State-of-the-art of the main objectives and challenges

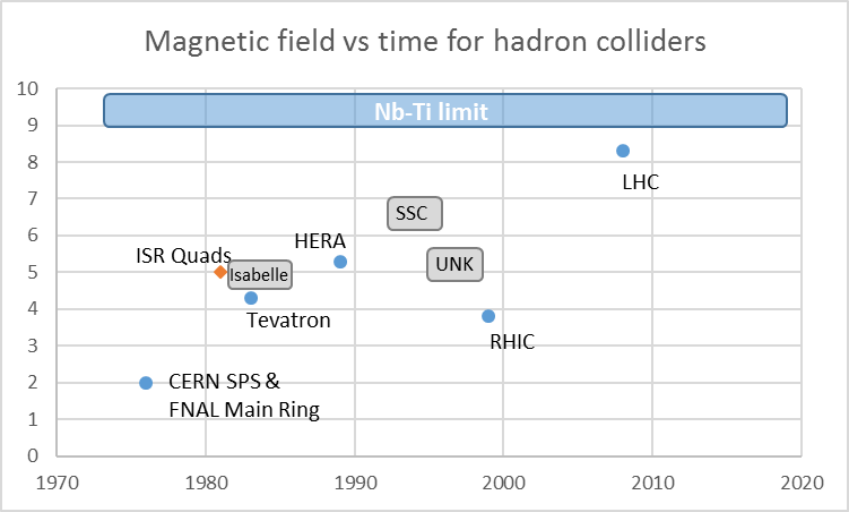
Lucio Rossi – CERN

High Luminosity LHC Project Leader

Plenary ECFA meeting – Open Session on Advanced Accelerator Technologies: HTS magnets
CERN 14 November 2019

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

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

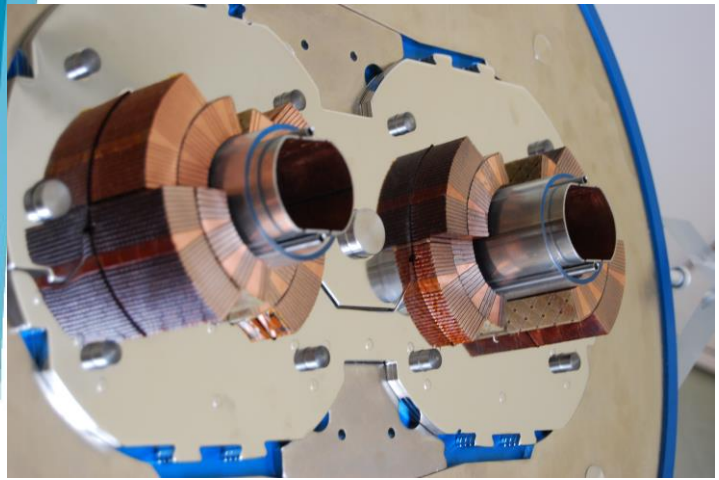


Consideration on LHC

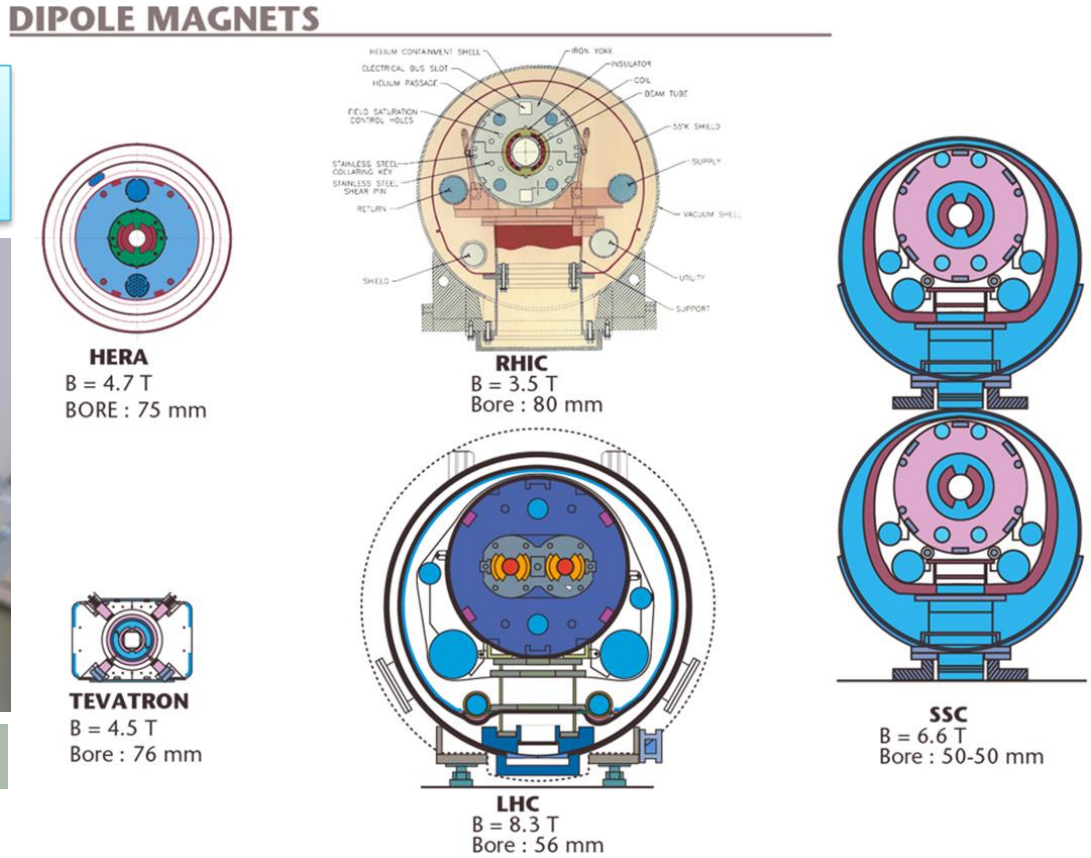
- Designed for 8.33 T (14 TeV c.o.m.) with margin to go to 9 T (15 TeV c.o.m)
- Today operating at **7.75 T** (13 TeV)
- **8.33 T in 2021 possibly**
- **9 T may be in 2026/2030 with HiLumi but very difficult (trade off with loss of lumi)**

Hadron Collider Magnets: Hall of fame

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



LHC Dipole Cross section: Cosϑ layout



The 25 y LHC construction time line

9 T - 1 m single bore

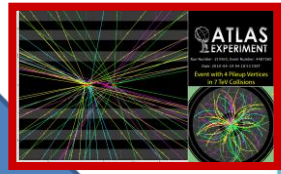
10 T-1m Nb3Sn dipole

9 T -10 m long protoype

9 T-15 m final protoype

Last LHC dipole

1985 1987 1990 1994 2000 2006 2010

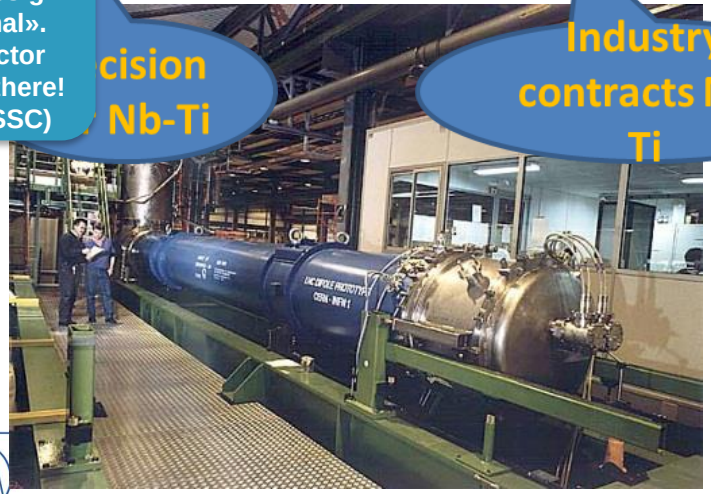


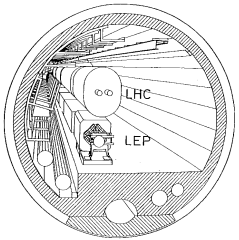
Striking: only 4 y to make a design «near to final». The conductor was almost there! (thanks to SSC)

cision Nb-Ti

Industry contracts Nb-Ti

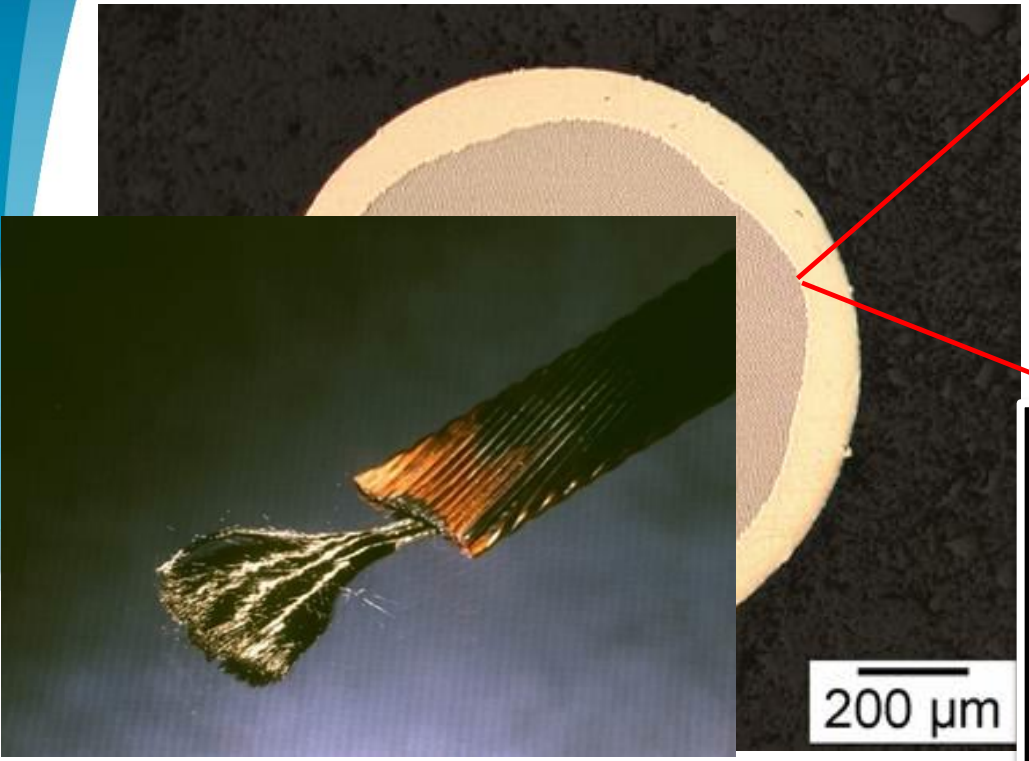
LHC start-up

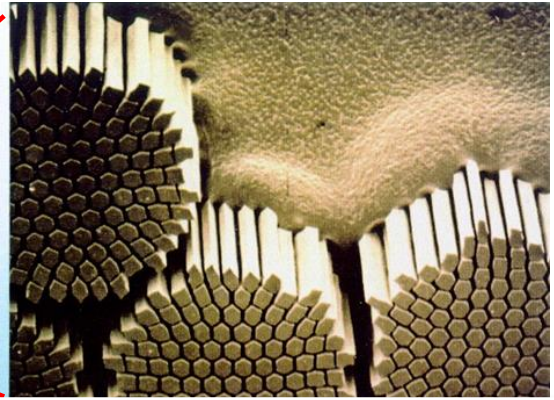




LARGE HADRON COLLIDER
IN THE LEP TUNNEL

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

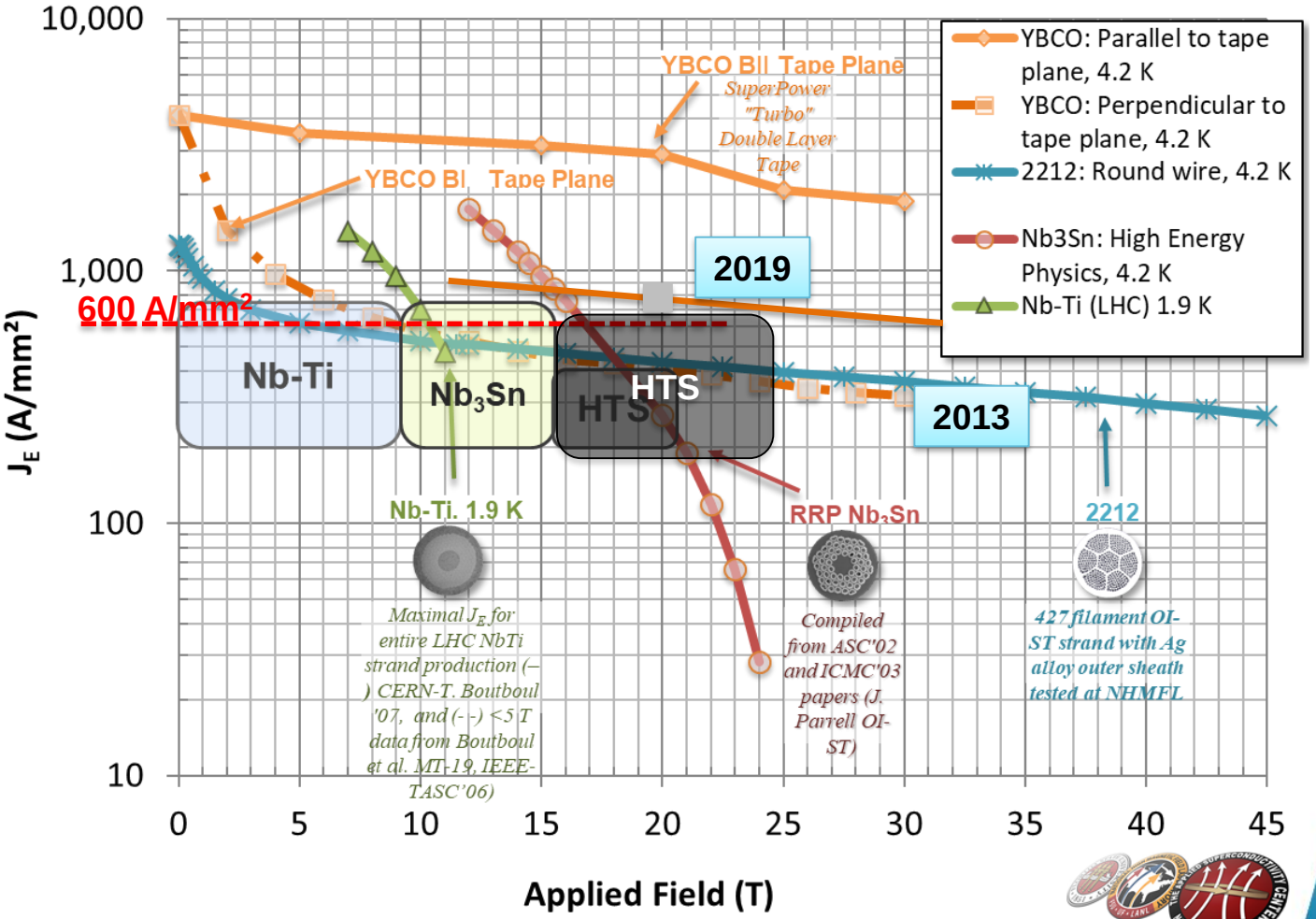


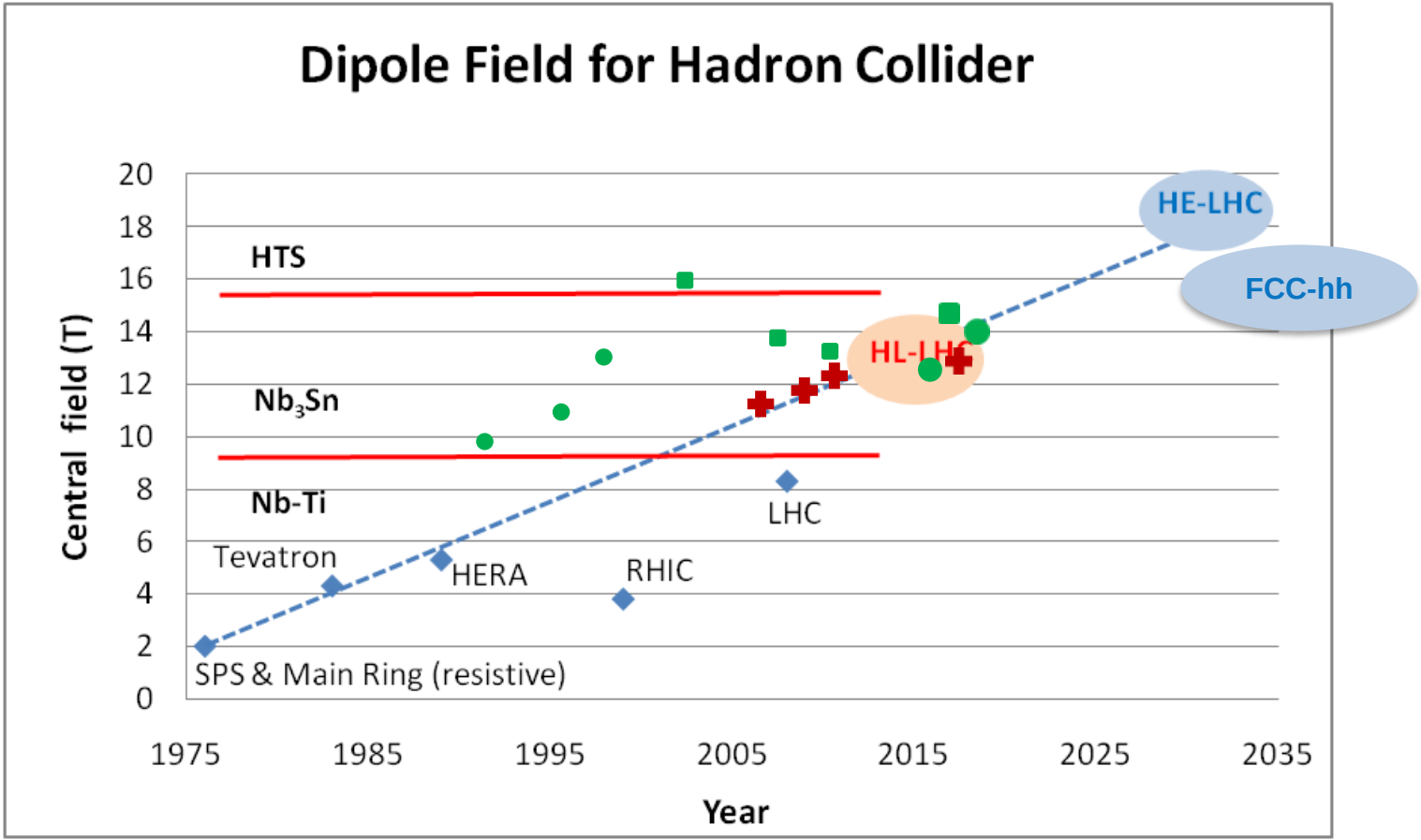


Developing SC is the key in SC accelerators. LHC is indebted to SSC

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

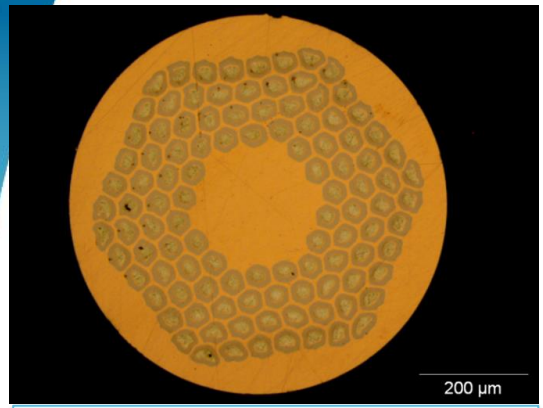
The superconductor space: Accelerators Magnets need J_E > 500 A/mm² @ 20 T



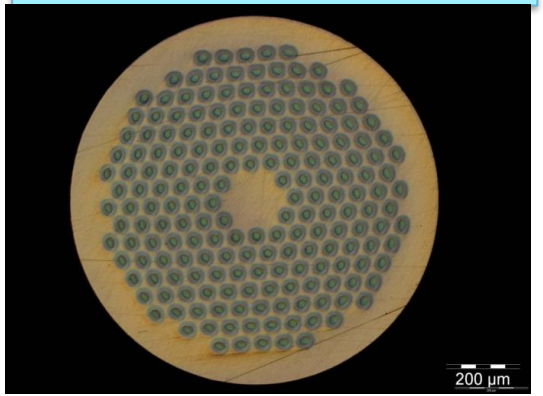


- Nb-Ti operating dipoles;
- Nb3Sn cosϑ test dipoles
- Nb3Sn block test dipoles
- Nb3Sn cosϑ HiLumi QUADs

Nb_3Sn DOE-CDP in USA and (less) in EU took basically 15 y of development and was key for HiLumi LHC

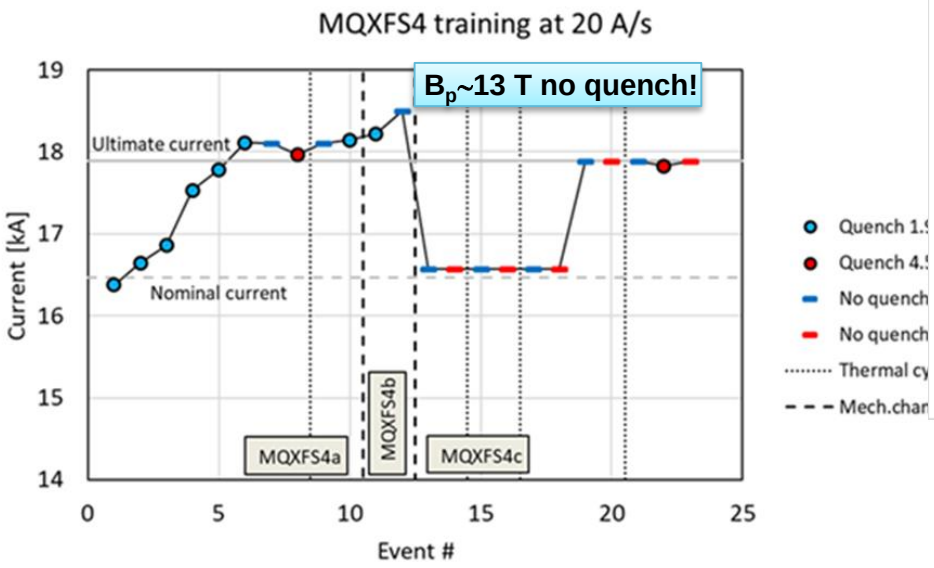


0.7 mm, 108/127 stack RRP from **Bruker OST (USA)**

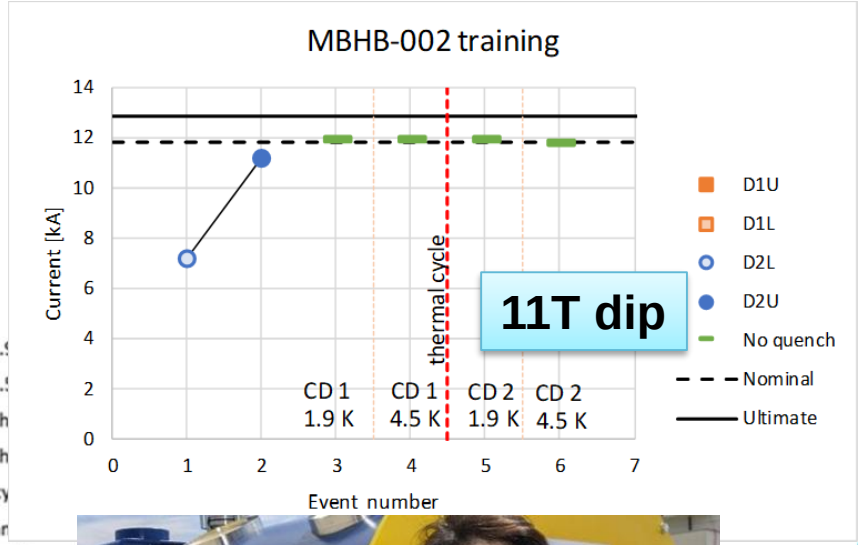


1 mm, 192 tubes PIT from **Bruker EAS (EU-De)**

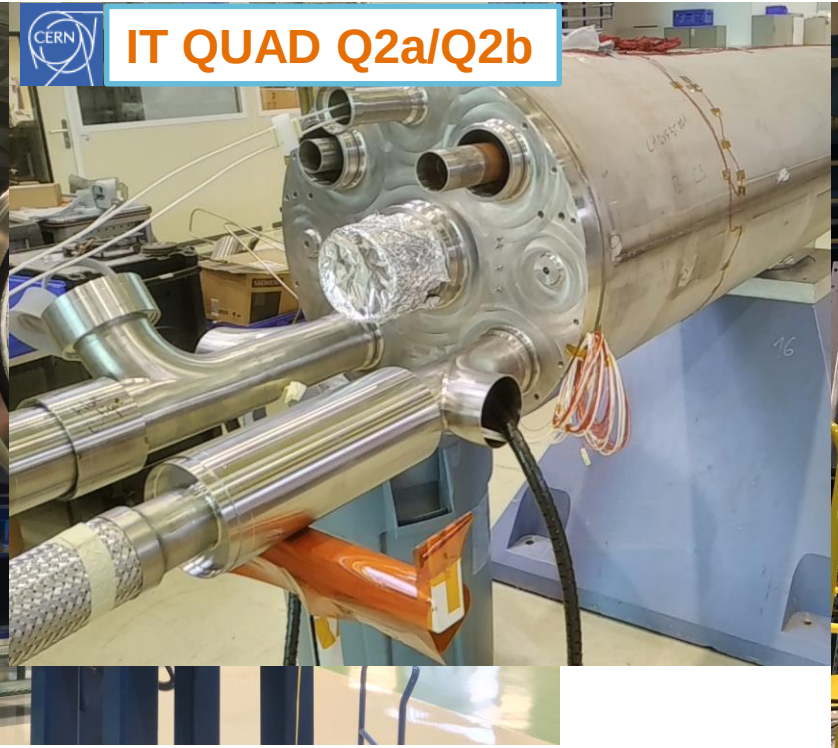
And HiLumi HF magnets magnets follows!



IT QUAD



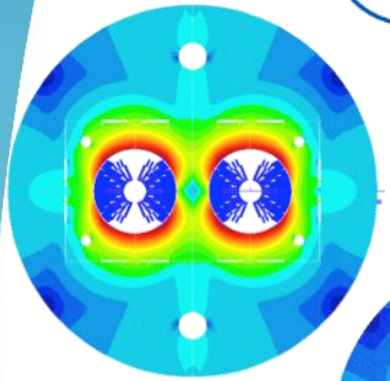
After 15 y of R&D Nb_3Sn magnets are coming… first time in an accelerator…



16 T dipole design activities and options

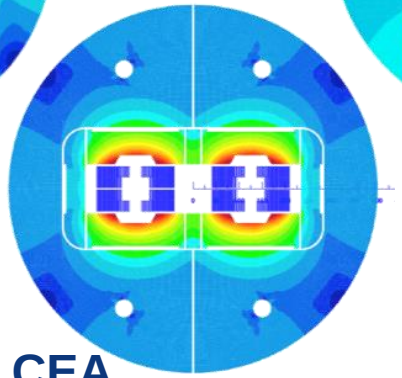
H2020 EuroCirCol A key to New Physics

Cos-theta



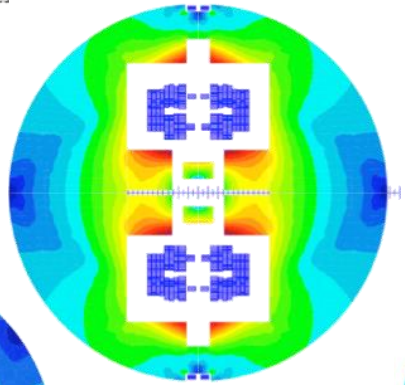
INFN

Blocks



CEA

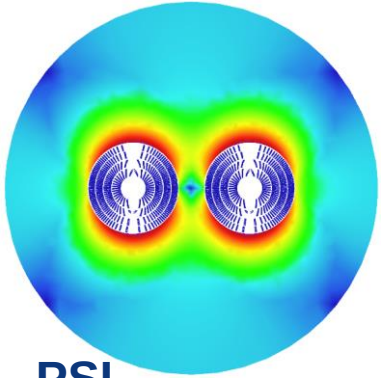
Common coils



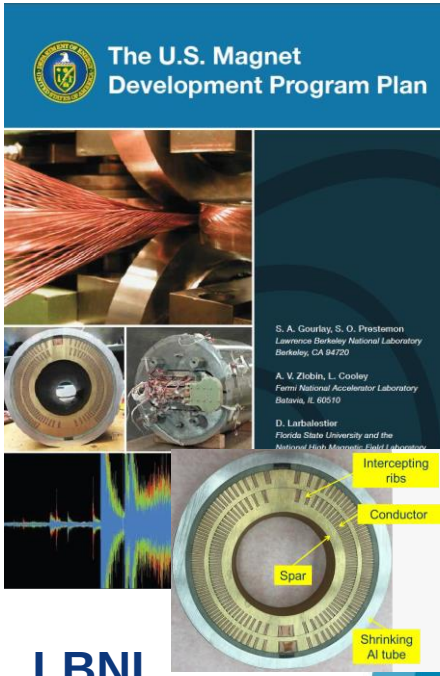
CIEMAT

Swiss Program

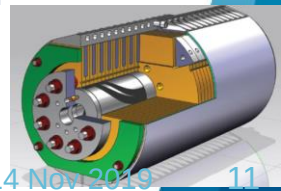
Canted Cos-theta



PSI



LBNL

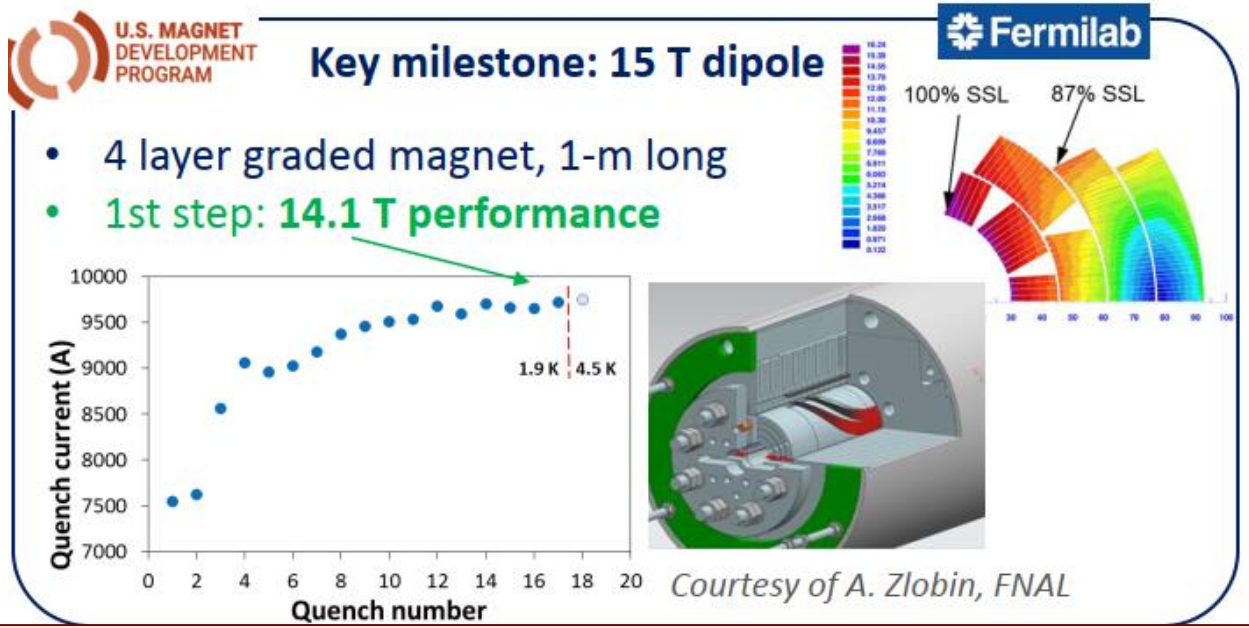


FNAL

Short model magnets (1.5 m lengths) to be built from 2018 – 2022

Russian 16 T magnet program launched by BINP recently.

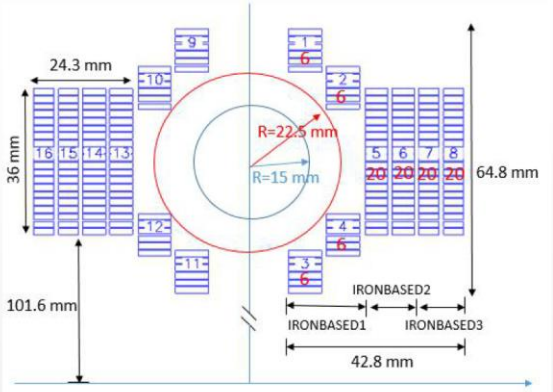
Recent very successful 14 T magnet reached by US MDP cosϑ dipole at FNAL

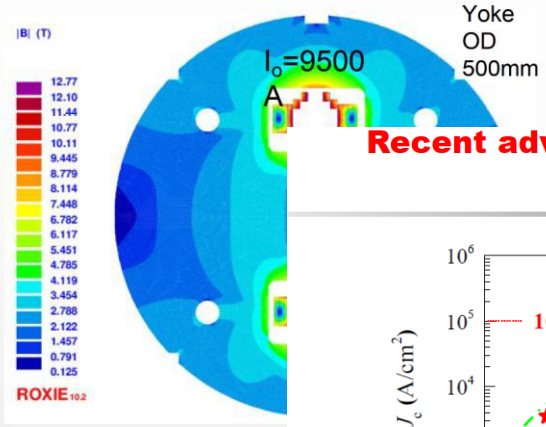


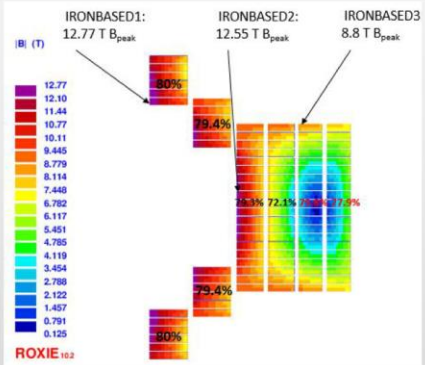
Basically wiht HiLumi type wire.
But the route is long… To operate really at 14-16 T one need sto develop very high field Nb_3Sn and demonstrate magnets at least in the 8 T range

high-field magnet R&D for SppC

The 12-T Fe-based Dipole Magnet







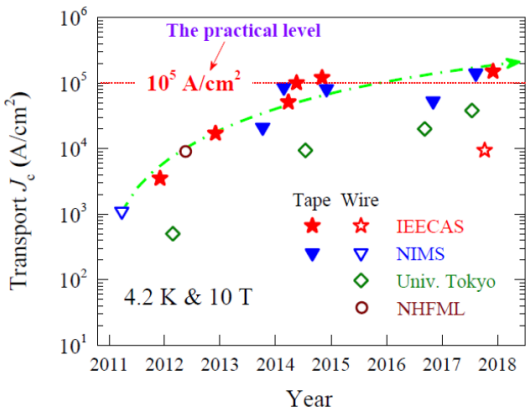
Design with expected J_e of

Strand	diam.	cu/sc	RRR	Tref
IBS	0. 802	1	200	4. 2

- For 100-km SPPC, **300** needed
- Target cost of IBS: **20 R**
- Total cost for IBS conductors: **~10B RMB**

Is Iron-Based Superconductor good?
Not yet but improving…
It is the «bet» of the China National Program

Recent advances in transport J_c of PIT processed 122 wires and tapes



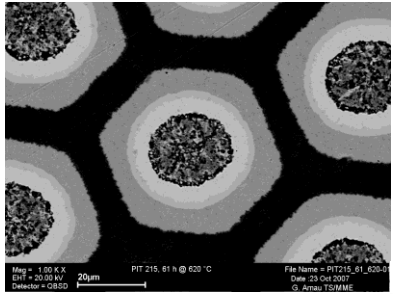
2018
1.5×10^5 A/cm^2

10^5A/cm^2 at 18 T

Next target: 10^5A/cm^2 at 30 T

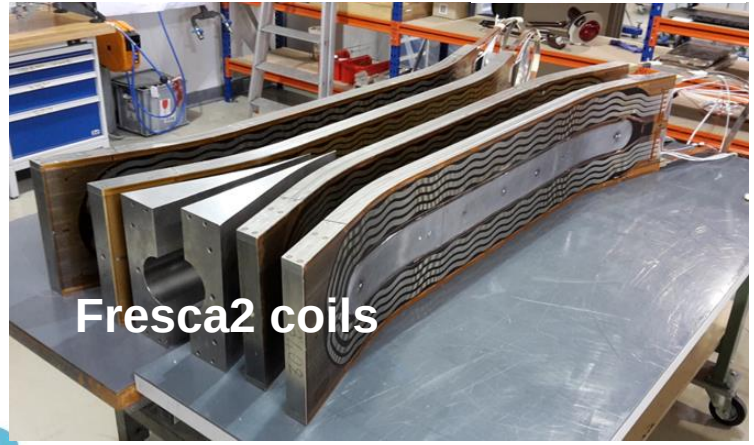
◆ **An scalable process is required to fabricate high performance long length tapes, e.g.,** ***Rolling (hard sheath), Hot Rolling or Hot isostatic press (HIP)…***

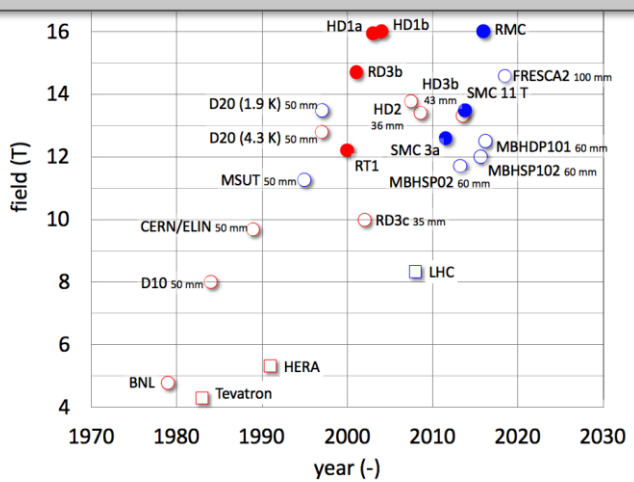
CARE – EuCARD/EuCARD2: 15 y Nb_3Sn development in EU



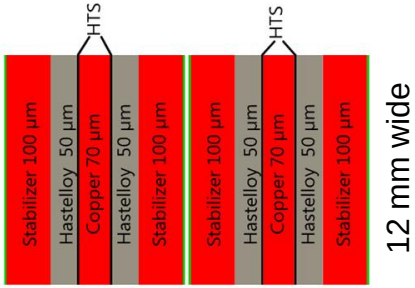
CARE-NED 2004-2008 then CERN + CEA
Development of PIT conductor and first HF dipole design
PIT of 1300-1500 J_c at 15T

Fresca2 all Nb3sn (RRP+PIT) record field dipole: 14.6 T in 100 m free bore





EuCARD HTS (2008-13), CEA-CERN collab. (2014-17)



Cable: 0.92 mm thick

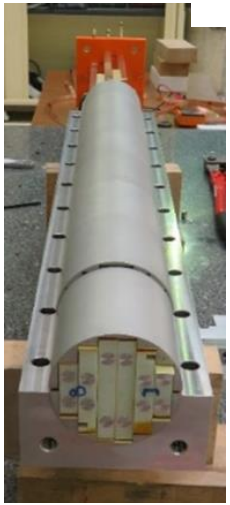
First attempt –in EU – to go for dipole-like coil. Stacked tapes, no transposition, with large amount Cu

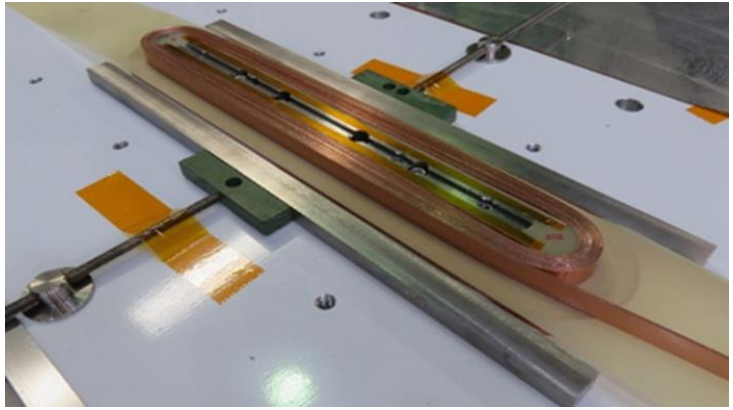
Simple racetrack.

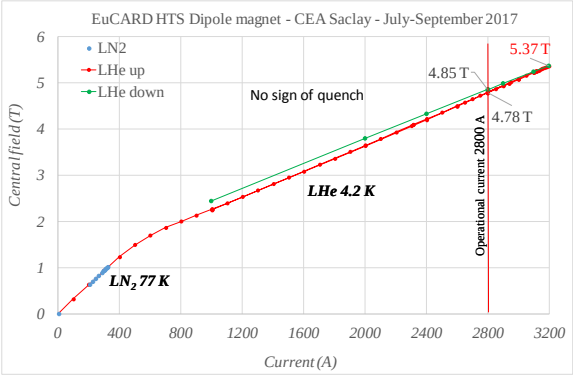
Transposition between the two sub-cables of top and bottom pole.

HTS conductor By SuperPower

Magnet design, construction,test. Technological support by INP Grenoble

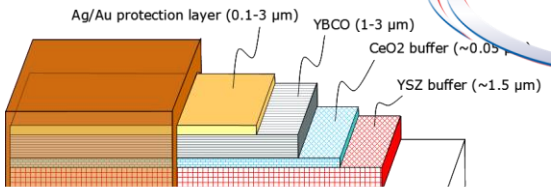


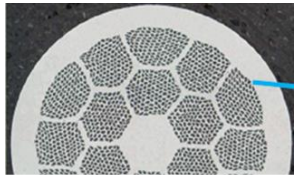




M. Durante et al., CEA

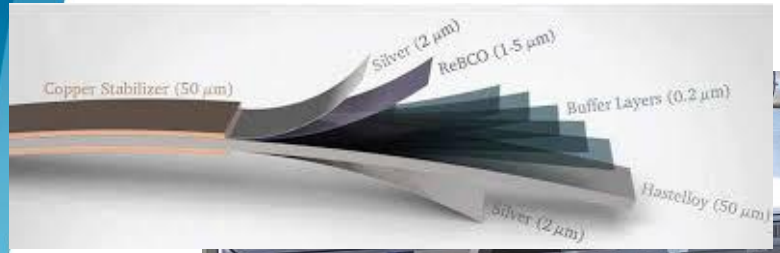
YBCO (or REBCO) Conductor: the choice of EuCARD²





REBCO	characteristics	Bi-2212
High, steadily improving	**Critical current**	High, more stagnant
Roebel cable (waste), ready to use, 50-200 m unit length	**Cabling and general**	Easy Rutherford cable, but need special H.T., very long length possible
Very bad (tape).	**Magnetization**	Worst than NbSn but manageable
Excellent, better than Nb_3Sn	**Mechanical prop.**	**Weak vs. transv. stress**
Difficult bend in non-easy way, joints not easy, **NO Heat Treatment**	**Coil technology**	**Very complex HT**, large scale coils may be difficult. Easy joints
Various suppliers and projects everywhere	**Supply**	Limited number

CERN-Bruker complement to EuCARD2



Pulsed Laser Deposition PLD600: production equipment of Bruker

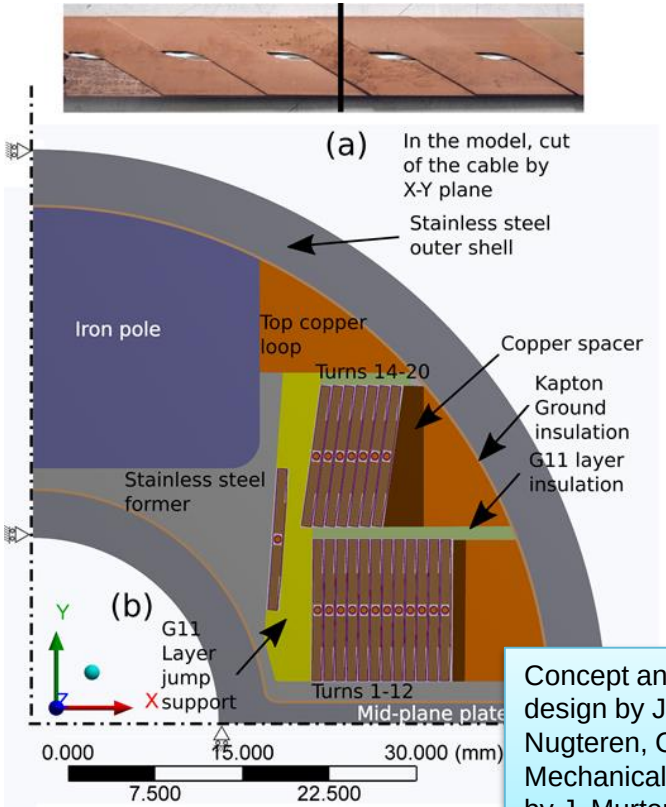
PROCESSING CHAIN OF HTS PILOT-LINE PRODUCTION
SUBSTRATE PREPARATION (SUB)
BUFFER LAYER COATING (ABAD)
HTS LAYER COATING (PLD)
METAL COATING (MET)
COPPER PLATING (PLA)
FINAL TAPE INSPECTION (INS)

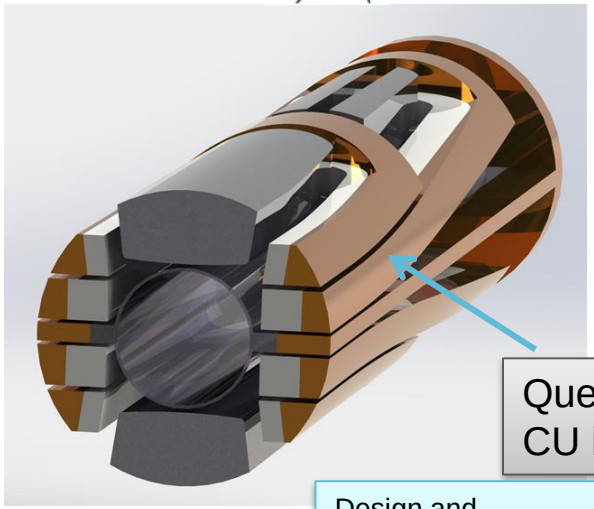
Pulsed Laser Deposition PLD300: R&D line: CERN-Bruker

Roeble cable by KIT for the EuCARD2

- Large currents ~ 10 kA with **good FF ~ 85%** (same range Ruth. Cable)
  - **Transposed** (good FQ also in ramping)
- **Good contact resistance despite impregnation: 10-30 μΩ (not low - not high)**

Results of Eucard2: demonstrator dipole



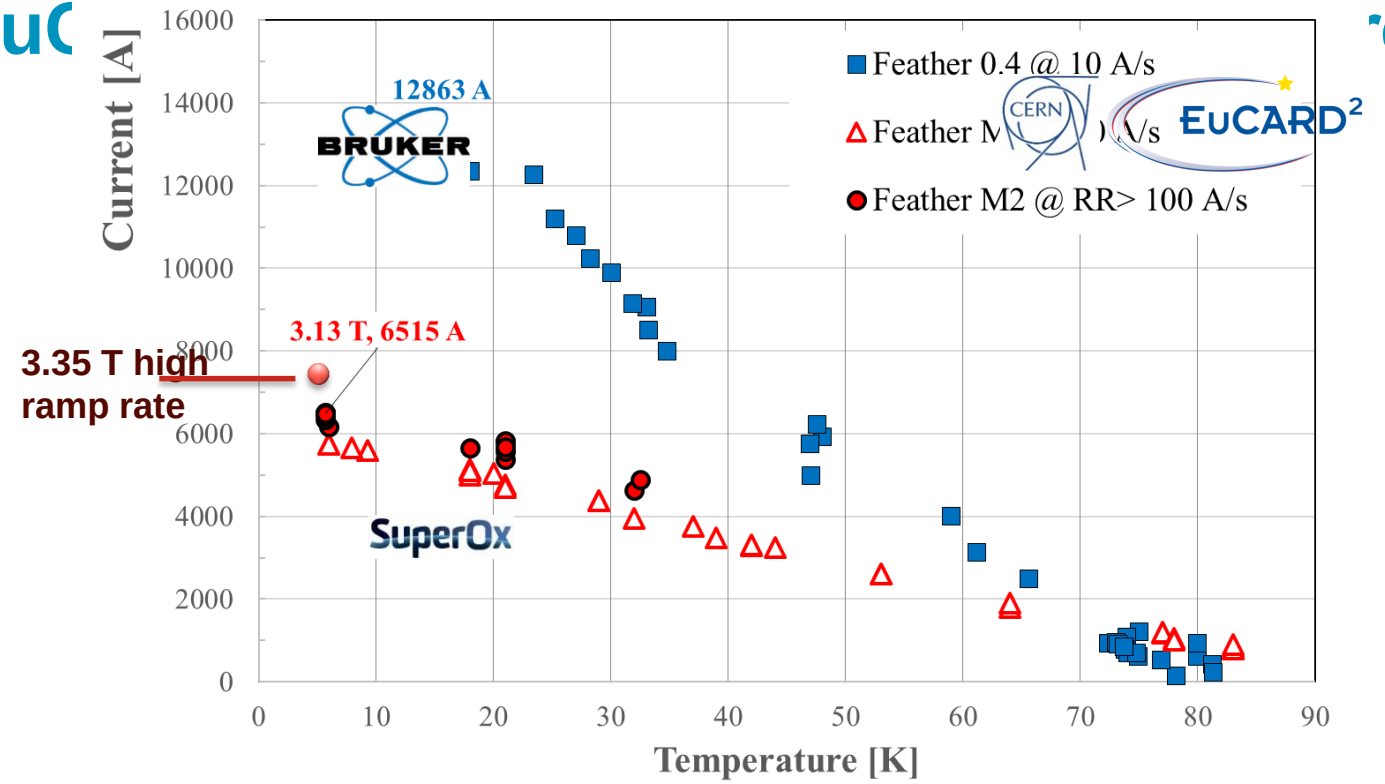


Quench CU bars

Design and technology innovation by G. Kirby, CERN

Concept and e.m. design by J. van Nugteren, CERN
Mechanical analysis by J. Murtomaki, CERN

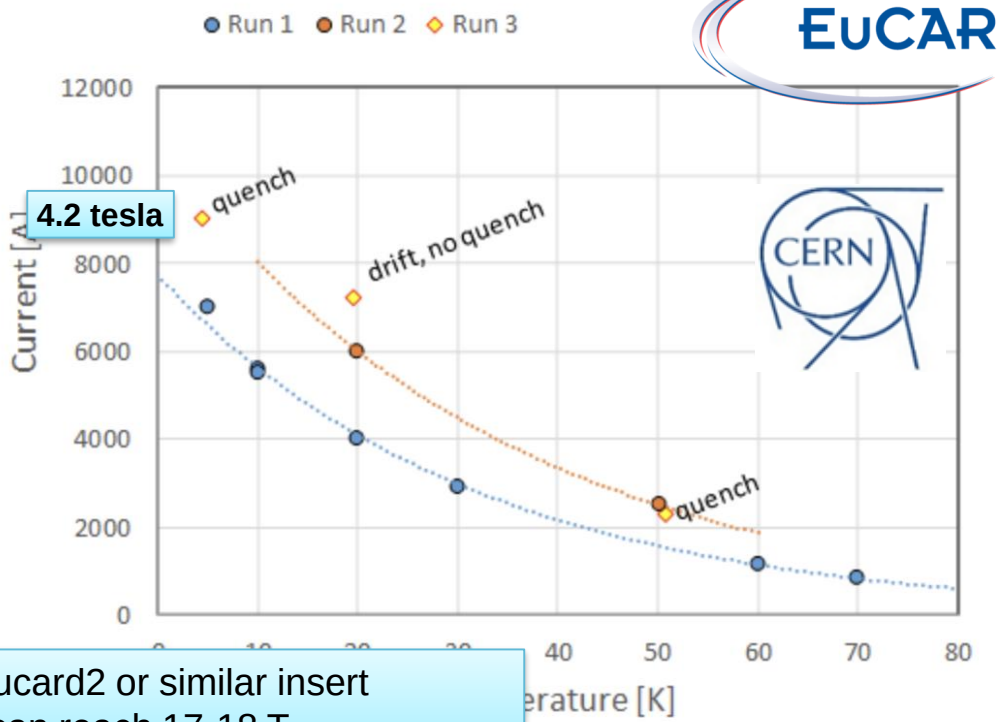
EuC… re…



3.35 T high ramp rate

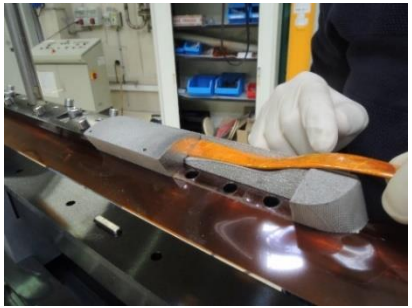
Recent test at CERN of 2nd open race-track

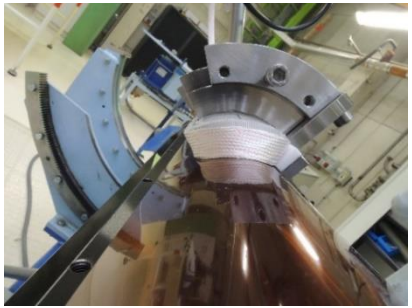
FeatherM2-3.4

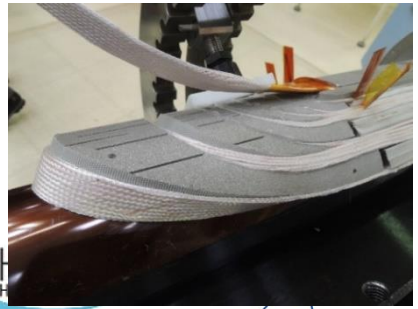


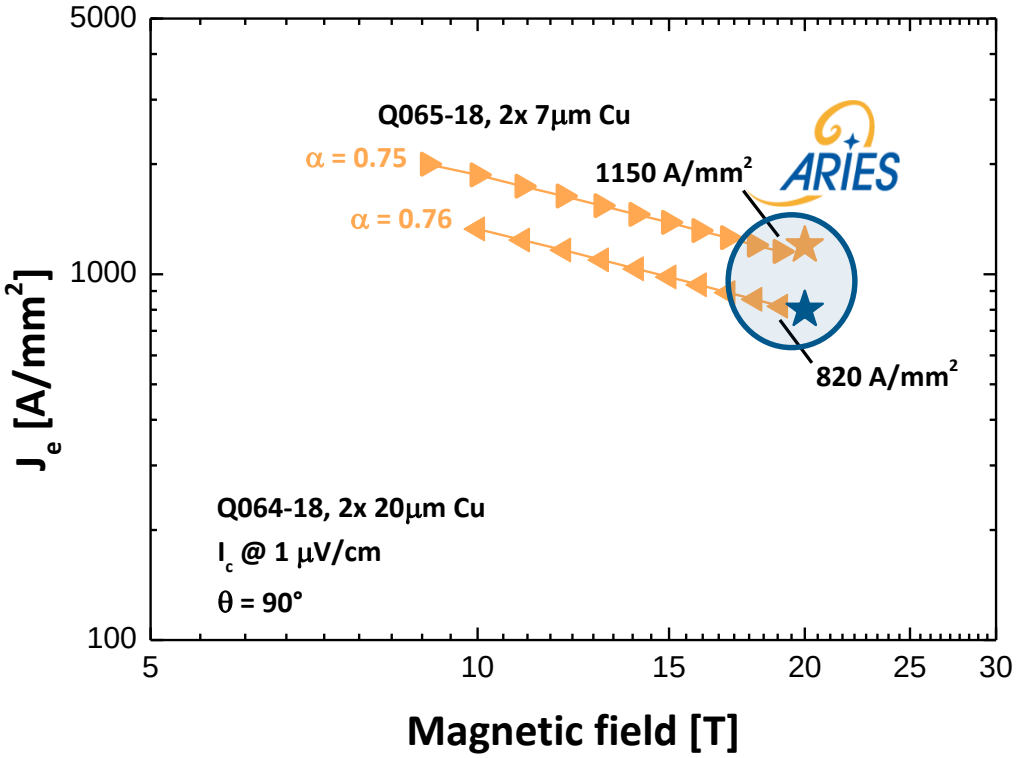
Inside FRESCA2 this Eucard2 or similar insert (Eucard1, but no bore) can reach 17-18 T

Cosϑ dipole at CEA with EuCARD2 Roebel



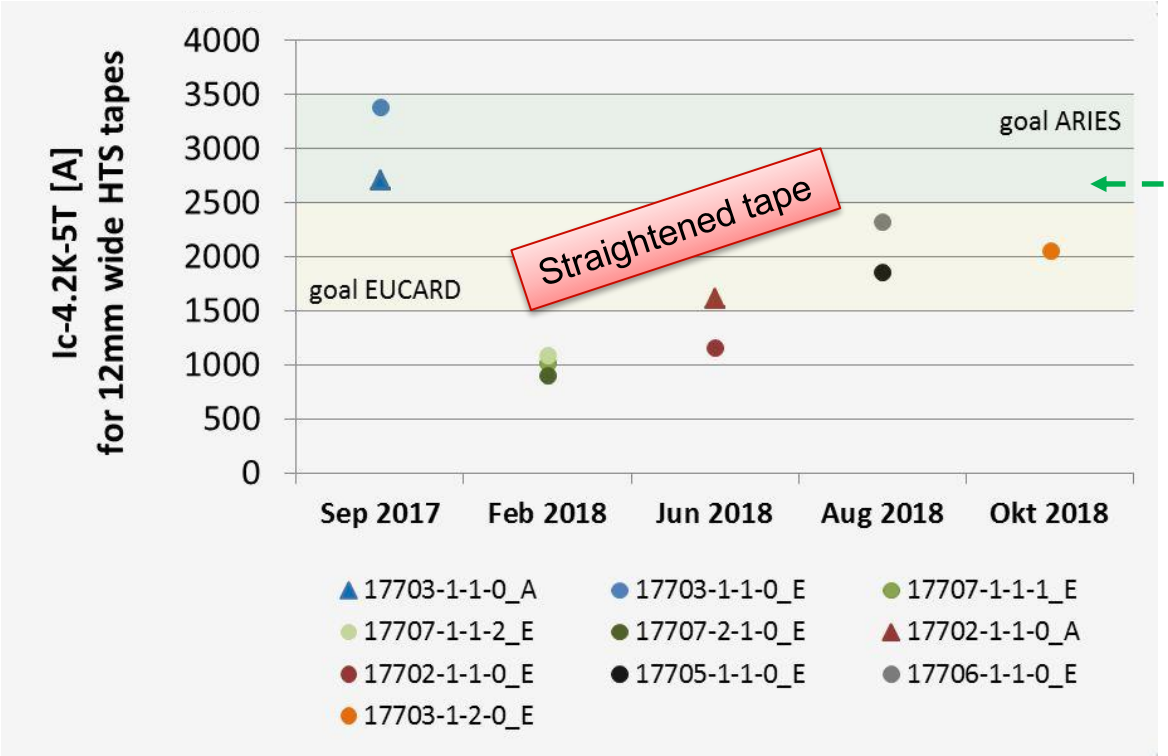






Tape Q065-18 (with 2x 7μm Cu) reached a very high performance of 1150 A/mm² at 4.2 K, 19 T, 90°

Result from ARIES miniproduction: repeatibility not fully successful…

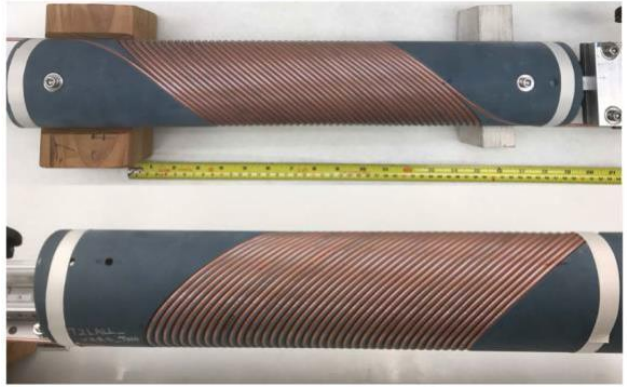


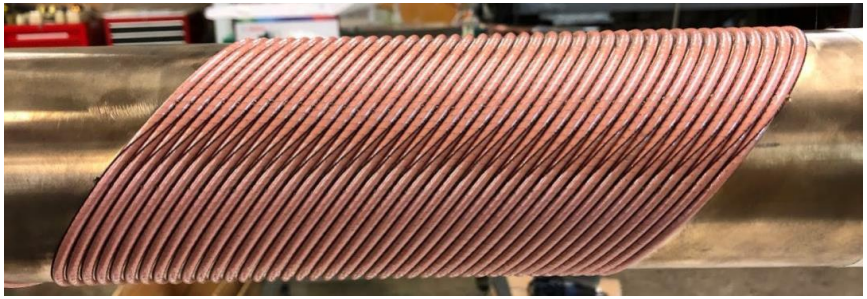
800 A/mm2 at 20 T, 4.2K

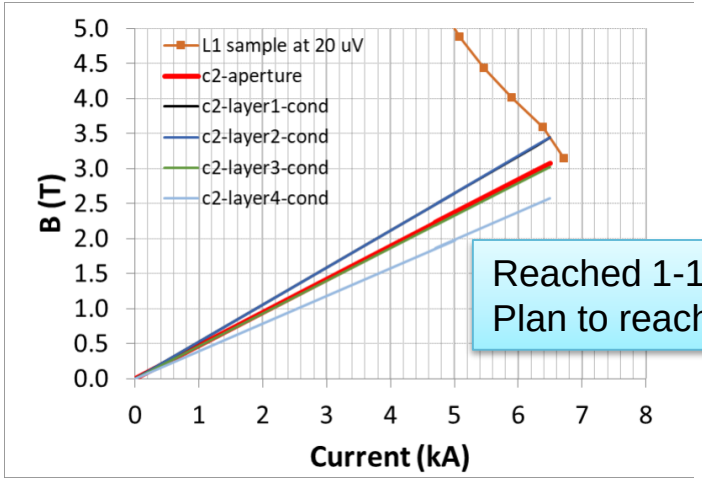
We need to review the process since the yield is not satisfactory (about 50%):

LBNL: CCT with CORC™ cable (ACT LLC)

Advanced Conductor Technologies LLC
www.advancedconductor.com

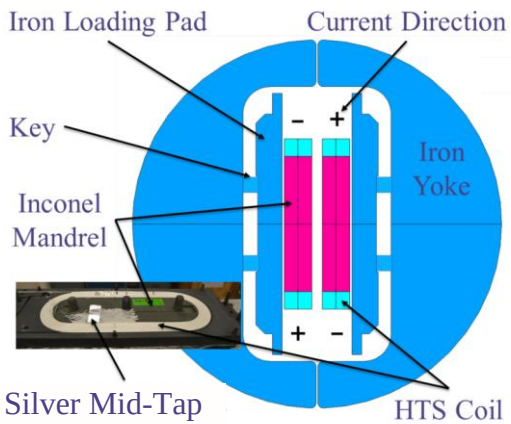




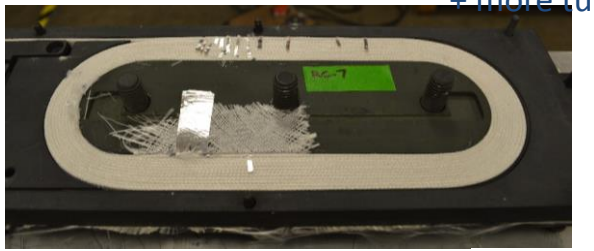


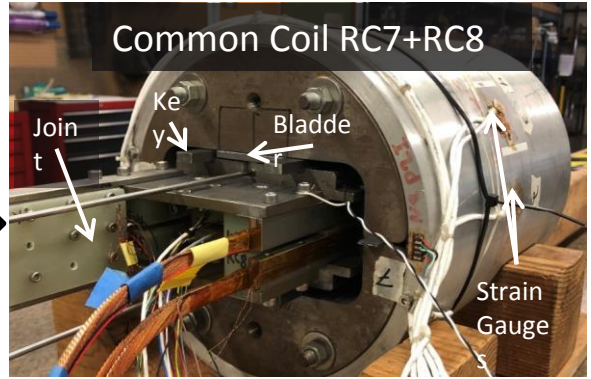
Reached 1-1.5 T
Plan to reach 3 T at 4.2 K

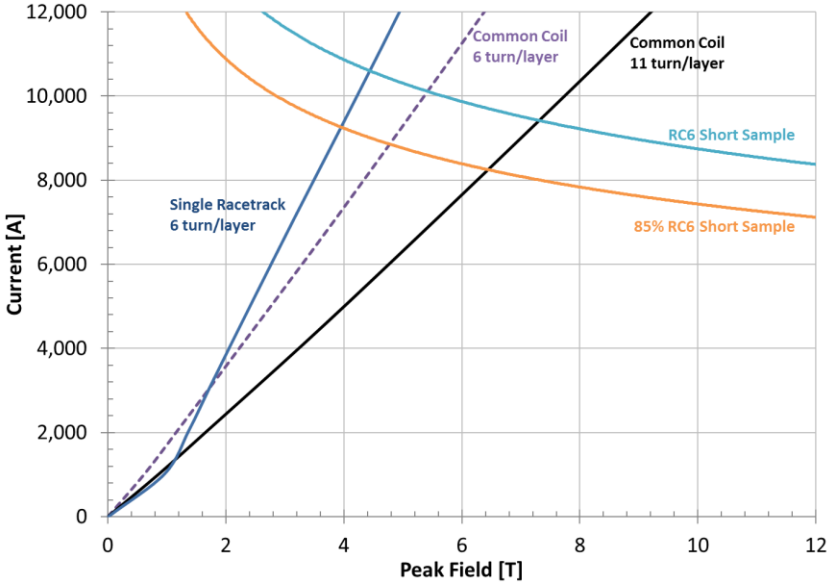
LBNL: Bi-2212 racetracks and CCT program



RC 7 - Twisted wires
+ more turns

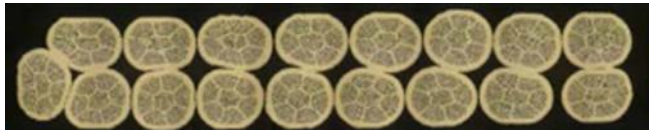


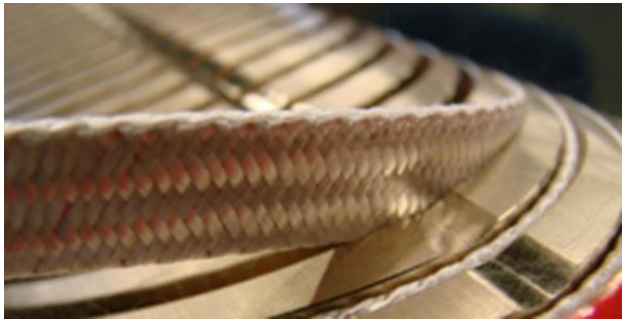


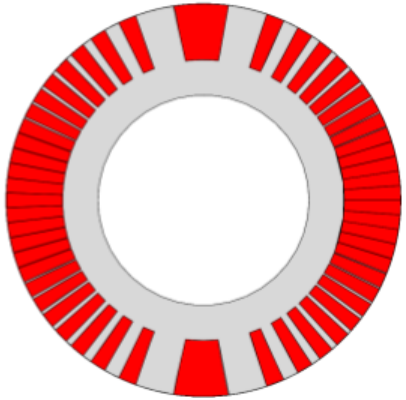


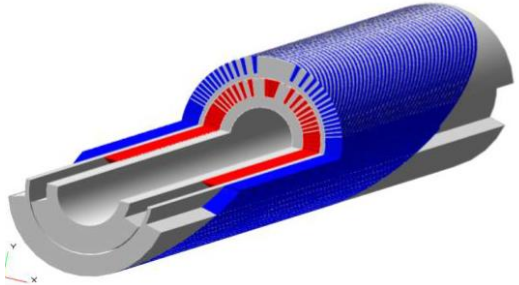
Mechanical Assembly: Jim Swanson, Josh Herrera, Daniel Davis, Tengming Shen. Bladders used: Courtesy of Daniel Cheng

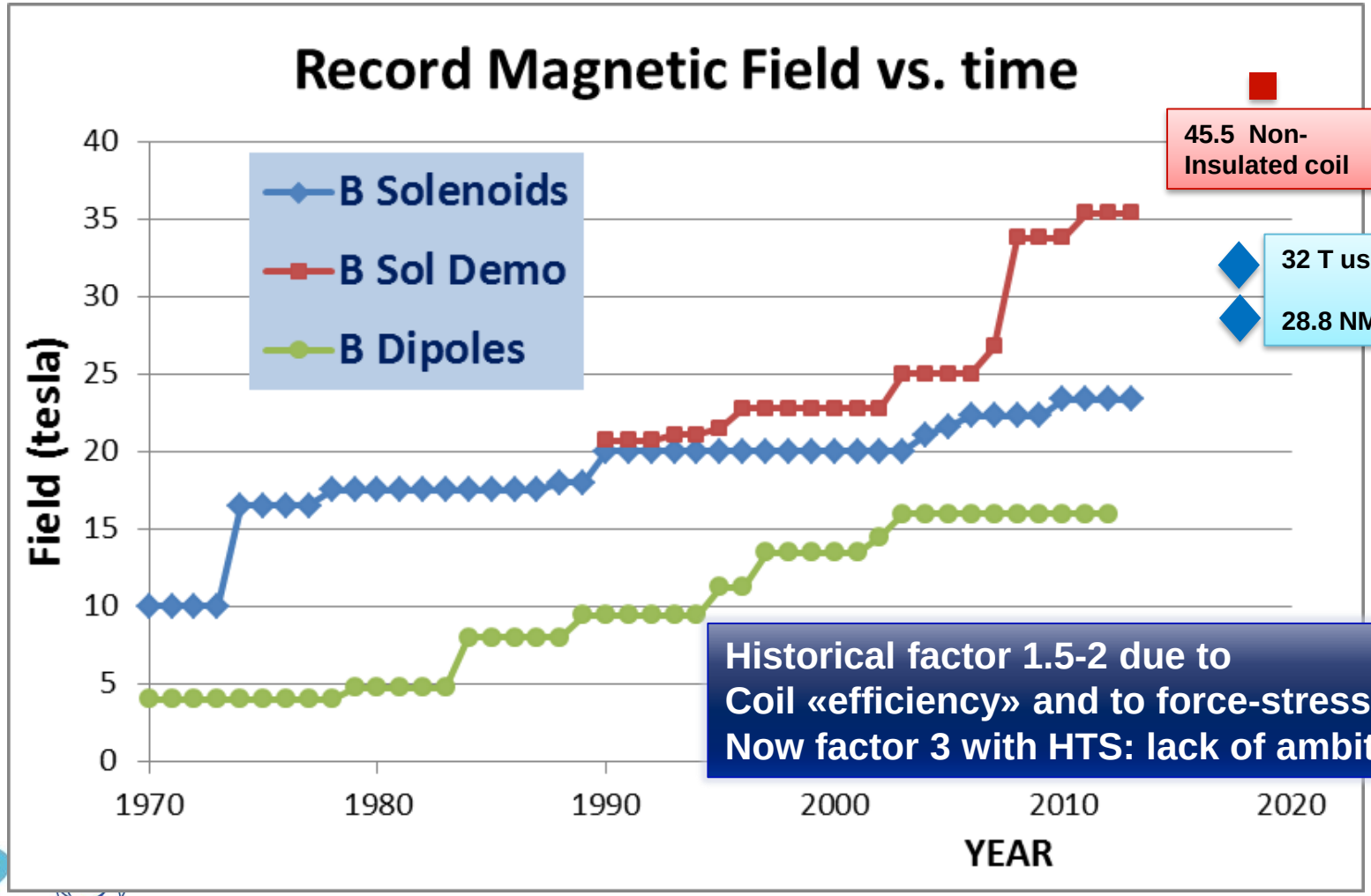
And then use B-2212 cable for CCT
Always in the 3-7 T range; to be used as insert





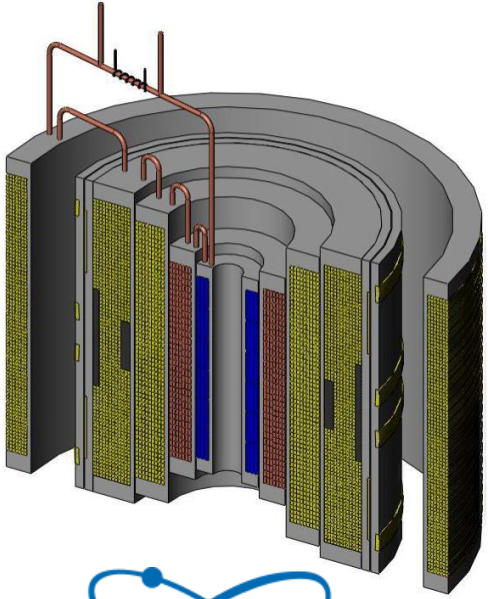


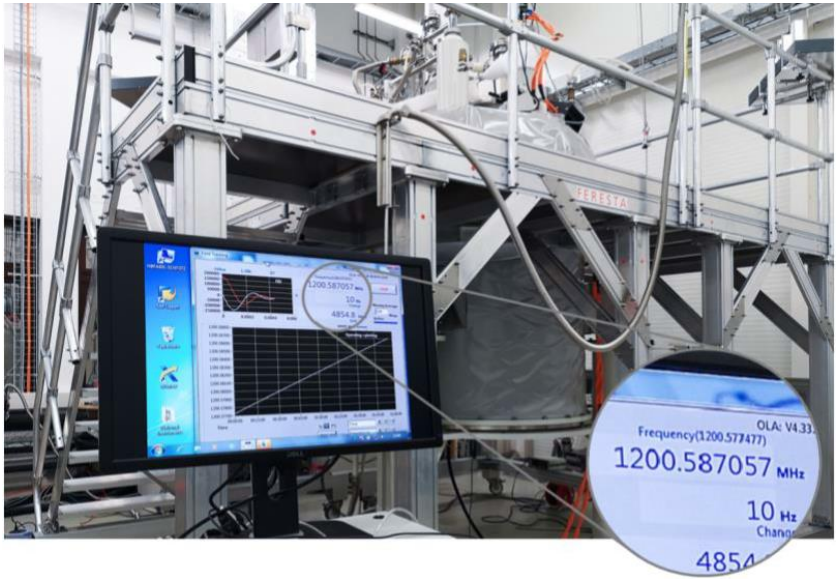




Historical factor 1.5-2 due to
Coil «efficiency» and to force-stress
Now factor 3 with HTS: lack of ambition?

A big leap forward by a private company… Bruker Biospin





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

EuCARD2/ARIES has triggered a International collaboration also beyond EU labs

WAMHTS-1 in Hamburg 21-23 May 2014
HTS Con

WAMHTS-2 in Kyoto 21-23 May 2014
HTS Coil technology – 55 participants

WAMHTS-3 in Lyon 10-11 September 2015
HTS Magnet protection
participants

WAMHTS-4 in Barcelona 15-17 February 2017
HTS Magnet design – 87 participants

WAMHTS-5 in Budapest 11-13 April 2019
HTS Magnet applications – 66 participants

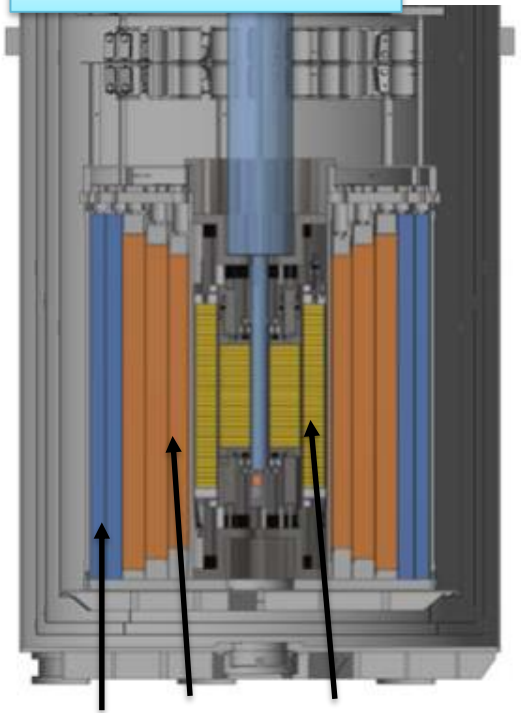
Conclusion

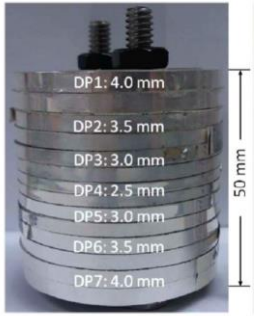
- Accelerator Magnets are the **most challenging for superconductivity,** requiring current density of $J_E \geq 500$ A/mm^2 in operating condition (+ 20% margin)
- The homogeneity must be excelent and the screening currents (magnetization) sufficiently small not to hamper Field Quality (or very predictable and repeatable to be corrected with field-forward systems)
- The cost is high. Today 5 times the best Nb_3Sn. Cost decrease is being pushed by other community (Fusion).
- **But HTS can gain us the 15-25 T range at 4.2 K with training-free magnets**
  - **Operating at 15 T at 10-20 K should also be explored (factor 10 energy saving wrt FCC baseline)**
- The only way to make progress is a **continuous and focussed program** of size 2-3 times of EuCARD2: **3 M€/year in material + 15-20 FTE**. The program should ~ 5+5 years (two phases), like US-LARP.
  - 5 years are needed just to complete assessment if HTS can be suitable for colliders
  - A good part of issue of HTS magnets are shared with other HF conductors (Nb_3Sn)
  - Specific disadvantage (shape) and gain (stability and NI technology) needs to be addressed.

Thanks

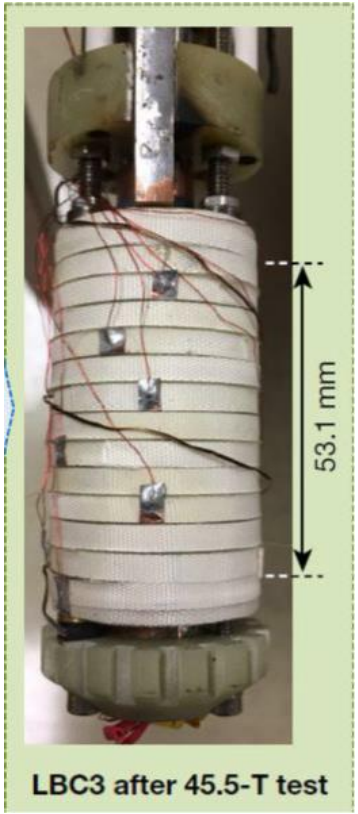
Nat. High Mag. Field Lab in Florida

32 T reached in 2018!





30 T coil Non-insulated



Courtesy of M. Bird, FSU/NHMFL USA