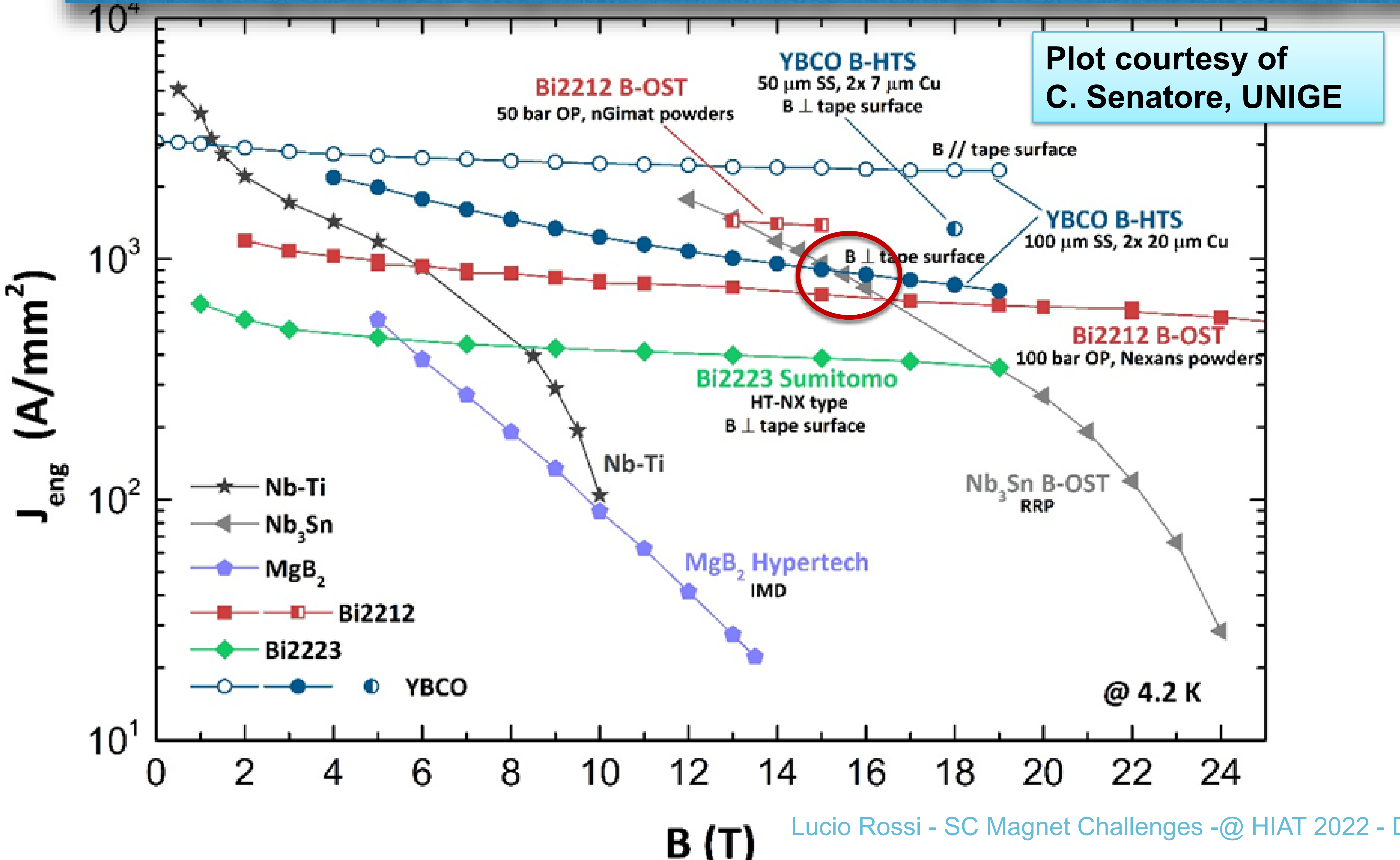

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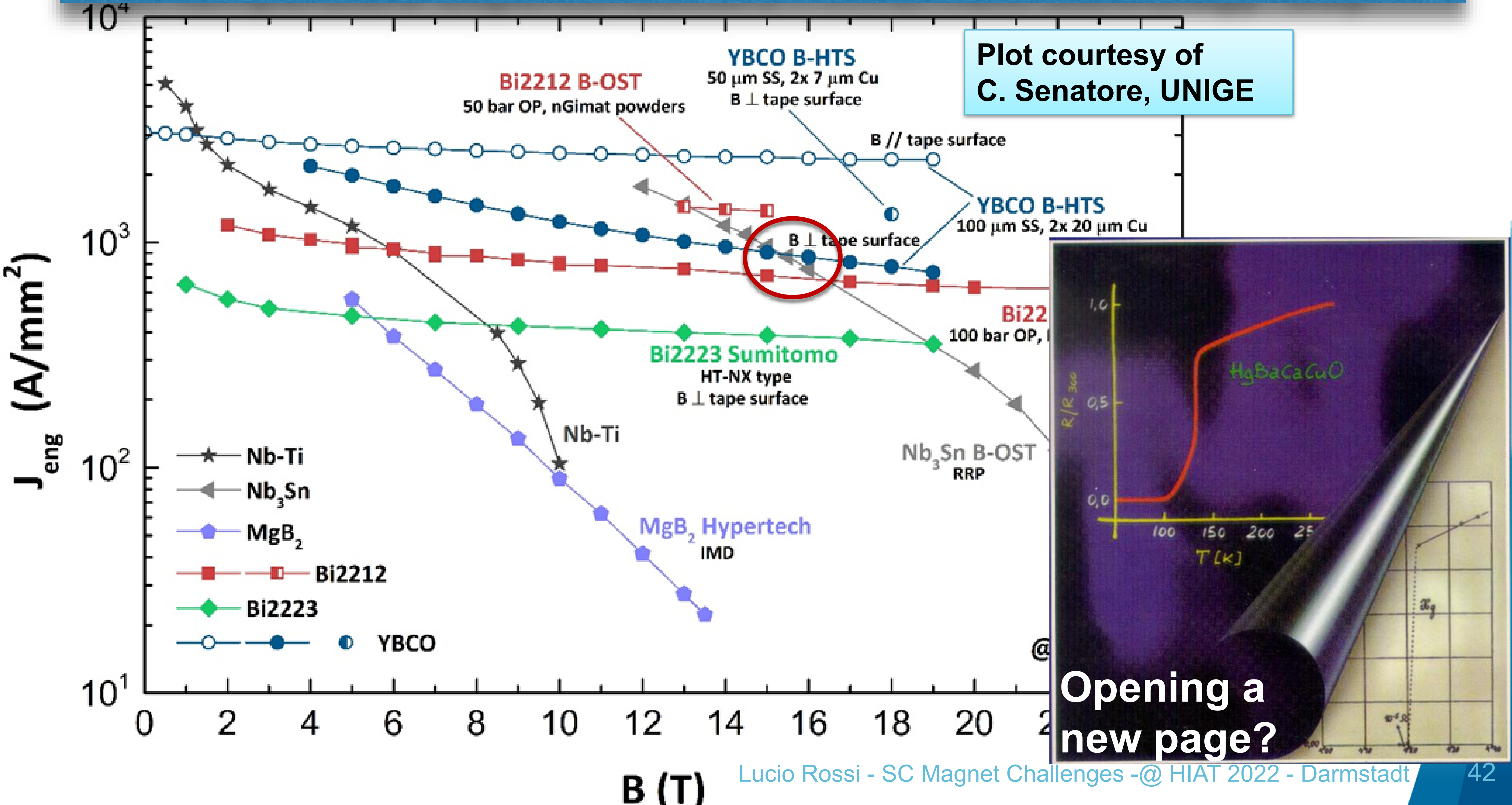
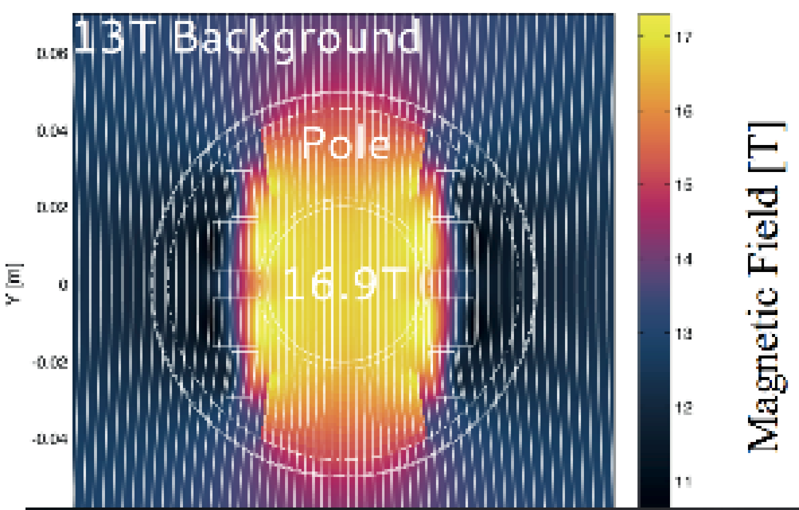
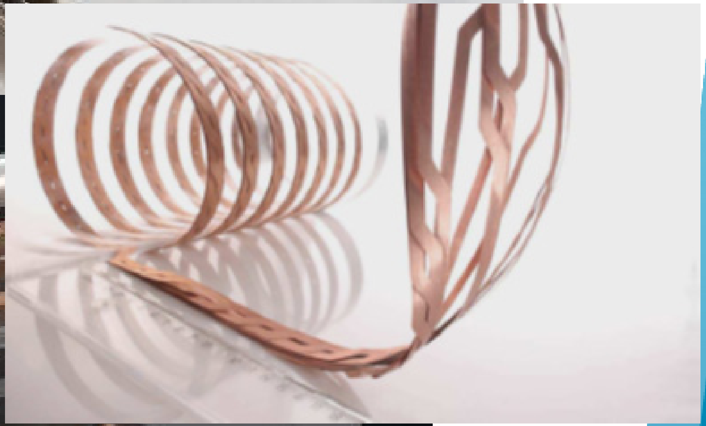
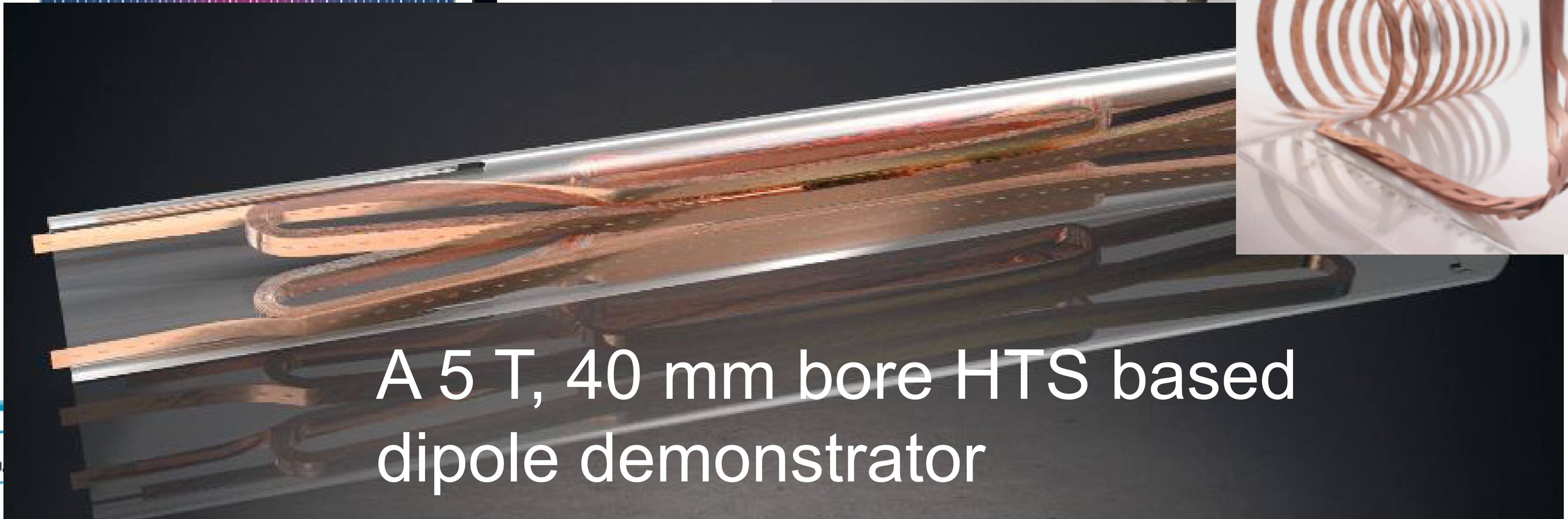


High Temperature Superconductors – HTS
The dream of 20-25 tesla! (2 x HilumiLHC!)

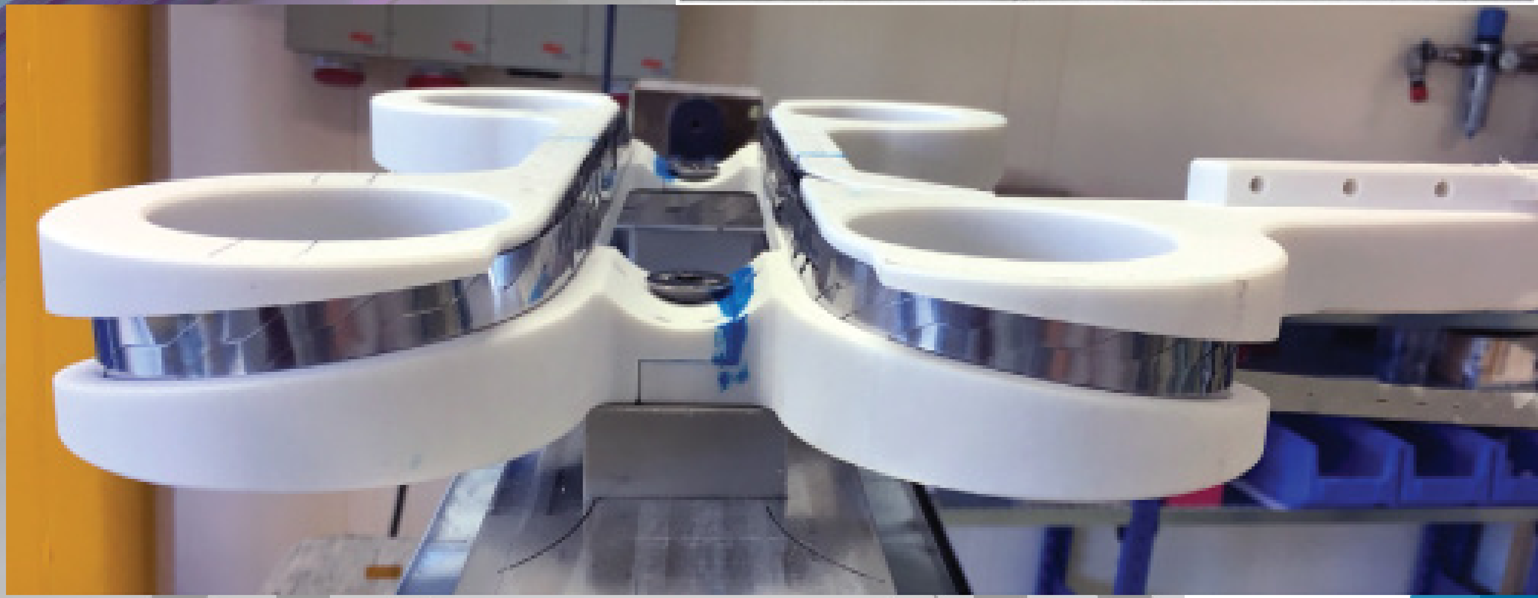






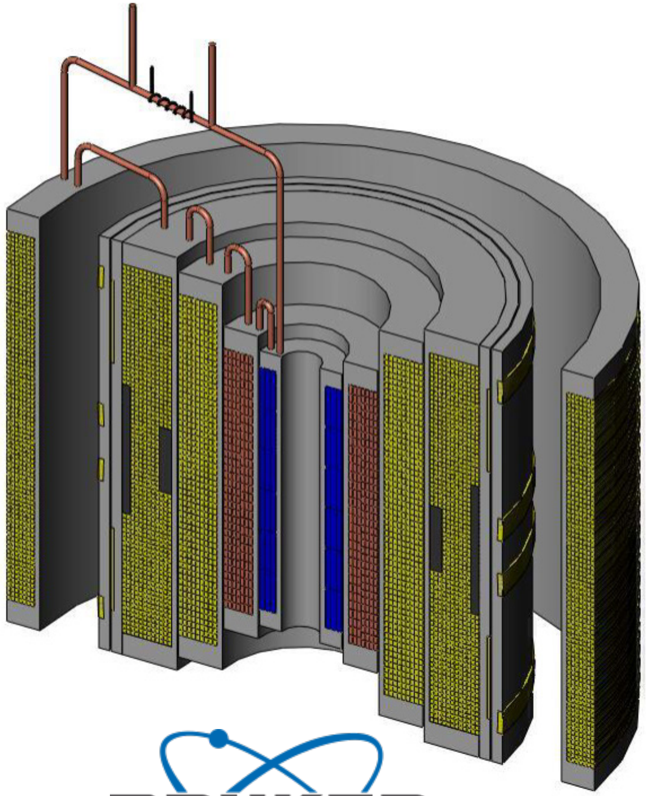
A 5 T, 40 mm bore HTS based dipole demonstrator

Trying the magnets of the future… 20 tesla or more...

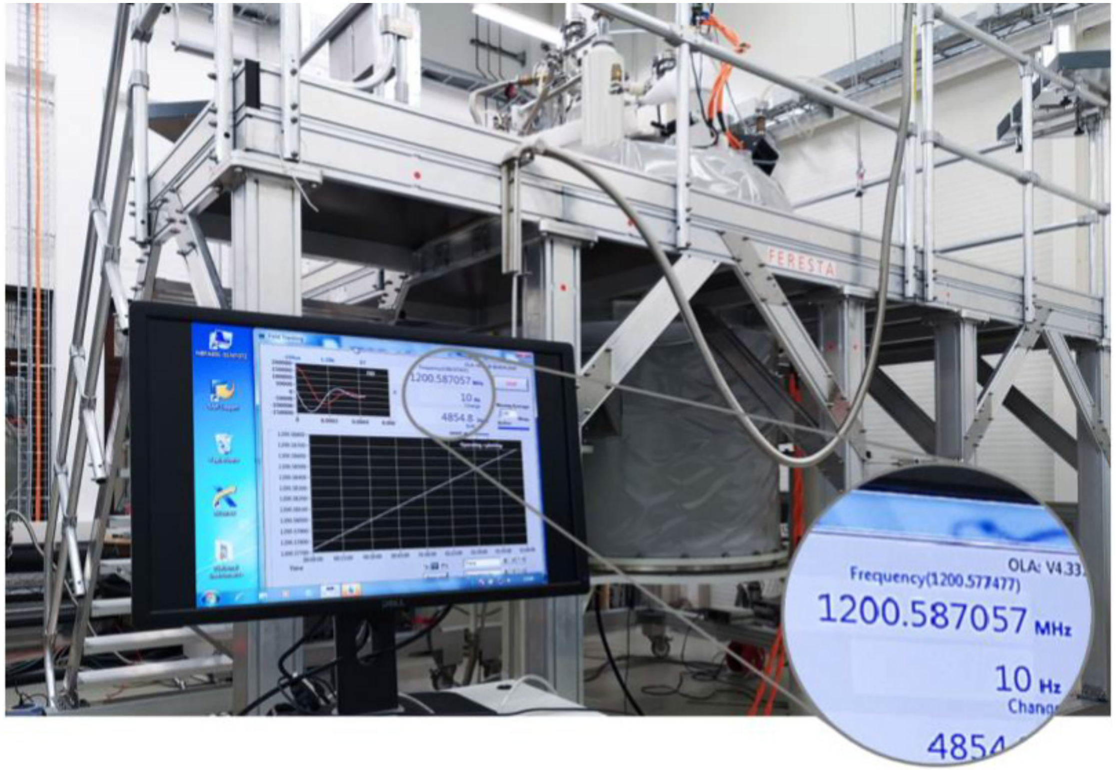


J. Van Nugeteren – Little Beast Enginering,
Glyn Kirby CERN

A big leap forward by a private company…
Bruker Biospin



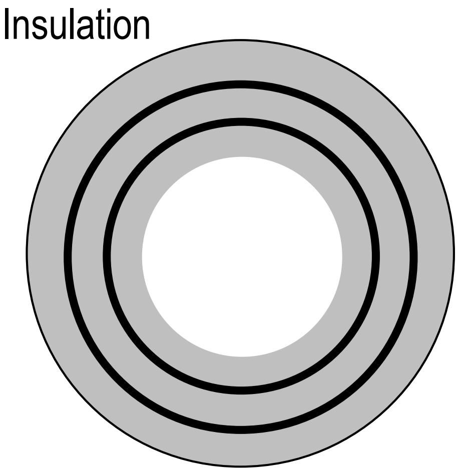
BRUKER

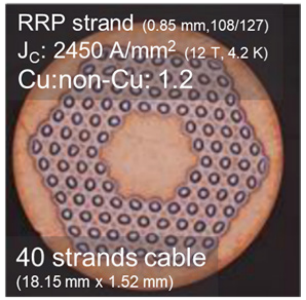


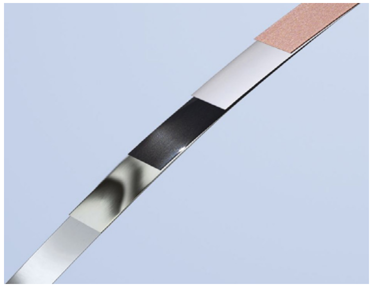
The First 1.2 GHz (28.2 T) NMR Magnet Reached Full Field in 2019, with HTS insert coil

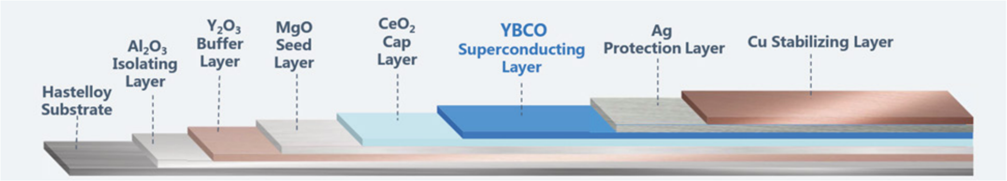
The new frontier: why to insulate a coils?
The raise of NI (non-insulated) coil…

Courtesy Prof. S. Hahn, NHMFL









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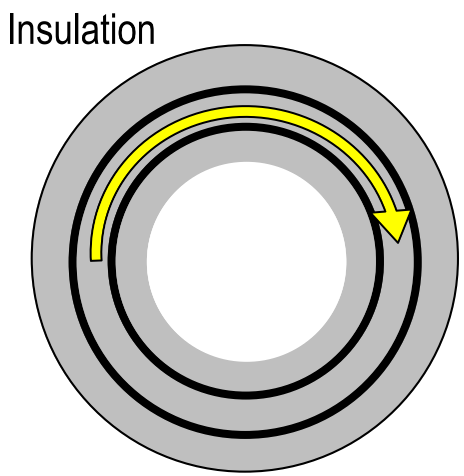

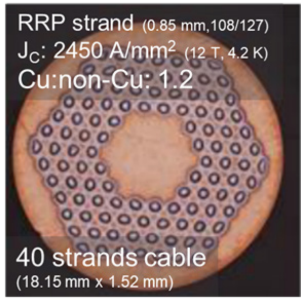

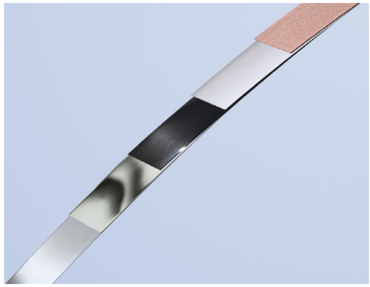

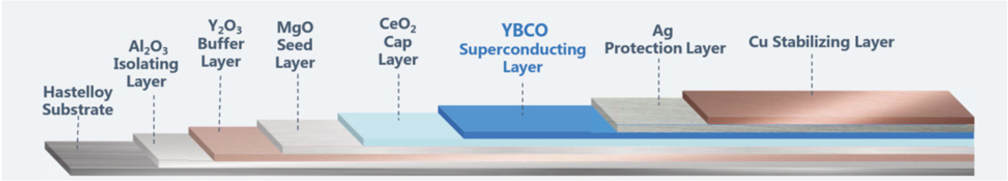

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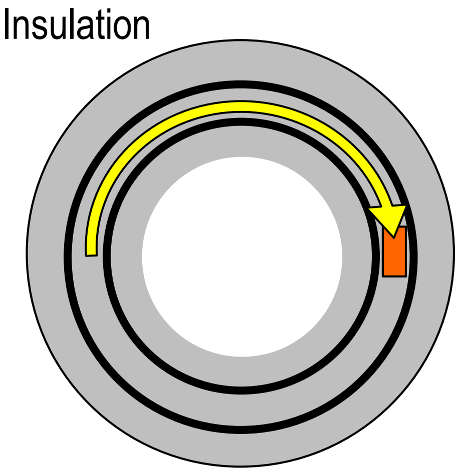

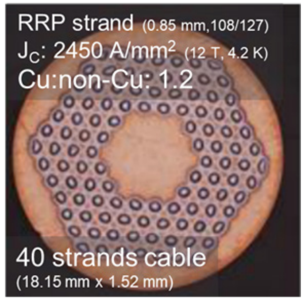

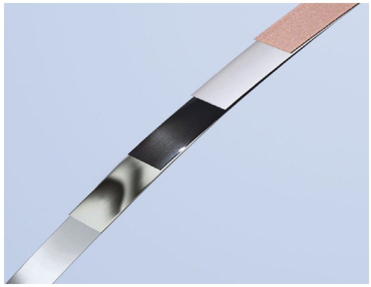

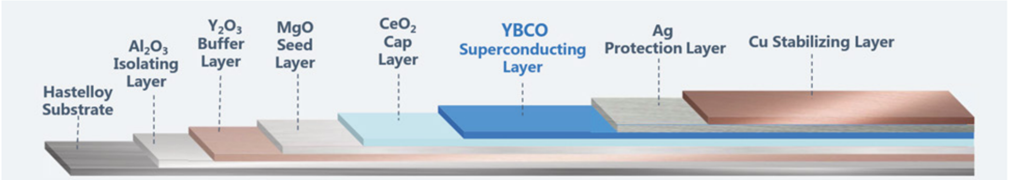

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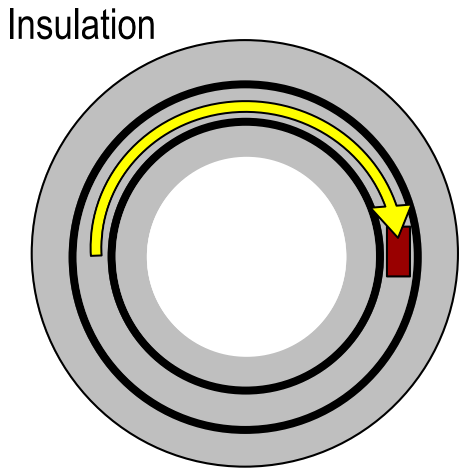

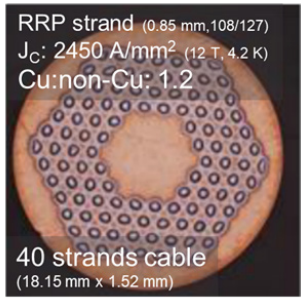

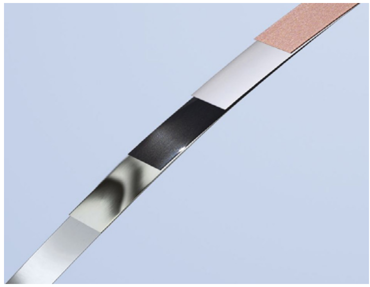

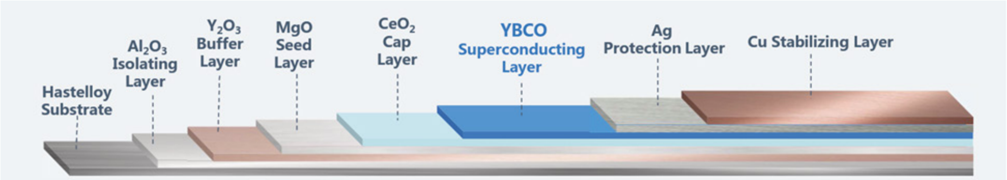

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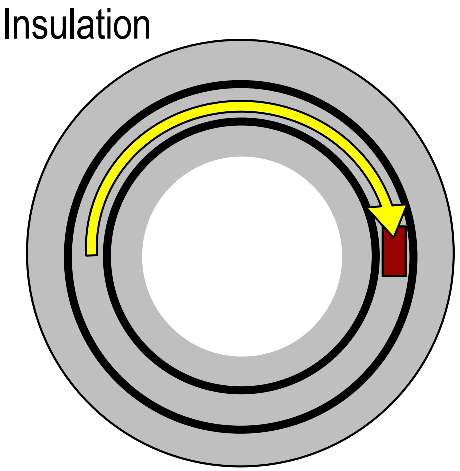
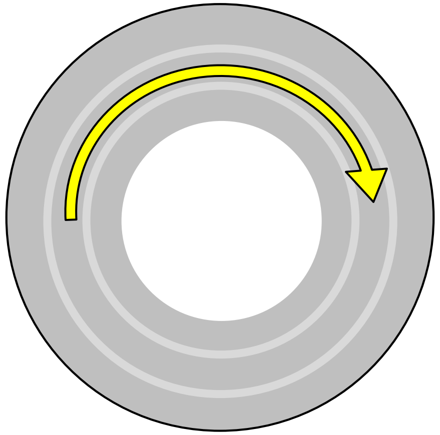
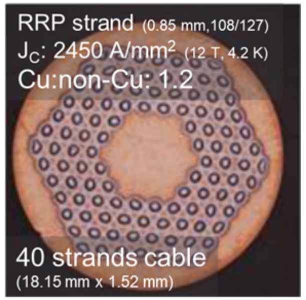
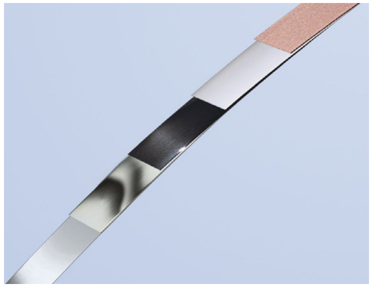
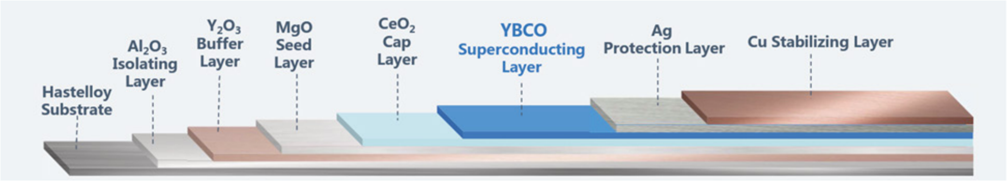






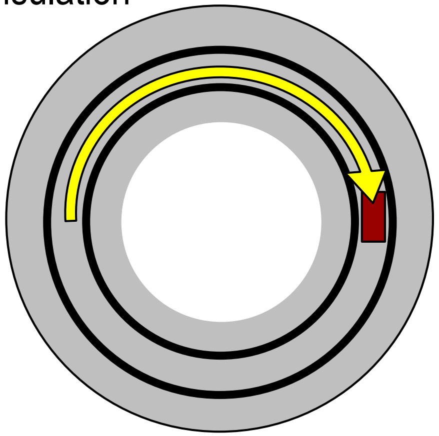


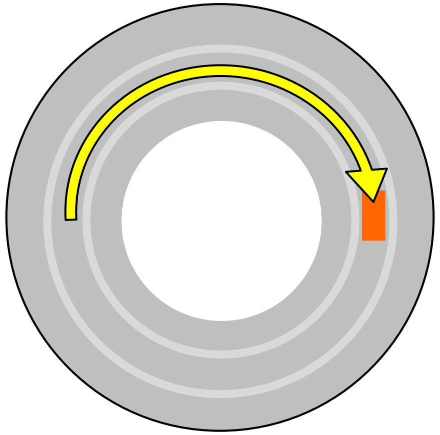


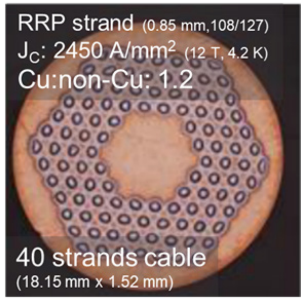
The new frontier: why to insulate a coils? The raise of NI (non-insulated) coil…

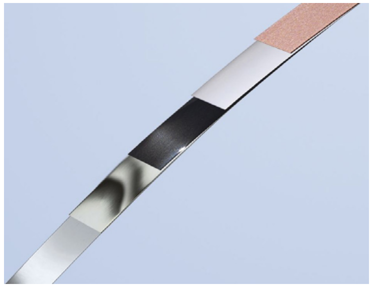
Courtesy Prof. S. Hahn, NHMFL

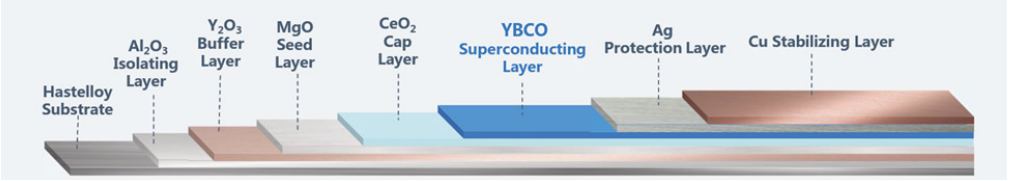
Insulation











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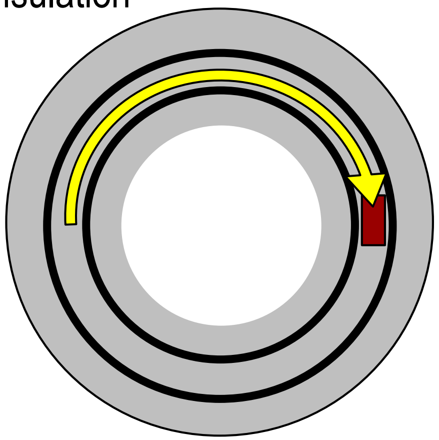

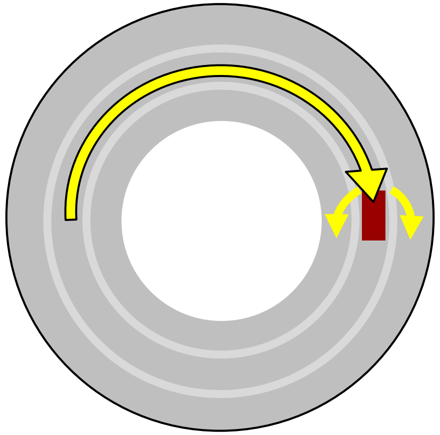

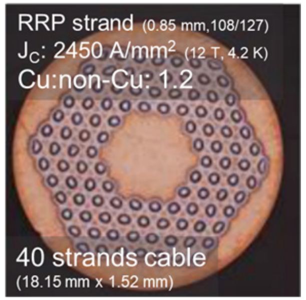

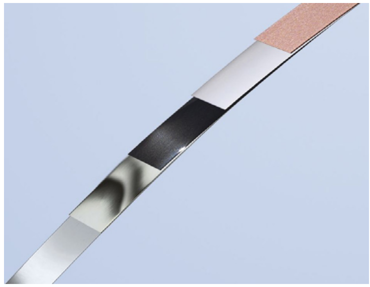

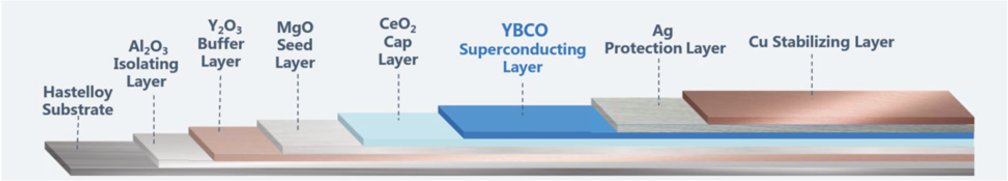

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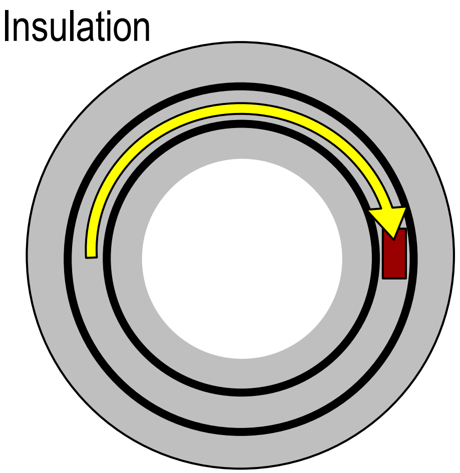

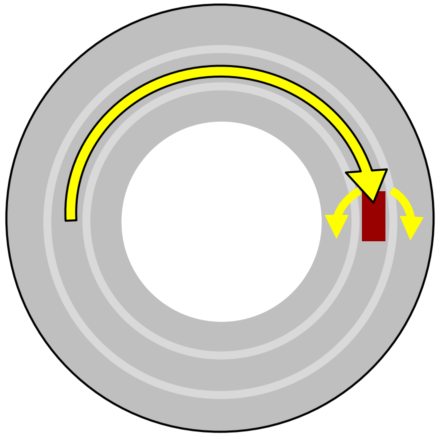

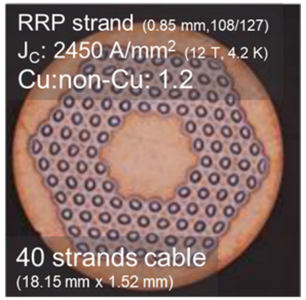

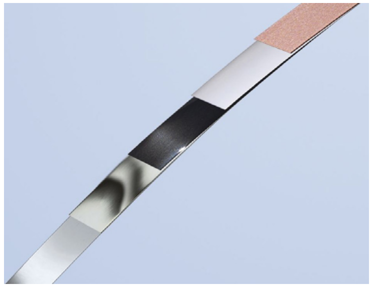

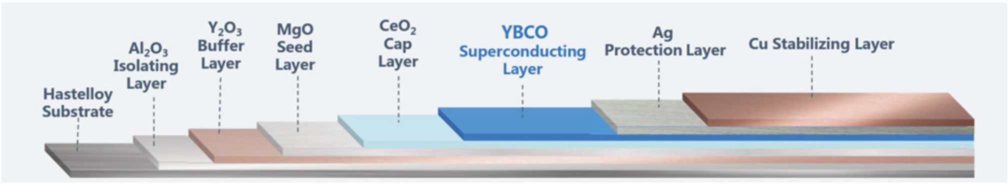

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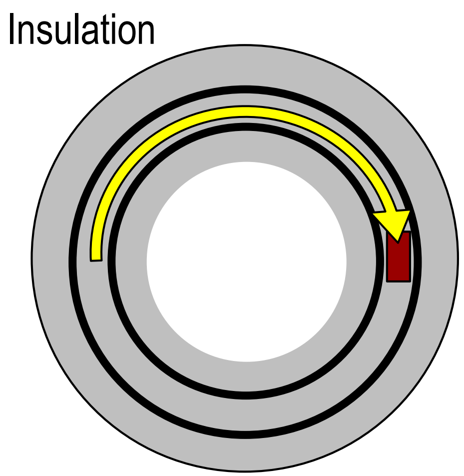

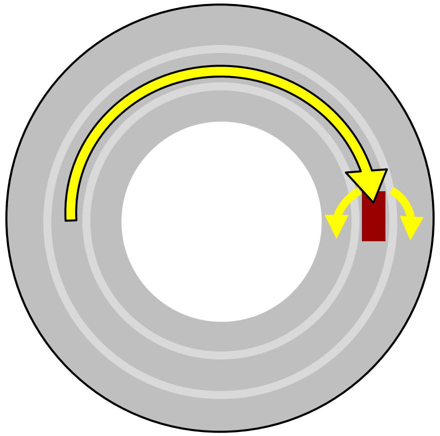

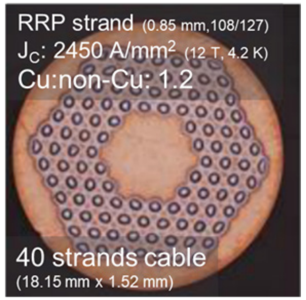

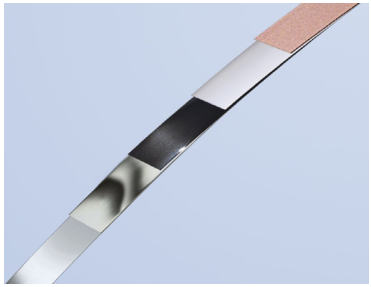

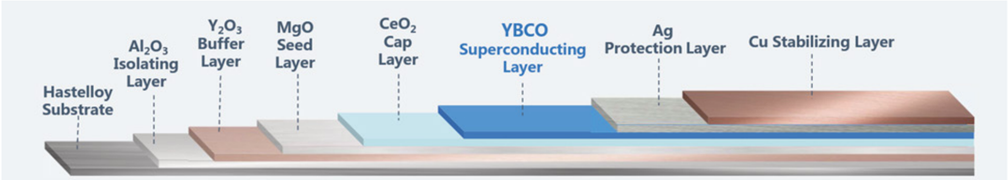

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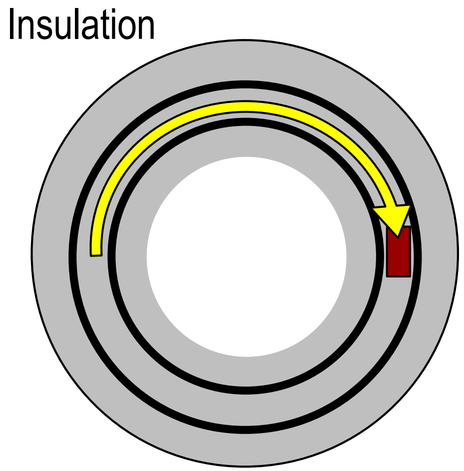
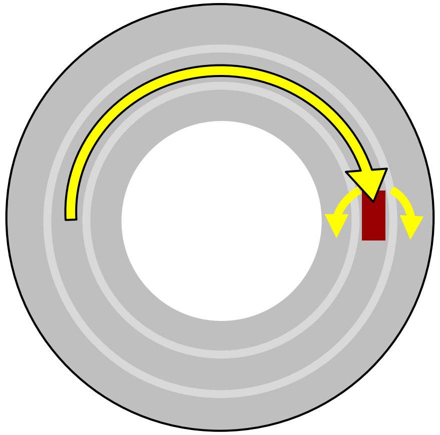
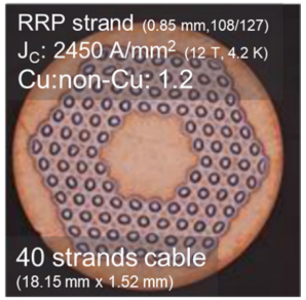
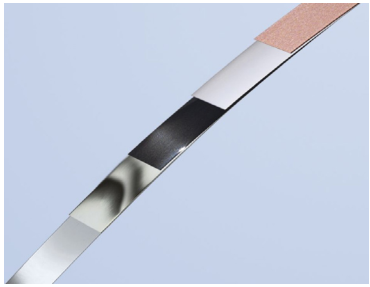
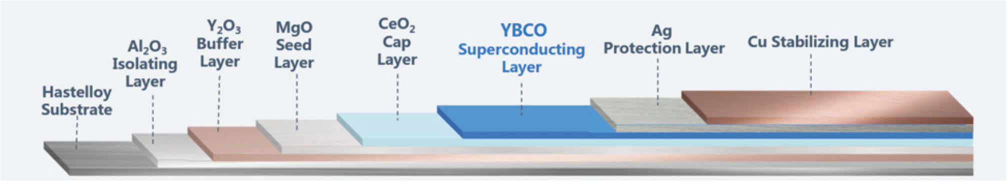




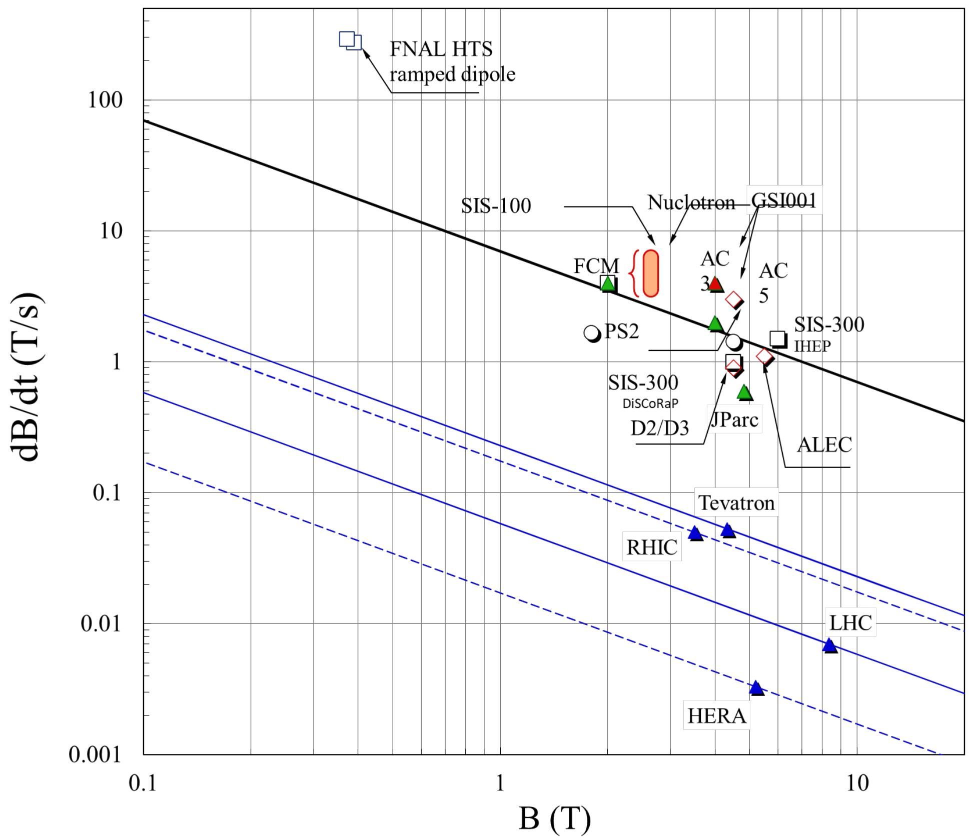


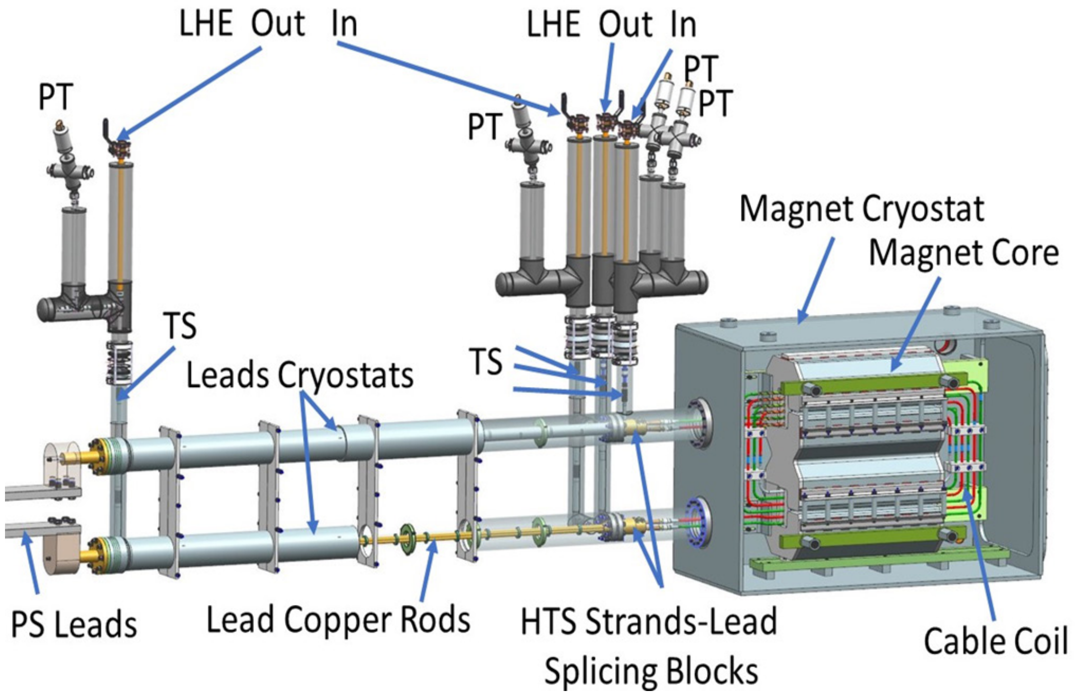




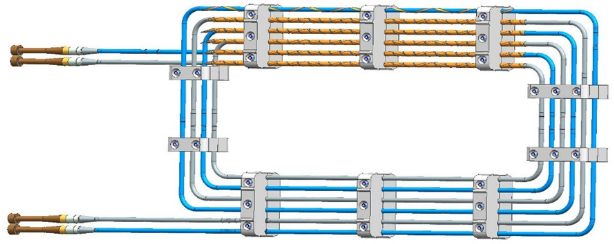
Need to understand and control transient effects and control Field Quality during ramping up

SC Magnets for ramped operation
RCS for hadrons, Muon-C acceleration, Hadron Therapy





B= 0.3 T
dB/dt ~ 300 T/s
RepRate: 10 Hz
For RCS, for Muon-C…



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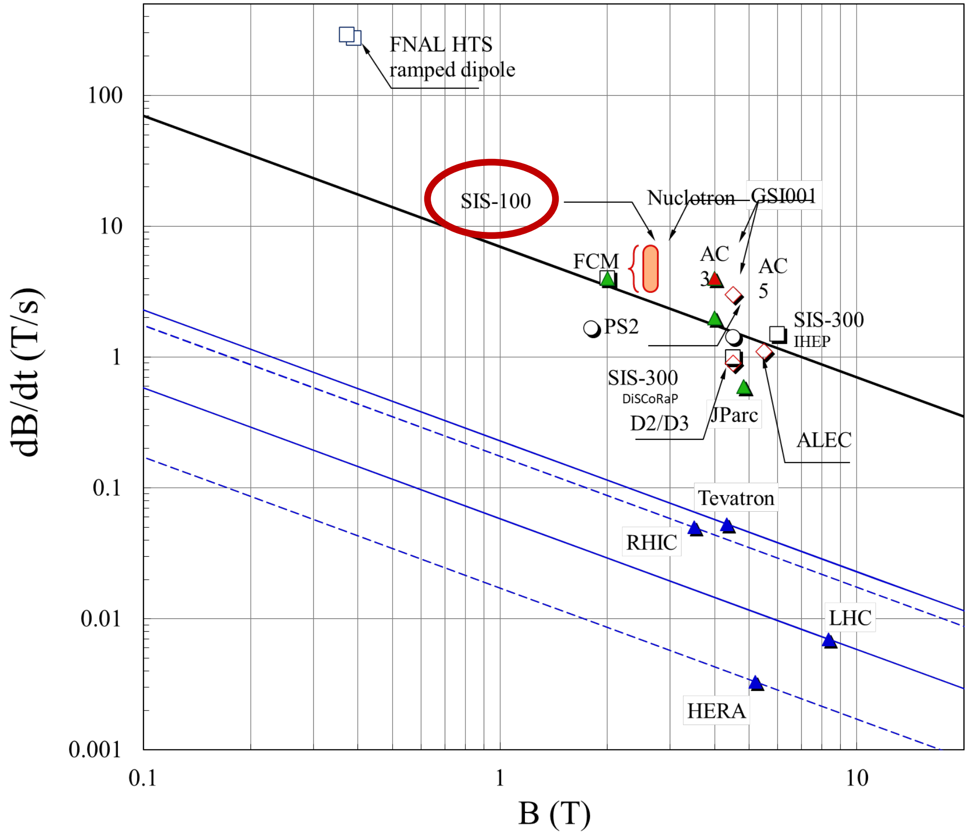

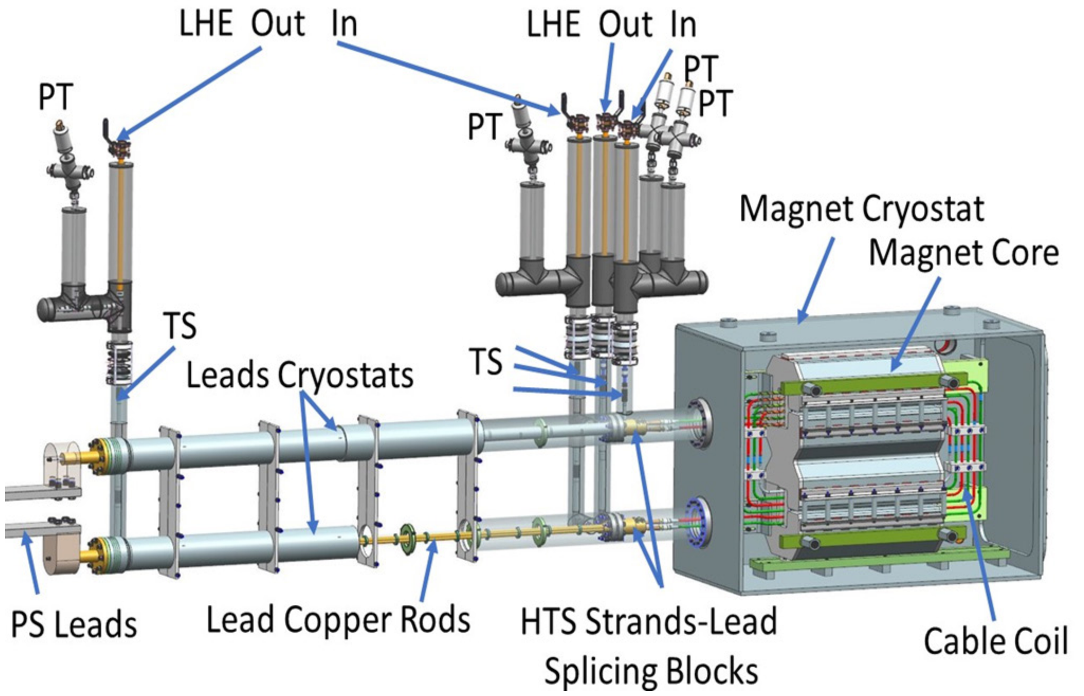

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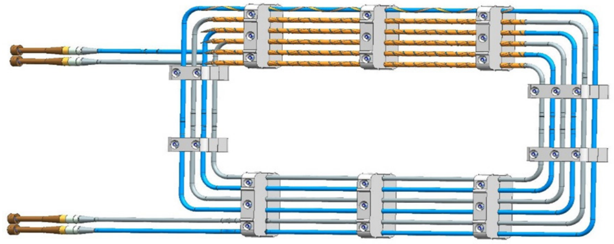

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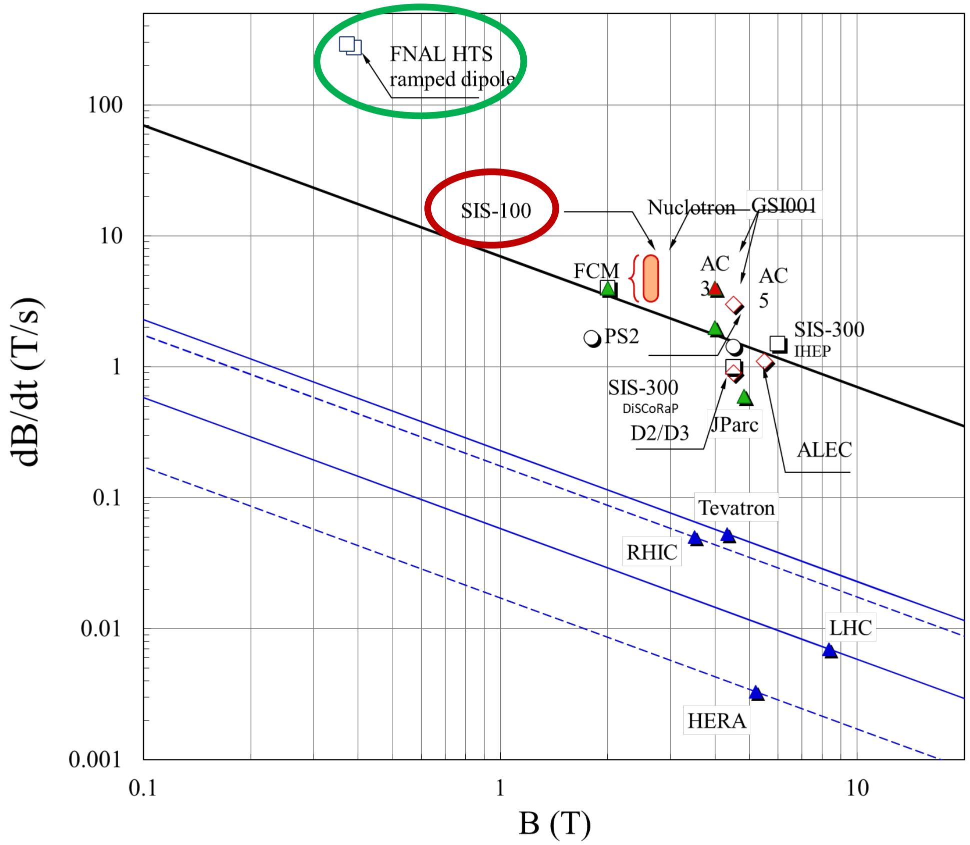

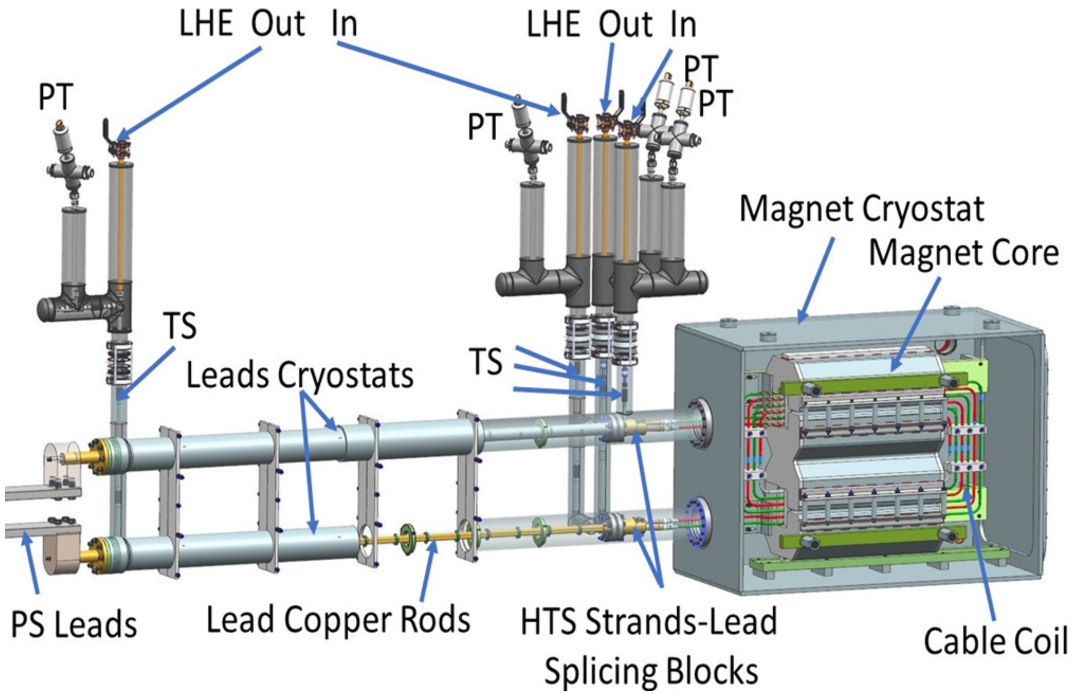

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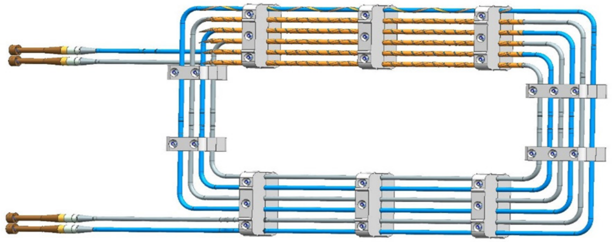
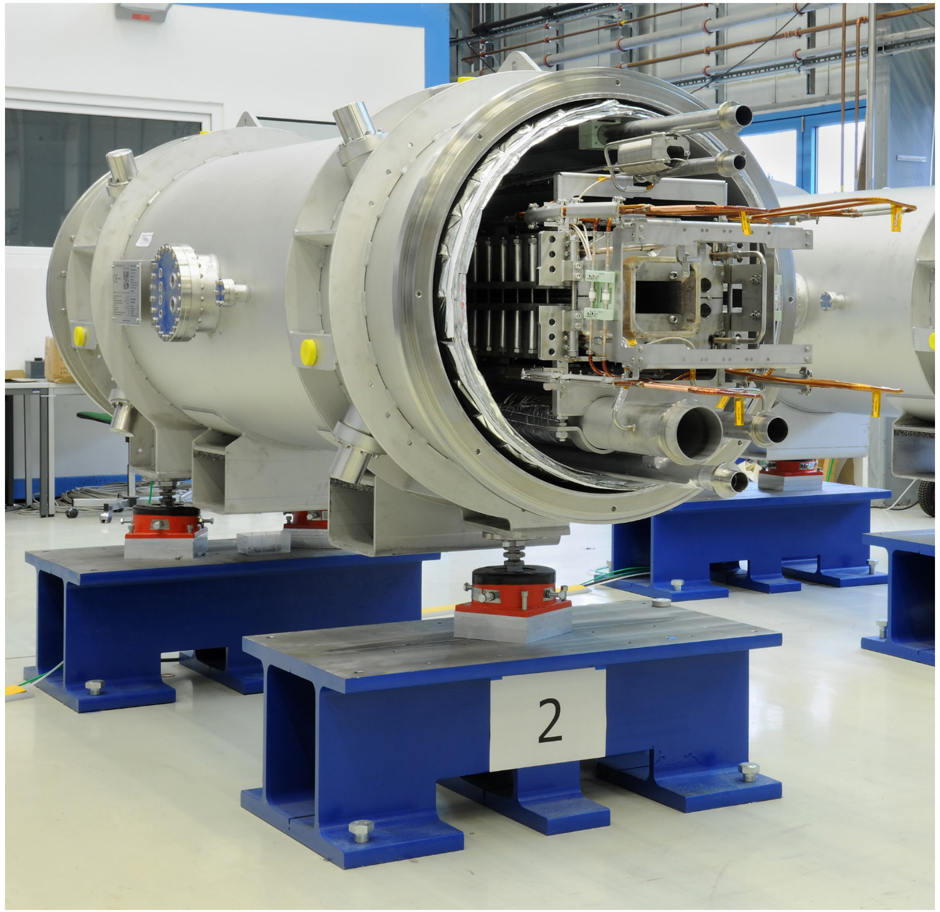


FoS reminder

Courtesy of C. Roux and P. Spiller, GSI_FAIR

FoS1: "proof of principle"

first time:
- steel
- high current cable
- single layer coil



SIS100 dipole

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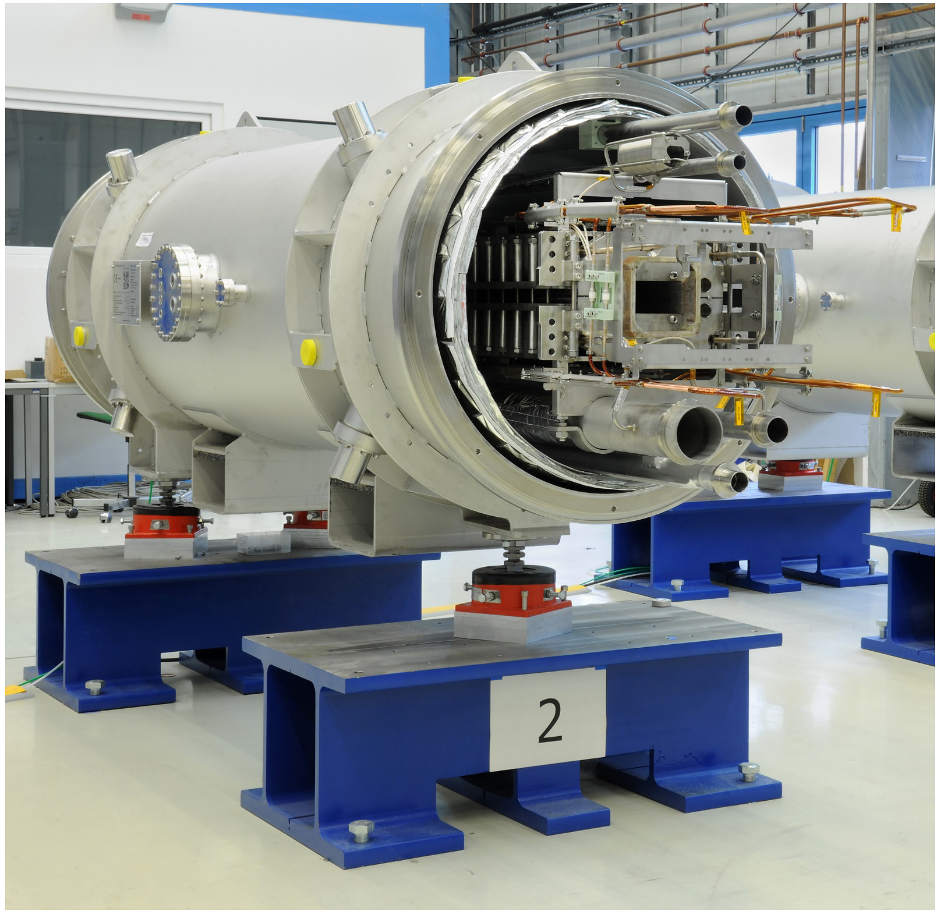
low losses, stable operation



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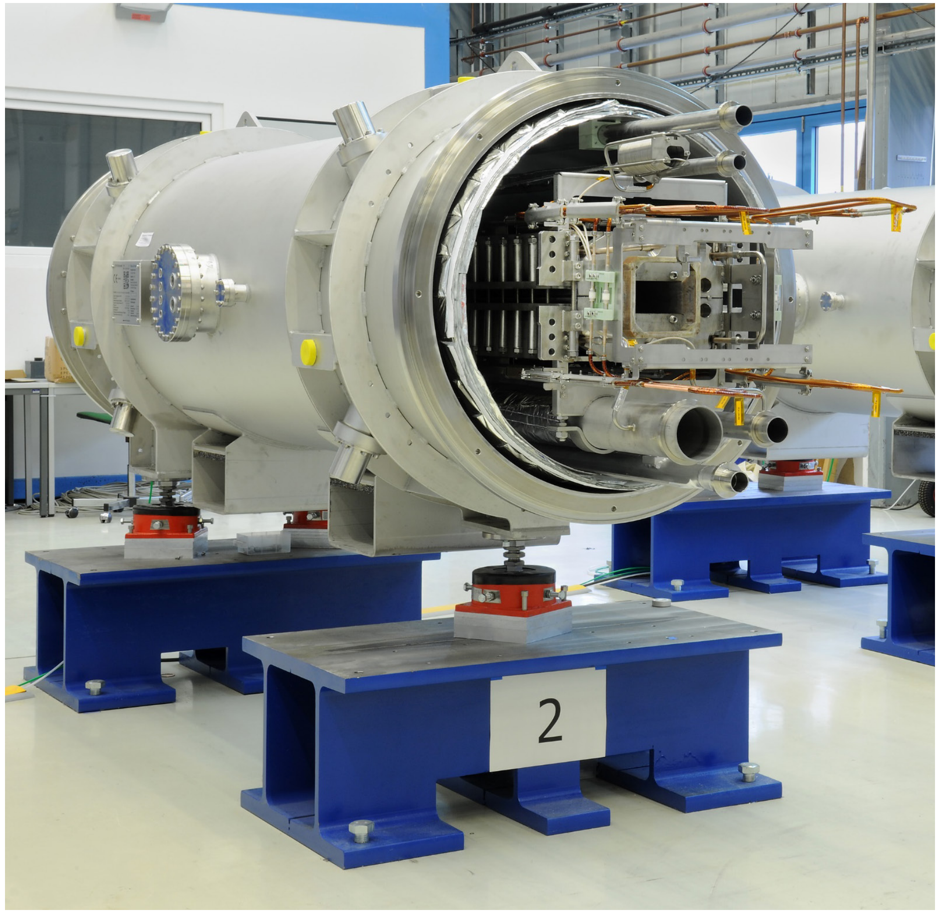

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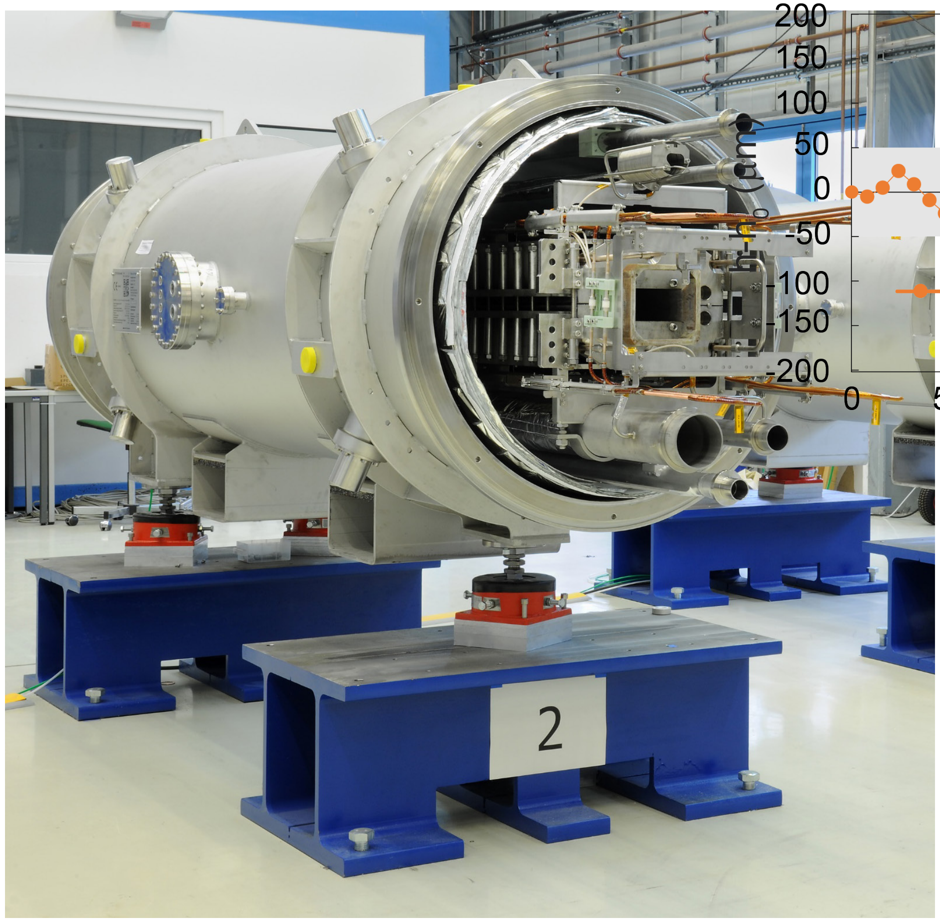

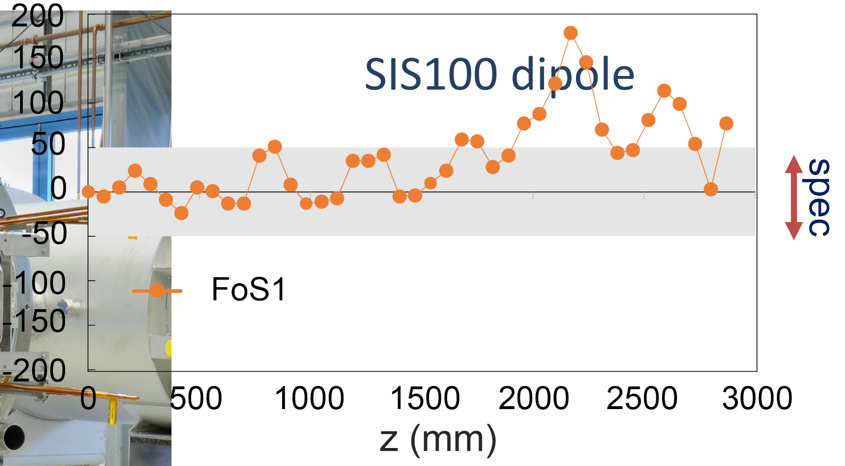

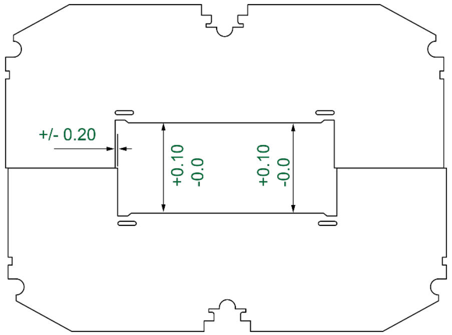

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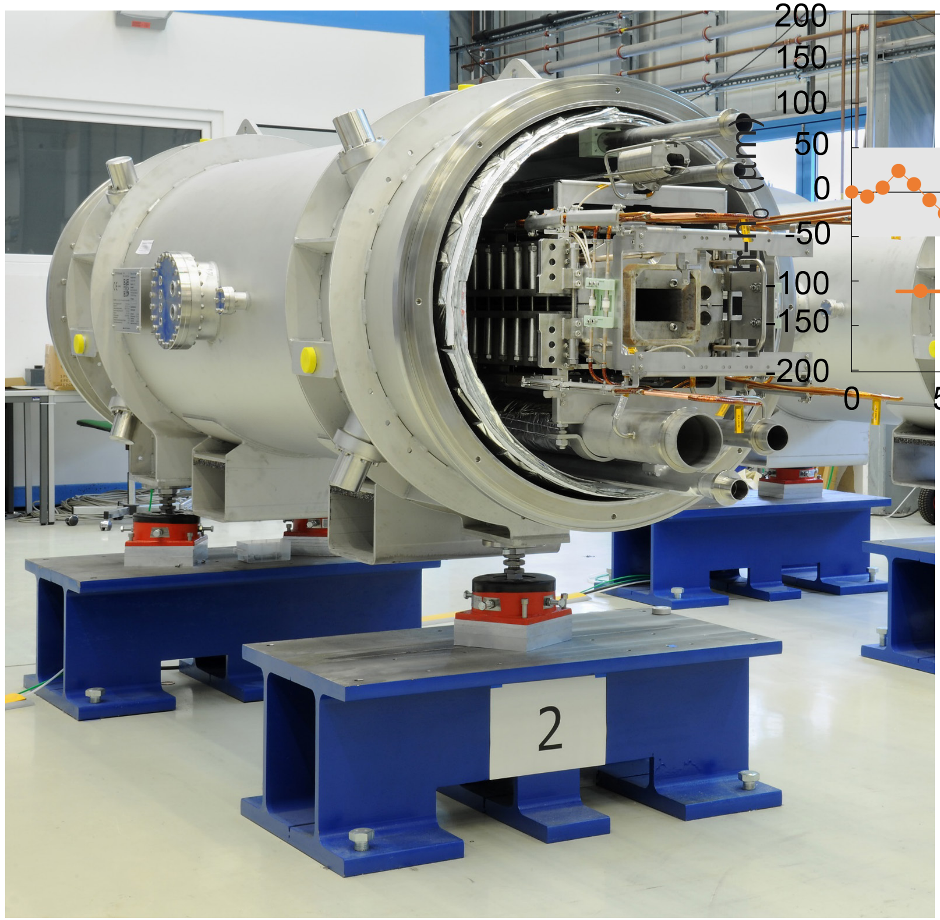
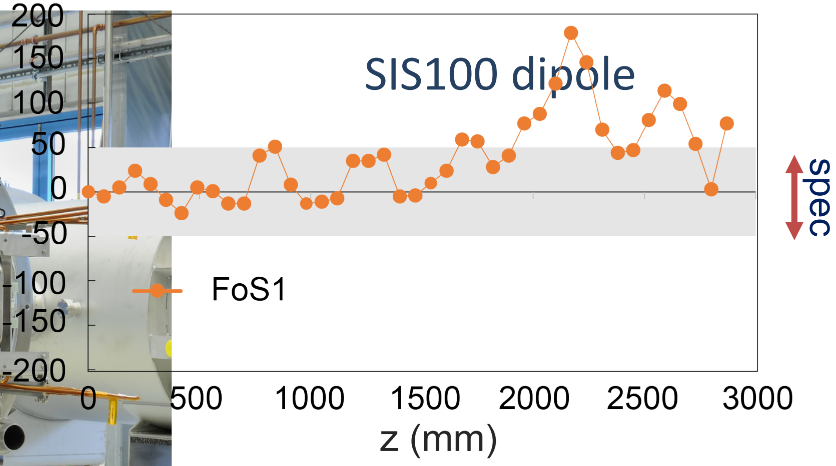
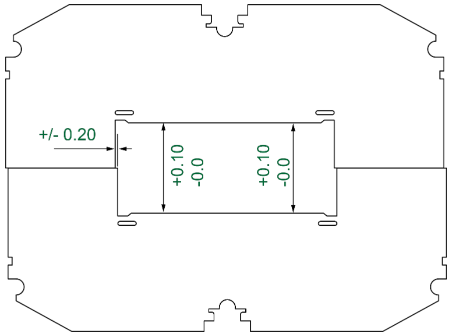
FoS2

precise stamping of lamination

laser welding:
- minimization of tension
- increase of reproducability







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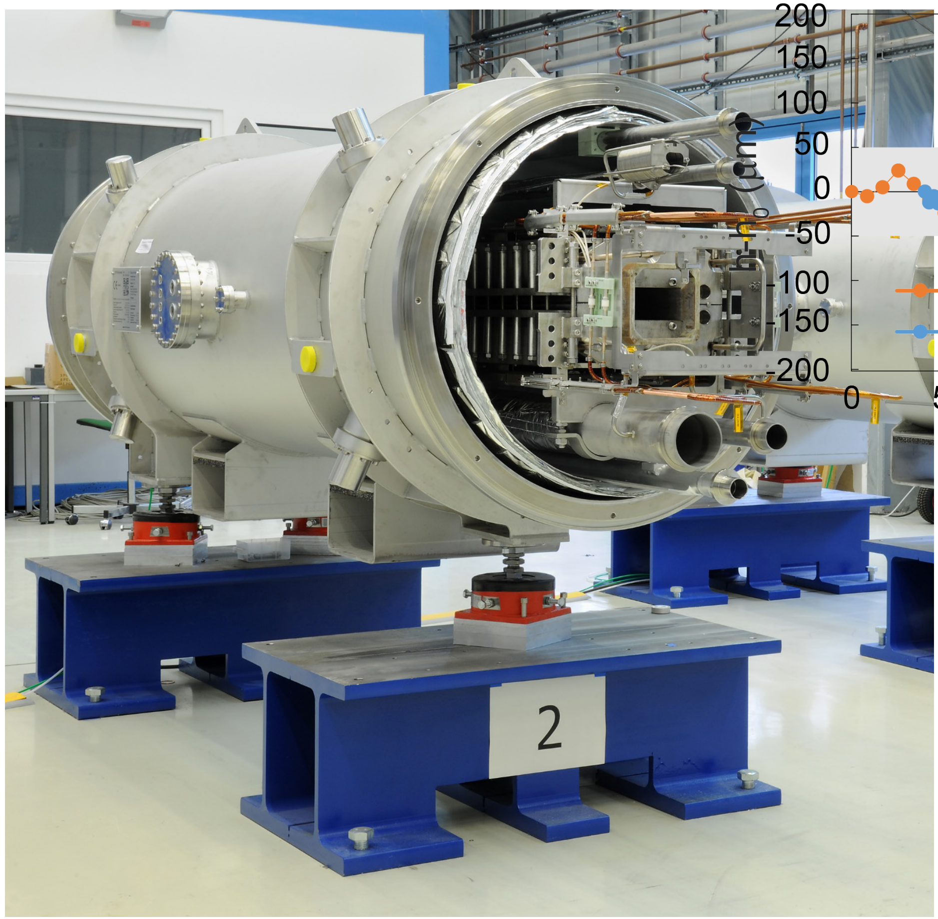

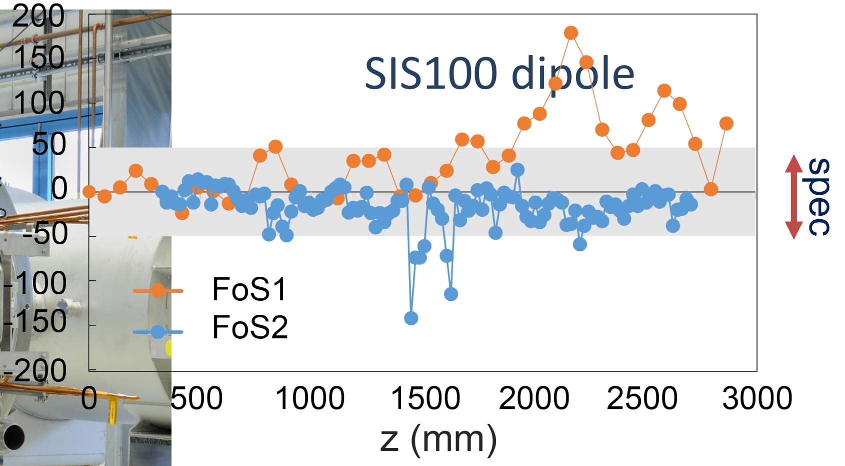

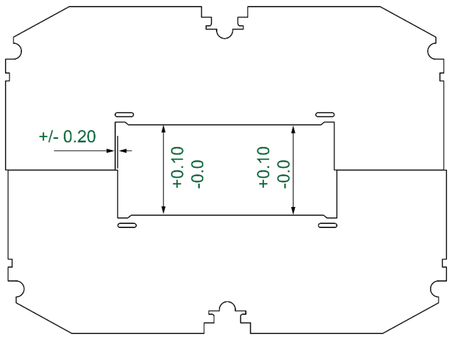


Series of industry manufctured (BNG – Wurzburg) SIS-100 dipoles for FAIR!
(courtesy of C. Roux and P. Spiller, FAIR)
Thanks for the attention