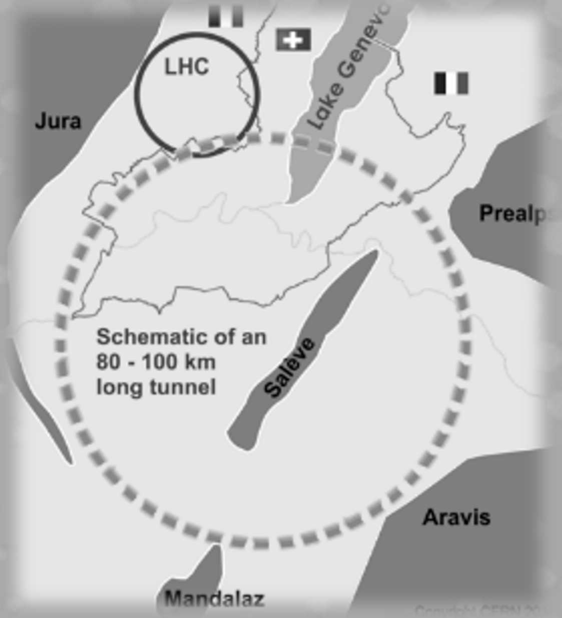
FCC-hh

and

The High Field Magnet R&D

RoadMap



Pierre Vedrine
CEA Paris Saclay

Outline

Future Circular Collider for hadrons

Introduction on Accelerator Magnets for Colliders

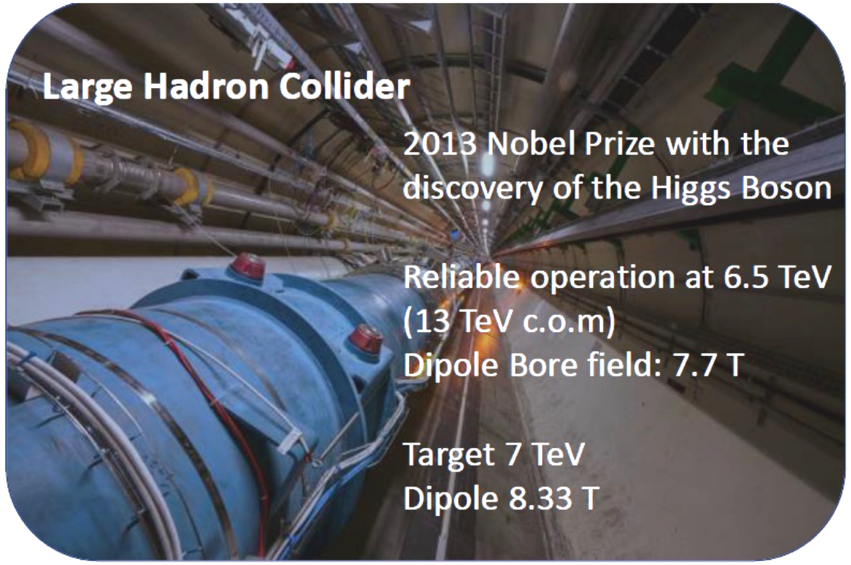
Context of Magnet R&D for a Future Collider

High Field R&D Roadmap for the future

Other applications of high field magnets

Summary comments

Future Circular Collider for Hadrons

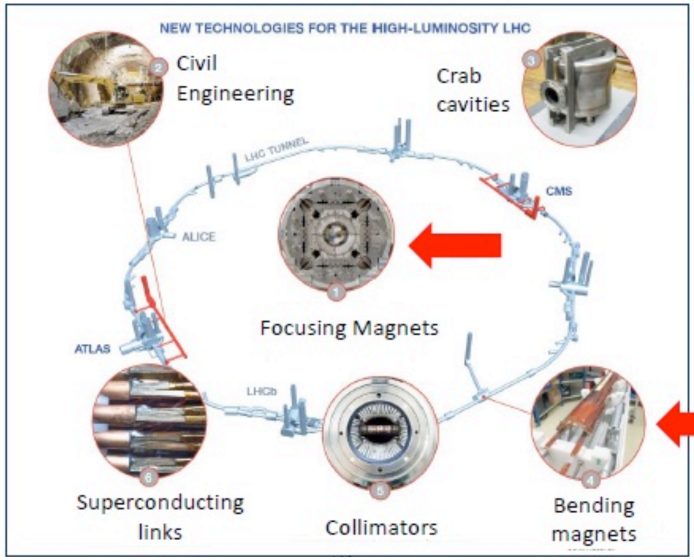


Large Hadron Collider

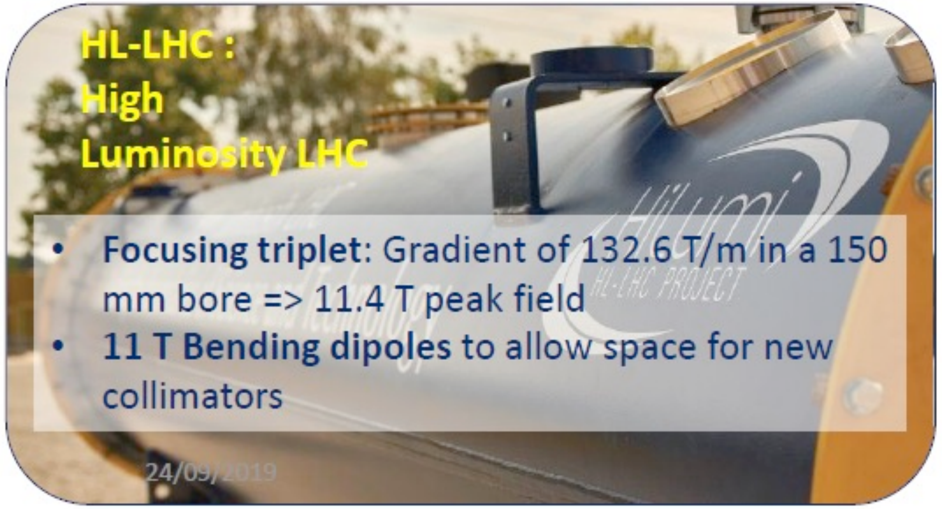
2013 Nobel Prize with the discovery of the Higgs Boson

Reliable operation at 6.5 TeV (13 TeV c.o.m)
Dipole Bore field: 7.7 T

Target 7 TeV
Dipole 8.33 T



Courtesy of CERN



HL-LHC : High Luminosity LHC

- **Focusing triplet**: Gradient of 132.6 T/m in a 150 mm bore => 11.4 T peak field
- **11 T Bending dipoles** to allow space for new collimators

24/09/2019

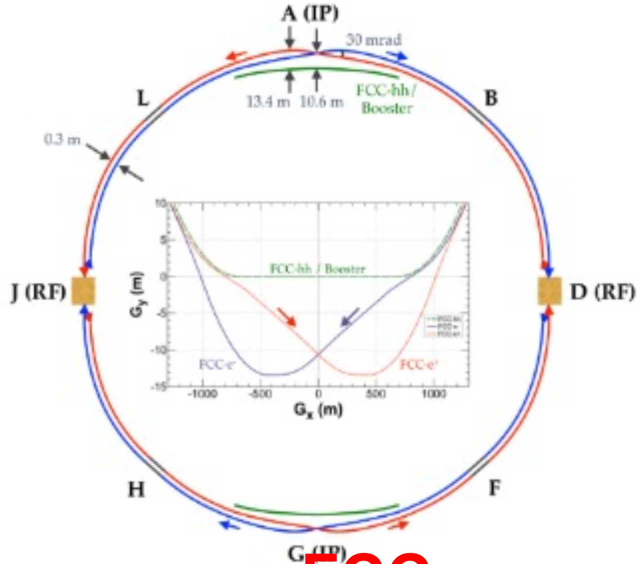
FCC-hh
Future Circular Collider

100 km - 16 T: 100 TeV (c.o.m)

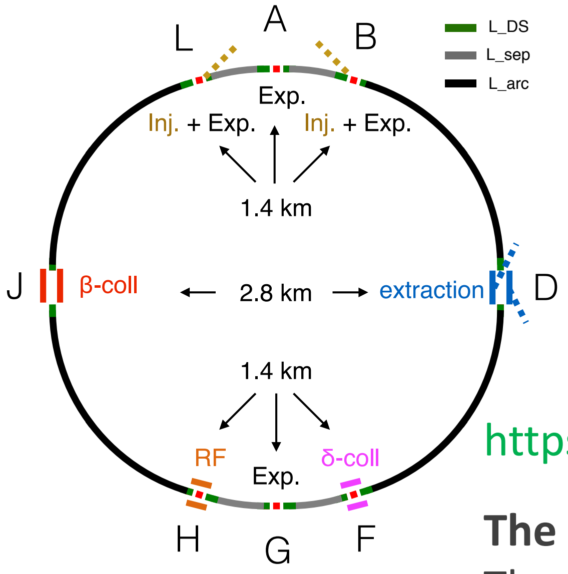
Courtesy of CERN

▶ Comprehensive cost-effective program maximizing physics opportunities

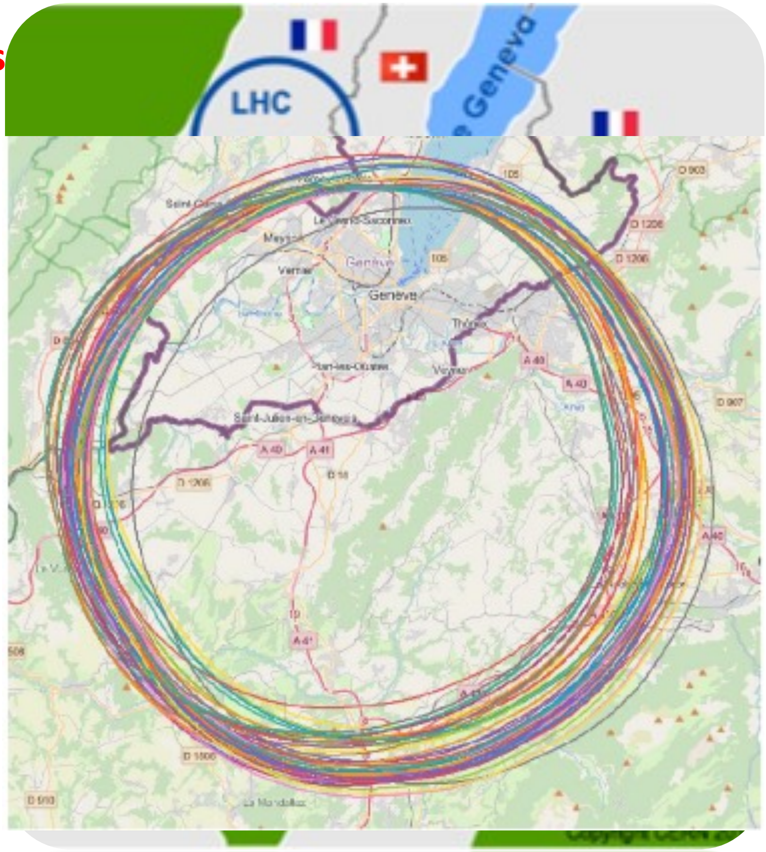
- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- **Complementary physics**
- **Common civil engineering and technical infrastructures**
- **Building on and reusing CERN's existing infrastructure**
- **FCC integrated project allows seamless continuation of HEP after HL-LHC**



FCC-ee



FCC-hh

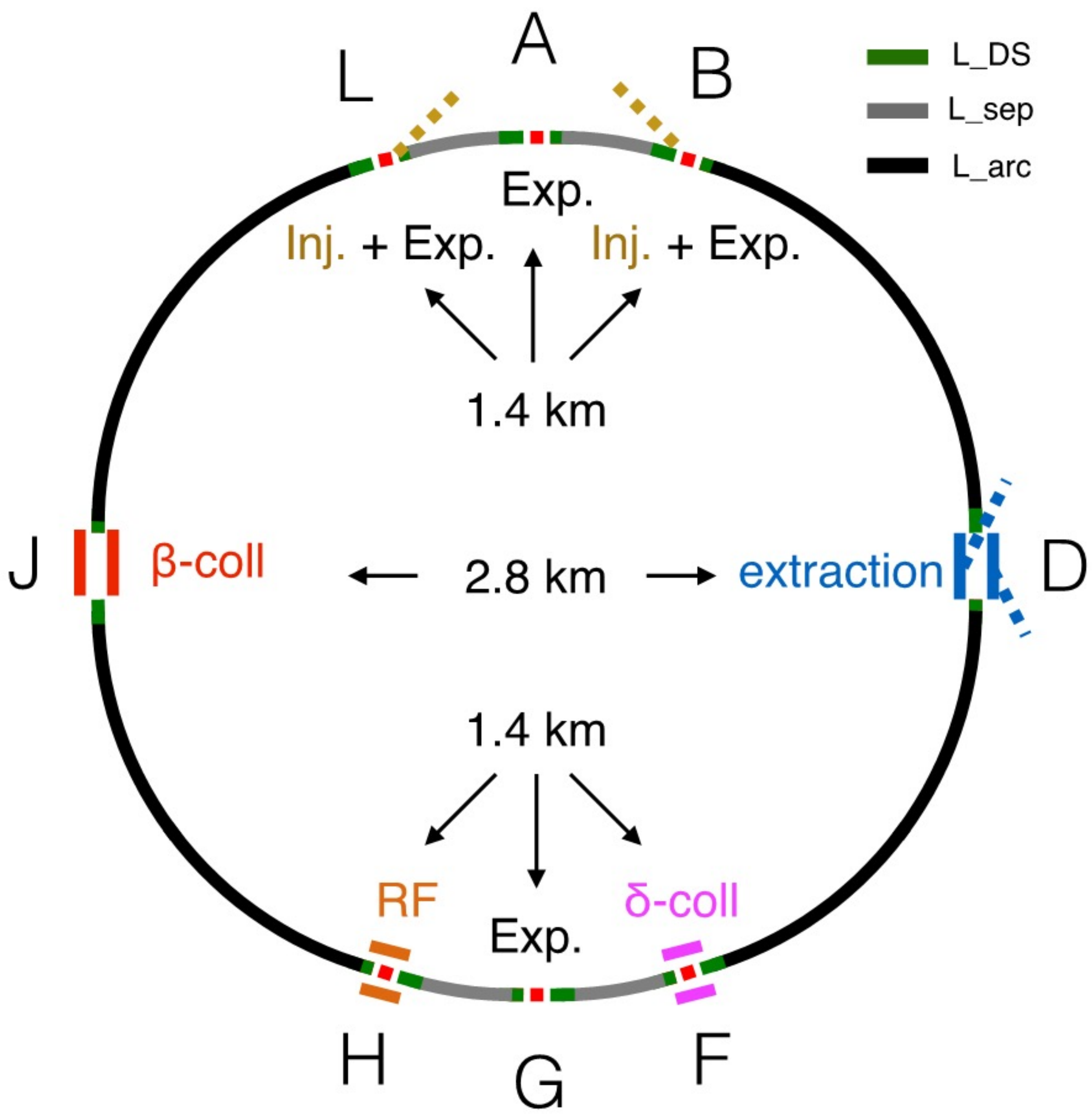


https://fcc-cdr.web.cern.ch/

The total circumference of the FCC hh collider is 97.75km.
The arcs of the collider have a total length of 83.75km with about 4700 - 16 T dipole magnets and 800 - 367 T/m quadrupole magnets.

FCC-HH COLLIDER PARAMETERS (STAGE 2)

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	**100**		14	14
dipole field [T]	**16**		8.33	8.33
circumference [km]	**97.75**		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	**2400**		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [mm]	2.1		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	**5**	**30**	5 (lev.)	1
events/bunch crossing	**170**	**1000**	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

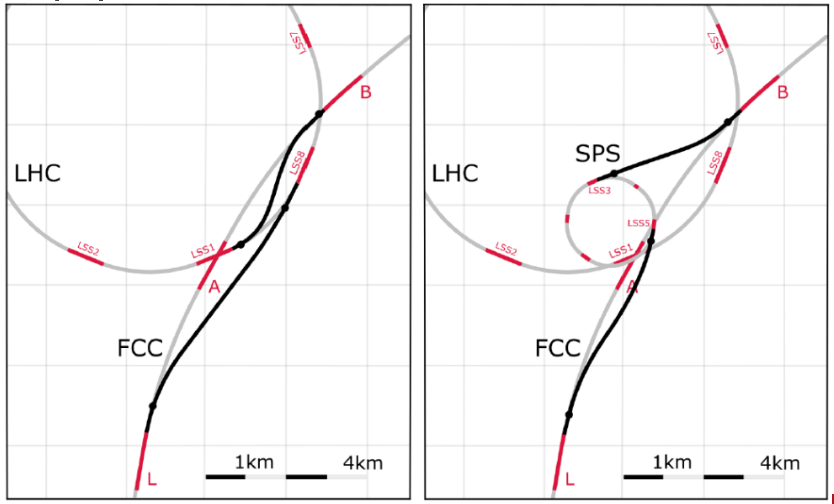


Layout for CERN site Layout for CERN

- Two high -luminosity experiments (A and G)

- Two other experiments combined with injection at 3 TeV (L and B)
- Two collimation insertions
  - Betatron cleaning (J)
  - Momentum cleaning (F)
- Extraction insertion (D)
- Clean insertion with RF (H)

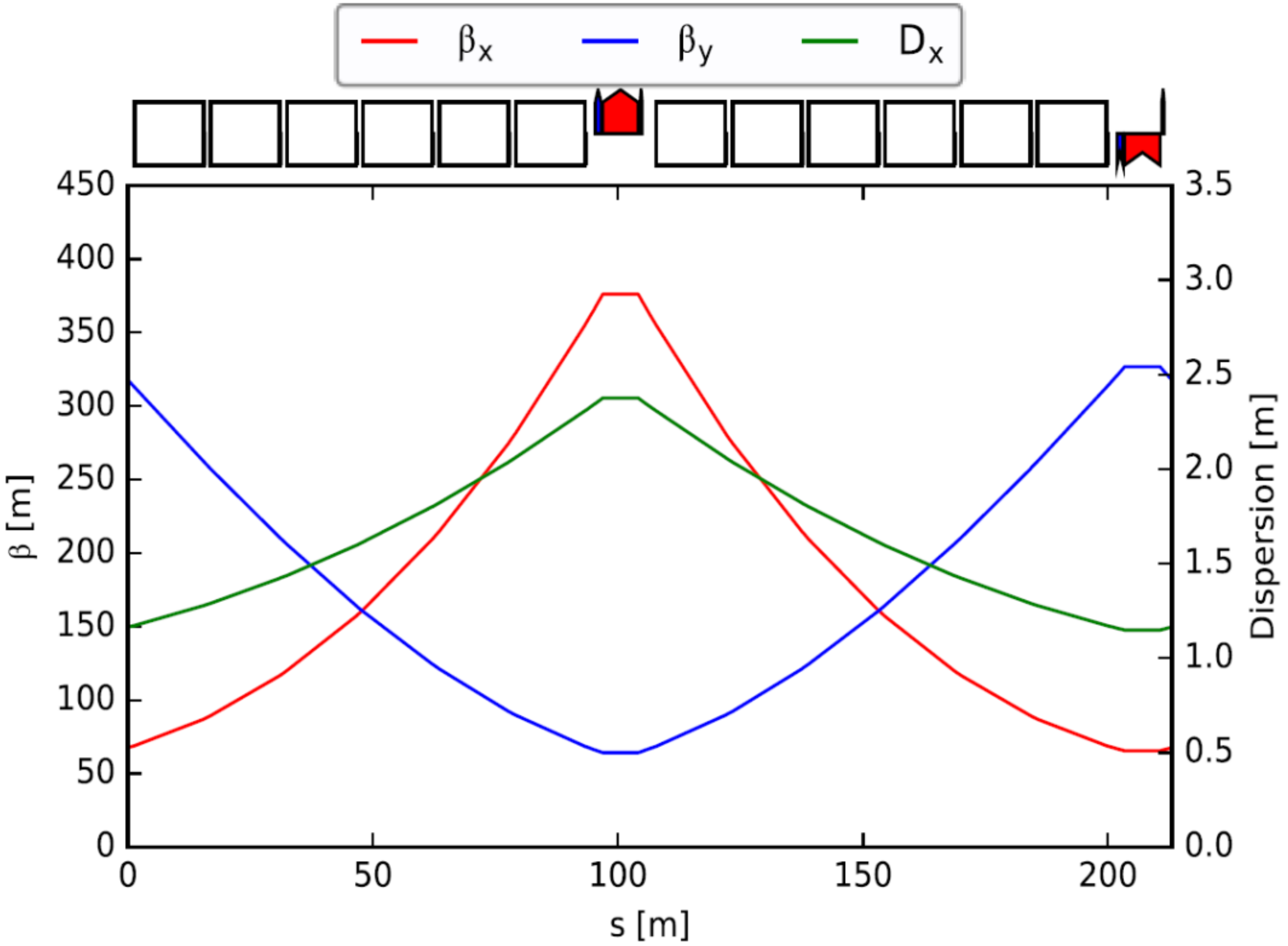
Can use LHC or SPS as injector



Arc Layout

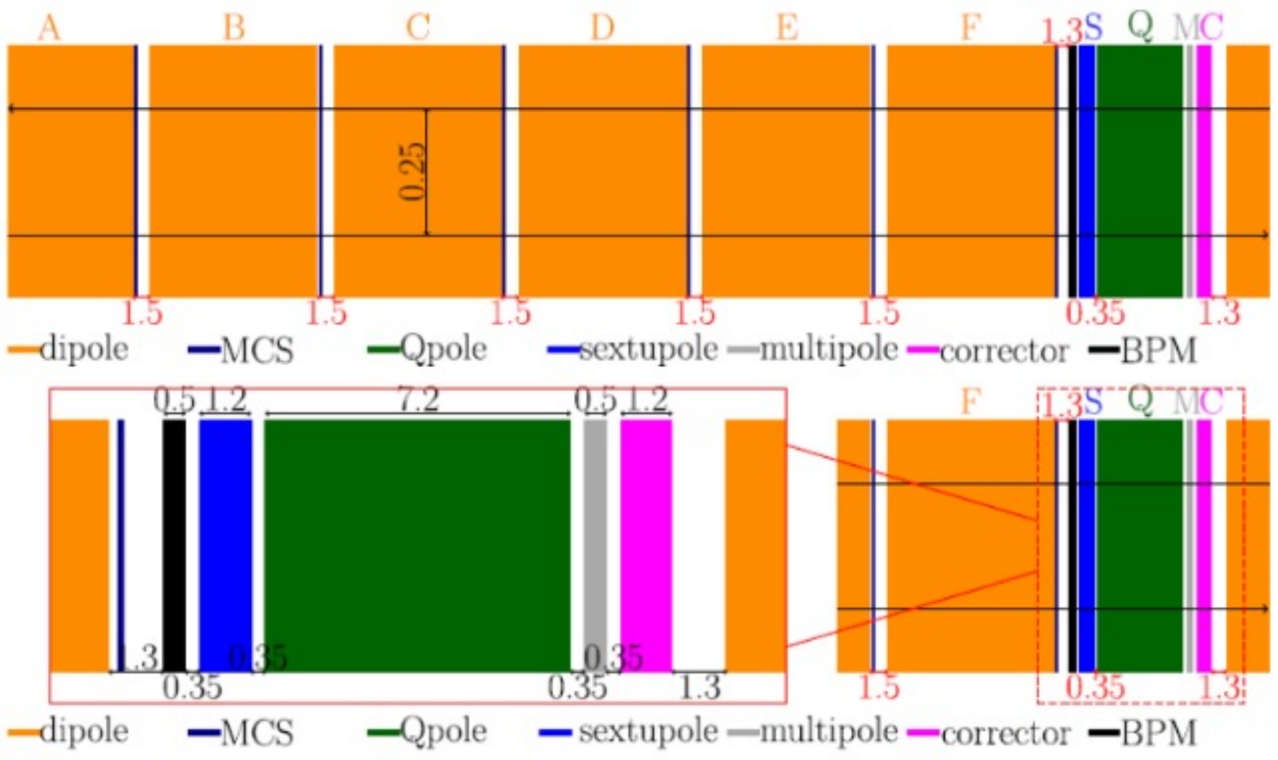
Arc cell length is 213.04 m
- 90° FODO cells
- Contains 12 dipoles
  - Each 14.07 m long
- Also quadrupoles, sextupoles, spool pieces, correctors, …

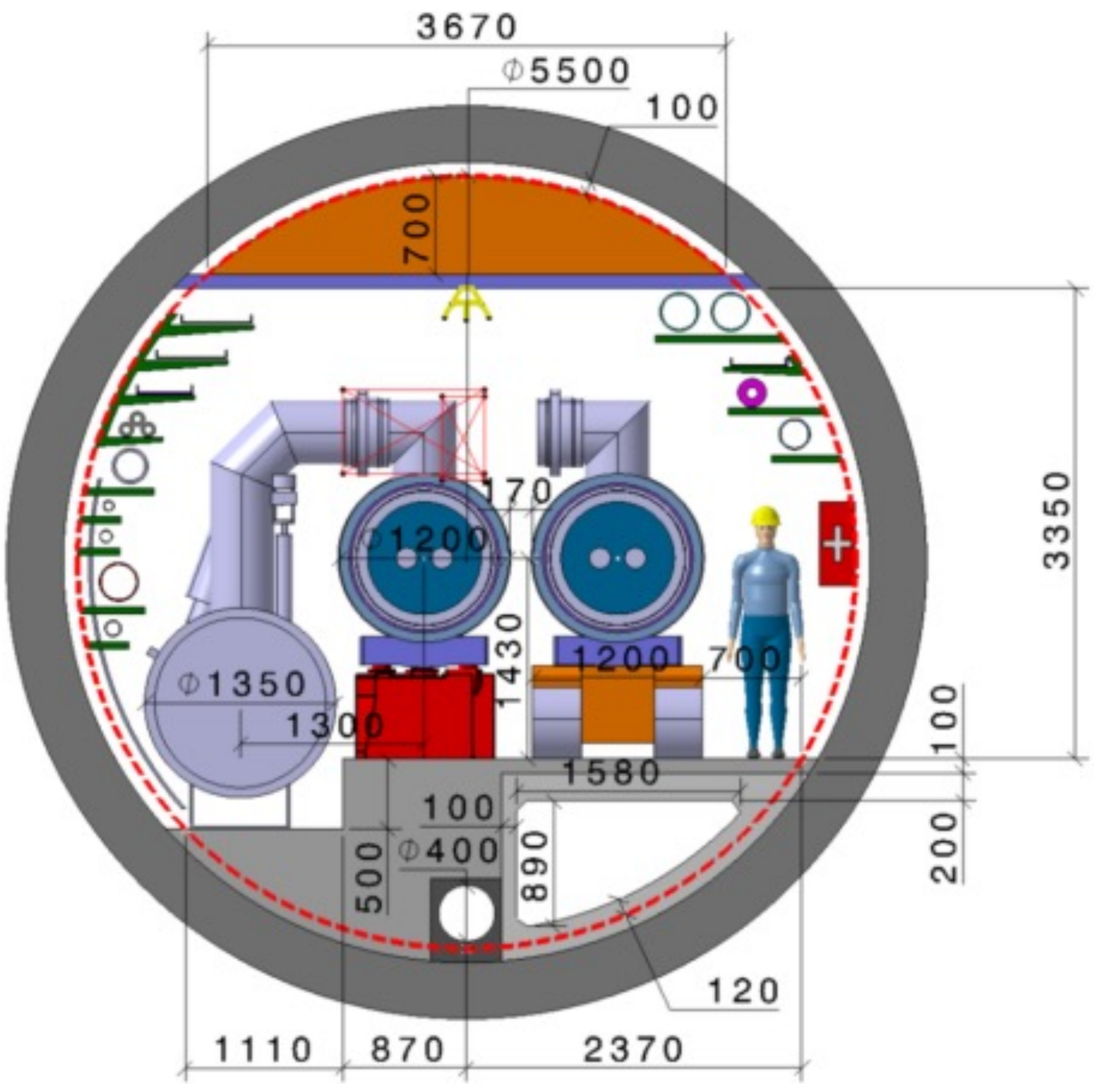
- Needed dipole field is 15.96 T



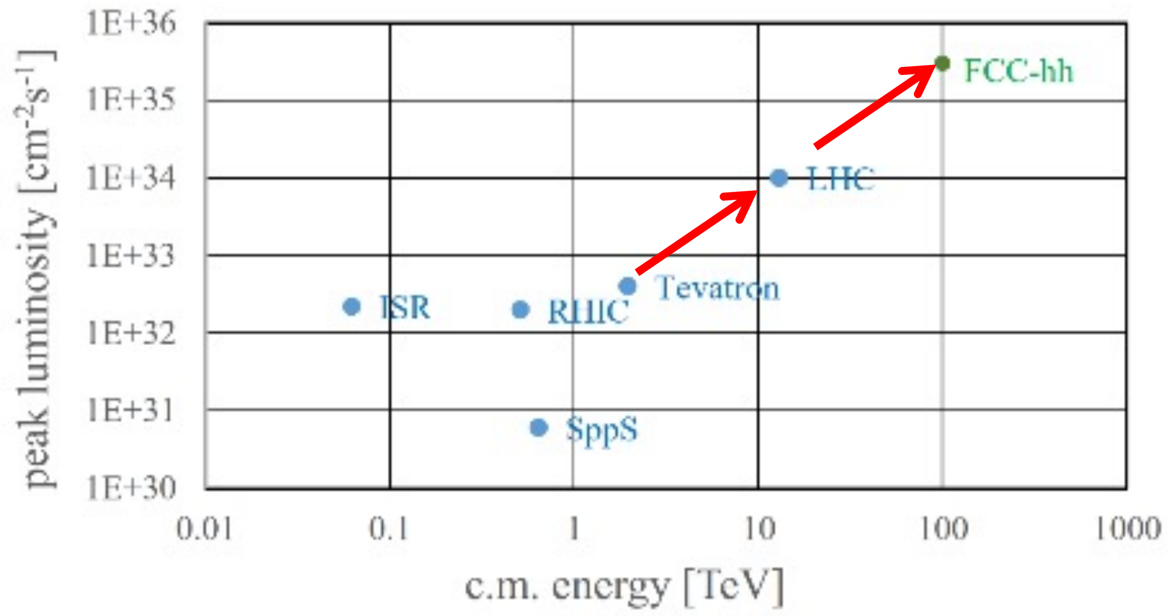
FCC-TUNNEL INTEGRATION IN ARCS

FCC-hh tunnel 5.5 m inner diameter





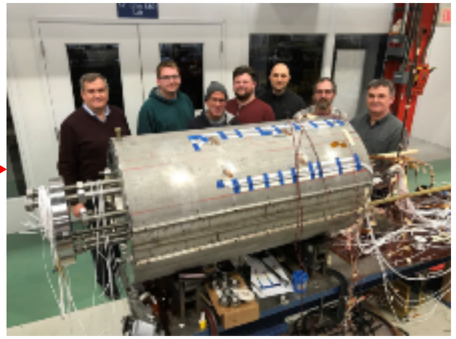
FCC-HH: HIGHEST COLLISION ENERGIES



- **Order of magnitude performance increase in both energy & luminosity**
- **100 TeV cm collision energy (vs 14 TeV for LHC)**
- **20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)**
- **similar performance increase as from Tevatron to LHC**
- **key technology: high-field magnets**
- **Efficiency and cost (**efficient cryogenics refrigeration distribution, energy storage and release to reduce energy consumption, efficient power distribution**)**

from
LHC technology
8.3 T NbTi dipole

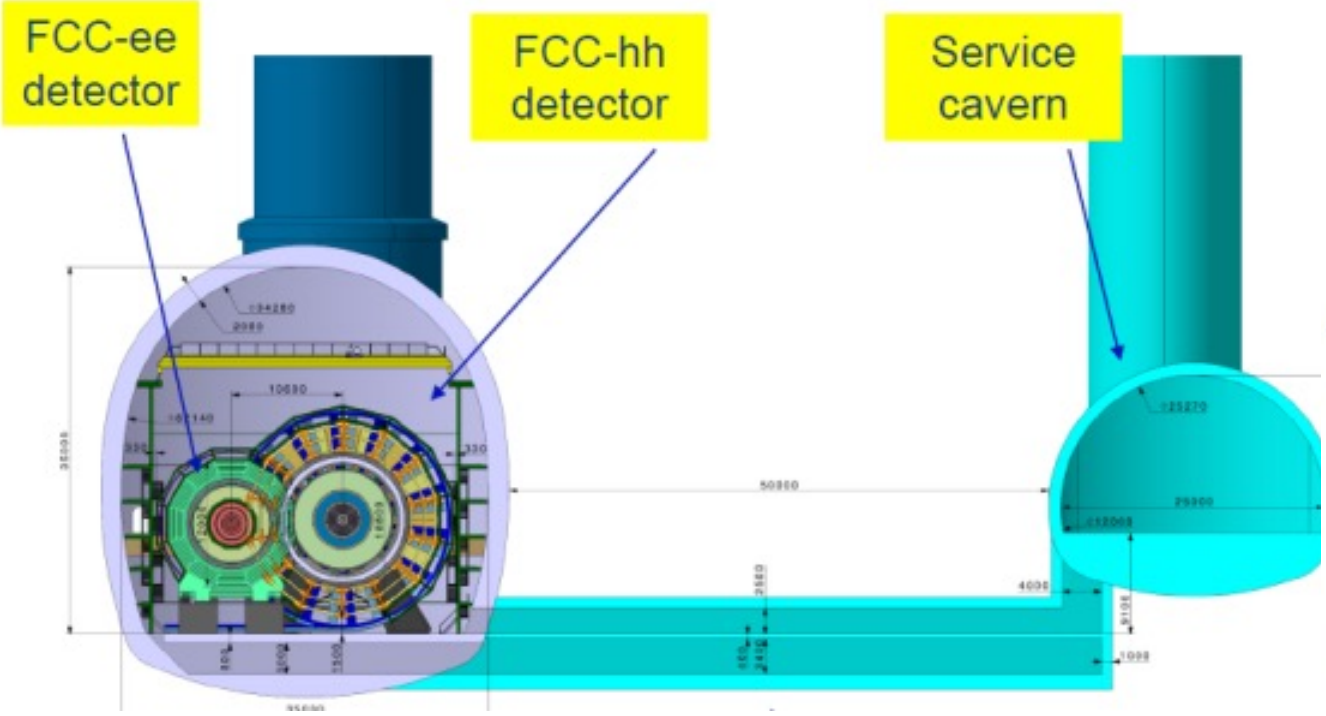
via
HL-LHC technology
12 T Nb_3Sn quadrupole



FNAL dipole demonstrator
14.5 T Nb_3Sn

Detector At the Interaction Point

Distance between detector cavern and service cavern 50 m.
Strayfield of unshielded detector solenoid < 5mT.



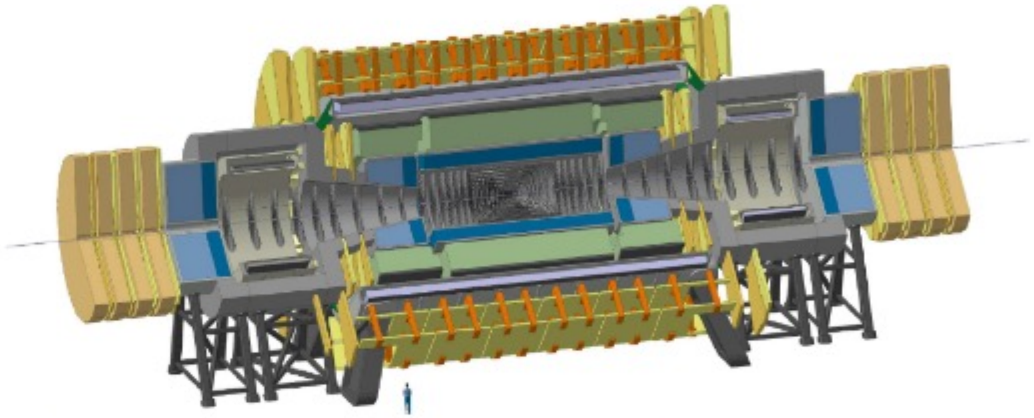
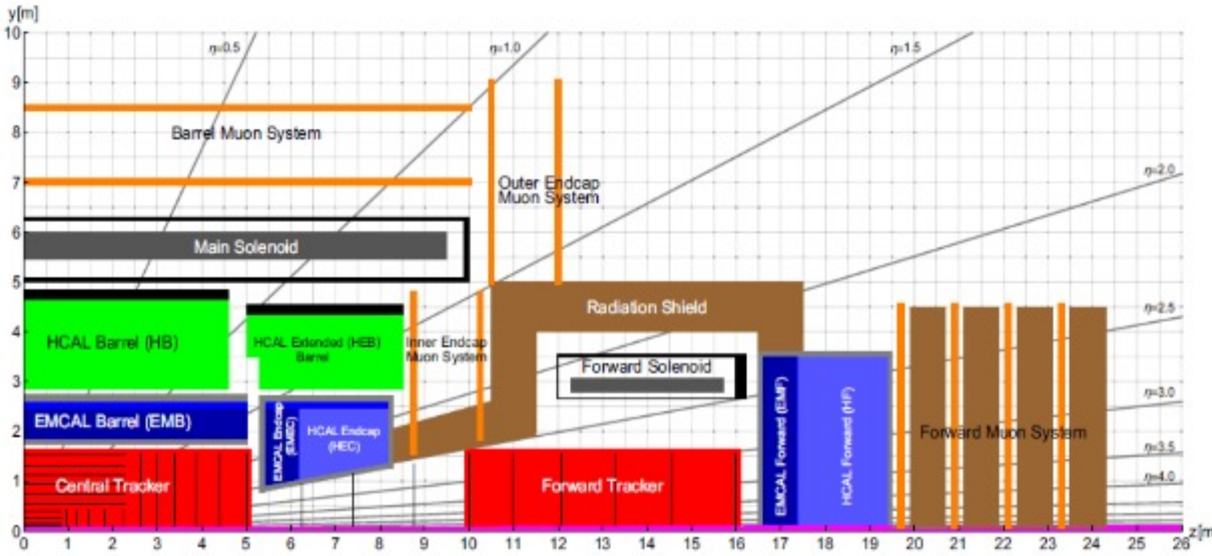
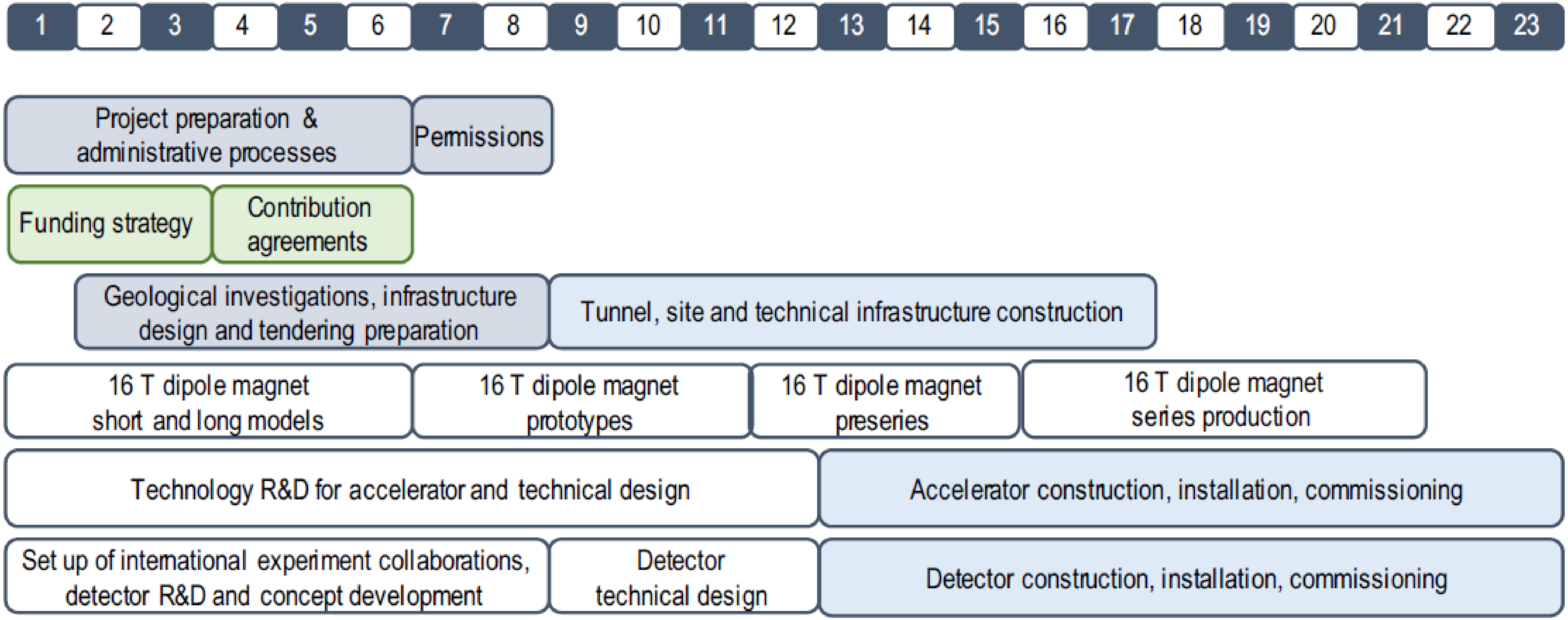


Fig. 7.1. The FCC-hh reference detector with an overall length of 50 m and a diameter of 20 m. A central solenoid with 10 m diameter bore and two forward solenoids with 5 m diameter bores provide a 4 T field for momentum spectroscopy in the entire tracking volume.



STATUS OF GLOBAL FCC COLLABORATION

FCC hh Stand Alone project technical schedule



FCC INTEGRATED PROJECT TECHNICAL SCHEDULE

1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | ………………. | 19 | 20 | ~ 15 years operation | 7 – 10 years | ~ 25 years operation | 70

Feasibility Study

EPPSU

Project preparation & administrative processes

Permis-sions

Update Permis sions

~2040: start of FCC-ee

~2065: start of FCC-hh

Funding strategy

Funding and in-kind contribution agreements

Funding and in-kind contribution agreements

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Set up of international experiment collaborations, detector R&D and concept development

FCC-ee detector technical design

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

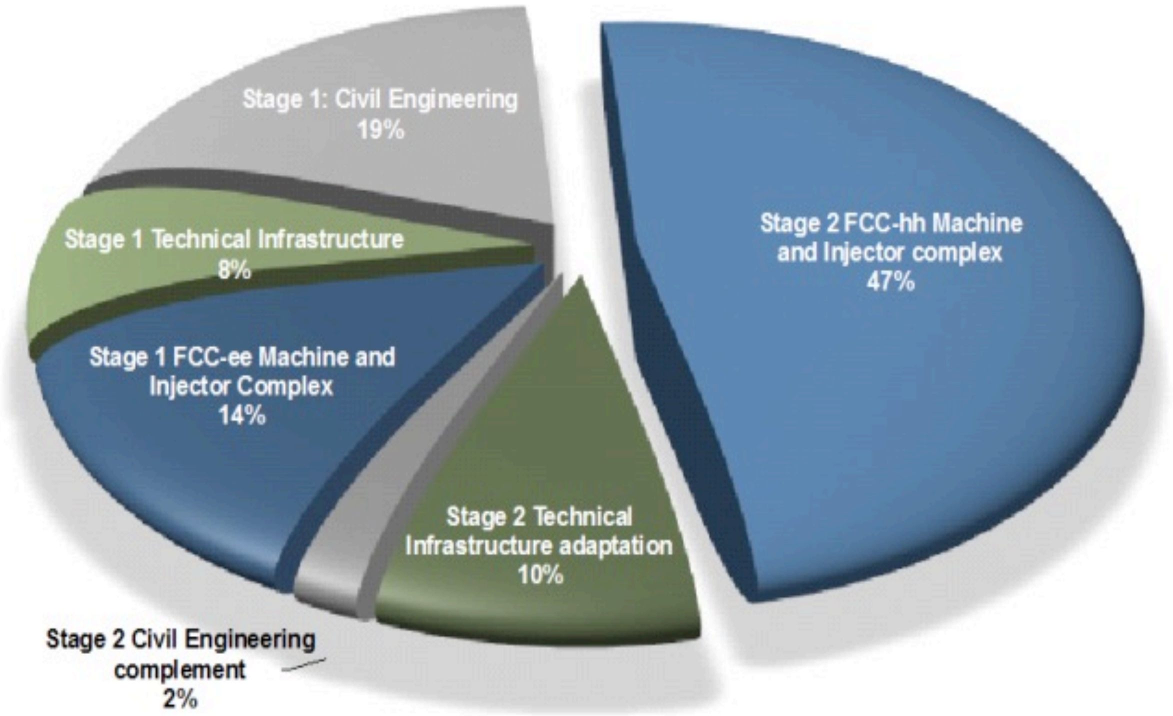
Superconducting wire and magnet R&D, short models

Long model magnets, prototypes, preseries

High-field magnet industrialization and series production

FCC-INTEGRATED COST ESTIMATE

Domain	Cost in MCHF
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**



Total construction cost FCC-ee (Z, W, H) amounts to 10,500 MCHF & 1,100 MCHF (tt).

- Associated to a total project duration of ~20 years (2025 – 2045)

Total construction cost for subsequent FCC-hh amounts to 17,000 MCHF.

- Associated to a total project duration of ~25 years (2035 – 2060)
- (FCC-hh stand alone 25 BCHF)

INTRODUCTION ON ACCELERATOR MAGNETS FOR COLLIDERS

MAGNETS ARE EVERYWHERE!!!

The very first magnet!

0,5 Gauss / 5.10-5 T
in Madrid

Permanent magnet
(NdFeB, 0.5T)

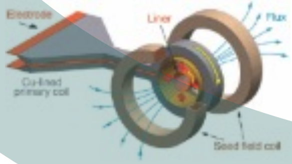
Resistive magnet
(2T)

MRI magnet (Siemens 3T)

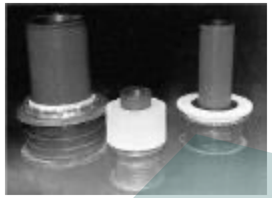
LHC Dipole
(8,3T)

Bruker 1 GHz NMR
(23,5T)

NHMFL
Tallahassee
Hybrid magnet
(40 T)

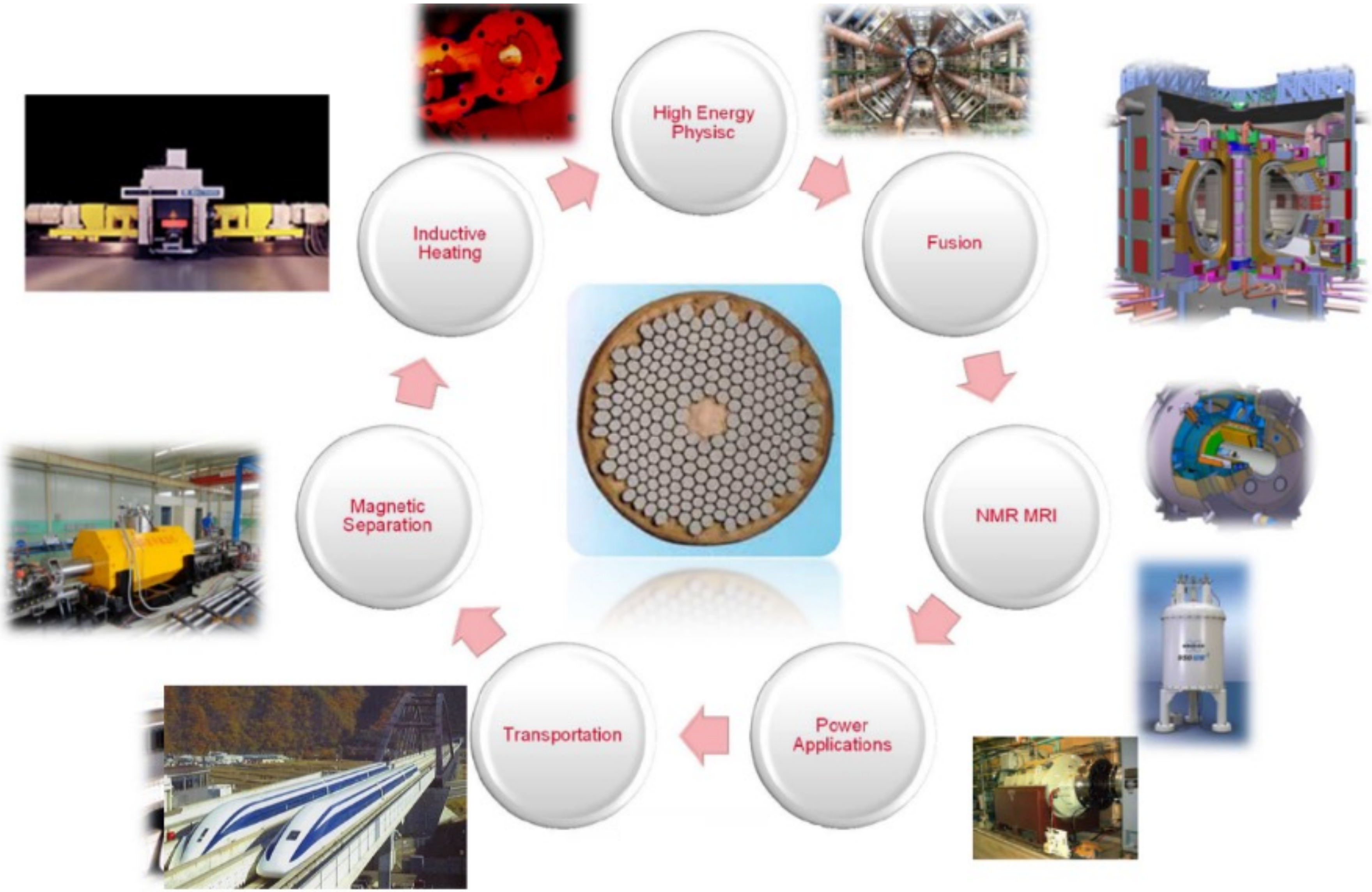


ISSP (Japan)
(750 T)



VNIIEF MC-1 (Russia)
2,8 kT

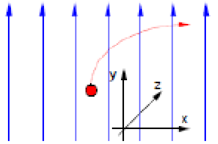
AND SUPERCONDUCTIVITY HAS A LOT OF APPLICATIONS!



A magnet creates a force that acts on any other magnet, electric current, or moving charged particle.

Increase BEAM ENERGY →

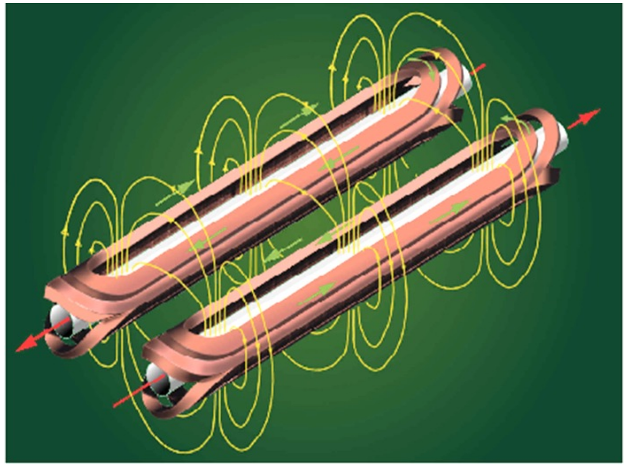
Dipoles to bend the trajectory of the beam



Beam energy — Bending radius

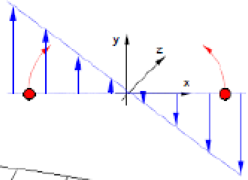
$$E[GeV] = 0.3\, B[T]\, \rho[m]$$

Dipole field



Increase collider LUMINOSITY (number of collisions) →

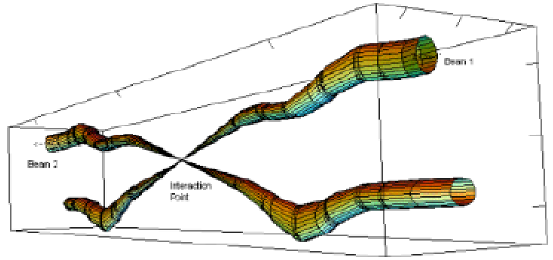
Final focus quadrupoles to reduce the beam dimension at the interaction point



Peak coil field

$$B\ell_q \approx \frac{1}{\sigma^*}$$

Quadrupole length — Beam size at the collision point



Relative beam sizes around IP1 (Atlas) in collision

Courtesy of B. Bordini

Performance factor ~ B^3 R^2

Fusion machine

$$\frac{S}{B} \propto B_0^{\frac{3}{2}}$$

NMR/MRI

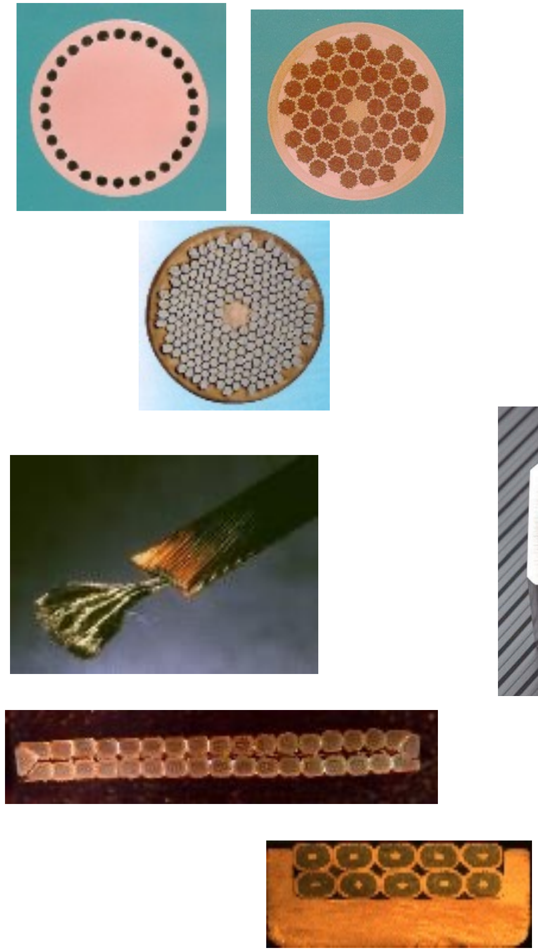
$$\frac{\Delta p}{p} \propto \frac{p}{qBL^2}$$

Detector

A Large choice of SC materials

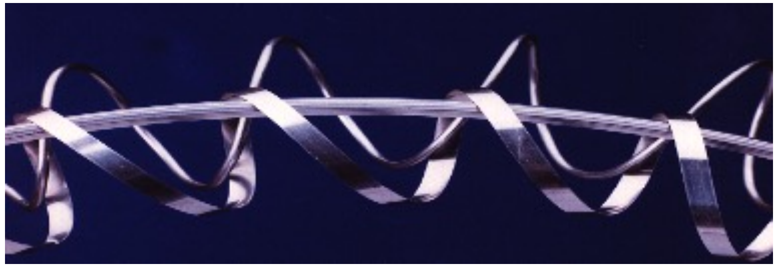
2 K → 150 K

NbTi

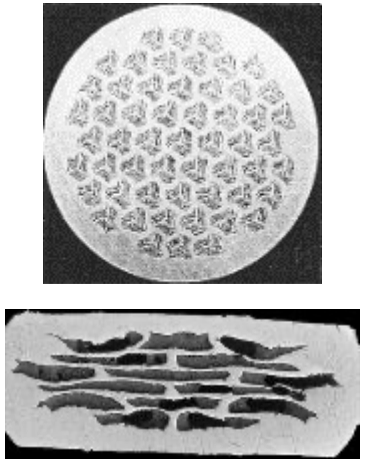


Nb_3Sn, Nb_3Al

ReBCO



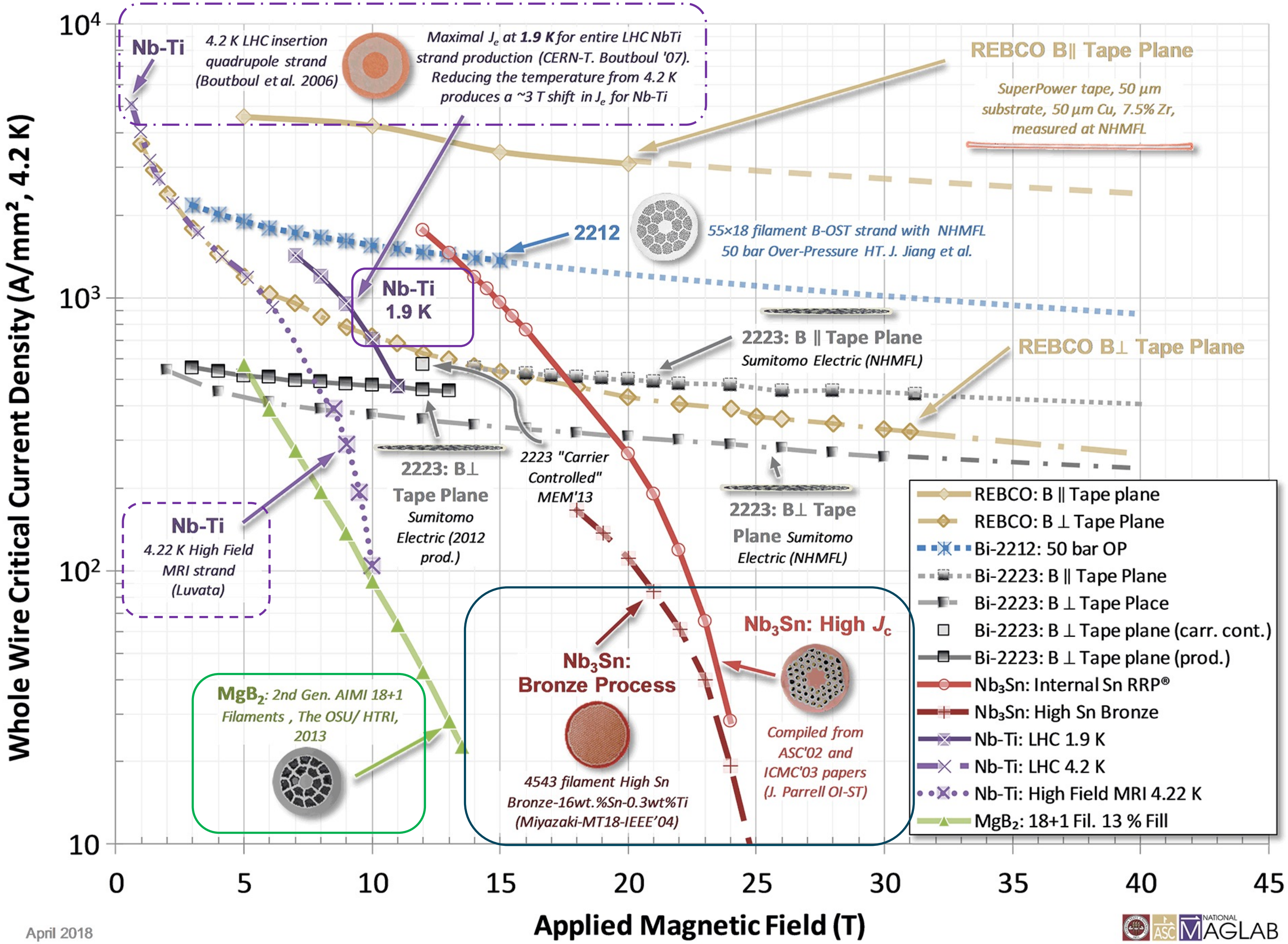
BSCCO



MgB_2

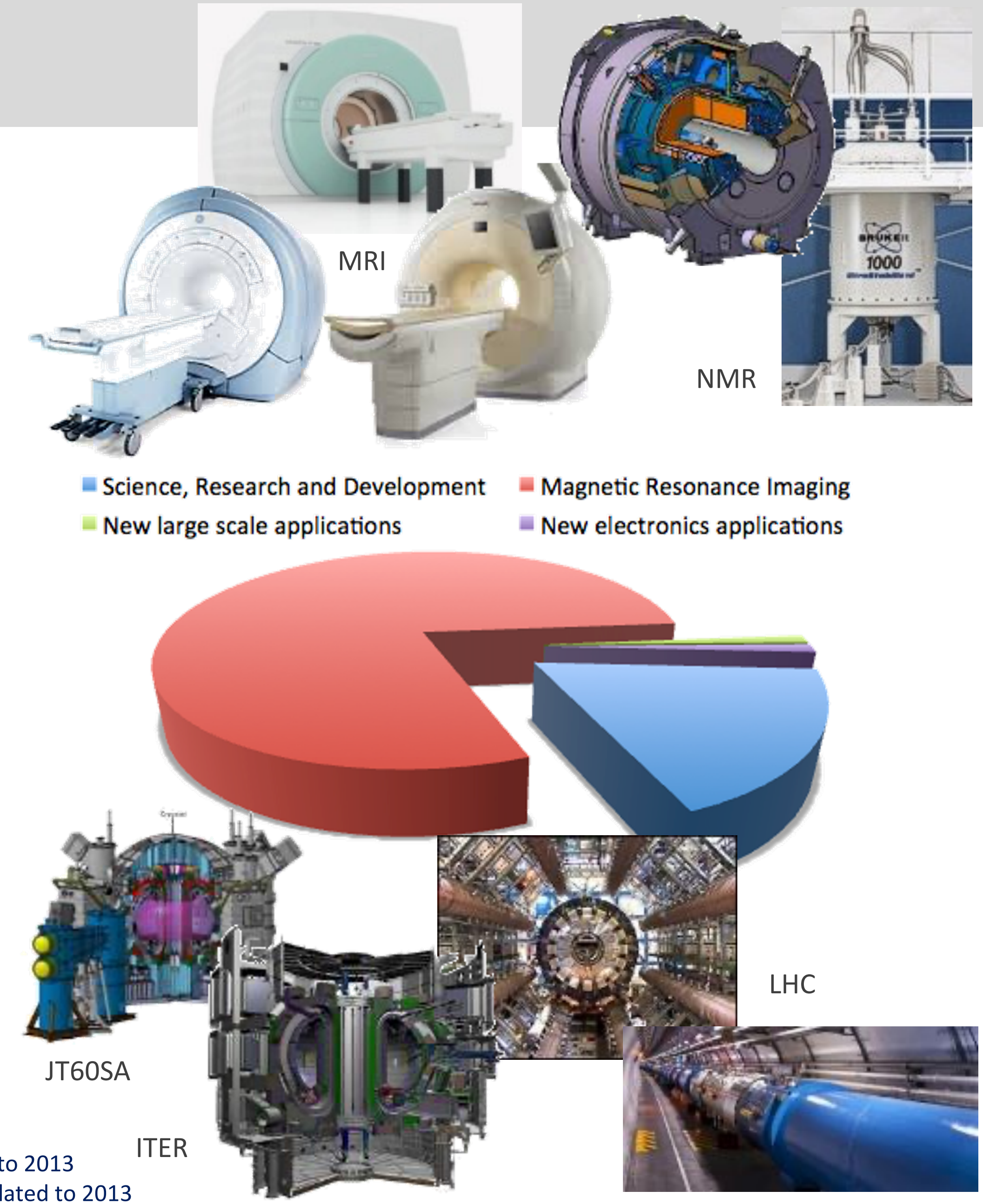
Large variety of wires/tapes/cables

JENG IN LTS AND HTS CONDUCTORS AT 4.2K AND 1.9K



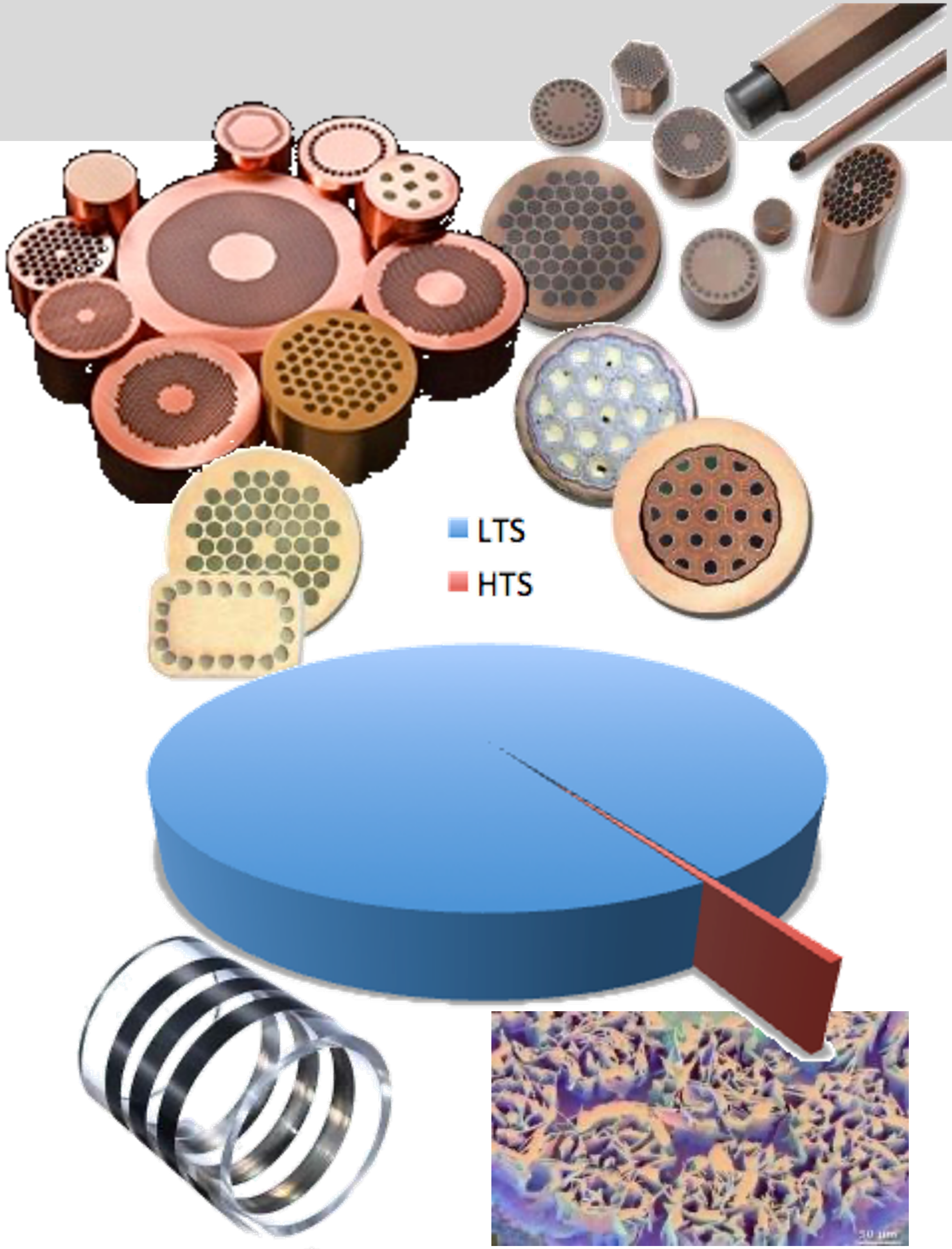
Conductor Source: http://fs.magnet.fsu.edu/~lee/plot/plot.htm

- **At present, the vast majority of the use of superconductors is for magnet applications:**
  - MRI: 5.5 BUSD/year[1]
  - NMR, science and research: approximately 1 BUSD/year[1]
- **Large scale projects (HEP, Fusion) represent only a fraction of the total market:**
  - Evaluated cost of LHC magnet system (material): 2 BUSD[2]
  - Quoted cost of ITER magnet system (material): 1.4 BUSD[3]

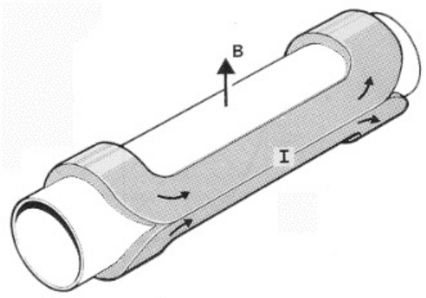


Sources:
(1) from market report at Conectus.org, converted from repored 5.3 BEUR in 2013
(2) Report to the CERN Finance Committee, 2008, reported 1.7 BCHF(2008) escalated to 2013
(3) DOE Assessment of the ITER Project Cost Estimate, reported 1.09 BUSD(2002) escalated to 2013

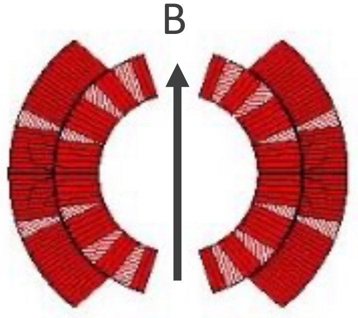
- **Nb-Ti: 1000 t/year, mostly driven by MRI**
- **Nb_3Sn: 10 t/year, mostly driven by NMR and laboratory systems**
- **Big-science projects result in dramatic demands, occasional and time-bound, which need to be accommodated**
  - LHC required 1300 tons of Nb-Ti (300 t/year peak production)
  - ITER requires 300 tons of Nb-Ti and 685 tons of Nb_3Sn (150 t/year peak production)
- **All of HTS (BSCCO, YBCO) and MgB_2 (MTS) is below 1 ton/year, mostly driven by Fusion and Power application R&D**



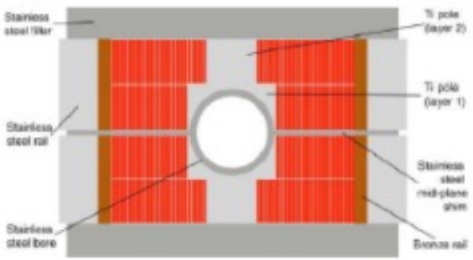
- Most superconducting accelerator magnets rely on saddle-shape coils which in their cross section approximate cos($p\theta$) conductor distributions where p is the number of poles.



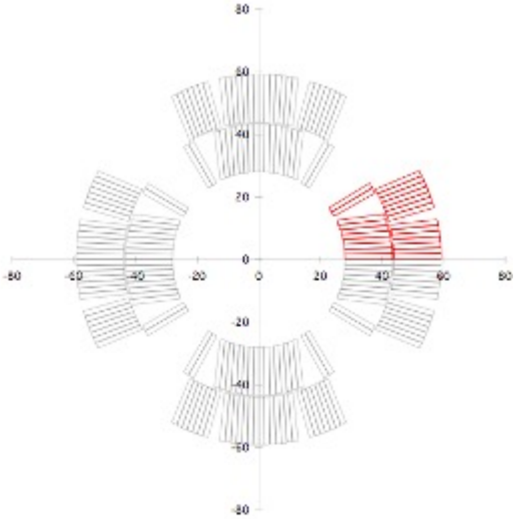
Saddle-shape coil assembly



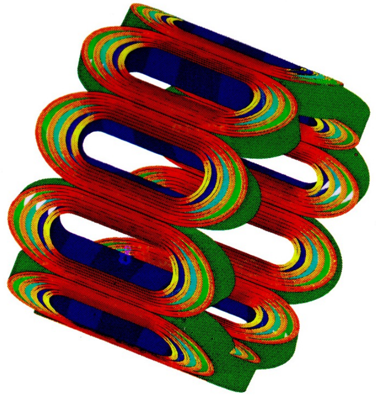
Cosθ dipole coil configuration



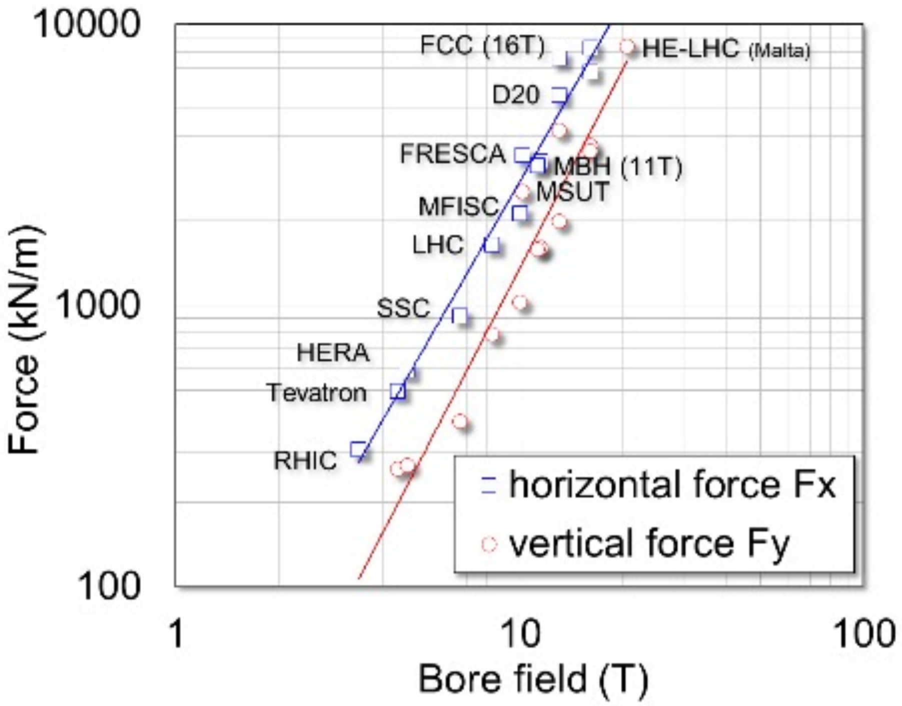
Block dipole coil configuration



Cos(2θ) quadrupole coil configuration



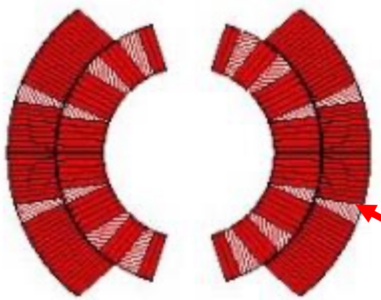
Cos(5θ) decapole magnet configuration



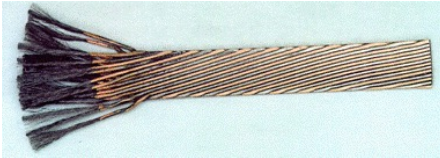
Force per coil quadrant in high-field dipoles built or designed for accelerators applications and R&D

- For a dipole, force proportional to the square of the bore field
- Requires massive structures (high-strength materials, volume, weight)
- Stress limit is usually inside the superconducting coil
- Cooling effects (thermal contraction of materials inside the coil/structure) and gravity are usually negligible

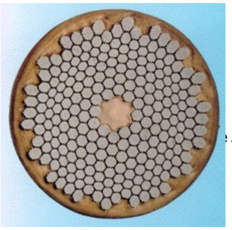
Design of high field magnets is strongly driven by mechanics!!!



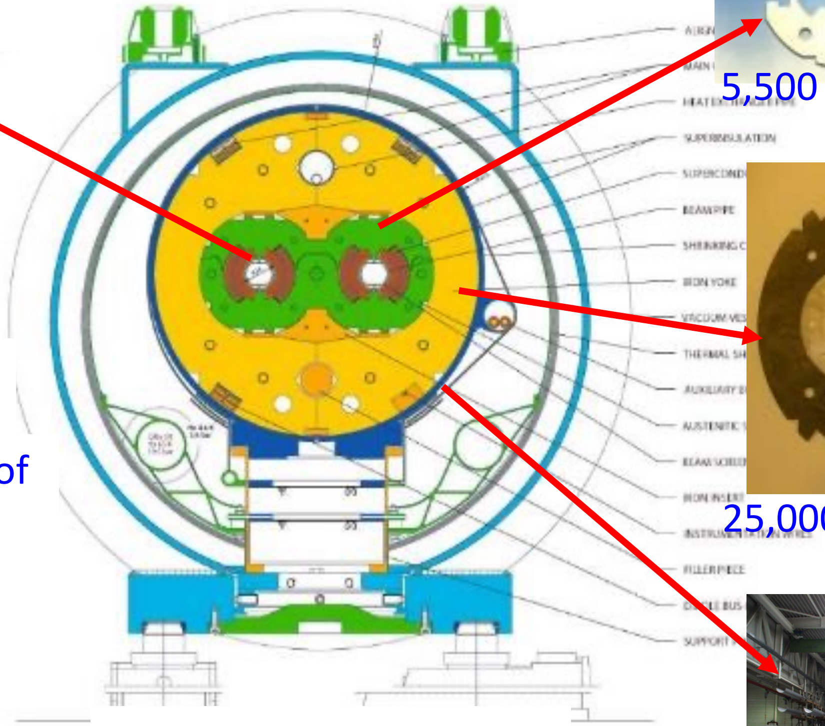
4928 cosθ, two-layer, graded poles



2370 (inner) + 4600 (outer) km of Rutherford-type cables

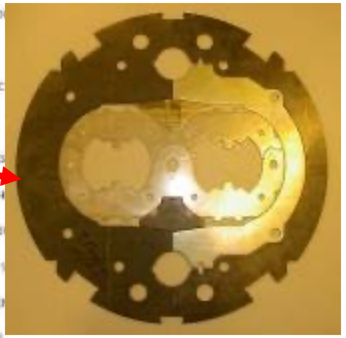


474 (inner) + 736 (outer) tons of Cu/NbTi multifilament composite wires



1232, 2-in-1, arc dipole magnets

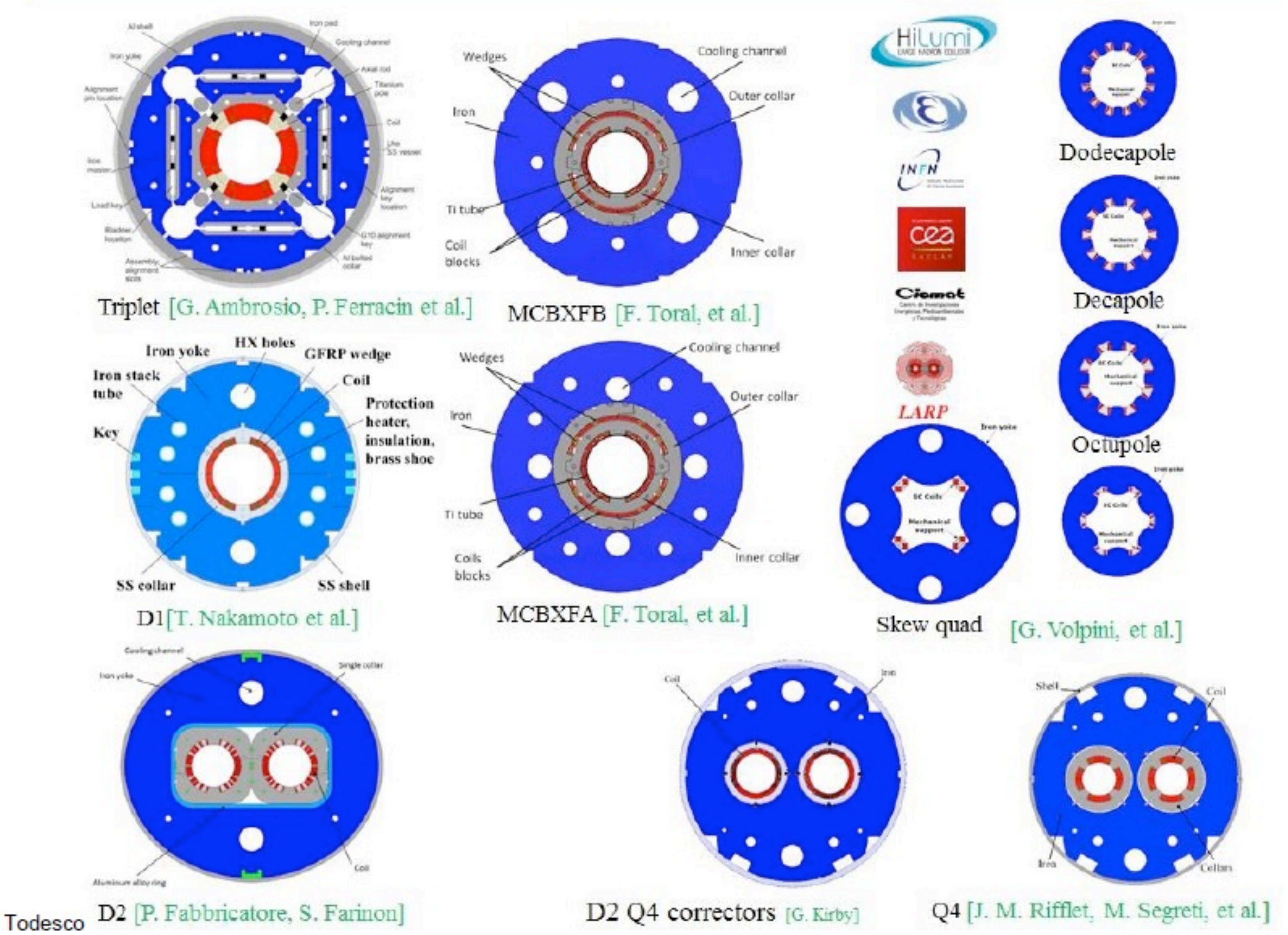
5,500 t of austenitic steel collars



25,000 t of Low-carbon steel yoke

2464 stainless steel half shells

HL LHC SUPERCONDUCTING MAGNET ZOO

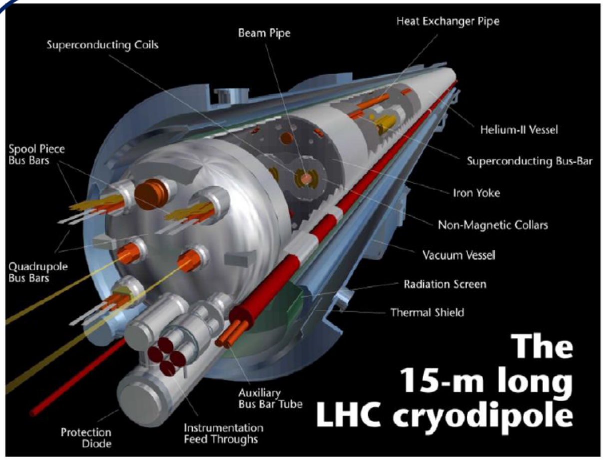


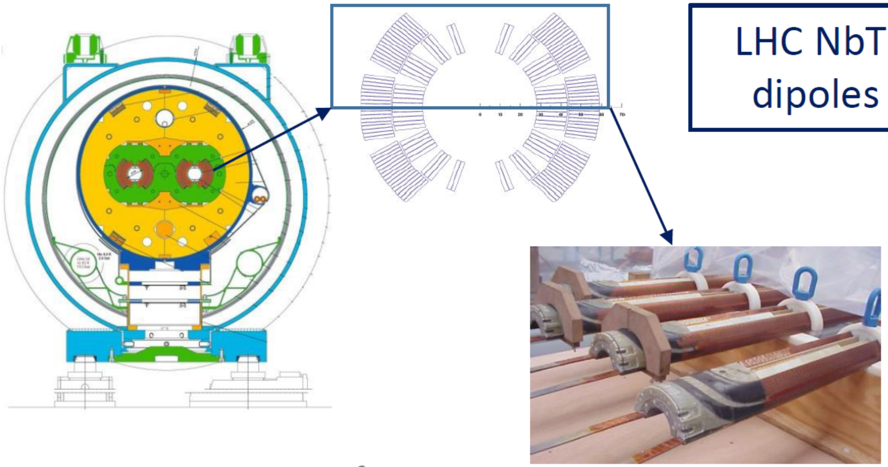
Courtesy E. Todesco

CONTEXT OF MAGNET R&D FOR A FUTURE COLLIDER

LHC Technology

NbTi



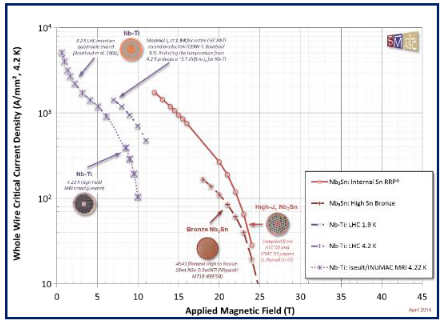


LHC NbTi dipoles

Courtesy of CERN

Beyond LHC

Nb_3Sn



Courtesy of P. Lee

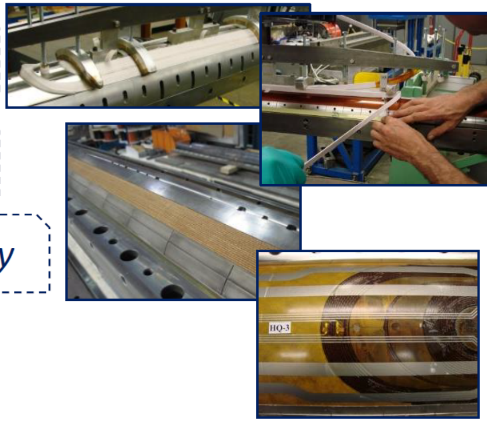
Courtesy of H. Felice

Coil technology

Heat treatment around 650°C

Wind and react technology

Vacuum impregnation with Epoxy



Nb_3Sn strain sensitivity

I_c reduction (reversible)

I_c degradation (permanent)

Strain sensitivity: a challenge impacting all the aspects of Nb_3Sn magnet design & fabrication

TOWARDS 16 T MAGNET - CHALLENGES

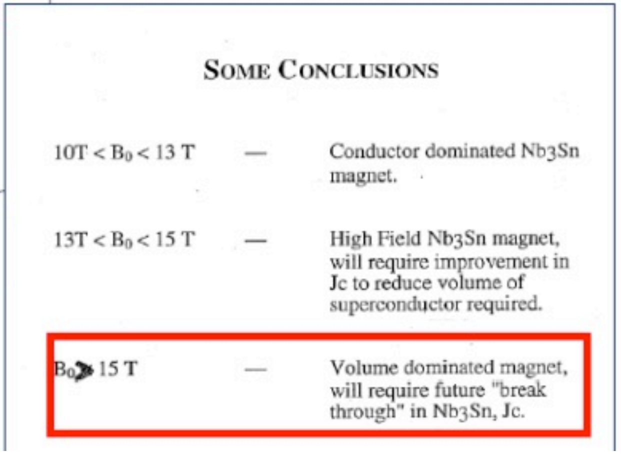
FCC-hh
Future Circular Collider

100 km - **16 T**: 100 TeV (c.o.m)

- Compact cost effective magnets
- Reliable series production
- Field quality
- Fast training magnets

- High Je > 600 A/mm2
- Large Cu fraction Cu/NonCu > 1.2
- Jc (@4.2 K , 16 T) > 1500 A/mm^2
- RRR > 100
- Φ_{eff}< 20 µm

Operation close to critical surface => Ensuring Nb_3Sn integrity during its life cycle



SOME CONCLUSIONS

10T < B_0 < 13 T	—	Conductor dominated Nb3Sn magnet.
13T < B_0 < 15 T	—	High Field Nb3Sn magnet, will require improvement in Jc to reduce volume of superconductor required.
B_0 > 15 T	—	Volume dominated magnet, will require future "break through" in Nb3Sn, Jc.

8

Courtesy of H. Felice

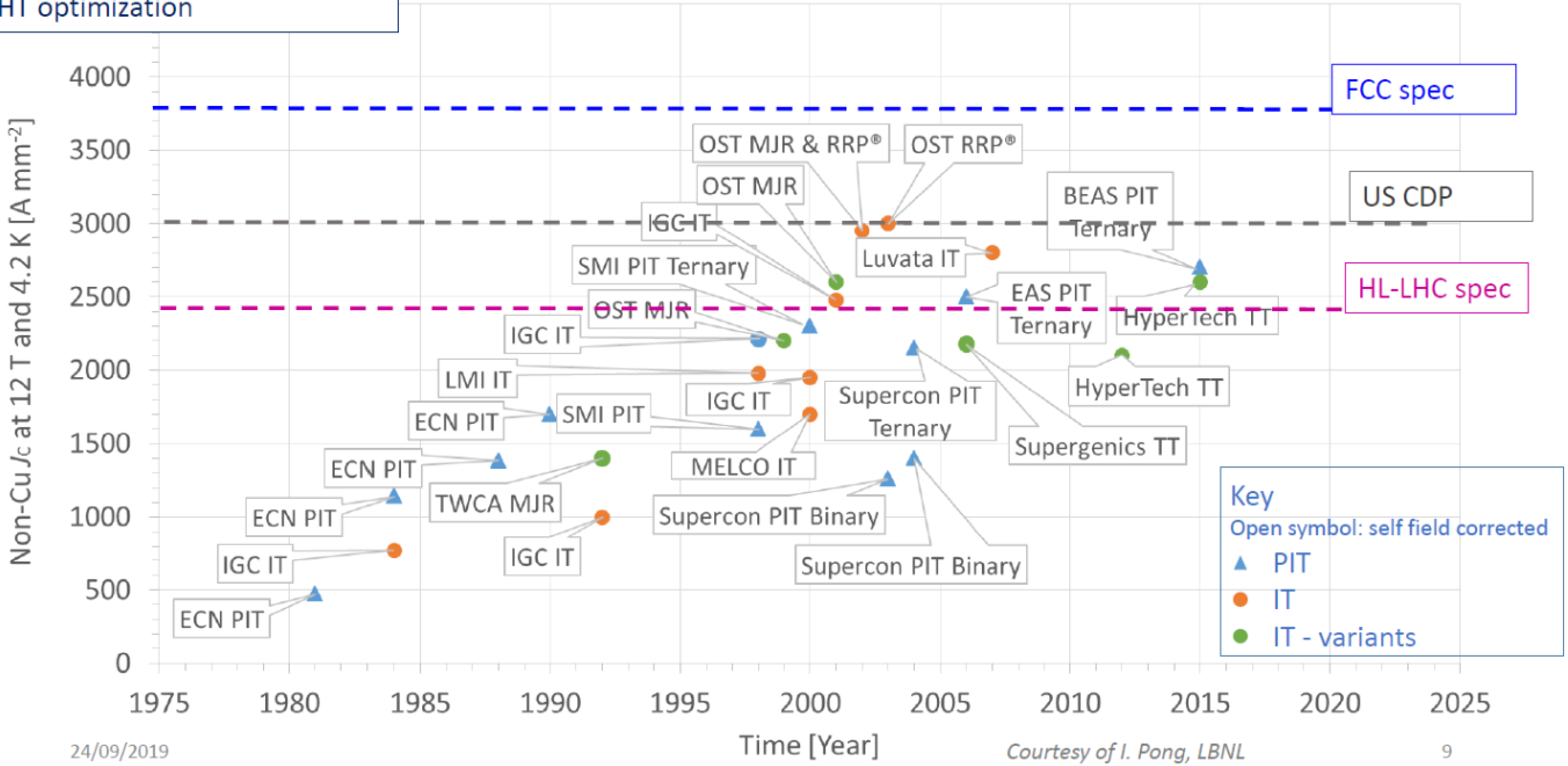
24/09/2019

From LBNL internal report
By Shlomo Caspi, 1990s

Nb$_3$Sn Critical Current Improvements (1/2)

Non Cu Jc improvement through
- Strand architecture
- Strand fabrication process
- HT optimization

A constant Non-Cu J_c improvement



Courtesy of I. Pong, LBNL

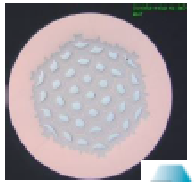
Nb_3Sn Critical Current Improvements (2/2)

CERN FCC Conductor Development Program

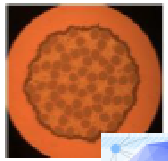
Courtesy of A. Ballarino

Many institutes and industry in Japan, Korea, Russia and Europe

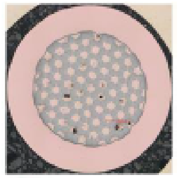
TVEL, Φ = 1mm



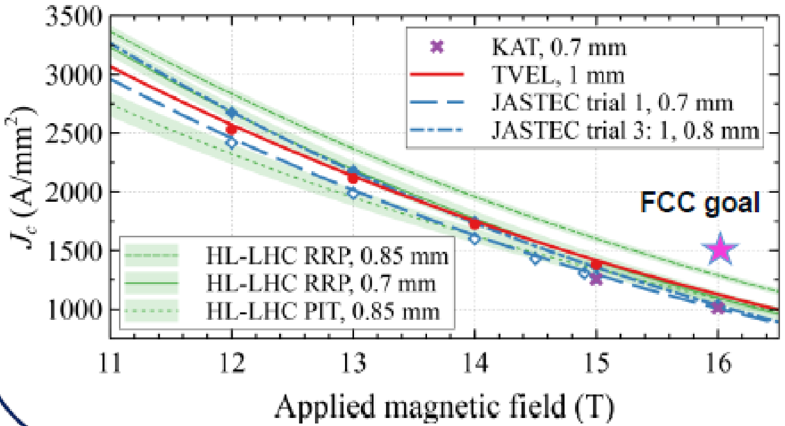
KAT, Φ = 1 mm



Jastec, Φ = 0.8 mm



TVEL · KAT · JASTEC



24/09/2019

Courtesy of H. Felice

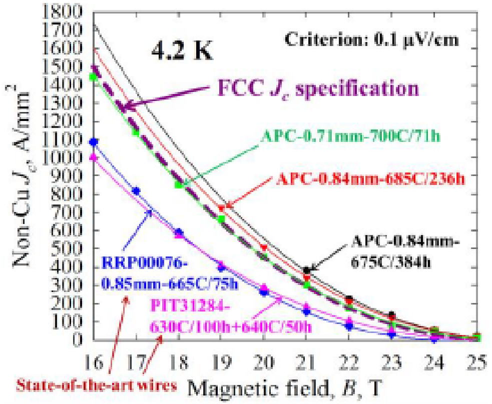
Artificial Pinning Center

Courtesy of X. Xu

Internal oxidation of Nb-1%Zr

- Pinning point: ZrO_2 particles
- enhance J_c

- High J_c but stability < 16 T compromised
- Small Magnetization but J_c compromised



Collaboration between FNAL [LDRD], Hypertech and OSU

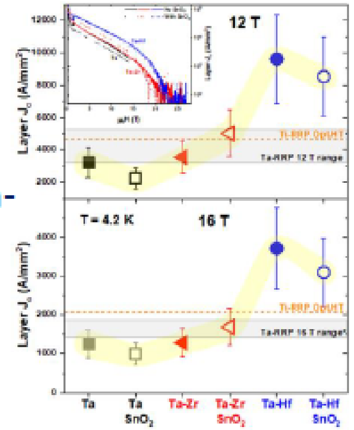
U.S. MAGNET DEVELOPMENT PROGRAM

Hf alloying of Nb-Ta

Courtesy of S. Balachandran

- Improved pinning through Hf dopping
- Nb or NbTa rods can be replaced by Nb-Ta-Hf alloy without change of architecture
- Prototype wire *(Extrapolated values)*

Alloy	SnO_2	$J_{c layer}$ (A/mm²) 12 T	$J_{c layer}$ (A/mm²) 16 T (A/mm²)	Eq. RRP non-Cu J_c
Nb-Ta-Hf	No	9609 ±2744	3714 ±1061	2229 ± 636
Nb-Ta-Hf	Yes	8523 ±2434	3093 ± 883	1856 ± 530



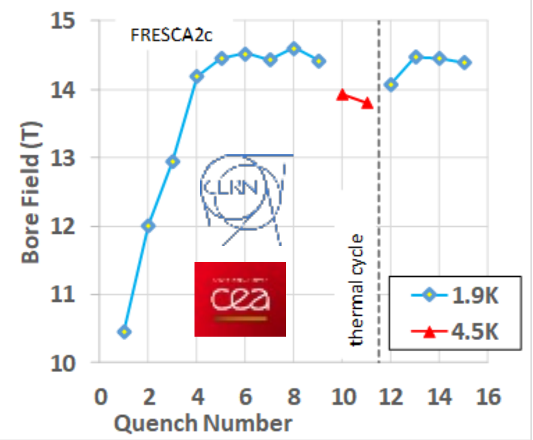
Jan Evetts SUST Award 2019

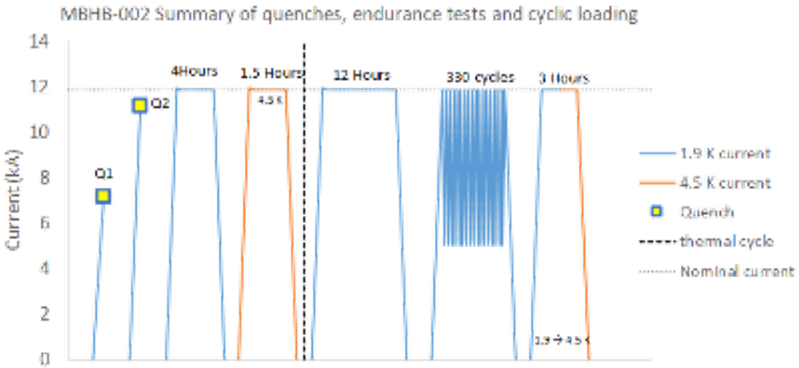
ASC/NHMFL, FSU

11

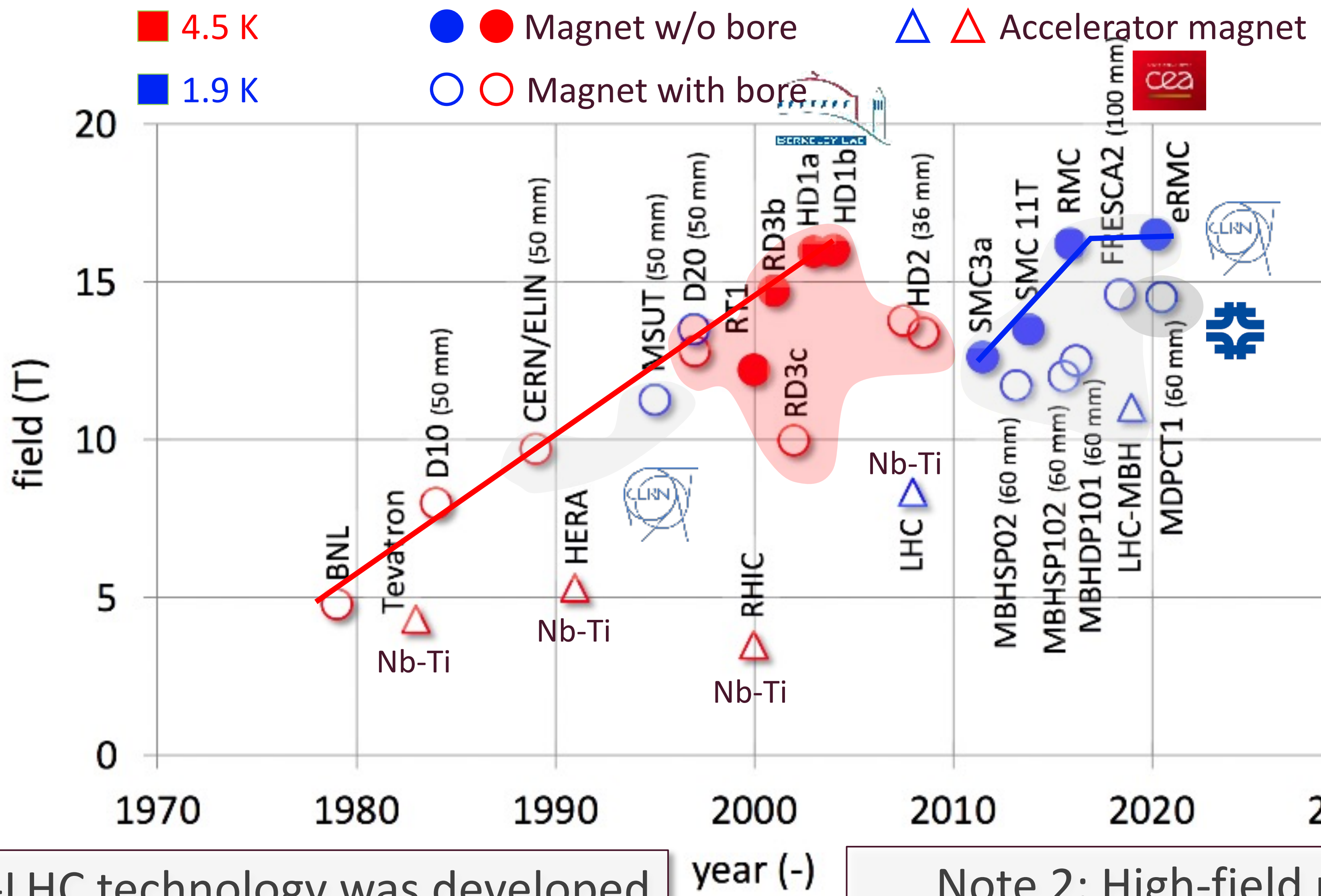
Shows untapped potential of Nb_3Sn
Optimization in progress

Best-of-breed LTS dipoles





Nb$_3$Sn Magnet Summary

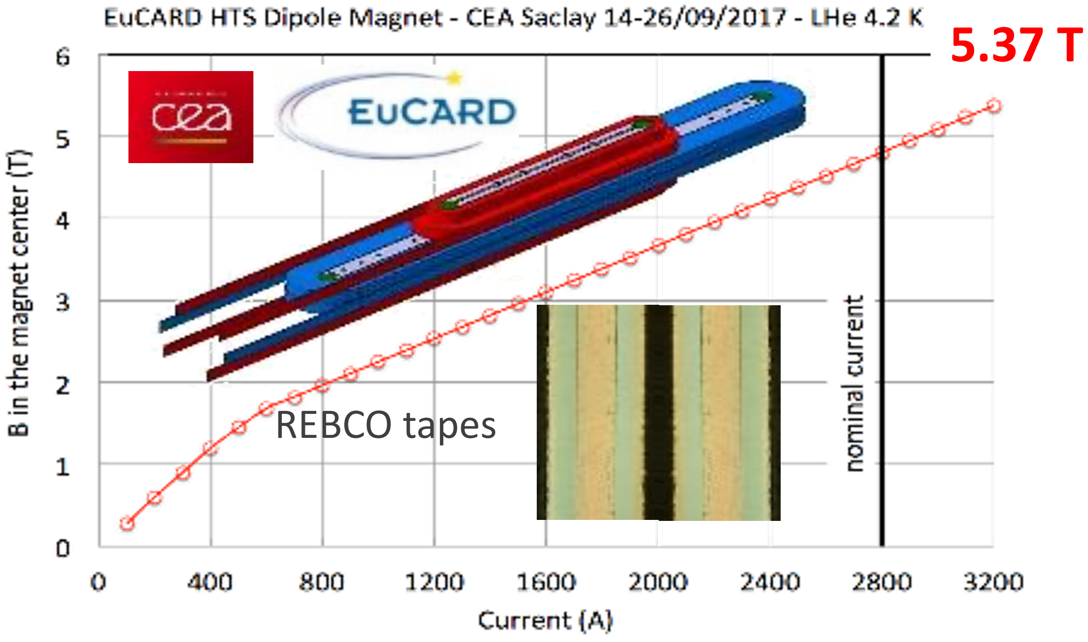


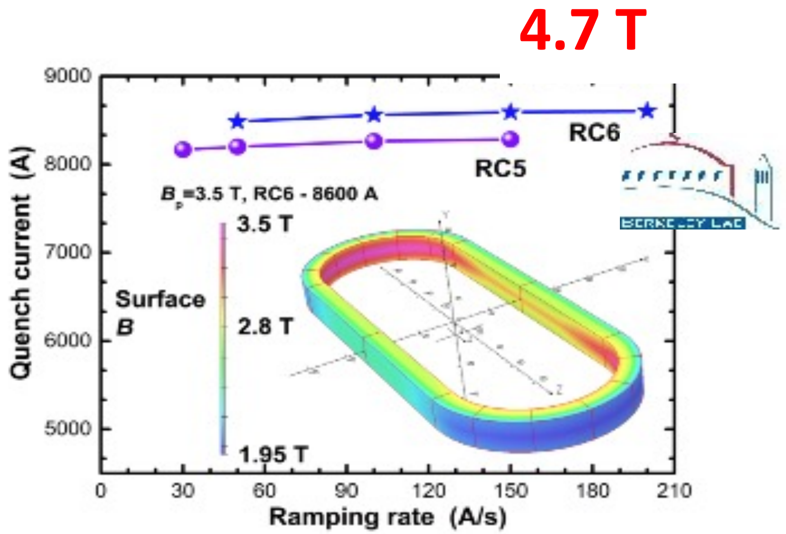
Note 1: HL-LHC technology was developed *well before* inception (1990's to 2000's)

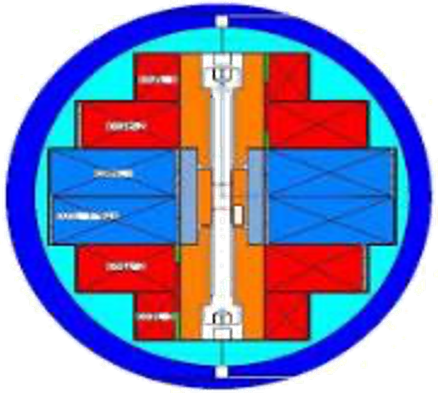
Note 2: High-field magnets are a *long-term business* and continuity is an asset

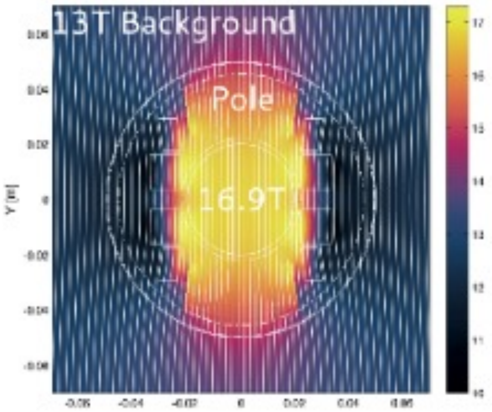
A true worldwide effort on Nb$_3$Sn magnets

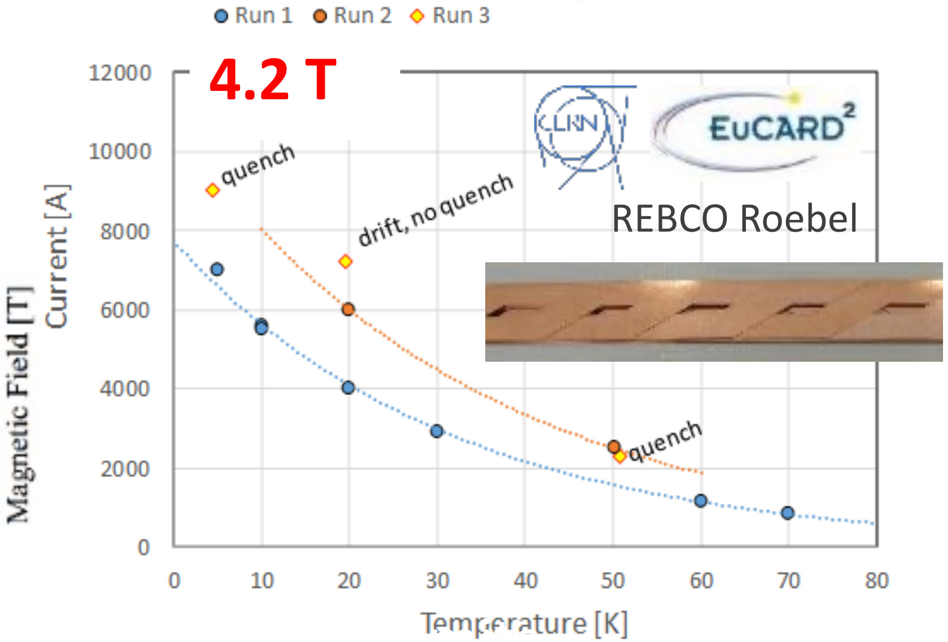
BEST-OF-BREED HTS DIPOLES

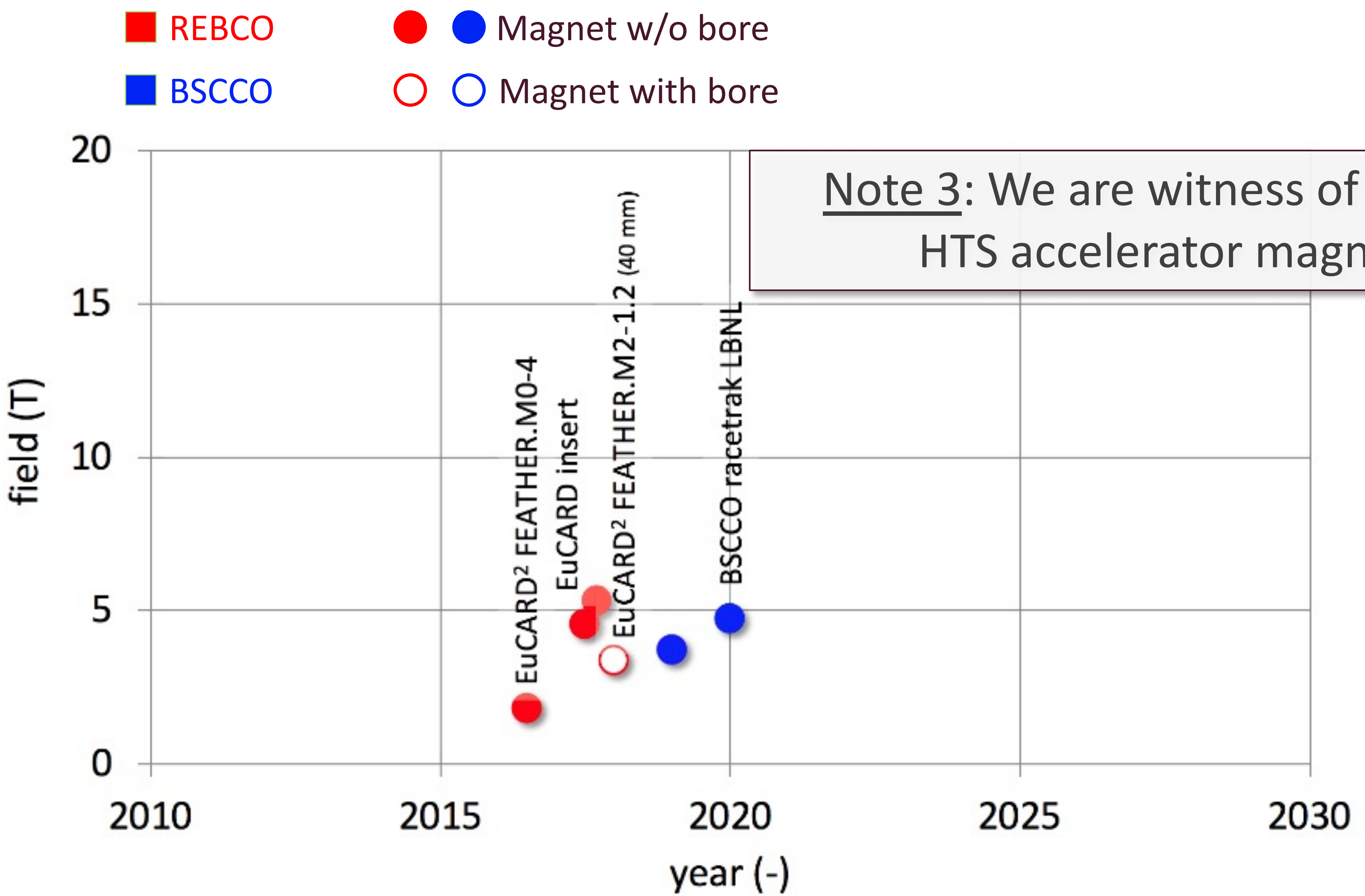












Note 3: We are witness of the infancy of HTS accelerator magnet technology

Record HTS magnets

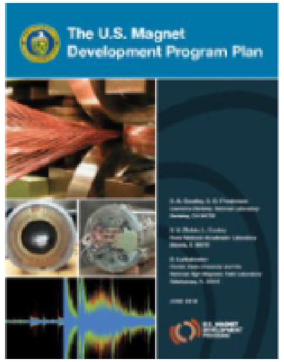
U.S. MAGNET DEVELOPMENT PROGRAM *ASC/NHMFL, BNL, FNAL, LBNL*

Leveraging past experience

Item 2.2 : High Field Dipole Development to Explore the Limits of Nb_3Sn

Item 2.4 : Magnet Science: Developing Underpinning Technologies

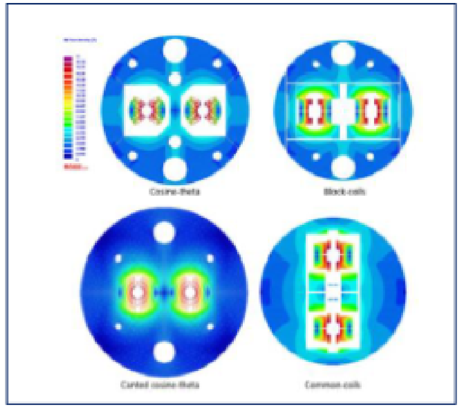
Item 2.5: Superconducting Materials -Conductor Procurement and R&D (CPRD)



FCC hh ee he — EuroCirCol

CEA, CERN, CIEMAT, UNIGEneva, KEK, INFN, TampereU, UTwente

- Design study for FCC CDR
- Conductor development & procurement
- R&D magnets and associated development
- Model magnets

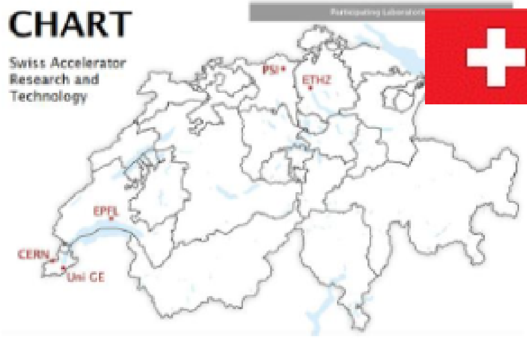


Series of Worskhops on Nb_3Sn technology for accelerator magnets

- **2017:** https://indico.cern.ch/event/665458/
- **2018 :** https://indico.cern.ch/event/743626/
- **2020 in preparation**

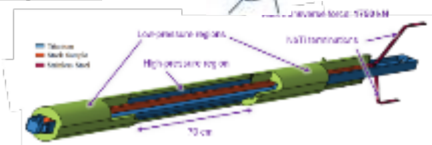
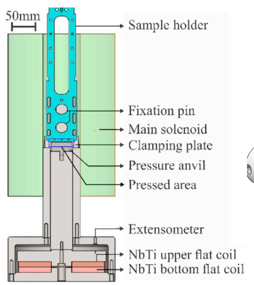
Budker INP Novosibirsk

Ongoing discussion on high field dipole program definition



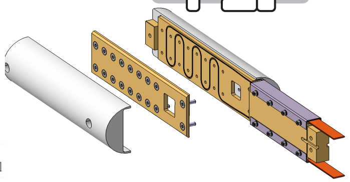
High field magnets development
Focus on innovative concept

Powered Samples

UNIVERSITY OF TWENTE.

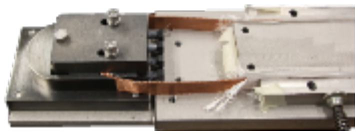
PAUL SCHERRER INSTITUT PSI



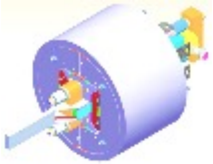
BOnding eXperiment

Mock-ups and Mechanical models

EPFL




SD

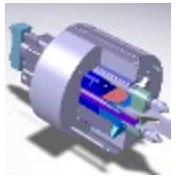


Existing Subscale Magnets

U.S. MAGNET DEVELOPMENT PROGRAM

CCT subscale

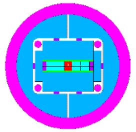
SMC



RMC

Model magnets under development

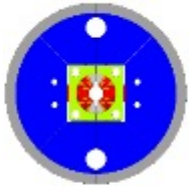
R2D2



10-12 T
Graded racetrack

FALCOND

INFN



12-14 T Double Layer cosθ

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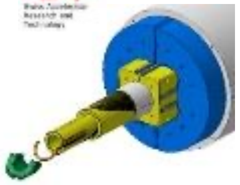
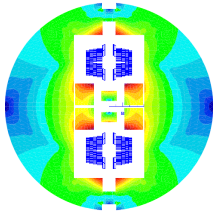
CCT



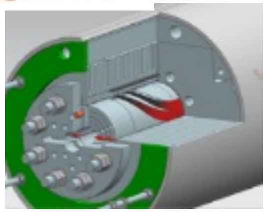
Ciemat

Common Coil



Recent or unique Existing model magnets

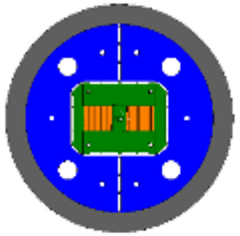
U.S. MAGNET DEVELOPMENT PROGRAM



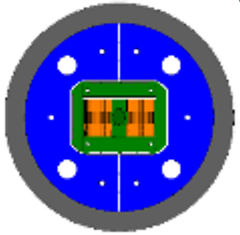
MDPCT

HD3

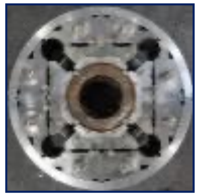
eRMC



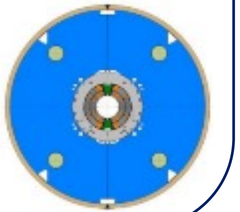
RMM



MQXFS



11 T



Courtesy of S. Izquierdo Bermudez, J.C. Perez, S. Farinon, F.Toral, E. Rochepault, B. Auchman, M. Daly, P. Ferracin, F. Lackner, S. Zlobin, M. Dhallé, B. Bordini, P Bruzzone

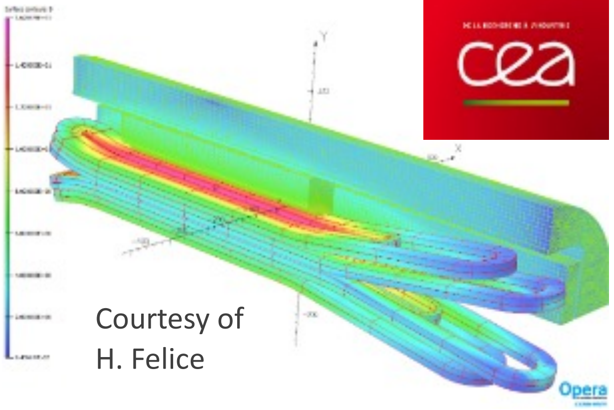
Nb_3Sn MAGNET R&D RESULTS

FCC hh ee he

INFIERI

Conceptual design of **16 T** *block* model dipole for FCC

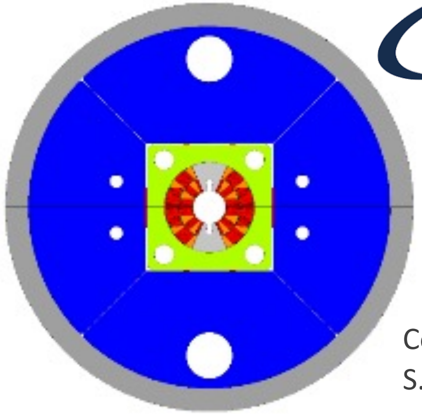
Focus on manufacturing SMC (*process validation*), design and manufacturing of a graded R2D2 (12 T)



cea

Courtesy of H. Felice

INFN



Courtesy of S. Farinon

Conceptual design of a **16 T** *cos-theta* model dipole for FCC

Focus on design and manufacturing a cos-theta, two-layers dipole (12 T)

- Coils manufactured at ASG (Genova),
- Magnet assembly at INFN-LASA (Milano)

CCT technology development towards a **16T** dipole for FCC

CD1 magnet test is on-going in LBNL (11.1 kA/6.1 T reached !)

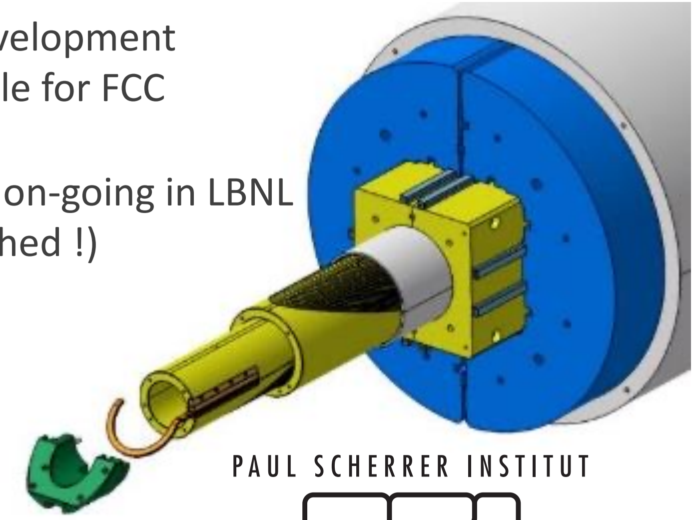


CHART
Swiss Accelerator Research and Technology

Courtesy of B. Auchmann

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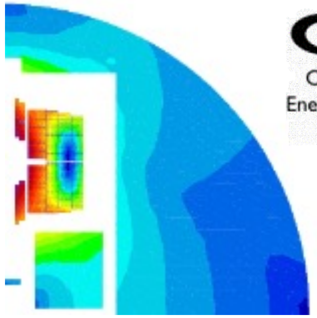


Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Courtesy of F. Toral

Conceptual design of a **16 T** *common coil* dipole model for FCC

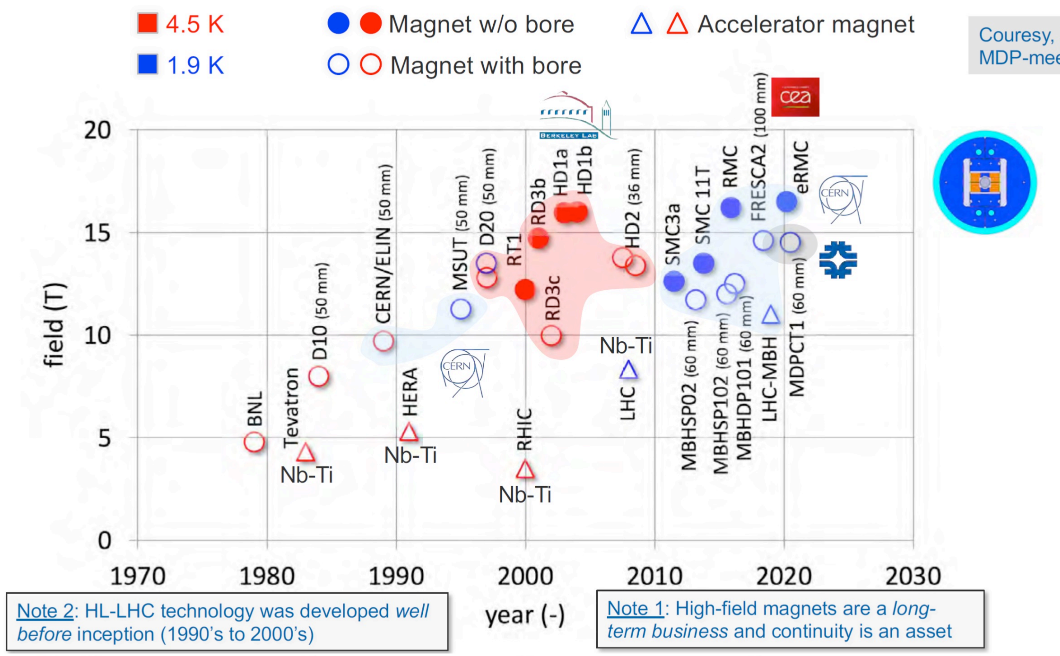
HIGH FIELD R&D ROADMAP FOR THE FUTURE

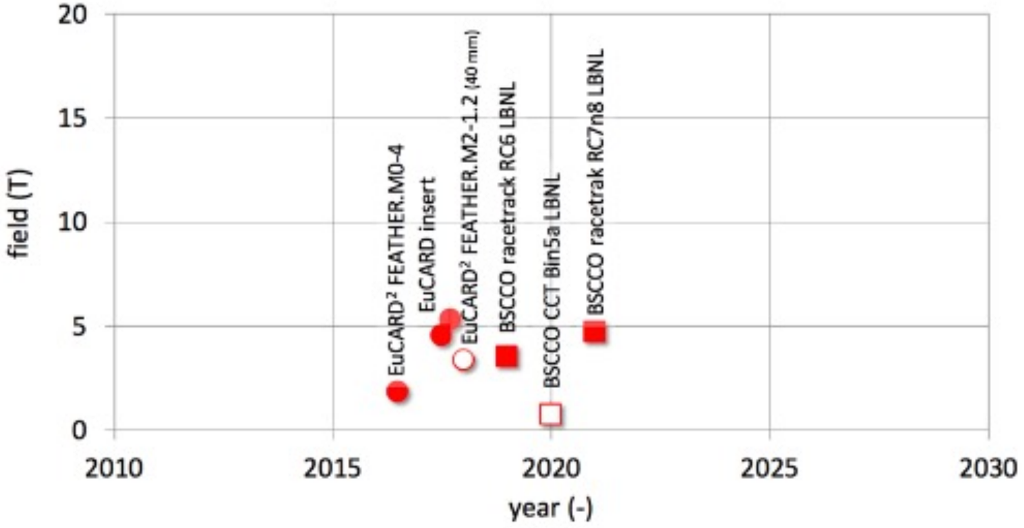
MOTIVATION

- **High Field Magnets (HFM) are among the key technologies** that will enable the search for new physics at the energy frontier.

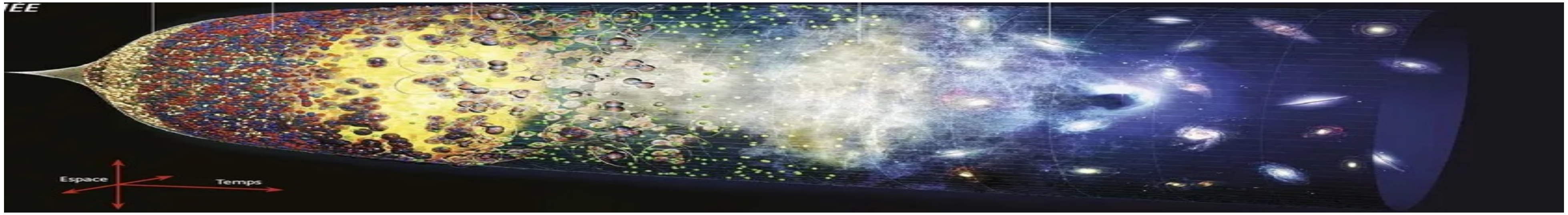
- Approved projects (HL-LHC) and studies for future circular machines (FCC, SppC) call for the **development of superconducting magnets that produce fields beyond those attained in the LHC** .

- **Progress in highest field attained** in European and international programs (EU-FP6 CARE , EU-FP7 EuCARD, EuCARD2, HL-LHC , ARIES, on-going I-FAST, HFM & US-DOE programs, etc…) **are encouraging**





WHICH TIMELINE FOR THE FCC ?



Background on magnet development

Where are we?

What do we need for FCC-hh?

Strong R&D programs in 2000s

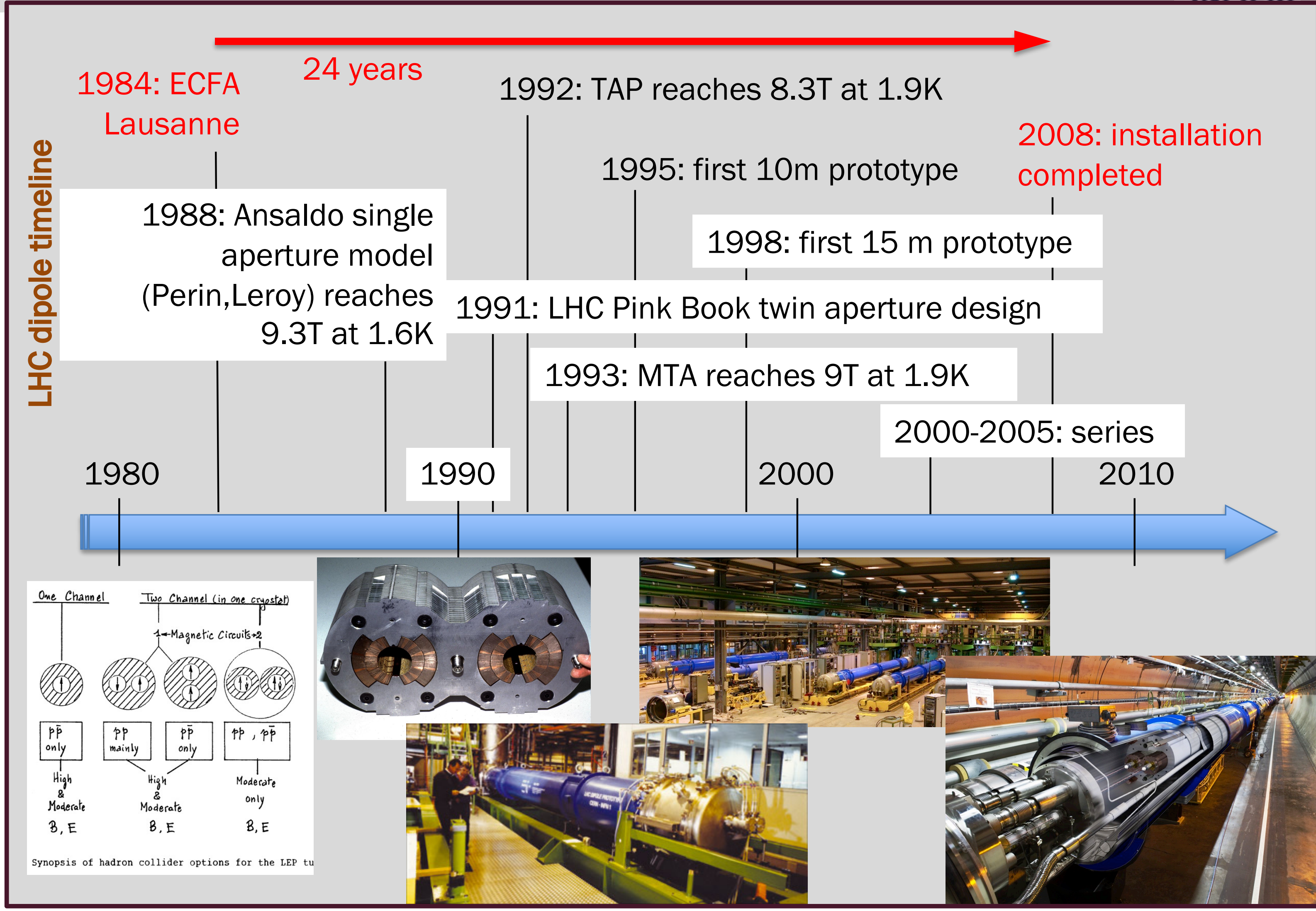
Courtesy of H. Felice

- Successful 16 T Nb_3Sn magnets without bore
- Encouraging 13-14$^+$ T Nb_3Sn short models
- Successful 11$^+$ T Nb_3Sn <u>long</u> dipoles and quadrupoles <u>**to be installed in HL-LHC**</u>

The path to next generation magnet technology for a collider is complex:

- Need R&D to probe concepts, develop and understand potential
- Need robust industrial suppliers of conductor
- Need to ready a given technology for a project
- Need to develop industrial partners for magnet production
- And finally need to produce reliable, cost effective magnets for the next collider

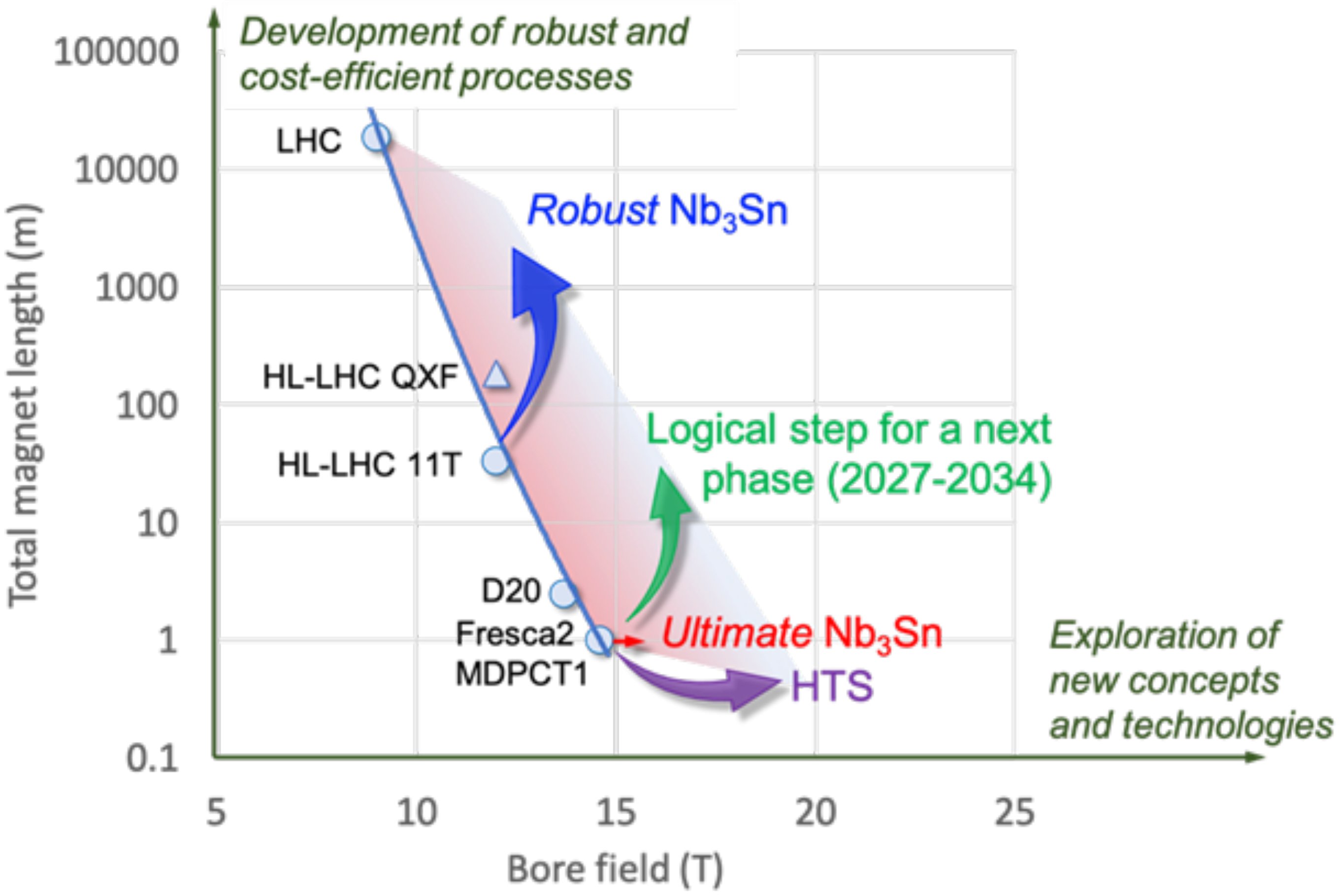
Requires a strong ecosystem of laboratory, University, and industrial partners



Courtesy of Luca Bottura and Soren Prestemon

Goals of a High Field Magnets R&D Program for FCC

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



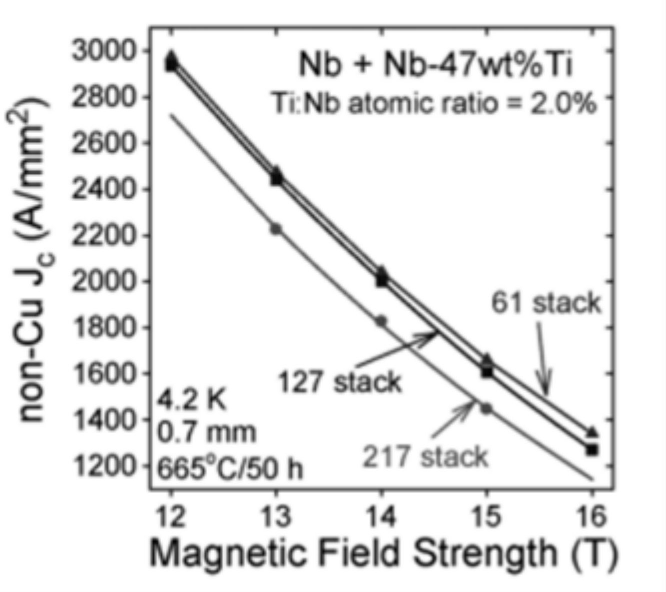
- **Other key parameters:**
  - Cost of Magnets & R&D
  - Timeline of a realistic development
  - Potential for wider societal applications
  - Training and education

STATE OF THE ART - INITIAL FINDINGS - 1

▶ Conductors – Nb3Sn

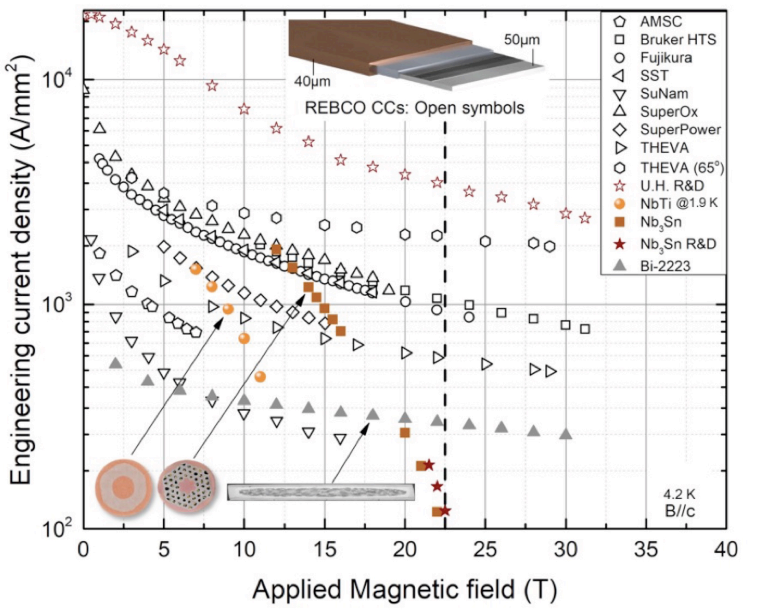
Nb3Sn is reaching the upper limit of performance.

Advances in composition and architecture need to be consolidated (laboratory), and made practical for large-scale production (industry), including considerations on all performance parameters (mechanics, magnetization – laboratory; homogeneity, unit length, cost – industry).



PARRELL et al. IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 19, NO. 3, JUNE 2009

Supercond. Sci. Technol. **34** (2021) 053003 A.C. Wulff et al.



▶ Conductors – HTS

Spectacular electrical performance of HTS tapes, the challenge is now to combine critical current with mechanical and protection properties.

High temperature operation (20 to 65 K) is an interesting option also driven for other fields (fusion and power machinery).

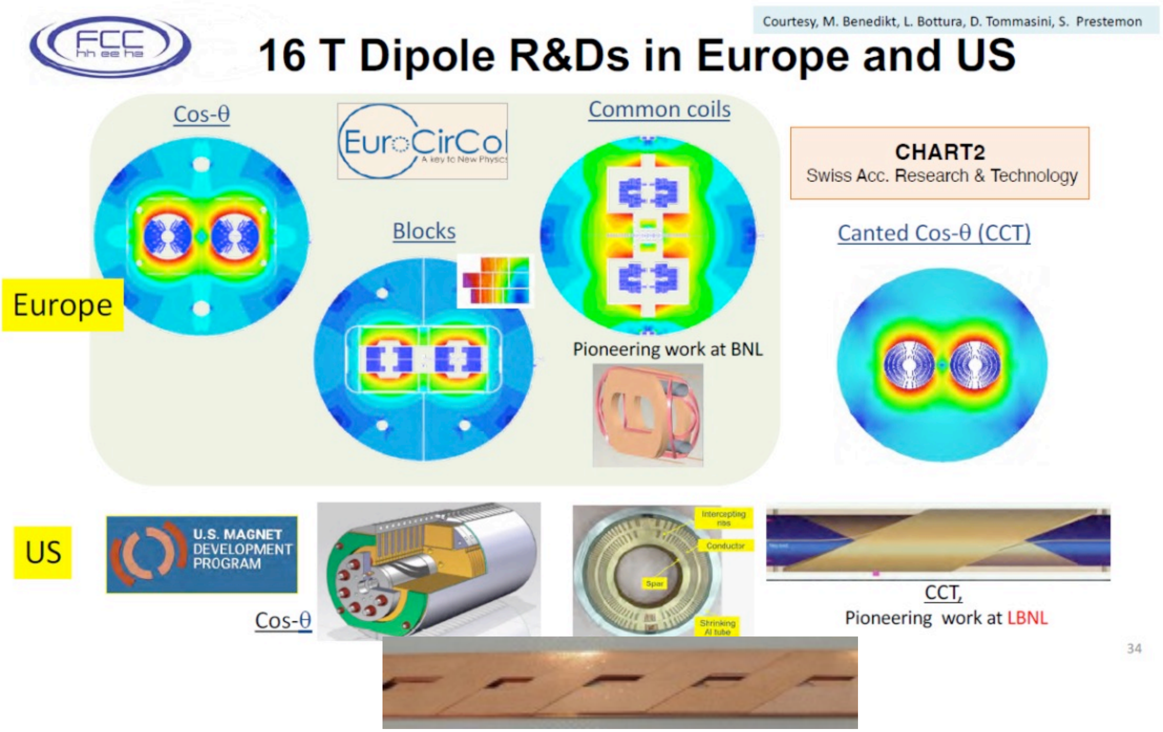
Industry drive for high-field performance is independent of HEP (cost of HTS will decrease because of substantial investment from fusion and power applications).

STATE OF THE ART - INITIAL FINDINGS - 2

- **Magnets** Length effects and electro-thermo-mechanics of Nb3Sn magnets are a crucial issue (11T experience). R&D should be based on a combination of models and real length prototypes.

An initial tentative to identify suitable design options for the various field levels targeted:

- 2-layer cos-theta suitable up to 12 T
- 4-layers cos-theta or blocks for the 14-16 T range
- Common coils to resolve the issue of the end
- CCT or other stress managed concept beyond 15-16 T



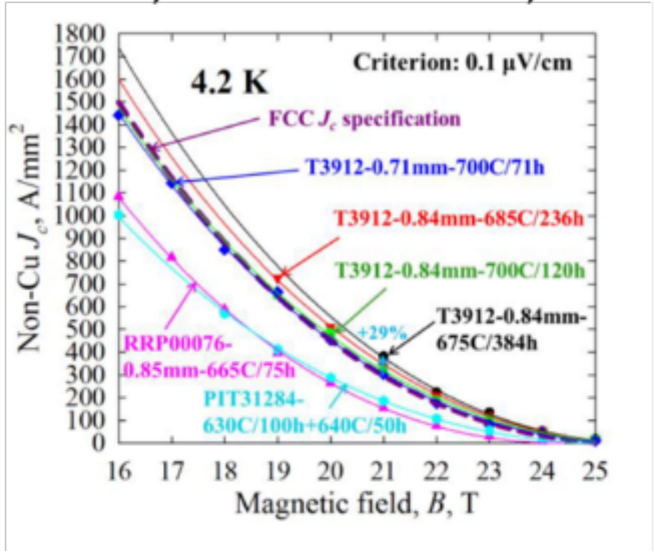
A decision on a feasible, cost-effective and practical operating field will be one of the main outcomes of the development work planned in the coming years.

We need a focused study on what is the best HTS cable configuration for magnet applications , targeted at magnet construction (winding of the ends) and operation (transposition)

▶ Nb_3Sn Conductor

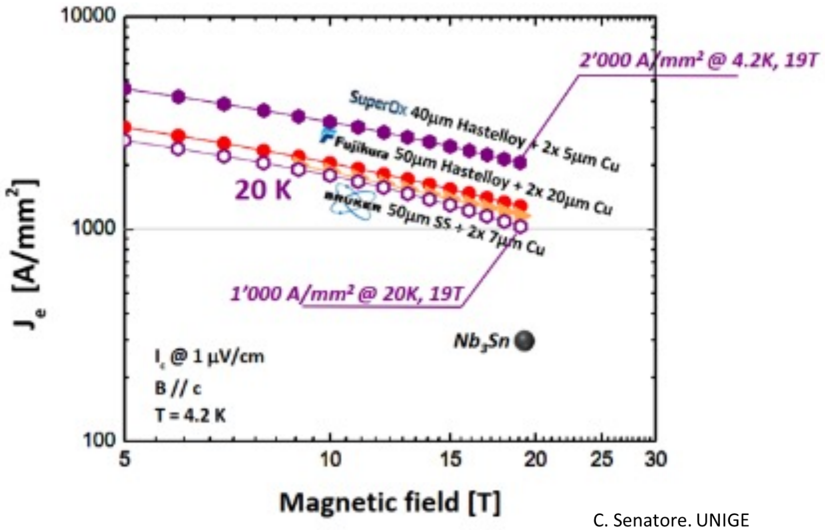
- Advance performance of Nb3Sn wires beyond present state-of-the-art, with a target 1500 A/mm2 at 16 T (mechanical properties, magnetization & stability, cost…).
- Develop cables with high engineering current density, $J_E \approx 600$ A/mm^2, appropriate to yield a compact and efficient coil design.
- Increase the number of qualified manufacturers of HEP-class Nb3Sn conductor and make the material less expensive in view of a demonstration of production scale-up.

X. Xu et al, arXiv:1903.08121, 2019



▶ HTS Conductor

- Focus is on **REBCO** conductor (exploit complementarity with US for Bi-2212)
- Industrialize production to assure feasibility of long - 1 km target – unit lengths and reduce the cost to make future large-scale applications affordable.
- Develop, qualify and identify the type of cable suitable for accelerator quality magnets (stack, CORC, Roebel, novel concepts);
- Study electrical insulation and suitable impregnation processes;



C. Senatore. UNIGE

- Develop ultimate (towards 16 T) field designs in parallel to samples and subscales in an agile mode that incorporates insights from previous steps.

- Develop Nb3Sn magnet technology for robust (first step 12 T target) and scalable manufacturing for long magnets and promotion of automation and innovations leading to simplified manufacturing processes,

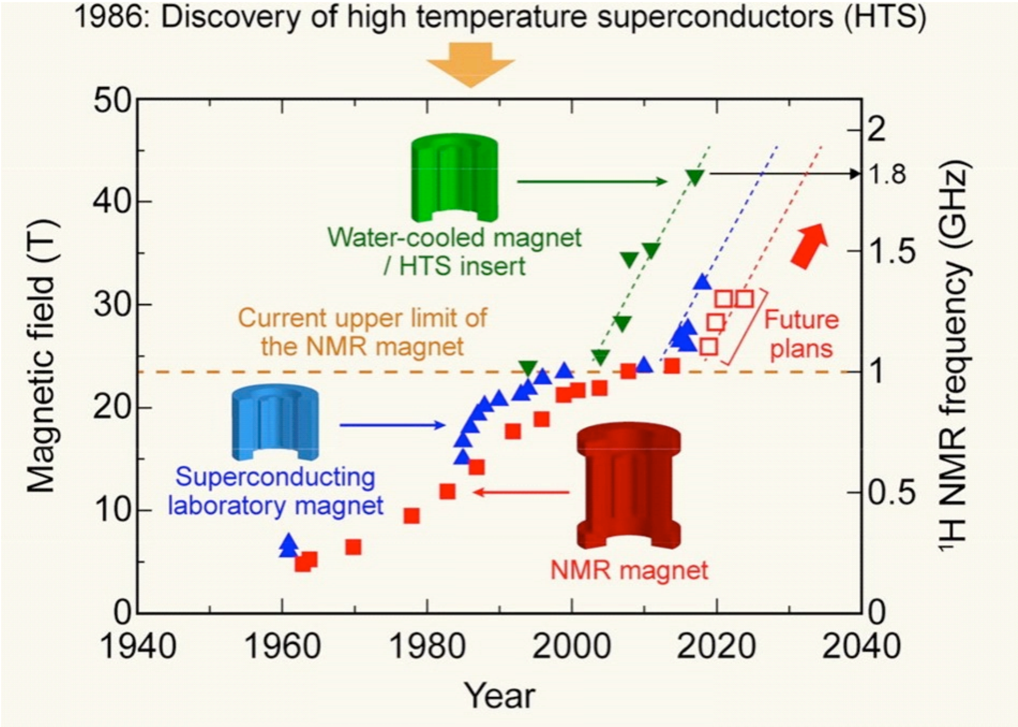
- Complete the knowledge of material parameters and proper implementation of coil and other materials as well as interfaces in 3D models

- Manufacture and test HTS sub-scale and insert coils as a "R&D vehicle" and demonstration of operation beyond the reach of Nb_3Sn.

- Explore the possibility of intermediate temperature range (10-20 K) and dry magnet (conduction cooled).

Other Applications of high field magnets

Historical Evolution of NMR Magnets



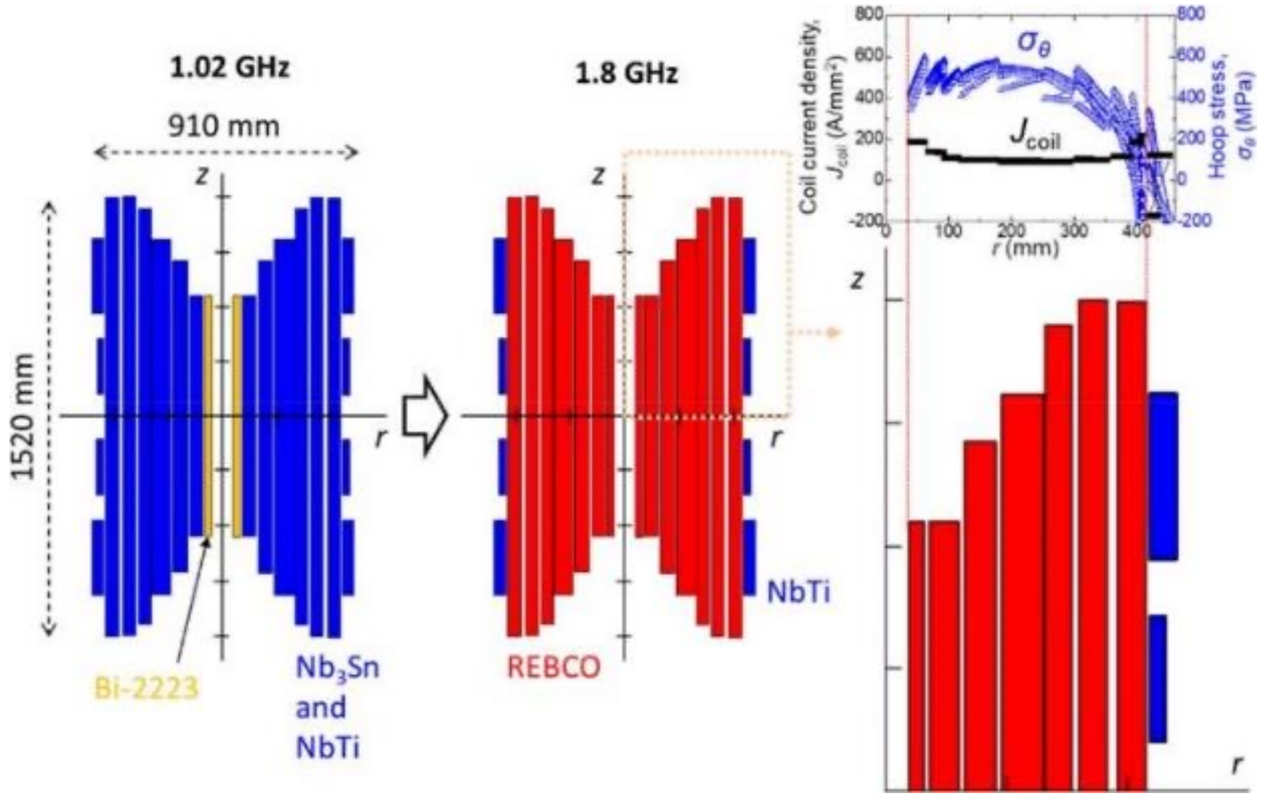
SOURCE: Maeda H., Yanagisawa Y. "Future prospects for NMR Magnets: A Perspective". Journal of Magnetic Resonance 306 (2019) 80-85

The Bruker Ascend 1.2GHz NMR installed at the ETH (Zurich)

SOURCE: https://chab.ethz.ch/en/news-and-events/d-chab-news/2020/06/8-tons-of-hope-worlds-strongest-nmr-magnet-at-eth.html

Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

FUTURE: NMR Magnets with more HTS



Example of preliminary design of the 1,8 GHz LTS/REBCO NMR Magnet. Red-colored área represents REBCO coil while the blue-colored área corresponds to the LTS coils . Lower table shows the main figure of merits for the different HTS options

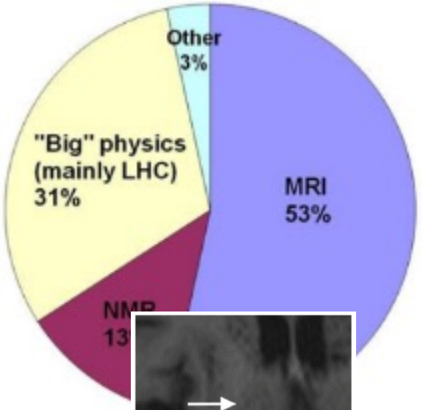
SOURCE: Maeda H., Yanagisawa Y. “Future prospects for NMR Magnets: A Perspective”. Journal of Magnetic Resonance 306 (2019) 80-85

Table 1
Comparison of three promising HTS wires.

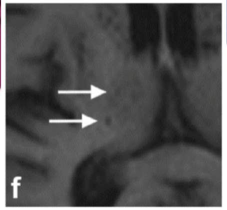
	Bi-2223 wire	Bi-2212 wire	REBCO wire
Critical current density at 30 T at 4.2 K	Lowest	Middle	Highest
Stress tolerance	200–400 MPa	200 MPa	500–700 MPa
Effect of screening current	Medium	Smallest	Largest
Single piece length of the HTS wire (2019)	<1 km	A few hundred m	<500 m

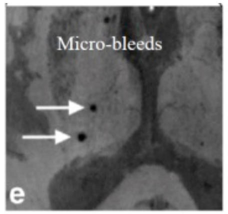
Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

PRESENT: State of the Art in Conventional SC MRI Systems & HFM MRI Systems



MRI represents the biggest magnet sector for applications of superconductivity



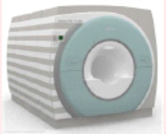


Increasing the field means increasing the resolution

ASG Magnet for NHI (USA) & NRI (Korea)

2 MRI Systems @ 11.7T

ISEULT Magnet for NEUROSPIN
11.72 teslas on July 18, 2019.

Field	1,5 T	3 T	7 T	10,5T	11,75 T
					
	GE-SHFJ/CEA	Siemens	Siemens	Minneapolis	Iseult/ Neurospin
Length (m)	1,25 - 1,7	1,6 - 1,8	~ 3	4,1	4
Diameter (m)	1,9 - 2,1	1,90 - 2,1	> 2,50	3,2	4,6
Mass (tons)	~ 5	~ 8	~ 25	~110	~ 135

75% of the market | 25% of the market | 75 units since 1998 — ULTRA HIGH FIELD MRI

	NIH/NRI	Iseult
Nominal current	246 A	1483 A
Inner diameter	**68 cm**	**90 cm**
Outer diameter	2.7m	5m
Length	4m	5.2m
Shielding	Passive	Active
Mass	820 tons (magnet: 70 tons iron: 750 tons)	132 tons
Operation mode	Persistent	Driven-mode
Temperature	**2.3K (saturated)**	**1.8K (superfluide)**
Helium bath pressure	64 mbar	1.2 bar
Helium volume	3000L	7000L
Stored energy	194 MJ	338 MJ
Inductance	6400 H	308 H

49

SOURCE: L. Quettier "Magnetic Resonance Imaging". October 2020

Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

NEXT STEP: Boost MRI Technology and magnet technology in general to 14+ Tesla, 600 + MHz

	500 MHz Iseult	600 MHz
Center field, tesla	11.7	14.1
Uniformity	0.5 ppm @ 22 cm DSV – brain imaging	
Warm bore	90 cm	60 – 70 cm
Magnet length	5.2 m	3 – 3.5 m
Peak field	11.8 T	14.5 T
Operating temperature	1.8 K	4.2 K
Persistent operation	Driven	TBD
Stored energy	338 MJ	120 – 180 MJ
Current	1.5 kAmp	TBD
Current density	25 to 39 Amp/mm²	50 – 70 Amp/mm²
Magnet technology	Double-pancakes, shielded	Compensated solenoid, shielded
Conductor type	NbTi	NbTi and Nb_3Sn
Conductor weight total Nb_3Sn and/or HTS	84 tons -	12 to 25 tons 1 to 2.5 tons

FUTURE: Even higher HFM MRI

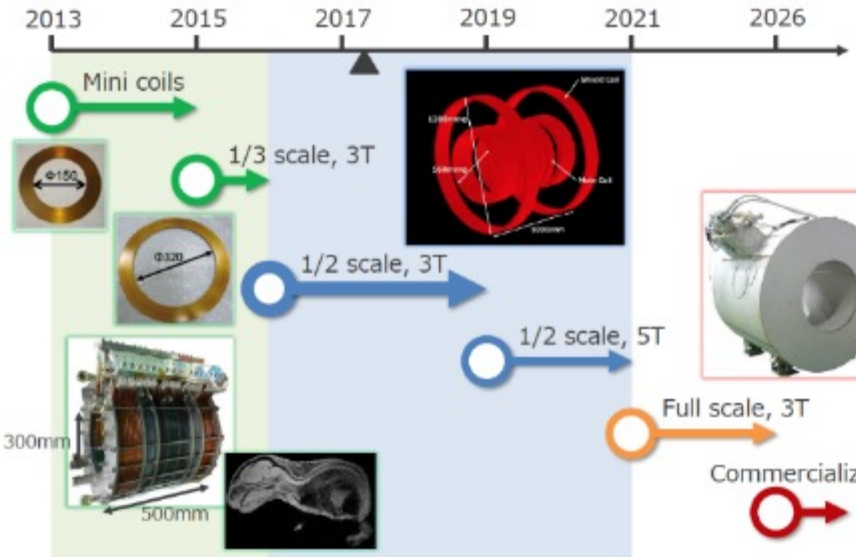
SOURCE:L. M. Parizh. "Ultra-High Field Superconducting Magnets for Magnetic Resonance Imaging "-MT26 Vancouver 2019

FUTURE: Ultra Compact MRI based on HTS

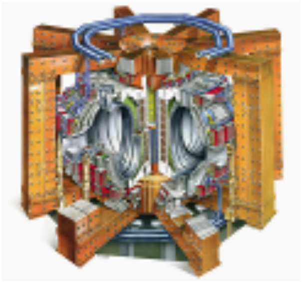
Since 1999, different configurations have been proposed to develop ultra compact MRI systems based on BiSCCO, YBCO or ReBCO at moderate fields. The absence of He and the compactness allows the integration and even the mobility for emergency diagnostics.

Mitsubishi Electric is involved in a program for developing a full scale 3T HTS MRI system.

SOURCE: M.Oya et a. "Development of a 3T HTS Magnet for MRI" Mitsubishi Electric Corporation . 25th Conference on Magnet Technology.



Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe



Tore Supra

25 m³

Q ~ 0

400 s

1,5 MA

4.2 T

JET

80 m³

Q ~ 1

30 s

5 MA

3.5 T

Fusion Power: 500 MW

Plasma Volume: 840 m^3

Q ≥ 10

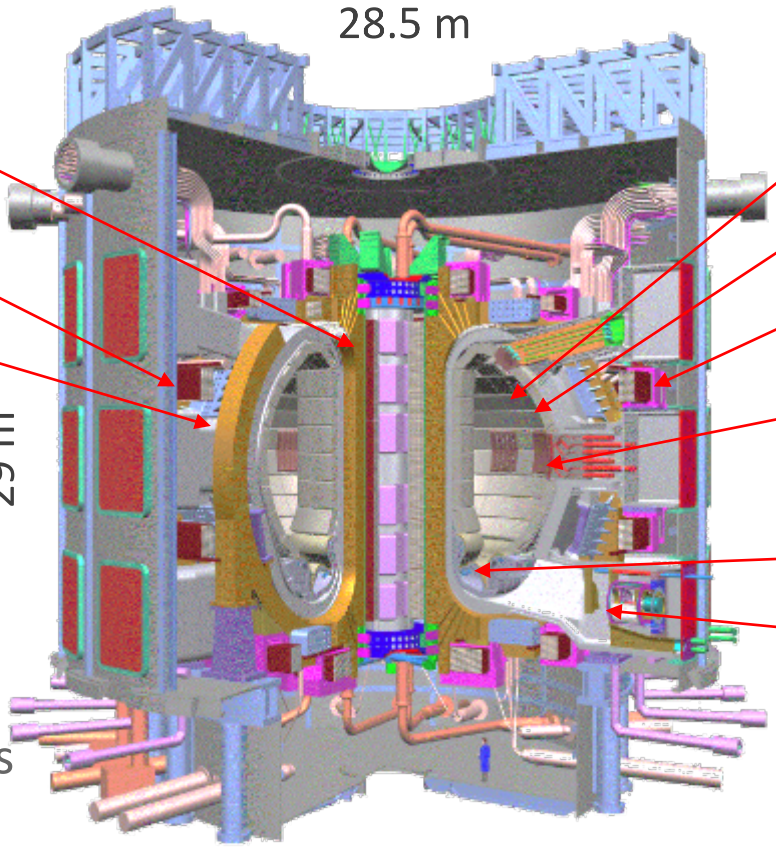
Plasma Inductive Burn Time ≥ 400 s

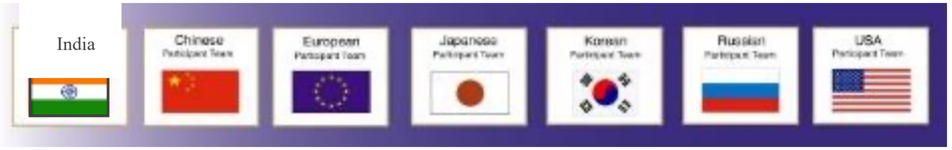
Nominal Plasma Current: 15 MA

Toroidal field 5.3 T

Major radius 6.21 m

Minor radius 2 m





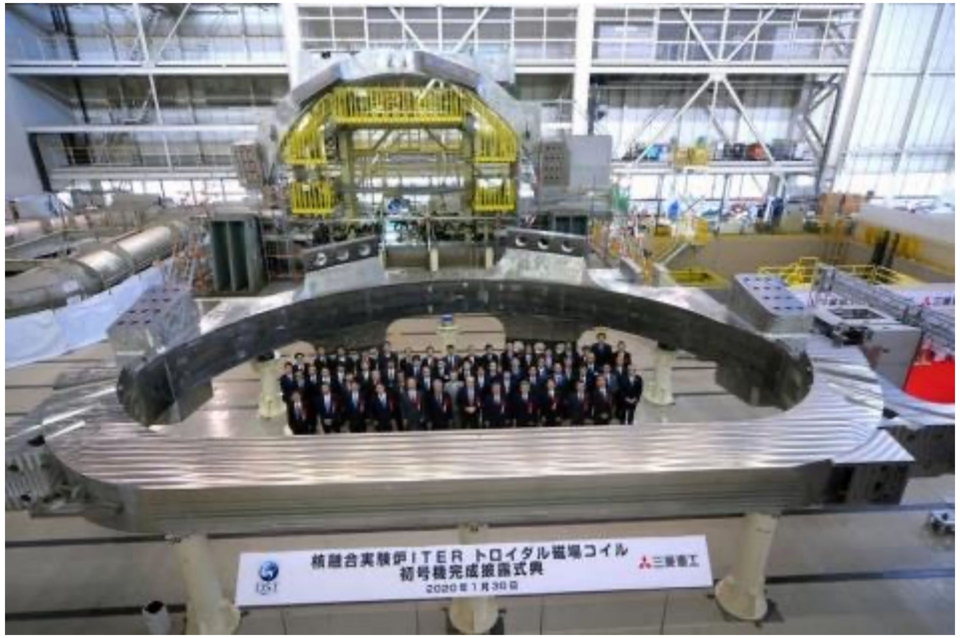
Typical Temperature: 20 keV

Typical Density: 1020 m-3

State of the Art

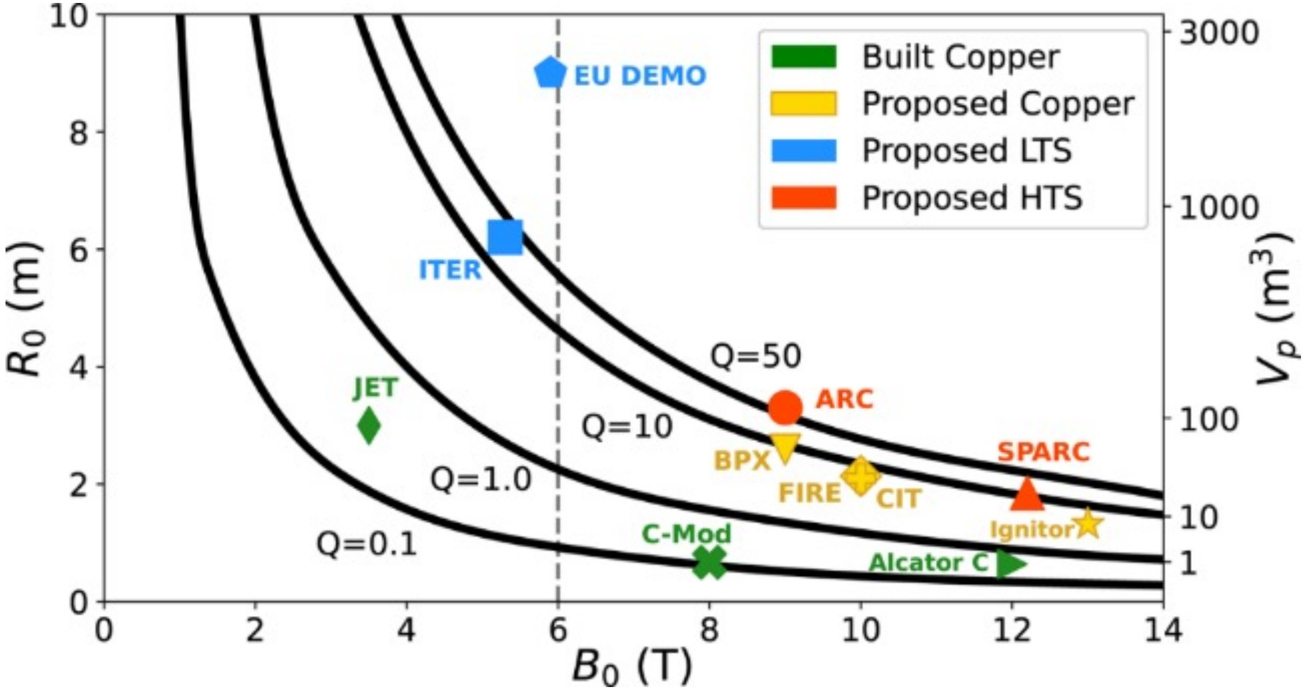
April 2021
PF5 coil leaves manufacturing
Outer diameter 17 m
weight 330 tonnes

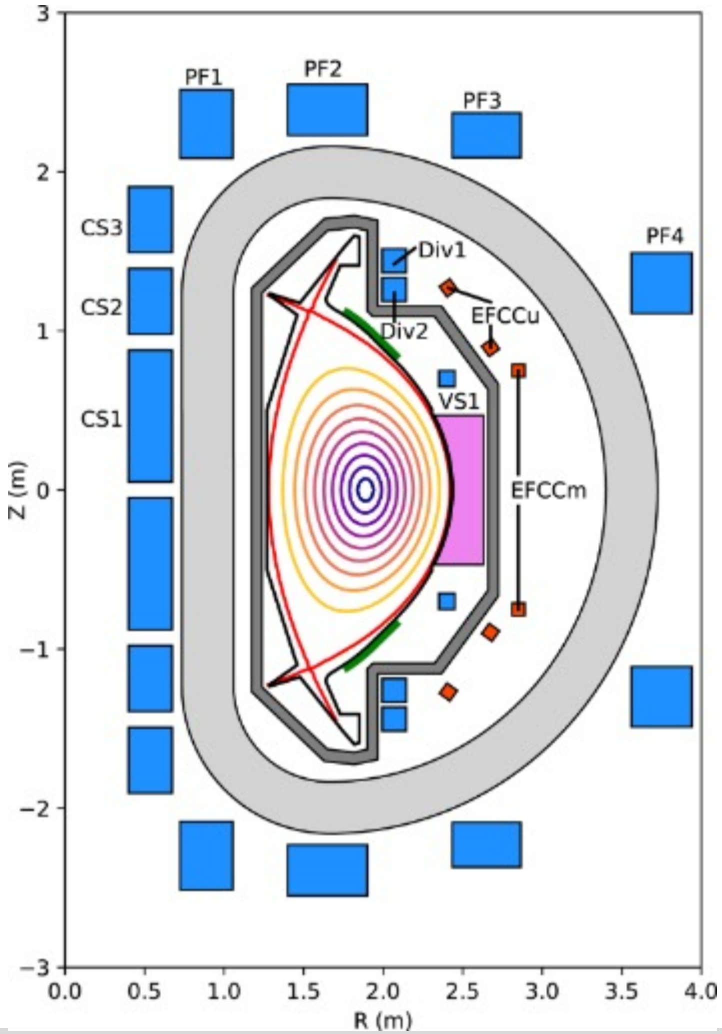
Feb 2020
First Japanese Toroidal Field Coil completed
Magnetic field 11.8 tesla
Stored energy 41 gigajoules
Weight 360 tonnes
Dimensions 9x17 m



Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

Two private initiatives at Tokamak Energy (UK) and Commonwealth Fusion Systems (US)





Source: A.J. Greely, et.al. Overview on the SPARC Tokamak, Published online by Cambridge University Press: 29 September 2020

Timeline

Building HTS magnet in progress

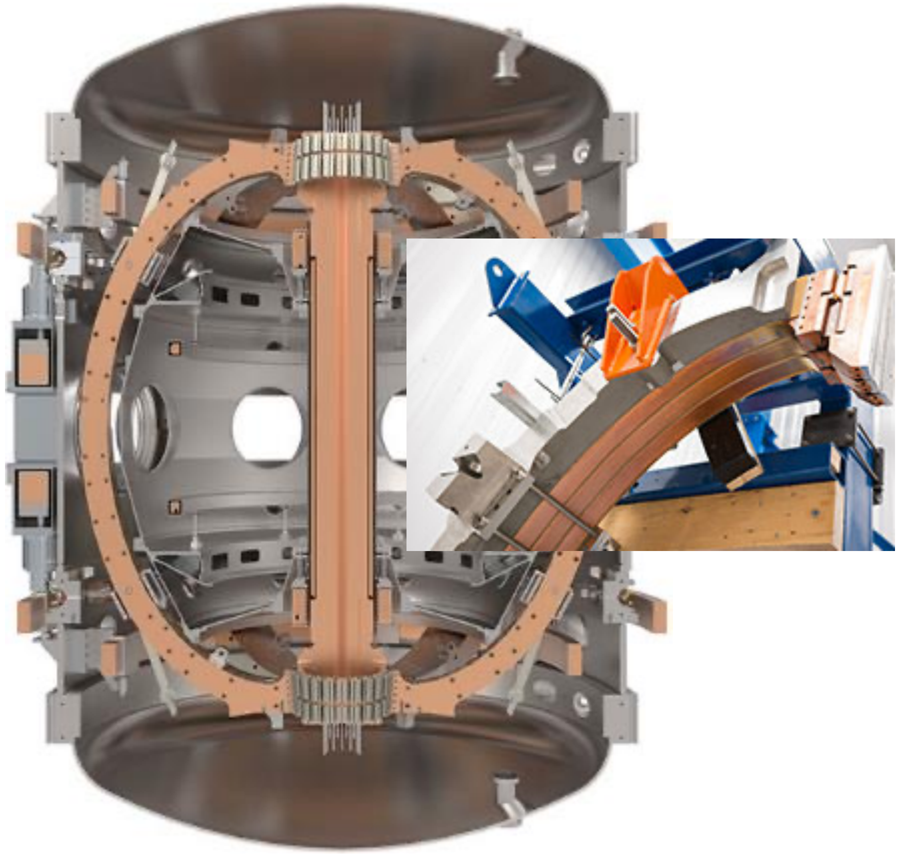
Start SPARC Fusion Energy Demonstration in 2021

Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

FUSION MAGNETS: COMPACT HTS FUSION MAGNETS - 2

Two private initiatives at Tokamak Energy (UK) and Commonwealth Fusion Systems (US)

Tokamak ST40 is with copper and power supply from Supercapacitors



Non insulated HTS magnet has achieved magnetic field of 24.4 T at a temperature of 21 K in 2019

Conceptual design of ST 135

P_{fus} = 200 MW
Q_{fus} = 5
R_0 = 1.35 m
B_{HTS} = 20,2 T
I_{plasma}=7.2 MA

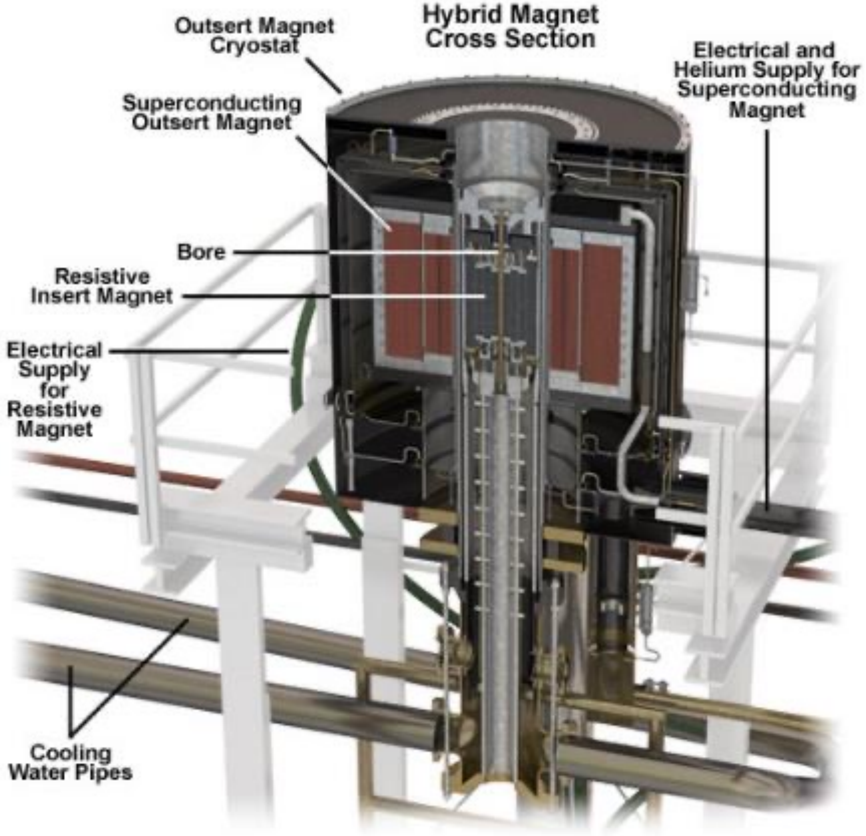
There is a strong mismatch in timelines of ITER and DEMO development in comparison to compact HTS Fusion Magnet development

Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

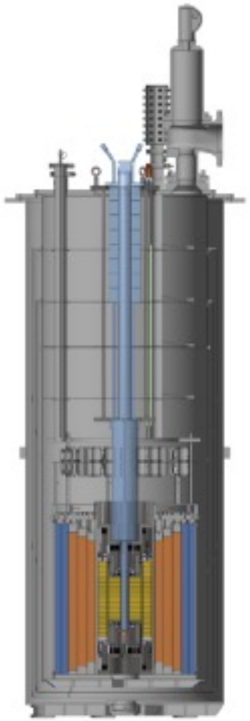
Source: picture and data from https://www.tokamakenergy.co.uk/

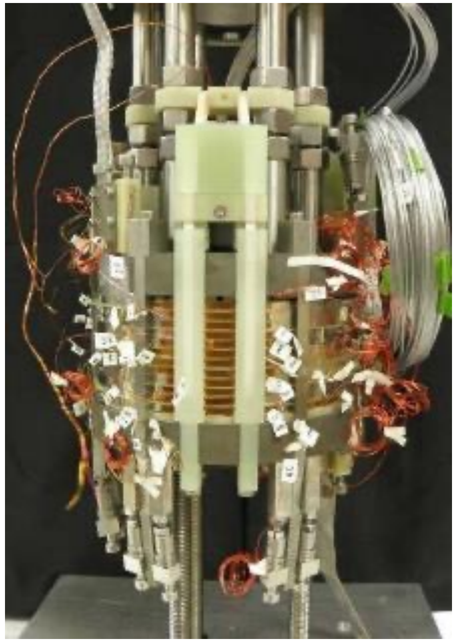
National High Magnetic Field Laboratory (MagLab)

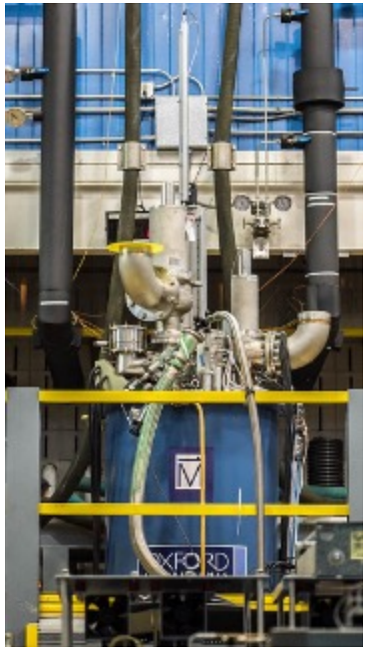
Hybrid magnet
45 Tesla, 32 mm bore
33.5 T resistive insert
30 MW power
11.5 T LTS outsert



32 T all superconducting **user magnet** with HTS insert
34 mm bore, 0.5 T/min ramp rate







In addition:
32.25 T achieved in full superconducting magnet in China in 2019

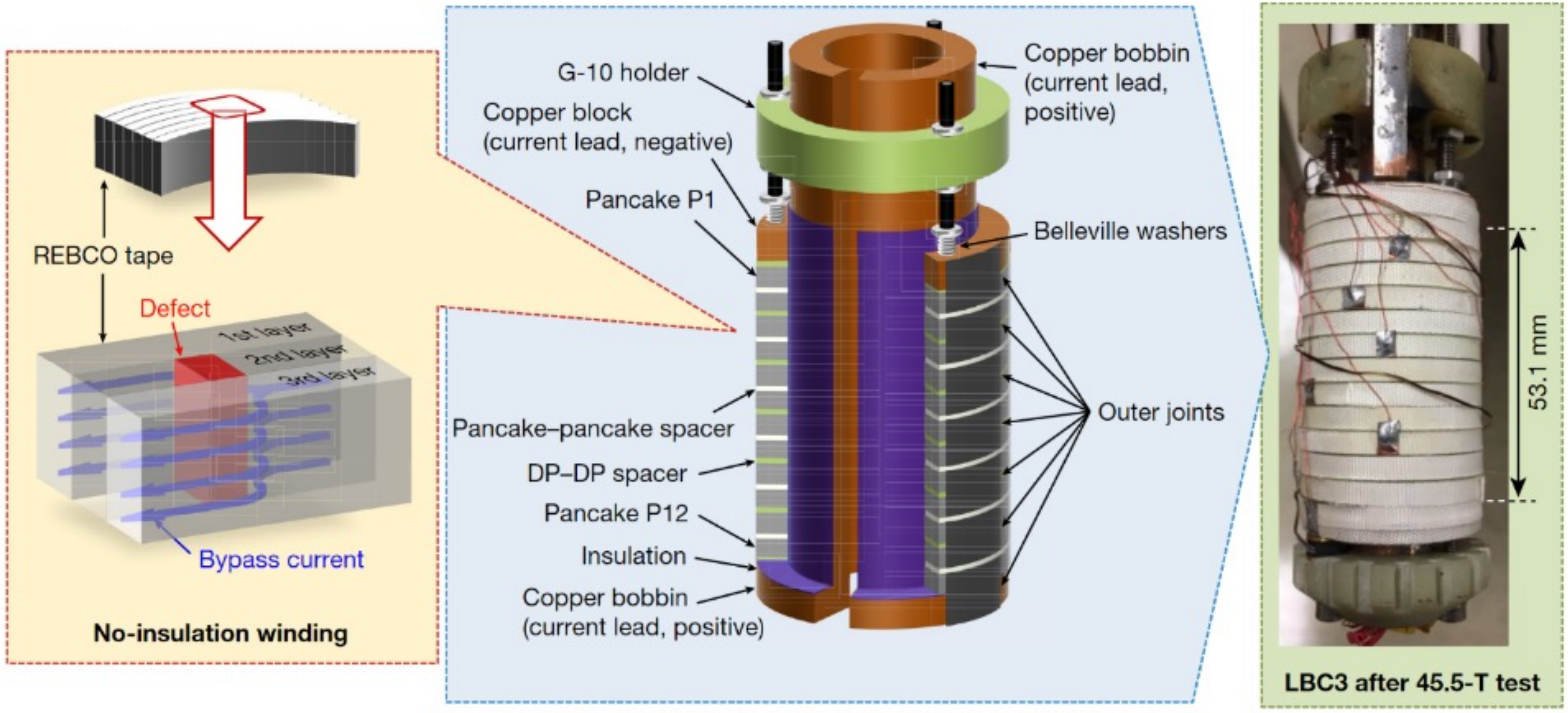
Source: https://nationalmaglab.org/user-facilities/

Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

45.5 T Hybrid Magnet with HTS insert

Hybrid magnet
45.5 Tesla with HTS insert
31.1 T resistive background field with 50mm warm bore

14.4 T with HTS insert
12 pancakes
4 mm wide tape, 30µm substrate, SuperPower



Source: https://doi.org/10.1038/s41586-019-1293-1

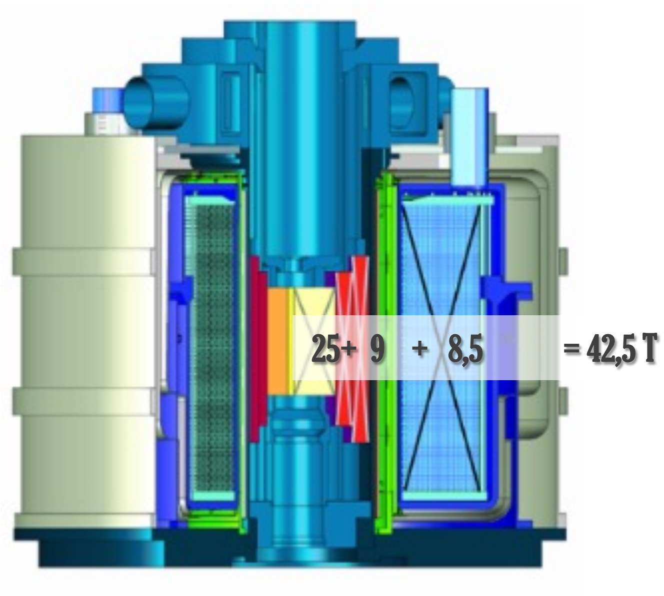
„no electrical burnout at high field quench“

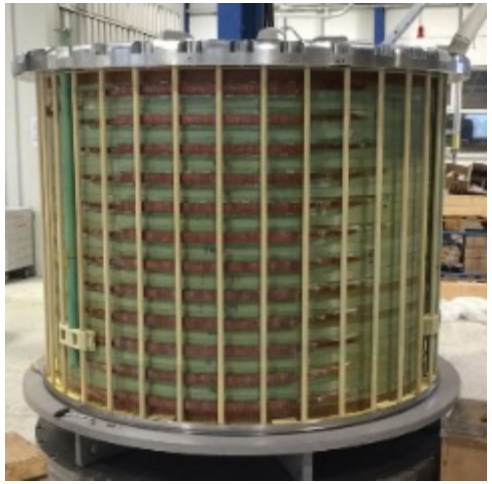
Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

Hybrid Station EMFL-G (LNCMI Grenoble): Construction of 43 T hybrid magnet

EMFL-NL (HFML-Nijmgen): Construction 45 T Hybrid magnet

- Superconducting magnet alone 8,5 T
  - 8,5 T ■ Φ 800 mm ■ (700 kW)
- Supercond. + Bitter (9 T)
  - 17,5 T ■ Φ 376 mm ■ (12 MW)
- Supercond. + Bitter + Polyhelix (25 T)
  - 42,5 T ■ Φ 34 mm ■ (24 MW)





- **NbTi 8.5 T – 500 mm Outsert**

Magnet manufacturing

(BNG, Allemagne)

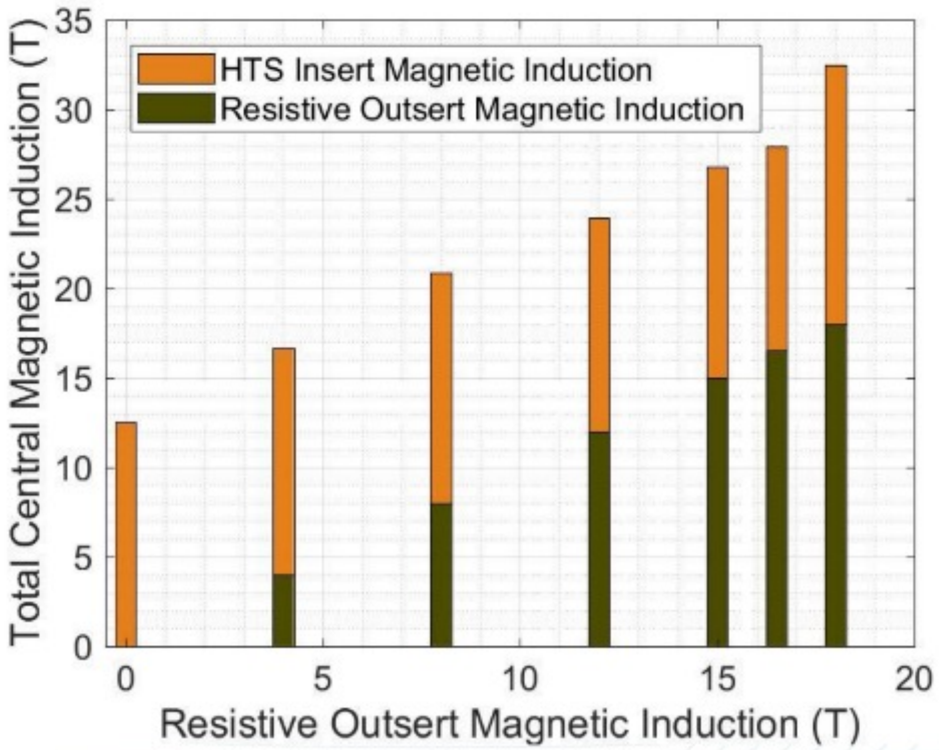
Superconducting outsert arrived, final assembly & testing started
Commissioning mid-2021

Assembly and testing ongoing

Commissioning expected in the course of 2021

Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

European Magnetic Field Laboratory (EMFL)



The HTS insert NOUGAT:
- 32.5 T at 38 mm useful diameter
- 9 double pancakes
- Metal insulated HTS insert

Ongoing 48-months **SuperEMFL design-study towards full superconducting user magnet beyond 40 T.**

Partners:
Centre National de la Recherche Scientifique (FR)
Helmholtz-Zentrum Dresden-Rossendorf e.V.(DE)
Radboud University (NL)
Commissariat à l'Énergie Atomique et aux Énergies Alternatives (FR)
European Magnetic Field Laboratory AISBL (BE)
Université de Genève (CH)
Universiteit Twente (NL)
Institute of Electrical Engineering, Slovak Academy of Sciences (SK)
Theva Dünnschichttechnik GmbH (DE)
Oxford Instruments Nanotechnology Tools Limited (UK)
Bilfinger Noell GmbH (DE)

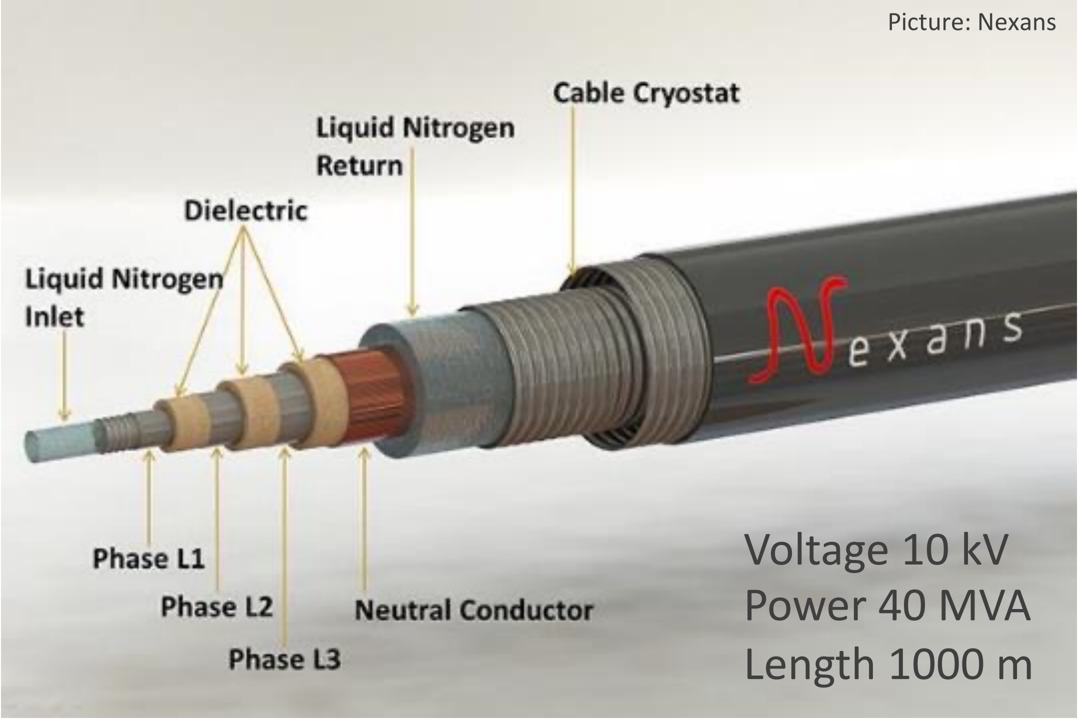
Kick-off: Jan 2021

Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

Source: EMFL Annual Report 2019

State of the Art

Cables



Voltage 10 kV
Power 40 MVA
Length 1000 m

Reliable long term operation since April 2014 in inner city of Essen, Germany.

Fault Current Limiters

Nominal voltage 220 kV
Nominal current 1200 A rms
Size one phase LxWxH 5500 x 2850 x 6500m
Weight 1 phase 27 tonnes
10 km 12 mm HTS tape per phase

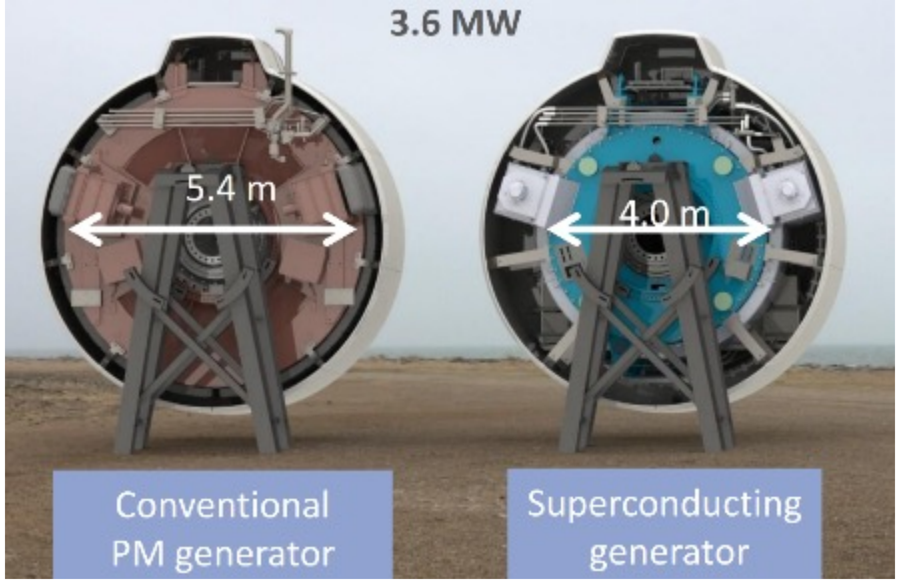
SuperOx superconducting fault current limiter with Izolyator high voltage bushings at the Mnevniki electrical substation of the United Energy Company in Moscow

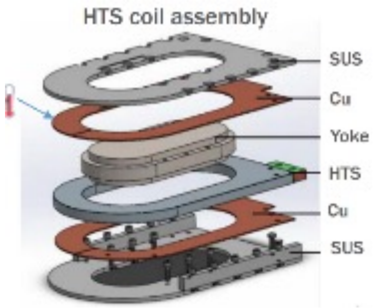
Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

State of the Art

Rotating Machines

15 rpm, 40 HTS coils
~ 20 km 12 mm wide tape
Rotor weight 30 tonnes





Superconducting DC rotor with conduction cooling

Pictures: M. Bauer, "Development, test, installation, and commissioning of the 3 MW superconducting EcoSwing wind power ,MT26, September 26 , 2019, Vancouver, Canada

Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

SUMMARY COMMENTS

R&D on High Field Magnets for Accelerators is progressing well, taking into account the needs of the high energy physics community for future colliders at higher energies. (FCC hh,..)

European and international collaborations are being set up to take advantage of the complementary strengths and technical capabilities of the various partners.

The impact of High Field Magnets development on the industrial ecosystem, on the training and education of future generations of magnet builders, and on the sustainability of the technologies developed will also be explored.

It is time for young applied physicists, engineers and technicians to get on the ship.

The challenge for the next 10 to 20 years is inspiring but considerable, and the engine room is ready to respond ….Full speed.