R&D on HFM (FRESCA2 & FCC)

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CERN

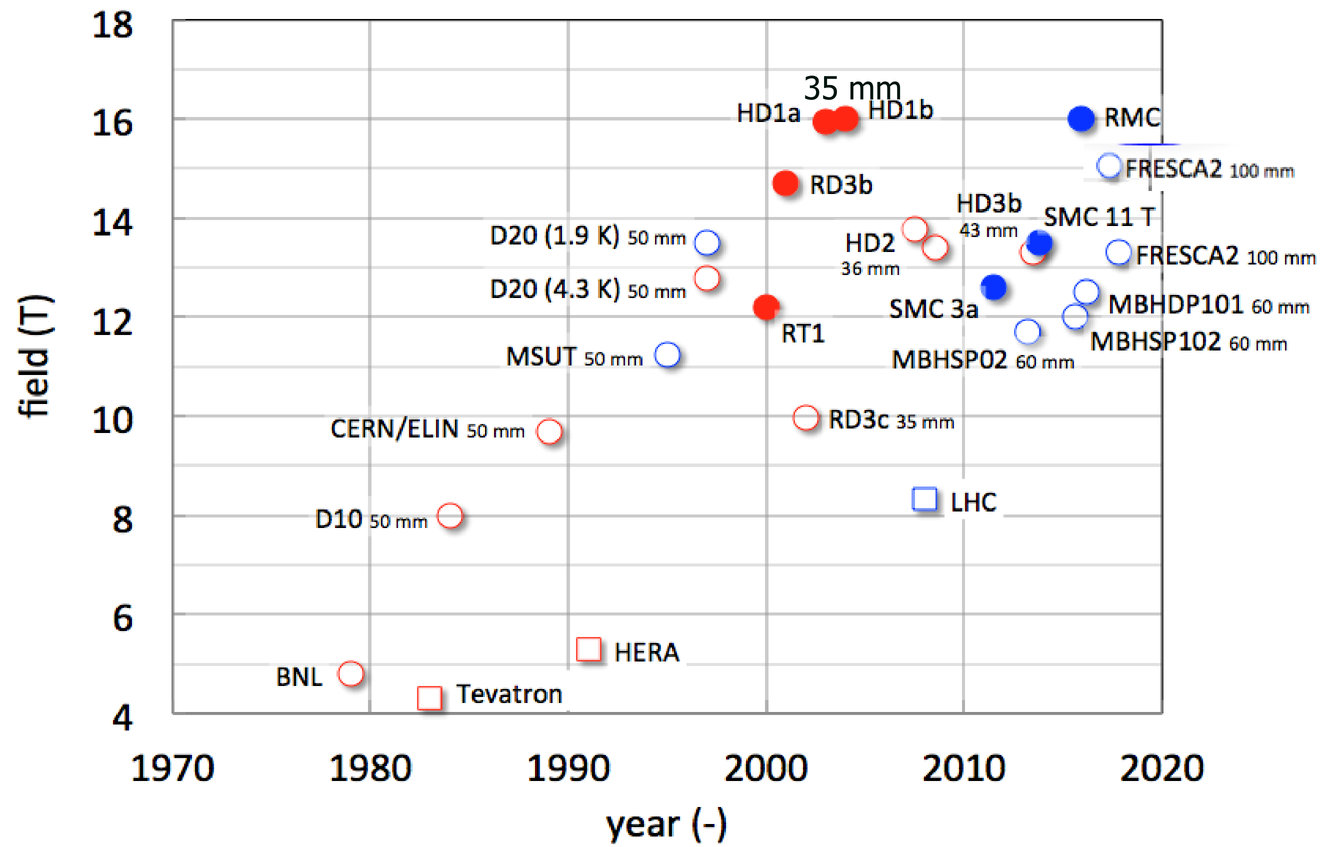
18th October 2018

Contents

- A bit of history
- The HL-LHC HFM era : going up to 12 T
- Optimizing the HL-LHC HFM technology: Fresca2
- FCC Nb_3Sn: moving up to 16T
- Shooting even higher : 20T with HTS

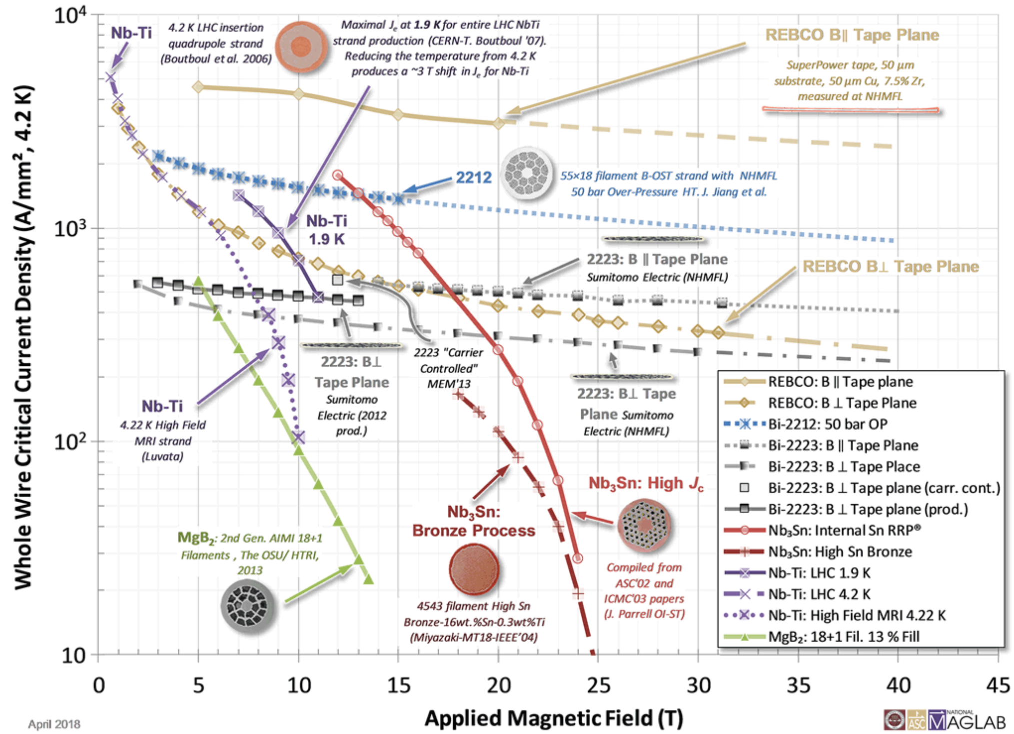
Superconducting accelerators magnets; the state of the art

- Maximum attainable field slowly approaches 16 T
  - 20% margin needed (80% on the load line): for a 16 T nominal field we need to design for 20 T



R&D on HFM,HL-LHC, 18 Oct 2018, GdR

Available Superconductors



Nb-Ti: the workhorse for 4 to 10 T

- Up to ~2500 A/mm^2 at 6 T and 4.2K or at 9 T and 1.9 K
- Well known industrial process, good mechanical properties
- Thousands of accelerator magnets have been built
- 10 T field in the coil is the practical limit at 1.9 K

Nb_3Sn: towards 20 T

- Up to ~3000 A/mm^2 at 12 T and 4.2 K
- Complex industrial process, higher cost, brittle and strain sensitive
- 25+ short models for accelerator magnets have been built
- ~20 T field in the coil is the practical limit at 1.9 K, but above 16 T coils will get very large

HTS materials: dreaming 40 T (Bi-2212, YBCO)

- Current density is low, but very little dependence on the magnetic field
- Used in solenoids (20T range), used in power lines – no accelerator magnets have been built (only a few models) – small racetracks have been built

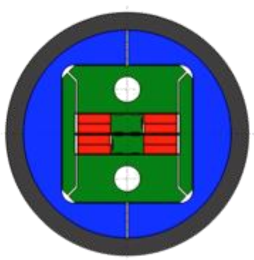
HFM pure development projects in Europe

- 2004-2008 CARE-NED → Nb_3Sn conductor, dipole design, insulation etc.
- 2009-2013 EuCARD-WP7 HFM → Fresca2, HTS insert, Current Link, Helical undulator, Rad studies and heat flow studies
- 2013-2017 EuCARD2 WP10 → ReBCO performance improvements, Roebel cable, Feather2 magnet, CosTh Roebel cable magnet (being built)
- 2017-2021 ARIES → ReBCO performance improvements

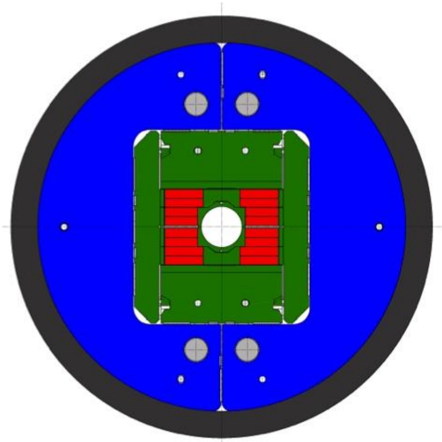
CERN-European development evolution on dipoles

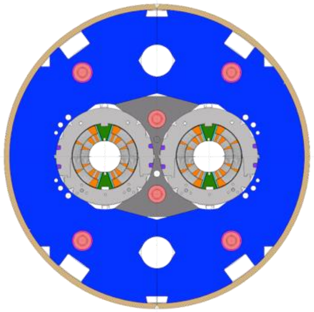
Short Model Coil

Race-track Model Coil



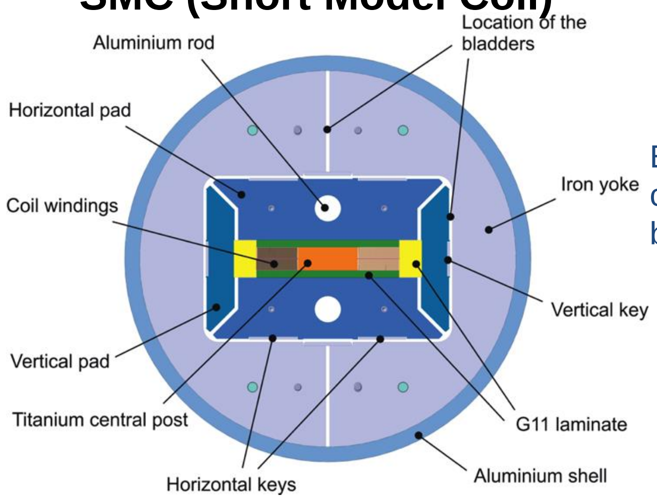
FReSCa2 13T Nb_3Sn Dipole



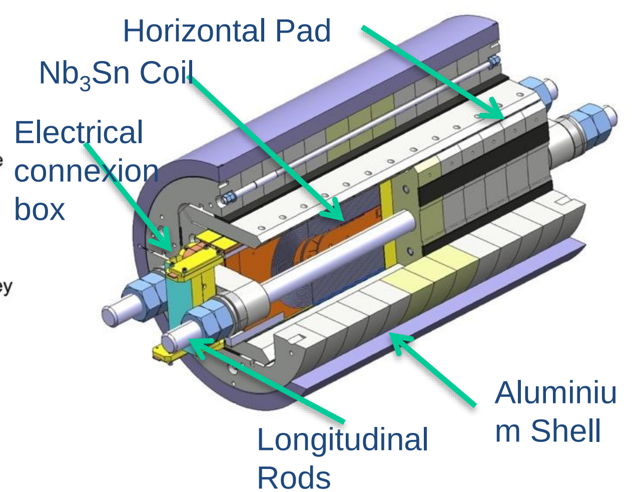


11 T dipole (CERN)

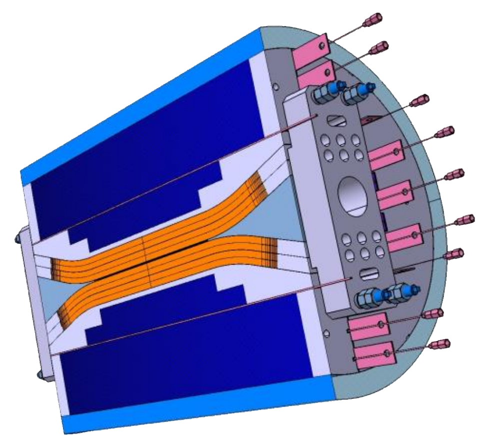
SMC (Short Model Coil)



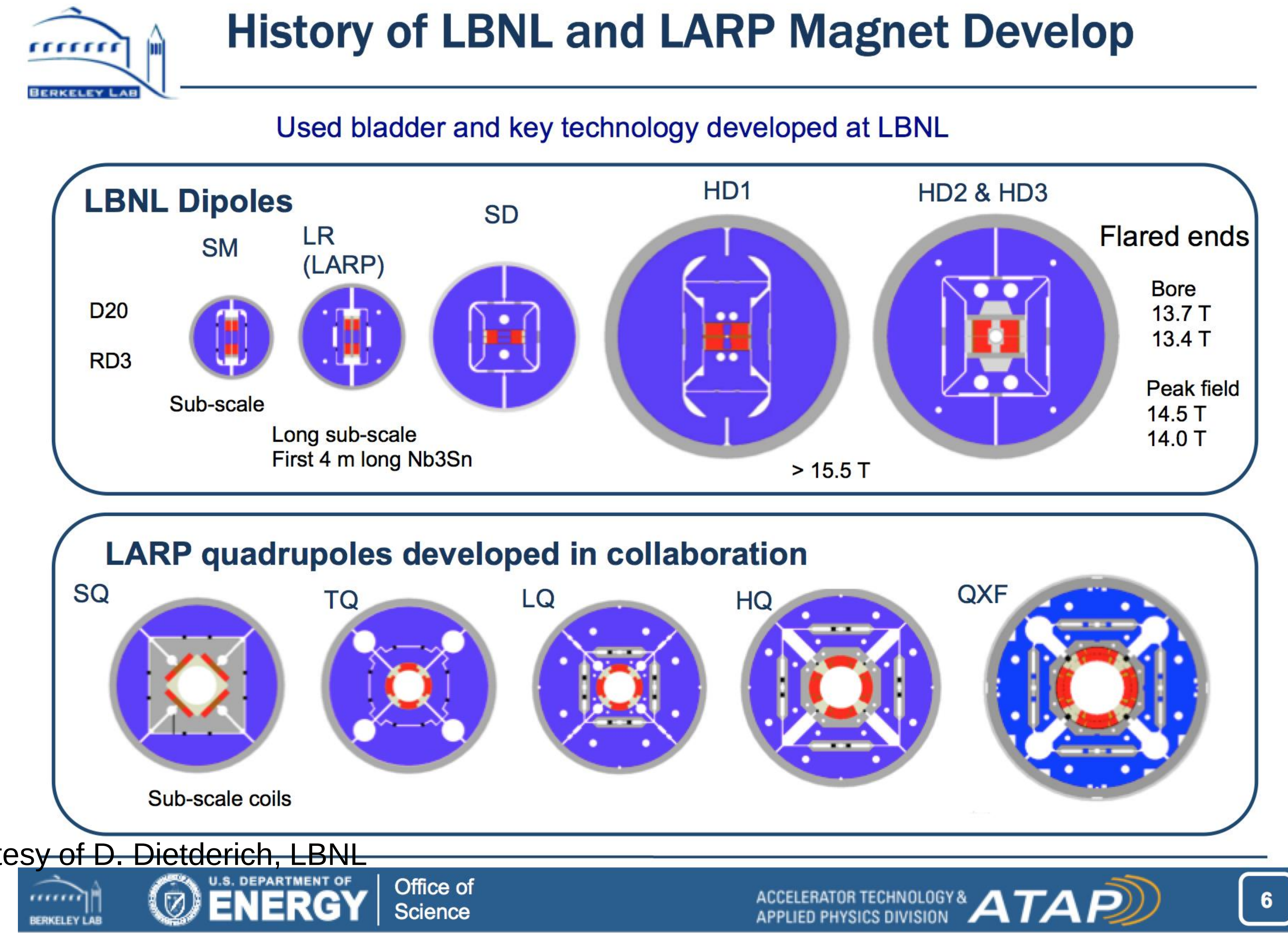
RMC (Racetrack Model Coil)



FReSCa2



Basic magnet technology development for HILUMI and beyond (2004-2013) ; US development evolution



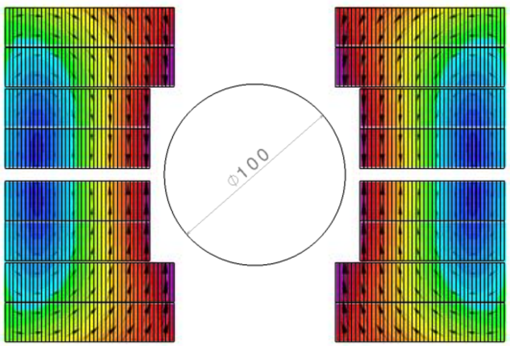
By courtesy of D. Dietderich, LBNL

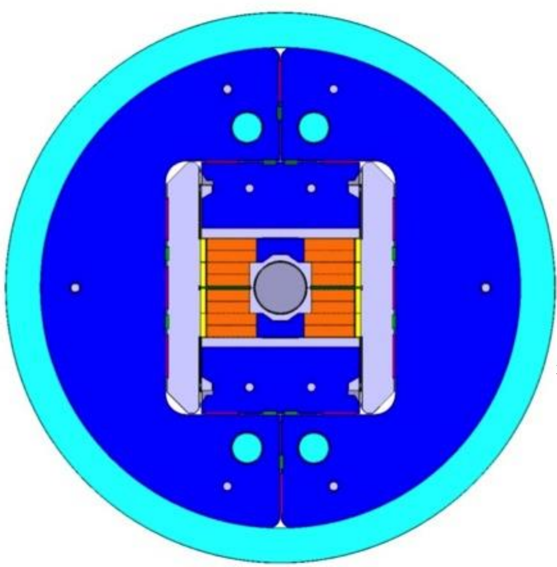
Basic HFM development : EuCARD high field dipole (Fresca2):

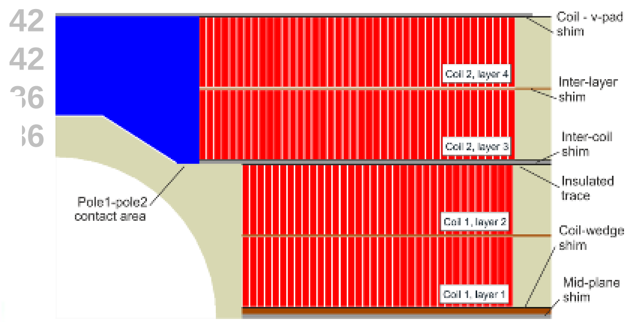
- Fresca2 : CERN, CEA construction phase
- First tests 2014

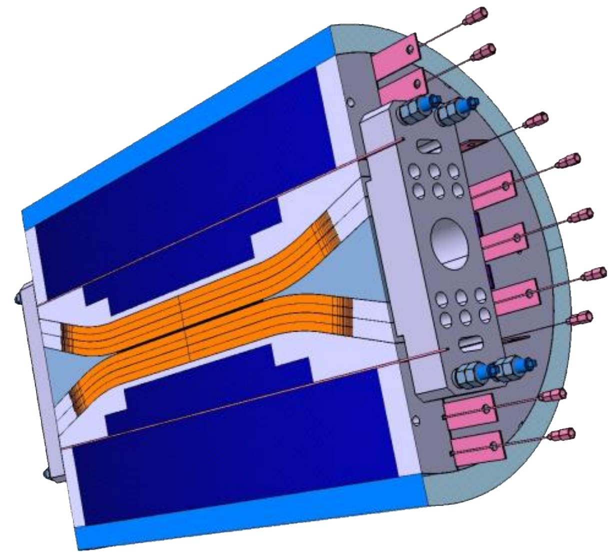
- 156 turns per pole
- Iron post
- B_{center} = 13.0 T
- I_{13T} = 10.7 kA
- B_{peak} = 13.2 T
- E_{mag} = 3.6 MJ/m
- L = 47mH/m

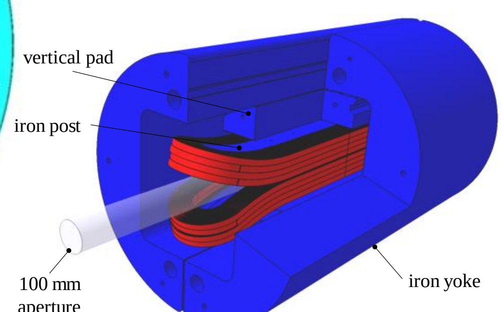
- Diameter Aperture = 100 mm
- L coils = 1.5 m
- L straight section = 700 mm
- L yoke = 1.6 m
- Diameter magnet = 1.03 m

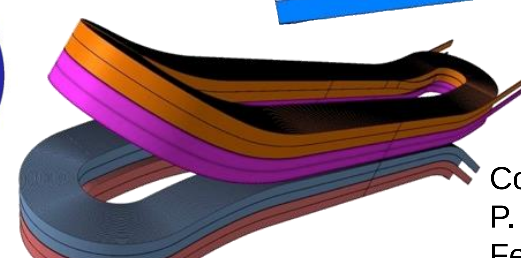












Courtesy: A. Milanese, P. Manil, J-C Perez, P. Ferracin, F. Rondeaux, M. Durante

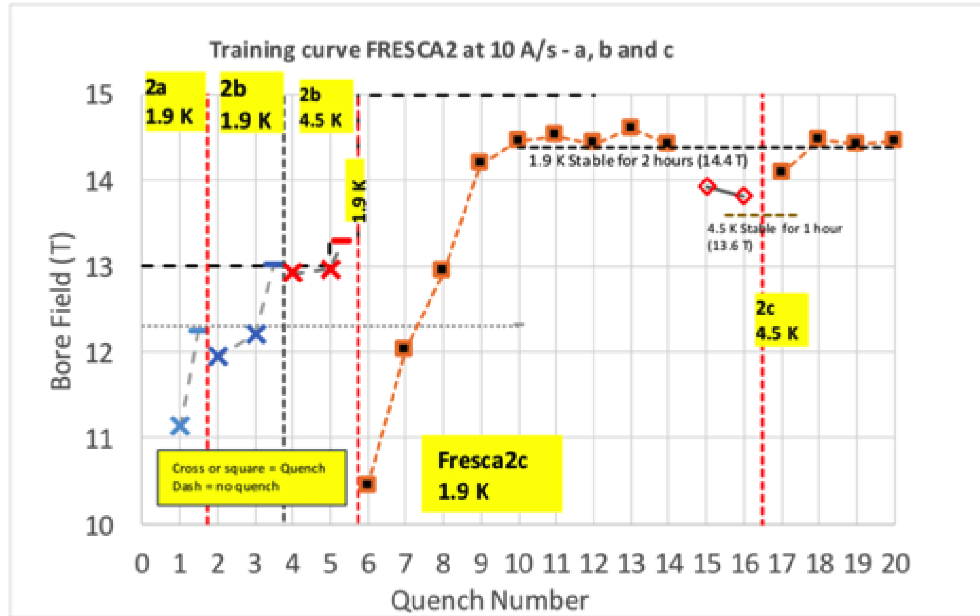
Fabrication of Fresca2

Straightforward technology to wind block coils with flared ends:

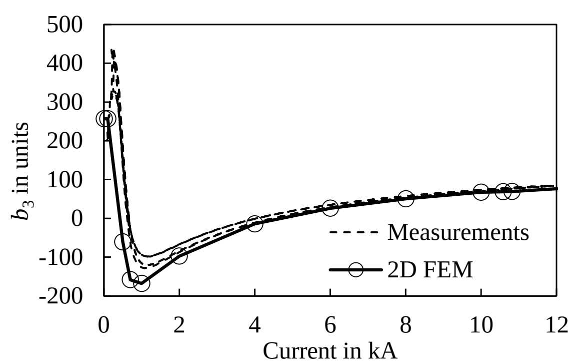
This is a lesson for FCC magnets !

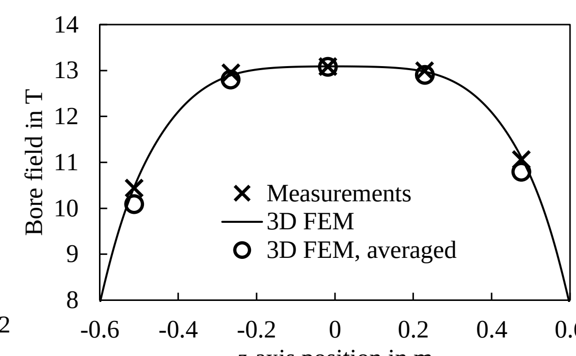
Test of the magnet

- Only short training to 13T@1.9K
- Record field 14.6T at higher pre-stress
- DC ops at 14.4T

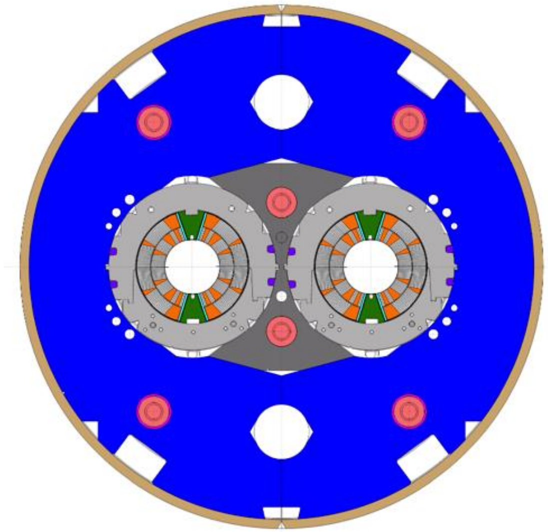


Still some optimisations to do on coil manufacturing: where to slip and where not…





HL-LHC: 11 T Dispersion suppressor magnet



- First Nb3Sn magnet to go into an accelerator (2019) !
- Present model program (CERN and FNAL)
  - demonstrated the required performance (11.25 T at 11850 A) and Achieved accelerator field quality

Nominal Field 11 T

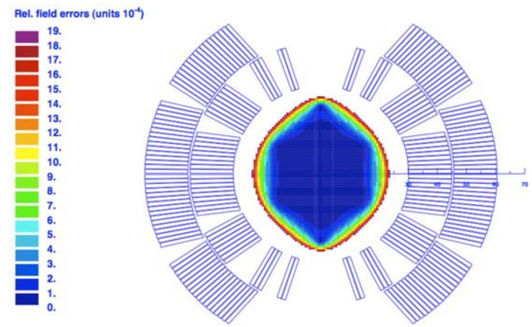
Aperture diameter 60 mm

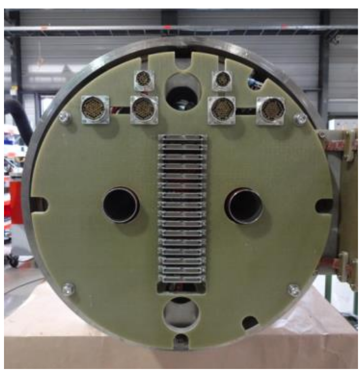
Peak Field 11.35 T

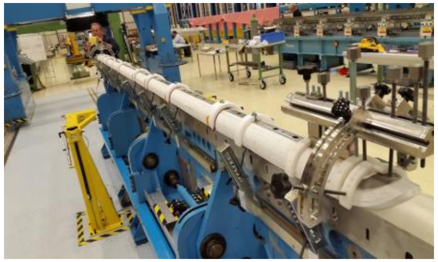
Current 11.85 kA

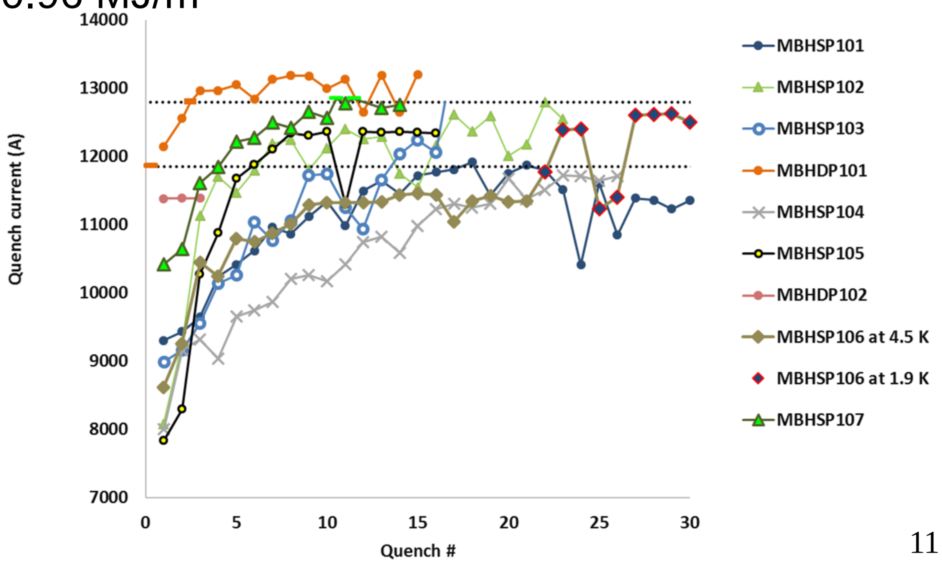
Loadline Margin 19.7% @ 1.9 K

Stored Energy 0.96 MJ/m









Courtesy F. Savary

HL-LHC: MQXF low beta Nb_3Sn quadrupole

Model have good performance, long prototypes are being fabricated

A CERN LARP collaboration.

Nominal Gradient 132.6 T/m

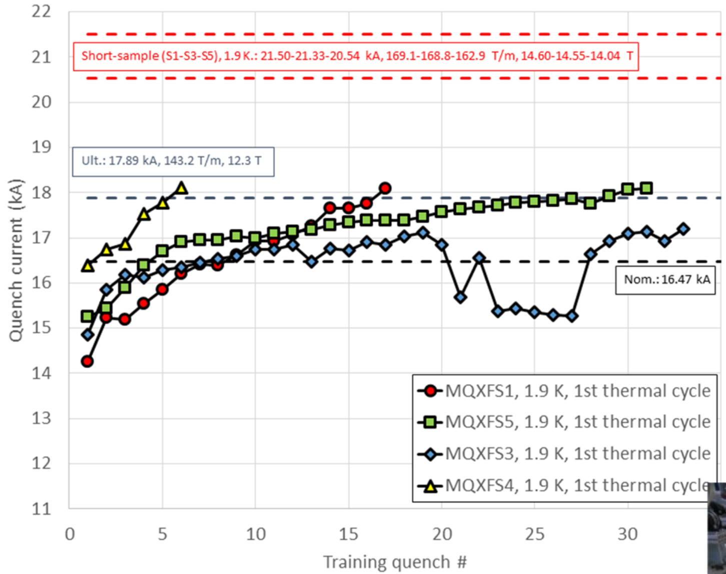
Aperture diameter 150 mm

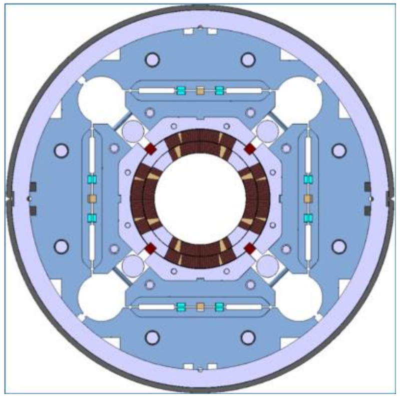
Peak Field 12.1 T

Current 17.5 A

Loadline Margin 20% @ 1.9 K

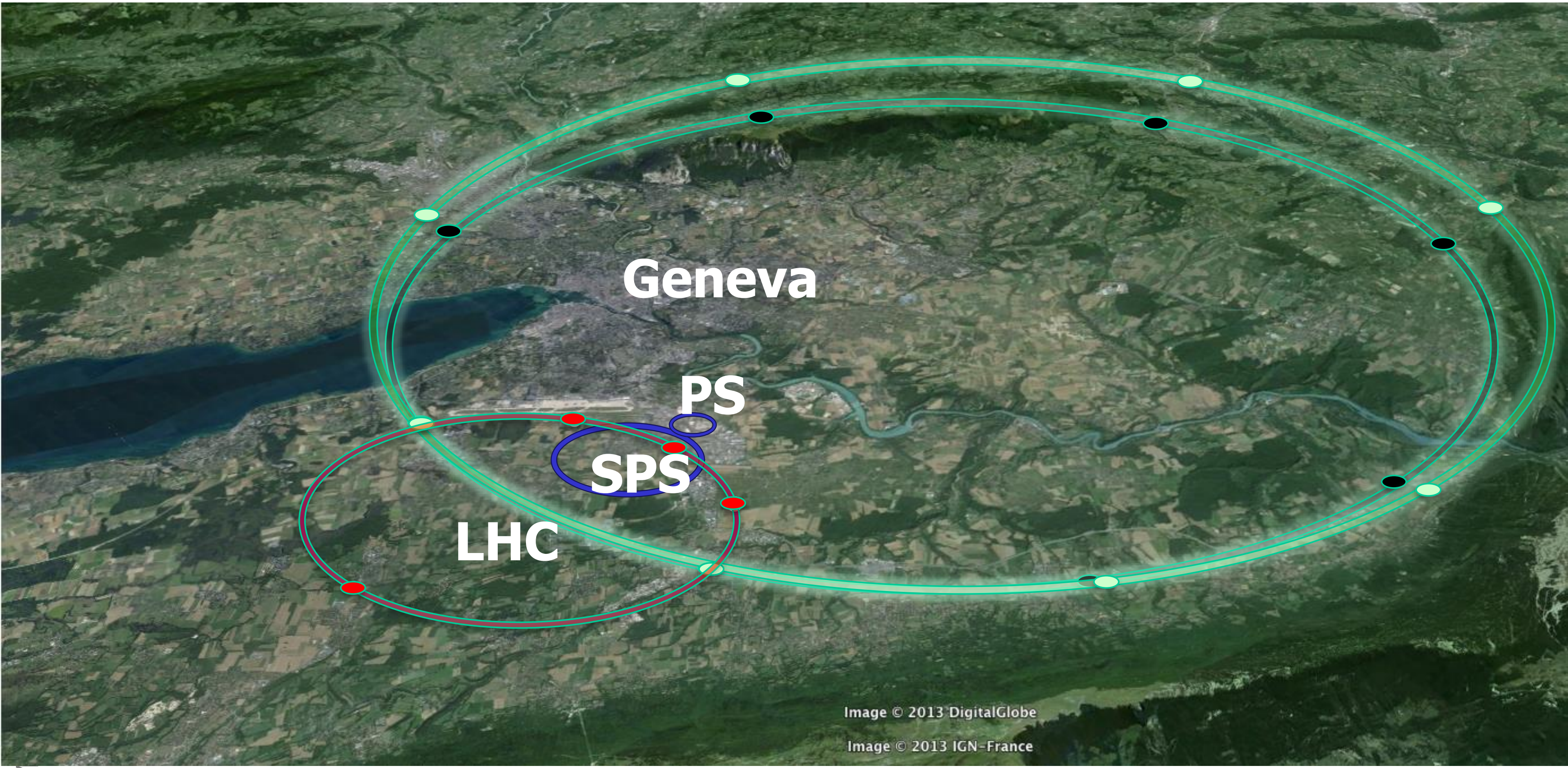
Stored Energy 1.32 MJ/m





Courtesy P. Ferracin

FCC development (2014 - ...)



LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, 20 T	80 km, 20 T	100 km, 16 T
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)

FCC Nb_3Sn performance targets

D_{strand}: 0.5 - 1 mm — Large cables, cabling !

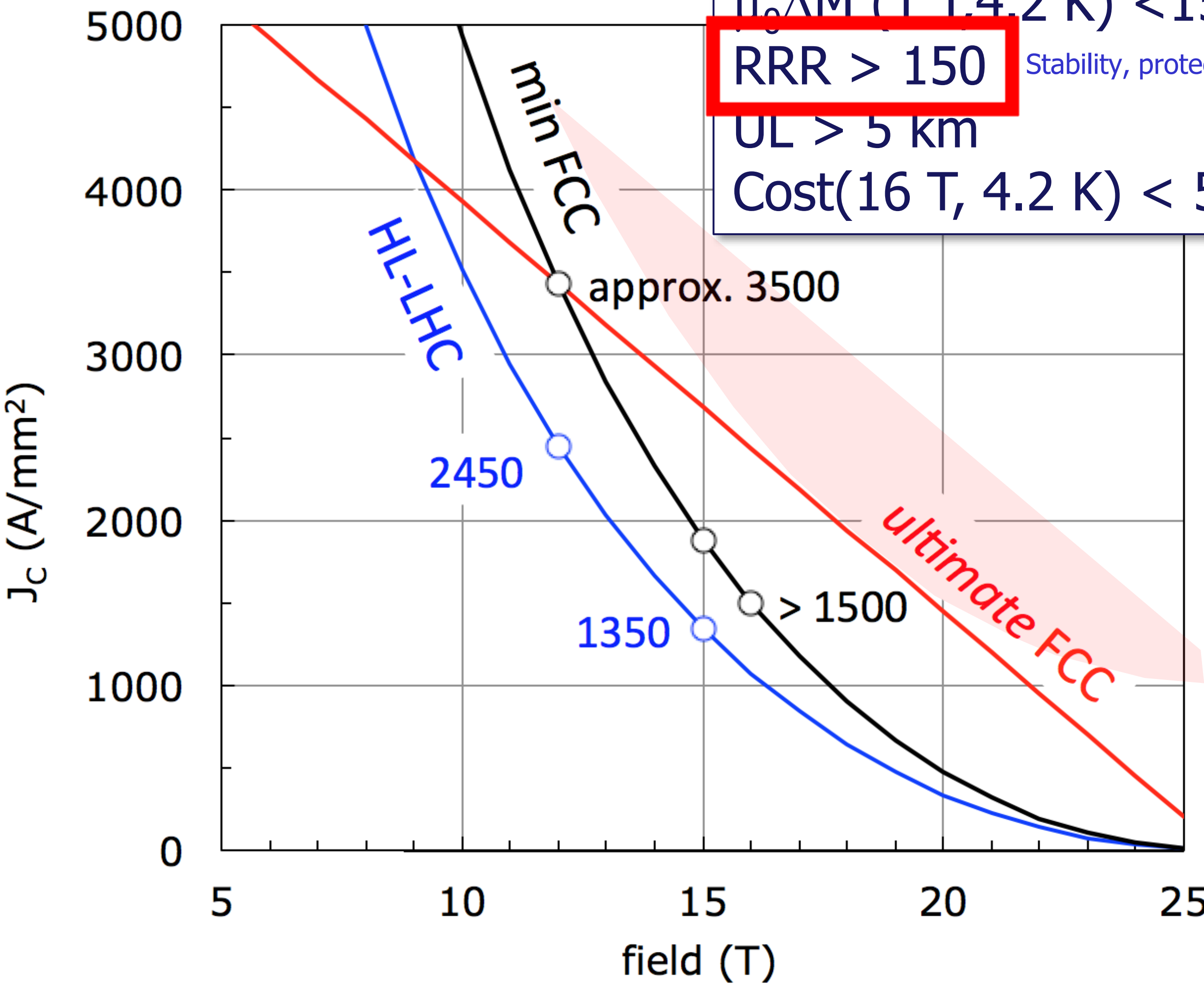
J_C (16 T, 4.2 K) > 1500 A/mm^2

$\mu_0\Delta M$ (1 T, 4.2 K) < 150 mT (D_{fil} < 20 μm) — Field quality

RRR > 150 — Stability, protection

UL > 5 km

Cost(16 T, 4.2 K) < 5 USD/kAm — ITER material cost per kg



All single parameters are in reach, their combination is the challenge !

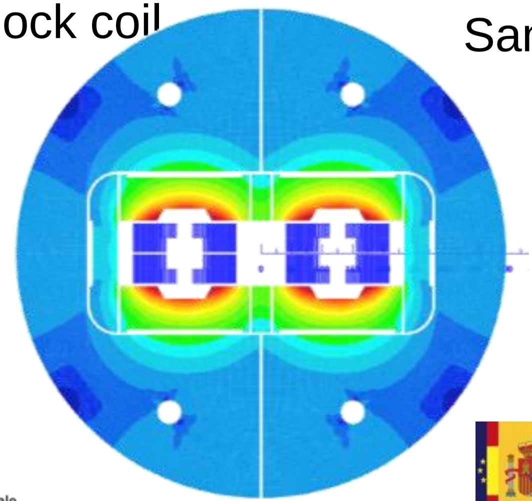
Ultimate Nb_3Sn ? Pursue the idea of improved high field pinning

(D. Dietrich and R. Scanlan, A. Godeke)

FCC: 16T dipole options

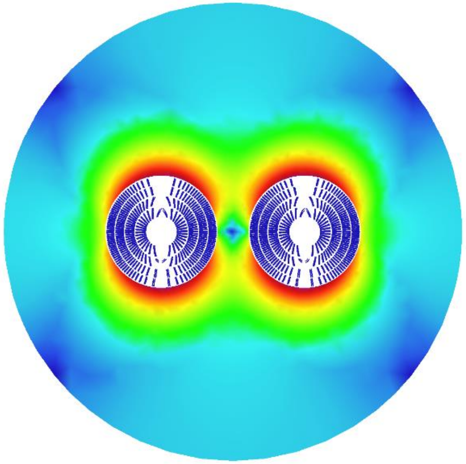
Same specification !

Block coil



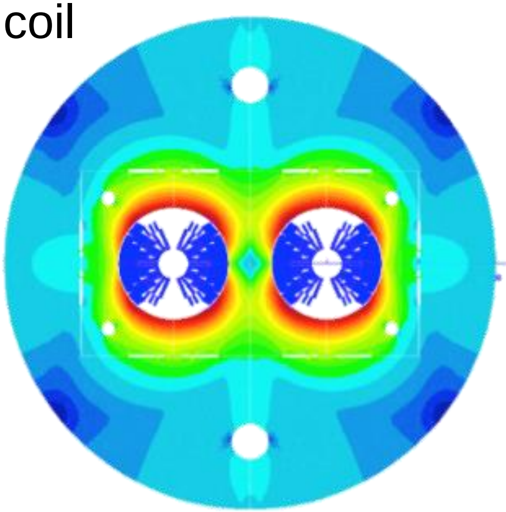
C. Lorin, M. Durante (CEA)

Canted Cos-theta



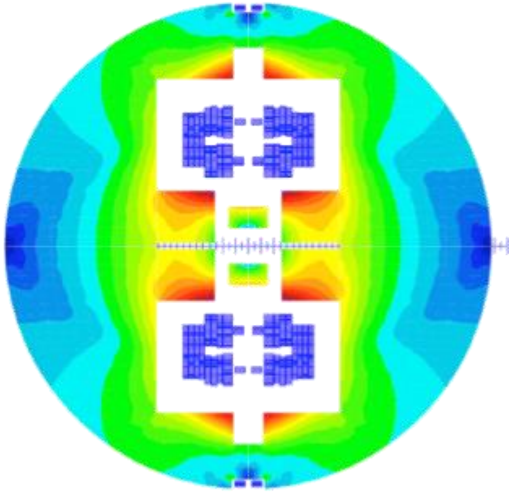
B. Auchmann (CERN/PSI)

Cos-theta coil



S. Farinon, P. Fabbricatore (INFN)

Common coils



F. Toral (CIEMAT)

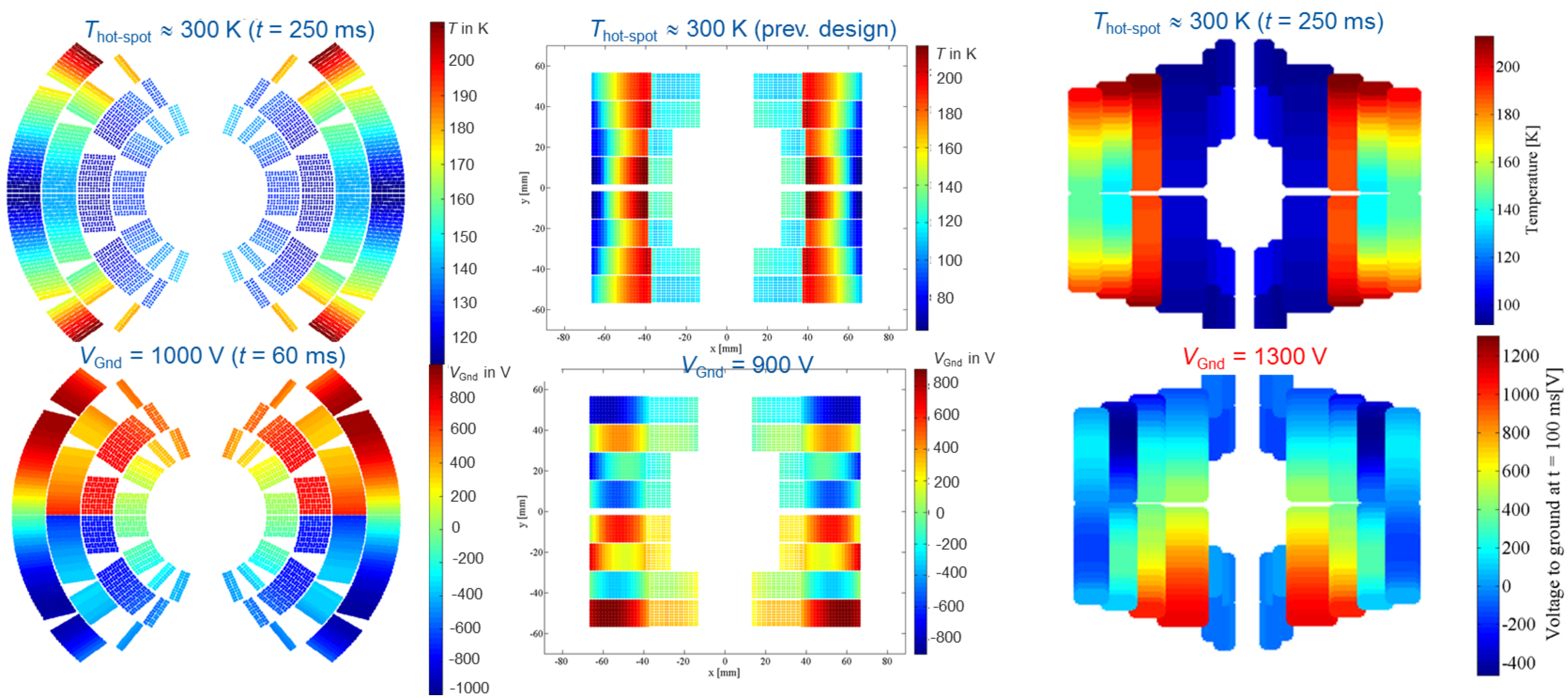
Courtesy: D. Tommasini
D. Schoerling

EuroCirCol – detailed studies, quench

- Quench protection was integrated into the magnet design since an early state, using the same software tools under the same assumptions.

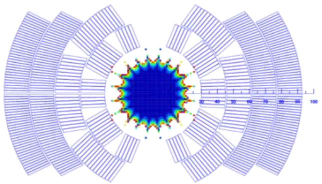
- All designs fulfill the required targets:
  - $T_{hot} < 350$ K at 105 % I_{nom}
  - $V_{max} < 1.2$ kV at 105 % I_{nom}

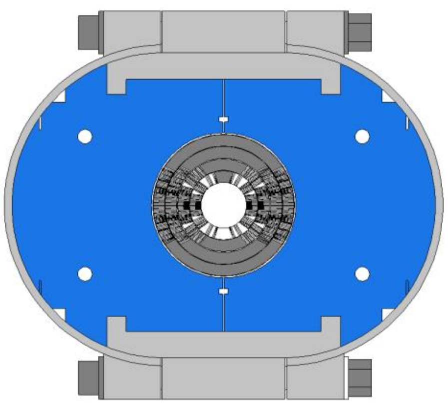
CLIQ has been selected as the baseline protection design.



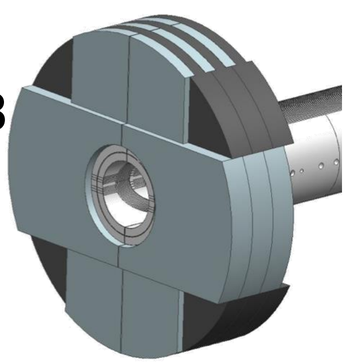
US program lines

cos-θ

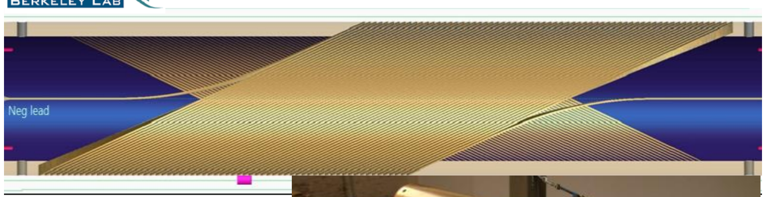




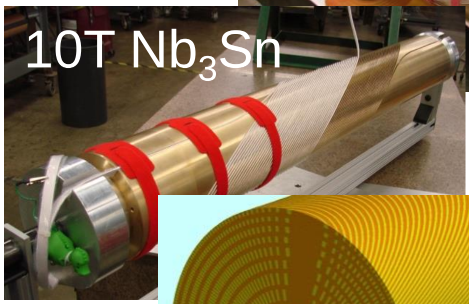
2018



canted-cos-θ

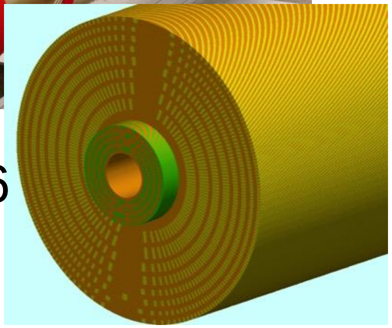


2014-2015

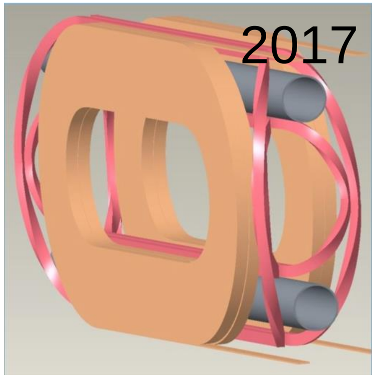


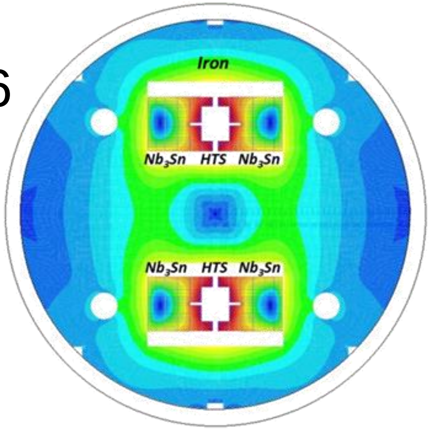
2015-2016

2016



common coils





Nb_3Sn HFM development @ CERN

Hi-Lumi R&D

SMC

OD = 530 mm
L = 500 mm
No Ap.
B_{op}= n.a.
B_{ult} = 14 T

No aperture

RMC

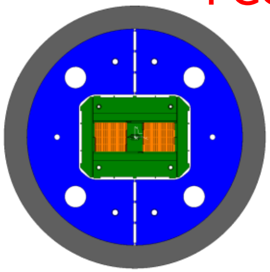
OD = 570 mm
L = 820 mm
No Ap.
B_{op}= n.a.
B_{ult} = 16 T

No aperture

FCC R&D

eRMC

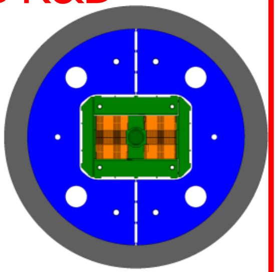
OD = 800 mm
L = 1.2-1.4 m
No Ap.
B_{op}= 16 T
B_{ult} = 18 T



No aperture

RMM

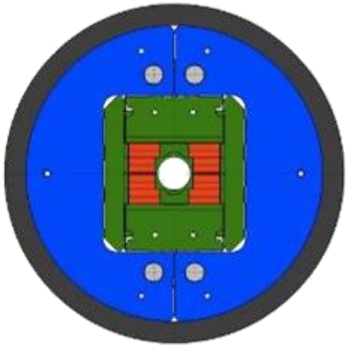
OD = 800 mm
L = 1.2-1.4 m
50 mm closed Ap.
B_{op}= 16 T
B_{ult} = 18 T



cavity

FRESCA2

OD = 1.03 m
L = 1.6 m
100 mm Ap.
B_{op}= 13 T
B_{ult} = 15 T



Large aperture

OD = Outer diameter
L = Magnet length
AP = Aperture
B_{ult}= Ultimate field, defined as the maximum design field for the magnet structure

Courtesy S. Izquierdo, P. Ferracin, J-C. Perez

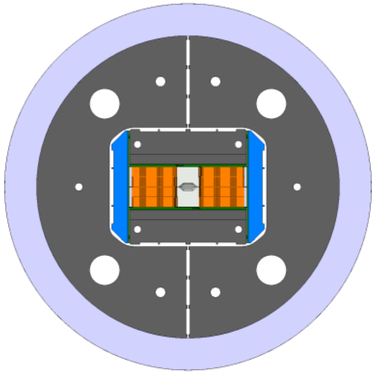
16 T , CERN approach , go in steps

1 Extended Racetrack Model Coil , ERMC

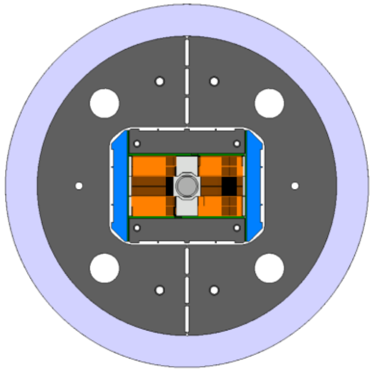
2 Racetrack Model Magnet, RMM

3 Demonstrator, DEMO

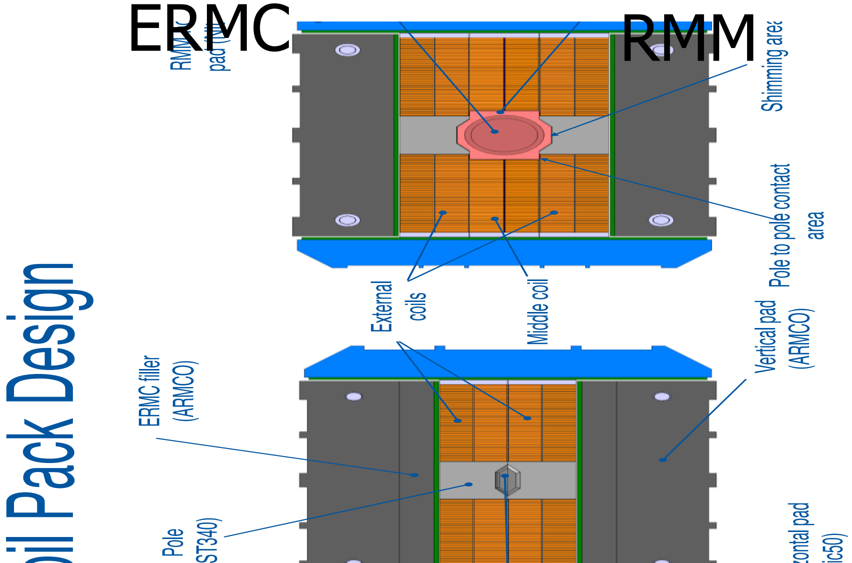
First with one conductor , then with 2 different ones to optimise the coil: Grading

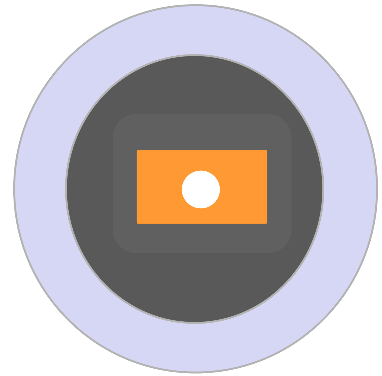


ERMC

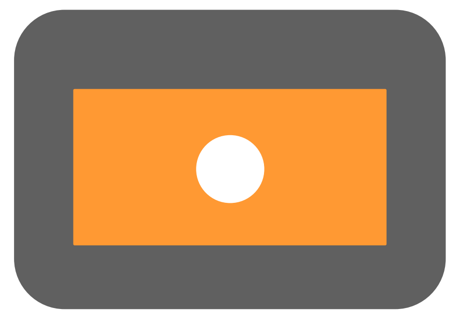


RMM





DEMO



Real aperture
Flared ends

First test ERMC Dec 2018

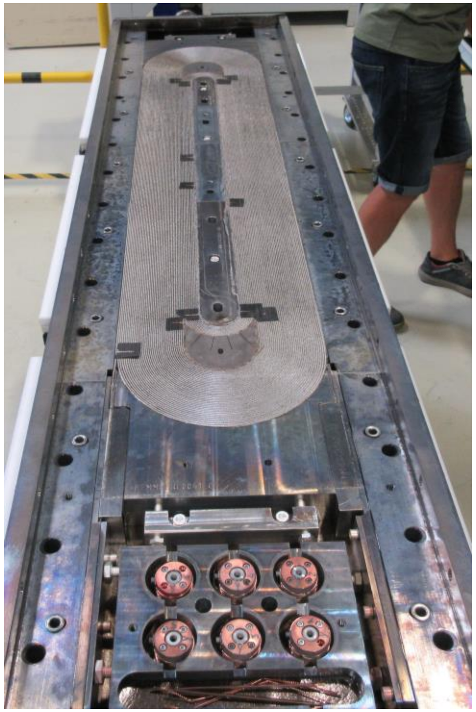
16 T program

- Subjects to be studied (@CERN or with collaborating institutes or industry)
  - Improved conductor (strand)
  - New large cable designs
  - Slip planes, detaching surfaces
  - Different epoxies
  - Insulation: Mica sleeves, glass-fibre socks, etc
  - Grading with internal Nb_3Sn - Nb_3Sn splices
  - Quench protection (CLIC, QH etc)
  - Mechanics
    - Prestress optimisation
    - Stress-strain function “elastic modulus” of coils
  - …

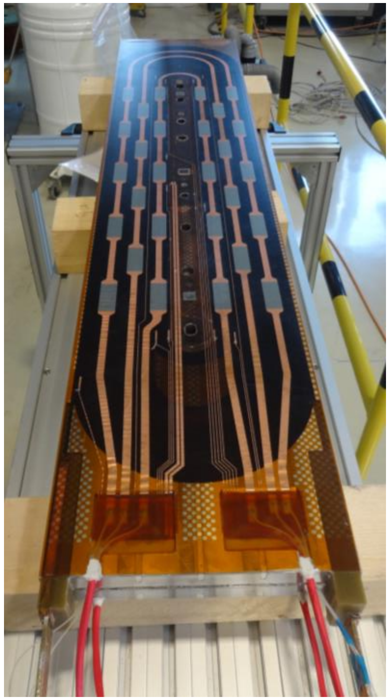
ERMC

winding

Coil before reaction



Coil after reaction

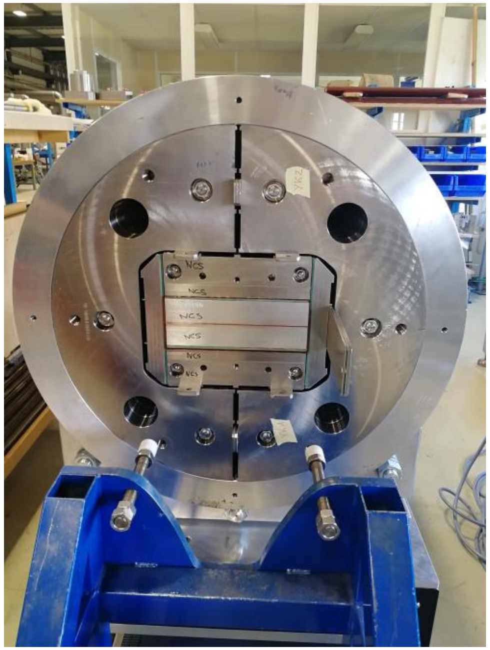


Coil completed

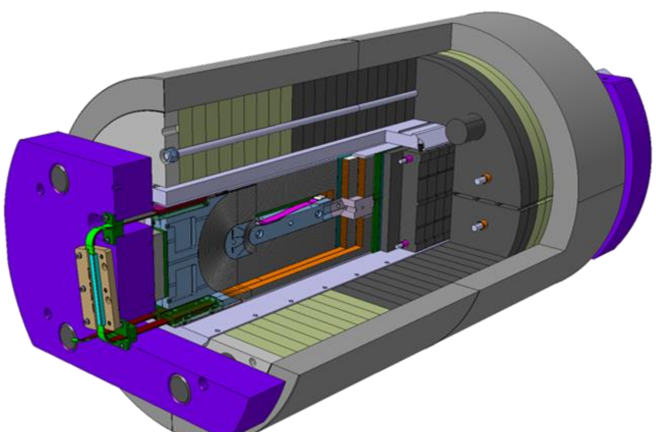
First test ERMC after Dec 2018

Courtesy: S. Izquierdo

ERMC (dummy) assembly



Assembly with dummy coils

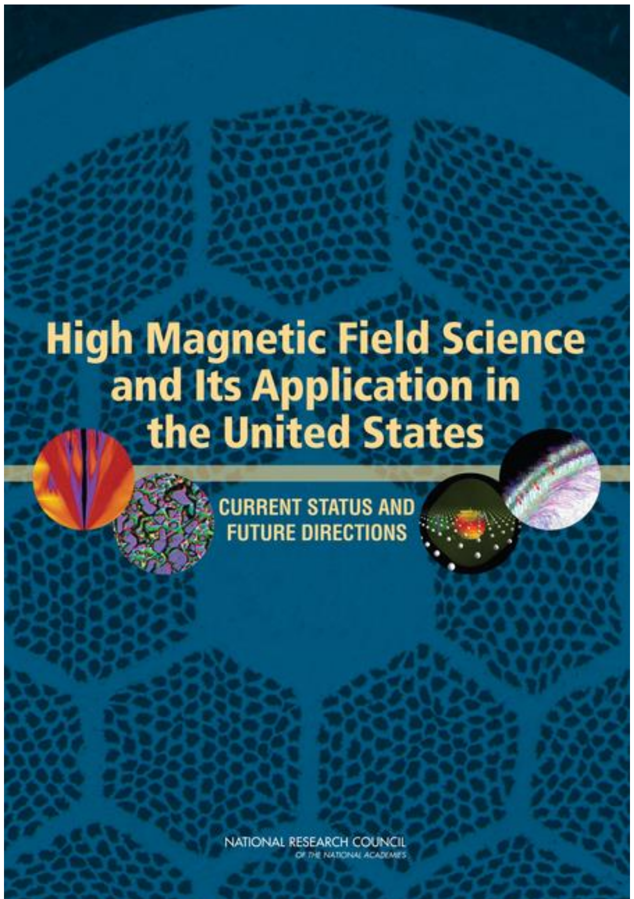


Structure with dummy coils now in SM18 for mechanical validation tests at cold

Courtesy: S. Izquierdo

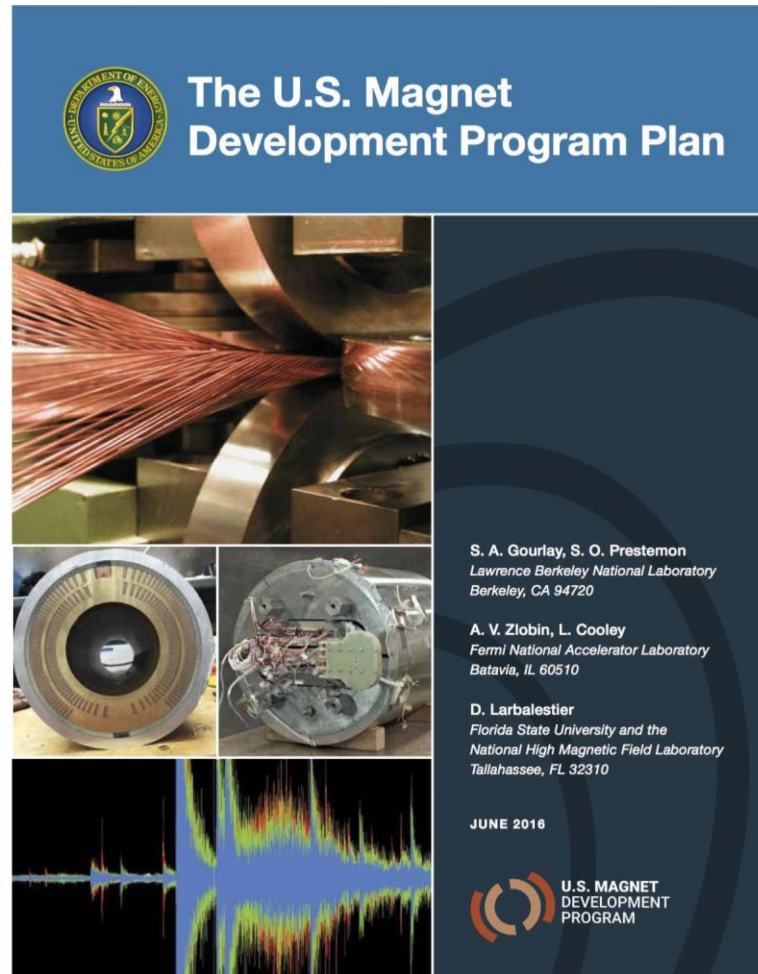
Synergy programs

16 T LTS and 20 T HTS accelerator dipoles and associated technologies



ISBN: 978-0-309-28634-3

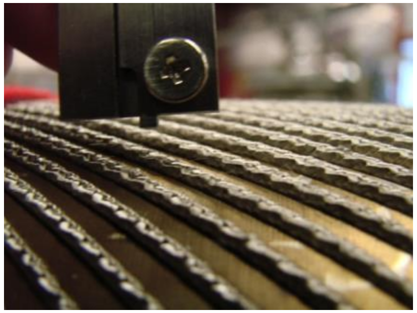
30 T (NMR) to 60 T (user facilities) HTS solenoids

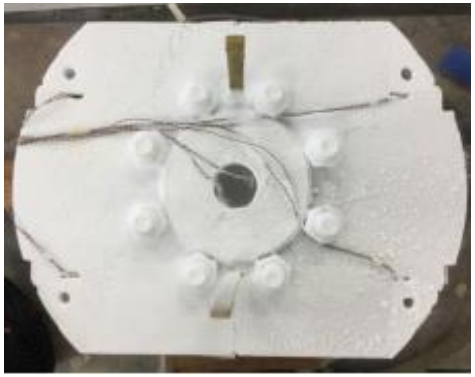


By courtesy of S. Gourlay (LBNL)

US Magnet Development Program

- **CCT technology** and understanding has advanced through the development of two layer models
- Issues with conductor damage have been resolved (CCT 4 reached 9.1 T (86% of SS limit)).
- Next main focus is on training reduction





- Fabrication of a 15 T cos-theta demonstrator on progress.
  - Design and procurement completed.
  - Coil fabrication on-going.
  - Mechanical structure have been tested.
- Design studies for an “utility” structure on-going

HTS program: towards and beyond 20T

Thee main efforts:

- Europe

  CERN HTS program : using ReBCO tape conductor

  Collaborations being formed (eg. with CEA)

- US

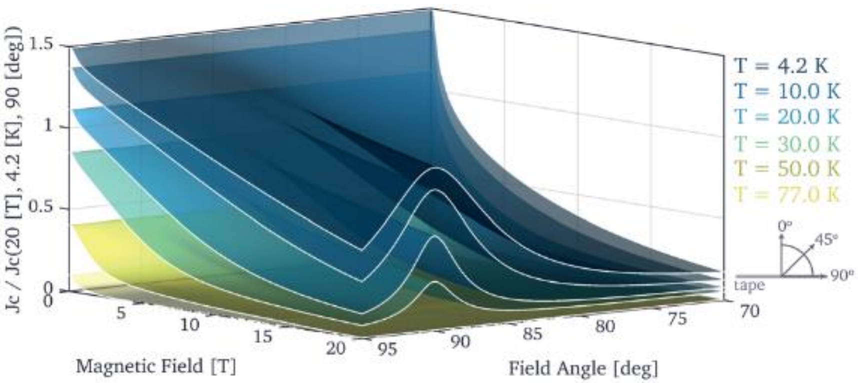
  LBNL program: using Bi2223 round wire in Rutherford cable

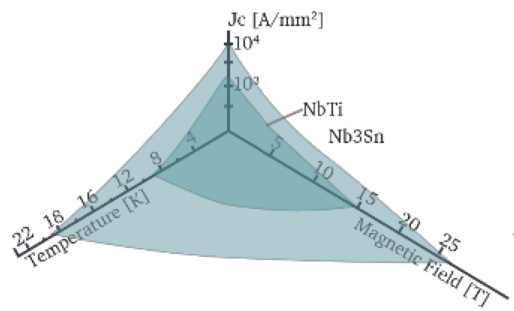
- Asia

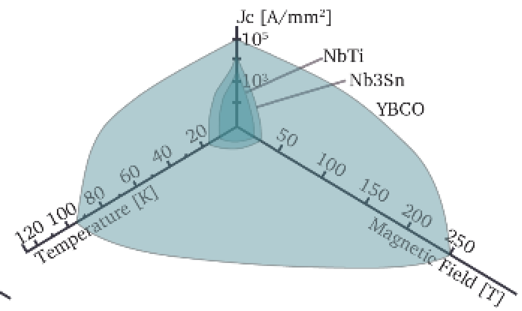
  Chinese SPPC magnet development program using Iron Based Superconductors (IBS) (See: Q. XU, TE-MSC Seminar, CERN, Oct 9 2018)

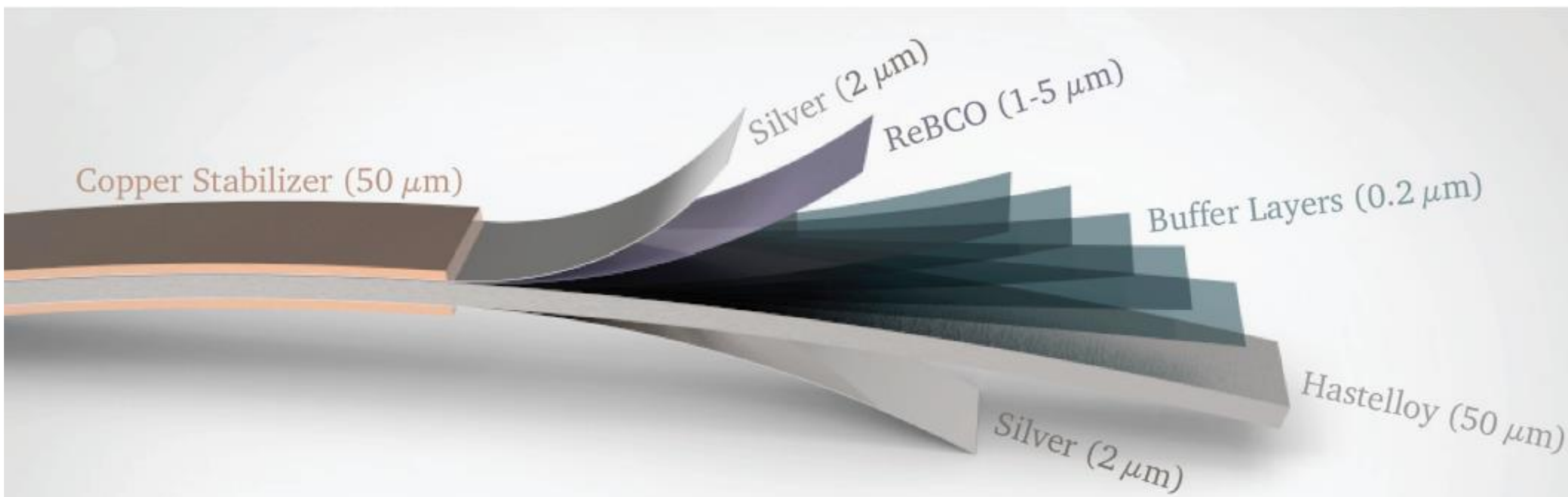
ReBCO Coated Conductor Tape

High Tc (93 K) , High B_c&J_c @ 4.2K, J_c depends on B angle wrt tape







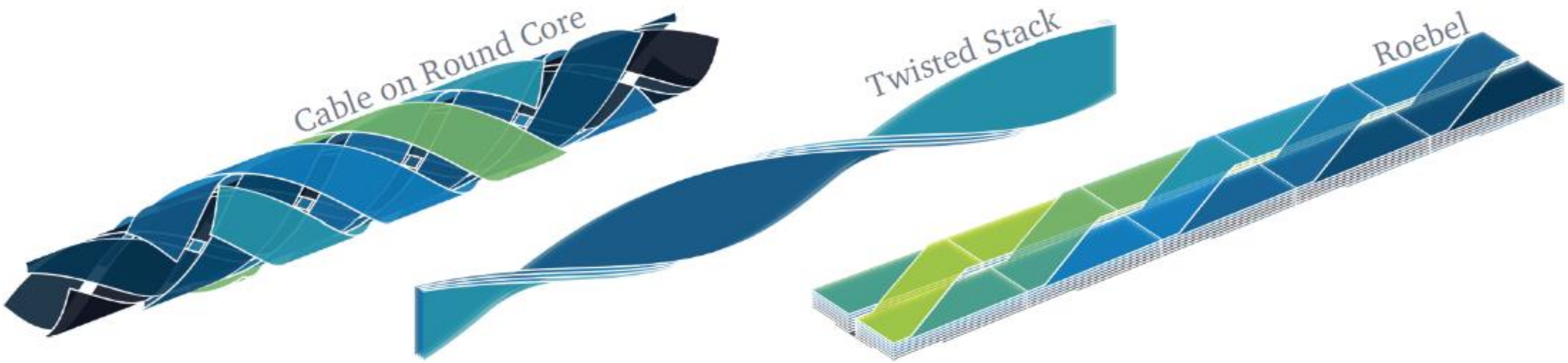


Courtesy J van Nugteren

Substrates:
100, 50, 25 μm

(present) Cable options REBCO

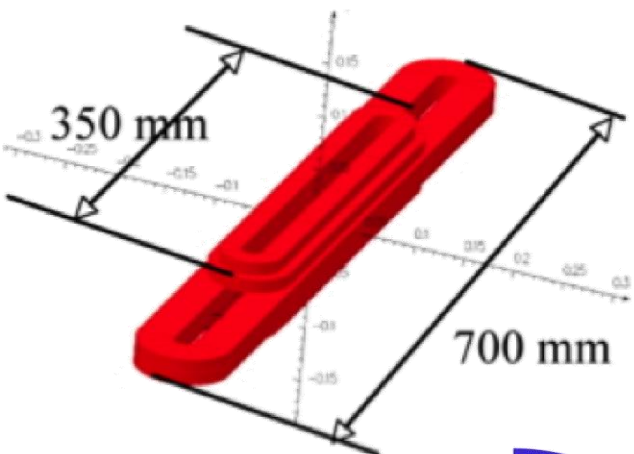
Three cable option exist at the moment:

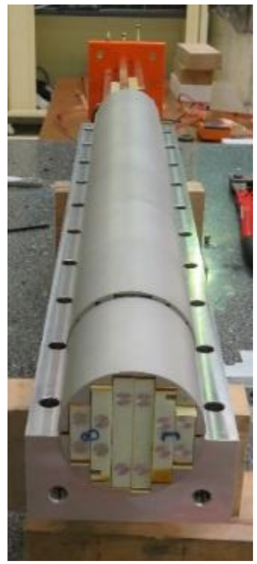


	Stacks	Twisted Stacks (TST)	Helically Twisted Stacks (HTST)	Conductor on Round Core (CORC)	Roebel
J_E (A/mm^2)	*1000*	**400**(@16 T)	**100** (@12 T)	**360** (@ 17 T)	**1000** (@ 20T)
I_{OP} (kA)	*3…5*	**4** (@19 T)	*10…20*	**7** (@ 17 T)	**10** (@ 10T)
ε (%)	as for tape	unknown	unknown	+0.6…0.7	unknown
σ (MPa)	as for tape	unknown	unknown	**> 300**	**> 400?(*)**

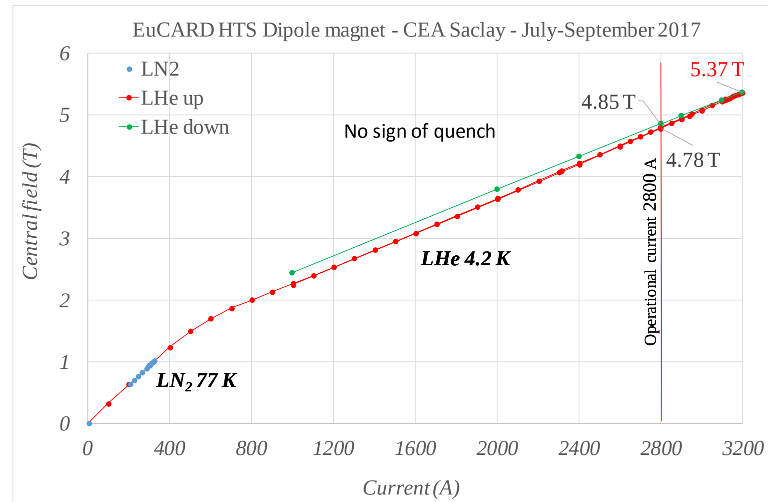
HTS: First attempt towards 20 T

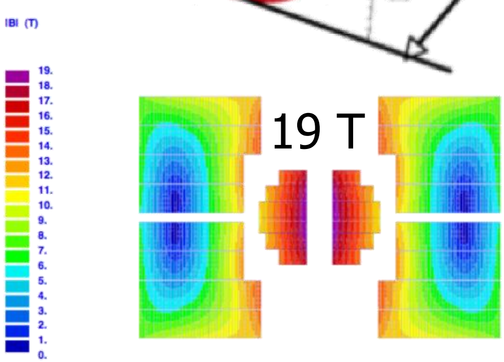
6 T HTS (YBCO) insert for test in Fresca2 , to get to 19 T
But without bore

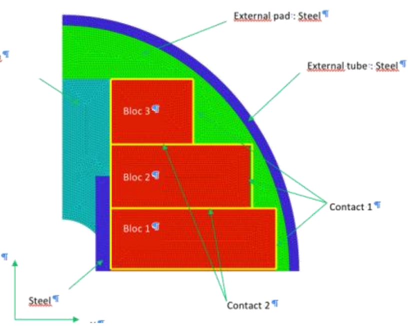


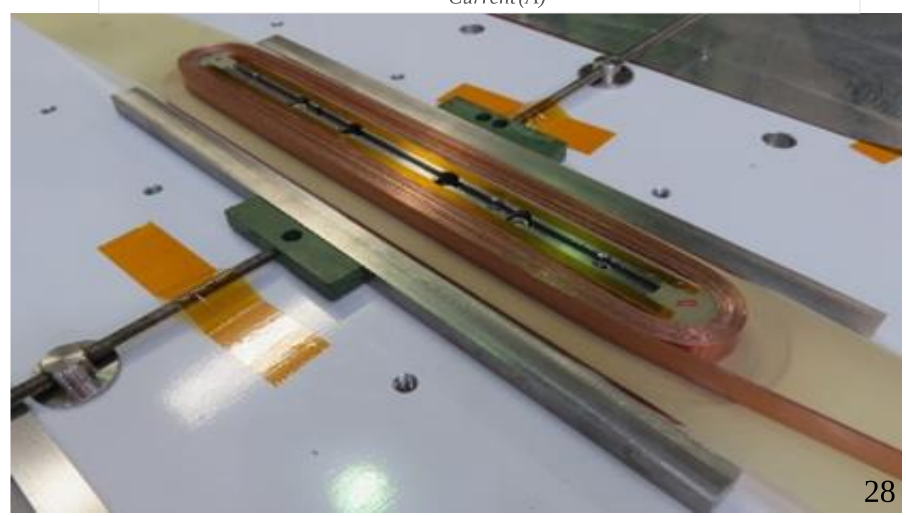


Stand alone tested Sept 2017:
Reached 5.37 T @ 4.2K (I=3200A)
Next test mid 2019 inside Fresca2







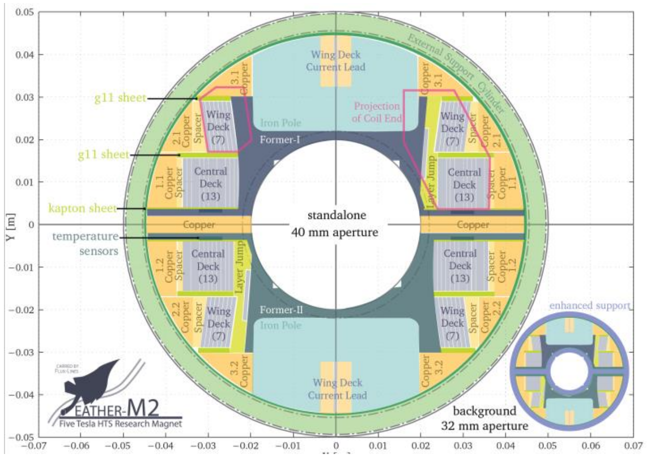


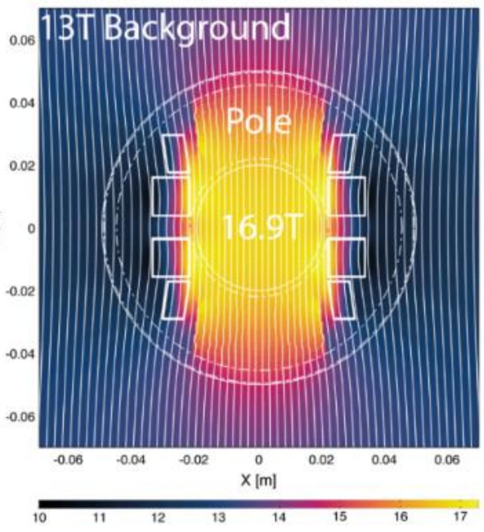
CEA + CRNS Grenoble

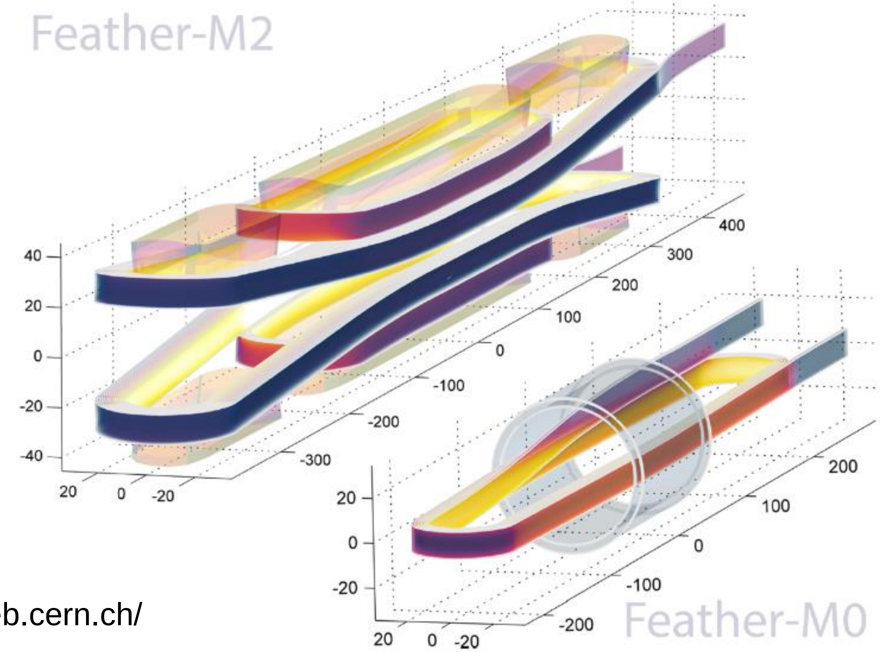
J.M. Rey, F. Borgnolutti, M. Durante, CEA-Saclay

EuCARD2 5T accelerator quality ReBCO magnet

5 Tesla stand alone, (18 T in 13 T background), @ 4.5K,
40 mm aperture, 10 kA class cable, Accelerator Field quality

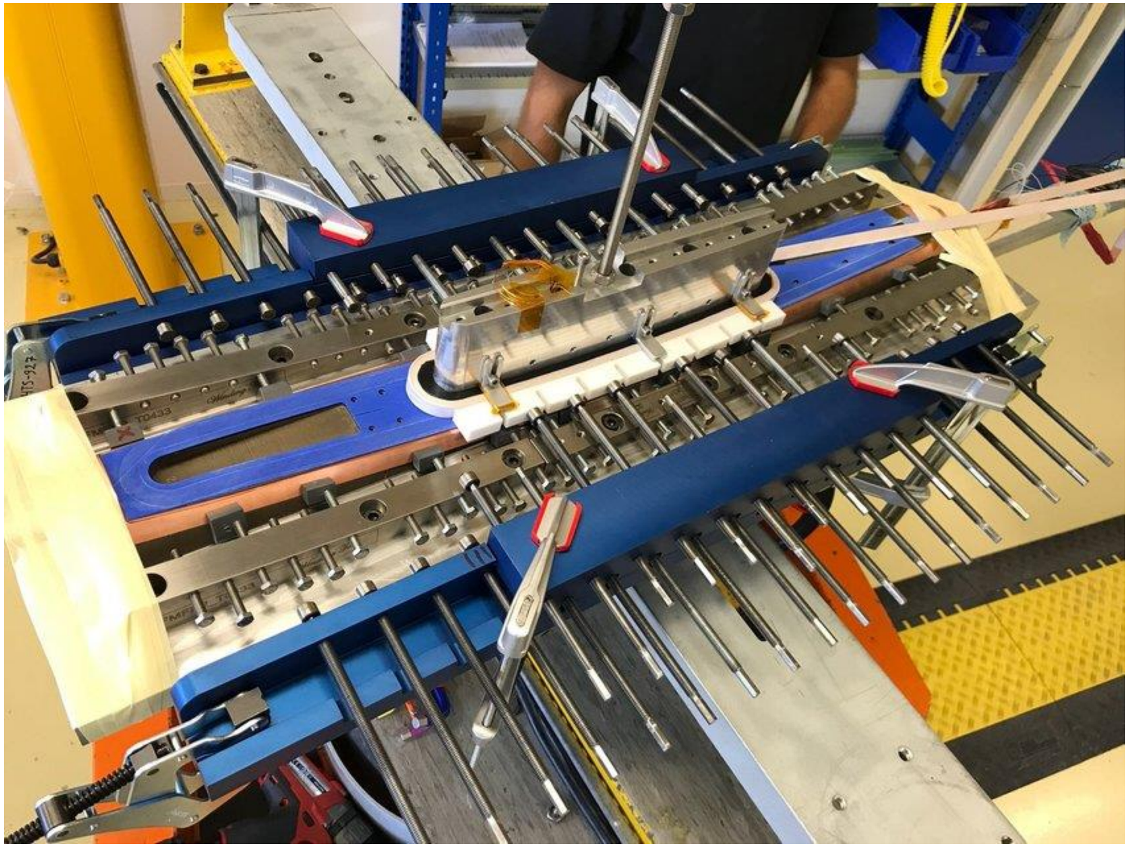






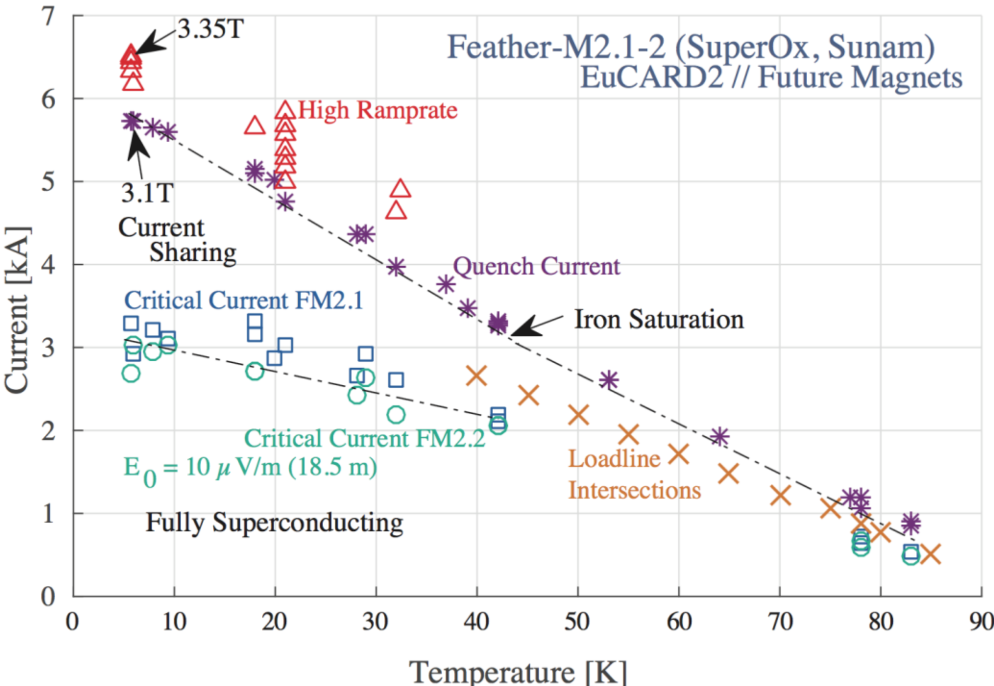
http://eucard2.web.cern.ch/

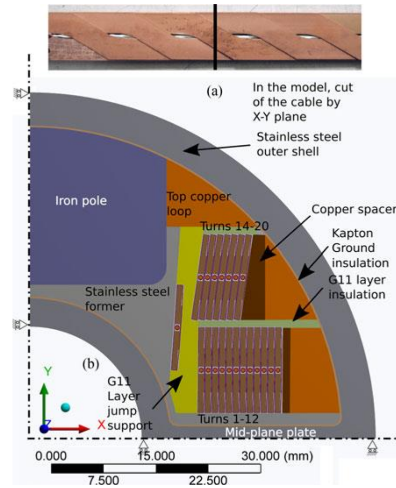
Feather2 Magnet assembly

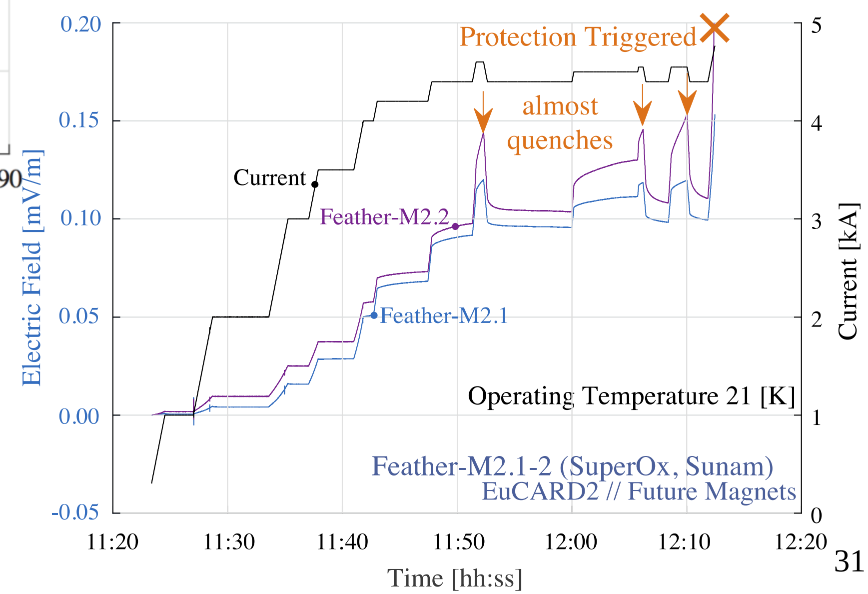


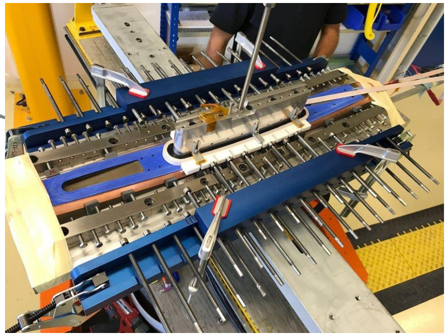
Feather-M2.0 test results

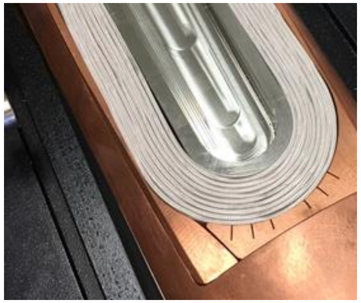
HTS magnets work differently than LTS magnets due to a larger enthalpy margin.











CERN 20T program

Program aiming at a 20T model by 2023-ish

- Build up on experience with the Feather models
- Define other intermediate steps based on what we experience

20T

- Start from basics
- Build up models also taking care of the conductor availability
- Be open to all types of cables

Spread the technology

- Participate, take initiatives for other magnet types
  - Novel gantry design
  - ASI space spectrometer
  - Compaclight wiggler

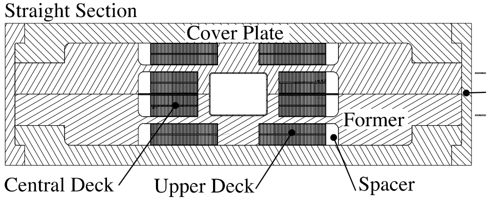
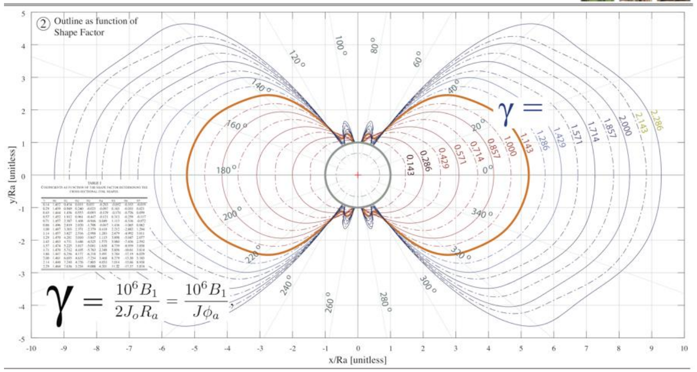


Fig. 8. Conceptual cross-sectional mechanical desi
to coil layout 5 in Table I).



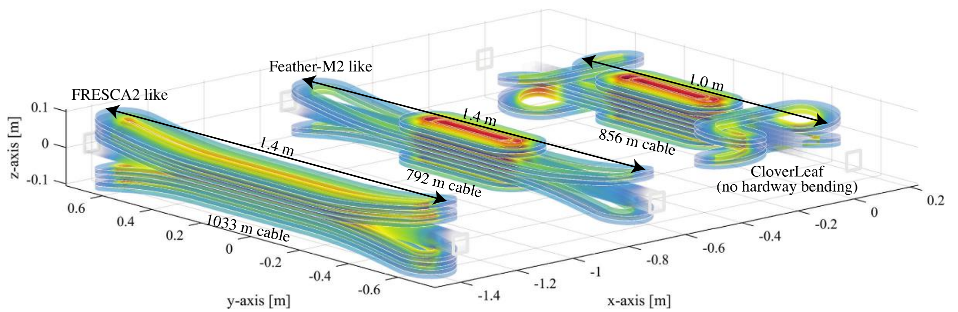


Fig. 10. Illustration showing the three-dimensional coil layouts with the three different coil-end types that are considered. The cross-section of these coils correspond exactly to coil layout 5 in Table I.

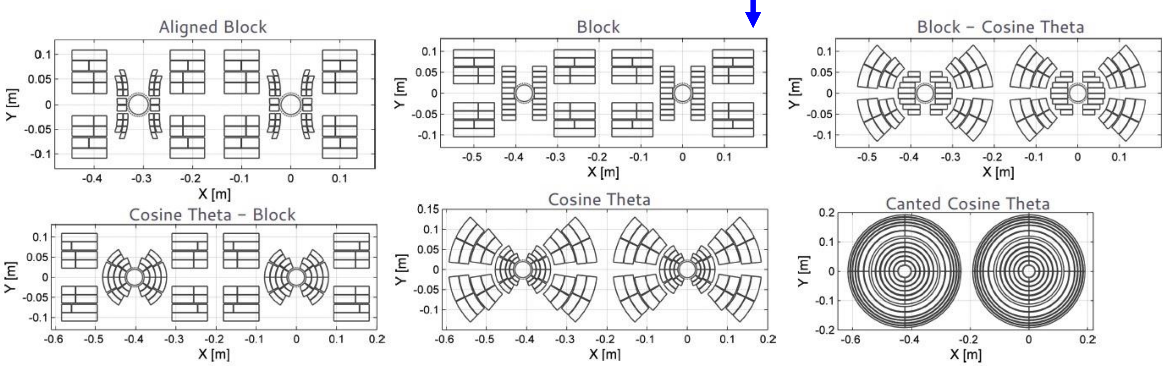
Courtesy J. van Nugteren, G. Kirby

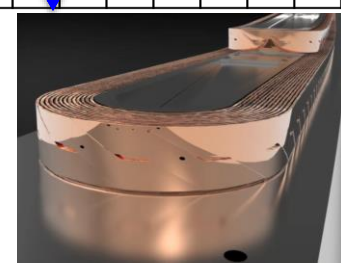
CERN HTS program plan (planning phase)

Twisted stack | CORC | Roebel | "DOCO"

?

Activity	Begin	End	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
HTS Conductor Development	01.01.2017	31.12.2021												
Conceptual design 20T dipole model	01.01.2017	30.06.2019												
Design 20T dipole model	01.06.2019	30.06.2021												
EuCARD/EuCARD2 demonstrators	01.01.2015	31.07.2018												
Subscale HTS models	01.06.2017	31.12.2021												
Construction 20T dipole model	01.06.2021	30.06.2024												





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Conclusions

- Over the last 15 years we went from the 8T (LHC) to the 12T (HL-LHC) domain
- The next challenge is 16T with Nb_3Sn
- Meanwhile we shoot far ahead with HTS on the +20T scale
- The effort runs on 3 continents in “collaborative competion”

Lots of fun ahead !

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