Superconducting Materials for Large Scale Applications

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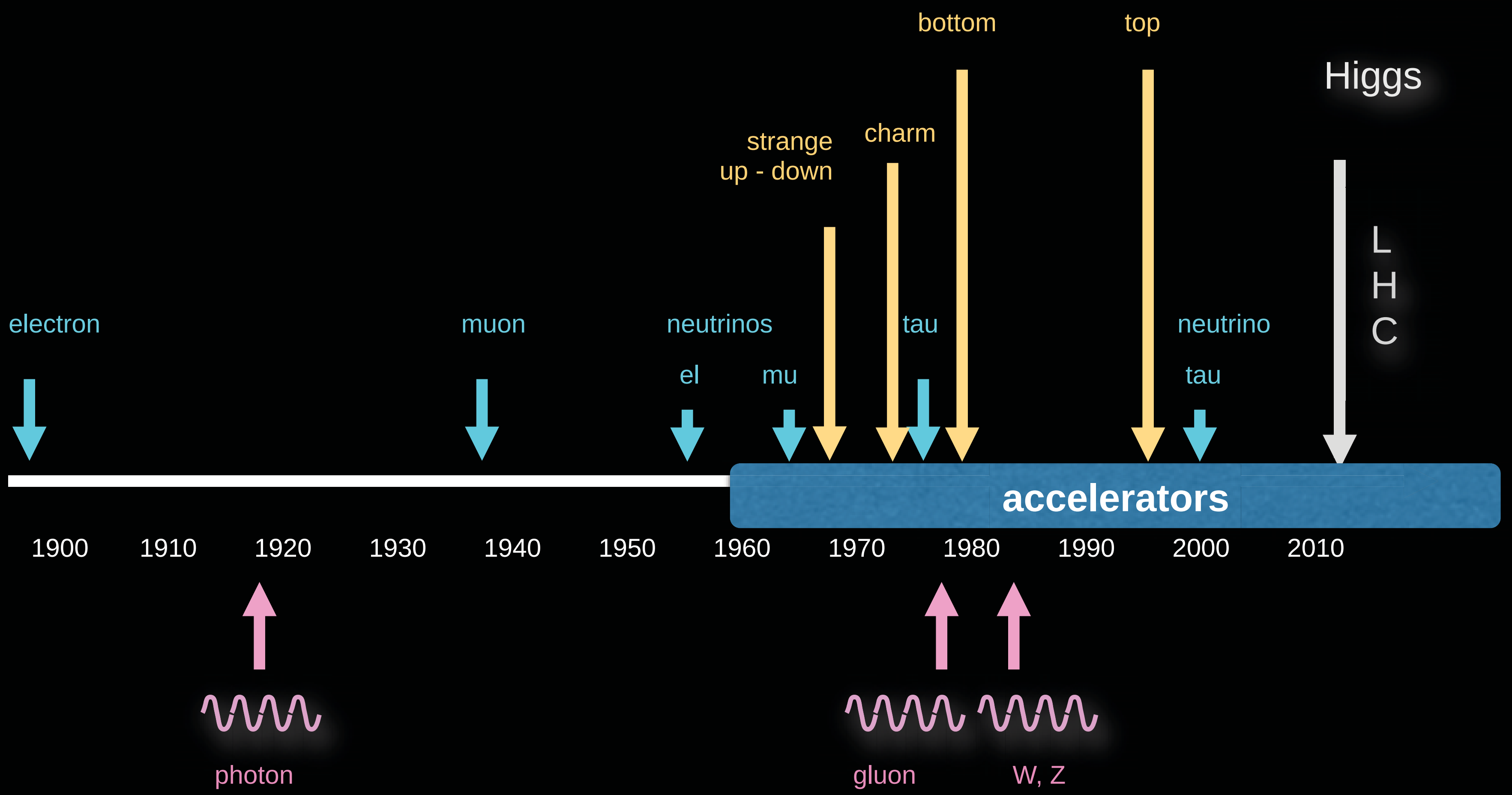
High Luminosity LHC Project Leader

PASSION FOR SCIENCE
NEW ELEMENTS AND NEW MATERIALS

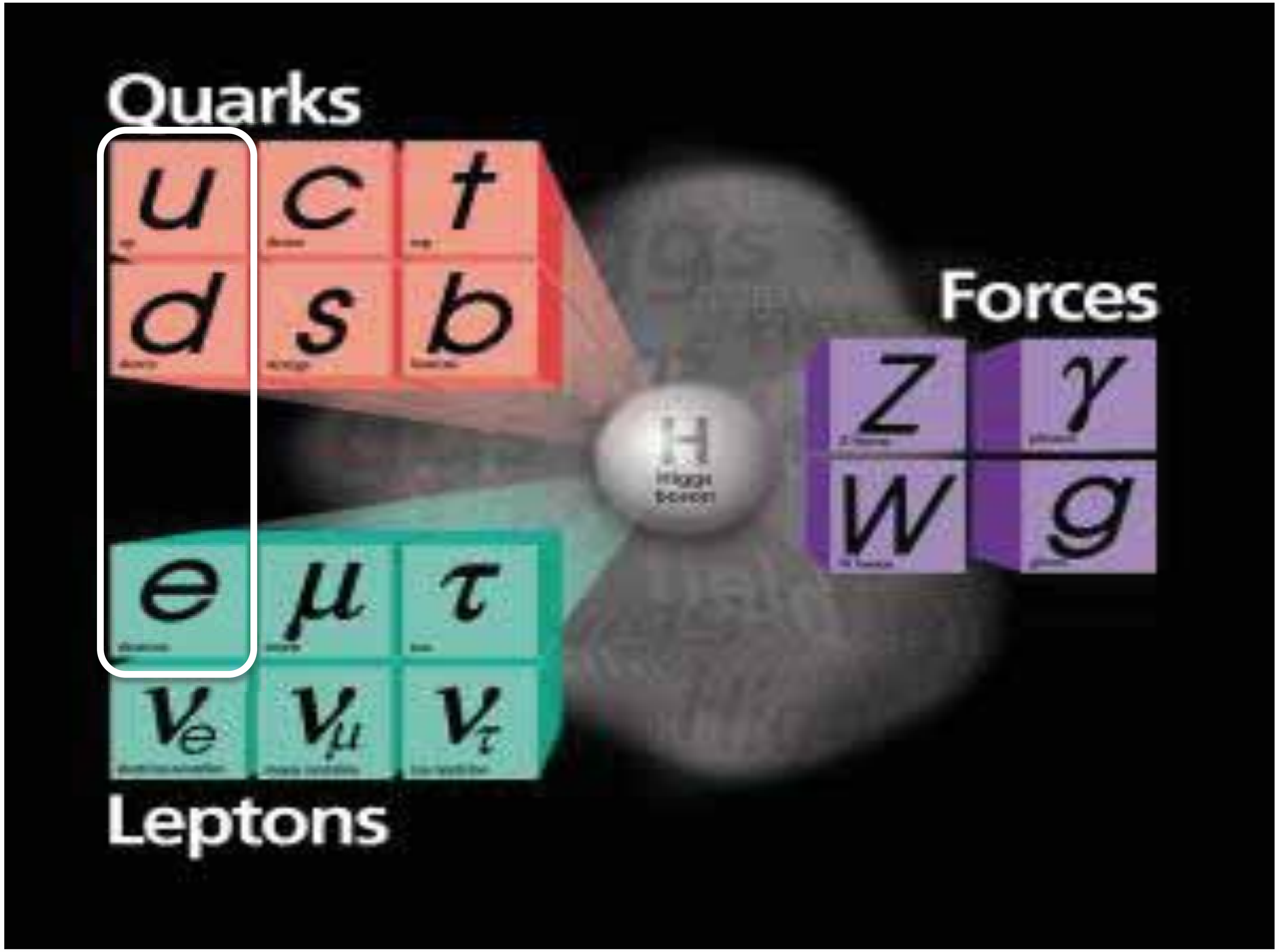
CERN
Società Italiana di Fisica
Società Chimica Italiana
ACCADEMIA DELLE SCIENZE DELL'ISTITUTO DI BOLOGNA

6-7 November 2019
Sala Ulisse
Accademia delle Scienze dell'Istituto di Bologna

60 years of experiments at accelerators have discovered the set of fundamental particles



So also thanks to accelerators we have the new periodic table…



gives particles their masses

Superconducting accelerators

- Circular (relativistic) Accelerators

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

  → superconducting bending and focussing magnets

  - high-energy hadron synchrotrons

- Linear Accelerators

  $E_{beam} = \boldsymbol{E}\ L$ [MeV] [MV/m] [m]

  → superconducting acceleration cavities

  - high-energy e^+-e^- linacs

Superconductivity: an enabling technology

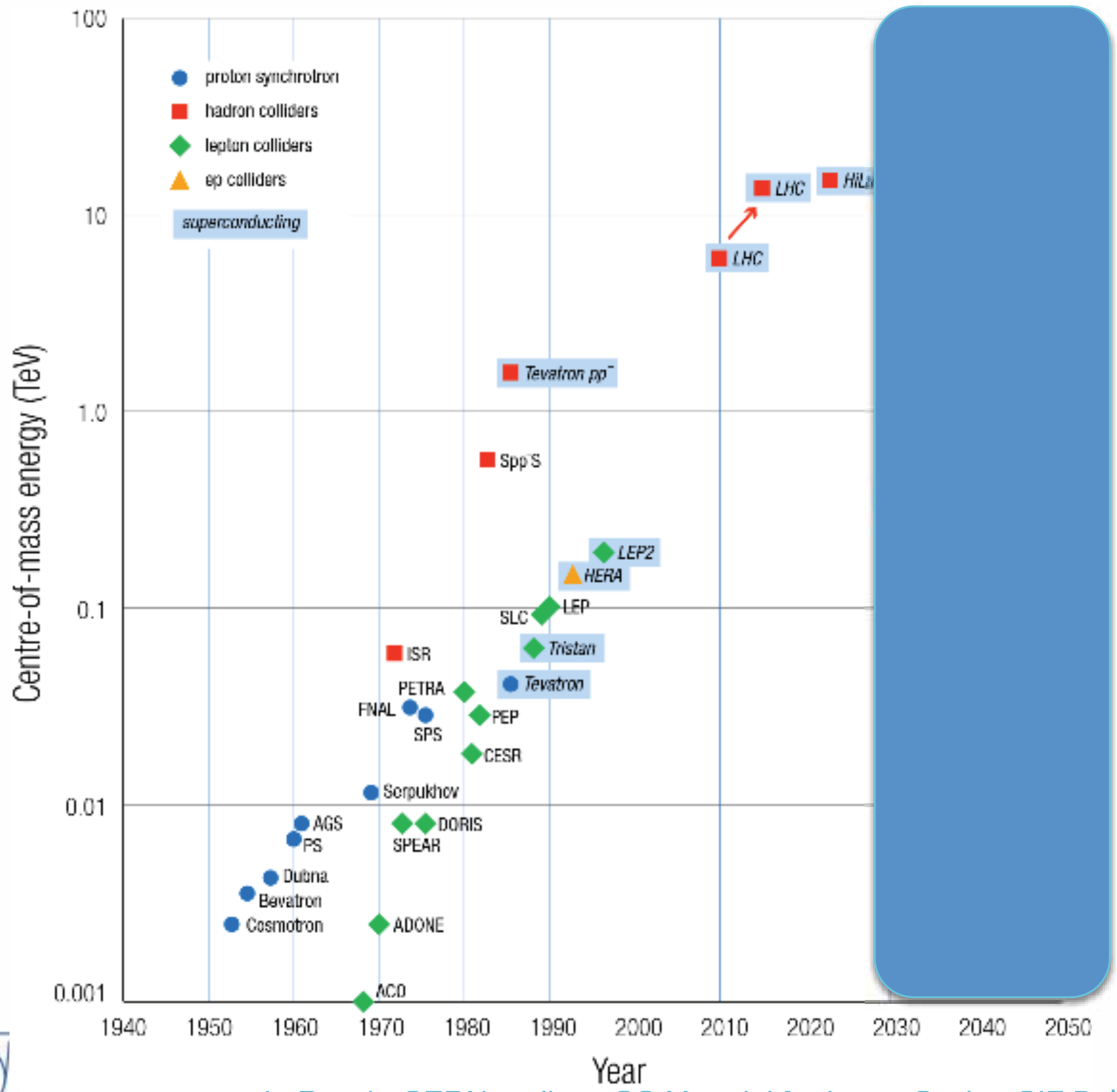
- Superconducting LHC

Normalconducting LHC

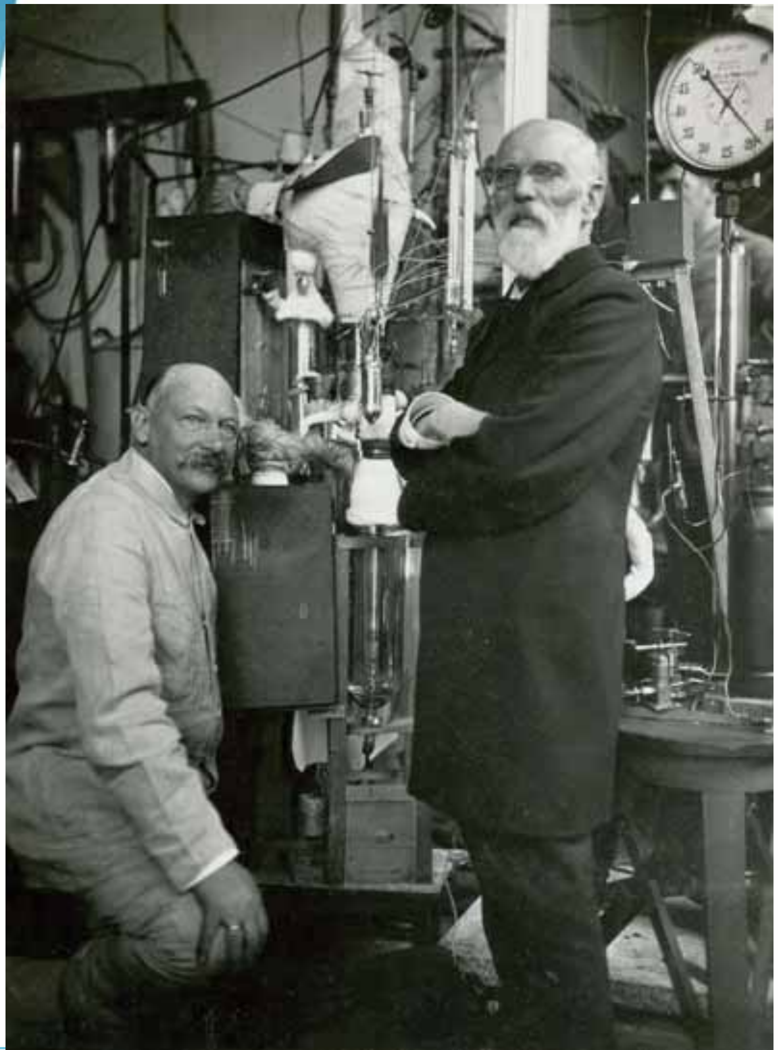
- Tunnel : 27 km
- Field : 8.3 T
- Cryoplant power at the plug: 40 MW: **always on**
- ~ 70
- 150 acce
- 180 N

- Tunnel 120 km
- Field : 1.8 T
- Dissipated power at collis MW
- Avera .4 coeffi MW only f tor

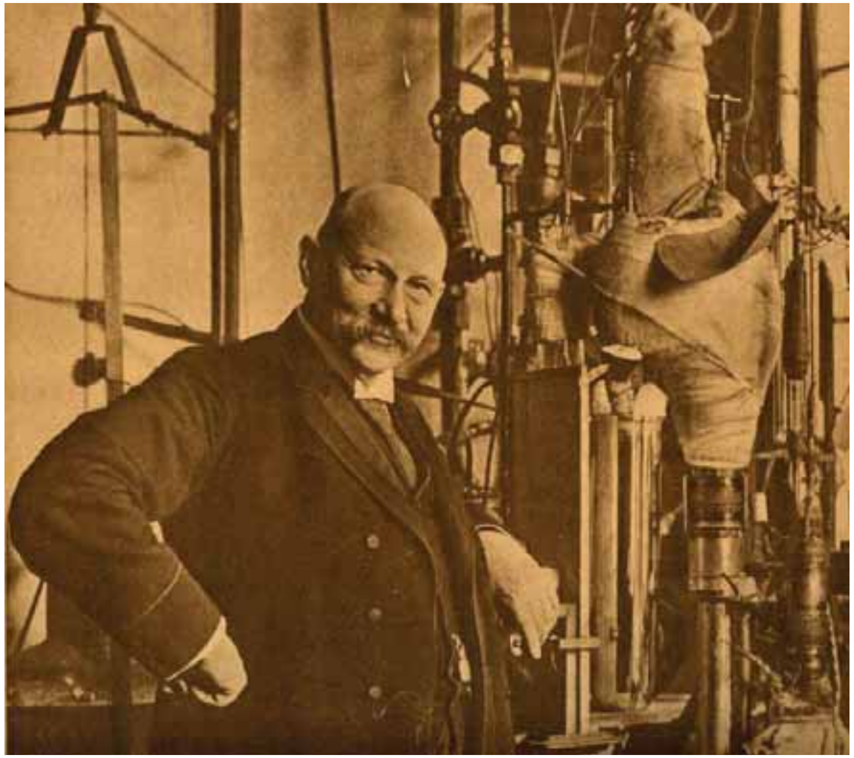
Accelerators progress: SC domination



University of Leiden: leading physics center at turning of XIX to XX century



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

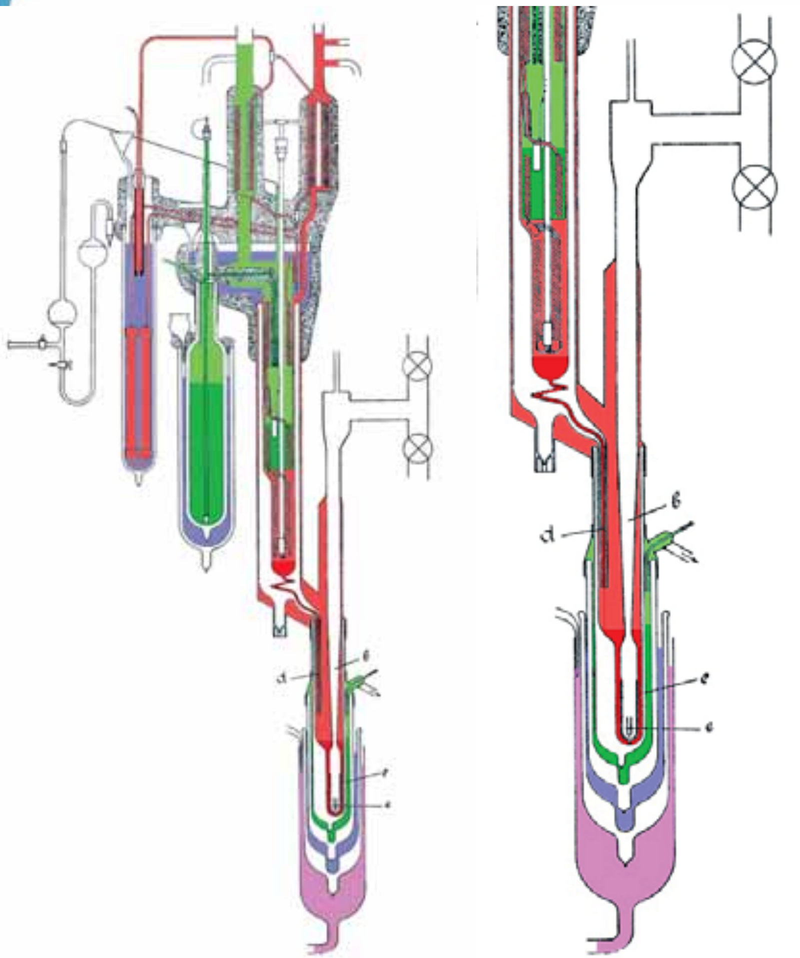


Onnes engaged in gas liquifaction race: he first liquified oxygen in 1894, he lost the race with Dewar (who liquified hydrogen in 1898) and eventually he first liquified helium in 1908!

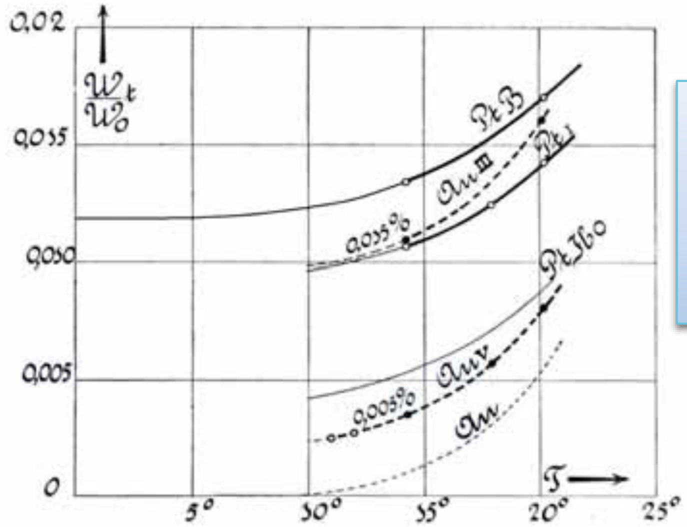
Onnes He liquifaction opened a new territory:
low temperature → low thermal noise

Onnes for 10 y did not publish: but founded a school for technicians…

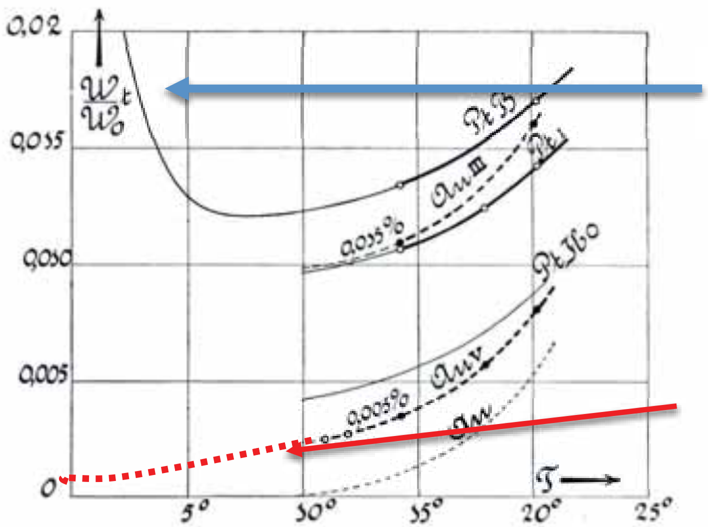
Onnes: he developed instruments to verify an hypothesis



His Technical idea: separate the sample measurements cryostat from liquifaction dewar.



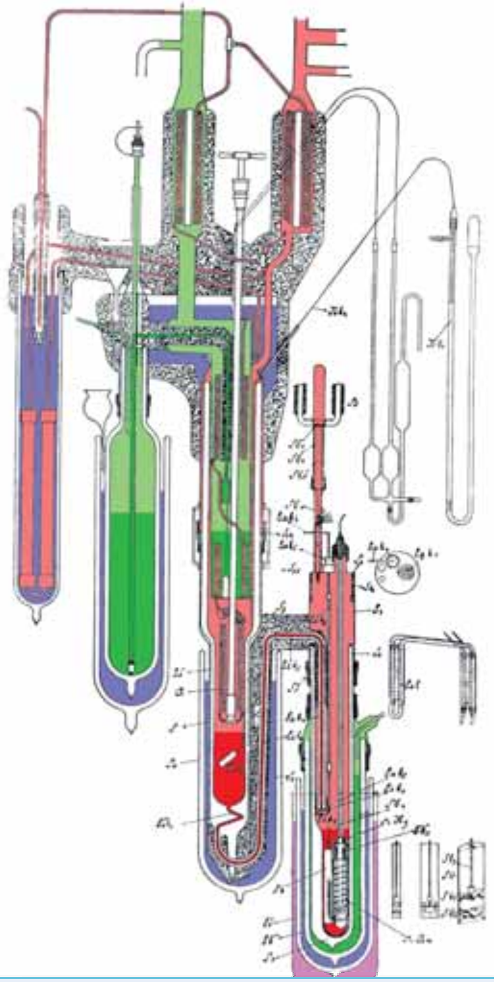
Hypothesis : zero resisitivity without thermal and impurity scattering…

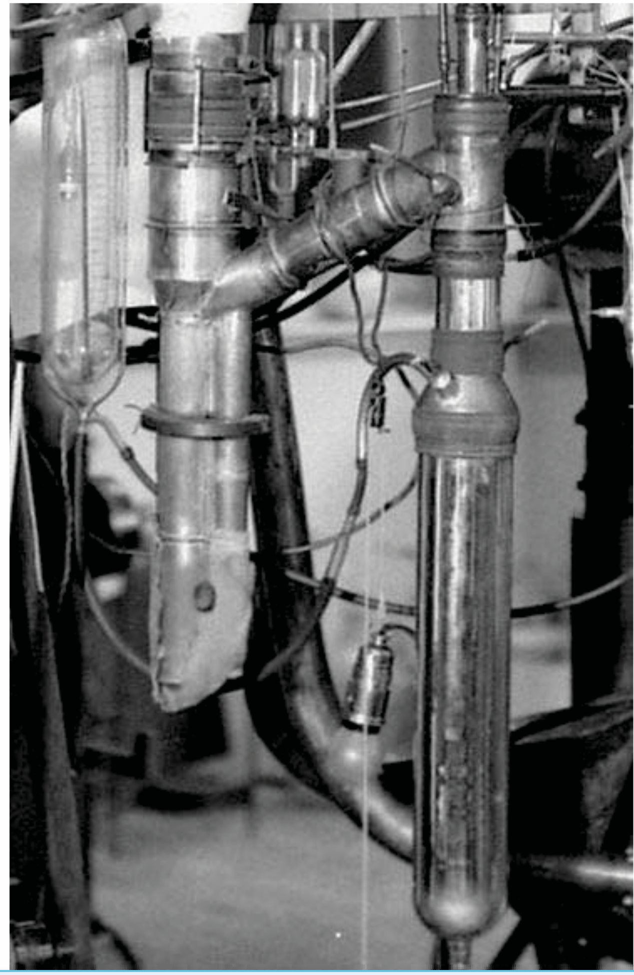


Lord Kelvin thought resisitivity went to infifite due to electron «freezing» for lack of energy.

Onnes thought resisitivity went to zero smoothly…

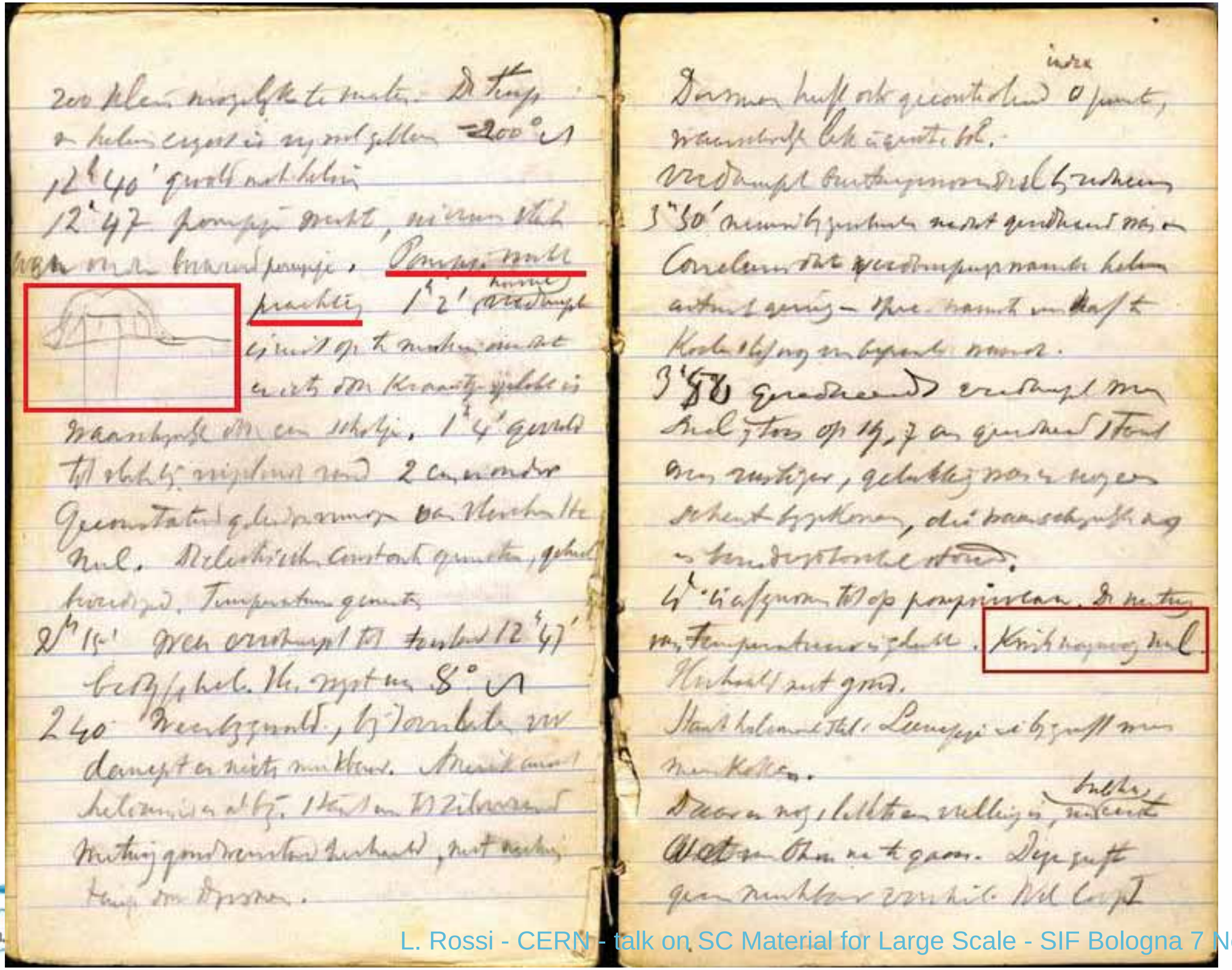
After years of patient work all is ready in Leiden…



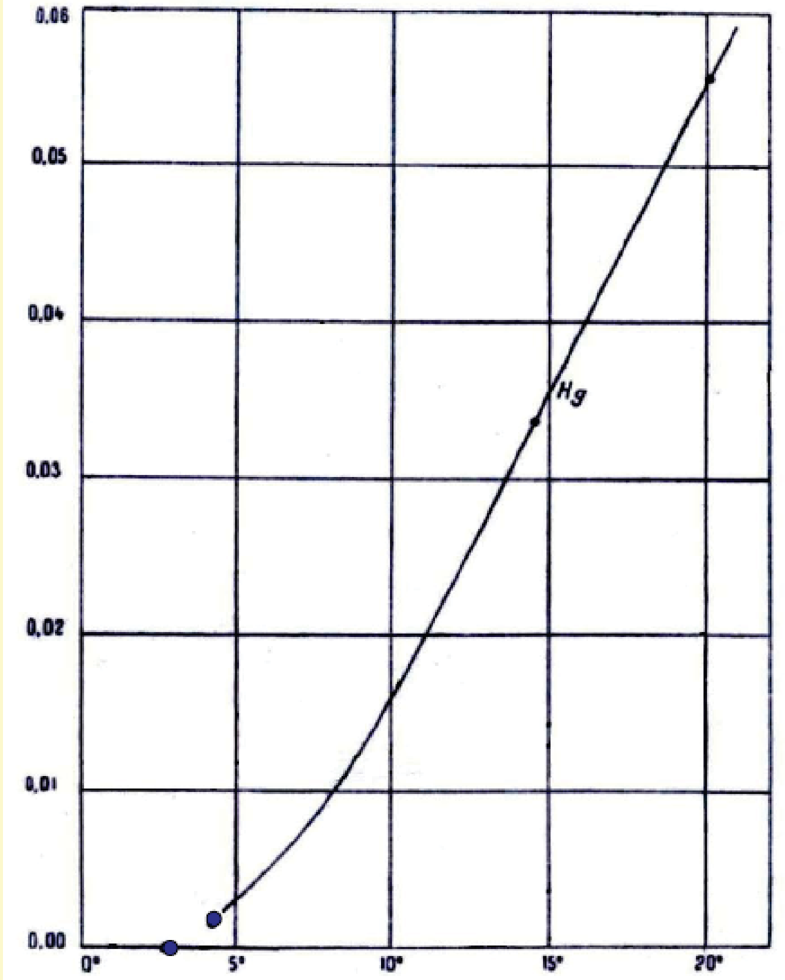


Set up of 8 April 1911: Onnes and collaborators used mercury resistors since by distillation he coud get very pure samples…

The log book found only in 2009-10
8 April 1911: zero resistance…



23 May 2011: Onnes theory demonstrated?



Experiment of 23 May 1911

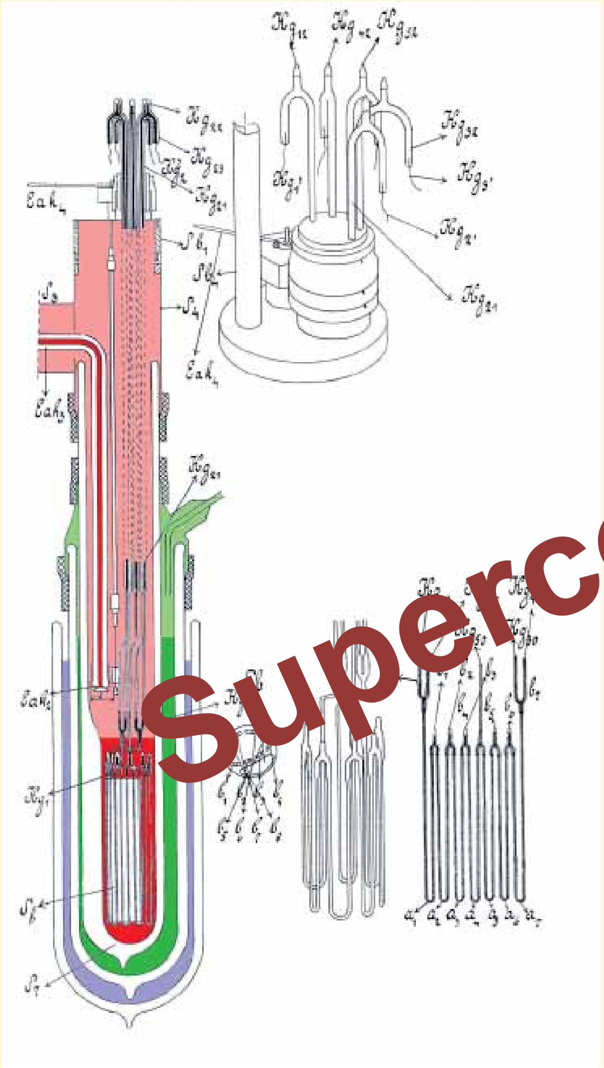
They increased the temperature from 3.0 K

HKO's notebook says:
At 4.00 [K] not yet anything to notice of rising resistance.
At 4.05 [K] not yet either.
At 4.12 [K] resistance begins to appear.

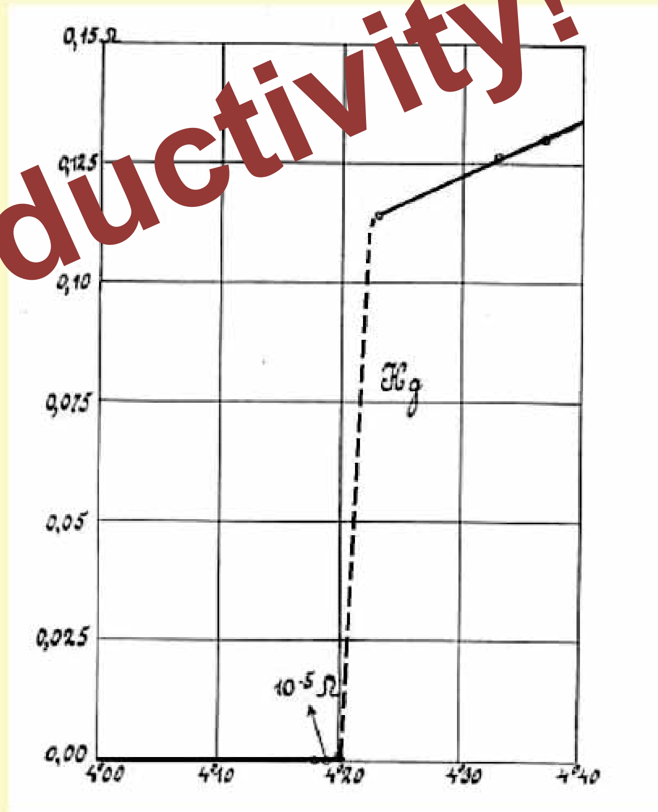
Notebook entry of May 26: no short circuit!

Only two points were measured.
HKO: my model works indeed!
The superfluid transition of He was not mentioned in the publications.

As frquently happens, reality goes beyond our expectations…



Experiment of 26 October 1911 with the historic plot showing the resistance jump at 4.20 K.

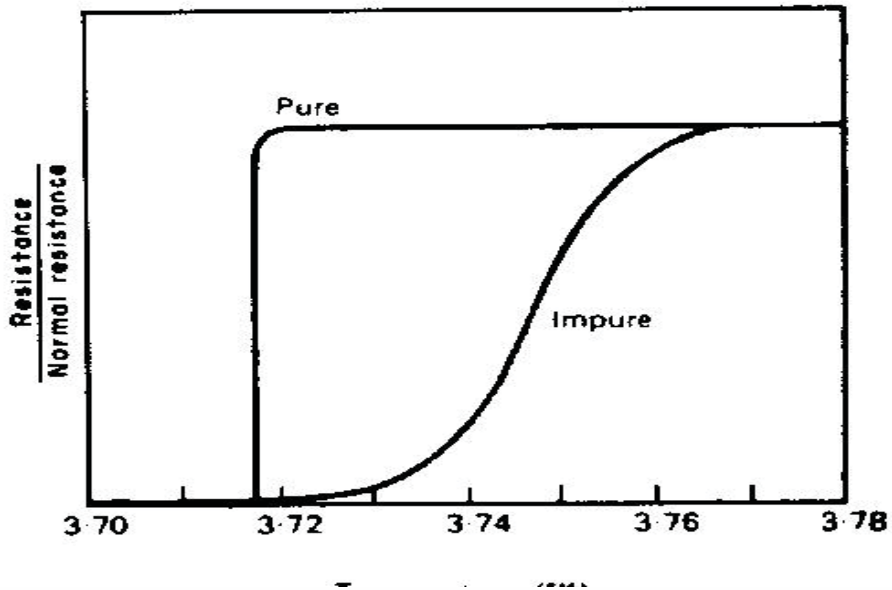


Superconductivity!

Paltes posted in Leiden: 2008 and 2011

10 July 2008: memorial of 100 y from He liquefaction (above)
8 april 2011: memorial plates by IEEE for the 100 y of SC discovery

It is a real transition? How «narrow»?



Transition of tin (x-axis in kelvin). (from book of Rose-Innes & Rhoderick)

For Gallium ΔT_{tr} = 10 μK in macroscopic samples !!!

⇒ collective phenomenon, with coherence on macroscopic scale !!!

⇒From BCS (end of '50s) we know it is a boson condensation…

Zero resistance: really?

Gallop experiment on the current decay in a superconducting loop:

$\rho < 10^{-26}\ \Omega m$

One experiment lasted two years, with no sign of current decay and had to stop because the supply of LHe was interrupted by transport strike !

Resistivity table

Materials	ρ (Ωm)
↓	↓
Vacuum	∞
Insulators	$10^{20} \div 10^{10}$
Semiconductors	$10^{5} \div 10^{-3}$
Metals	$10^{-5} \div 10^{-10}$
Superconductors	≈ 0

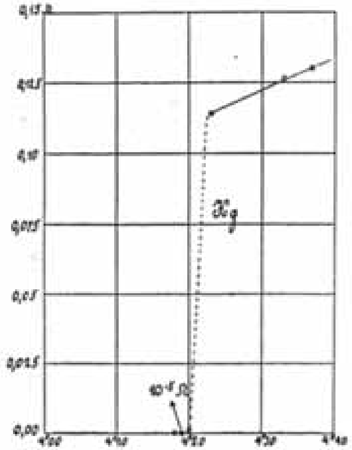
Zero Resistance: lest's use it!
HK Onnes in Chicago* 1913 (IIR)

H. Kamerlingh Onnes, Comm. Physical Lab., Univ. of Leiden, Suppl. **34b** to **133–144**, 37 (1913).

Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state. . . . The behavior of metals in this state gives rise to new fundamental questions as to the mechanism of electrical conductivity.

It is therefore of great importance that tin and lead were found to become superconductive also. Tin has its step-down point at 3.8 K, a somewhat lower temperature than the vanishing point of mercury. The vanishing point of lead may be put at 6 K. Tin and lead being easily workable metals, we can now contemplate all kinds of electrical experiments with apparatus without resistance. . . .

The extraordinary character of this state can be well elucidated by its bearing on the problem of producing intense magnetic fields with the aid of coils without iron cores. Theoretically it will be possible to obtain a field as intense as we wish by arranging a sufficient number of ampere windings round the space where the field has to be established. This is the idea of Perrin, who made the suggestion of a field of 100 000 gauss being produced over a fairly large space in this way. He pointed out that by cooling the coil by liquid air the resistance of the coil . . . could be diminished. . . . To get a field of 100 000 gauss in a coil with an internal space of 1 cm radius, with copper cooled by liquid air, 100



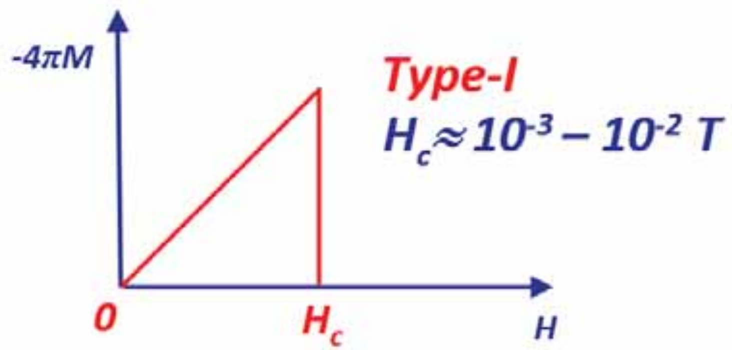
*Actually Keesom gave the talk as Kamerlingh Onnes was indisposed

Courtesy of D. Larbalestier, FSU/NHMFL USA

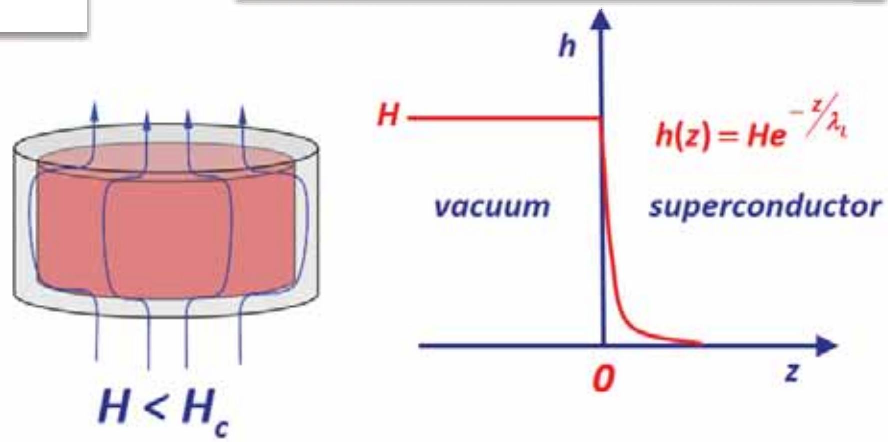
Onnes' dream of 1913 had to wait 50 years!

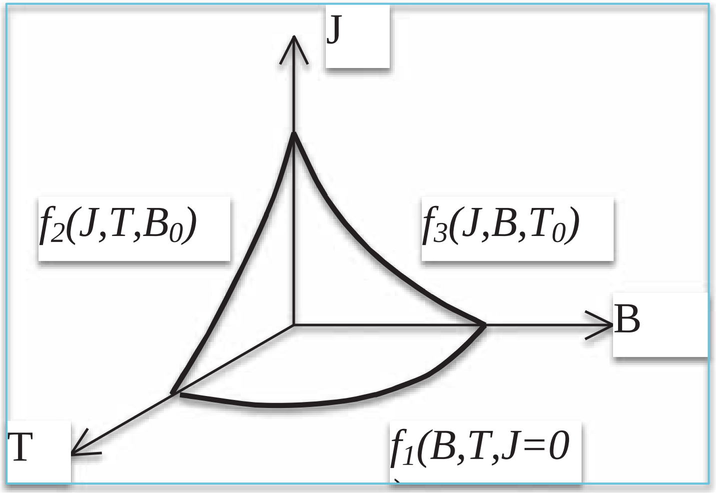
- The conception of a 10 T magnet
  - The **impossibility** of doing this with Cu cooled by liquid air (as expensive as a warship)
  - The **possibility** of doing it with superconductor (1000 A/mm^2 with a Hg wire, 460 A/mm^2 with a Pb wire
- A little problem!
  - **Resistance developed at 0.8 A, not 20 A**
  - **48 years had to go by** before the path to high field superconducting magnets was cleared
  - Superconductivity was there but it took a lot of time ot understand it… and application could not come until the physics was clear…
  - **Basic science is not only an added value, is a pre-condition for applications…**

Superconductor is more than a zero-resistance material…



Meissner-Ochsenfeld effect



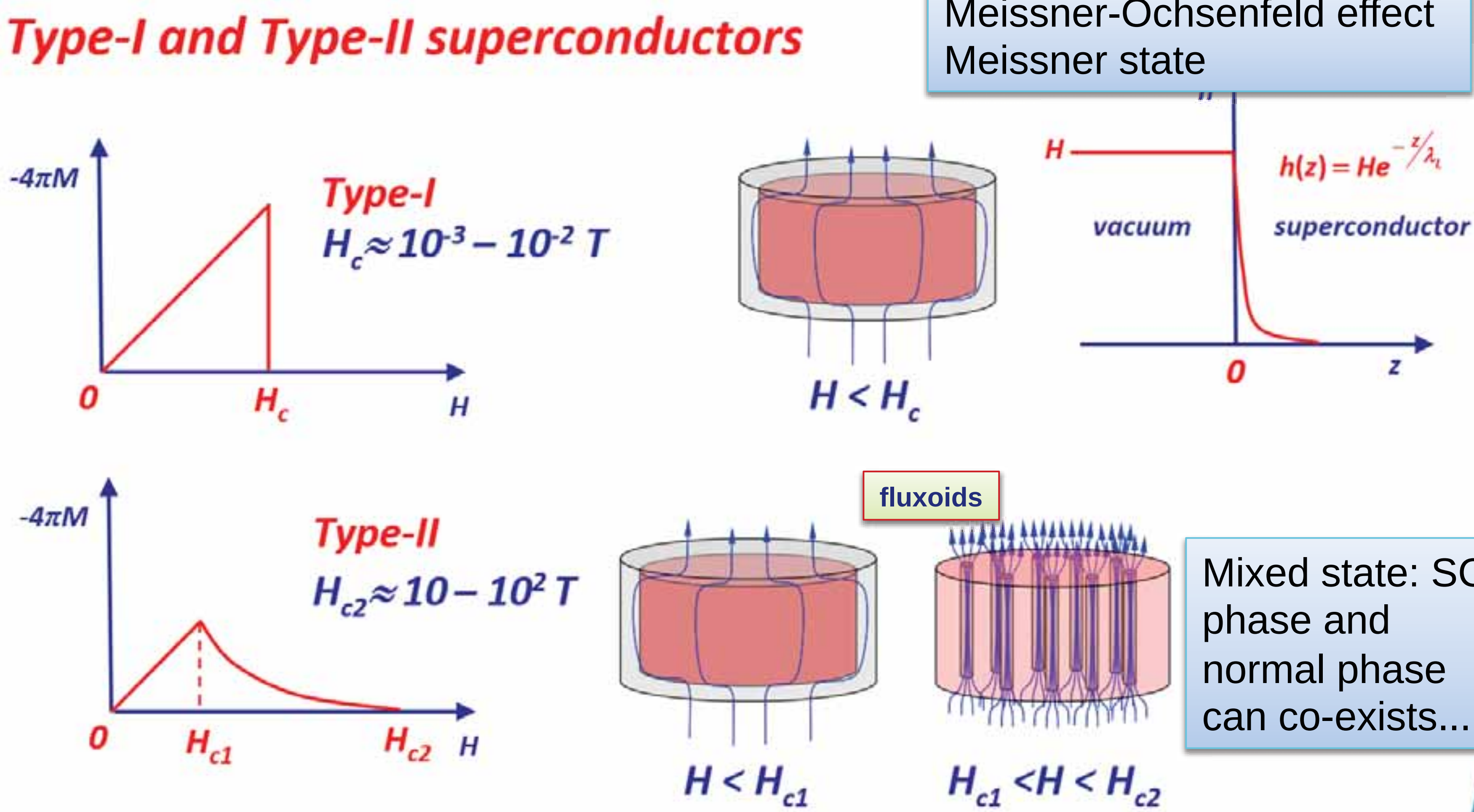


Superconductivity is a thermodynamic state defined by T, B, J similar to T,P,V for the ideal gas: P ⇔ B, V ⇔ J
Superconductivity exists only below the critical surface: increase one parameters depress possible value of others...
B and J are linked by consideration of free-energy and by Maxwell equations… So inevitably an increase in current brings also an increase in field…

Deception! B_c is very low: ~1-10 mT !

Superconductor is more than a zero-resistance material…

Meissner-Ochsenfeld effect
Meissner state

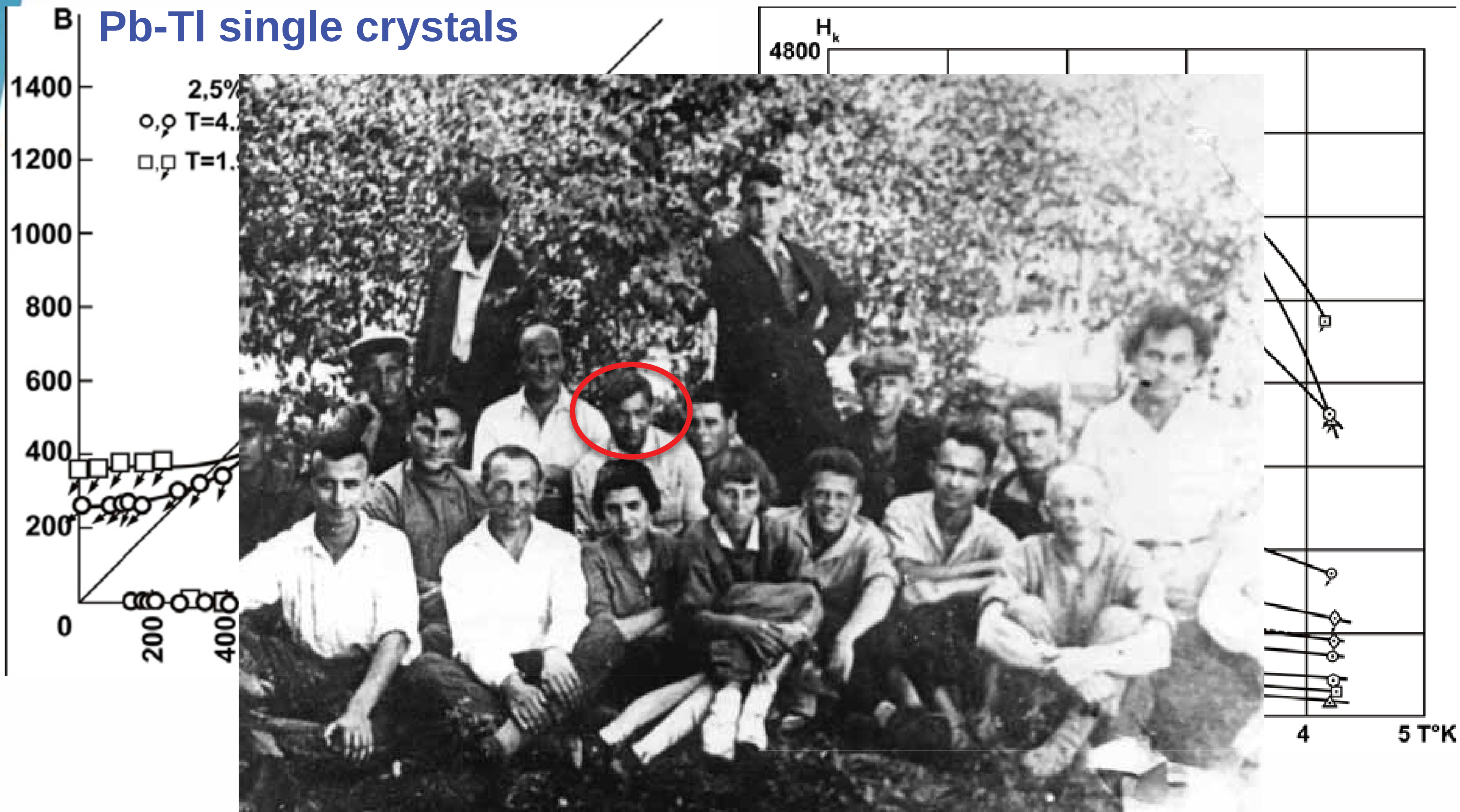


Mixed state: SC phase and normal phase can co-exists...

$-4\pi M = H - B$

Cortesy of C. Senatore- Univ. of Geneva

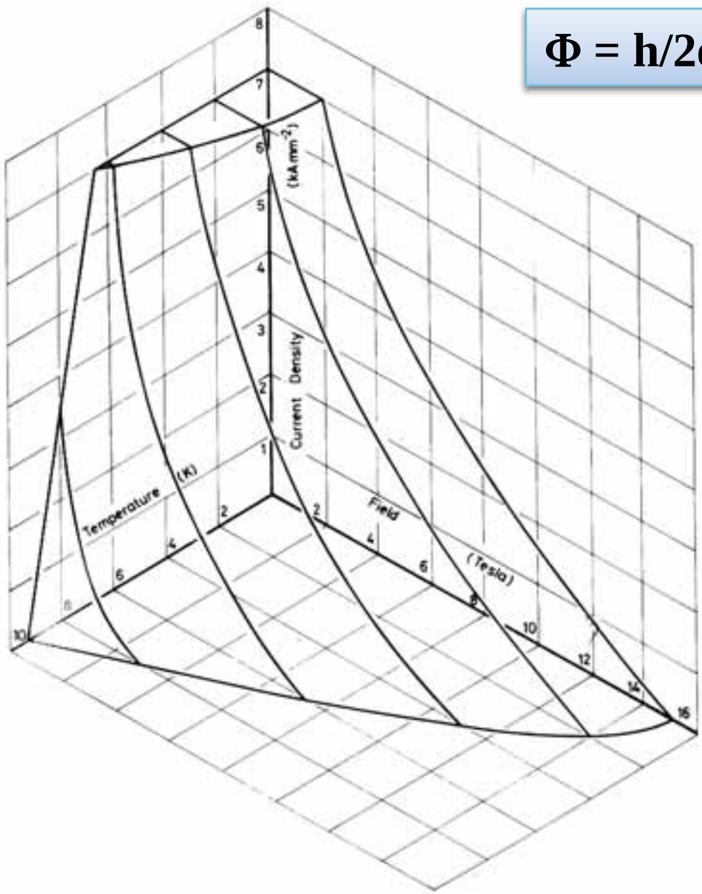
1936: Type II Superconductivity discovered – and unappreciated – by Russian scientist Shubnikov….



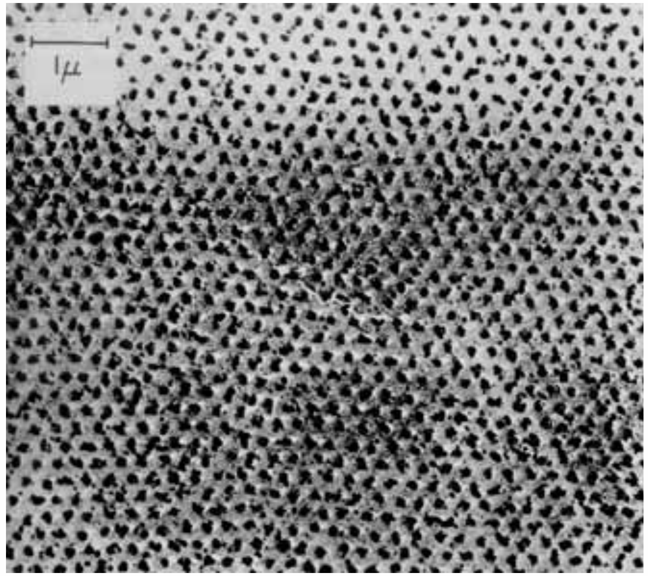
Shubnikov returned to Kharkov from Leiden to start single crystal alloy studies – persistence of superconductivity beyond the Meissner state - then imprisoned and shot

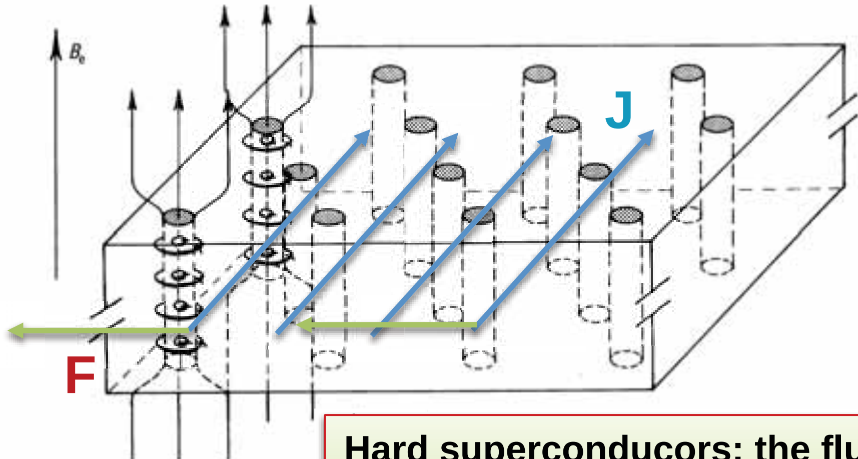
A.G. Shepelev, In: Superconductor (ed. A.M. Luiz), Sciyo, Rijeka (2010), p.17; http://www.intechopen.com/books/show/title/superconductor

Type Superconductivity worked out in’50s by Ginzburg (Landau), Gorkov, Abrikosov



$\Phi = h/2e \cong 2\ 10^{-15}$ Wb





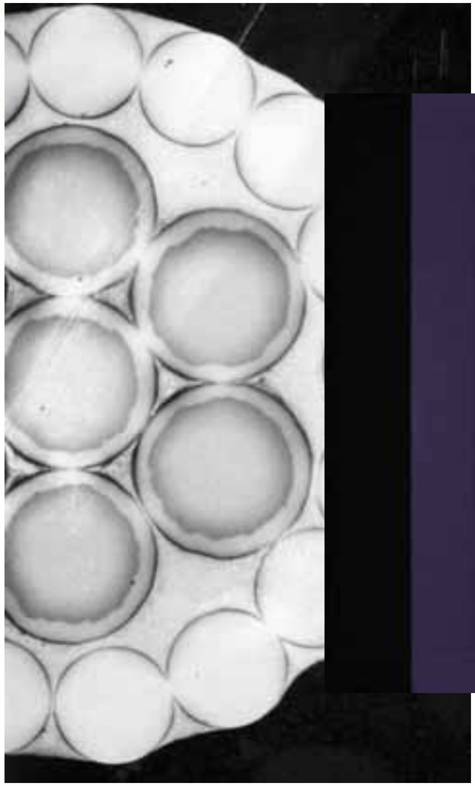
Hard superconducors: the fluxoid are pinned, large current can flow

1962 : the 1st EU SC coil: Nb-Zr in UK

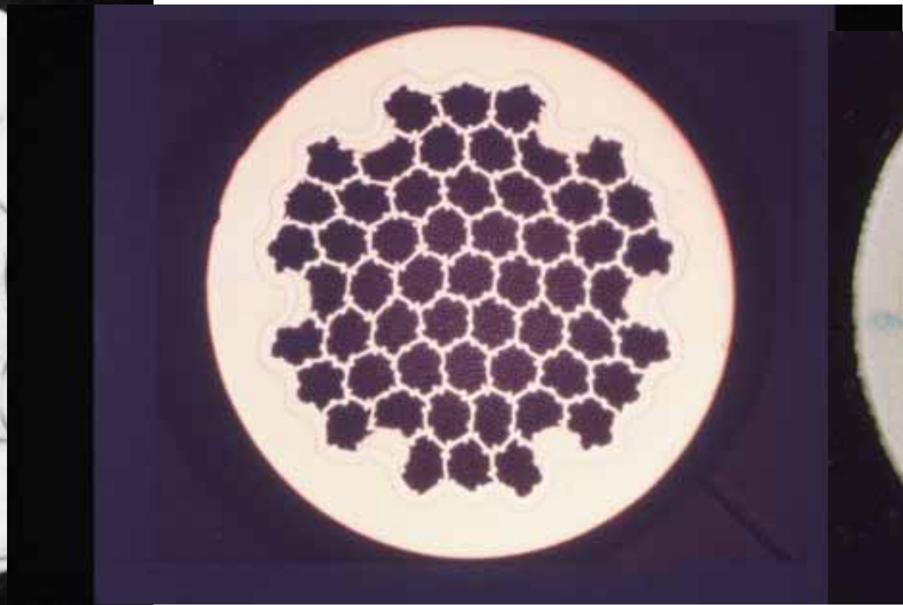
Courtesy of D. Larbalestier, FSU/NHMFL USA

I_c = 17 A, B_{max} ~ 4 T

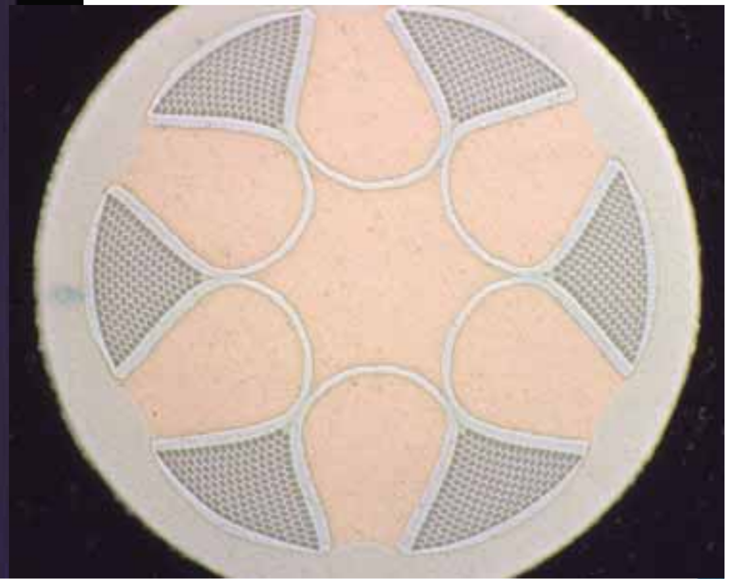
In 1965 Nb-Ti took quickly over Nb-Zr and its development was very rapid



Atomics International: Cabled Monofilament ~1965



Rutherford Lab/IMI twisted multifilament ~1967

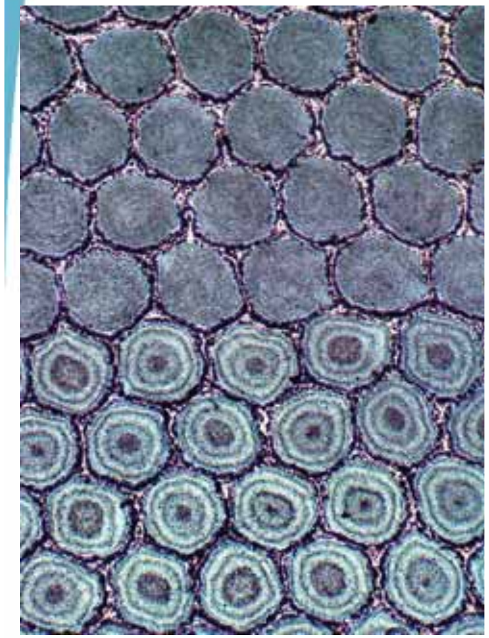


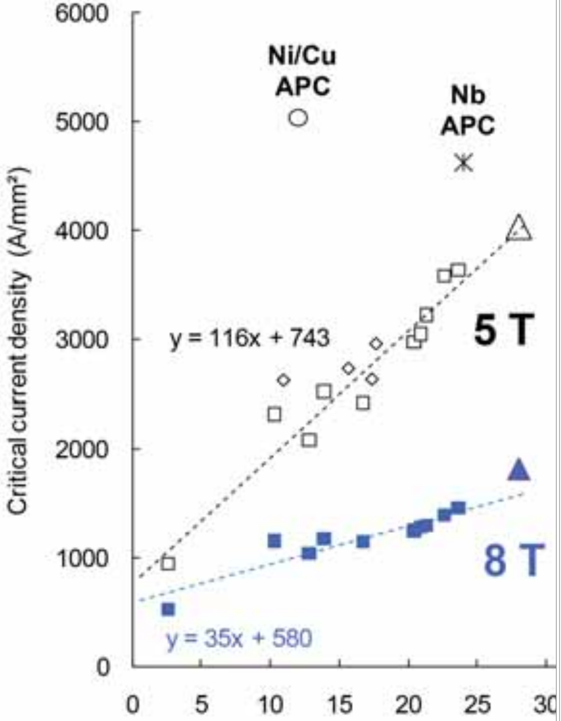
Tulip conductor for POLO by Vacuumschmelze ~1978

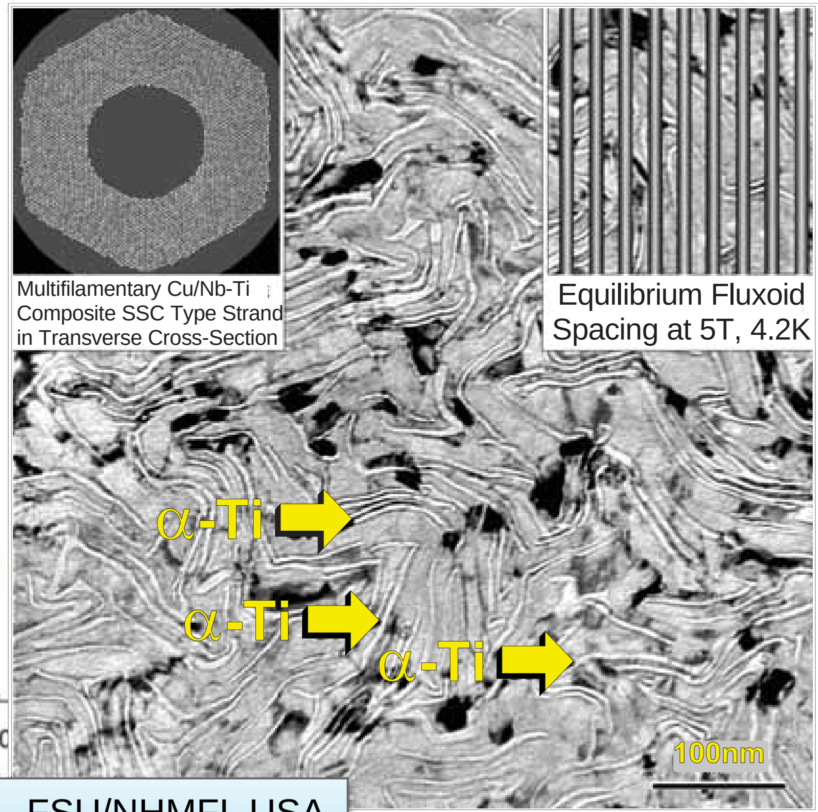
Optimal Nb-Ti properties by understanding the processing-nanostructure to pin the fluxoids: where basic science meets material science

Start with homogeneous Nb-Ti

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





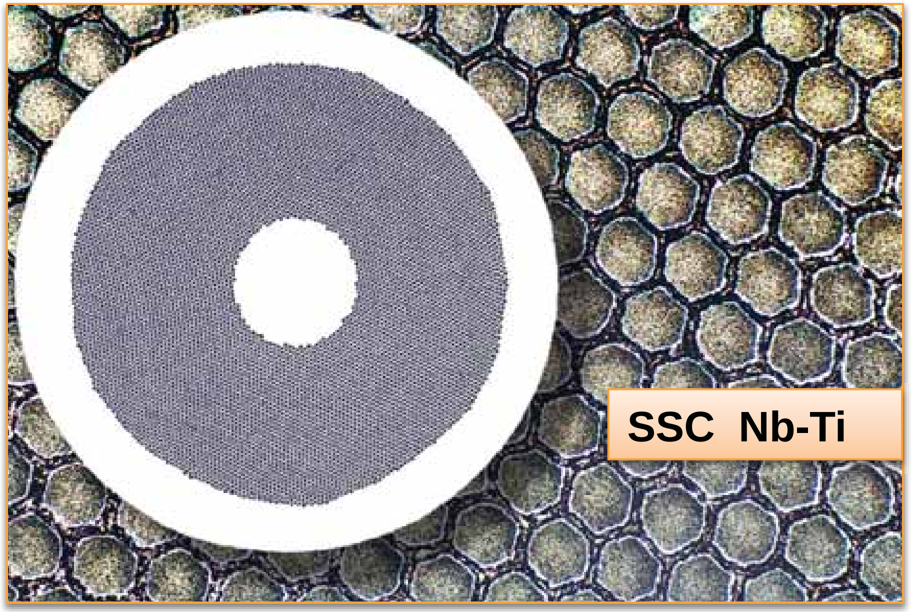


Tremendous support by Wah Chang (Bill McDonald especially)

Courtesy of D. Larbalestier – FSU/NHMFL USA

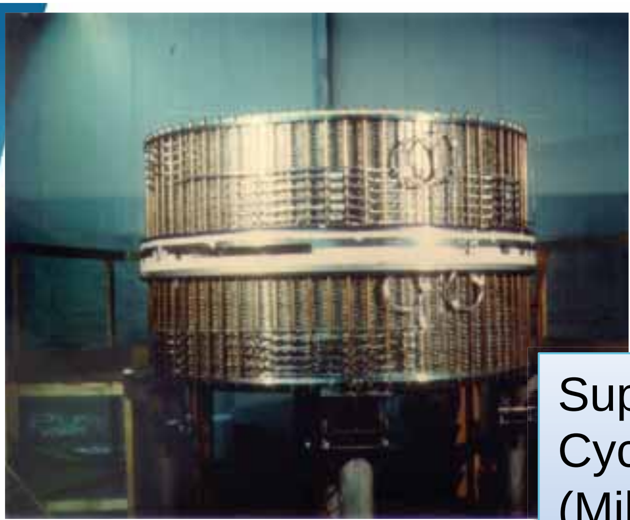
Tevatron@Fermilab: > 100 tons of Nb-Ti
Energy frontier form 1984 till 2010

The fine filaments and high homogenity-high performance Nb-Ti allowed Tevatron and MRI

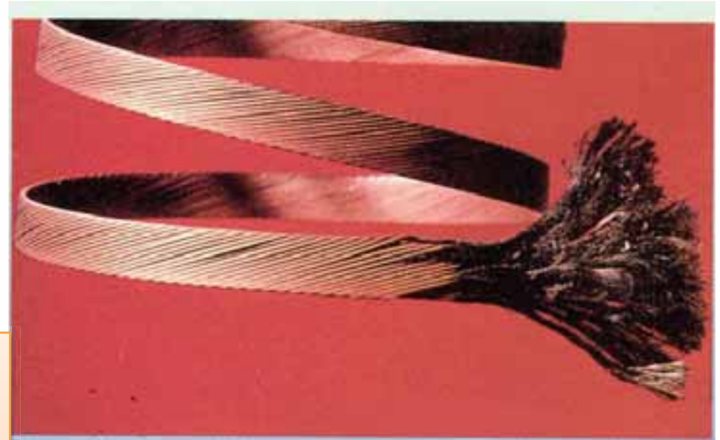


Accelerators is the most demanding application for SC.
Non only high current: field quality, low losses, full transpositions, homogeneity and –not last- affordable price!
Not surprising from accelerator (Tevatron & other) that came the SC wire that allowed MRI application. Today >4,000 systems/year!

And in EU? Thanks also to INFN from 1982 a strong activity…



Superconducting Cyclotron (Milano then Catania LNS)



HERA: 7 km proton ring based on SC magnets Half as in-kind from Italy-INFN

Thanks to Prof. Zichichi

The development continued focussed to LHC

First SC dipoles prototype for LHC: fabricated by INFN for the CERN-INFN collaboration for SC. Development sustained for 20 y, under a sequence or INFN presidents:

A. Zichichi — CS, HERA dipole, ZEUS solenoid

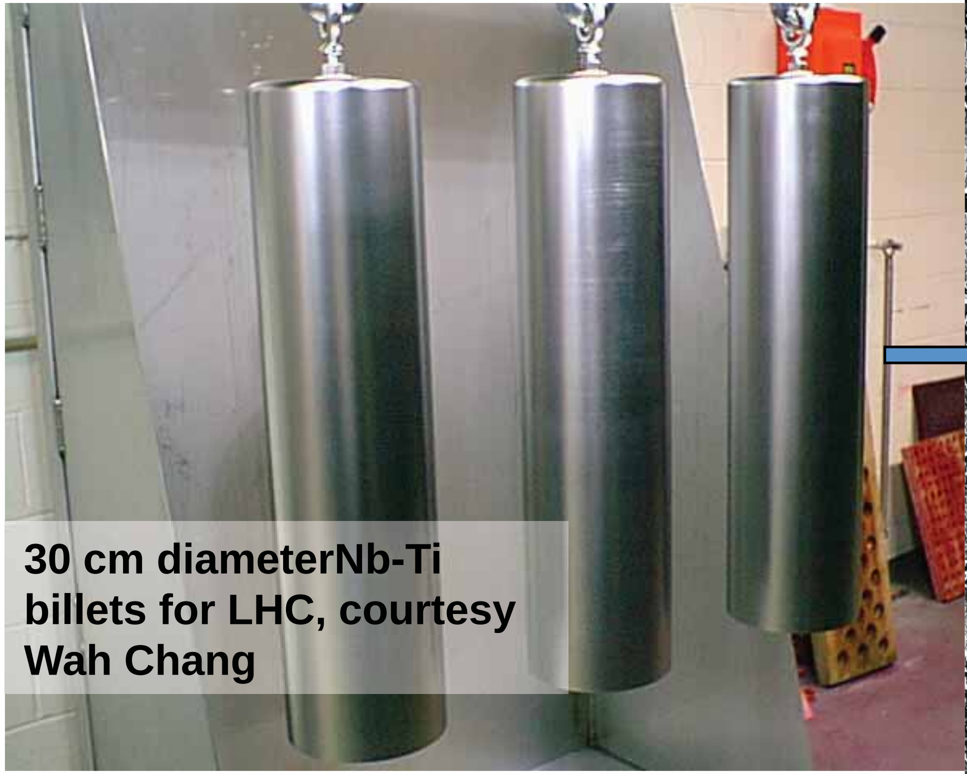
N. Cabibbo — LHC Sc dipoles

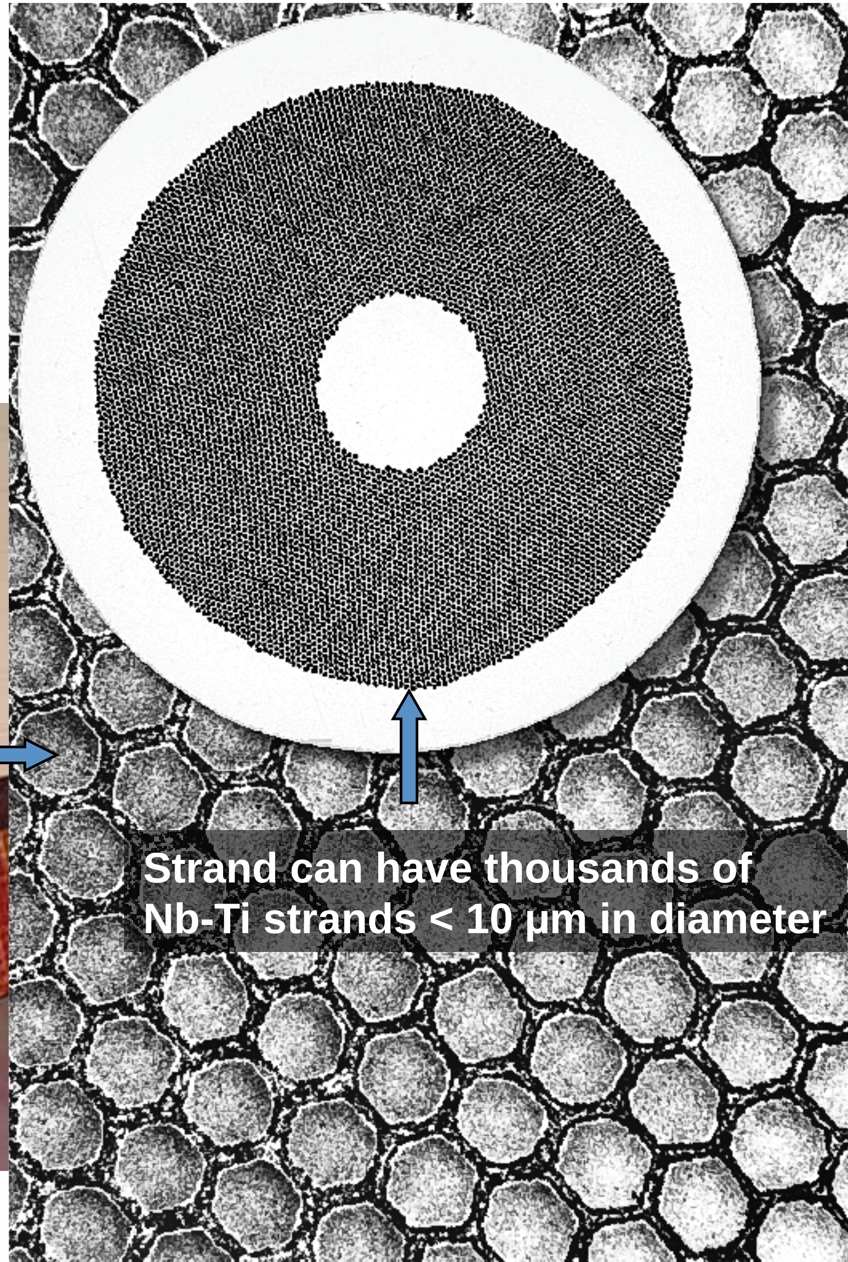
L. Maiani

E. Iarocci — ATLAS & CMS SC coils

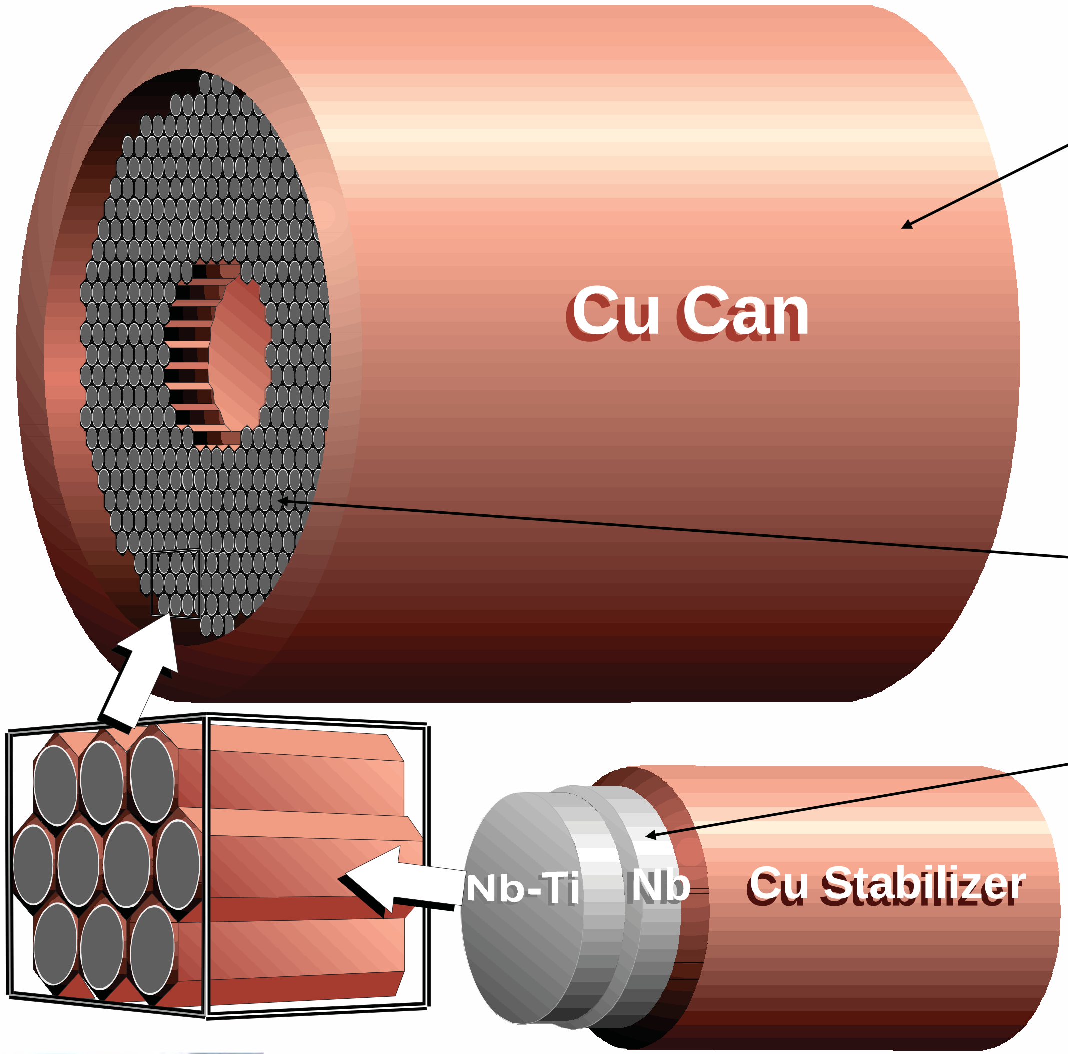
(G. Bellini and L. Mandelli, Milano)

How Nb-Ti superconductor is fabricated





Nb-Ti Composite Overview



Cu stabilizer (Al can also be used)

Multifilamentary Extrusion Billet

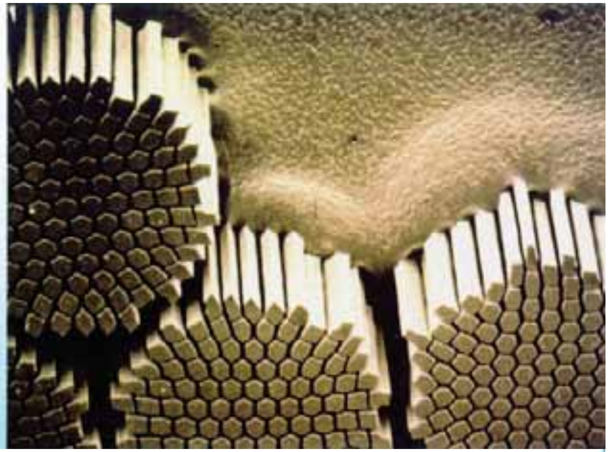
47-2000+ filaments

Nb sheet or tube prevents reaction between Ti and Cu

Monofilament assembly

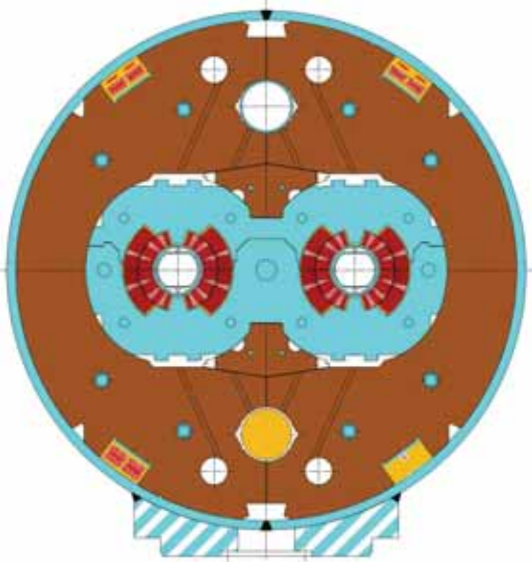
The LHC superconductor
1200 tonnes - 7000 km of Cu/Nb-Ti cable
300,000 km of wire, i.e. 1,500,000 km of filaments

STRAND	Type 01	Type 02
Diameter (mm)	1.065	0.825
Cu/NbTi ratio	1.6-1.7 ± 0.03	1.9-2.0 ± 0.03
Filament diameter (μm)	7	6
Number of filaments	8800	6425
Jc (A/mm^2) @1.9 K	1530 @ 10 T	2100 @ 7 T
μ_0M (mT) @1.9 K, 0.5 T	30 ±4.5	23 ±4.5
CABLE	**Type 01**	**Type 02**
Number of strands	28	36
Width (mm)	15.1	15.1
Mid-thickness (mm)	1.900 ±0.006	1.480 ±0.006
Keystone angle (degrees)	1.25 ±0.05	0.90 ±0.05
Cable Ic (A) @ 1.9 K	13750 @ 10T	12960 @ 7T
Interstrand resistance (μΩ)	10-50	20-80



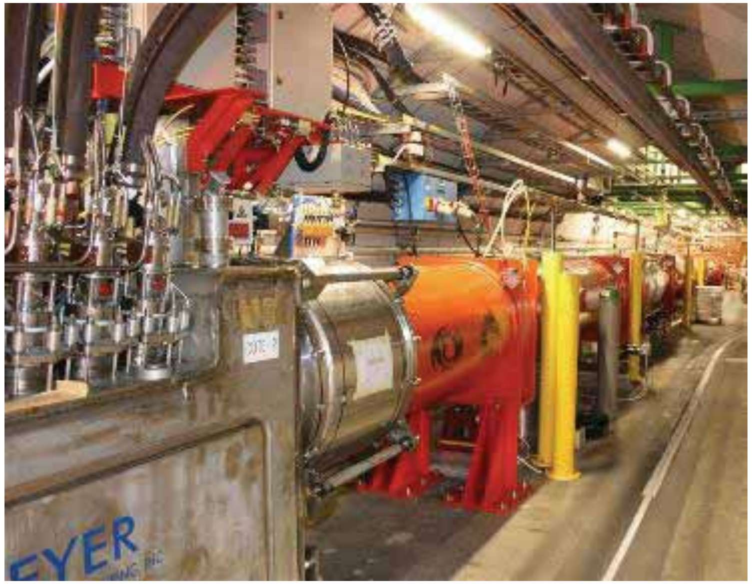
LHC; the largest instrument

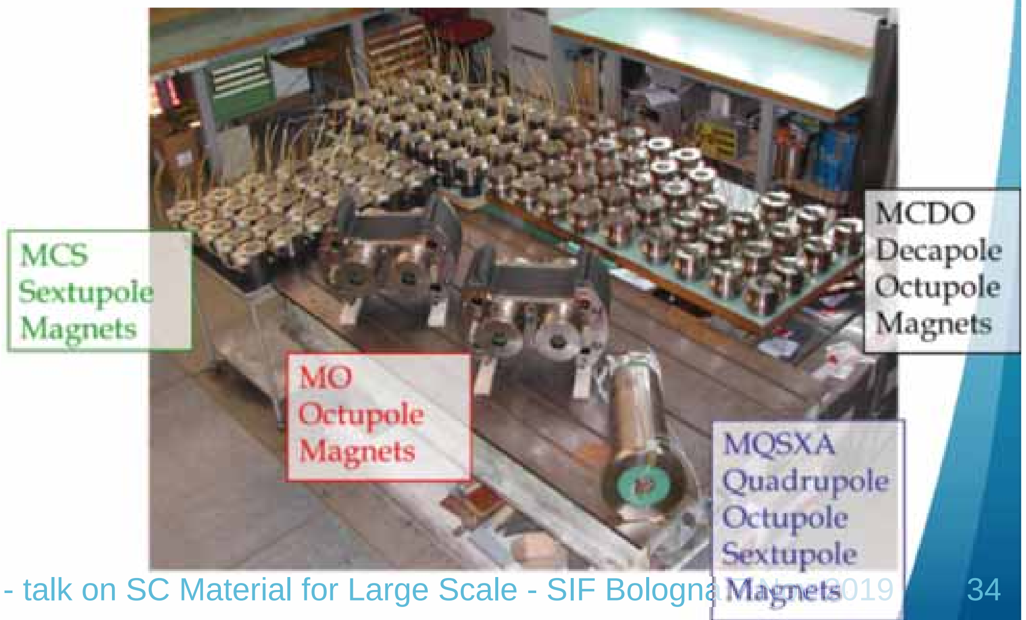
- 27 km, p-p at 7+7 TeV
  3.5+3.5 2010, 6.5+6.5 since
  2014
- 1232 x 15 m Twin Dipoles
- Operational field 8.3 T
  @11
  (9 T (
- **HEII** **h 3**
  km c **s He**
  inve

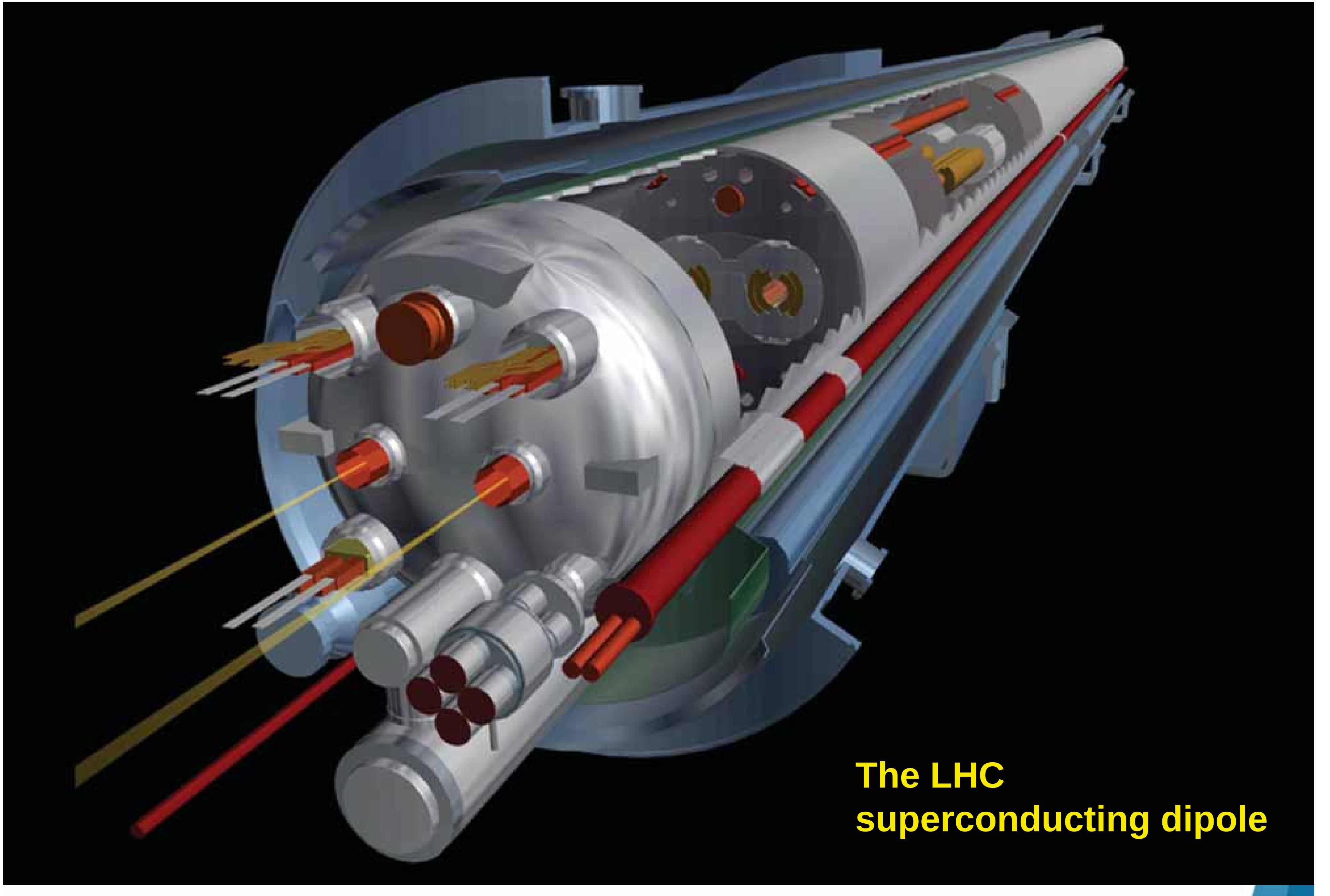


LHC , cont.

- 1700 large SC magnets
- A «zoo» of 7600 «small» Sc magnets (correctors and higher order magnets
- Total: 9 MJ stored energy (at nominal)
- Large detector magnets ATLAS toroid – 25 m long 1.2 GJ
  CMS solenois – 12 m long 2.5 GJ







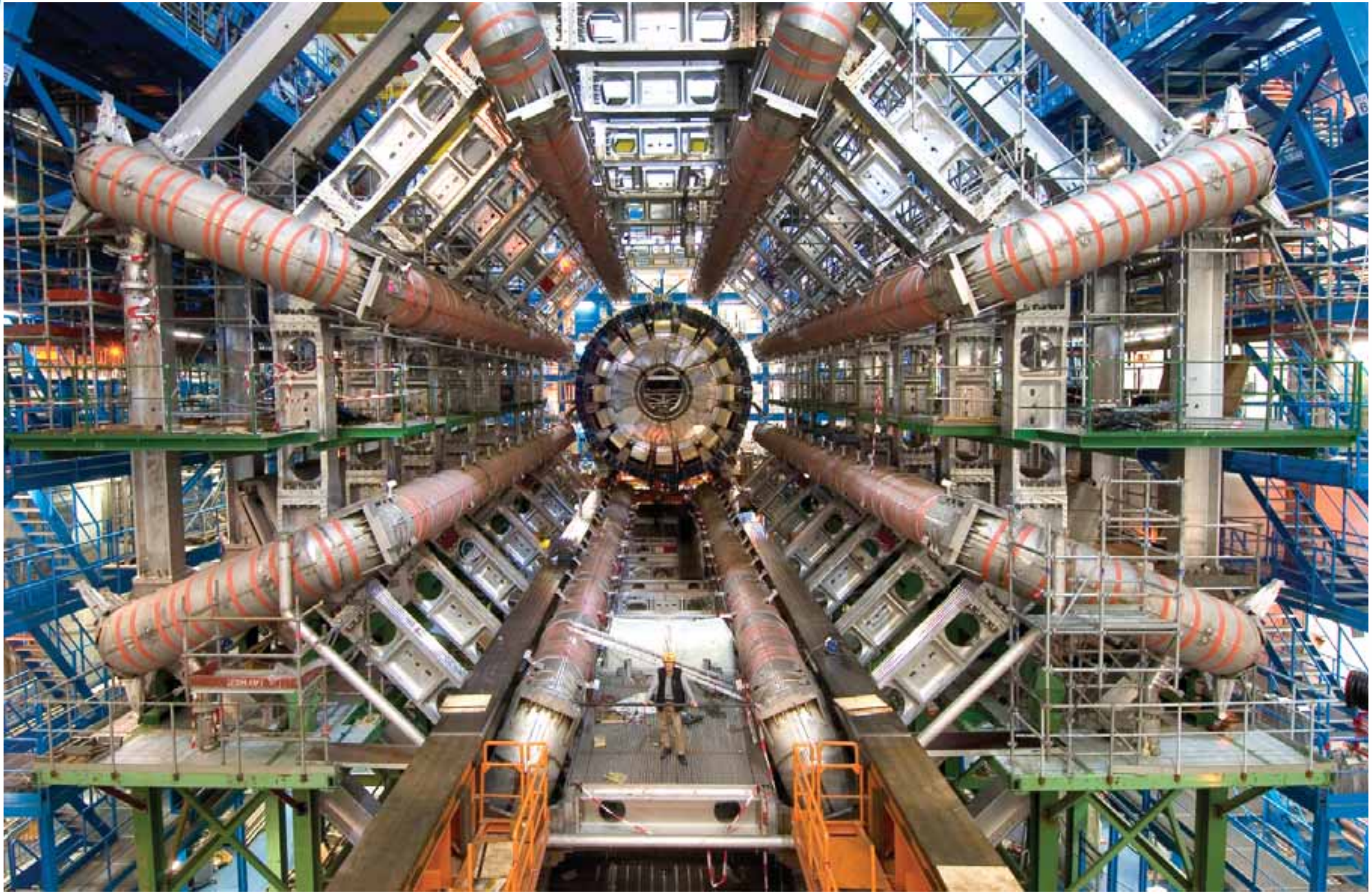
The LHC superconducting dipole

SCRF, Cryo…

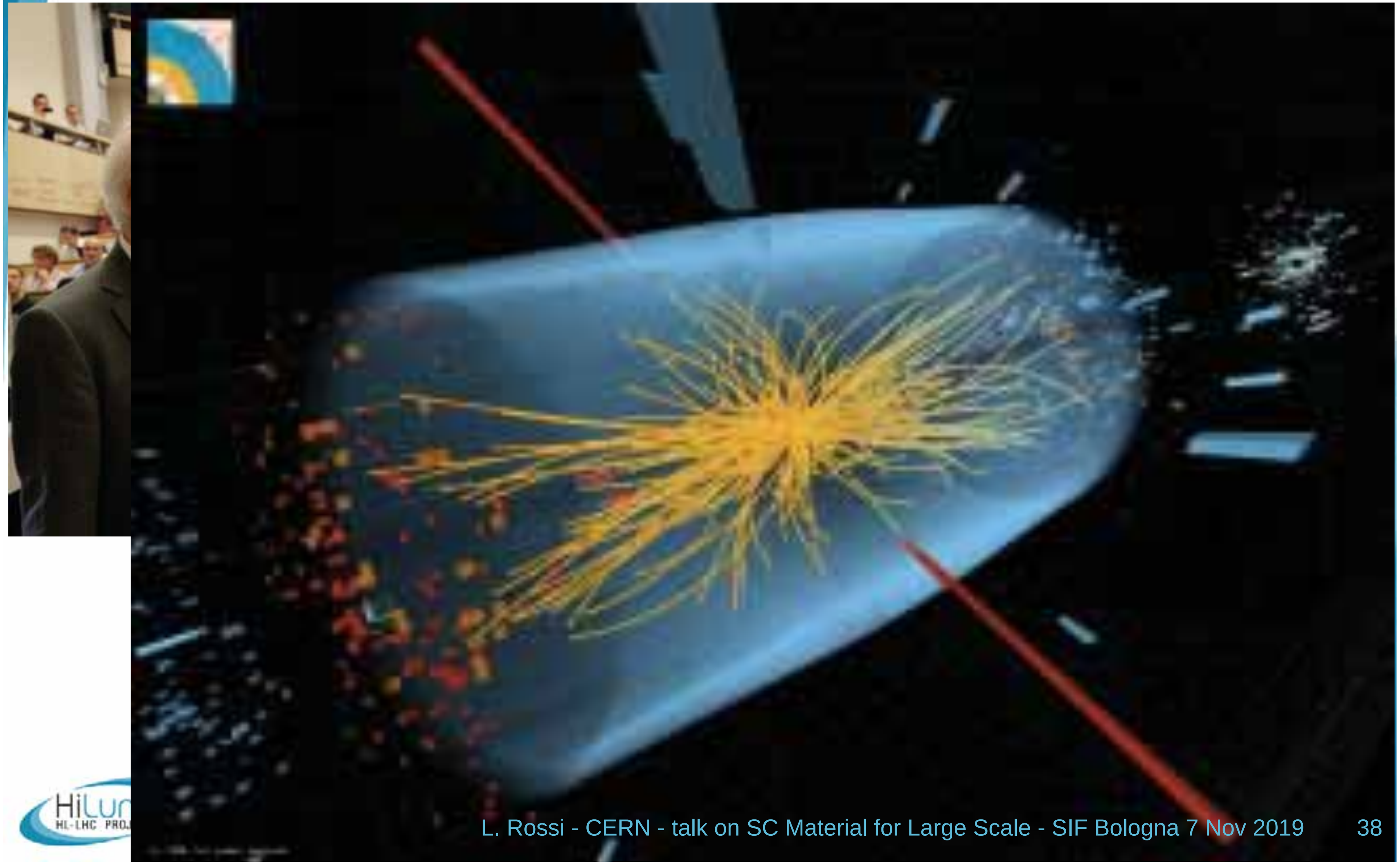
400 MHz Standing wave RF

- 4 single cell cavities in cryomodule, 2 crym per beam. Total 16 cavities.
- Sputtered niobium design (as LEP)
- Gradient 5.5 MV/m nominal (8 MV/m available)

ATLAS SC TOROID



4 July 2012 : discovery of higgs-like boson



Nb-Ti limited to 8-9 T for accelerators … but can deliver 10-12 T in solenoid

Neurospin cente

Beyond 10 T : an older material… Nb_3Sn (A15)

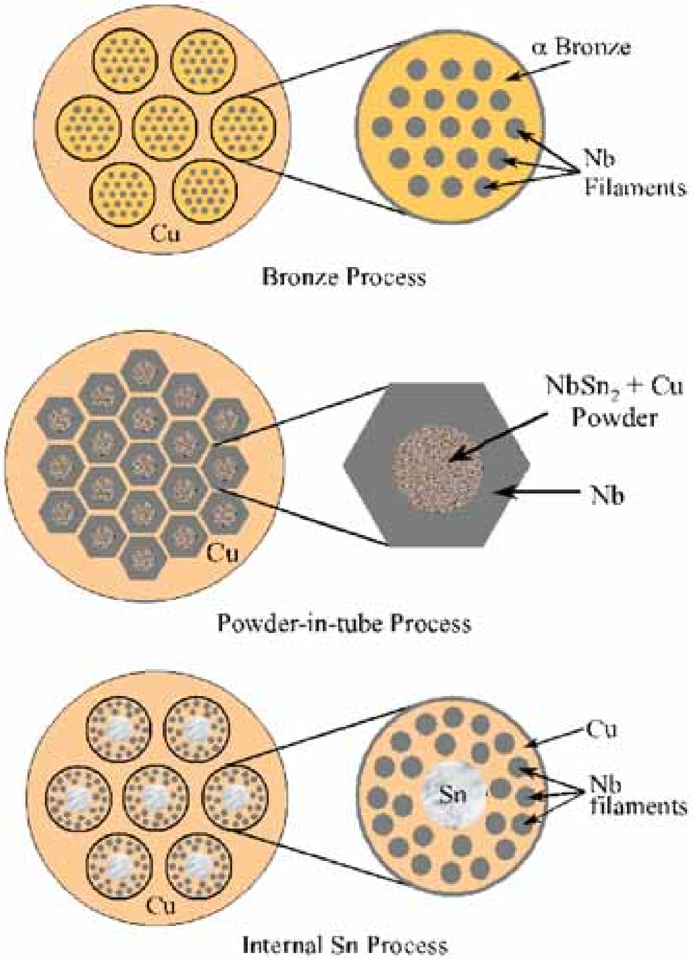
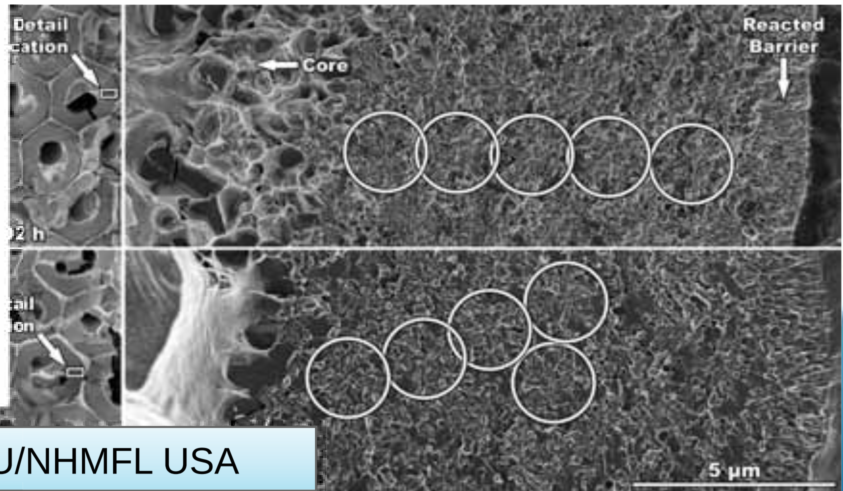


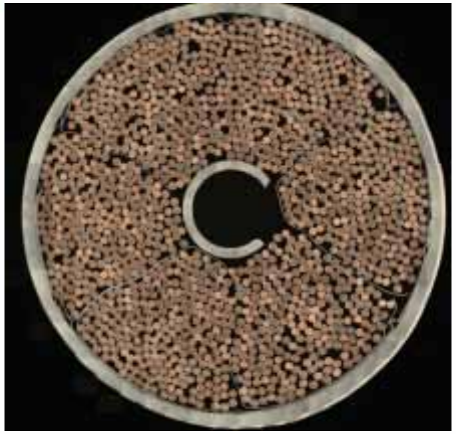
Figure 13. Schematics of the three main Nb_3Sn wire fabrication techniques.

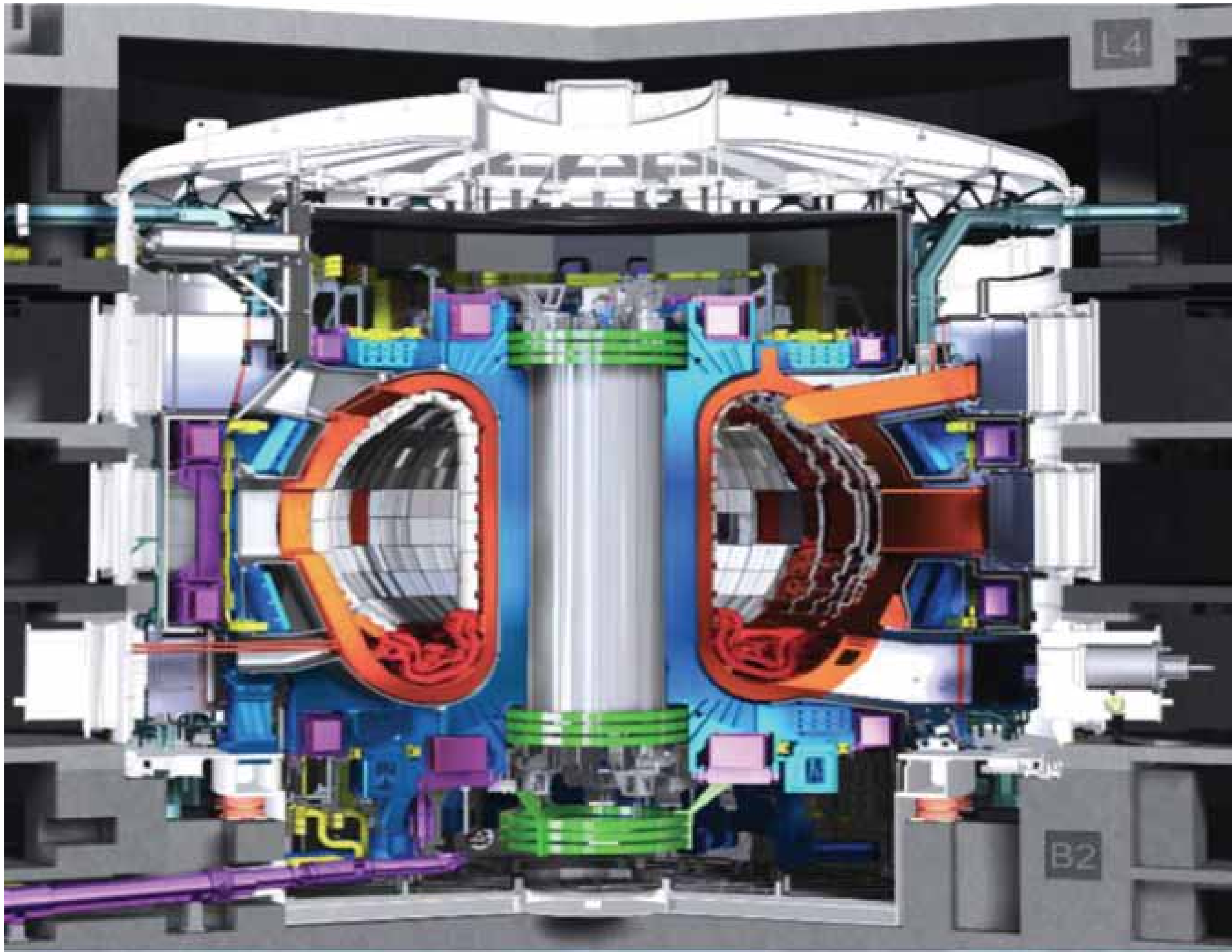
- **activity is highest in Powder In Tube, est in bronze**
- ctions are slowest at low Sn:Nb ratios
- nze and Internal Tin RRP are most duced
- **made by diffusion processes that er equilibrate in wires**
- **in growth at high T (or long t) also uces GB vortex pin density**



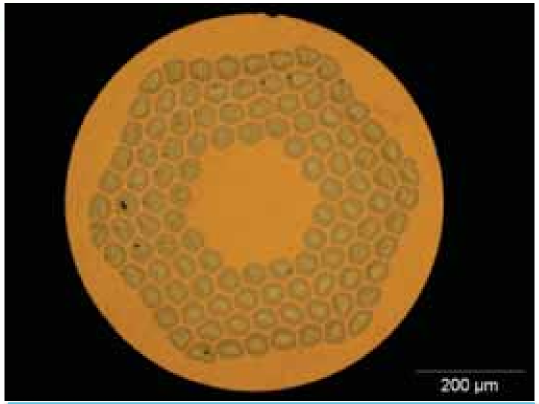
Courtesy of D. Larbalestier, FSU/NHMFL USA

The energy of the star: ITER based on 400 tons of Nb_3Sn

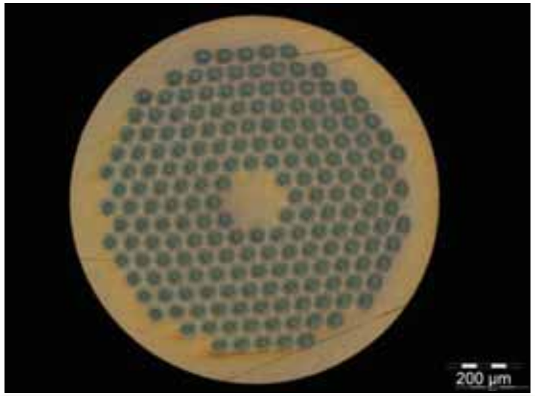




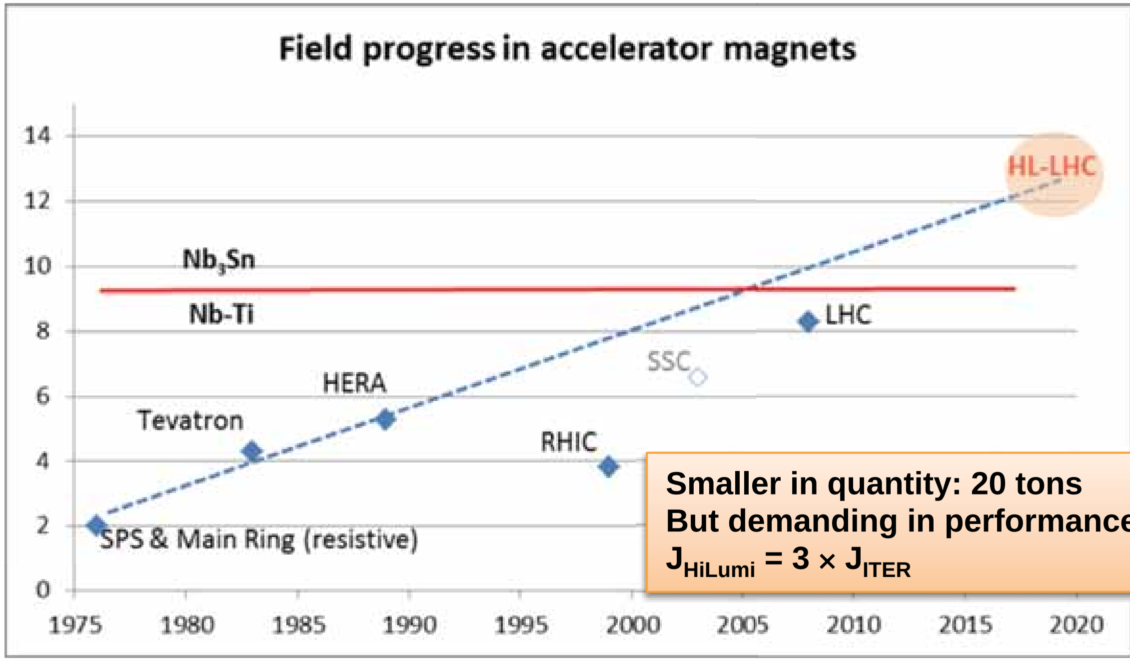
High Luminosity LHC: Magnets for 11-12 T to go break LHC limits and illuminate a new territory



0.7 mm, 108/127 stack RRP from **Bruker OST (USA)**



1 mm, 192 tubes PIT from **Bruker EAS (EU-De)**



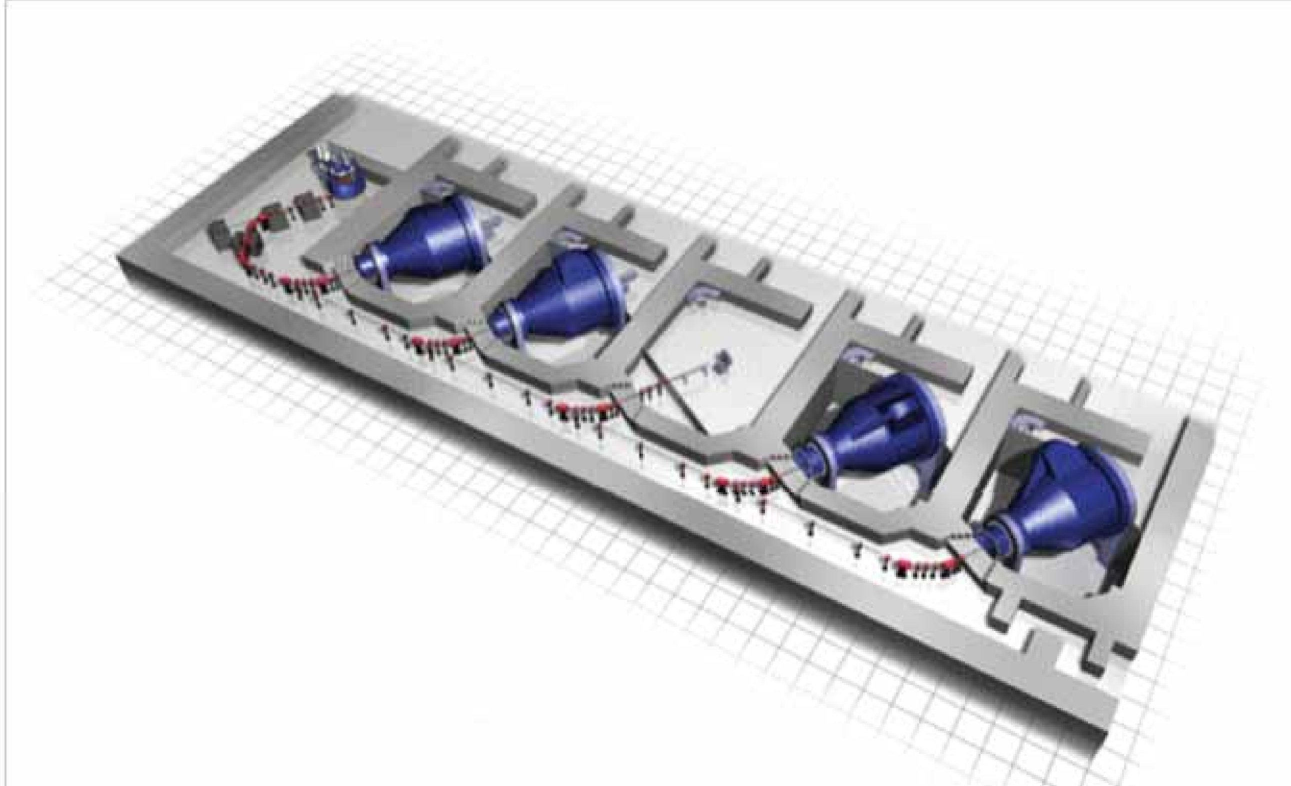
Smaller in quantity: 20 tons
But demanding in performance
$J_{HiLumi} = 3 \times J_{ITER}$

Re-elected CERN DG Fabiola Gianotti near the first 11 tesla dipole for HiLumi LHC

HiLumi HL-LHC PROJECT CERN

Medical application:
Hadroterapy for cancer treat.

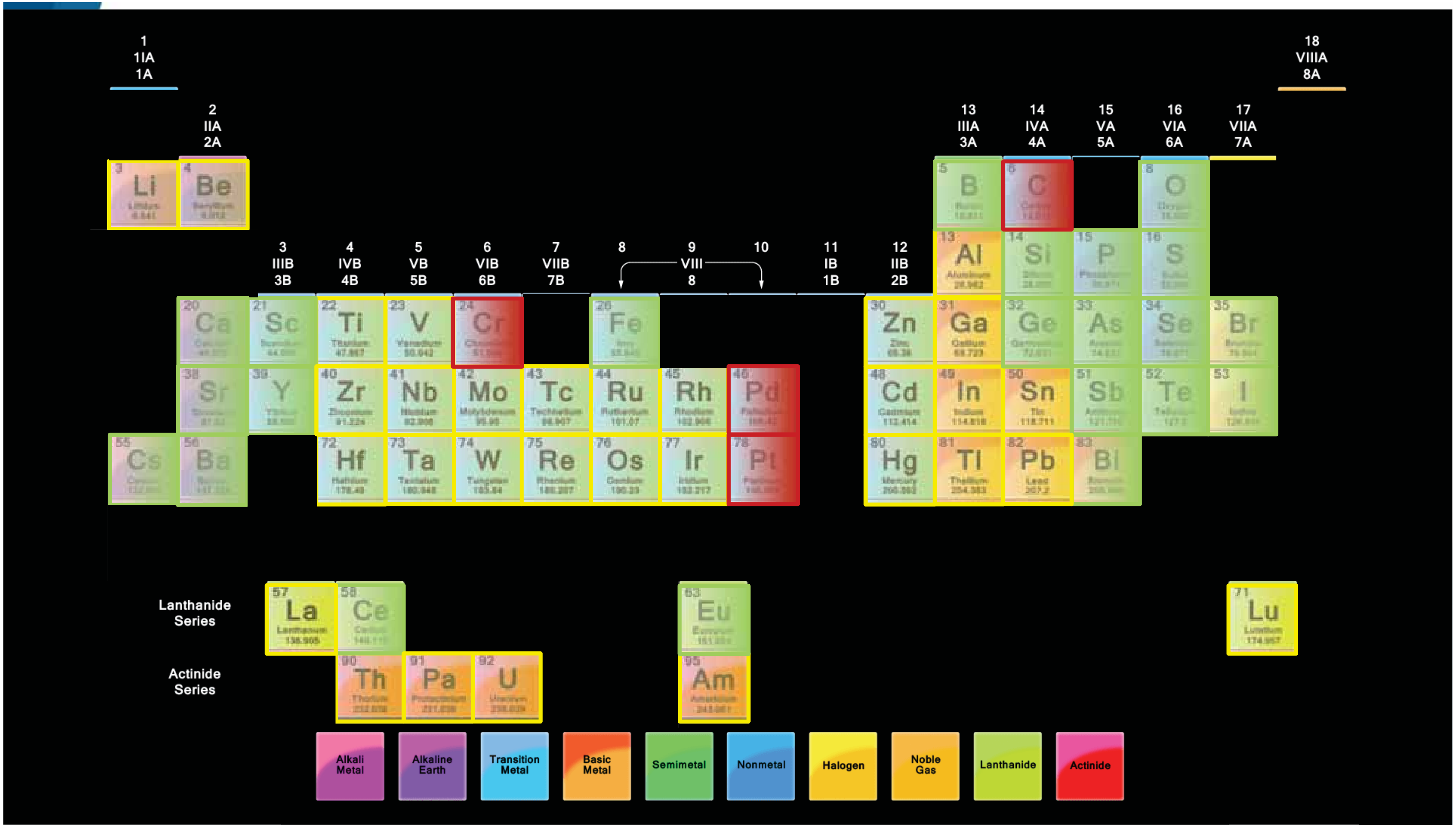
Proton Therapy System for RPTC, Munich
By Accel



First European Commercial Clinical PT Center

Is SC so rare that we have only two?

- Are there other superconductors?
- 95% of Sc magnets so fare are Nb-Ti
- 5% of Nb_3Sn (once ITER and HiLumi will be completed)
- Nb_3Sn mainly for High Field NMR
- 950 MHz system in Nb-Ti/ Nb_3Sn: field 23 T!



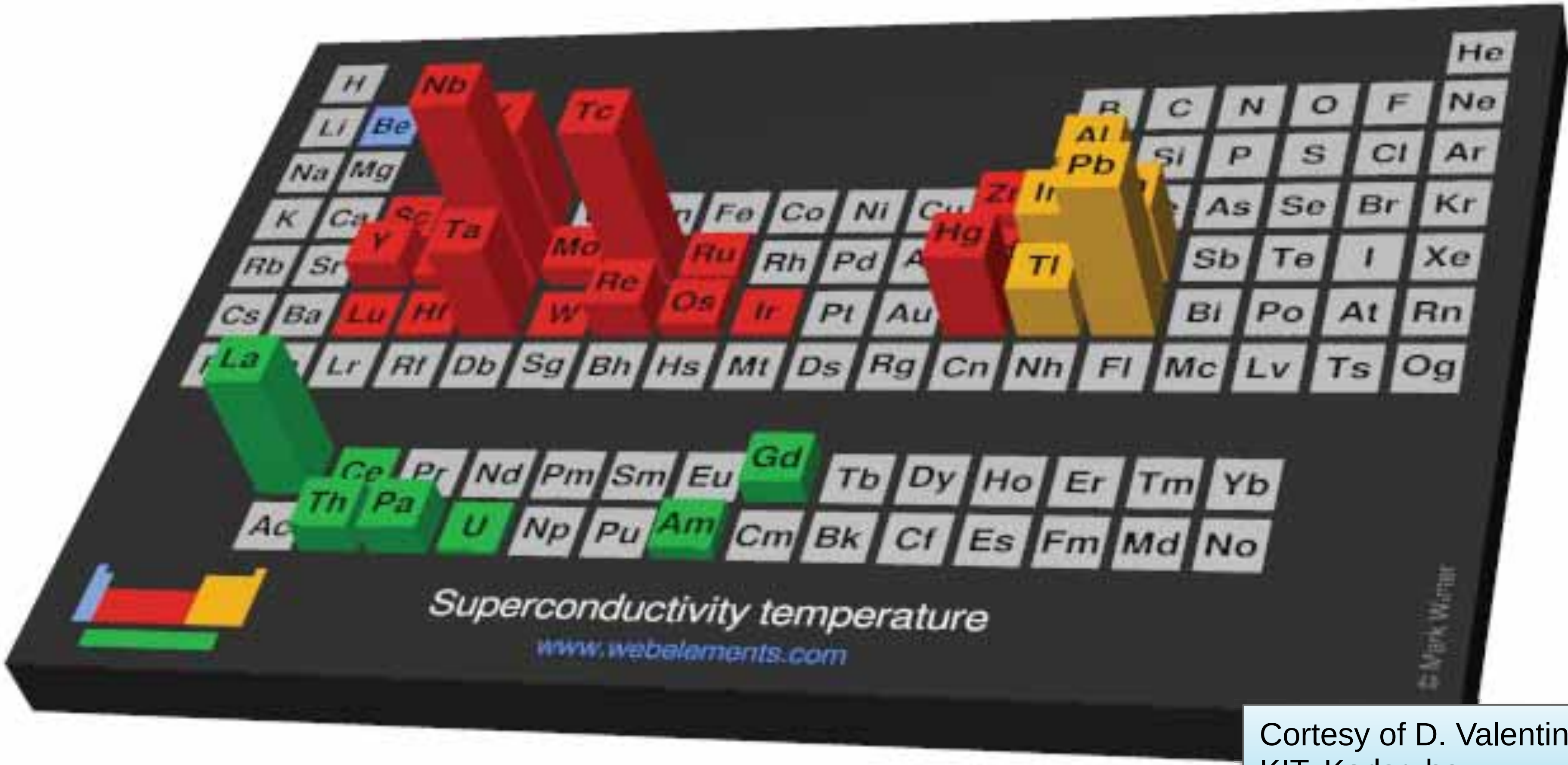
Superconductors at atmospheric pressure

Superconductors at high pressures

Superconductors in modified form

Cortesy of D. Valentinis, KIT, Karlsruhe

Critical temperatures on the Mendeleev table



Cortesy of D. Valentinis, KIT, Karlsruhe

So superconductivty is not rare…

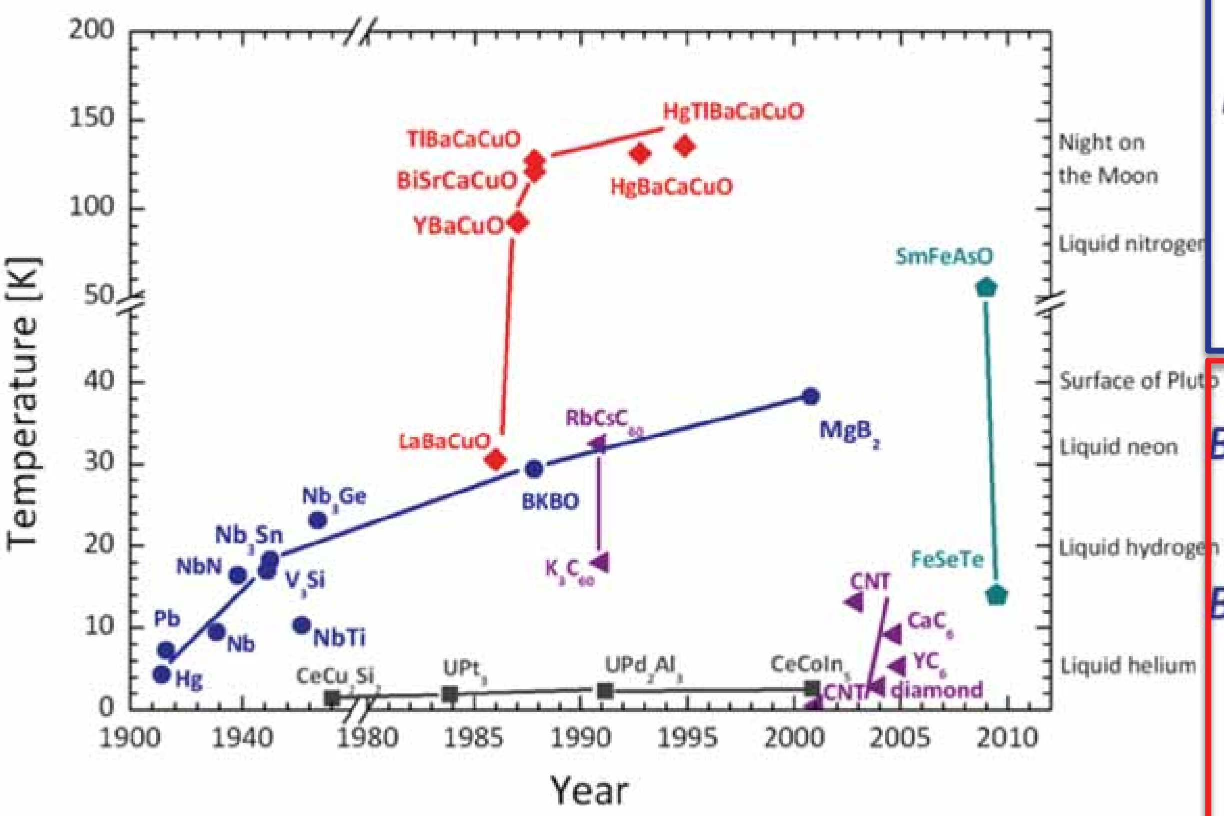
Iwasa table on the long route

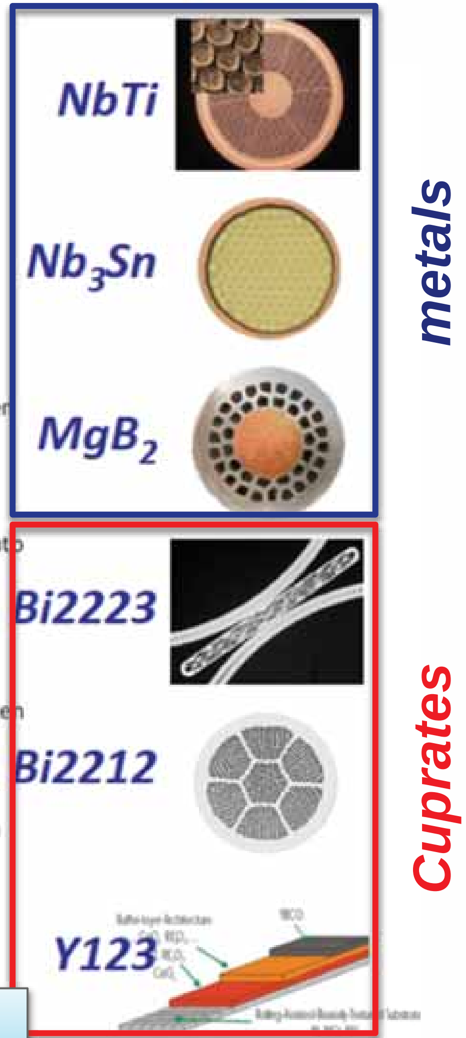
Criterion	*Number*
Superconducting	~ 10,000
$T_c \cong 10$ K .and. $B_{c2} \cong 10$ T	~ 100
$J_c \cong 1000 A/mm^2$ @ B > 5 T	~ 10
Magnet-grade superconductor	~ 1

× 5 now!

The race toward high temperatures guided discovery of new materials and classes

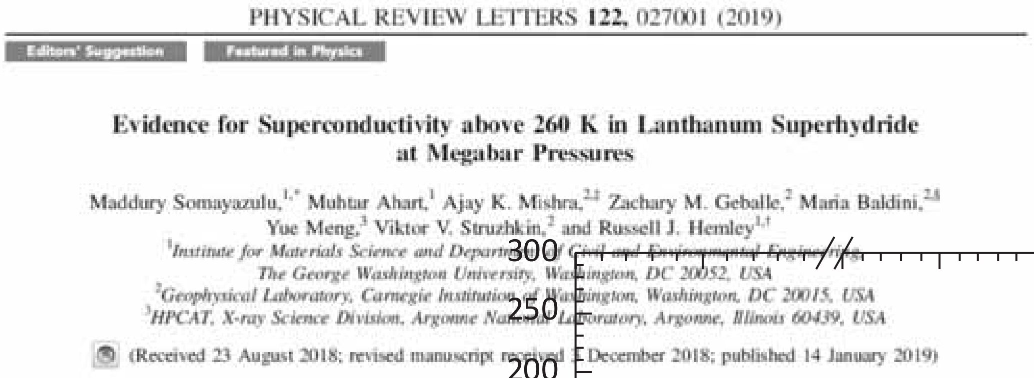
Superconductors History





Cortesy of C. Senatore- Univ. of Geneva

Last date: Tc of 190 K! But at 190 Gpa!



PHYSICAL REVIEW LETTERS 122, 027001 (2019)

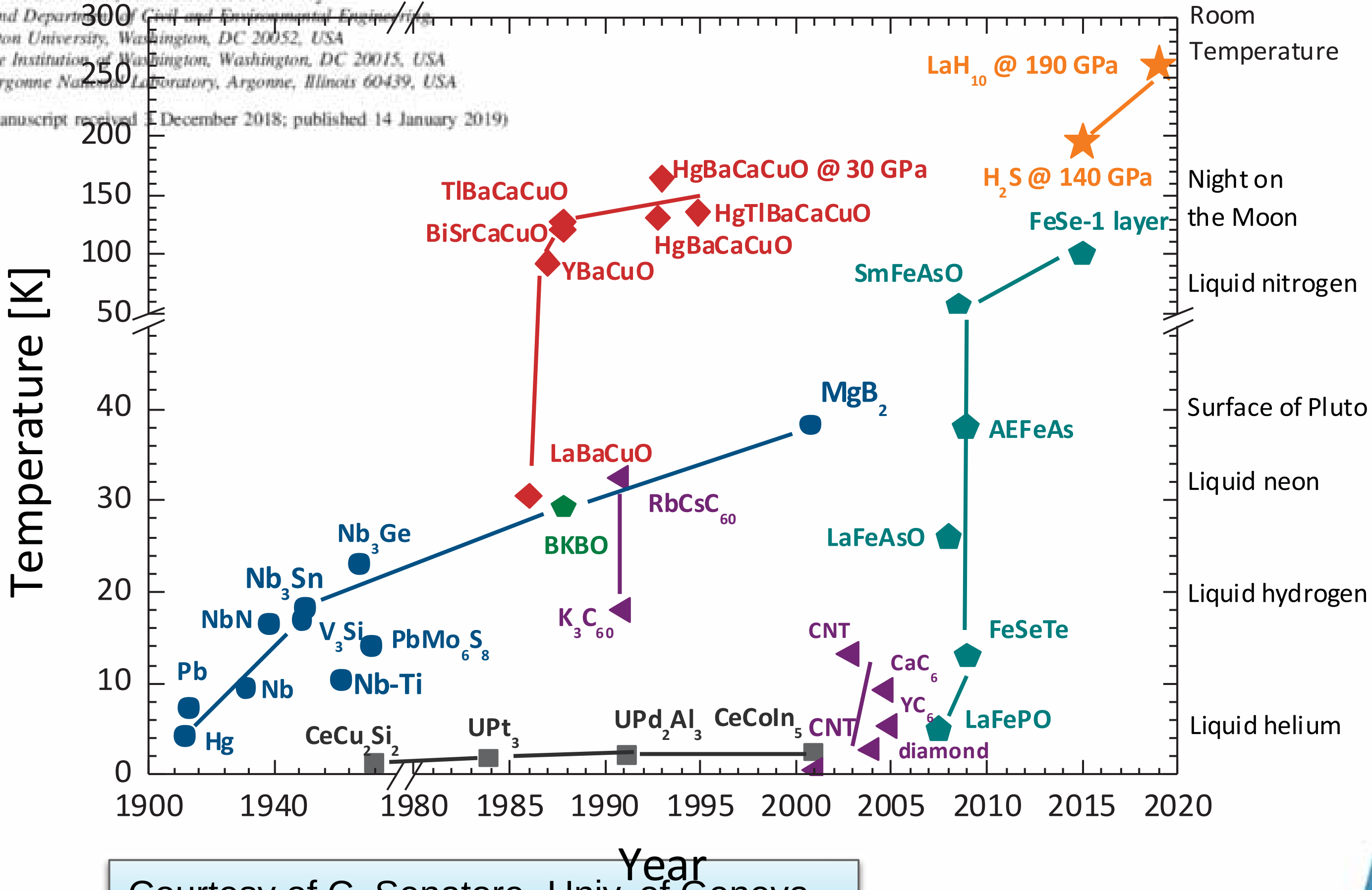
Editors' Suggestion | Featured in Physics

Evidence for Superconductivity above 260 K in Lanthanum Superhydride at Megabar Pressures

Maddury Somayazulu,[1,*] Muhtar Ahart,[1] Ajay K. Mishra,[2,‡] Zachary M. Geballe,[2] Maria Baldini,[2,§] Yue Meng,[3] Viktor V. Struzhkin,[2] and Russell J. Hemley[1,†]

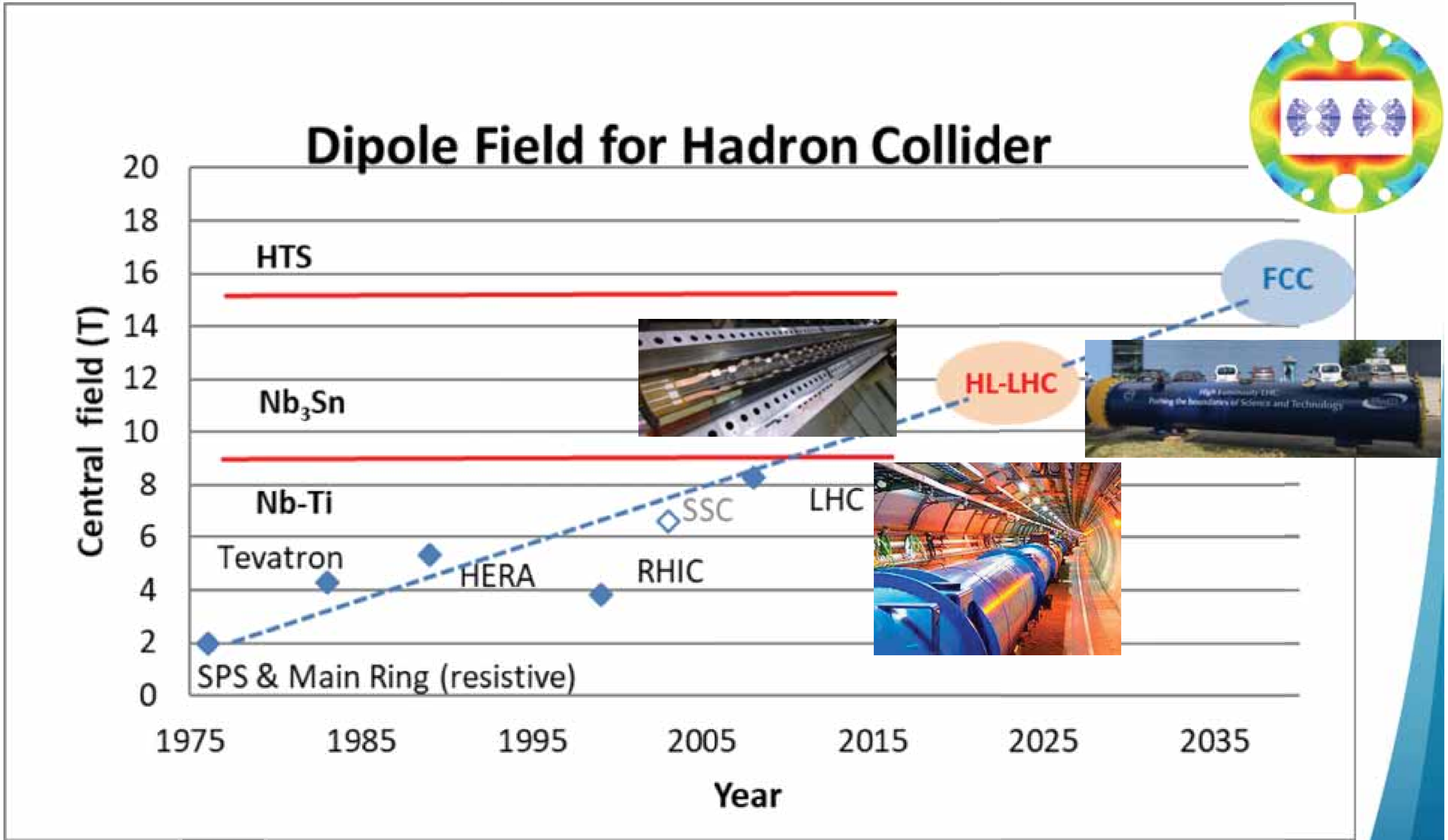
[1]Institute for Materials Science and Department of Civil and Environmental Engineering, The George Washington University, Washington, DC 20052, USA
[2]Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC 20015, USA
[3]HPCAT, X-ray Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

(Received 23 August 2018; revised manuscript received 1 December 2018; published 14 January 2019)

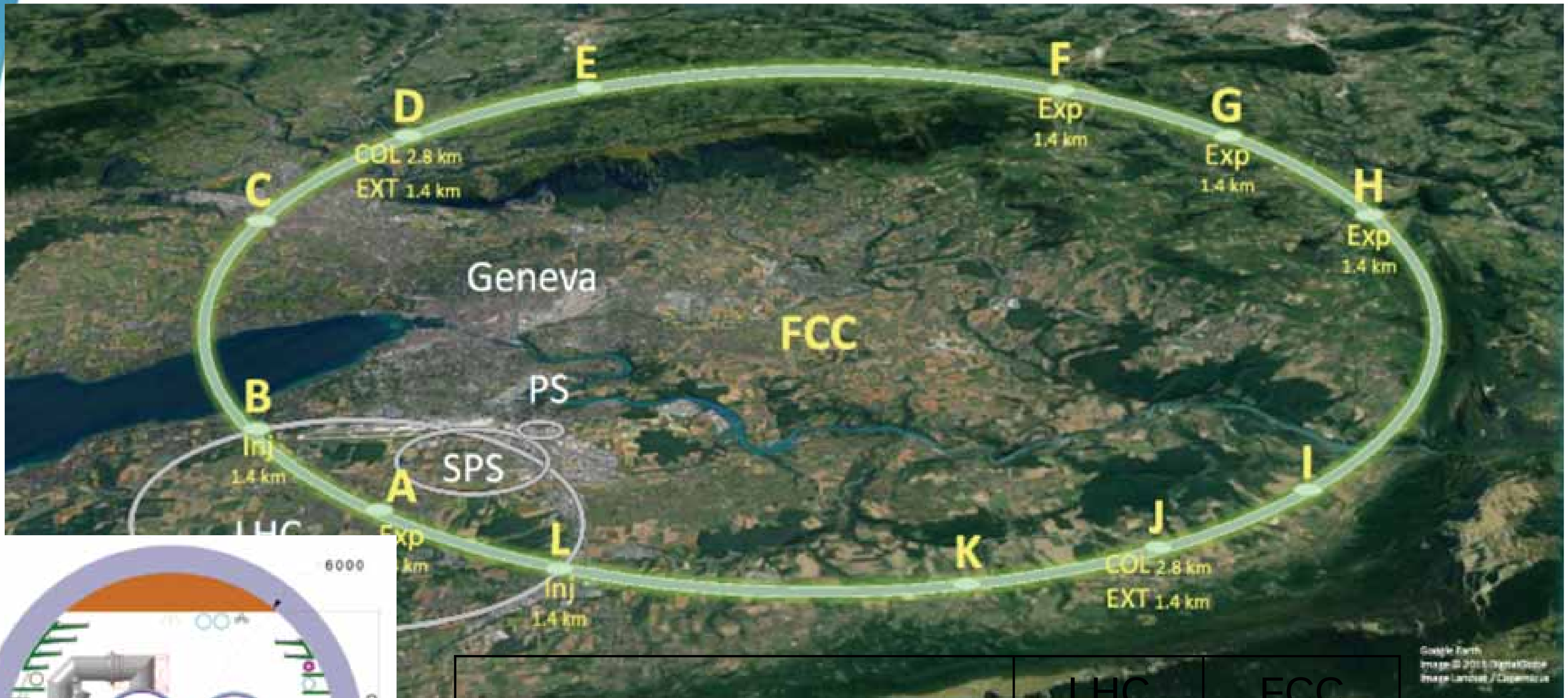


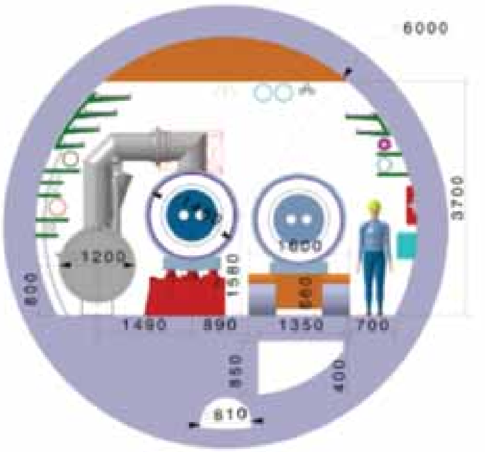
Courtesy of C. Senatore- Univ. of Geneva

HiLumi LHC:
preparing technology for next big steps



Future Circular Collider



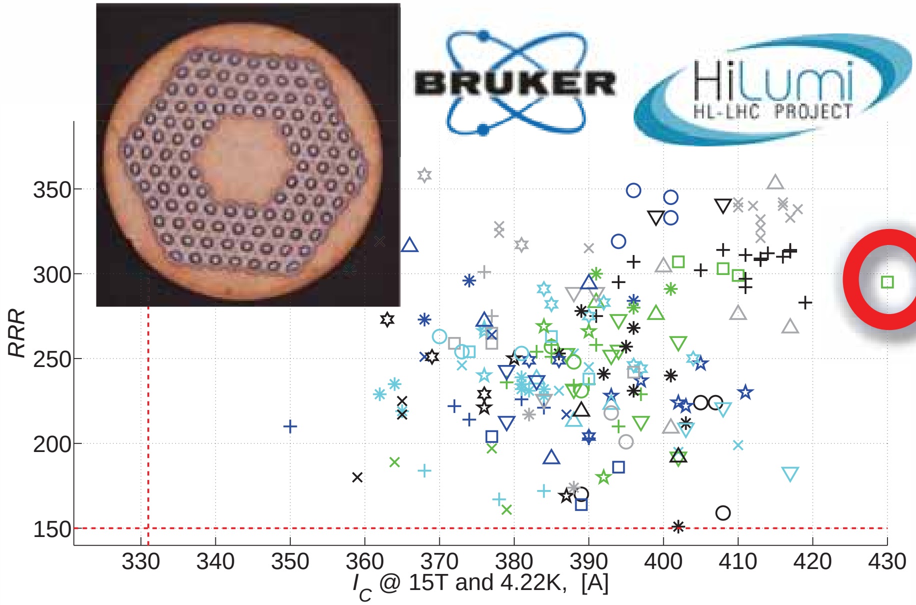


	LHC	FCC
Circumference (km)	26.7	97.5
Dipole field (T)	8.33	16
C.o.M. energy (TeV)	14	100

Courtesy of M. Benedikt, FCC

Conductor R&D

Specification: 1500 A/mm^2 @ 16T, 4.2K

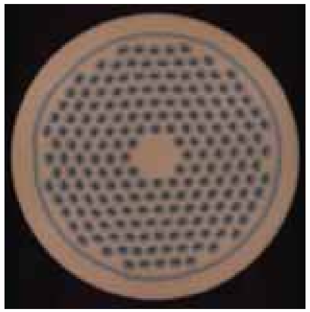


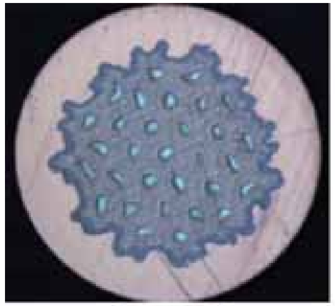
1750 A/mm^2 @ 15T, 4.2K

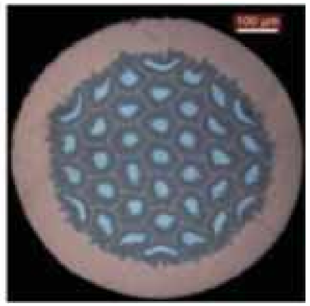
≈ 1400 A/mm^2 @ 16T, 4.2K

1274 A/mm^2 @ 15T, 4.2K

≈ 1000 A/mm^2 @ 16T, 4.2K

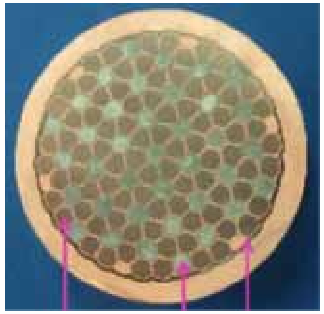


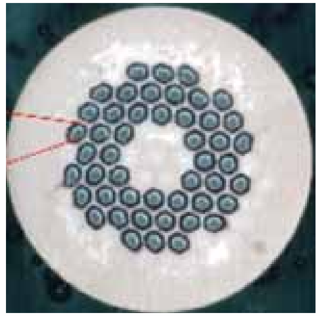




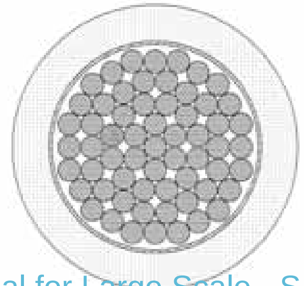
2850 A/mm^2 @ 12T, 4.2K

≈ 1250 A/mm^2 @ 16T, 4.2K



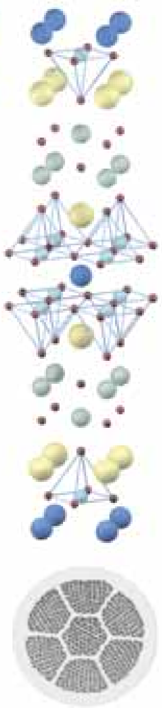


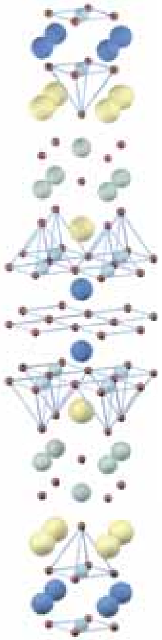
≈ 950 A/mm^2 @ 16T, 4.2K

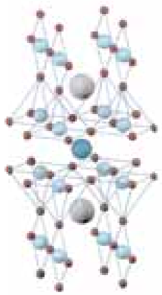


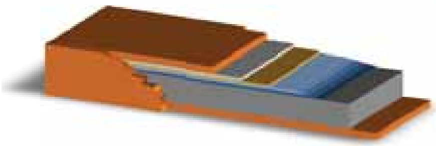
ed

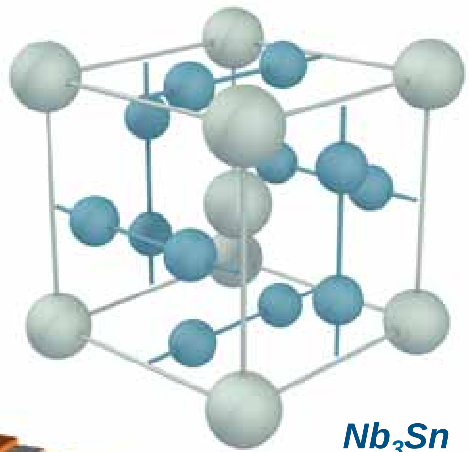
Cuprates are very complex material



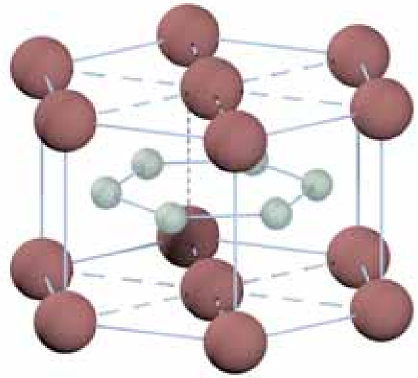






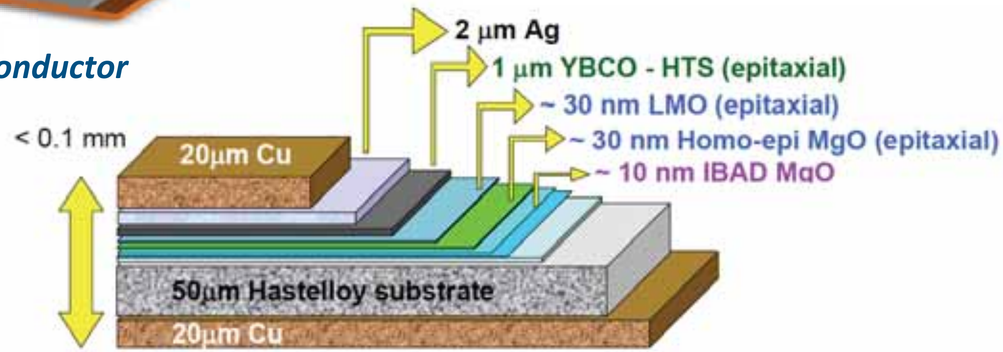


Nb_3Sn



MgB_2

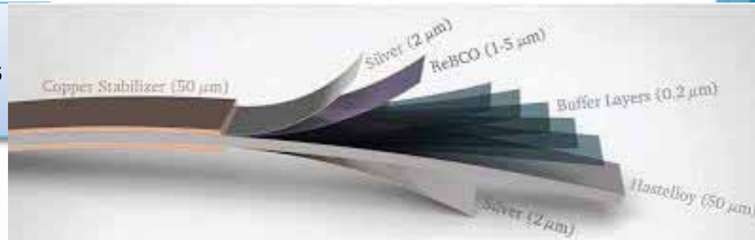
Y123 Coated Conductor



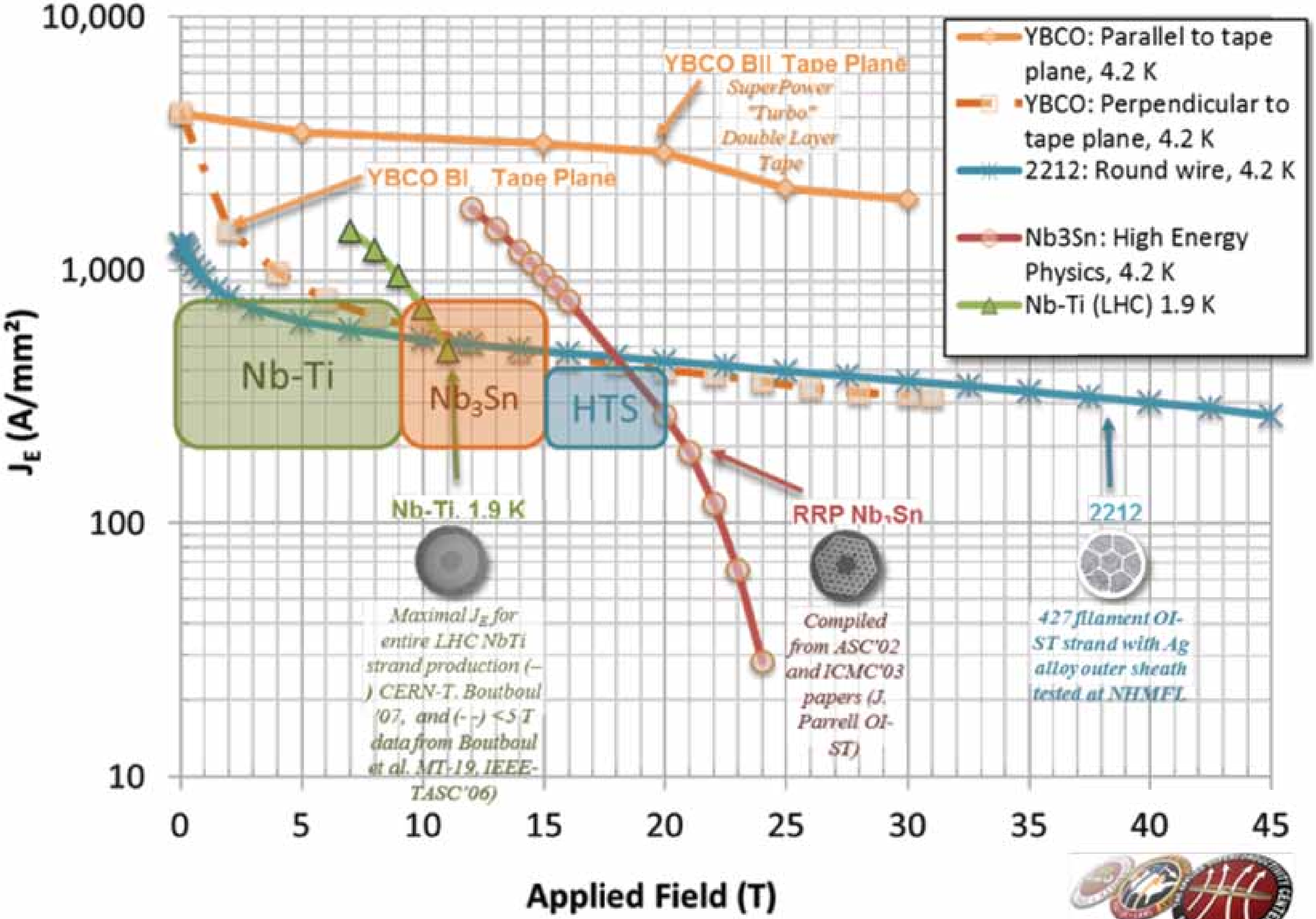
Bi2223 Powder-In-Tube tape

Bi2212 Powder-In-Tube wire

REBCO – Rear Earth Barium Copper Oxide
Ion Beam assisted deposition for buffer layers
Plasma Laser Deposition for HTS layer…



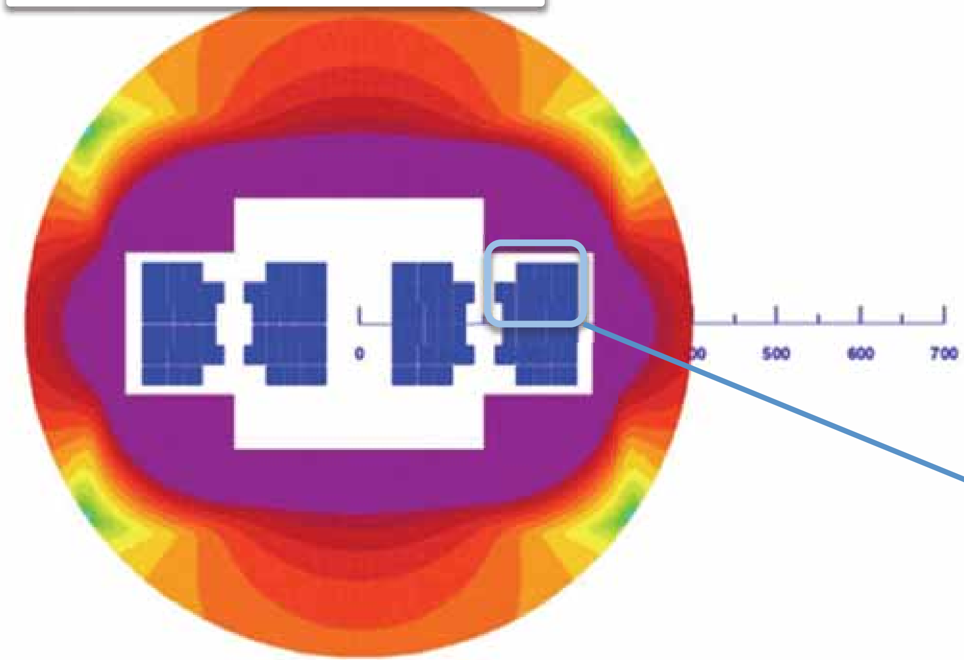
Are we stuck with 15-16 T of FCC? NO!

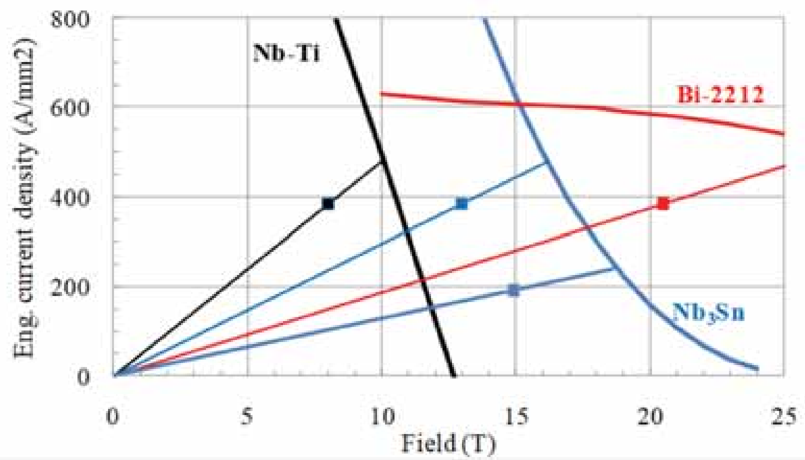


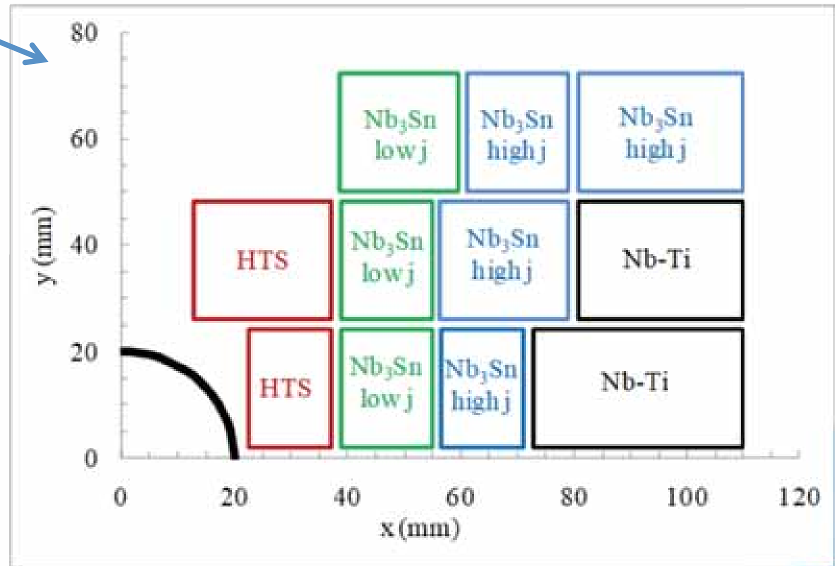
Re-adapted from P. Lee, FSU/NHMFL USA

20 T dipole hybrid proposed in 2010 for HE-LHC

L. Rossi – E. Todesco

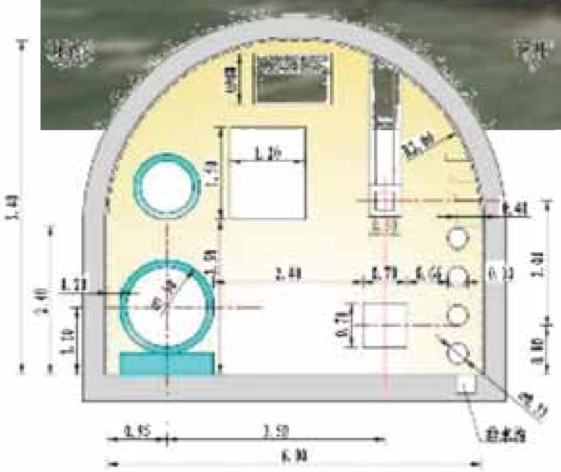






40 mm aperture
Now the standard is more 50 mm

Super proton-proton Collider in China



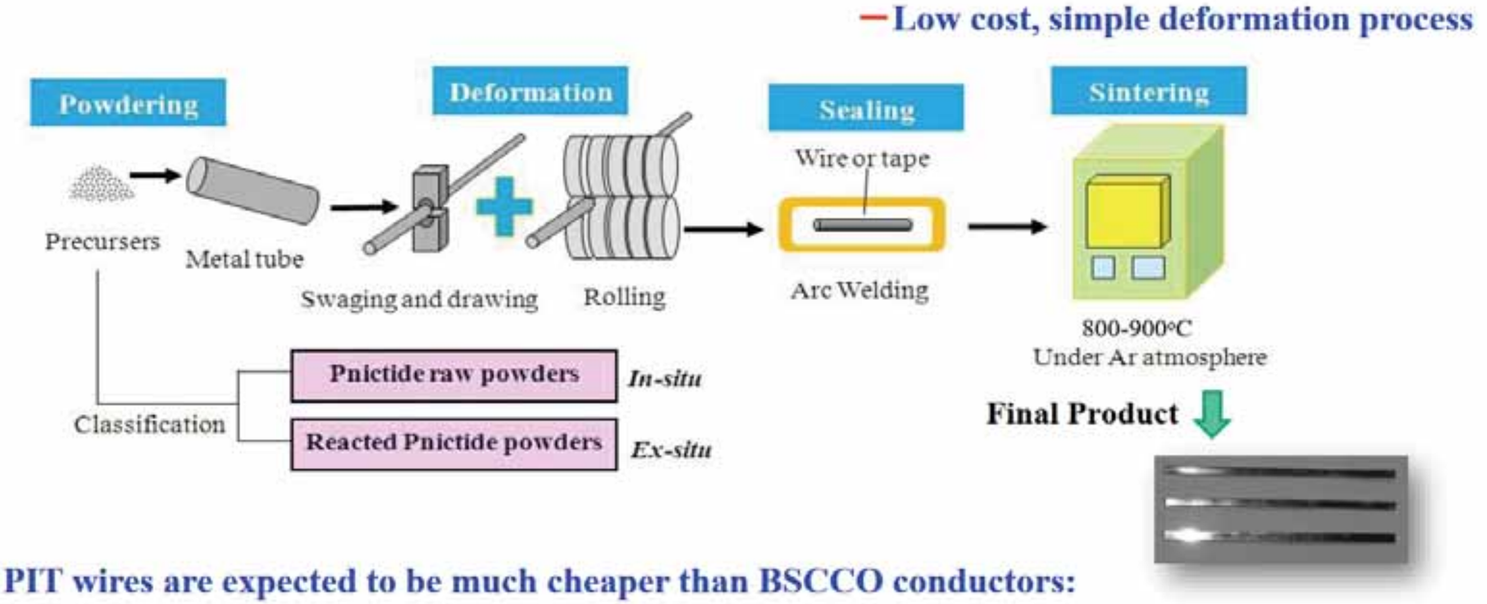
	LHC	FCC	SppC
Circumference (km)	26.7	97.5	100
Dipole field (T)	8.33	16	12…24
C.o.M. energy (TeV)	14	100	70…125

Courtesy of Q. Xu, IHEP, CN

National Chinese Program on IBS in view (among other) of HEP collider

Fabrication process for IBS wires and tapes

(*Powder-in-tube method*)



122 PIT wires are expected to be much cheaper than BSCCO conductors:

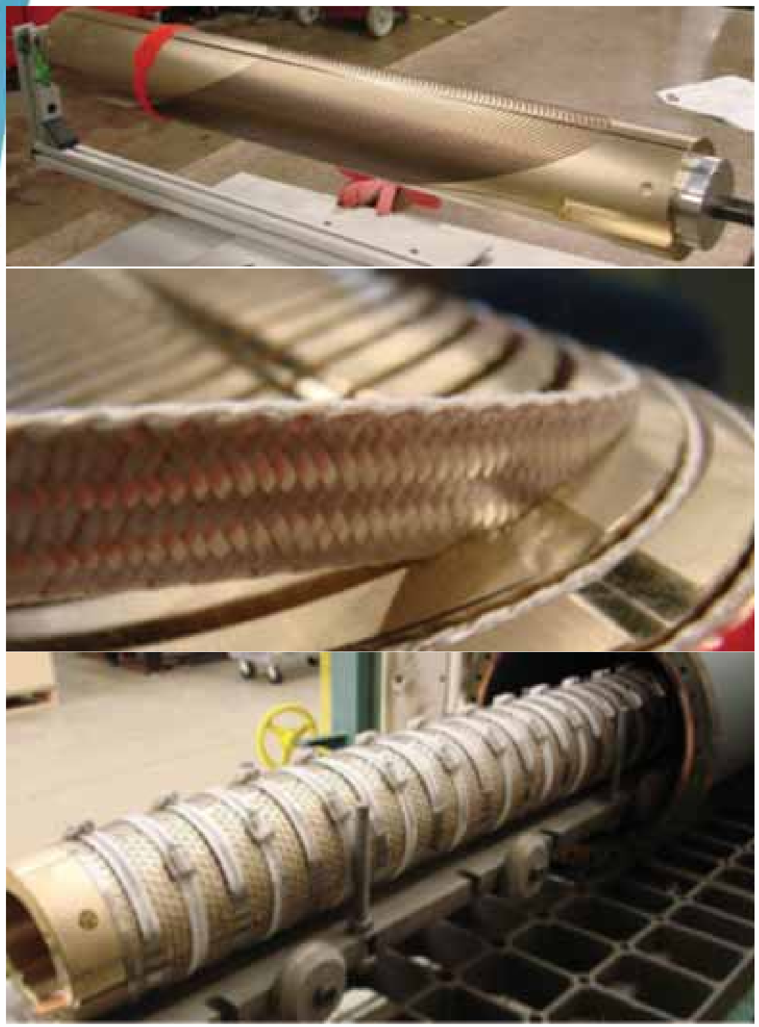
1. Many types of sheaths of Ag, Cu, Fe, and Ag-based composites (Ag/Fe, Ag/Cu, Ag/stainless steel) can be employed.

2. For BSCCO, Ag is the only material that is inert to the BSCCO superconductor and permeable to oxygen at the annealing temperature.

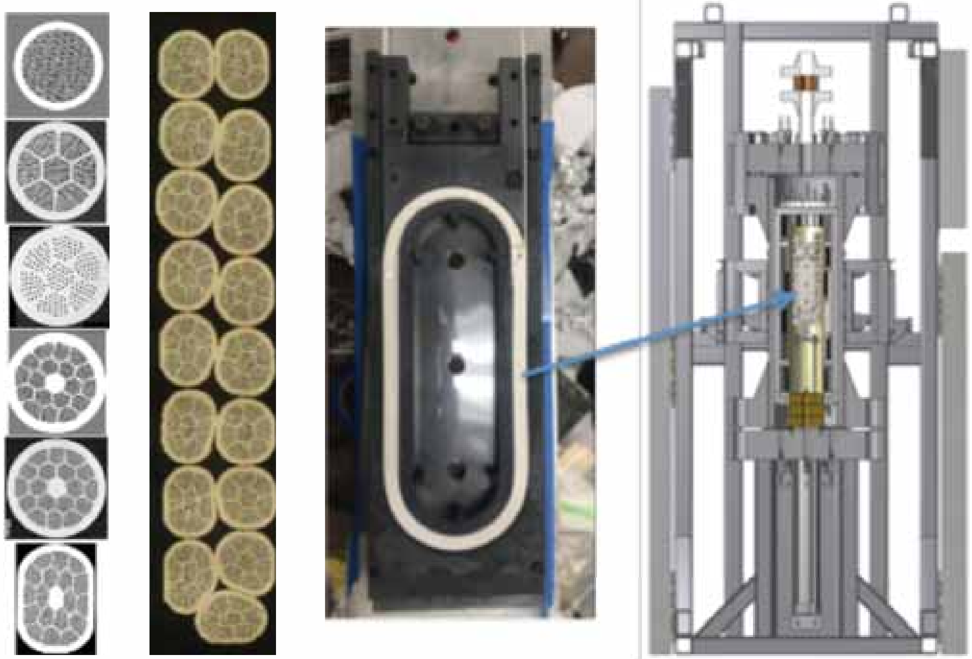
Courtesy of Prof. Yanwei Ma
Institute of Electrical Engineering,
Chinese Academy of Sciences,
Beijing, China

US CCT and HTS programs

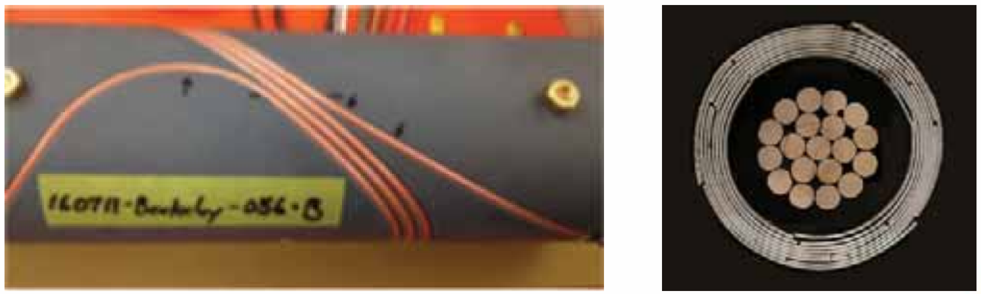
Nb_3Sn cable in CCT geometry



Bi-2212 cable in racetrack

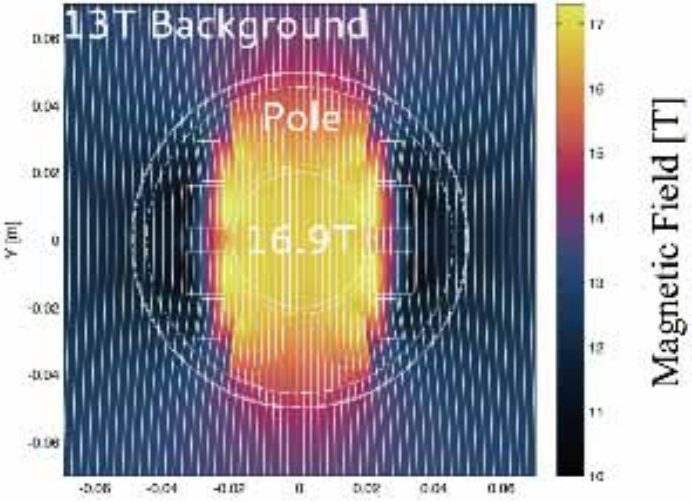


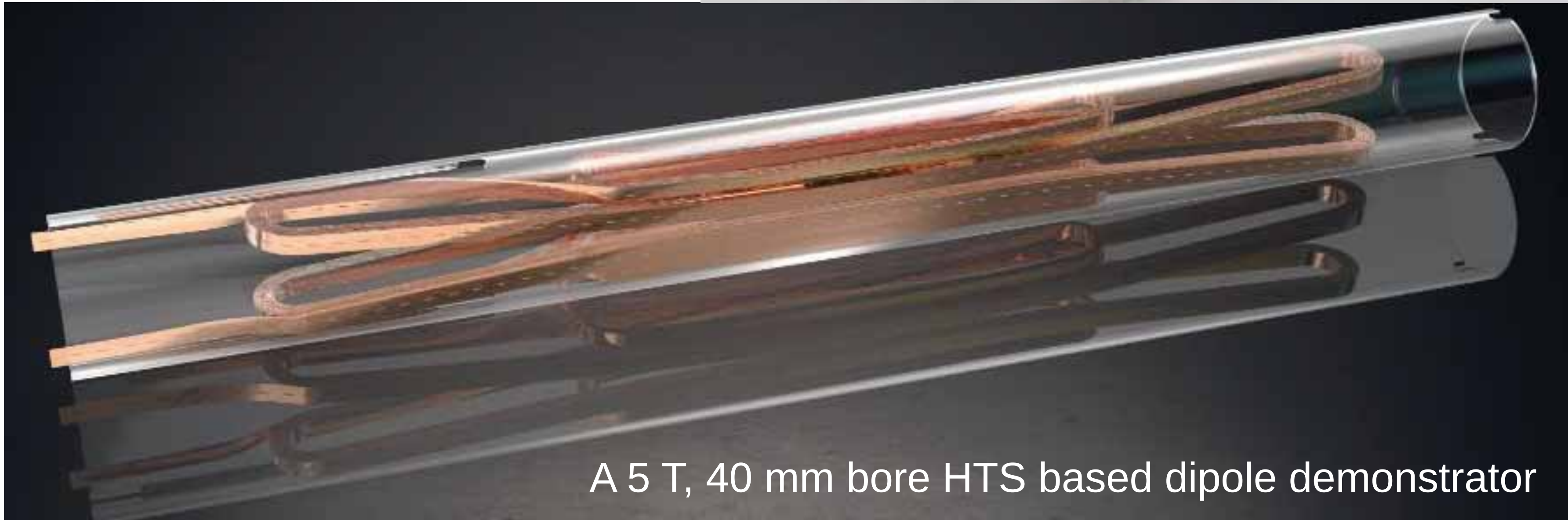
REBCO CORC in CCT geometry



Courtesy of S. Prestemon, LBNL

Short accelerator dipole demonstrator 40 mm aperture, cable (not single element)

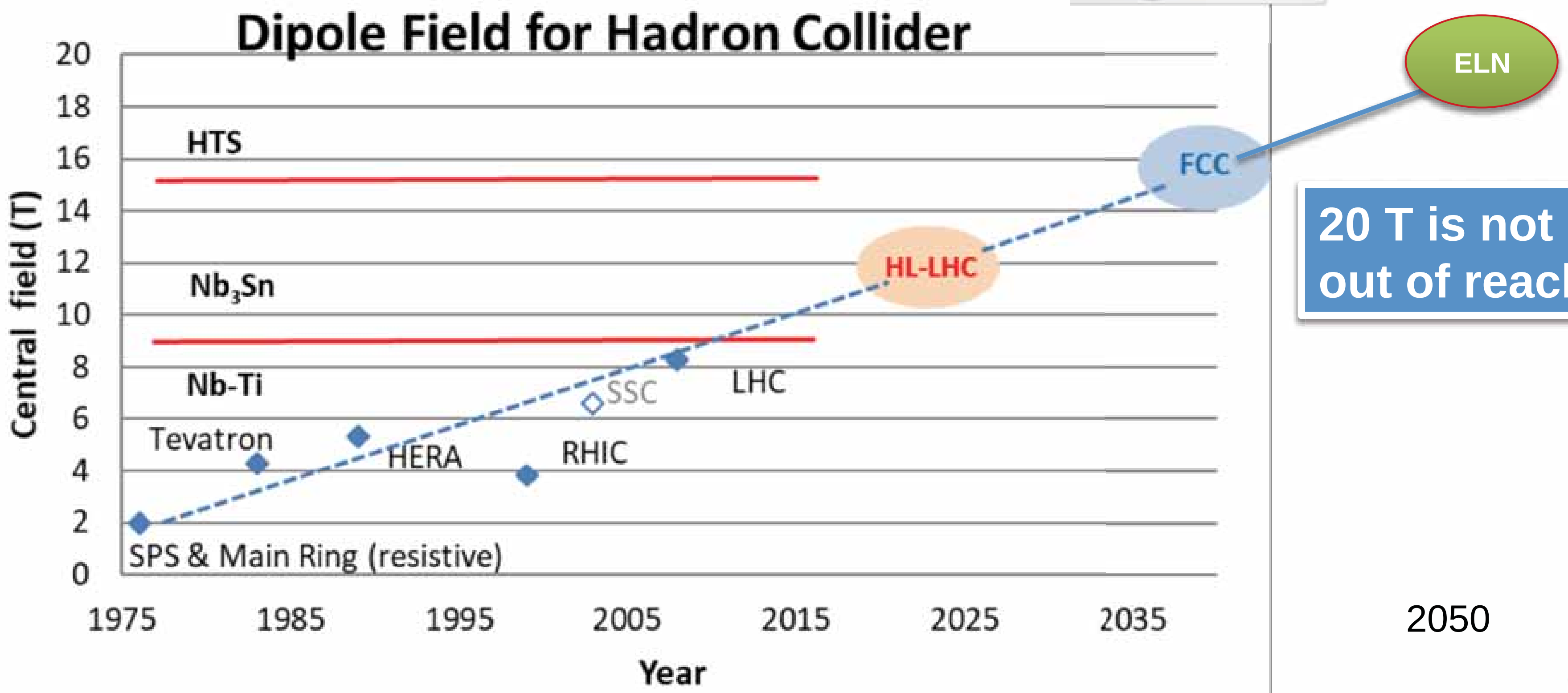




Can we extrapolate linearly from the past
To go BEYOND FCC? ⇒ ELN?

EUCARD²

5T HTS demos



20 T is not out of reach

SuST publication 2018

Towards REBCO 20 T+ Dipoles for Accelerators

J. van Nugteren, G. Kirby, J. Murtomäki, G. de Rijk, L. Rossi and A. Stenvall

***Abstract*—ReBCO High Temperature Superconducting (HTS) coated conductor tapes are a promising candidate for pushing the magnetic fields in accelerator magnets well beyond 20 T. They are capable of very high current densities in intense applied magnetic field, have a very high thermal stability, can withstand high transverse pressures and allow operation in 20 to 30 K helium gas flow, potentially reducing operating cost significantly. During the EuCARD2 program significant developments have been made in terms of coil design, manufacturing and testing. Now that EuCARD2 has come to an end, CERN and collaborators are initiating a new program to continue the development of HTS accelerator magnets. This paper presents our initial thoughts on the conceptual design of a 20 T+ accelerator magnet, using the results and technologies from EuCARD2 combined with some new ideas. The paper discusses the options available for the cross-sectional layout, the use of a hybrid configurations including Aligned Block, the design of the coil-ends and dual aperture configurations. Also discussed is the quench protection of the magnets. Due to the high thermal stability of the conductor and high energy densities it will be required to explore an entirely new approach.**

***Index Terms*—Accelerator Dipoles, HTS Magnets, Quench Protection, Magnet Stability, Magnet Structure**

I. Into the Future with HTS

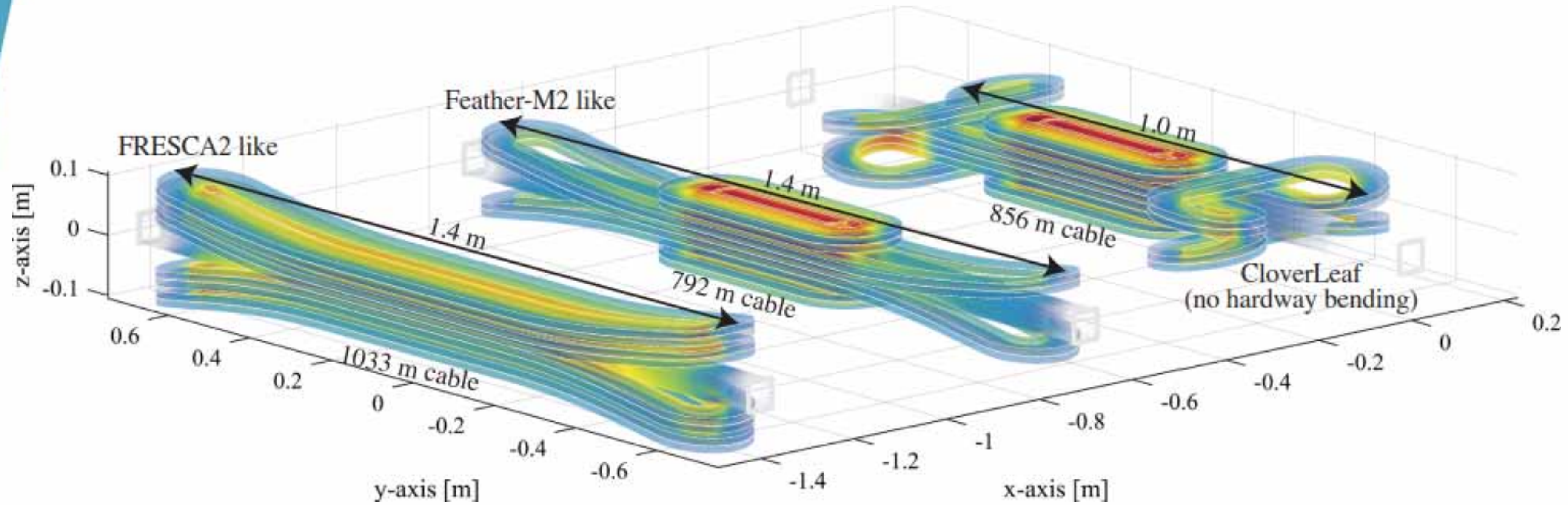
WITH the successful stand-alone cold powering test of the first Feather-M2.1-2 magnet in helium gas [1], (FCC) [11] tunnel and, as a possible intermediate step, beyond a considerable 30 TeV in the existing 27 km circumference LHC tunnel [12]. Due to the higher critical temperature it is possible, provided sufficient improvement of the engineering current density (see Section II), to operate HTS magnets in forced-flow helium gas at intermediate temperatures of 20 K − 30 K, greatly reducing the complexity and cost for operating them in a large accelerator. This would also allow the beam-screen, responsible for absorbing the synchrotron radiation, to be operated at a higher temperature or even become integral part of the magnet. Furthermore, in contrast to the Nb_3Sn [13], REBCO coated conductor (the HTS of choice) does not require heat treatment considerably simplifying the manufacturing process.

This paper presents our initial thoughts, based on the experience gained from EuCARD2, on the conceptual design of a 20 T+ demonstrator accelerator magnet and the implications of using HTS inside a particle accelerator.

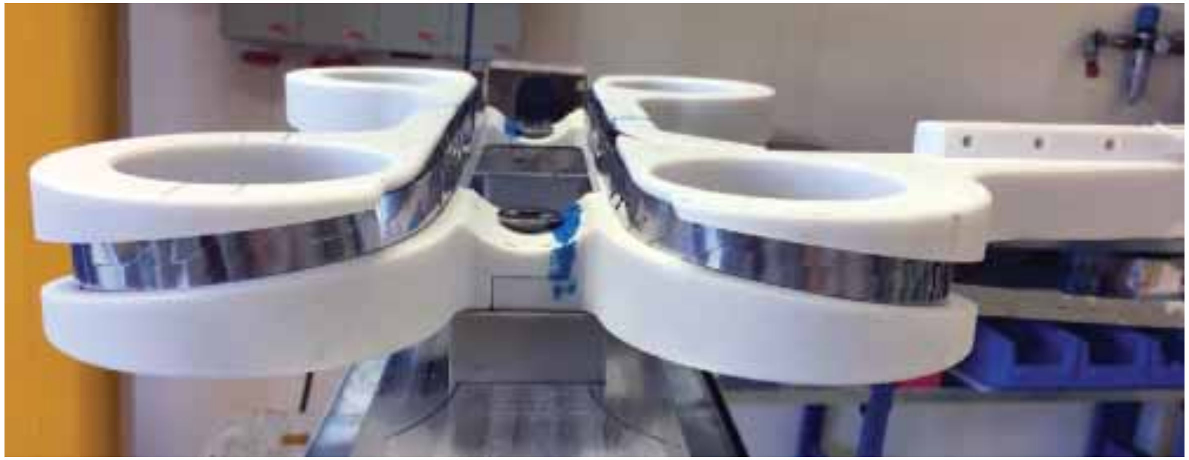
II. Anisotropy and Current Density

The overall current density is an important parameter from a magnet design point of view, since it determines in large part the cross-sectional area of the conductor and thus the conductor volume needed for the magnet. In essence, higher current

Working on even nmore unconventional desing of the end shape

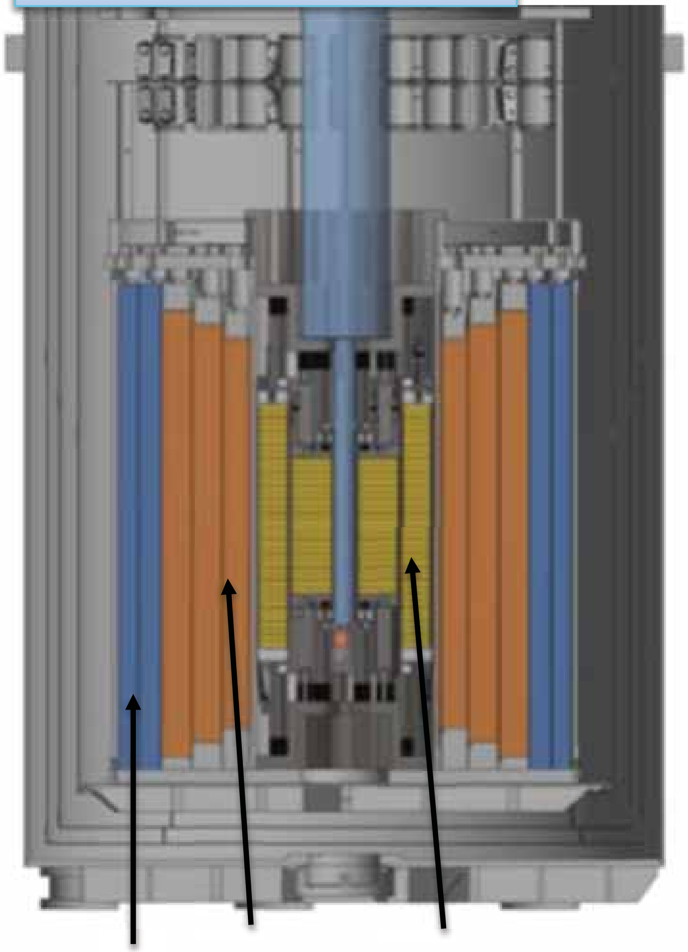


From Jeroen van Nugteren and Glyn Kirby -CERN

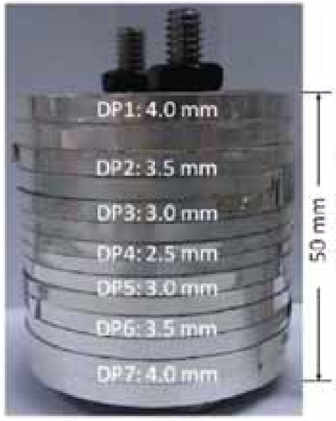


Nat. High Mag. Field Lab in Florida

32 T reached in 2018!

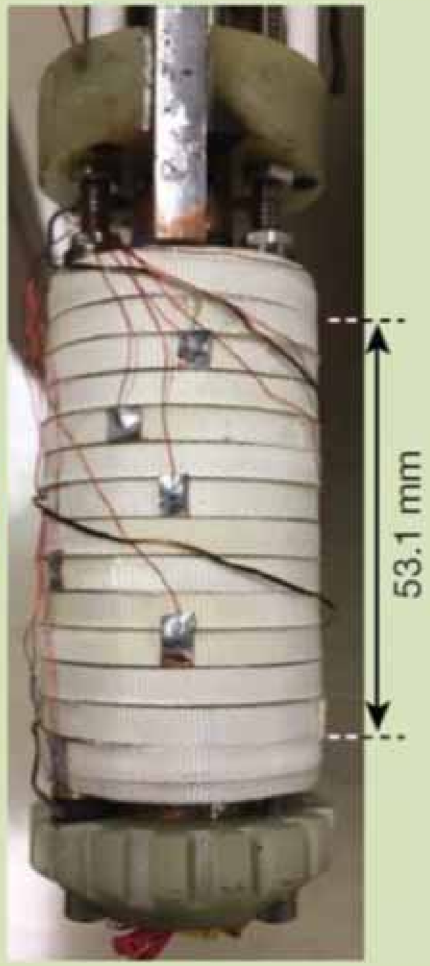


Nb-Ti Nb3Sn REBCO



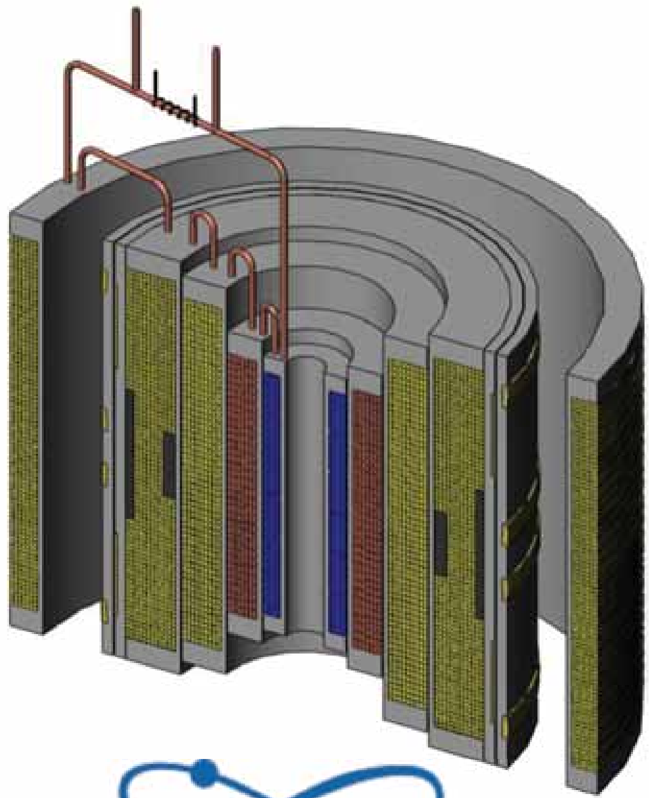
30 T coil Non-insulated

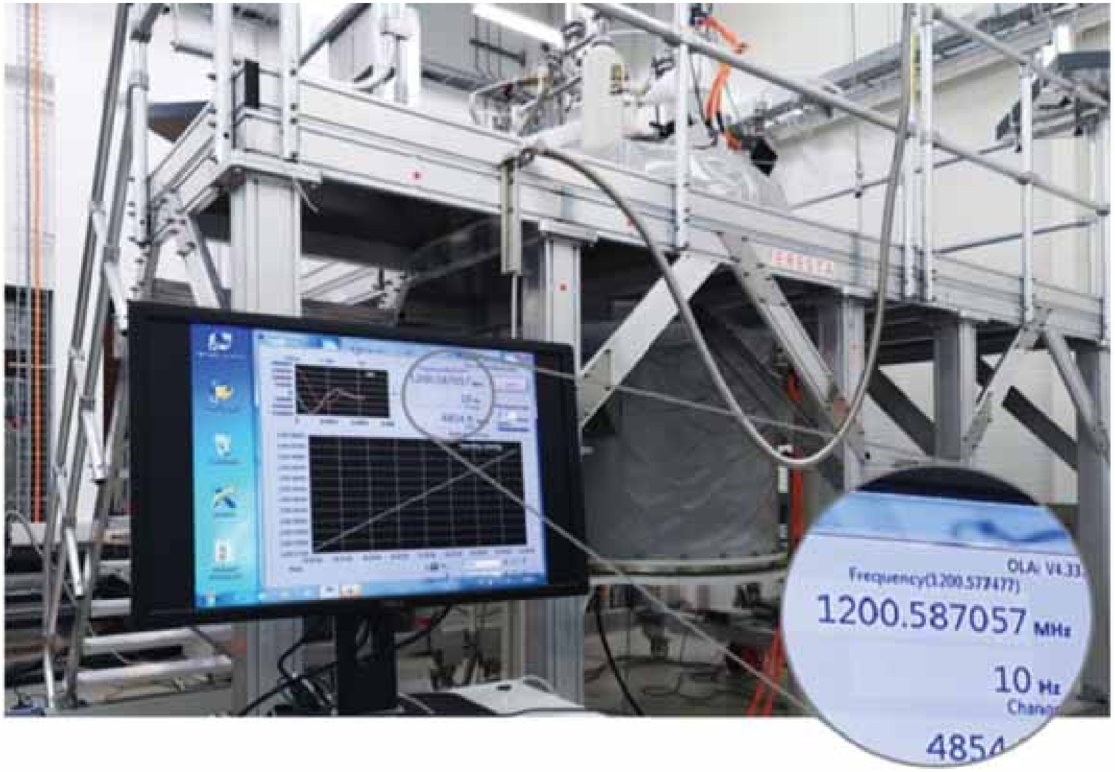
Courtesy of M. Bird, FSU/NHMFL USA



LBC3 after 45.5-T test

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

30 km MagLev prototype line working…
600 km Tokyo-Osaka under construction (1h)

Classical Nb-Ti

Application under studies:
Ion therapy
Avionics
Energy (transmission lines, storage, power quality, etc…)

Superconductivity is an enabling technology
And the superconductor is the key
A SC magnet cannot be better than its superconductor
(but can be much worst if badly engineerized or built)

Thanks