High field superconducting magnets for the high energy frontier and for technology innovation

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INFN

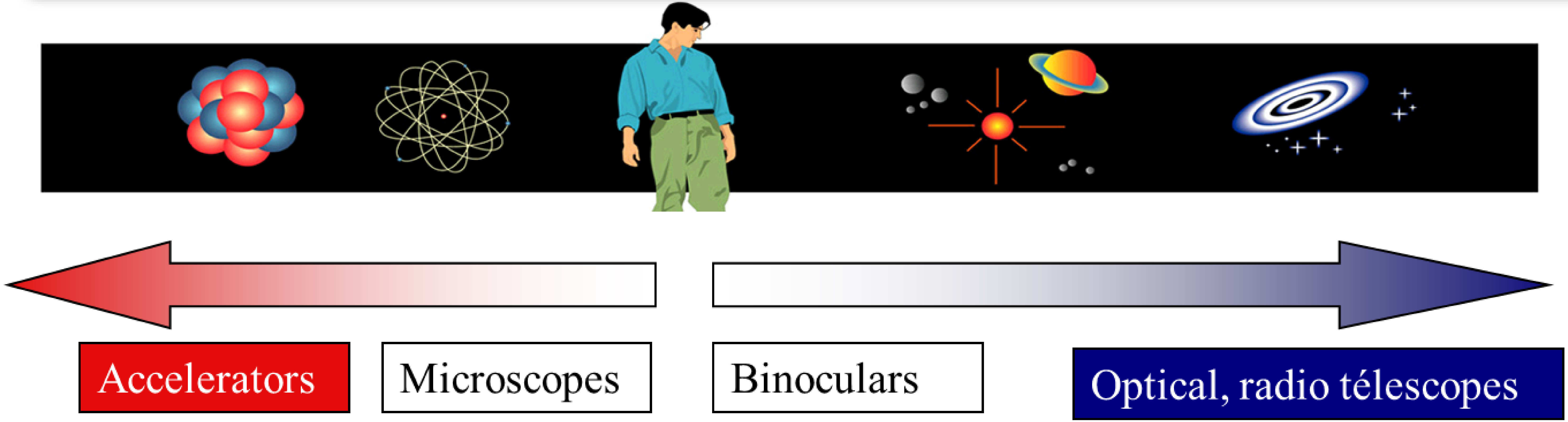
107° CONGRESSO NAZIONALE della SOCIETÀ ITALIANA DI FISICA

HITRI plus

Heavy Ion Therapy Research Integration

iFAST

What's are particle accelerators?



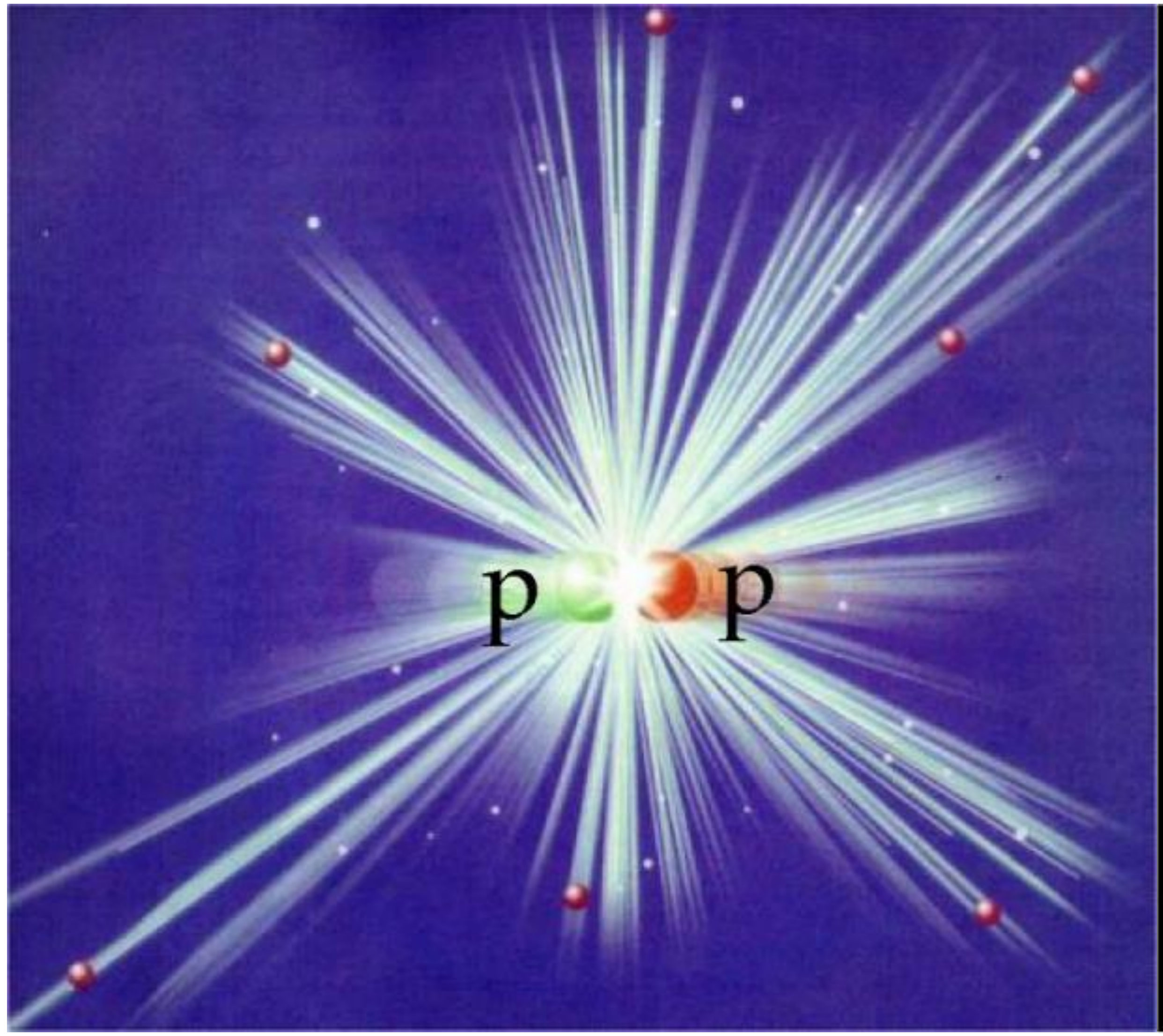
Particle physics looks at matter in its smallest dimensions and accelerators are very fine microscopes or, better, ***atto-scopes!***

$\lambda = h/p$; @LHC: $T = 1$ TeV $\Rightarrow \lambda \simeq 10^{-18}$ m

Actually today we know quarks are point-like at ~ 10 zm!)

Accelerators also bring us toward the Big Bang

- Trip back toward the Big Bang: $t_{\mu s} \cong 1/E^2_{Gev}$
- T ≅ 1 ps for single particle creation
- T ≅ 1 μs for collective phenomena QGS (Quark-Gluon Soup)



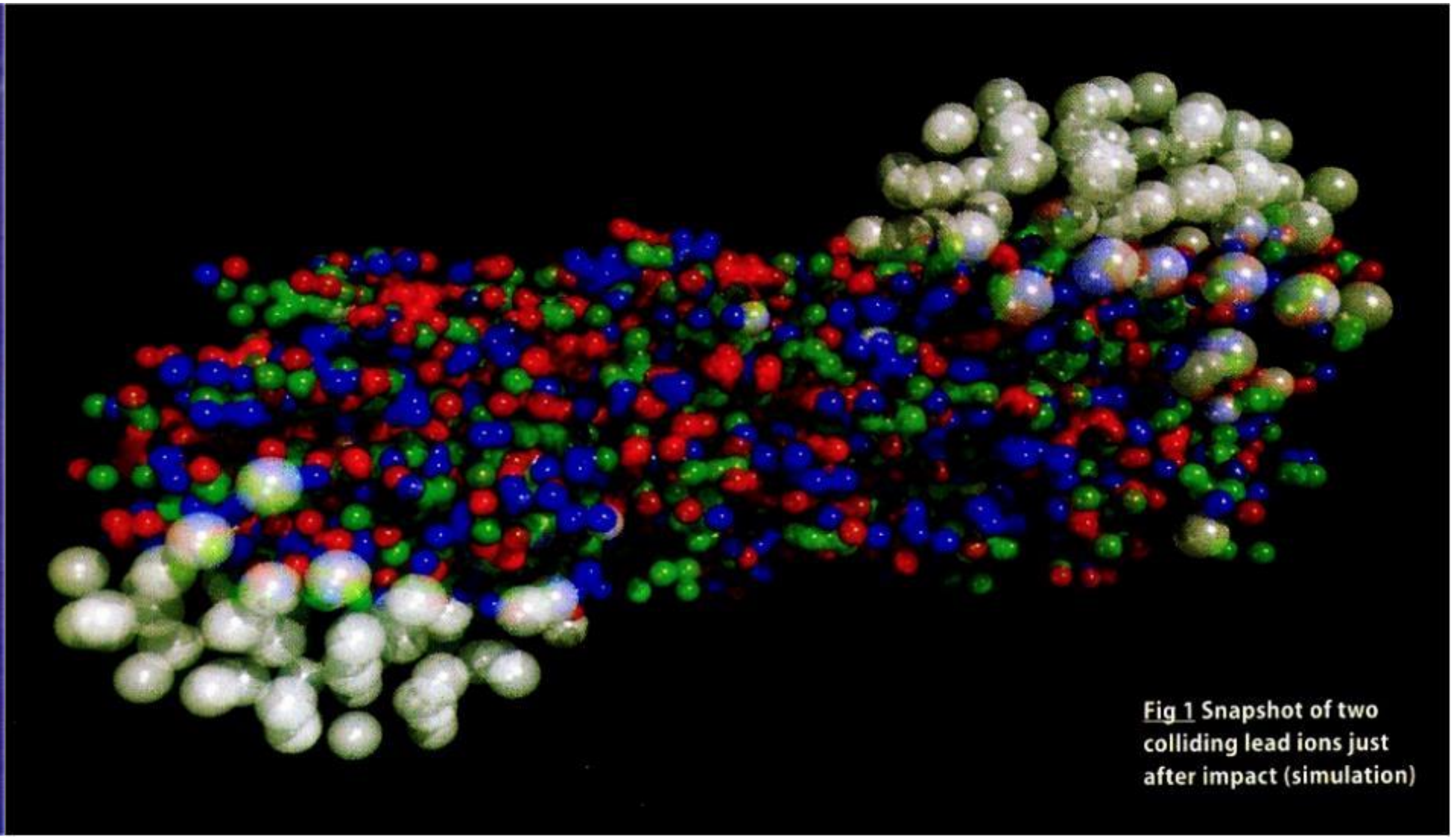
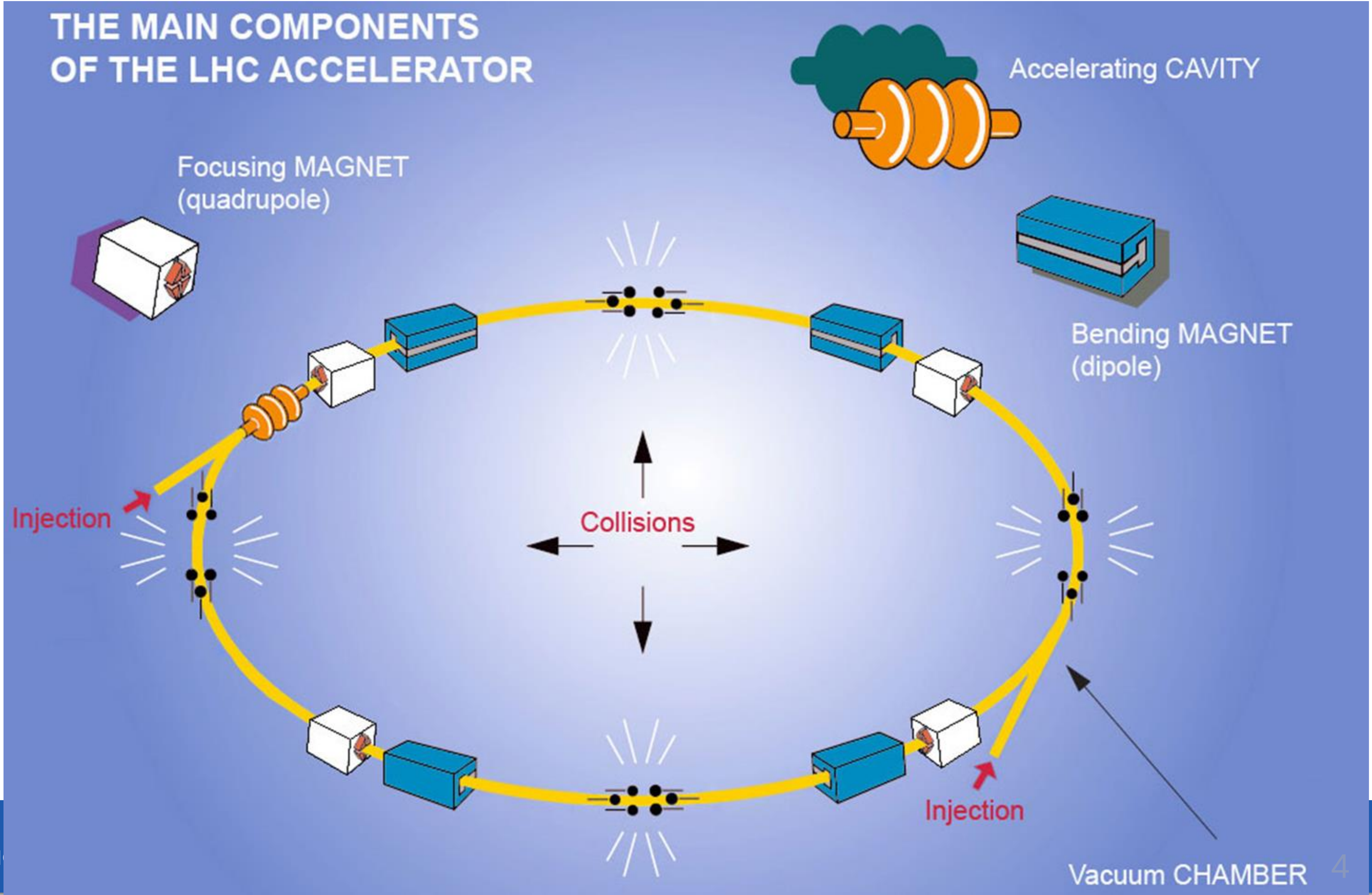
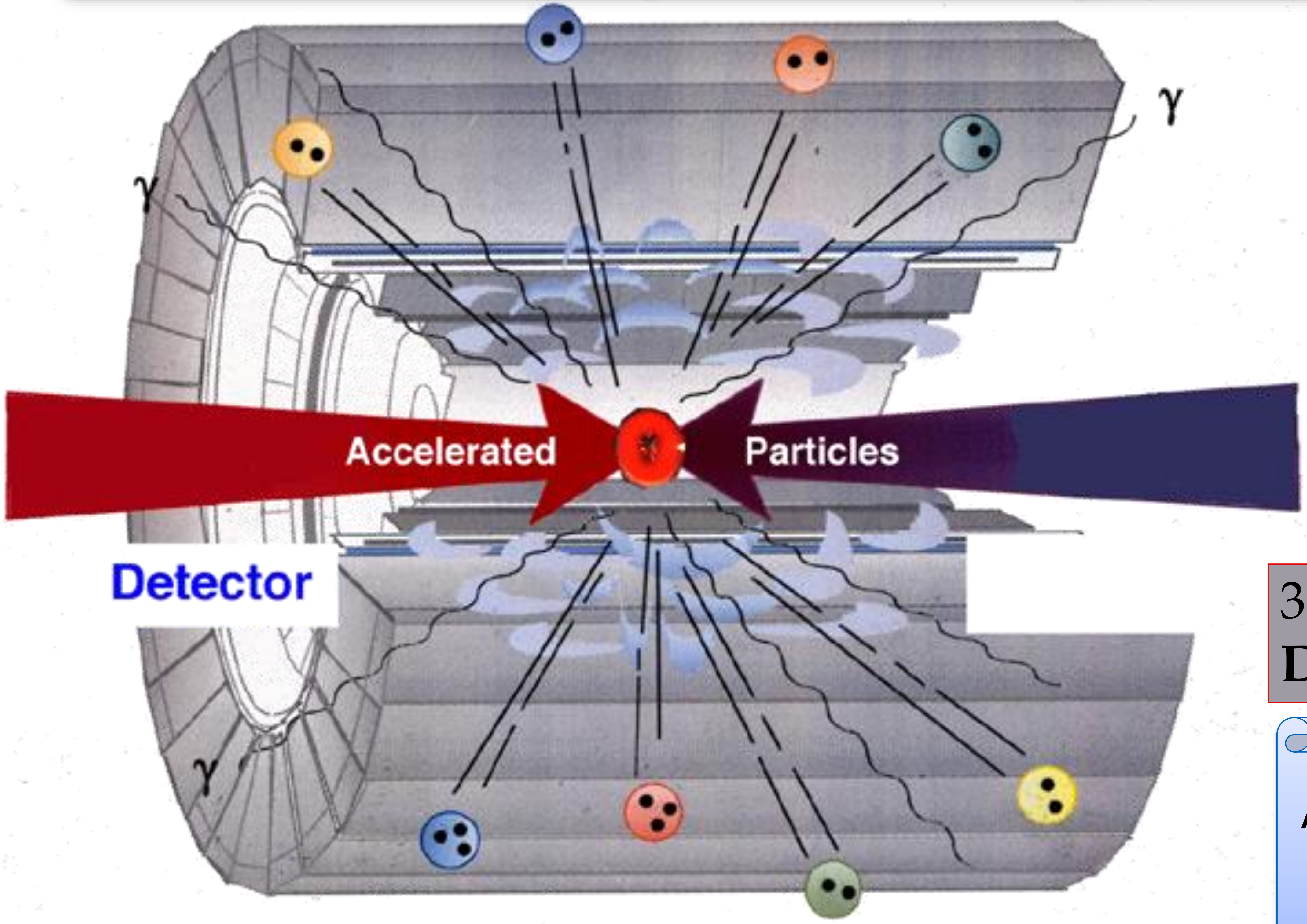


Fig 1 Snapshot of two colliding lead ions just after impact (simulation)

But we are left with the task of explaining how the rich complexity that developed in the ensuing 13.7 billion years came about… a much complex task!


THE MAIN COMPONENTS
OF THE LHC ACCELERATOR
Accelerating CAVITY
Focusing MAGNET
(quadrupole)
Bending MAGNET
(dipole)
Injection
Collisions
Injection
Vacuum CHAMBER

Method of Particle Physics with Colliders

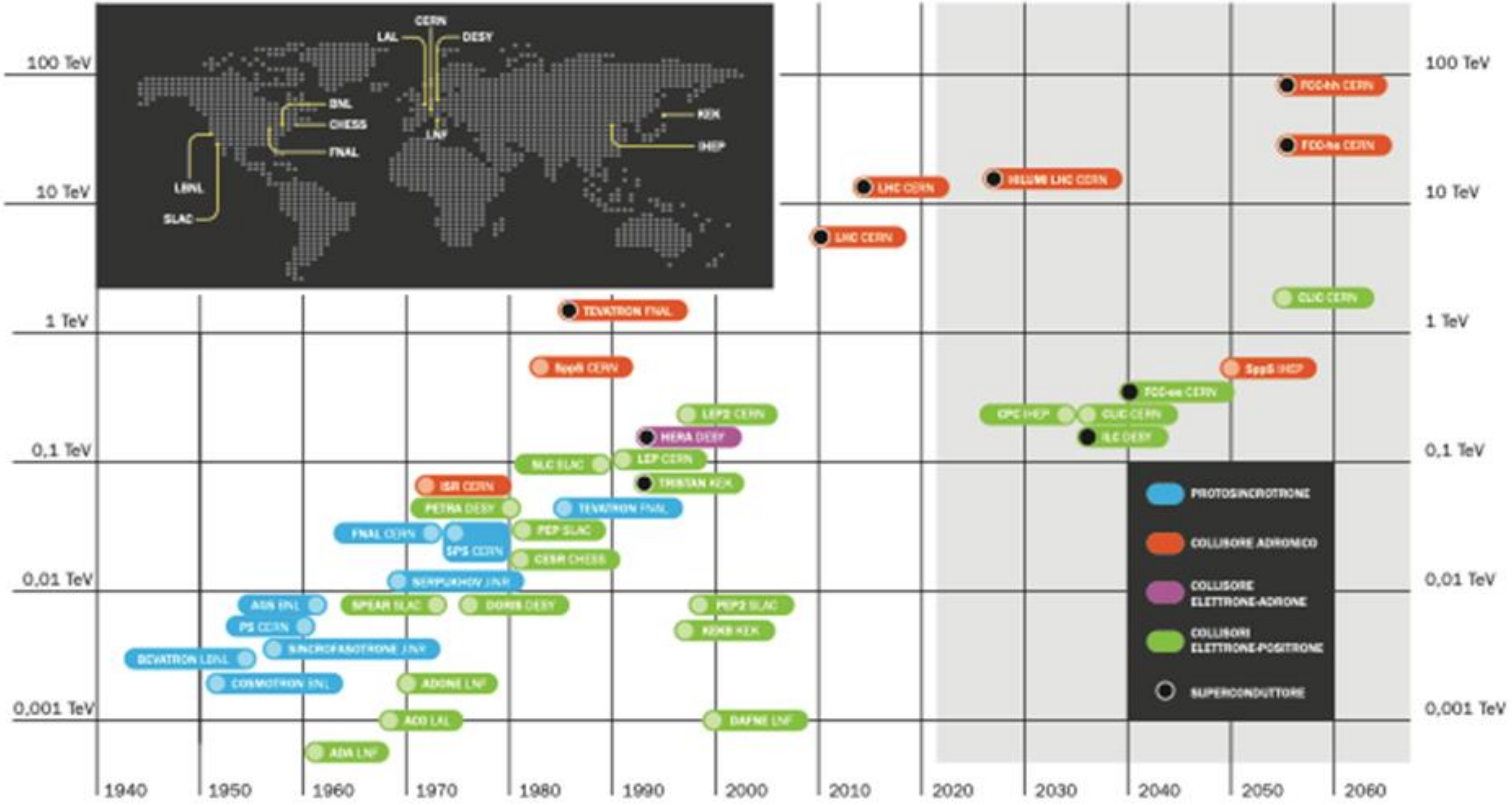


1) Concentrate energy on particles (**accelerator**)

2) **Collide** particles (recreate conditions after Big Bang)

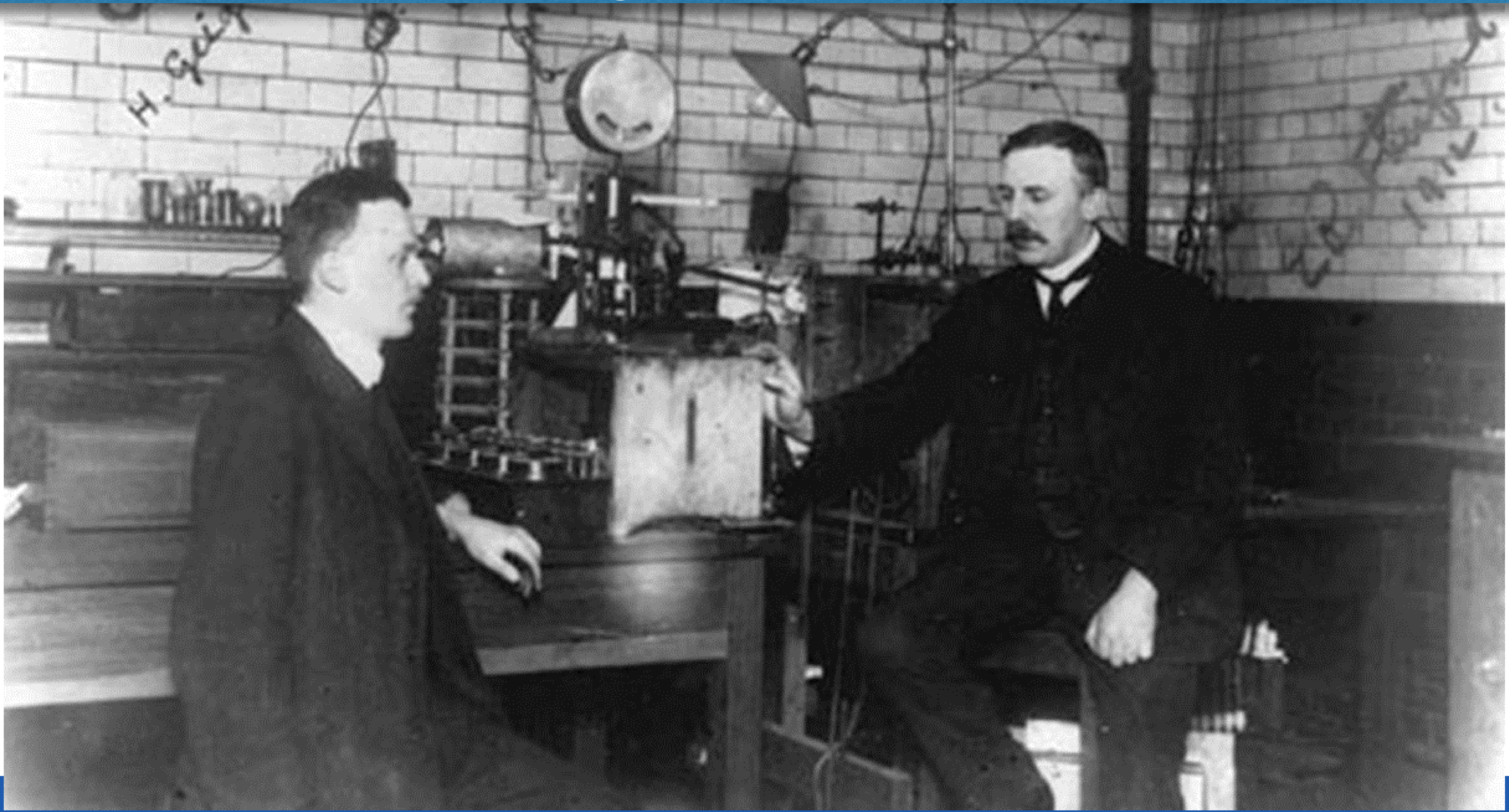
3) Identify created particles in **Detector** (search for new clues)

And both Accelerators (Colliders) and Detectors need Superconductivity!

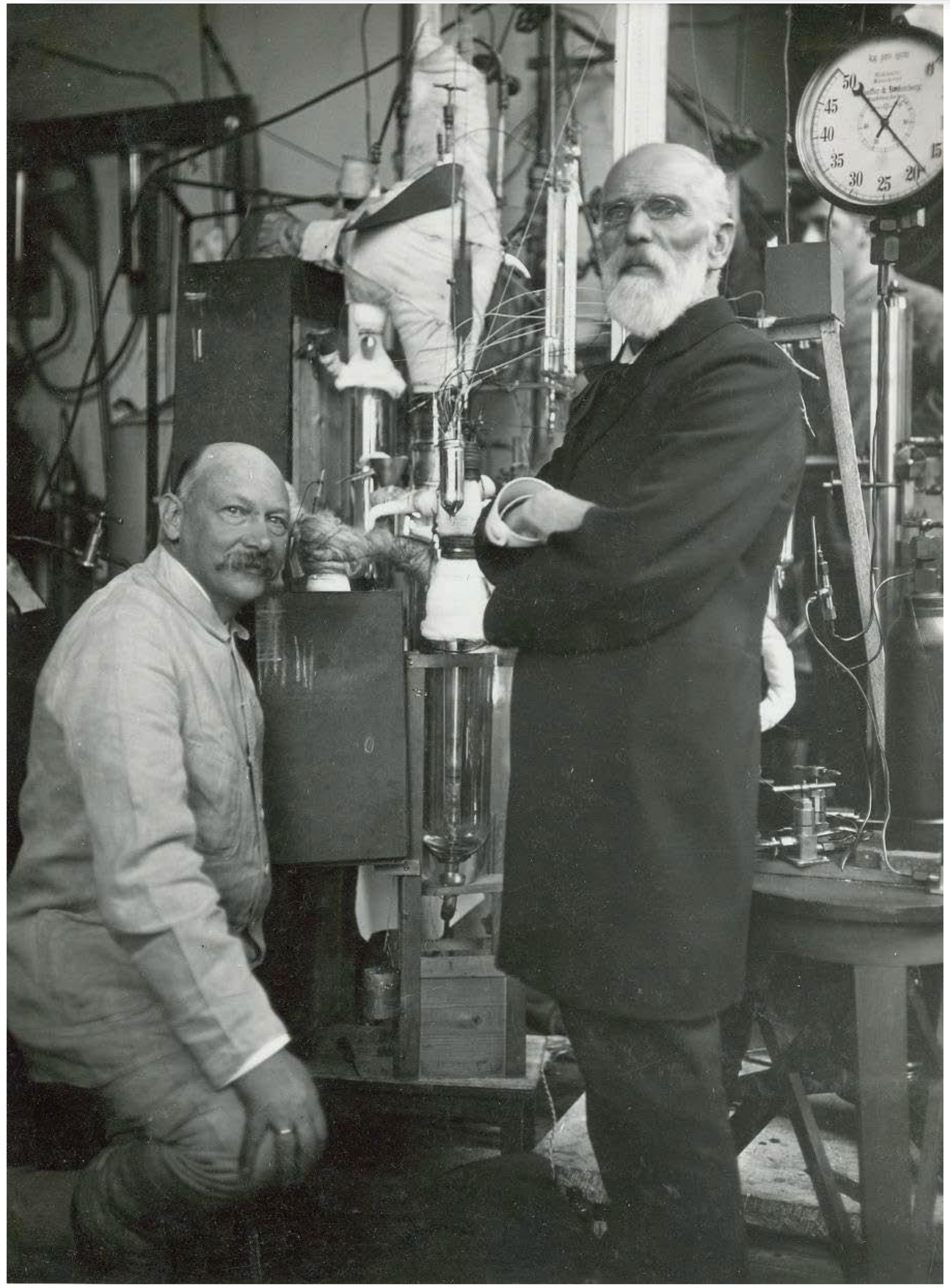


CERN
LAL
DESY
BNL
CHESS
FNAL
LNF
KEK
IHEP
LBNL
SLAC
100 TeV
10 TeV
1 TeV
0,1 TeV
0,01 TeV
0,001 TeV
FCC-hh CERN
FCC-he CERN
HILUMI LHC CERN
LHC CERN
LHC CERN
CLIC CERN
TEVATRON FNAL
SppS CERN
SppS IHEP
FCC-ee CERN
CEPC IHEP
CLIC CERN
ILC DESY
LEP2 CERN
HERA DESY
SLC SLAC
LEP CERN
TRISTAN KEK
ISR CERN
PETRA DESY
TEVATRON FNAL
SPS CERN
PEP SLAC
CESR CHESS
SERPUKHOV JINR
AGS BNL
SPEAR SLAC
DORIS DESY
PEP2 SLAC
KEKB KEK
PS CERN
SINCROFASOTRONE JINR
BEVATRON LBNL
COSMOTRON BNL
ADONE LNF
ACO LAL
DAFNE LNF
ADA LNF
PROTOSINCROTRONE
COLLISORE ADRONICO
COLLISORE ELETTRONE-ADRONE
COLLISORI ELETTRONE-POSITRONE
SUPERCONDUTTORE
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060

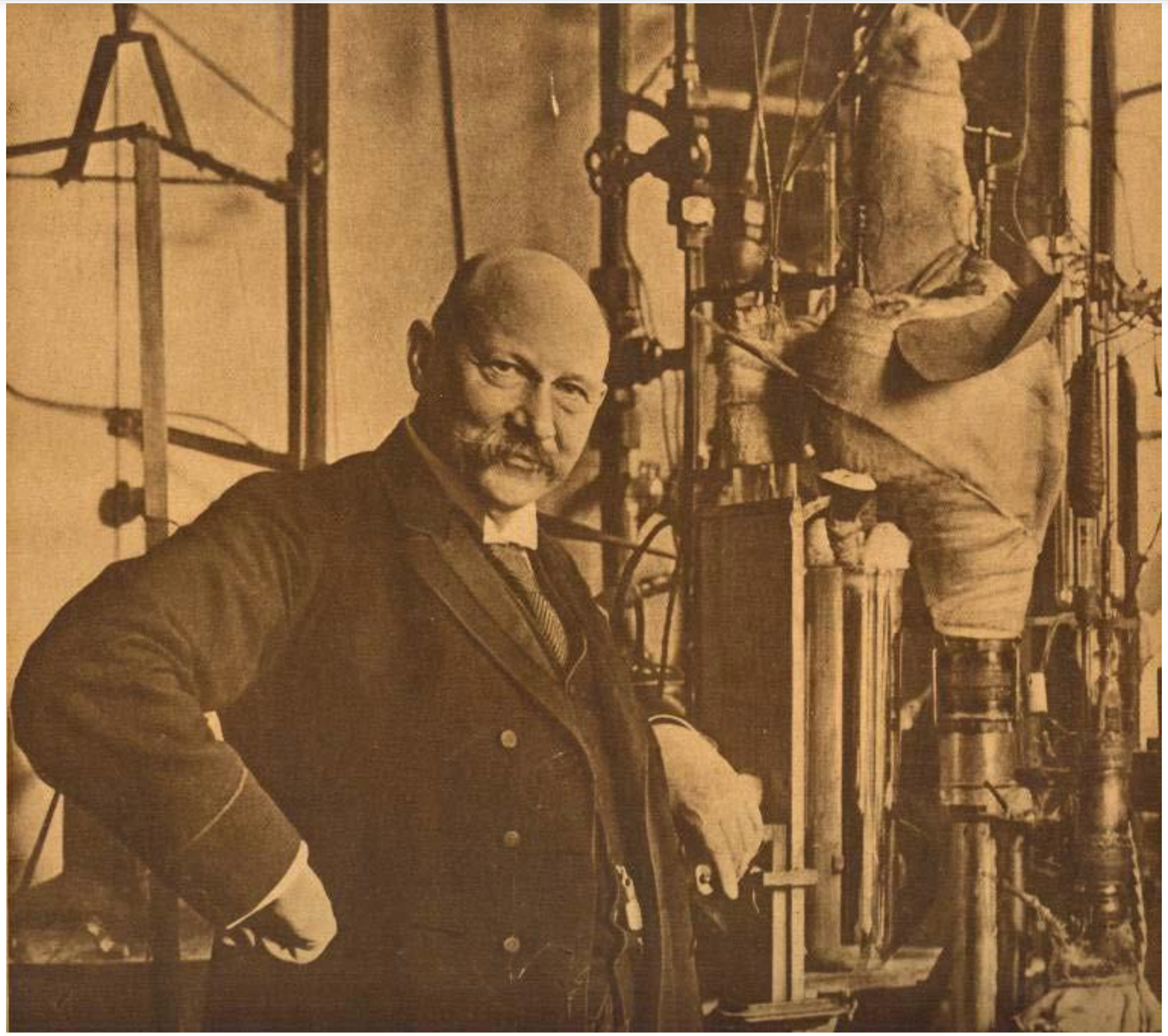
A new frontier: smashing atoms in Manchester 1909-11



A frontier of Physics turning 1800s into 1900s



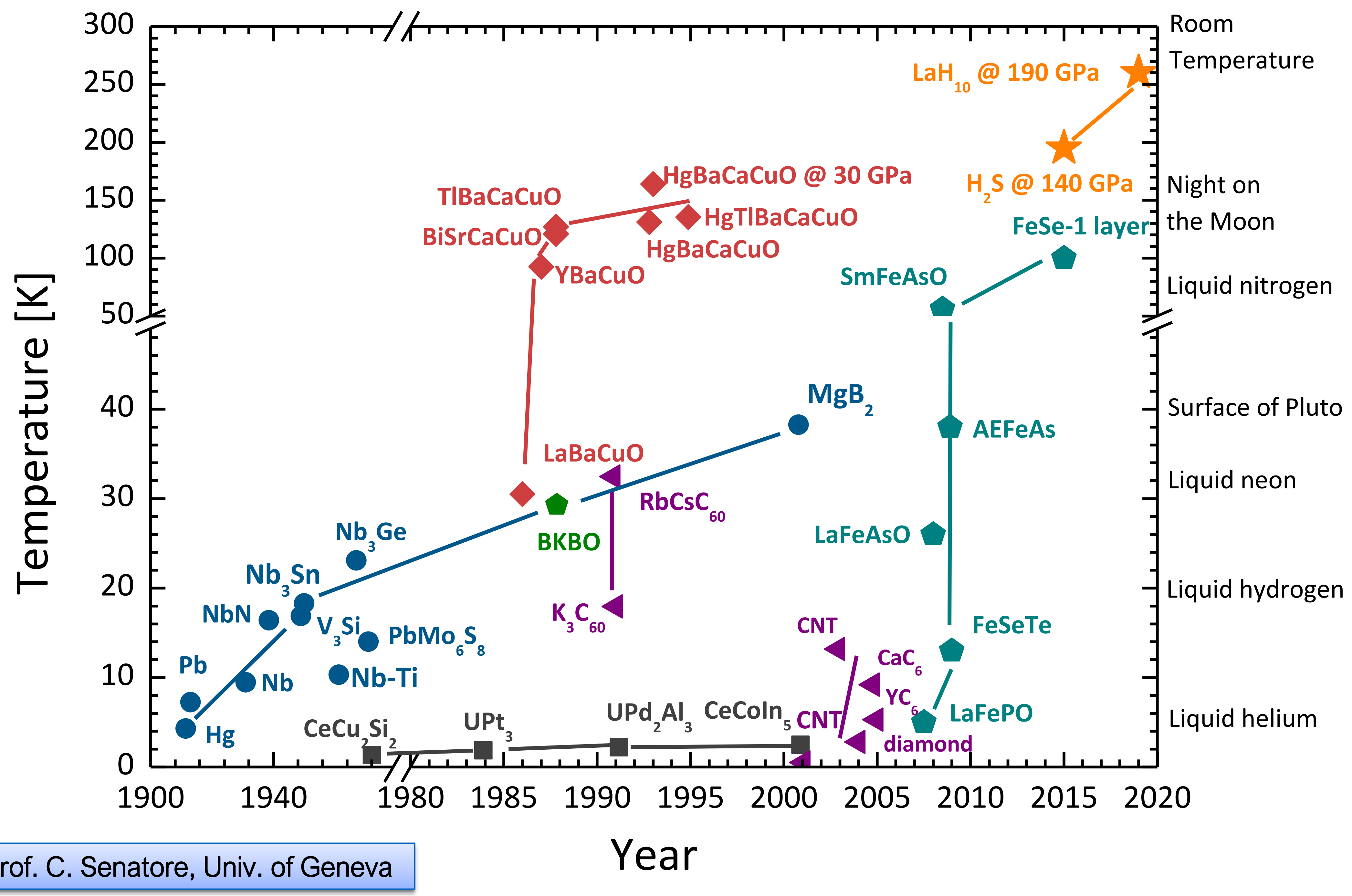
Heike Kamerlingh Onnes with Johannes Diderik van der Waals in front the first Liquid Helium liquifiers



Leiden (NL): Onnes first liquifies helium in 1908He opened a new territory:

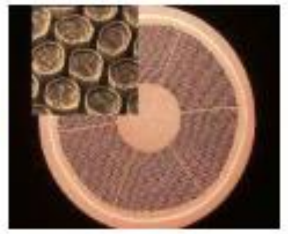
low temperature → low thermal noise

Superconductivity: a rare phenomenon?
The endless race toward high temperature



Courtesy: Prof. C. Senatore, Univ. of Geneva

NbTi



Nb_3Sn

n

MgB_2

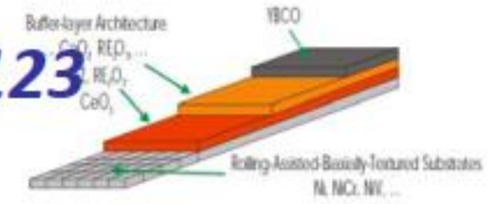
to

Bi2223

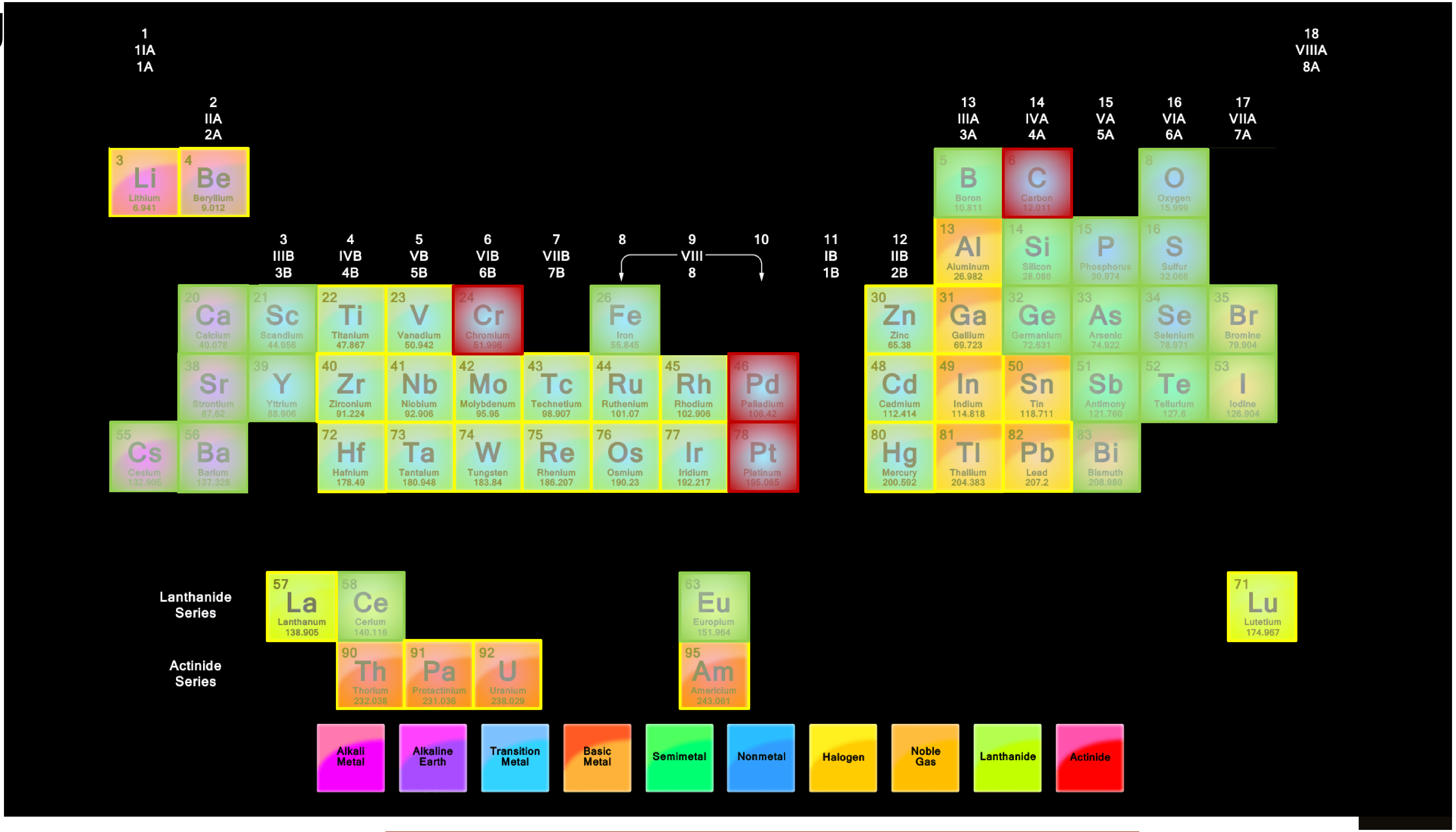
en

Bi2212

Y123



F 107 Cong

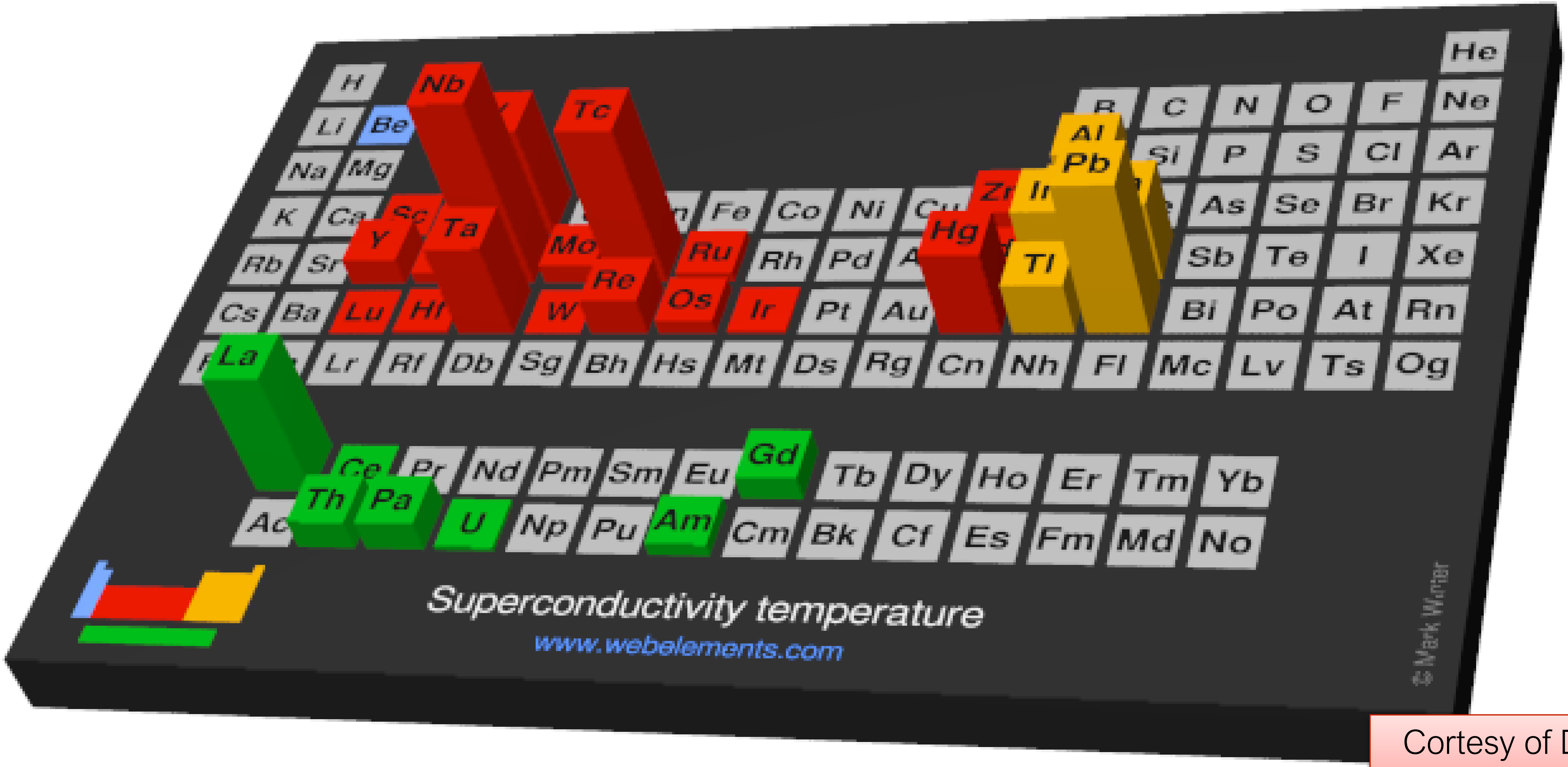


Superconduttori a pressione ambiente

Superconduttori ad alta pressione

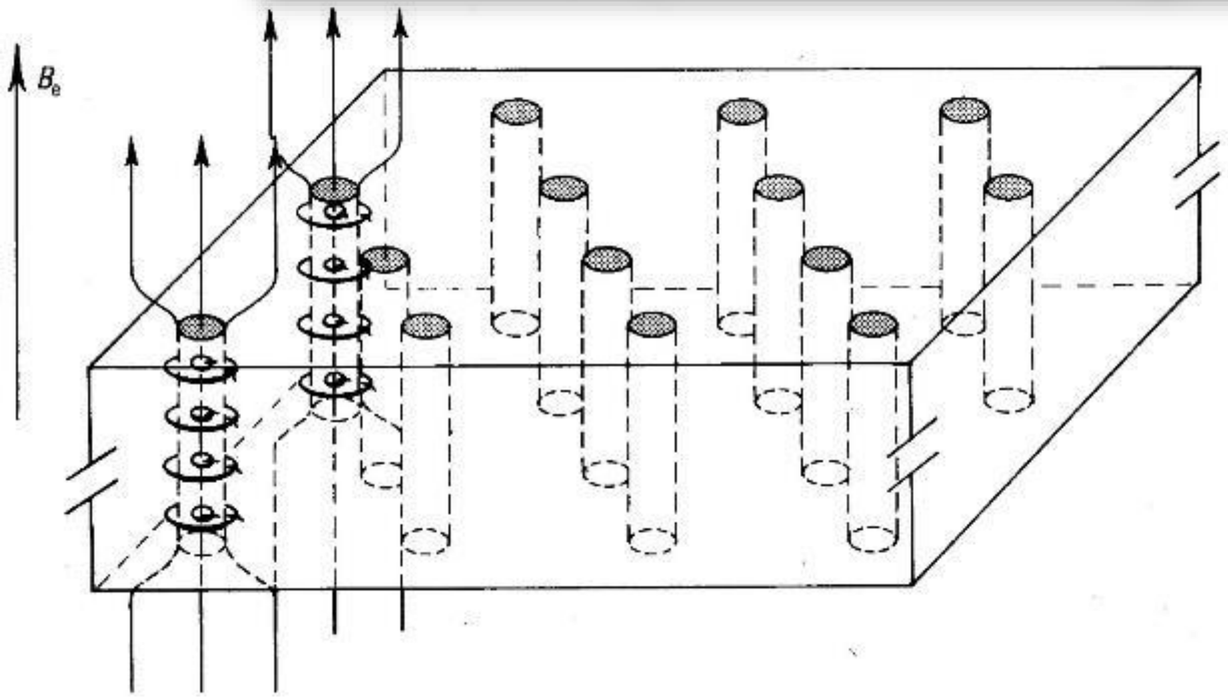
Superconduttori in forma modificata

Critical temperatures on the Mendeleev table



Cortesy of D. Valentinis, KIT, Karlsruhe

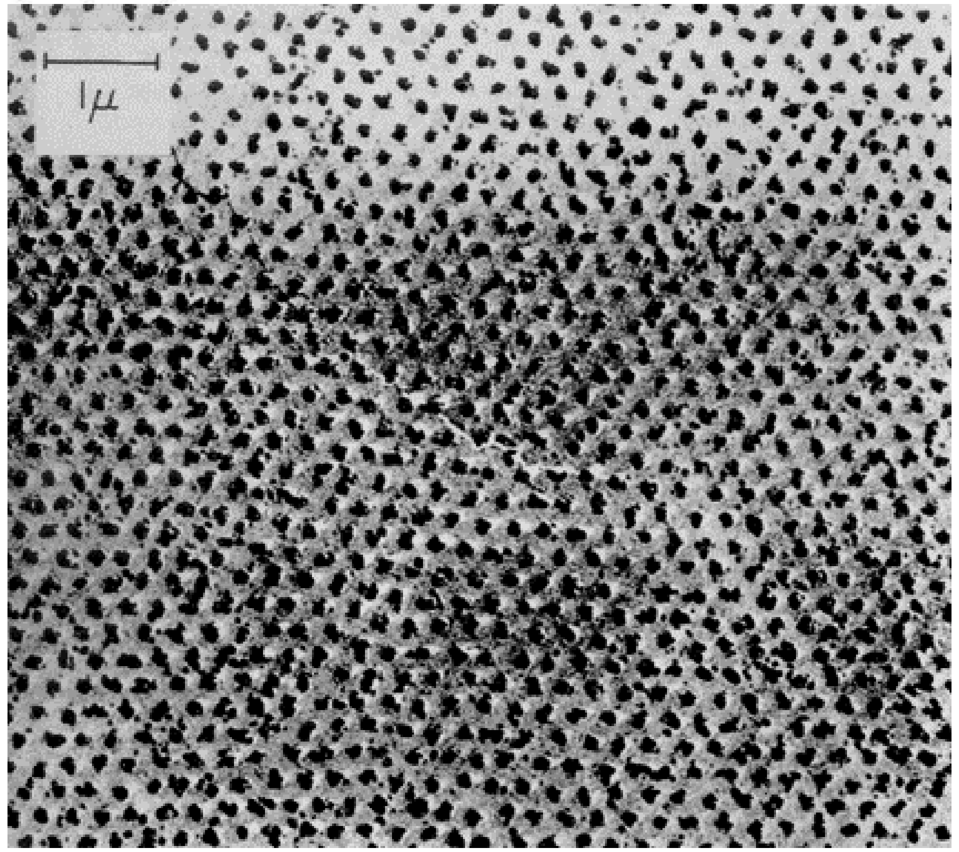
Optimal Nb-Ti properties developed by understanding the processing-nanostructure-Jc feedback cycle

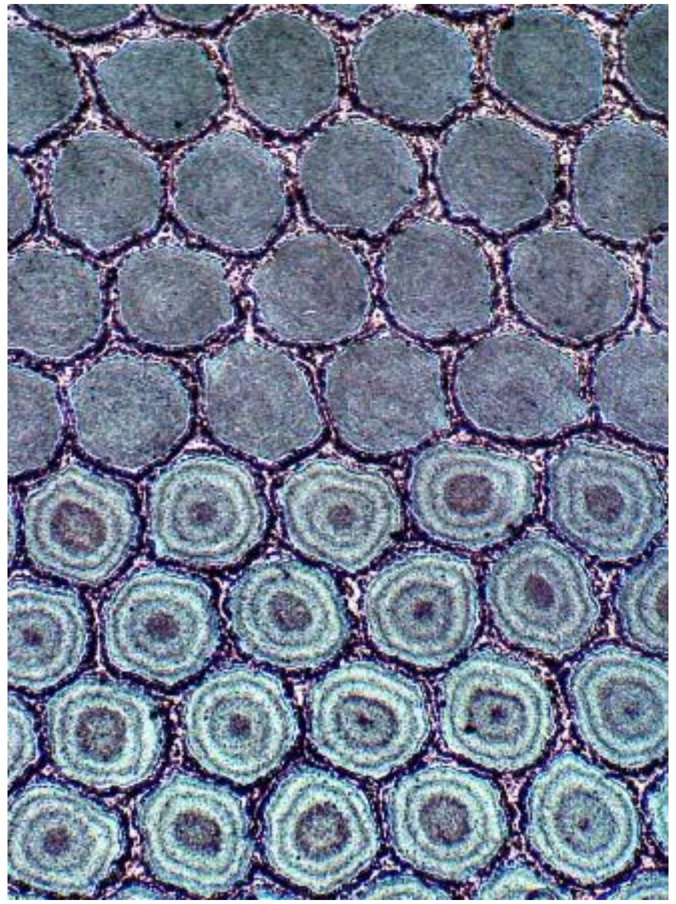


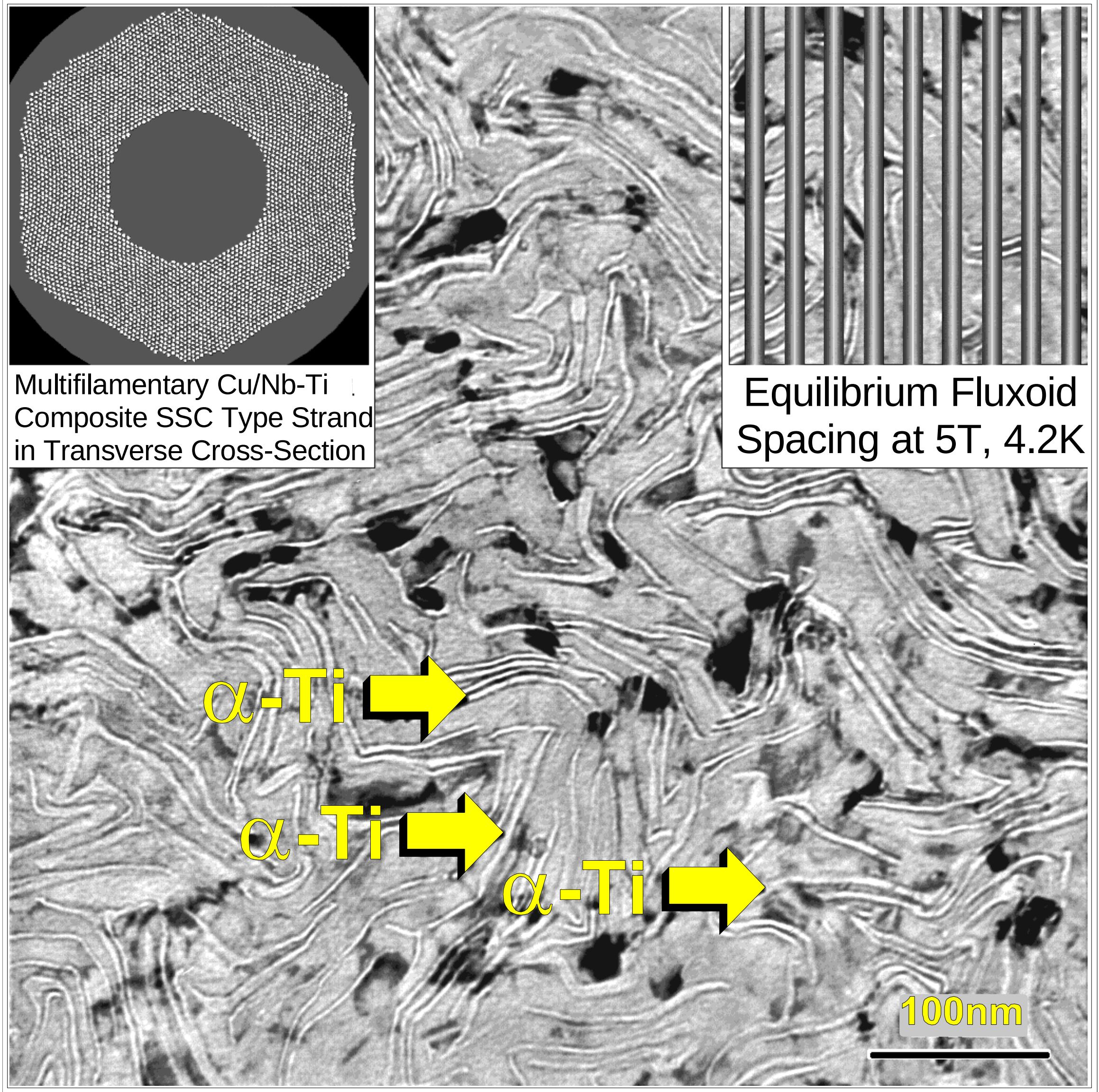
$(P, V, T) \rightarrow (B, J, T)$

Precipitate 20-25vol.% α-Ti to pin vortex cores

Start with homogeneous Nb-Ti

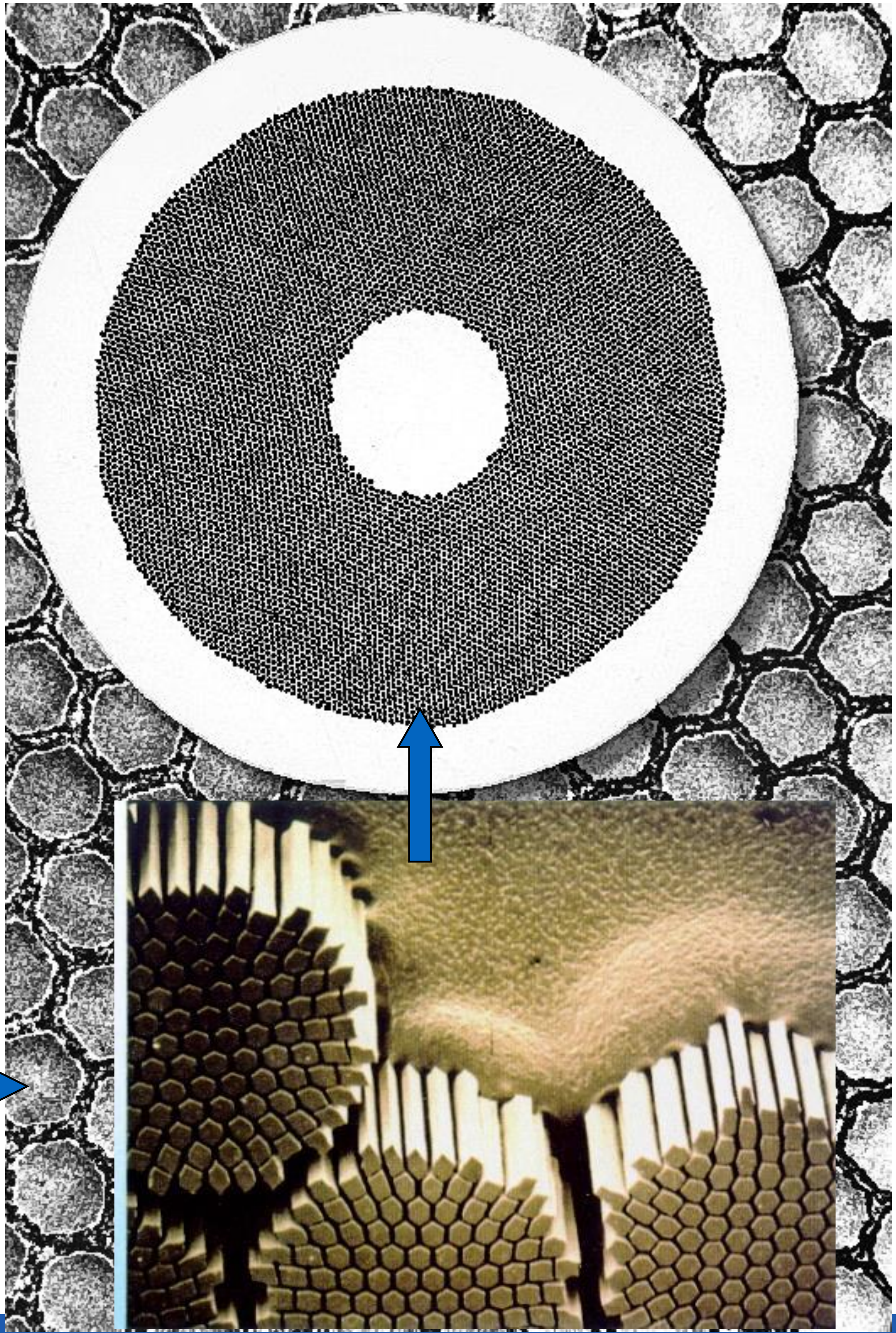




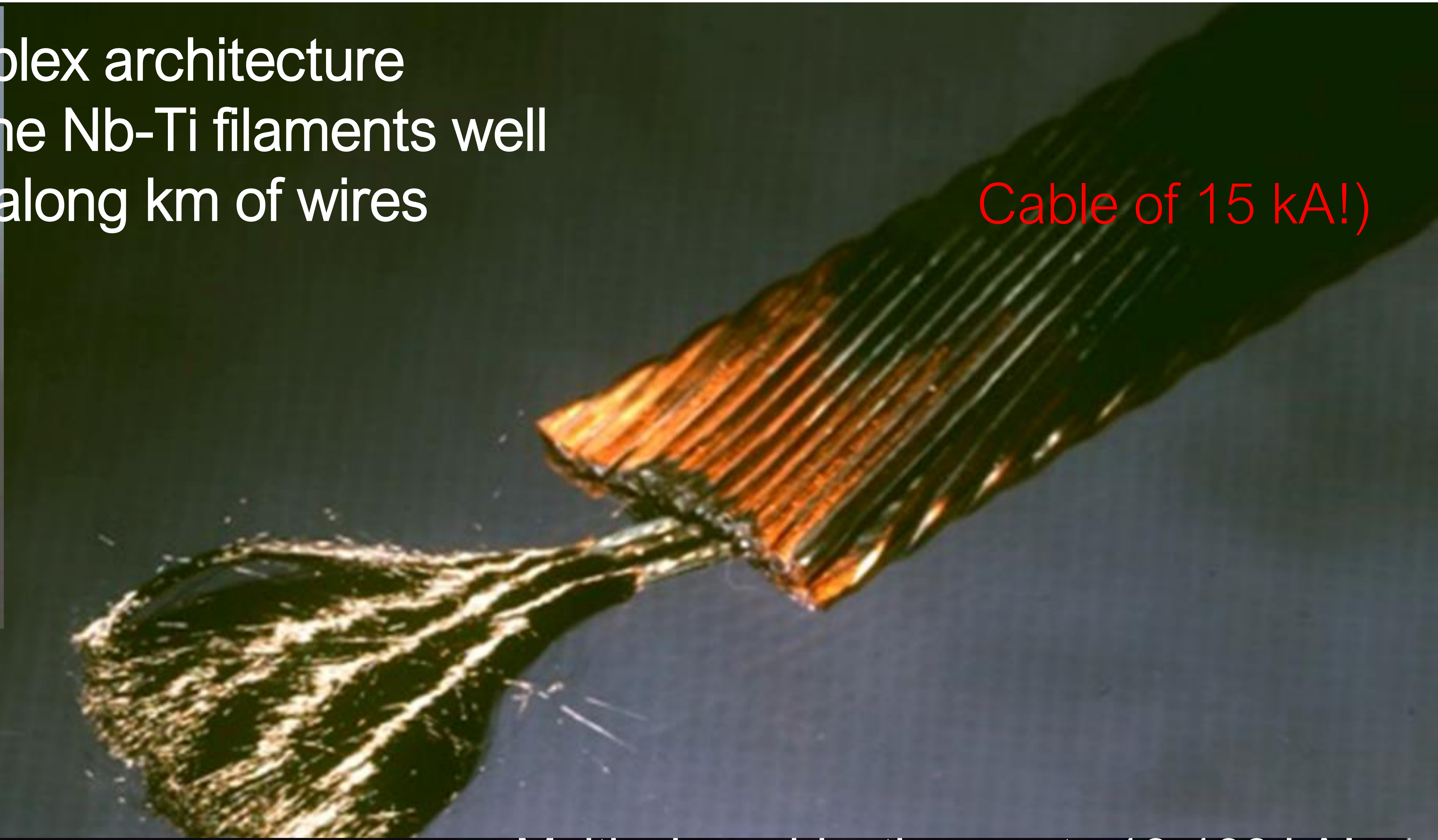


Nb-Ti: from HO (high homogeneity) ingots to wires

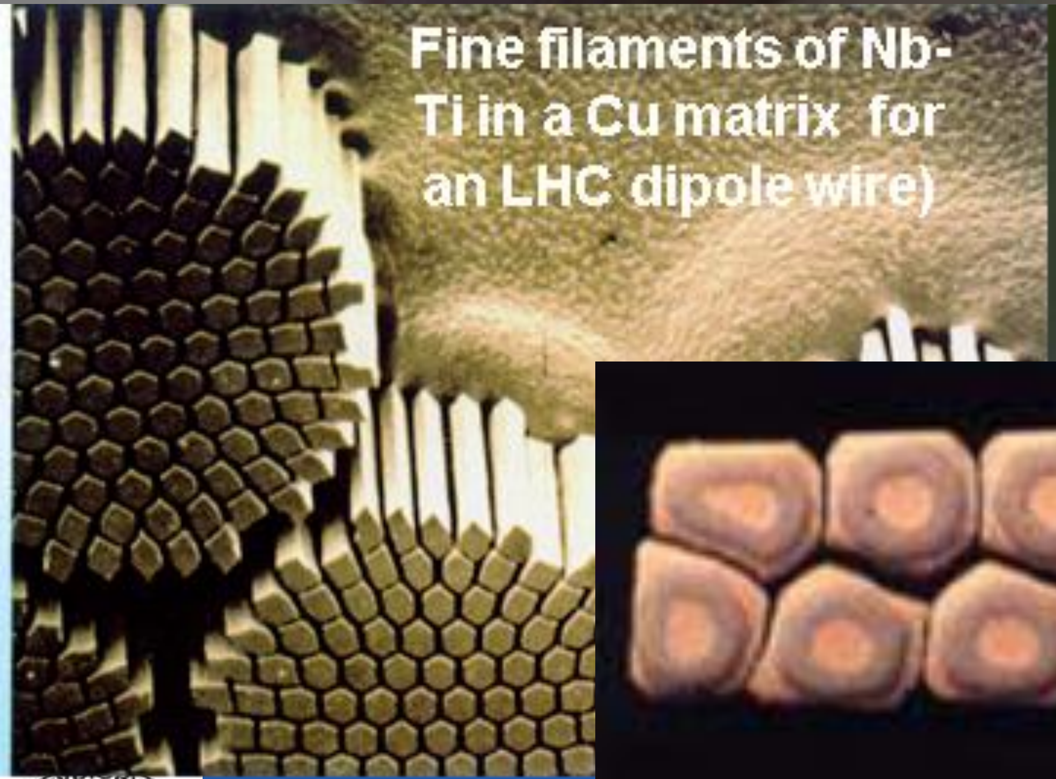
Nb-Ti billets for LHC, courtesy Wah Chang



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

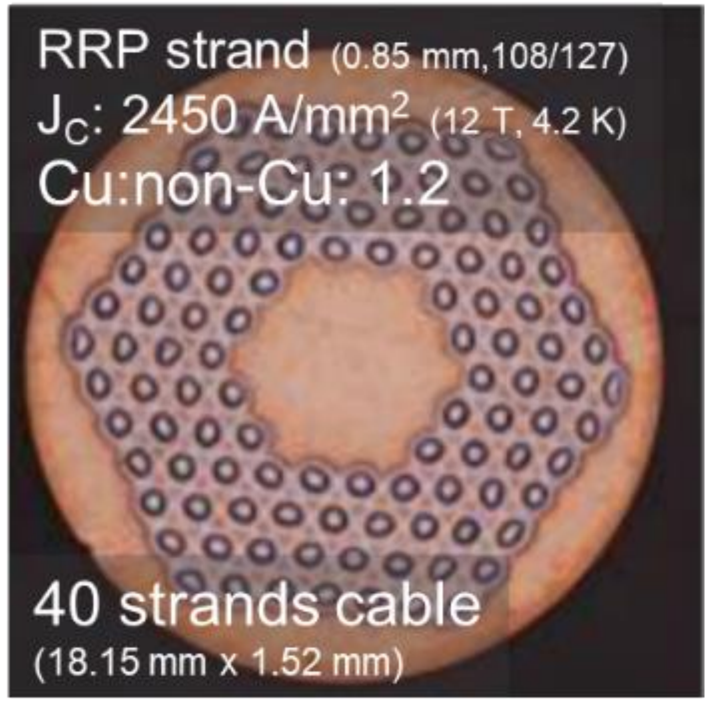


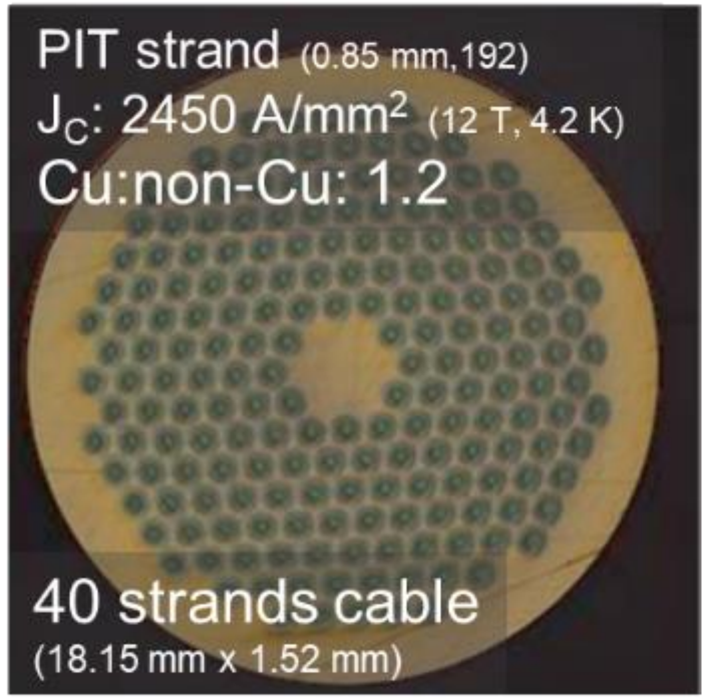
Cable of 15 kA!)

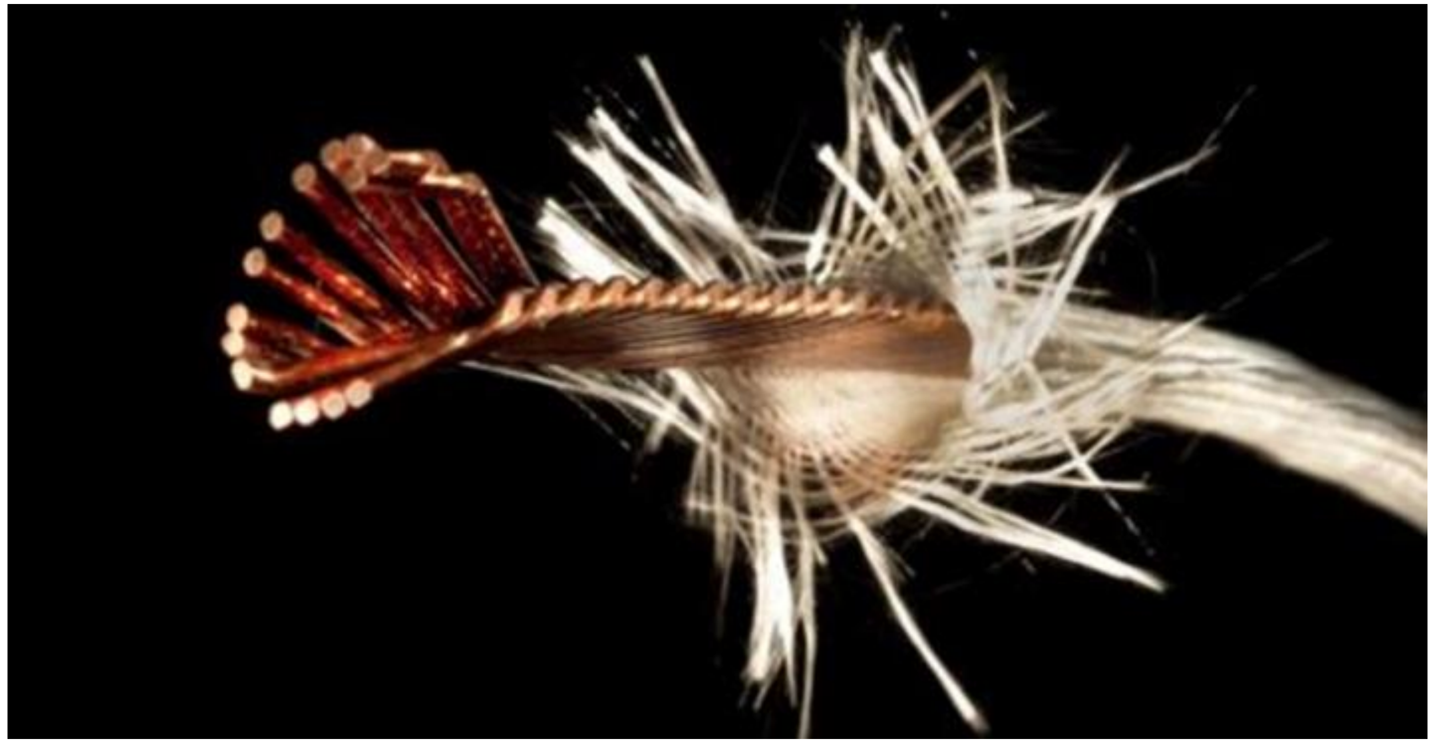


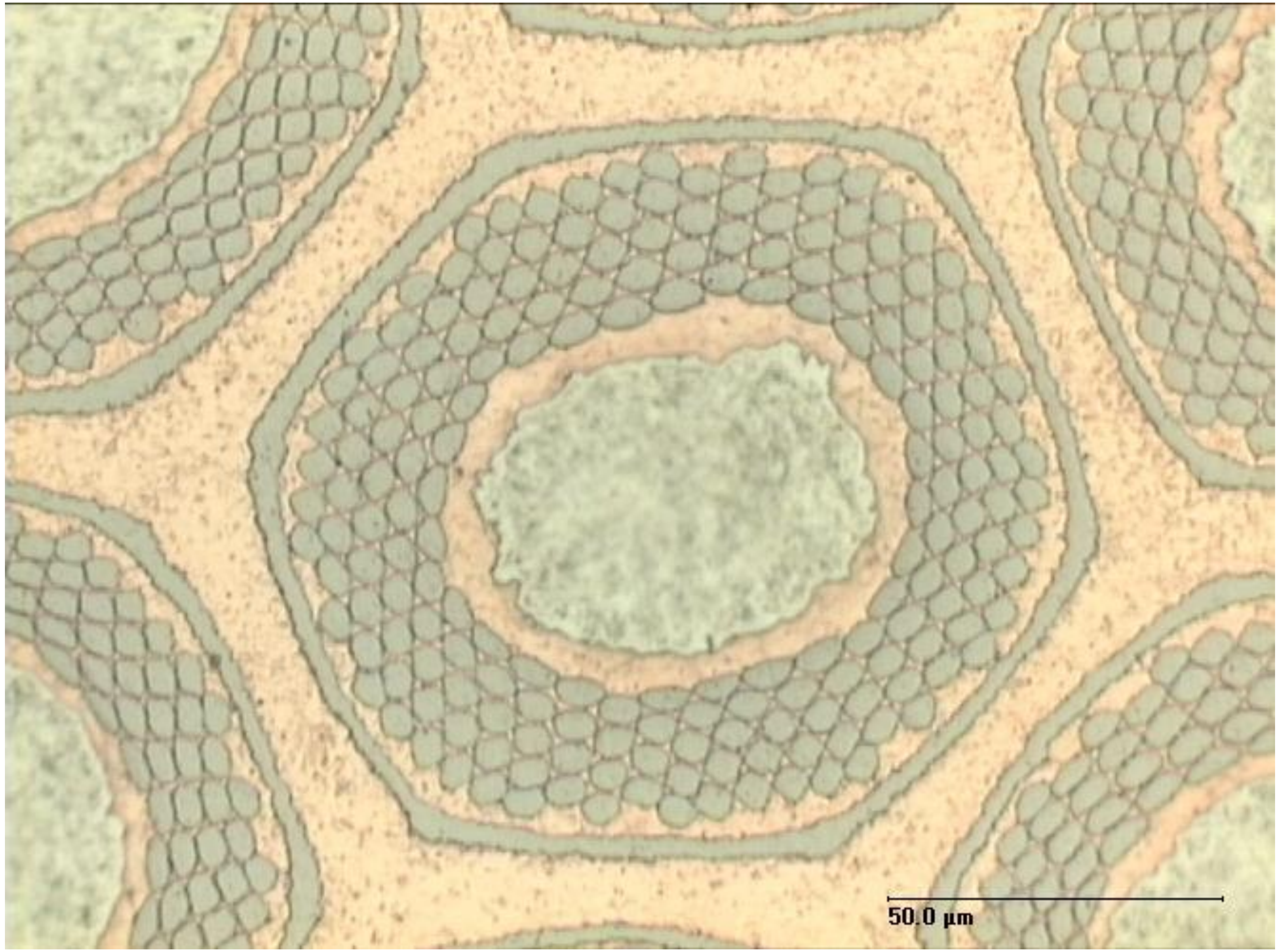
Multi-wire cable: the way to 10-100 kA!

Materiali innovativi: Nb_3Sn ad alta Jc

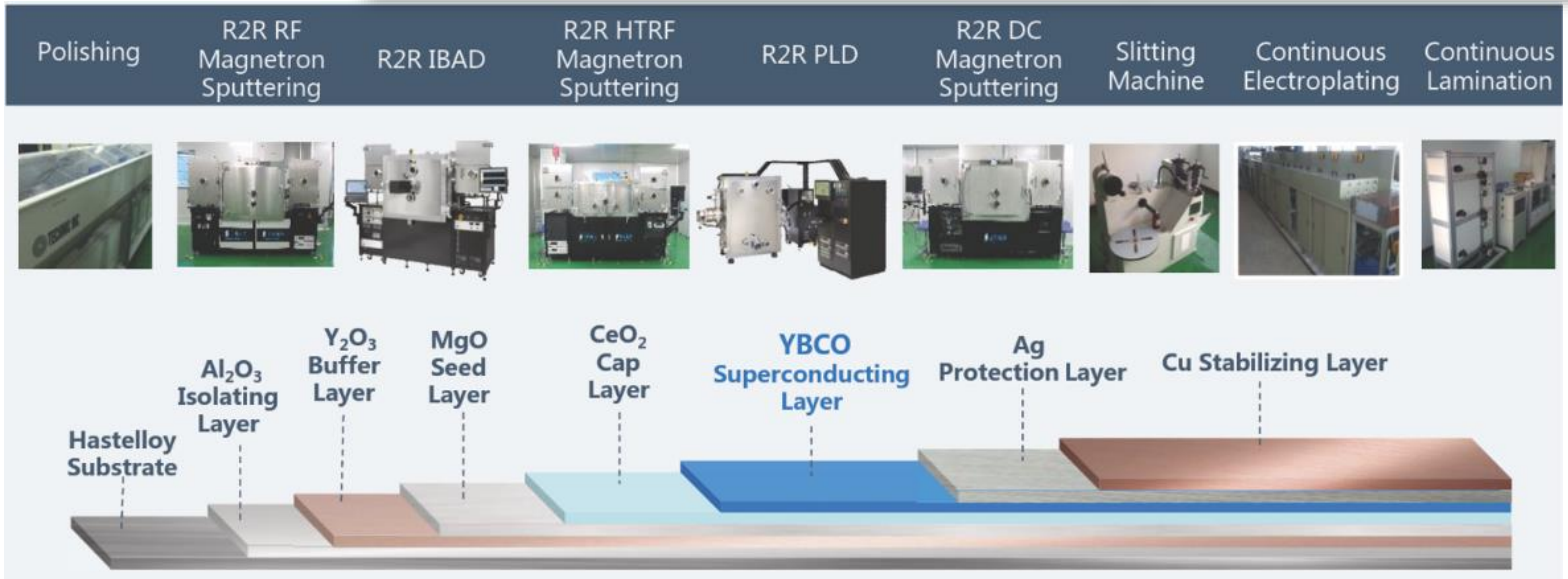


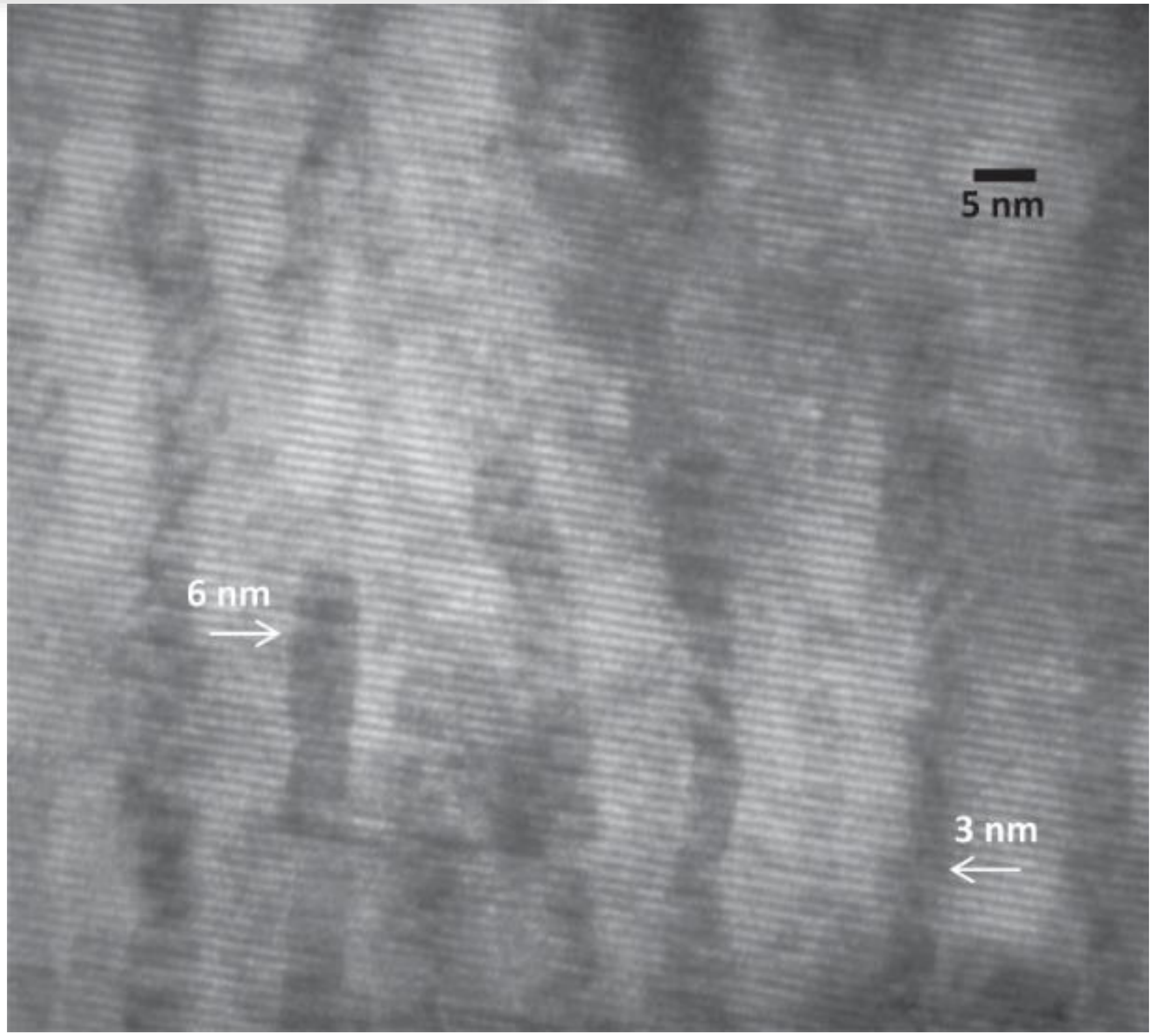






Materiali innovativi: HTS
Bi-2212 e soprattuttoYBCO

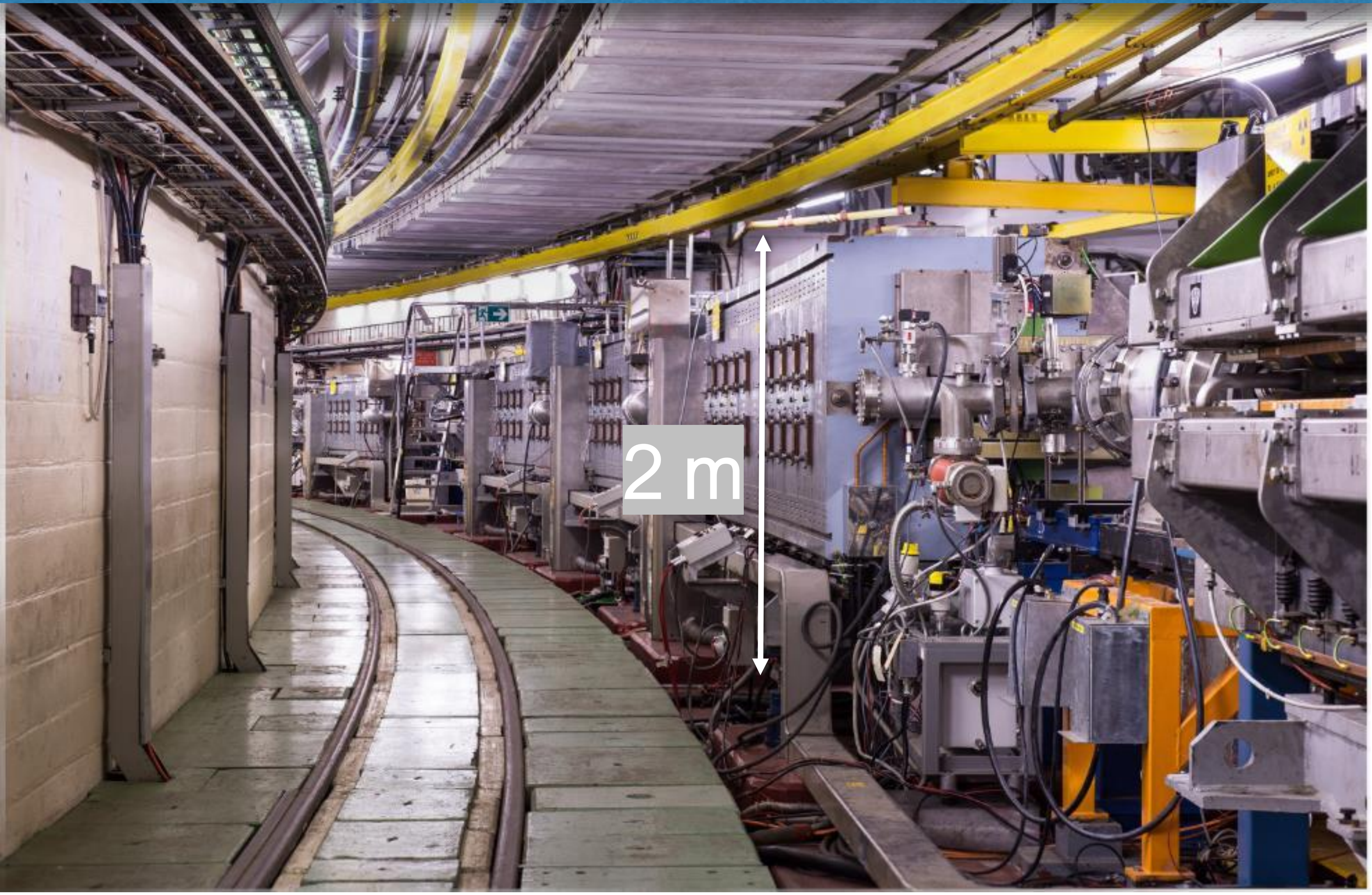




Double disordered YBCO coated conductor of industrial scale: high currents in high magnetic field

D Abraimov[1], A Ballarino[2], C Barth[3], L Bottura[2], R Dietrich[4], A Francis[1], J Jaroszynski[1], G S Majkic[5], J McCallister[1], A Polyanskii[1], L Rossi[2], A Rutt[4], M Santos[1], K Schlenga[4], V Selvamanickam[5], C Senatore[3], A Usoskin[4] and Y L Viouchkov[1]

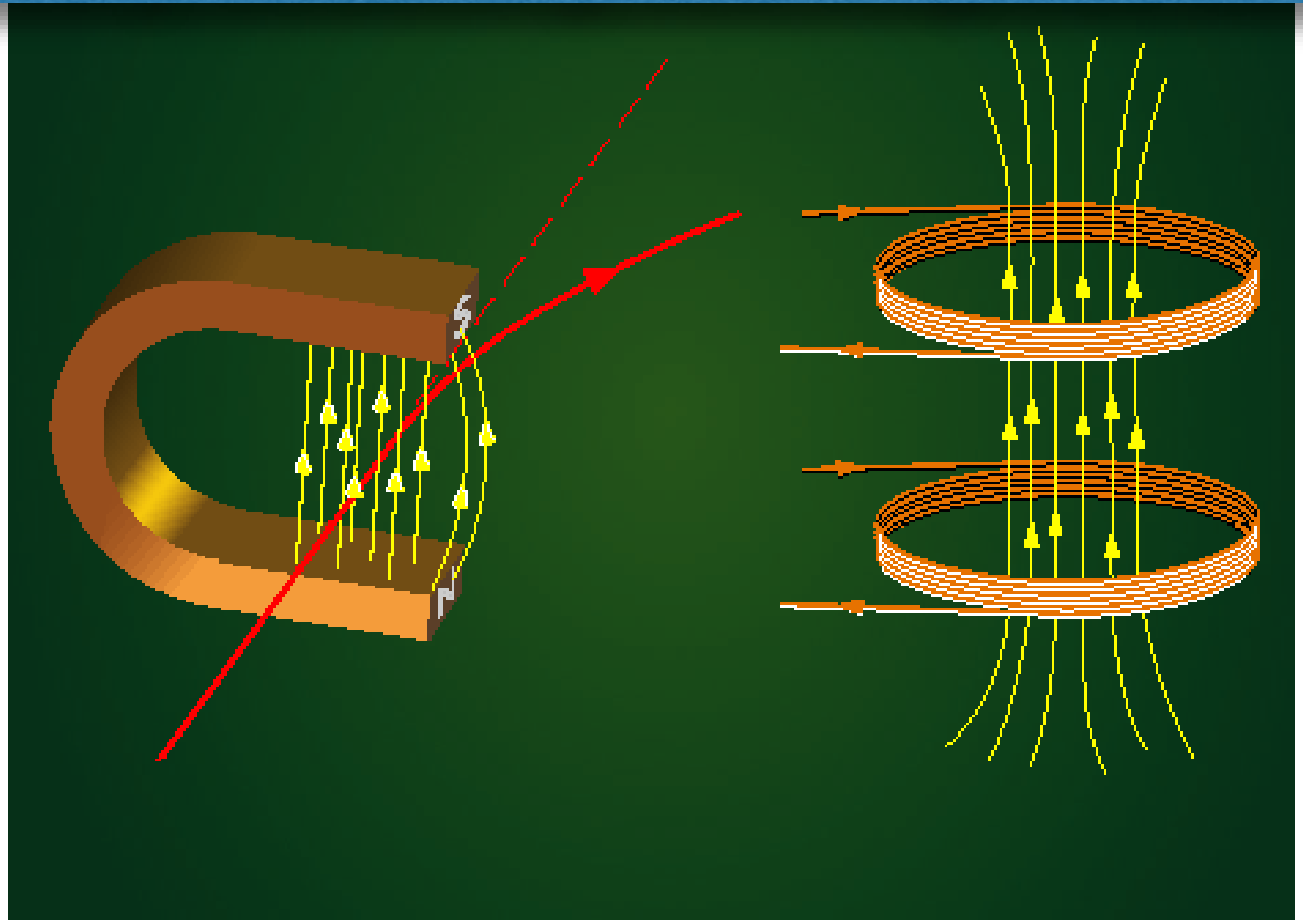
Carrying a lot of current: what a difference for magnets!

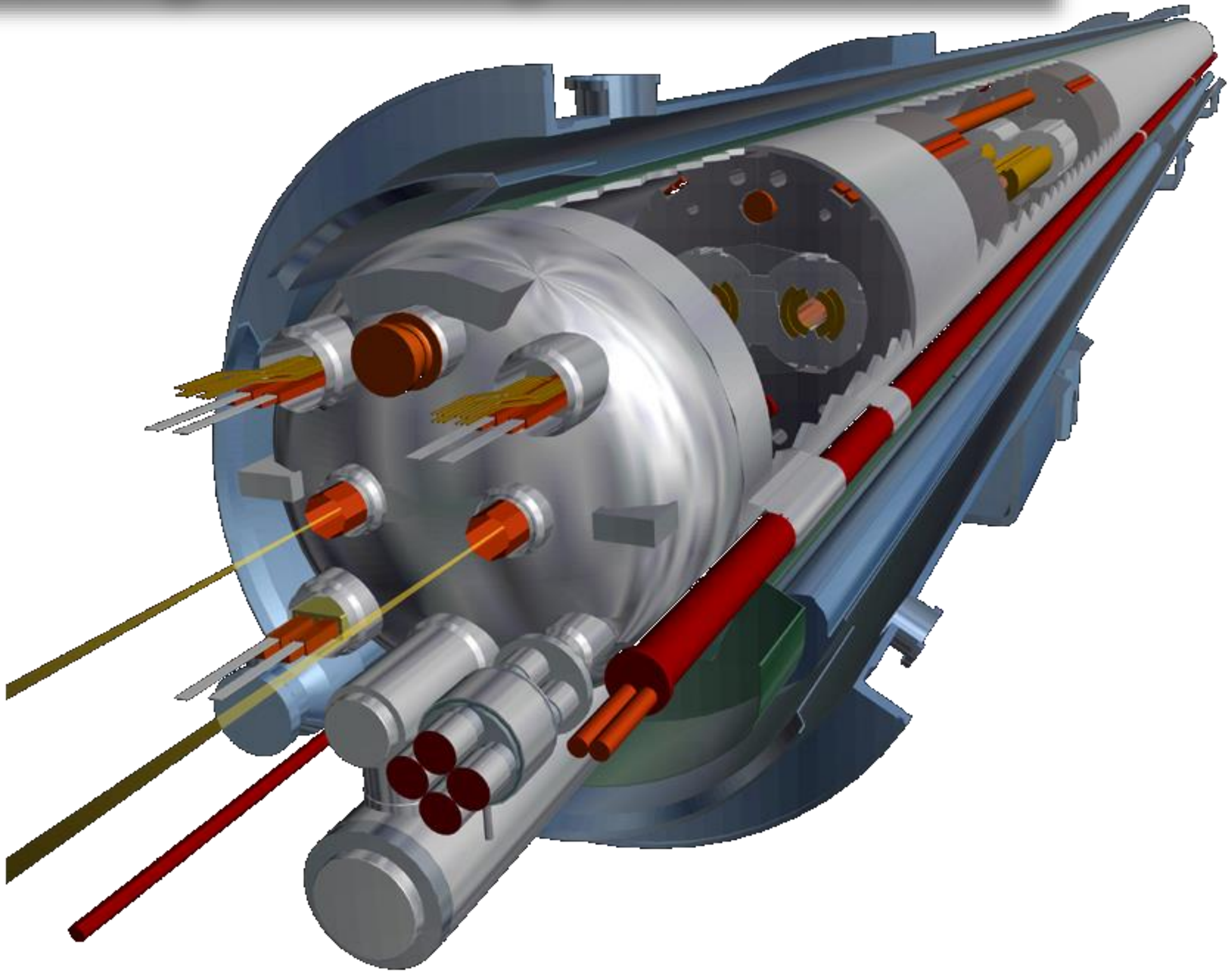


Resistive magnets of PS accelerator at CERN (1.5 tesla)

SC magnets at Tevatron at Fermilab (USA) 3 times more powerful!

Why looking for higher and higher magnetic field?

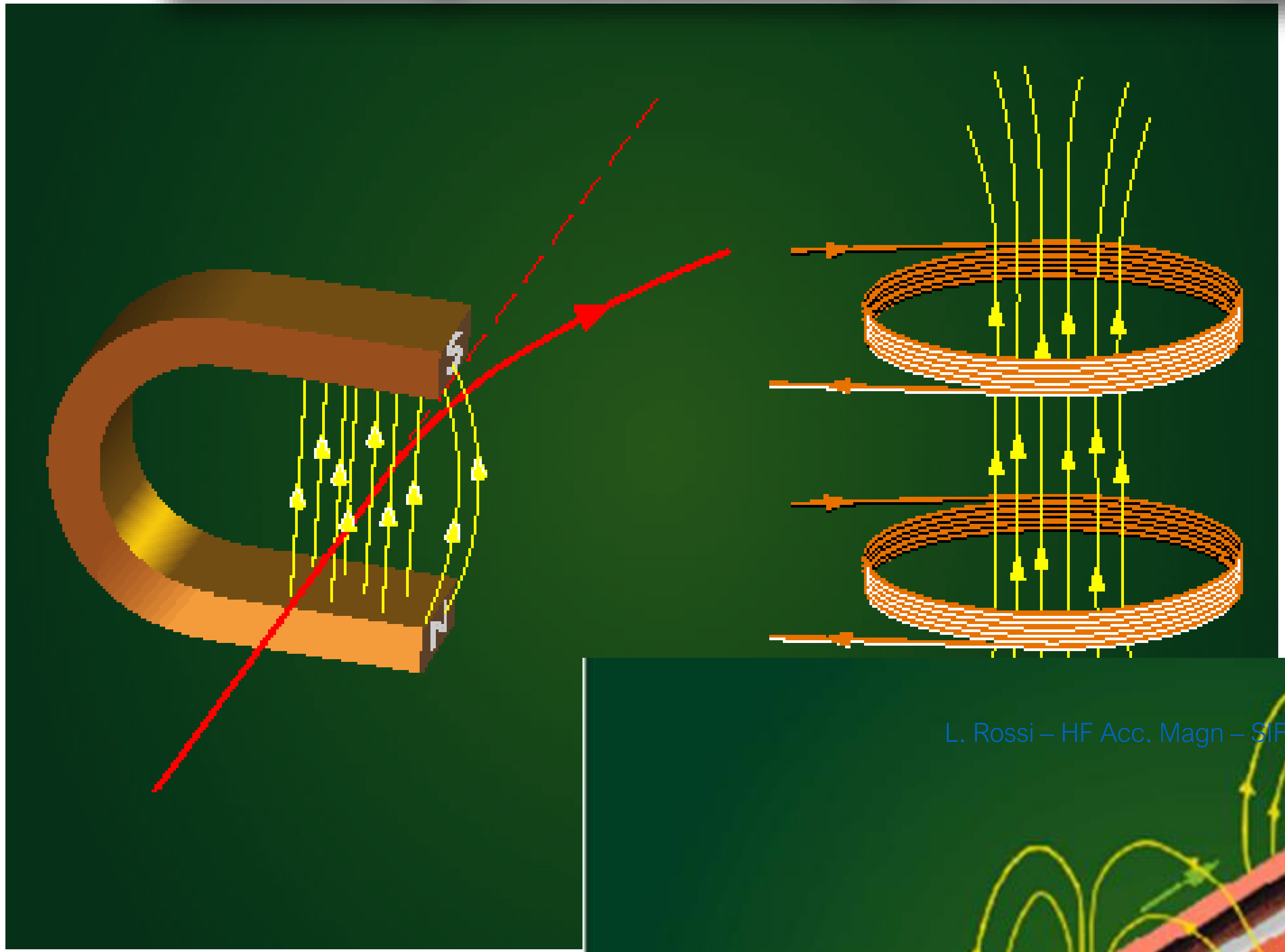


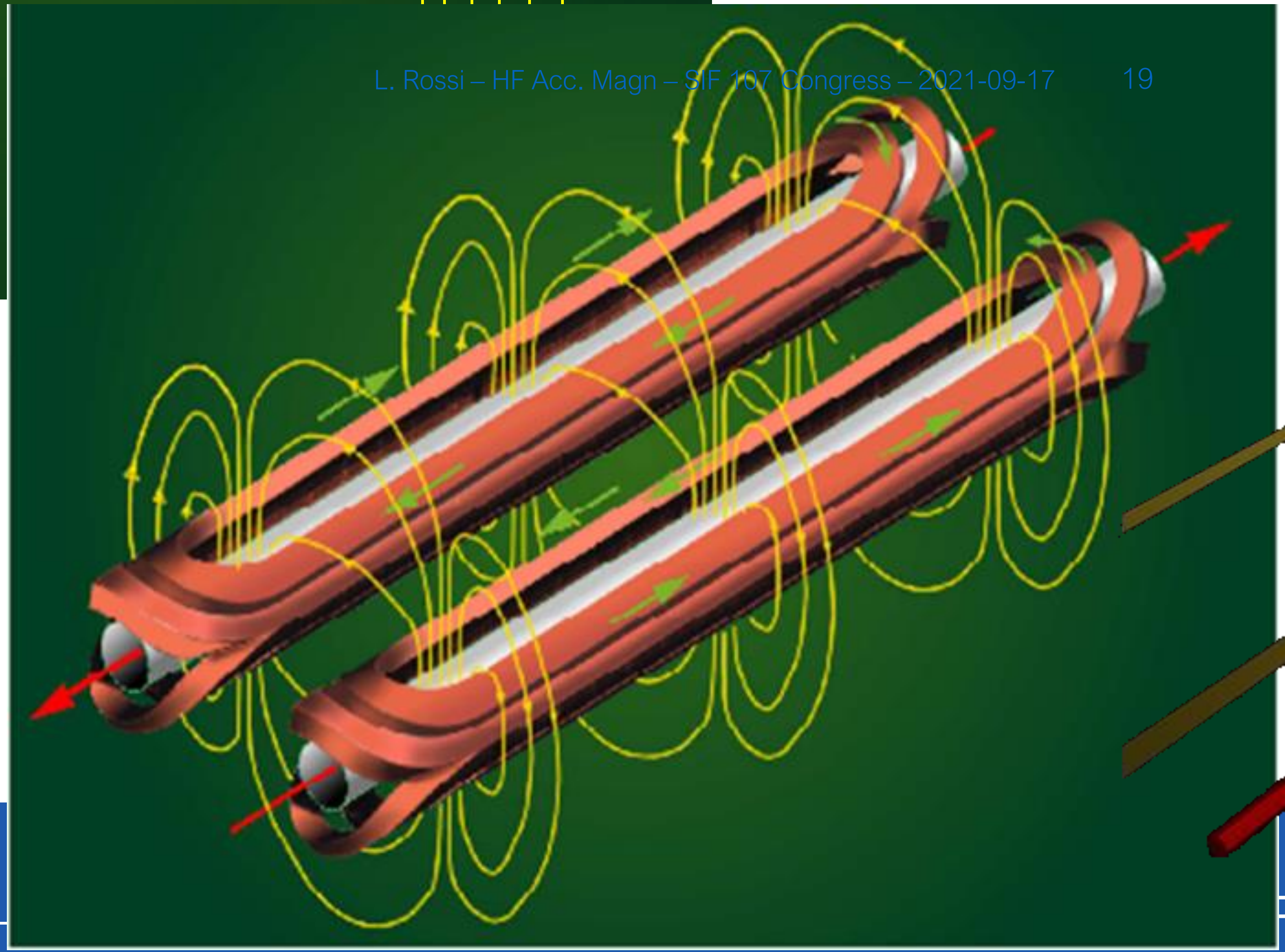


- Circular Accelerators

$$E_{beam} = 0.3\ B\ r \quad [GeV]\ [T]\ [m]$$

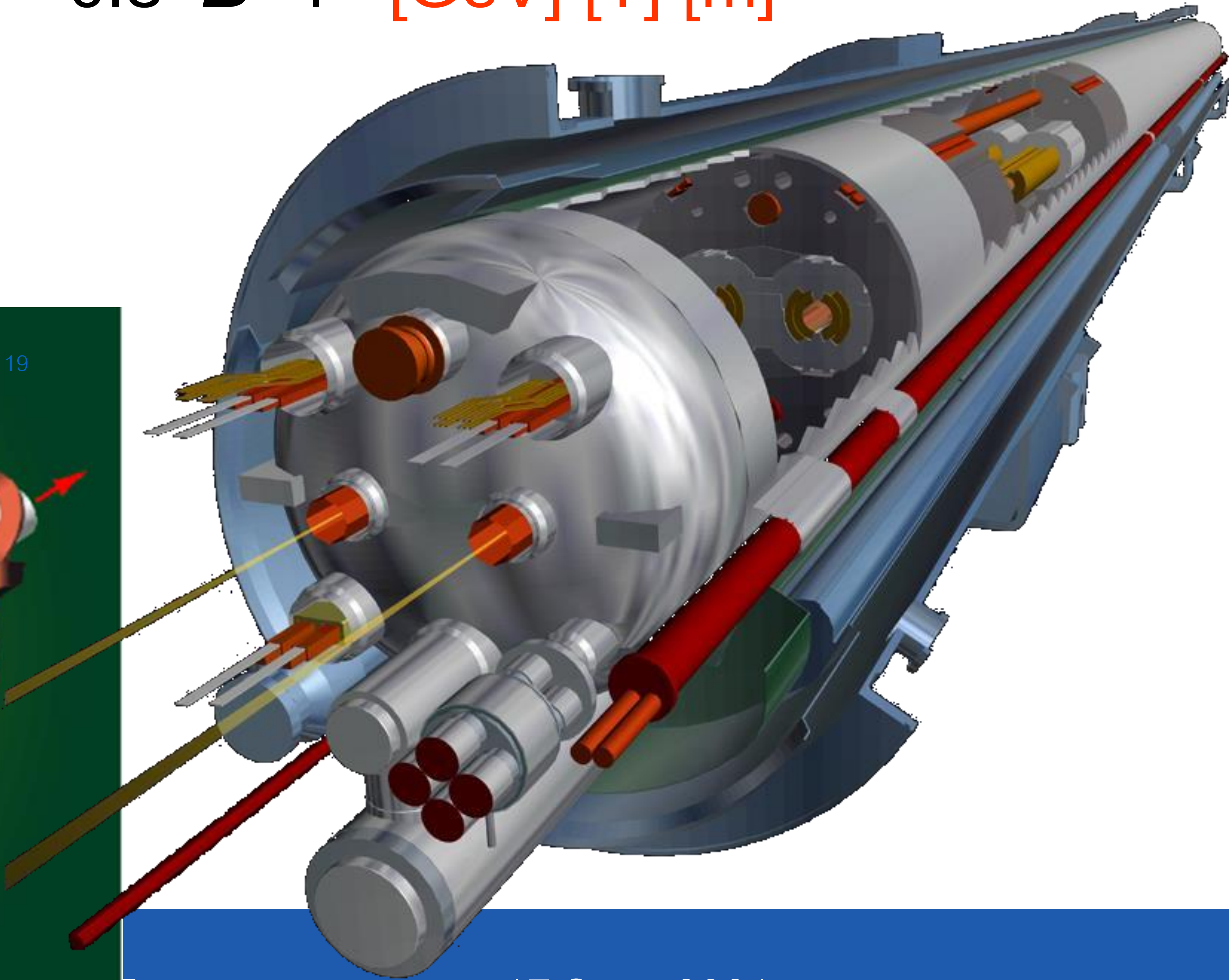
Why looking for higher and higher magnetic field?





In un acceleratore circolare

$E_{beam} = 0.3\ \boldsymbol{B}\ r$ [GeV] [T] [m]



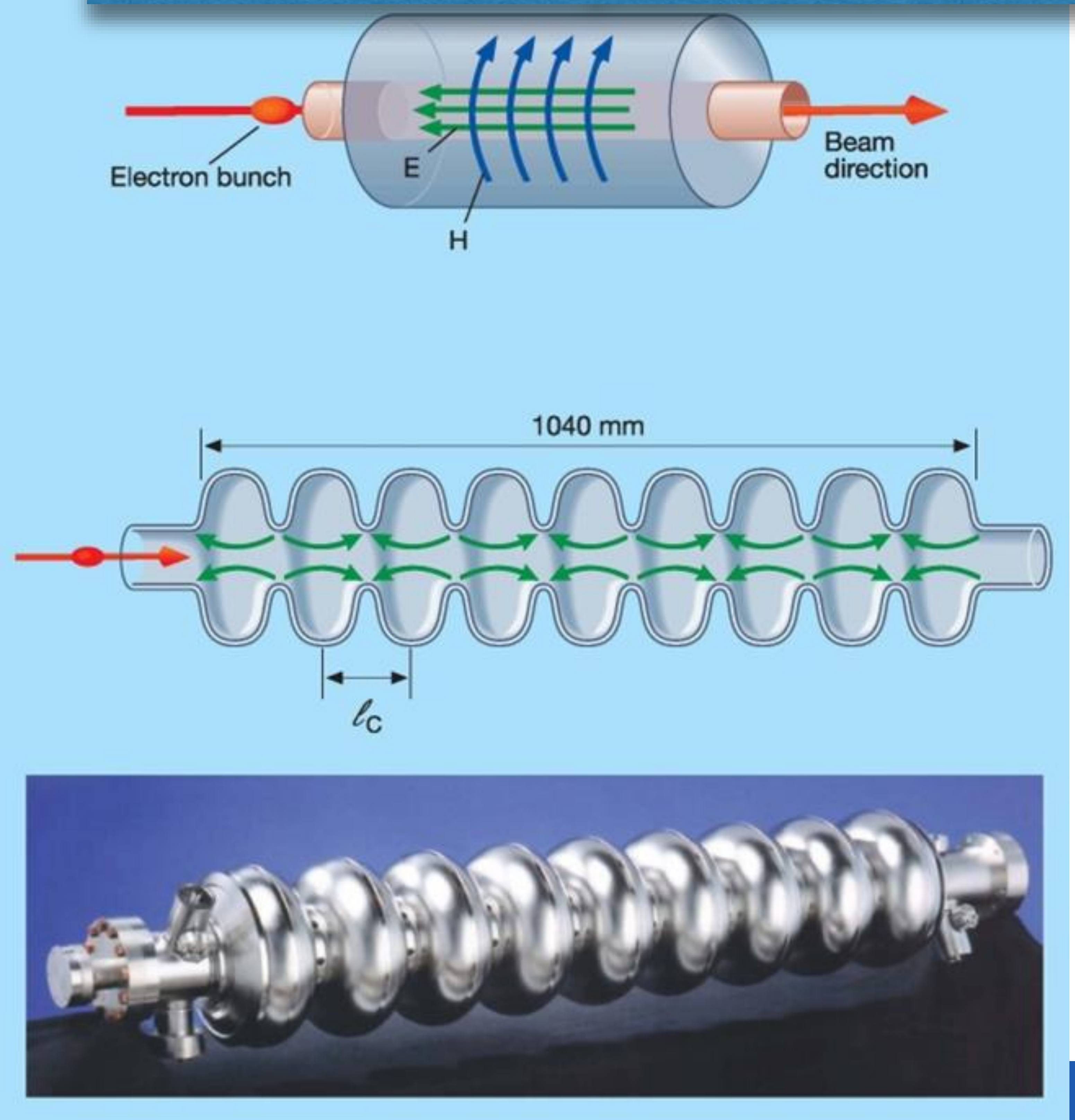
Superconducting LHC

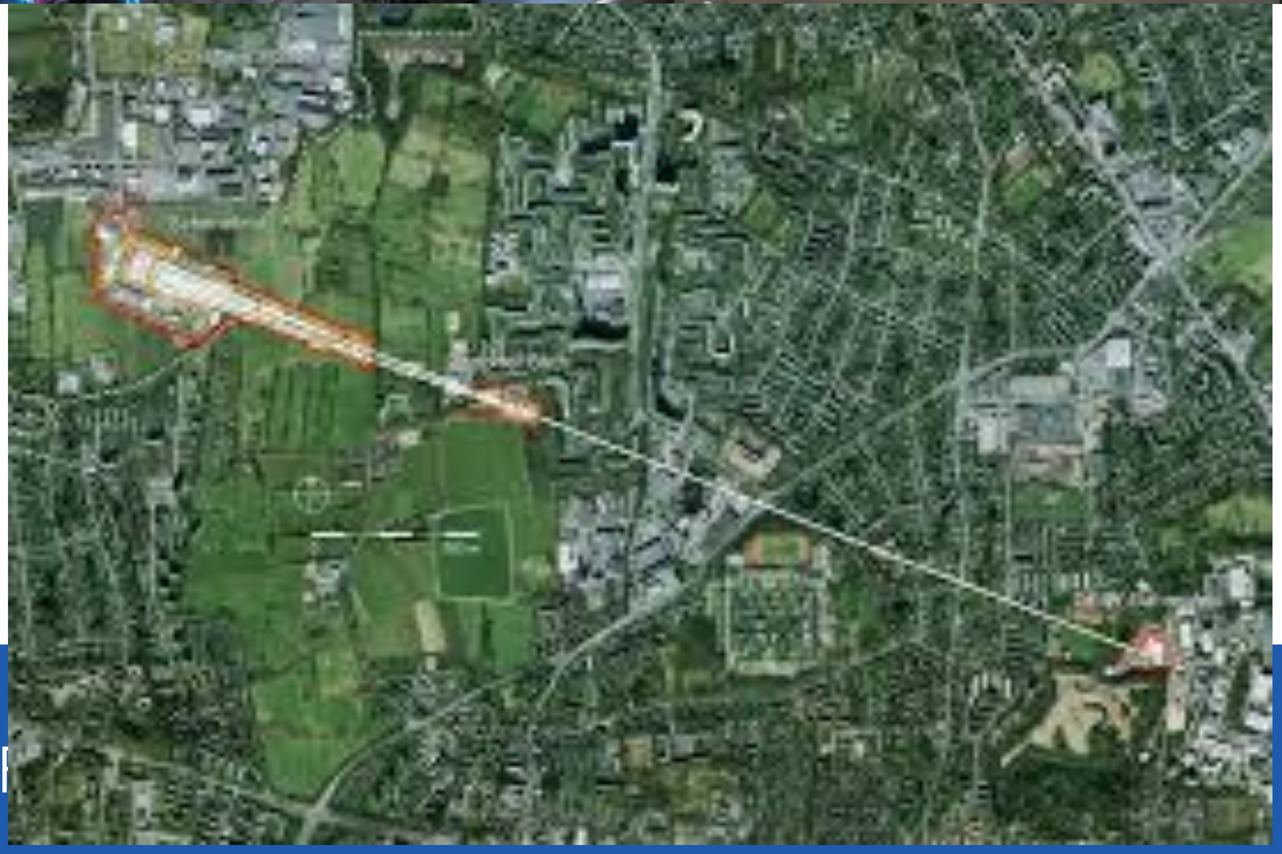
- Tunnel : 27 km
- Field : 8.3 T
- Cryoplant power at the plug: 40 MW: **always on**
- ~ 70 MW for LHC.
- 150 MW for the accelerator complex
- 180 MW for the whole CERN complex

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

Superconductors (usually pure Niobum) are used to accelerate particles: electric fields in RF cavities

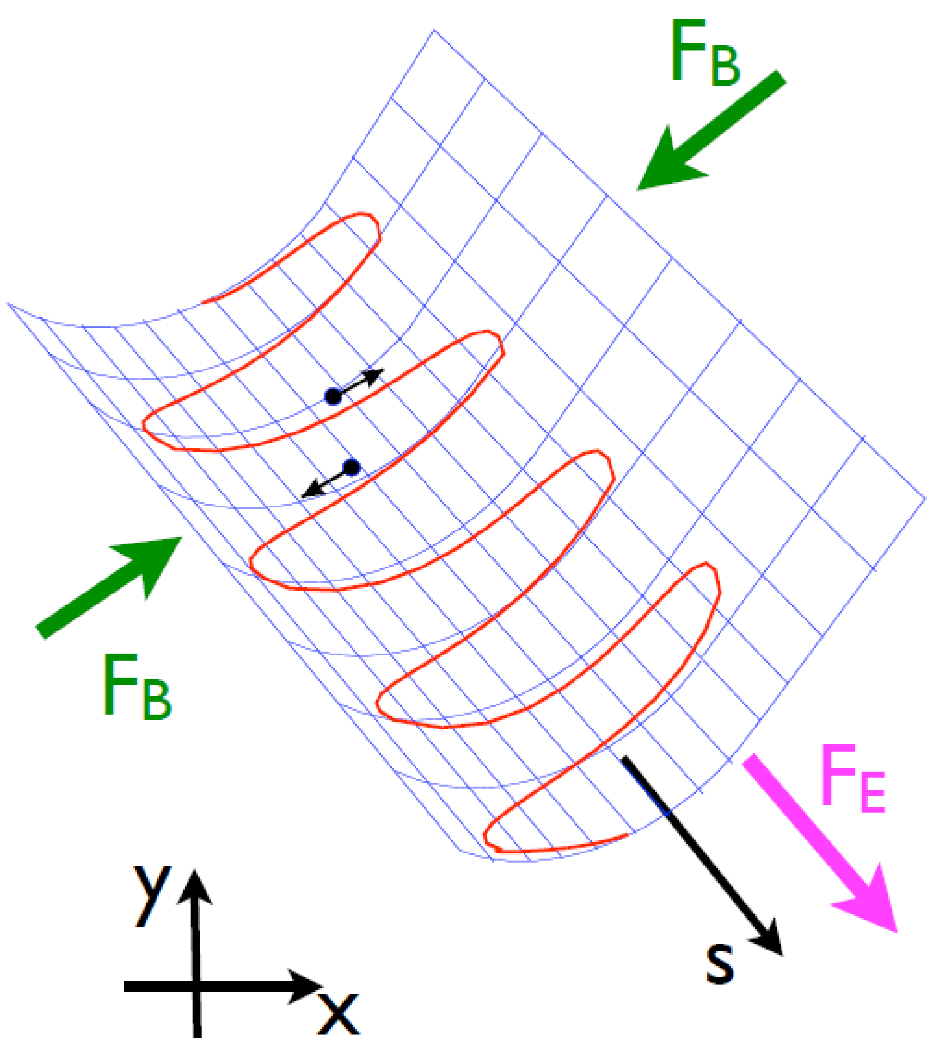




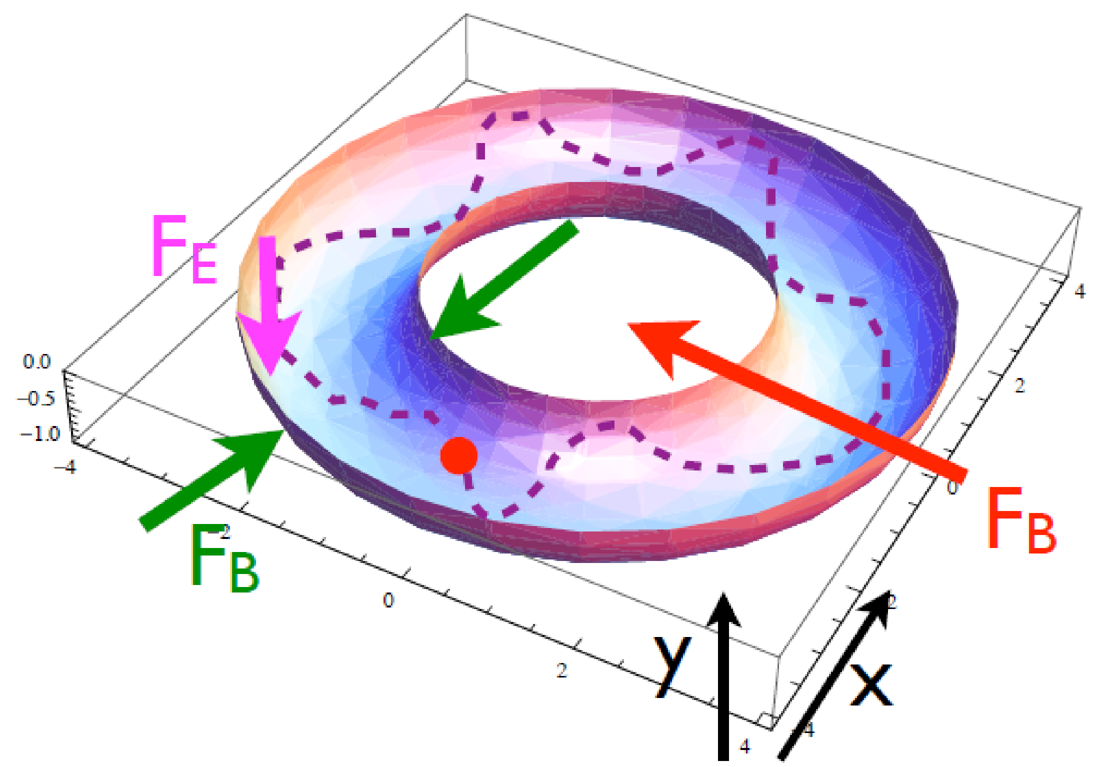
And is snot enough to circualte particle or to send then stright: a beam need –strong- focalisation

$$\overline{F(t)} = \underbrace{q\left(\overline{E(t)}\right.}_{F_E} + \overline{v(t)} \underbrace{\otimes \overline{B(t)}}_{F_B}\left.\right)$$

Linear Accelerator

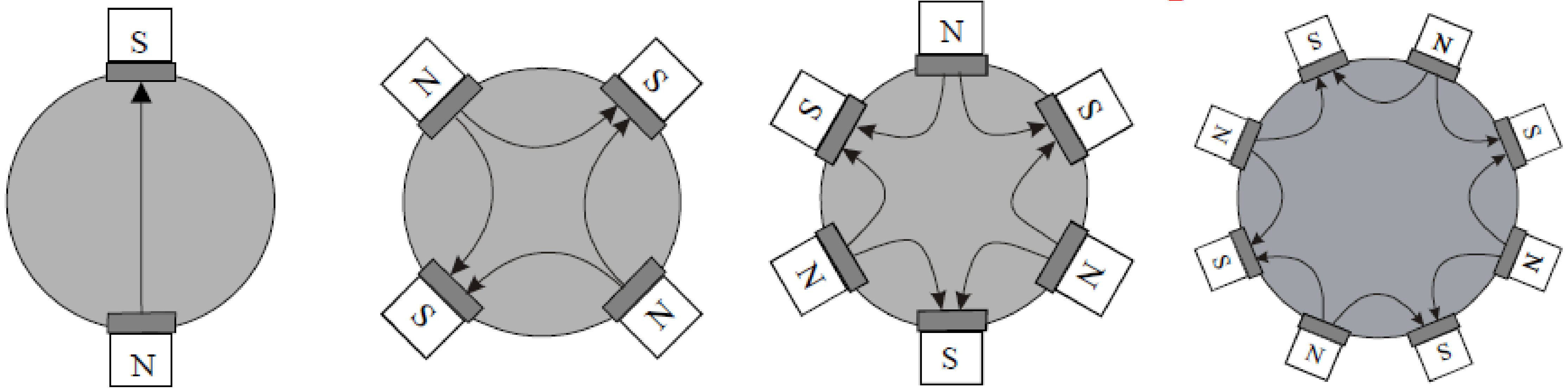


Circular Accelerator

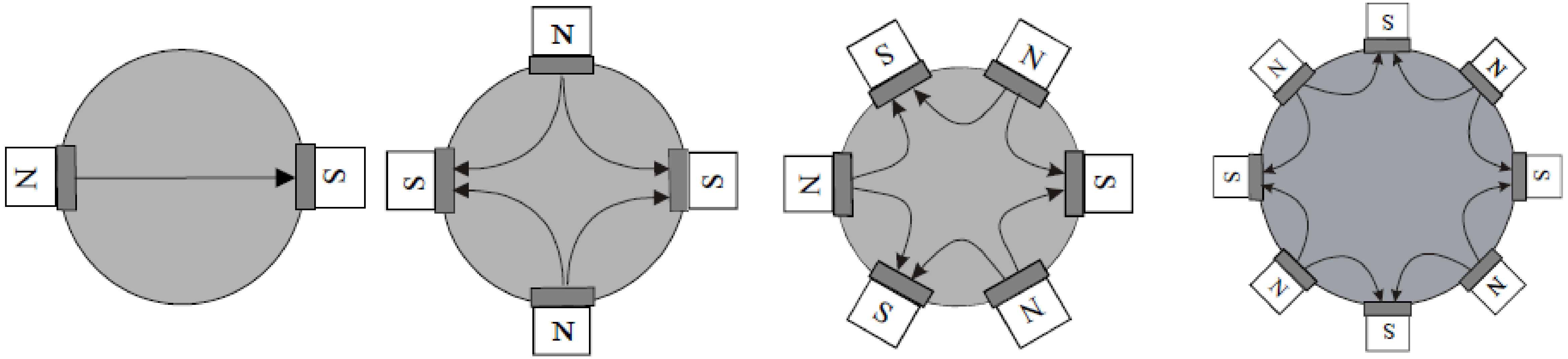


Dipoles, quadrupoles and higher order harmonics (or multipoles)

NORMAL : vertical field on mid-plane



Dipole	Quadrupole	Sextupole	Octupole
$\|B\|=const$	$\|B\|=G\cdot r$	$\|B\|=1/2\cdot B''\cdot r^2$	$\|B\|=1/6\cdot B'''\cdot r^3$



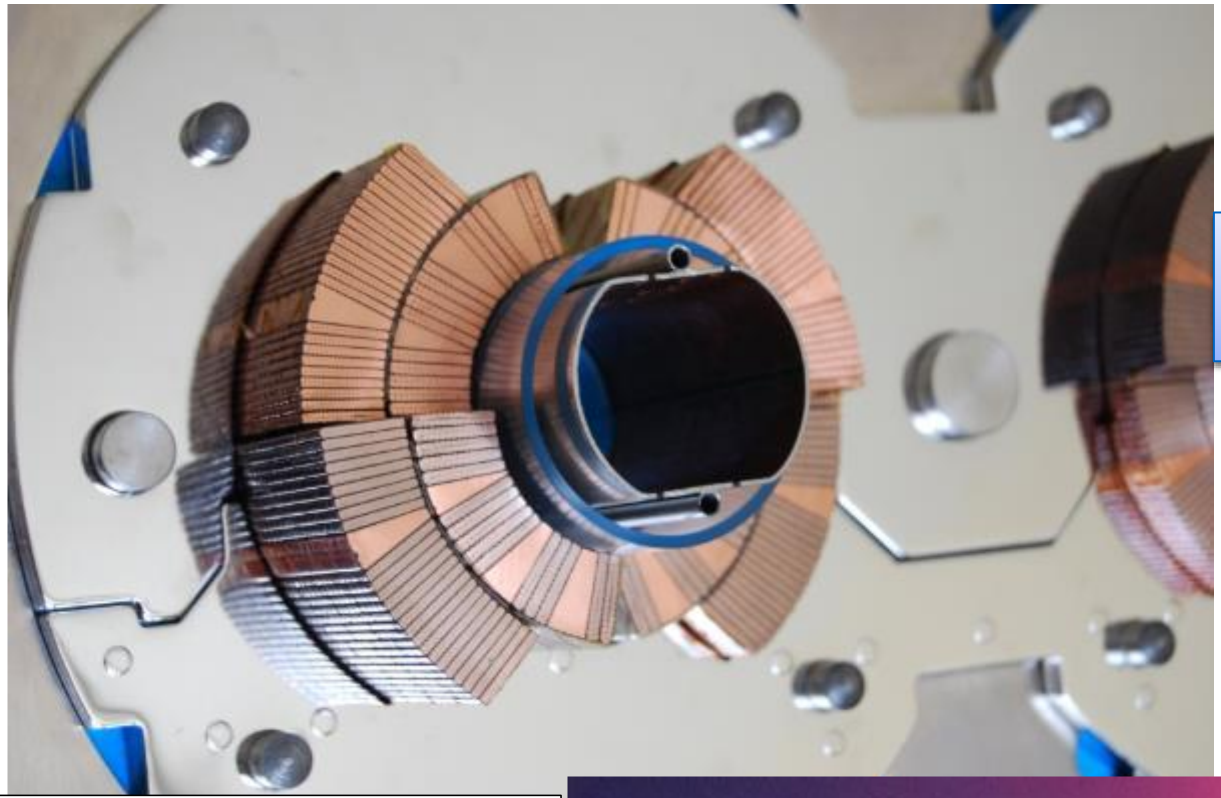
SKEW : horizontal field on mid-plane

Accelerator Magnets: basics

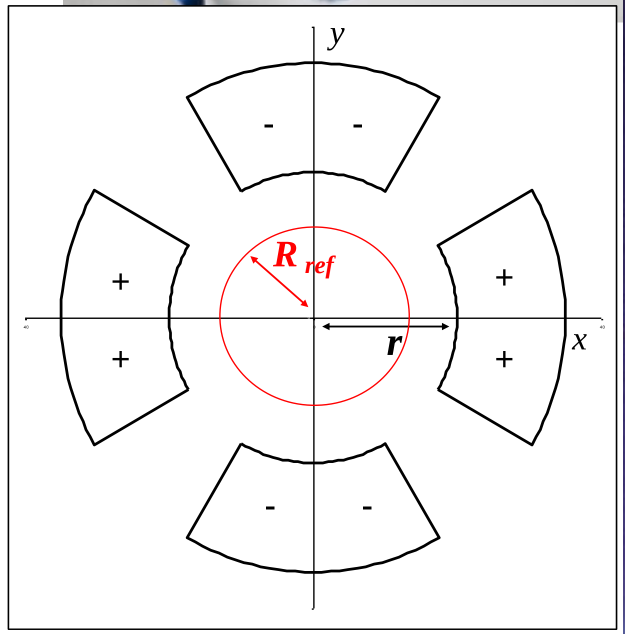
- The basic shape : cosϑ shell
- Shells with const J is a very good approximation
- Field expansion

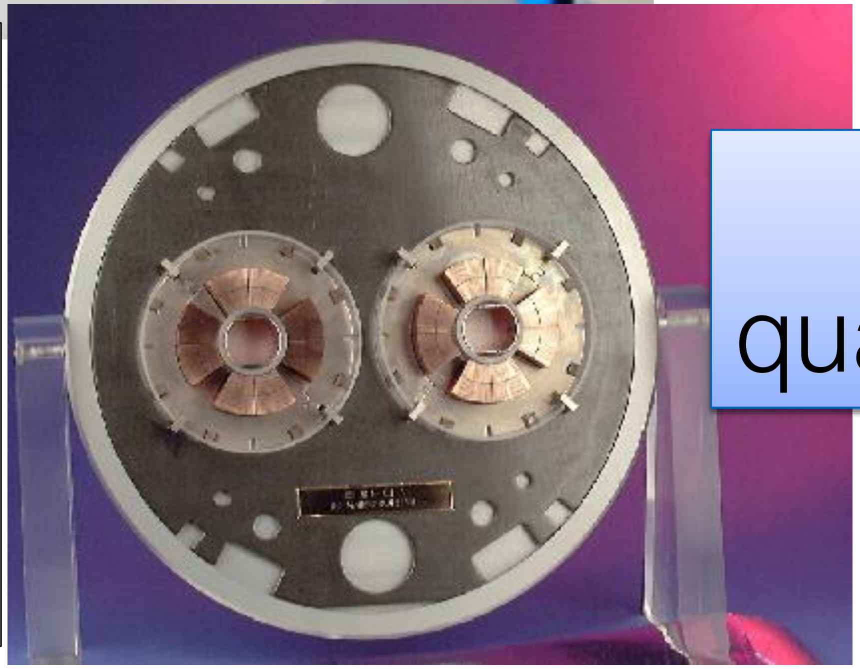
$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

Field quality at 0.1÷1 10^{-4} level
→ Coil accuracy: 10÷50 μm
over 15 m !



LHC dipole



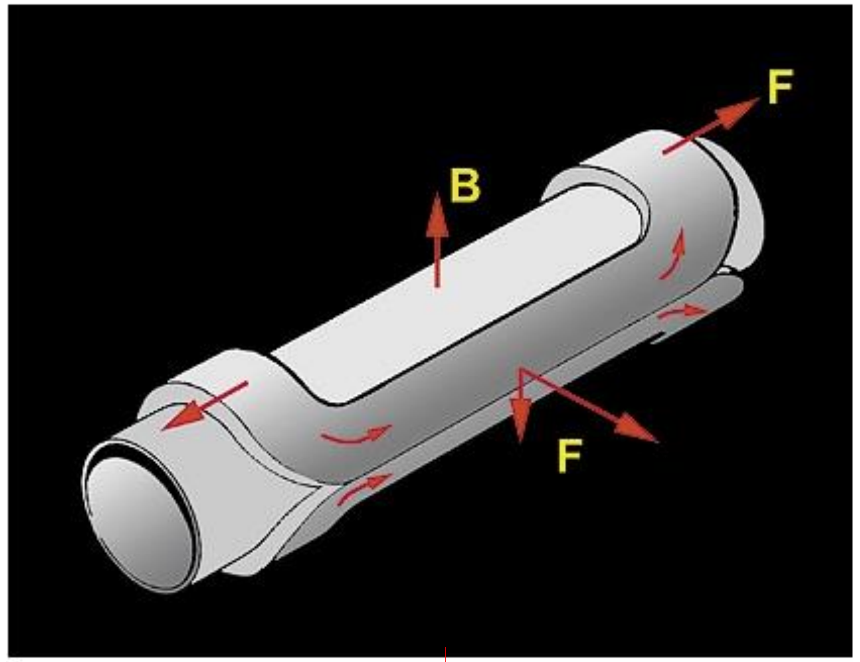


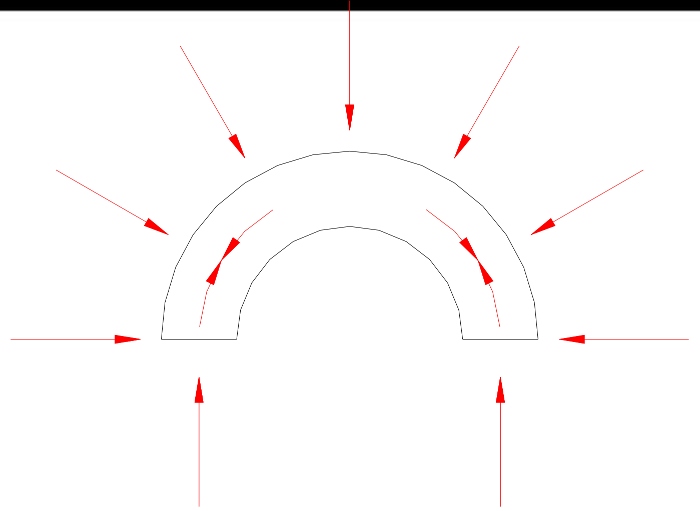
LHC quadrupole

Accelerator Magnets: basics - II

$J_{overall}$ ≈ 500 A/mm² ! **e.m. forces are not kept by conductors but tend to torn apart the winding.**

Principle





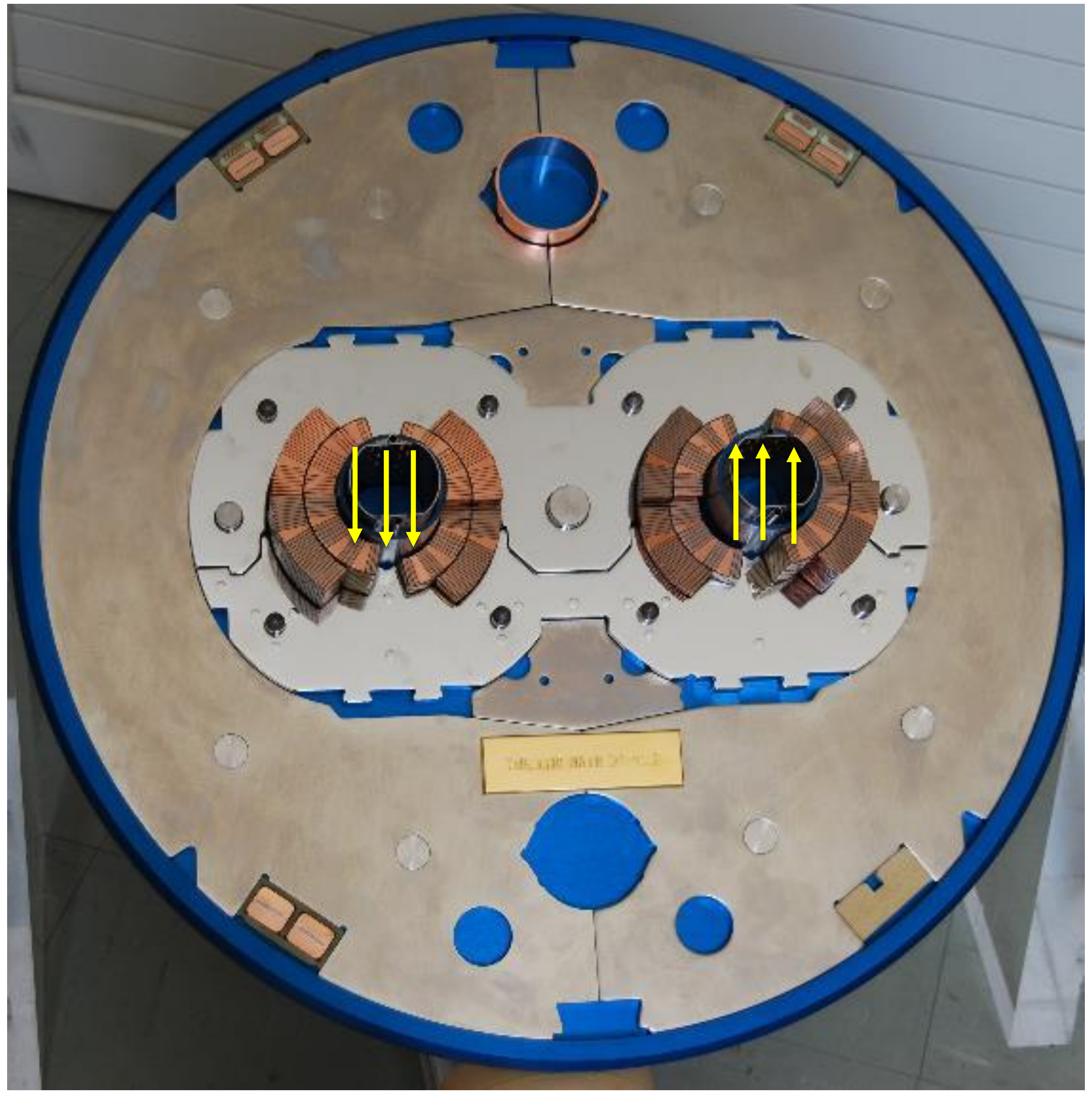
e.m. forces

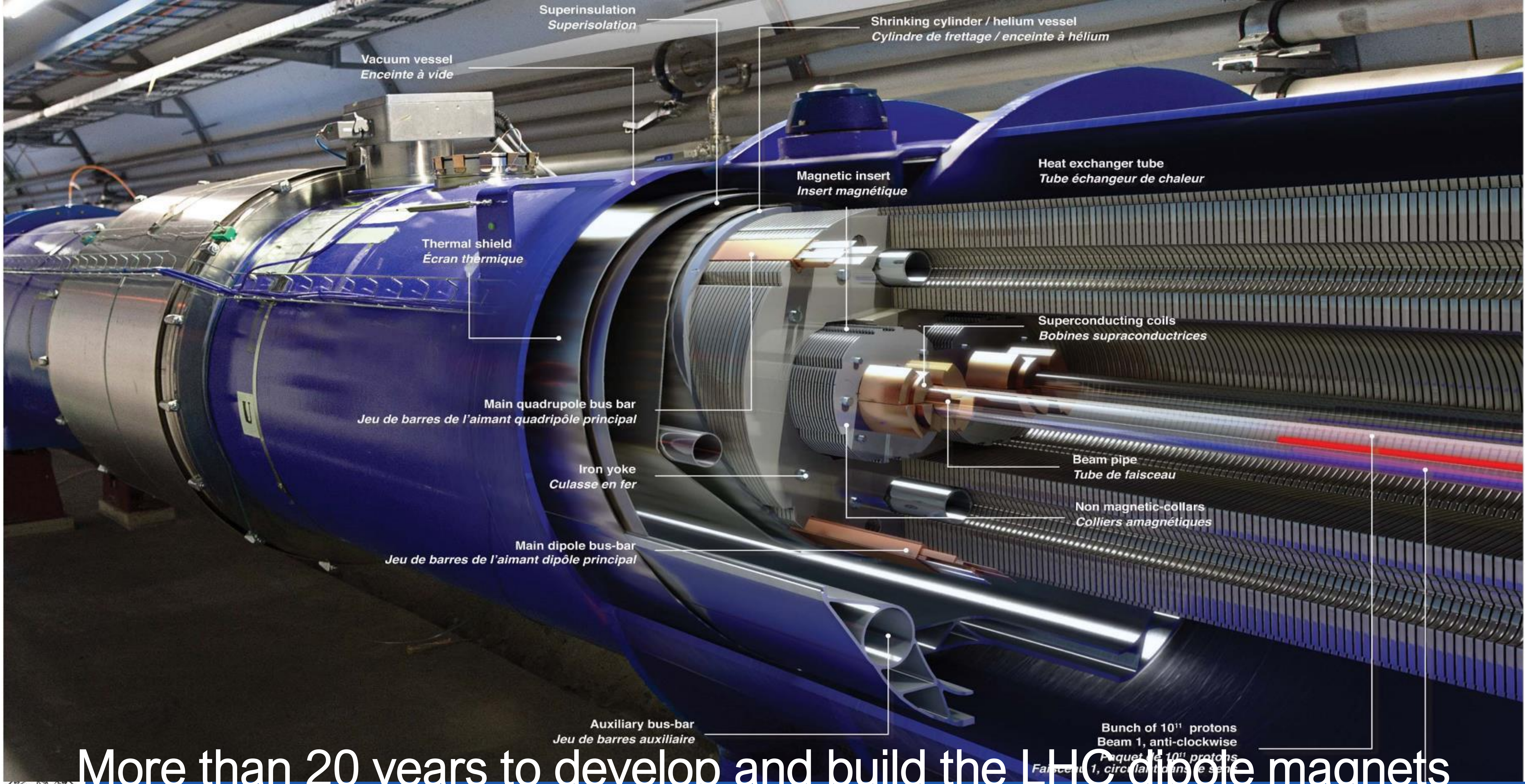
NOT SELF-SUPPORTING

How to contain them

More difficult in twin magnets!

Reality

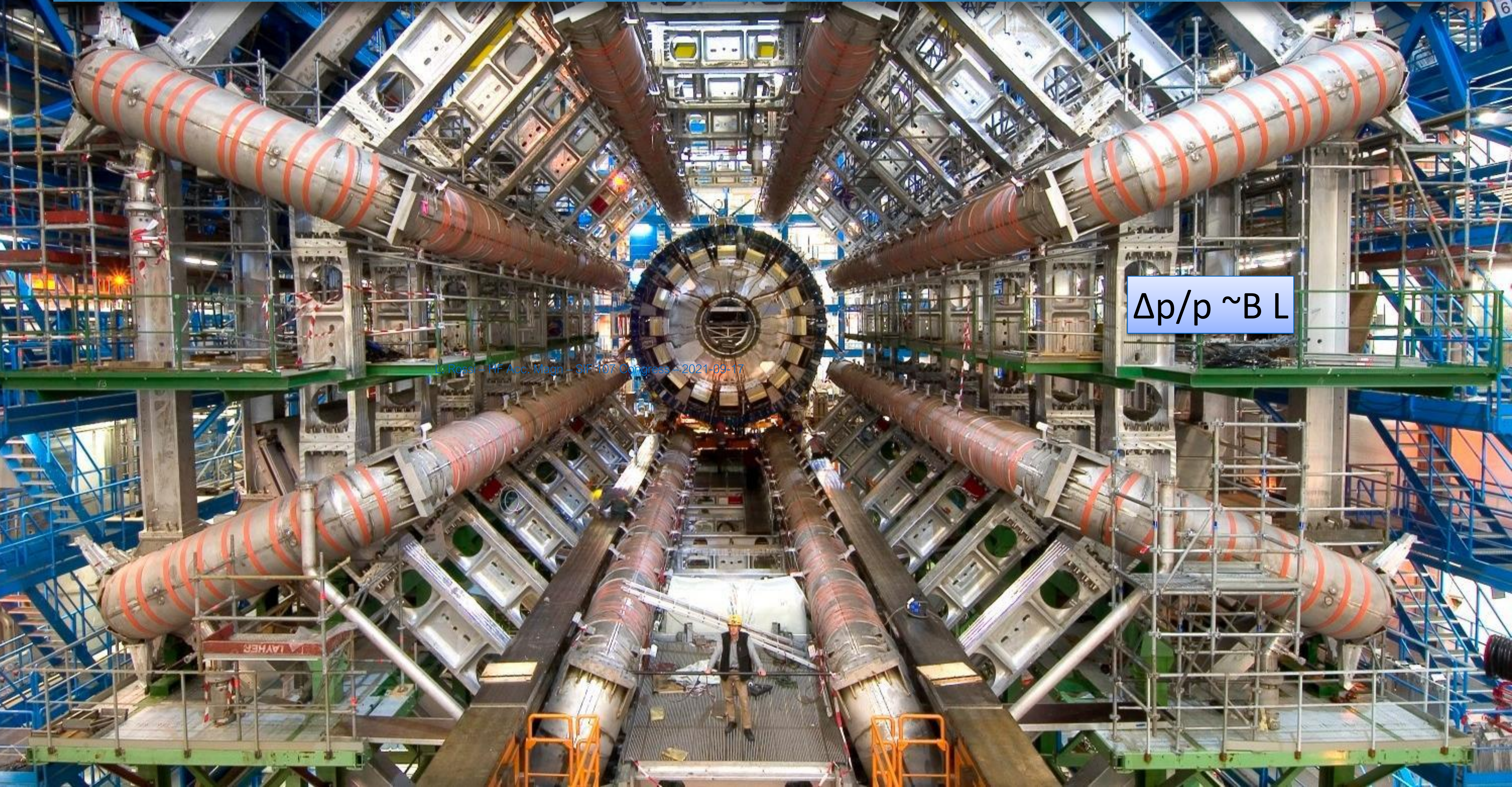




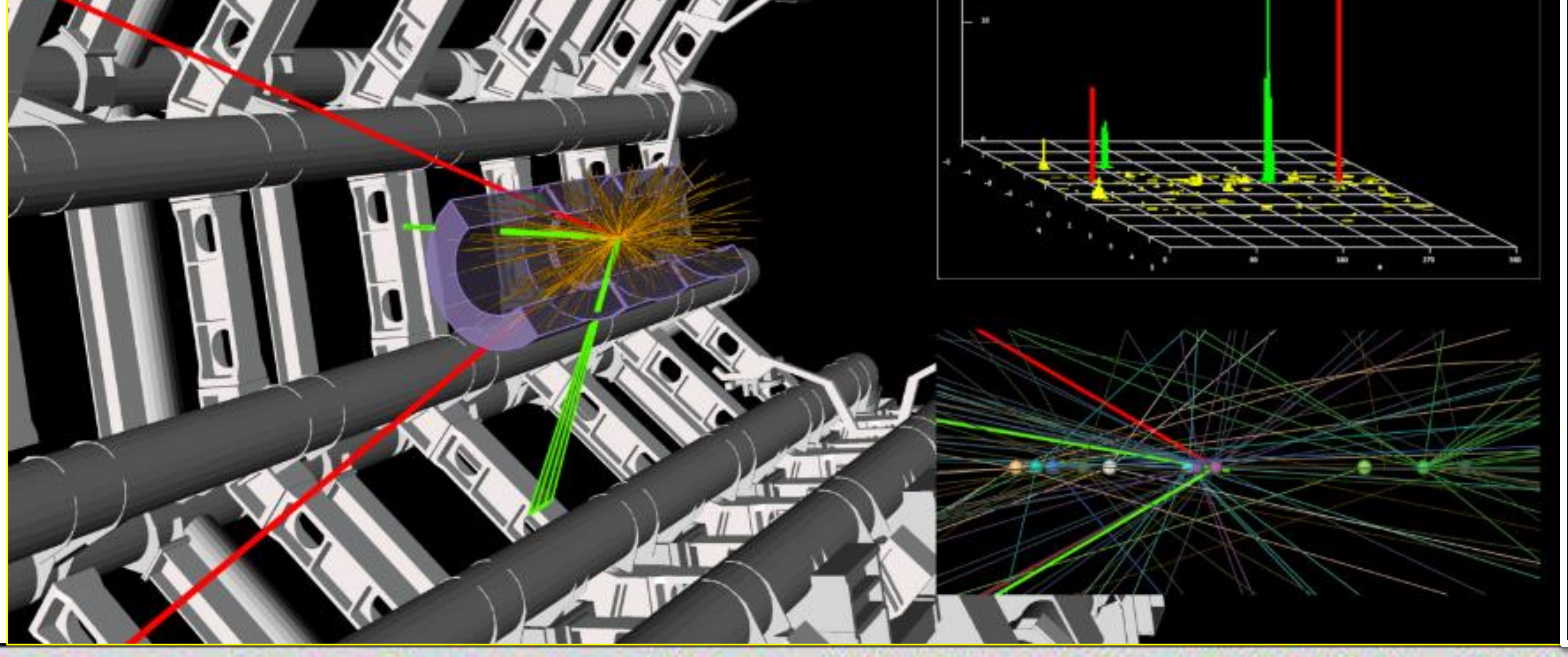
More than 20 years to develop and build the LHC dipole magnets

LHC and its big four eyes

Particle detectors may use huge SC Magnets: **ATLAS**@LHC

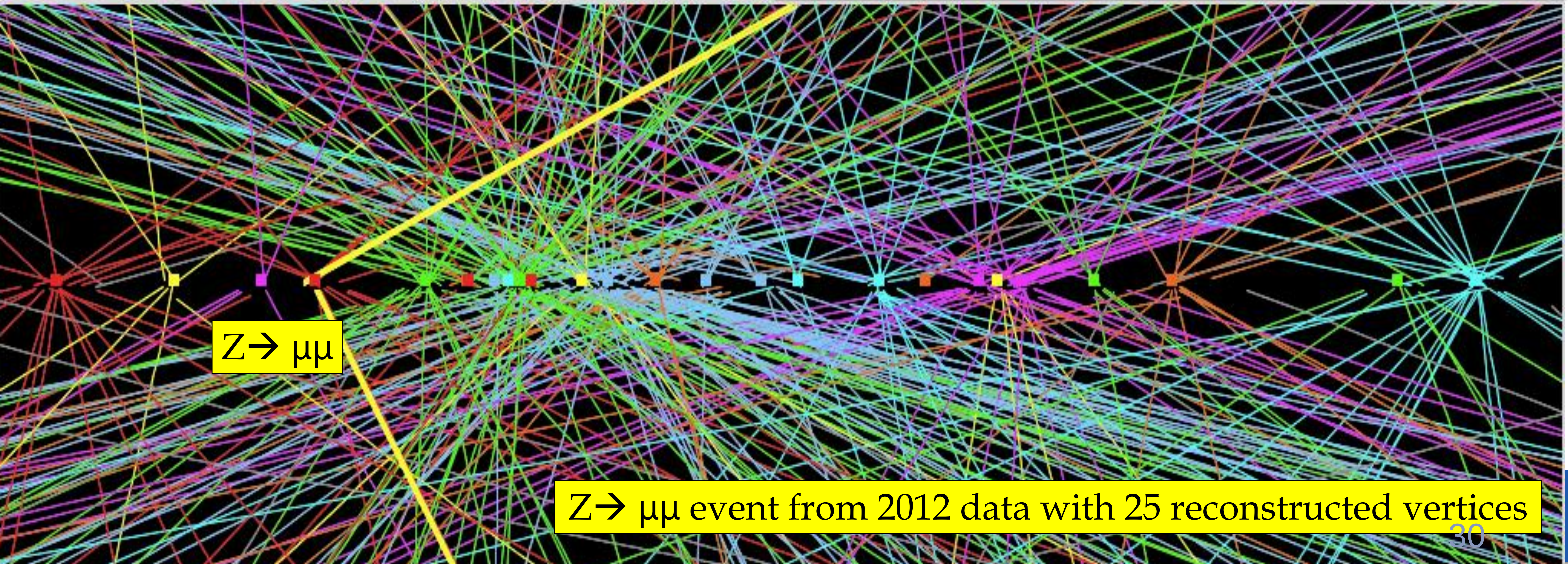


$\Delta p/p \sim B\,L$

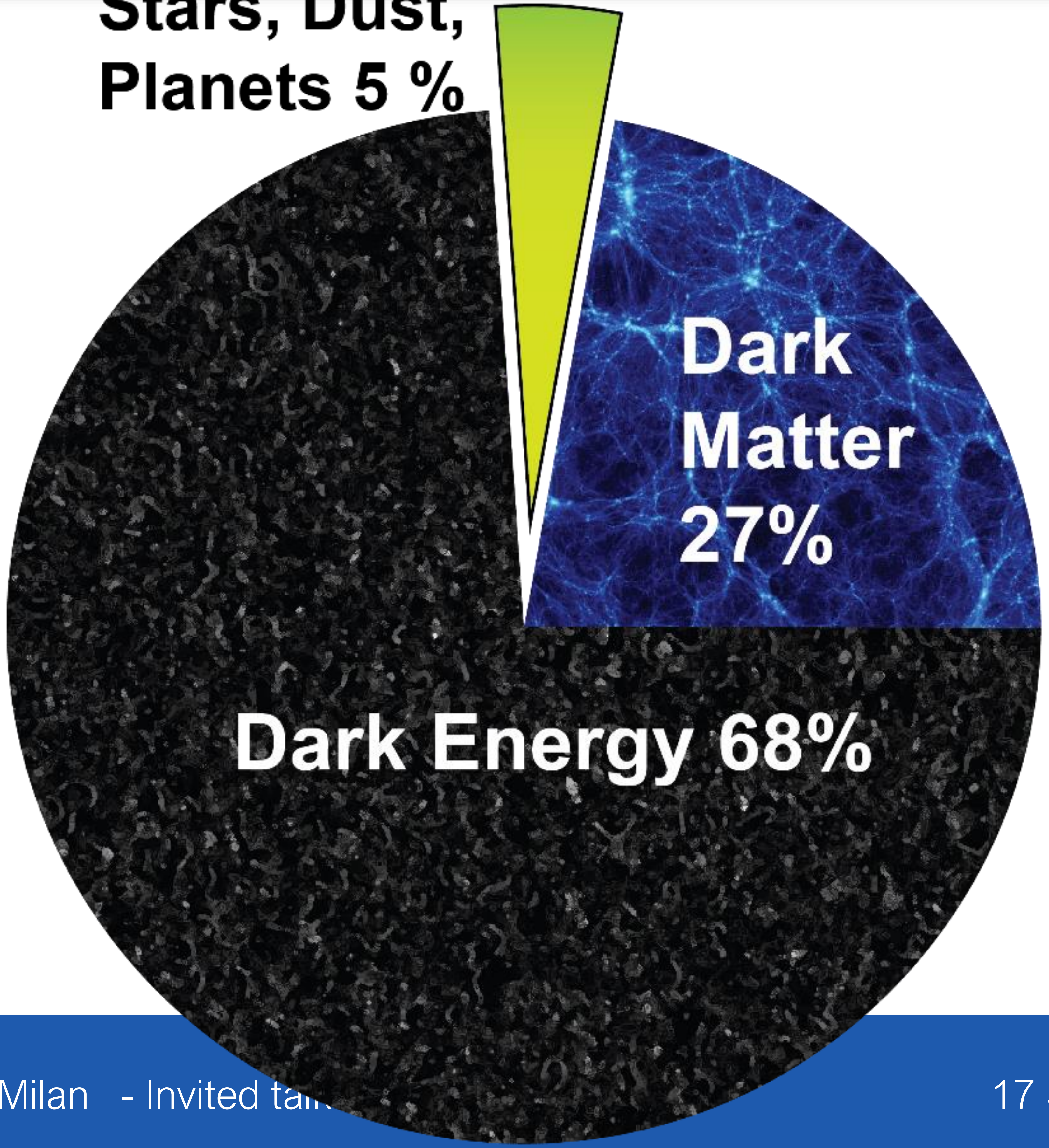


Only 1/10 Bil we “can see” a Higgs boson!

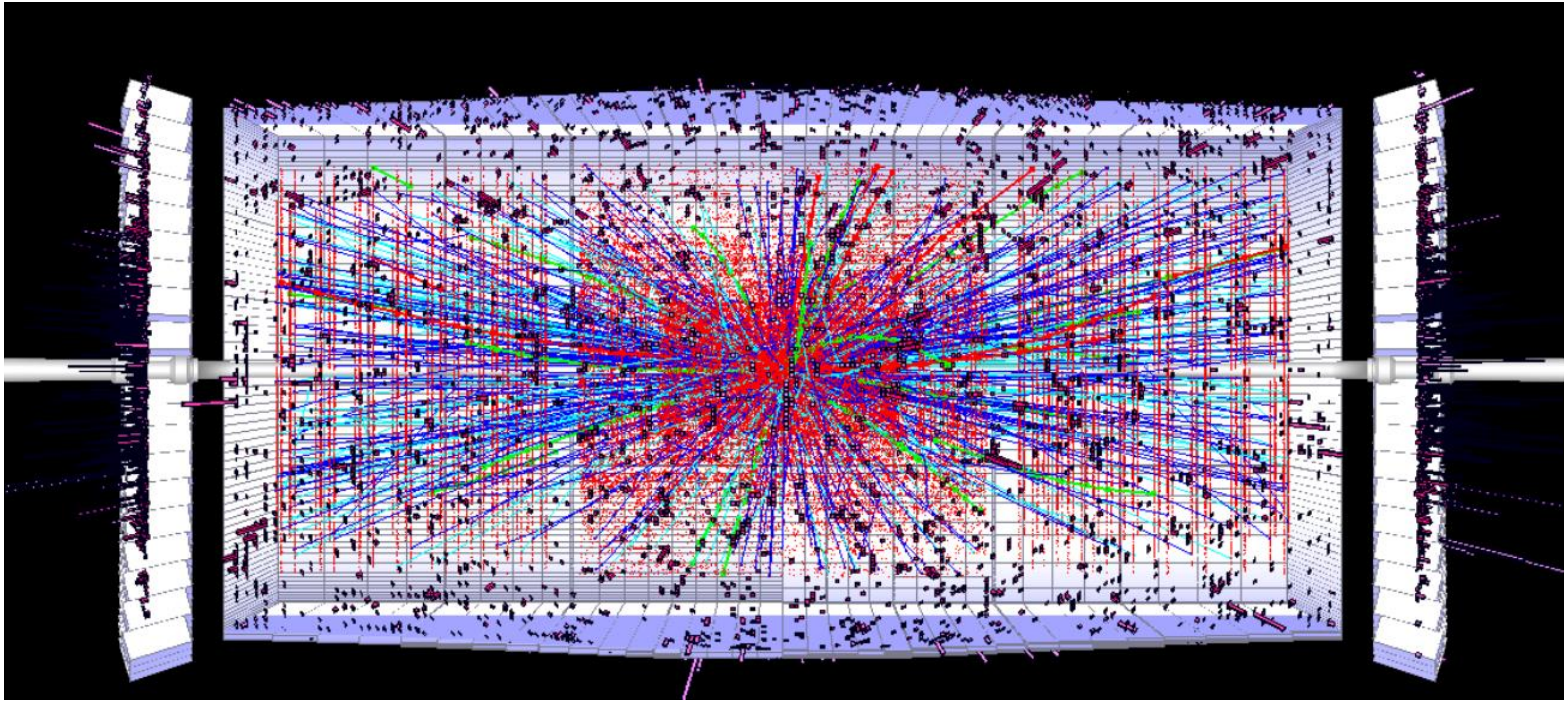
It si really searching for the needle in a haystack!



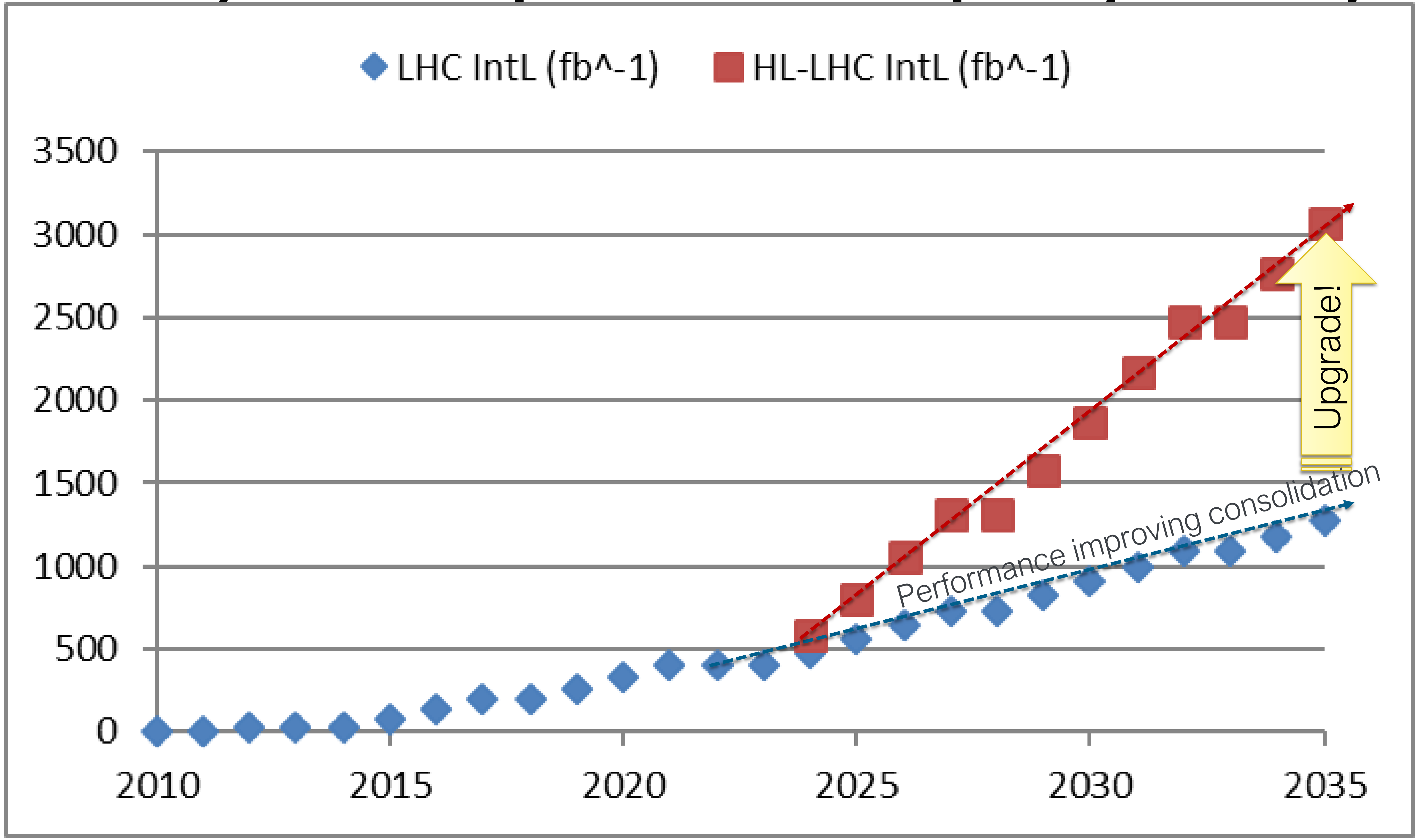
Cosmology tells us that we still miss the most!



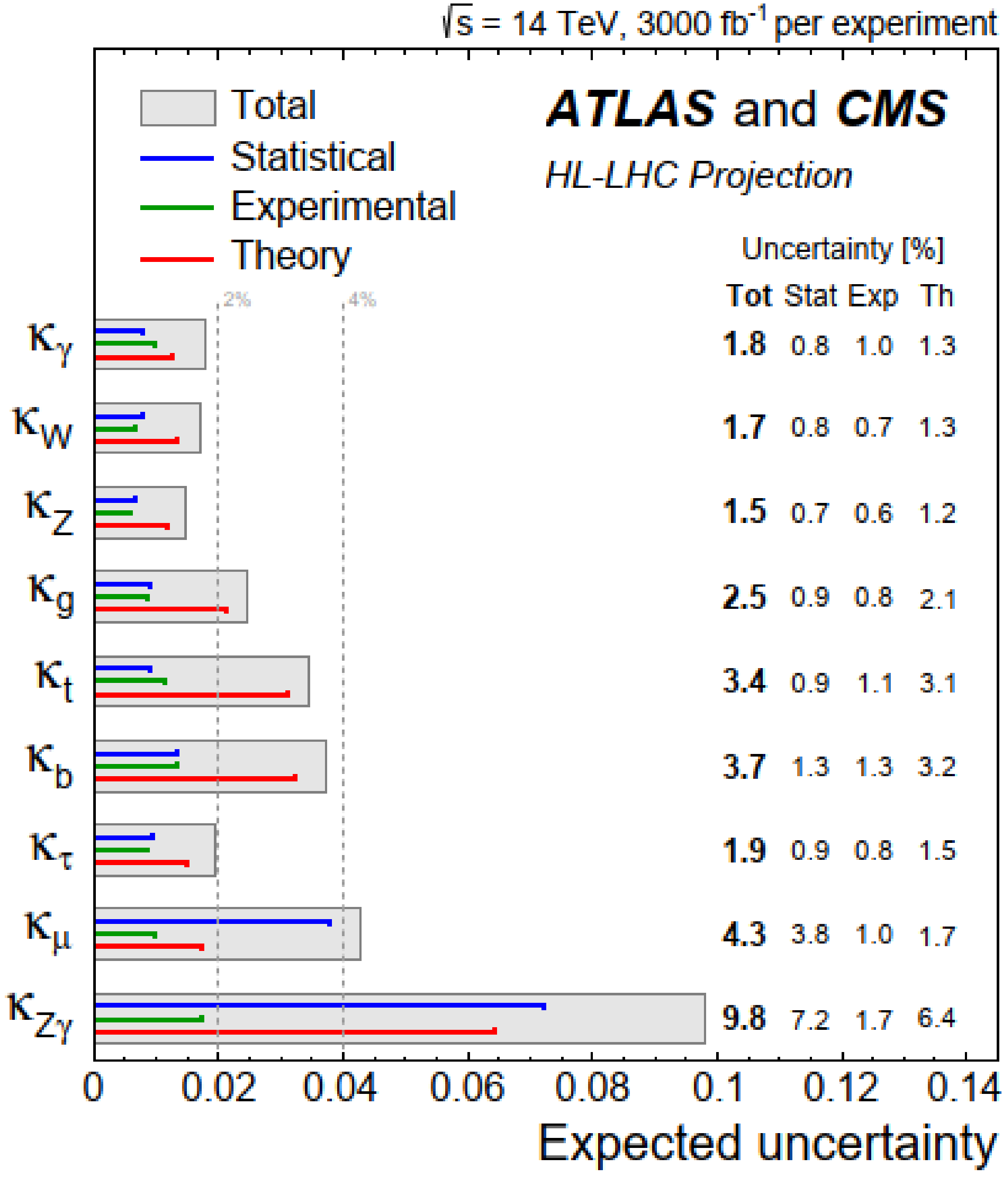
High Luminosity: a bright future for the LHC
Generate more light → machine upgrade
Better eyes to profit of higher luminosity → detector upgrade

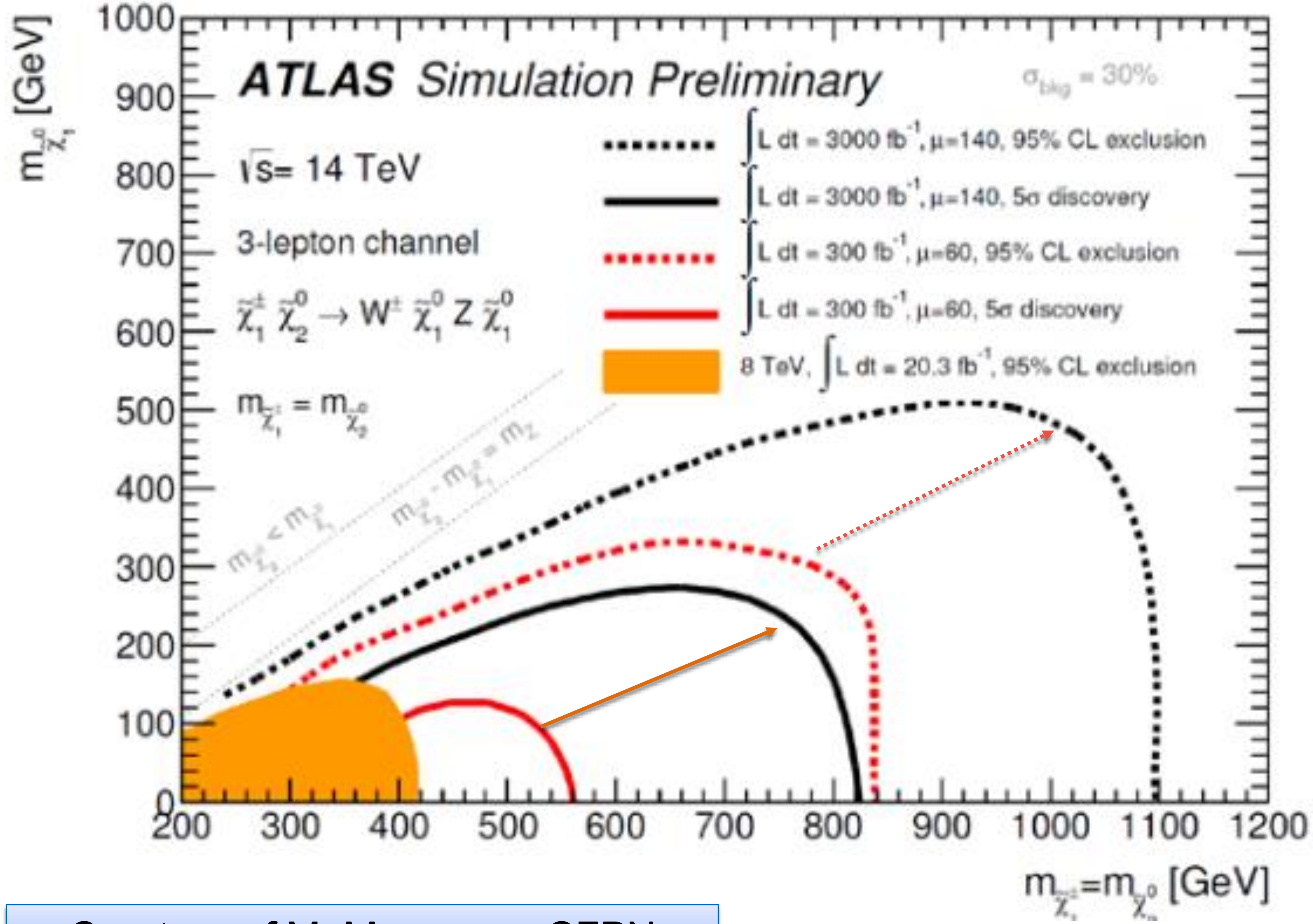


Why not just keep going



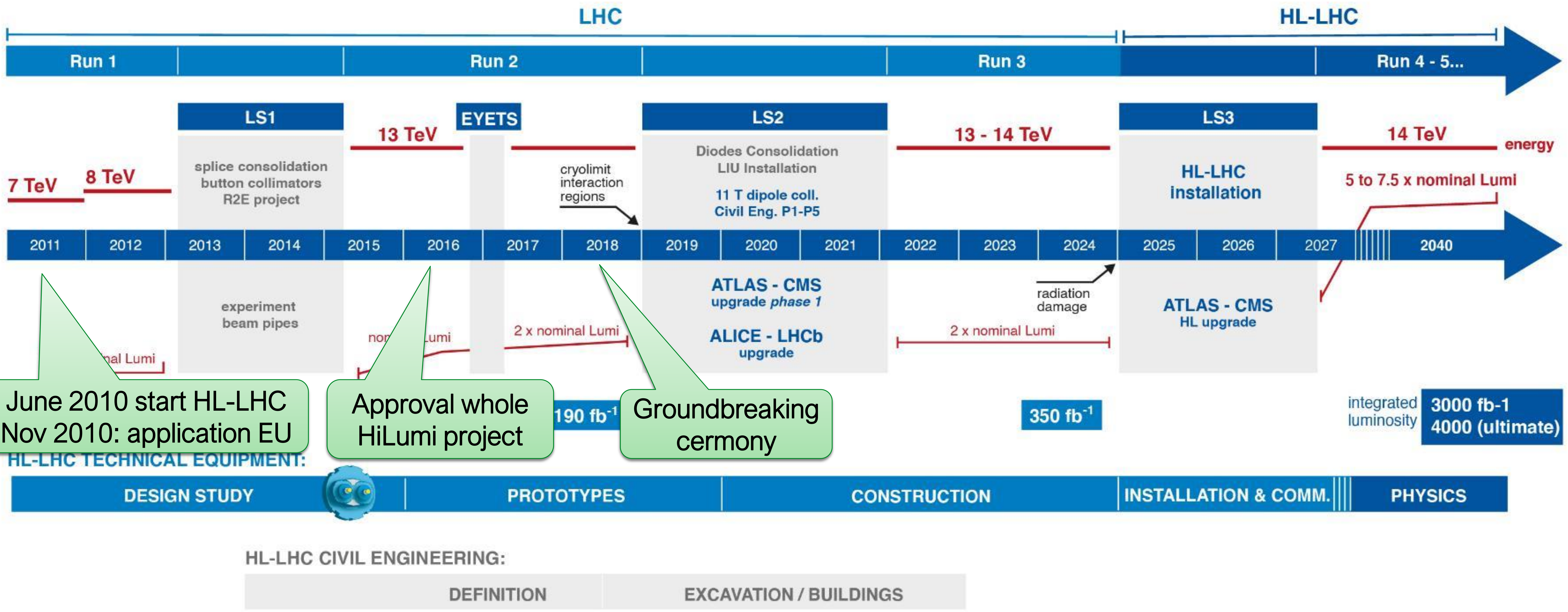
HL-LHC expands the Physics reach of LHC





Courtesy of M. Mangano , CERN

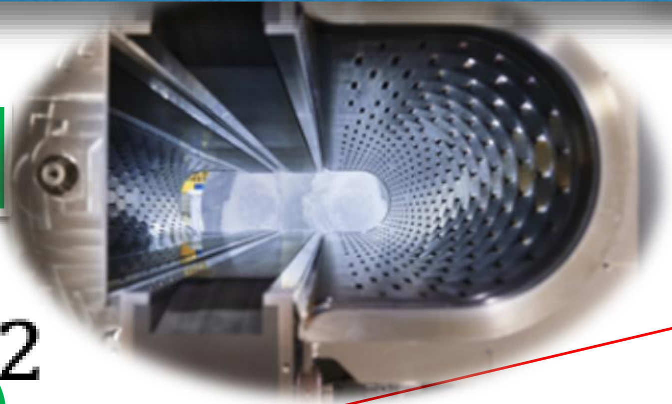
LHC / HL-LHC Plan



Parameters governing the luminosity in H-Colliders

LHC Injectors Upgrade

Beam current

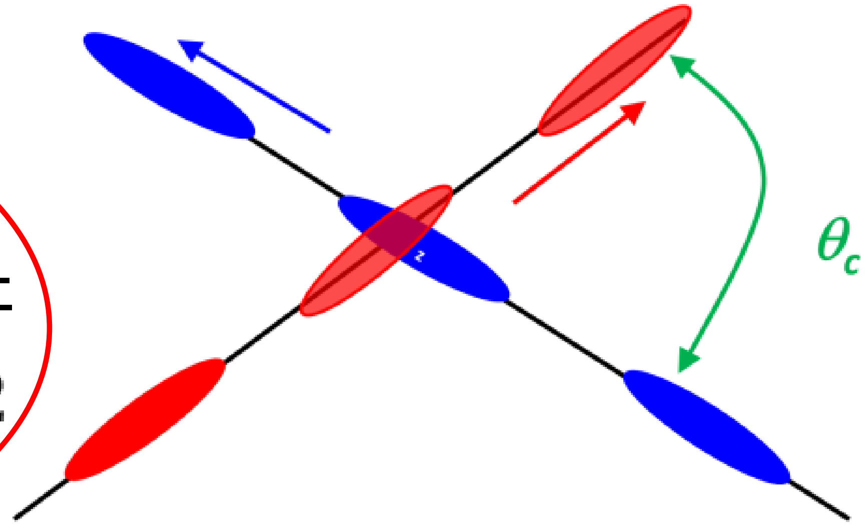


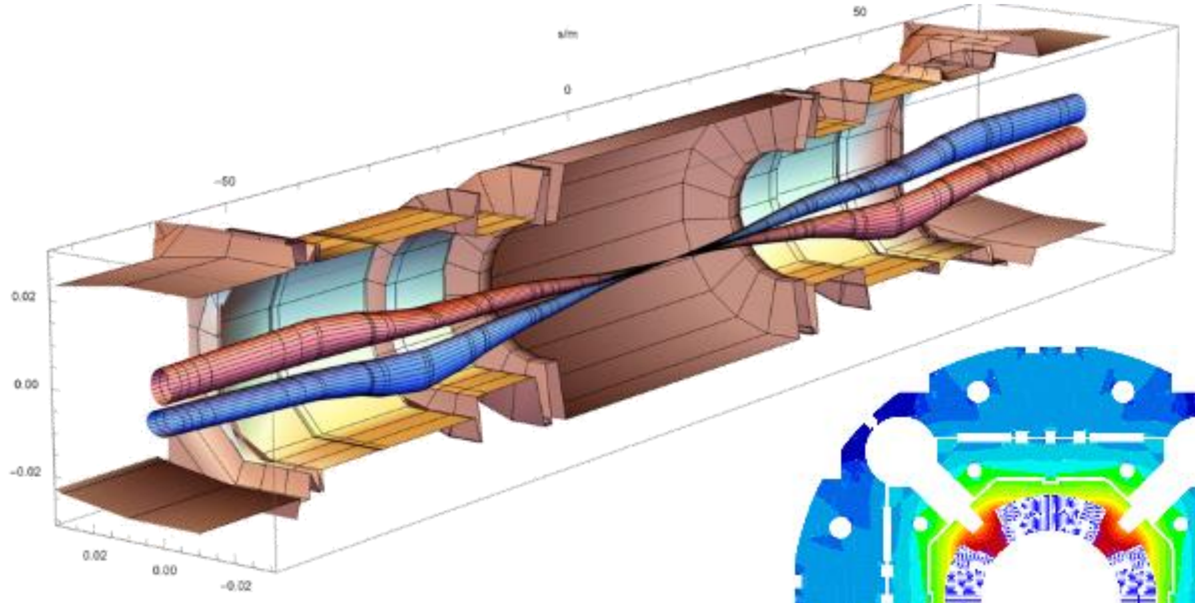
$$L = \gamma \frac{f_{rev}\, n_b\, N_b^{\,2}}{4\pi \varepsilon_n \beta^*} R$$

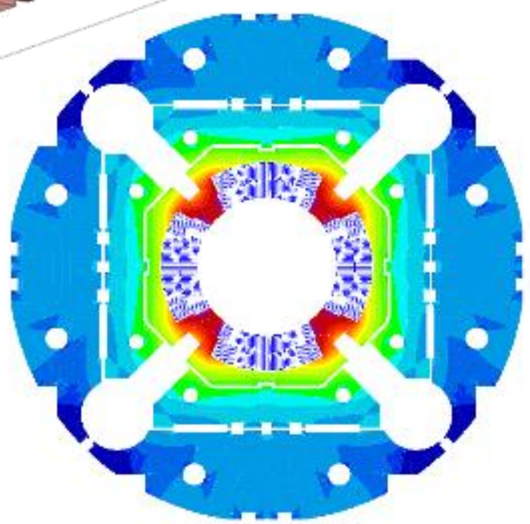
energy

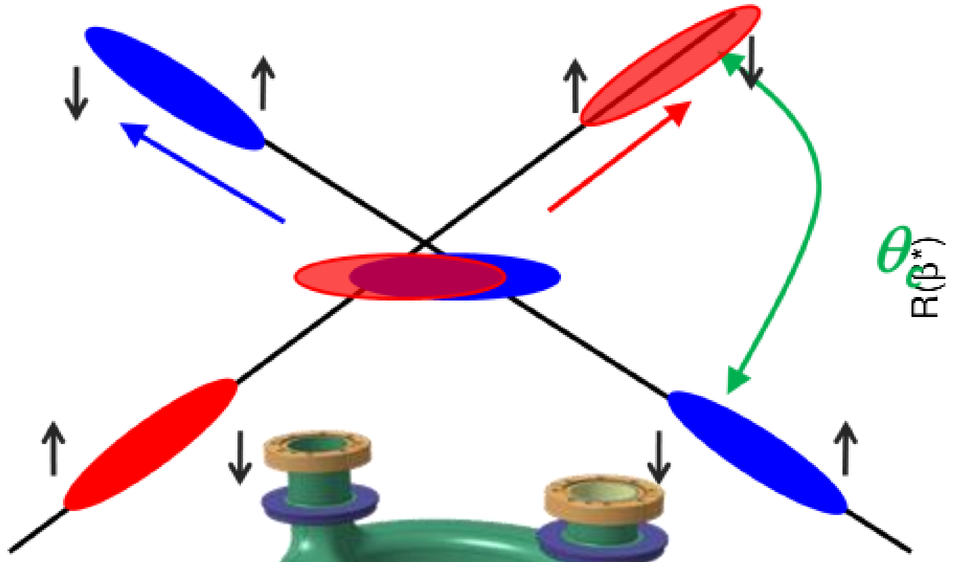
Beam size

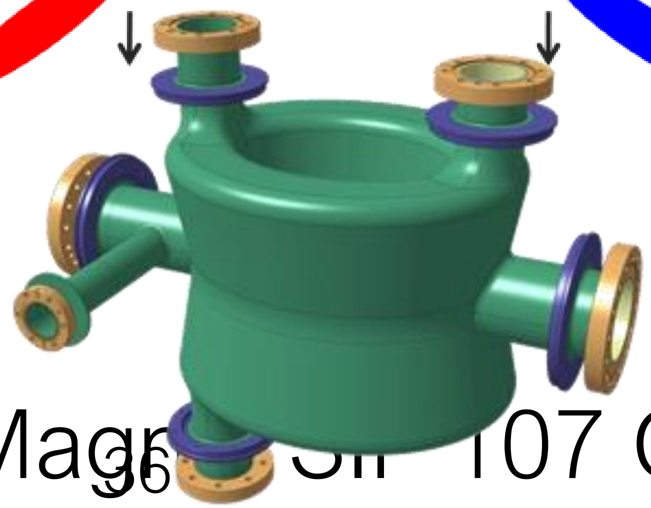
$$R = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_s}{2\varepsilon_n \beta^*}\gamma\right)^2}}$$

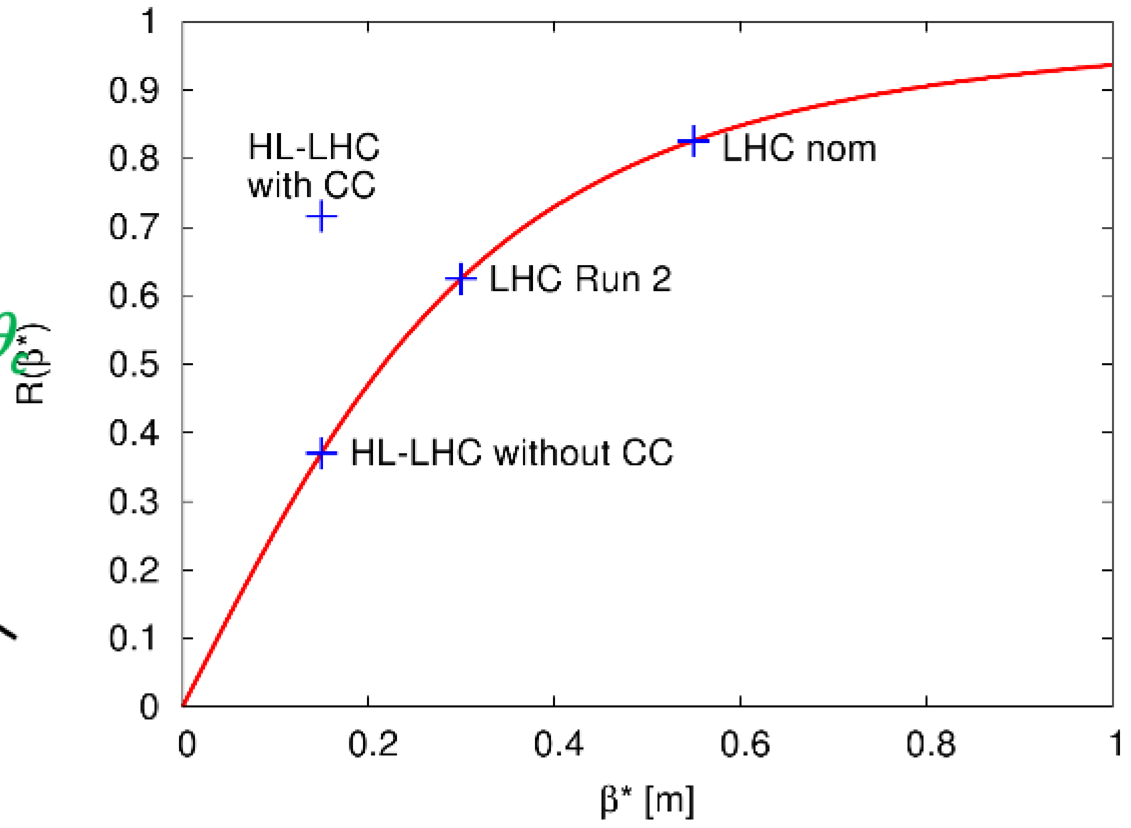








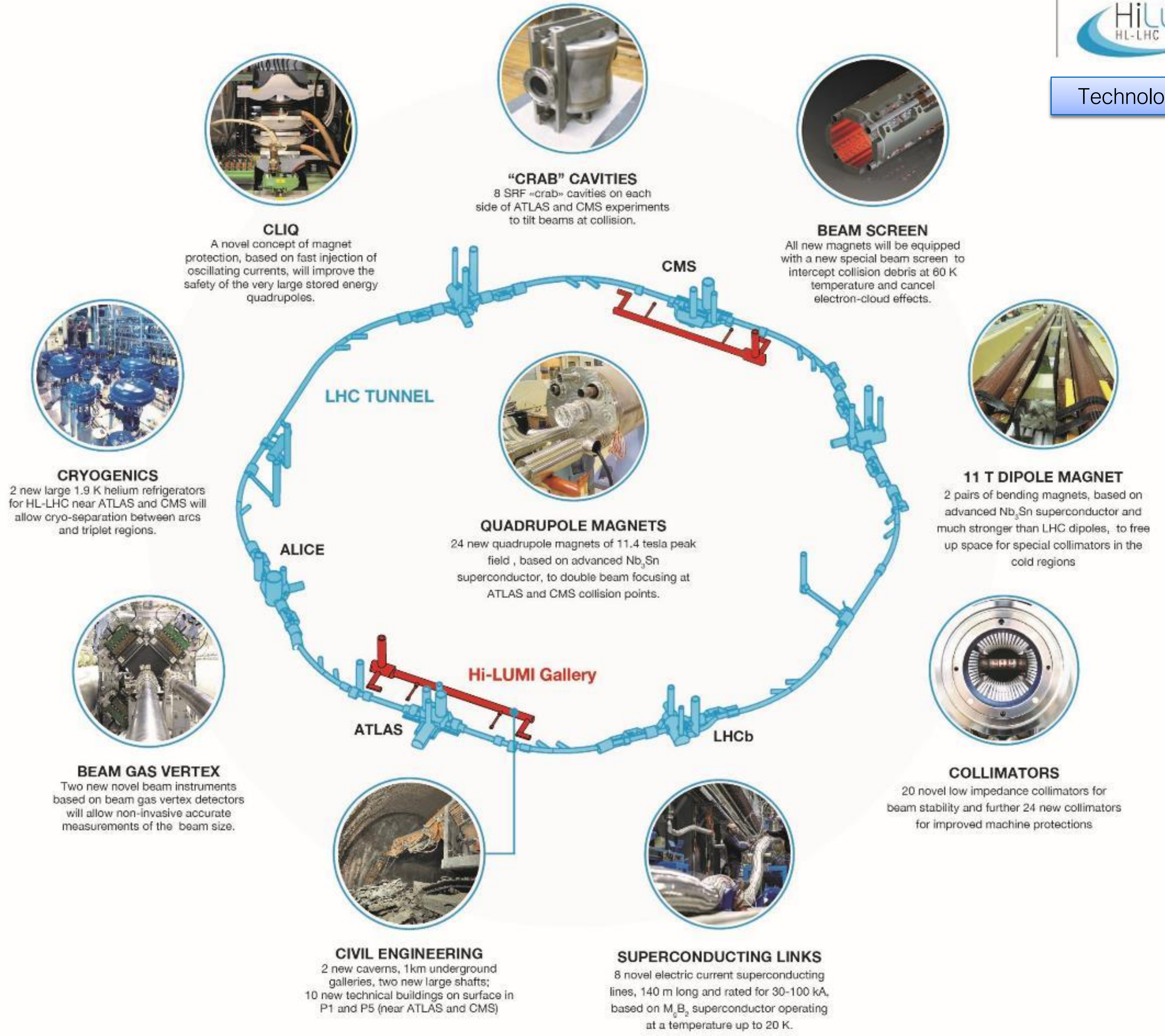




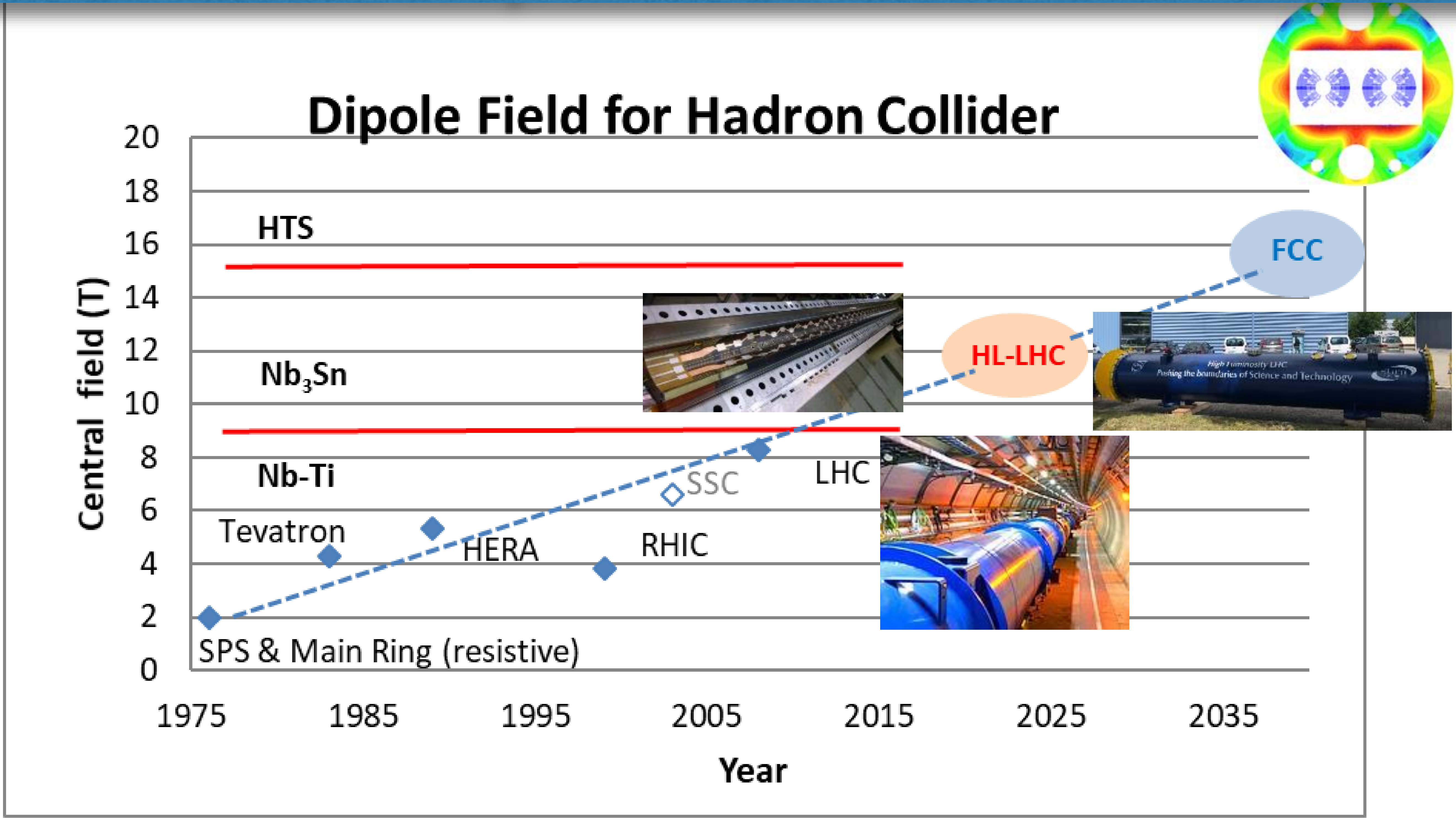
Technology landmarks

No accelerator project has so many absolute novelties and in such a broad technology spectrum

Technology intensive project!



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

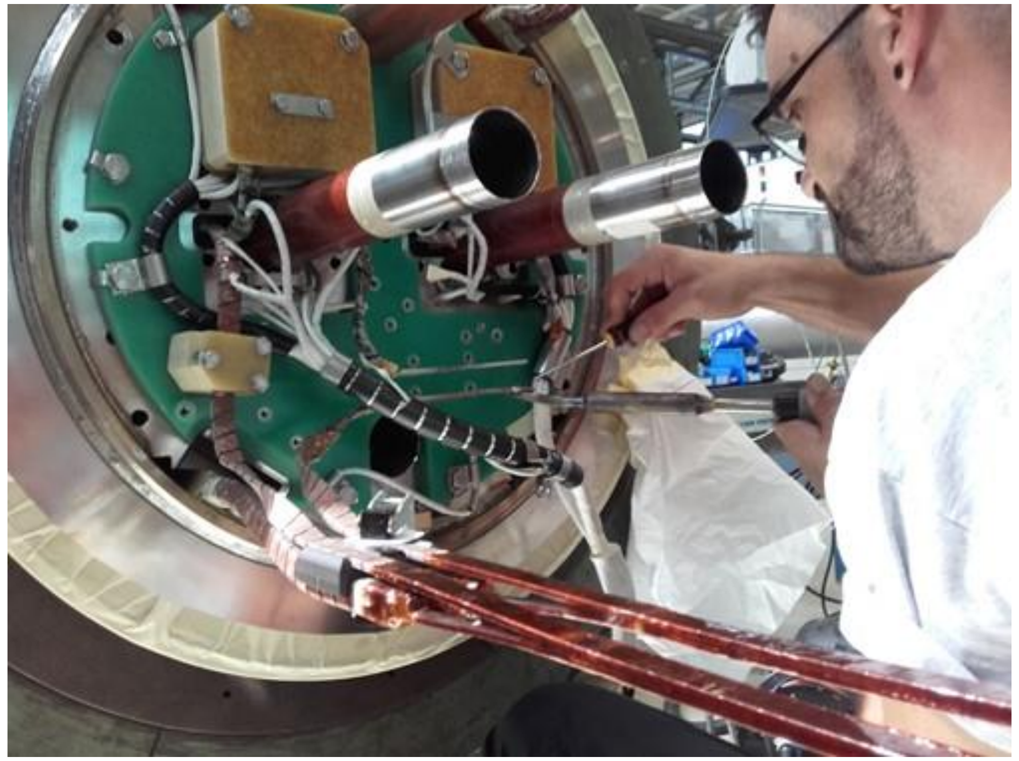


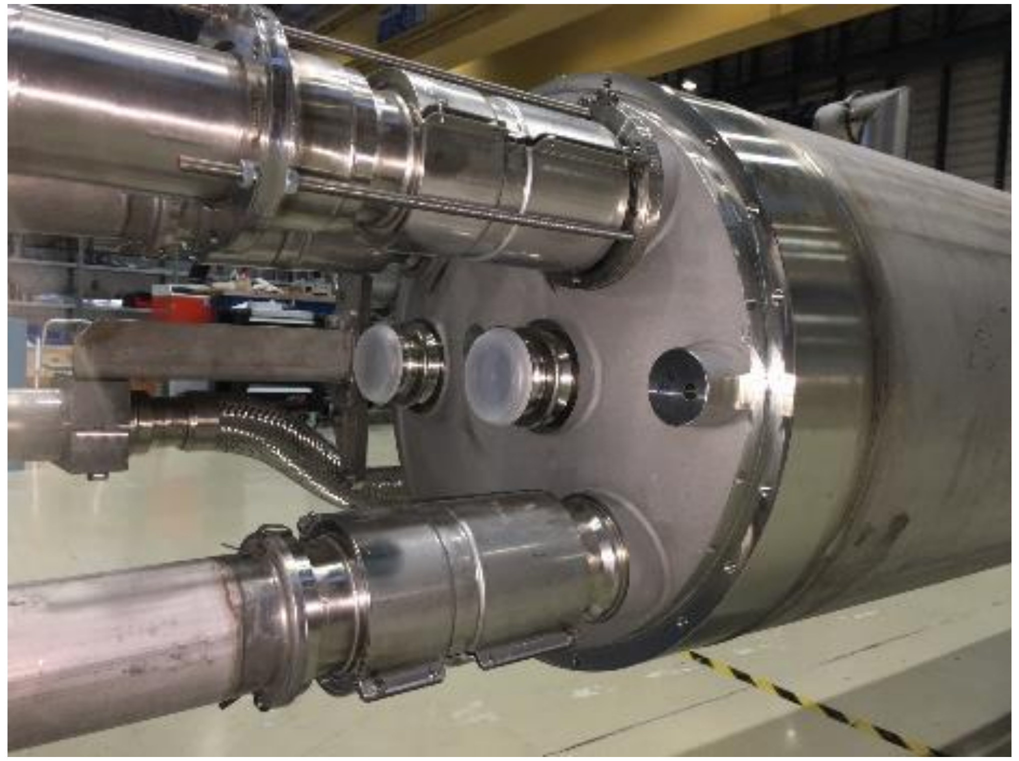
High Luminosity LHC Project: ten time more collisions than originally planned in the LHC (start 2026)

HL-LHC new equipment + service in the new gallees
1.2 km of new accelerator and 1 km new service tunnels ri

HiLumi
HL-LHC PROJECT

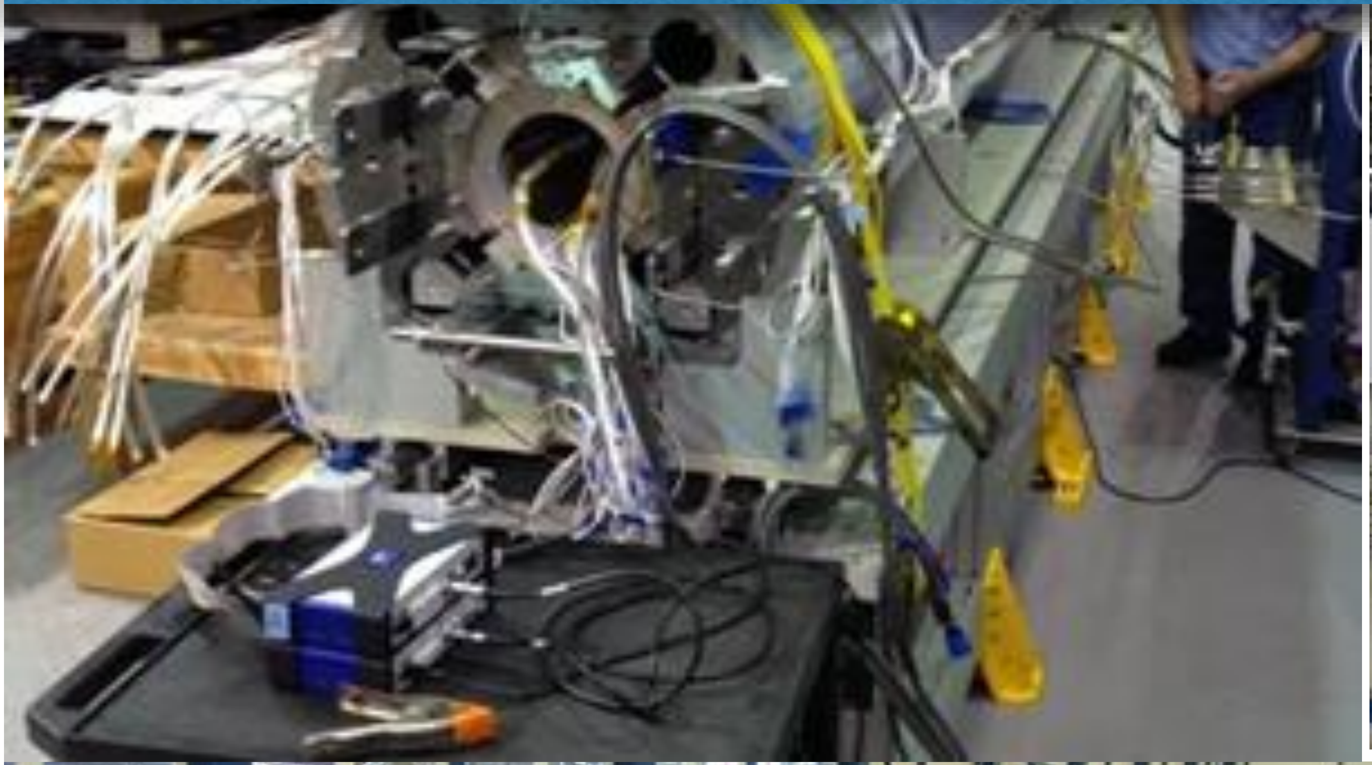
11 T durig production installation delayd to LS3 to take care of the stress sensitivity of Nb_3Sn



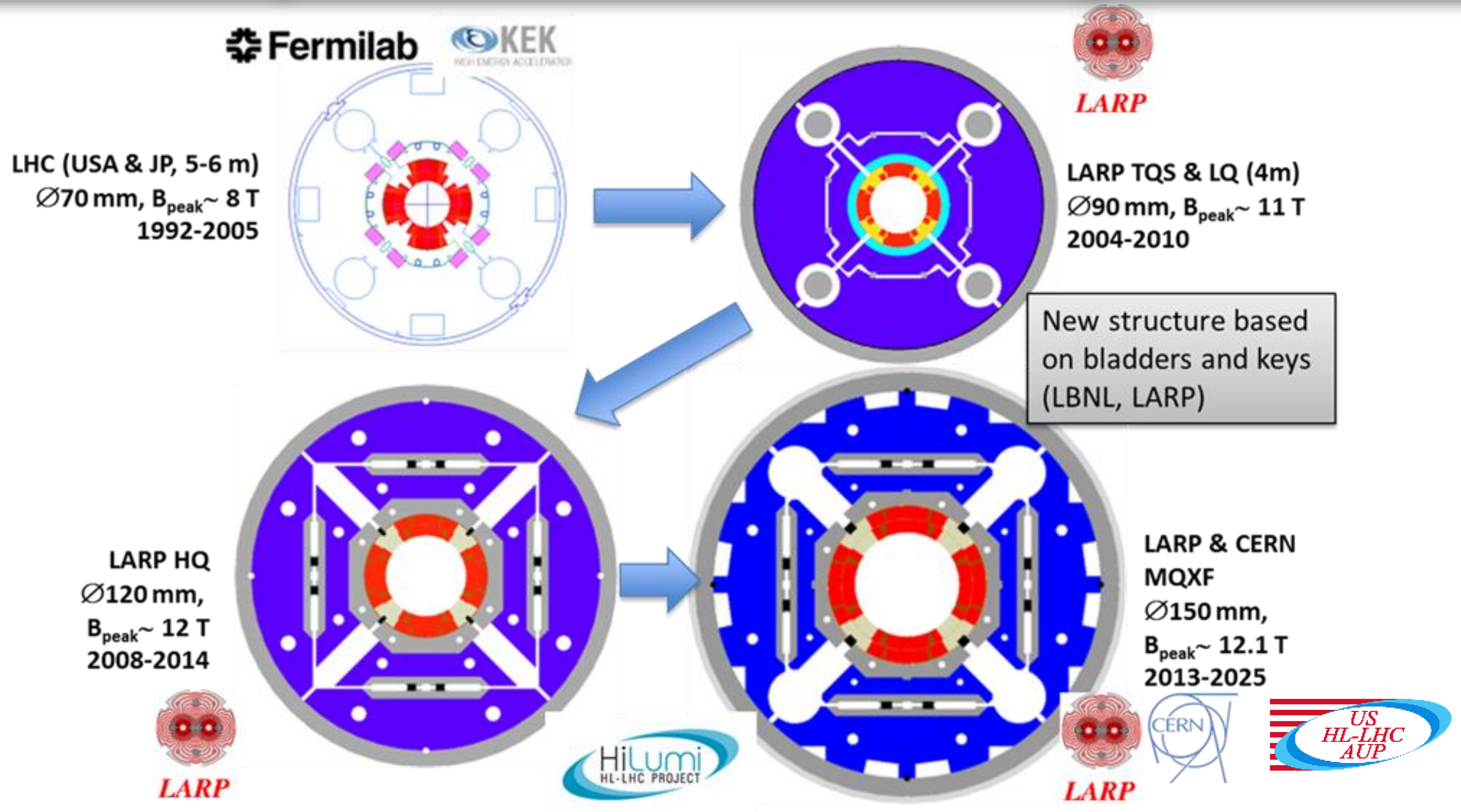


MBH-002 – first out of four 11 T dipoles.
Coils after impregnation;
magnet on test bench @ SM18 (July 2019)

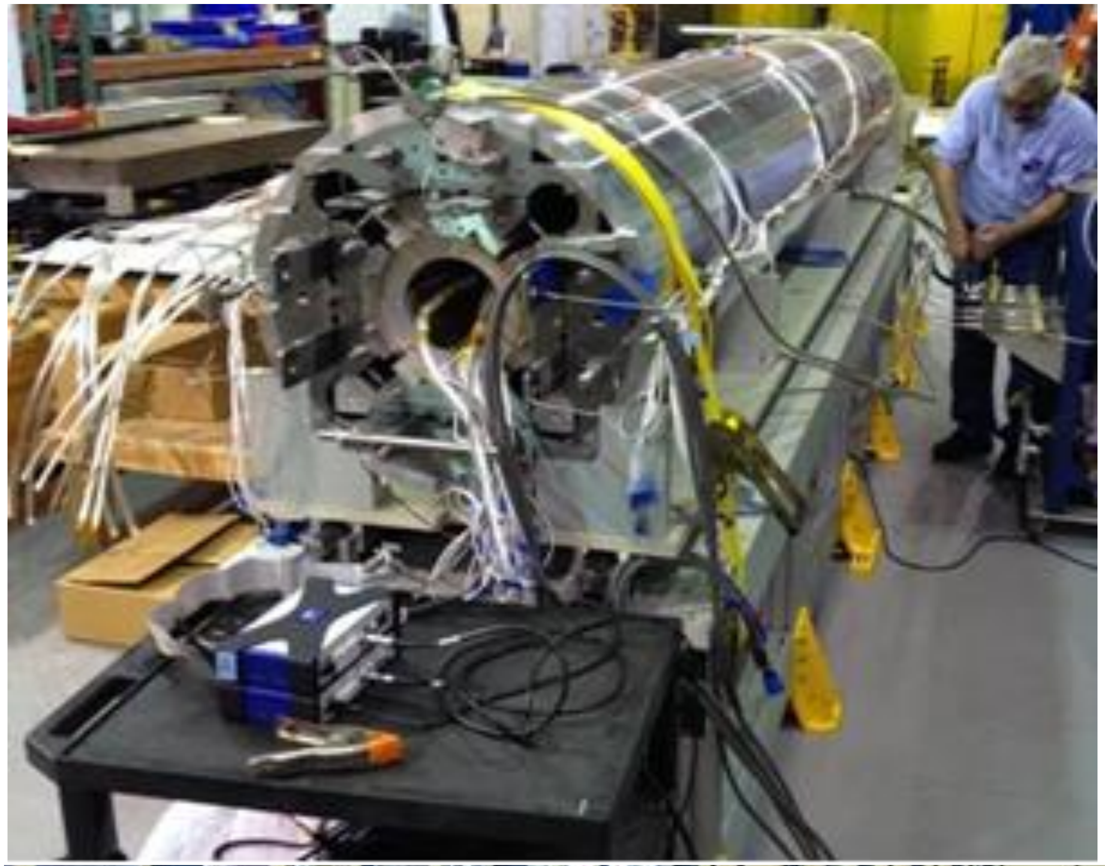
Breaking the LHC limit: Large QUADRUPOLE for HiLumi



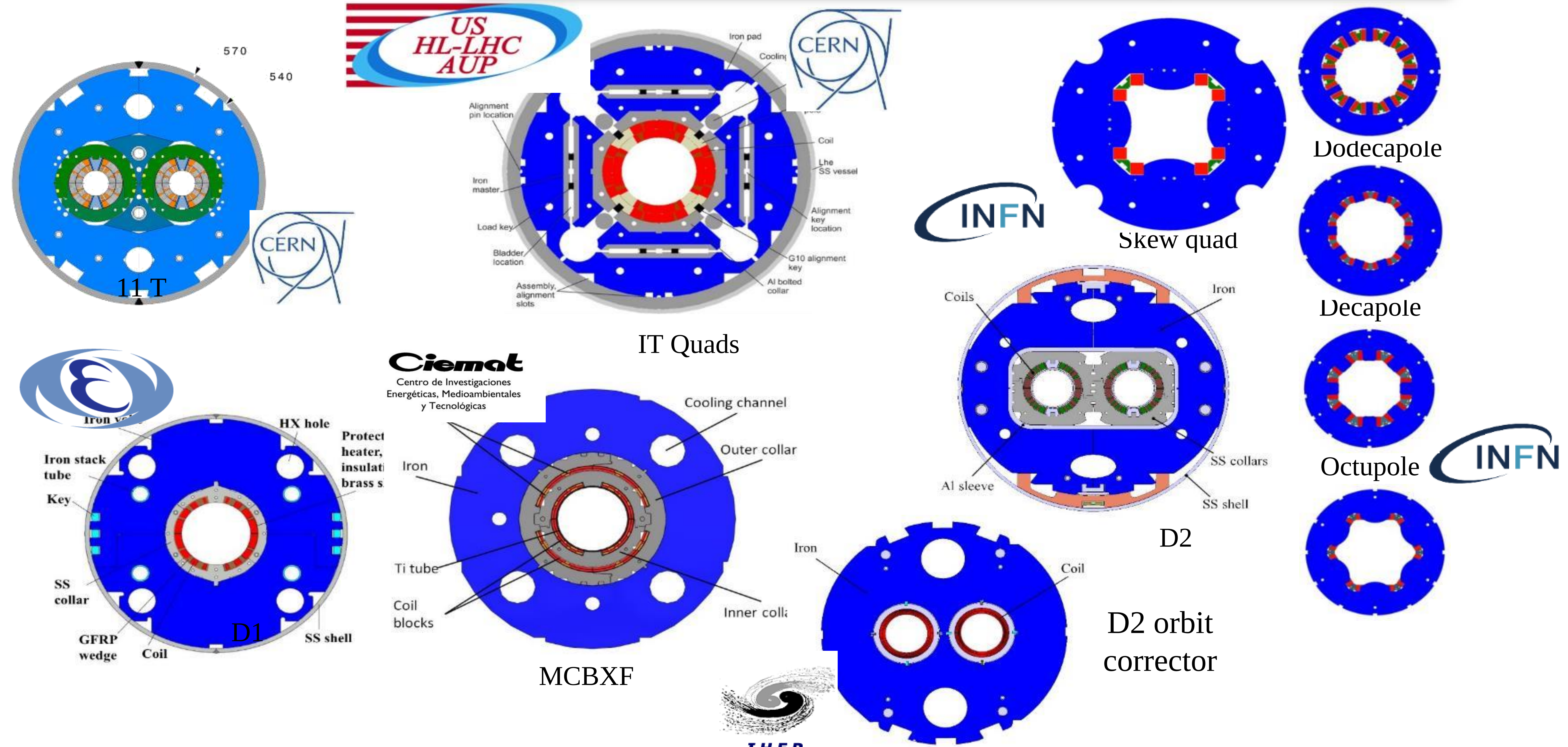
IT quadrupole. Increase in field but also in size wrt LHC. Very relevant also for FCC magnets



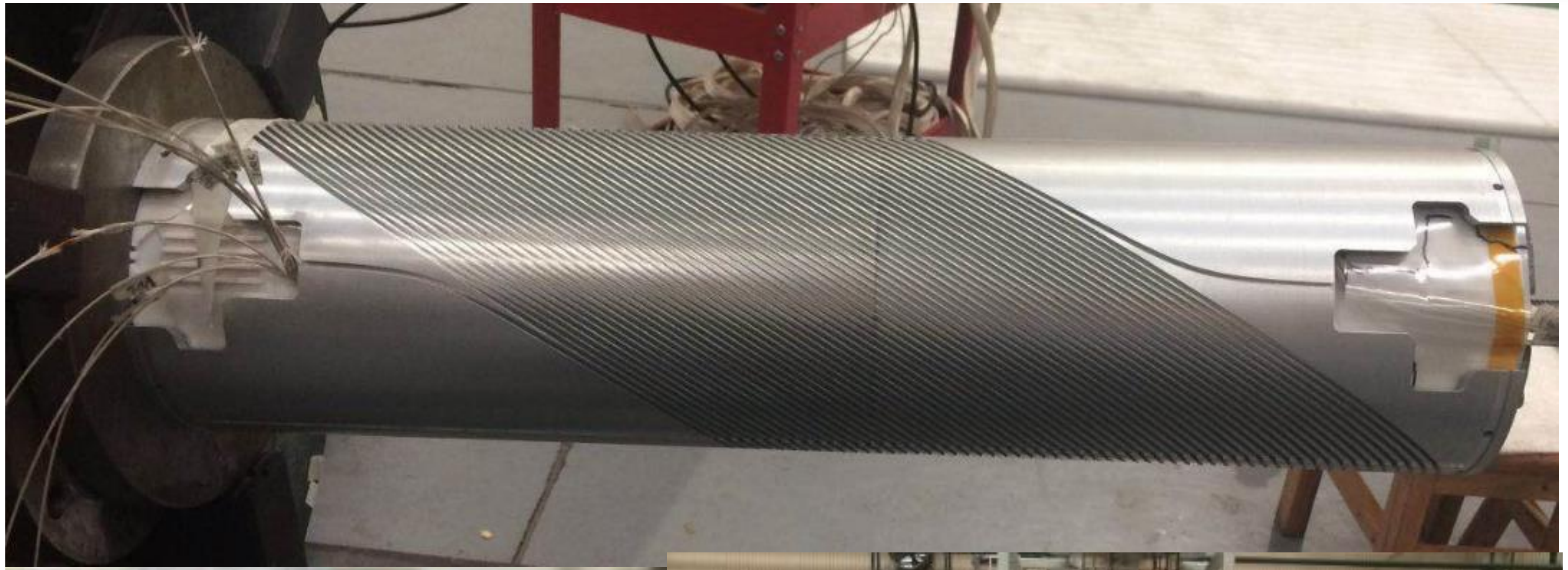
Construction of the 1st and 2nd long (7.5 m!) IT Quad in CERN; in USA winding 4th long magnet

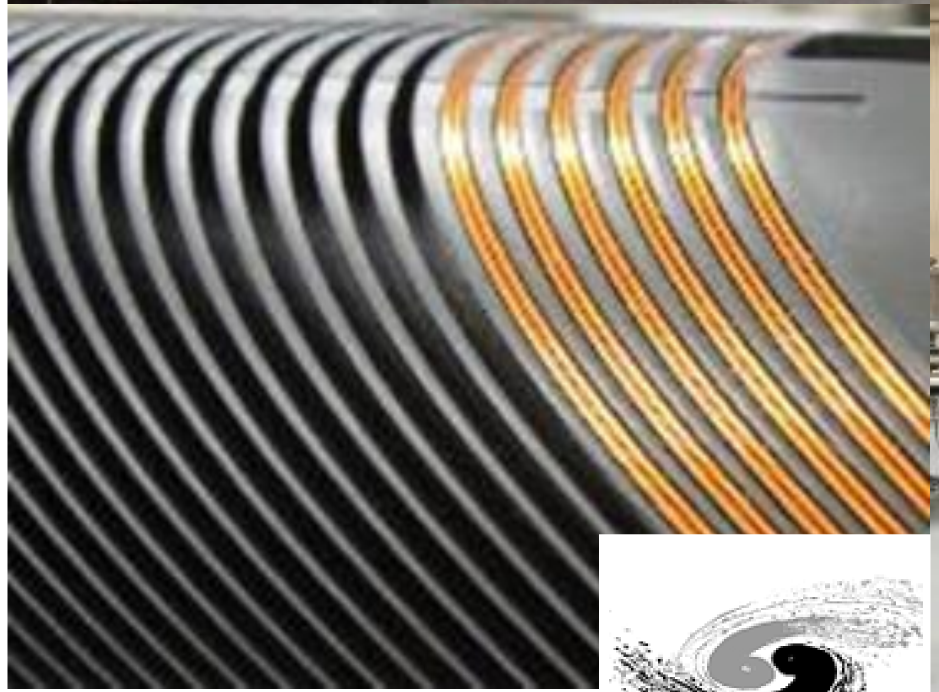


The HiLumi LHC new magnets zoo

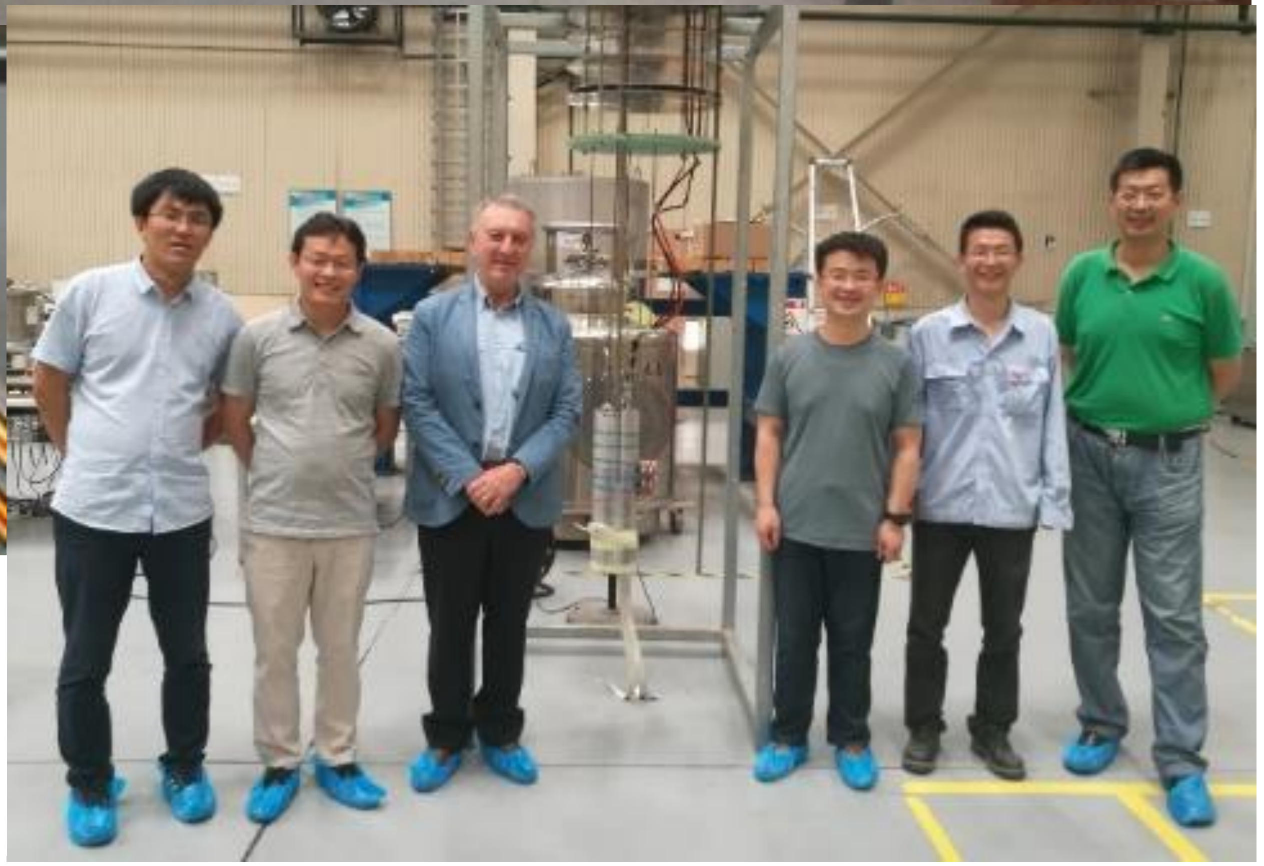


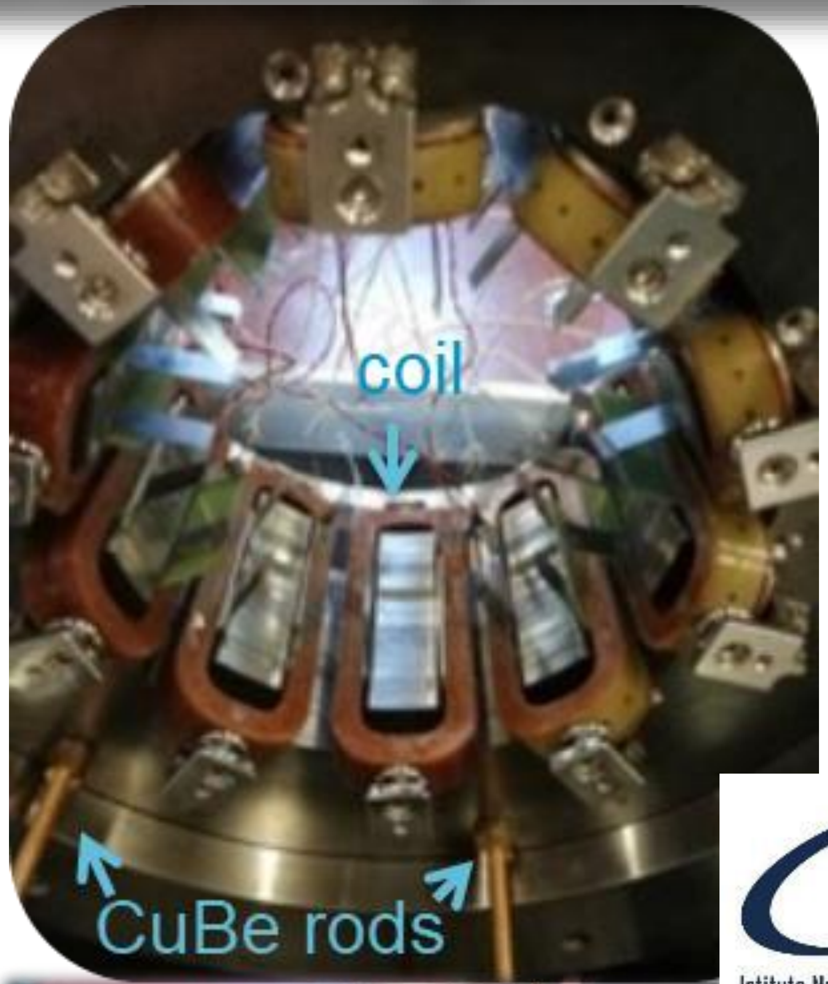
Nb-Ti new technologies: CCT and SF magnets





IHEP





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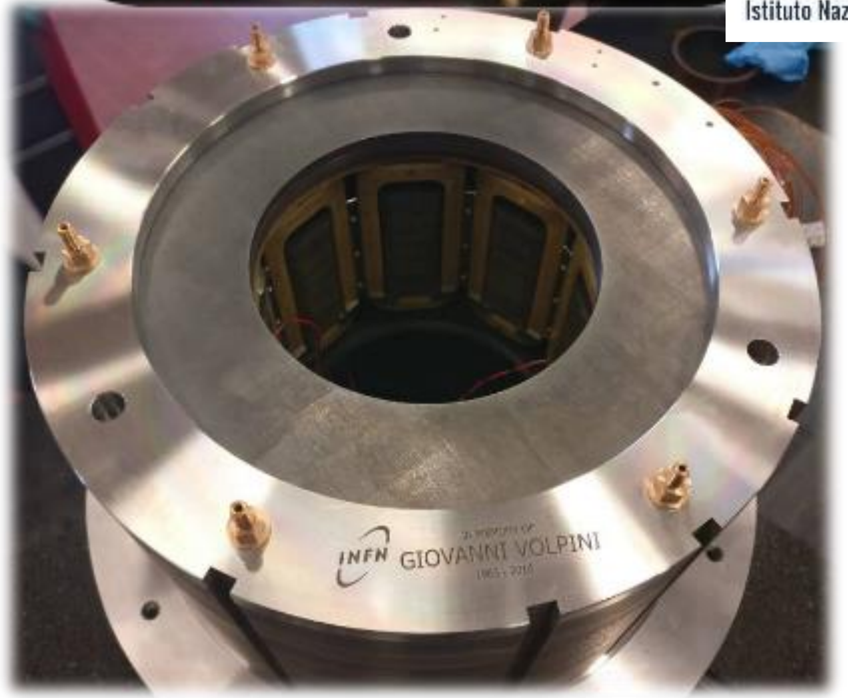
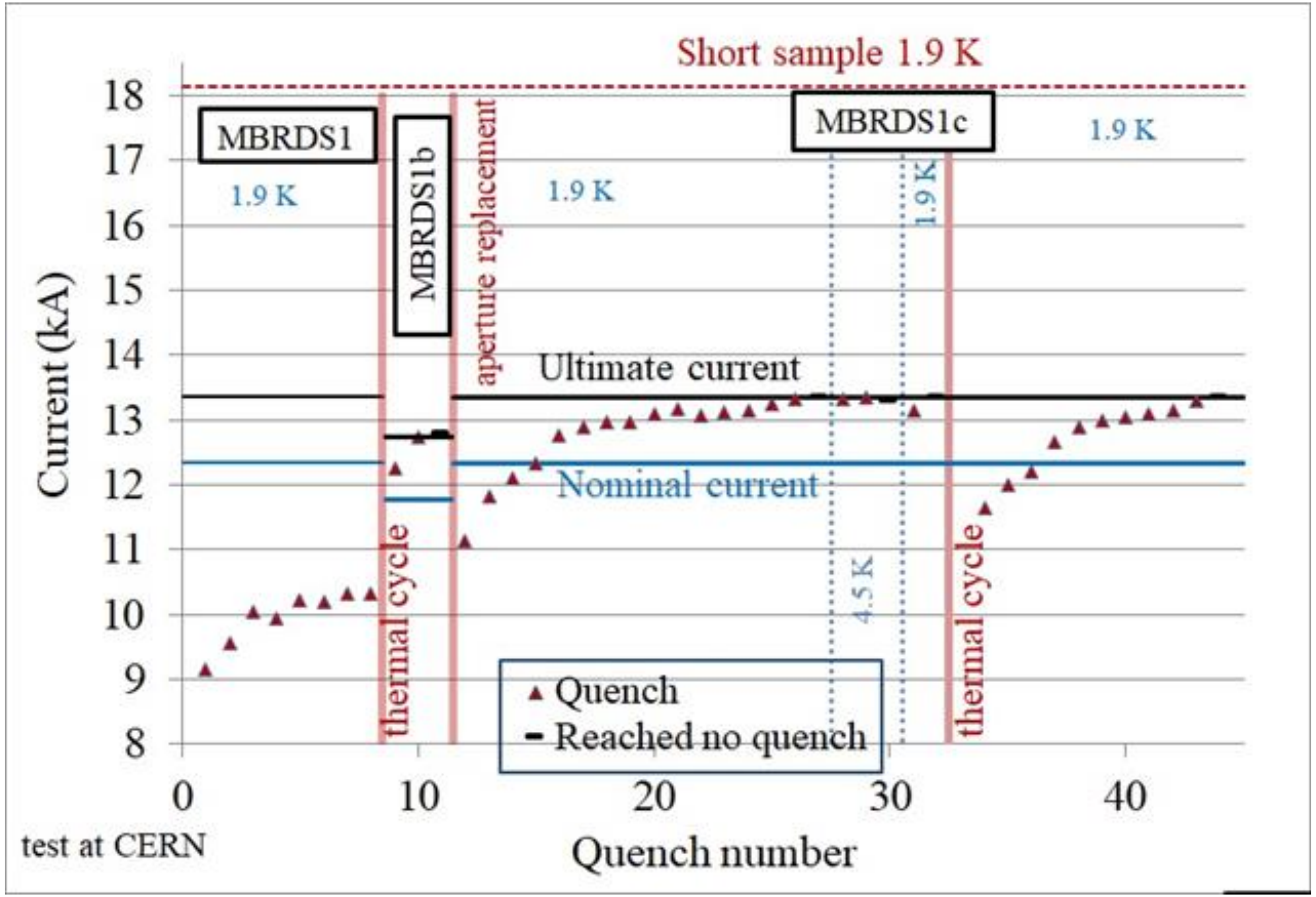
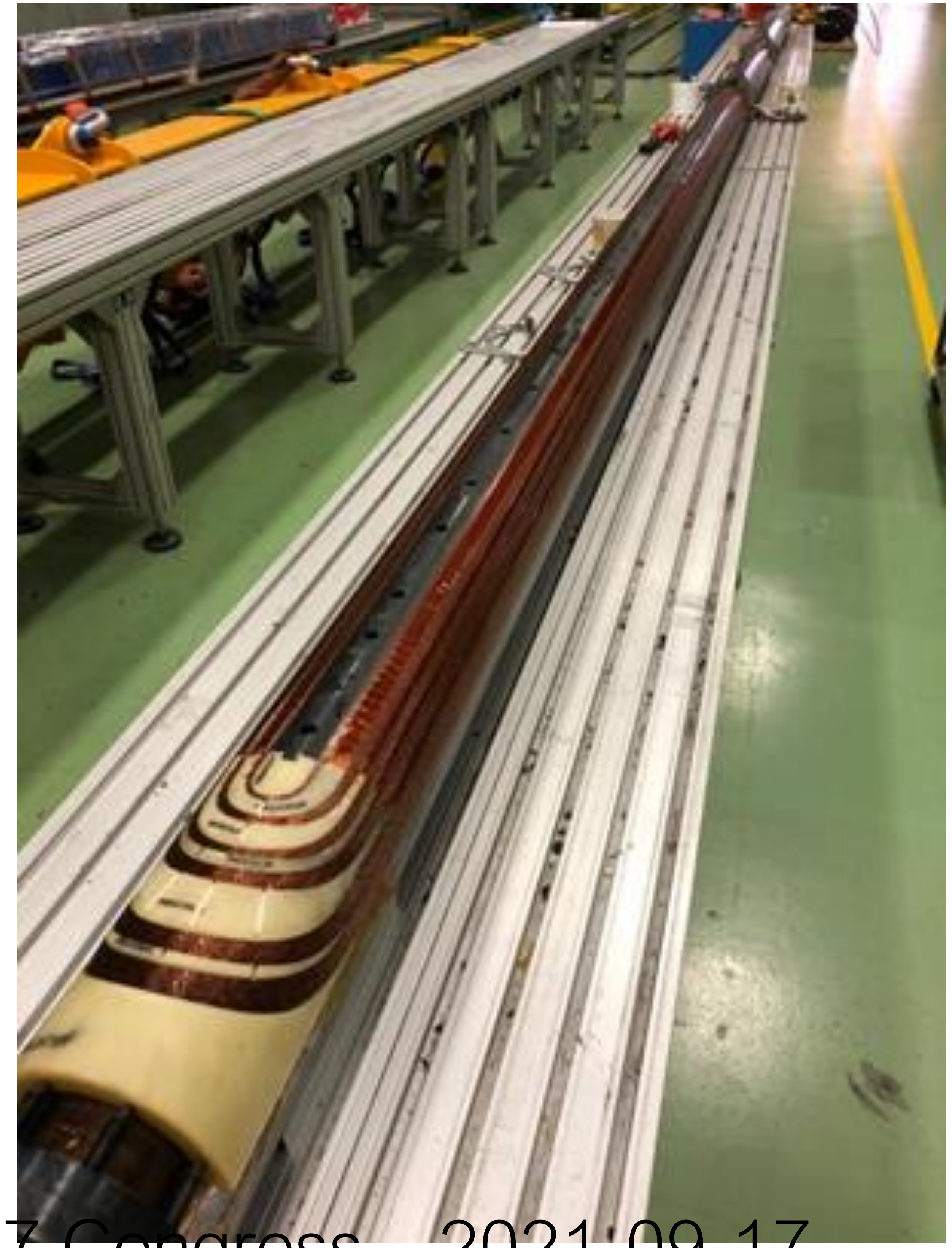
Istituto Nazionale di Fisica Nucleare



D2 Dipole for HiLumi LHC (INFN Genova)

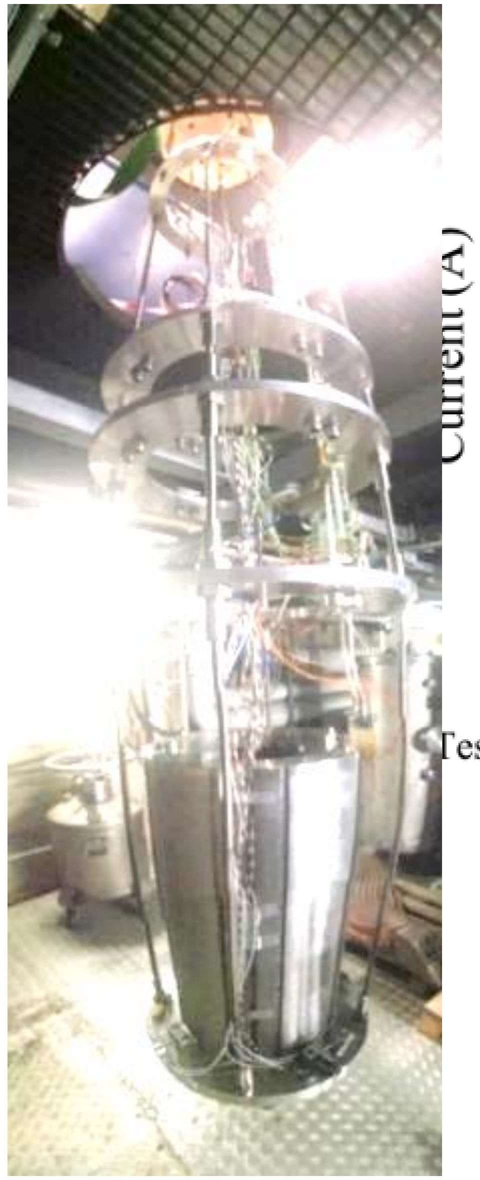




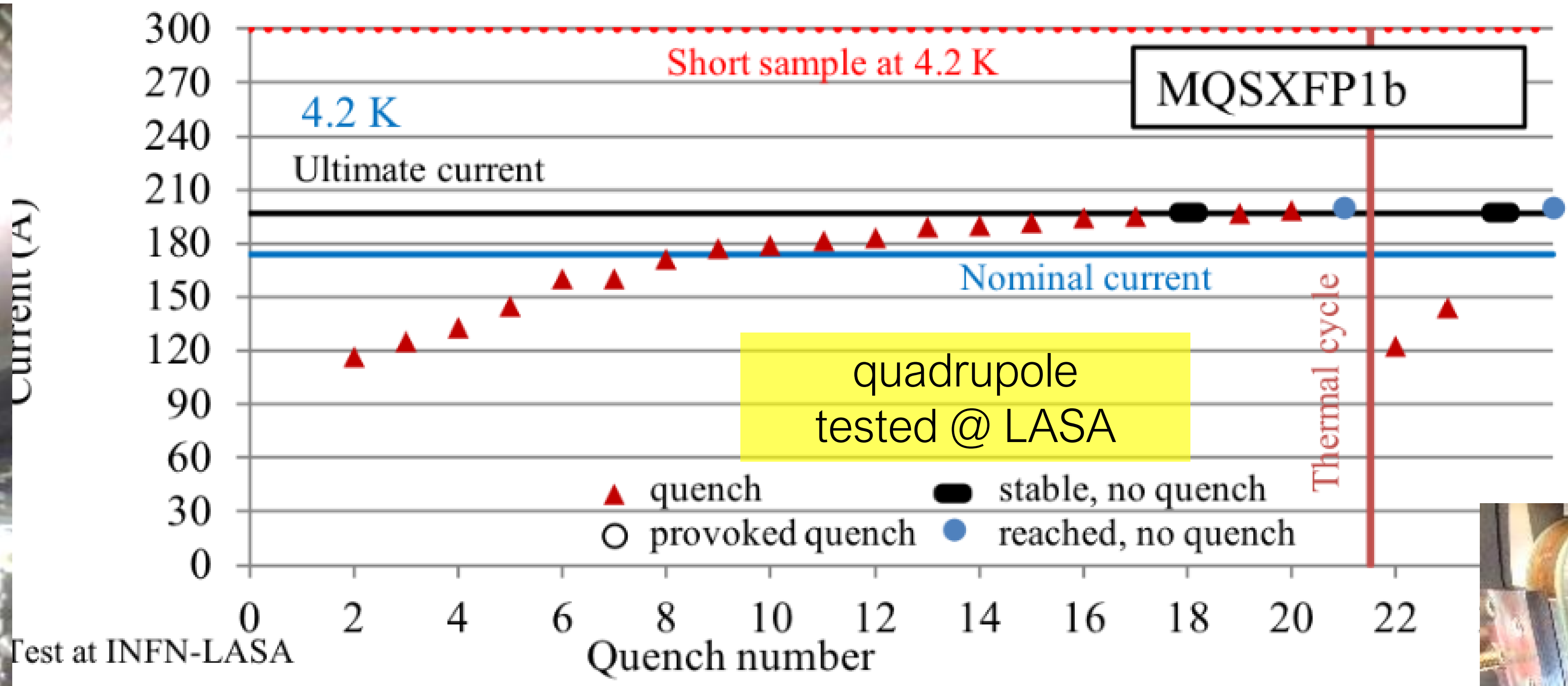
54 High Order Corrector Magnets for HILumi From INFN-Milano-LASA

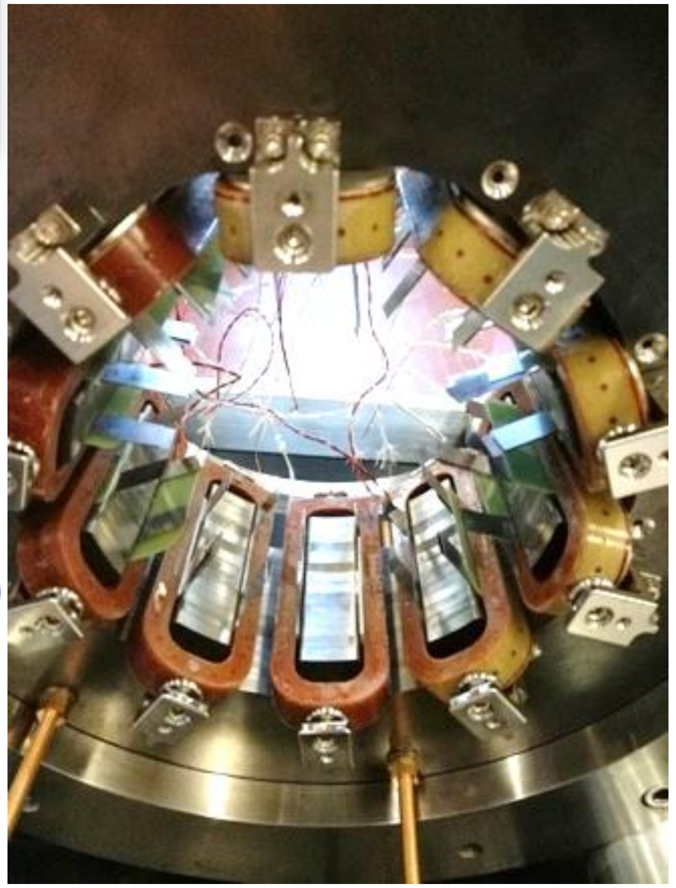
From LASA to industry (SAES Rial)

6pole
Coils: LASA
Ass.bly: LASA



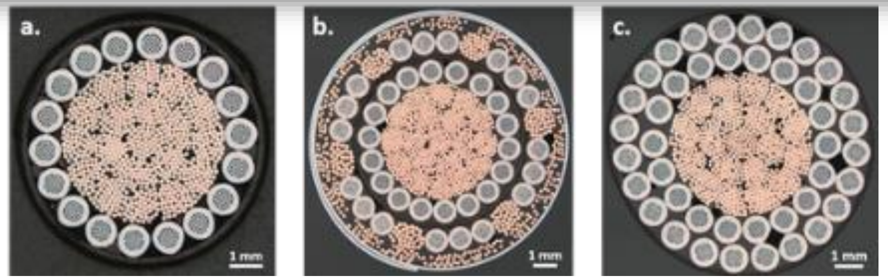
12pole prototype
Coils and ass.bly:
Saes Rial Vacuum



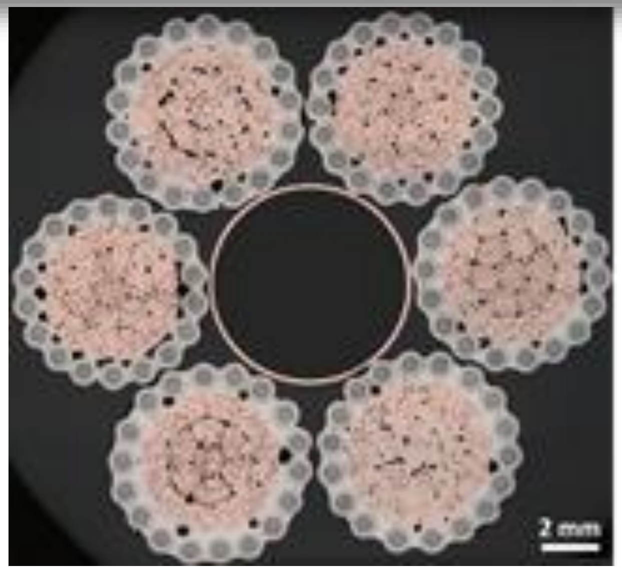


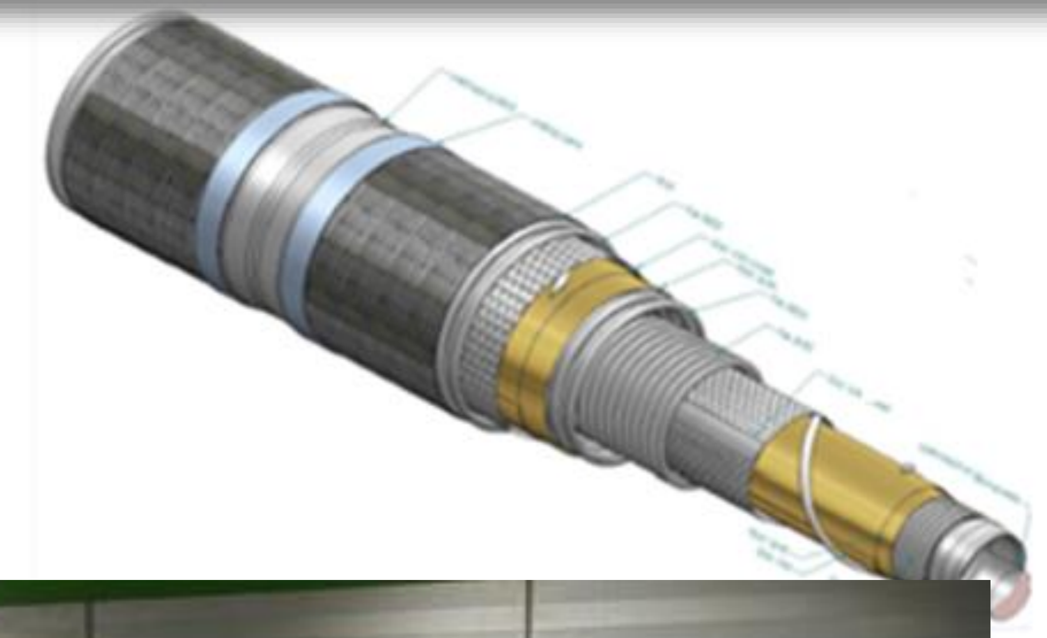
- 6pole – 8pole -10 pole tested 2016-2018
- 12pole first prototype built in industry tested 2018
- 4pole built in industry tested 2019

SC links : cable for 100 kA!

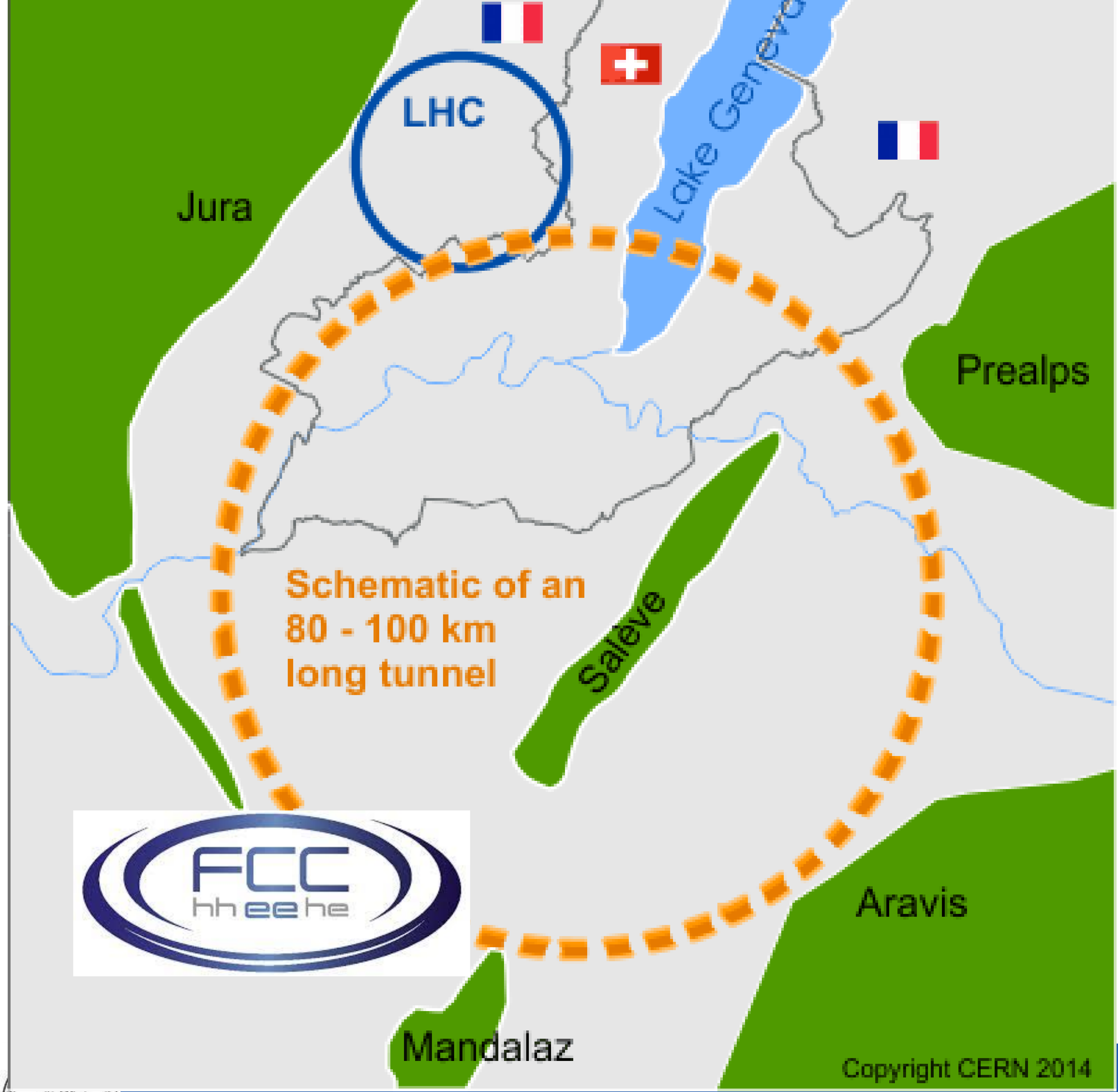


MgB_2 superconductor





Amalia Ballarino, CERN



Circular collider in new tunnel

80- 100 km circumference

Circular proton-proton collider
100 TeV collision energy (p+p)
Preceeded by a e+e- collider

Circular electron-positron collider (VLEP)
(***350 GeV c.m.*** energy, t-tbar threshold)

Lepton-Hadron collider (like HERA)
(***50 TeV p + 100 GeV e***)

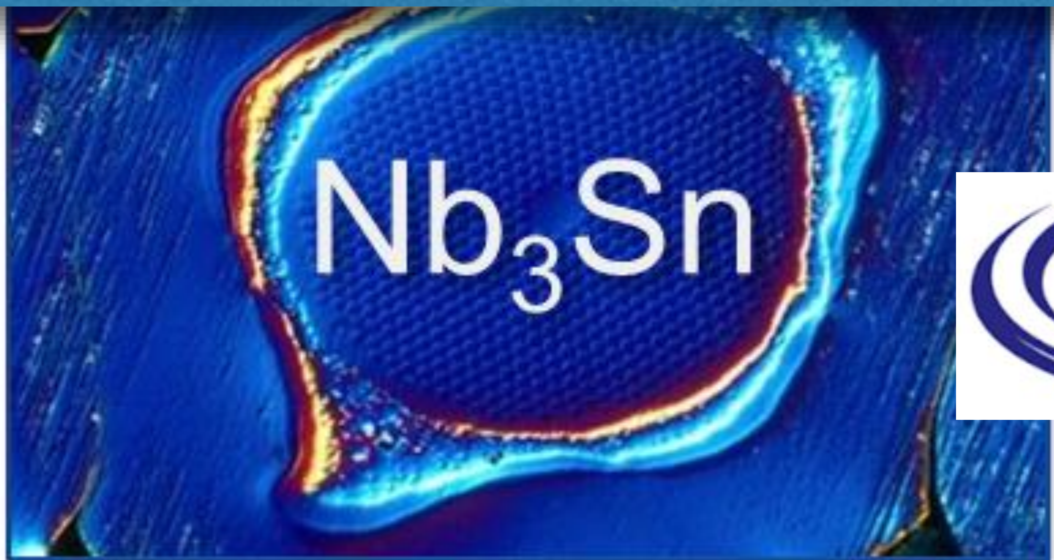
Alternatively:

30 TeV p-p collider in LHC tunnel ?
(***16 T magnets***)

Conceptual design report ~ late 2018

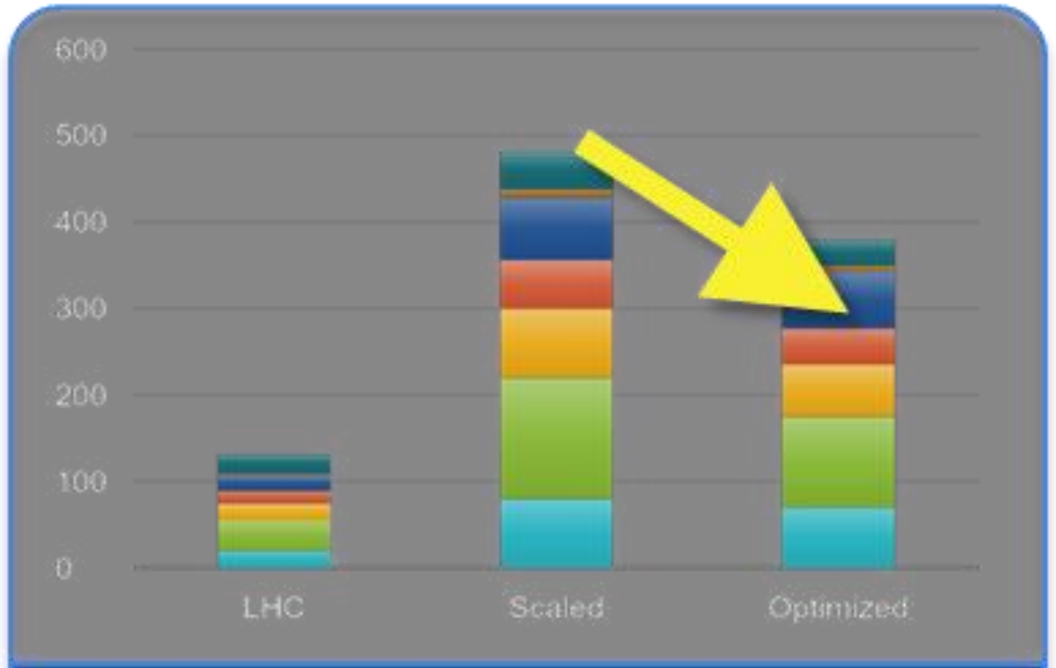
FCC is the natural evolution of HL-LHC with new technology advancement

High-field Magnets



Novel Materials and Processes

Large-scale Cryogenics



Power Efficiency

Reliability & Availability

Global Scale Computing

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 Europea
seventeen Strateg
2006. A first upda
May 2013. This
during its six-day
Group, which had
held in Granada ir
working groups w
discussed at the B

Working Group 1:
Working Group 2:

Working Group 3:
Working Group 4:
Working Group 5:
Working Group 6:

This Deliberation
Recommendation
organisational ma
structure of the 2
motivation, follow

1. two statement
2. three statemer
3. two statement
4. four statemen
5. two statement
6. three statements on **Organisational issues**
7. four statements on **Environmental and societal impact**

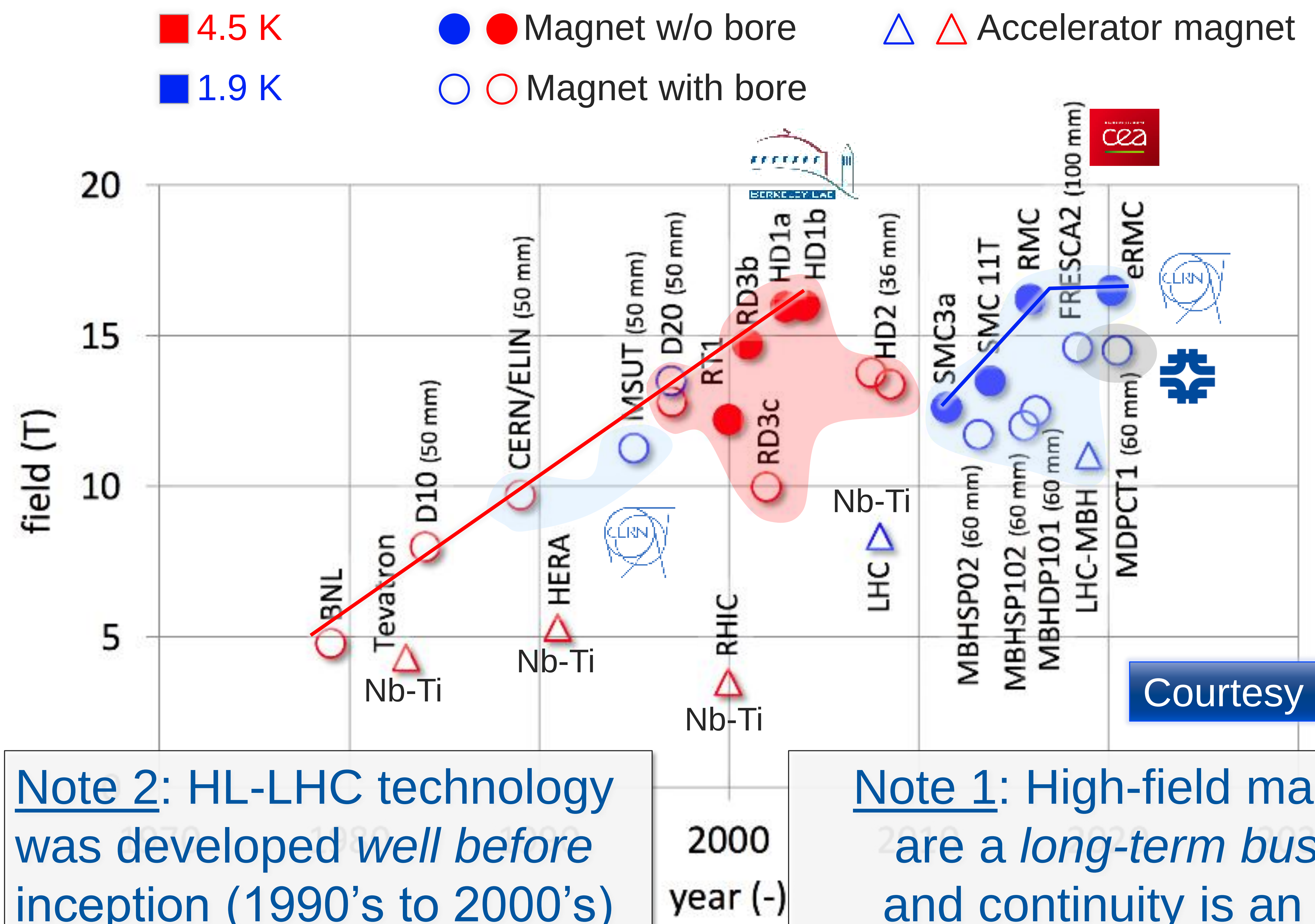
Each Strategy statement gives a short description of the topic followed by the recommendation in italic text. Within the numbered sections there is no intention to prioritise between the lettered statements. In this Deliberation Document the Strategy statements are presented in blue indented text, and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

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.



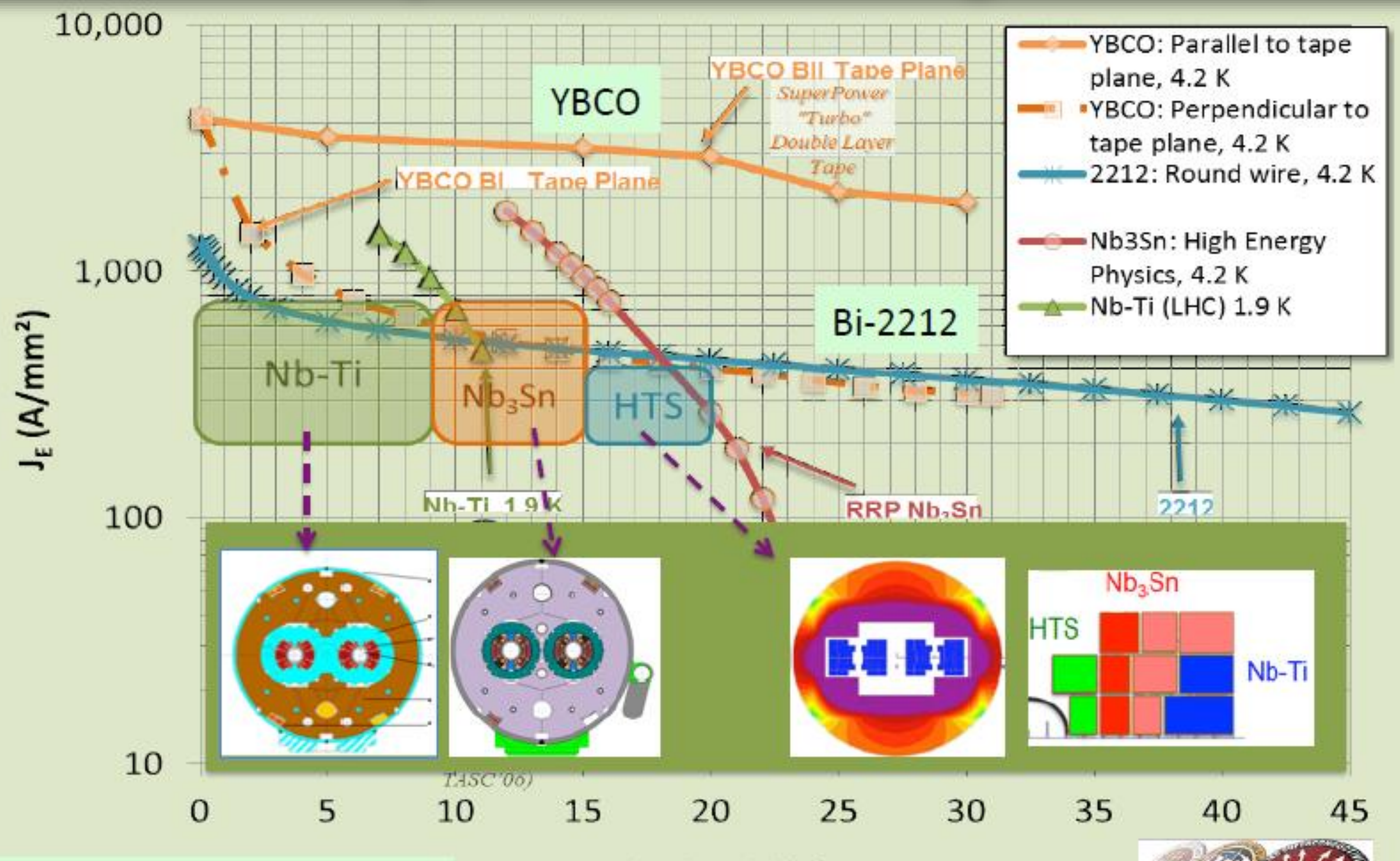
Courtesy Luca Bottura, CERN

Note 2: HL-LHC technology was developed *well before* inception (1990's to 2000's)

Note 1: High-field magnets are a *long-term business* and continuity is an asset

A true worldwide effort on Nb_3Sn magnets

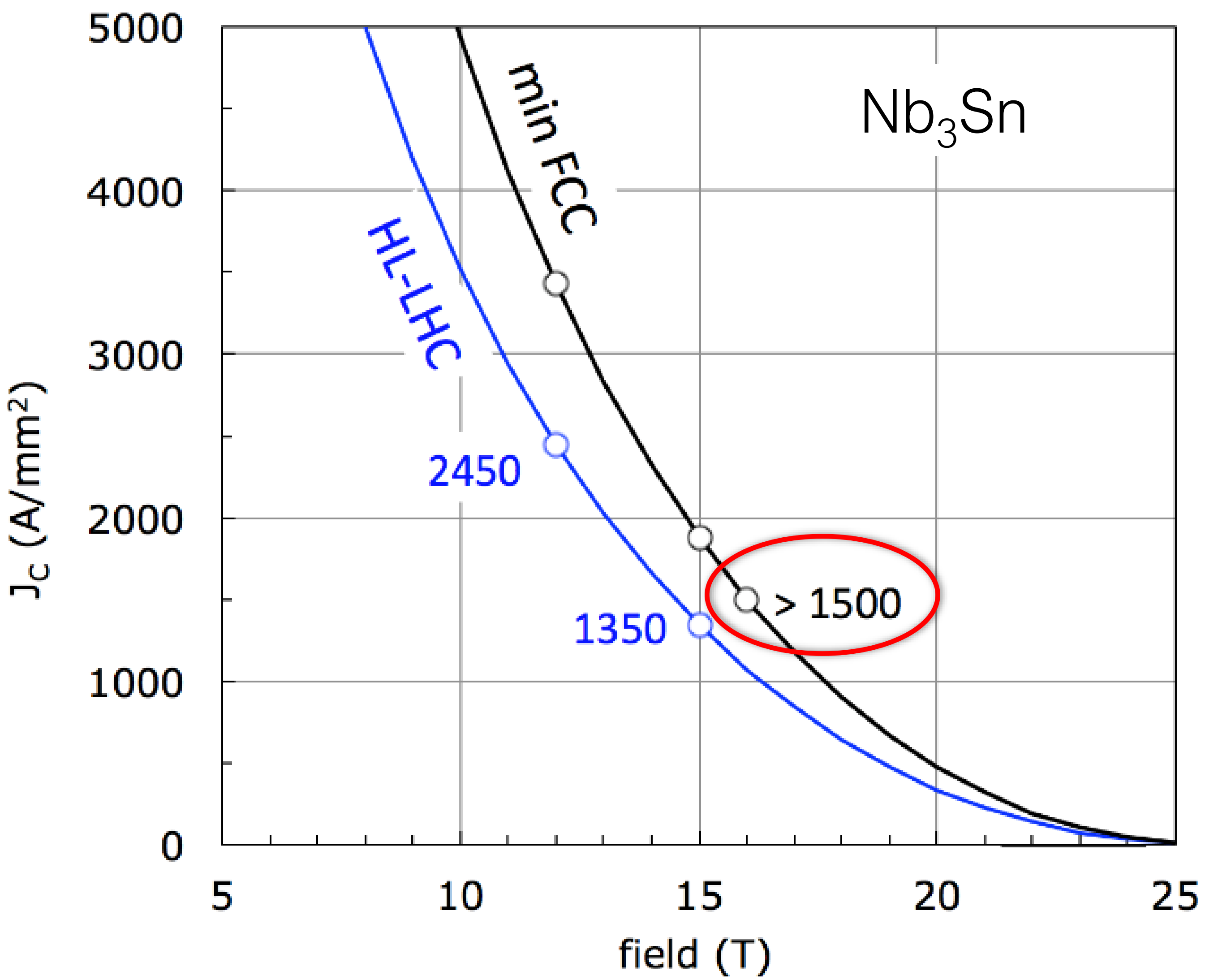
New technology for High Luminosity LHC, first step toward FCC-hh: More powerful SC magnets in Nb3Sn



Original conductor plots by P. Lee

Nb_3Sn: the workhorse of the "near Future"

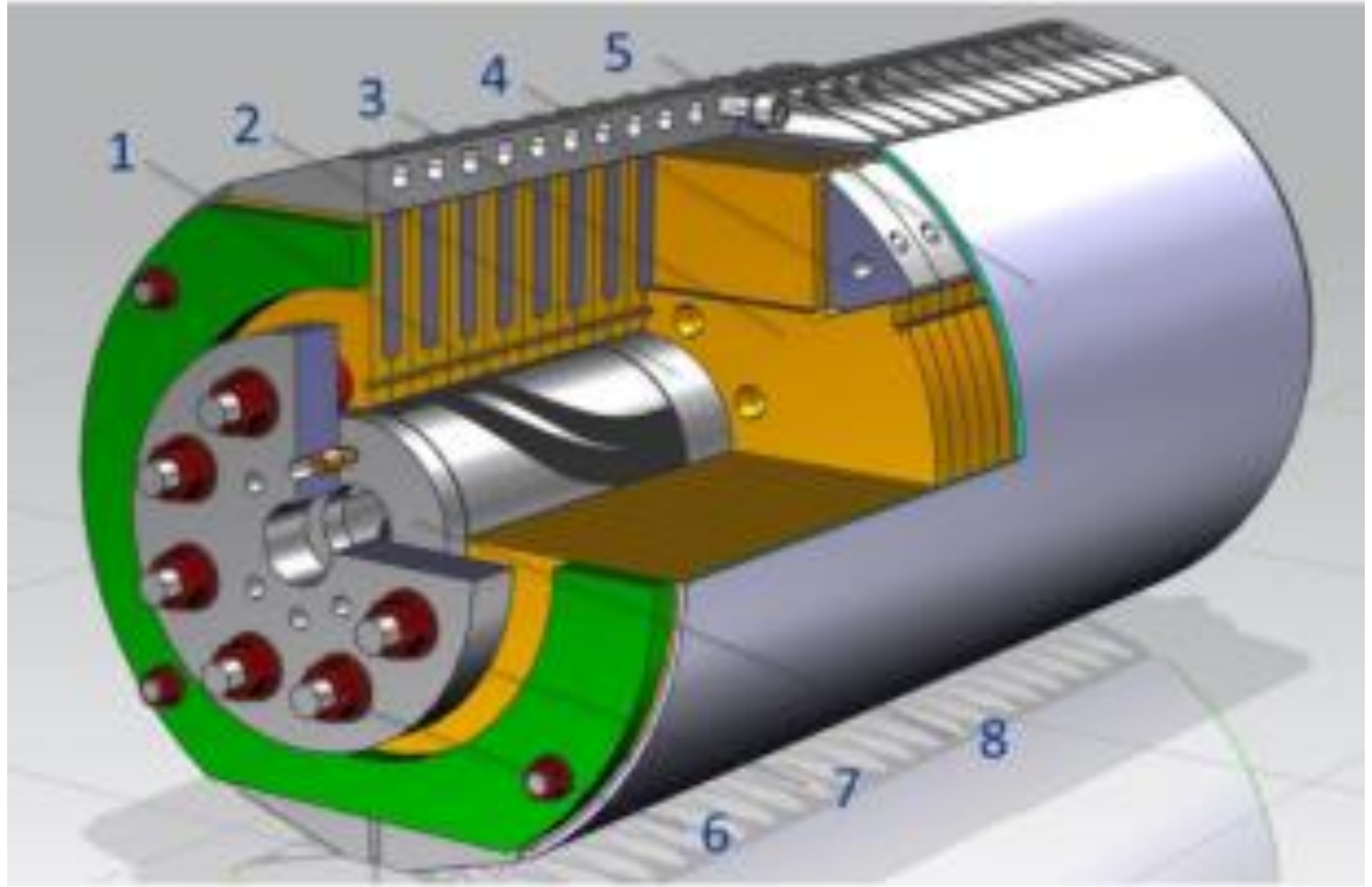
Solid objectives for the FCC conductor R&D



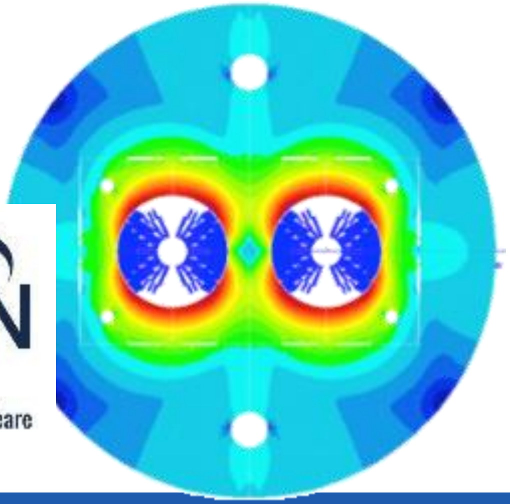
D_{strand}: 0.7…1 mm
J_C (16 T, 4.2 K) > 1500 A/mm^2
M (1 T,4.2 K) <150 mT (D_{fil} < 20 μm)
RRR > 150
UL > 5 km
Cost(16 T, 4.2 K) < 5 USD/kA m

The goal is ambitious but not impossible.
Cost wil be probably the most challenging

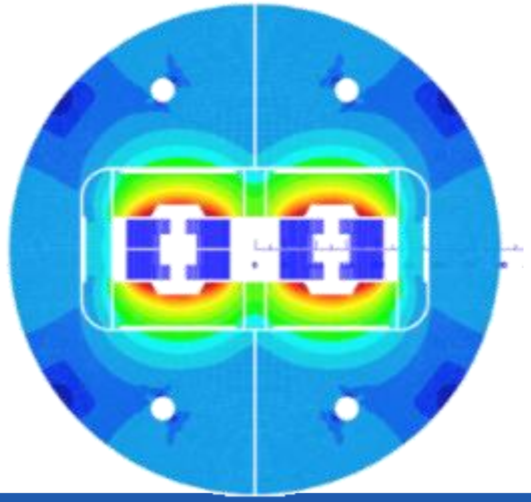
Expanding the Sc limits beyond LHC and HiLumi



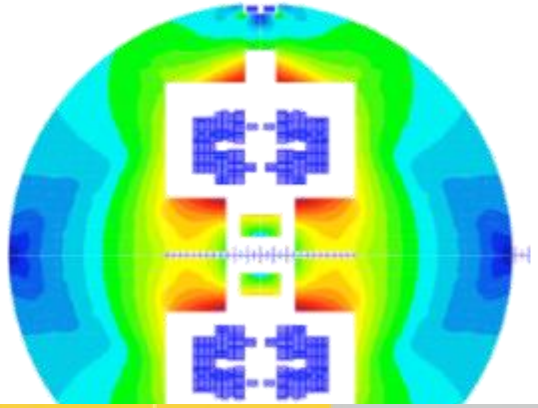
Cos-theta



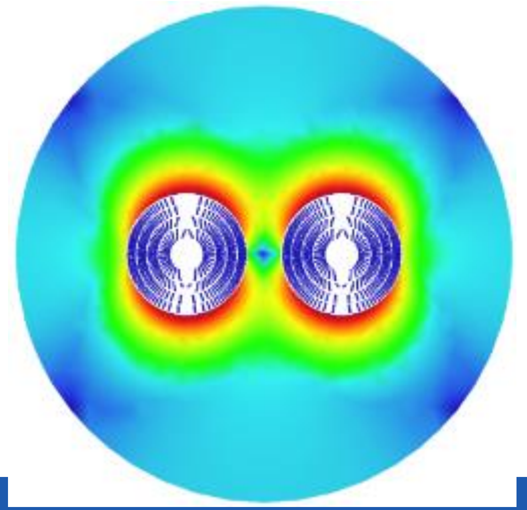
Blocks



Common coils



Canted Cos-theta



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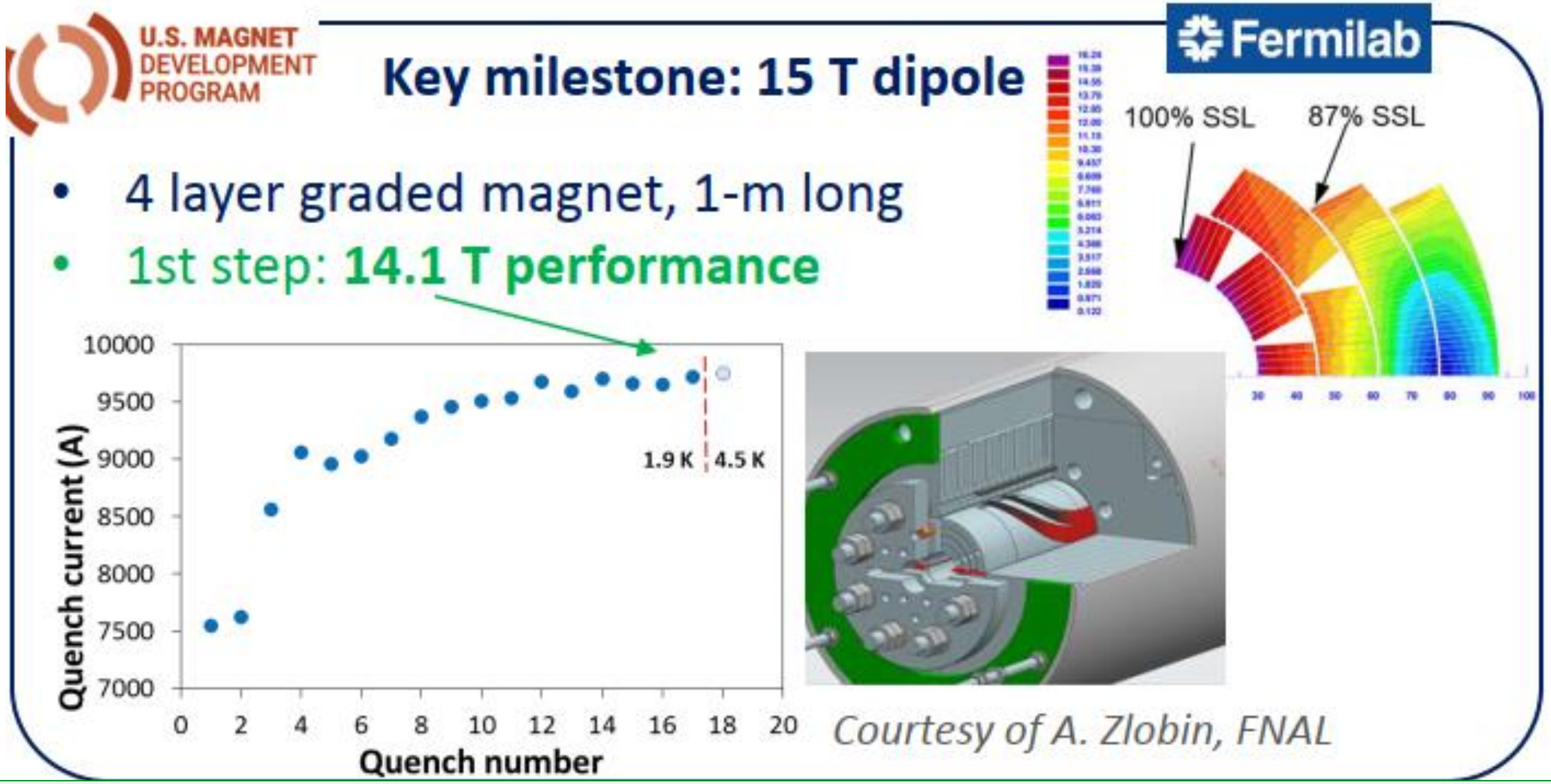
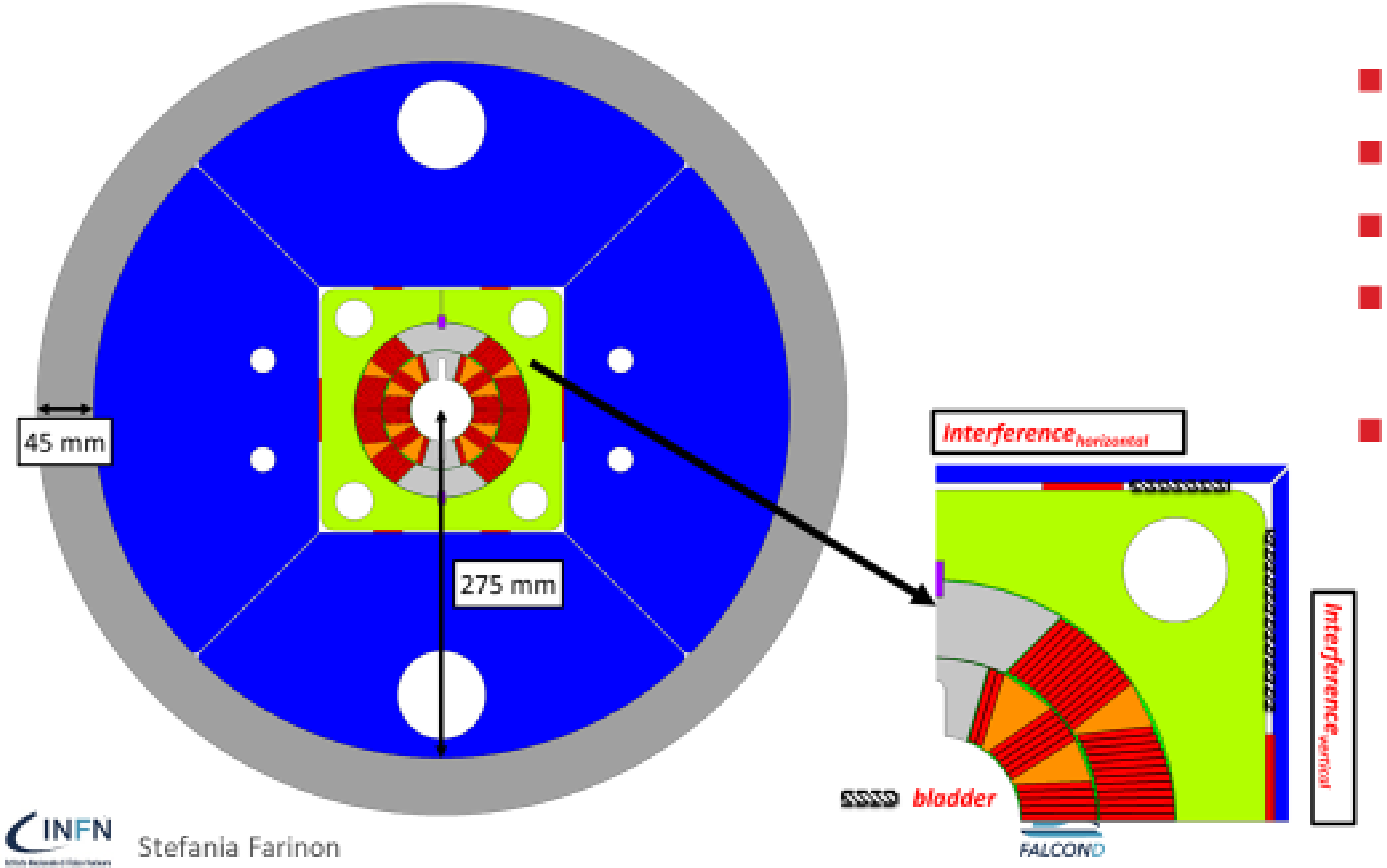
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Recent very successful 14 T magnet reached by US MDP cosθ dipole at FNAL



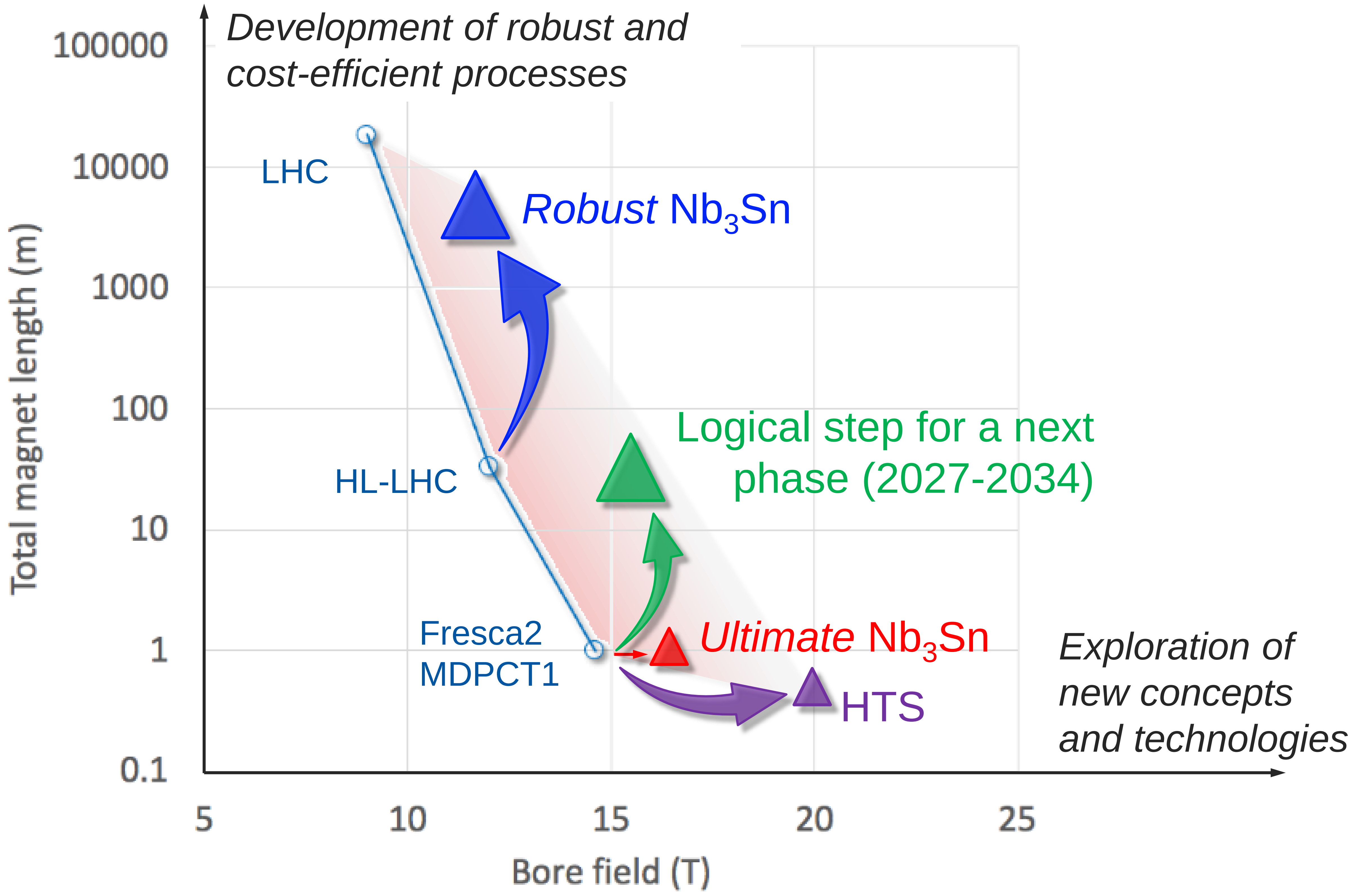
But the route is long… a 16 T 100 km accelerator is not yet at hand and a long R&D is necessary.
In May 2020 in Budapest the new ESPP whas been approved…

2D mechanical design – bladder&key



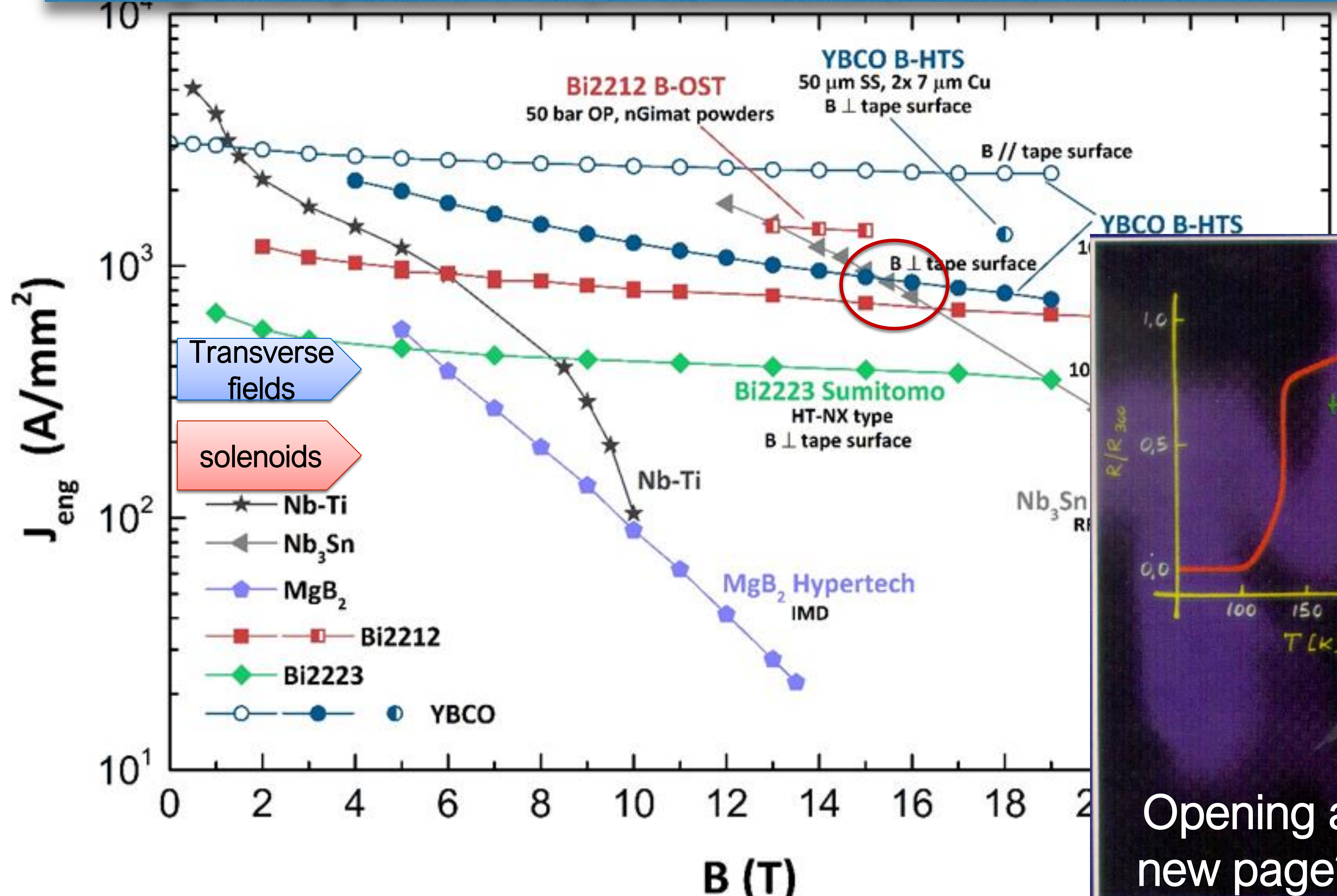
- Yoke outer diameter: 550 mm
- Al alloy shell thickness: 45 mm
- Outer magnet diameter: 640 mm
- The horizontal key interference is fixed (0.1 mm)
- The vertical key interference is variable depending on the magnetic field

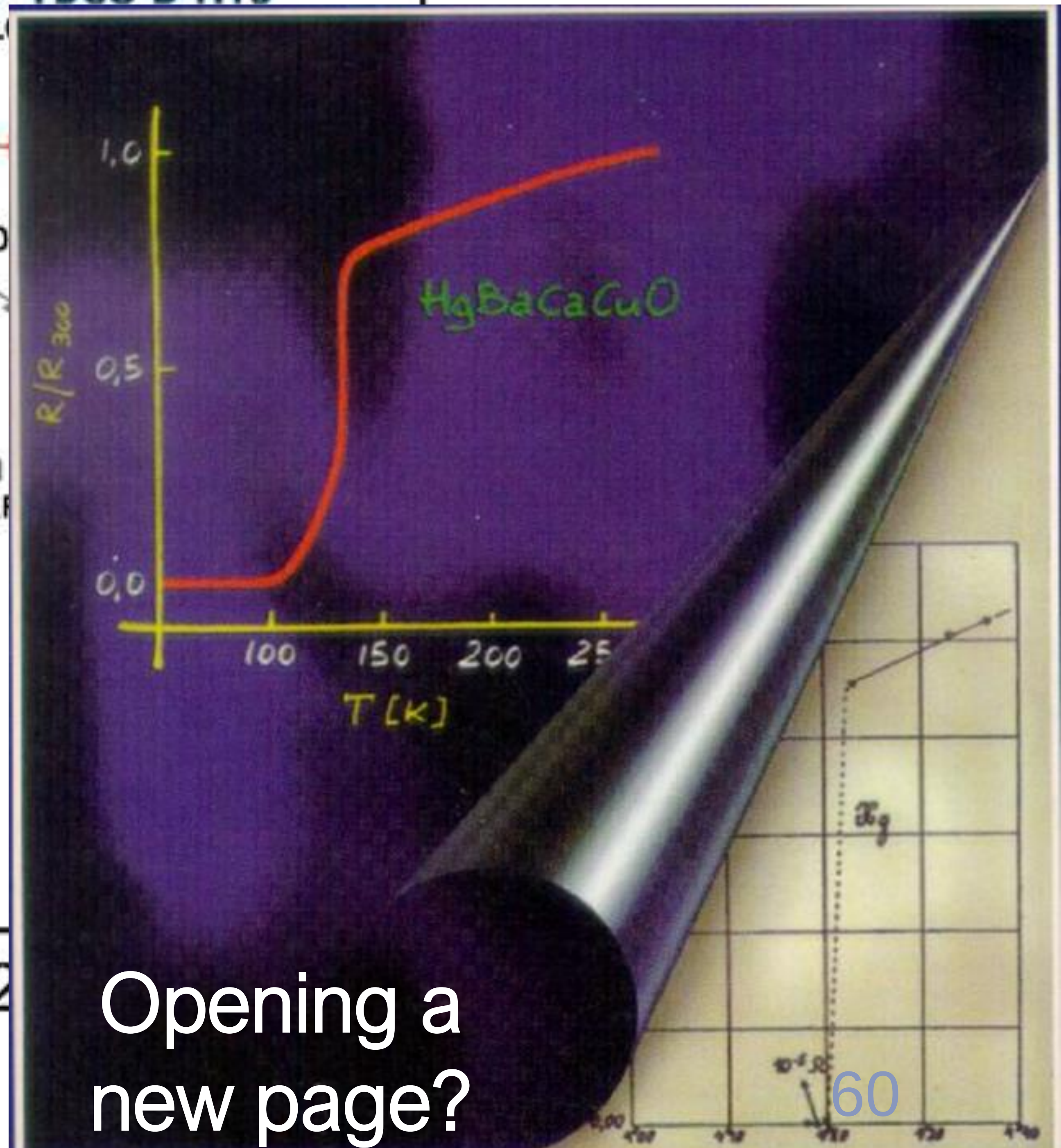
HFM Objectives (2021-2027)



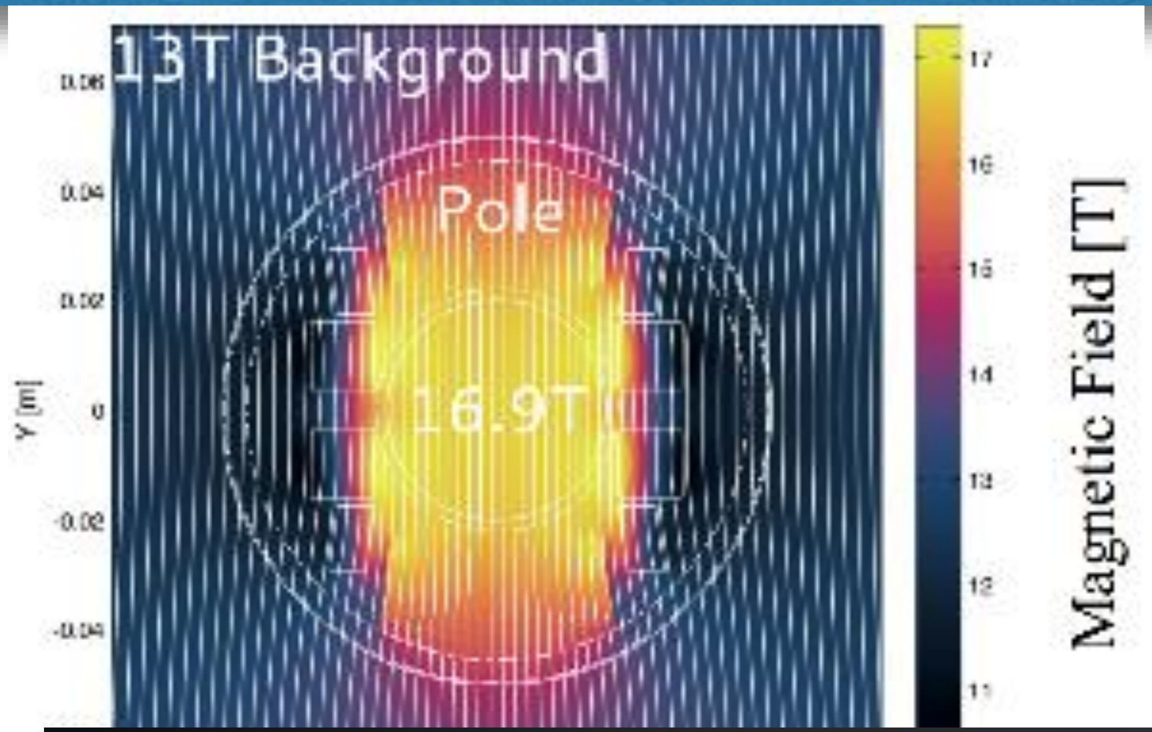
We have to move in parallel along both fronts !

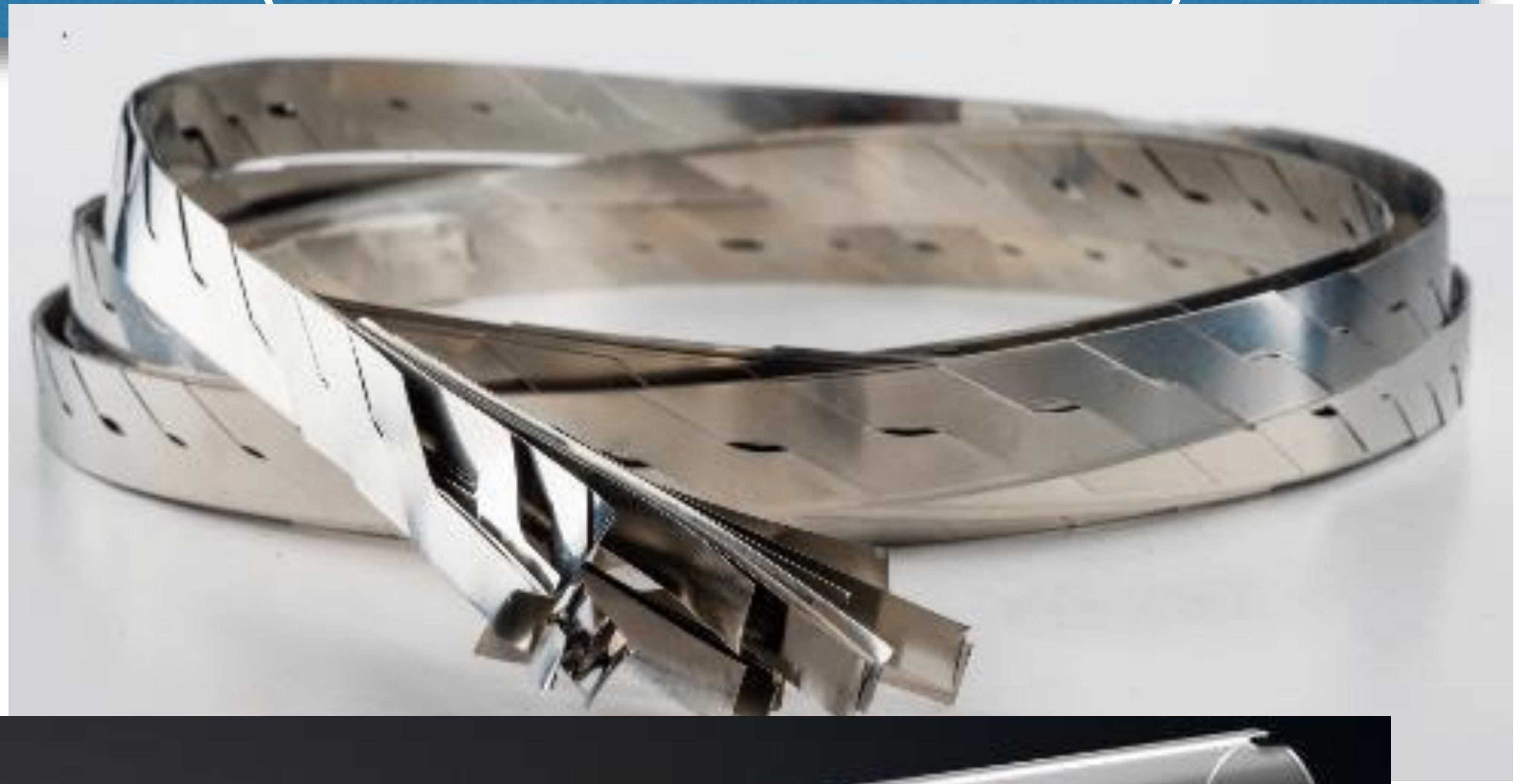
High Temperature Superconductors – HTS: next technology step

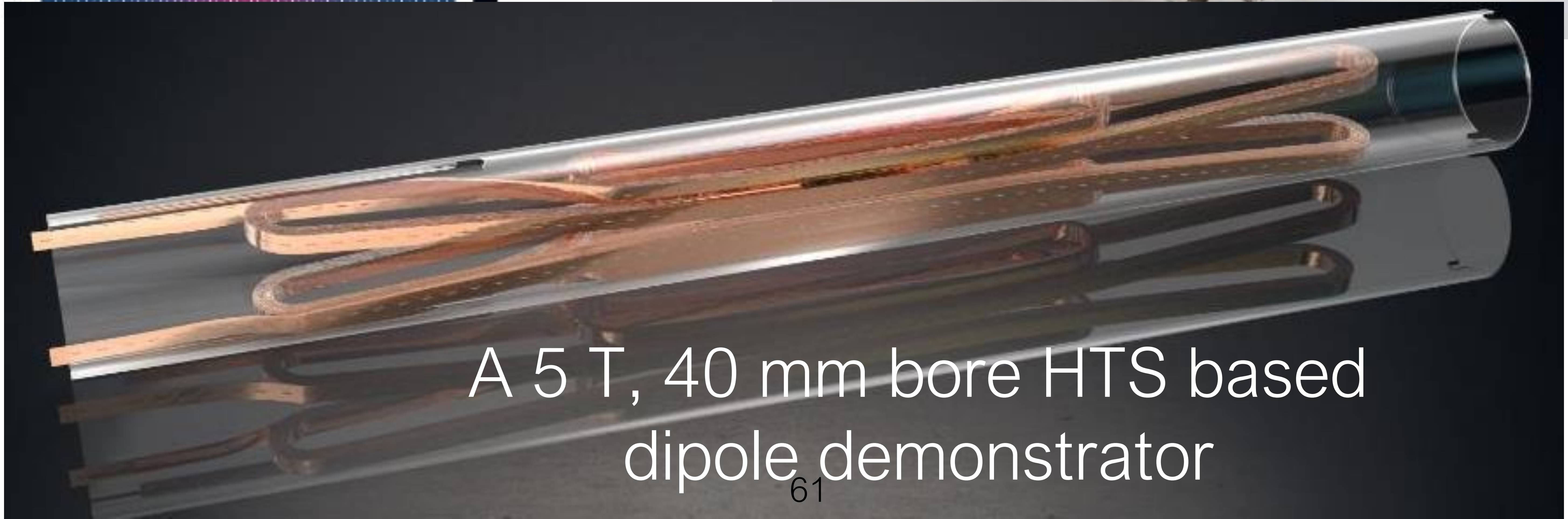




High Temperature Superconductors – HTS
The dream of 20-25 tesla! (2 x HilumiLHC!)

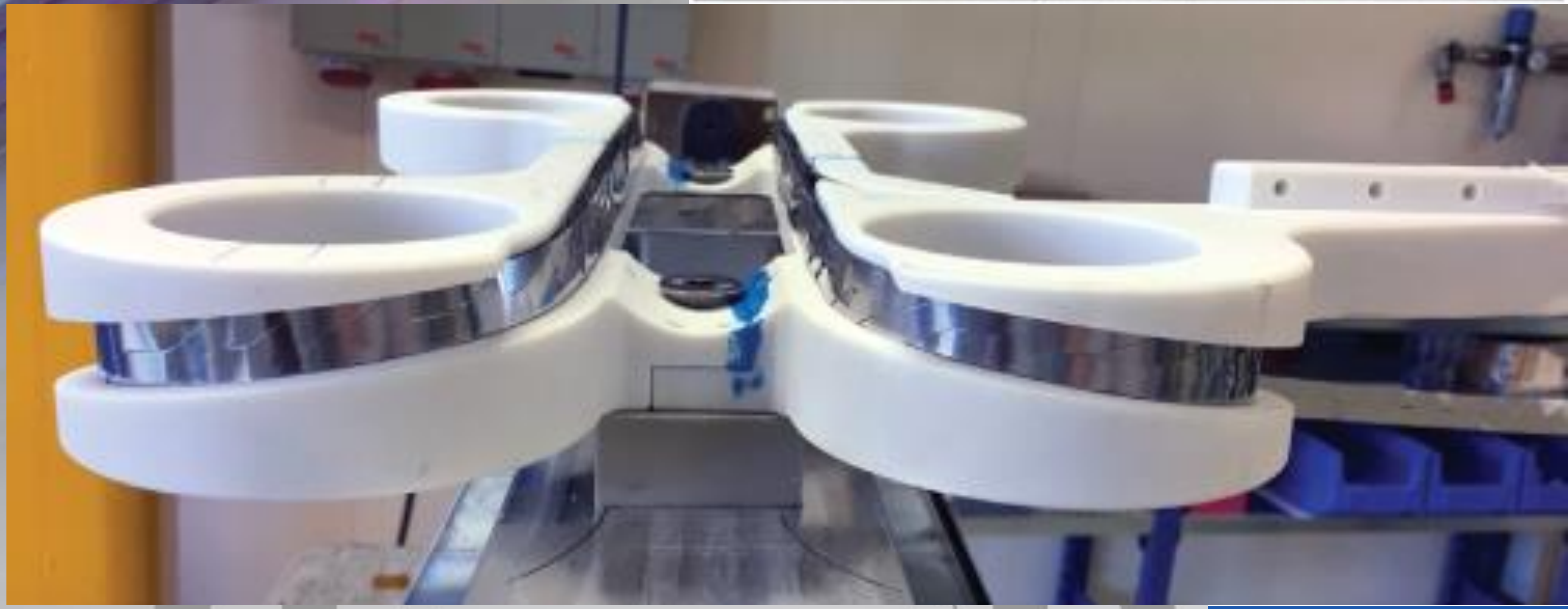


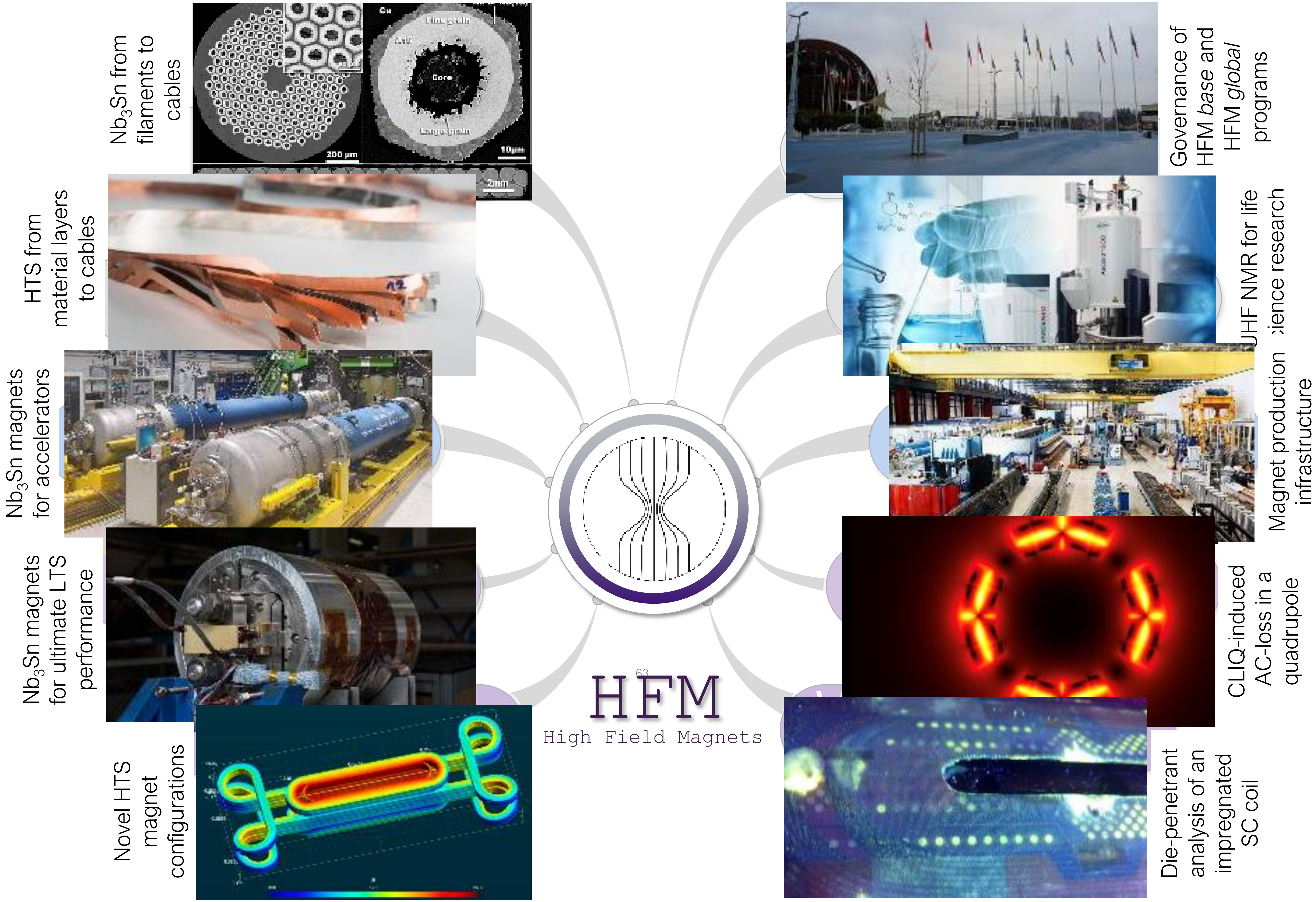




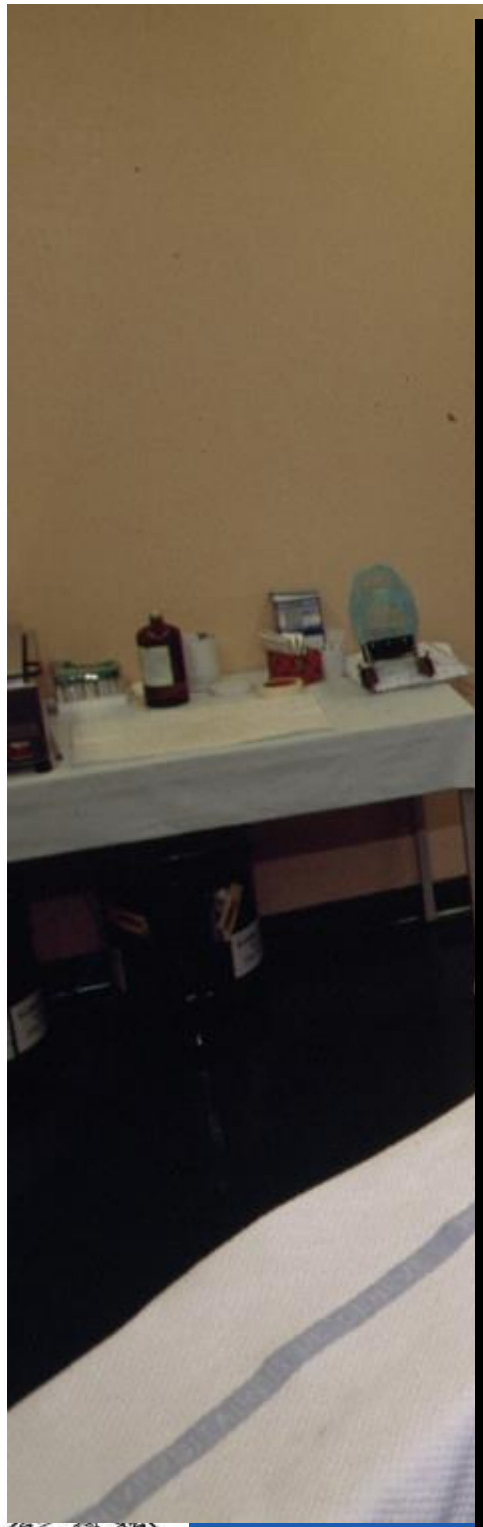
A 5 T, 40 mm bore HTS based dipole demonstrator

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




Nb$_3$Sn from filaments to cables
HTS from material layers to cables
Nb$_3$Sn magnets for accelerators
Nb$_3$Sn magnets for ultimate LTS performance
Novel HTS magnet configurations
Governance of HFM *base* and HFM *global* programs
UHF NMR for life science research
Magnet production infrastructure
CLIQ-induced AC-loss in a quadrupole
Die-penetrant analysis of an impregnated SC coil
HFM
High Field Magnets

New medical «eyes»: PET



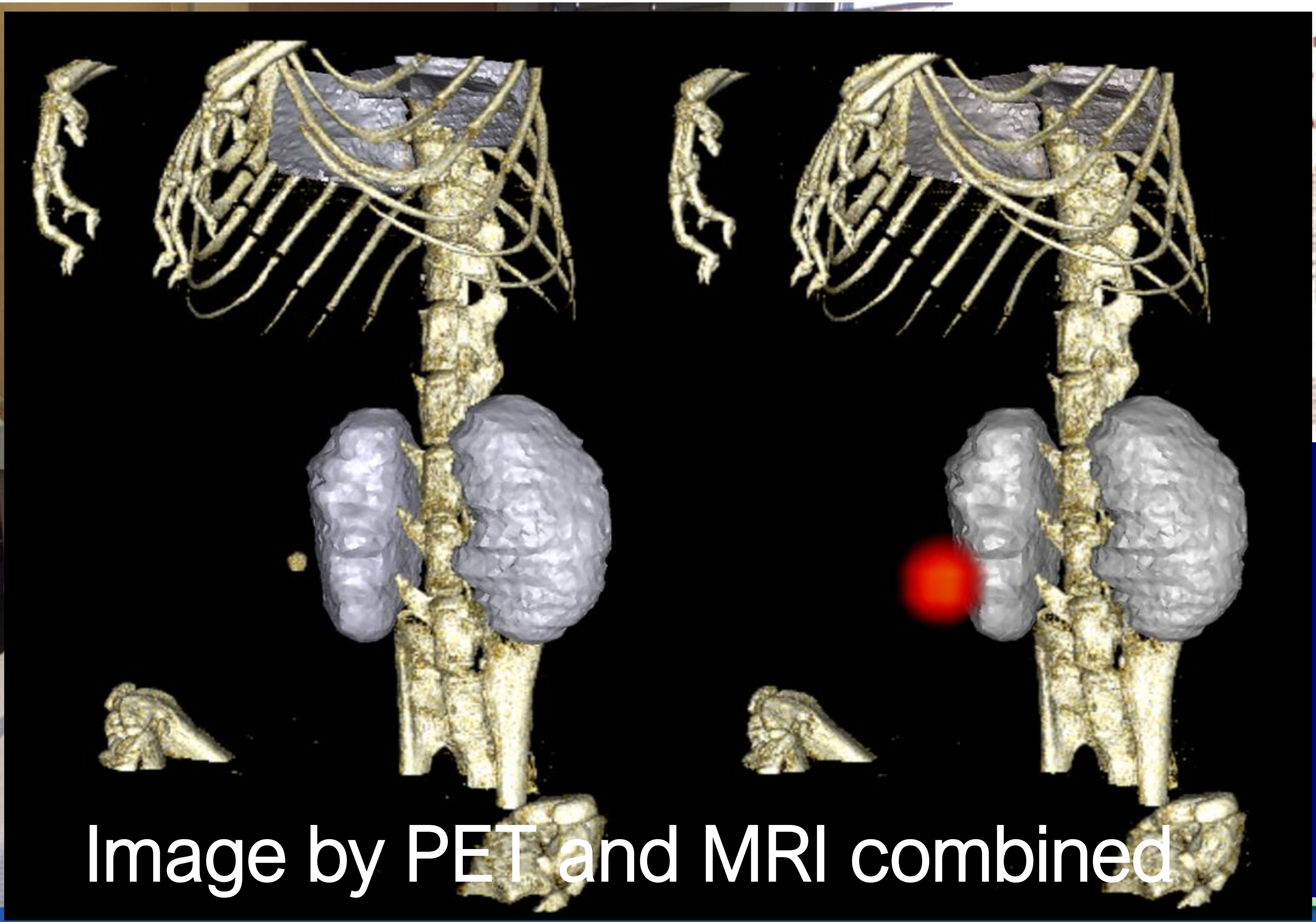
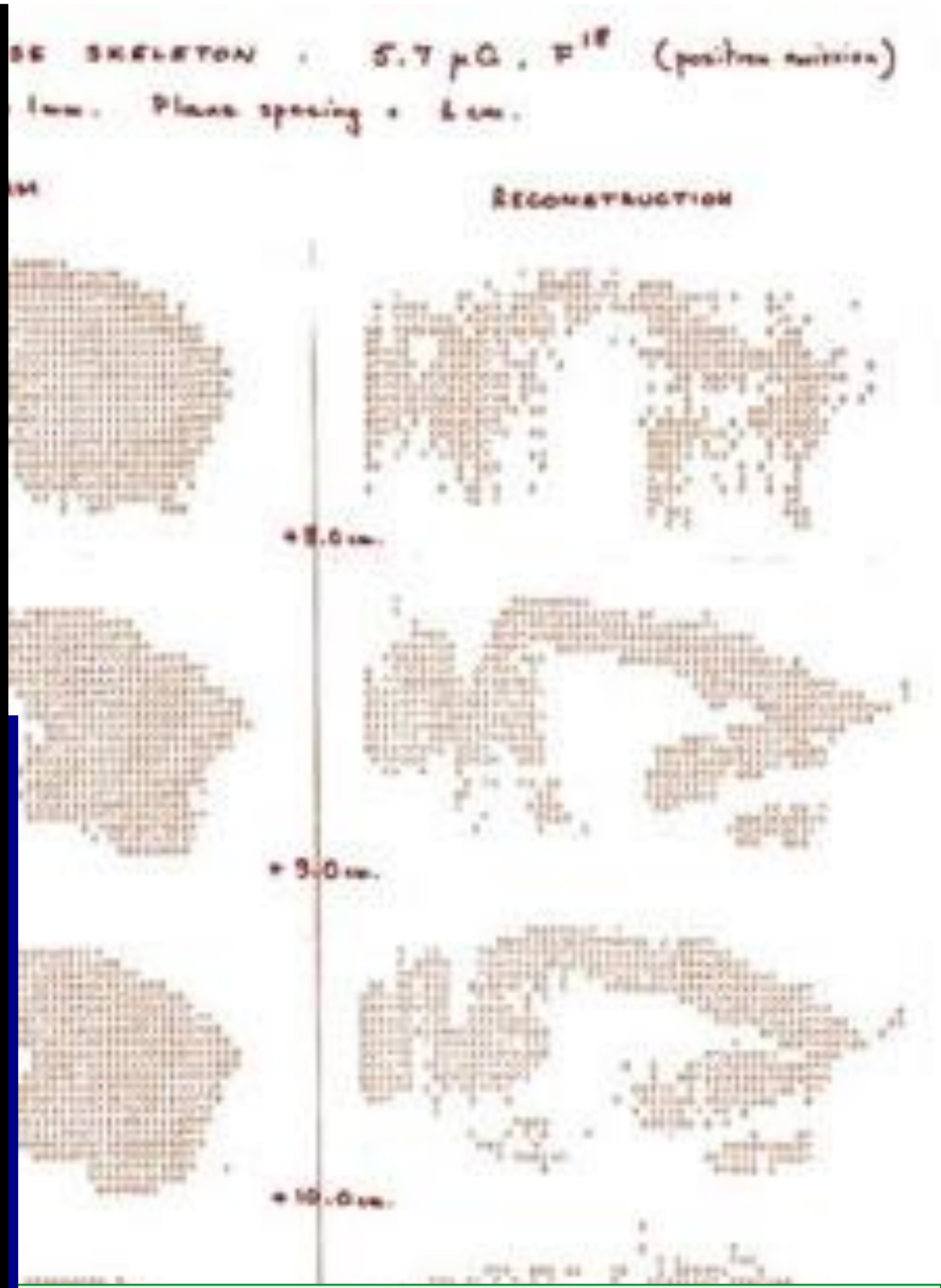


Image by PET and MRI combined



irst PET image: CERN, circa 1975

Parallel Route of MRI Magnets Development - Health Sector

- **All using LTS Materials**
- **>4000/yr. production**
- **>£ 5 Billion Euro/yr. market**

1980 – 1st MRI

1986 – 1st Active shield (AS)

1989 – AS 1.5T

Tevatron 4 T

1994 – 1st Open MRI Magnet

1997 – AS 3T

2000 – AS 4T

2001 – 1.5T Small

2005 – 7T

LHC 8 T

2019 – 9.4 T

2021 – 11.

HiLumi 12 T

Courtesy of Siemens

Courtesy of CEA

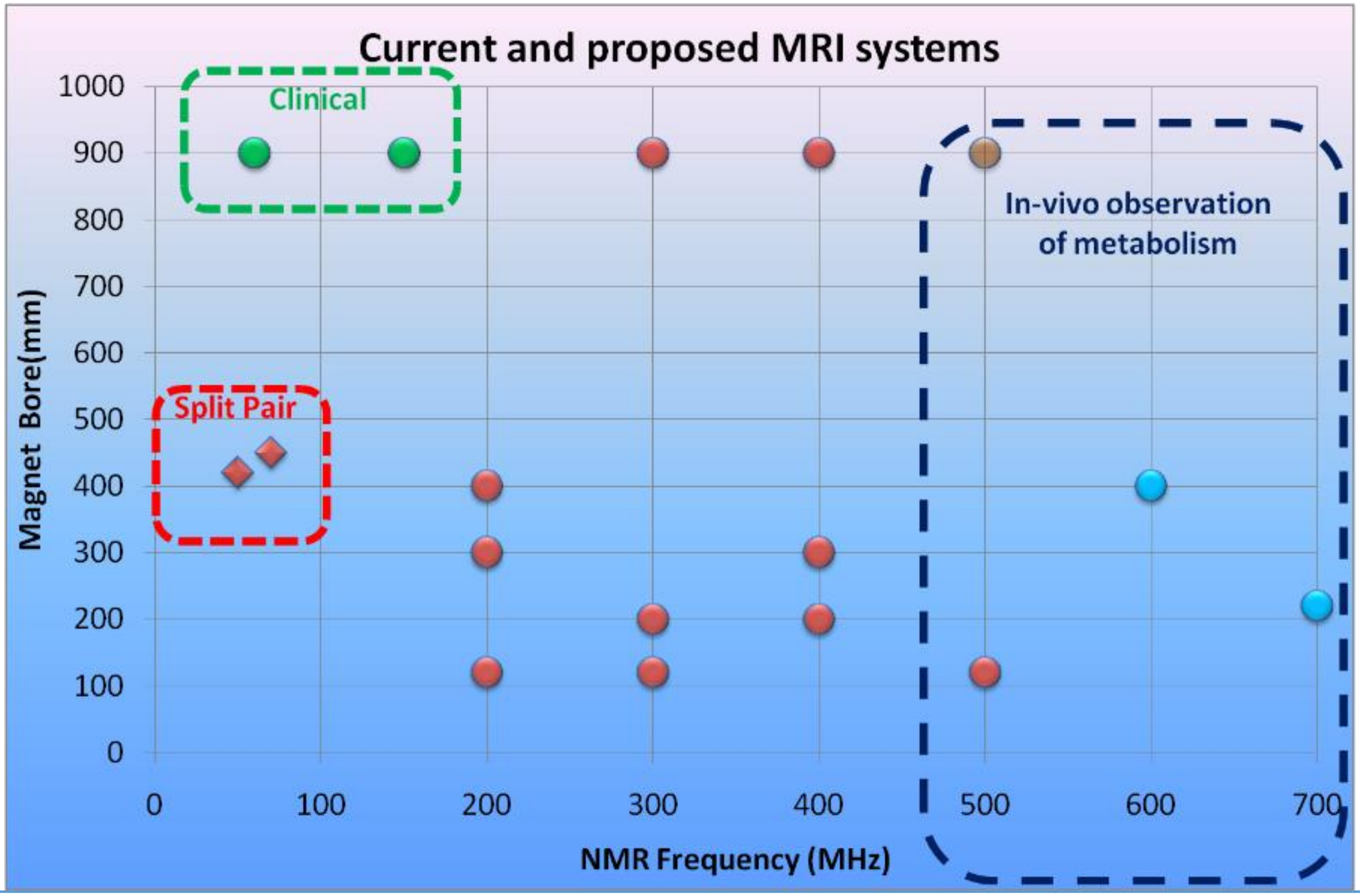
Courtesy: Ziad Melhem

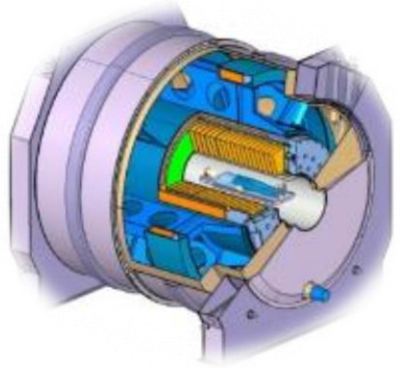
Key takeaway

- MRI scanning machines are commercial and > 50% of SC applications

MRI coverage

1.5T-3T	• Clinical MRI
7-9.4T	• Laboratory MRI
>11.4T	• Special &Future MRI

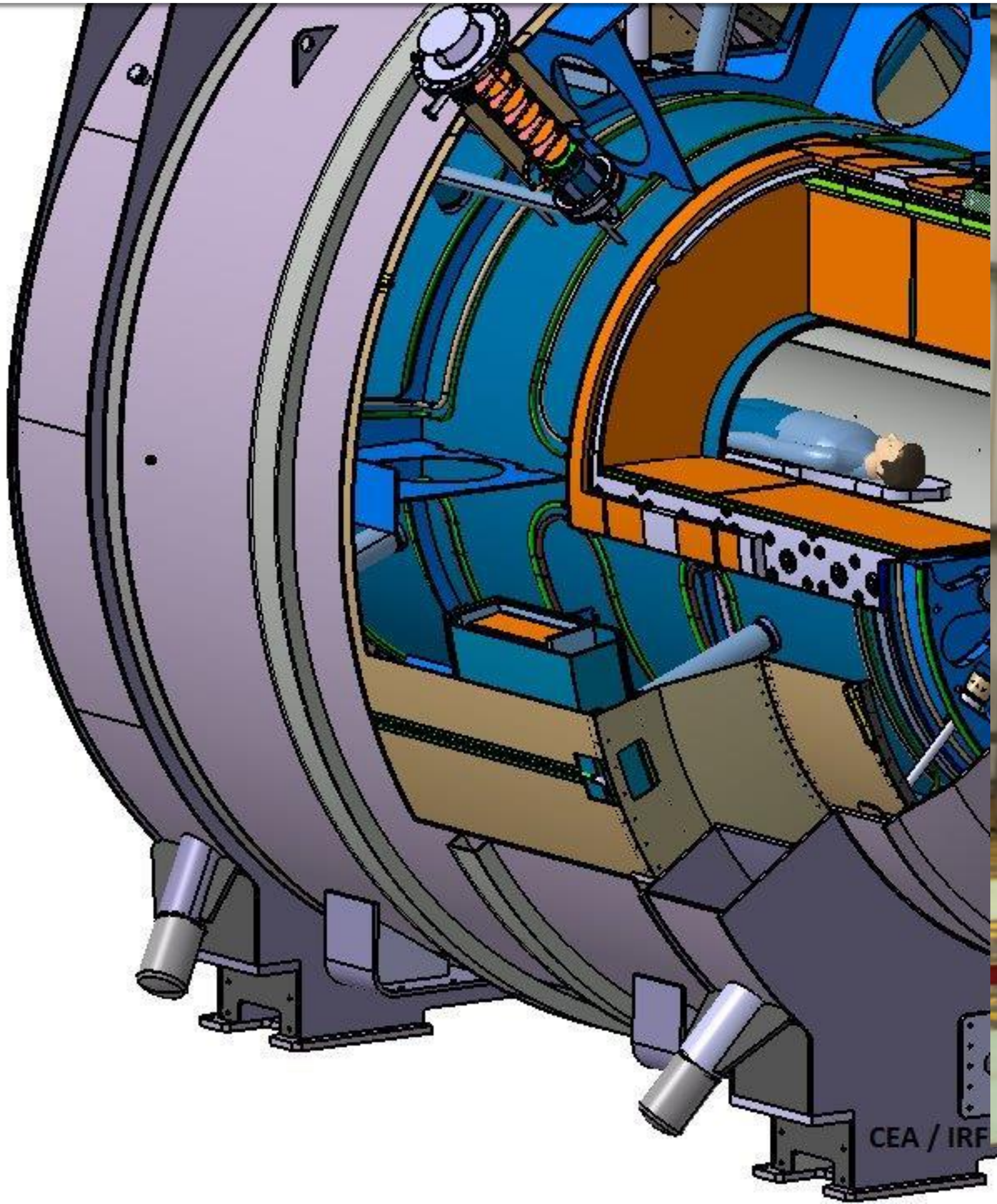




Courtesy: Ziad Melhem

ziad.melhem@oxqsol.com

Largest MRI for research: Iseult Magnet for 11.7 T, now under commissioning at Neurospin center in CEA Saclay (Paris)
FUNCTIONAL MRI: breakthrough in cerebral functions



SC and Renewable Energy Technology: wind genrators

AMSC SeaTitan Wind Turbine Generator
Image courtesy of American Superconductor

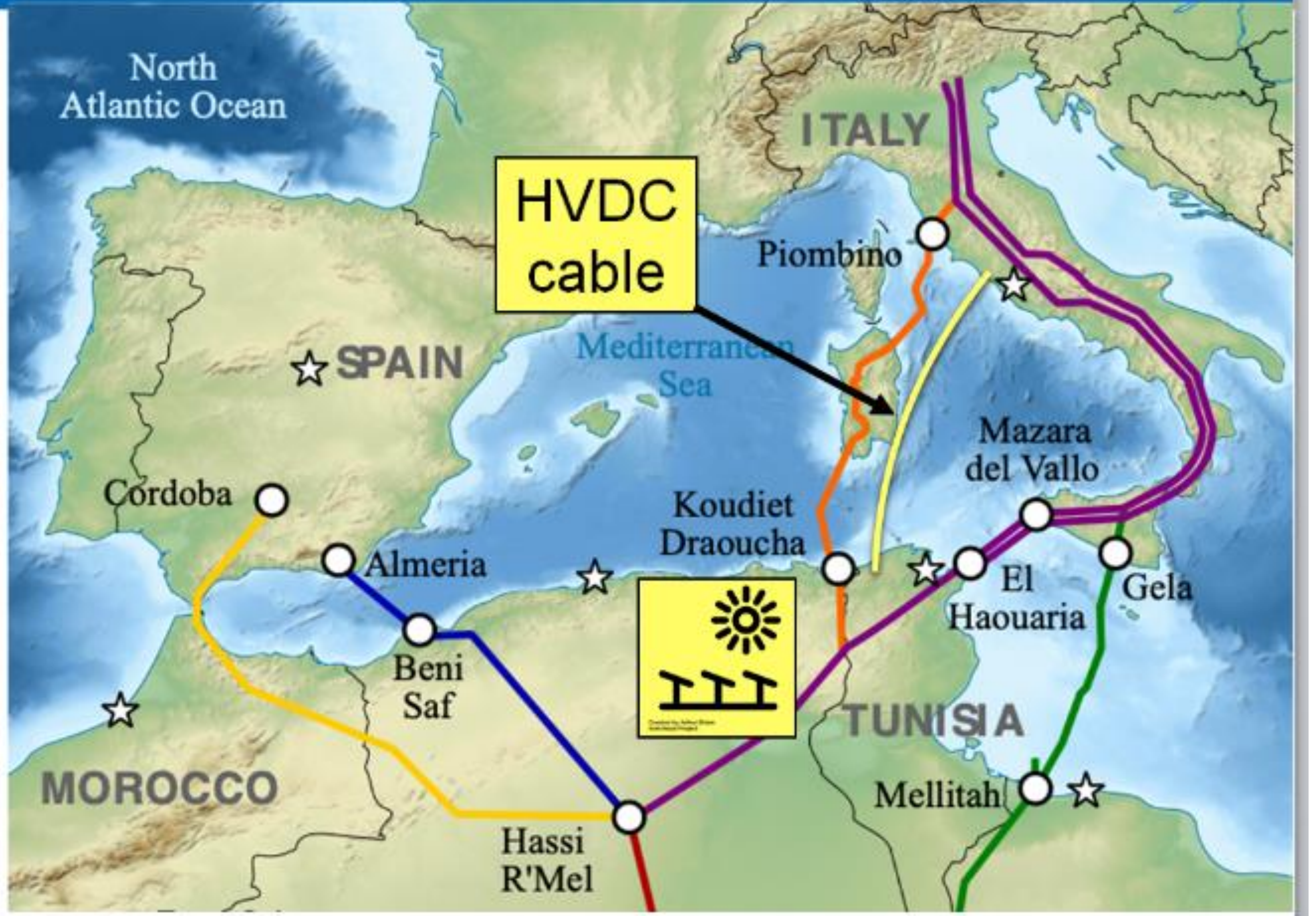
Cable test in a flexible cryostat

- All manufactured by 3 itaslian companies
- By increasing the voltage from 3 kV to a “modest” 30 kV this line can carry m1.5 GW d.c. power!!!
- It works at 20K
- At CERN in He gas
- Can be adapted to Liquid Hydrogen cooling!!!

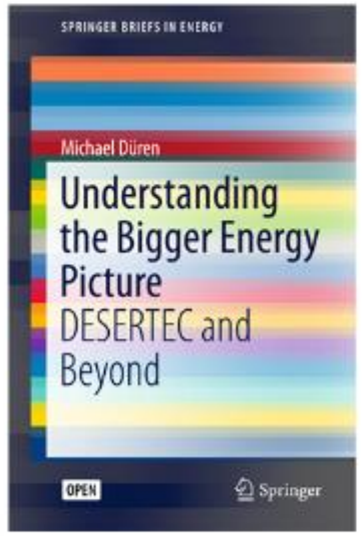
Italy is considered at cross-road for large cables!

Conclusion

The scientific community can play a leading role in demonstrating best practices for the energy transition



Acknowledgements
Thanks to all the colleagues that contributed from DLR, Desertec, Dii, CERN, DESY, ZEU, …



More in my book:

Michael Düren
Understanding the Bigger Energy Picture
Springer 2017
Open Access: https://dx.doi.org/10.1007/978-3-319-57966-5

M.Düren, University Giessen

Icons: Noun Project

28.11.2019 Michael Düren Justus-Liebig-Universität Gießen 28

SC and Renewable Energy Technology: Ship Propulsion

Picture from:
Nature Physics 2, 794 - 796 (2006)
doi:10.1038/nphys472
Wired for the future
John Clarke & David C. Larbalestier

AMSC
36.5 MVA, 6 kV
120 rpm
8 poles, 75 tons
Efficiency > 97 %
Dimensions: 3,4 m x 4,6 m x 4,1 m

Technical advantage (mass, cost, energy saving)
Regulation on emission may drive this change!

Superconductivity and Renewable Energy Technology
Fault current limiters

12 kV, 1600 A resistive fault current limiter installed at Western Power Distribution, Chester Street, Birmingham, since end 2015

Aviation: the last frontier for superconductivity?

Electrification in Aviation (propulsion)

SIEMENS
Ingenuity for life

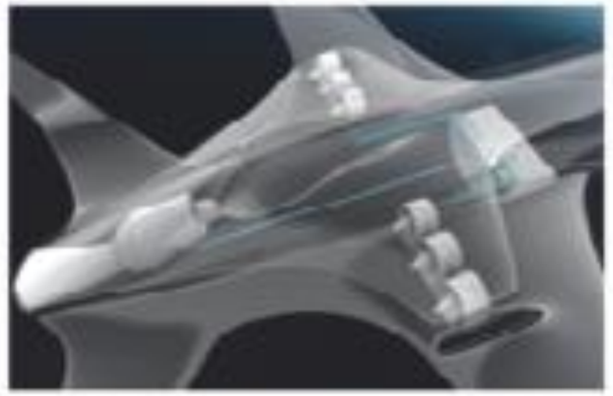
Electrified aircrafts enables more **sustainable aviation**

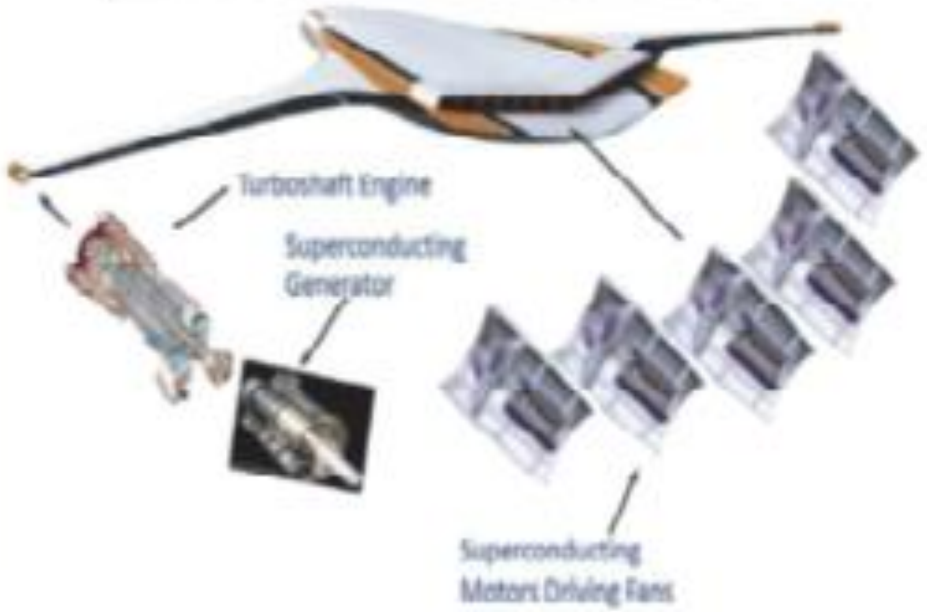
Aspects

Transport efficiency $\propto \left(\frac{\text{Lift}}{\text{Drag}}\right) \times (\text{Power Train Efficiency})$

- less noise & emissions

  (Green Hous Gases, target "European Flightpath 2050": -75%)
- higher efficiency in propulsion
- new degrees of freedom in design
- reduces "over-the-top design"
- "decentralization and decoupling" of power generation and propulsion

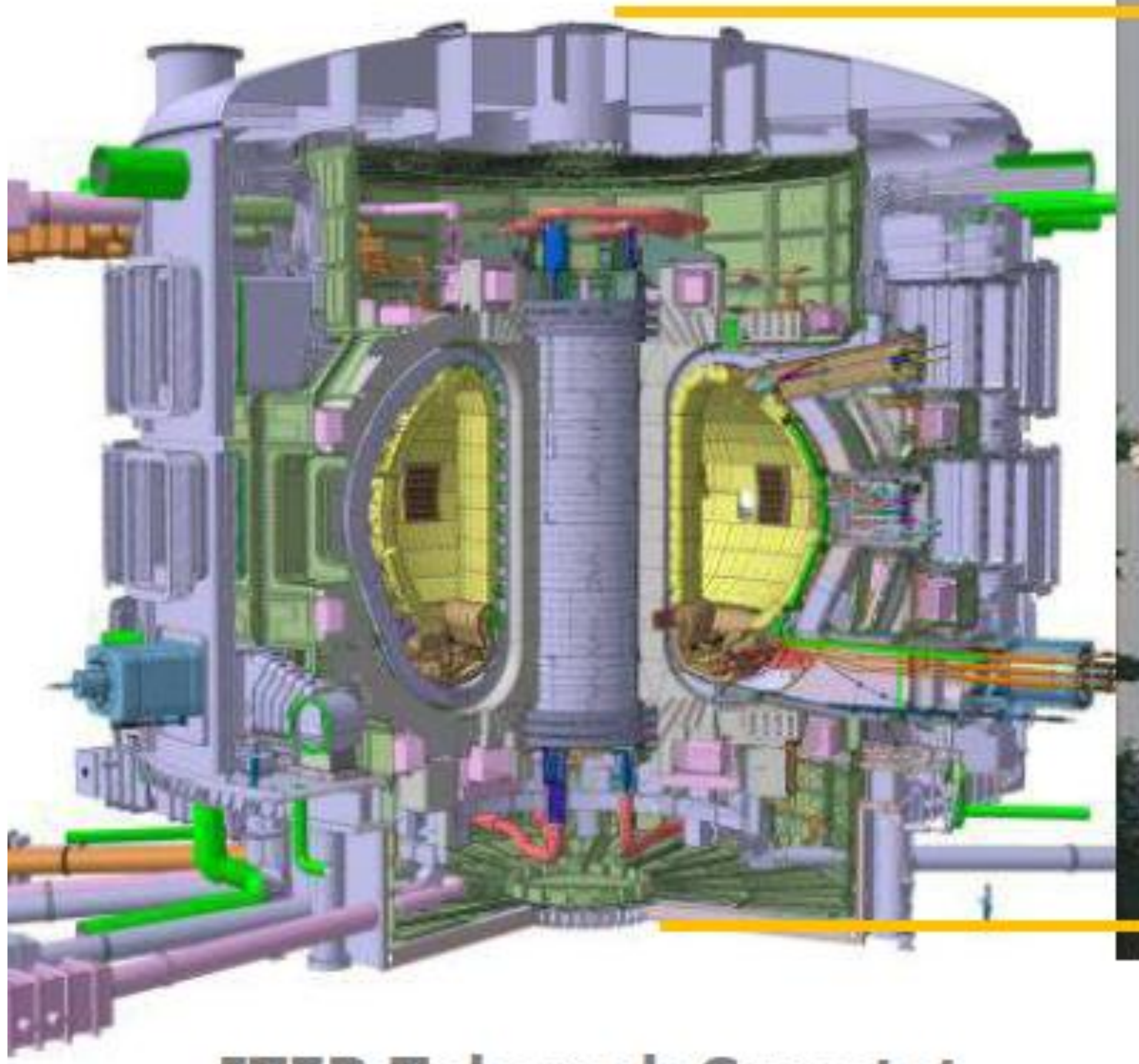




Unrestricted © Siemens AG 2018

Page 23 20181030 – Tabea Arndt Corporate Technology

The present frontier of SC for power generation:ITER and the energy of the star: **fusion!**



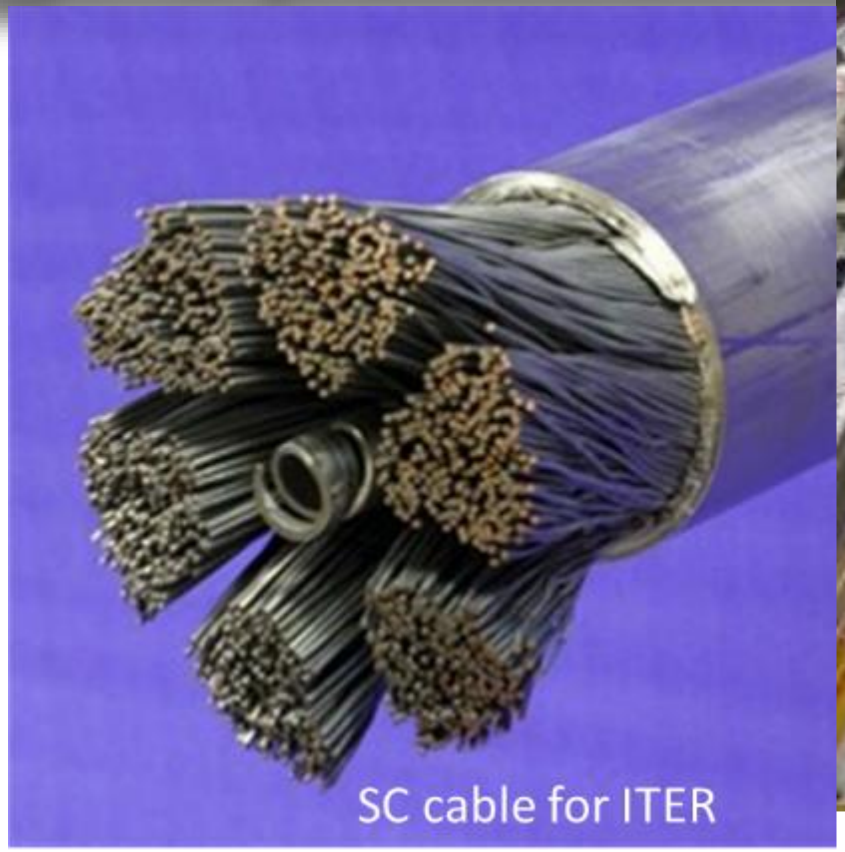
ITER Tokamak Cryostat
~28 m Tall x 29 m Dia.

Jefferson Memorial (Washington DC)
~29 m Tall (floor to top o

From A. Devred (CERN)

Courtesy of G. Johnson
(formerly ITER-IO)

ITER is progressing! Operation in ten years



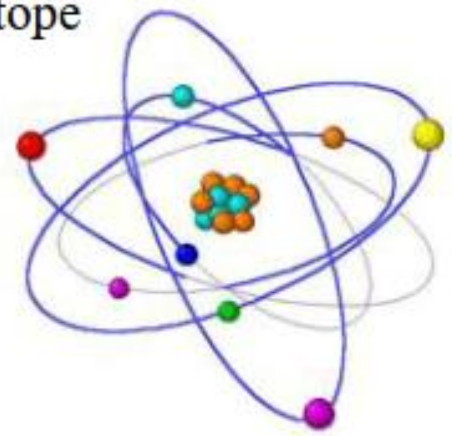
12 T SC Magnets
Nb_3Sn (low J)
High current : 70 kA
Supercritical Helium

From N. Mitchell (ITER)

Production of radioisotopes for PET is critical

Radioisotopes in Nuclear medicine

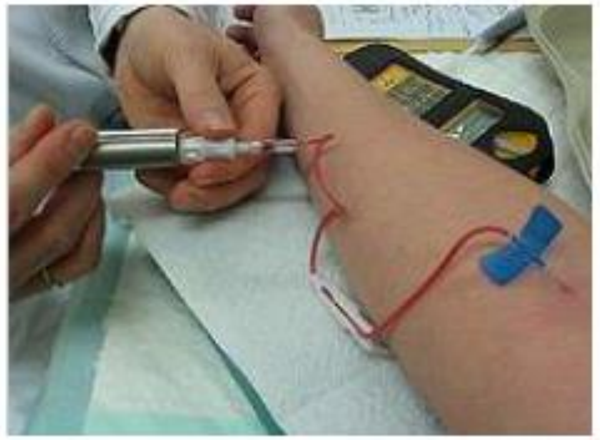
Radioisotope



Radiopharmacy

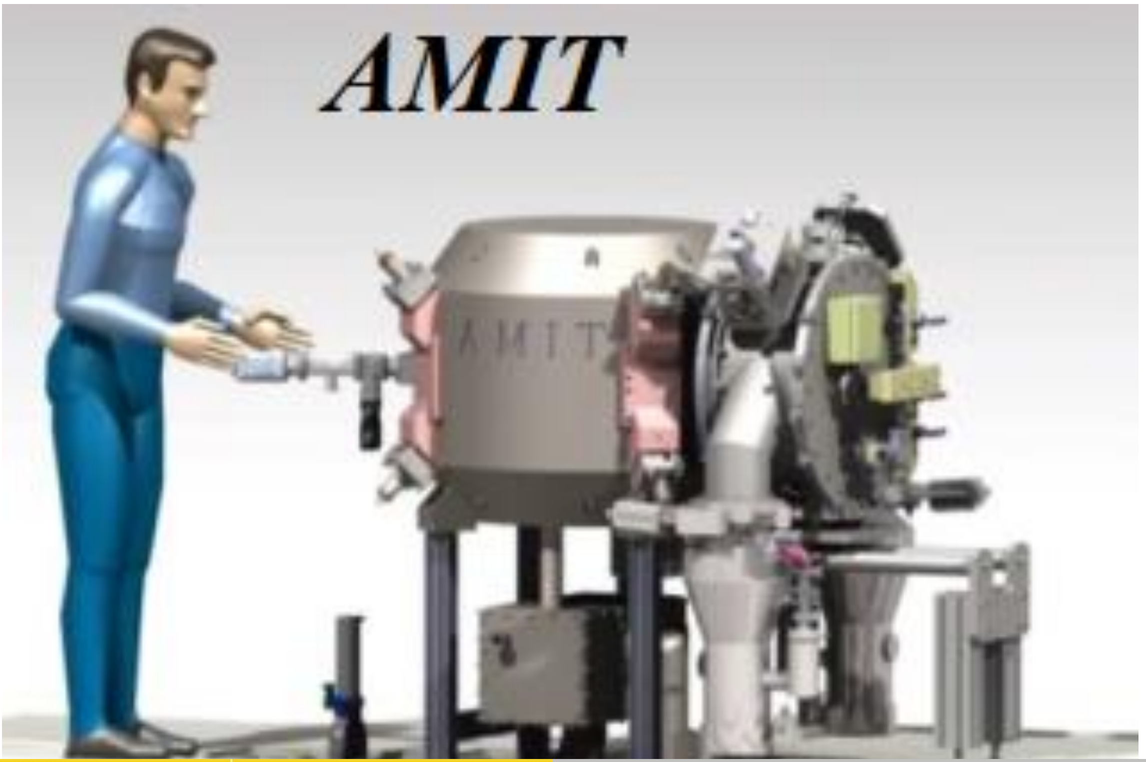
Radiopharmaceutical

A ^{11}C labeled radiopharmaceutical



Localized in some organs or tumors

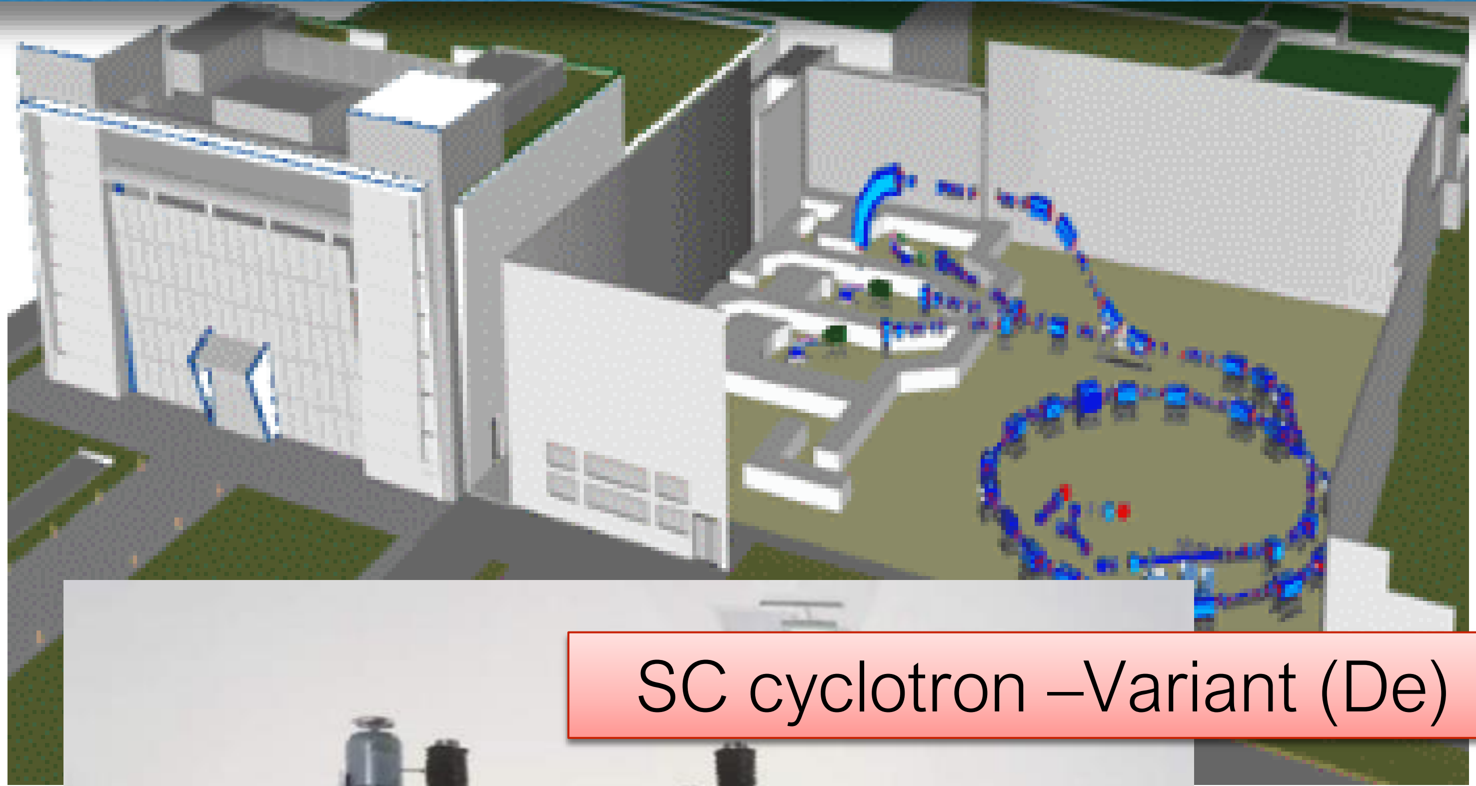
Last decade crisis in reactor-production



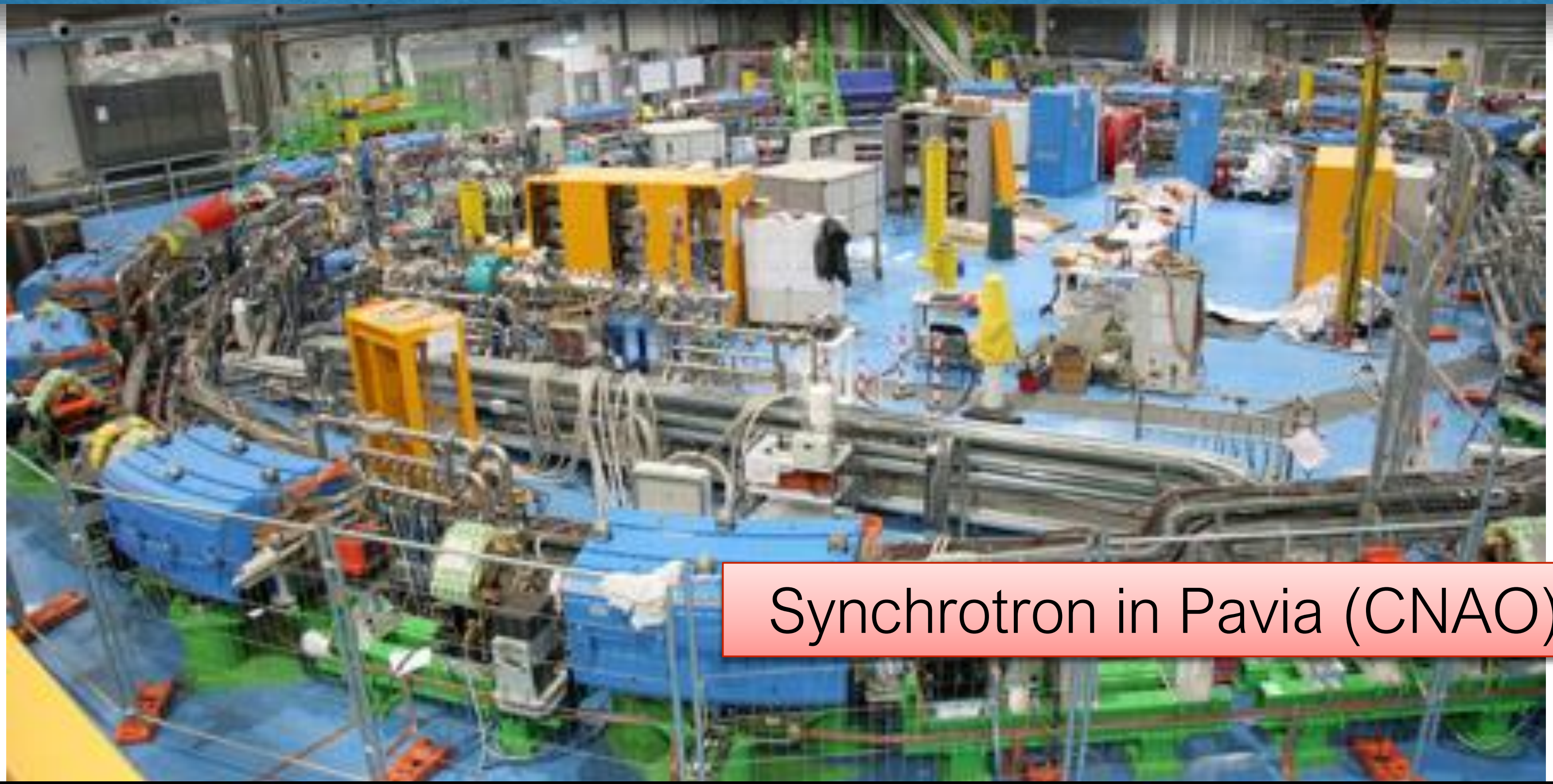
GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

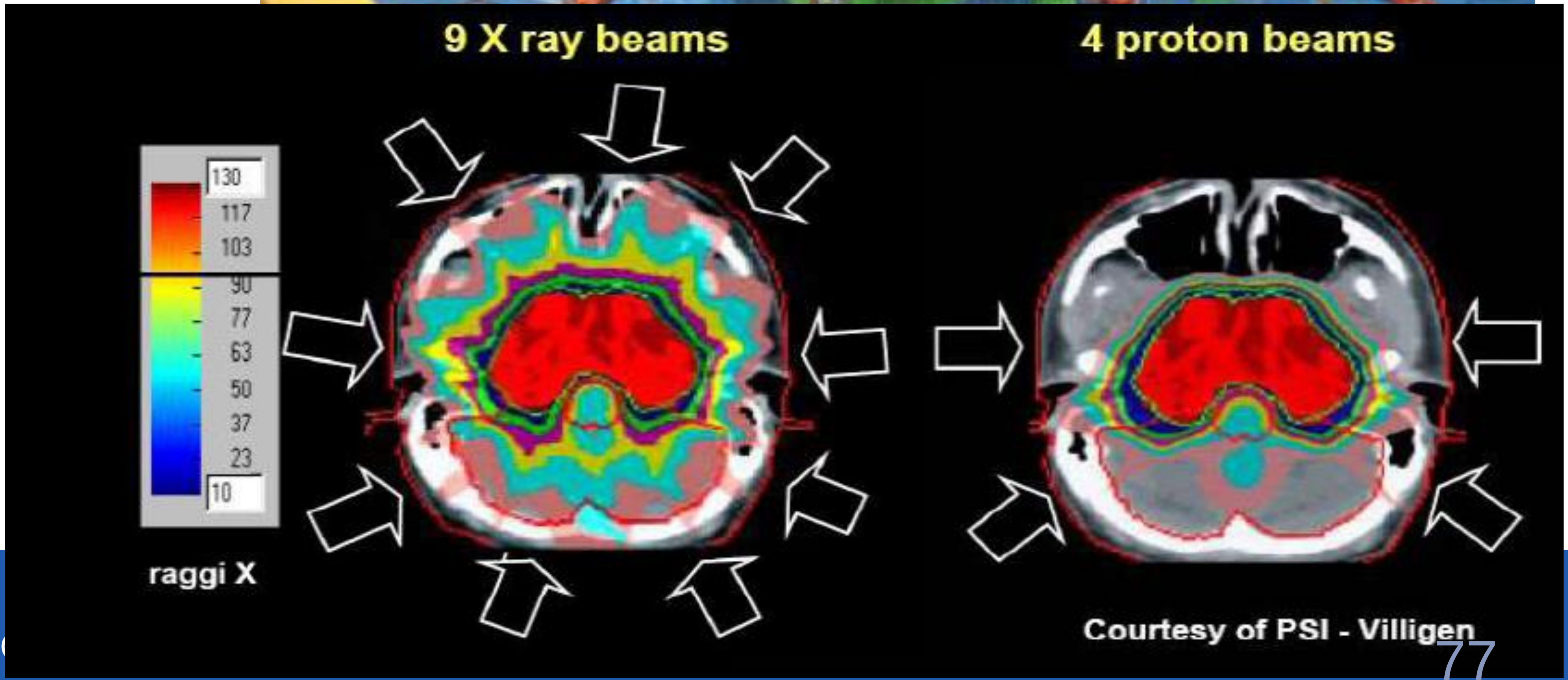
Hadron therapy



SC cyclotron –Variant (De)



Synchrotron in Pavia (CNAO), It



What's next for particle therapy?

- Multiple ions delivered with light-weighted Gantry
- Treatment rooms equipped with patient imaging
- Dose Delivery and Range Verification Systems able to adapt online the dose delivered

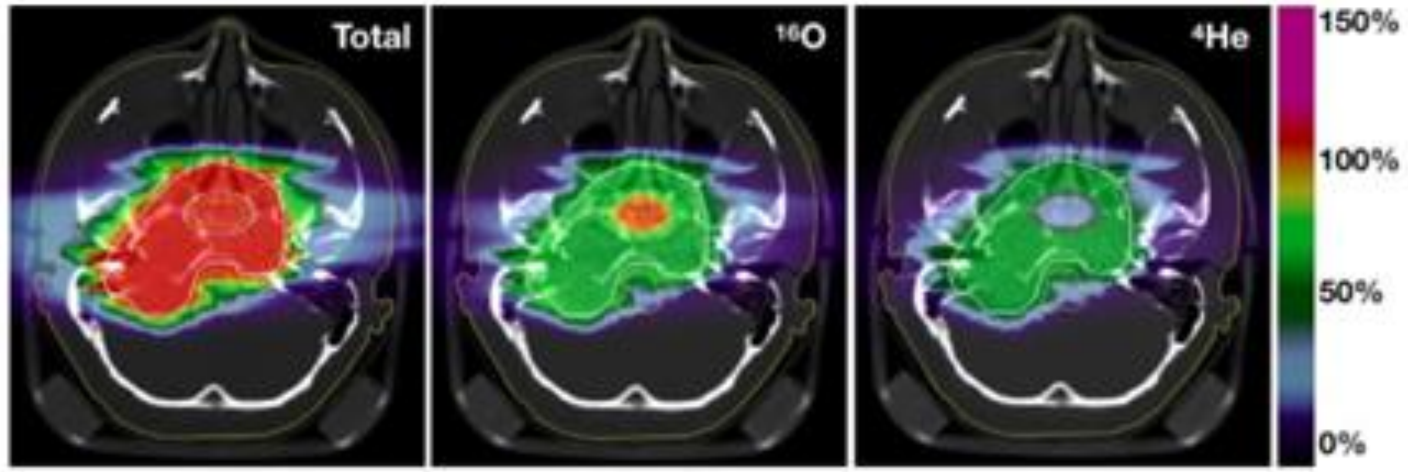
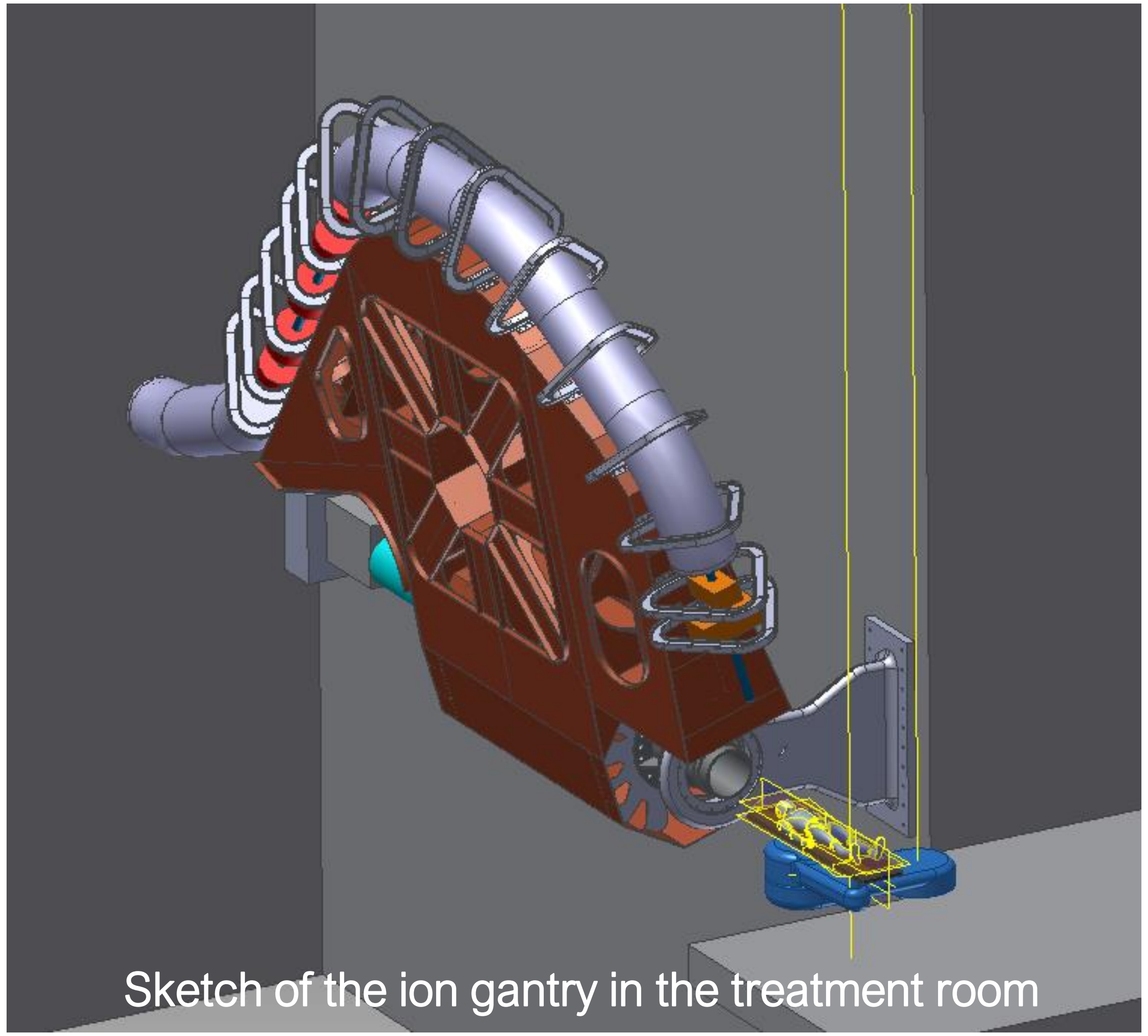


Figure1: Total profile of biologically effective (RBE and OER weighted) dose and single particles' contributions, arising from the Multiple-ion full biological optimization (MIBO) with 2 pairs of ^{16}O and ^{4}He fields.

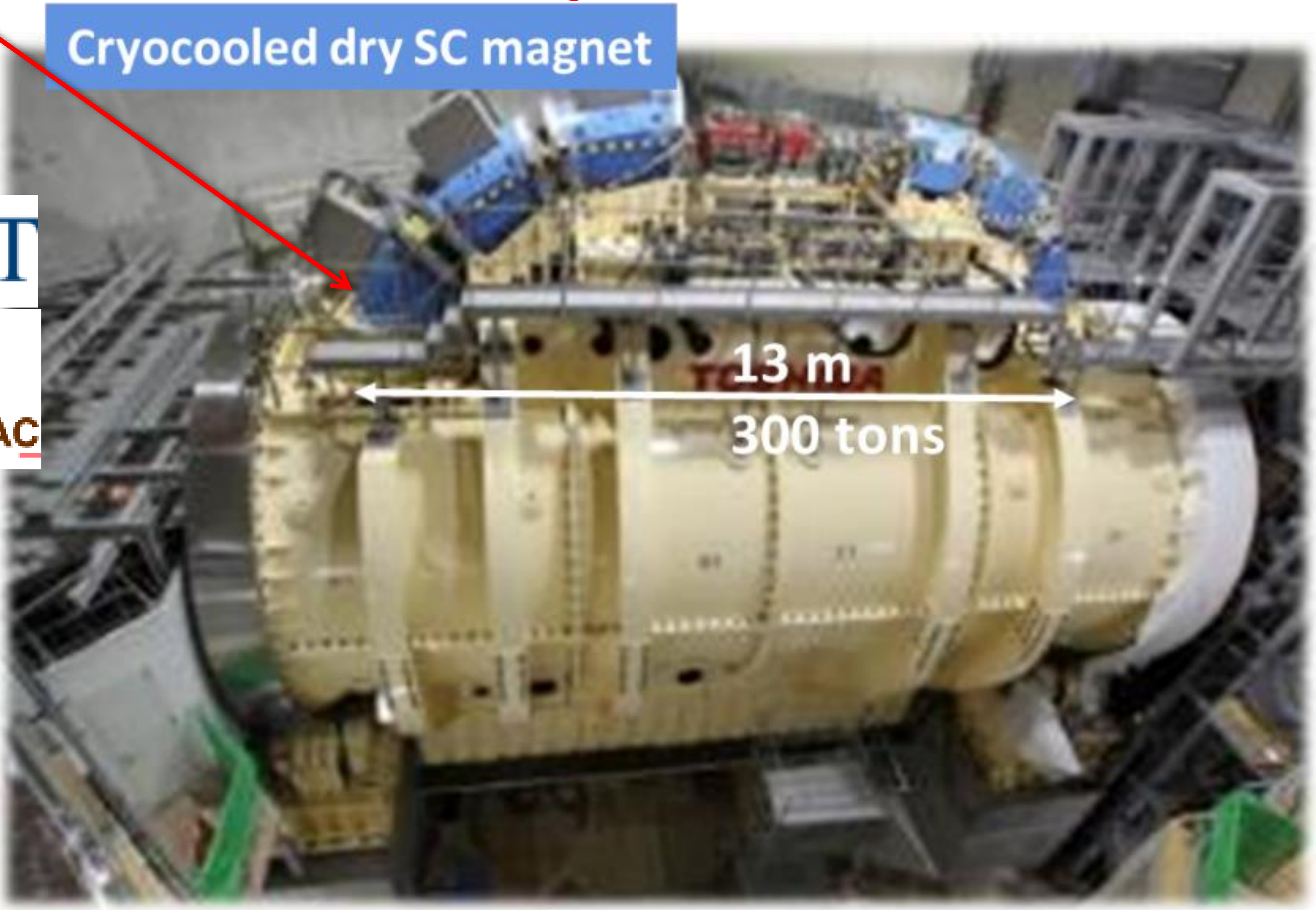
Ion gantry @ Himac (Jp)

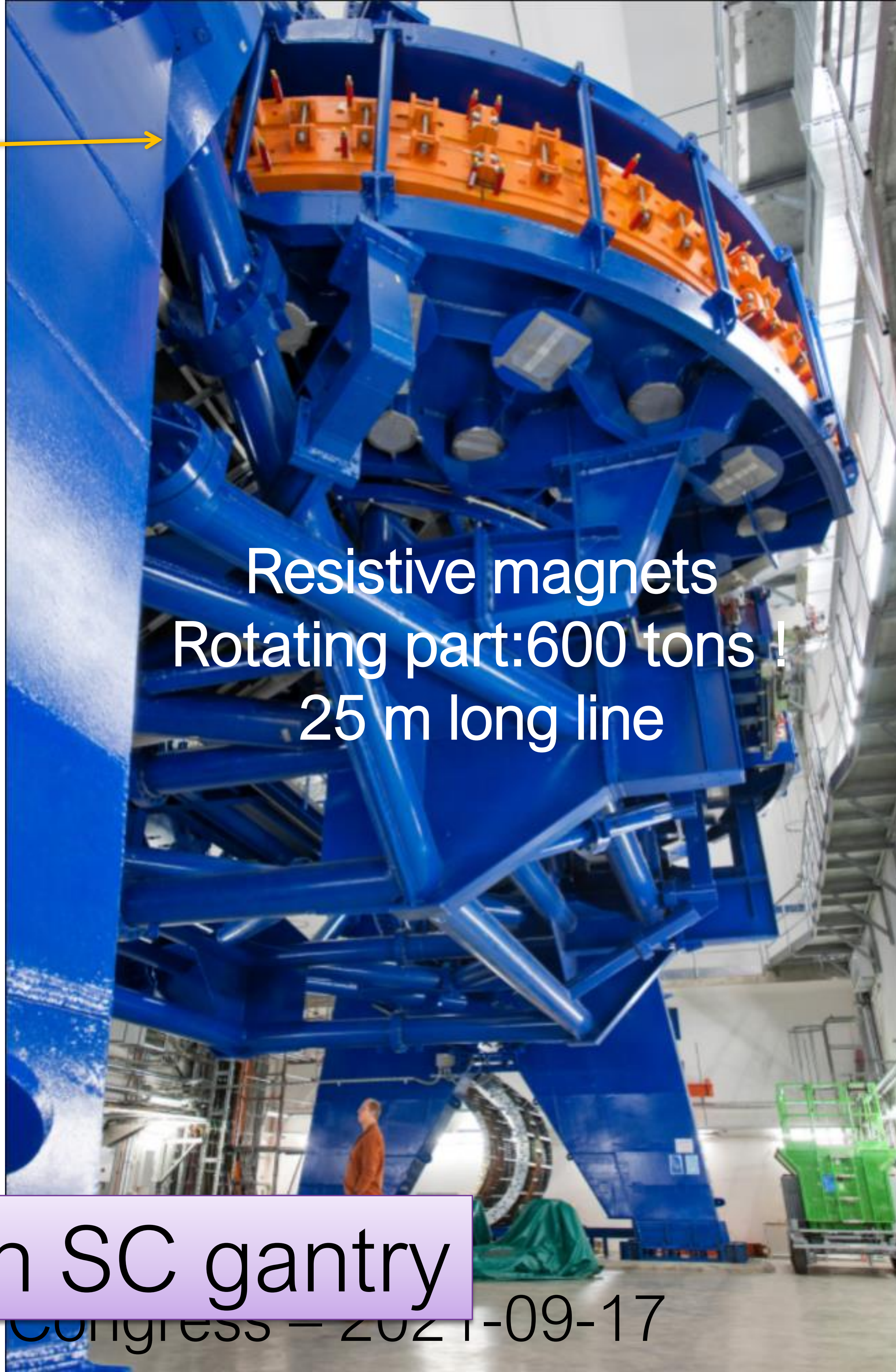
Gantry and imaging system of a proton therapy center



Sketch of the ion gantry in the treatment room

State of the art of ion gantry:
HIT – Heidelberg (2013)
Japan: HIMAC at QST-NIRS by Toshiba
First SC Gantry in operation 2018



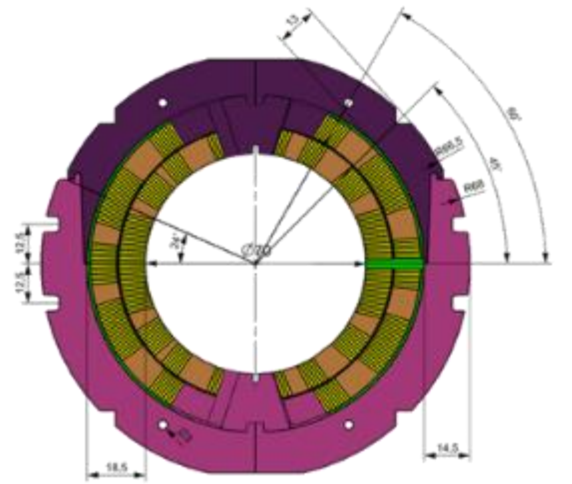


QST
NIRS
HIMAC

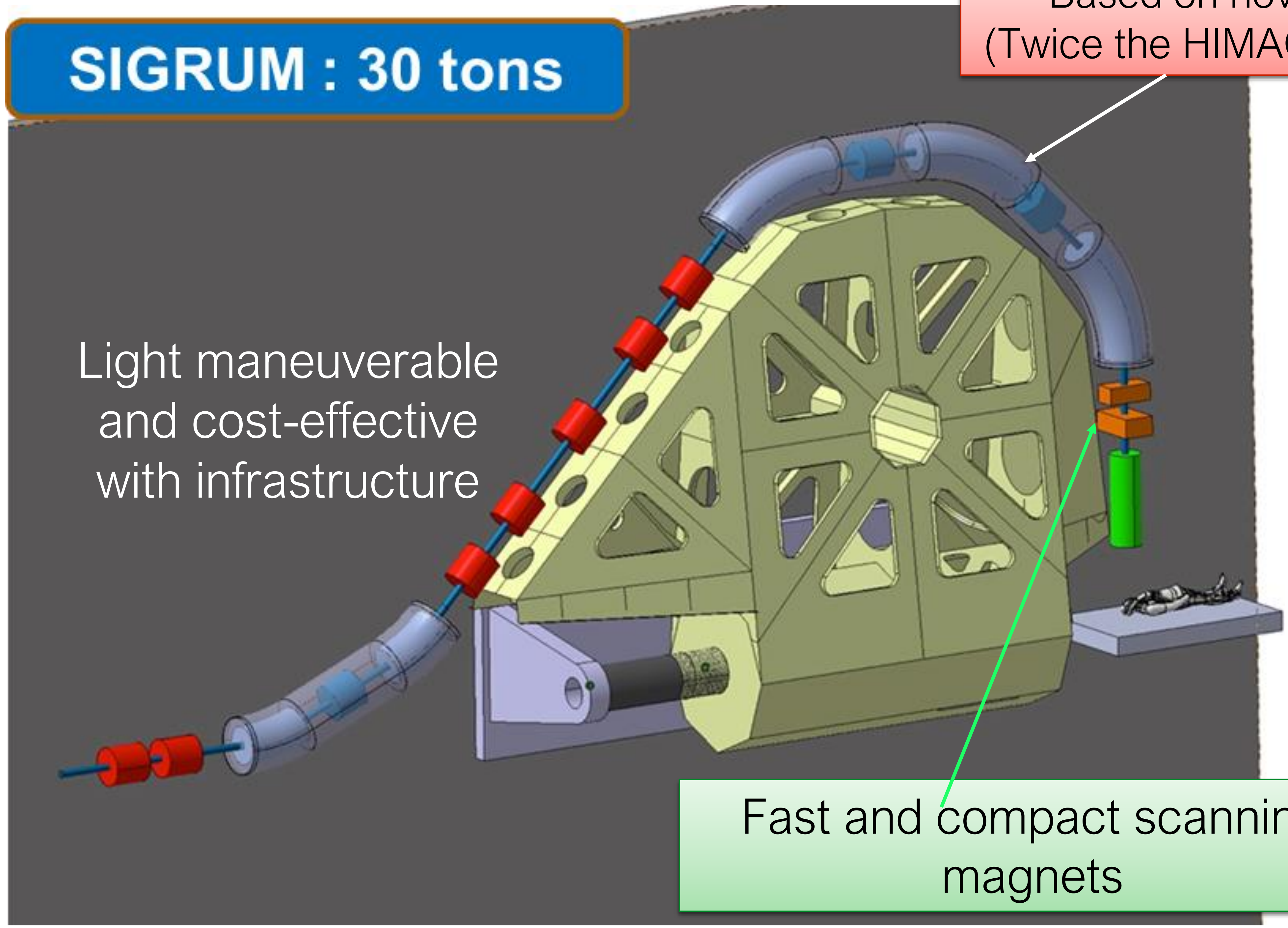
Courtes

Now HIMAC working for a 150 ton SC gantry

Internatl. collaboration CERN-CNAO-INFN-MedAustron for an advanced ion SC Gantry



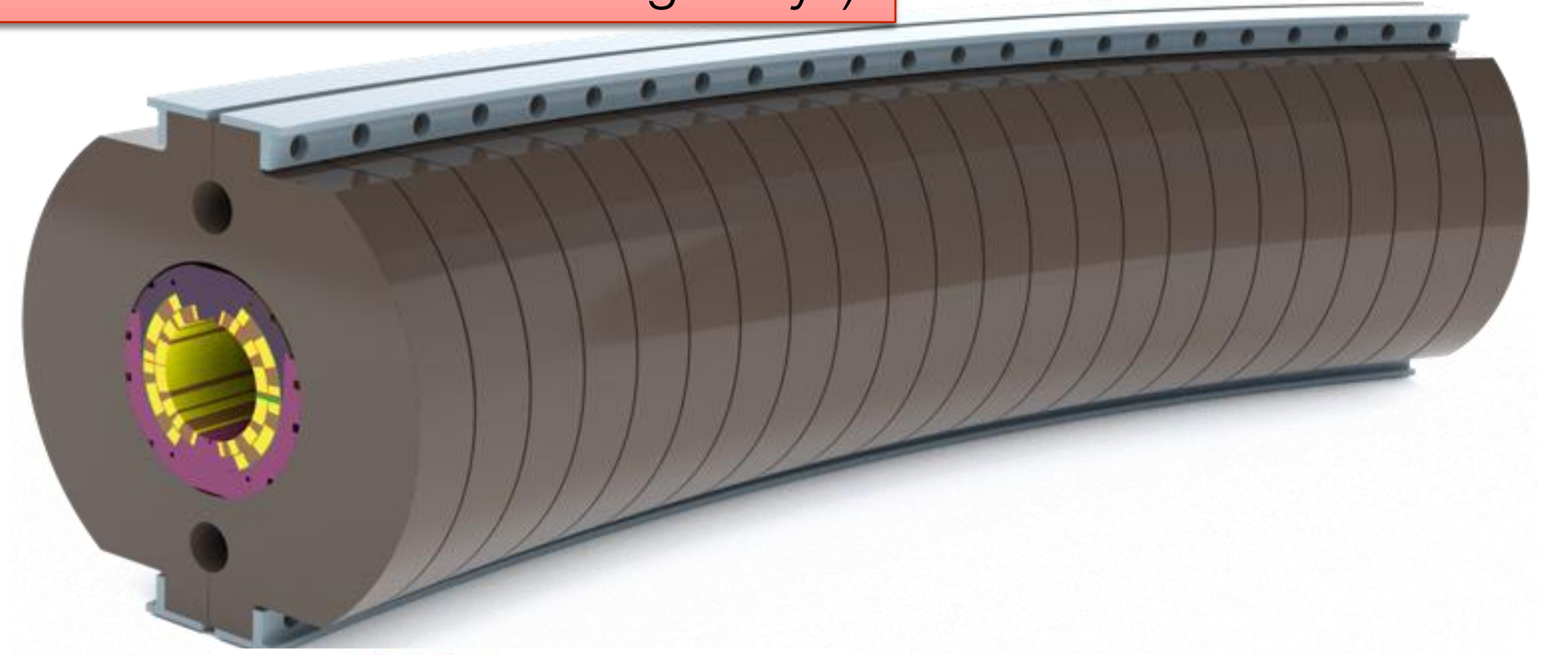
Based on novel CURVED SC dipole of 4- 5 T
(Twice the HIMAC-Toshiba state-of-the-art gantry!)

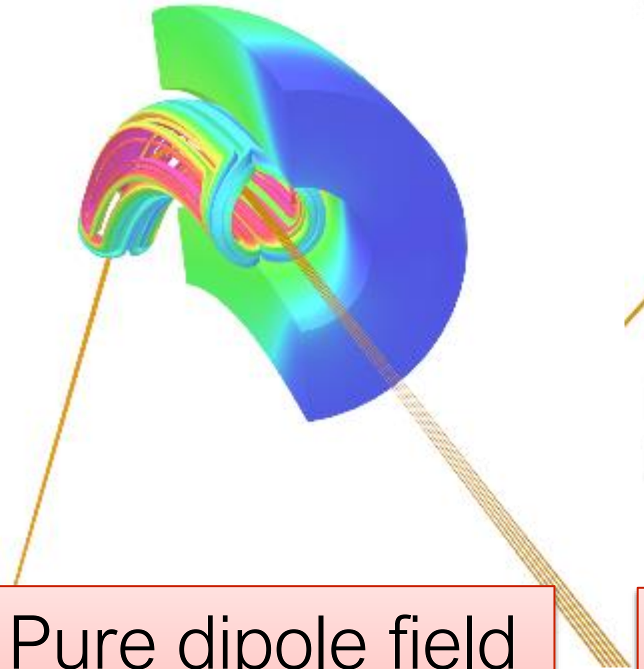


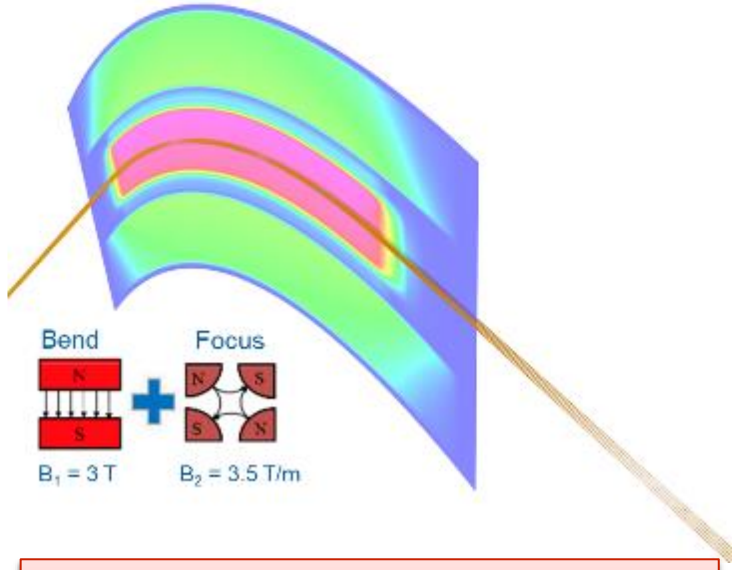
SIGRUM : 30 tons

Light maneuverable and cost-effective with infrastructure

Fast and compact scanning magnets

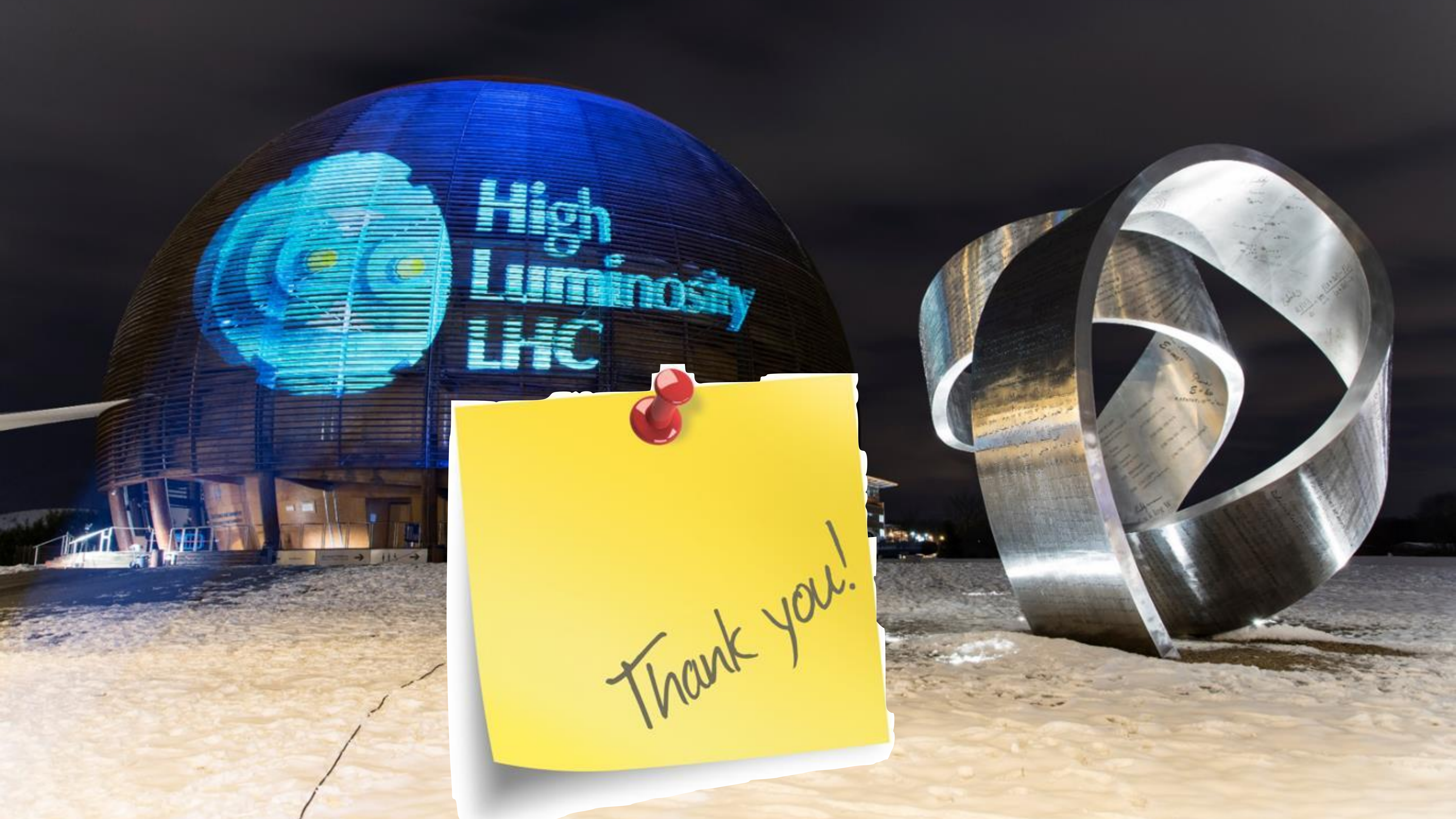






Pure dipole field SIG demonstrator

Final design: Dip+Quad = combined funtion


High
Luminosity
LHC
Thank you!