High Field Magnets and Multifaceted Applications

Pierre Vedrine
CEA Paris Saclay

Outline

Superconductivity and High Field Magnets

Application to future particle colliders : high energy hadron colliders and muon colliders

Application to MRI

Application to Fusion

Summary comments

FCC

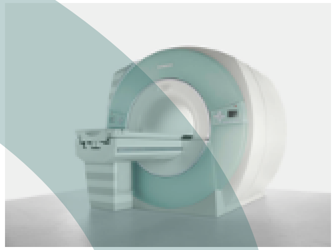
SUPERCONDUCTIVITY AND HIGH FIELD MAGNETS

The very first magnet!


0,5 Gauss / 5.10^{-5} T
in Sao Paulo

Permanent magnet
(NdFeB, 0.5T)

Resistive magnet
(2T)

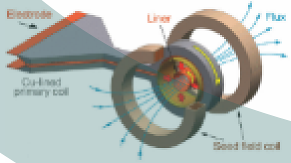


MRI magnet (Siemens 3T)

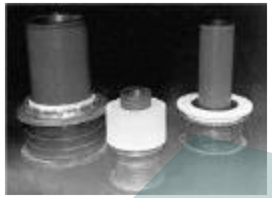
LHC Dipole
(8,3T)

Bruker 1 GHz NMR
(23,5T)

NHMFL
Tallahassee
Hybrid magnet
(40 T)



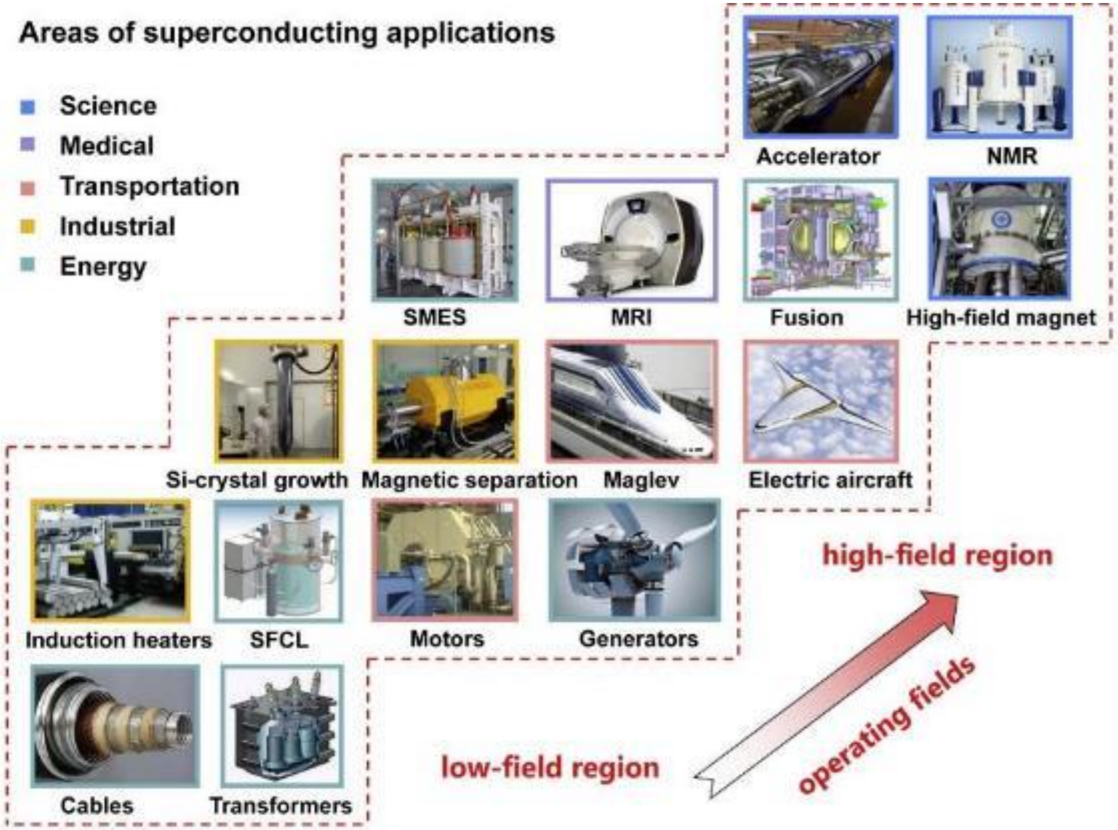
ISSP (Japan)
(750 T)



VNIIEF MC-1 (Russia)
2,8 kT

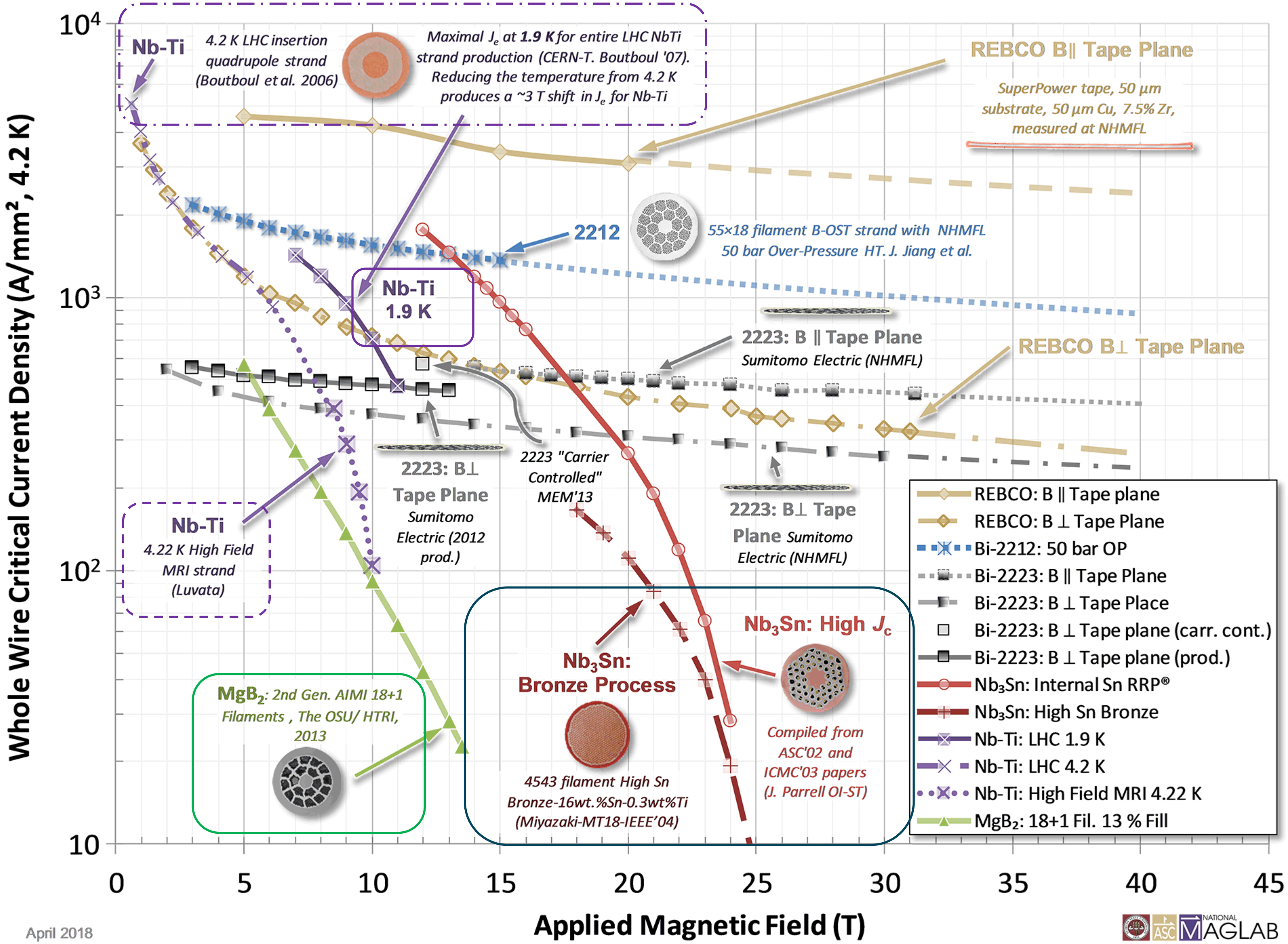
Superconductivity…

- Has been a strong technology enabler since its discovery
- Allowed several important societal breakthroughs in the last decades: MRI magnets, Higgs Boson
- Could play a wider role in society but has been slowed down due to high cost, large infrastructures, cryogenics, etc.



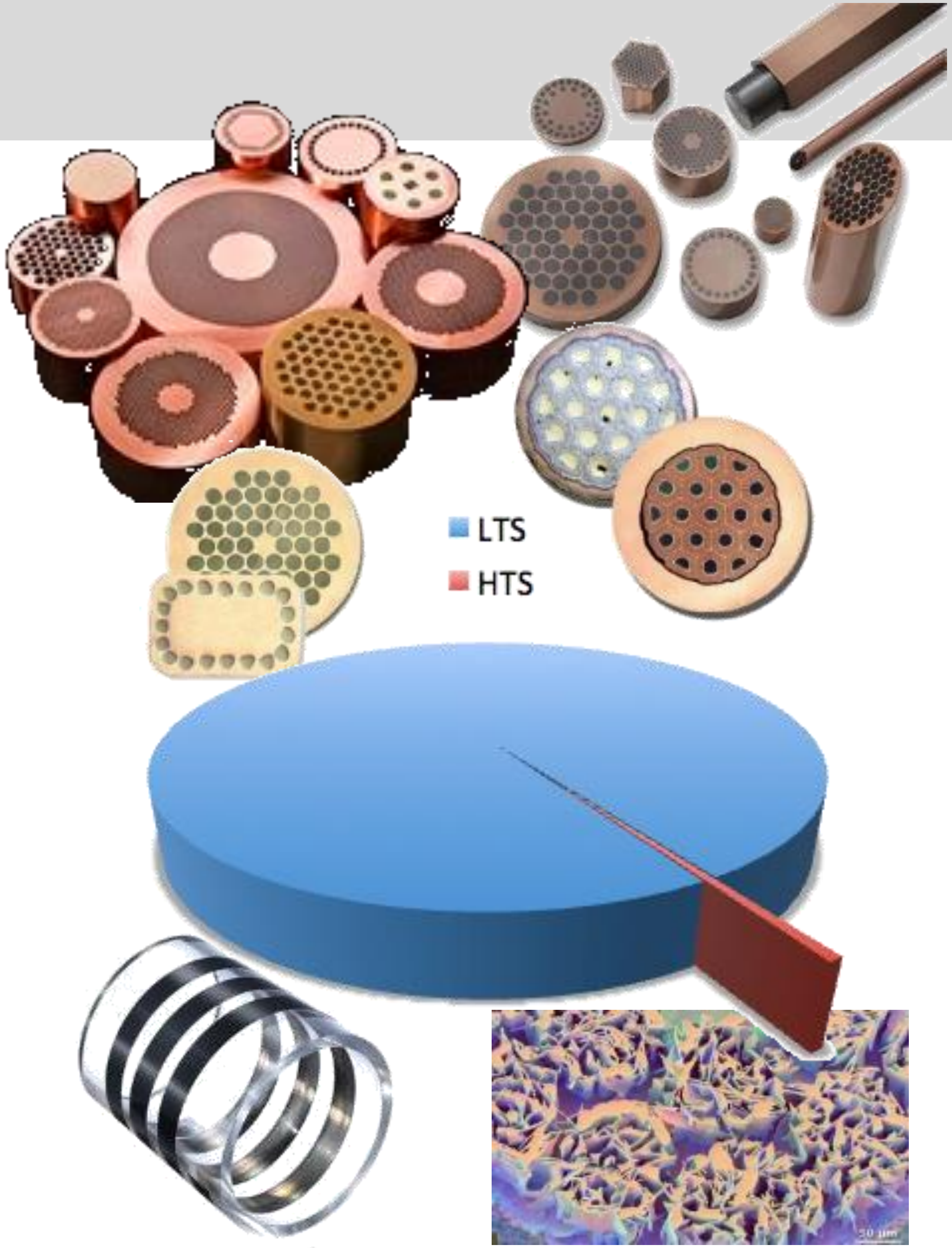
MAIN APPLICATIONS OF SUPERCONDUCTING TECHNOLOGIES IN THE FIELD OF ENERGY AND MAGNETISM
(https://doi.org/10.1016/j.isci.2021.102541)

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



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

- 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

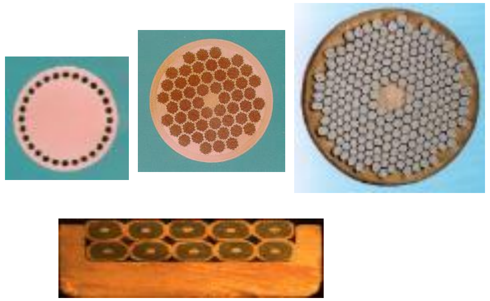


A LARGE CHOICE OF SC WIRES AND CABLES...

MRI is biggest user of NbTi SC wire

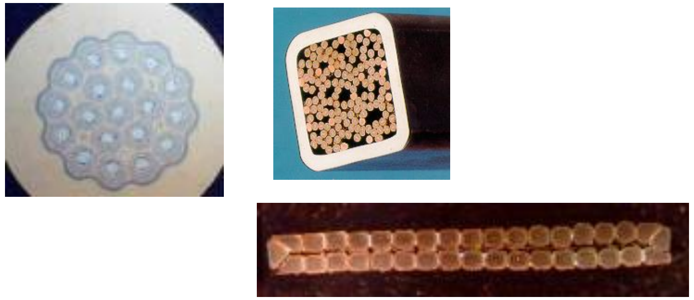
NbTi

- *Dominant commercial superconductor*
- *MRI is biggest user of NbTi SC wire*
- *Bendable, ductile, low cost ($1/kA.m)*
- *Tc=9,3K, Bc2=11,4 @ 4,23K*



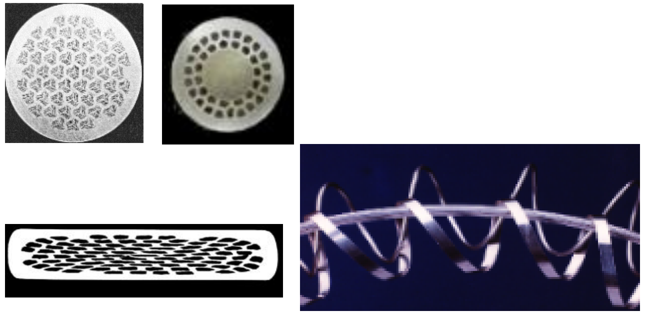
Nb3Sn

- *Primary high field SC*
- *Brittle*
- *Tc=18K, Bc2 ≈ 23-29K*
- *Higher cost (x 5 price of NbTi)*



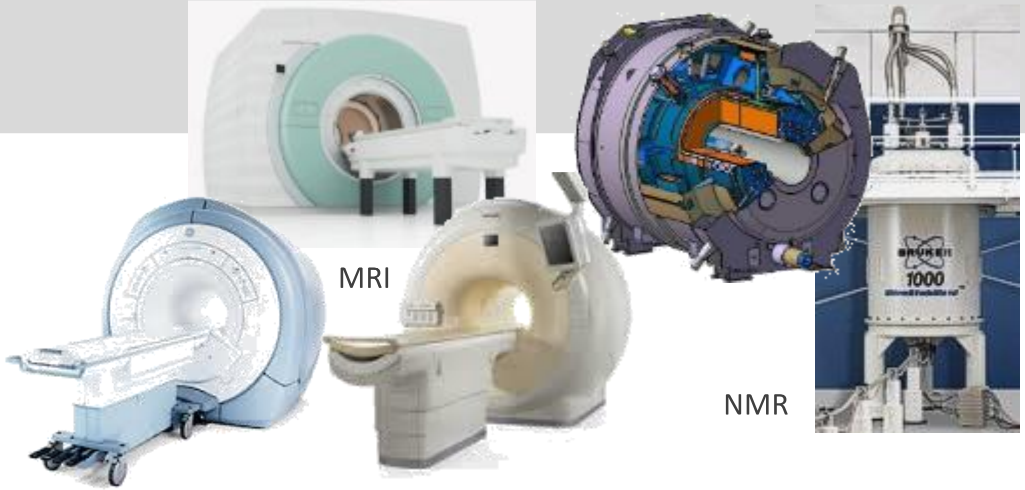
MgB2

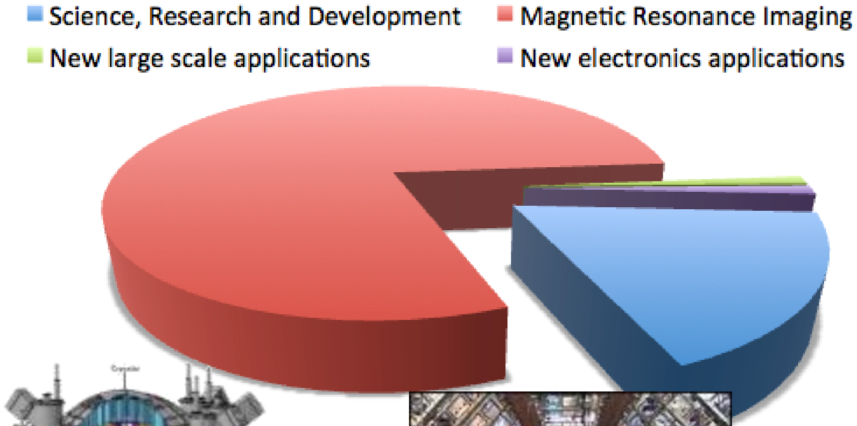
- *Brittle*
- *Tc=39K, Bc2=40T*
- *Higher cost (x 5 price of NbTi)*

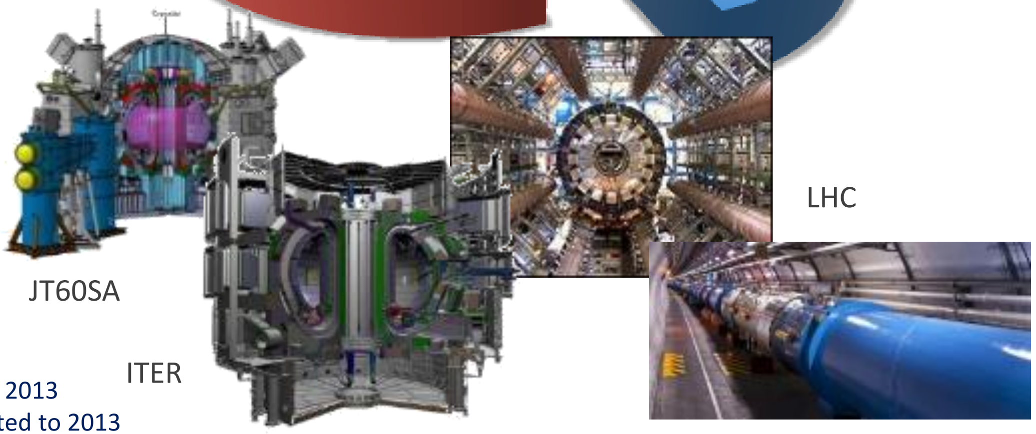


Technology based on **ReBCO and BSCCO** is expensive (~$10-50/kA.m) and not mature enough for large industrial applications

- **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 today 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]





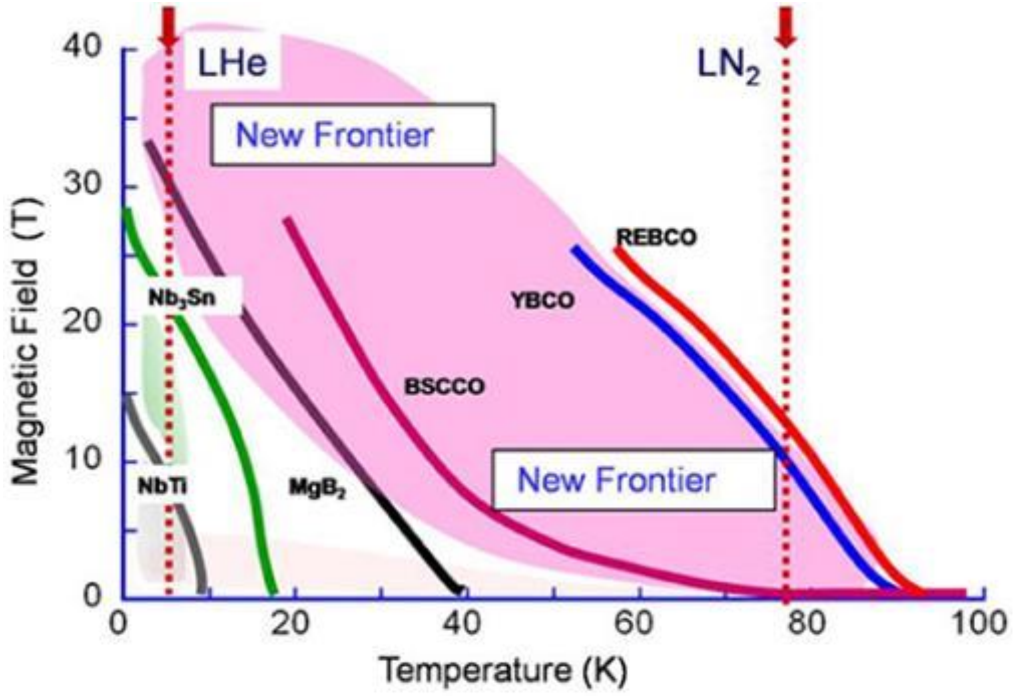


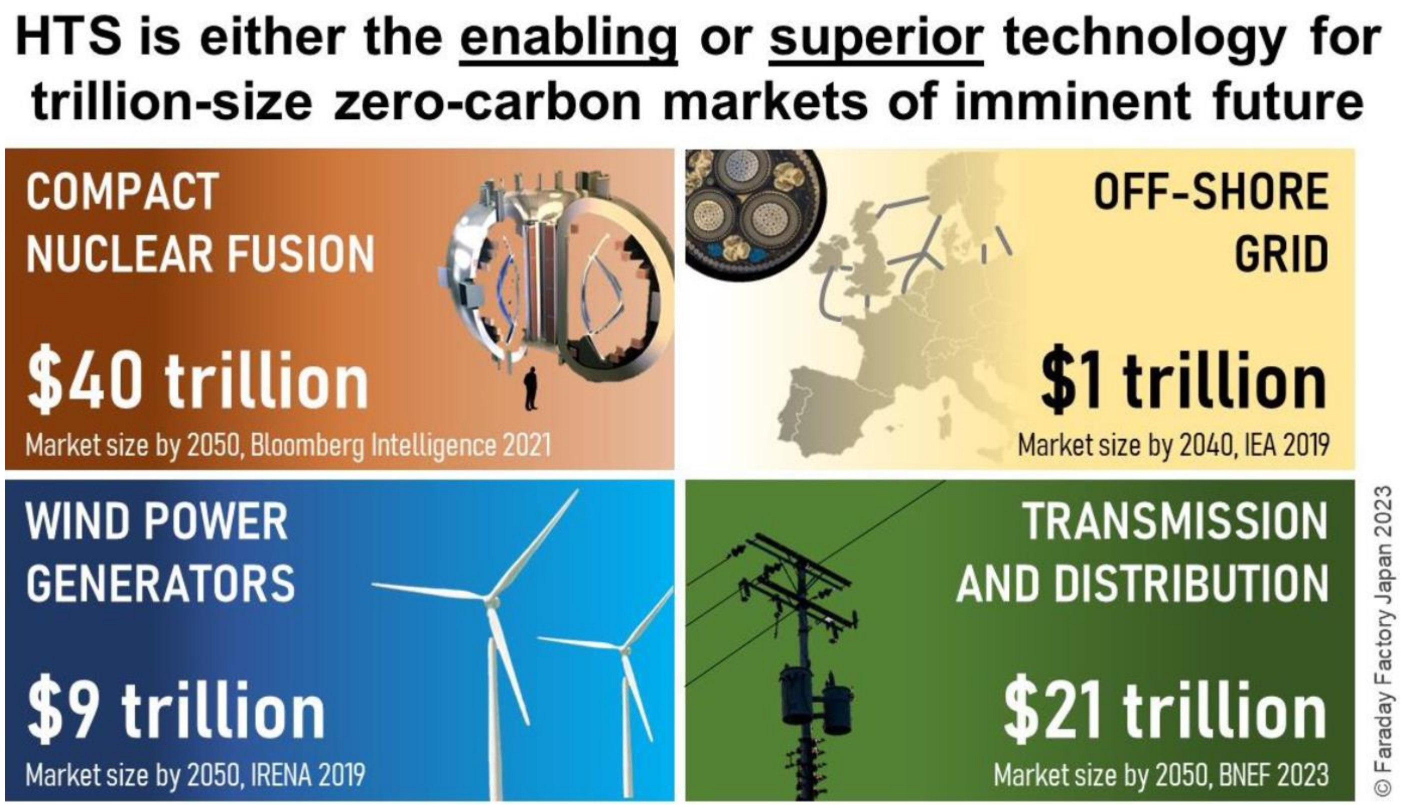
Sources: (1) from market report at Conectus.org, converted from repored 5.3 BEUR in 2013
(2) Report to the CERN Finance Committee, 2008, reported 1.7 BCHF(2008) escalated to 2013
(3) DOE Assessment of the ITER Project Cost Estimate, reported 1.09 BUSD(2002) escalated to 2013

HTS material can…

- For low/mid fields: work at higher temperatures close to the LN_2 one (77 K) → important gain in infrastructures
- At low temperatures: enable higher fields (> 20 T) and current densities → machine compactness and wider physics

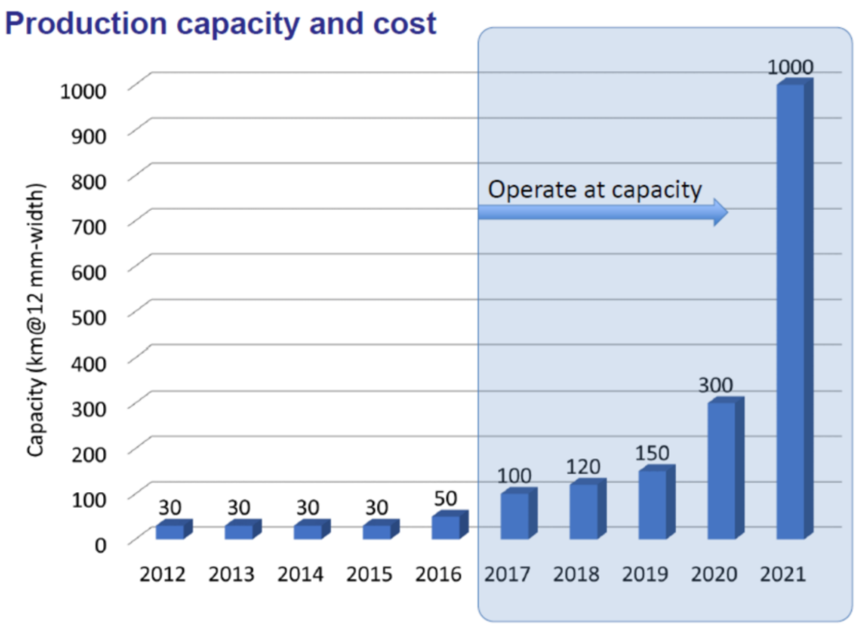
Very high potential for future zero-carbon energy markets



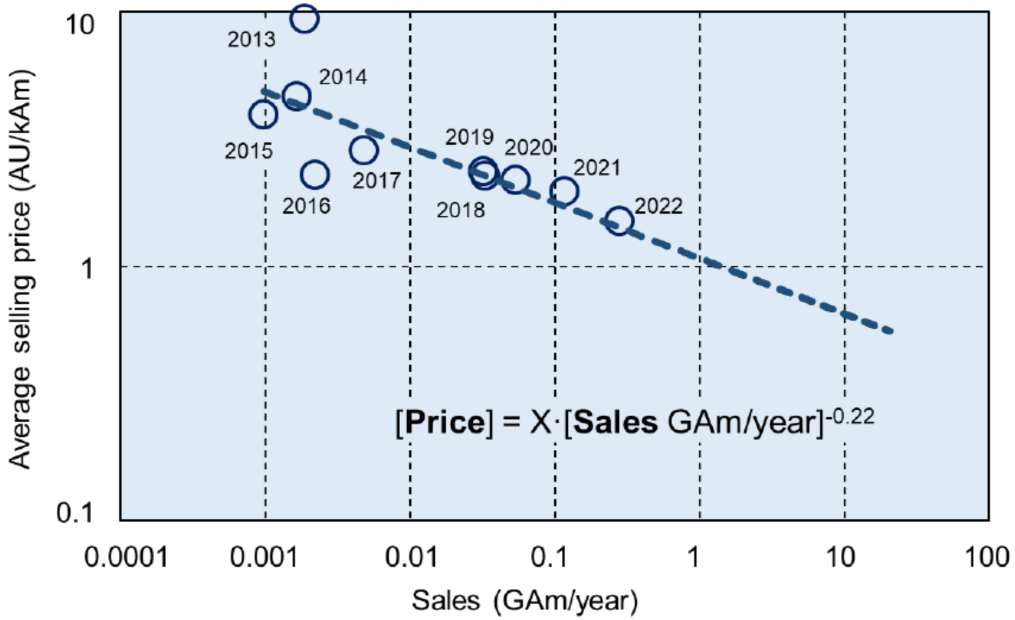


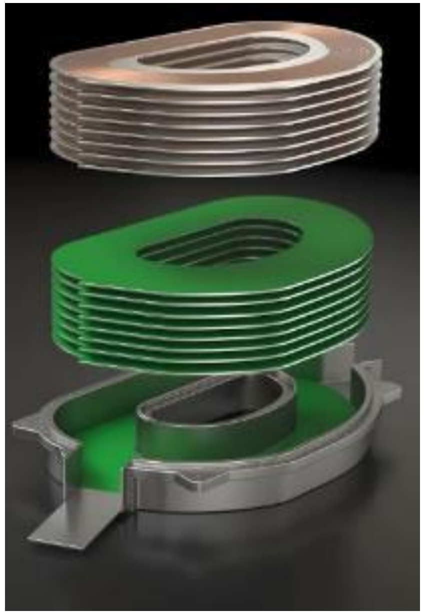
REBCO HTS material

- Is a very could candidate today for next generation of high energy applications
- Important technological and economical progress achieved in the last years driven by new fusion reactors initiatives
- Will benefit to all applications



SuperOx REBCO tape production

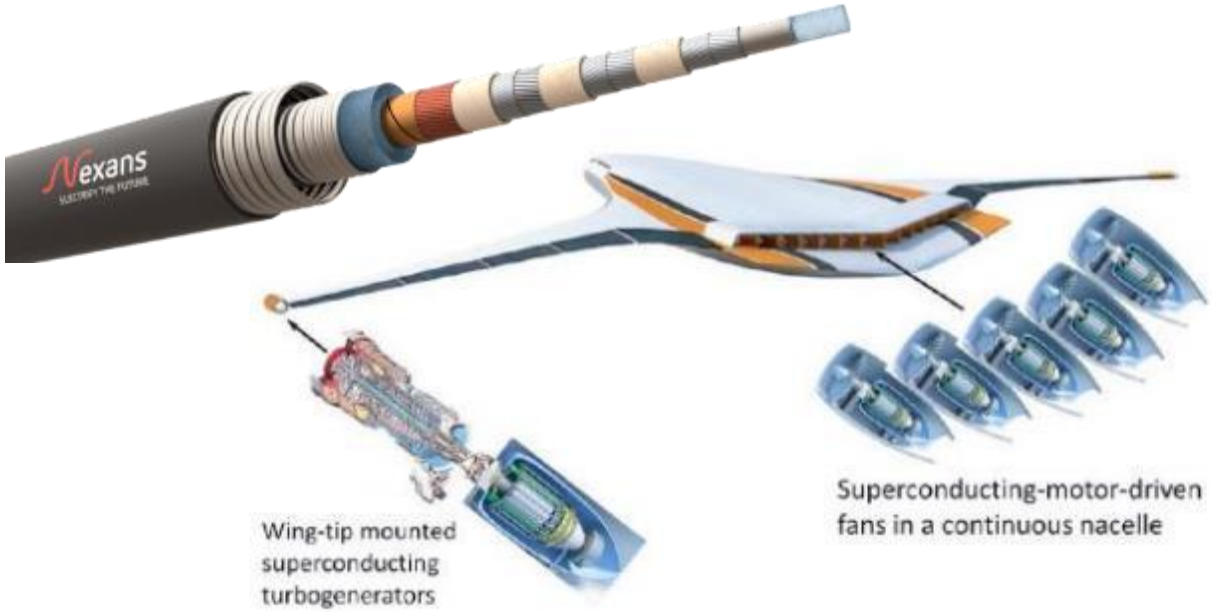




SPARC TFMC: 300 km of REBCO tape

Several international initiatives are exploring the societal potential of HTS materials applications for…

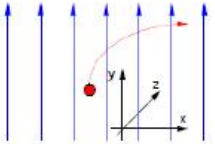
- Energy production by magnetic fusion: ARC in US (1.8 Md$ of private funds), STEP in UK, BEST in China
- Wind energy production: EcoSwing in EU, WIND in US
- Zero emission aircrafts: Ascend (Airbus), N3X (NASA)
- Power cables: Chicago central business district (Nexans), AMPACITY (Nexans), Gare Montparnasse in Paris (Nexans)
- High Energy Physics: CERN roadmap, FCC, Muon Collider



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

Increase BEAM ENERGY →

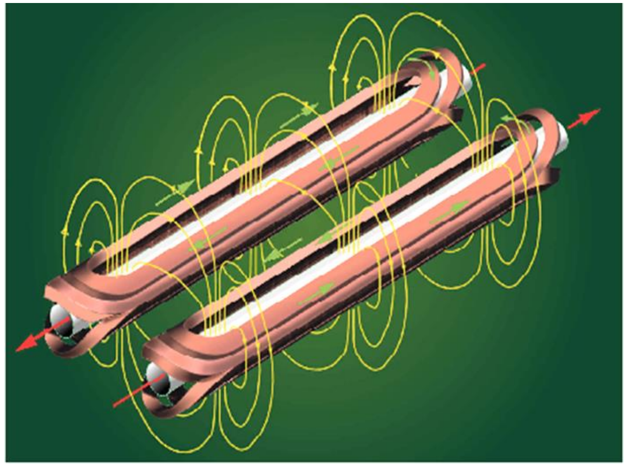
Dipoles to bend the trajectory of the beam



Beam energy — Bending radius

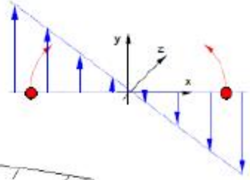
$$E[GeV] = 0.3\,B[T]\,\rho[m]$$

Dipole field



Increase collider LUMINOSITY (number of collisions) →

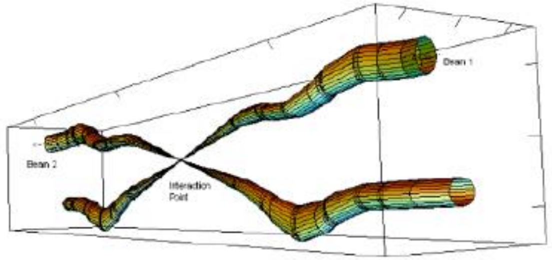
Final focus quadrupoles to reduce the beam dimension at the interaction point



Peak coil field

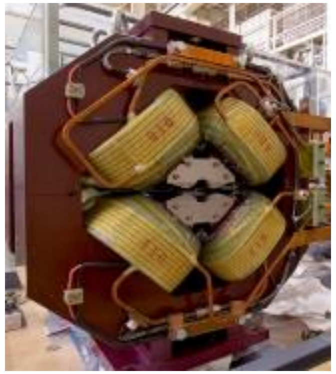
$$B\ell_q \approx \frac{1}{\sigma^*}$$

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

- **Main parameters for the specification**

. *Field B, length L, radius R*

. *Field shape and homogeneity, field stability, radiation thickness, interaction length, etc…*

- **Parameters relevant for the physics**

. *B, BL^2 (sagitta), BL^2 (momentum resolution), $B^3 R^2$ (performance factor)…*

- **Parameters relevant for the magnet designer**

. *$B^2 R$ (mechanical forces)*

. *$B^2 R/e$ with e coil thickness (stresses , protection in case of quench)*

- **Parameters relevant for the ressource manager**

. *Cost :* $C = \alpha (RL)^{0.8} + \beta (B^2 R^2 L)^{0.7}$ *(from A. Hervé)*

$C(M\$) = 0.5(E_s(MJ))^{0.662}$

$C(M\$) = 0.4(B(T)V)^{0.635}$ *(from Green and Lorant)*

- **High magnetic field B** : *intrinsic value : B_c* *~ 10 T for NbTi*

  ~ 20 T for Nb_3Sn

- **High mechanical forces/stresses**

  . Forces must be held by the conductor and/or the external support structure

  (coil thickness $\propto RB^2/(E/M) \propto RB^2 \rho/\sigma_h$ (ρ =density))

  . Electrical insulation must also withstand the stress (shear stress in particular)

- **Protection in case of quench**

  . Importance of the value of the stored energy per unit of cold mass (E/M ratio)
  peak temperature at homogeneous energy dump ($E = 0.5\mu_0\int B\cdot dV$; $E/M=H= \int C_p dT$)

  . Necessity of fast quench propagation (active/passive propagation techniques, high RRR in stabilizer, energy extraction by external dump)

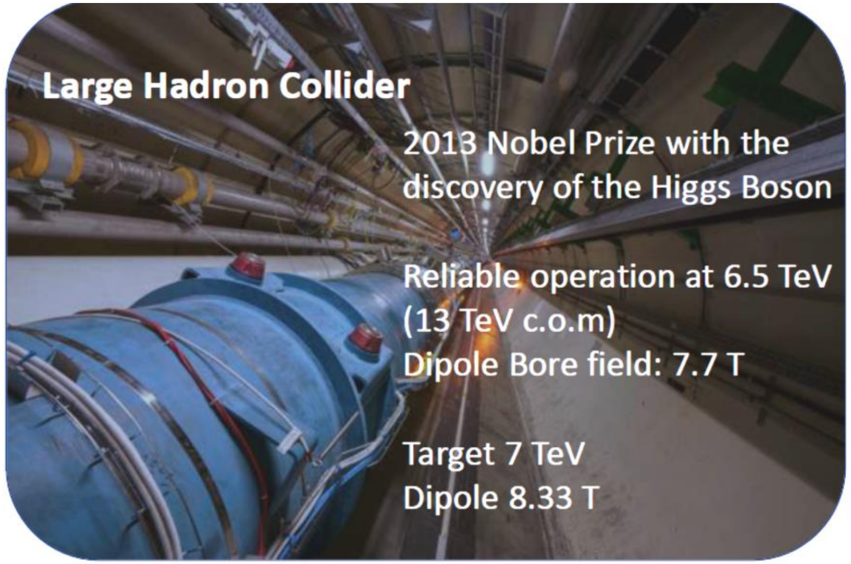
- **Dimensions:** *. Manufacturing dimensions and tolerances, handling*

  . Road transportation R_{max} ~ 3.5 m

- **Enabling technologies** : *SC Conductor, Electrical insulation, cooling, manufacturing techniques*

▶ FCC

Application to future particle colliders :
High energy hadron colliders and muon colliders

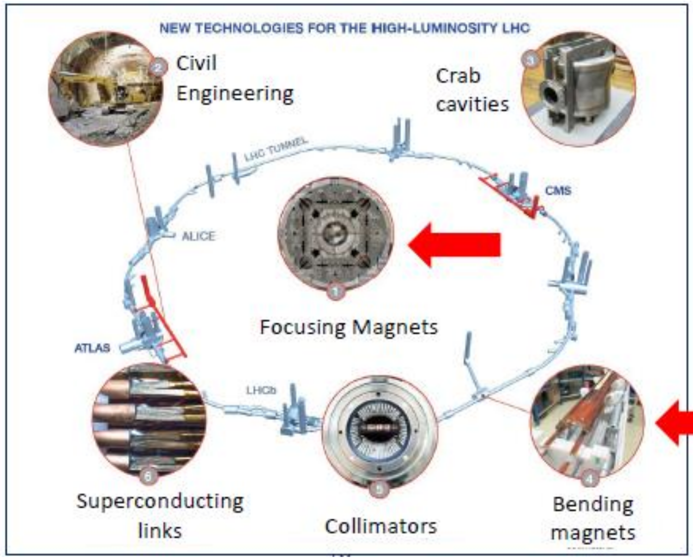


Large Hadron Collider

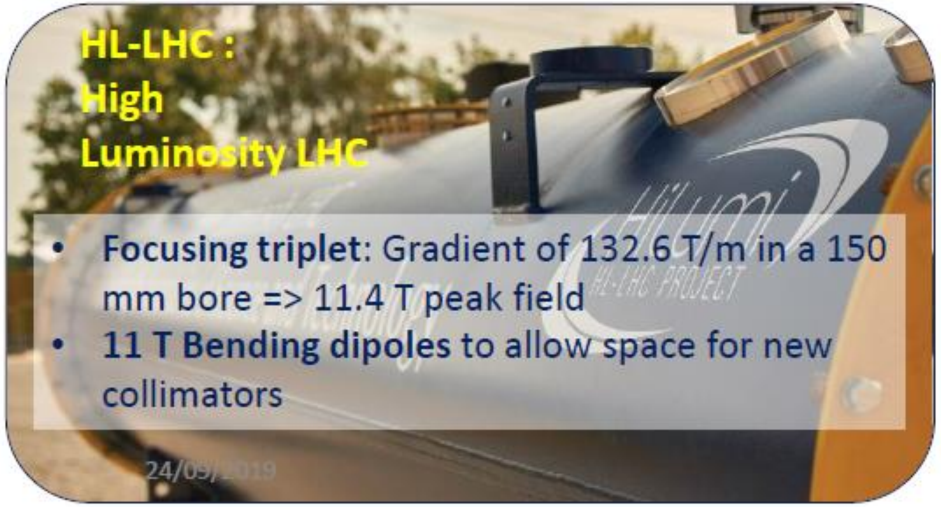
2013 Nobel Prize with the discovery of the Higgs Boson

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

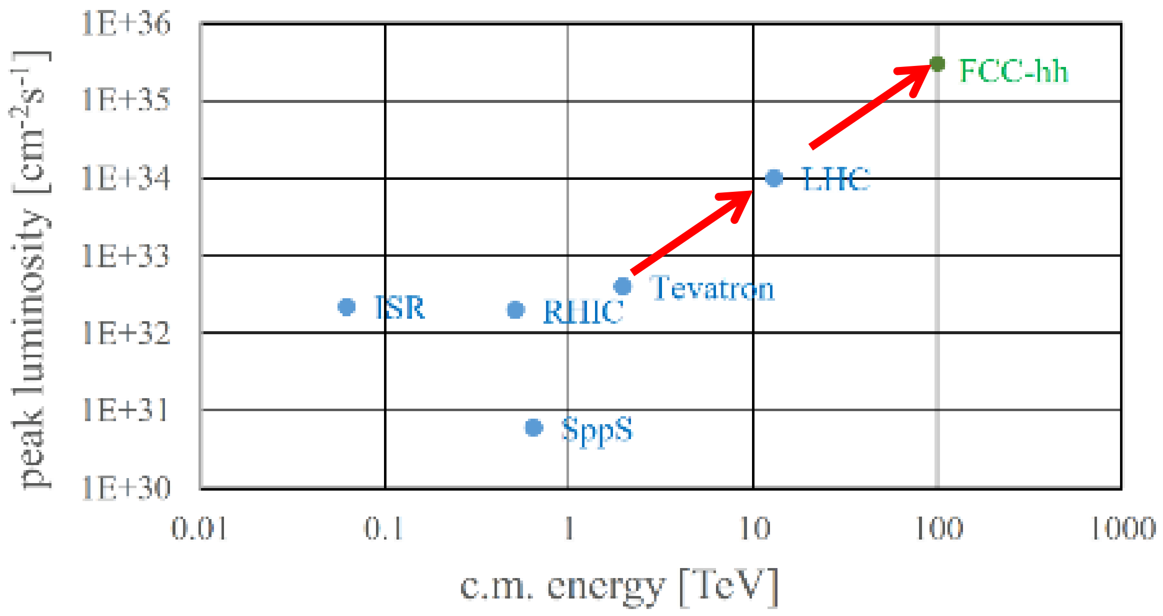
- **Focusing triplet**: Gradient of 132.6 T/m in a 150 mm bore => 11.4 T peak field
- **11 T Bending dipoles** to allow space for new collimators

FCC-hh
Future Circular Collider

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

Courtesy of CERN

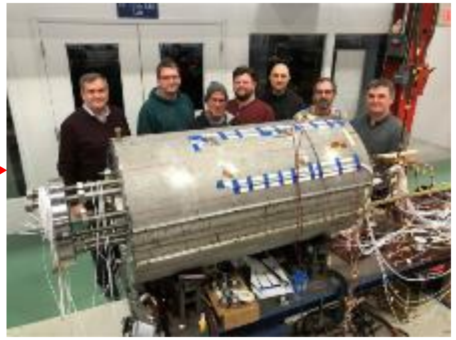
FCC-hh: HIGHEST COLLISION ENERGIES



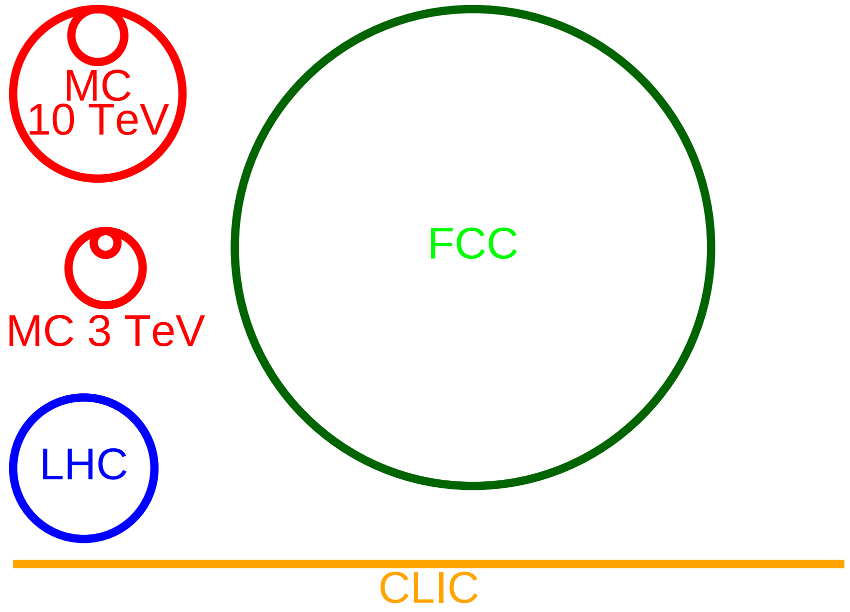
- **Order of magnitude performance increase in both energy & luminosity**
- **100 TeV cm collision energy (vs 14 TeV for LHC)**
- **20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)**
- **similar performance increase as from Tevatron to LHC**
- **key technology: high-field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

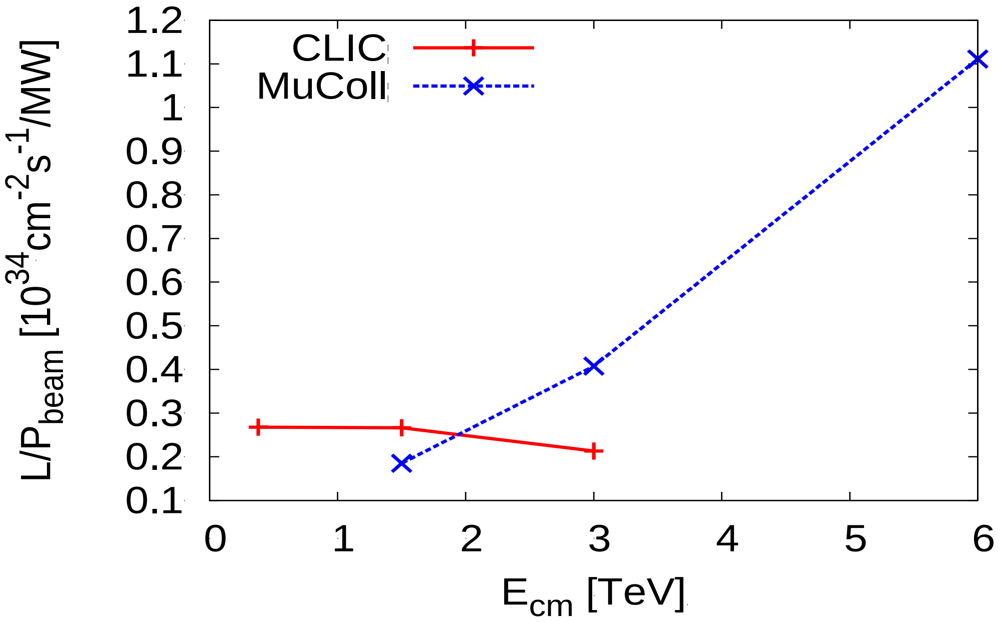
from
LHC technology
8.3 T NbTi dipole

via
HL-LHC technology
12 T Nb_3Sn quadrupole



FNAL dipole demonstrator
14.5 T Nb_3Sn





Compactness promises **cost effectiveness**
And low CO_2 footprint for construction

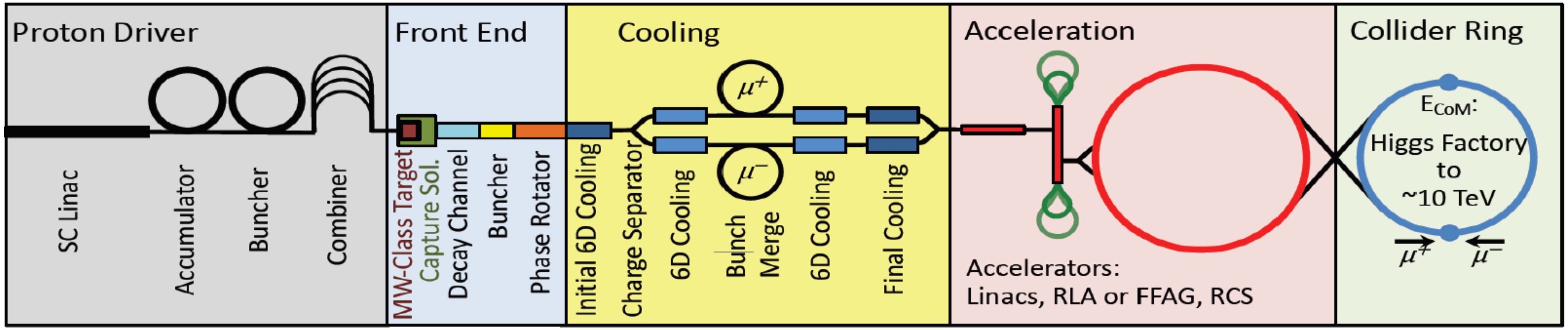
Increasing luminosity per beam power promises **power efficiency**

Muon Collider Overview

Muon collider has been studied in the US ("MAP"), experiments have been performed in the UK ("MICE") and some alternatives have been considered at INFN ("LEMMA")

Renewed interest thanks to **technology and design advances** and new goal of **very high-energy, high-luminosity lepton collisions**

Would be easy if the muons did not decay
Lifetime is $\tau = \gamma \times 2.2\ \mu s$



Short, intense proton bunch

Protons produce pions which decay into muons muons are captured

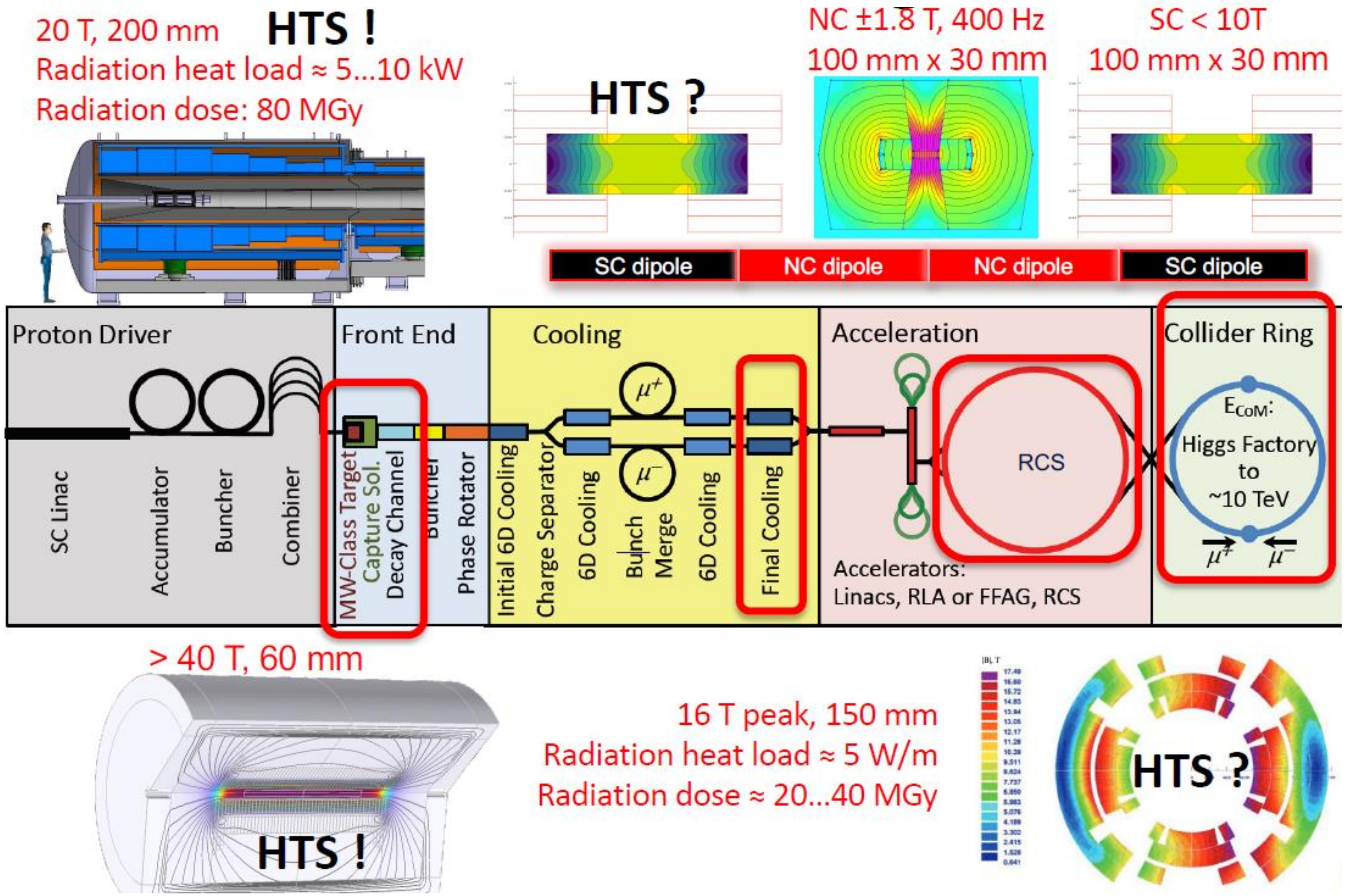
Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

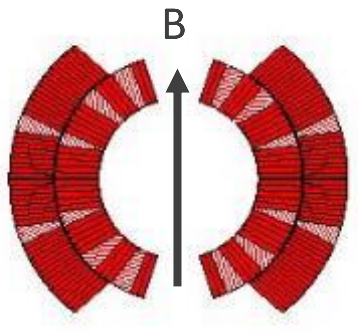
D. Schulte Muon Collider and Synergy Workshop Goal, Orsay, June 2023

MuCol

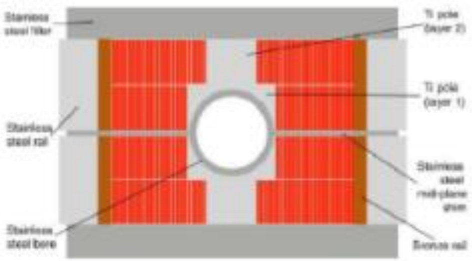

20 T, 200 mm
HTS !
Radiation heat load ≈ 5…10 kW
Radiation dose: 80 MGy
HTS ?
NC ±1.8 T, 400 Hz
100 mm x 30 mm
SC < 10T
100 mm x 30 mm
SC dipole
NC dipole
NC dipole
SC dipole
Proton Driver
Front End
Cooling
Acceleration
Collider Ring
SC Linac
Accumulator
Buncher
Combiner
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
Initial 6D Cooling
Charge Separator
6D Cooling
Bunch Merge
6D Cooling
Final Cooling
μ+
μ−
RCS
Accelerators:
Linacs, RLA or FFAG, RCS
E_CoM:
Higgs Factory
to
~10 TeV
> 40 T, 60 mm
HTS !
16 T peak, 150 mm
Radiation heat load ≈ 5 W/m
Radiation dose ≈ 20…40 MGy
HTS ?

- 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.

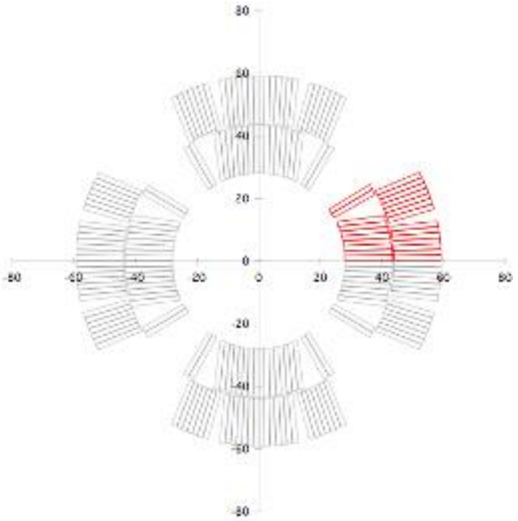
Saddle-shape coil assembly



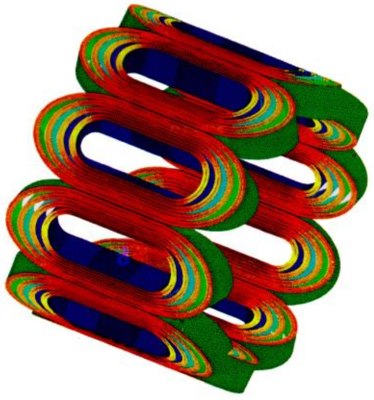
Cosθ dipole coil configuration



Block dipole coil configuration

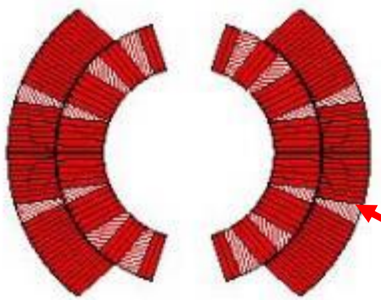


Cos(2θ) quadrupole coil configuration

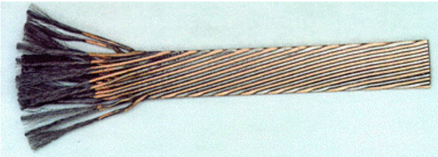


Cos(5θ) decapole magnet configuration

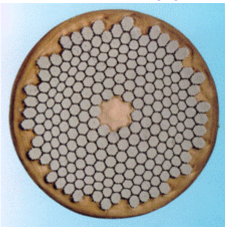
COMPLEX ENGINEERING - LHC MAGNET COMPONENTS -



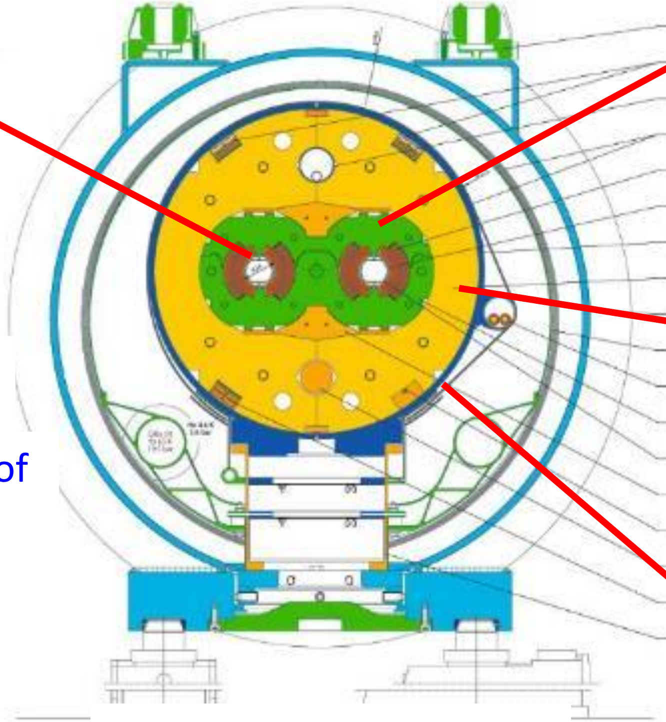
4928 cosθ, two-layer, graded poles



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

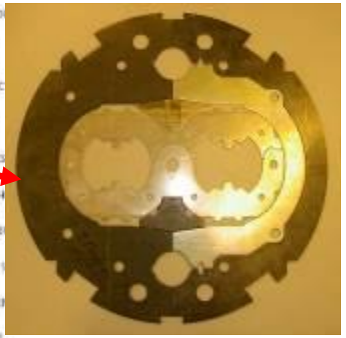


474 (inner) + 736 (outer) tons of Cu/NbTi multifilament composite wires

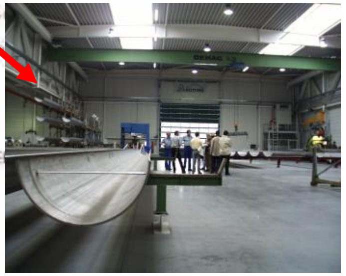


1232, 2-in-1, arc dipole magnets

5,500 t of austenitic steel collars



25,000 t of Low-carbon steel yoke

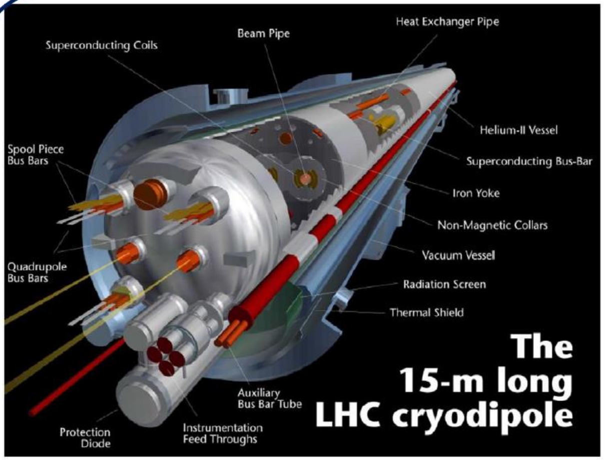


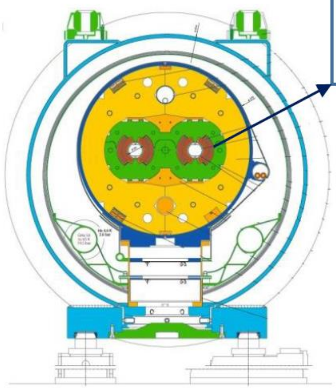
2464 stainless steel half shells

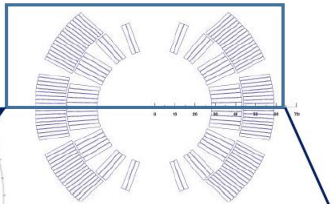
FROM NBTI TO NB3SN

LHC Technology

NbTi





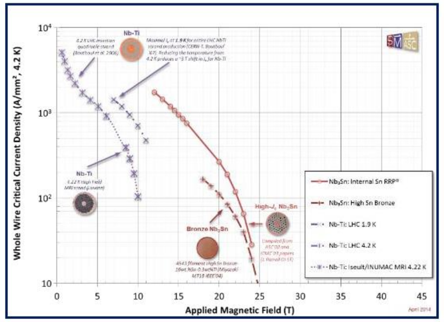


LHC NbTi dipoles

Courtesy of CERN

Beyond LHC

Nb_3Sn



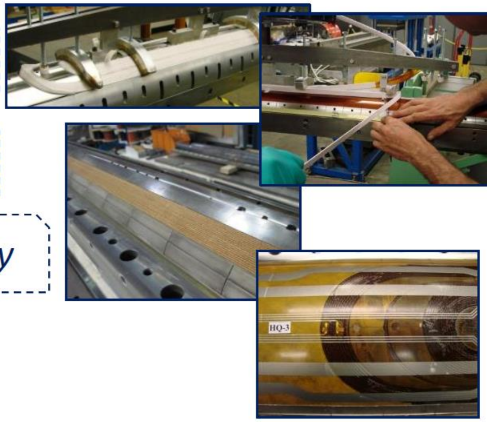
Courtesy of P. Lee

→ **Coil technology**

Heat treatment around 650°C

Wind and react technology

Vacuum impregnation with Epoxy



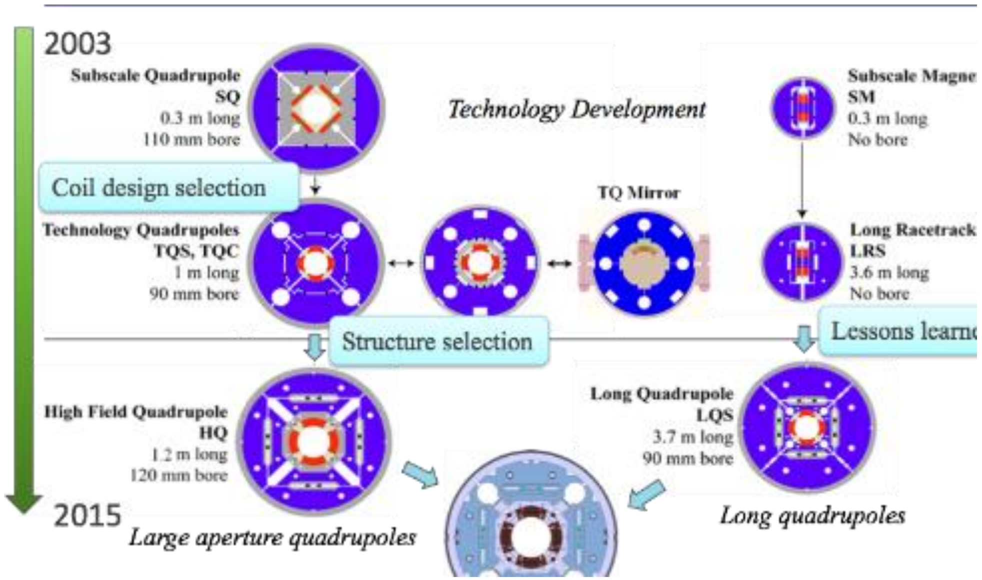
→ **Nb_3Sn strain sensitivity**

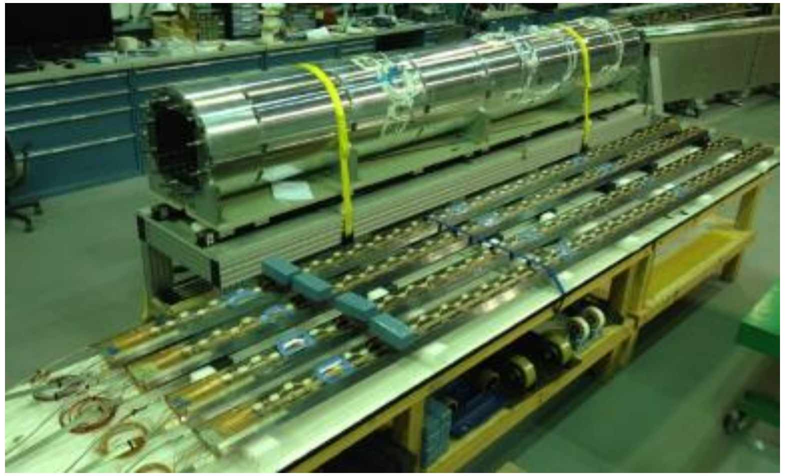
I_c reduction (reversible)

I_c degradation (permanent)

Courtesy of H. Felice

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

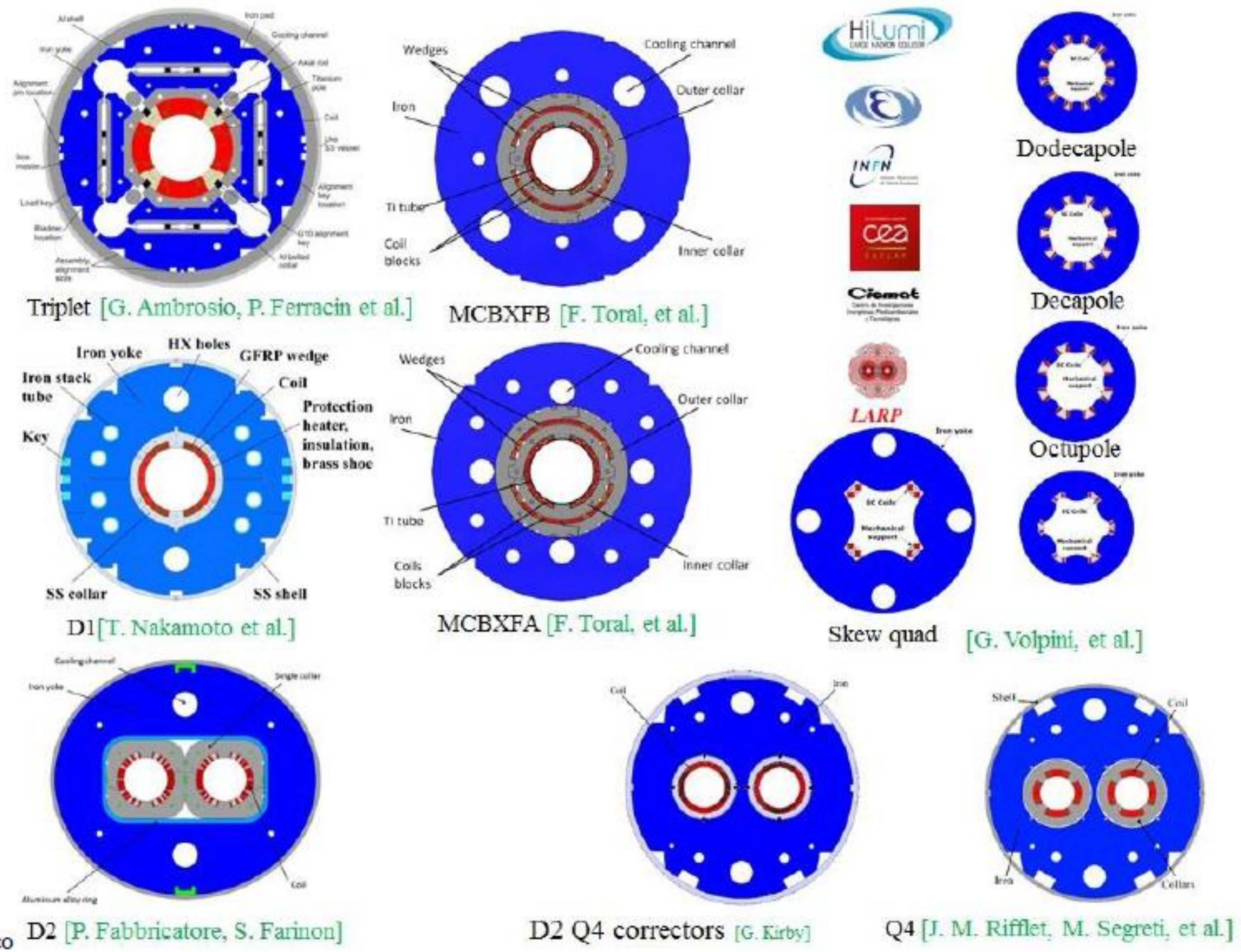




HL LHC magnet production

- First implementation of Nb_3Sn superconductor in a collider
- Analyses the risks and benefits of large-scale industrial production of Nb3Sn magnets
- Defines which elements of the design are "robust" and which generate performance risks/limits.

⇒ *There is significant value-engineering that can be performed*



Courtesy E. Todesco

TOWARDS 16 T MAGNET - CHALLENGES

- 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/mm²
- 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

From LBNL internal report
By Shlomo Caspi, 1990s

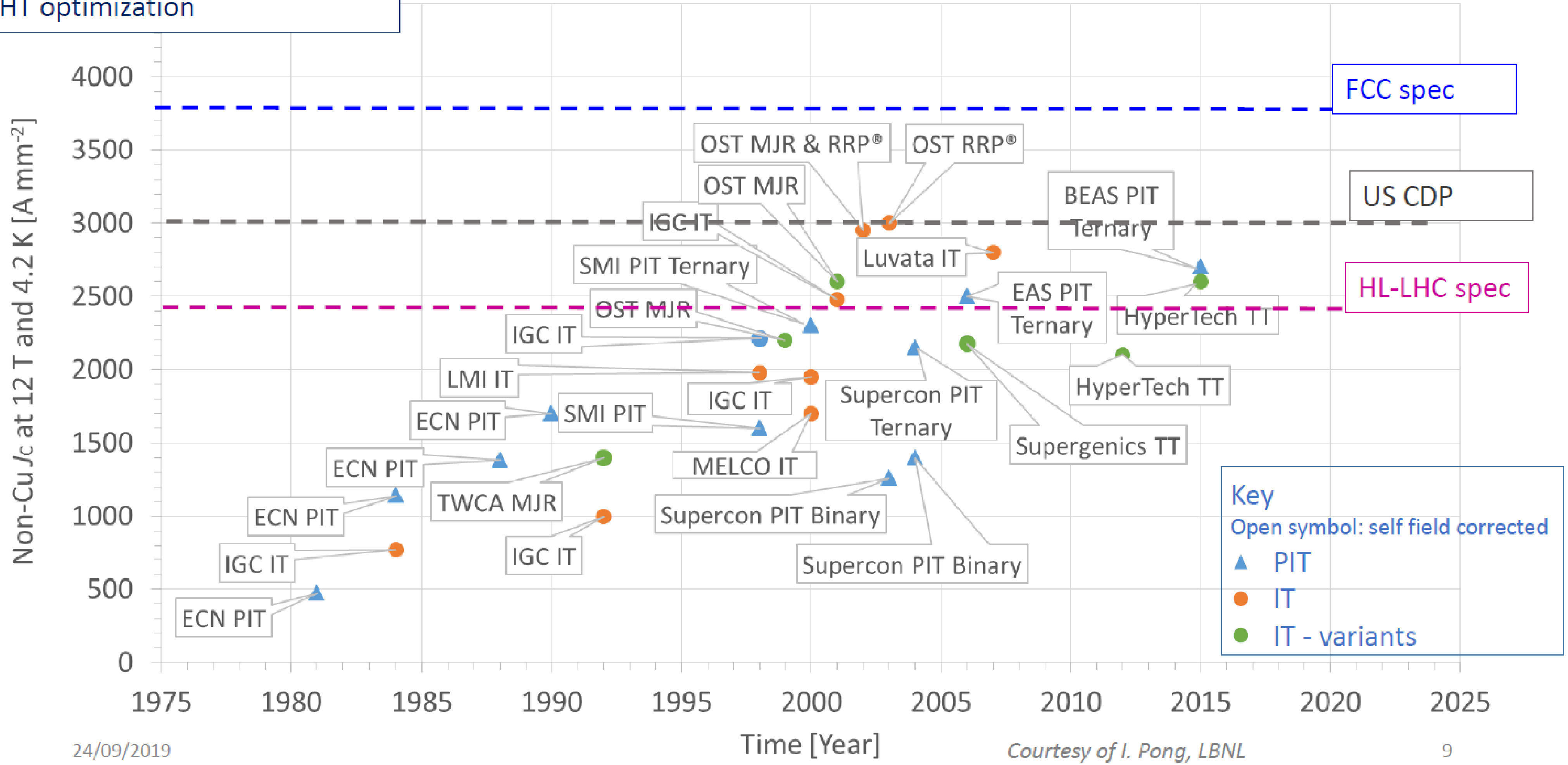
Courtesy of H. Felice

24/09/2019

Non Cu Jc improvement through

- Strand architecture
- Strand fabrication process
- HT optimization

A constant Non-Cu J_c improvement



24/09/2019

Courtesy of I. Pong, LBNL

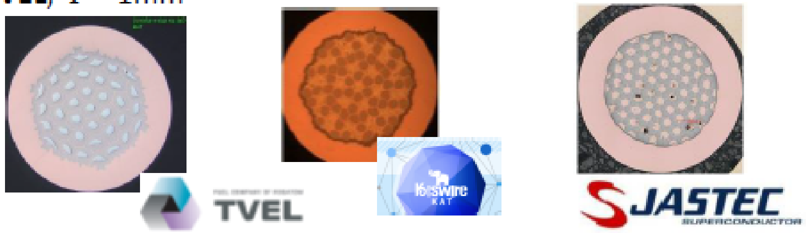
9

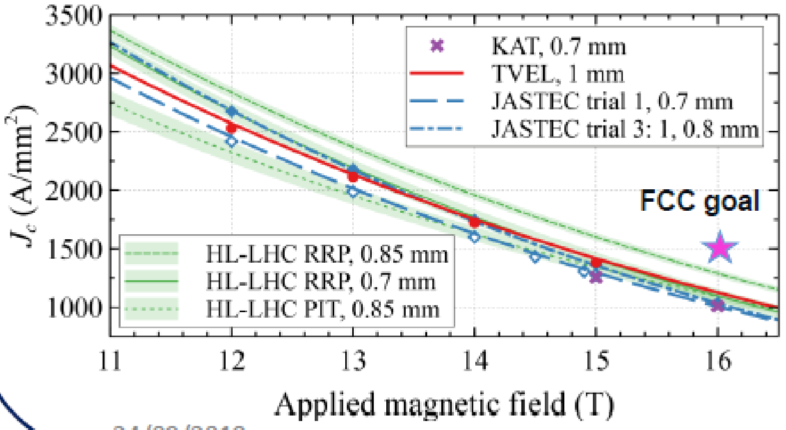
CERN FCC Conductor Development Program

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





24/09/2019

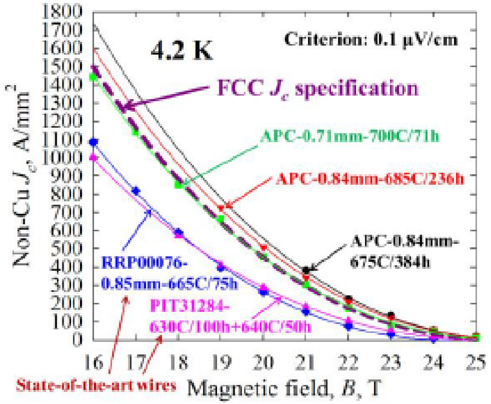
Courtesy of H. Felice

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

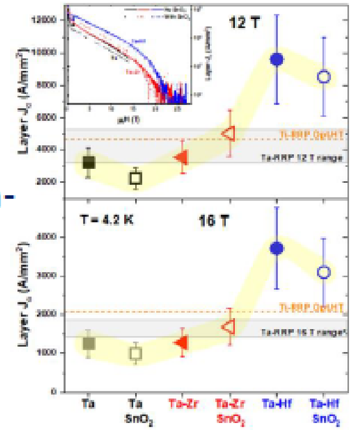
U.S. MAGNET DEVELOPMENT PROGRAM

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

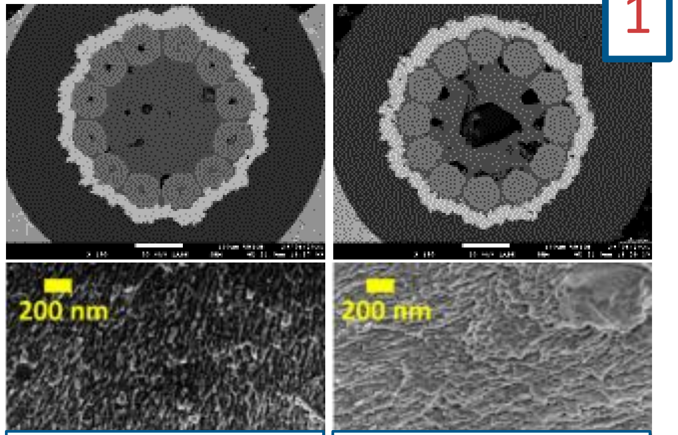


Jan Evetts SUST Award 2019

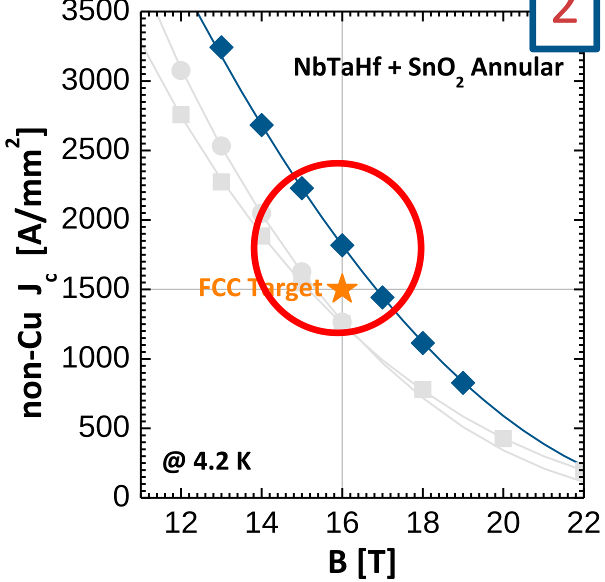
Shows untapped potential of Nb_3Sn
Optimization in progress

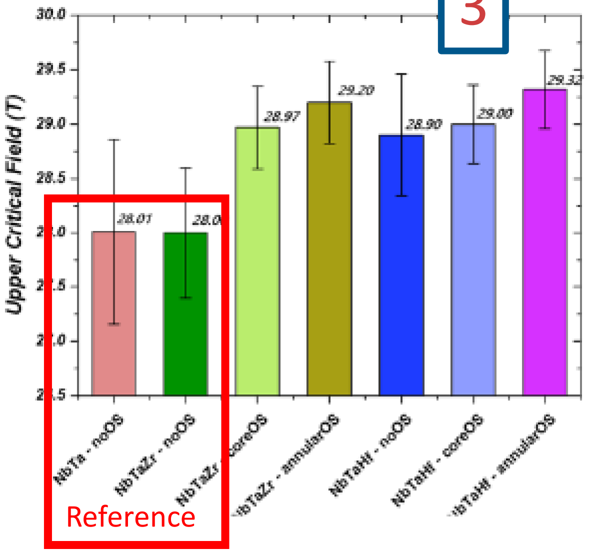
ASC/NHMFL, FSU   11

Internal Oxidation in prototype multifilamentary wires



Average grain size ~ 47 nm	Average grain size ~ 45 nm



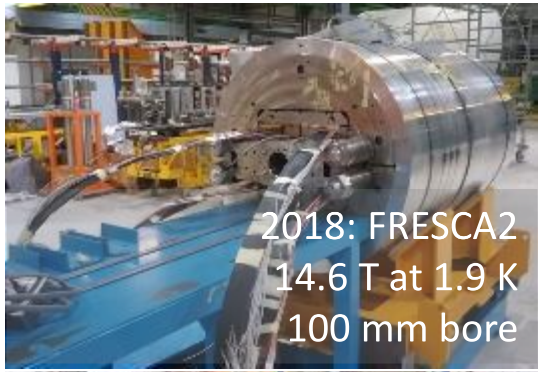


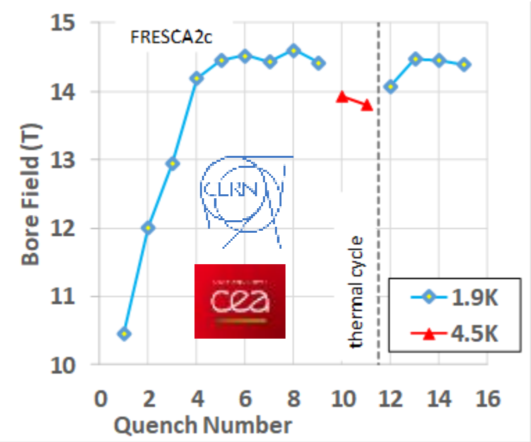
Pushing Nb_3Sn towards its ultimate performance

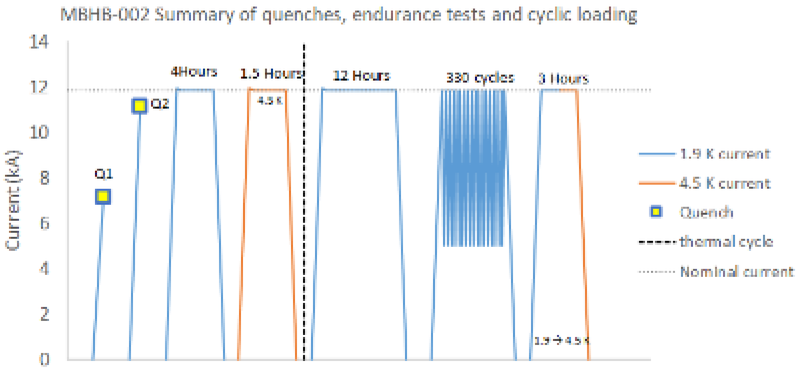
1. Refinement of the grain size: 100 nm → 50 nm
2. Large increase of the layer J_c → exceeding the FCC target
3. Enhancement of B_{c2} by > 1 T → improved in-field performance

Larger billets under development

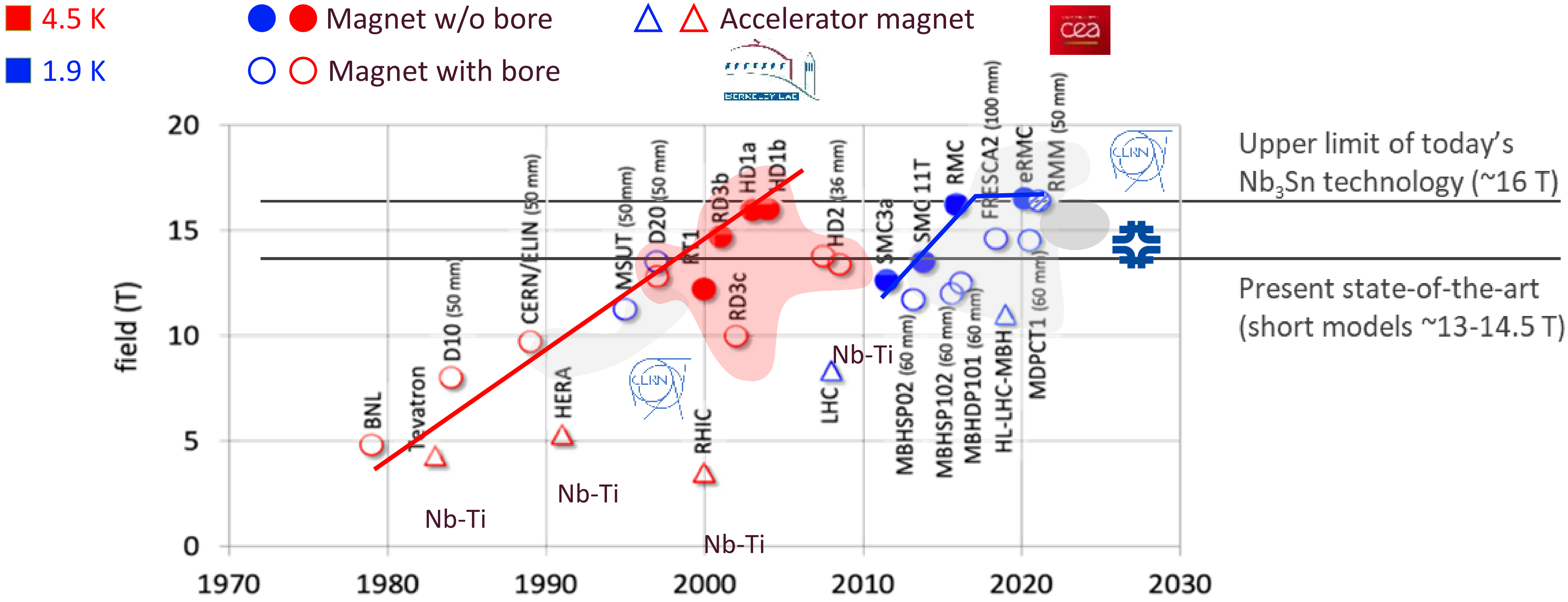
Courtesy of C. Senatore







Each of these realizations is a 10-years adventure

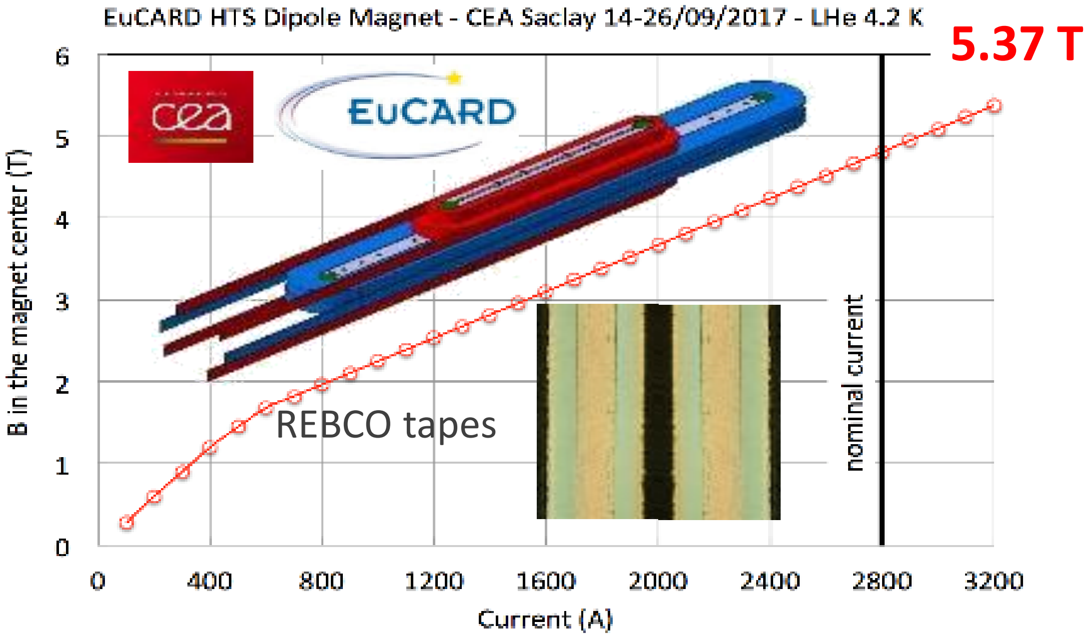


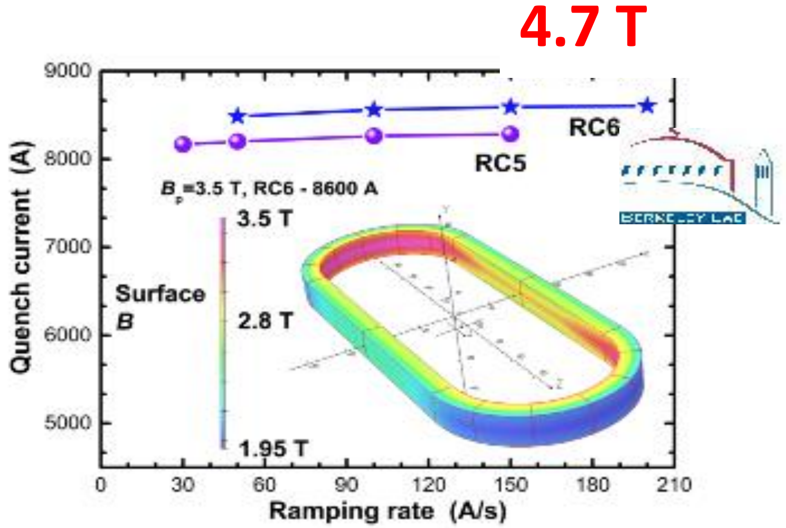
Note 1: HL-LHC technology was developed *well before* inception (1990's to 2000's)

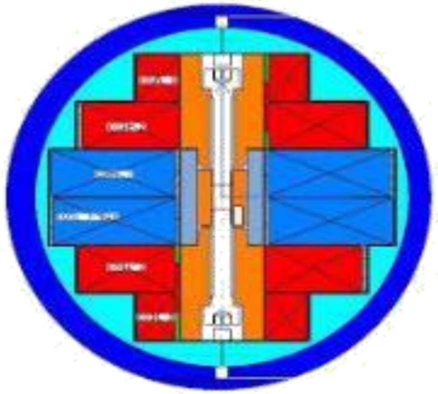
Note 2: High-field magnets are a *long-term business* and continuity is an asset

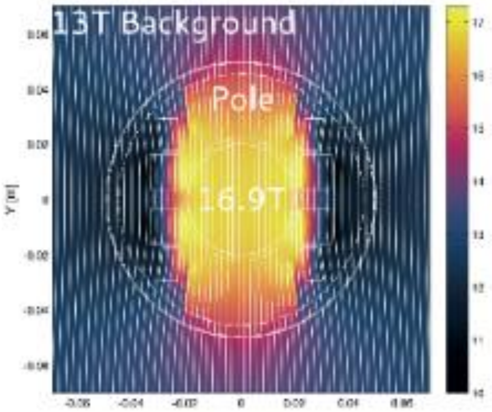
A true worldwide effort on Nb_3Sn magnets

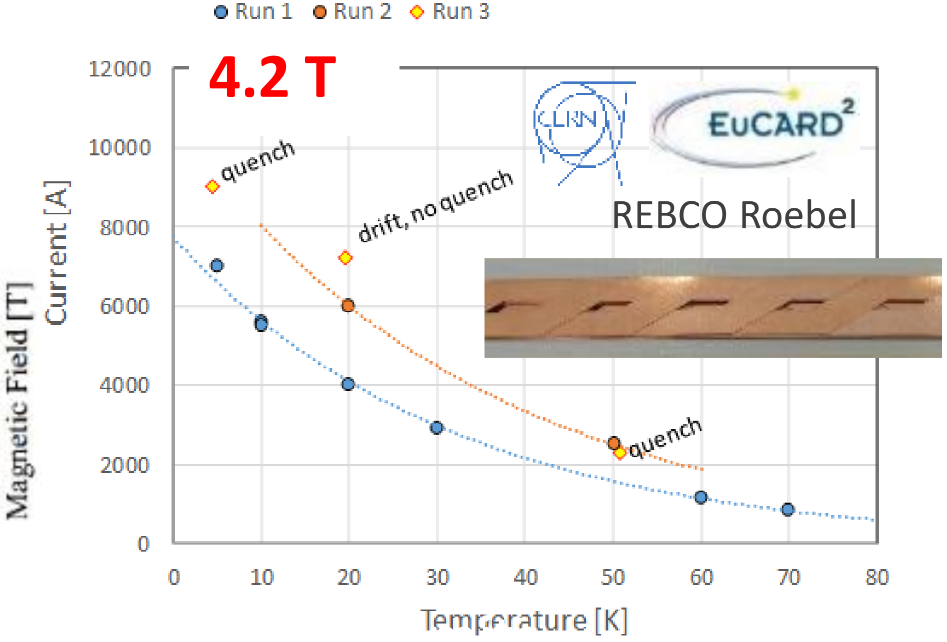
ACHIEVEMENTS IN HTS DIPOLE MAGNETS





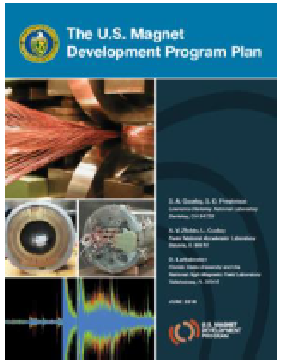






U.S. MAGNET DEVELOPMENT PROGRAM *ASC/NHMFL, BNL, FNAL, LBNL*

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

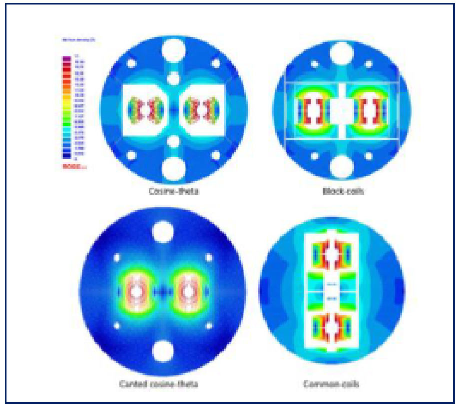
Item 2.5: Superconducting Materials -Conductor Procurement and R&D (CPRD)

FCC hh ee he

EuroCirCol A key to New Physics

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

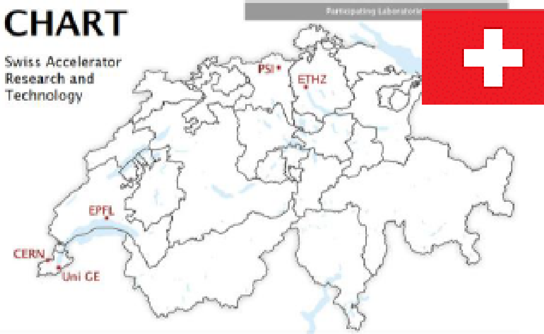
- **2017:** https://indico.cern.ch/event/665458/
- **2018 :** https://indico.cern.ch/event/743626/
- **2020 in preparation**

Budker INP Novosibirsk

~~Ongoing discussion on high field dipole program definition~~

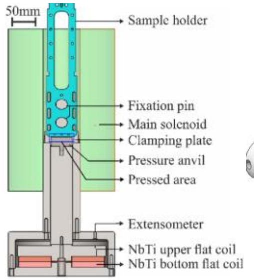
CHART

Swiss Accelerator Research and Technology

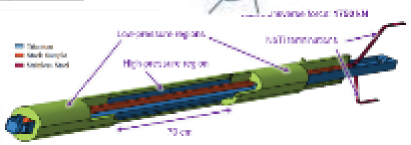


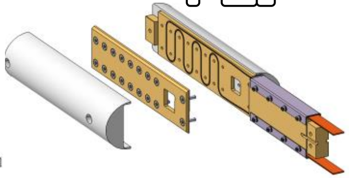
High field magnets development
Focus on innovative concept

Powered Samples



UNIVERSITY OF TWENTE.

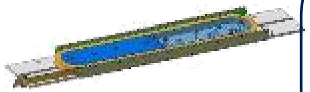




BOnding eXperiment

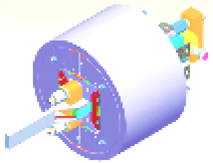
Mock-ups and Mechanical models

EPFL



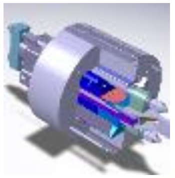
Existing Subscale Magnets

SD



CCT subscale

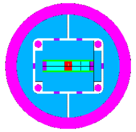
SMC



RMC

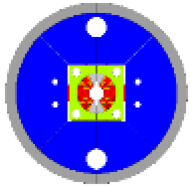
Model magnets under development

R2D2



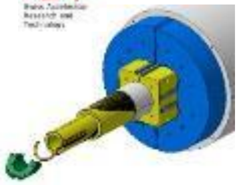
10-12 T
Graded racetrack

FALCOND

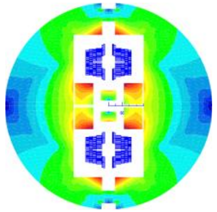


12-14 T Double Layer cosθ

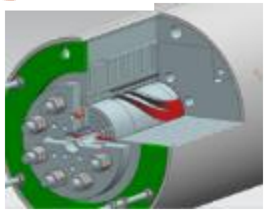
CCT



Common Coil



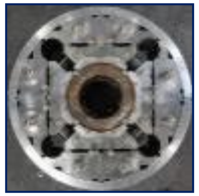
Recent or unique Existing model magnets



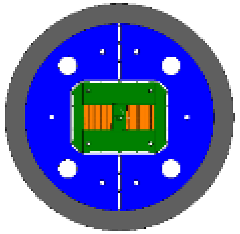
MDPCT

HD3

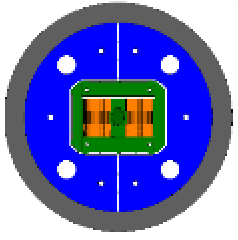
MQXFS



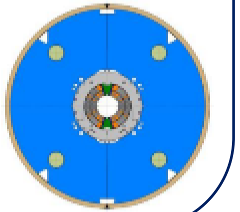
eRMC



RMM



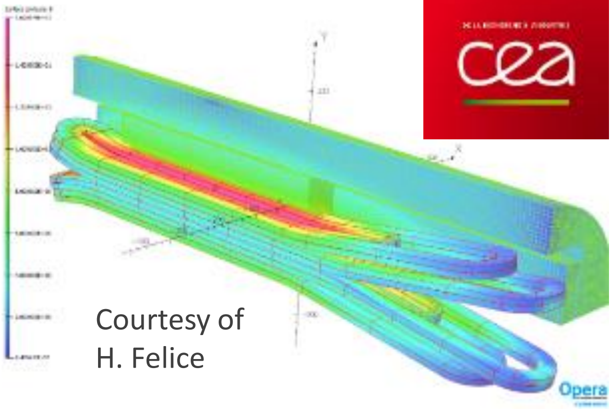
11 T



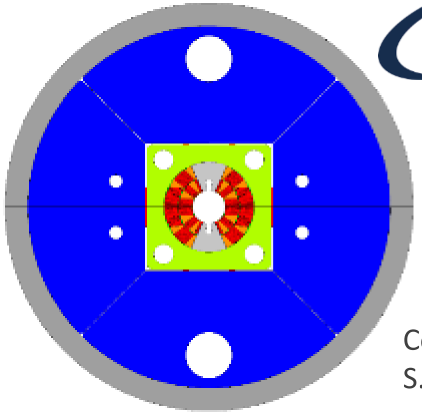
Courtesy of S. Izquierdo Bermudez, J.C. Perez, S. Farinon, F.Toral, E. Rochepault, B. Auchman, M. Daly, P. Ferracin, F. Lackner, S. Zlobin, M. Dhalle, B. Bordini, P Bruzzone

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)



Courtesy of H. Felice



Courtesy of S. Farinon

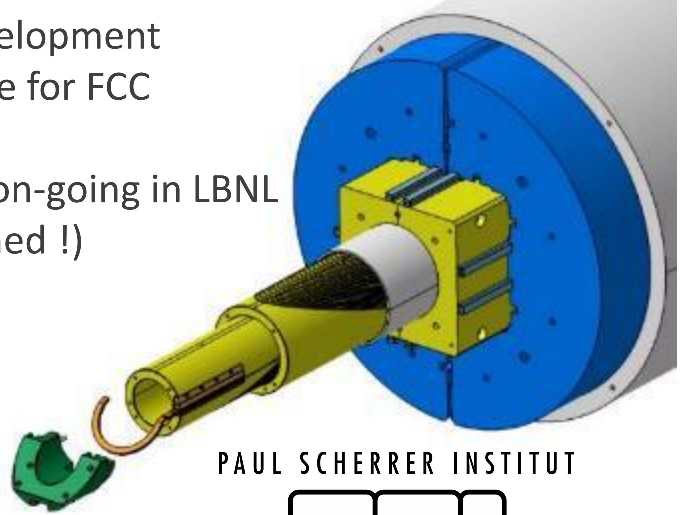
Conceptual design of a **16 T** *cos-theta* model dipole for FCC

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

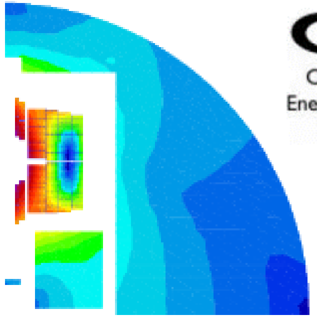
CD1 magnet test is on-going in LBNL (11.1 kA/6.1 T reached !)



Swiss Accelerator Research and Technology

Courtesy of B. Auchmann

PAUL SCHERRER INSTITUT



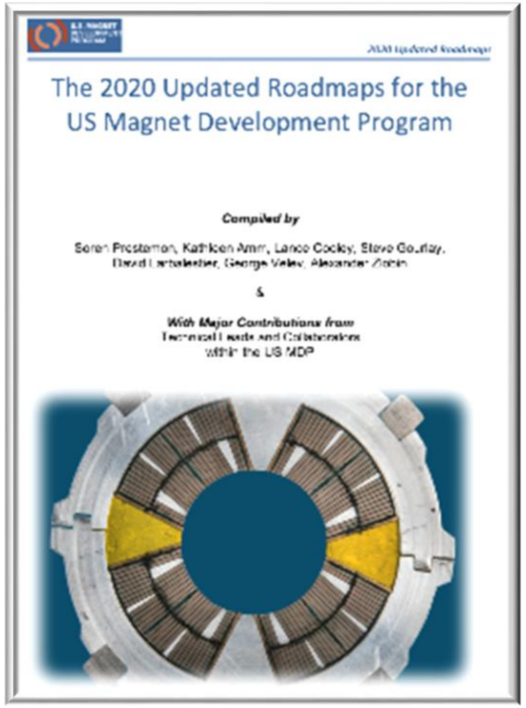
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Courtesy of F. Toral

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

FUTURE MAGNET AND CONDUCTOR R&D PLANS & ROADMAPS

- US Magnet Development Plan (MDP) – *well established*
- European High Field Magnet Program (HFM) – *recently established*
- Japan efforts at KEK - coordinated with CERN and MDP
- China efforts led by IHEP – *progressing well*



Updated US MDP Roadmaps have been published
https://arxiv.org/abs/2011.09539

https://arxiv.org/abs/2201.07895

中国科学院电工研究所
Institute of Electrical Engineering, CA

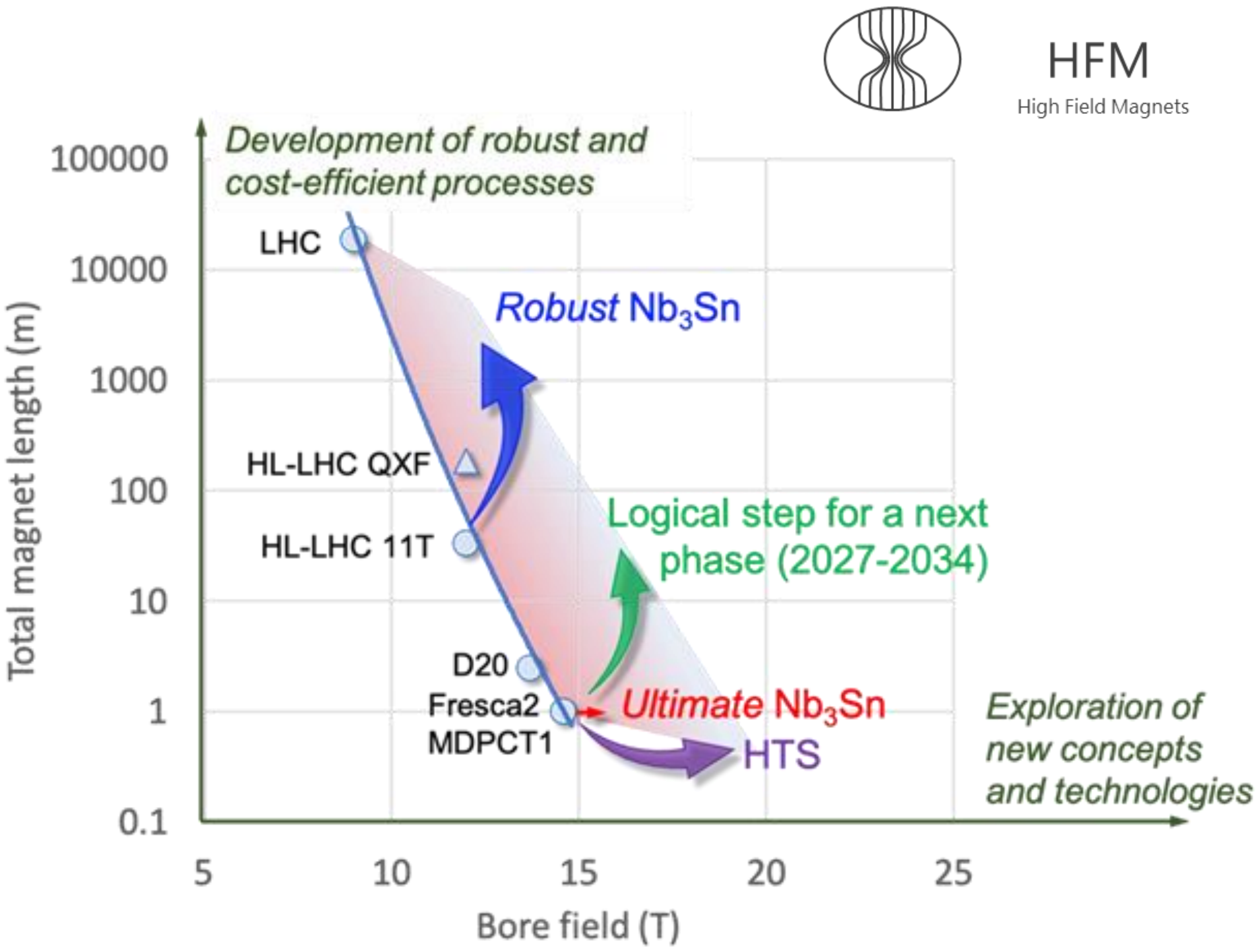
中国科学院高能物理研究所
Institute of High Energy Physics, CAS

This is ***not*** a comprehensive list of collaborators… our community is broad and diverse!

- **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)**

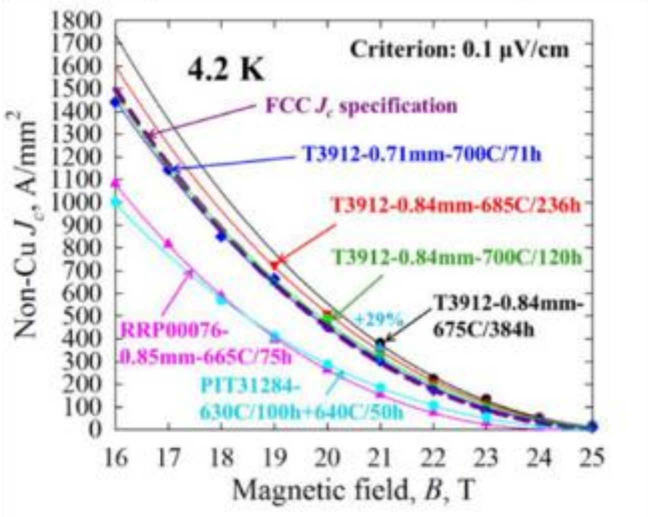
  - **Other key parameters:**
    - Cost of Magnets & R&D
    - Timeline of a realistic development
    - Potential for wider societal applications
    - Training and education



▶ Nb_3Sn Conductor

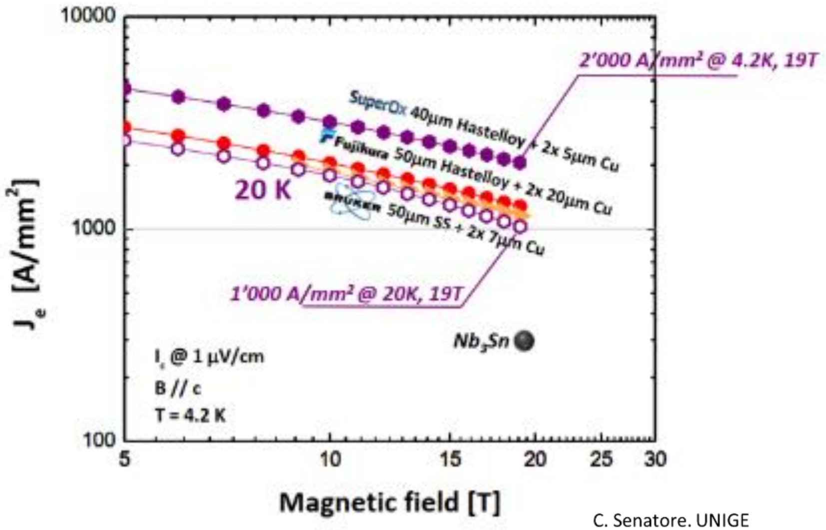
- Advance performance of Nb3Sn wires beyond present state-of-the-art, with a target 1500 A/mm2 at 16 T (mechanical properties, magnetization & stability, cost…).
- Develop cables with high engineering current density, $J_E \approx 600$ A/mm², appropriate to yield a compact and efficient coil design.
- 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

HFM R&D PLANS RELATED TO MAGNETS

- 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).

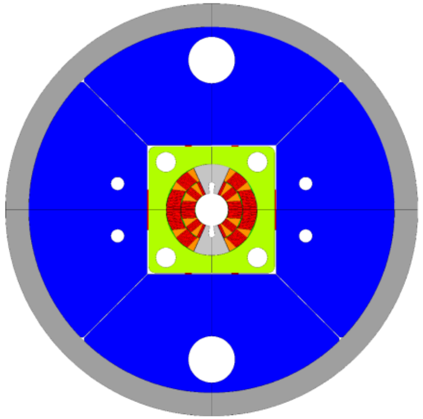
Development of a single aperture "12 T Robust Dipole" in INFN, Genova

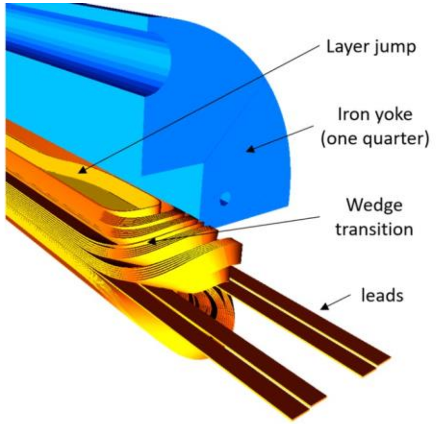
INFN Istituto Nazionale di Fisica Nucleare

CERN

Main characteristics :

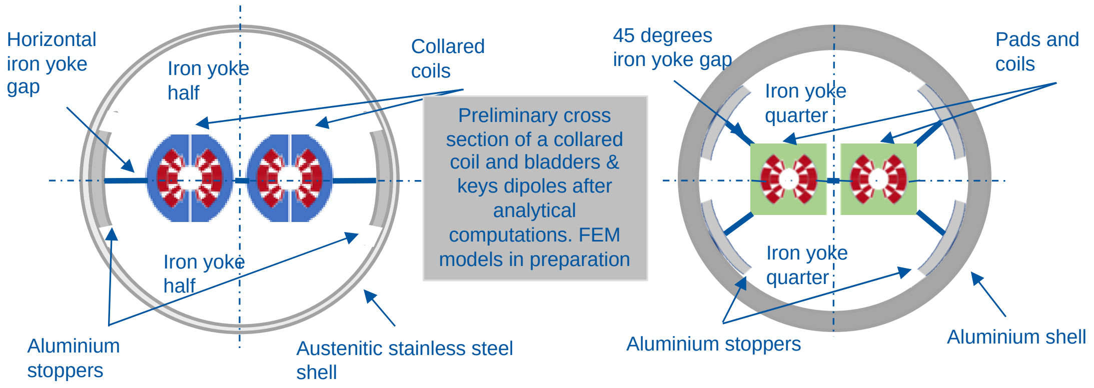
- 2 layers ; 50 mm bore
- Rutherford 40 strands (φ = 1 mm J_C(4.5 K, 16 T)=1200 A/mm^2)
- Nominal magnetic field: 12 T
- Ultimate (mechanical limit) field: 14 T
- Short sample limit : 15.7 T
- Mechanical structure: bladder & key
- Stress in conductors ≲150 MPa in all conditions
- Outer diameter: 640 mm (LASA test)





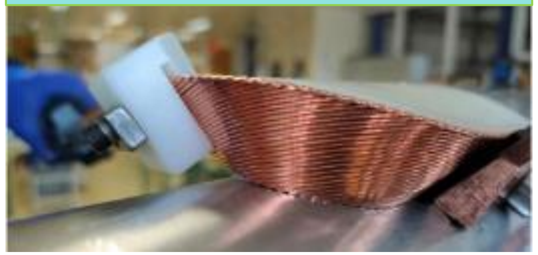
Courtesy of S. Farinon

Development of twin "12 T Robust Dipole" at CERN



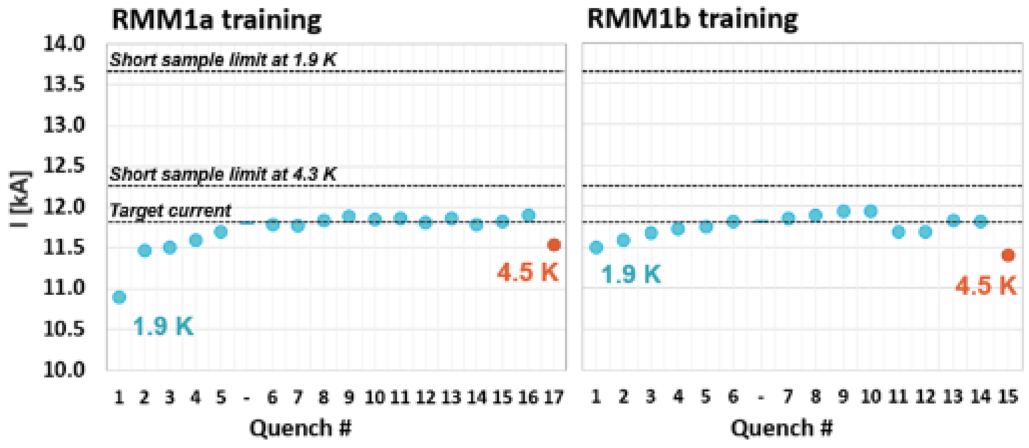
Courtesy of D. Perini

Winding tests are ongoing in INFN Genova



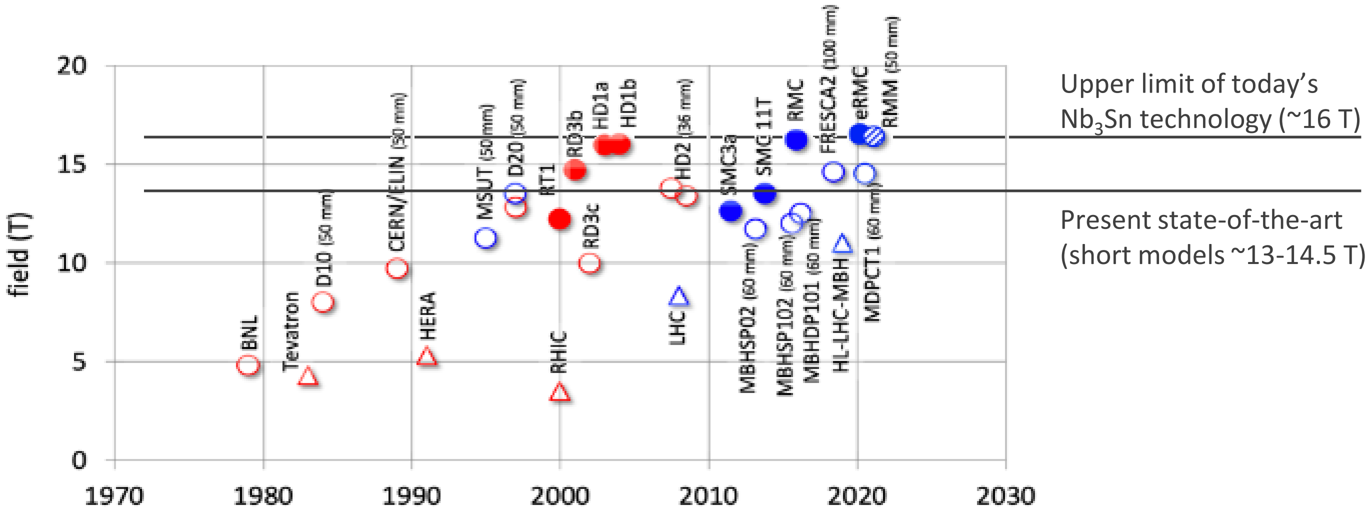
Both the INFN and CERN 12 T short robust dipole models are expected to be ready in 2025.

ONGOING PROJECTS: CERN RMM



Courtesy of J. C. Perez

RMM1c magnet has been assembled with increased pre-load and will be tested in few weeks.



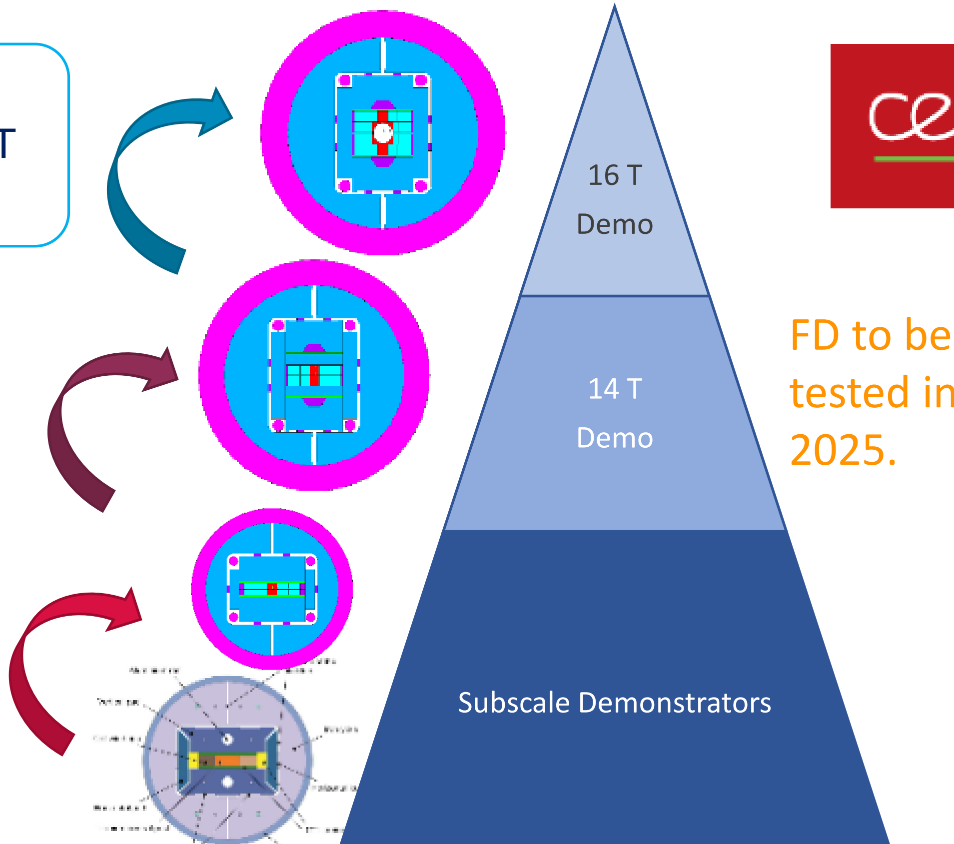
HFM
High Field Magnets

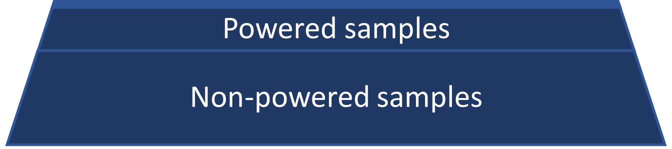
F2D2 Short model → Planned
Grading + Flared-ends + Aperture, 16 T
1.5 m, 50 mm bore **with aperture**

FD Demonstrator → Planned
Grading + flared-ends, 14 T
1.5 m, No bore **with flared ends**

CEA-CERN R2D2 → Ongoing
Demonstrate grading ≥ 12 T
1.5 m, No bore **with grading**

CEA-CERN SMC-11T coil ✓ Done
Demonstrate Nb_3Sn tech. ≥ 12 T





FD to be tested in 2025.

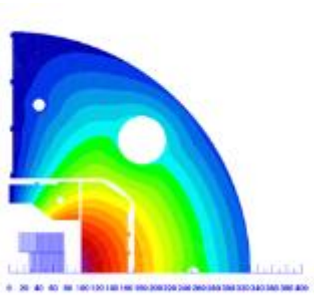


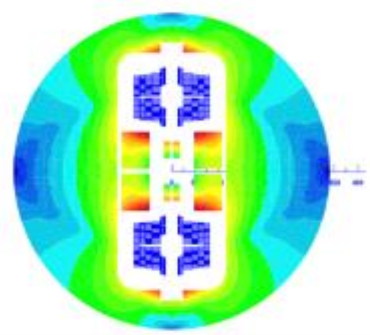

Courtesy of E. Rochepault

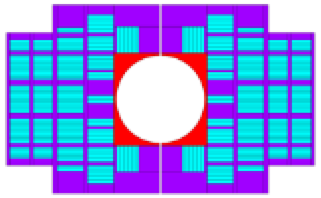
Development of technological steps **towards 16-T block coil Nb_3Sn magnets with stress management**: conceptual design has started.

Development of technological steps **towards 16-T** Nb_3Sn magnets with **low-prestress common coil** structure: preparation of workshops for the implementation phase.

Collaboration agreement for the development of technological steps **towards 16 T common coil** Nb_3Sn magnets **with stress management**: collaboration agreement is finalized. **First test 14.5-15 T in 2025/26.**

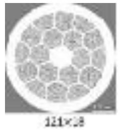


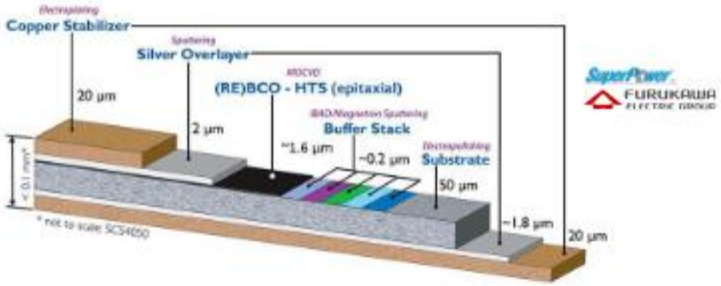




Collaboration agreement for the

- **REBCO: TAPE**
  - Unit length ~300m (cable ~50 m)





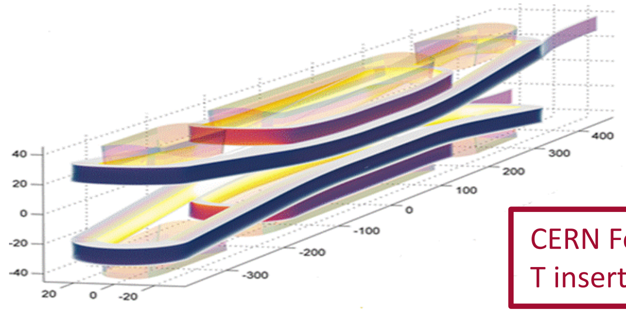
- **BiSCCO 2212: WIRE**
- **IBS: "powder in tube" wire**
  - Ba-122 has Tc~38K Hc2~70T
  - China builds a plant for ~km wires
  - CERN/SPIN: >100m, >1kA/mm2 at 16 T
    - Iron Based Superconductors laboratory →

- **Magnets:**
  - CERN FCC aims at 15T+5T tests
  - PSI 20 T HTS solenoids
  - Also CEA, UNIGE, U.Twente, etc
- **Hope: fusion will develop REBCO industry**
  - >10,000km per year → Expect cost reduction

Amalia Ballarino

From "FCChh & Magnets" | Vladimir Shiltsev, FCC week 2023

- EUCARD2 magnets at CERN and CEA represent the communities most targeted attempts to build accelerator magnets from ReBCO tape (here, Roebel bar cable).
- Both magnets were performance limited; Feather-M2 at CERN likely due to mechanical / thermo-mechanical effects; CEA's cos-theta coil due to over-heating of coils during manufacturing.



CERN Feather-M2 HTS 5 T insert magnet

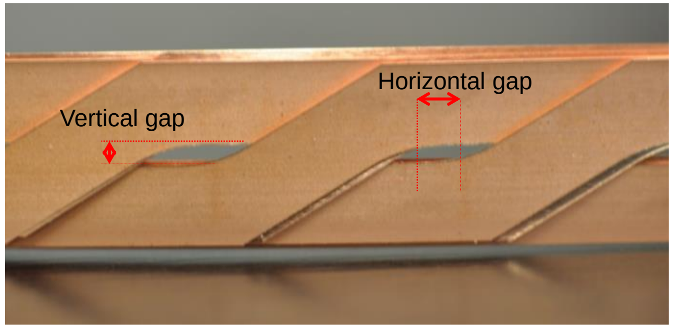
Courtesy of G. Kirby, J. Van Nugteren

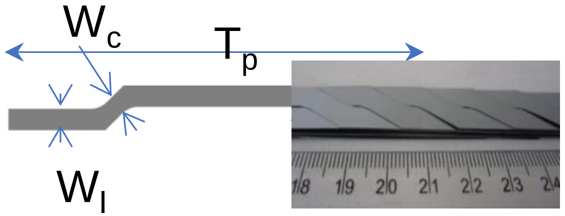
CEA cos-theta magnet, insulated and impregnated

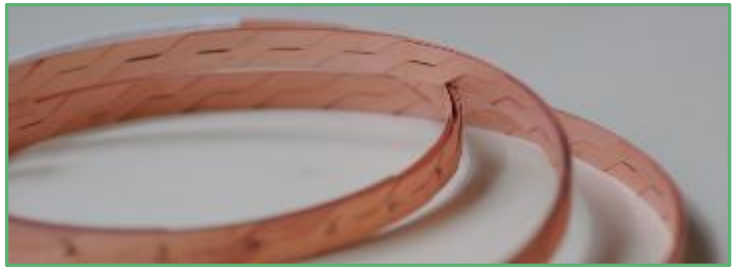
Courtesy of T. Lecrevisse

Feather M2	9 kA – 4.5 T (4.5 K)	Degradation: after thermal cycle and during powering with Fresca2	Probably stress in the Roebel cable, or caused by the induction copper rings
Cos-theta	3 kA – ~1.5 T (4.5-6 K)	Yes, but stable and distributed	Known: overheating during manufacturing

Roebel flat cables for EU Eucard 2







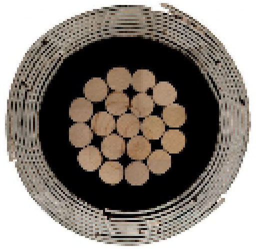
Unit length ~ 54 m

KIT

CORC® round cables

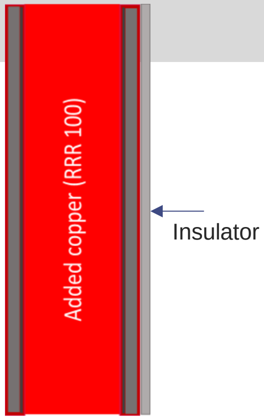
3 kA @ 60 K (B = 0.7 T)

Twisted + insulated, CERN



Advanced Conductor Technologies

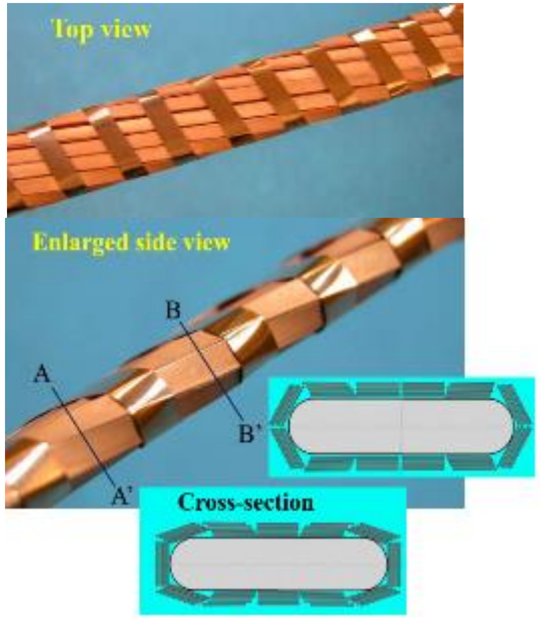
Stack of tapes



MI, IFAST, CEA

Twisted, MIT

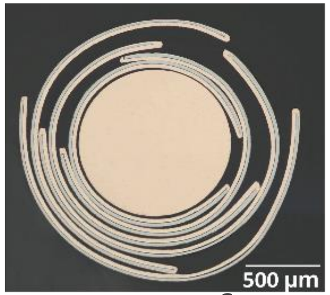
Stacked tapes on a flat former



MIT

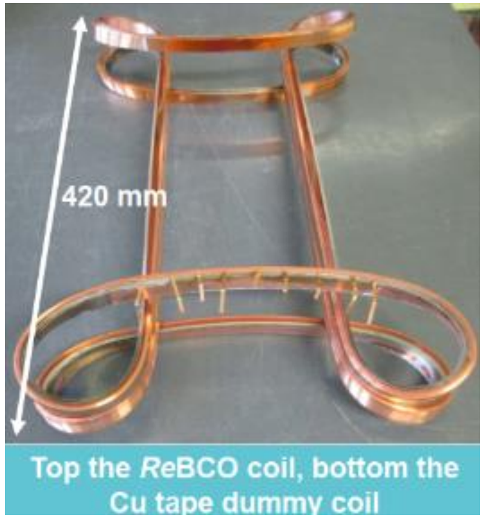
STAR® REBCO Wire

(Φ~0.8 mm)

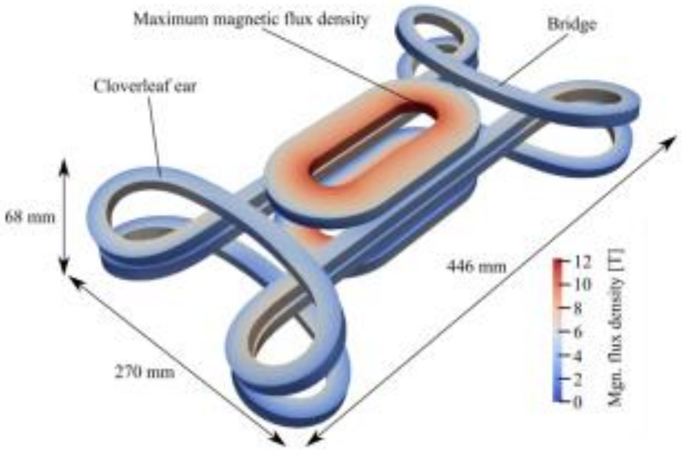


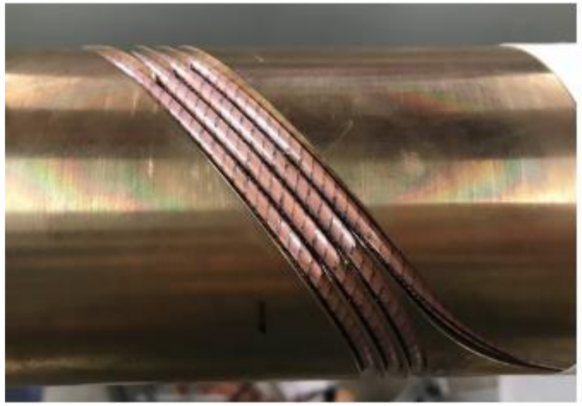
University of Houston

Courtesy A. Ballarino – HTS Developments - FCC Week – June 2023

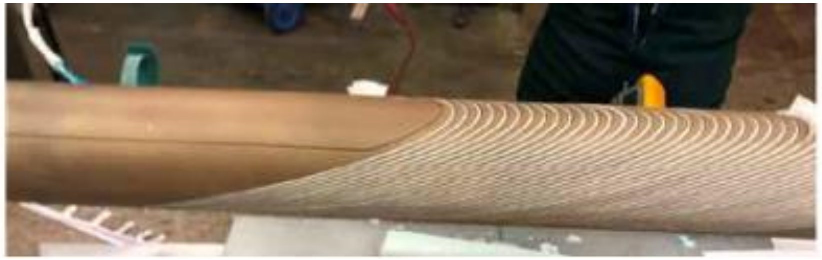


REBCO Cloverleaf, CERN and KIT
PhD Thesis of Th. Nes

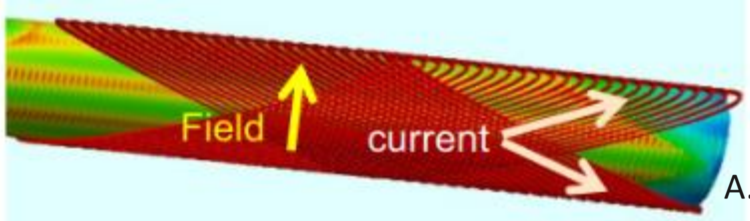


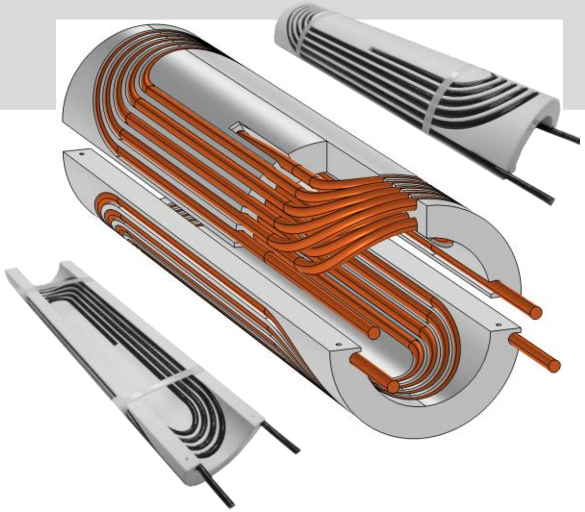


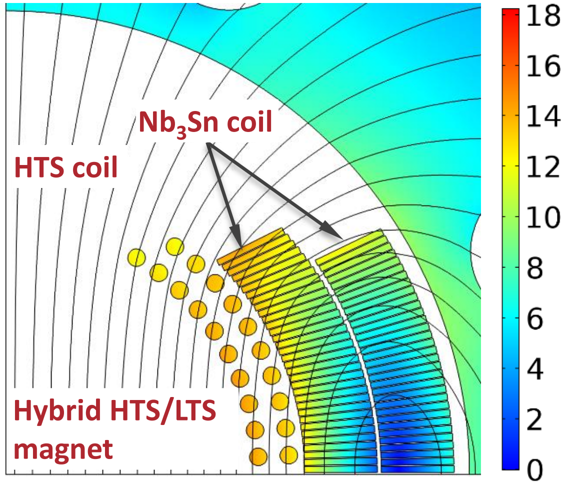
REBCO CORC® CCT, LBNL



BSCCO 2212 CCT, LBNL and ASC
Rutherford cable



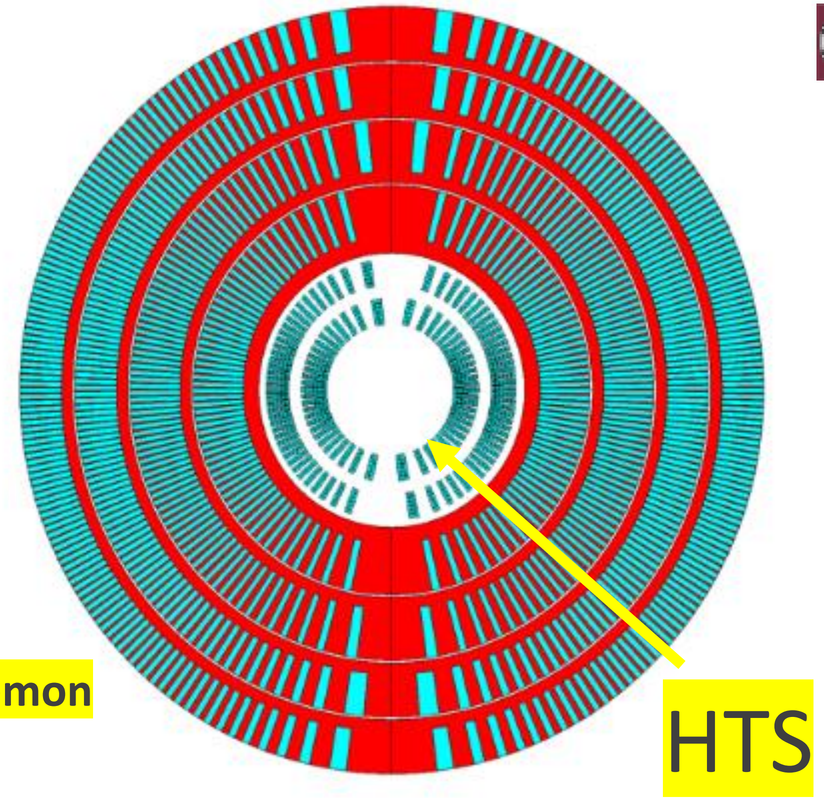




REBCO **C**onductor **O**n **M**olded **B**arrel (COMB)
Fermilab, STAR Wires

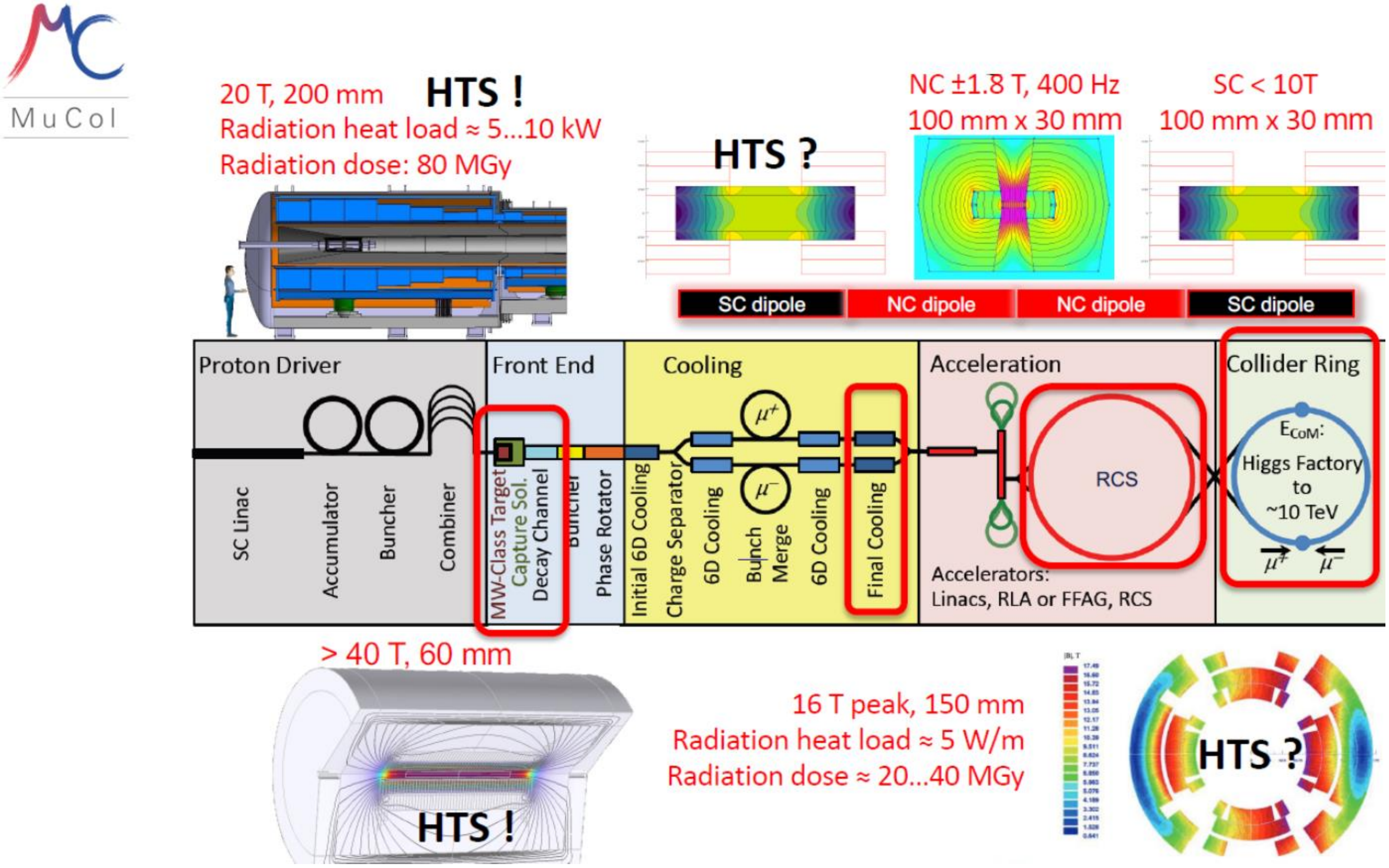
A. Ballarino – HTS Developments - FCC Week – June 2023

- **Three labs and University… FCChh and MuCollider**
- **Focus on stress management 14-16 T Nb3Sn**
  - 120 mm aperture to fit 5T HTS insert
- **Goal: in 3-4 years 16-17 T hybrid (Nb3Sn+REBCO) dipole**
- **Recent advances:**
  - **14.5T FNAL 4-layer Nb3Sn → 2 layers**
  - **1st Nb_3Sn CCT coil wax impregnated had no quenches!**
  - **Diagnostics! E.g.:**
    - Rayleigh backscatter fiber optics for area-level strain monitoring
  - **Significant promise of REBCO**

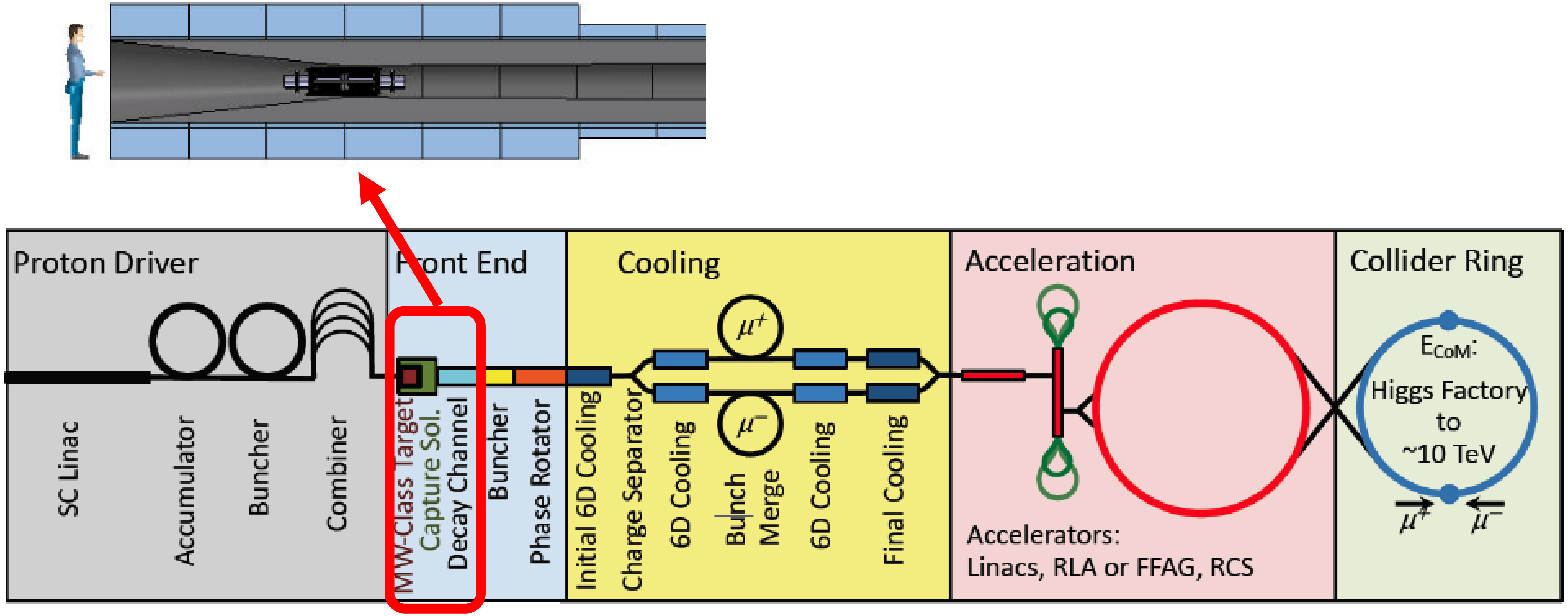


Courtesy Soren Prestemon

FCChh & Magnets | Vladimir Shiltsev


MuCol
20 T, 200 mm
HTS !
Radiation heat load ≈ 5…10 kW
Radiation dose: 80 MGy
HTS ?
NC ±1.8 T, 400 Hz
100 mm x 30 mm
SC < 10T
100 mm x 30 mm
SC dipole
NC dipole
NC dipole
SC dipole
Proton Driver
Front End
Cooling
Acceleration
Collider Ring
SC Linac
Accumulator
Buncher
Combiner
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
Initial 6D Cooling
Charge Separator
6D Cooling
Bunch Merge
6D Cooling
Final Cooling
μ+
μ−
RCS
Accelerators:
Linacs, RLA or FFAG, RCS
E_CoM:
Higgs Factory
to
~10 TeV
> 40 T, 60 mm
HTS !
16 T peak, 150 mm
Radiation heat load ≈ 5 W/m
Radiation dose ≈ 20…40 MGy
HTS ?

20 T, 200 mm
Radiation heat load ≈ 5…10 kW
Radiation dose: 80 MGy

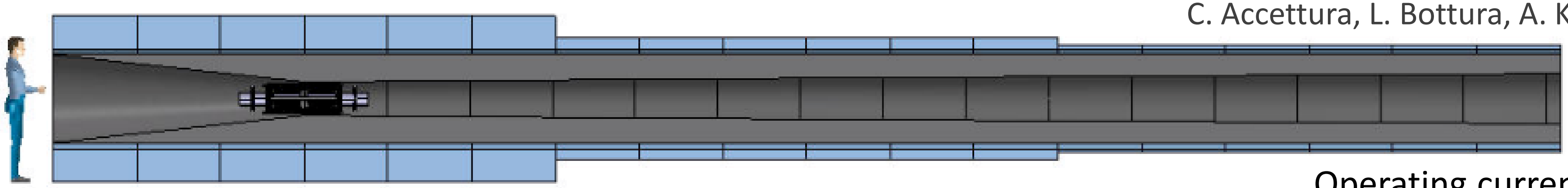


- **Large stored energy o(1) GJ, mass o(300) tons, cost o(100) M**
- **Considerable RT and cryogenic heat load: RT power o(1) MW**
- **Radiation dose o(80) MGy and radiation damage o(10^{-2}) DPA**

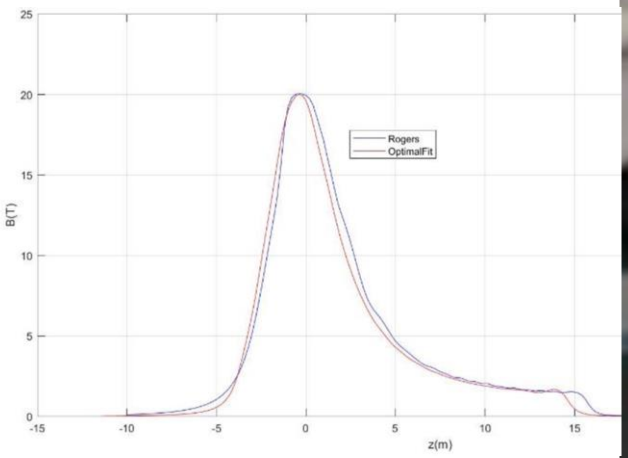
TARGET AND CAPTURE MAGNETS - 2

A. Portone, P. Testoni, J.Lorenzo Gomez (F4E)
C. Accettura, L. Bottura, A. Kohleimainen (CERN)

E_M = 1 GJ
T_{op} = 10…20 K
M_{coils} = 110 tons
M_{shield} = 196 tons
P = 1MW



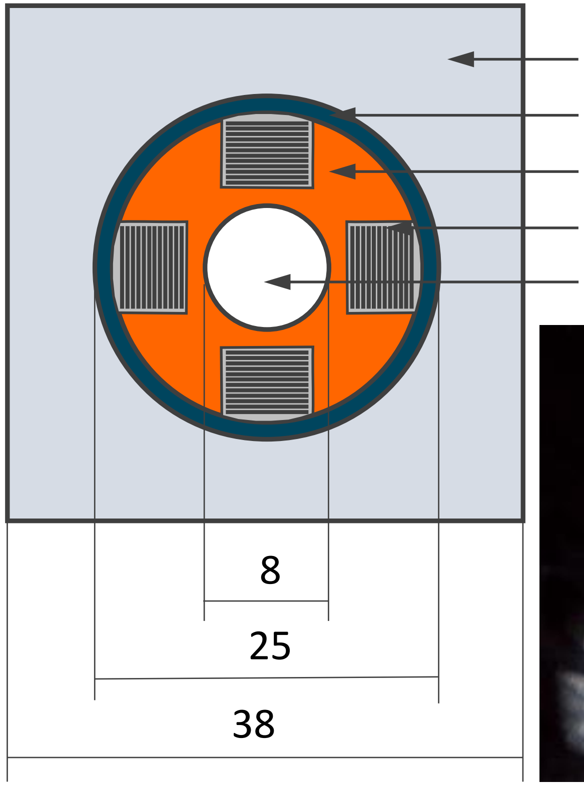
Operating current: 58 kA
Operating field: 20 T
Operating temperature: 20 K



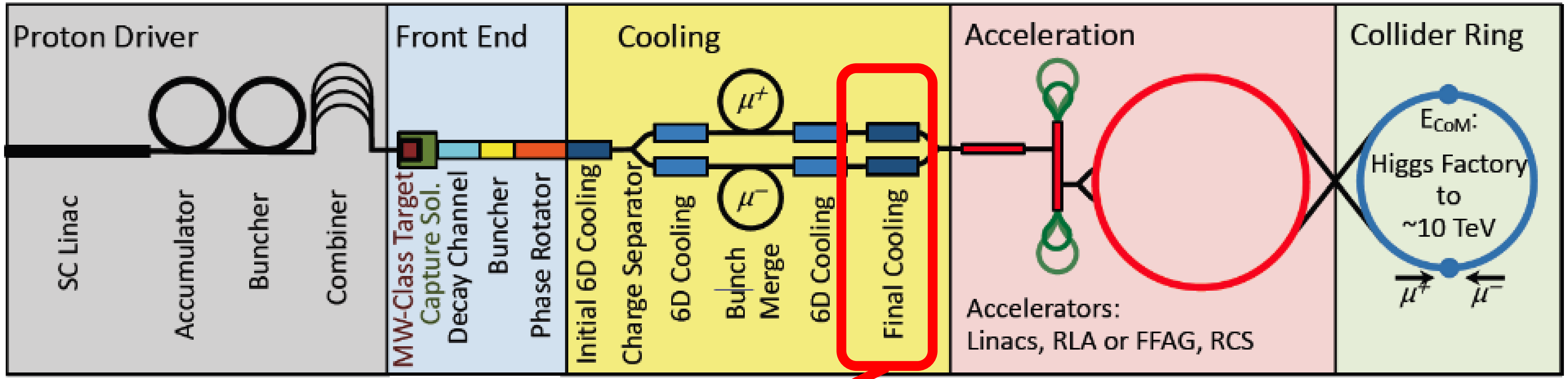
MIT "VIPER" conductor

M. Takayasu et al., IEEE TAS, 21 (2011) 2340
Z. S. Hartwig et al., SUST, 33 (2020) 11LT01

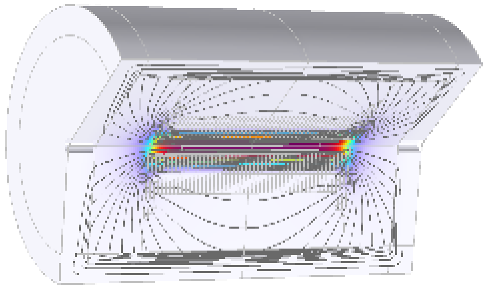
HTS conductor design



- **Total 1 km, o(1600) units of solenoid magnets up to o(20) T requires compact windings and careful cost optimization**
- **UHF solenoids, with field beyond state-of-the-art o(40…60) T, calls for novel HTS technology**



> 40 T, 60 mm



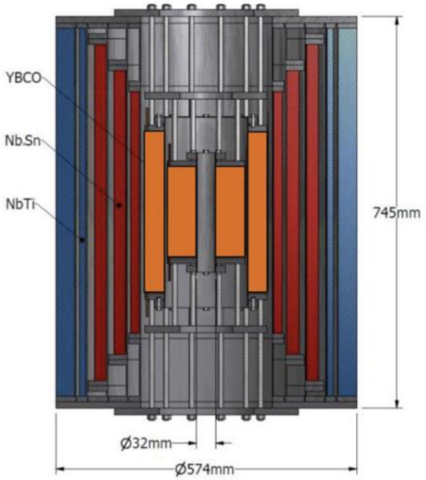
- Probe the limits of UHF solenoid magnets for the final cooling (performance)
- Make windings compact to reduce mass (CAPEX)

LTS/HTS hybrids

Vertical magnets

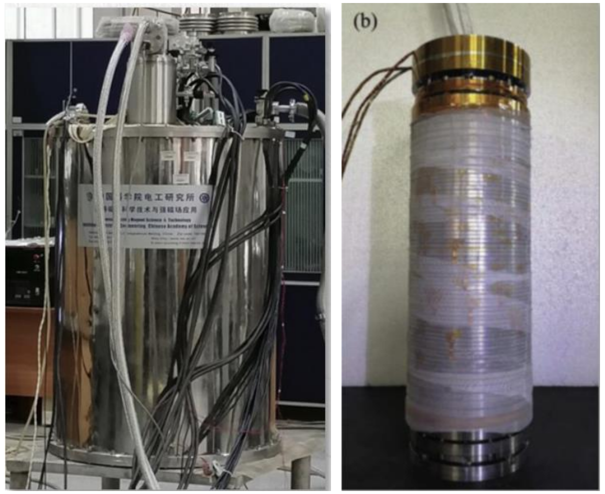
All-HTS

Cross section of
32 T, 32 mm user
facility solenoid
at NHMFL



I. Dixon, NHMFL

Images of
32.35 T, 21 mm user
facility solenoid
at CAS-IEE



REBCO insulated coil
achieved 24.1 T
at CAS-IPP

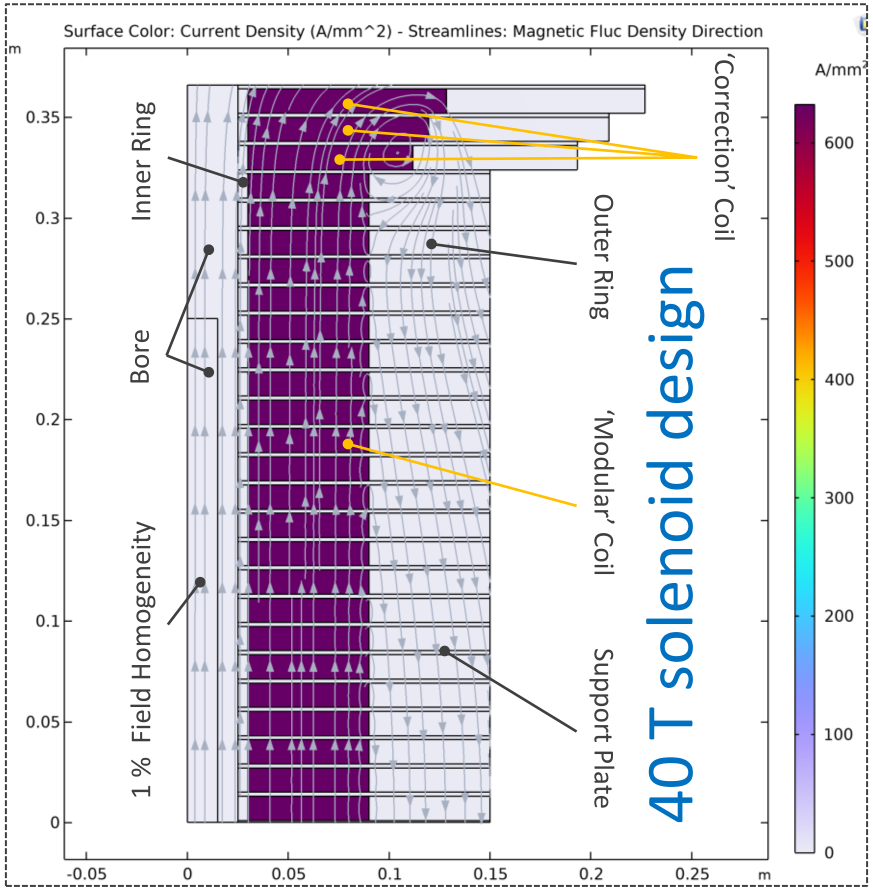
R&D NI *insert coil*
achieved 32.5 T
at LNCMI/CEA

J.-B. Song, LNCMI

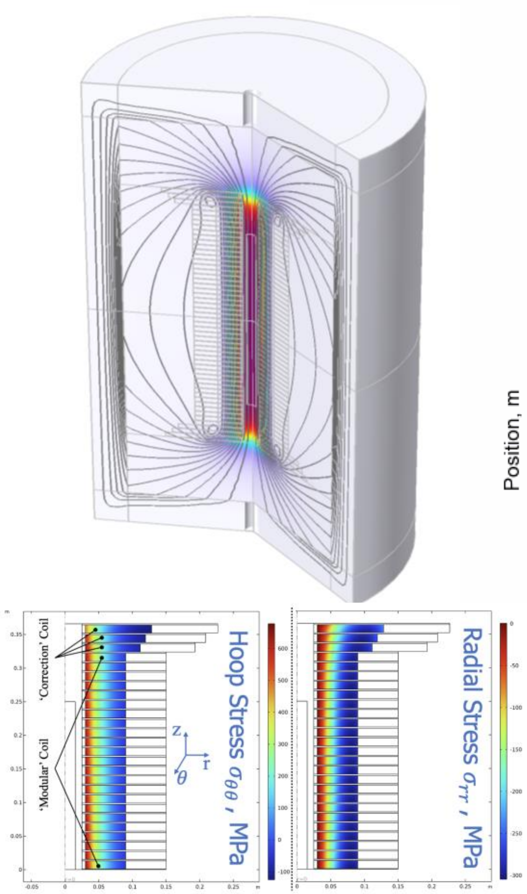
Final Cooling Magnets – 40 T Horizontal

$$B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0} \xrightarrow{\sigma_{max} = 600\ \text{MPa}} B_{max} \approx 55\ \text{T}$$

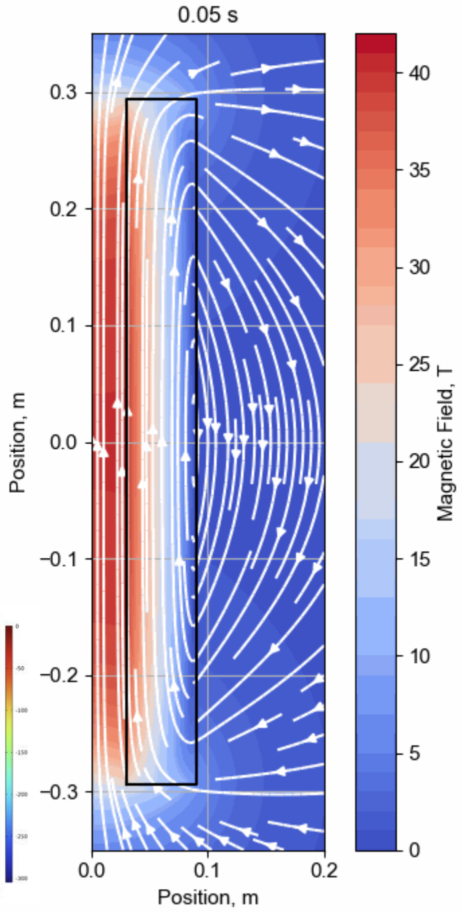
A. Dudarev, CERN



B. Bordini, CERN



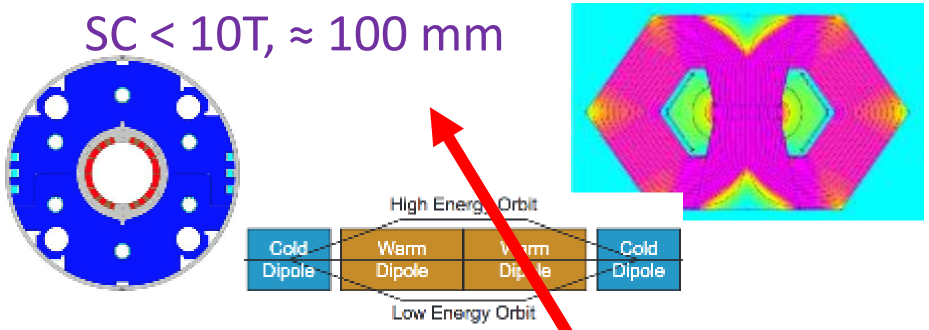
B. Bordini, CERN

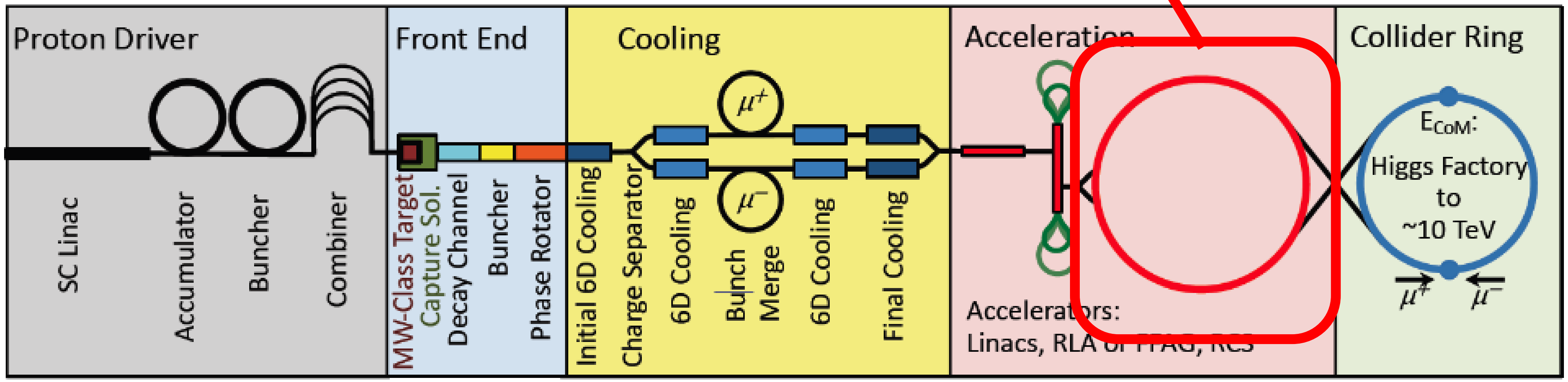


T. Mulder, CERN

NC ±1.8 T, 400 Hz, 100 mm x 30 mm

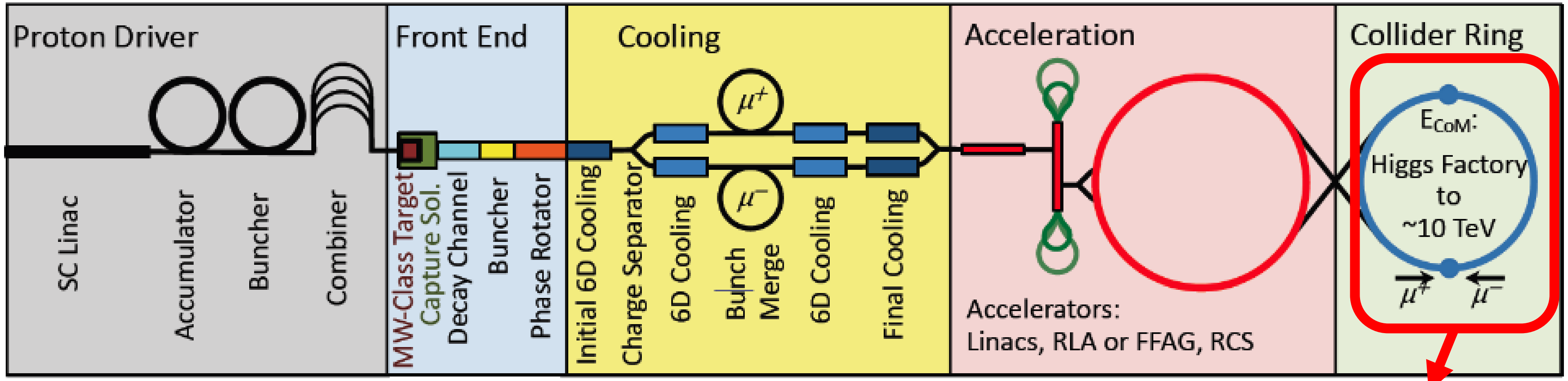
SC < 10T, ≈ 100 mm





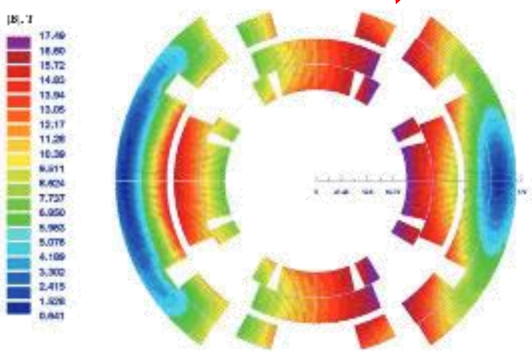
- **Energy storage and power management o(50) GW**
- **Ramp linearity control, requirement (TBD)**
- **Medium field o(10 T) SC dipoles subjected to radiation load**

- Large bore o(150mm), high field o(10…20T) arc and IR magnets result in large e.m. stress o(300…400MPa) and require novel stress management concepts
- Significant Energy deposition o(5 W/m) and dose o(40 MGy)



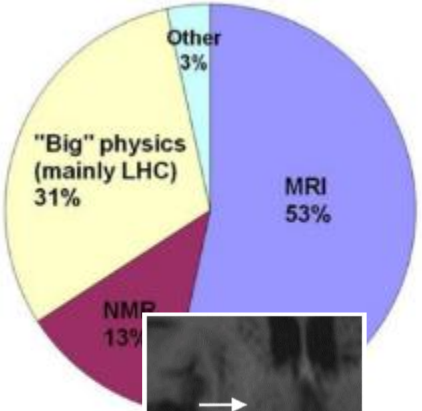
Stress managed dipoles and quadrupoles

16 T peak, 150 mm
Combined functions
Radiation heat load ≈ 5 W/m
Radiation dose ≈ 20…40 Mgy

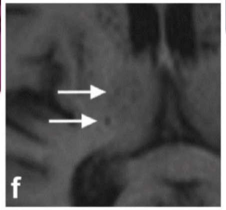


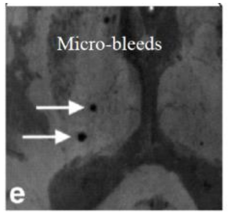
Application to MRI

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 (1,5 T) | 25% of the market (3 T) | 75 units since 1998 (7 T – 11,75 T)

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

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

Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

UHF MRI PARK EVOLUTION 2001-2023

2001
- 3T: ≈ 100 systems
- 2 systems 7T WB
- 1 system 8T WB

11.7T Saclay

11.7T Bethesda

11.7T Seoul

10.5T Minneapolis

2023
- Over 50,000 superconducting and conventional MRI scanners are installed around the world (mainly 1,5T and 3T)
- 7T : about 80 systems installed (3 in France) - 6 to 10 new units per year
- **1 system 8T Whole Body: Ohio State Univ (80cm)**
- **6 systems 9.4T WB: Minneapolis (65cm), Chicago (80cm), Tübingen (82cm), Jülich (90cm), Maastricht (82cm) Beijing (83cm)**
- **1 system 10,5T WB: Minneapolis - 88cm - passive shielding / images on human brain since 2020**
- **4 projects WB 11.7T:**
  - **Iseult - 90cm - active shielding / commissioning in progress**
  - **NIH (Bethesda): 68cm - passive shielding / ready for cooldown on site**
  - **NRI (Seoul): 70cm - passive shielding / delivered in may 2019**
  - **University of Nottingham (UK) - 11T WB (83 cm) project funded in 2022 (£29 million)**

Emerging projects 14T and more: Heidelberg (Germany), USA (Boston, Stanford), Nijmegen (Nerthelands), China (Beijing, Shenzhen)

Medical Applications : Next Generation of MRI Systems

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

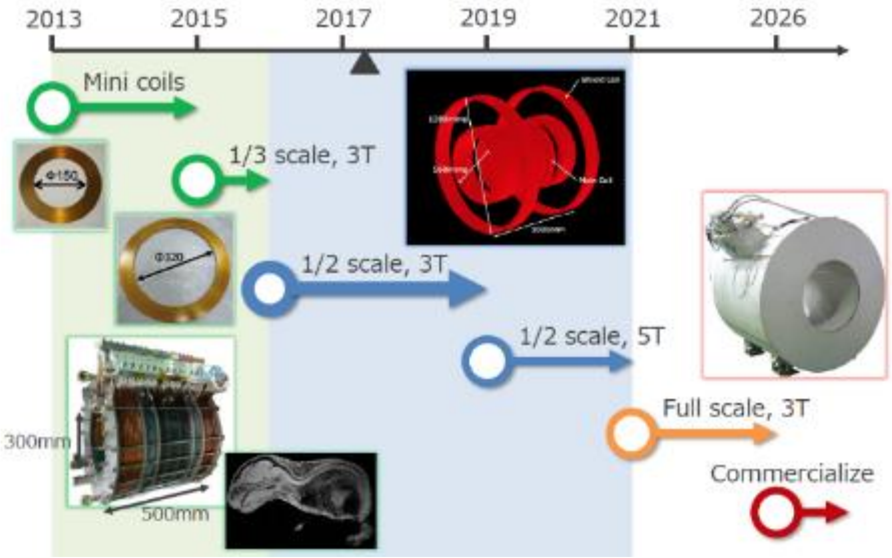
SOURCE:L. M. Parizh. "Ultra-High Field Superconducting Magnets for Magnetic Resonance Imaging "-MT26 Vancouver 2019

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.

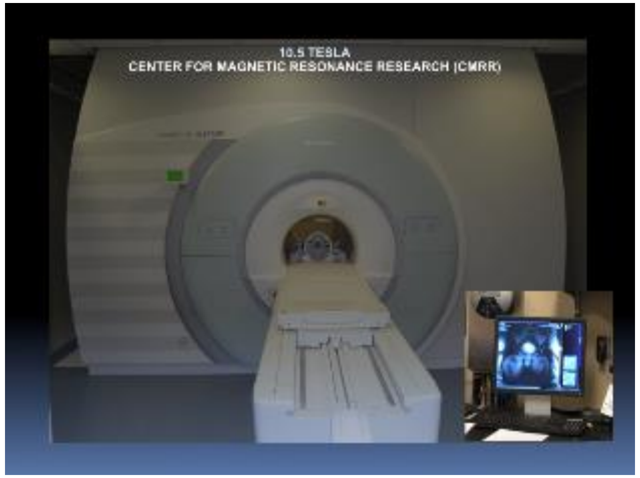
Mitsubishi Electric is involved in a program for developing a full scale 3T HTS MRI system.

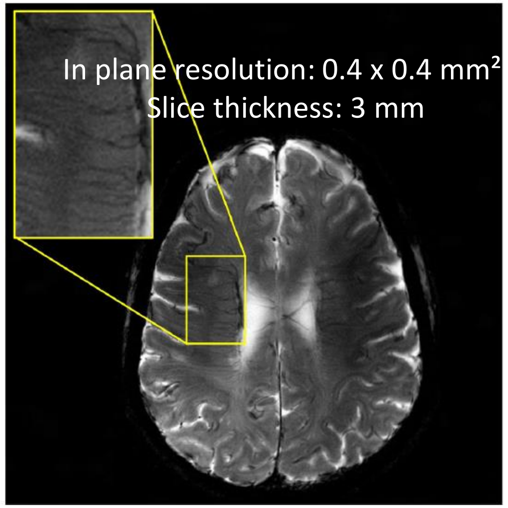
SOURCE: M.Oya et a. "Development of a 3T HTS Magnet for MRI" Mitsubishi Electric Corporation . 25th Conference on Magnet Technology.



Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

CENTER FOR MAGNETIC RESONANCE RESEARCH (CMRR), MINEAPOLIS
FIRST IN-VIVO HUMAN BRAIN IMAGE OBTAINED IN 2020





Magnetic Resonance in Medicine,
Volume 84, Issue 1, July 2020

CMRR
10.5T

Magnet mass	110 tones
Bore diameter	**88 cm**
Length	4.1m
Diameter	3.2m
Conductor	NbTi (433km)
Passive shielding	**600 tons of iron**
Temperature	3K

Magnet mass	132 tones
Bore diameter	**90 cm**
Length	5.2m
Diameter	5m
Conductor	NbTi (180km)
Active shielding	**No iron**
Temperature	1.8K

Iseult
11.7T

11.7 T AND BEYOND

- Re-fabrication by ASG (Italy) of the NIH 11.7T magnet (Bethesda, USA) (permanently damaged in 2012 after a quench) ⇒ Helium supply difficulties
- Similar design for the NRI (Seoul, Korea) ⇒ in field, magnet tests finalized

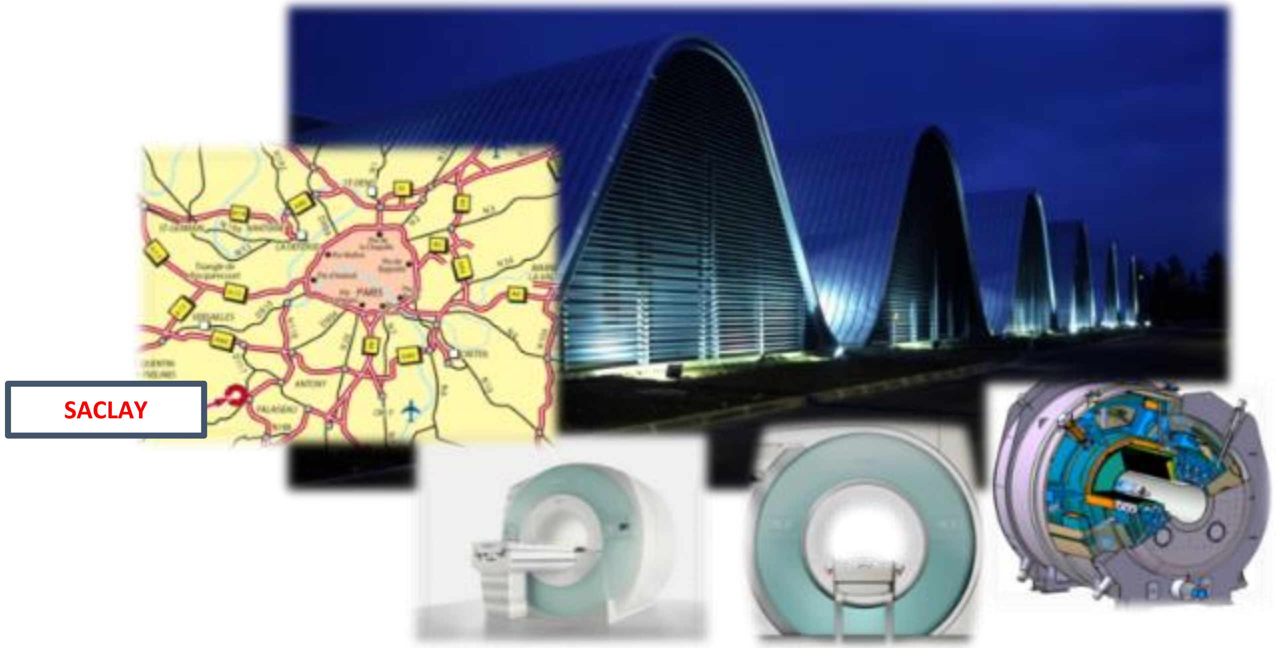
NIH magnet - delivered in March 2019

NRI magnet - delivered in May 2019
First on-site ascent to 11.7T achieved

	NIH / NRI	Iseult
Courant	246 A	1483 A
Diamètre intérieur	**68 cm**	**90 cm**
Diamètre extérieur	2.6 m	5 m
Longueur	4 m	5.2 m
Blindage	Passif	Actif
Masse totale	**820 tonnes** (70 aimant + 750 fer pour blindage)	**132 tonnes**
Température bain	**2.3 K (saturé)**	**1.8 K (superfluide)**
Pression bain hélium	64 mbar	1.2 bar
Volume hélium	3000 L	7000 L
Inductance	6400 H	308 H
Energie stockée	**194 MJ**	**338 MJ**

- China equips itself with a Siemens 10.5T (Ø 88cm, 2.2 K, passive shielding); magnet identical to the one used in Minneapolis, magnet manufactured by ASG (Italy).
- Purchase of a Siemens 11.7T by the University of Nottingham (Ø 83cm, 2.2 K, passive shielding), magnet manufacture by ASG; commissioning **scheduled for 2025.**
- *German (Heidelberg) 14T project on stand-by for lack of funding*
- *Dutch project (Nijmegen) 14T re-filed (design with HTS superconductor proposed by Neoscan, Germany)*

A French-German initiative launched in 2005 to develop high resolution imaging



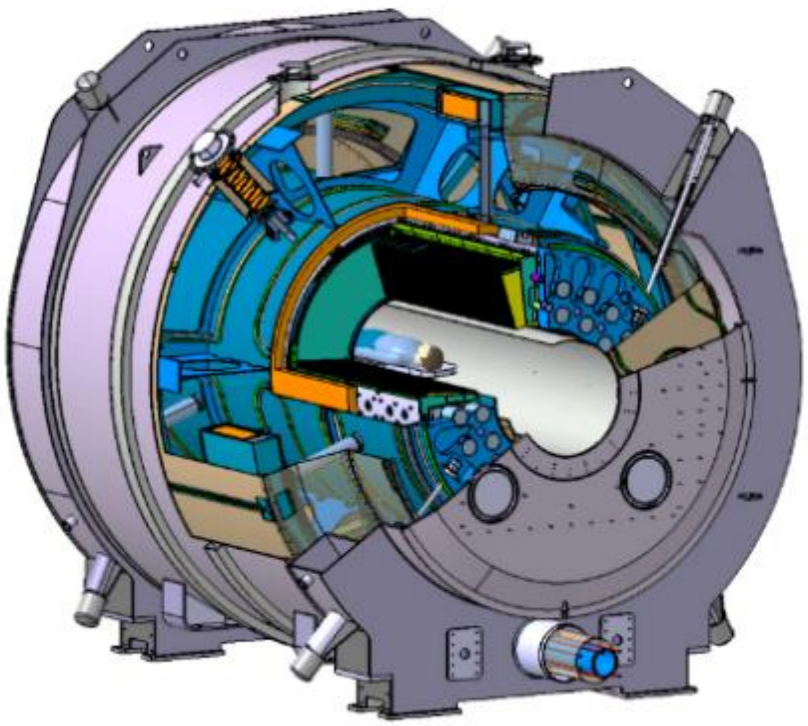
Neurospin
CEA Saclay, France

Project partners: *CEA(F), GE – ex Alstom (F), Guerbet (F), Siemens Healthcare (G), Friburg University (G), Bruker Biospin (G)*

- **Develop a ultra high field MRI system (11.7T)**
- Develop a new generation of gradient system
- Develop a new generation of contrast media

A very ambitious specification:

- **B0 / Aperture 11.72T / 900mm**
- **Field stability +/-0.05 ppm/h**
- **Homogeneity < 0.5 ppm on 22 cm DSV**

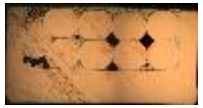
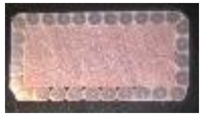


Innovative solutions for a MRI magnet

- **170 NbTi double pancakes** for the main coil
- **2 NbTi shielding coils** to reduce the fringe field
- **Dedicated cryoplant operated at 1.8 K**
- **Driven mode operation**, with two 1500 A power supplies for redundancy
- In case of quench, **stored energy dissipated into a dump resistance**

Stored Energy	338 MJ
Inductance	308 H
Current	1483 A
Length	5.2 m
Diameter	5 m
Weight	132 t

2006 – 2009 : R&D AND PROTOTYPES



ALSTOM

cnrs

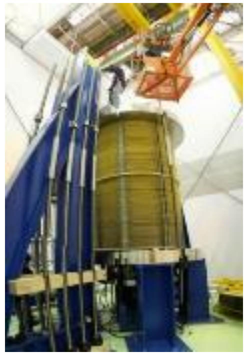
NÉEL institut

All new concepts supported by mockups and prototypes
Conductors, winding techniques, mechanics, cryogenics, thermo-hydraulic studies…

2010 – 2017 : CONDUCTOR AND MAGNET MANUFACTURING


LUVATA
A Group Company of MITSUBISHI MATERIALS

ALSTOM



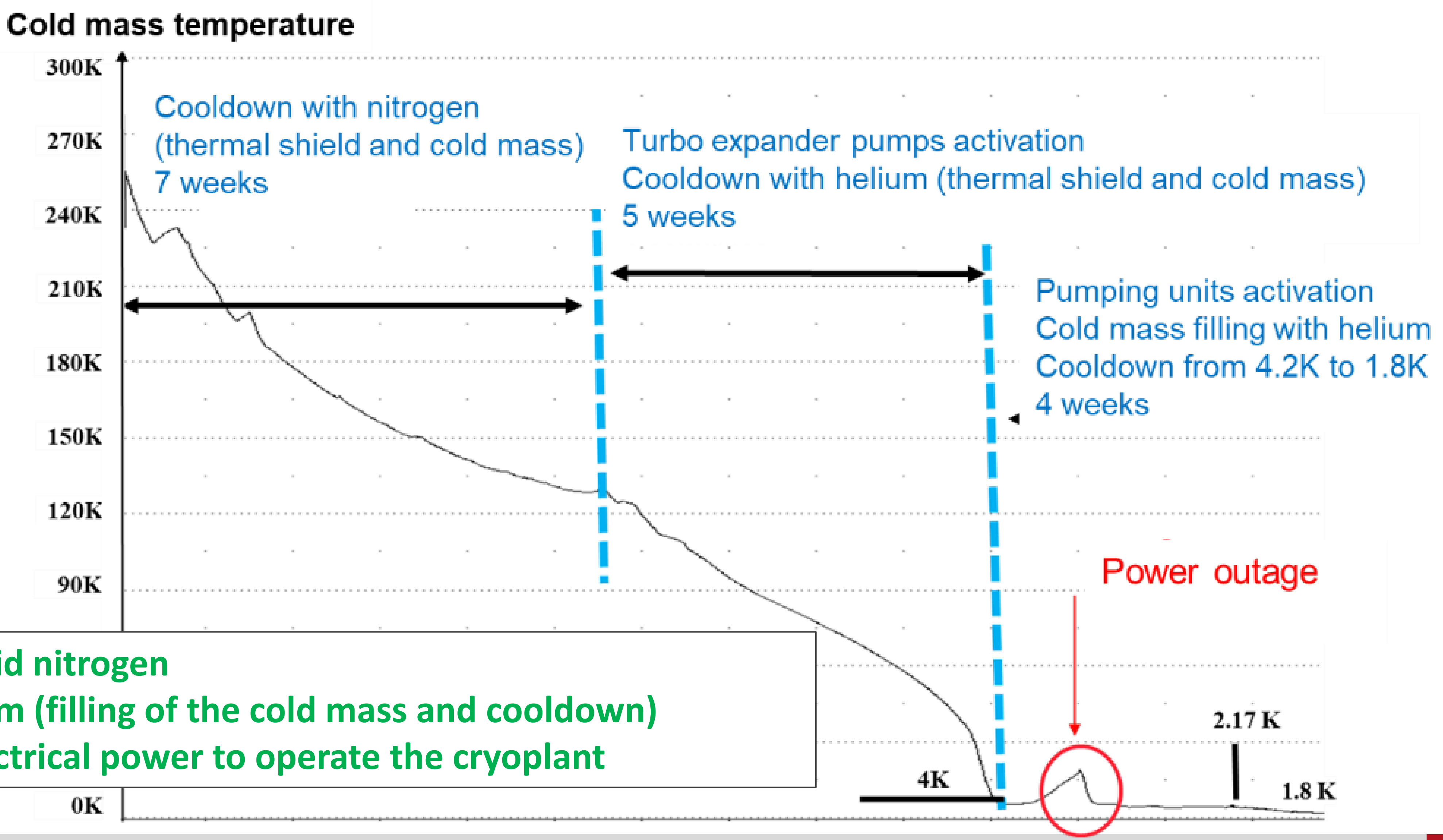

SIEMENS Healthineers





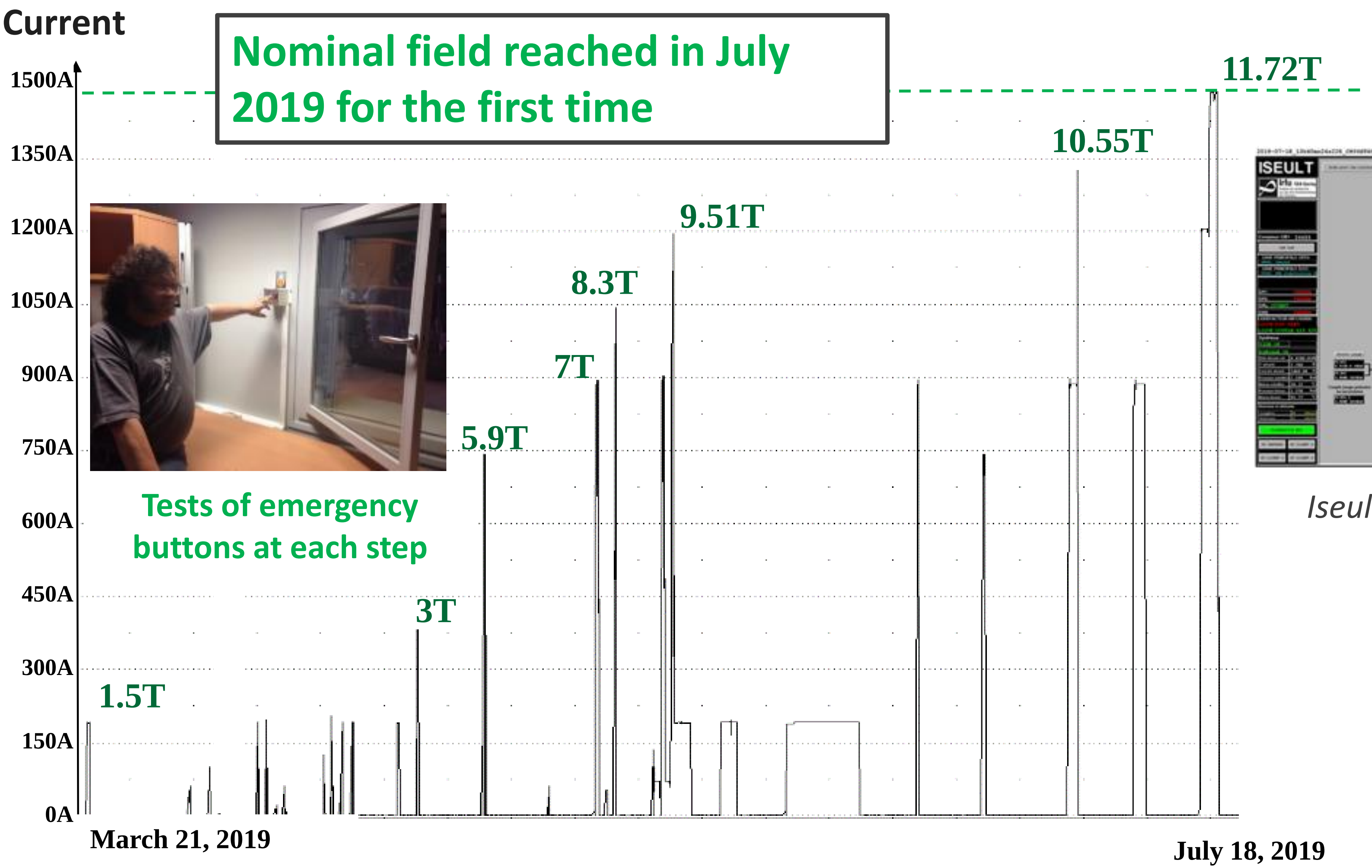

Magnet installed in its arch in June 2017

COOLDOWN: 14 WEEKS NOVEMBER 2018 – MARCH 2019

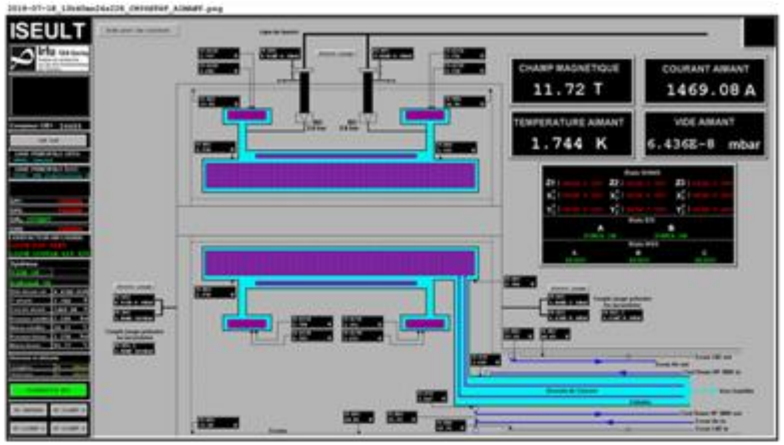


250 000 L liquid nitrogen
18 500 L helium (filling of the cold mass and cooldown)
150 kW of electrical power to operate the cryoplant

Nominal field reached in July 2019 for the first time



Tests of emergency buttons at each step

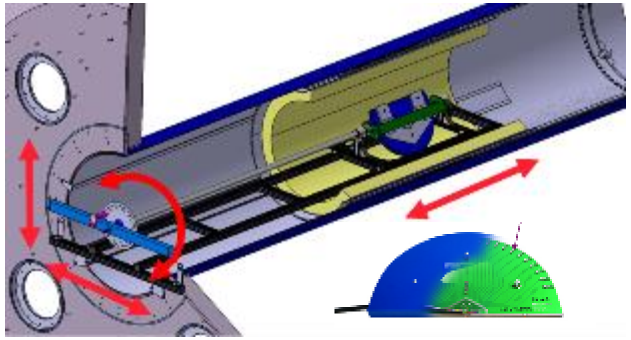


Iseult magnet control panel

Passive shimming

5904 iron pieces can be used to adjust the field homogeneity

Field measured using NMR probes



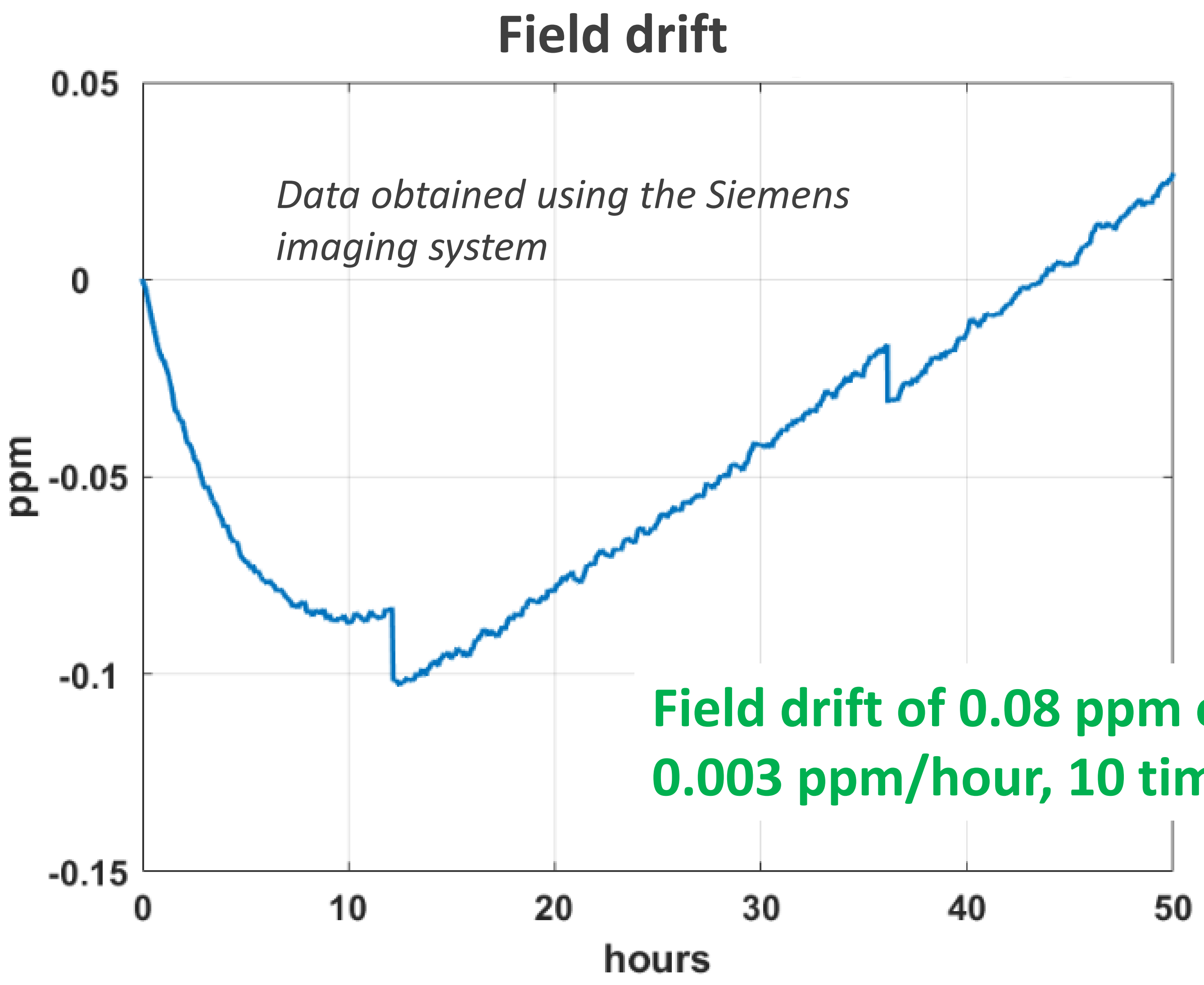
Spherical harmonics expansion

$$B_z(r,\theta,\varphi) = B_0 + \sum_{n=1}^{\infty} r^n \left[\begin{array}{l} Z_n P_n(\cos\theta) + \\ \sum_{m=1}^{n} \left(\begin{array}{l} X_n^m \cos m\varphi + \\ Y_n^m \sin m\varphi \end{array} \right) \\ W_n^m P_n^m(\cos\theta) \end{array} \right]$$

with $W_n^m = \frac{(n-m-1)!!}{(n-m+1)!!}$

Peak-peak homogeneity of 1,75ppm after 7 iterations

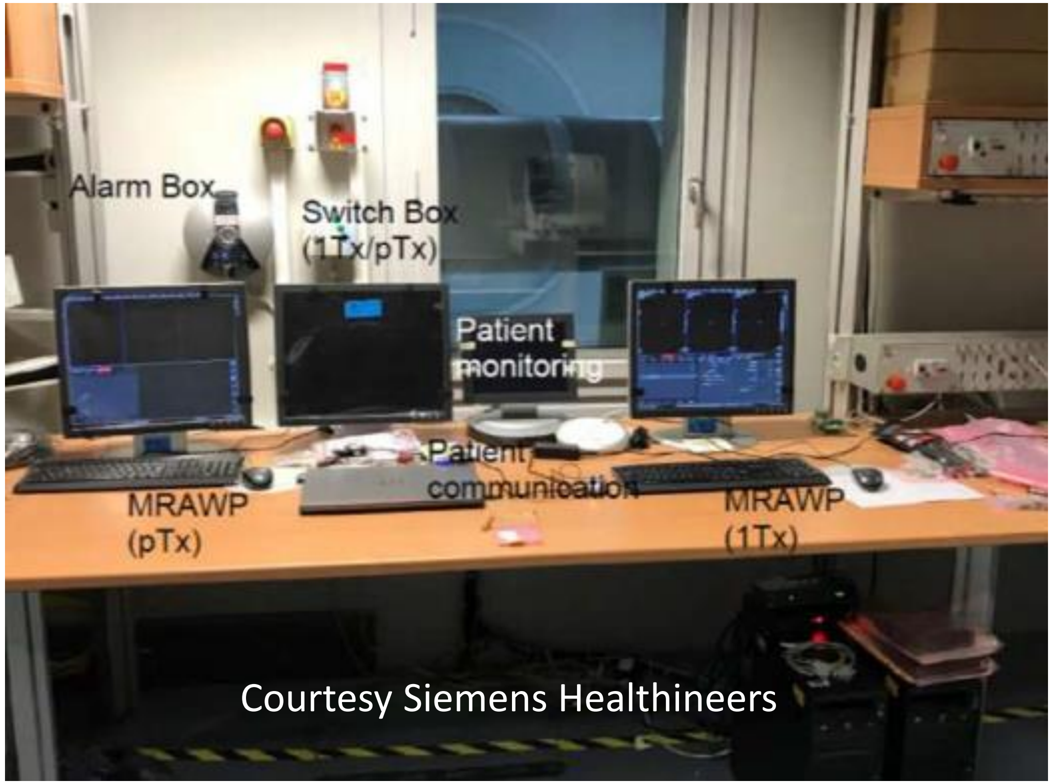
	300K	1.8K 1.5T	1.8K 3T	1.8K 7T	1.8K 11.7T	1.8K 11.7T – after 7 iterations
Z_1 [PPM]	-132	-16	-7	-5	9	0.037
Z_2 [PPM]	-105	-22	-16	-15	-17	-0.072
Z_3 [PPM]	20	2	2	2	2	0.138
X_1^1 [PPM]	-1	22	21	22	24	0.275
Y_1^1 [PPM]	59	63	59	60	62	0.394
X_2^1 [PPM]	-	2	2	2	2	-0.216
Y_2^1 [PPM]	-	-6	-6	-6	-7	0.337
X_2^2 [PPM]	-	-1	-1	0	-1	0.214
Y_2^2 [PPM]	-	0	-1	-1	-1	0.010



Stability adjusted using a fault current limiter

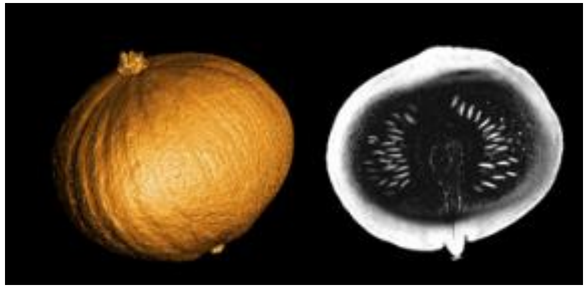
Field drift of 0.08 ppm over 24 hours
0.003 ppm/hour, 10 times better the specification !

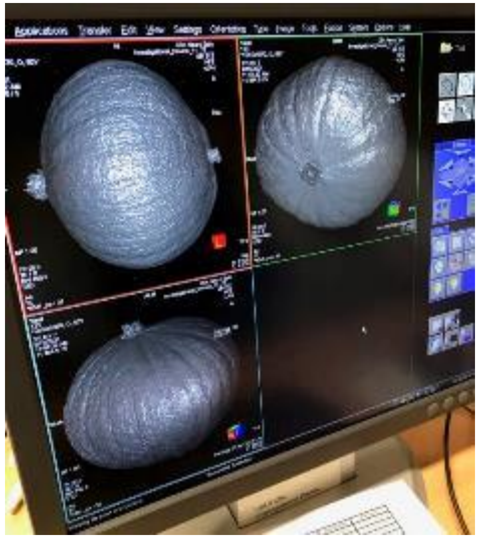
SIEMENS IMAGING EQUIPMENT INSTALLATION



Start-up of the imaging equipment

Use of a “service” RF antenna





Courtesy CEA/Neurospin/Joliot

Courtesy CEA/Neurospin/Joliot

- First image on a pumpkin
- 5 hours of acquisition, **0.4 mm of resolution**
- **The potentiel is there!**

Non-human primate brain
(*in-vivo*) – September 2022

Control of blood pressure and heart rate during the imaging time, **no variation observed**

Next steps for Iseult:

- **On-going preparation of the request for authorization to scan human volunteers at 11.7T**
- **First images of a human volunteer in Iseult expected in 2023**

Application to Fusion

Fusion energy assets in the context of the current energy crisis

- Abundant for millions of years, no CO_2 emissions, no long-lived radioactive waste, no risk of meltdown
- Very dynamic context with many new ambitious projects (US, UK, China) and start-up companies.

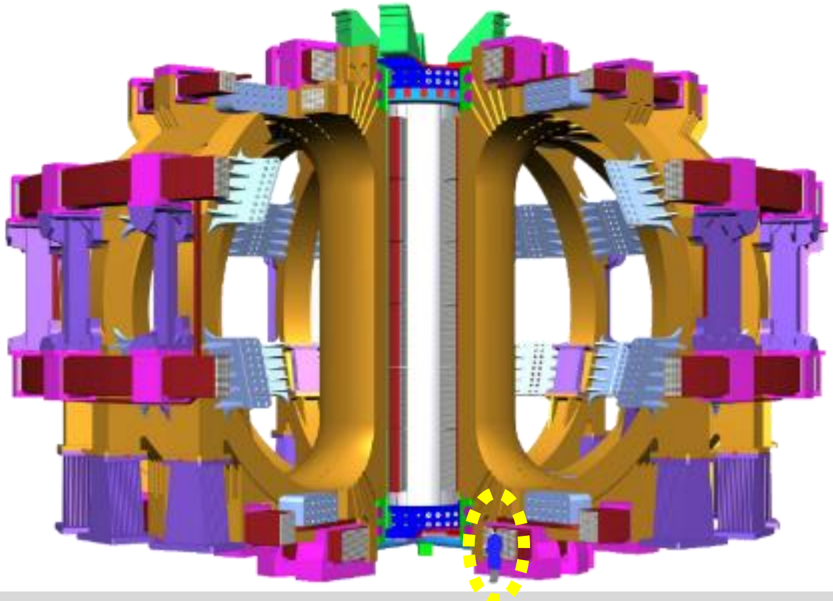
State of the art of magnetic fusion

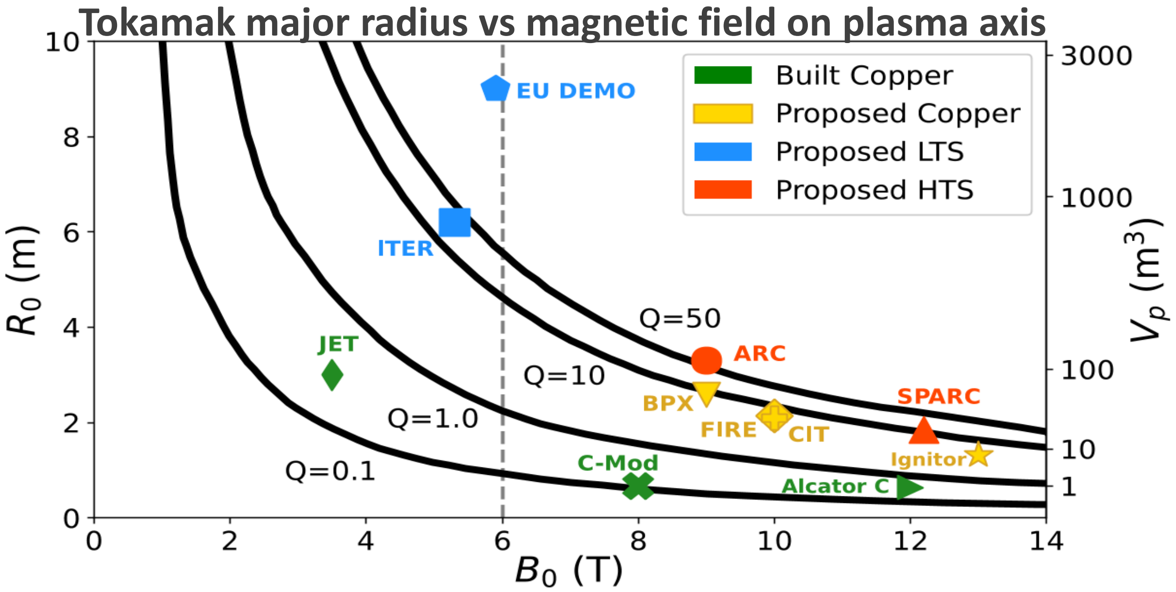
- 10MW of fusion power obtained steadily in JET tokamak (during 5s)
- ITER Project: demonstrate the feasibility of fusion as energy source (amplification Q=10)

HTS potential game changer to accelerate fusion energy development

- Magnet large fraction of the cost of the machine
- Machine size driven by the magnetic field amplitude

ITER Magnet System

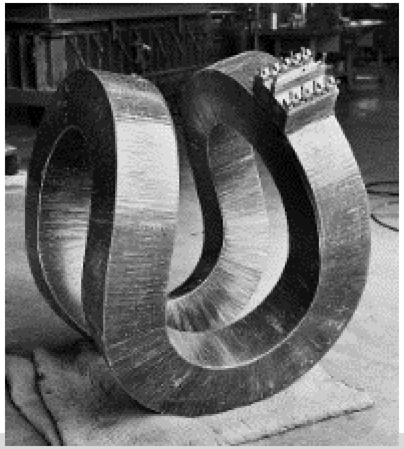


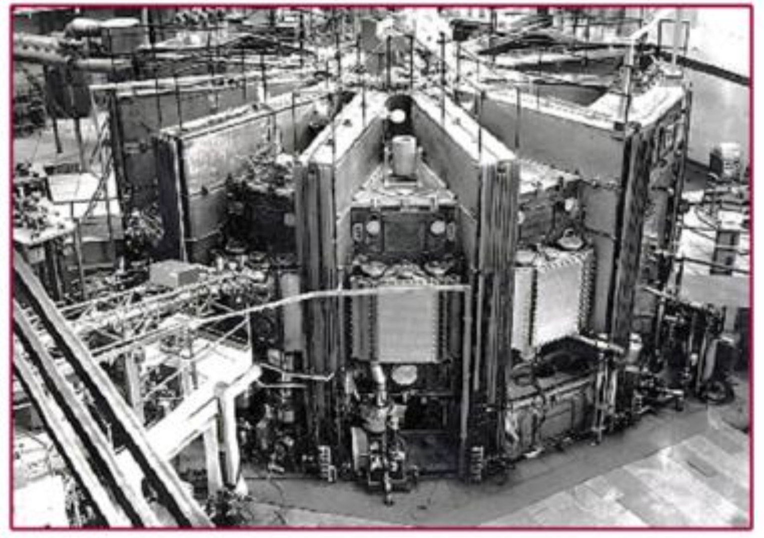


Magnetic Mirror SC coils in the early 70's and early 80s

Large tokamak SC experiment T-15, Tore Supra 1988

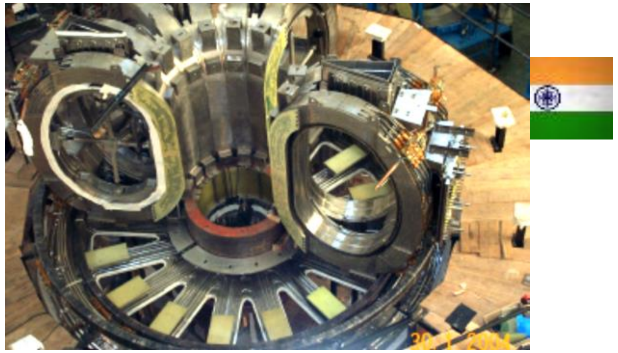
- Baseball I and II, hot plasma confined by magnetic mirrors. 1965





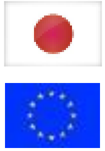
NEW SUPERCONDUCTING TOKAMAKS

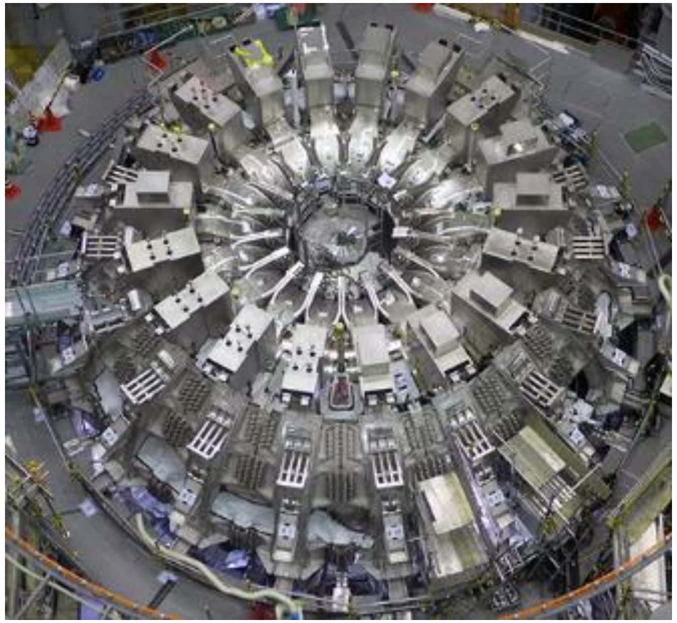
EAST: R = 1.7m, 2MA, 2006



SST-1: R =1.1m, 0.22MA, 2008

KSTAR: R = 1.8m, 2MA, 2008

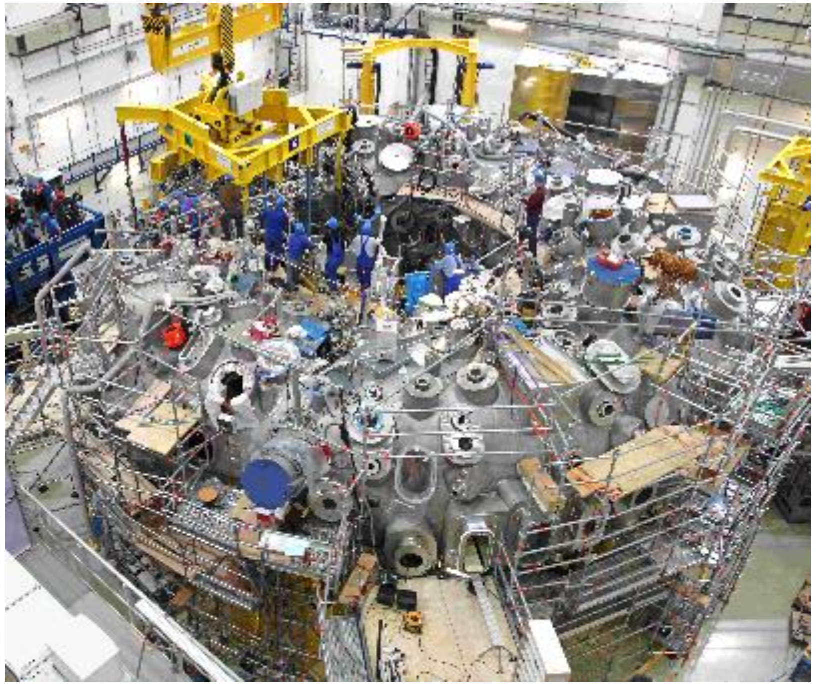




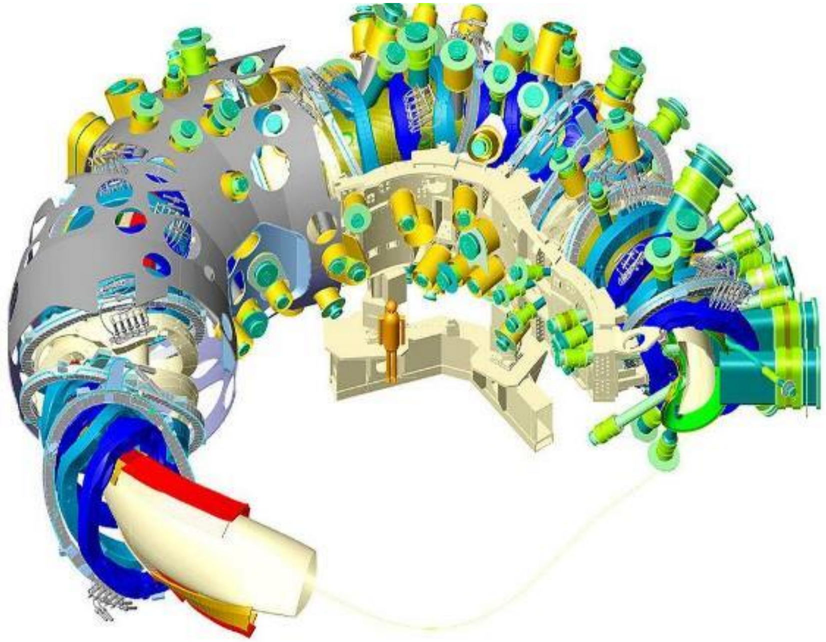
JT-60SA: R = 3m, 5.5 MA, 2019

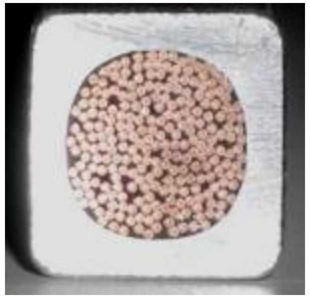
Stellarators use a single coil system with no longitudinal net-current in the plasma and hence without a transformer (continuous operation and inherent stability).

The W7-X magnet system includes 20 planar and 50 non-planar coils which rely on NbTi CIC conductors

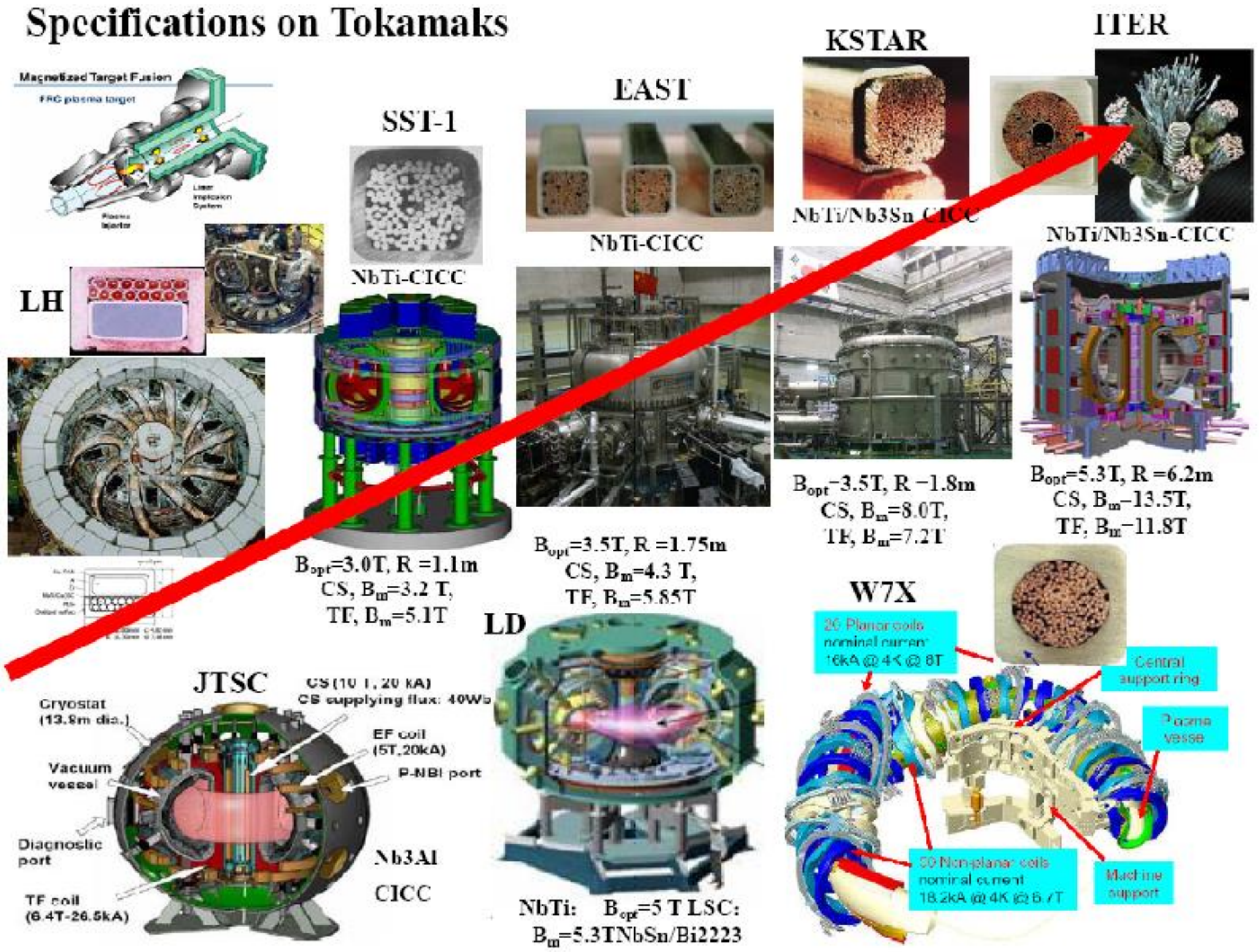


Major radius:	5.5 m
Minor radius:	0.53 m
Plasma volume	30 m^3
Induction on axis:	3T
Stored energy:	600 MJ
Machine mass:	725 t

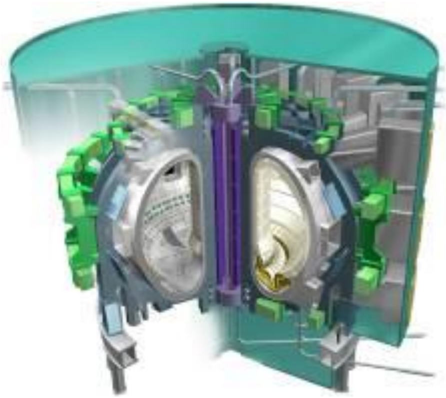


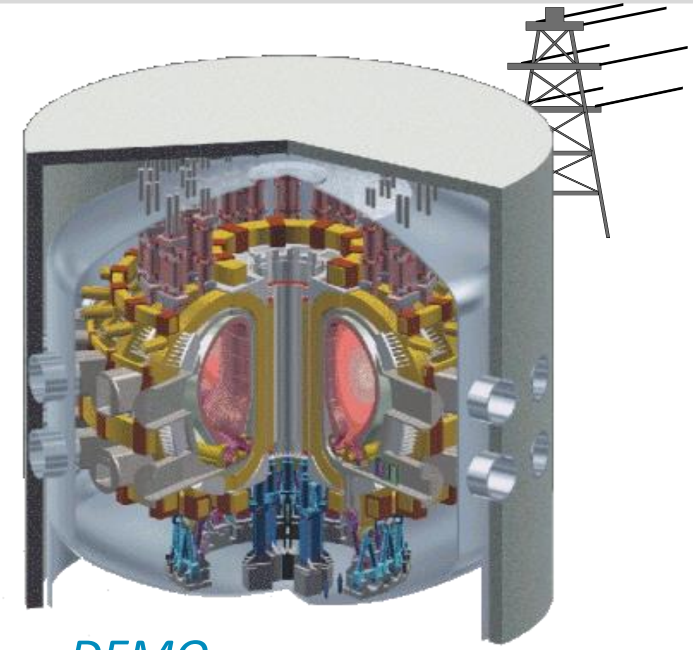


First Operation December 2015


Specifications on Tokamaks
Magnetized Target Fusion
FRC plasma target
LH
SST-1
NbTi-CICC
B_{opt}=3.0T, R =1.1m
CS, B_m=3.2 T,
TF, B_m=5.1T
EAST
NbTi-CICC
B_{opt}=3.5T, R =1.75m
CS, B_m=4.3 T,
TF, B_m=5.85T
KSTAR
NbTi/Nb3Sn CICC
B_{opt}=3.5T, R =1.8m
CS, B_m=8.0T,
TF, B_m=7.2T
ITER
NbTi/Nb3Sn-CICC
B_{opt}=5.3T, R =6.2m
CS, B_m=13.5T,
TF, B_m=11.8T
JTSC
CS (10 T, 20 kA)
CS supplying flux: 40Wb
Cryostat
(13.8m dia.)
EF coil
(5T,20kA)
Vacuum
vessel
P-NBI port
Diagnostic
port
Nb3Al
CICC
TF coil
(6.4T-26.5kA)
LD
NbTi: B_{opt}=5 T LSC:
B_m=5.3TNbSn/Bi2223
W7X
20 Planar coils
nominal current
16kA @ 4K @ 6T
Central
support ring
Plasma
vessel
50 Non-planar coils
nominal current
18.2kA @ 4K @ 6.7T
Machine
support

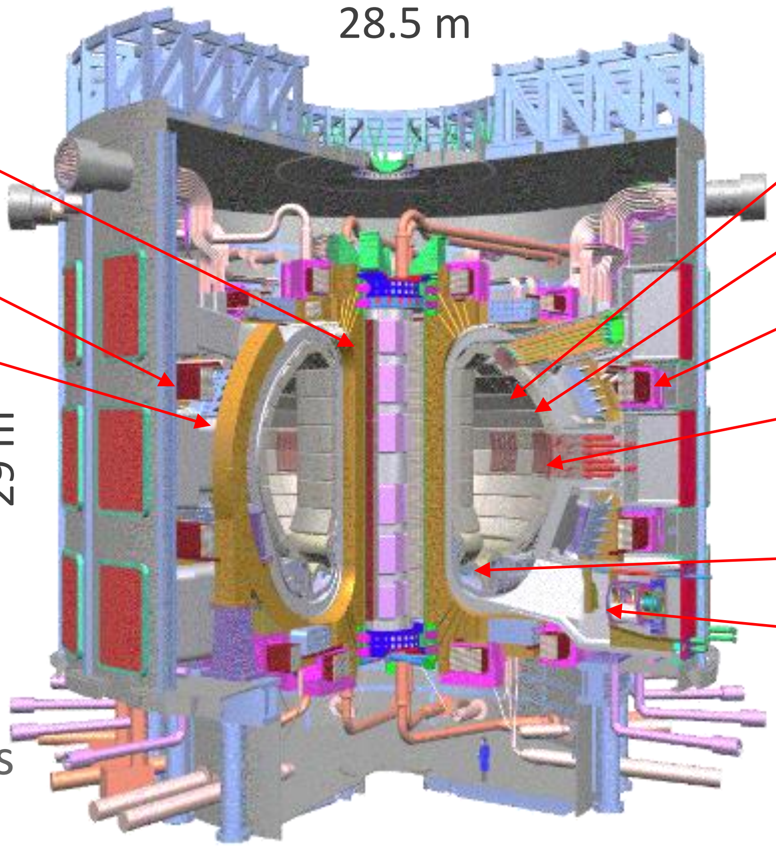
NEXT STEP TOWARDS FUSION ENERGY : ITER





Tore Supra	*JET*	*ITER*	*DEMO*
25 m³	*80 m³*	*800 m³*	*~ 1000 - 3500 m³*
400 s	30 s	400 s-1000 s	
1,5 MA	5 MA	15 MA	
4.2 T	3.5 T	5.3 T	
~ 0	*~ 16 MW_{th}*	*~ 500 MW_{th}*	*~ 2000 - 4000 MW_{th}*
Q ~ 0	Q ~ 1	Q ~ 10	Q ~ 30

NEXT STEP TOWARDS FUSION ENERGY : ITER



Tore Supra

25 m^3

Q ~ 0

400 s

1,5 MA

4.2 T

JET

80 m^3

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

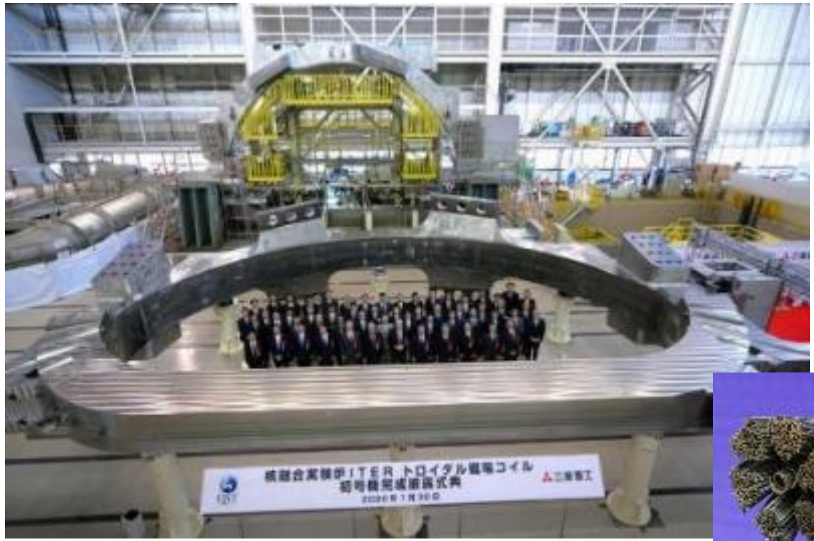
Typical Temperature: 20 keV

Typical Density: 1020 m-3

State of the Art

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

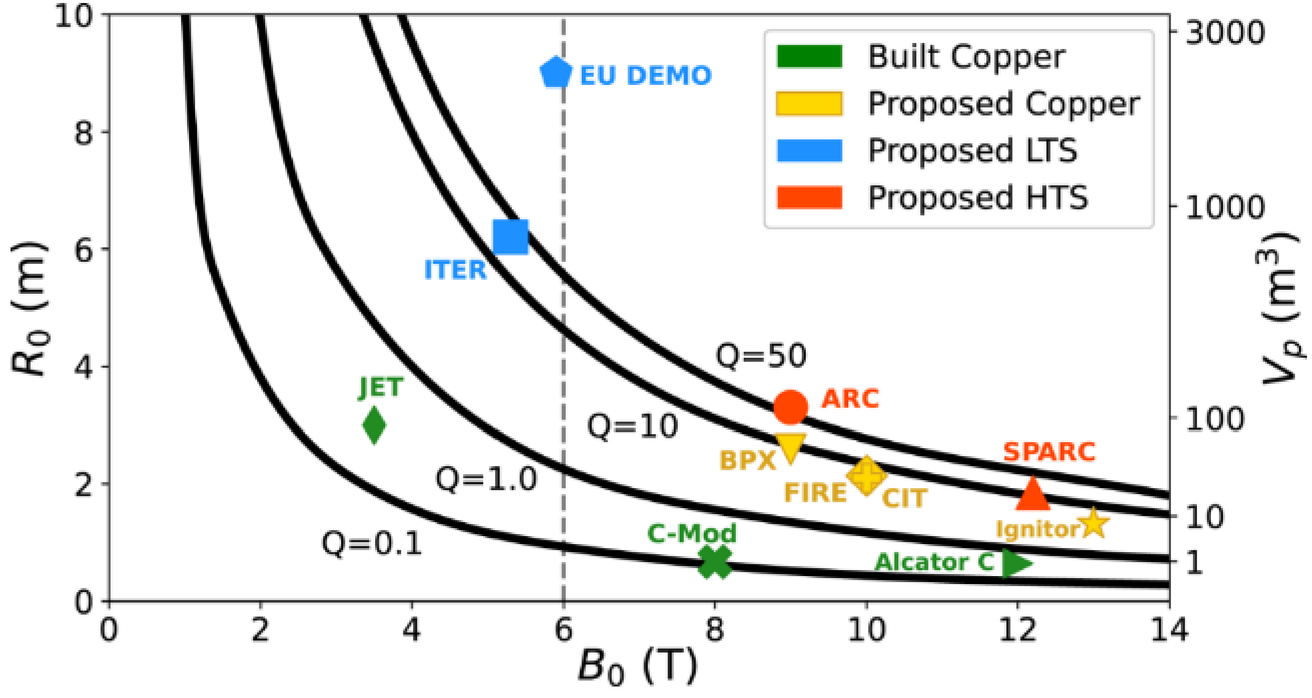
Feb 2020
First Japanese Toroidal Field Coil completed
Magnetic field 11.8 tesla
Stored energy 41 gigajoules
Weight 360 tonnes
Dimensions 9x17 m



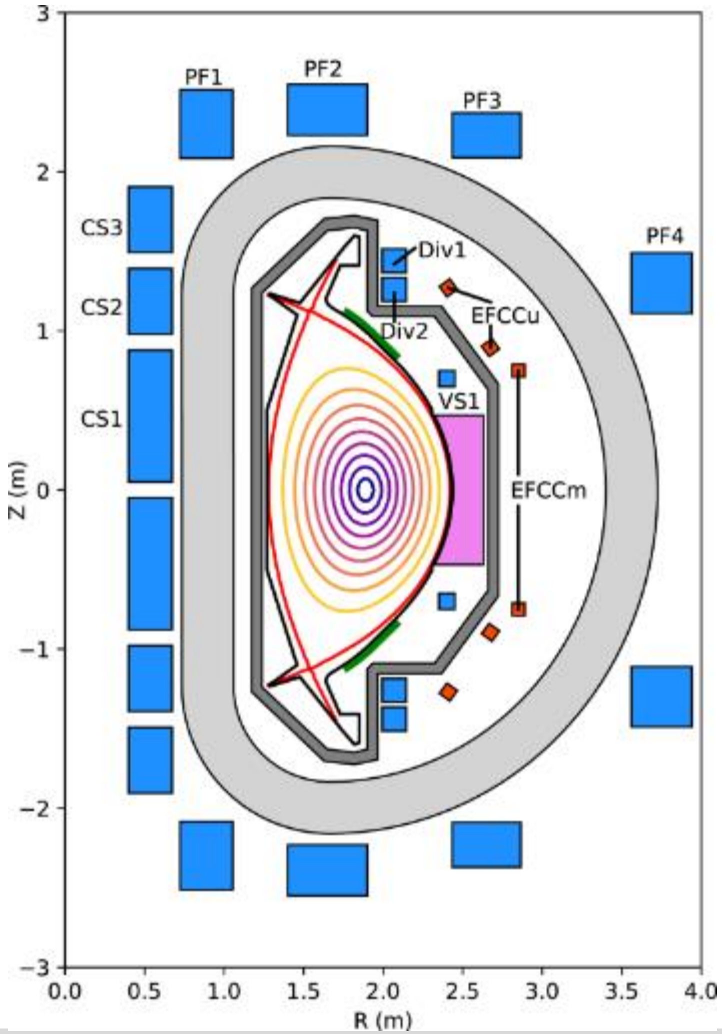
May 2022
First Toroidal Field Coil Module Assembled

Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

New Private initiatives using HTS :
as examples Commonwealth Fusion Systems (US) and Tokamak Energy (UK)



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



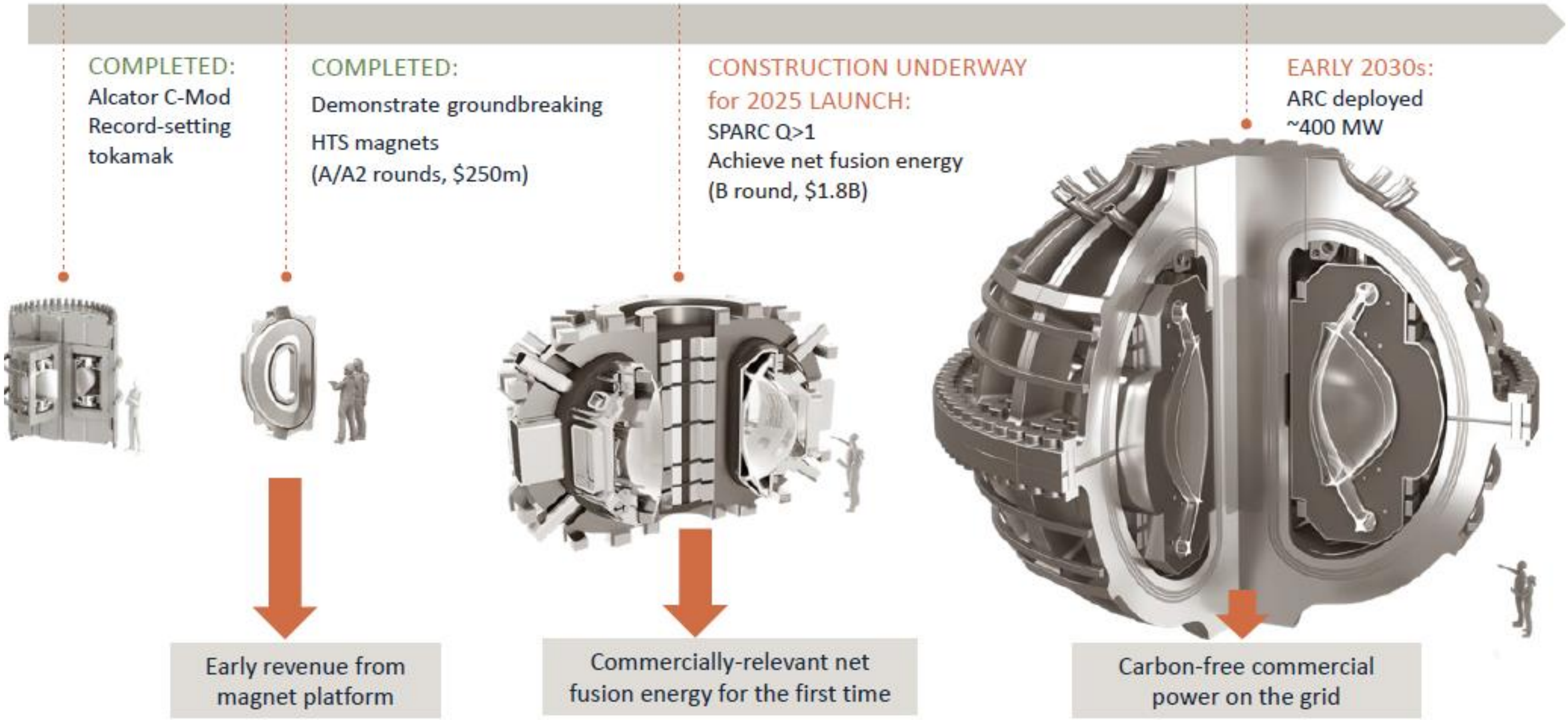
Timeline

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



Source: picture and data from CFS Bob Mumgaard,
presented at CERN Colloqiuum – Prospects for Fusion Energy using Magnetic Confinment– 15 December 2022

World's strongest HTS magnet demonstrated

The Boston Globe

Cambridge startup takes big step toward clean fusion power

By Hiawatha Bray Globe Staff, Updated September 8, 2021, 1:50 p.m.

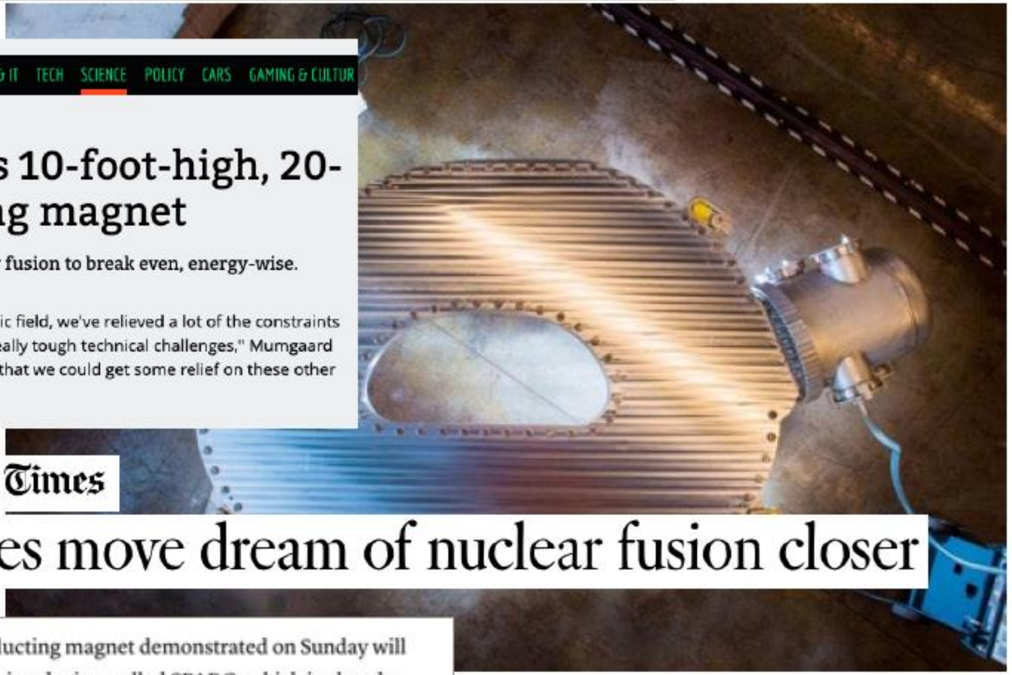
A team of engineers and scientists from CFS and MIT's PSFC lower the superconducting magnet into the test stand in which the magnet was cooled and powered to produce a magnetic field of 20 tesla. COMMONWEALTH FUSION SYSTEMS

The scientists from MIT and Commonwealth Fusion Systems said they may have a device ready for everyday use in the early 2030s.

"This was designed to be commercial," said MIT Vice President Maria Zuber, a prominent physicist. "This was not designed to be a science experiment."

CNBC

Fusion gets closer with successful test of new kind of magnet at MIT start-up backed by Bill Gates



ars TECHNICA BIZ & IT TECH SCIENCE POLICY CARS GAMING & CULTURE

IT'S ALIVE —

Fusion startup builds 10-foot-high, 20-tesla superconducting magnet

Calculations indicate the magnet should allow fusion to break even, energy-wise.

"Because we've been able to go to very high magnetic field, we've relieved a lot of the constraints that push all those other aspects up against some really tough technical challenges," Mumgaard said. "We really pushed hard on the magnet side so that we could get some relief on these other types of issues."

US News & World Report — Los Angeles Times

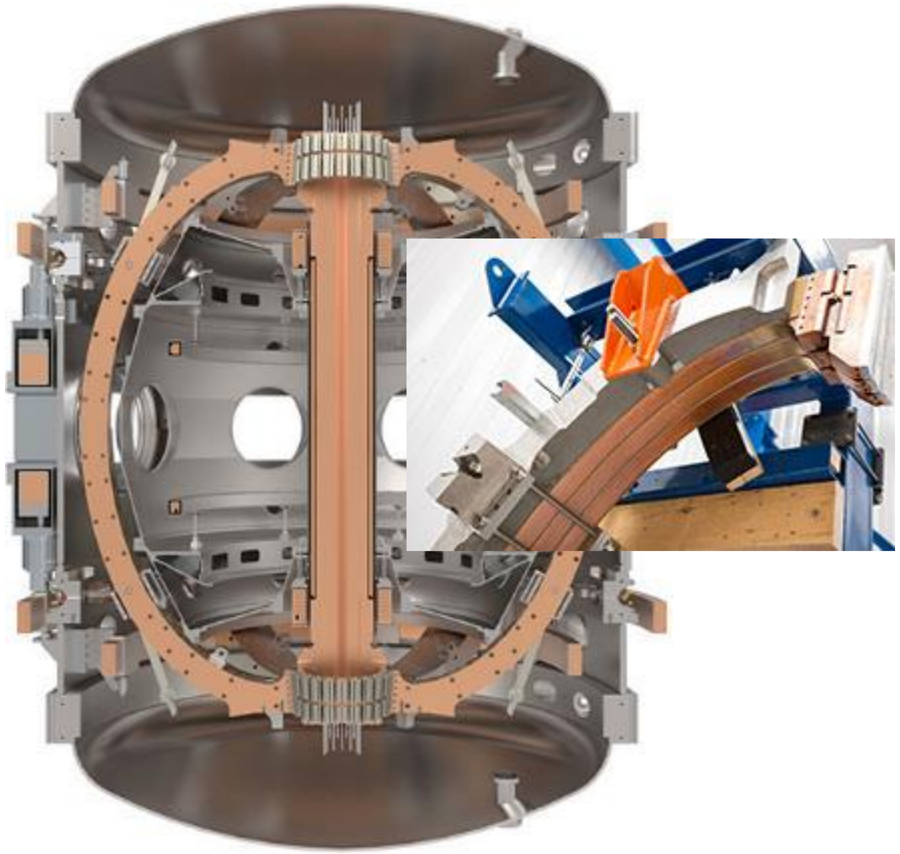
Magnet milestones move dream of nuclear fusion closer

AP

The high temperature superconducting magnet demonstrated on Sunday will be used in CFS and MIT's test fusion device, called SPARC, which is already under construction in Devens, Mass., and is and on track to demonstrate net energy from fusion by 2025, the teams said.

New Private initiatives using HTS :
as examples Commonwealth Fusion Systems (US) and Tokamak Energy (UK)

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

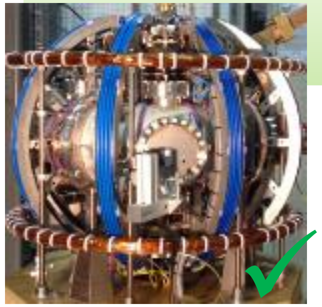
There is a strong mismatch in timelines of ITER and DEMO development in comparison to compact HTS Fusion Magnet development

Courtesy of Luis Garcia-Tabares Rodriguez, Mathias Noe

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

TOKAMAK ENERGY ST DEVELOPMENT TIME LINE

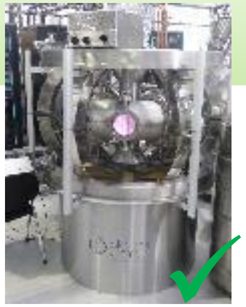
2014



ST25

ST25 Achievements
- ST Concept
- Plasma heating and current drive development

2015



ST25-HTS

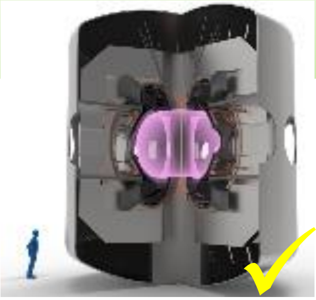
ST25-HTS Achievements
- First HTS TF coils
- H plasma held for 29 hours

2016 – on-going

ST40

ST40 Achievements
- Highest field ST worldwide at 2.1 T on-axis.
- 100M °C D-H plasma temperature
- On-going development programme

Build completion 2026



ST80-HTS

ST80-HTS Objectives
- Demonstrate long pulse operation
- Control and protection of mid-scale HTS magnets

Early 2030s

ST-E1

ST-E1 Objectives
- Up to 200MW of net electrical power
- Prototype energy generating ST
- Full scale HTS magnets
- Demonstrate plasma control and fault condition recovery at scale

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2018

QA NI coils

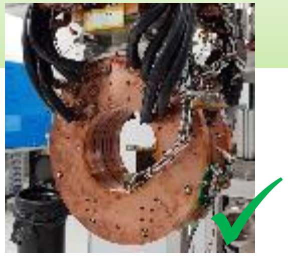
QA NI Coils Achievements
- Tape QA
- Defect tolerant coils
- Robust jointing & ETI plates
- Modular magnet build

2019

Demo3

Demo3 Achievements
- First, conduction-cooled all REBCO magnet to exceed 22T (field on tape) at 20K

2020



Demo2

Demo2 Achievements
- PI development
- Validation of bespoke transient modelling tools (Racoon)
- Quench resistant
- Magnet dynamics very closely correlated to model predictions

2020 -2022

AMR WP4

AMR Achievements
- Demonstrated cryogenic PSU technology
- Developed EFC coil design code
- Coil scale-up study
- Coil Cryogenic Compression System designed and built
- Quench modelling code developed and validated

2019 - 2023

Demo4

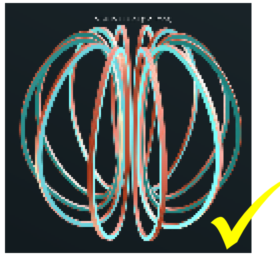
Demo4 Objectives
- Demonstrate PI for TF coils
- Operation of balanced set of TF coils
- Explore transient control and losses in PF coils
- Explore PF field shine on TF coils
- Quench protection and energy dumping trials

2023

Gamma

Gamma Objectives
- Irradiate small test coils wound from selected REBCO tapes
- Co60 irradiation up to 10MGy dose.
- Coils are cooled to 20K and energised to Ic
- Ic degradation measured in real time

2022 - 2026



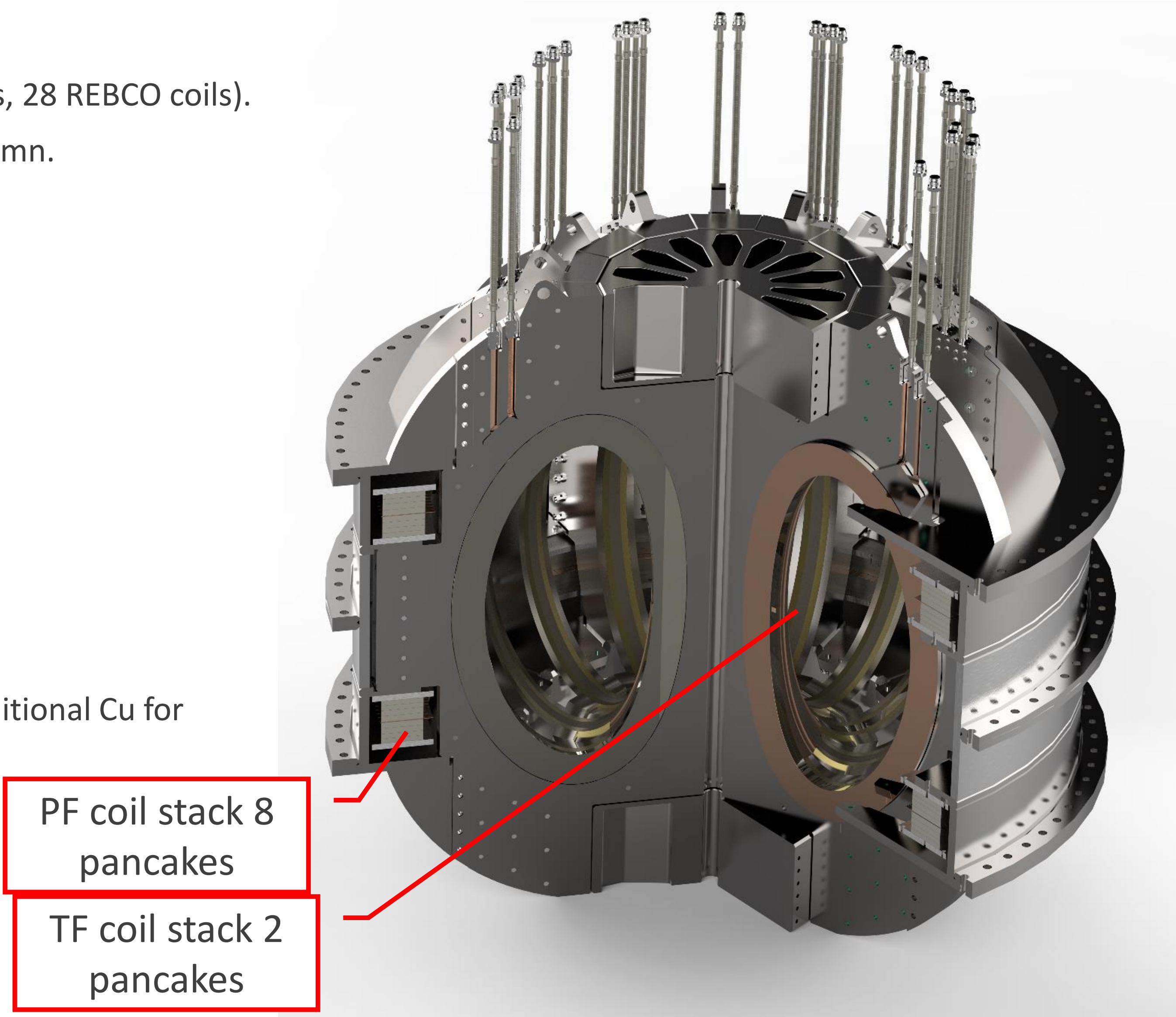
BB01

BB01 Objectives
- Developing prototype coils for ST80
- Developing coil manufacturing processes and tooling
- Developing magnet assembly processes and tooling

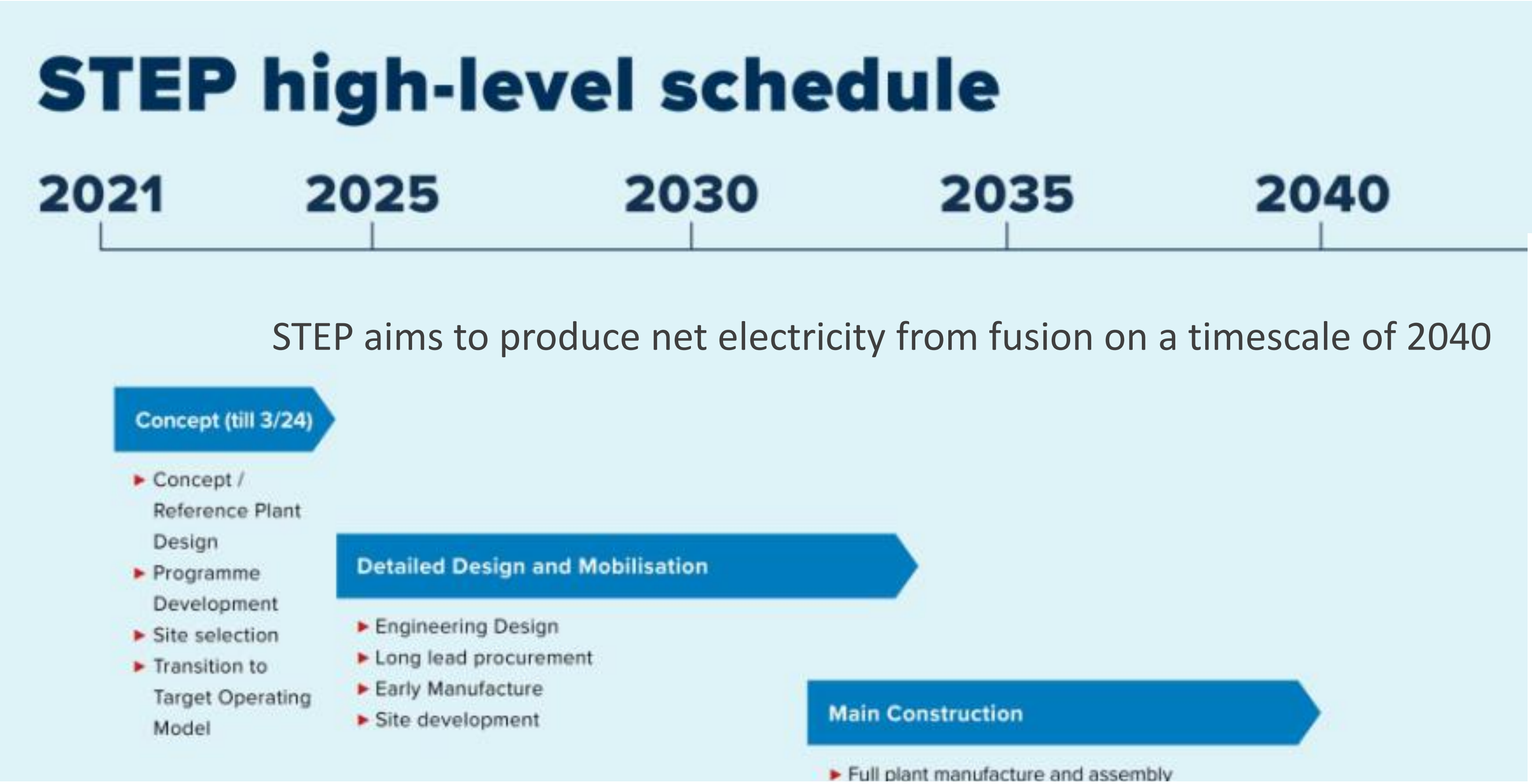
Source: picture and data from Tokamak Energy Rod Bateman, presented at HiTAT Workshop – March 2023

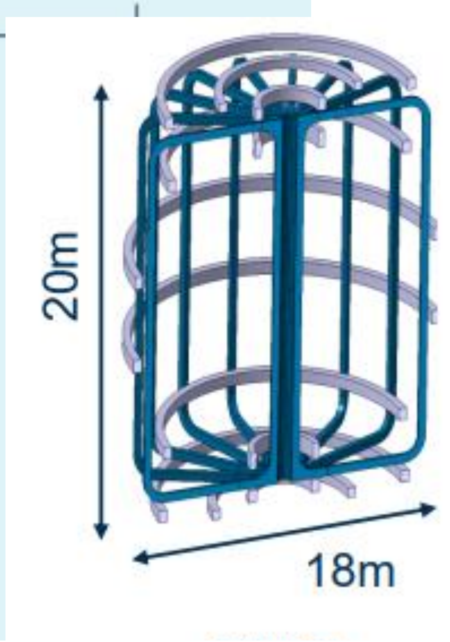
Tokamak Energy HTS magnet set: Demo4

- Develop ST80-HTS relevant magnet technology
- Demonstrate operation of a set of balanced TF limbs (14 limbs, 28 REBCO coils).
- Demonstrate representative compressive stress in centre column.
- Demonstrate coil protection at 16.5 MJ of stored energy.
- Demonstrate Partial Insulation system in TF coils.
- Explore the effects of PF field shine on TF coils.
- Simulate fusion pulse heat loads on the centre column.
- TF construction:-
  - Non-twisted, partially insulated stacked tape cable
  - 2 pancakes per TF limb, ETI jointing
  - 1 cooling loop per coil
- PF construction:-
  - Non-twisted, fully insulated stacked tape cable with additional Cu for stabilisation
  - 8 pancakes per PF stack, edge jointing
  - 1 cooling loop per stack



Source: picture and data from Tokamak Energy Rod Bateman, presented at HiTAT Workshop – March 2023


STEP high-level schedule
UK Atomic Energy Authority
2021
2025
2030
2035
2040
STEP aims to produce net electricity from fusion on a timescale of 2040
Concept (till 3/24)
Concept / Reference Plant Design
Programme Development
Site selection
Transition to Target Operating Model
Detailed Design and Mobilisation
Engineering Design
Long lead procurement
Early Manufacture
Site development
Main Construction
Full plant manufacture and assembly


20m
18m


2024
2026
2028
2030
2032
2034
2036
Concept Design
Preliminary Design
Final Design
~500km/yr HTS Procurement Commences
~10,000km/yr HTS Procurement Commences
HTS Supply Scale-Up

Summary comments

SUMMARY

Important developments in the technology over the last 40 years for the large scale applications of the superconductivity :

Field strength - Scale - Field volume - Stored energy
Conductors - advances in scale, strength, current
Coil winding and assembly   technology - materials – impregnation - bonding
engineering – scale + accuracy

Next step will be to increase the field level

R&D on High Field Magnets is progressing well, using Nb3Sn and HTS materials , to take into account the needs for future colliders MRI and fusion machines.

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 should also be explored. ***It's time for young applied physicists, engineers and technicians to get on board.***

The challenge of the next 10 to 20 years is stimulating but considerable, but we are ready to take it on.