High Field Magnet programs for Future Hadron Colliders

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CERN
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- Future collider field requirements and the state of the art
- Very short intro on superconductors and SC magnets
- The early High Field Magnet epoch (1986-2004)
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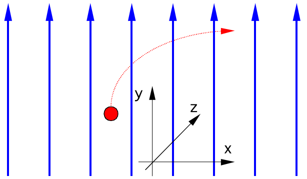
- Basic magnet technology development for HILUMI and beyond (2004-2013)
- The HILUMI magnet development (2013-2016)
- CERN driven FCC magnet development (2014 - ...)
- US magnet development plan
- Chinese magnet development program

Magnets for Accelerators

- Dipoles



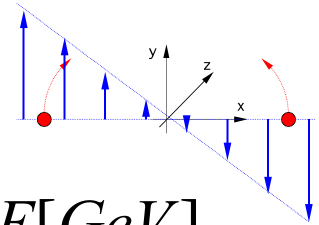
Beam energy **Bending radius**

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

Dipole field

  - Design for B field which is the highest feasible and economic, to reduce the bending radius and maximize the beam energy (NB. bending radius LHC = 2803.95m)

- Quadrupoles



Beam *size* **Emittance** **Lorentz factor**

$$\sigma = \sqrt{\frac{\beta\varepsilon}{\gamma}}$$

FODO cell length **Beta function**

$$\beta[m] \approx 3.4L[m]$$

Integrated quadrupole gradient

$$G\ell_q[T] = \frac{\sqrt{2}E[GeV]}{0.3L[m]}$$

  - Design for the largest feasible integrated gradient to reduce the magnet bore size, and largest feasible gradient to increase the dipole filling factor

Future collider dipole field requirements: FCC-hh

FCC-hh

A. E_{cm}=100 TeV , 100 km ring: B = 16 T Project Baseline

B. E_{cm}=100 TeV , 80 km ring: B = 20 T

What would this mean in the LHC ring for a potential HE-LHC ?

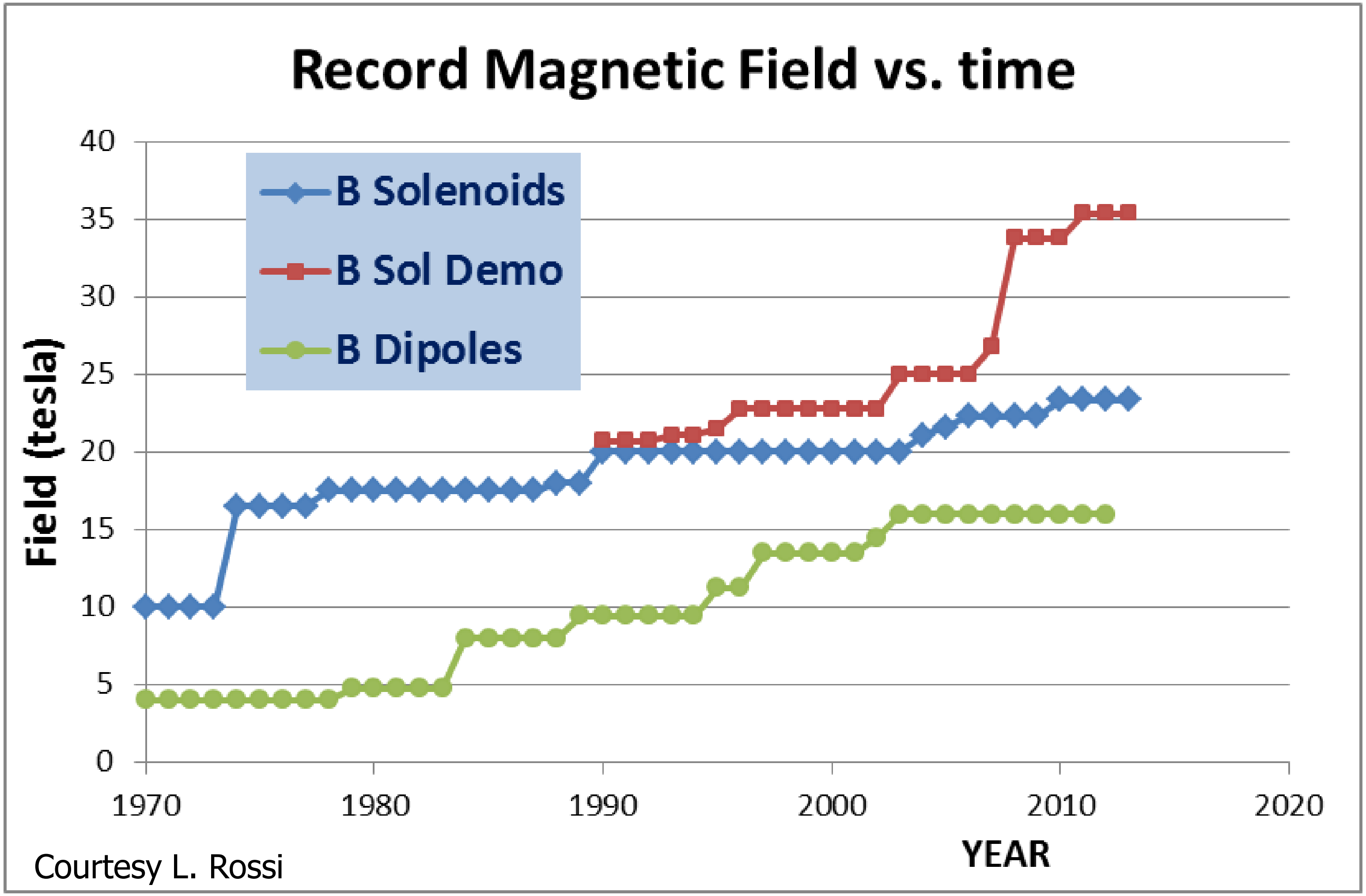
A. E_{cm}=25 TeV , 27 km ring: B = 16 T

B. E_{cm}=33 TeV , 27 km ring: B = 20 T

➔ Work towards 16 T in a first step and 20 T in a second step

The state of the art:
Comparison between dipoles and solenoids

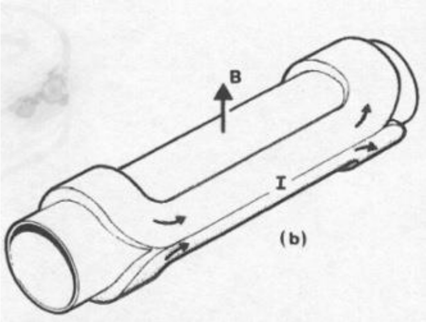
We can see roughly a factor 2 due to Coil «efficiency» and to force-stress management



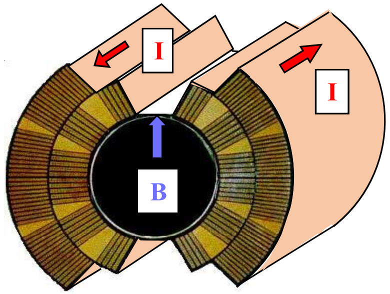
Courtesy L. Rossi

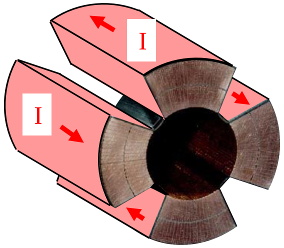
What is specific about accelerator magnets ?

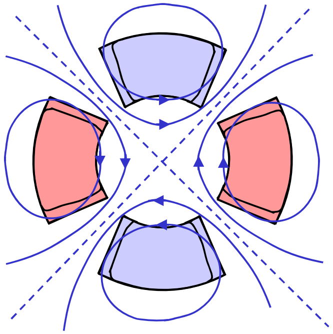
- Cylindrical volume with perpendicular field
- Dipoles, quadrupoles, etc



Artist view of a dipole, from M. N. Wilson « Superconducting Magnets »

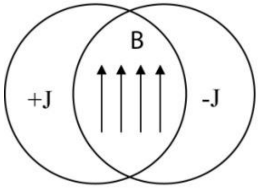






- Field quality: $\frac{\Delta B_z}{|B|} \le few \cdot 10^{-4}$

CosΘ coil : $J = J_0 \cos\Theta$



- Field quality formulated and measured in a multipole expansion,

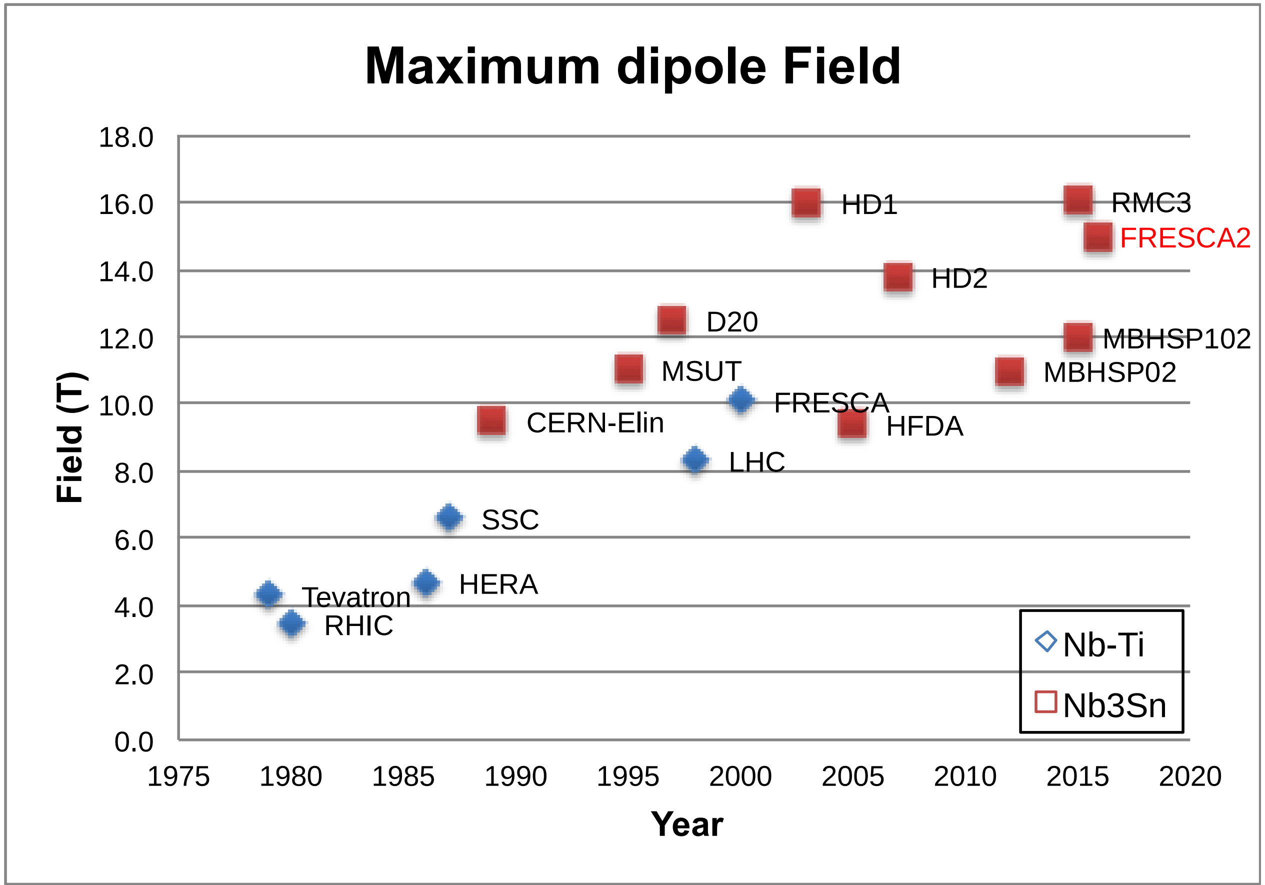
$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + i a_n) \left(\frac{x + iy}{R_{ref}} \right)^{n-1}$$

$$b_n, a_n \le few \cdot units$$

- Long magnets: dipoles from 6 m (Tevatron) to 15 m (LHC)
- Often magnets are bent (9.14 mm sagitta for the LHC dipoles)

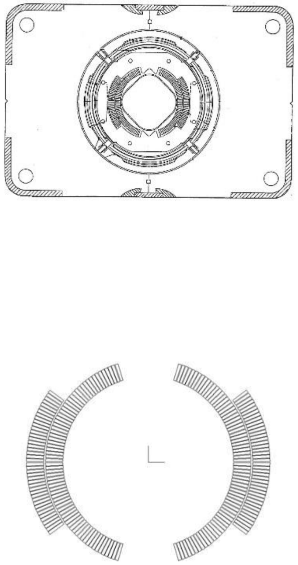
High Field accelerators magnets, the state of the art

- 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



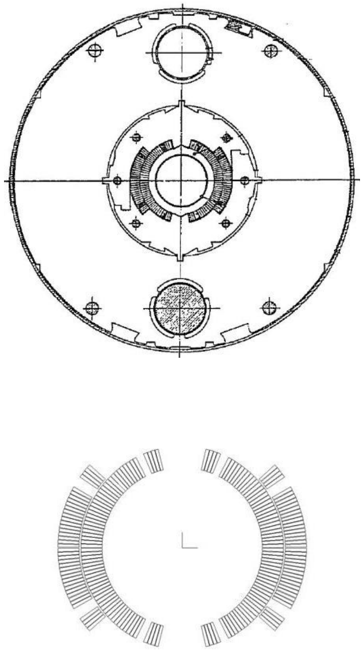
NB. HFM is a imprecisely defined term: It is mostly used to indicate magnets at a field level we do not yet have

Superconducting dipoles, used in real accelerators



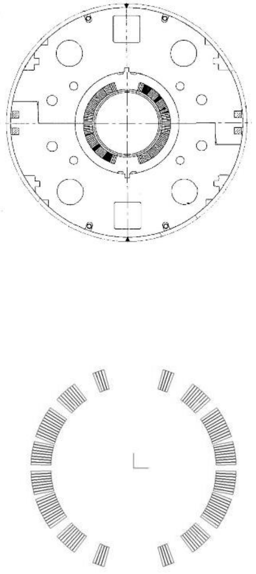
Tevatron

76 mm bore
B = 4.4 T
T = 4.2 K
first beam 1983



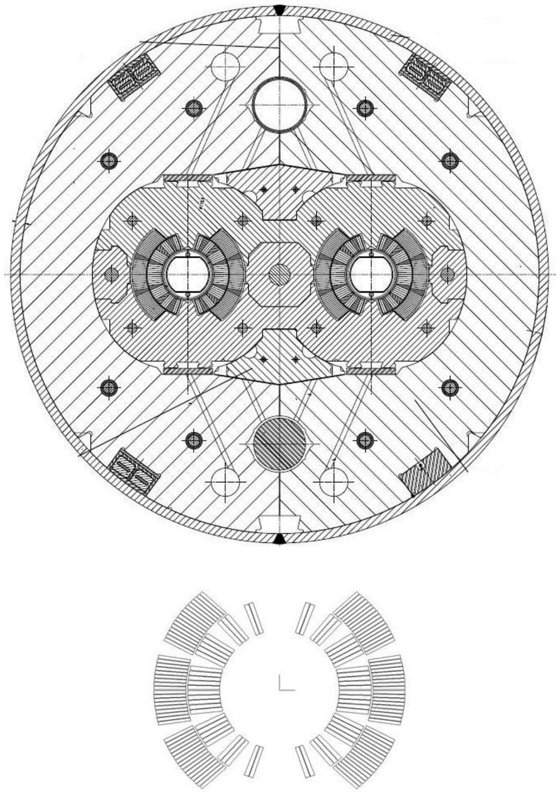
HERA

75 mm bore
B = 5.0 T
T = 4.5 K
first beam 1991



RHIC

80 mm bore
B = 3.5 T
T = 4.3-4.6 K
first beam 2000



LHC

56 mm bore
B = 8.34 T
T = 1.9 K
first beam 2008

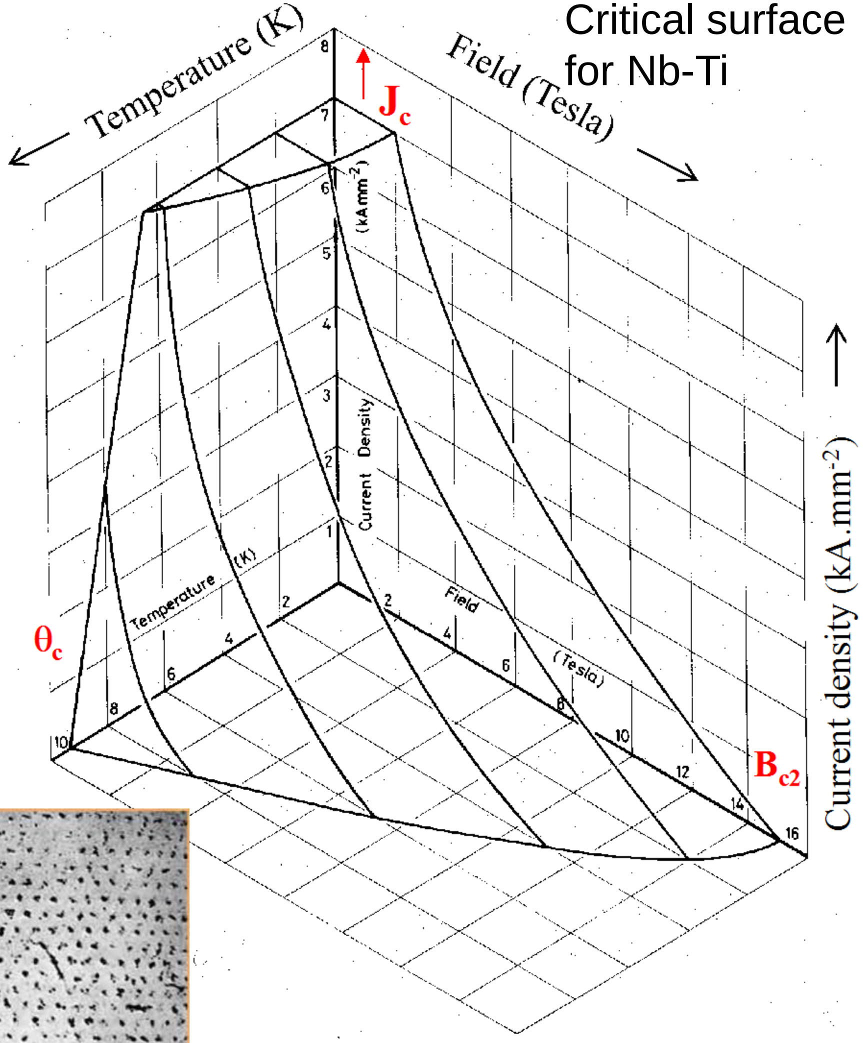
Courtesy P. Ferracin, CERN

Type II Superconductors

Below a the critical surface the material is “superconducting”. Above the surface it is “normal conducting”

- Θ_c Critical Temperature (at zero field and current density)
- B_{c2} Critical Field (at zero temperature and current density)
- J_c Critical Current Density (at zero temperature and field)

The Critical surface depends on the material type Nb-Ti, Nb_3Sn, etc) and the processing



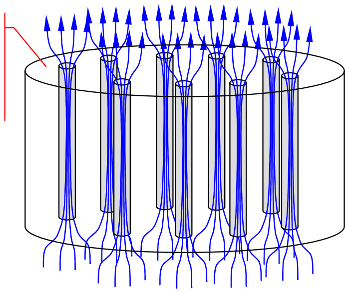
Critical surface for Nb-Ti

Courtesy M. Wilson

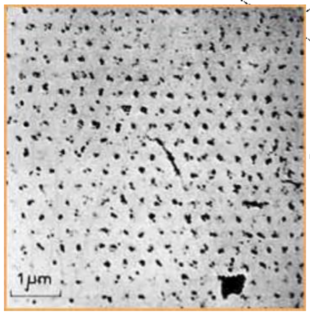
Superconducting means: R = 0

J: few x 10^3 A/mm^2 inside the superconductor

Type II (κ ☢📂✍📠📄☎)



Courtesy L. Bottura



Quantized fluxoids in a superconductor

Available Superconductors

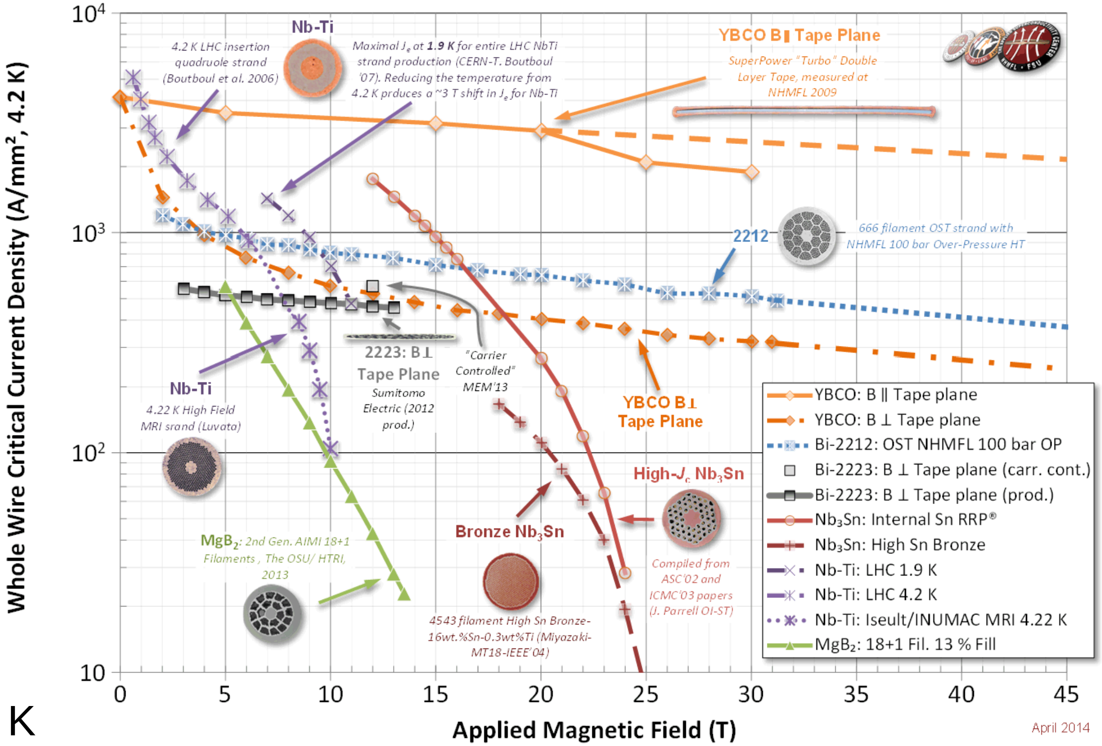
Nb-Ti: the workhorse for 4 to 10 T

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



April 2014

Nb$_3$Sn: 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

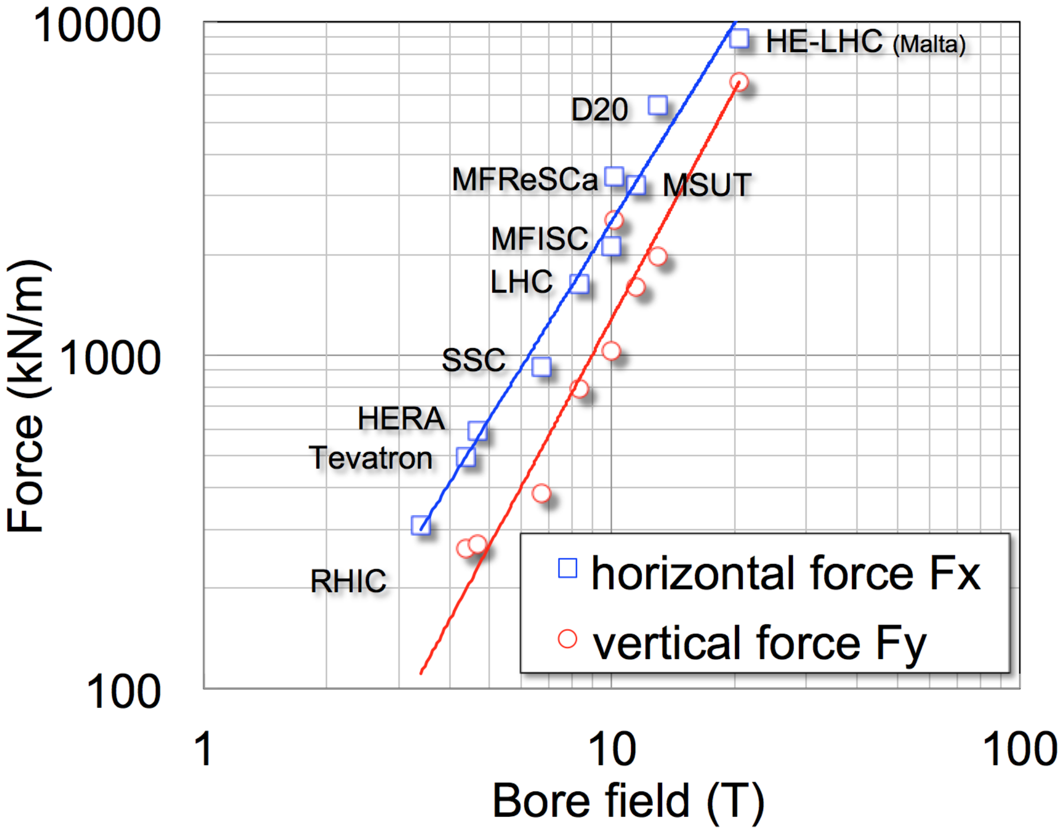
HTS materials: dreaming 40 T (Bi-2212, YBCO)

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 2 models) – small racetracks have been built

Forces

Scaling of force on coil quadrant vs. Field
Plot for recent production and R&D dipoles

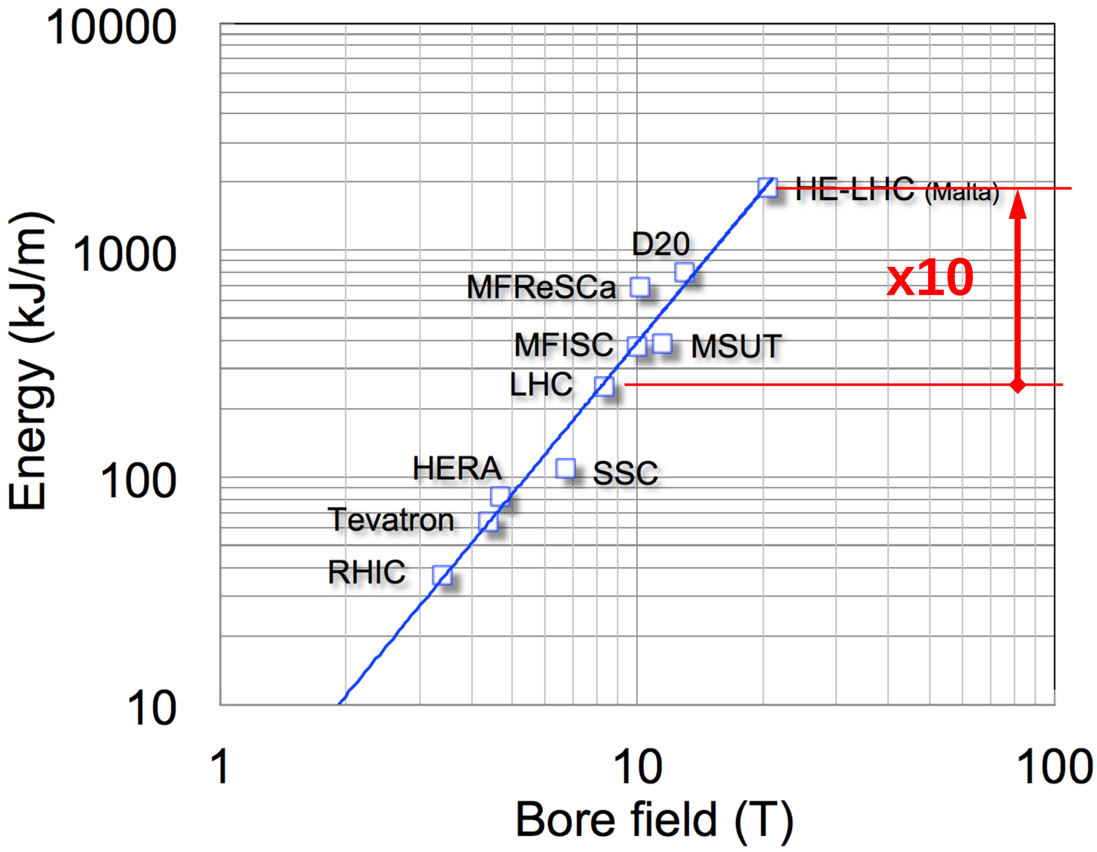


The electromagnetic loads in a 20 T dipole would be a factor 5 to 8 larger than in the LHC dipoles

Stored Energy

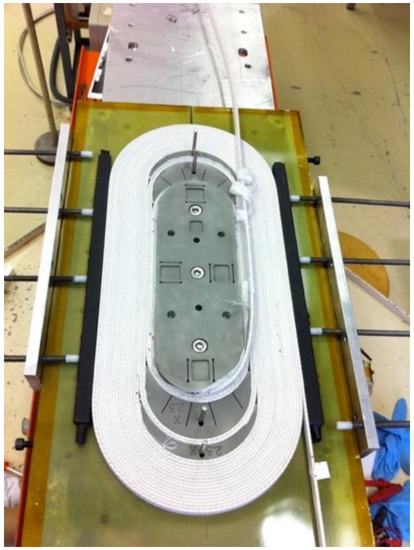
Scaling of the energy per unit length of magnet vs. Field

Plot for recent production and R&D dipoles

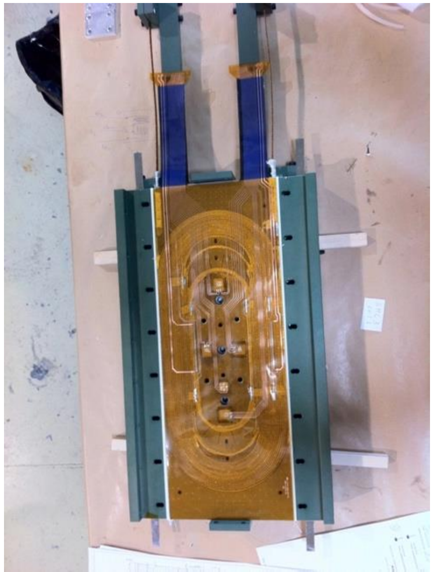


Scaling of the energy per unit length of magnet in recent production vs. R&D dipoles

Using Nb_3Sn conductor in magnets



- Nb_3Sn has to be reacted after winding for ~100 hours at 650° C (wind and react)
- Cables have to be insulated with a non-organic woven insulation: glass or ceramic fibres
- After reaction the coils has to be impregnated to prevent any movements and to take care that stresses are distributed, instrumentation connections are moulded in
- Reacted Nb_3Sn is brittle and stress sensitive



The early High Field Magnet epoch I ,
LHC options: 1988-1995

CERN

In 1986 Nb_3Sn was still considered an option for the 10T LHC magnets.

The magnet by A. Asner & R. Perin in 1989 went up to 9.5 T at 4.3 K.

It used a 17 mm cable an a wind and react technology.

A single coil in a mirror reached 10.1 T.

Many problems though remained in the fabrication

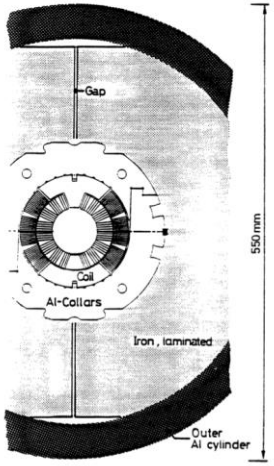
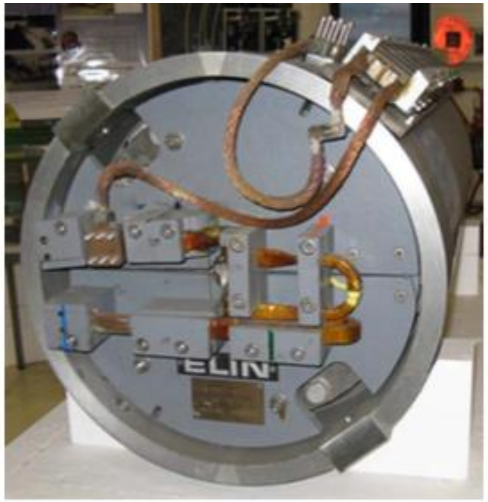


Fig.1: Schematic cross-section of the 1m long full aperture dipole magnet



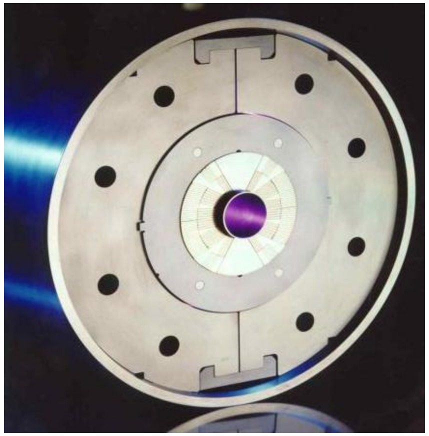
S. Wenger, A. Asner, F. Zerobin, IEEE Trans. Mag, 25(2) 1989

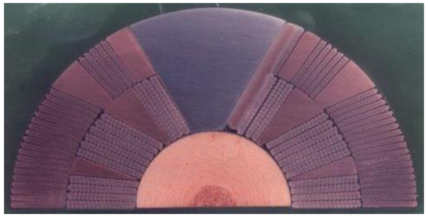
Twente

In 1995 Twente constructed the MSUT that was powered up to 11.3 T.

It had a 50 mm bore, graded, 33 PIT strand PIT cables with 192 filaments.

This magnet showed that fields above 10T are feasible.





A. den Ouden, H. H. J. ten Kate et al., in Proc. of 15th International Conference on Magnet Technology, Eds. Beijing, China: Science Press, pp. 137-140, 1998.

The early High Field Magnet epoch II, Mixed results (1995-2004)

CEA quadrupole

- A 210T/m @ 4.2K Nb_3Sn quadrupole as alternative to the Nb-Ti @ 1.9K design
- A very difficult construction with collars done like for the Nb-Ti version
- Lots was learned, only one was built, it did not reach nominal field.

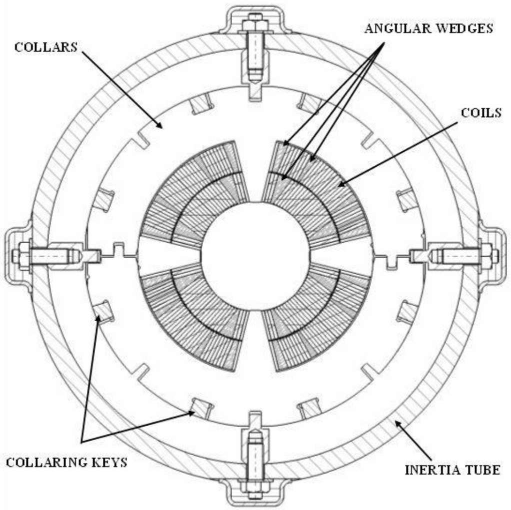
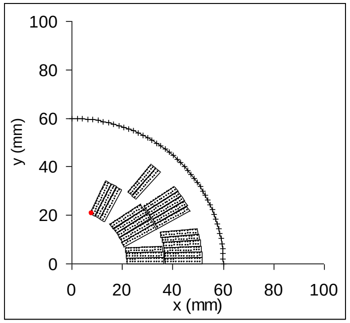
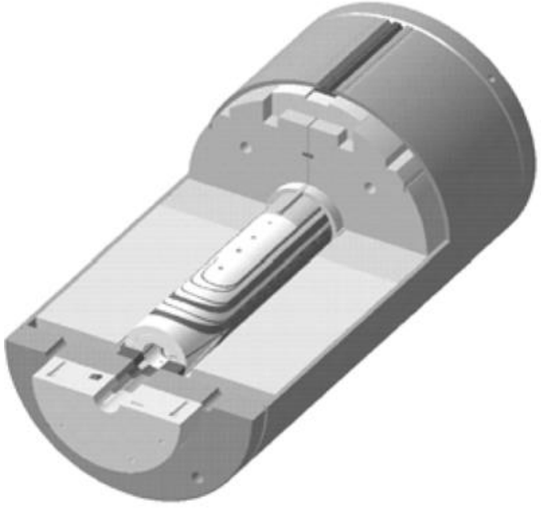


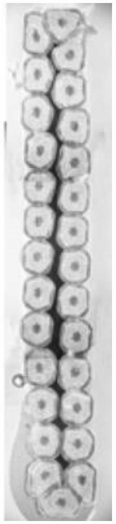
Fig. 4. Cross-sectional view of 56-mm-aperture, 210-T/m Nb_3Sn quadrupole magnet model under development at CEA/Saclay.

FNAL 10T program for VLHC (HFDA)

- Several magnets were built, reaching after long training 10T at 4.2K Rediscovery of conductor instabilities
- Tough to fabricate !







The early High Field Magnet epoch III, Some achievements at LBNL (1995-2004)

Since 20 years LBNL is running a high field dipole development program

Some achievements:

- D20, 50 mm aperture, $\cos(\Theta)$ 4 layer dipole, reached 13.5 T@1.9K
- HD1, flat block coil, 8 mm aperture, reached 16 T
- HD2, flared end block coil, 36 mm aperture, reached 13.8 T

These pose a clear breakthrough above 10 T with a new coil layout (block coil) and a mechanical structure aimed (shell-bladder and keys) at high fields

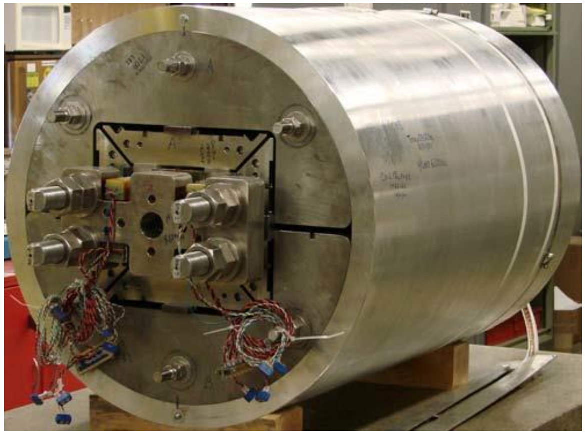


Fig. 1. HD2 assembled and pre-loaded.

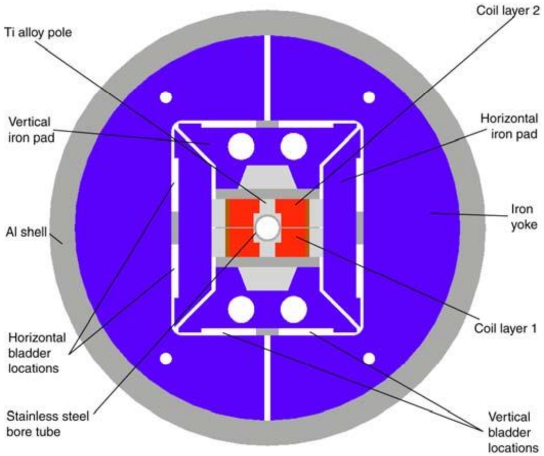
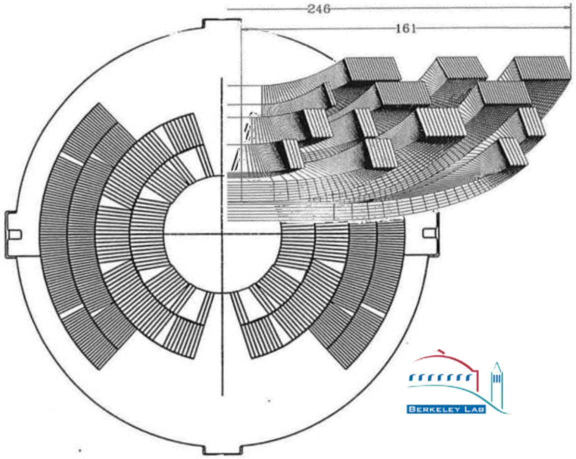


Fig. 2. HD2 cross-section.

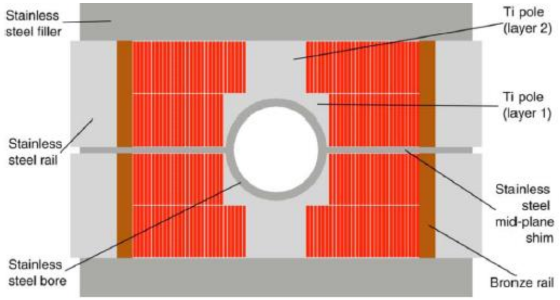


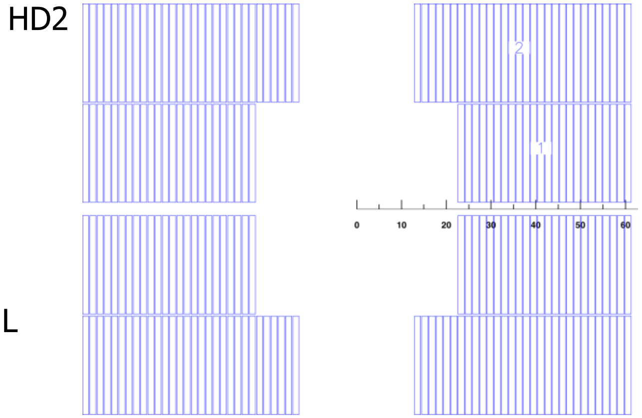
A.D. McInturff, et al., Proc. of PAC 1997, 3212

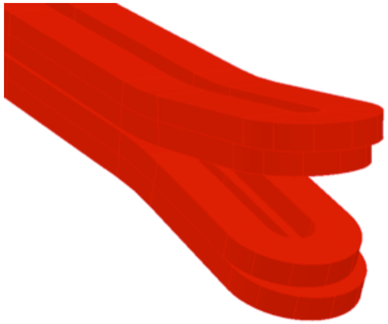
The early High Field Magnet epoch IV, New geometry: Block coils

LBNL block coil designs

- When used with wide coils the field quality is naturally homogeneous
- Not yet used in accelerators
  - Is less efficient (~10%) wrt to cos(Θ) for quantity of superconductor used
  - The EM forces cause a stress buildup at the outside edge of the coil where the fields are lower
  - The straight part is very easy : rectangular cable and wedges (field quality)
  - ‘flared ends’ look easy but there is little experience making them







Courtesy LBNL

The early High Field Magnet epoch V, Realizing what the challenges are

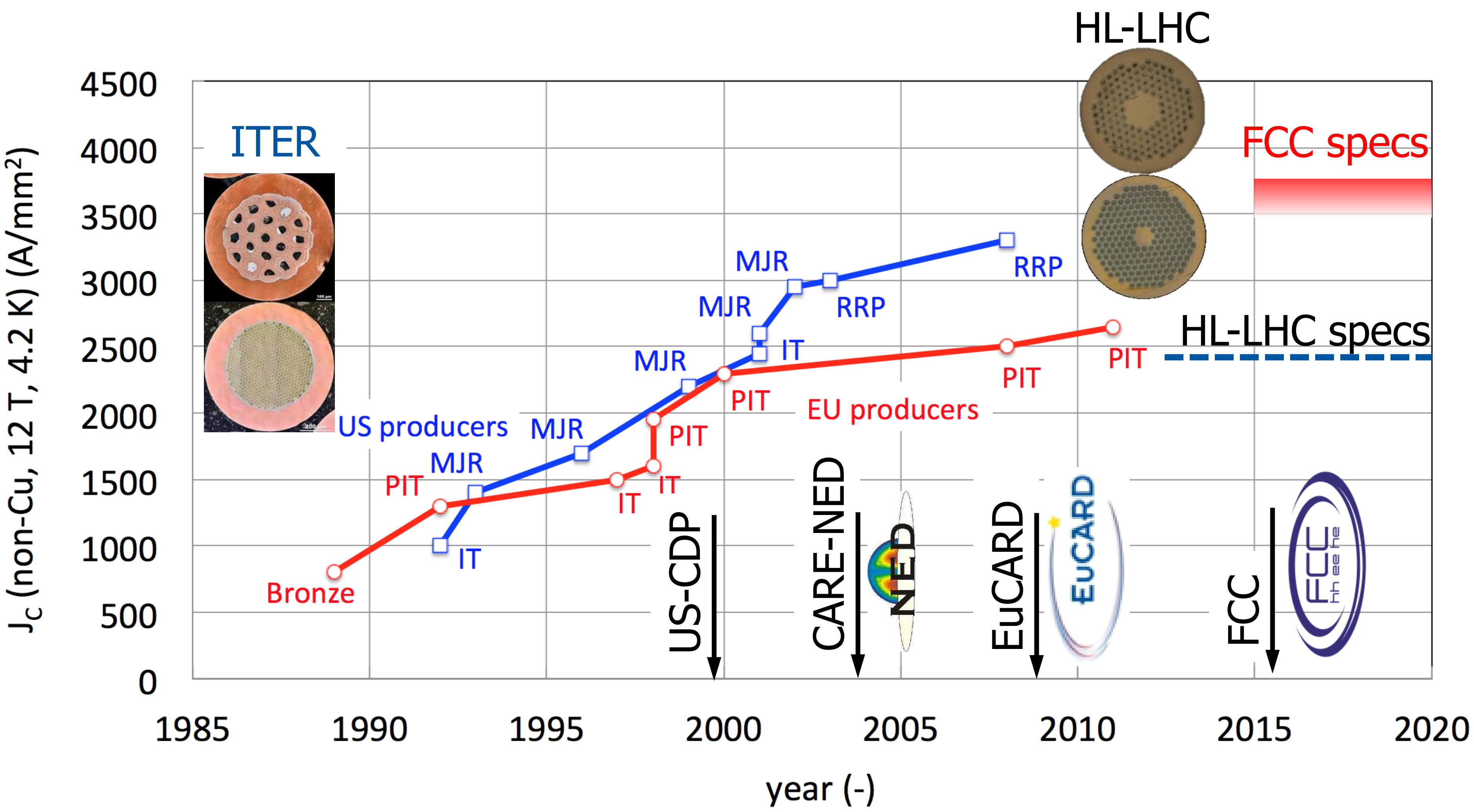
=== It should in principle be possible to go up to 16T with Nb_3Sn===

But: it will be hard to get there in a reliable way and good enough for an accelerator.

A number of issues were identified:

- High J_c (J_c>1500 A/mm^2) conductor is a must to reach high fields
- Conductor instabilities can occur at high current and low fields with certain types of Nb_3Sn strands (high J_c, thick strands, big sub-elements, low RRR of the Cu stabiliser)
- Insulation is tricky (650ºC reaction cycle)
- Nb_3Sn stress (strain) sensitivity can be an issue and is poorly understood
- Construction tooling are critical items, as important as the magnet itself
- The coils are very sensitive and fragile
- Putting a Nb_3Sn coil in a pure Nb-Ti structure does not work
- To get up to high fields other coil geometries and force containment / pre-stress structures will be needed

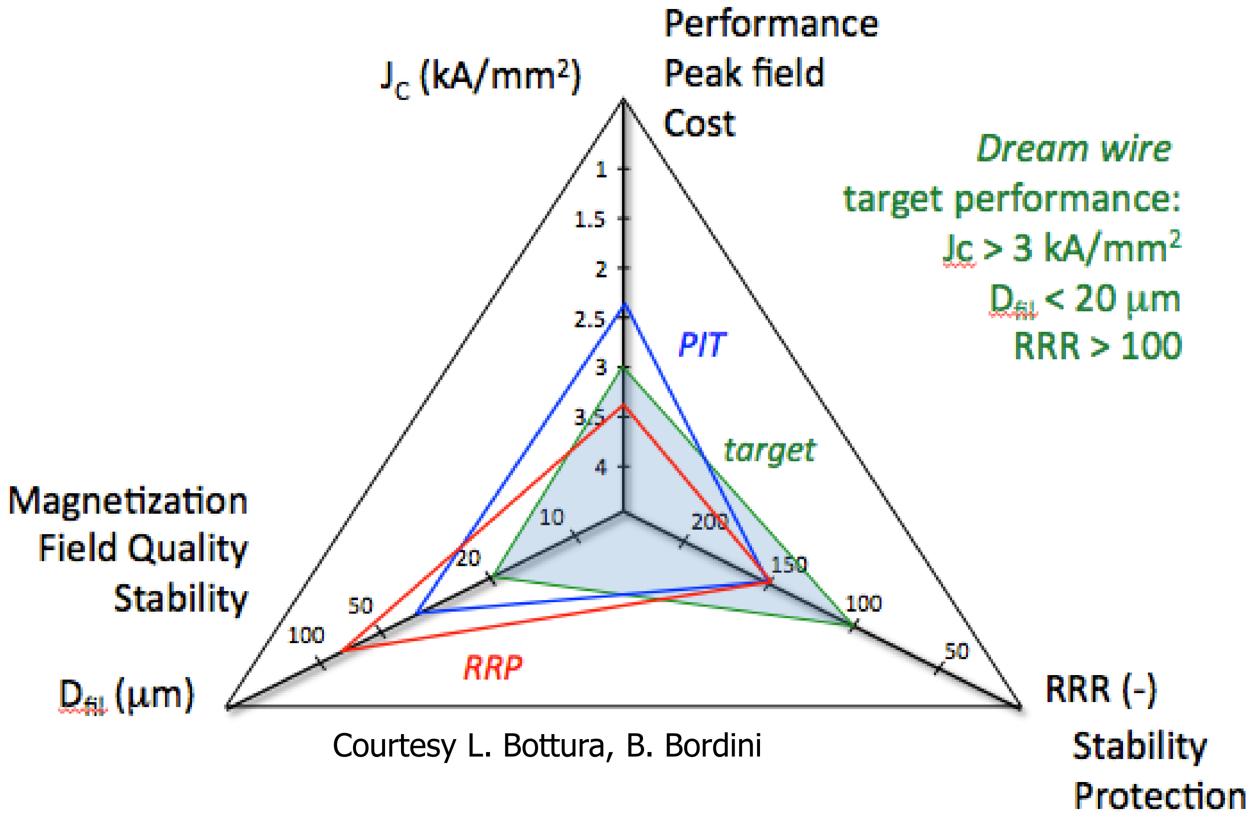
Conductor development (1998-2008)



after 10 years of development the US and EU development gave us the Nb_3Sn conductor for HILUMI.

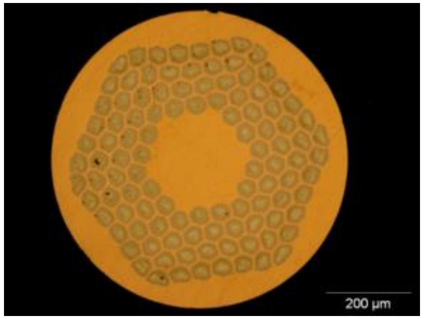
Nb_3Sn Conductor specification for HEP

A Nb_3Sn dream wire for the LHC

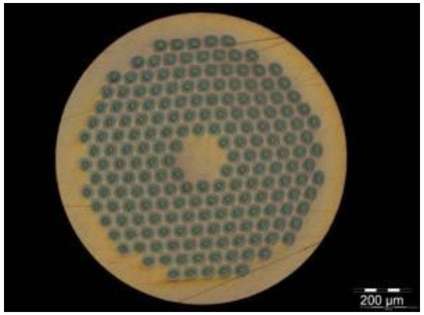


Dream wire
target performance:
$J_c > 3$ kA/mm²
$D_{fil} < 20$ μm
RRR > 100

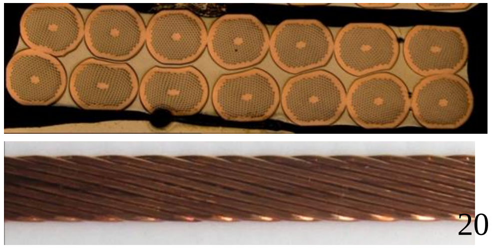
Courtesy L. Bottura, B. Bordini



0.7 mm, 108/127 stack
RRP from Oxford OST



1 mm, 192 tubes
PIT from Bruker EAS



Between HL-LHC and FCC the Jc target shifts from 12 T to 16 T !

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

European programs

- 2004-2008 FP7-CARE-NED project (Next European dipole)
  - European accelerator grade Nb_3Sn conductor ➔ Powder In Tube (PIT) conductor now available from Brucker
  - Various studies on design options and materials

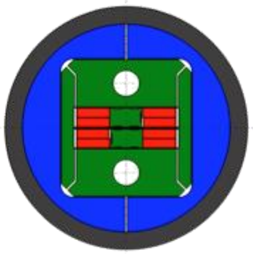
- 2009-2013 PF7-EuCARD-HFM project (High Field Magnets)
  - 100mm aperture 13 – 15 T Nb_3Sn dipole “Fresca2”
  - HTS insert with $\Delta B = 6$ T (inside Fresca2)
  - HTS current link
  - Nb_3Sn helical undulator

- 2008 – 2014 CERN High Field Magnet project
  - Development of Nb_3Sn technology magnets for LHC upgrades and new projects (conductor, small models, materials, etc)

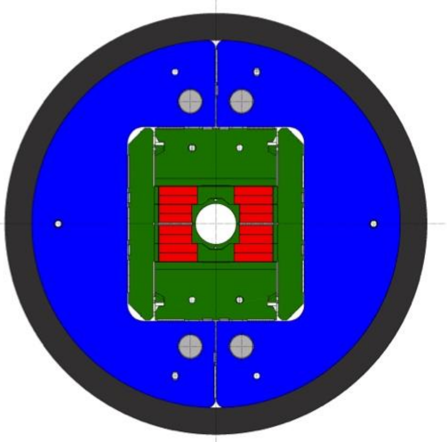
CERN-European development evolution

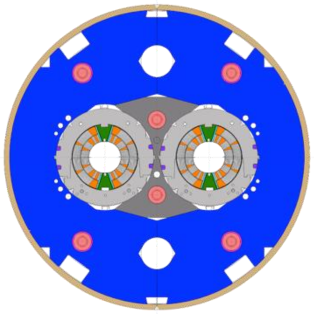
Short Model Coil

Race-track Model Coil



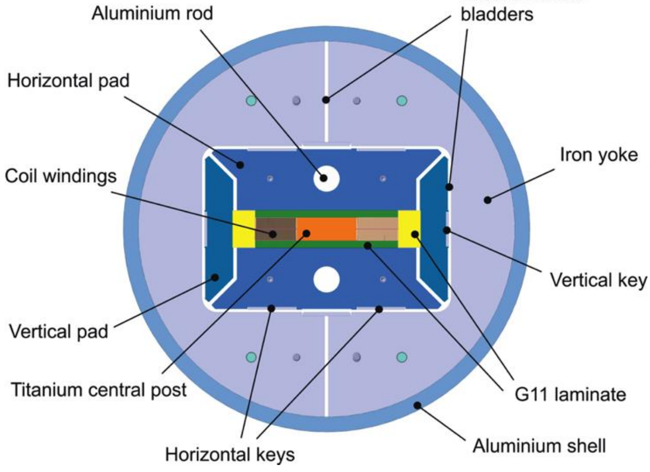
FReSCa2 Nb_3Sn Dipole



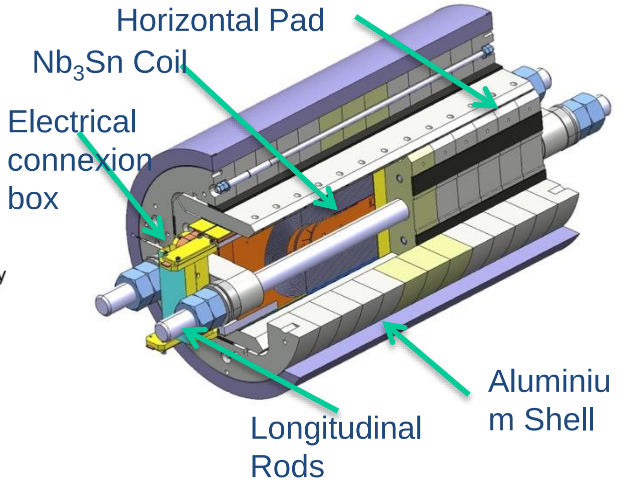


11 T dipole (CERN)

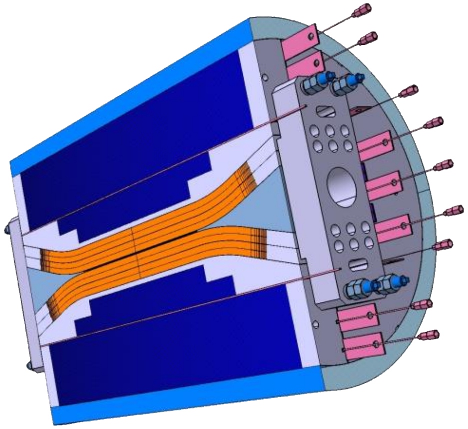
SMC (Short Model Coil)



RMC (Racetrack Model Coil)



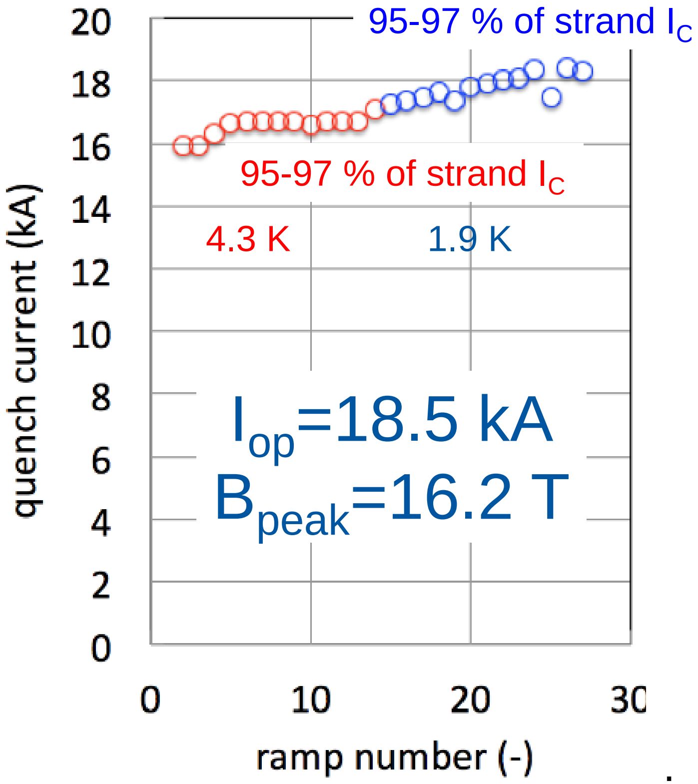
FReSCa2

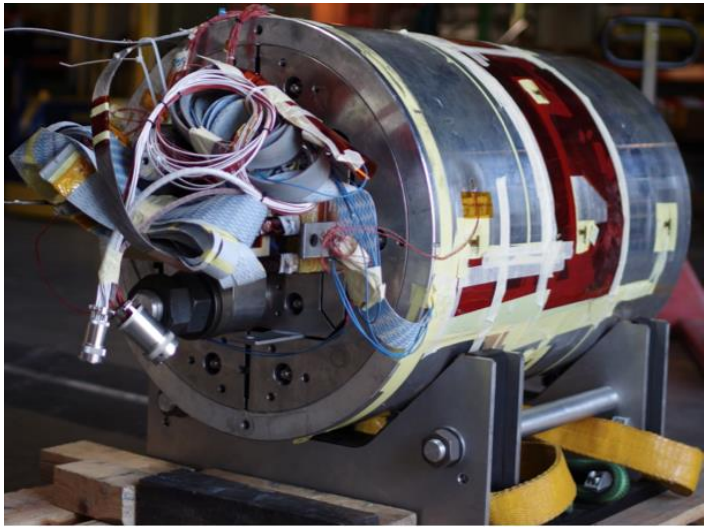


RMC3 16T: first milestone for FCC 16T !

RMC reached 16.2 T (on coil) end summer 2015 at CERN

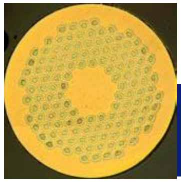
Joining LBNL at the 16T record level





Fresca 2 Dipole cable

40 Strands, Width = 20.9 mm

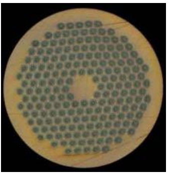


RRP 132/169

OXFORD INSTRUMENTS

BRUKER

PIT 192

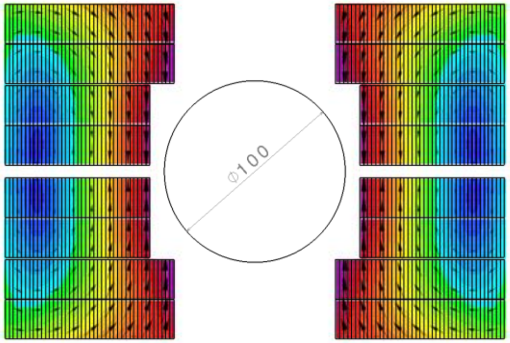


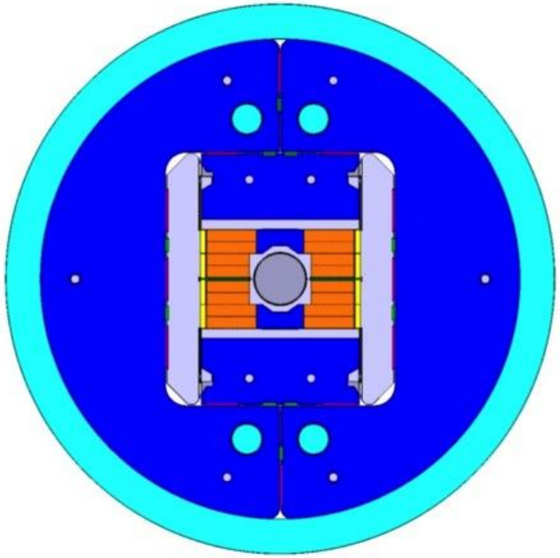
EuCARD high field dipole (FRESCA2)

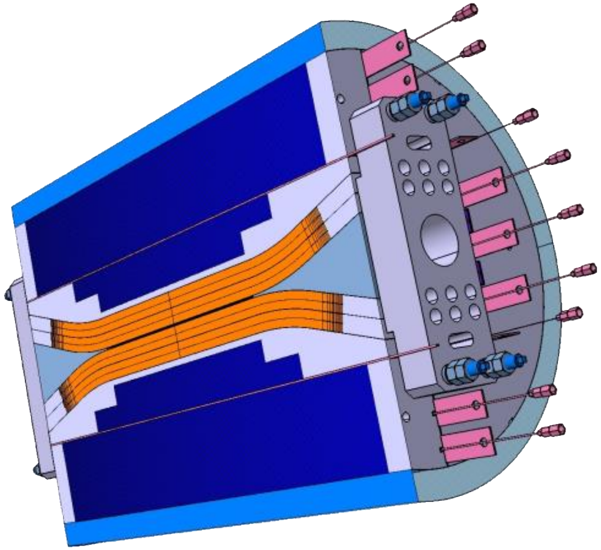
- FRESCA2 : a CERN, CEA EuCARD collaboration

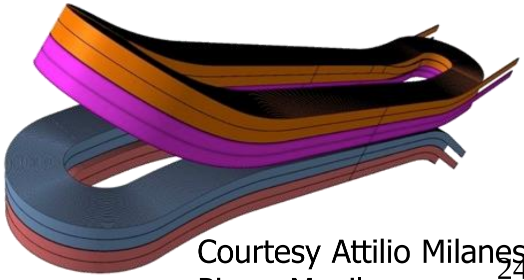
- 156 turns per pole
- Iron post
- B_{center} = 13.0 T
- I_{13T} = 10.7 kA
- B_{peak} = 13.2 T
- E_{mag} = 3.6 MJ/m
- L = 47mH/m

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









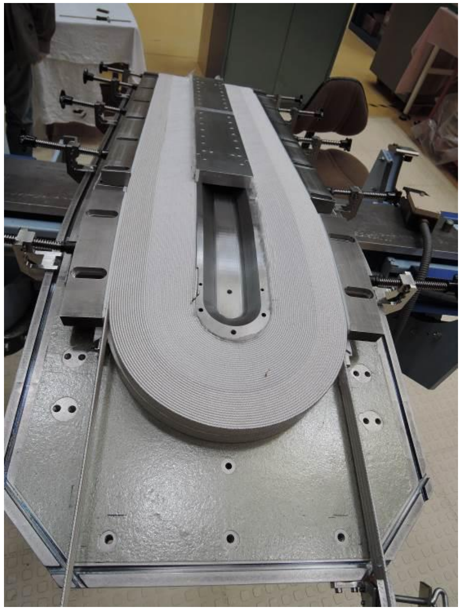
- 13 T bore field ("nominal")
  - ~79% of I_{ss} at 4.2 K
  - ~72% of I_{ss} at 1.9 K
- 15 T bore field ("ultimate")
  - 86% of 1.9 K I_{ss}

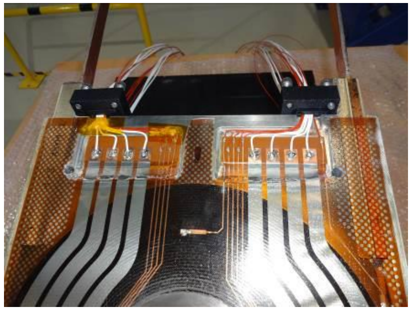
Courtesy Attilio Milanese,
Pierre Manil

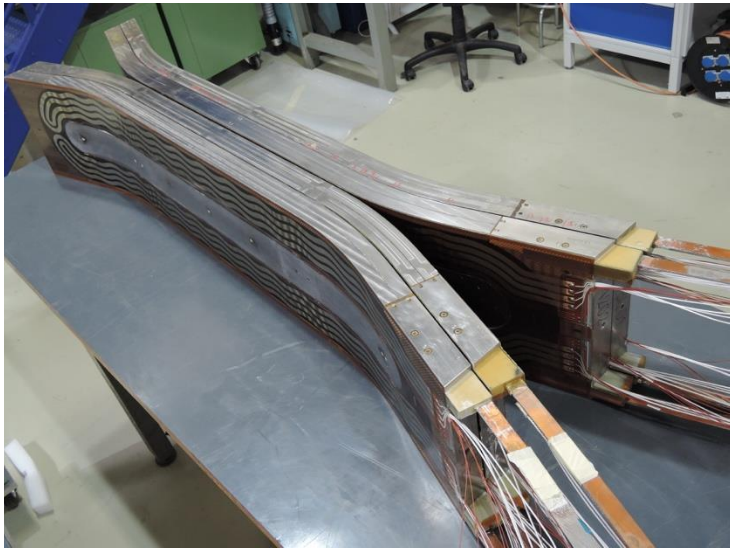
Fabrication of Fresca2 coils

Straightforward technology to wind block coils with flared ends:

This is a lesson for FCC magnets !

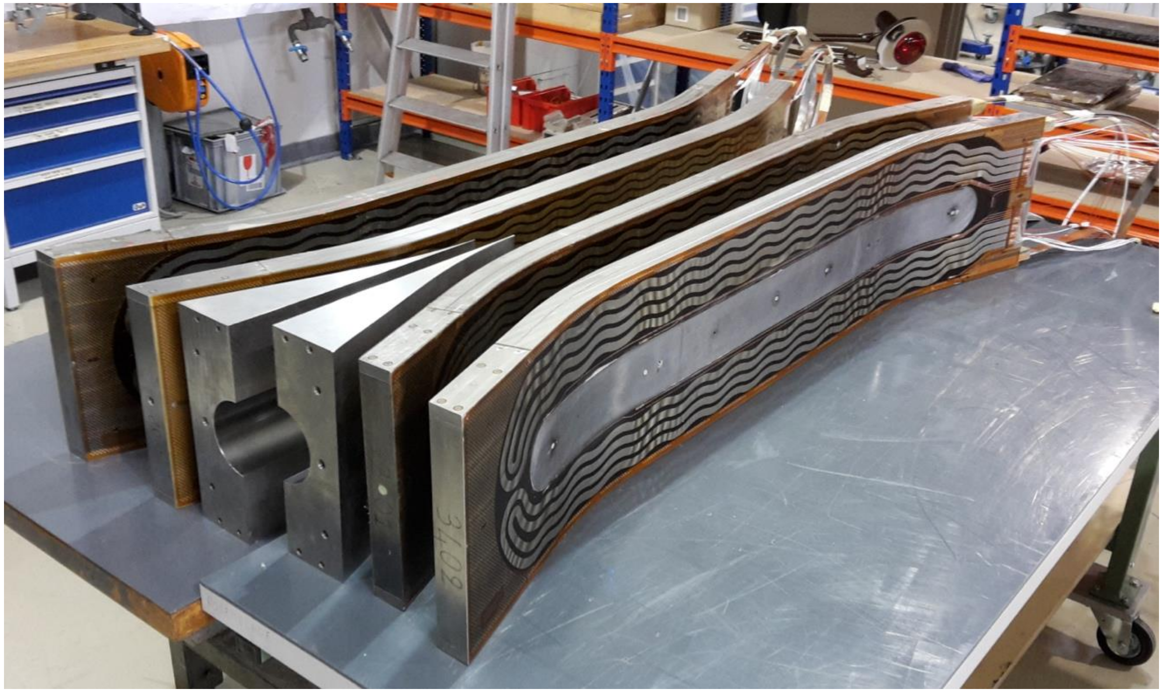






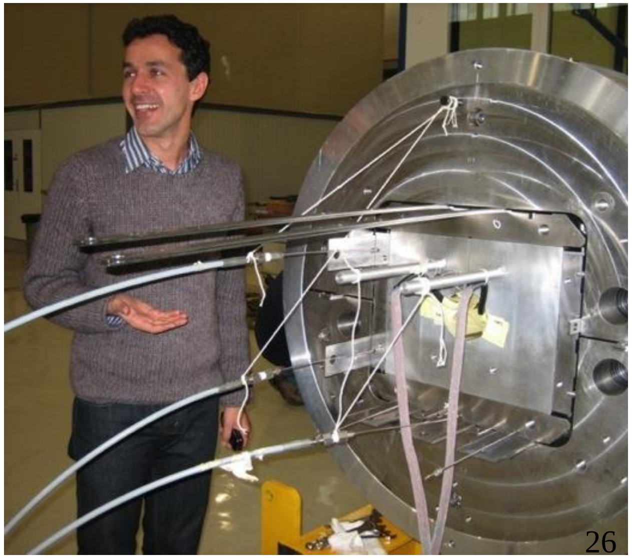
Fresca2 : get the 15T FCC milestone by begin 2017

Magnet assembly now, to be tested in Jan-Febr 2017

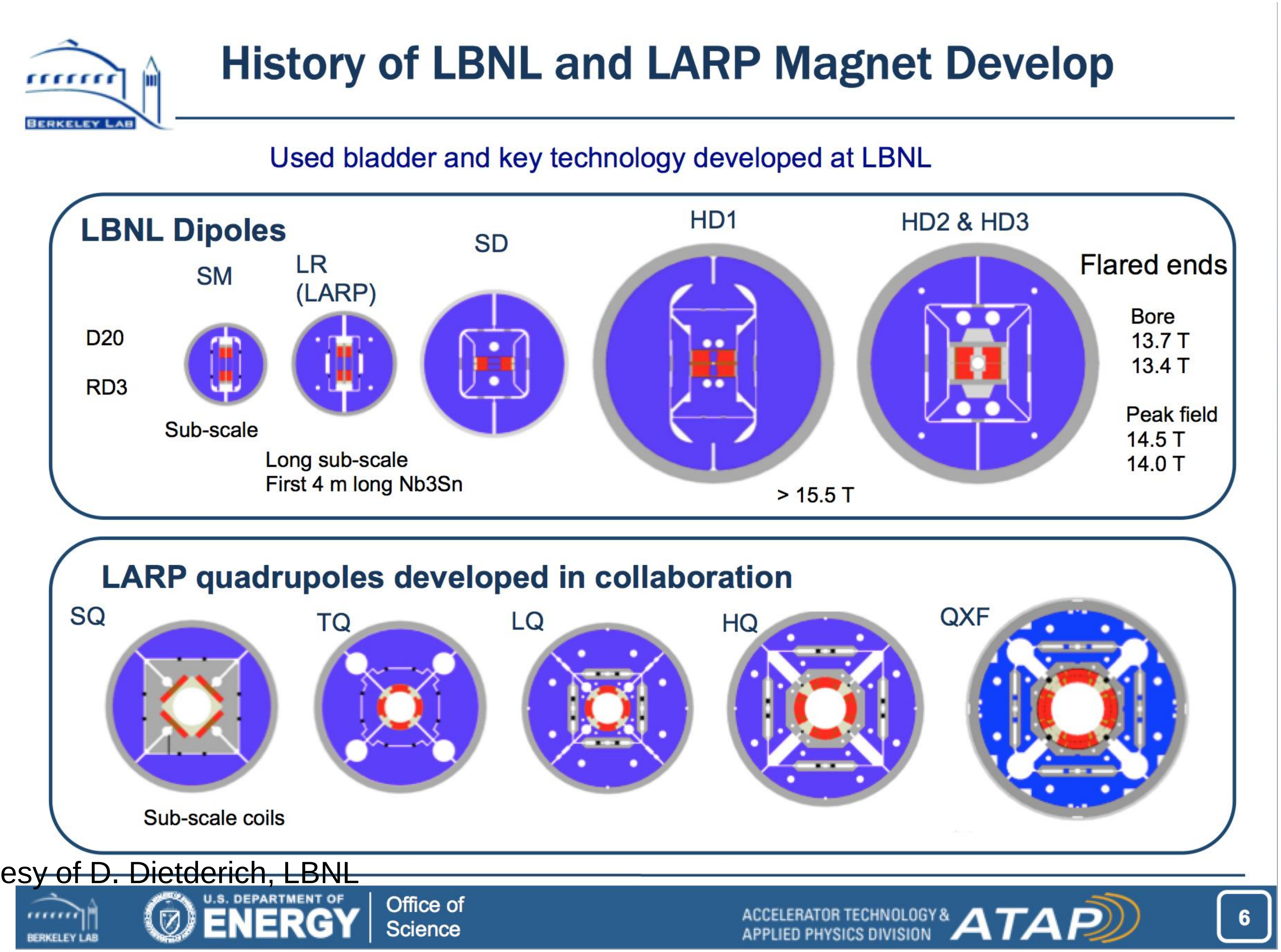


First test: 13T loading, then warm up and loading for 15T,

Second test: go up to 15T



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



History of LBNL and LARP Magnet Develop

Used bladder and key technology developed at LBNL

LBNL Dipoles

D20

RD3

SM

Sub-scale

LR
(LARP)

Long sub-scale
First 4 m long Nb3Sn

SD

HD1

> 15.5 T

HD2 & HD3

Flared ends

Bore
13.7 T
13.4 T

Peak field
14.5 T
14.0 T

LARP quadrupoles developed in collaboration

SQ

Sub-scale coils

TQ

LQ

HQ

QXF

By courtesy of D. Dietderich, LBNL

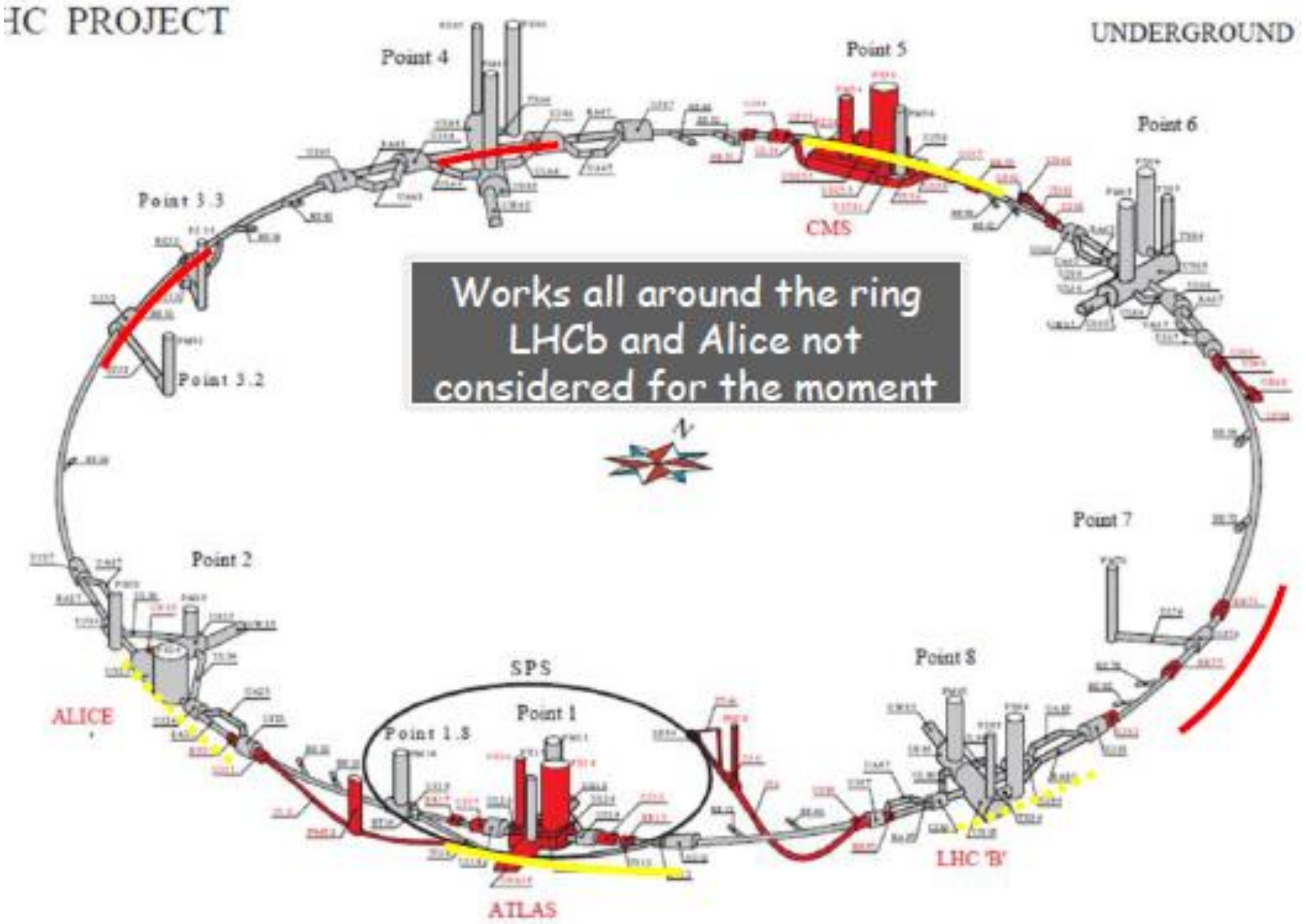
Basic magnet technology development for HILUMI and beyond: Results

- This phase of development gave us
  - Conductor pre-FCC grade in both US and EU
  - Basic coil manufacturing technology close to FCC standard
  - New coil and structure geometries

- 2 milestones
  - HD1 & RMC 16T on the coil (no aperture) Achieved mid 2015
  - Fresca2 13T→15T in a large aperture Assembly now, test Q1 2017

HILUMI magnet development (2013-2016)

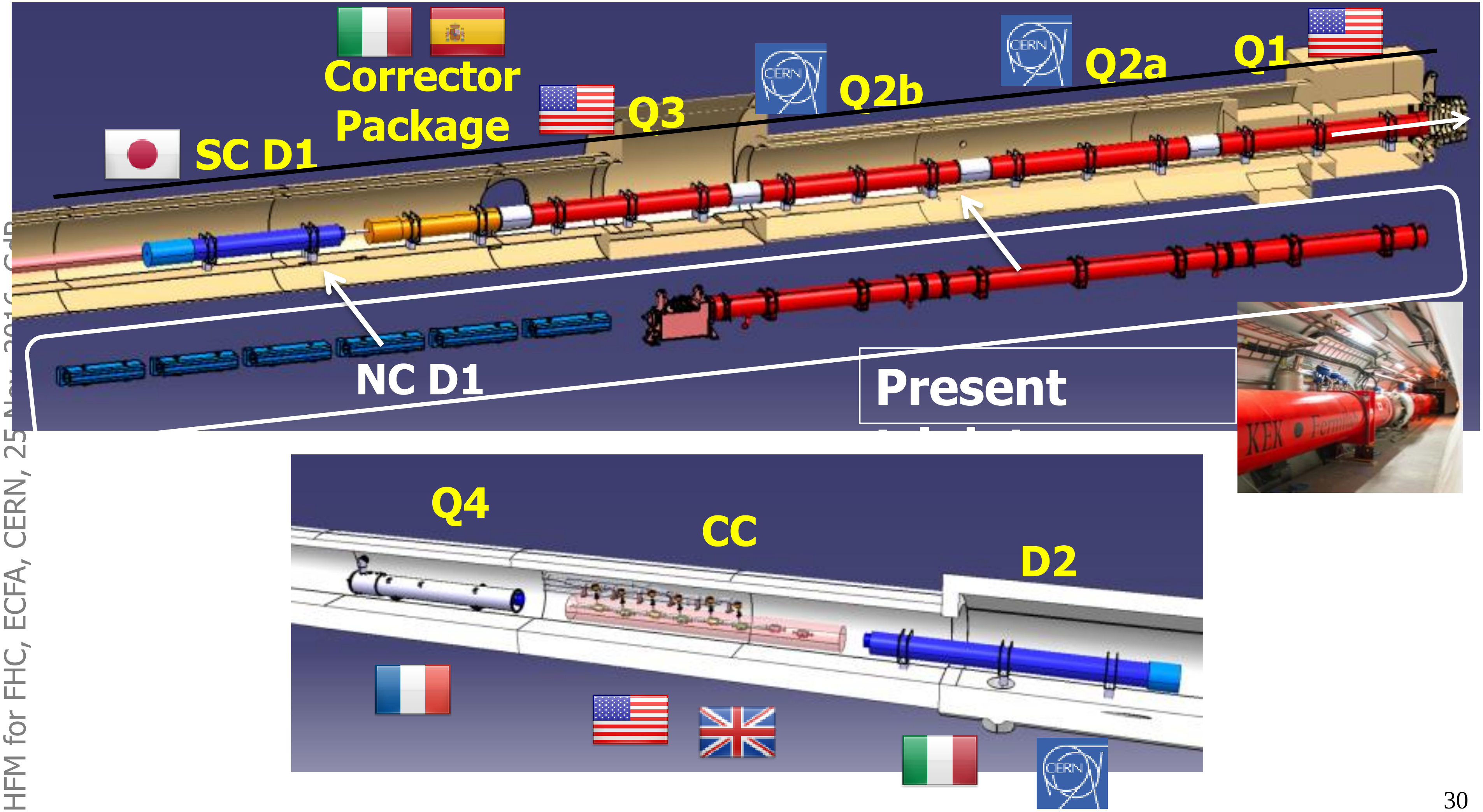
- HILUMI means new magnets in ~1 km of the the LHC main ring
- The ultimate test-bed for the feasibility of Nb_3Sn magnets in accelerators!



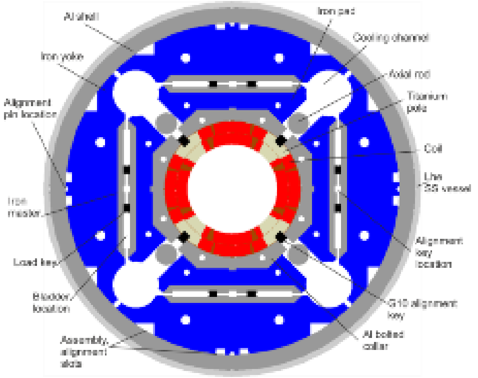
Works all around the ring
LHCb and Alice not
considered for the moment

New triplet for HHILUMI

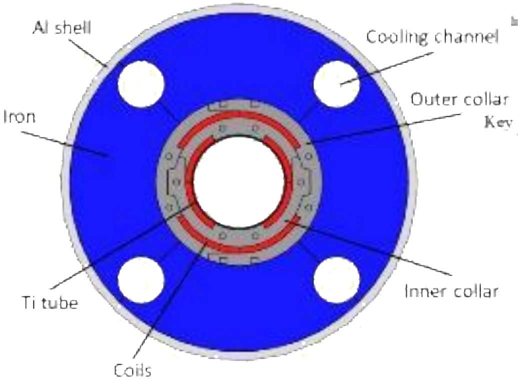
Lower β value in the interaction points : larger apertures needed in the triplet of the machine (from 70 mm to 150 mm)



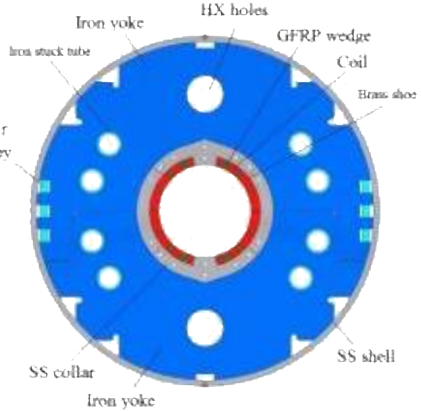
HILUMI IT magnet zoo



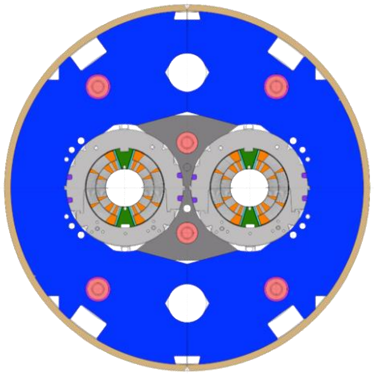
Triplet QXF (LARP and CERN)



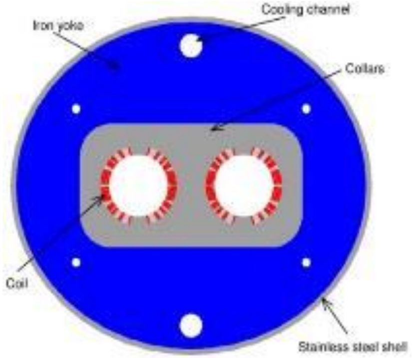
Orbit corrector (CIEMAT)



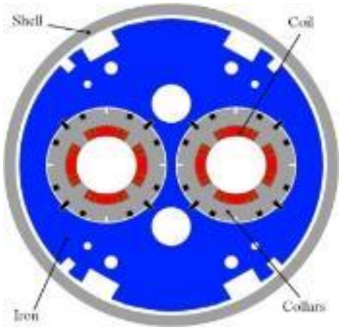
Separation dipole D1 (KEK)



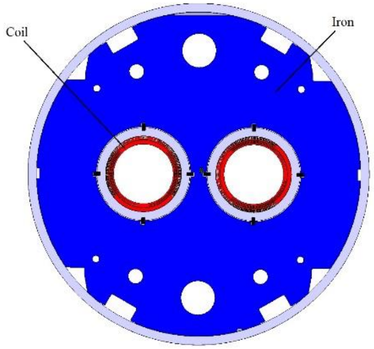
11 T dipole (CERN)



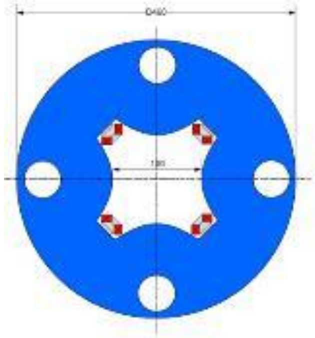
Recombination dipole D2 (INFN)



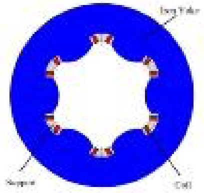
Q4 (CEA)



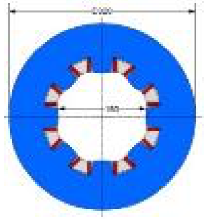
D2/Q4 orbit corrector (CERN)



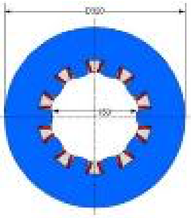
Skew quadrupole (INFN)



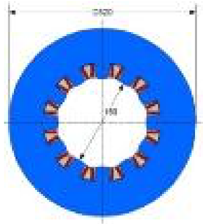
Sextupole (INFN)



Octupole (INFN)



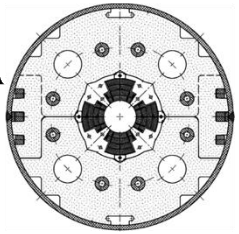
Decapole (INFN)



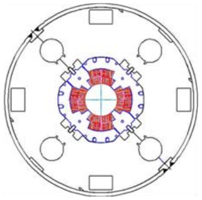
Dodecapole (INFN)

Courtesy E. Todesco

LHC IP Quadrupole design and technology evolution



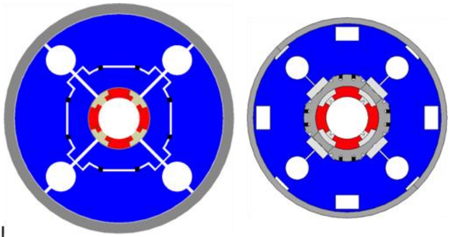
KEK MQXA
Nb-Ti, 6.6 m
70 mm apert.
205 T/m



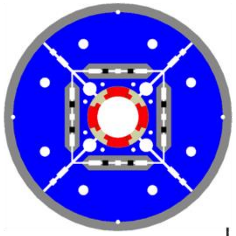
FNAL MQXB
Nb-Ti, 5.7 m
70 mm apert.
205 T/m

US/LHC

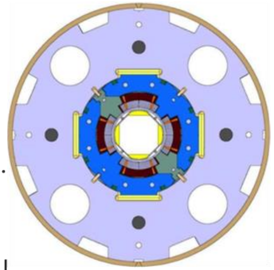
LARP



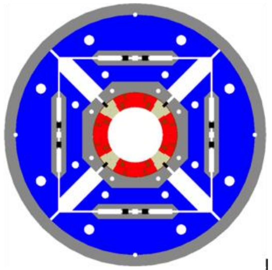
LARP TQS-TQC
Nb_3Sn, 1 m
90 mm apert.
200 T/m



LARP LQS
Nb_3Sn, 3.7 m
90 mm apert.
200 T/m

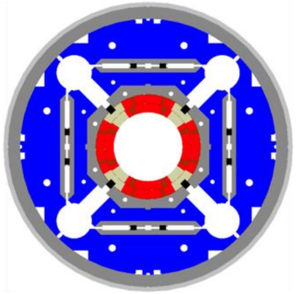


CERN-CEA MQXC
Nb-Ti, 2 m
120 mm apert.
118 T/m



LARP HQ
Nb_3Sn, 1 m
120 mm apert.
170 T/m

LARP

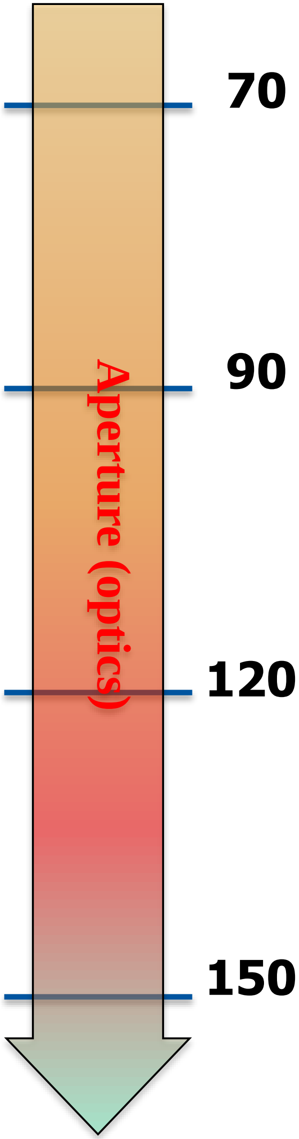


LARP-CERN QXF
Nb_3Sn, 1.5 m
150 mm apert.
140 T/m

Courtesy L. Bottura

US LARP

US LHC Accelerator Research Program
brookhaven - fermilab - berkeley

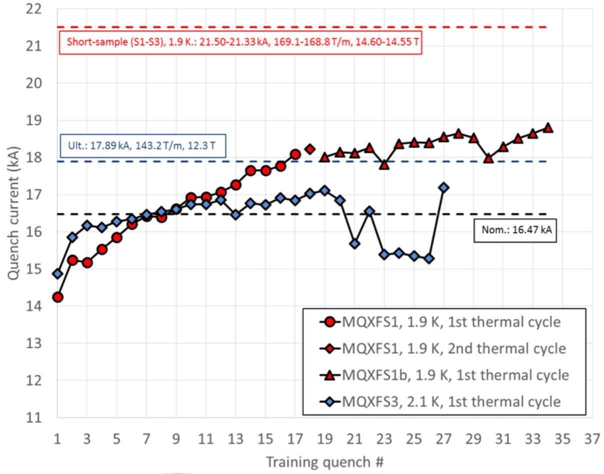


HL-LHC: MQXF low beta Nb_3Sn quadrupole

Spring 2016 the first model achieved the nominal and ultimate field at FNAL

A second model in under test at CERN

A single 4m coil is being tested at BNL in a mirror structure



A CERN LARP collaboration.

Nominal Gradient 132.6 T/m

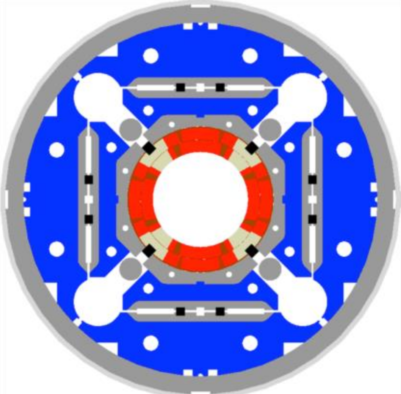
Aperture diameter 150 mm

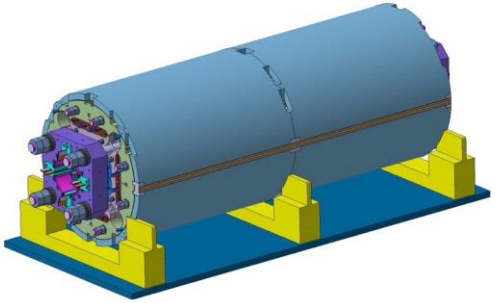
Peak Field 12.1 T

Current 17.5 A

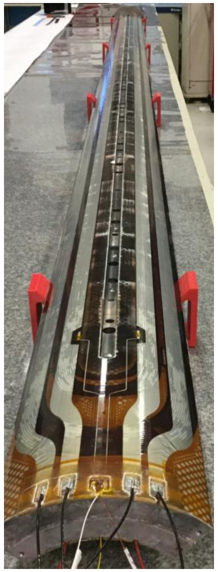
Loadline Margin 20% @ 1.9 K

Stored Energy 1.32 MJ/m



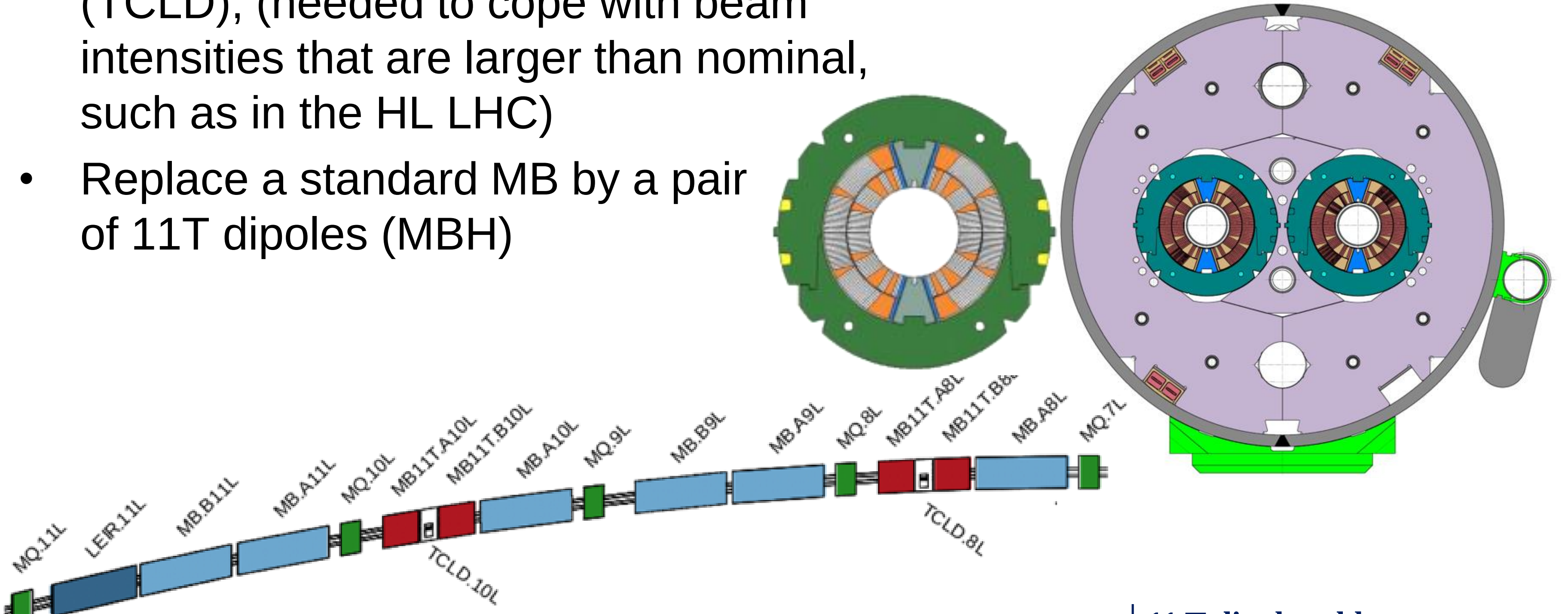


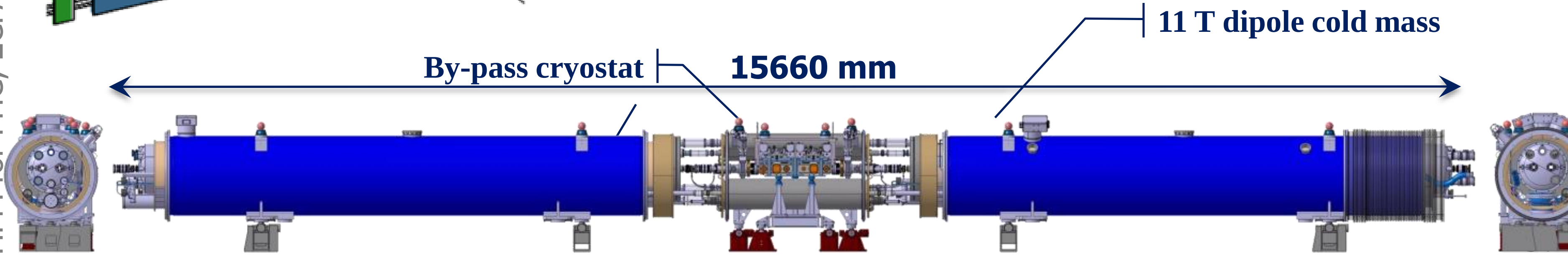
By courtesy of G. Ambrosio (FNAL), P. Ferracin (CERN)



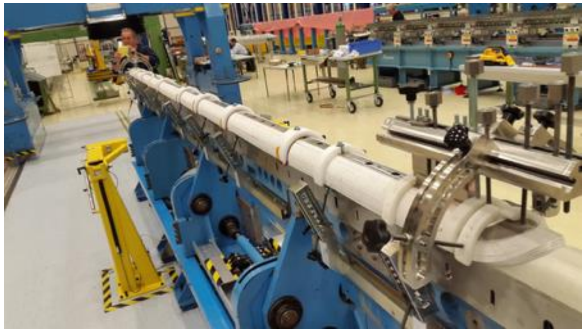
HILUMI: The 11T Dipole Two-in-One for DS

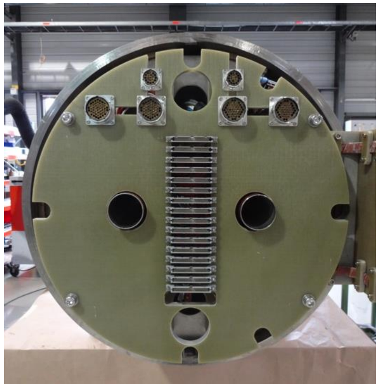
- Create space in the dispersion suppressor regions of LHC, i.e. a room temperature beam vacuum sector, to install additional collimators (TCLD), (needed to cope with beam intensities that are larger than nominal, such as in the HL LHC)
- Replace a standard MB by a pair of 11T dipoles (MBH)



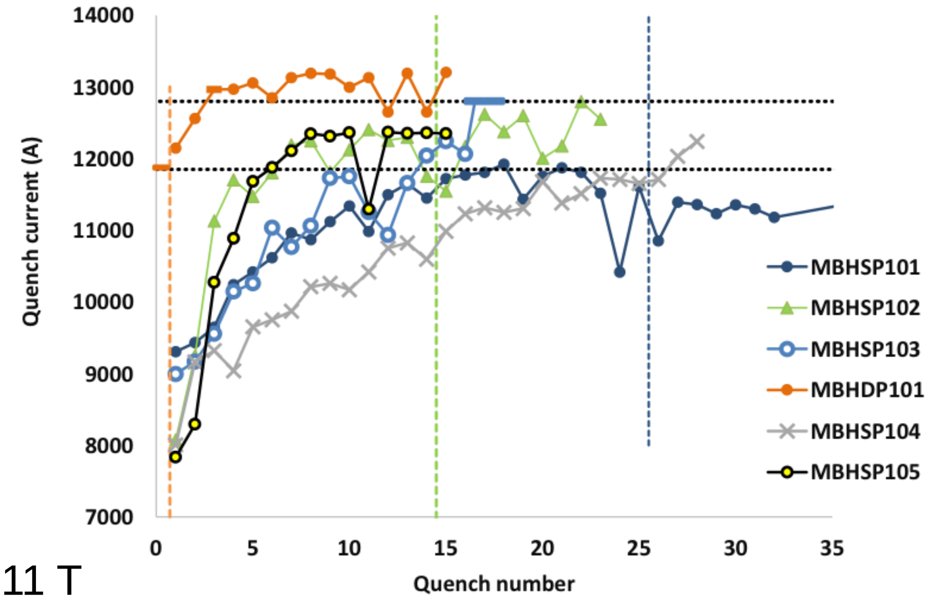


HL-LHC: 11 T Dispersion suppressor magnet





- First Nb_3Sn magnet to go into an accelerator ring (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

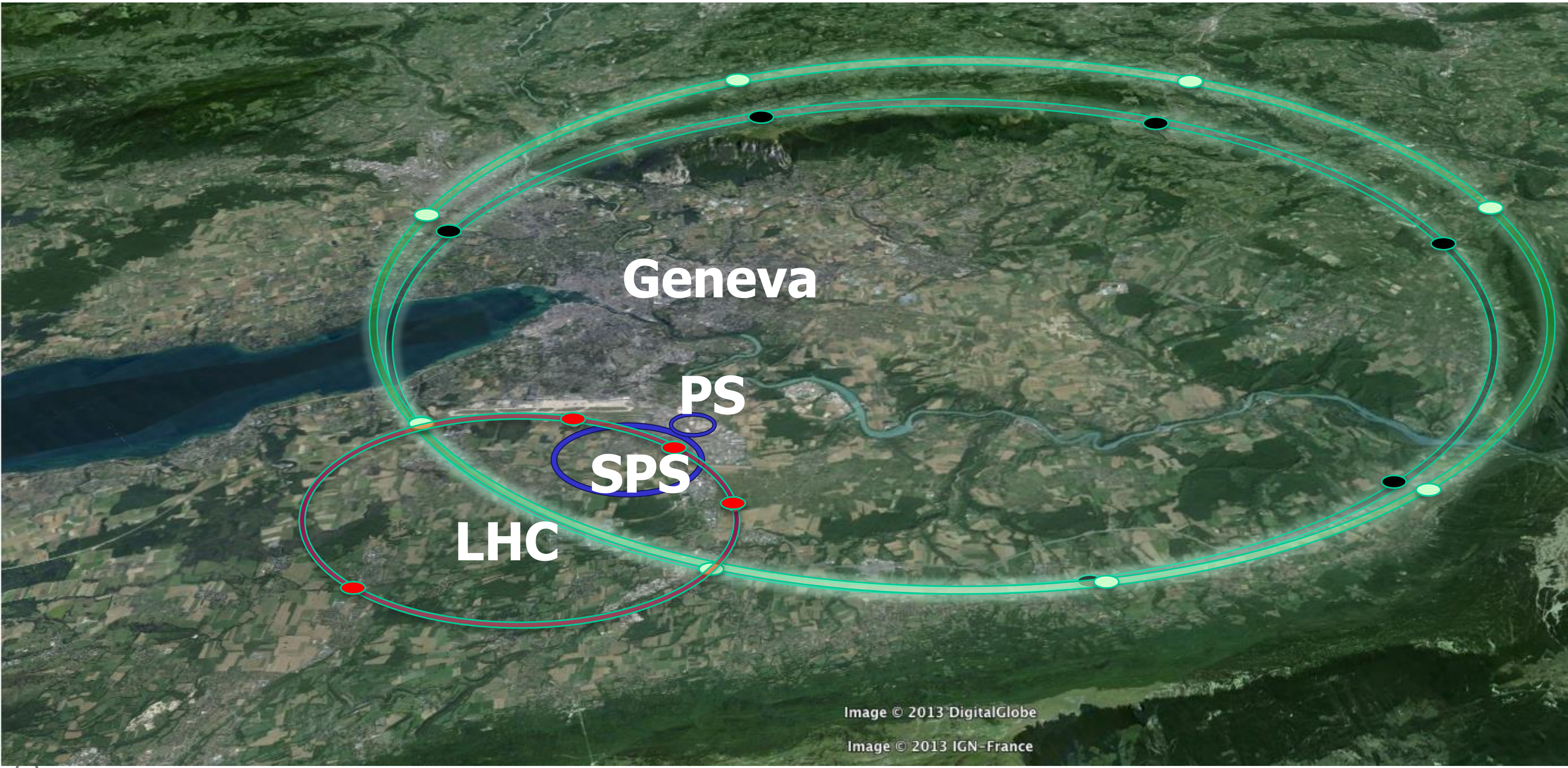
Stored Energy 0.96 MJ/m

conclusion from previous and running programs

We now have all the elements in hand to develop 16T magnets

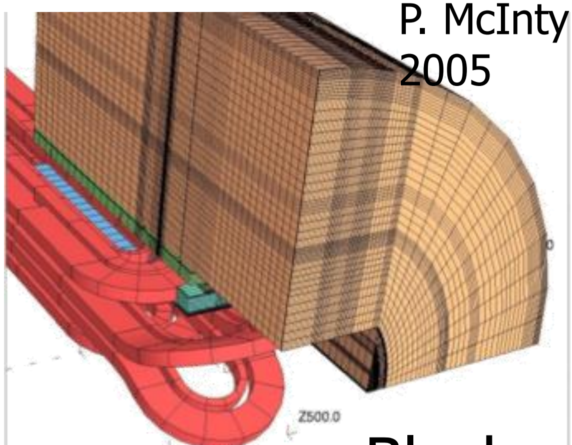
- 11 T dipoles: we have working models (at CERN and FNAL)
- 12 T quadrupoles: we have working models (made together by LARP and CERN)
- We showed 16T is feasible on flat coils (at LBNL and CERN)

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.)

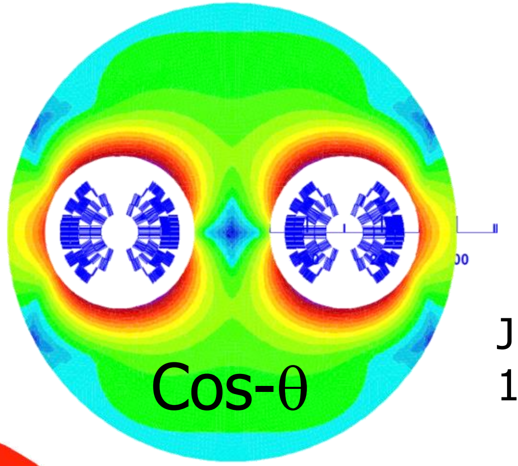
FCC: Magnet design for 16 T dipoles, LTS Nb_3Sn



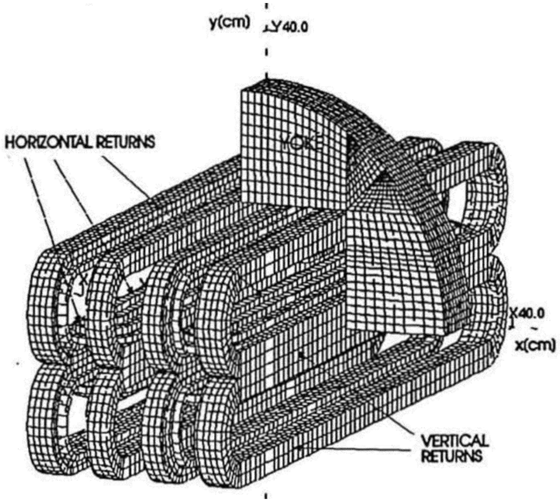
P. McIntyre, 2005

Blocks

E. Todesco 2013
D. Schoerling 2015

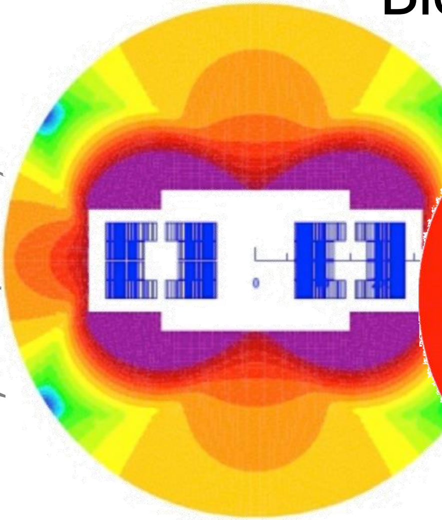


Cos-θ

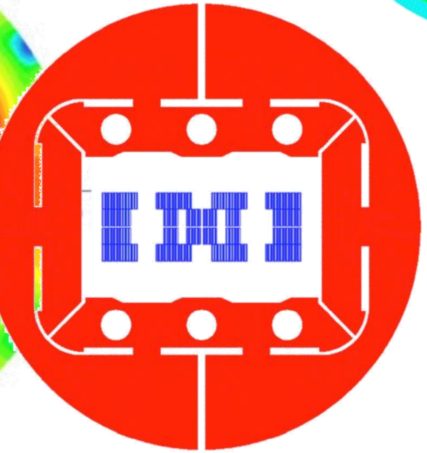


J.M. Van Oort, R. Scanlan, 1994

Common coils

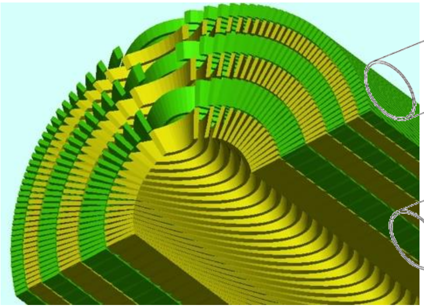


E. Todesco, 2013

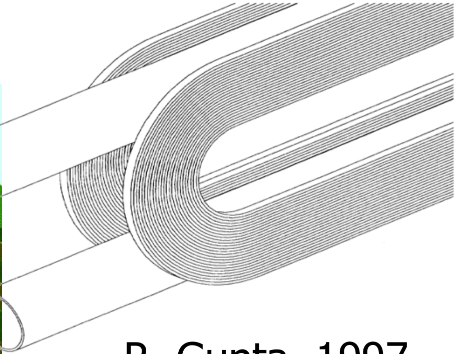


GL. Sabbi, 2014

Canted Cos-θ



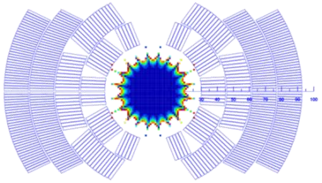
S. Caspi, 2014

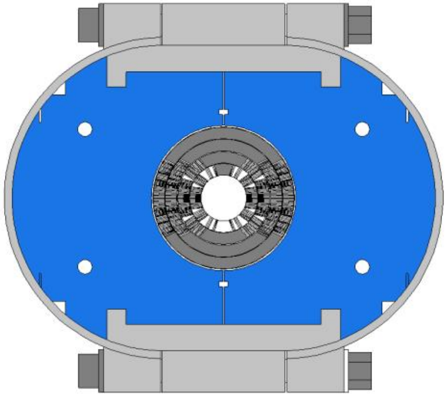


R. Gupta, 1997

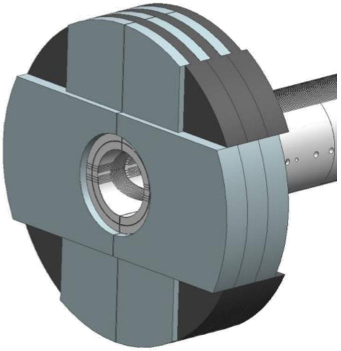
US program lines

cos-θ

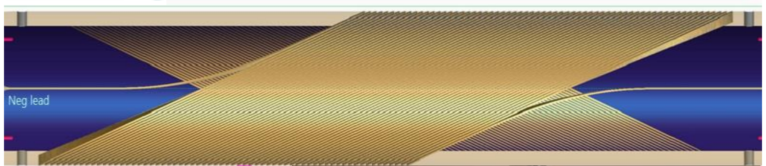


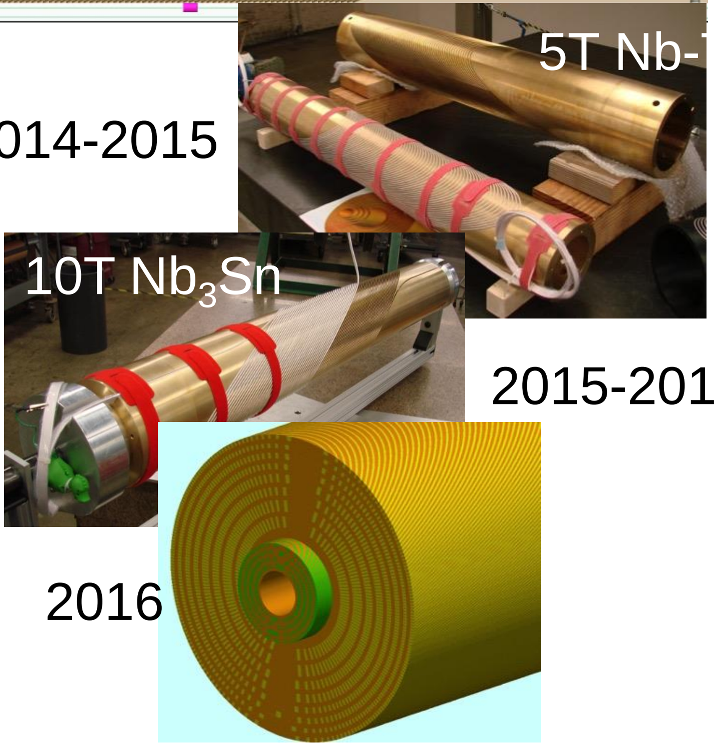


2018



canted-cos-θ



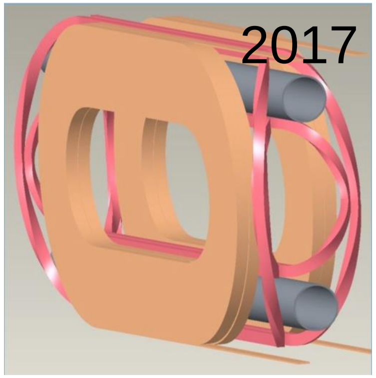


2014-2015

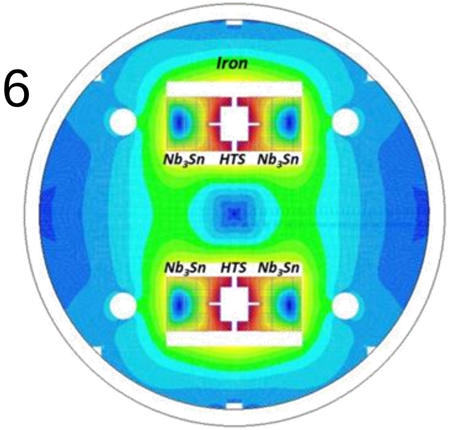
2015-2016

2016

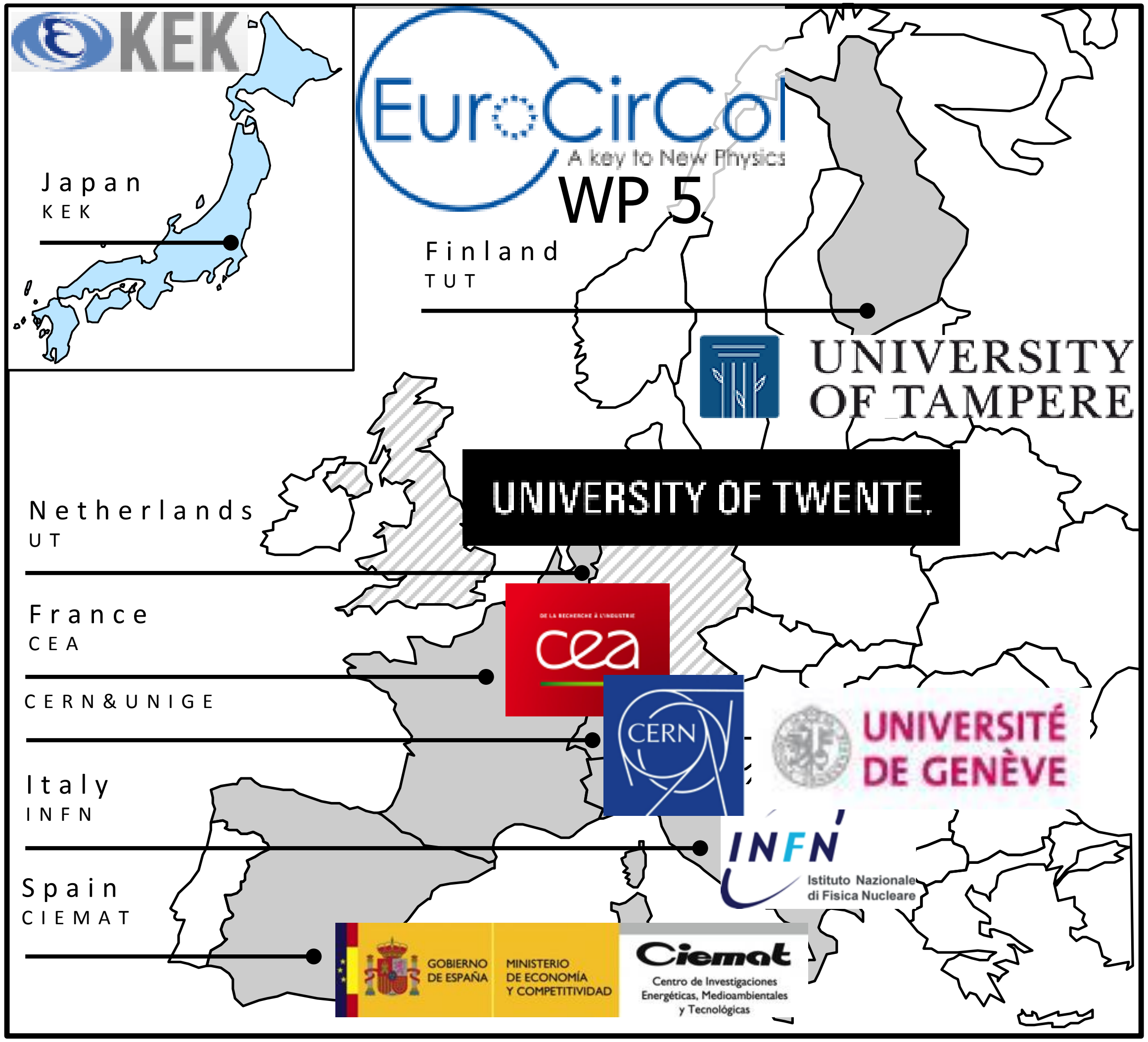
common coils



2017



EuroCirCol Program for FCC 16 T dipole



Complete conceptual design and select a baseline for the FCC accelerator dipole

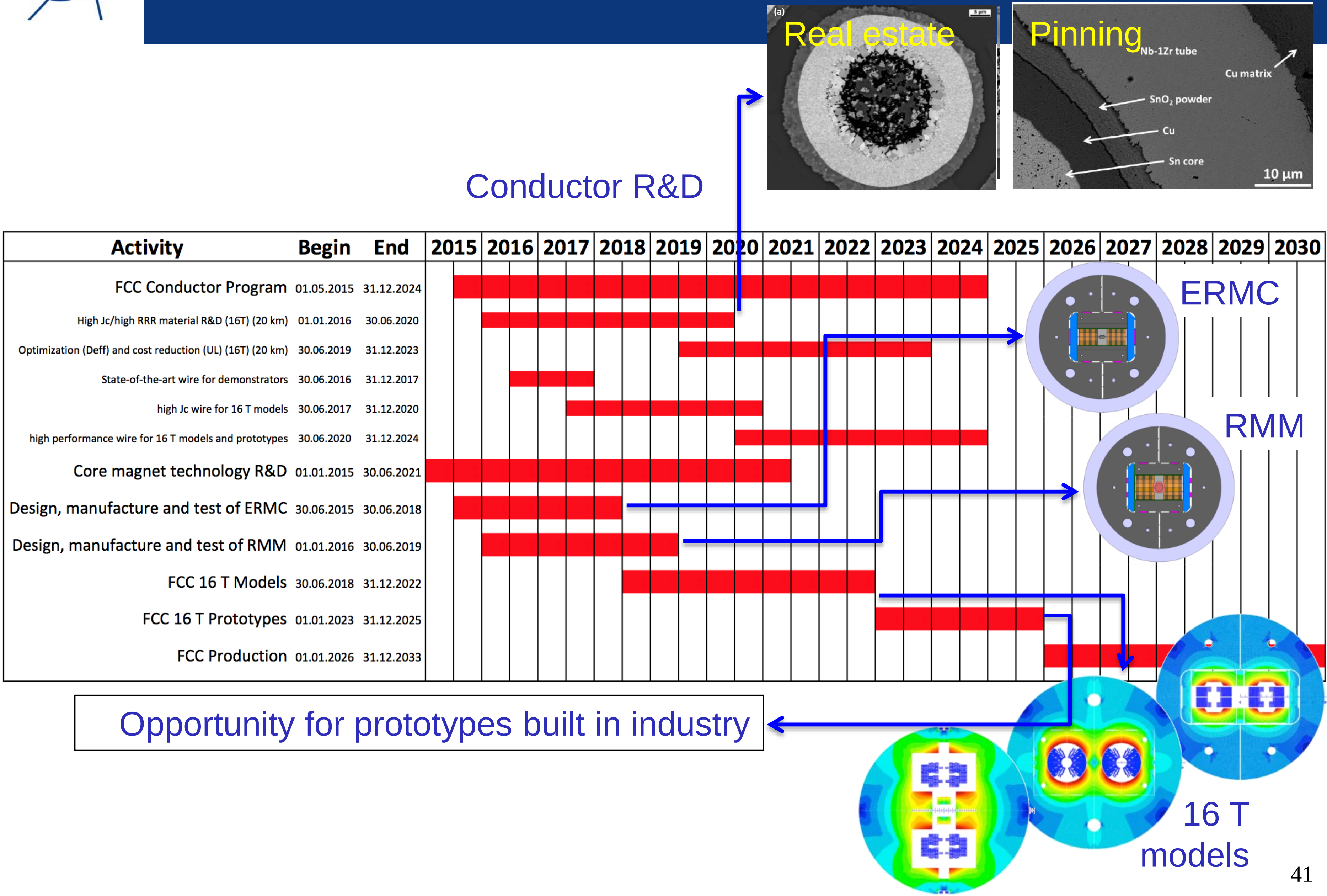
Engineering design of the FCC accelerator dipole (assuming high-performance wire)

Engineering design of 16T dipole model for the following R&D program (assuming existing wire performance)(*)

Manufacturing folder for 16 T dipole model

Manufacturing folder for the 16 T dipole model construction tooling(*)

FCC plan for 16T baseline



Conductor R&D

Activity	Begin	End	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
FCC Conductor Program	01.05.2015	31.12.2024	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥						
High Jc/high RRR material R&D (16T) (20 km)	01.01.2016	30.06.2020		🟥	🟥	🟥	🟥	🟥										
Optimization (Deff) and cost reduction (UL) (16T) (20 km)	30.06.2019	31.12.2023					🟥	🟥	🟥	🟥	🟥							
State-of-the-art wire for demonstrators	30.06.2016	31.12.2017		🟥	🟥													
high Jc wire for 16 T models	30.06.2017	31.12.2020			🟥	🟥	🟥	🟥										
high performance wire for 16 T models and prototypes	30.06.2020	31.12.2024						🟥	🟥	🟥	🟥	🟥						
Core magnet technology R&D	01.01.2015	30.06.2021	🟥	🟥	🟥	🟥	🟥	🟥	🟥									
Design, manufacture and test of ERMC	30.06.2015	30.06.2018	🟥	🟥	🟥	🟥												
Design, manufacture and test of RMM	01.01.2016	30.06.2019		🟥	🟥	🟥	🟥											
FCC 16 T Models	30.06.2018	31.12.2022				🟥	🟥	🟥	🟥	🟥								
FCC 16 T Prototypes	01.01.2023	31.12.2025									🟥	🟥	🟥					
FCC Production	01.01.2026	31.12.2033												🟥	🟥	🟥	🟥	🟥

ERMC

RMM

Opportunity for prototypes built in industry

16 T models

FCC Nb_3Sn performance targets

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

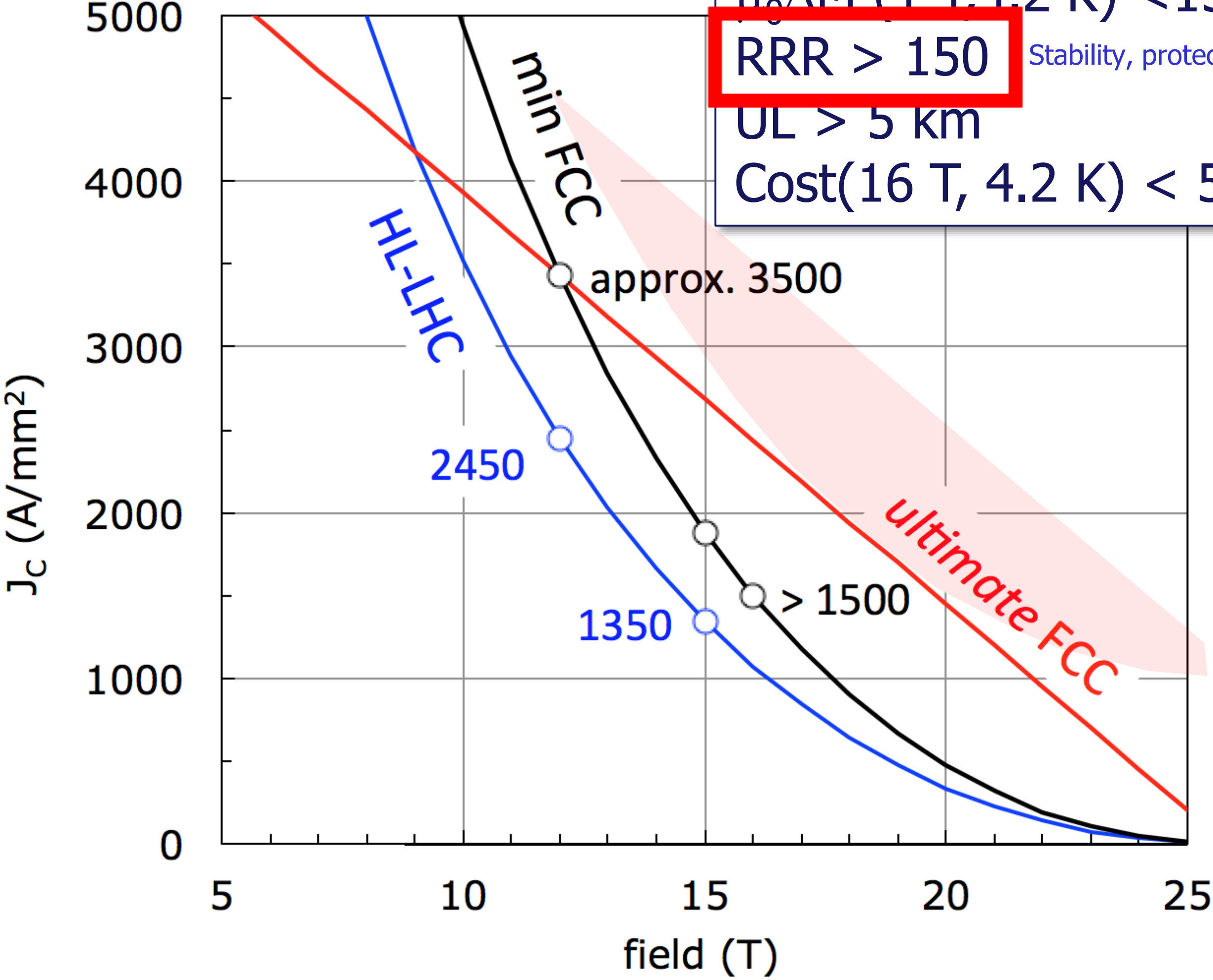
J_C (16 T, 4.2 K) > 1500 A/mm^2

$\mu_0\Delta M$ (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

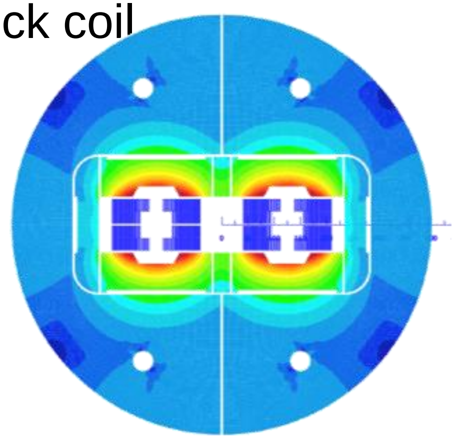
(D. Dietrich and R. Scanlan, A. Godeke)

FCC Conductor R&D Program

- Four year's program (2016-2019) focused on the increase of J_C(16 T, 4.2 K) ≥ 1500 A/mm2 with high RRR ≥ 150
- At this stage all "expedients" are considered: maximize Nb_3Sn fraction, grain refinement, APC
- Worldwide R&D, coordinated by national institutes:
  - EU – CERN: BEAS
  - JA – KEK: SH Copper, Furukawa, JASTEC; Tohoku University, NIMS
  - RU – Bochvar: TVEL
  - KO – KAT: Kiswire
- Material characterization and advanced analysis
  - EU – Technische Universitaet Wien (Atominstitut)
  - US – ASC at NHMFL

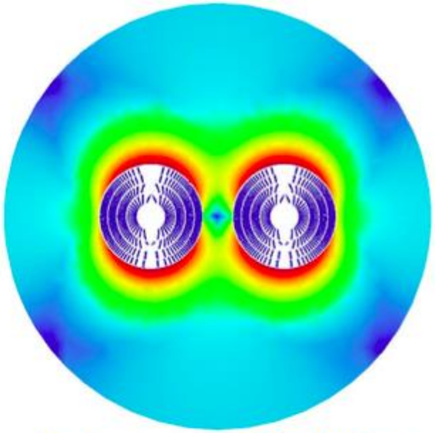
FCC: 16T dipole options

Block coil



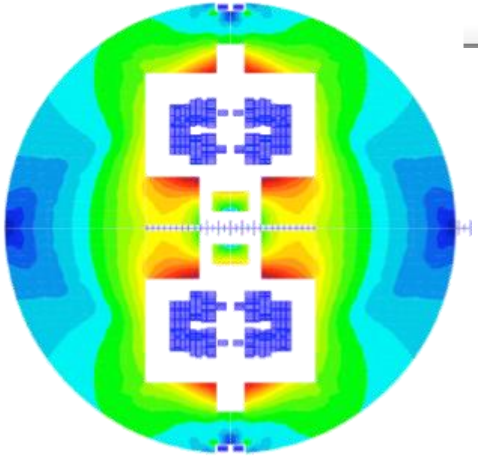
C. Lorin, M. Durante (CEA)

Canted Cos-theta



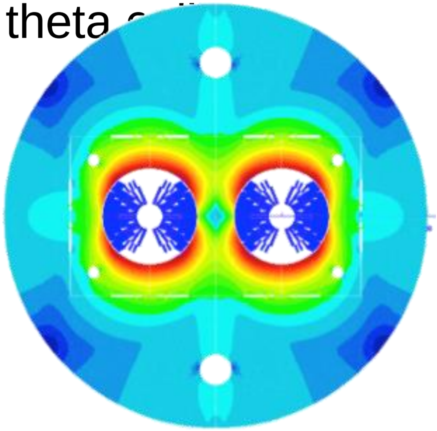
B. Auchmann (CERN/PSI)

Common coils



F. Toral (CIEMAT)

Cos-theta



S. Farinon, P. Fabbricatore (INFN)

FCC 20T option: HTS program

Early phase: EuCARD HTS insert magnet (2009 – 2016)

First step to an HTS accelerator magnet: EuCARD2 (2013 –)

  10kA rated ReBCO cable (Roeble cable)

  5T stand alone accelerator quality ReBCO magnet

We are now starting a long term HTS magnet development program at CERN and collaborating institutes (2016 – 2024)

FCC 20T option: HTS program

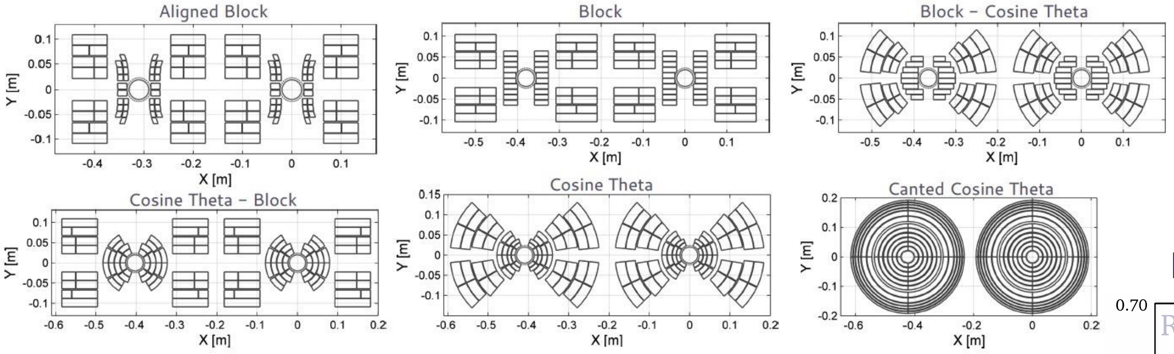
Preliminary HTS magnet development program

Activity	Begin	End	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
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							▨	▨	▨	▨						

HTS program:

- Based (for the moment) on ReBCO tape conductor
  - Cables types to be developed (Roebel, tape stack, CORC, ...)
- Continue to EuCARD2 work
- Conceptual Layout study
- Sub-scale magnet to test the new layouts
- Design and build models

FCC 20T option: HTS program



The HTS program comprises a study of all possible 20 T magnet layouts.

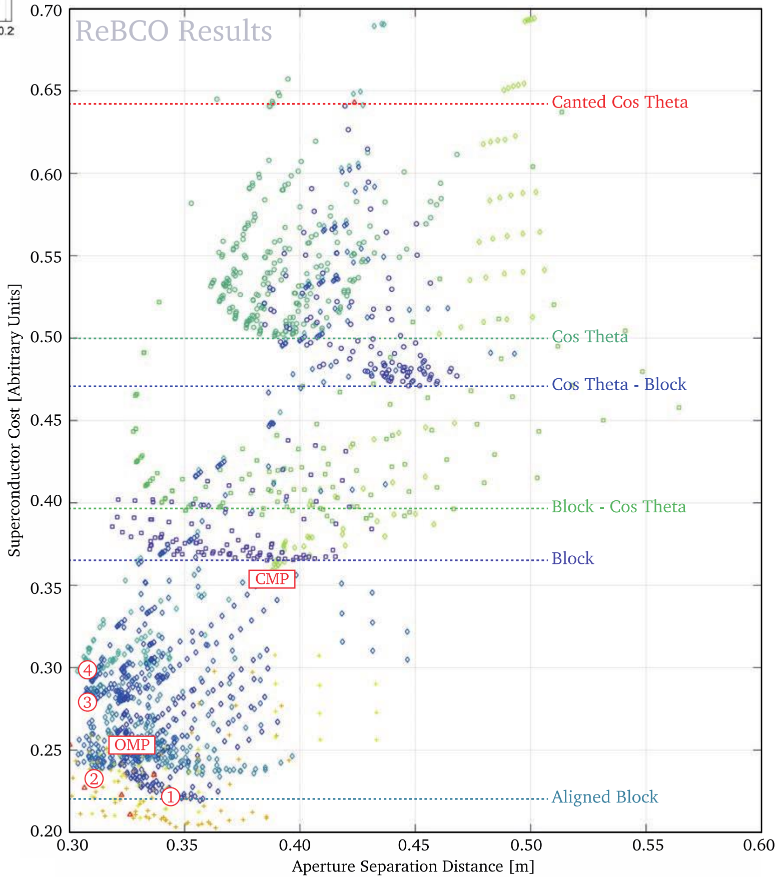
- Generate all possible combinations of inner (ReBCO) HTS inner part coil with Nb_3Sn and Nb-Ti outer parts
- Optimize for conductor amounts (=cost)

Study to be continued in 2017-2018

Should produce a few ‘best’ feasible layouts that can then be designed and (model) constructed at CERN and in EU labs

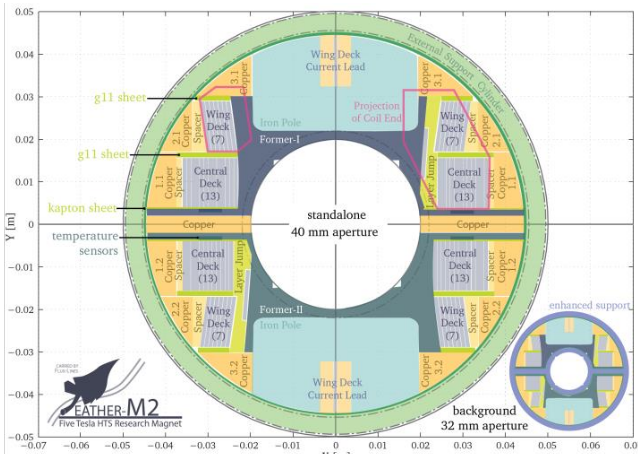
(eg. CEA, CIEMAT, INFN, etc...)

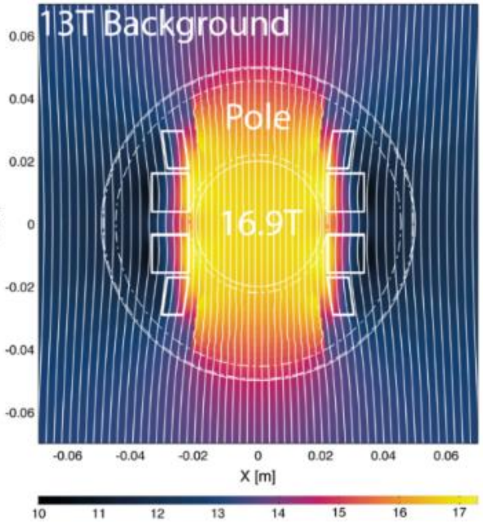
PhD , J. van Nugteren, U Twente & CERN

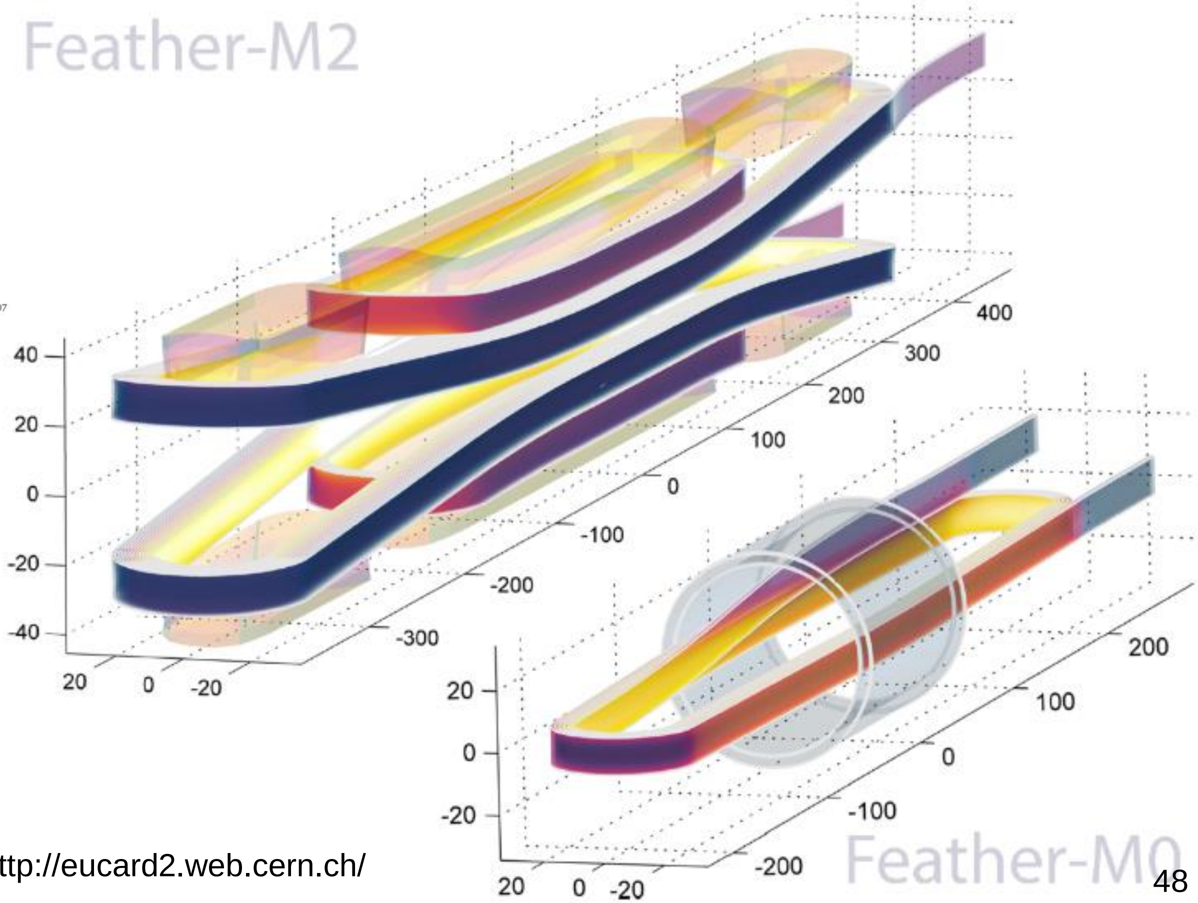


EuCARD2 5T accelerator quality ReBCO magnet

5 Tesla stand alone, (18 T–20 T in 13 T background or other), @ 4.5K, 40 mm aperture, 10 kA class cable, Accelerator Field quality



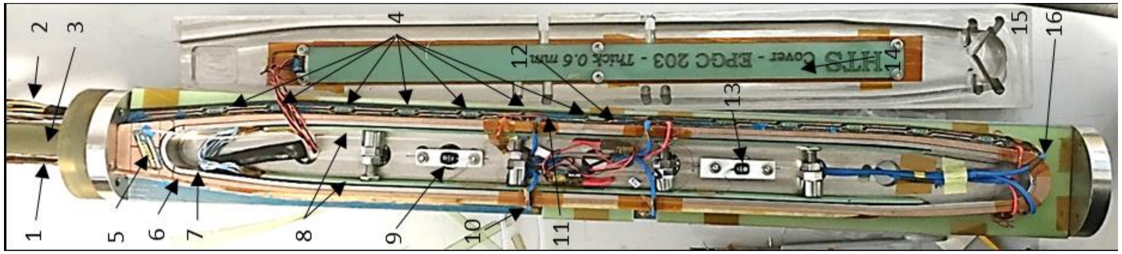


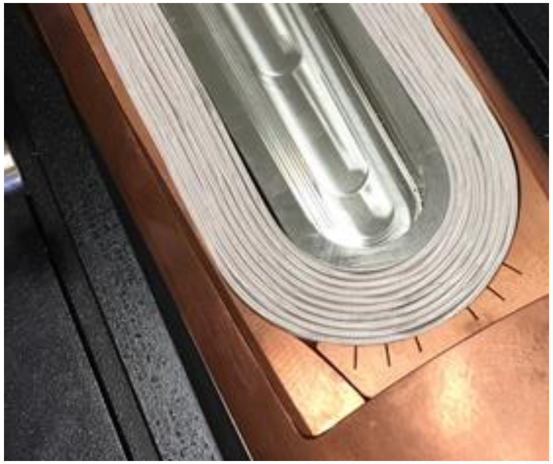


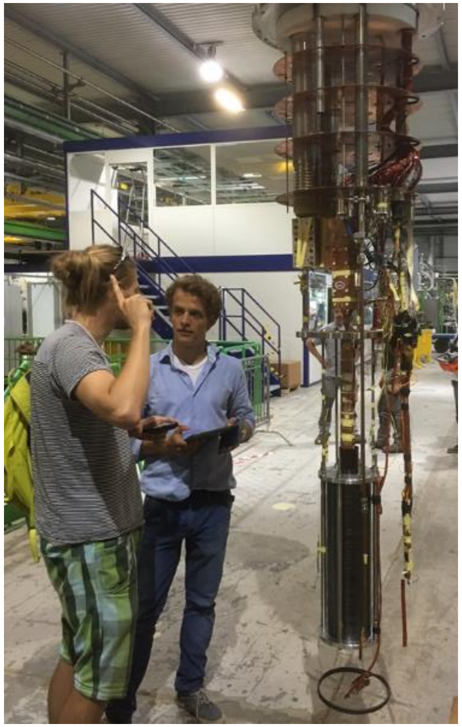
http://eucard2.web.cern.ch/

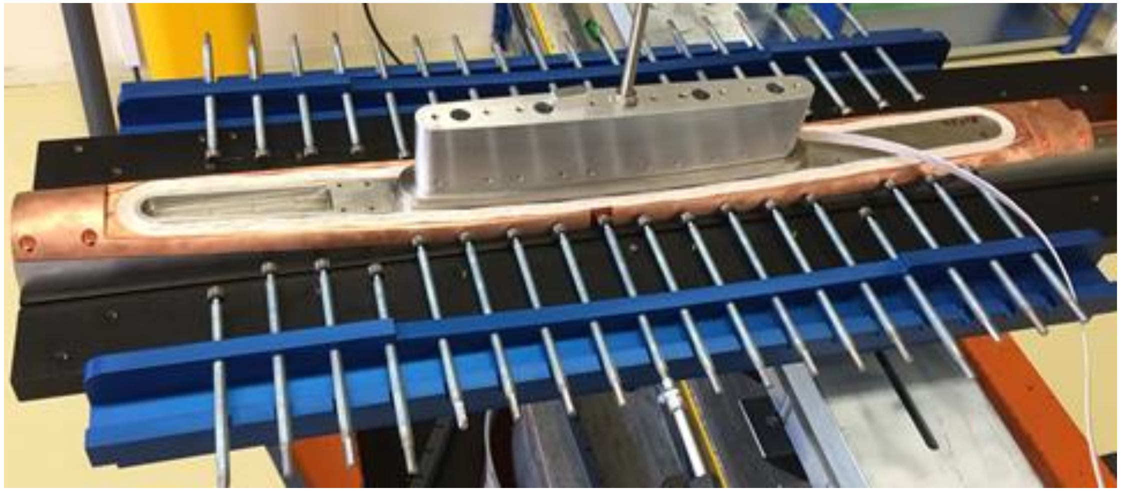
Feather0 - Feather-M2.0

- Feather0: First coil in the test station
- Feather2: winding of first coil with dummy cable in progress

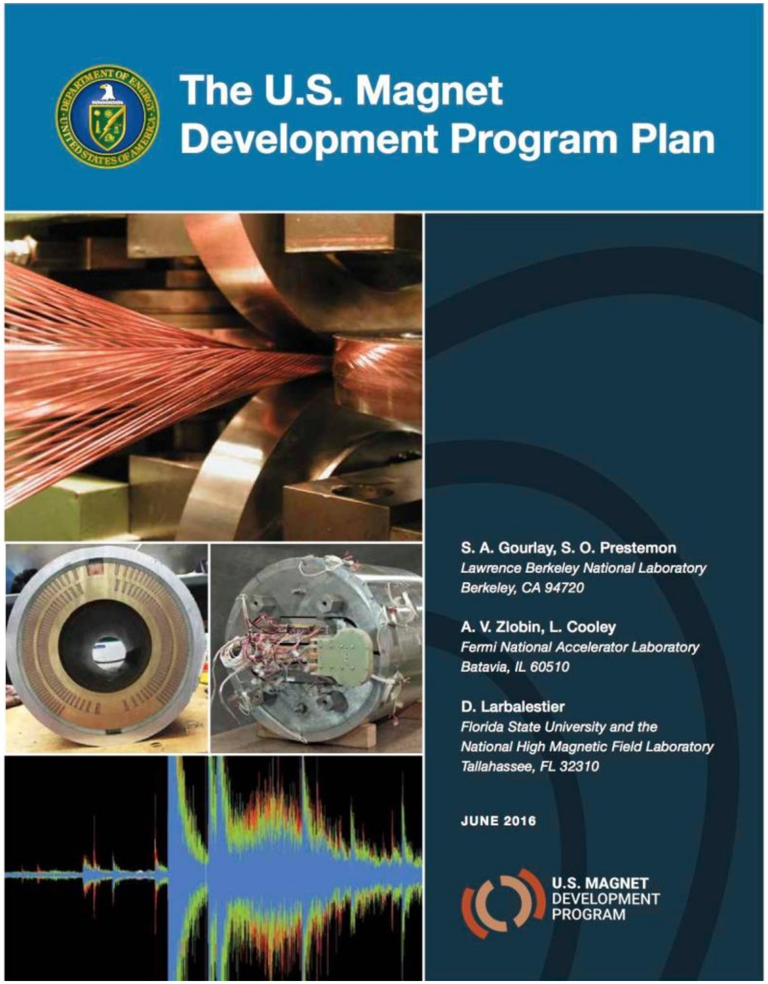








US magnet development plan



The U.S. Magnet Development Program Plan

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JUNE 2016

U.S. MAGNET
DEVELOPMENT
PROGRAM

By courtesy of S. Gourlay (LBNL), June 2016

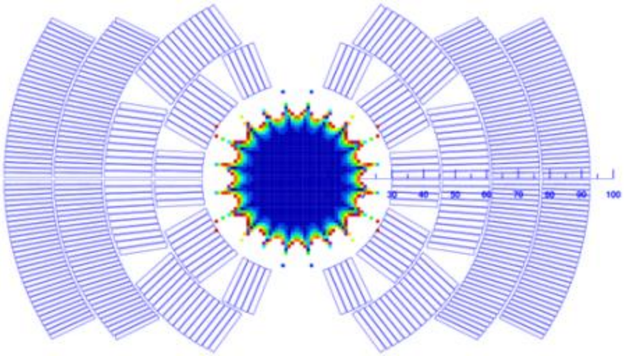
Four development goals:

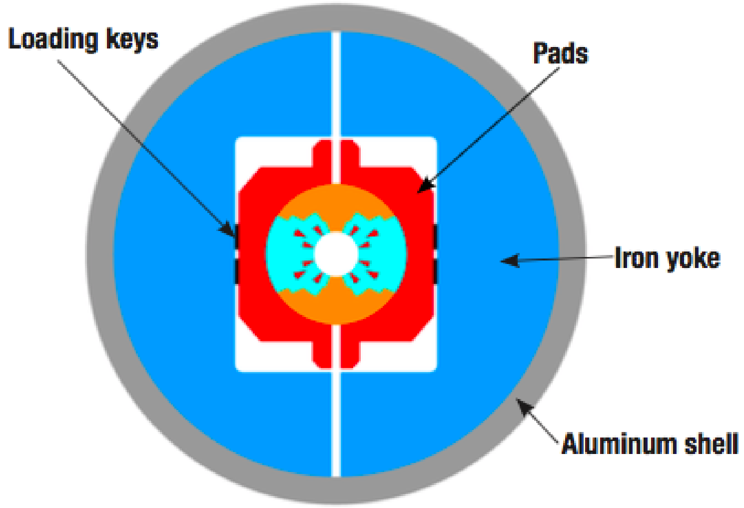
1. Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.
2. Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.
3. Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.
4. Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

US development lines for 16T Nb_3Sn dipoles

- Cosine-Theta

Design study started in 2015 at FNAL based on previous experience with CosTh magnets



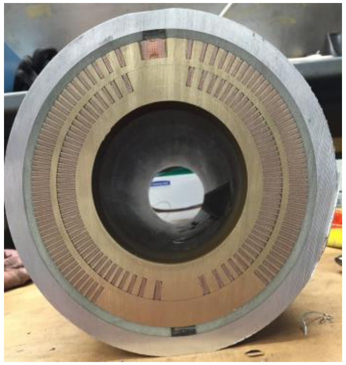


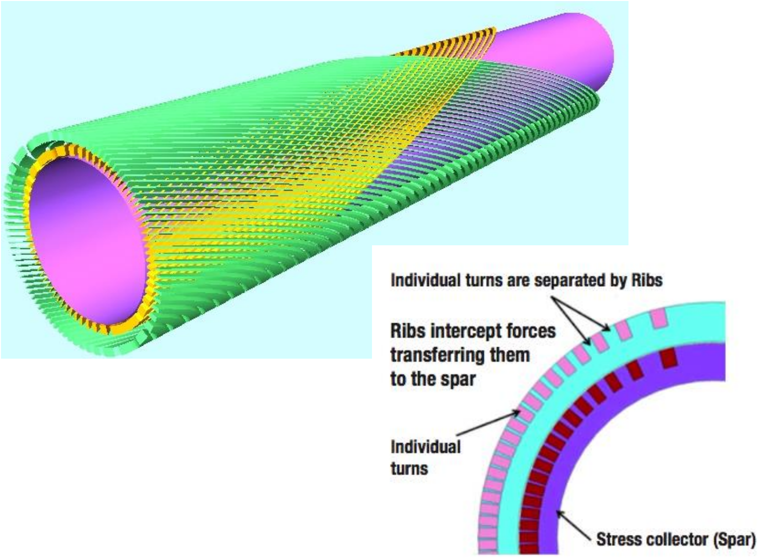
- Canted-Cosine-Theta (CCT) (LBNL)

Program running since several years.

2 layer 4.6 T Nb-Ti working

Working on 2 layer 7.8 T Nb_3Sn and stepping up to 4-6-8 layers by 2019



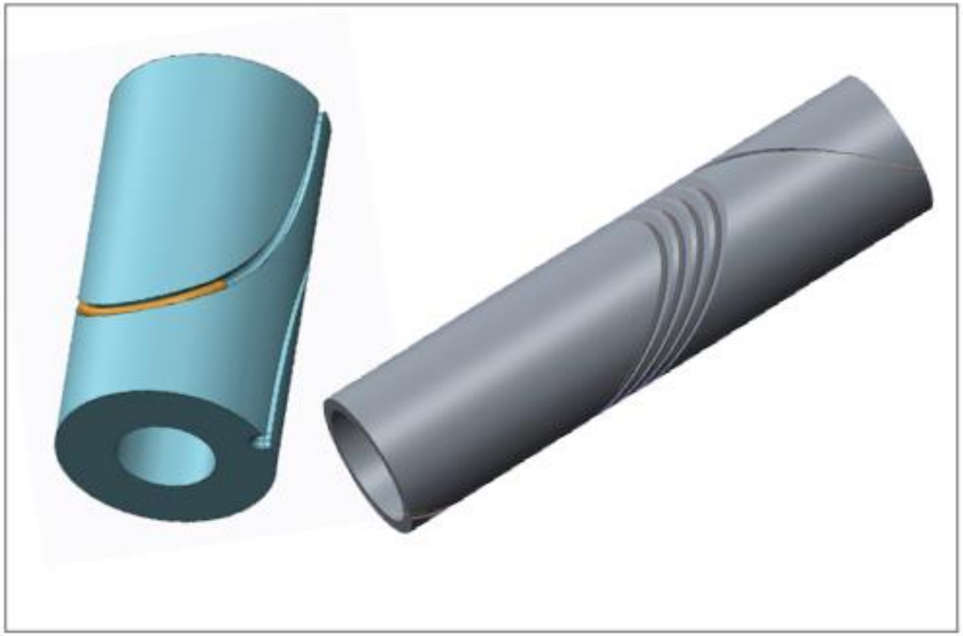


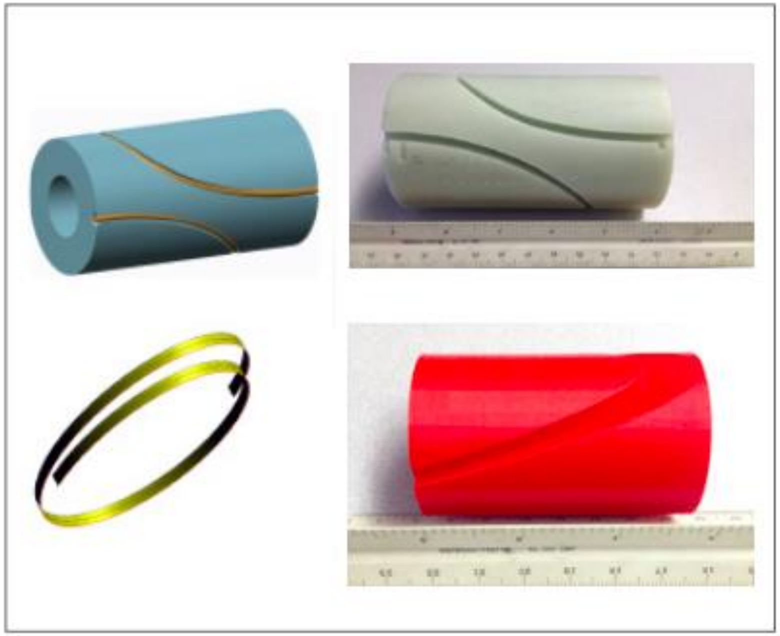
US development lines for 20T HTS-LTS dipoles

5 T stand alone models that can reach 20T in an 15T outsert

- Bi-2212 dipoles in CCT coil configuration

- ReBCO dipole and quadrupole models: tapes in various cable types (stacked tape, CORC, ...) in CCT or racetrack coil configuration

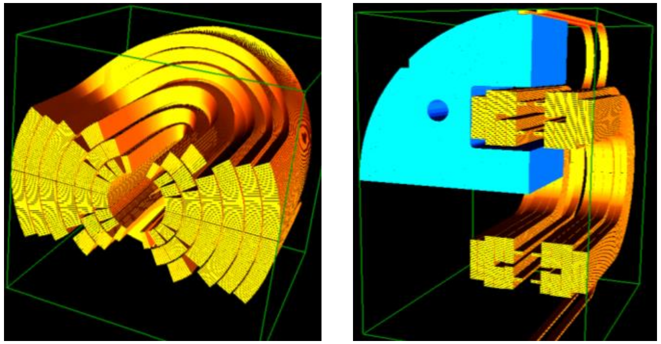


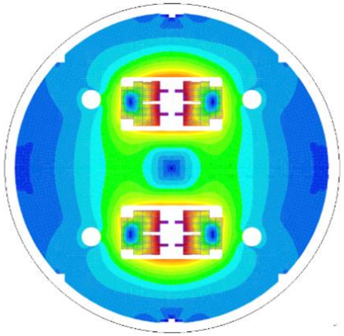


Chinese magnet development program

Design Study of the SPPC Dipole Magnet

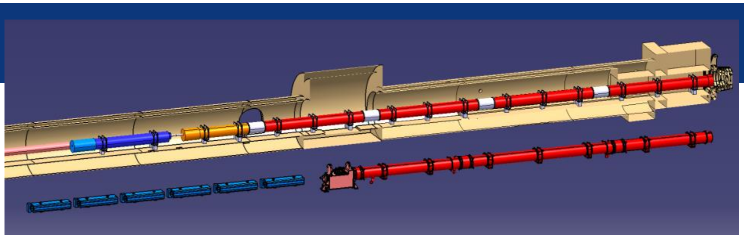
- Started in 2014 with a new group being formed in Beijing and work shared between institutes and firms in Beijing, Hefei, Xi’an and Shanghai
- Have started conductor development
- Are comparing several concepts: “Cosine-Theta vs “Common Coil”
- Defined a step wise approach in the development of a 20T “common coil’ dipole HTS-LTS
- First step: subscale 15T model for 2018 (funded)
- Have started to develop the fabrication of small sub-scale coils



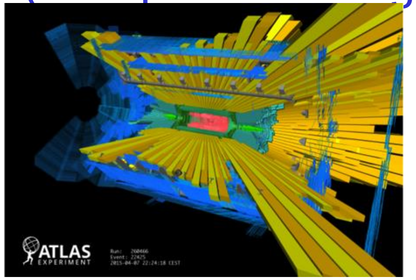


Courtesy Qingjin Xu, IHEP, Beijing

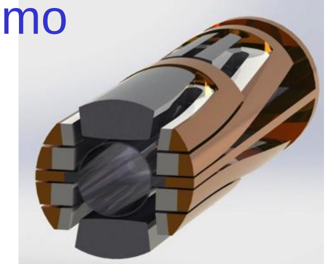
Conclusions



LHC Run-II provides results to define future HEP roadmap (European Strategy 2018)



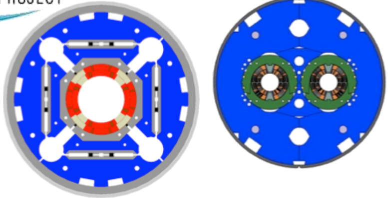
Accelerator-grade HTS 5 T demo

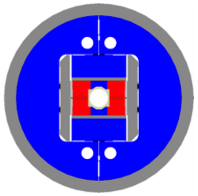


HL-LHC demonstrates large-scale use of Nb_3Sn

End of LHC useful life

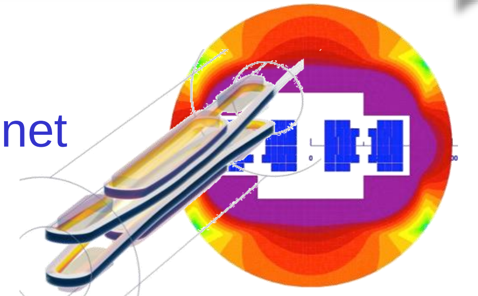
12 T accelerator technology

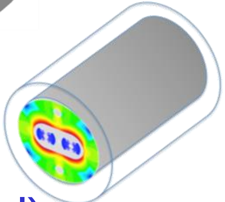




16 T magnet model(s)

20 T magnet model(s)





16 T accelerator technology

FCC CDR (EuroCirCol) propose a new energy frontier accelerator

FCC construction decision