Superconducting Magnets: an enabling technology for physics research and for society

INFN

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JAI John Adams Institute for Accelerator Science

John Adams Institute for Accelerator Science

Seminar Series - remote

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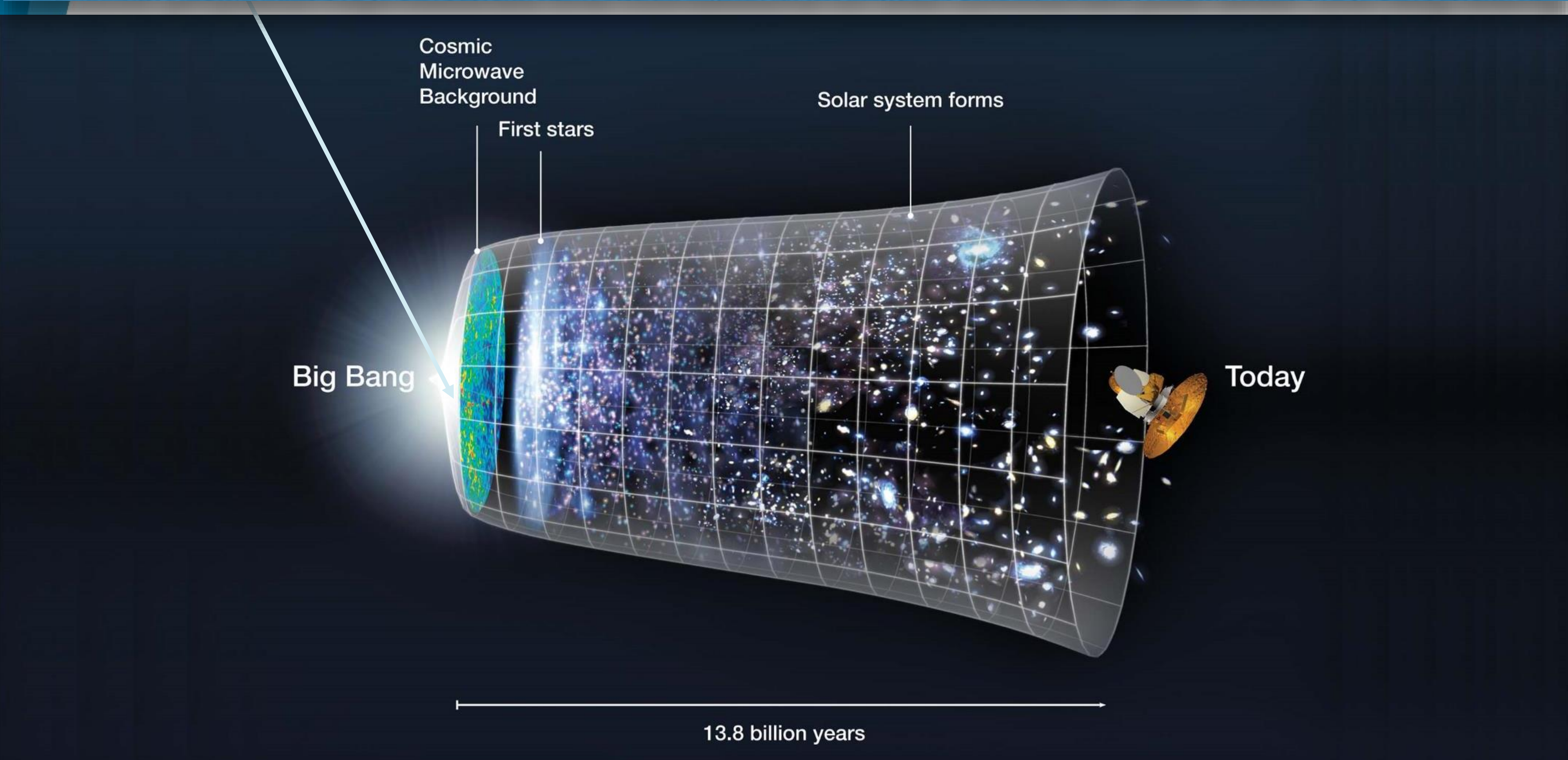
ARIES

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

The Universe (and all particles within) is 13.8 billion years old

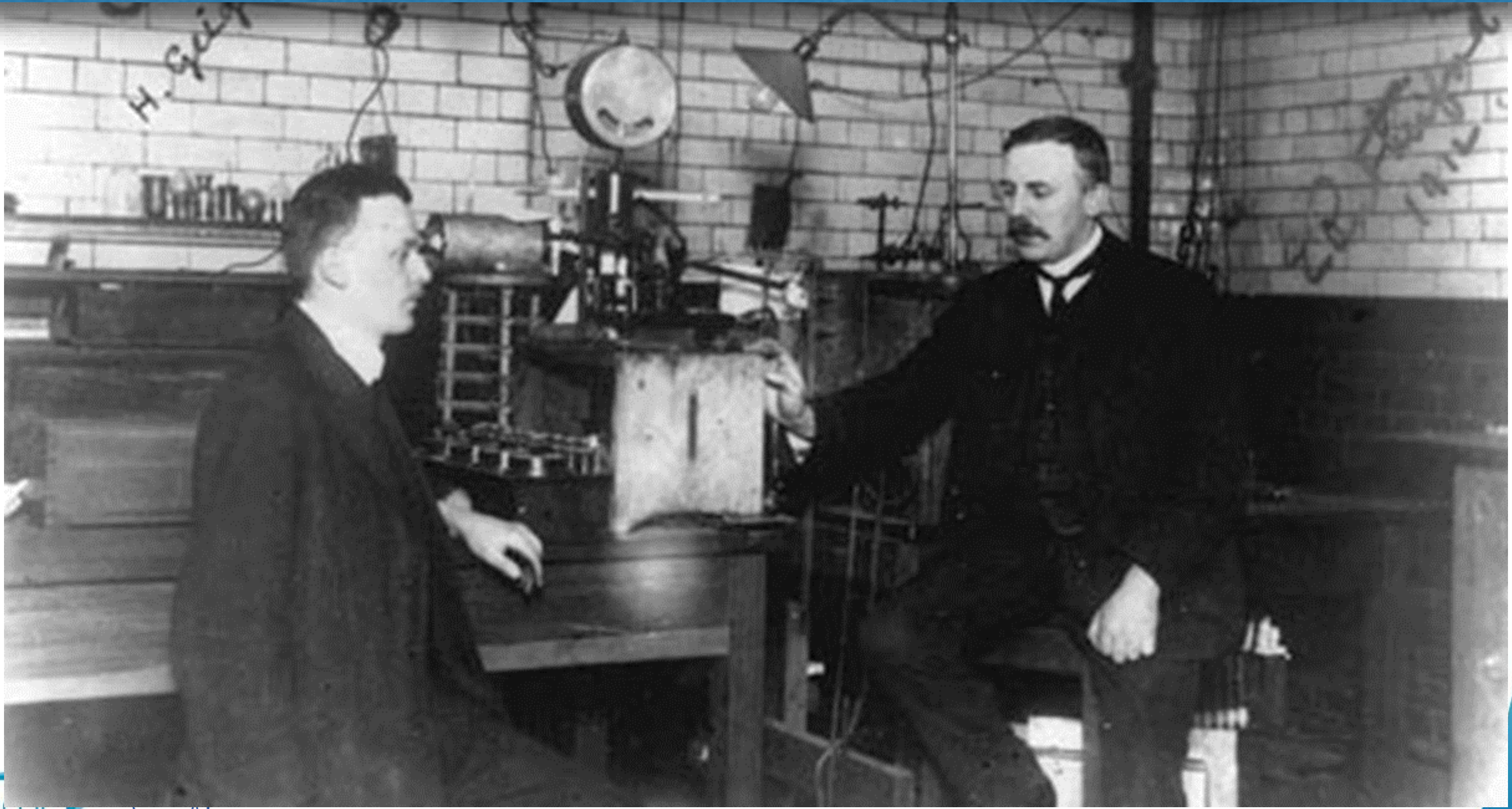
Particle physics reproduces the conditions of the Universe just after the Big Bang



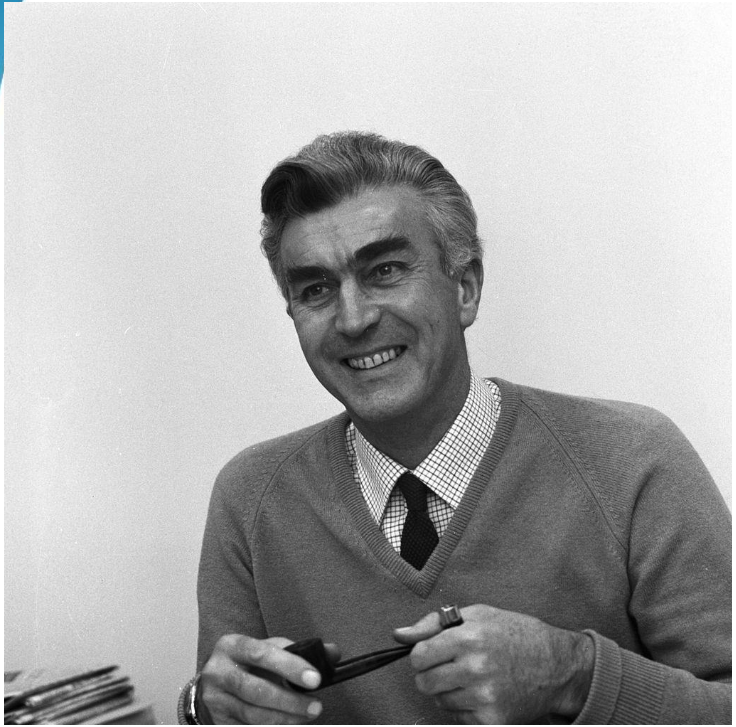
Padua, beginning 1610: « … things never seen before»


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, praesertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quae à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
[illegible]
[illegible]
[illegible]
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vsque diem cognitos, nouissimè Author depraehendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

A new frontier: smashing atoms in Manchester 1909-11



John Adams and SPS (450 GeV, 800 GeV collider

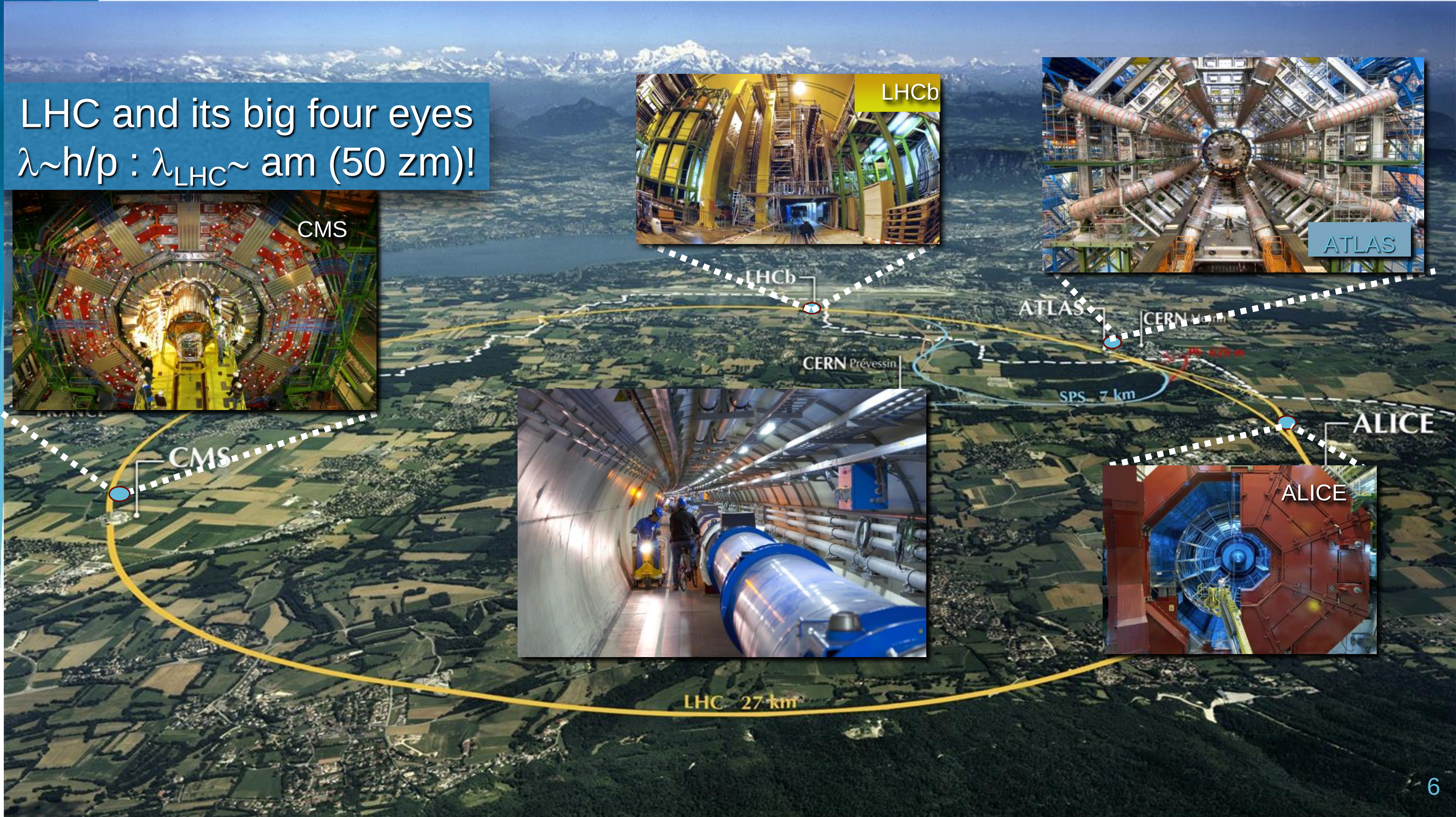


John Adams – the father of SPS
CERN archive

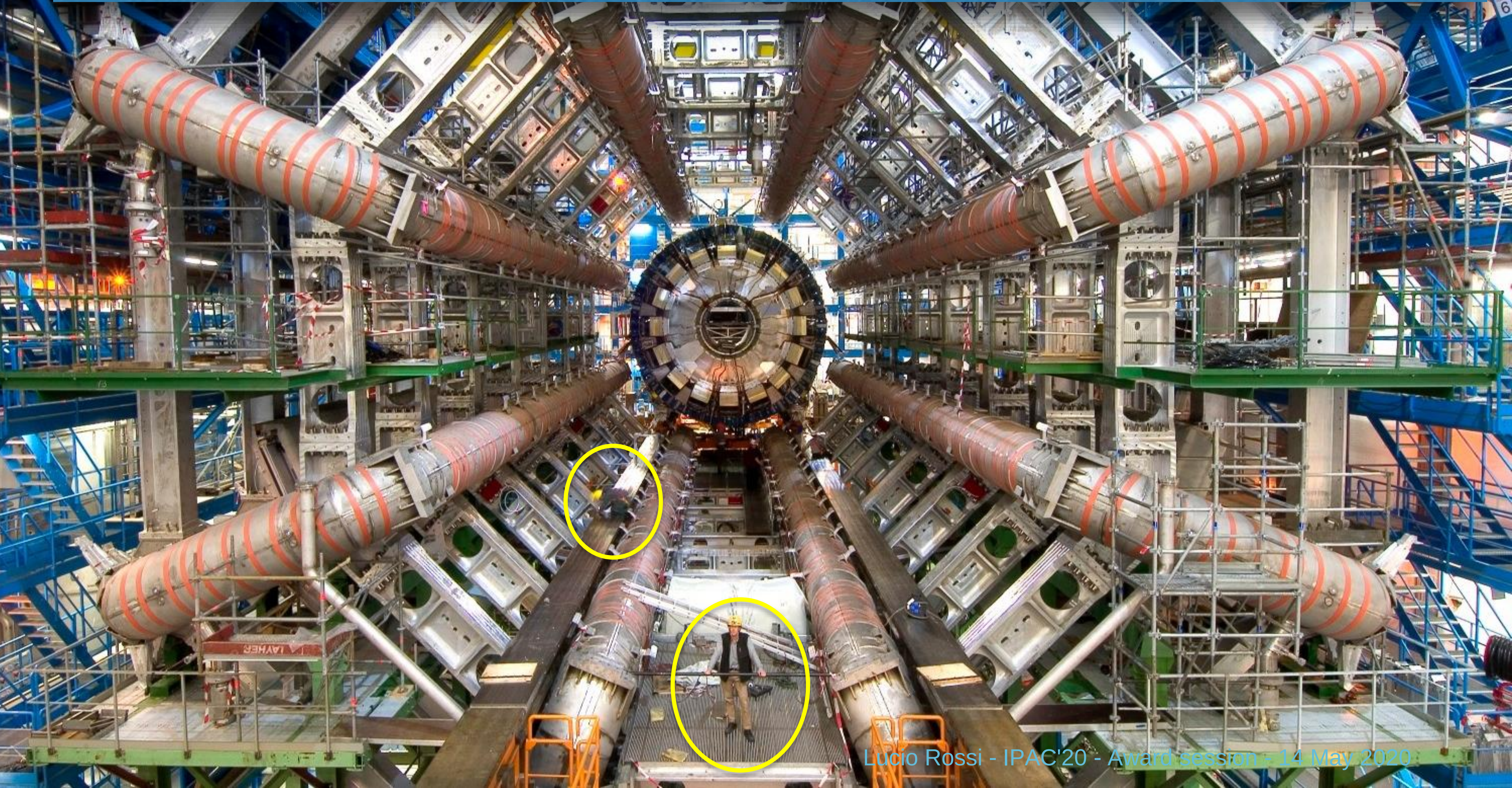
SC community could not convince JA to have the SPS with superconducting magnets… but he was right!

LHC and its big four eyes

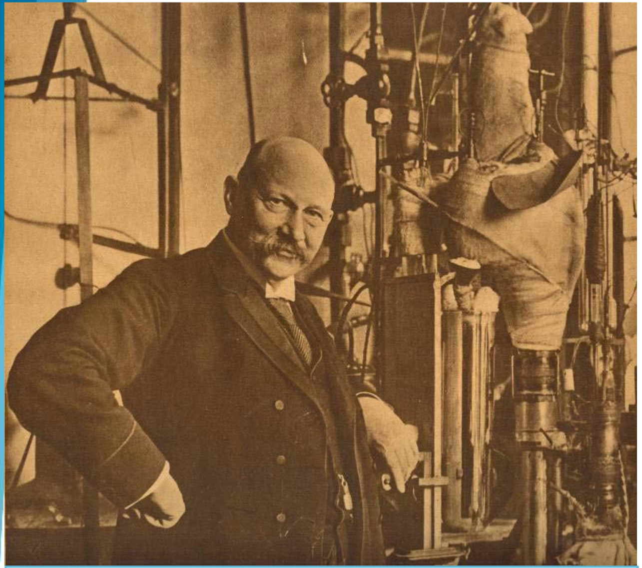
$\lambda \sim h/p$: $\lambda_{LHC} \sim$ am (50 zm)!



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



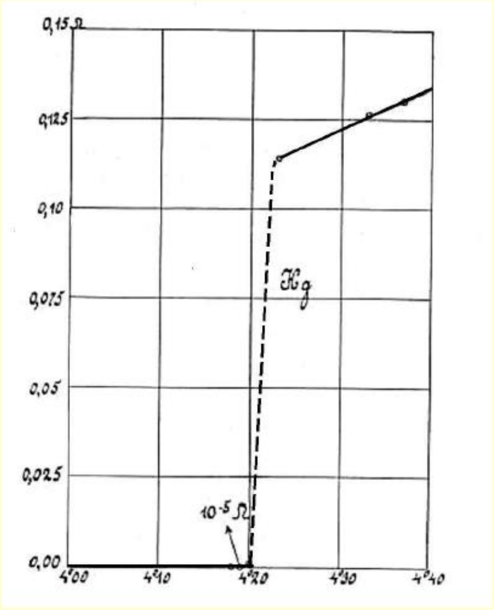
1911: superconductivity discovered in Leiden!



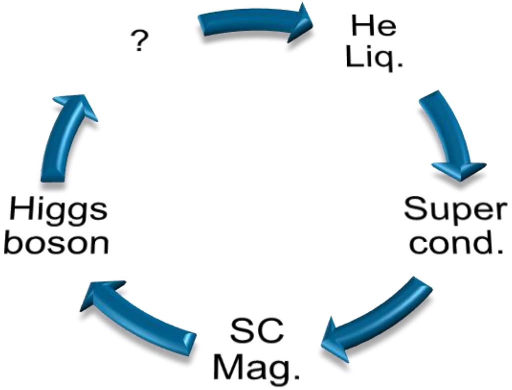
Onnes engaged in gas liquifaction race: he first liquified oxygen in 1894, he lost the race with Dewar (who liquified hydrogen in 1898) and eventually he first liquified helium in 1908!

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

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



Technology-Science: virtuous circle…

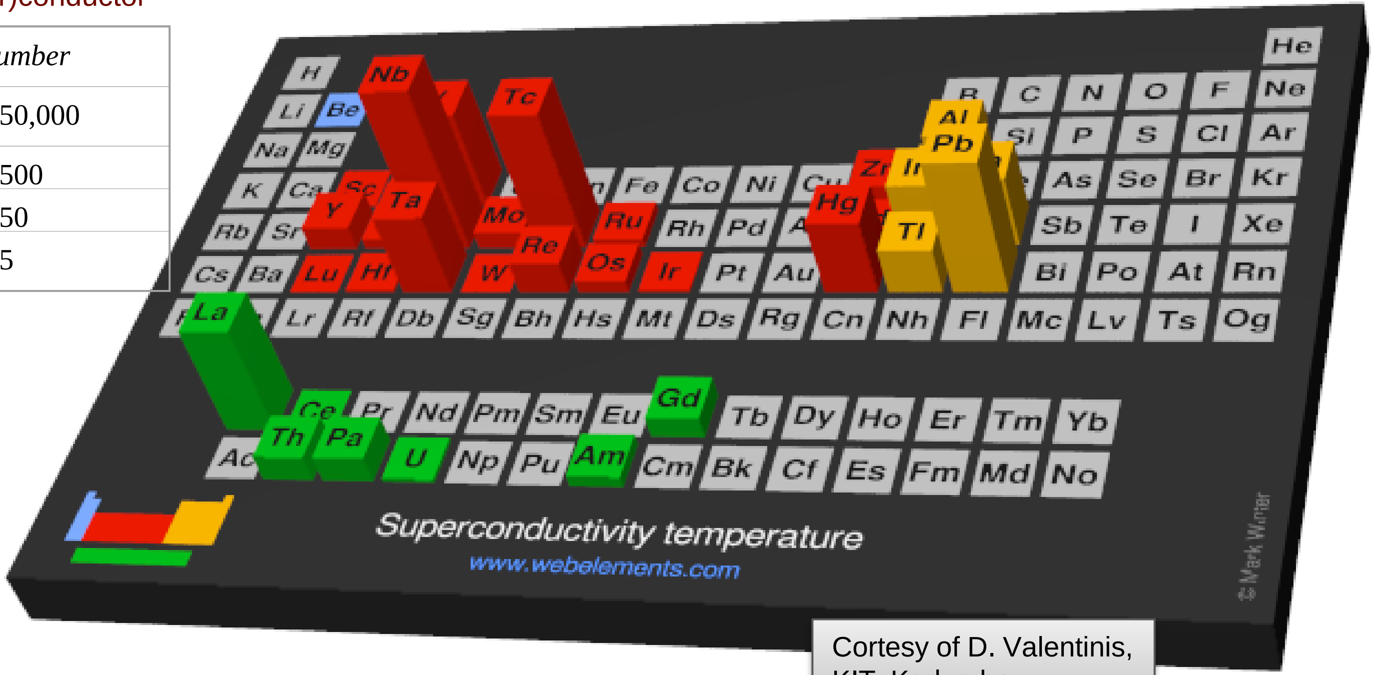


Critical temperatures on the Mendeleev table
Many elements are SC!

From superconductivity to real (super)conductor

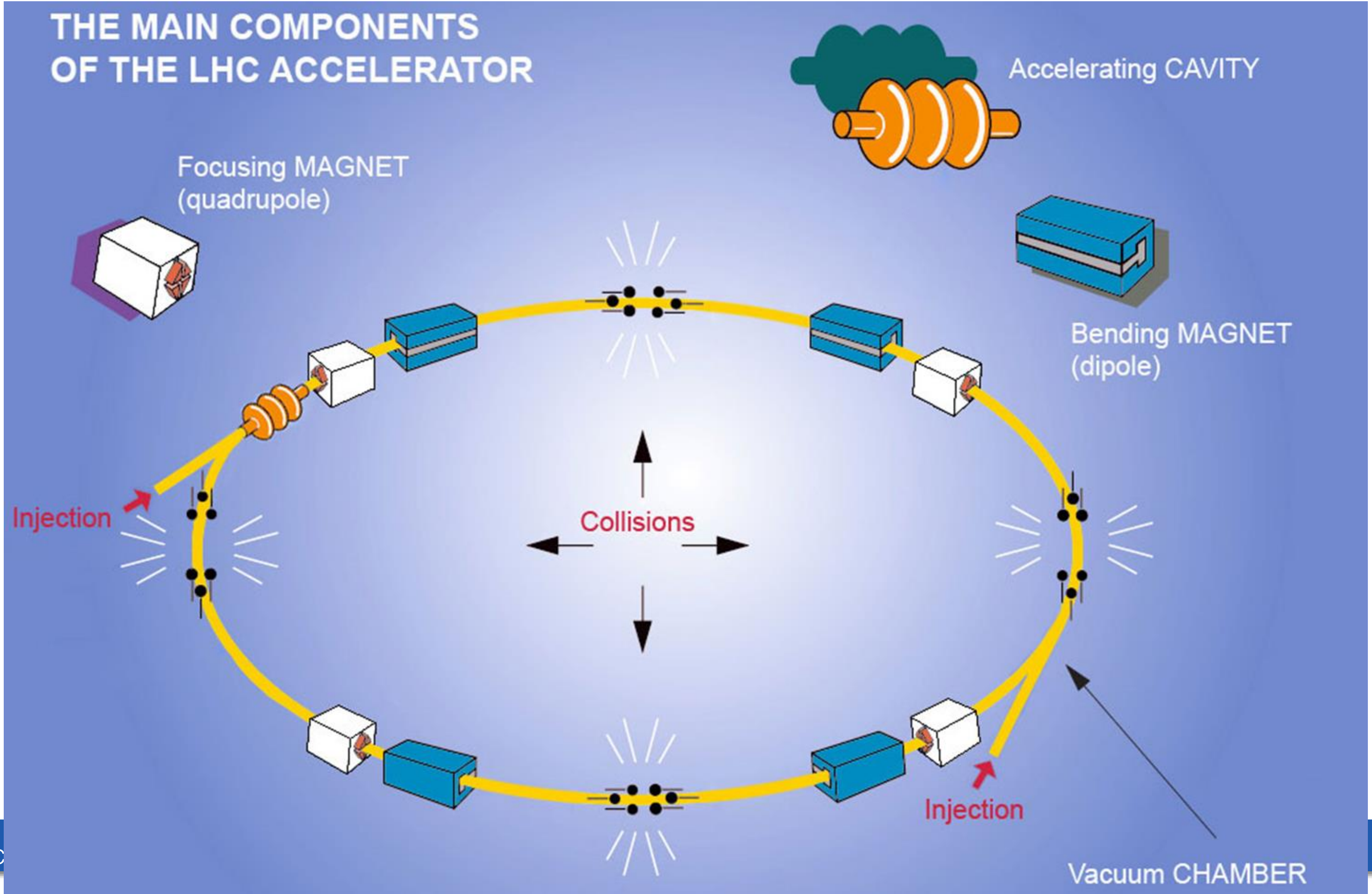
Criterion	*Number*
Superconducting materials	~ 50,000
$T_c \cong 10$ K .and. $B_{c2} \cong 10$ T	~ 500
$J_c \cong 1000 A/mm^2$ @ $B > 5$ T	~ 50
Magnet-grade superconductor	~ 5

Table re-worked from Y. Iwasa (MIT)

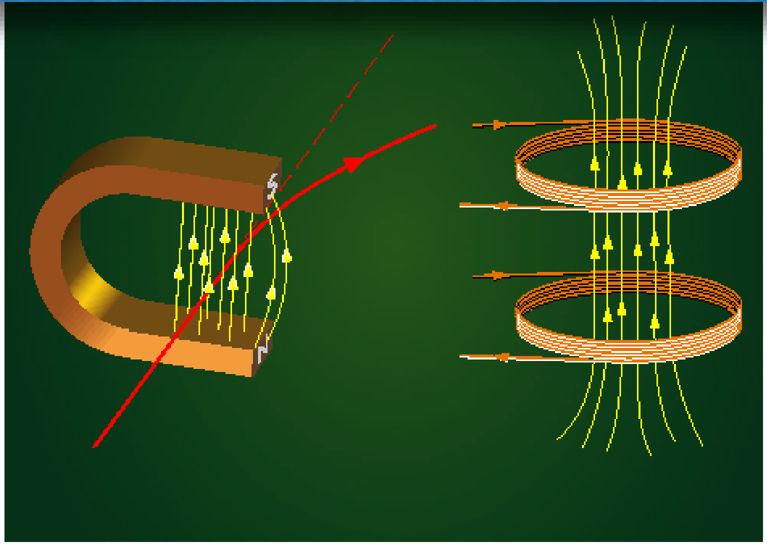


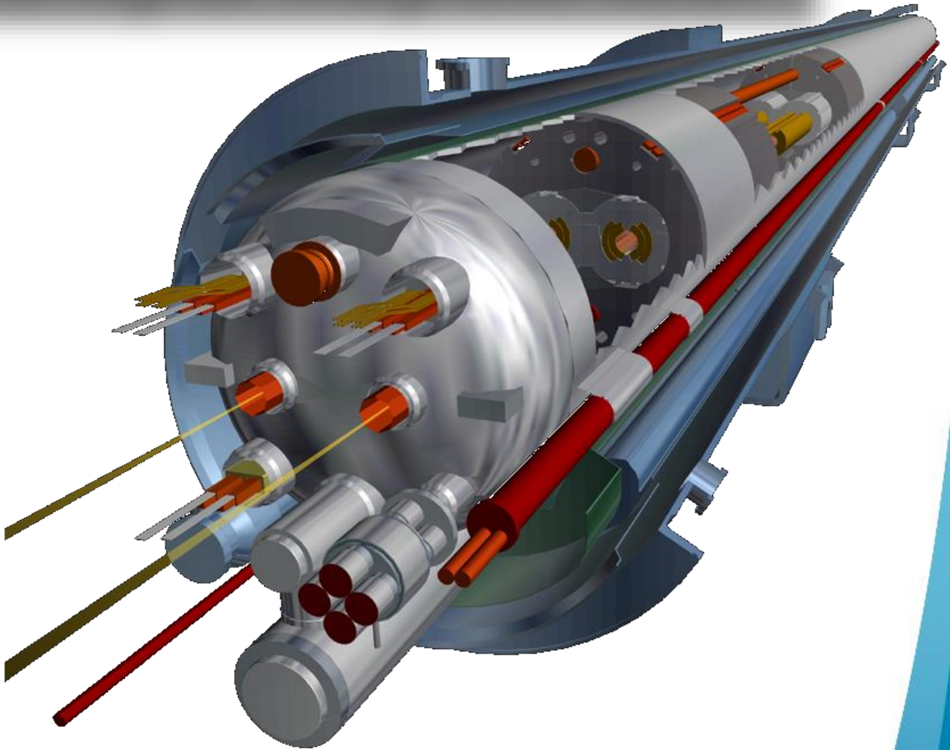
Cortesy of D. Valentinis, KIT, Karlsruhe

HiLumi HL-LHC PROJECT


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

Why looking for higher and higher magnetic field?



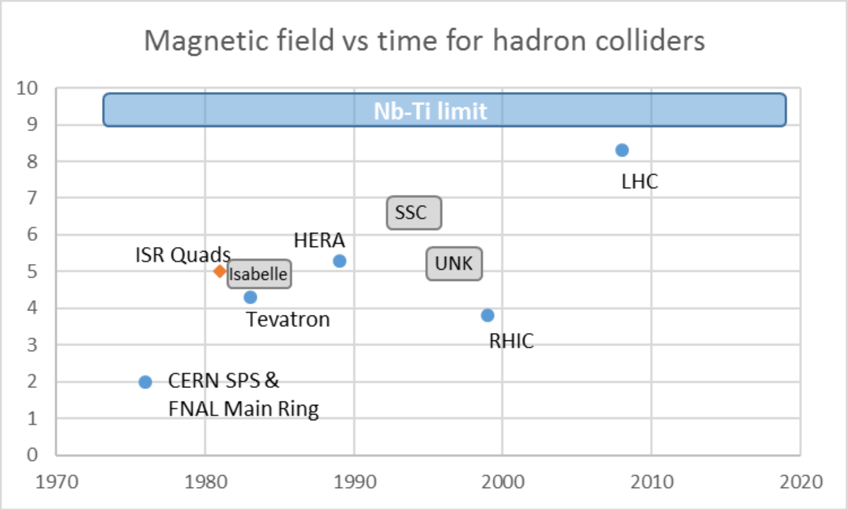


- <u>Circular Accelerators</u>

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

Hadron Colliders are ruled by:
$E_{beam} = 0.3\ R * B$ (TeV; km; T)

< 10 y to double field: 2 T MR→ 4 T Tevatron
> 20 y to double again in SC: → 8 T of LHC

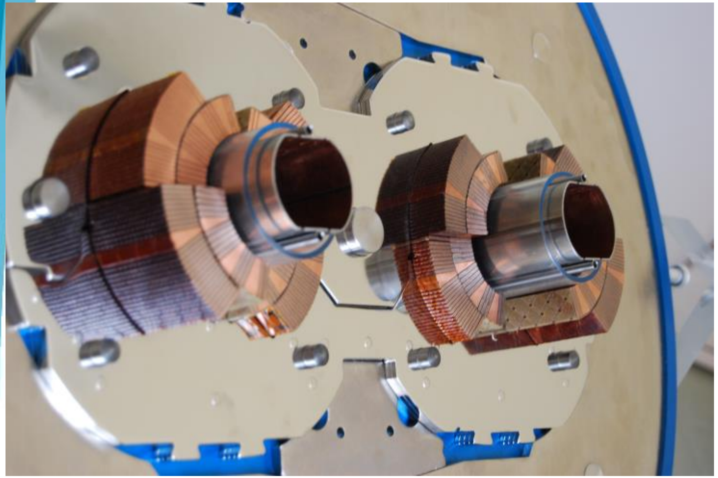


Consideration on LHC

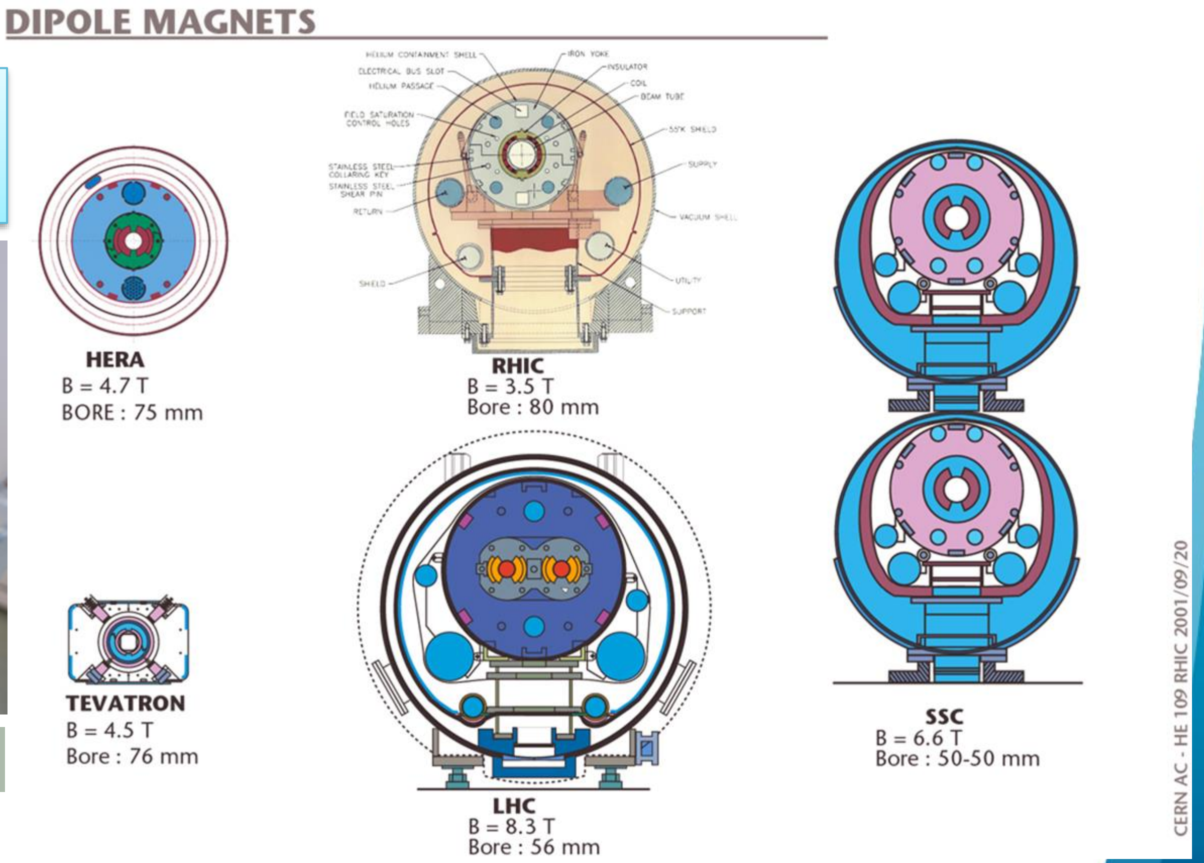
- Designed for 8.33 T (14 TeV c.o.m.) with margin to go to 9 T (15 TeV c.o.m)
- Today operating at **7.75 T** (13 TeV)
- **8.33 T in 2021 possibly**
- **9 T may be in 2026/2030 with HiLumi but very difficult (trade off with loss of lumi)**

Hadron Collider Magnets: Hall of fame

LHC has been the summit of > 40 y developements with SC Nb-Ti magnets. Magnet design soon converged to Cosϑ



LHC Dipole Cross section: Cosϑ layout

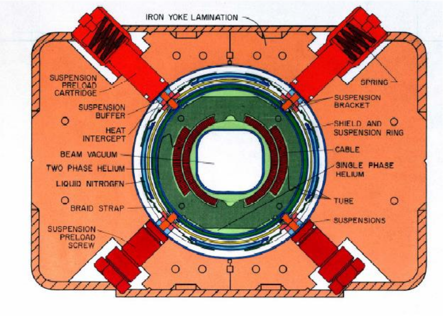


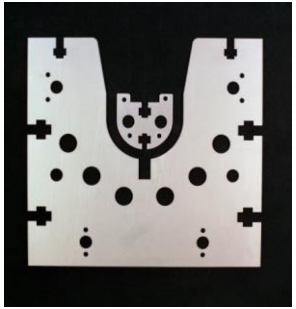
Tevatron@Fermilab: the pioneer all-in-house
The SC development was instrumental for MRI

LAB DIRECTOR WINDING A 1 FOOT MODEL MAGNET

THIS ONE DIDN'T WORK! BUT WE LEARNED!

Courtesy of
Al Tollenstrup





All done in the lab: R&D, tooling, prototyping, series construction and testing

The 25 y LHC construction time line

9 T - 1 m single bore

10 T-1m Nb3Sn dipole

9 T -10 m long protoype

9 T-15 m final protoype

Last LHC dipole

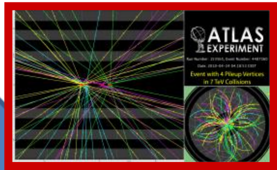
1985 1987 1990 1994 2000 2006 2010

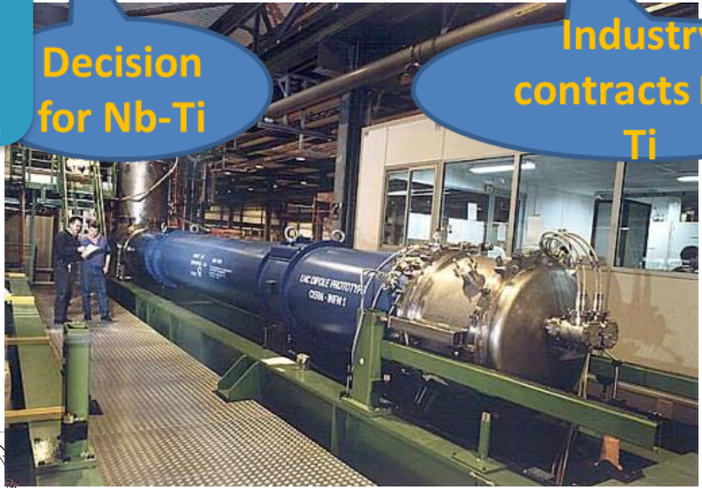
Striking: only 4 y to make a design «near to final». The conductor was almost there! (thanks to SSC)

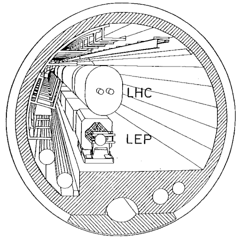
Decision for Nb-Ti

Industry contracts Nb-Ti

LHC start-up

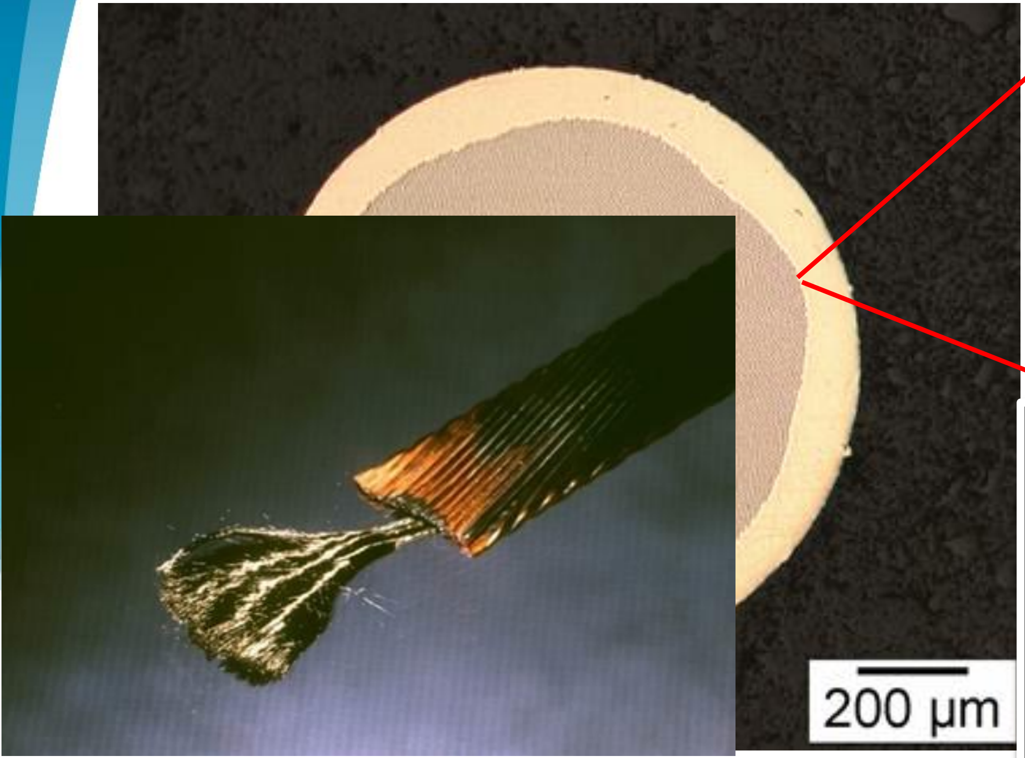


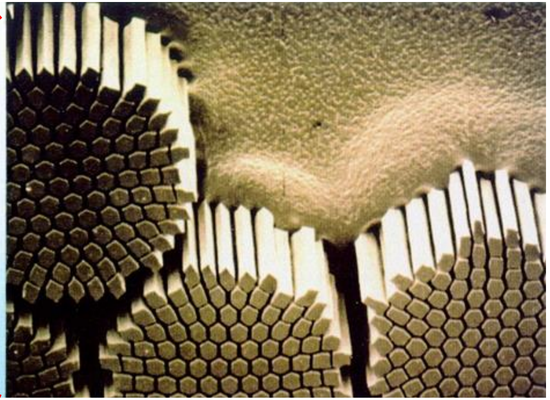




LARGE HADRON COLLIDER IN THE LEP TUNNEL

The key factor: superconductor (but not the only factor!)

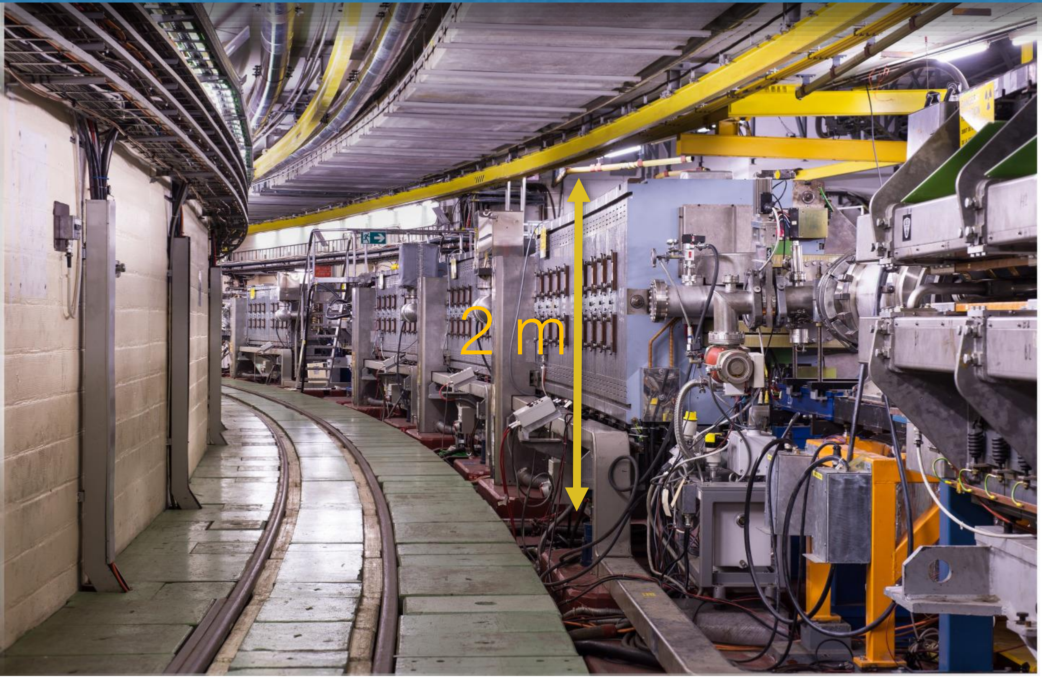




Developing SC is the key in SC accelerators. LHC is indebted to SSC

The perfection of LHC superconductor is such that we basically «forget» the SC effects and is the base of the repeatibility and optimal performance of the collider

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!

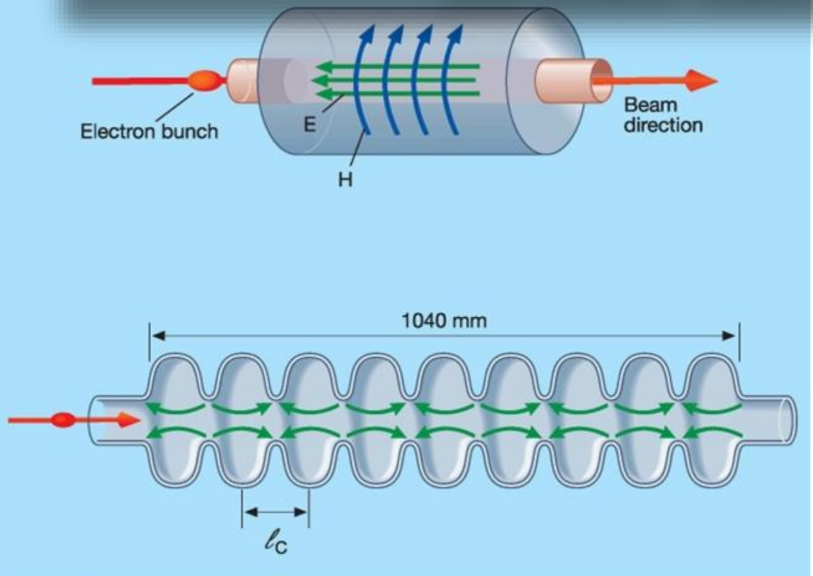
Superconducting LHC

- 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 for the whole CERN complex

Normalconducting LHC

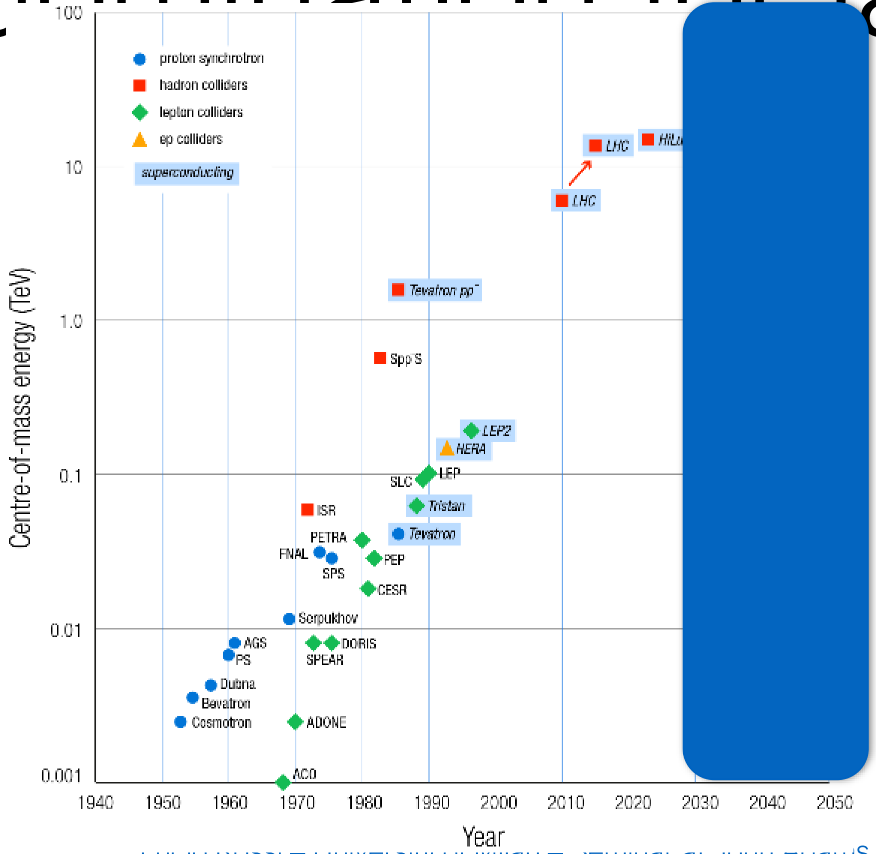
- Tunnel 120 km
- Field : 1.8 T
- Dissipated power at collision: ~ 2,200 MW
- Average power (0.4 coefficient): 900 MW only for accelerator

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



Accelerators progress: SC domination for large

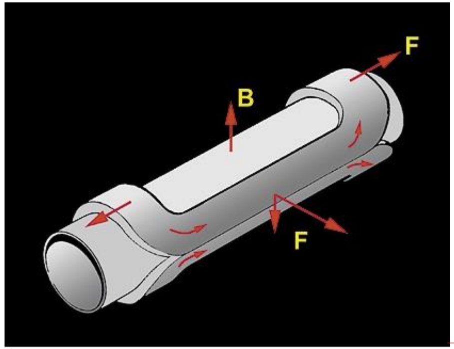
(table of 2013)



Accelerator Magnets Basic Design
e.m.Forces support - Protection following a quench

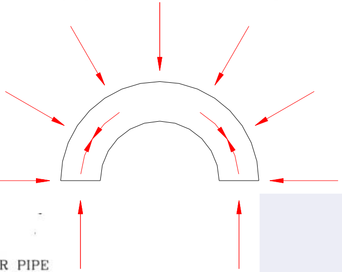
$J_{overall} \approx 500$ A/mm^2 ! e.m. forces are not kept by conductors but tend to torn apart the winding.

Principle

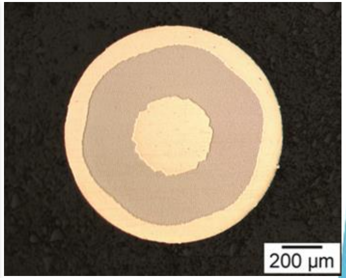


e.m. forces

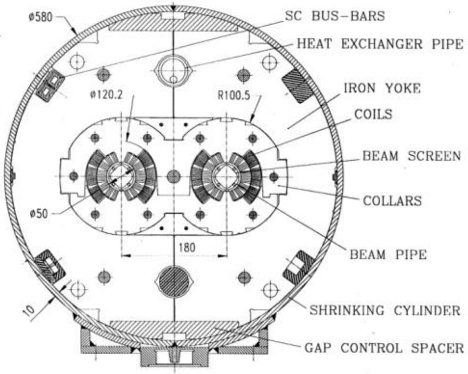
NOT SELF-SUPPORTING

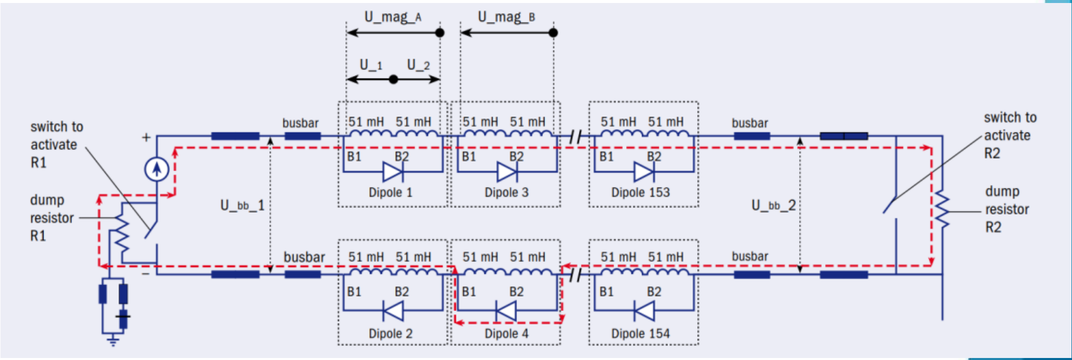


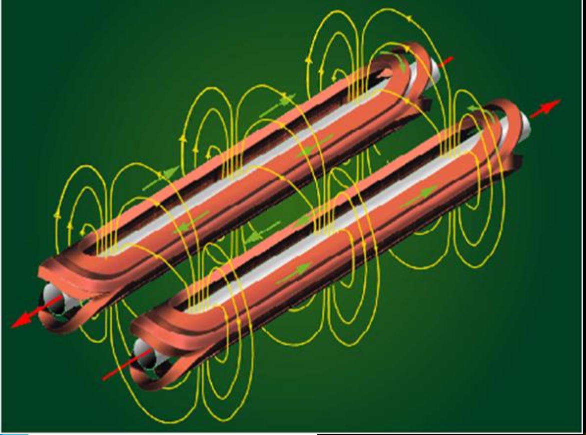
Protection: $P = \rho J^2$
$J = 1000$ A/mm^2 in Cu
$\Rightarrow P = 100$ W/cm^3 @ 4 K
$= 10$ kW/cm^3 @ 300 K
100 ms to cut down current in the LHC magnets (10 ms in HiLumiLHC)

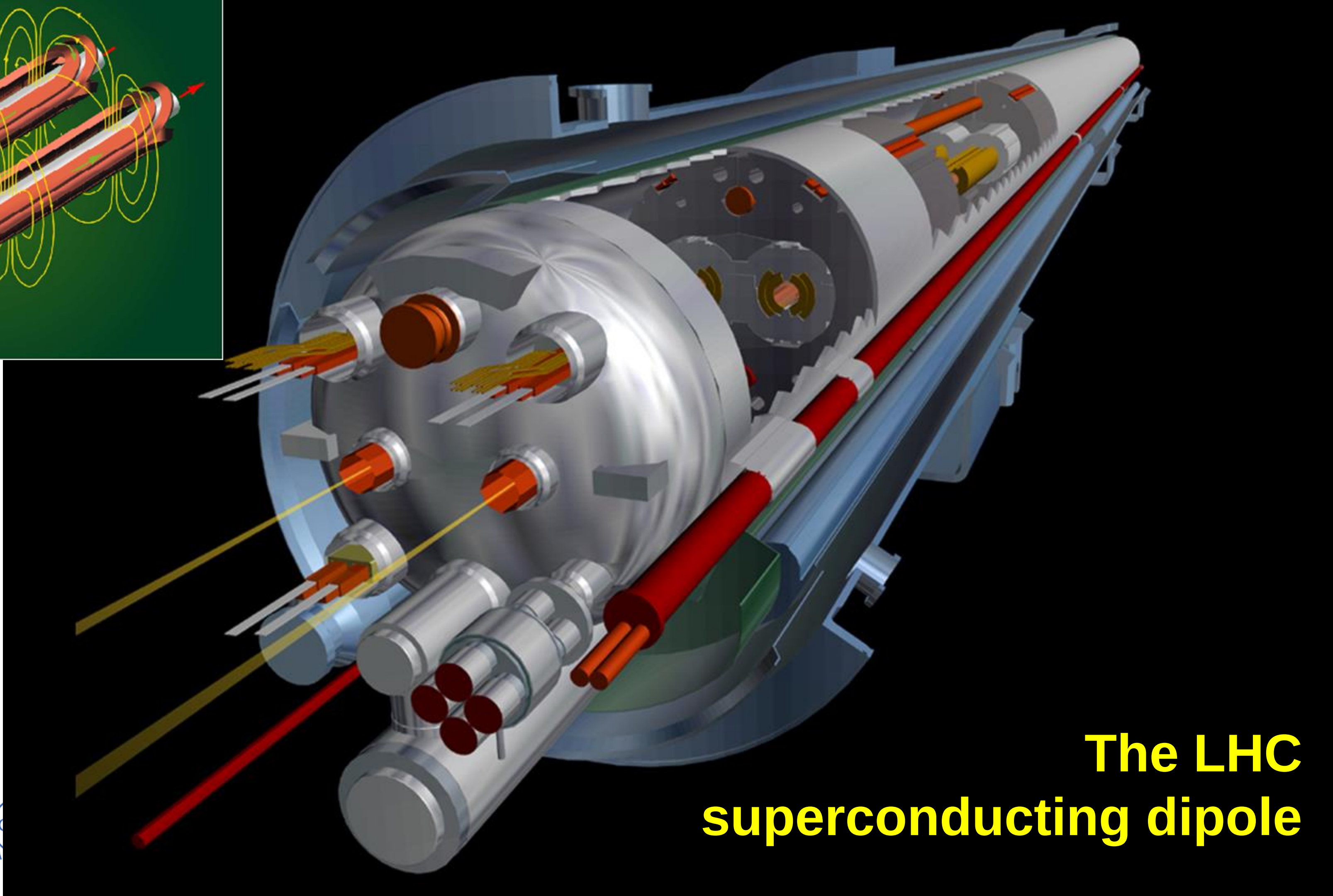


Reality



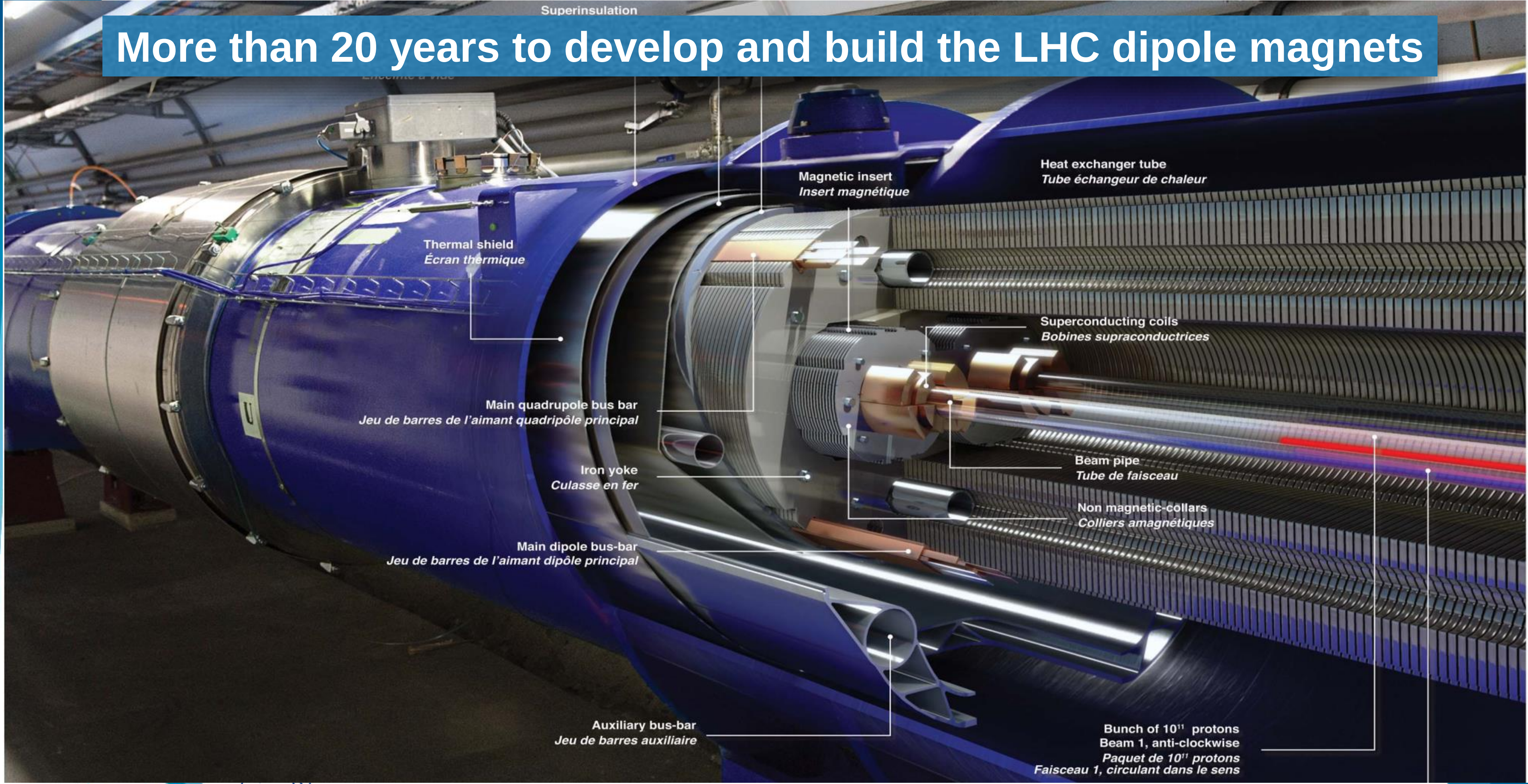






The LHC
superconducting dipole

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



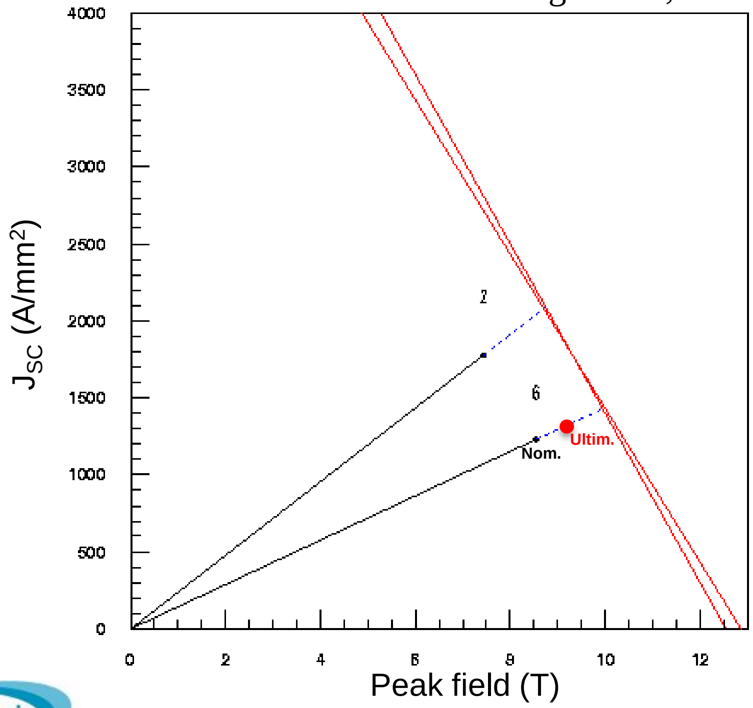
LHC, the largest instrument

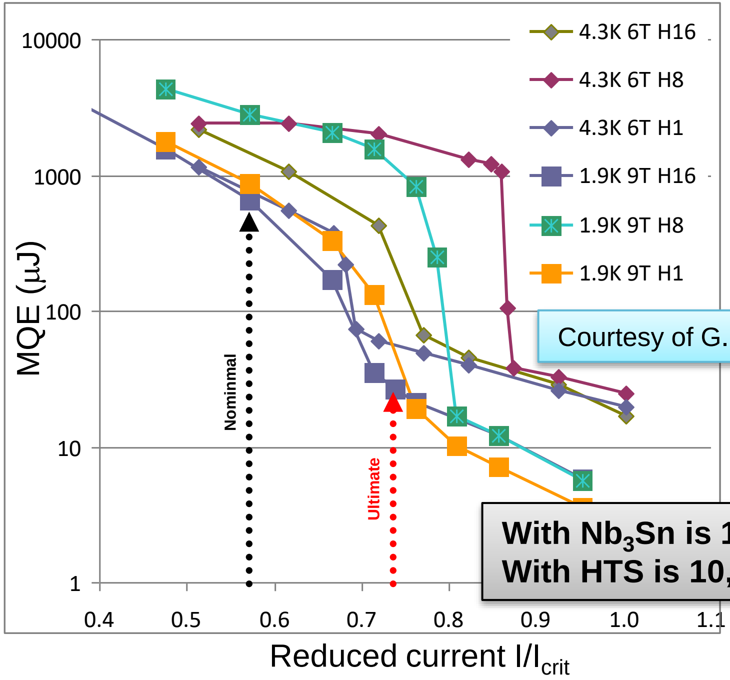
- 27 km, p-p 7+7 TeV (6.5+6.5 TeV at present)
- 1232 x 15 m Twin Dipoles 8.3 T @11.85 kA
- Nearly 500 large Quads (3-6 m), 7600 HO and correctors
- About 9 GJ stored energy (+ 4 GJ in ATLAS+CMS magnets)
- **HEII cooling, 1.9 K, 3 km long circuits, 130 tons He inventory.**
- **8 x 18 kW@4.5K of cooling power.**
- 16 SCRF cavities, Nb coated on Cu, in 4 cryomodules, 400 MHz

LHC inner triplet quad of the low-β insertions

Huge forces, and little margin: also stability at LHC is a problem! TRAINING!

If there is no stabiliser, only NbTi, we see that $l \cong 1\ \mu m \Rightarrow \Delta H \sim 1$ nJ only !!
If each strand behaved as single wire, $\Delta H \sim 1\text{-}10\ \mu J$;



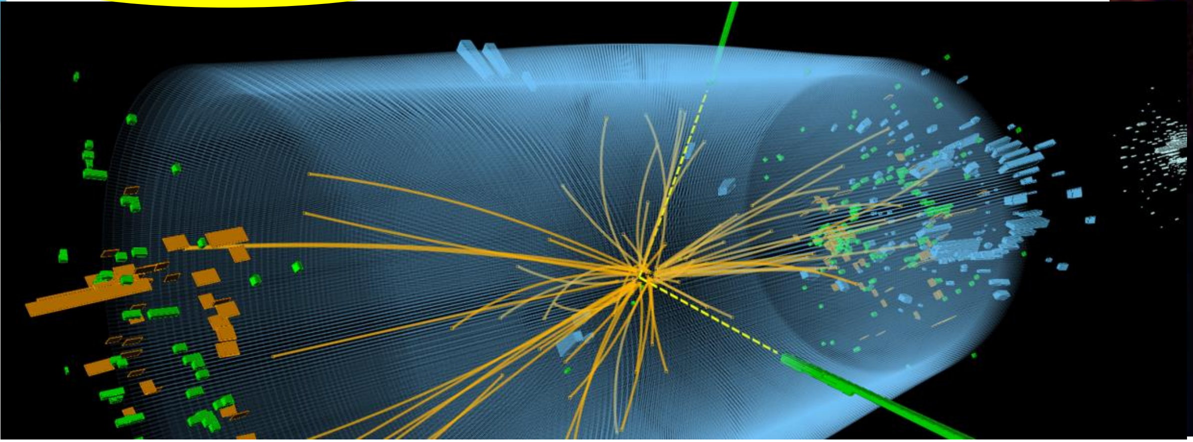


Courtesy of G. Willering, CERN

With Nb_3Sn is 10 times larger
With HTS is 10,000 larger

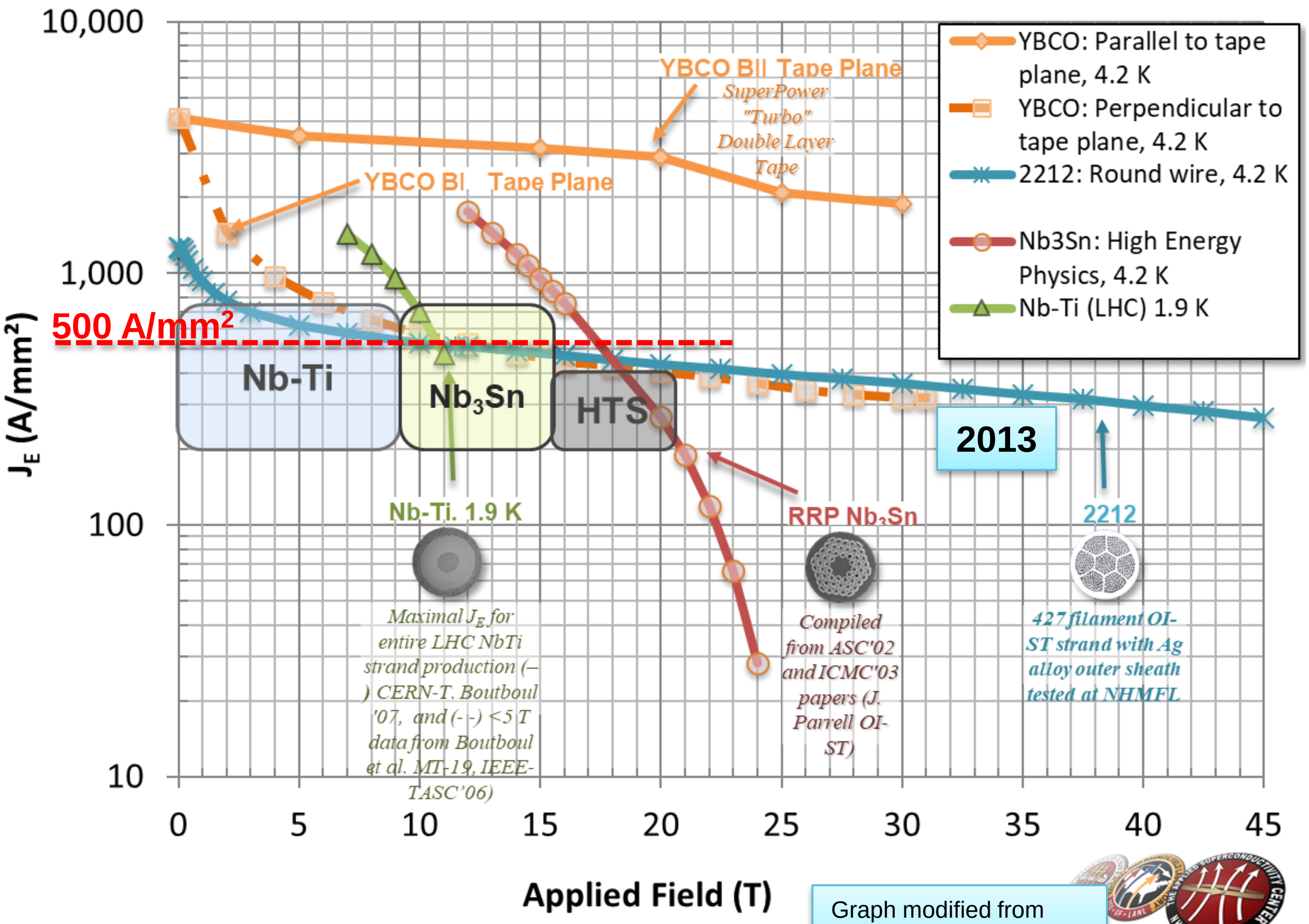


…for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider.



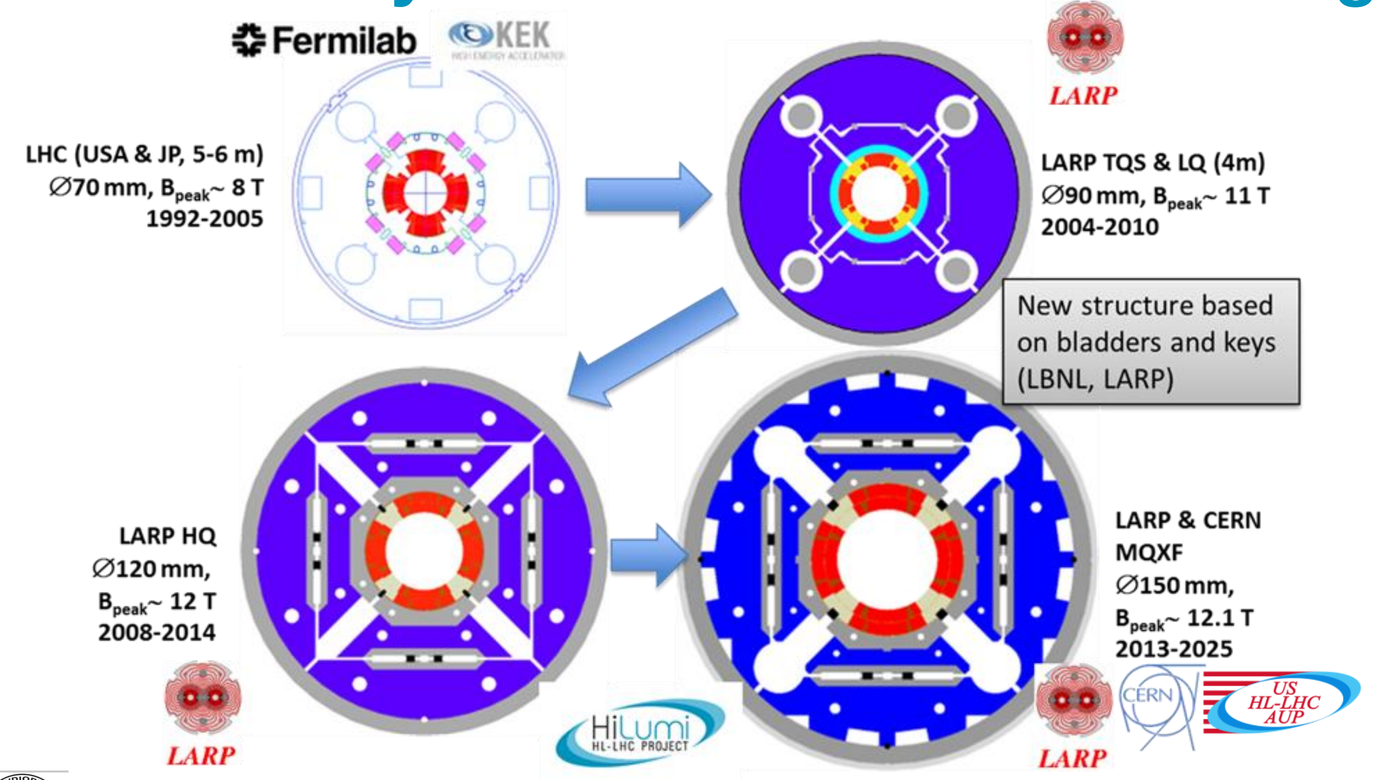

New, advanced technology for the SC magnets beyond LHC!

We need materials with $J_E > 500$ A/mm²



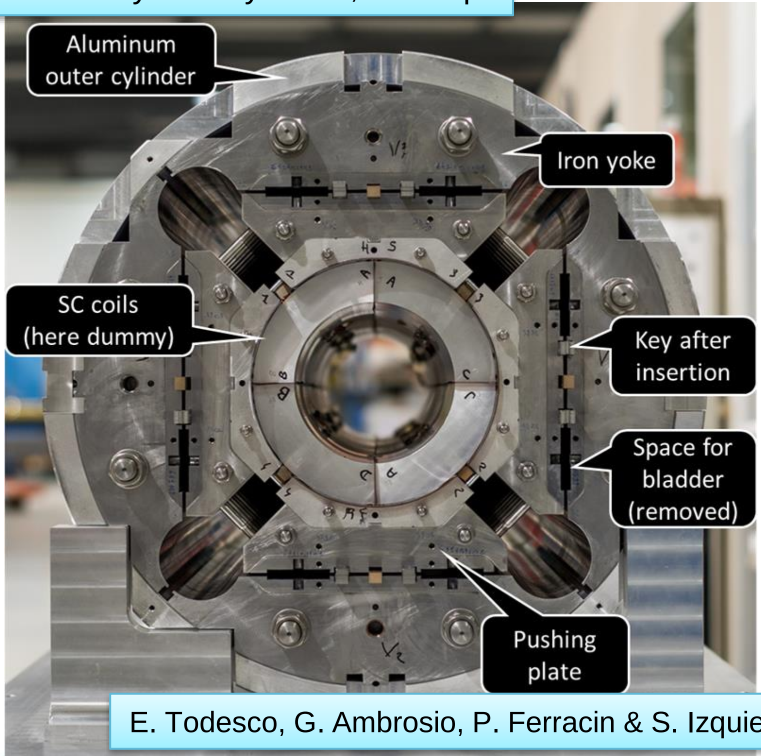
Graph modified from P. Lee, NHMFL, Florida

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

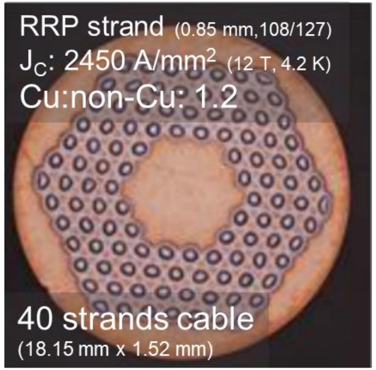


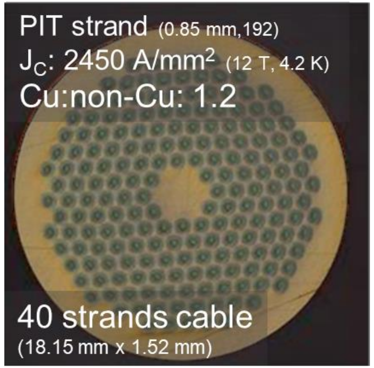
New structure to accomodate brittleness of the Nb_3Sn superconductor

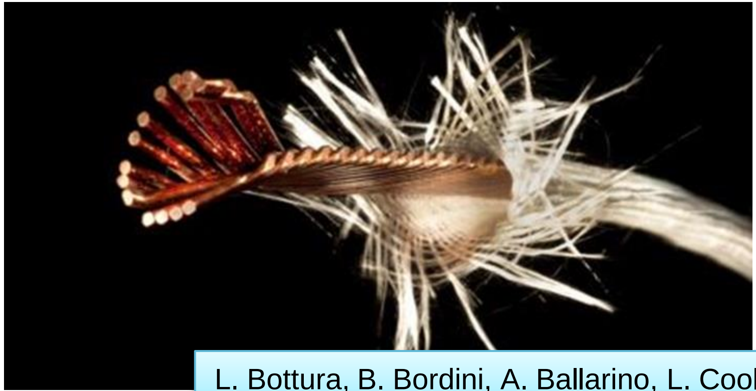
Key&Bladder system by LBNL, S. Caspi



E. Todesco, G. Ambrosio, P. Ferracin & S. Izquierdo





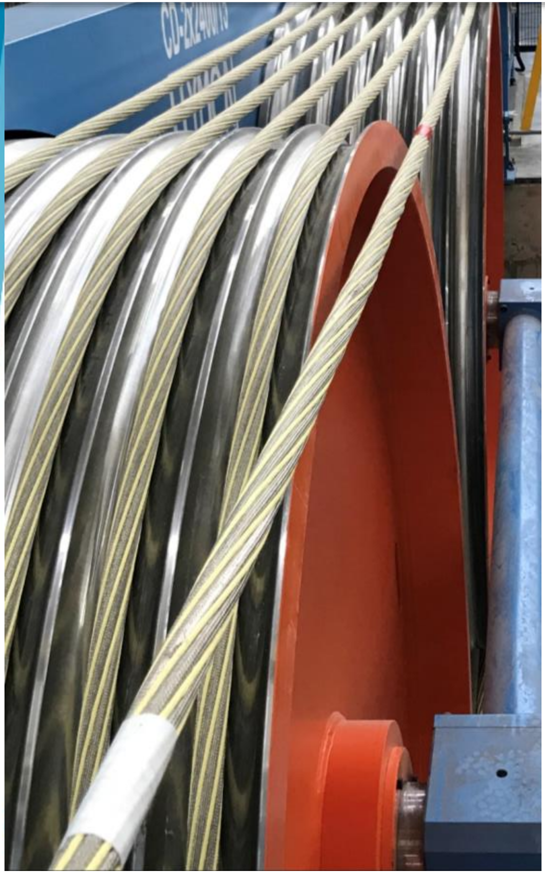


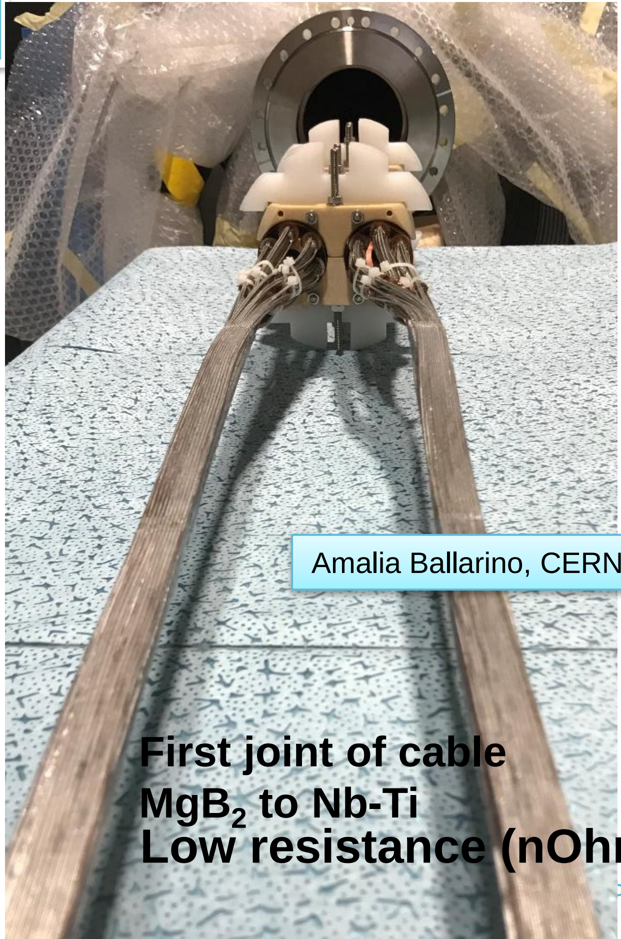
L. Bottura, B. Bordini, A. Ballarino, L. Cooley, A. Gosh

HiLumi: 15 years of Nb_3Sn R&D to go beyond the limitation of LHC Nb-Ti

SC Links inside flexible cryostat: first 60 m long prototype 20 kA cable tested at CERN

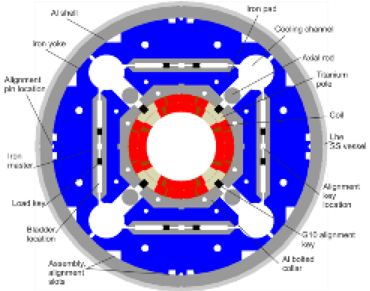
First long length of 20 kA MgB_2 cable (IT Quad circuit)



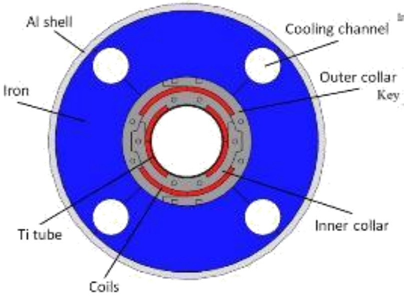


Amalia Ballarino, CERN

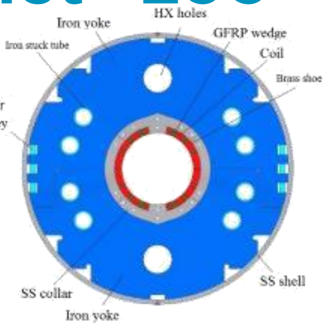
HL-LHC magnet “zoo”



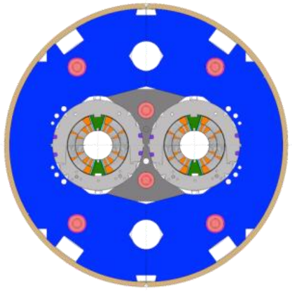
Triplet QXF (**US-AUP** and CERN)



Orbit corrector (**CIEMAT**)

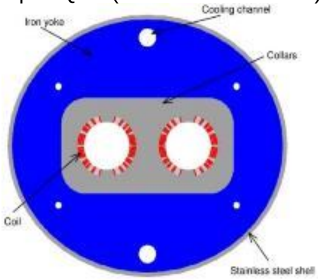


Separation dipole D1 (**KEK**)

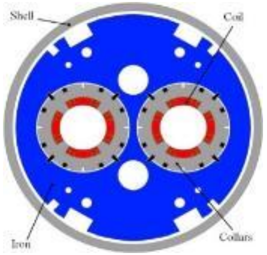


11 T dipole (CERN)

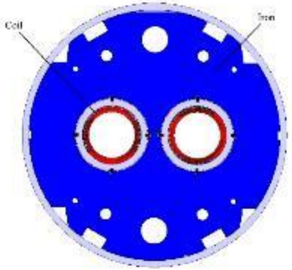
Courtesy of
E. Todesco,
HiLumi LHC
WP3 Leader



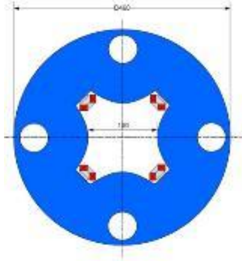
Recombination dipole D2 (**INFN**)



Q4 (**CEA**)

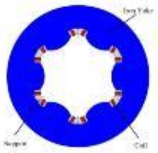


D2/Q4 orbit corrector (CERN)

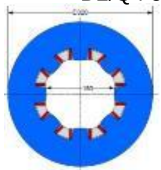


Skew quadrupole (**INFN**)

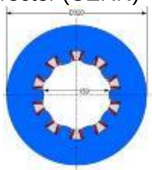
Approximately 150 single magnets and 50 cold masses for HL-LHC



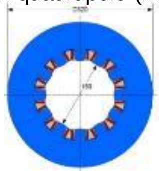
Sextupole (INFN)



Octupole (INFN)



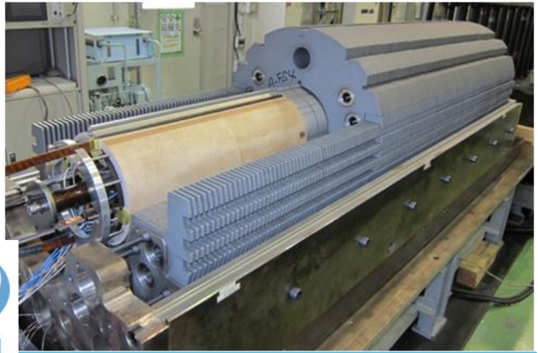
Decapole (INFN)



Dodecapole (INFN)

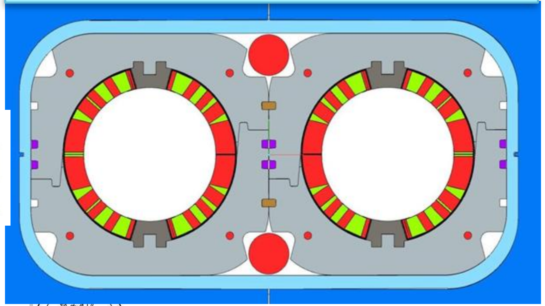
Many magnets designed and manufactured via collaboration

HL-LHC WP3
E. Todesco et al.

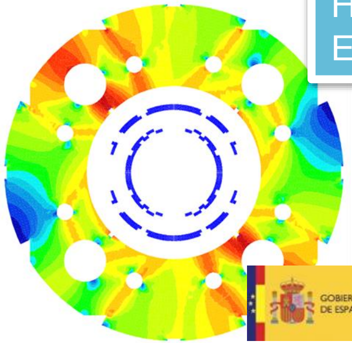


D1 – KEK

D2 – INFN Genova (model & full proto)



Q4 MQYY – CEA Saclay (QUACO)

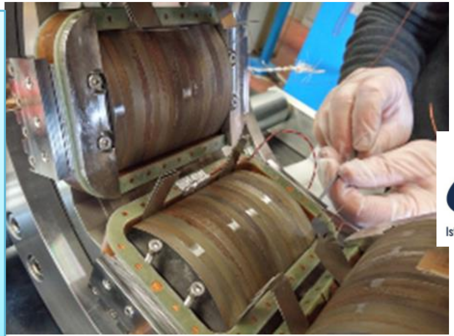


Iron field map when both dipoles are simultaneously powered

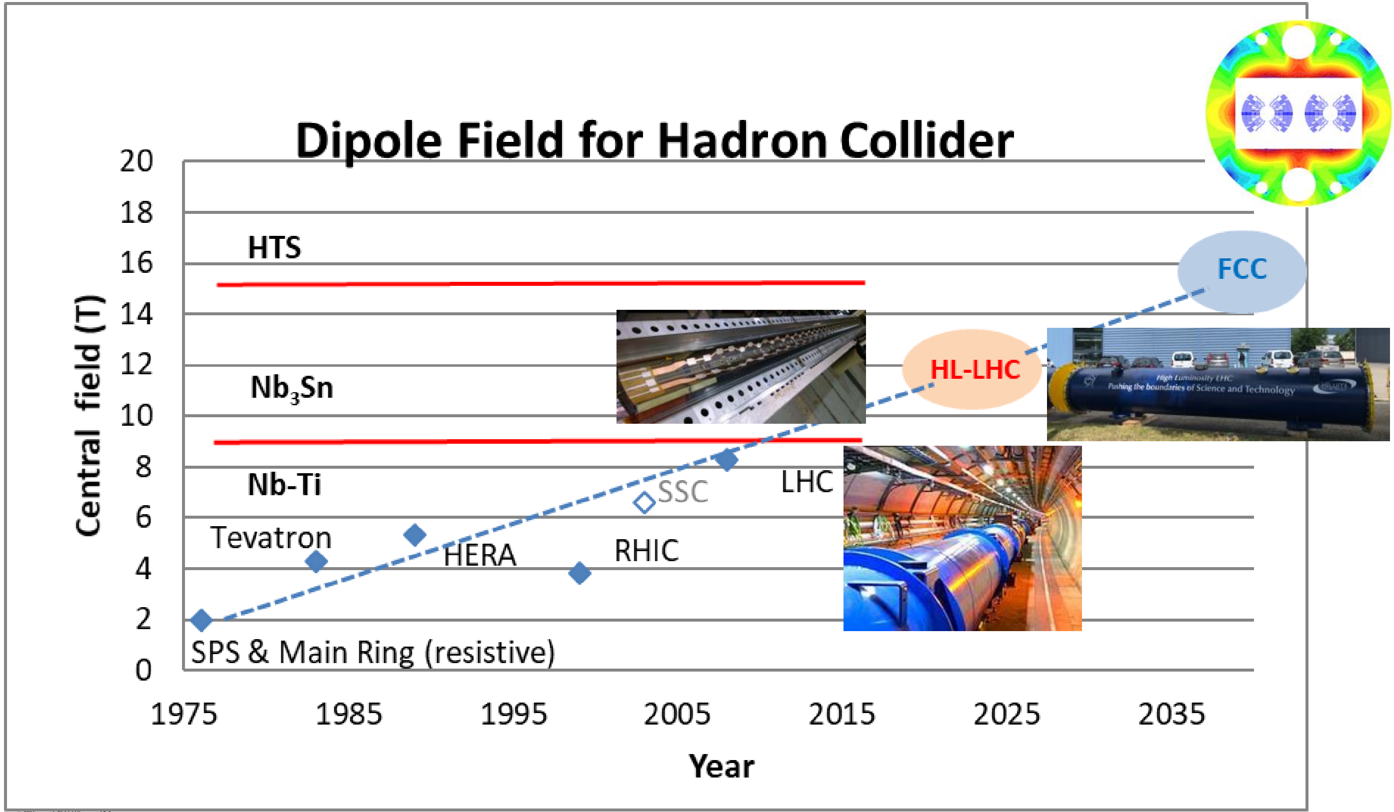
Nested orbit correctors – CIEMAT Madrid

Superferric HO Correctors
INFN-Milano LASA

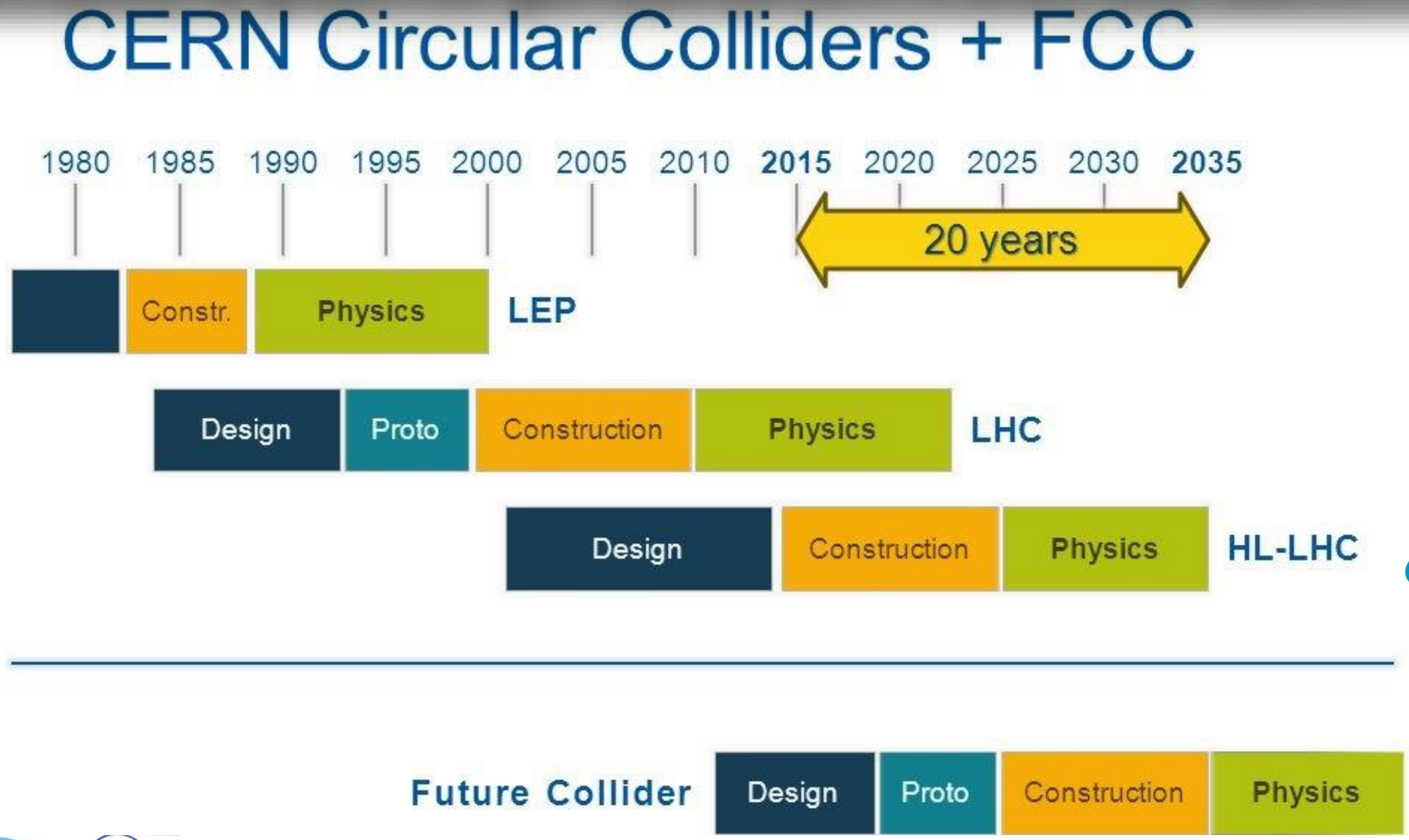
Test @ 2.17 K (1h @134.4 A i.e. 108% nominal current)
No-training
3 «natural» quenches @241 A, i.e. 97% of short sample limit 4.2 K

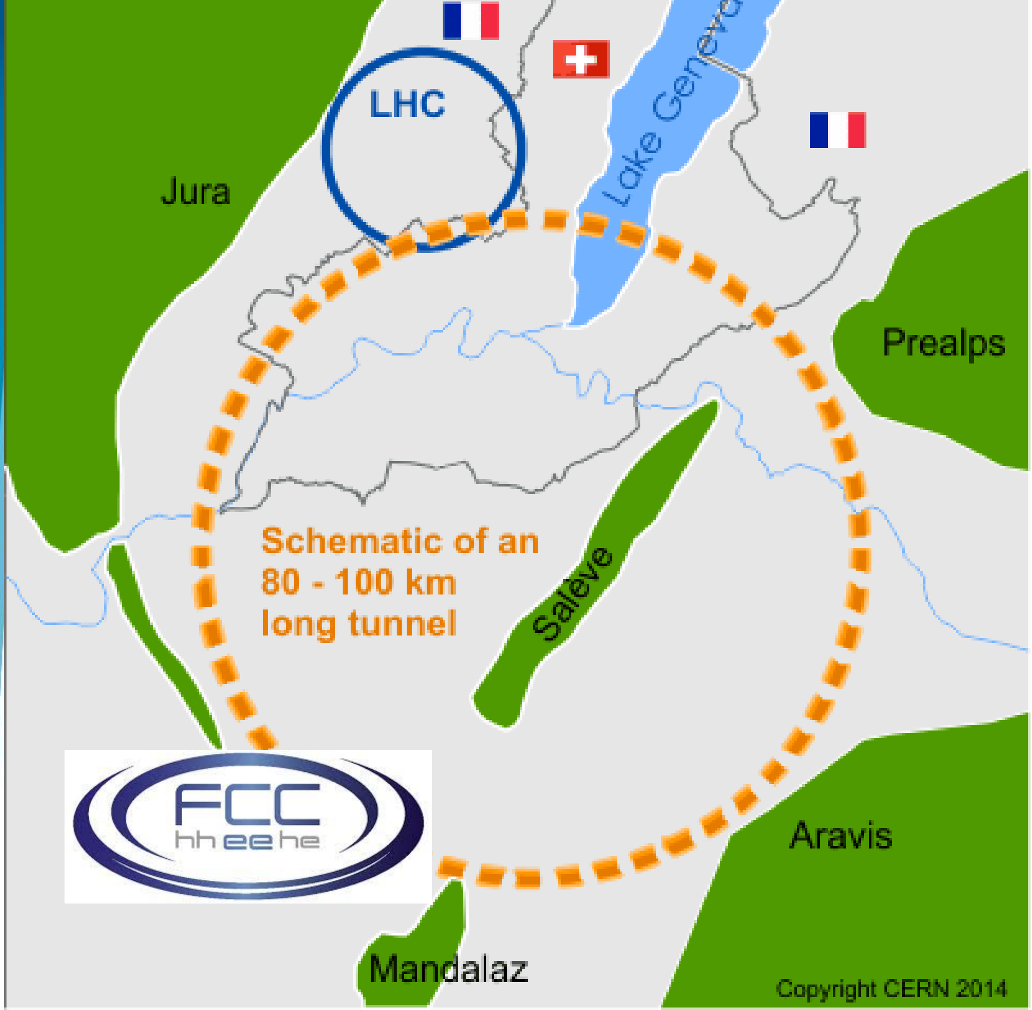


With HiLumi we prepare the technology for a future leap in hadron collider technology…



Do we have a plan to go behond? YES, we do...





Conceptual design report ~ late 2018

Circular collider in new tunnel

80- 100 km circumference

Circular proton-proton collider
100 TeV collision energy (p+p)

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

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

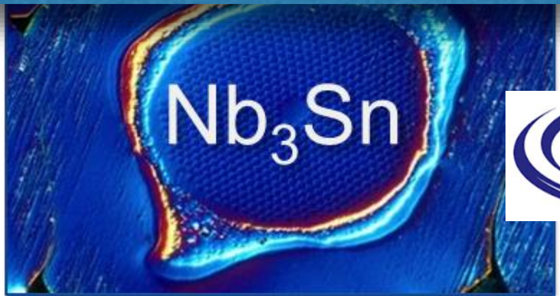
Alternatively:

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

Competition? Yes, guess form whom…

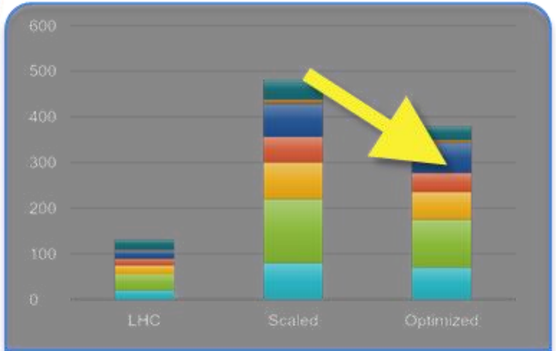
FCC is the natural evolution of HL-LHC with new technology advancement

High-field Magnets



Novel Materials and Processes

Large-scale Cryogenics

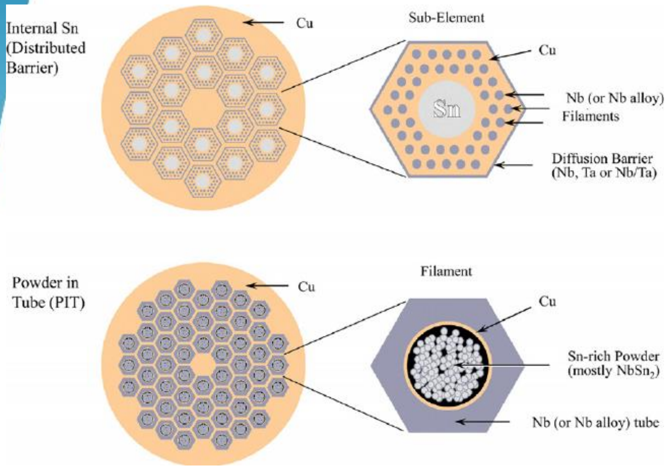


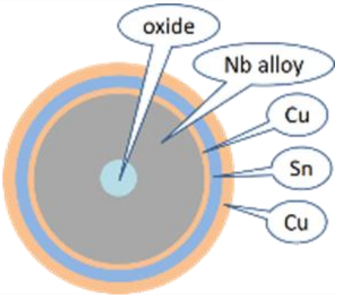
Power Efficiency

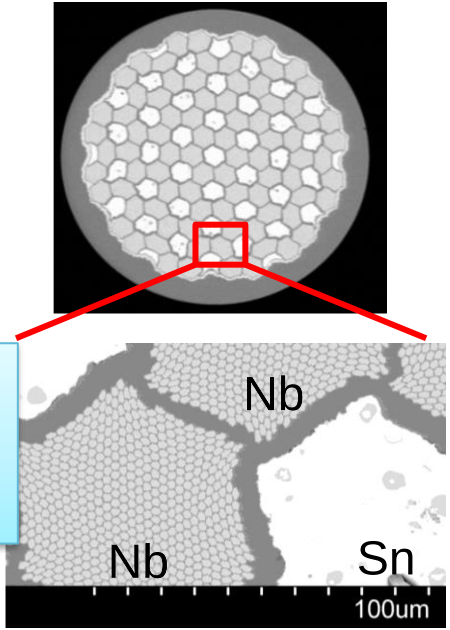
Reliability & Availability

Global Scale Computing

FCC - Nb_3Sn new development

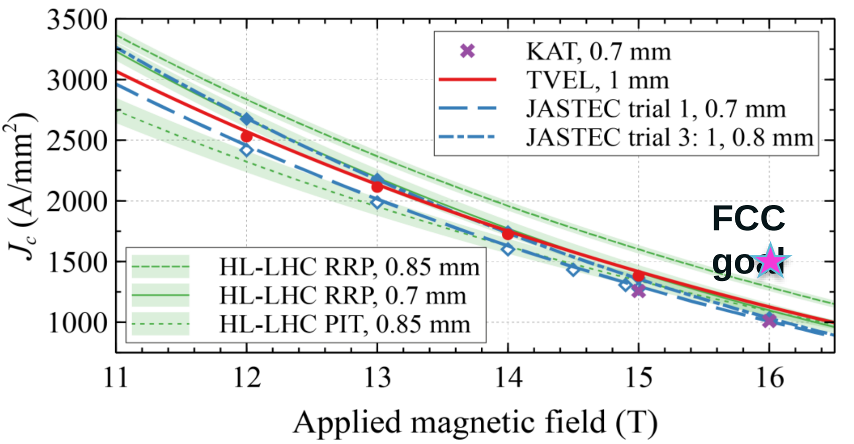




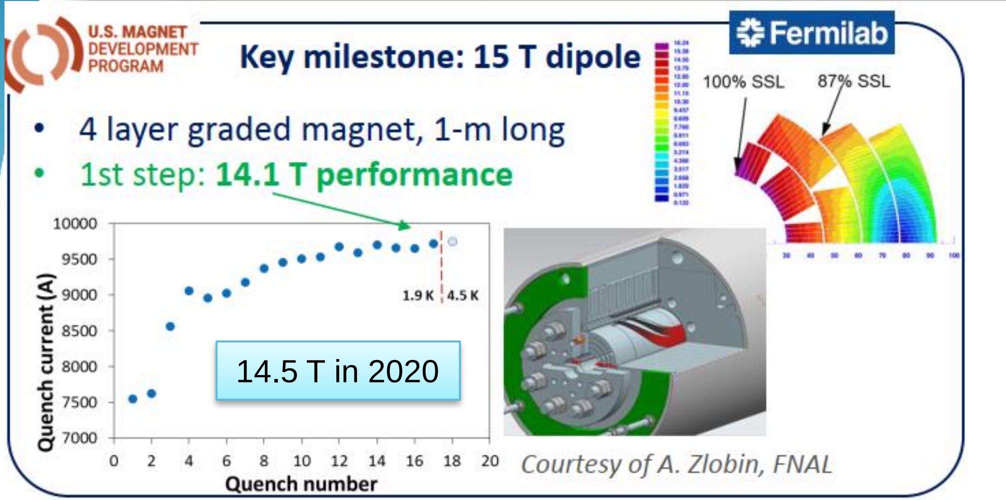


Novelties: doping of oxidized nanoparticle to increase Jc
Addition of elements to increase the heat cäpacity (stability)

Example of a distributed tin layout from JASTEC

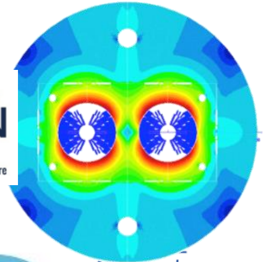


Beyond LHC and HiLumi: the R&D of the FCC!

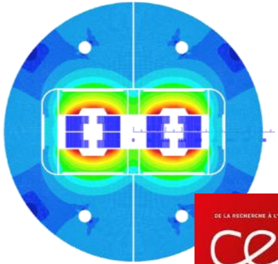


CERN FRESCA2 Dipole record 14.6 T 2018

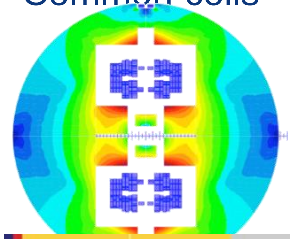
Cos-theta



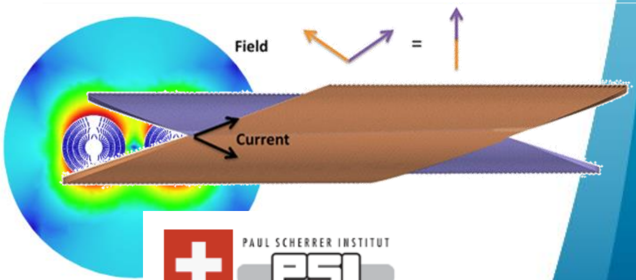
Blocks



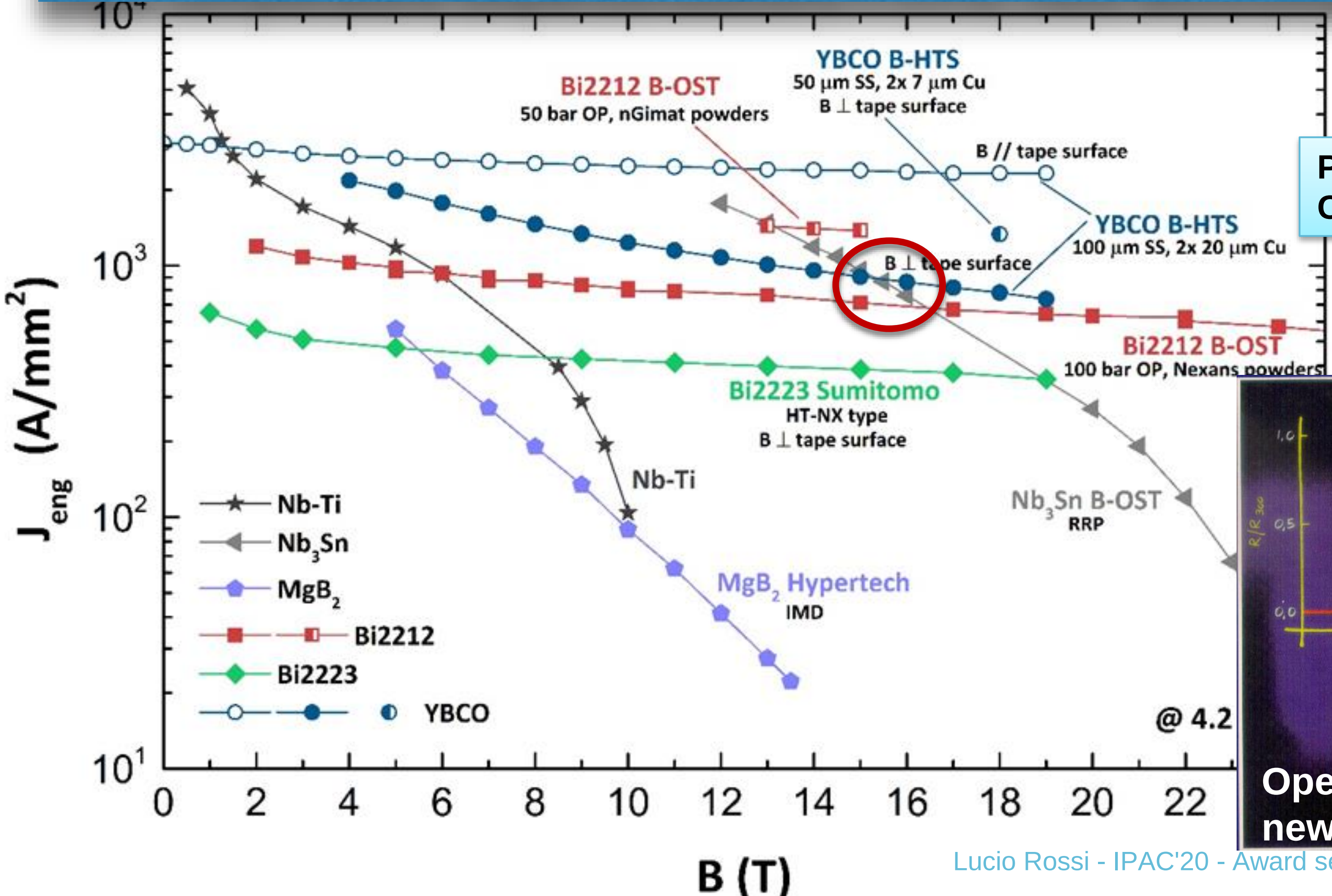
Common coils



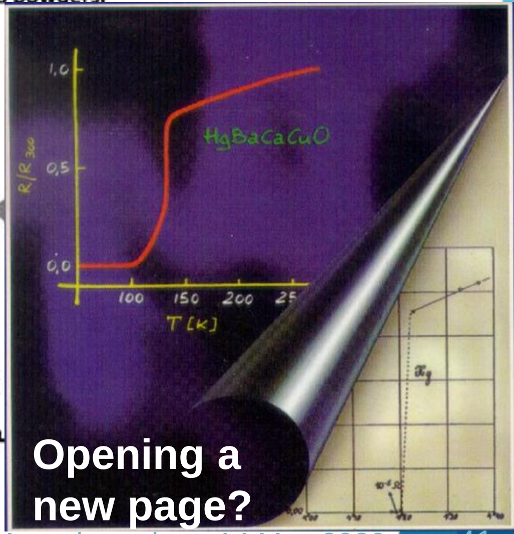
Canted Cos-theta



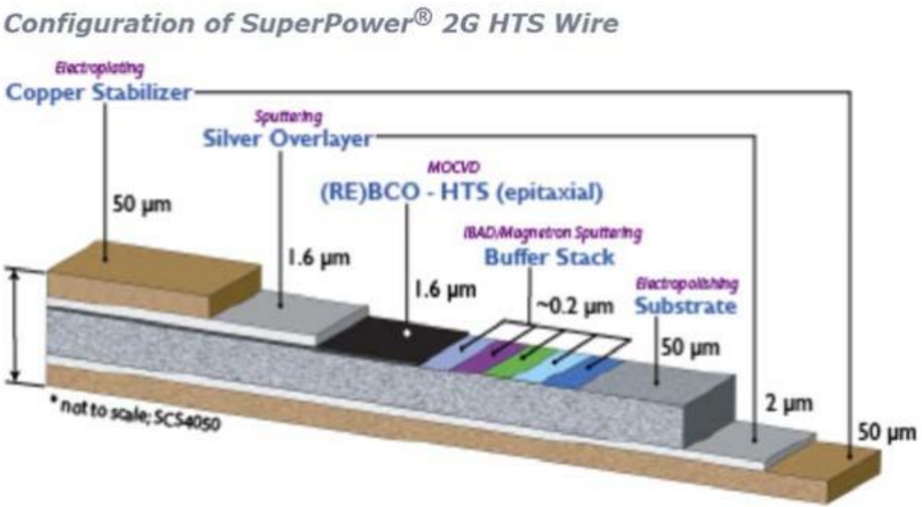
High Temperature Superconductors – HTS: next technology step

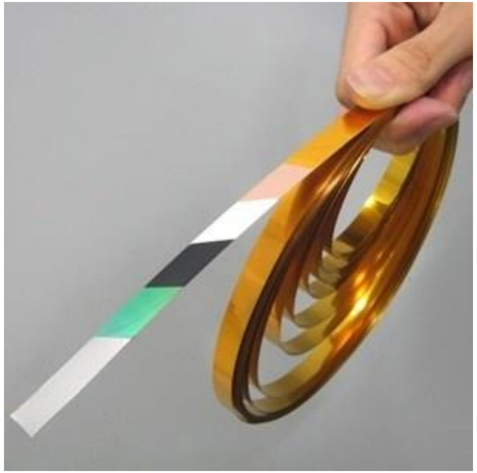


Plot courtesy of C. Senatore, UNIGE

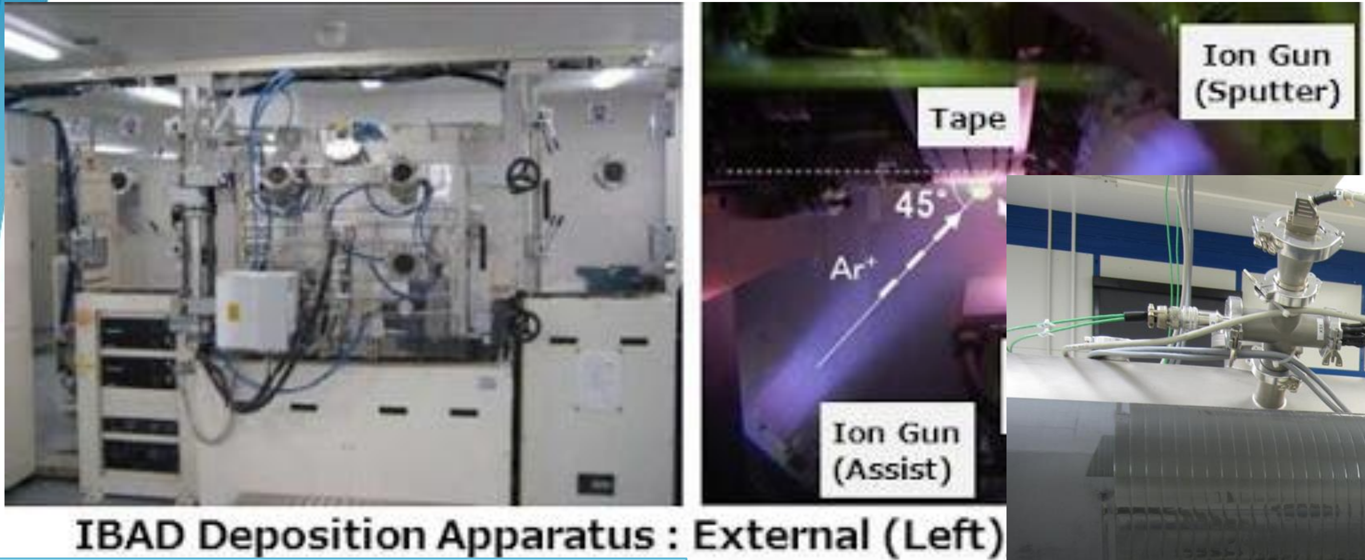


Yttrium based: YBCO (now REBCO)





Mastering complex process: IBAD then PLD

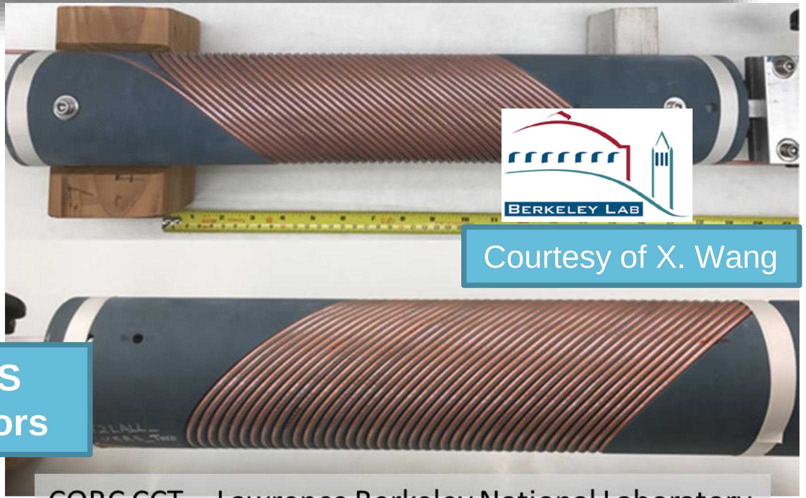


Courtesy of SuperOx (Ru)

Preceeded by electropolishing on Steel tape
Followed by Ag deposition, then Cu plating

PLD 300 at Bruker (CERN-Bruker collaboration)

HTS Renaissance: many new activities from 2013
The dream of 20-25 tesla! (2 x HilumiLHC!)



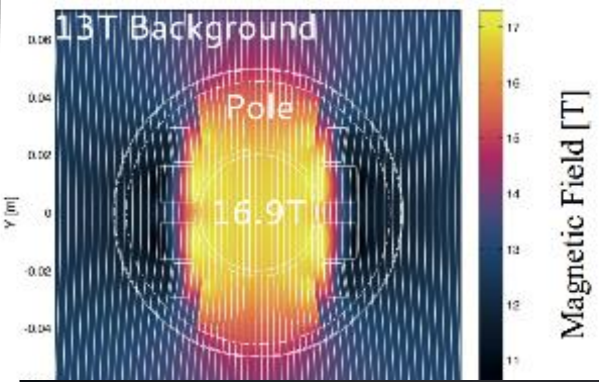
Courtesy of X. Wang

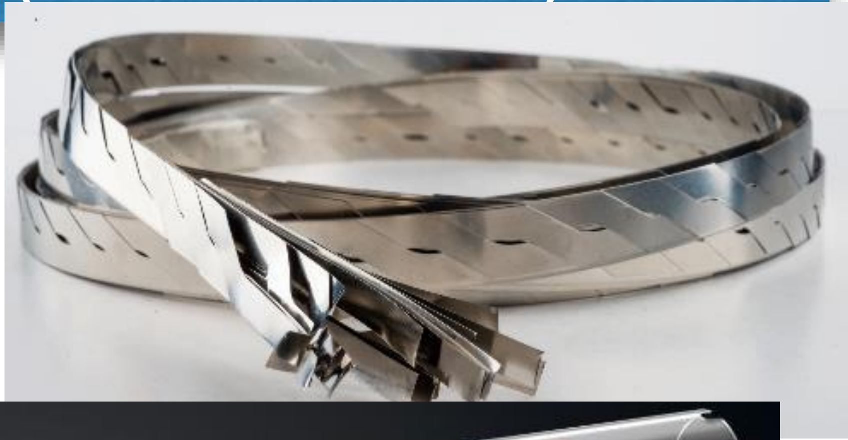
CORC CCT – Lawrence Berkeley National Laboratory

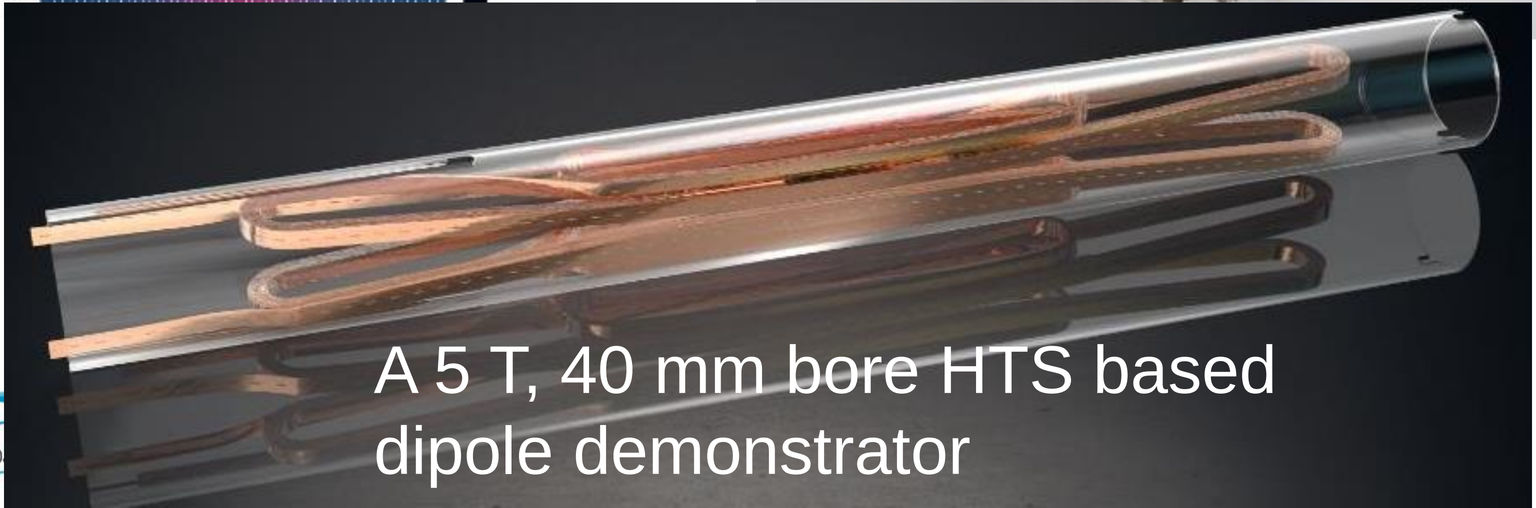
3-7 T, 40-70 mm bore HTS based dipole demonstrators

Roebel cable based dipole magnet – CERN

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

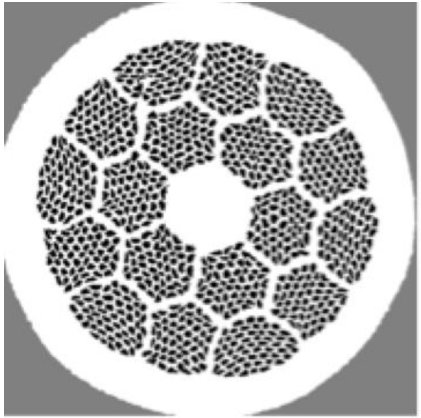


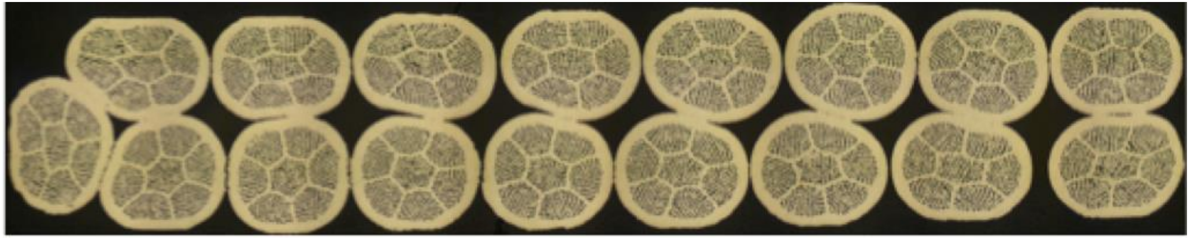


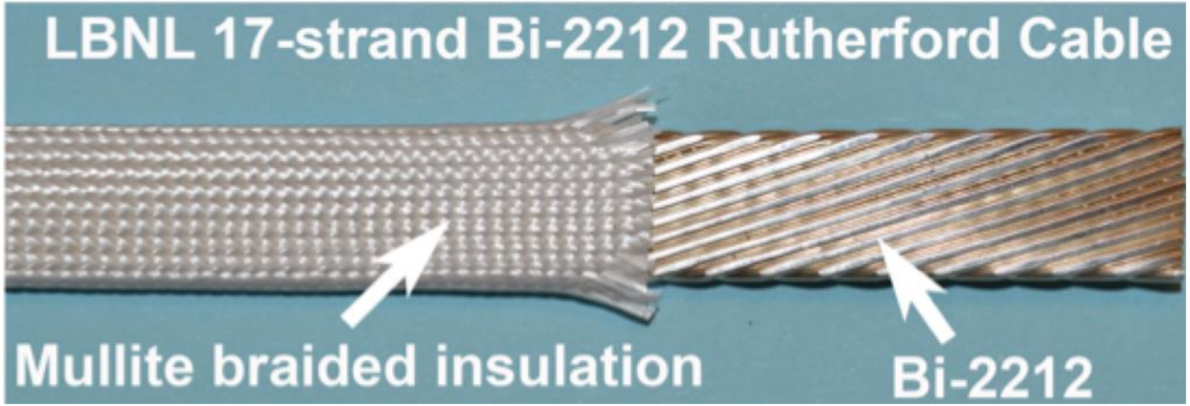


A 5 T, 40 mm bore HTS based dipole demonstrator

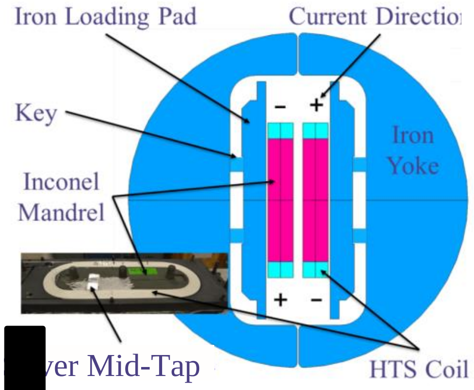
Bismuth based: Bi-2212

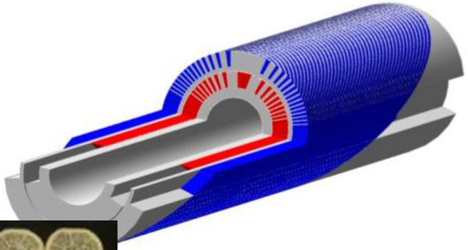




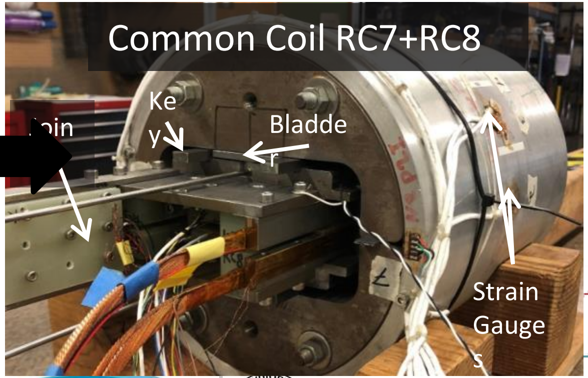


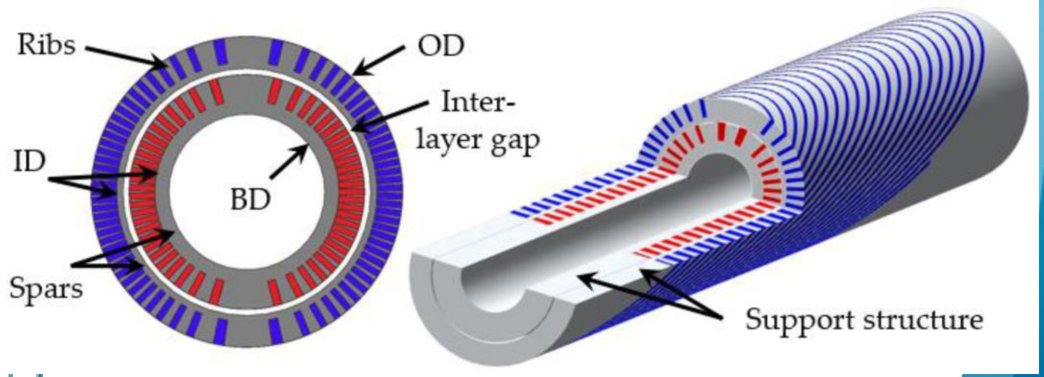
Consistent activity on Bi-2212 @ LBNL and in BNL (formerly on Bi-2212 now on REBCO)





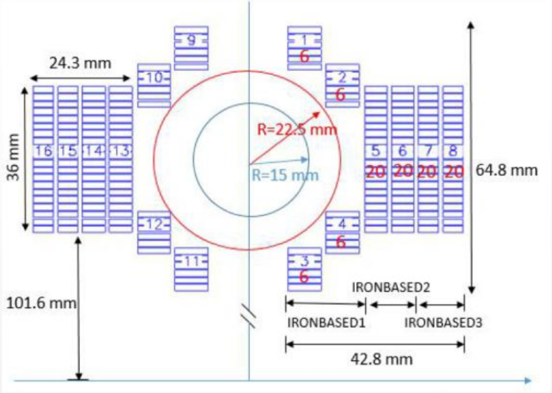
Courtesy of T. Shen

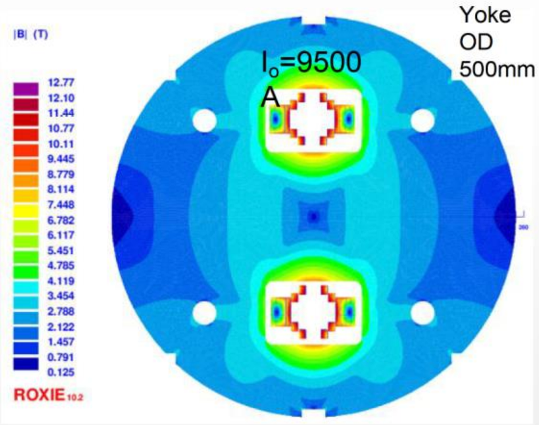


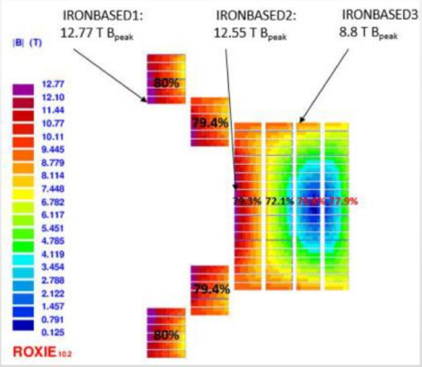


high-field magnet R&D for SppC in China

The 12-T Fe-based Dipole Magnet



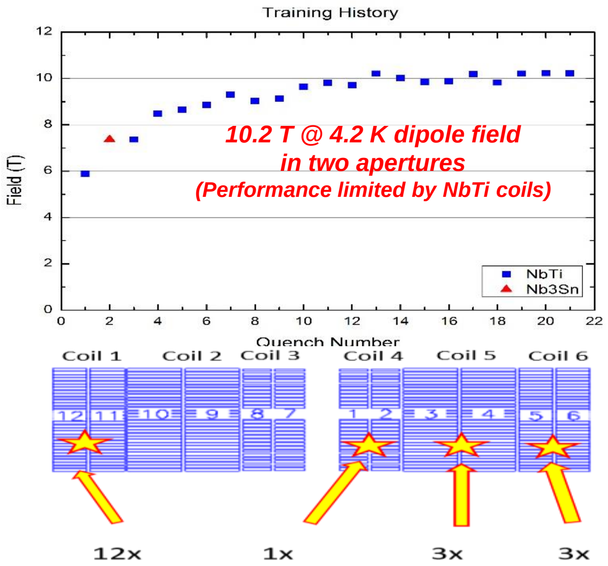


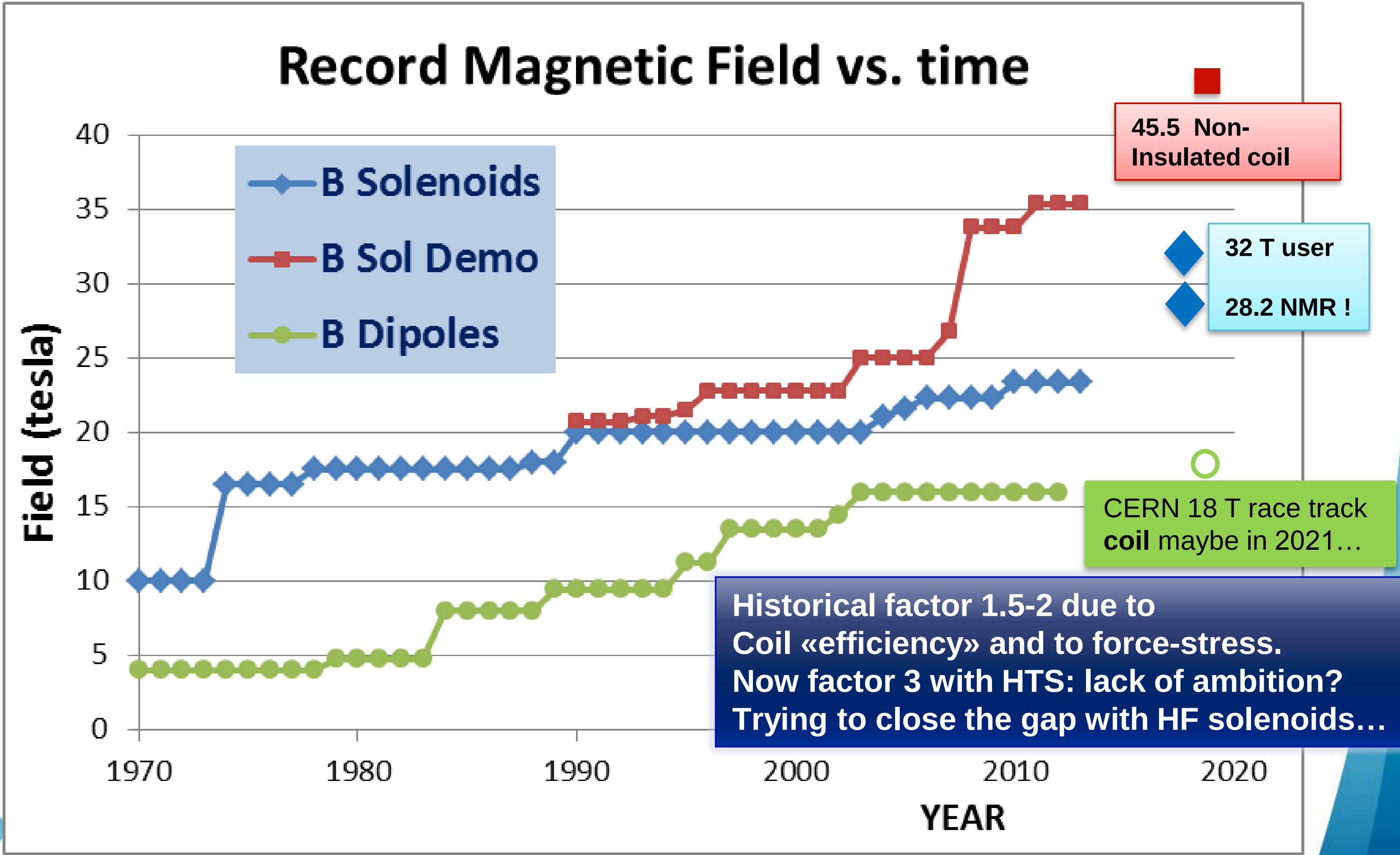


Design with expected J_e of IBS in 2025

Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IBS	0.802	1	200	4.2	10	4000	111

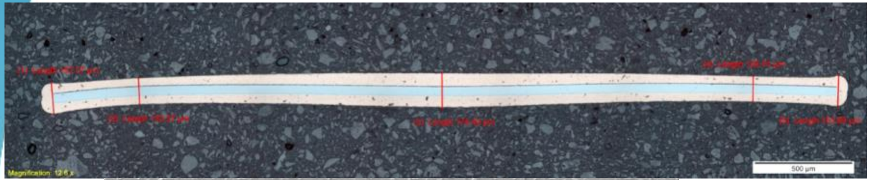
- For 100-km SPPC, **3000 tons of IBS** is needed
- Target cost of IBS: **20 RMB /kAm @12 T**
- Total cost for IBS conductors: **~10B RMB**

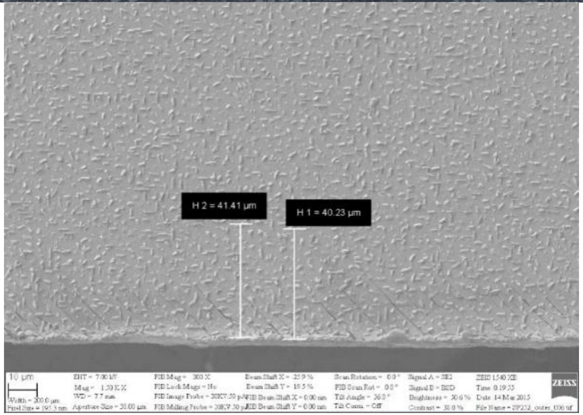


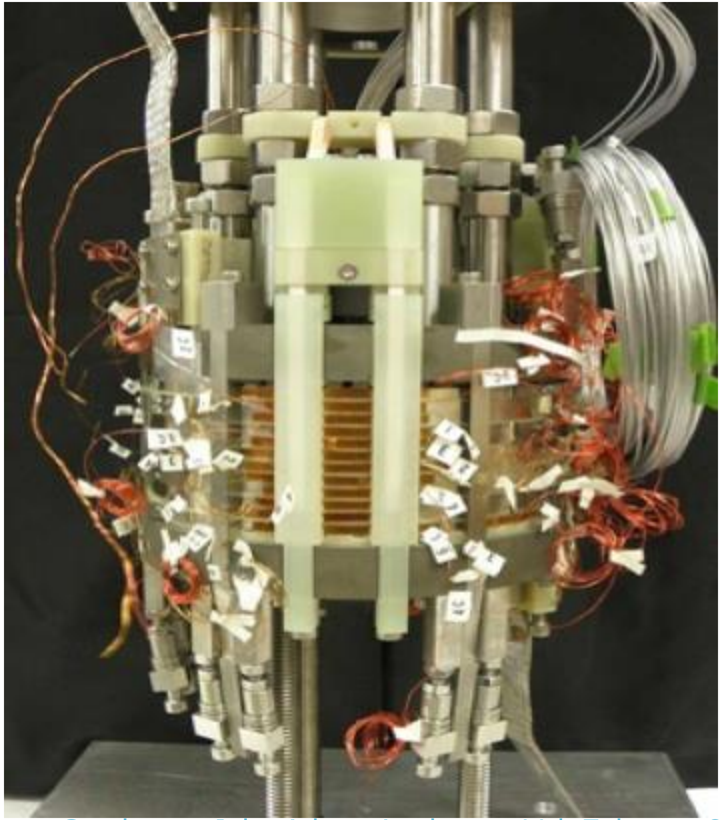


Historical factor 1.5-2 due to Coil «efficiency» and to force-stress.
Now factor 3 with HTS: lack of ambition?
Trying to close the gap with HF solenoids…

NHMFL – Tallahassee (Florida) : 32 T all HTS!!

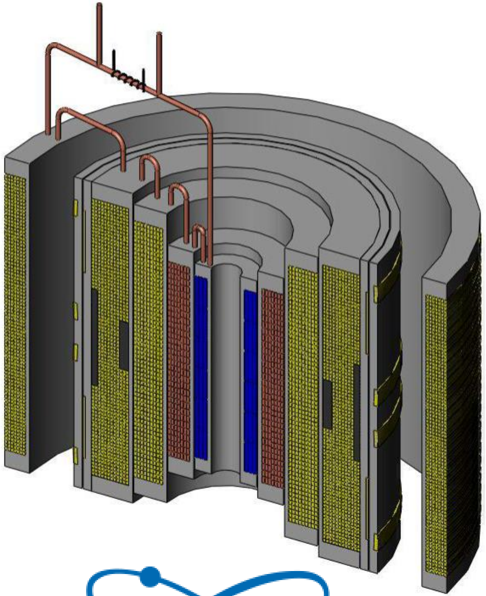


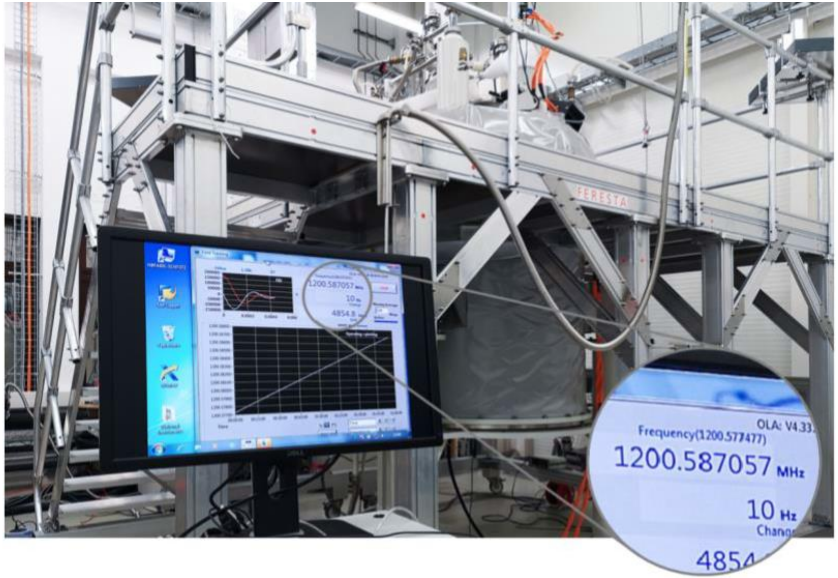




The solenoid made th filed despite some degradation in the REBCO tape

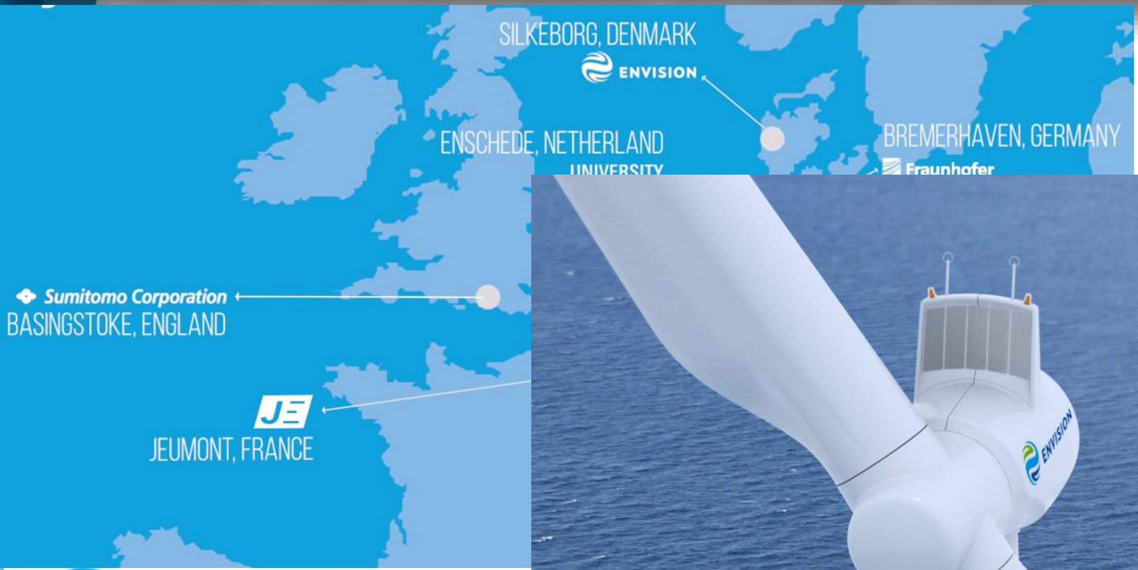
A big leap forward by a private company…
Bruker Biospin





The First 1.2 GHz (28.2 T) NMR Magnet Reached Full Field in 2019

SC and Renewable Energy Technology: wind genrators

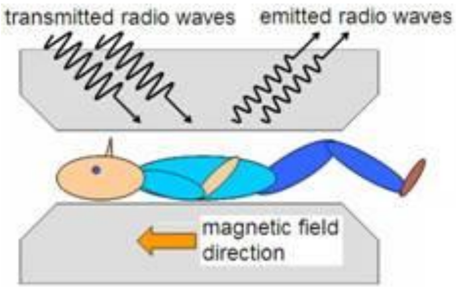


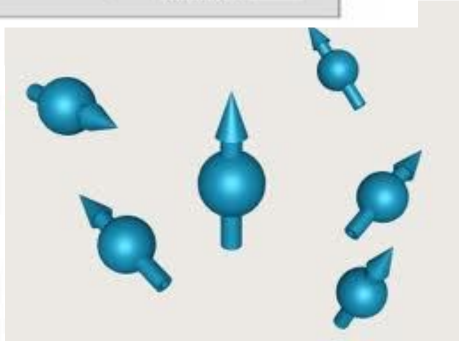
AMSC SeaTitan Wind Turbine Generator
Image courtesy of American Superconductor

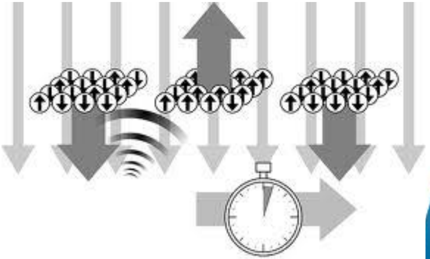
ecoswing

New medical «eyes»: MRI, 2000 large systems/year

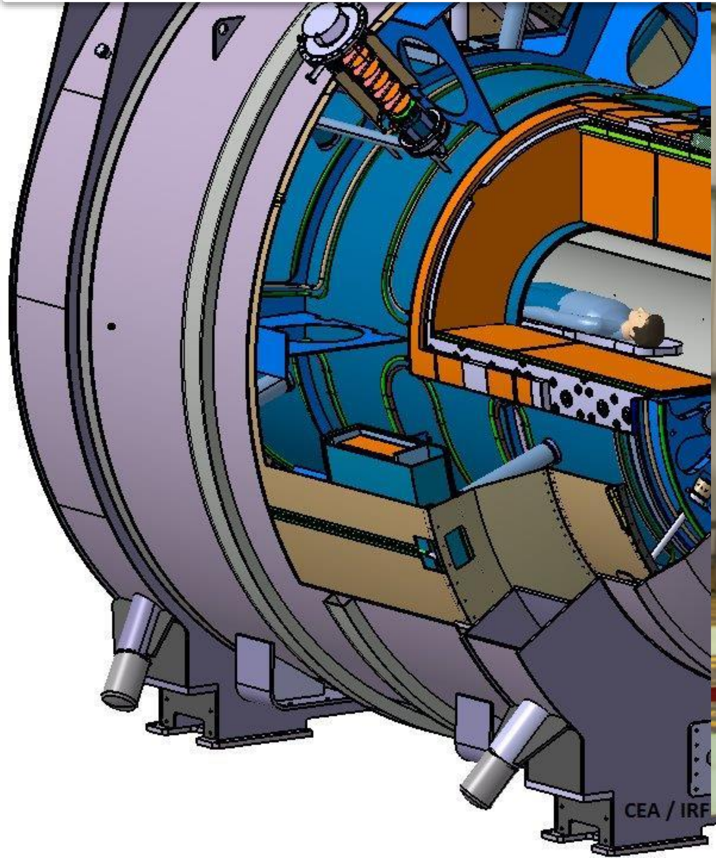
An example of an MRI brain scan
Image courtesy of Scott Camazine, MD



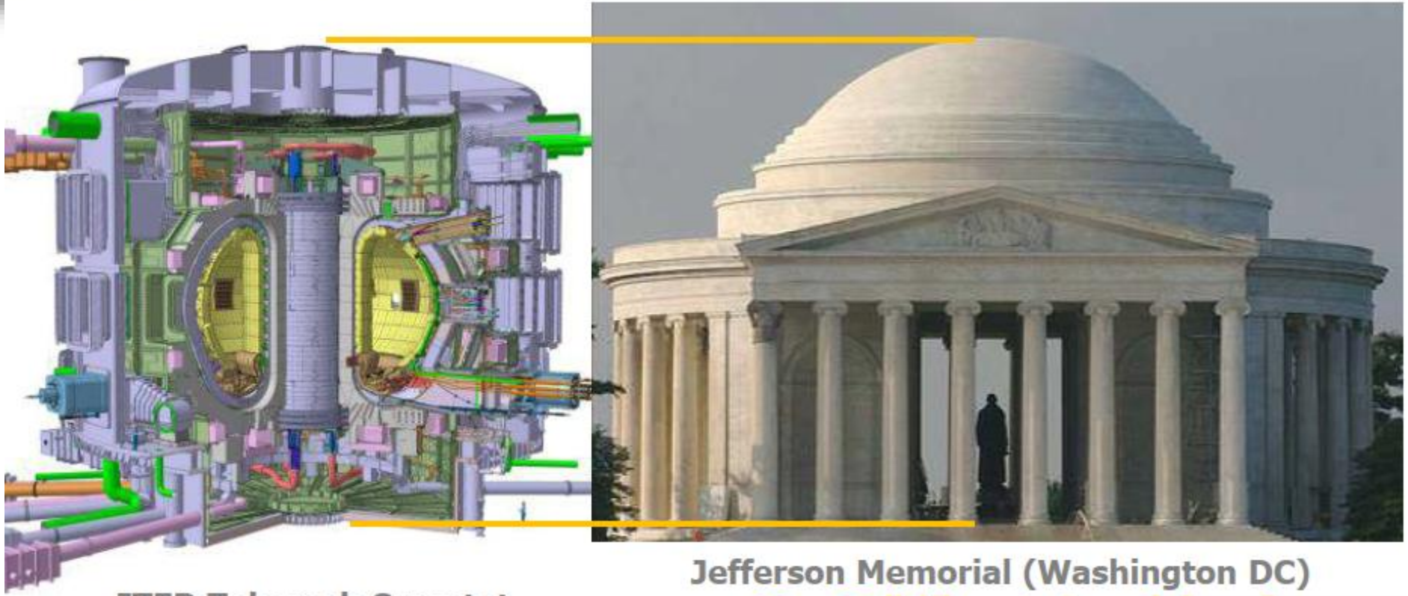




Largest MRI for research: Iseult Magnet for 11.7 T, TESED at Neurospin center in CEA Saclay (Paris)
FUNCTIONAL MRI: breakthrough in cerebral functions



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

From A. Devred (CERN)

Courtesy of G. Johnson
(formerly ITER-IO)

ITER is progressing! Operation in ten years

From N. Mitchell (ITER)

Aviation: the last frontier for superconductivity?

Electrification in Aviation (propulsion)

SIEMENS
Ingenuity for life

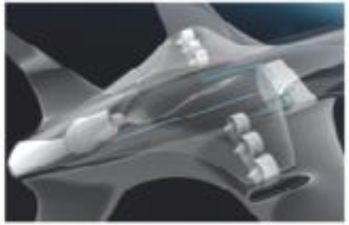
Electrified aircrafts enables more **sustainable aviation**

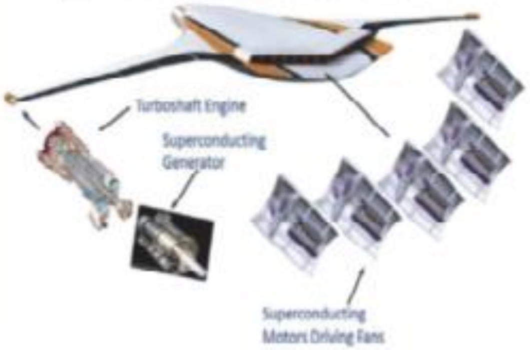
Aspects

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

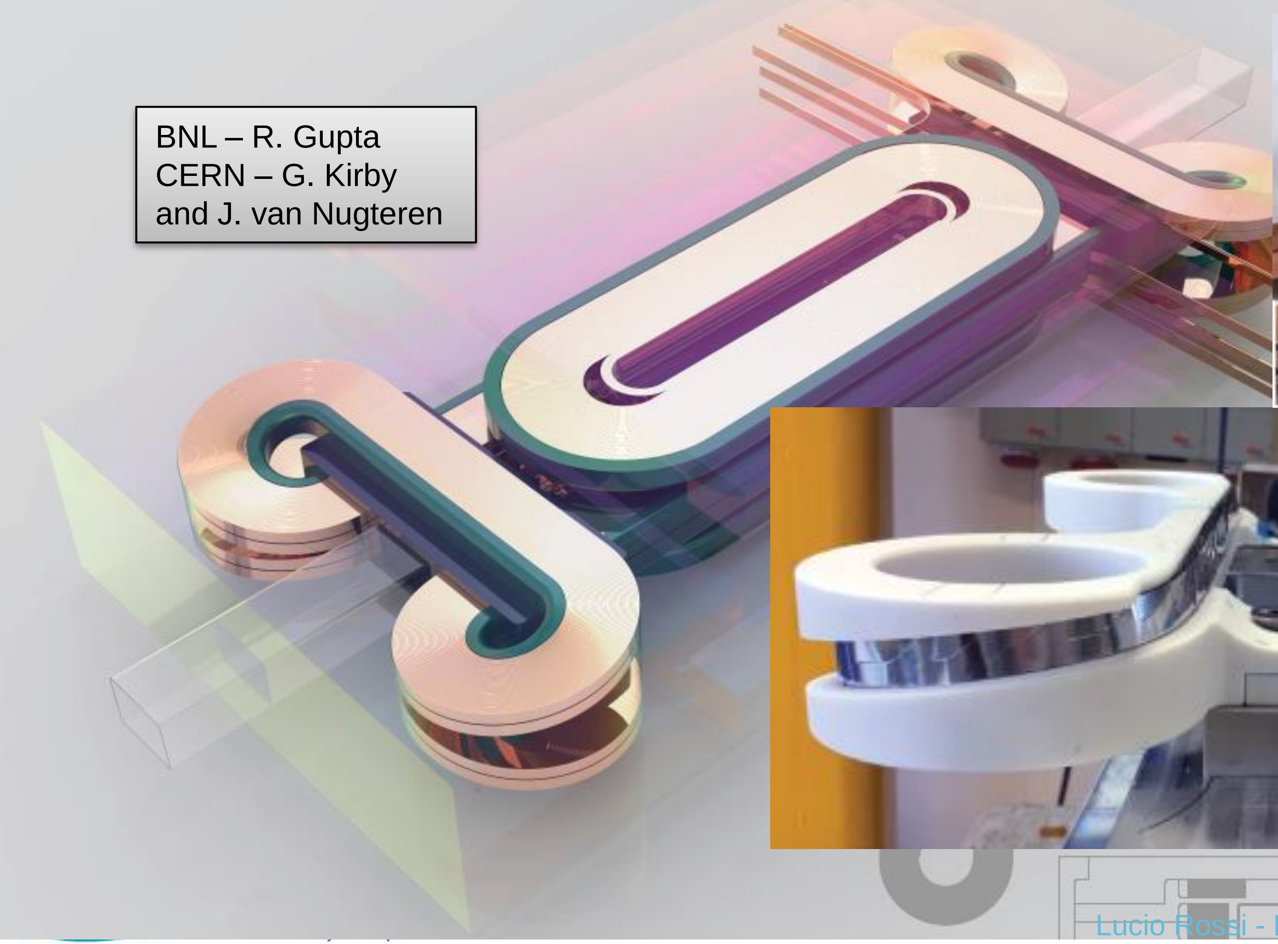
- less noise & emissions

  (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





Trying to imagine magnets of the future…20 tesla or more…
HEP is for that breaking barriers in science and TECHNOLOGY



BNL – R. Gupta
CERN – G. Kirby
and J. van Nugteren