Magnet challenges for FCC-hh

Gijs de Rijk
CERN
Workshop "Accelerators Revealing the QCD Secrets”
Thessaloniki
4 September 2016

Contents

- Very short intro on superconductors and SC magnets
- The early High Field Magnet epoch (1986-2004)
- Conductor development
- Basic magnet technology development for HILUMI and beyond (2004-2013)
- The HILUMI magnet development (2013-2016)
- FCC magnet development (2014 - ...)

FCC-hh requested B field levels

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

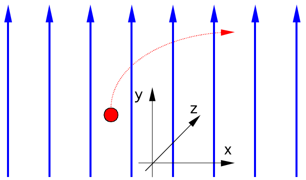
Magnets for Accelerators

- Dipoles

Beam energy **Bending radius**

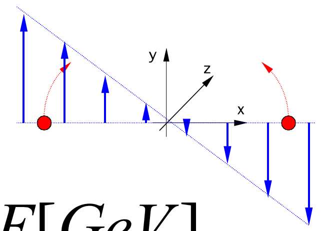
$$E[GeV]=0.3\times B[T]\times \rho[m]$$

Dipole field



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

- Quadrupoles



Beam *size*

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

Emittance

Lorentz factor

FODO cell length

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

Beta function

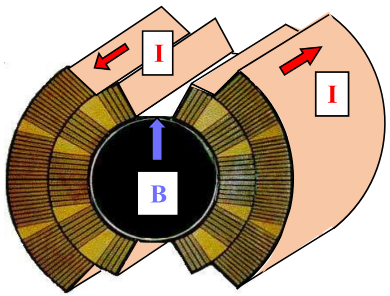
Integrated quadrupole gradient

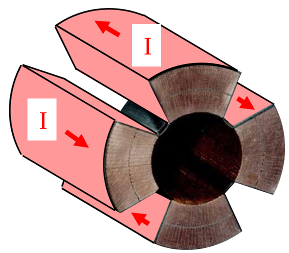
$$G\ell_q[T]=\frac{\sqrt{2}E[GeV]}{0.3L[m]}$$

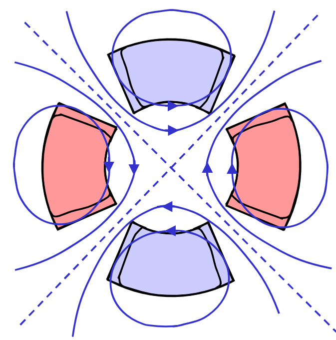
  - Design for the largest feasible integrated gradient to reduce the magnet bore size, and gradient to increase the dipole filling factor

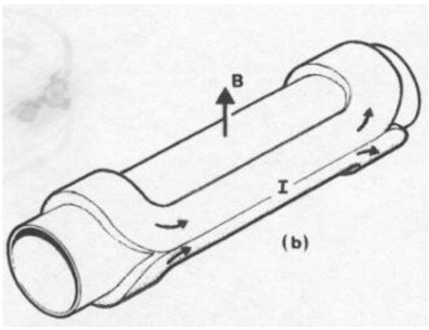
What is specific about accelerator magnets ?

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





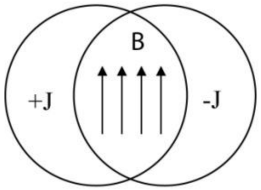




Artist view of a dipole, from M. N. Wilson « Superconducting Magnets »

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

CosΘ coil : $J = J_0 \cos\Theta$



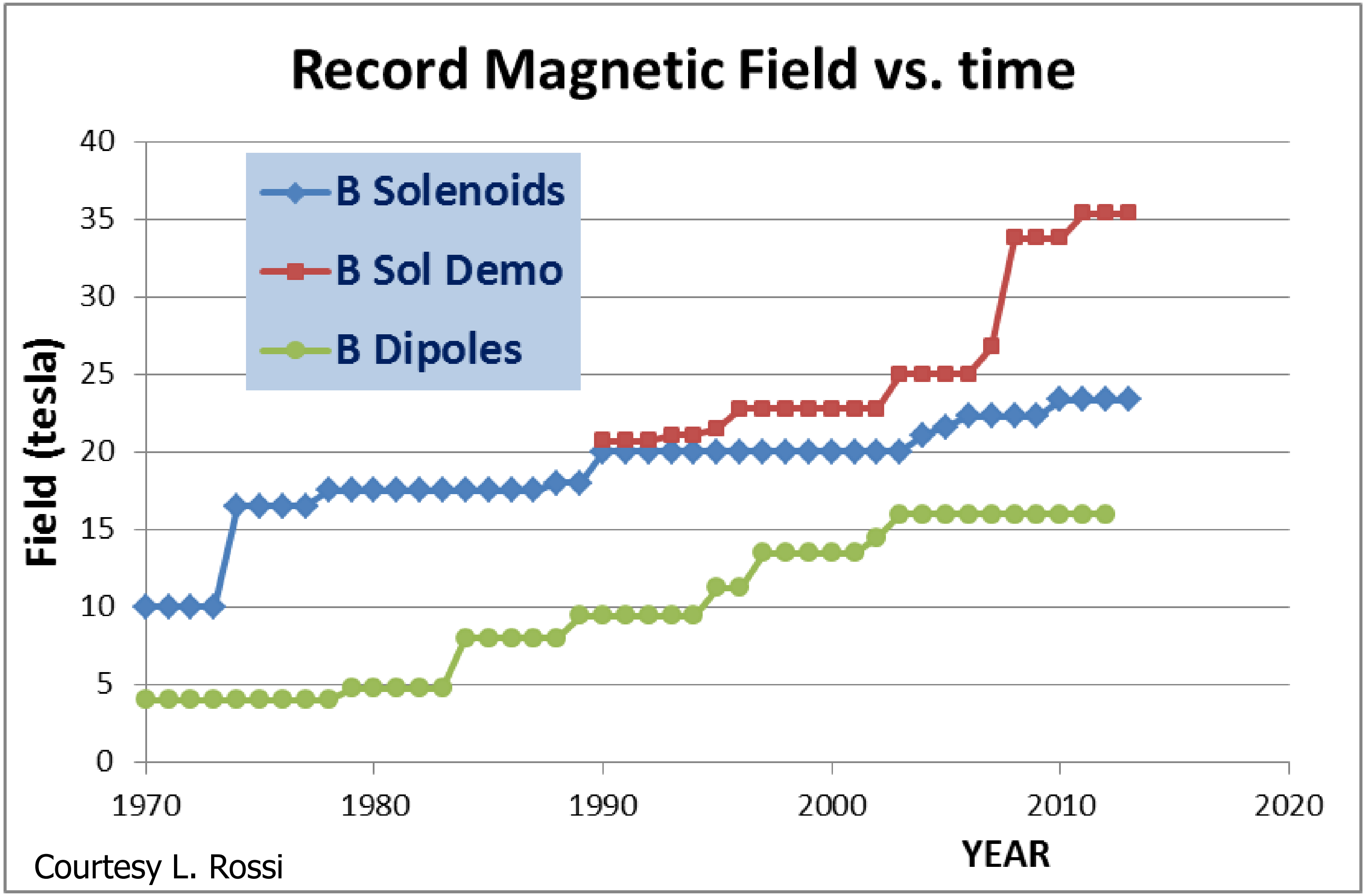
- Field quality formulated and measured in a multipole expansion,

$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1} \qquad b_n, a_n \leq few \cdot units$$

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

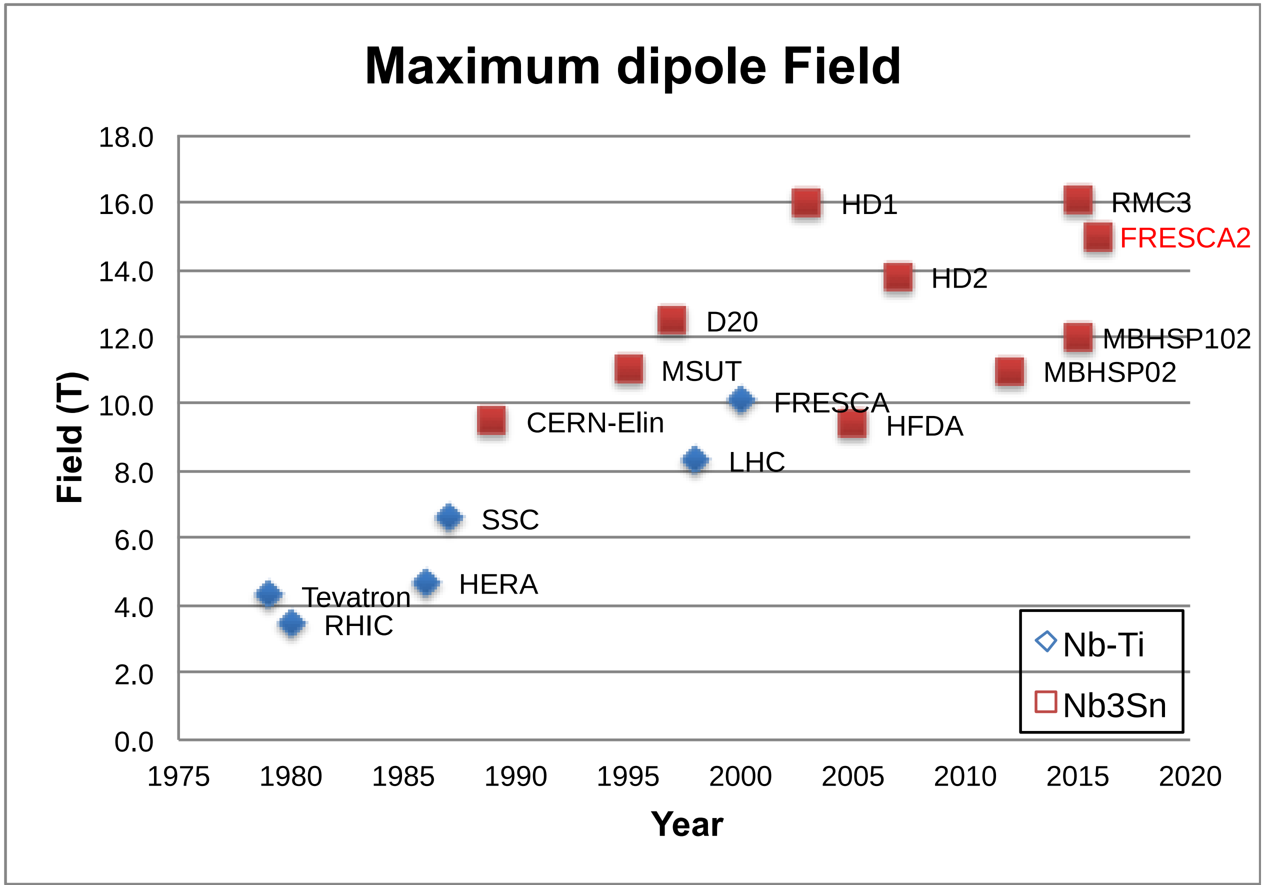
The state of the art:
Comparison between dipoles and solenoids

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



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

Superconductors

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

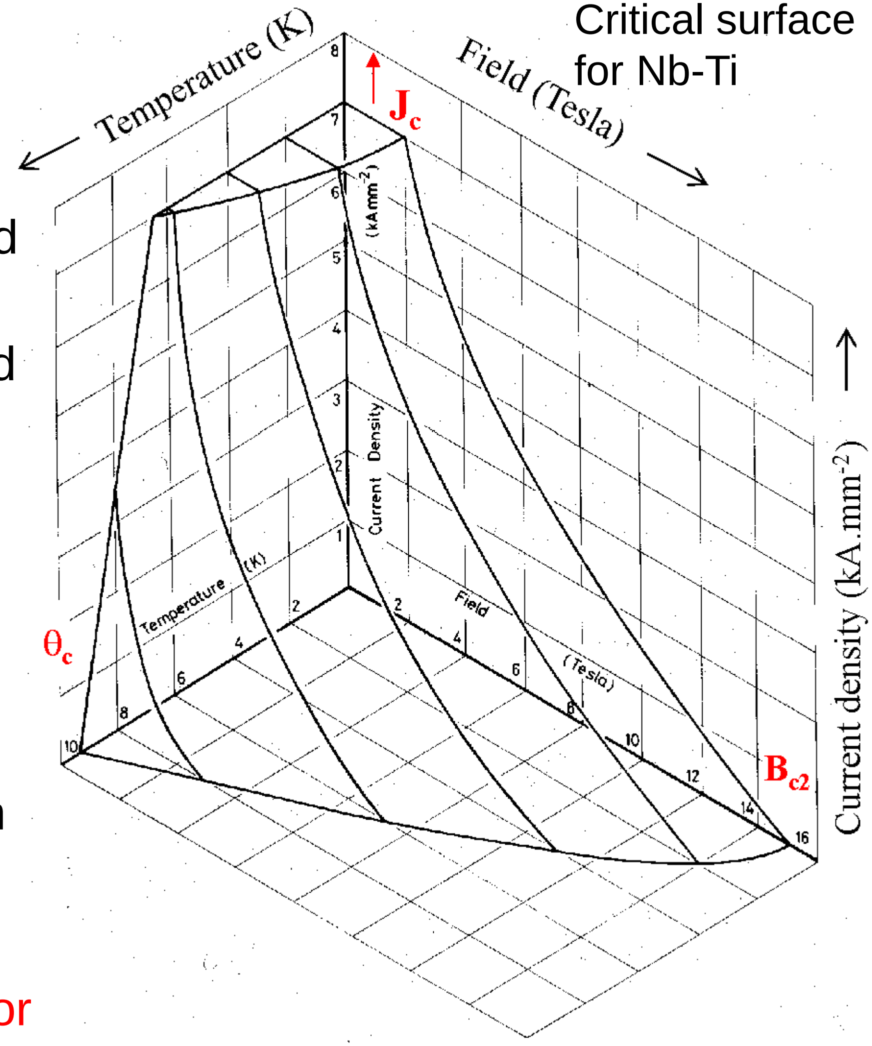
- Θ_c Critical Temperature (at zero field and current density)
- B_{c2} Critical Field (at zero temperature and current density)
- J_c Critical Current Density (at zero temperature and field)

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

Superconductivity is a macroscopic quantum effect. Resistance = 0

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

Critical surface for Nb-Ti



Courtesy M. Wilson

Available Superconductors

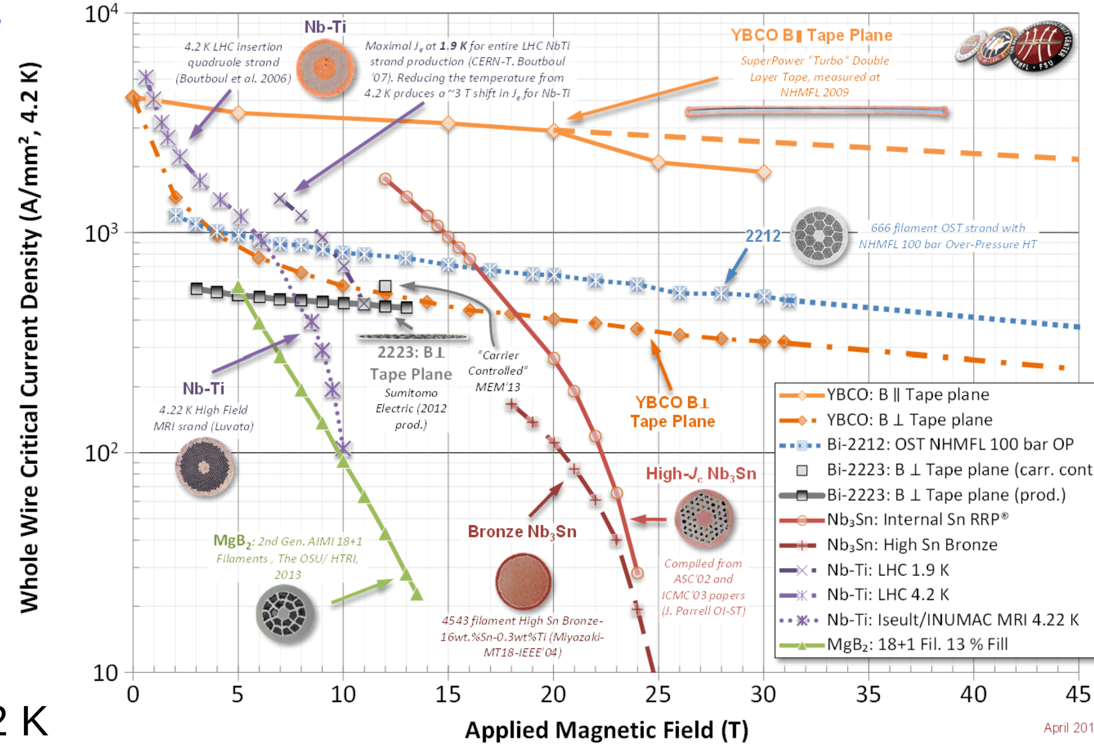
Nb-Ti: the workhorse for 4 to 10 T

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

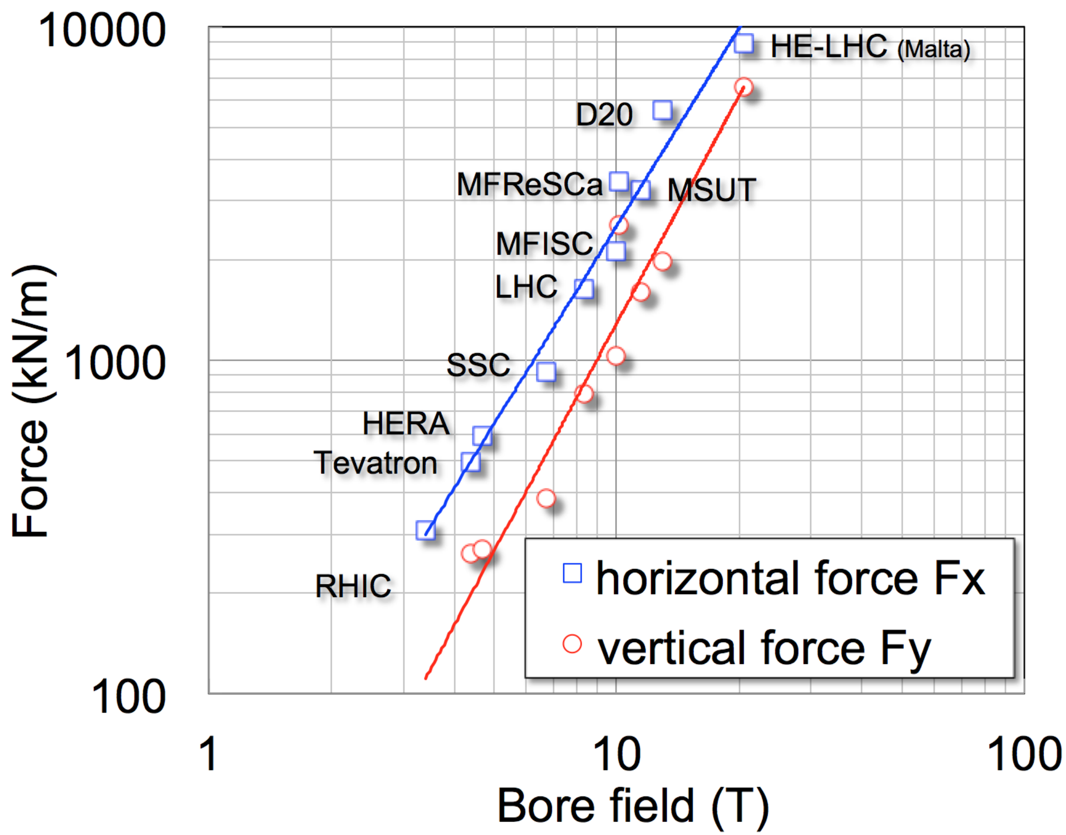
HTS materials: dreaming 40 T (Bi-2212, YBCO)

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 1 model) – small racetracks have been built

Forces

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

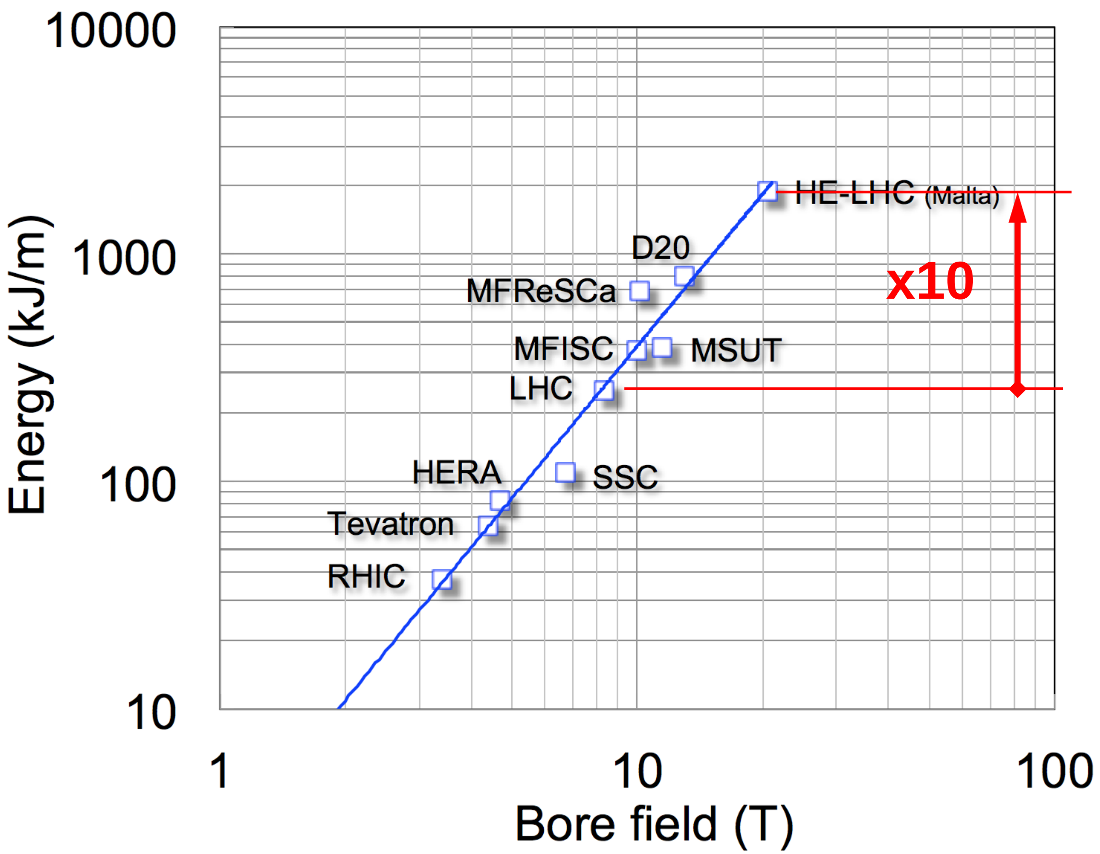


The electromagnetic loads in a 20 T dipole would be a factor 5 to 8 larger than in the LHC dipoles

Stored Energy

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

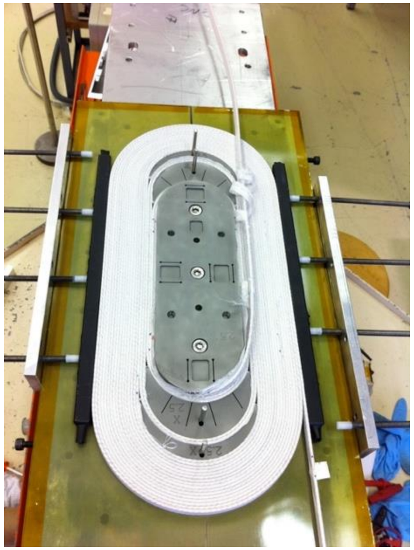
Plot for recent production and R&D dipoles

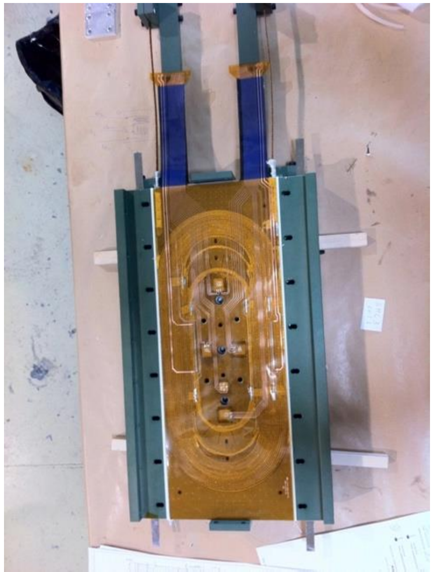


Scaling of the energy per unit length of magnet in recent production vs. R&D dipoles

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

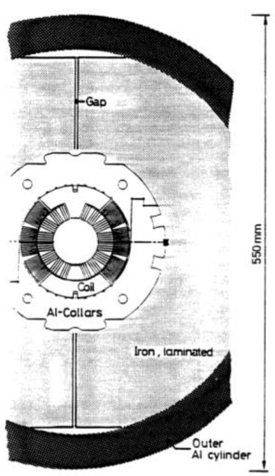


Fig.1: Schematic cross-section of the 1m long full aperture dipole magnet

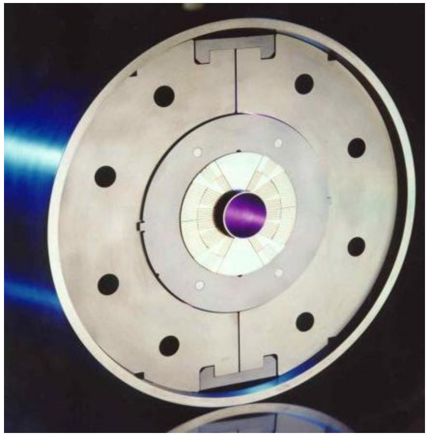
S. Wenger, A. Asner, F. Zerobin, IEEE Trans. Mag, 25(2) 1989

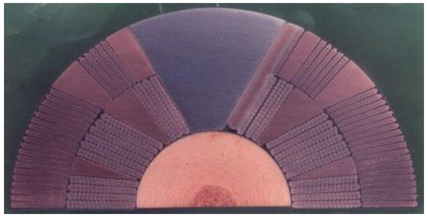
Twente

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.

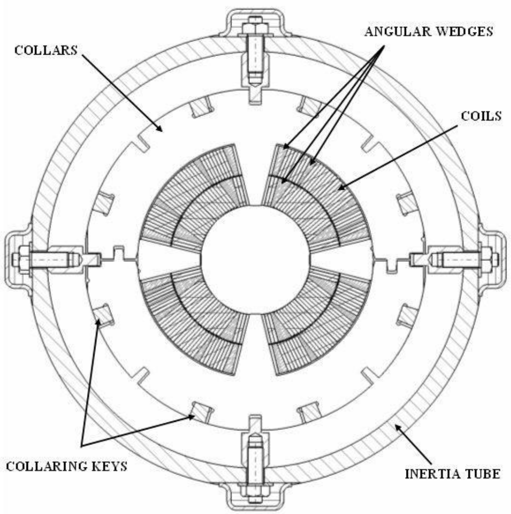
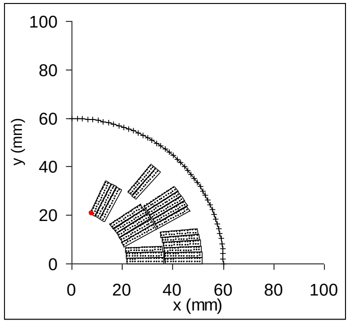
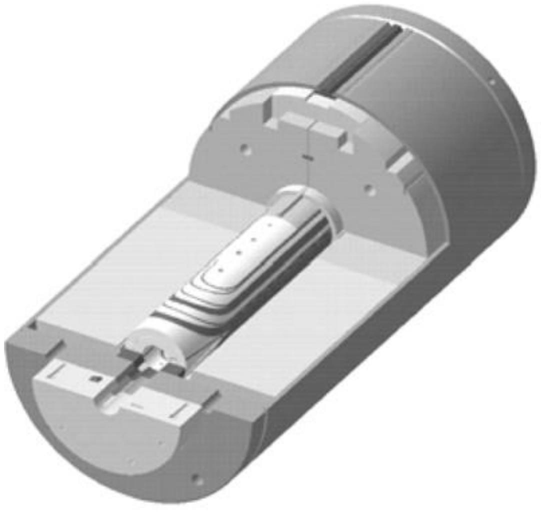


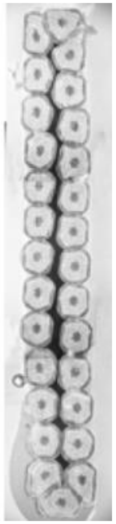
Fig. 4. Cross-sectional view of 56-mm-aperture, 210-T/m Nb_3Sn quadrupole magnet model under development at CEA/Saclay.

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, cosQ 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

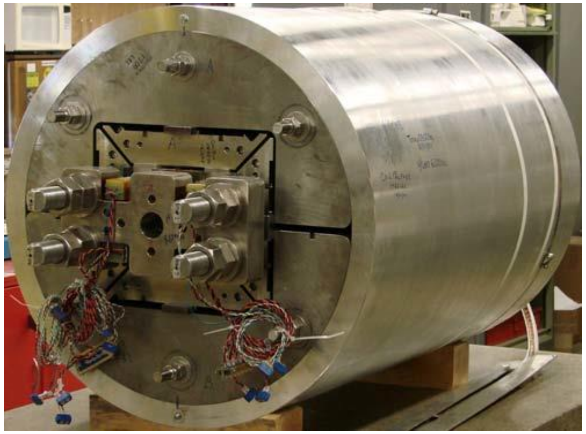


Fig. 1. HD2 assembled and pre-loaded.

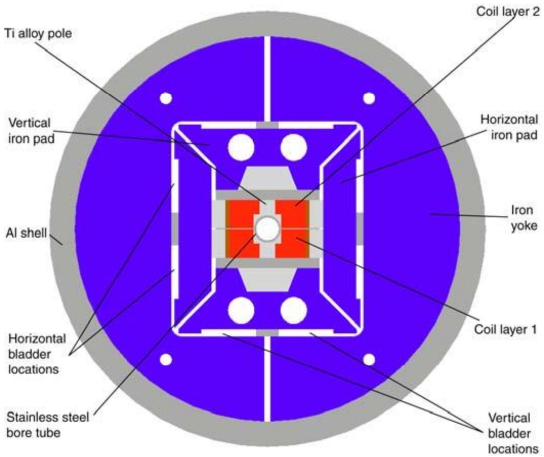
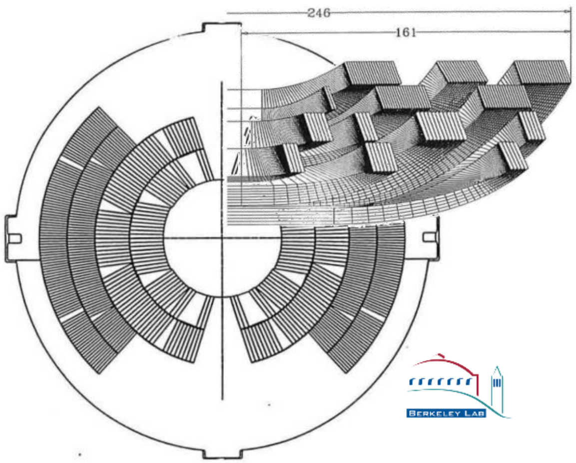


Fig. 2. HD2 cross-section.

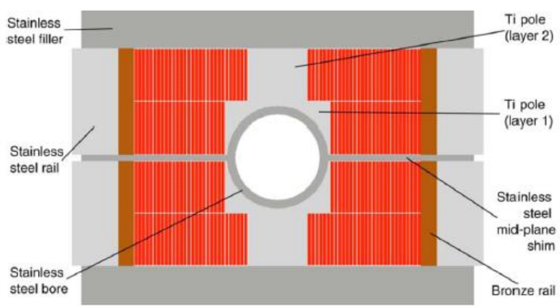


A.D. McInturff, et al., Proc. of PAC 1997, 3212

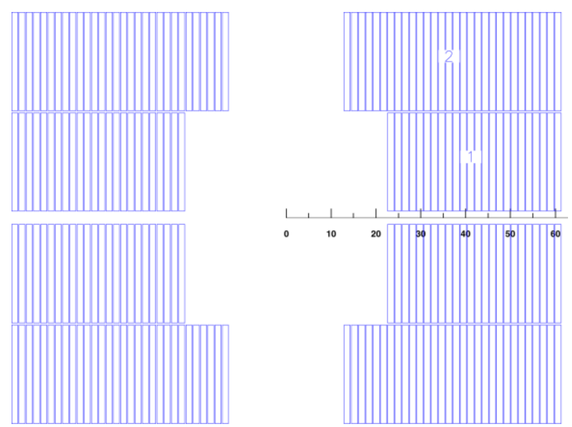
The early High Field Magnet epoch, IV
New geometry: Block coils

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



HD2



Courtesy LBNL

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

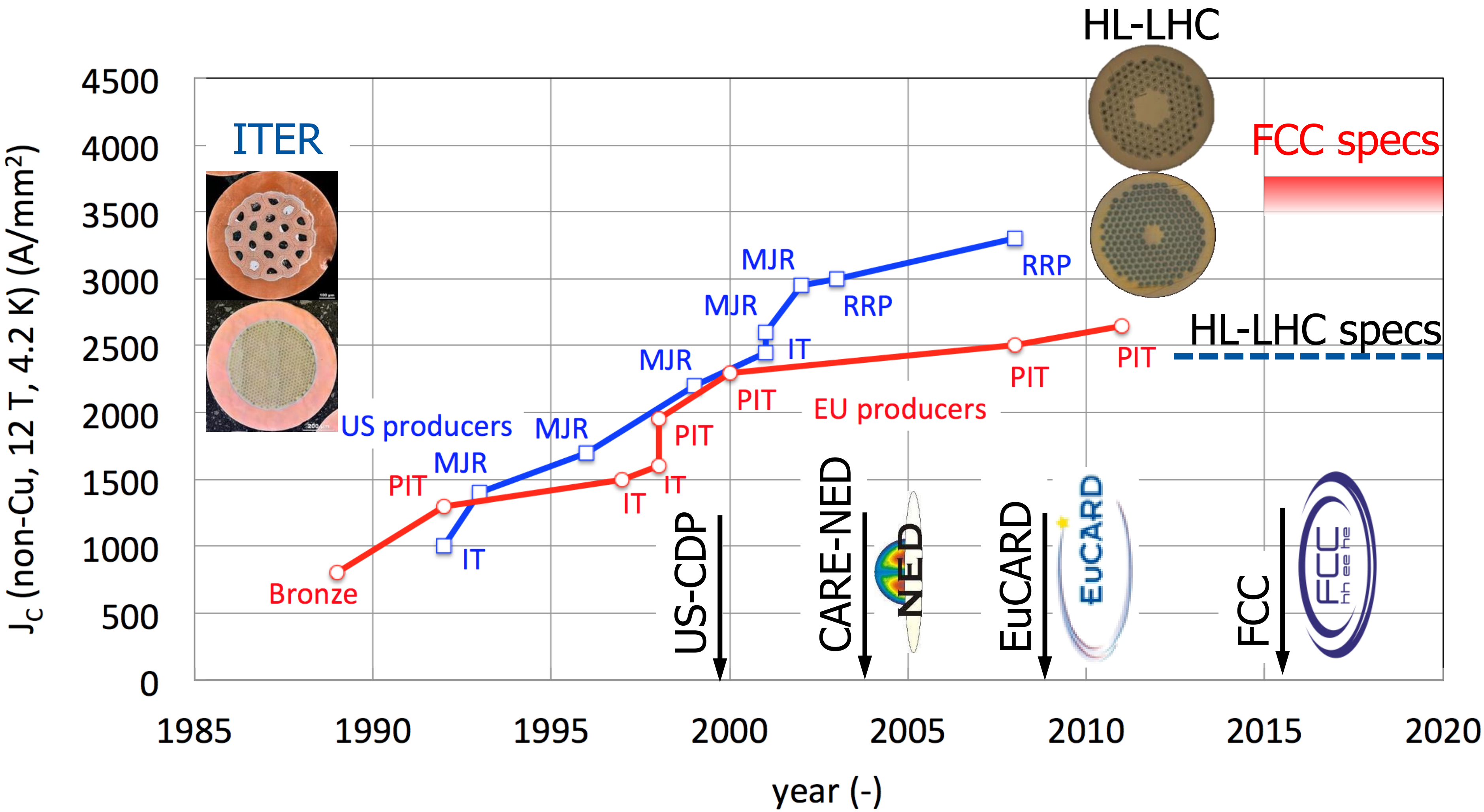
=== It should in principle be possible to go up to 16T with Nb_3Sn===

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 sensitivity can be an issue and is poorly understood
- Construction tooling are critical items, as important as the magnet itself
- Putting a Nb_3Sn coil in a pure Nb-Ti structure does not work
- The coils are very sensitive and fragile
- To get up to high fields other coil geometries and force containment / pre-stress structures will be needed

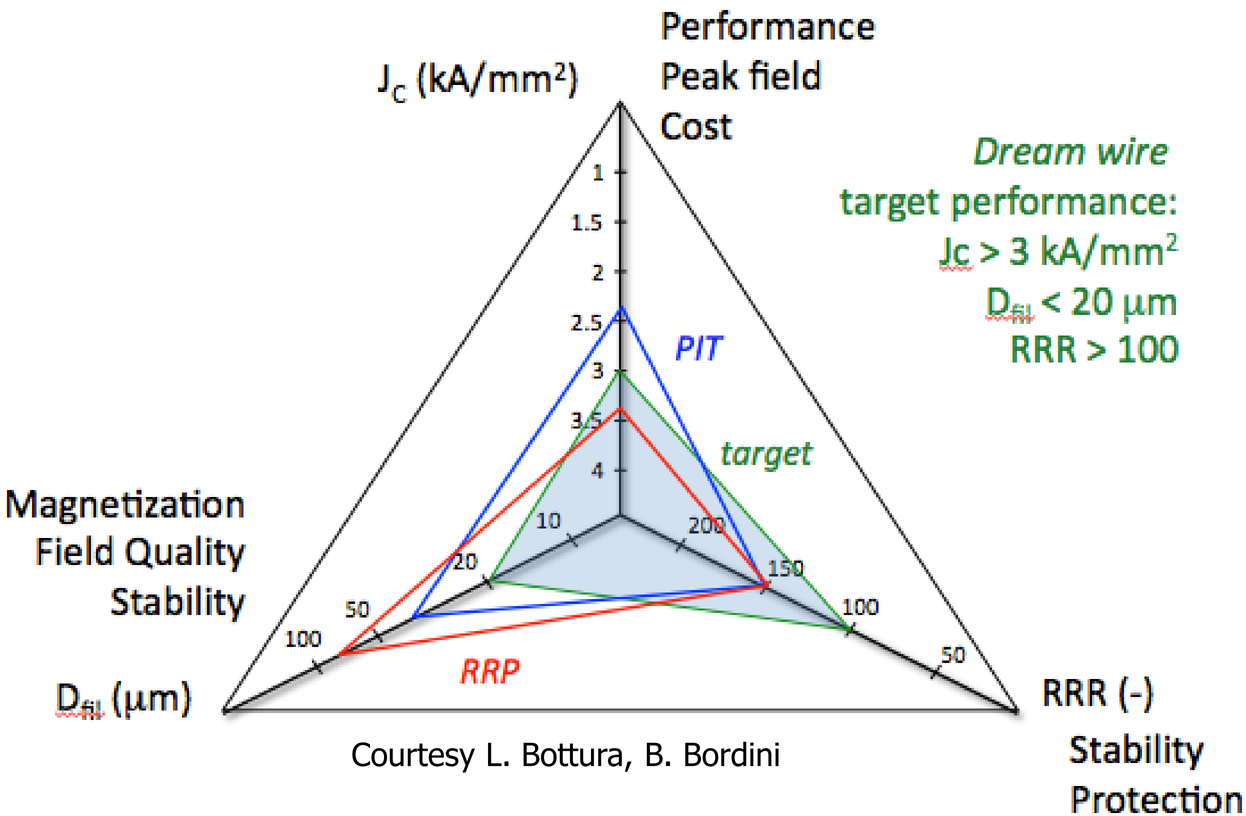
Conductor development (1998-2008)



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

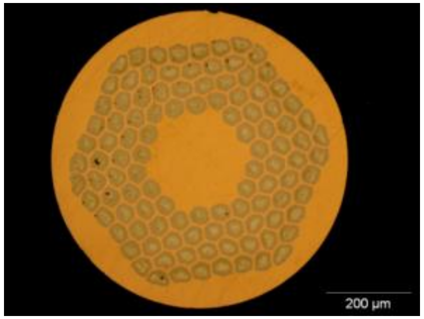
Nb_3Sn Conductor specification for HEP

A Nb_3Sn dream wire for the LHC

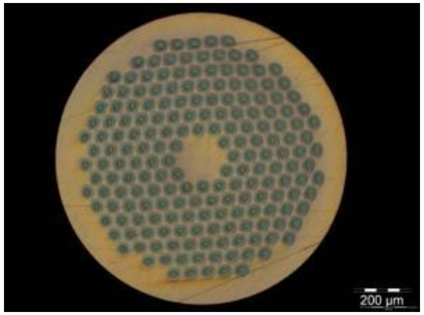


Courtesy L. Bottura, B. Bordini

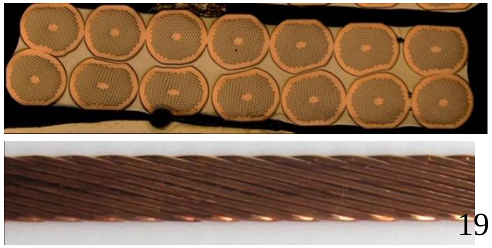
Between HL-LHC and FCC the Jc target shifts from 12 T to 16 T !



0.7 mm, 108/127 stack
RRP from Oxford OST



1 mm, 192 tubes
PIT from Bruker EAS



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

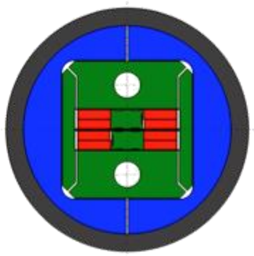
European programs

- 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 ΔB = 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)

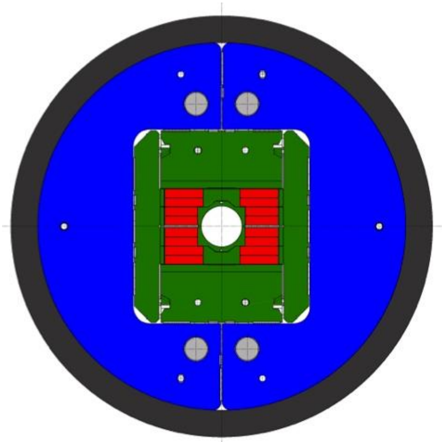
CERN-European development evolution

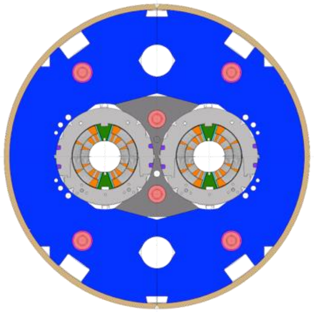
Short Model Coil

Race-track Model Coil



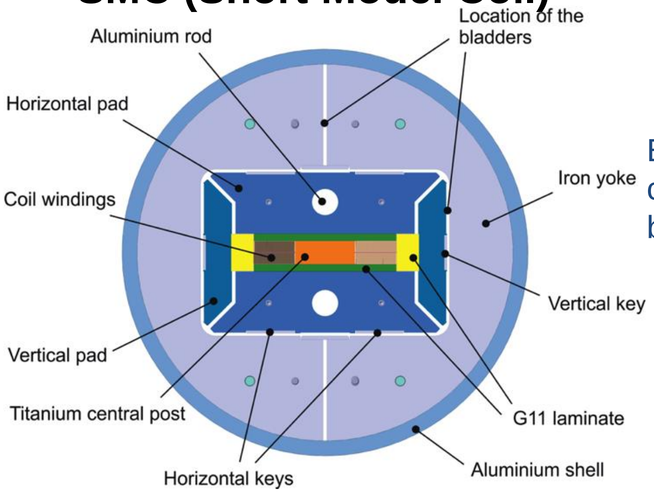
FReSCa2 Nb_3Sn Dipole



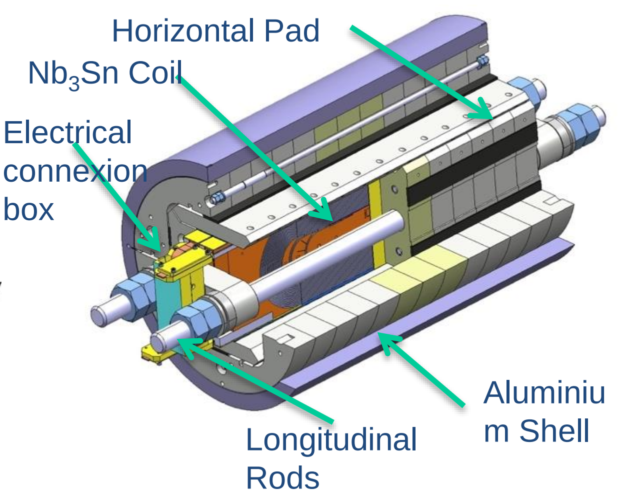


11 T dipole (CERN)

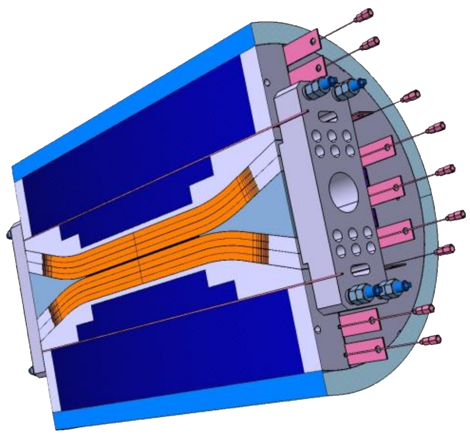
SMC (Short Model Coil)



RMC (Racetrack Model Coil)



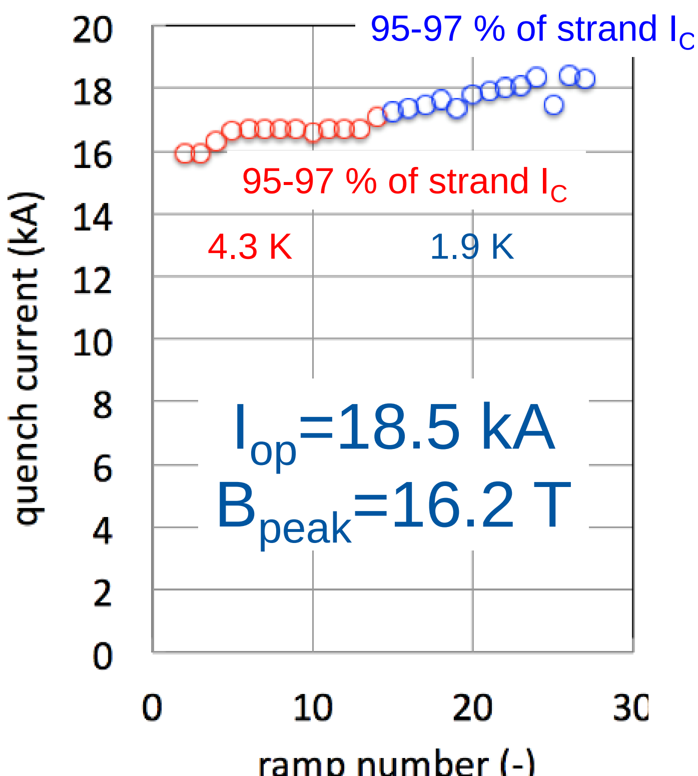
FReSCa2

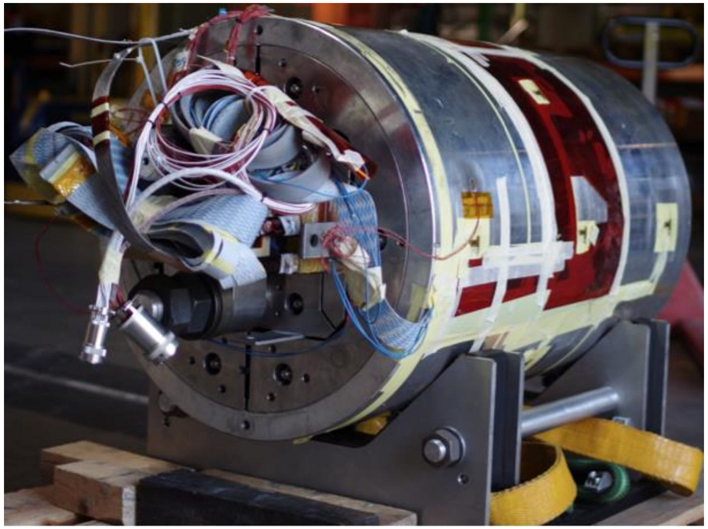


RMC3 16T: first milestone for FCC 16T !

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

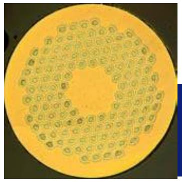
Joining LBNL at the 16T record level





Fresca 2 Dipole cable

40 Strands, Width = 20.9 mm

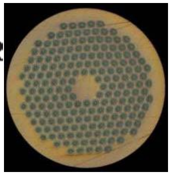


RRP 132/169

OXFORD INSTRUMENTS

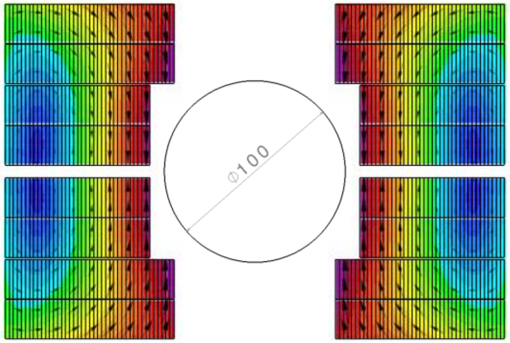
BRUKER

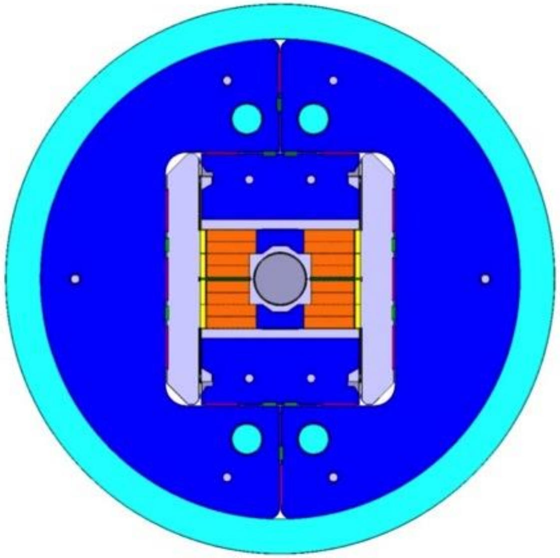
PIT 192



EuCARD high field dipole (FRESCA2)

- FRESCA2 : CERN, CEA construction phase
- First tests end 2015

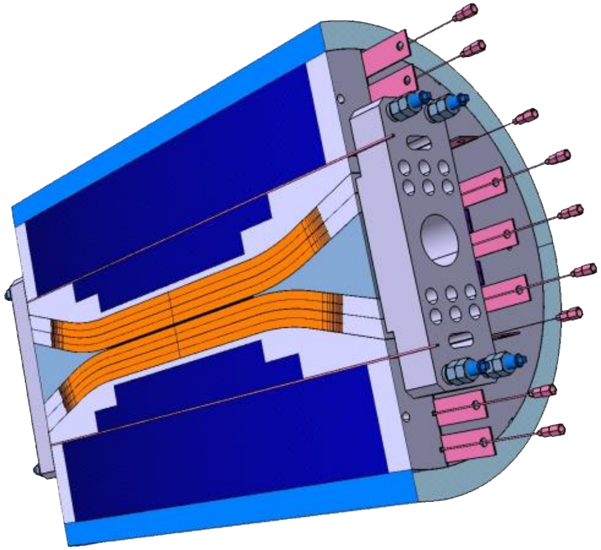


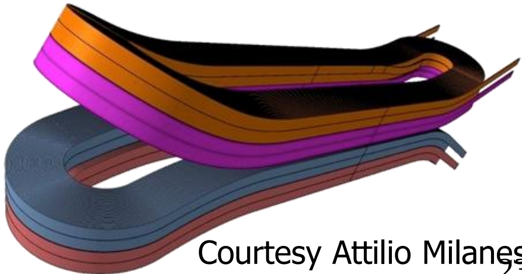


- 156 turns per pole
- Iron post
- B_{center} = 13.0 T
- I_{13T} = 10.7 kA
- B_{peak} = 13.2 T
- E_{mag} = 3.6 MJ/m
- L = 47mH/m

- 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}

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



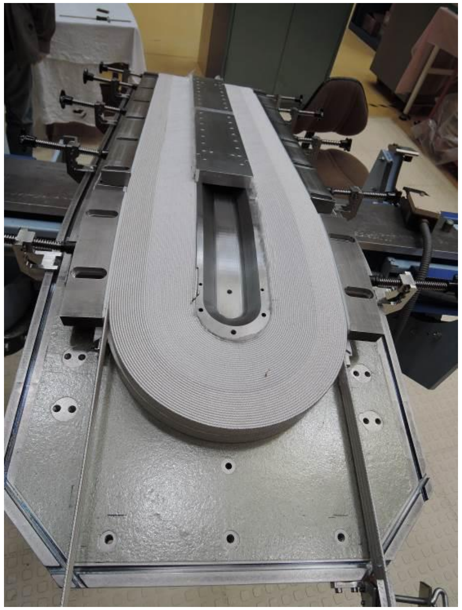


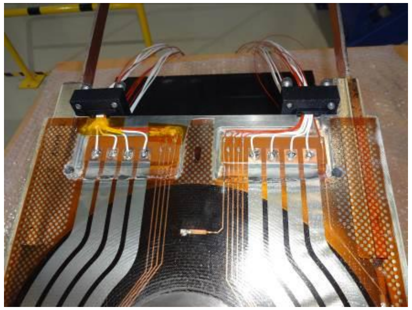
Courtesy Attilio Milanese, Pierre Manil

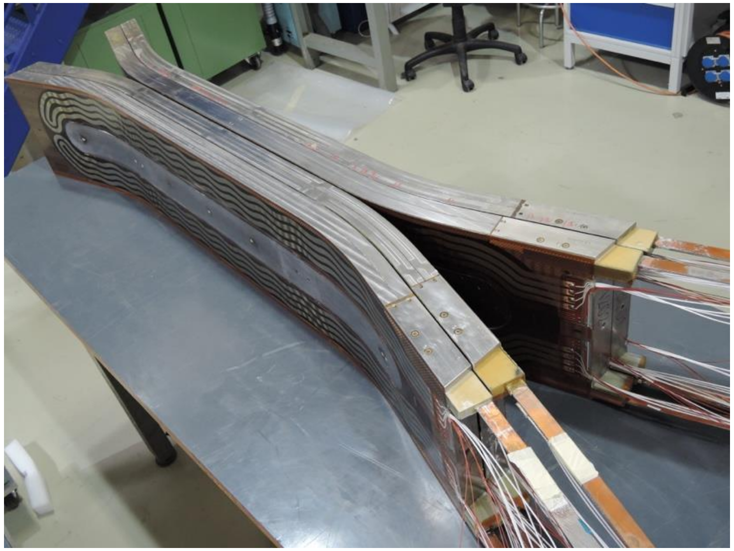
Fabrication of Fresca2 coils

Straightforward technology to wind block coils with flared ends:

This is a lesson for FCC magnets !

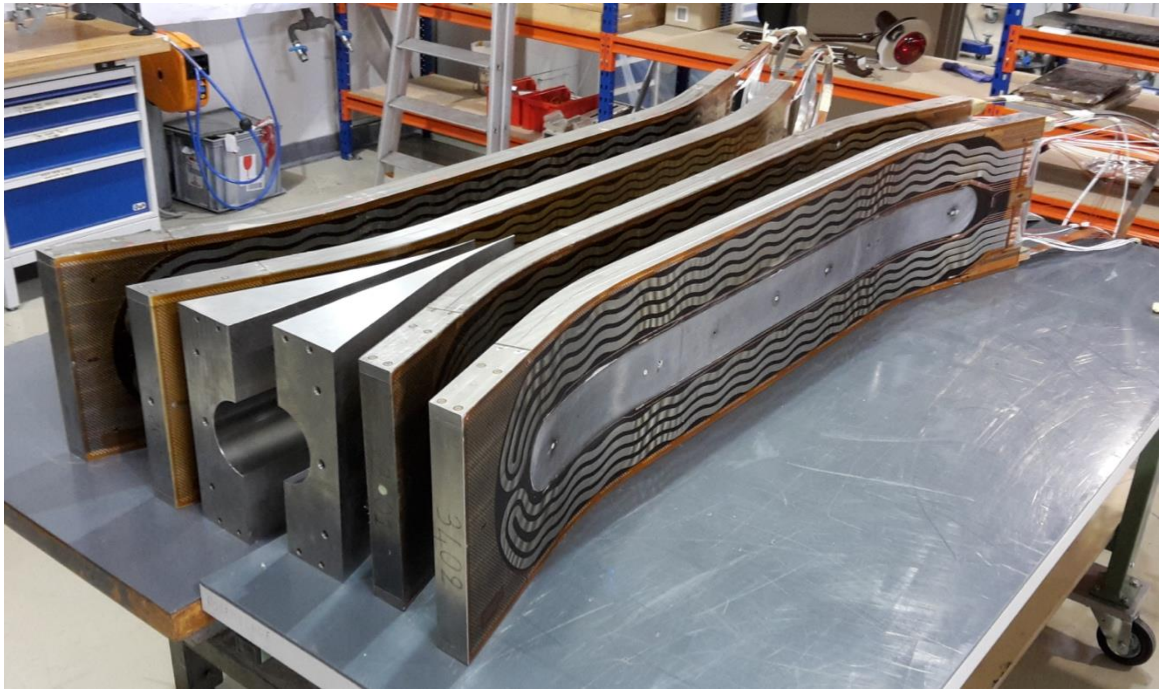






Fresca2 : the 15T FCC milestone by end 2016 ?

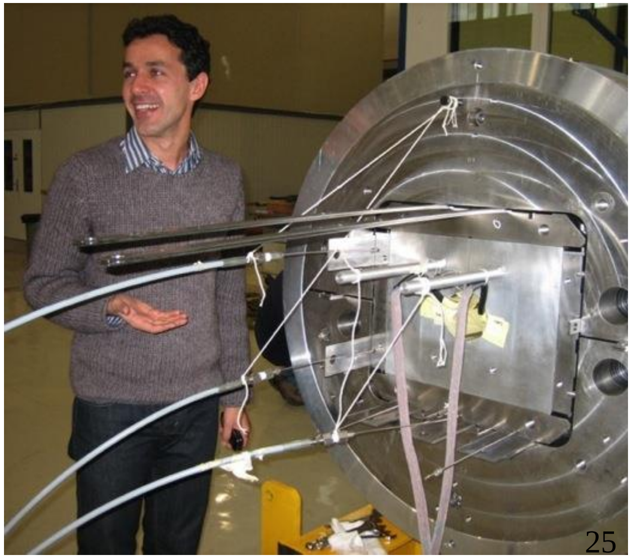
Magnet assembly in September, to be tested end this year



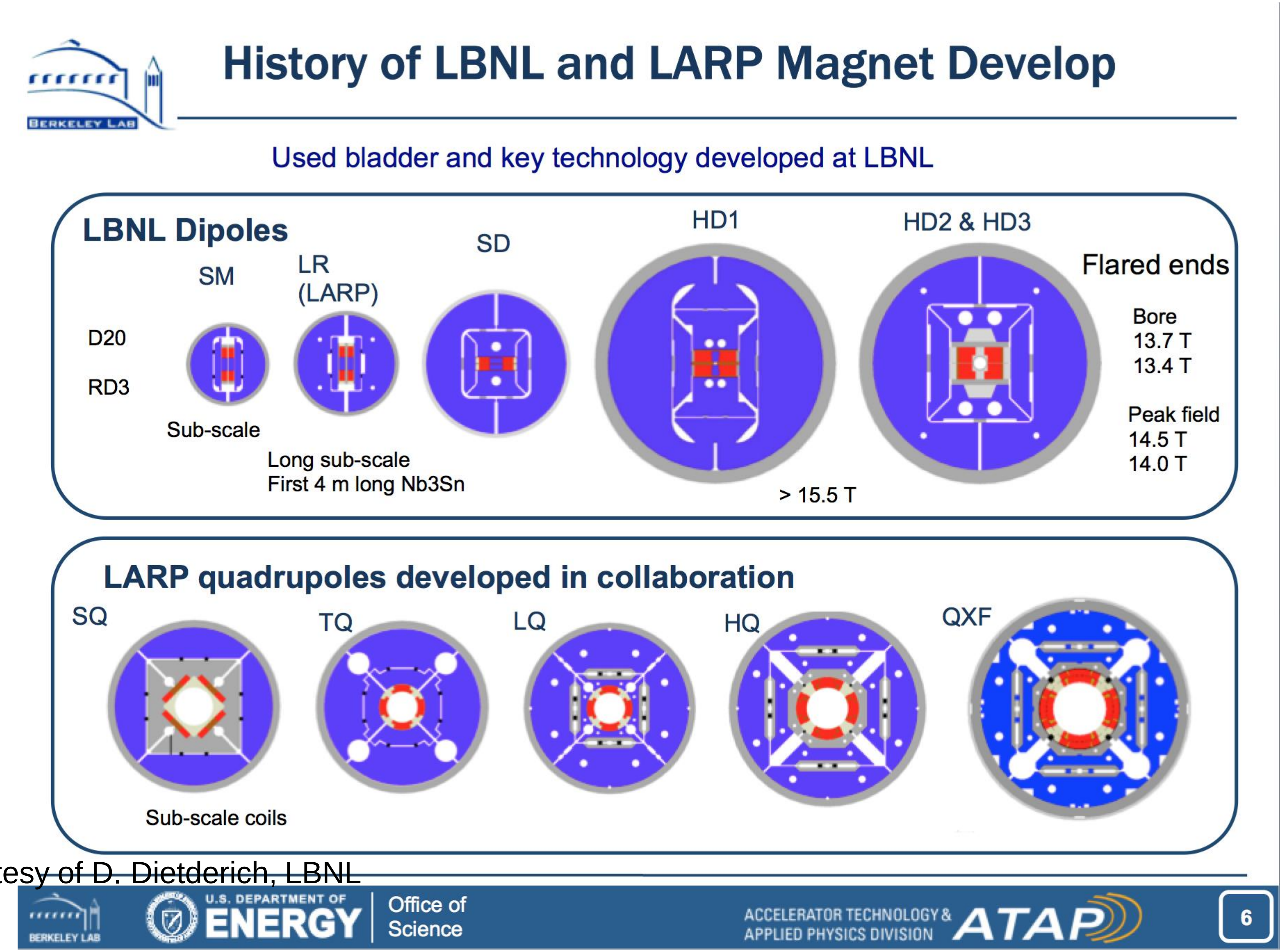
First test: 13T loading,

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



By courtesy of D. Dietderich, LBNL

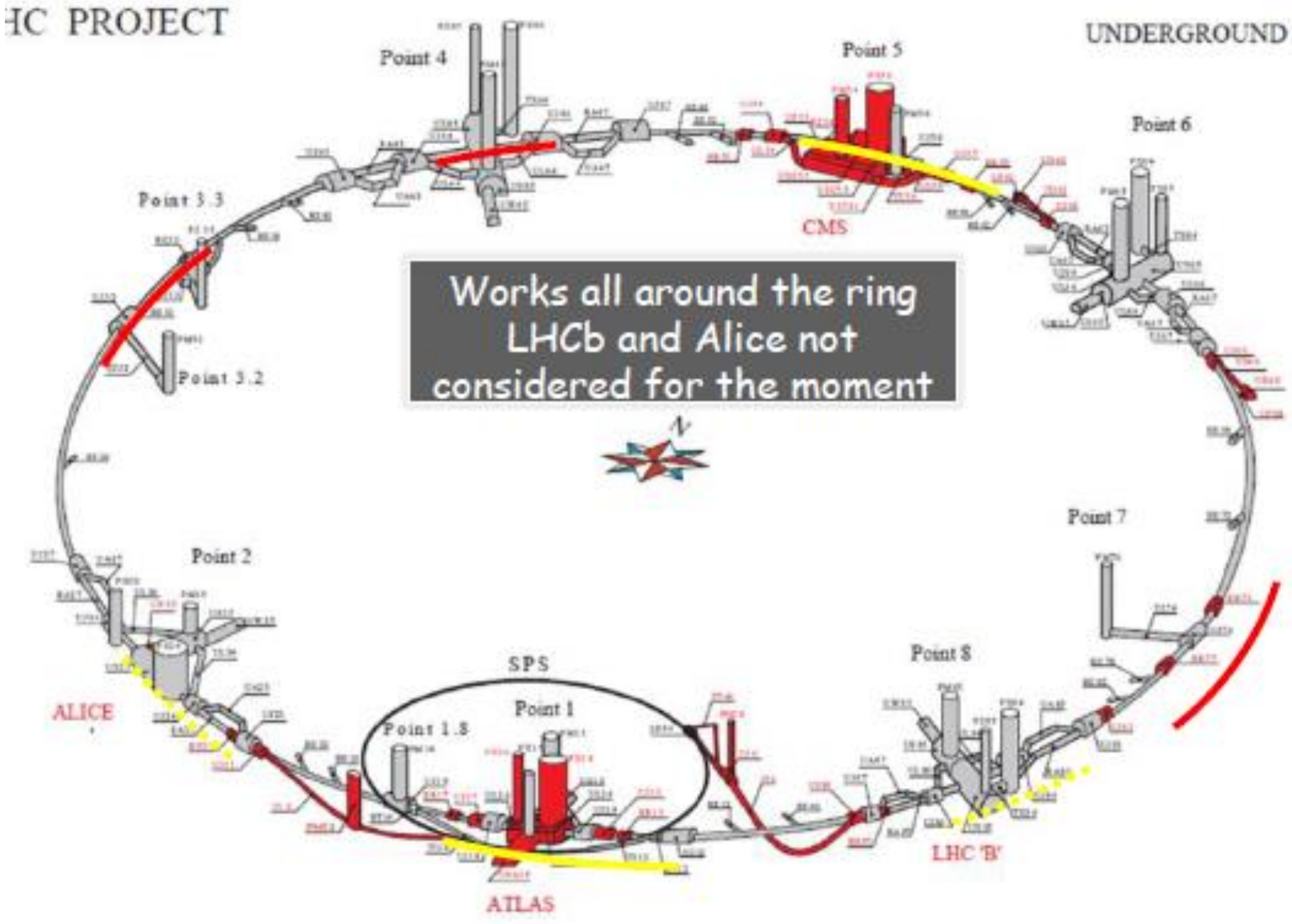
Basic magnet technology development for HILUMI and beyond: Results

- 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 end 2016 !

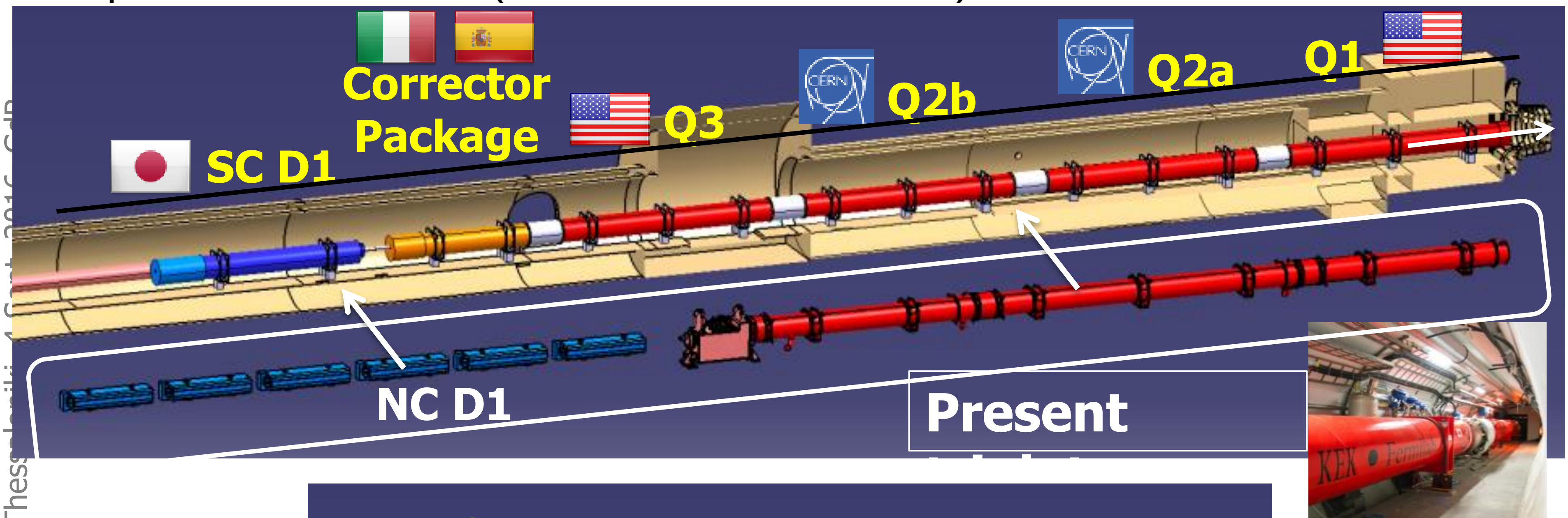
HILUMI magnet development (2013-2016)

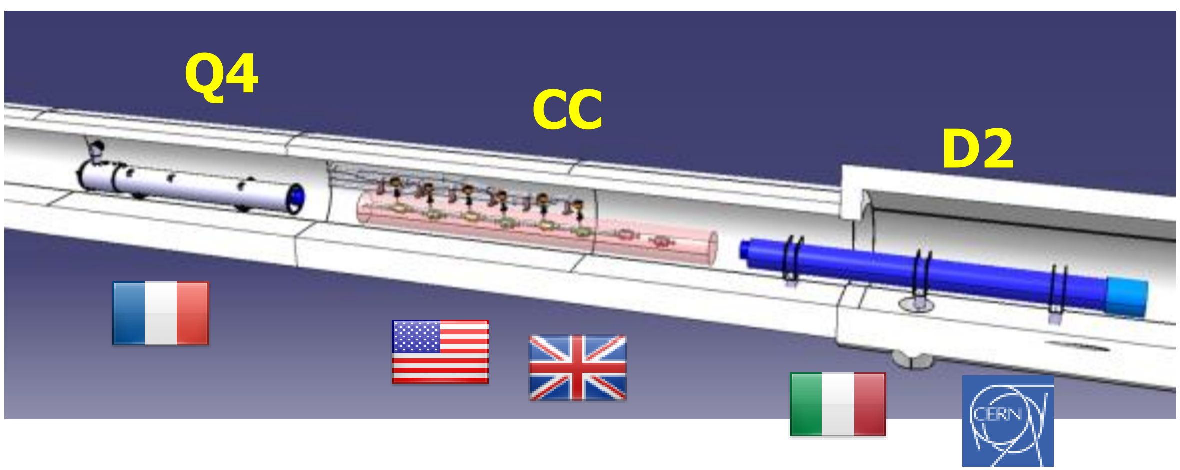
- HILUMI means new magnets in ~1 km of the the LHC main ring
- The ultimate test-bed for the feasibility of Nb_3Sn magnets in accelerators!



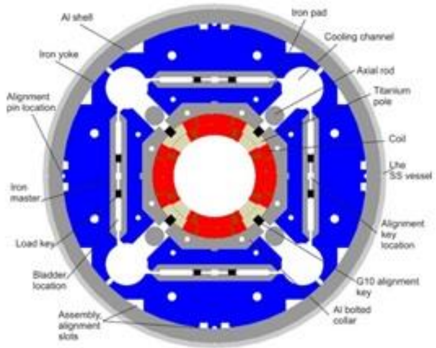
New triplet for HHILUMI

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

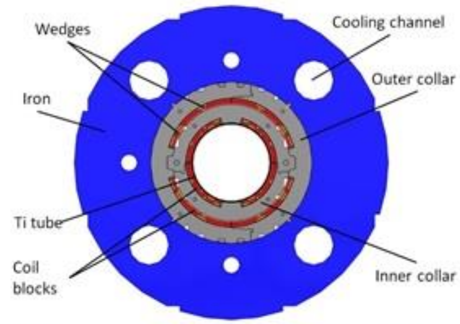




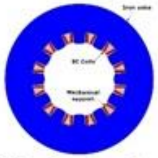
HILUMI IT magnet zoo

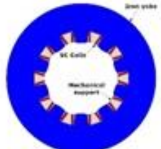


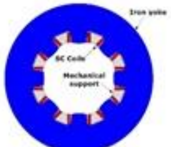
Triplet [G. Ambrosio, P. Ferracin et al.]

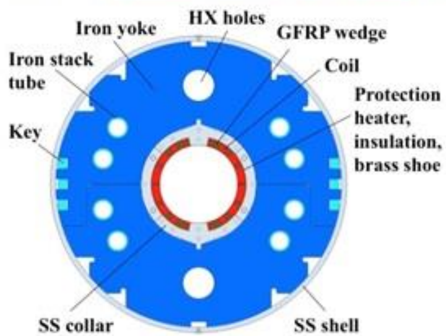


MCBXFB [F. Toral, et al.]

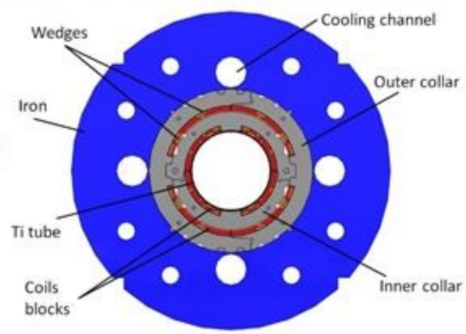

Dodecapole


Decapole

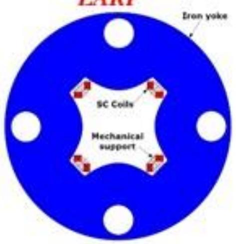

Octupole



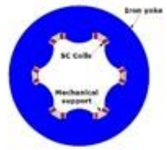
D1 [T. Nakamoto et al.]



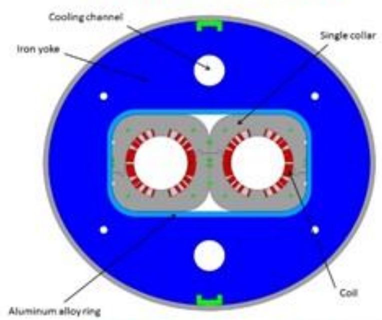
MCBXFA [F. Toral, et al.]



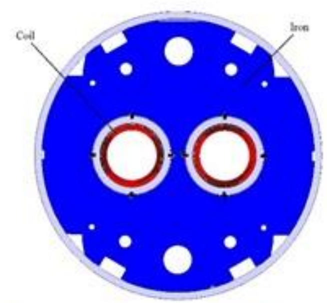
Skew quad



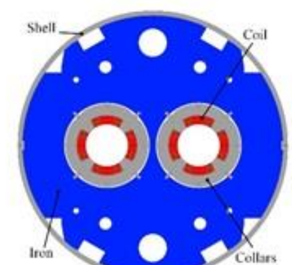
[G. Volpini, et al.]



D2 [P. Fabbricatore, S. Farinon]



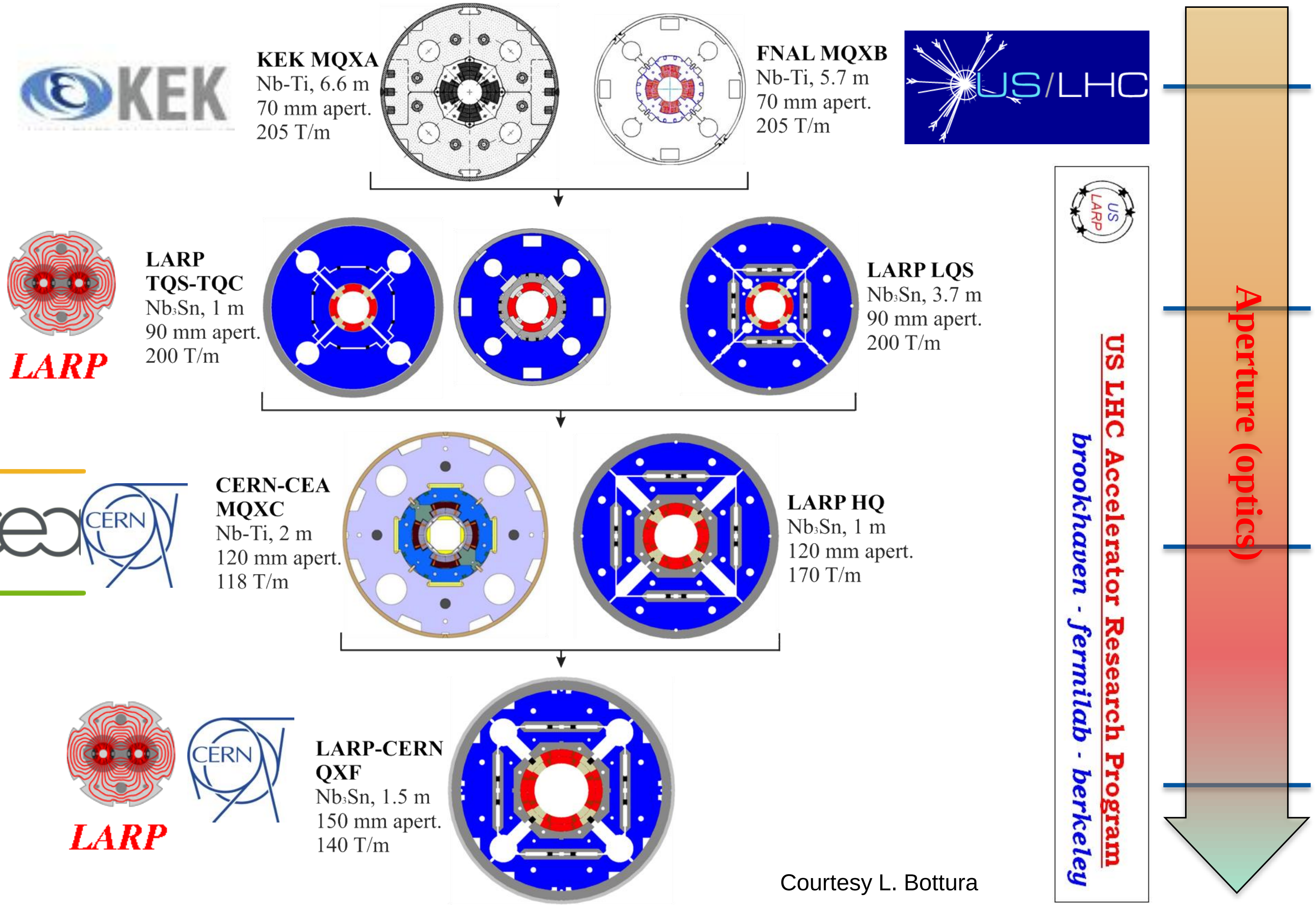
D2 Q4 correctors [G. Kirby]



Q4 [J. M. Rifflet, M. Segreti, et al.]

Courtesy E. Todesco

LHC IP Quadrupole design and technology evolution



Courtesy L. Bottura

HL-LHC: MQXF low beta Nb_3Sn quadrupole

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

A CERN LARP collaboration.

Nominal Gradient 132.6 T/m

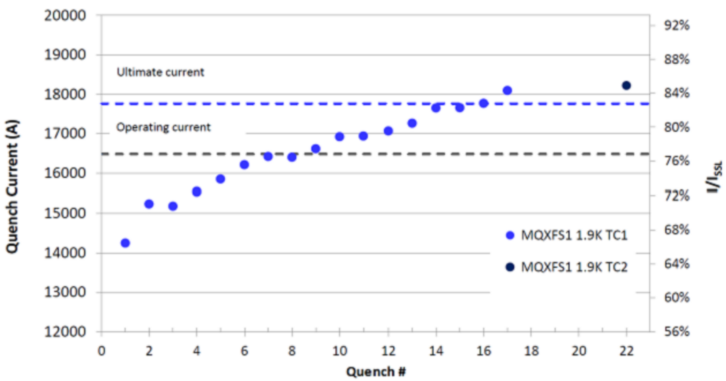
Aperture diameter 150 mm

Peak Field 12.1 T

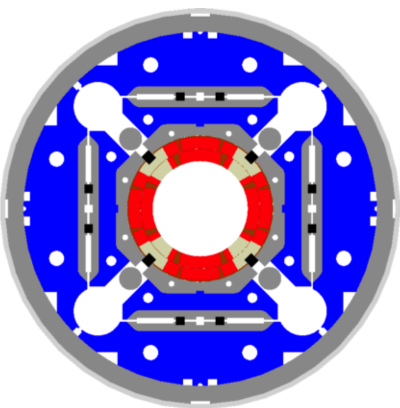
Current 17.5 A

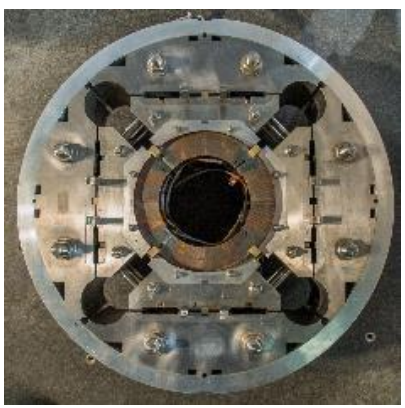
Loadline Margin 20% @ 1.9 K

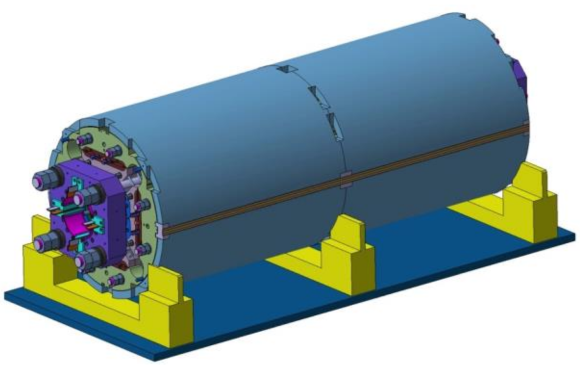
Stored Energy 1.32 MJ/m



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

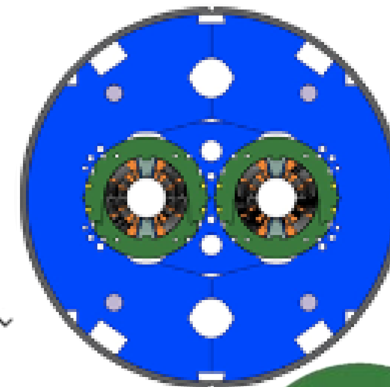


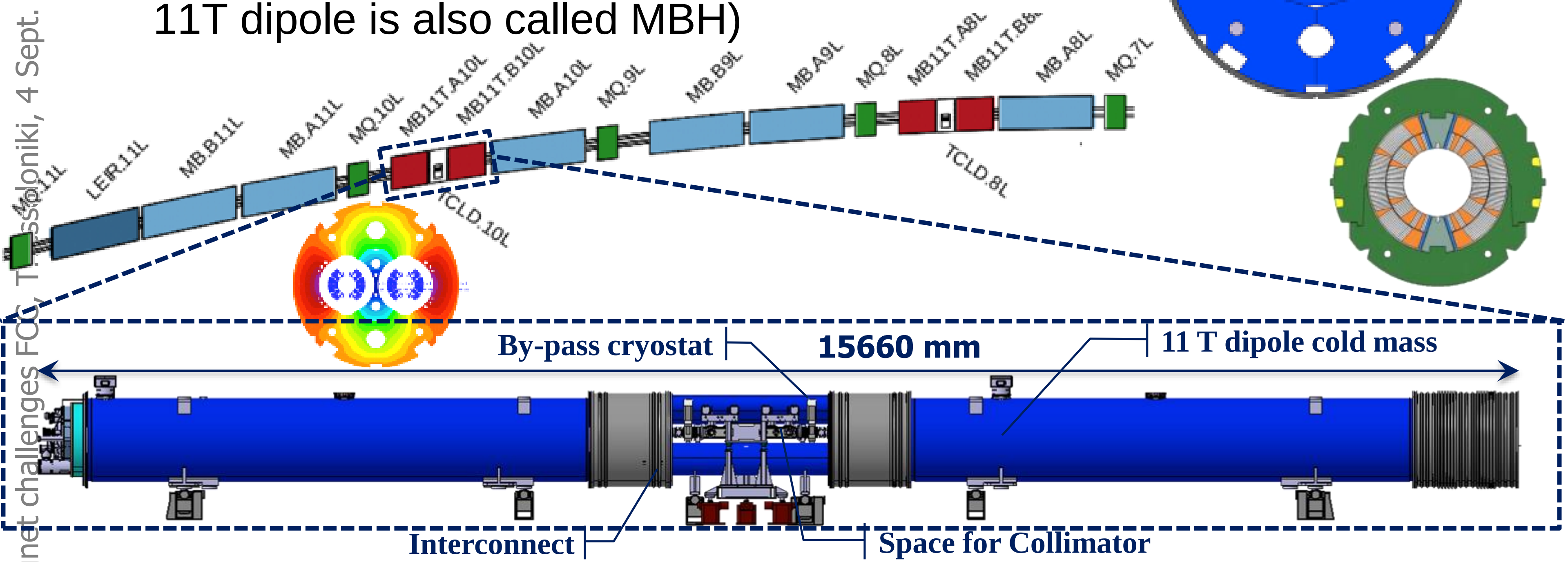




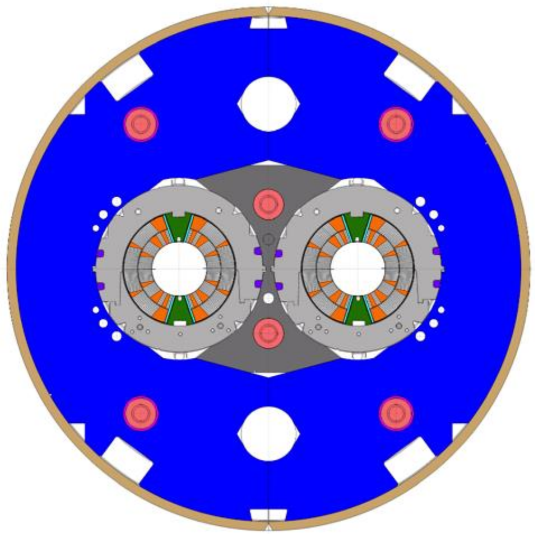
HILUMI: The 11T Dipole Two-in-One for DS

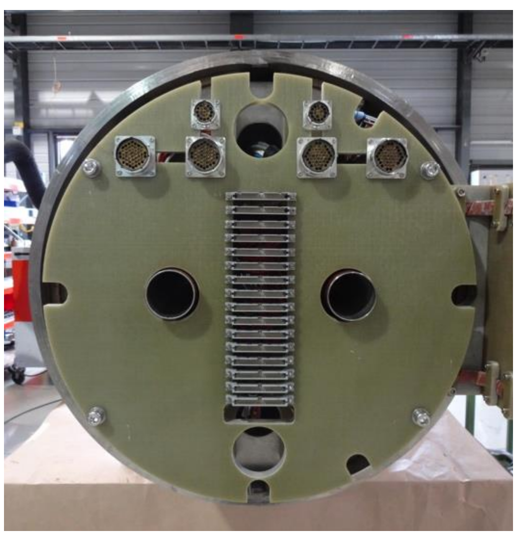
- Create space in the dispersion suppressor regions of LHC, i.e. a room temperature beam vacuum sector, to install additional collimators (TCLD), (needed to cope with beam intensities that are larger than nominal, such as in the HL LHC)
- Replace a standard MB by a pair of 11T dipoles 11T dipole is also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





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

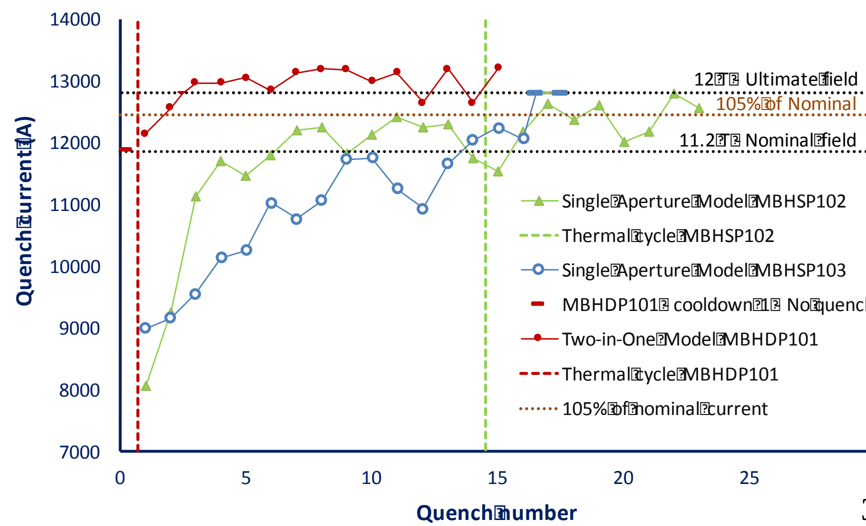
Aperture diameter 60 mm

Peak Field 11.35 T

Current 11.85 kA

Loadline Margin 19.7% @ 1.9 K

Stored Energy 0.96 MJ/m



conclusion from previous and running programs

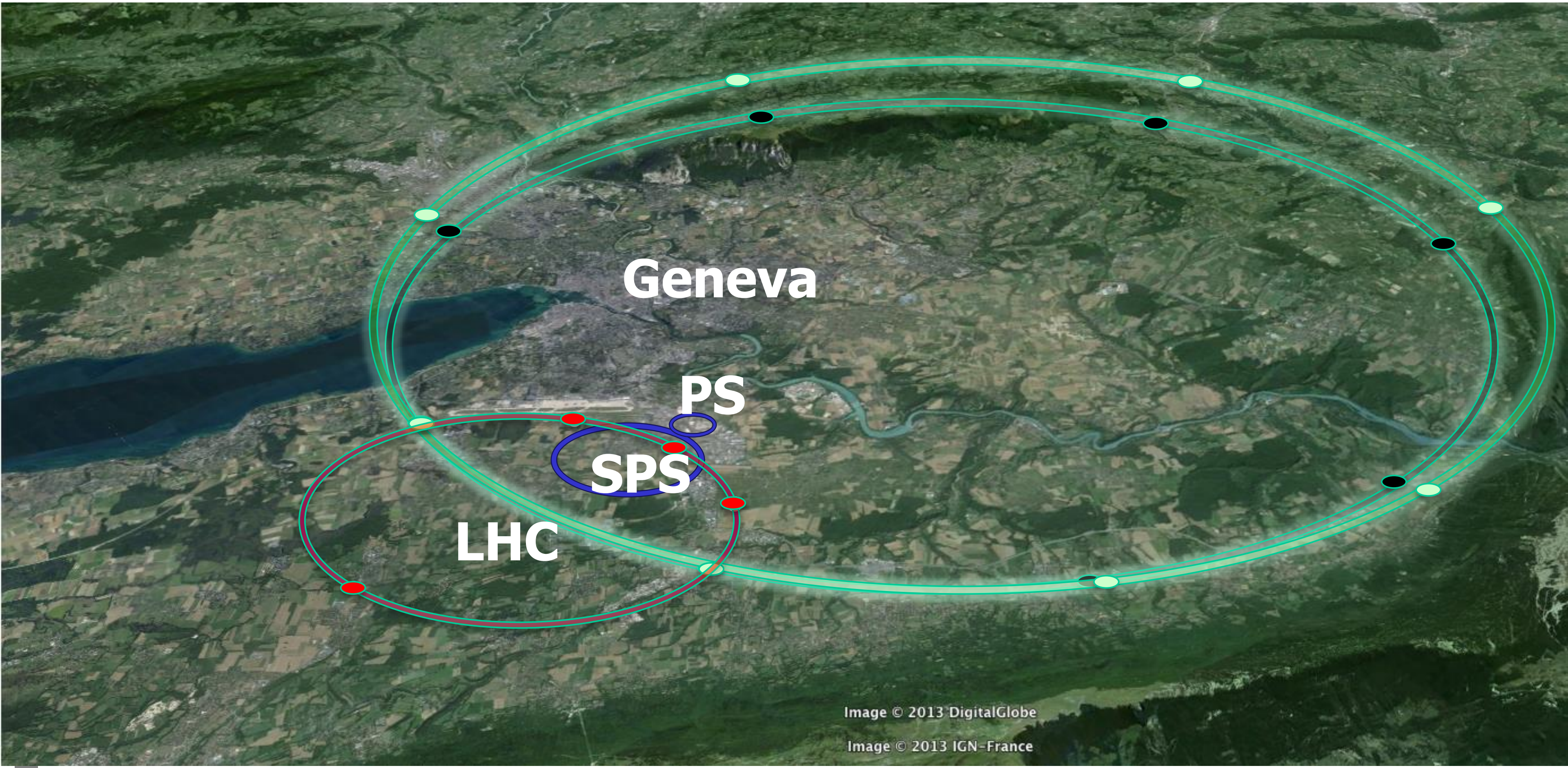
We now have all the elements in hand to develop 16T magnets

- 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)

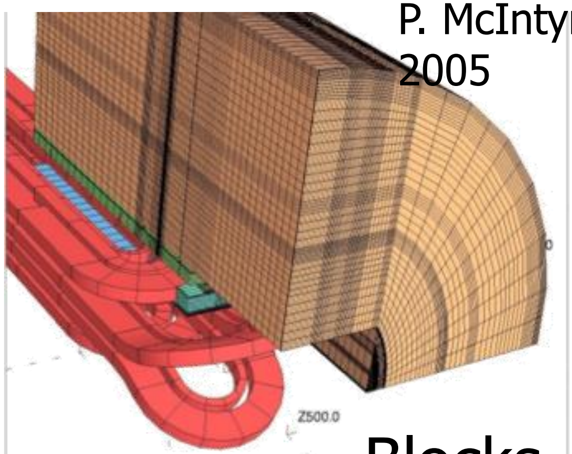
FCC development (2014 - ...)



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.)

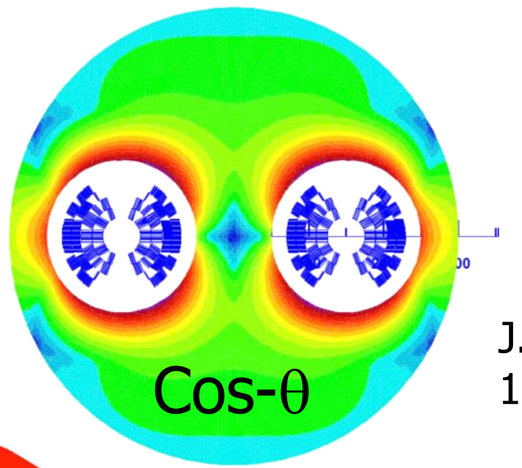
FCC: Magnet design for 16 T dipoles, LTS Nb_3Sn

P. McIntyre, 2005

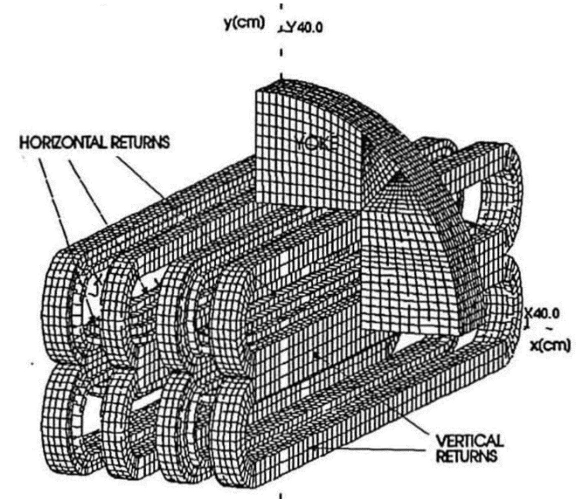


Blocks

E. Todesco 2013
D. Schoerling 2015

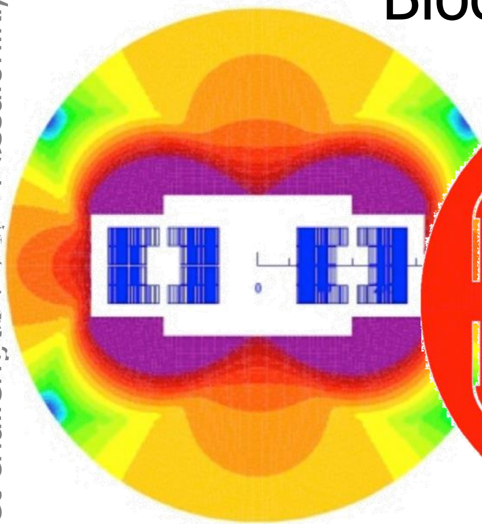


Cos-θ

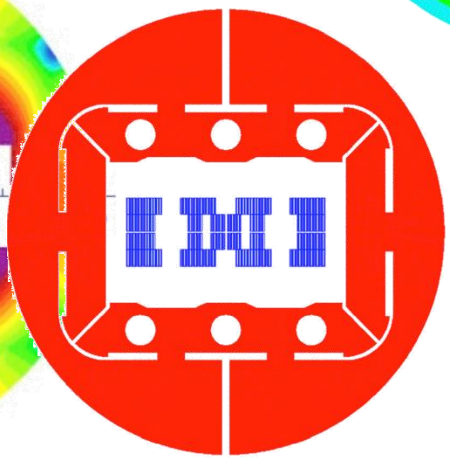


J.M. Van Oort, R. Scanlan, 1994

Common coils

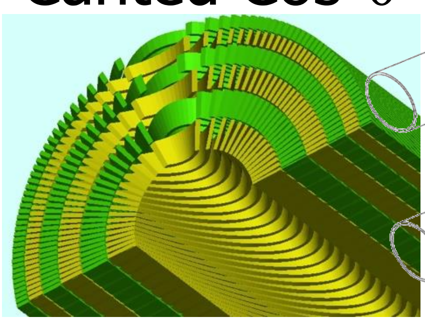


E. Todesco, 2013

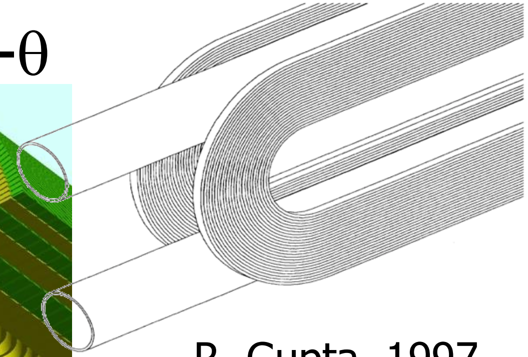


GL. Sabbi, 2014

Canted Cos-θ



S. Caspi, 2014



R. Gupta, 1997

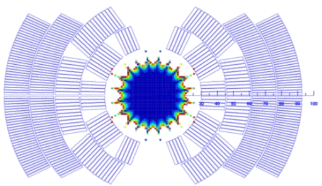
US program lines

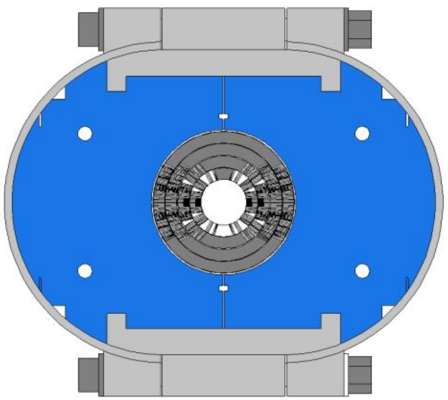
U.S. DEPARTMENT OF ENERGY | Office of Science

BERKELEY LAB

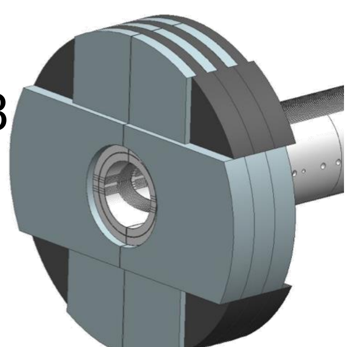
BROOKHAVEN NATIONAL LABORATORY

cos-θ

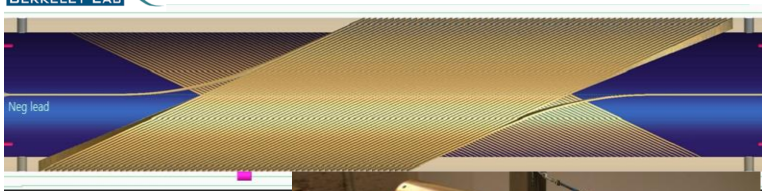




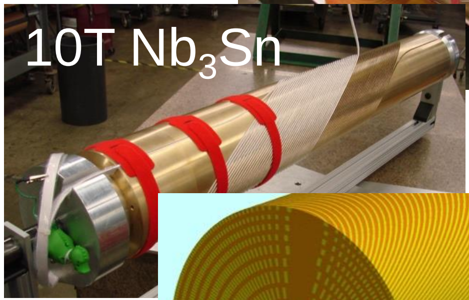
2018



canted-cos-θ

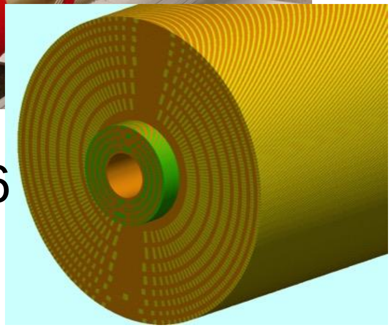


2014-2015

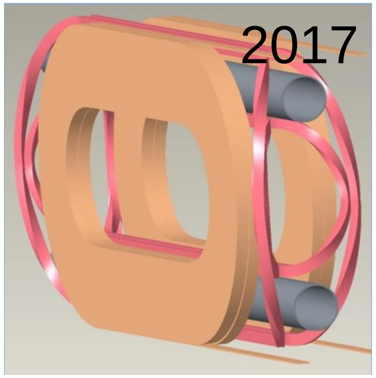


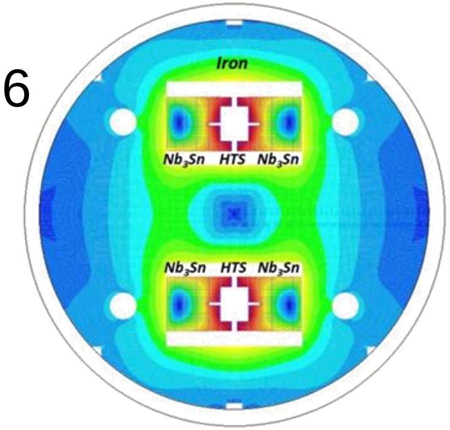
2015-2016

2016

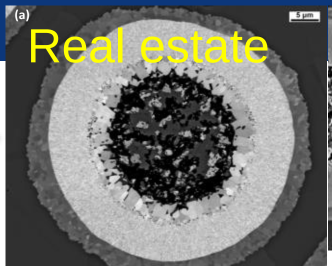


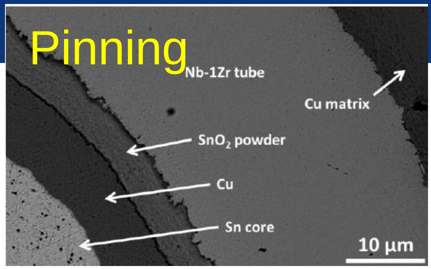
common coils





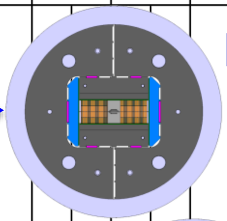
FCC plan for 16T baseline



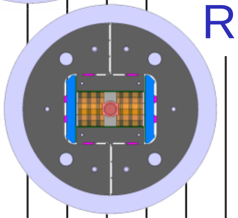


Conductor R&D

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																

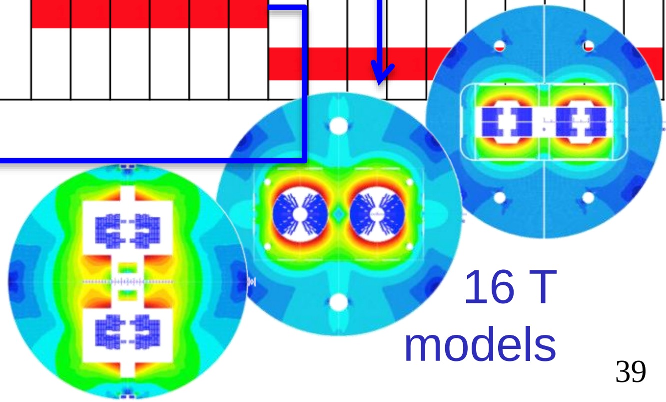


ERMC



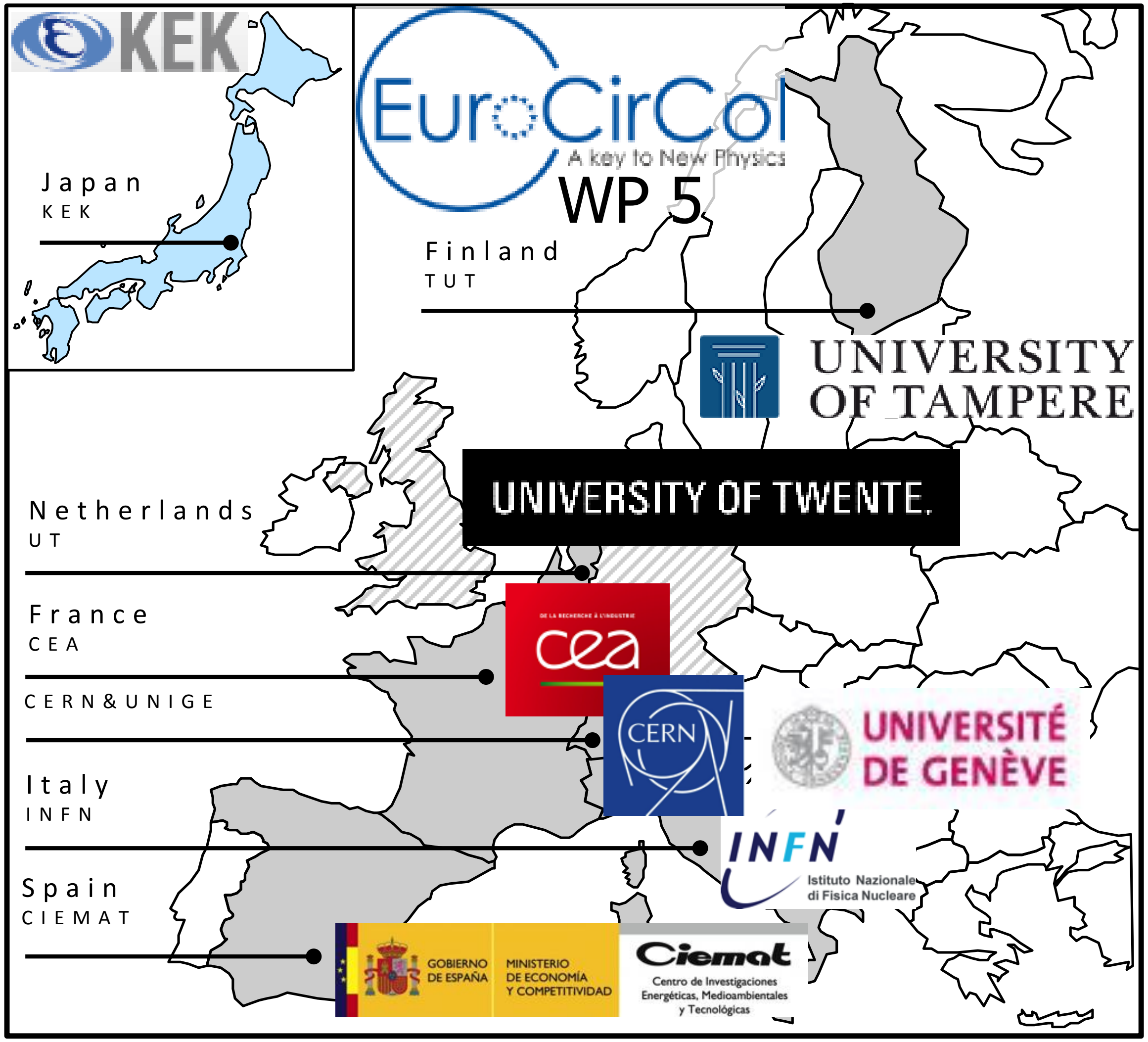
RMM

Opportunity for prototypes built in industry



16 T models

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 Nb_3Sn performance targets

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

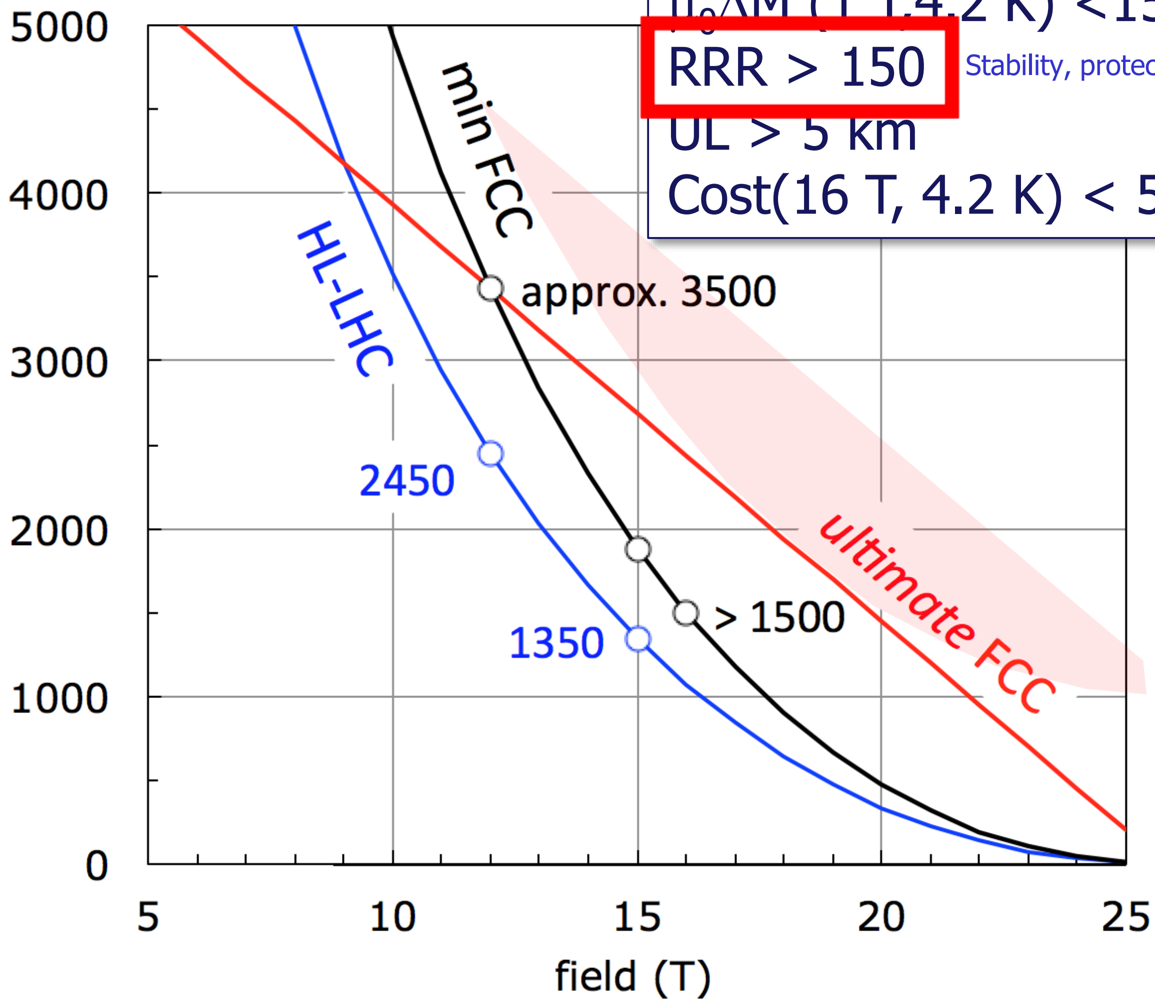
J_C (16 T, 4.2 K) > 1500 A/mm^2

$\mu_0\Delta M$ (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 !

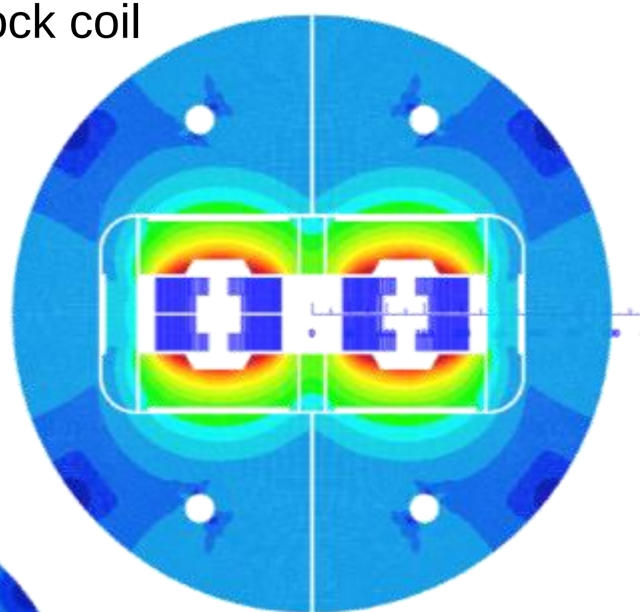
Ultimate Nb_3Sn ?
Pursue the idea of improved high field pinning
(D. Dietrich and R. Scanlan, A. Godeke)

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 (partly in preparation)
  - JA – KEK: SH Copper, Furukawa, JASTEC; Tohoku University, NIMS
  - RU – Bochvar: TVEL
  - KO – KAT: Kiswire
- Material characterization and advanced analysis
  - EU – Technisce Universitaet Wien (Atominstitut)
  - US – ASC at NHMFL

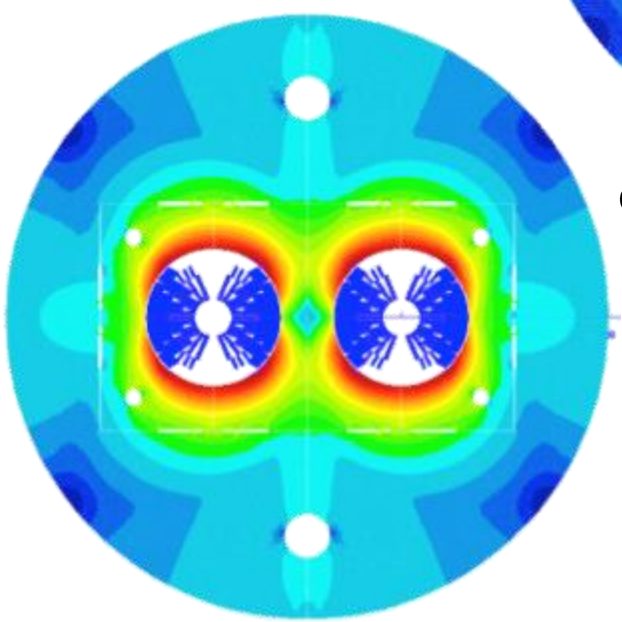
FCC: 16T dipole options

Block coil



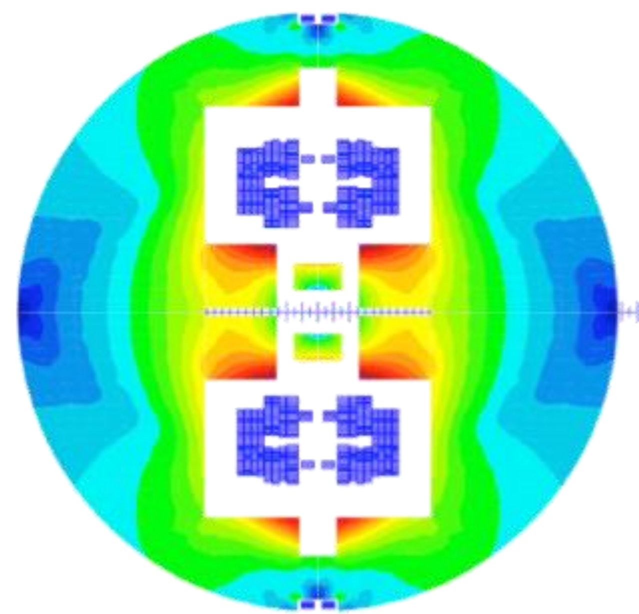
C. Lorin, M. Durante (CEA)

Cos-theta coil



S. Farinon, P. Fabbricatore (INFN)

Common coils



F. Toral (CIEMAT)

FCC 20T option: HTS program

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

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

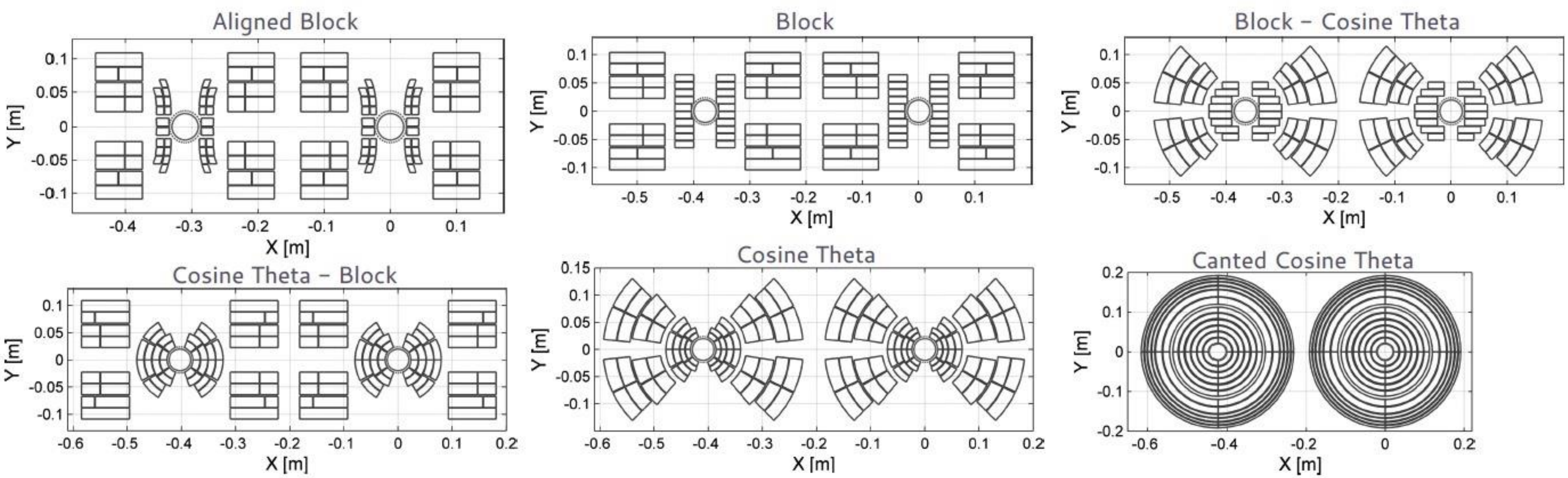
- 10kA rated ReBCO cable (Roeble cable)
- 5T stand alone accelerator quality ReBCO magnet

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

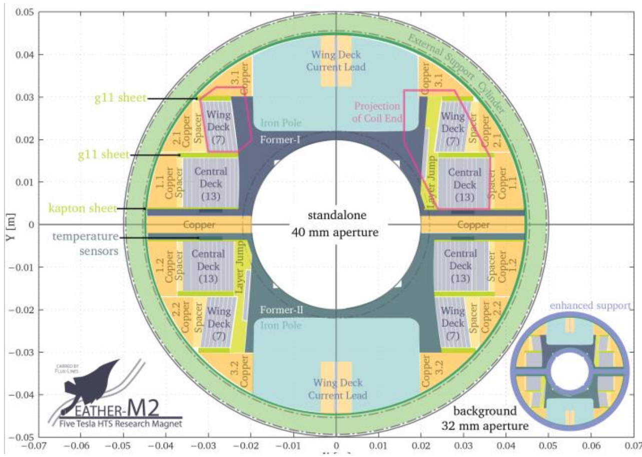
Activity	Begin	End	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
HTS$Conductor$Development	01.01.2017	31.12.2021																
Conceptual$design$20T$dipole$model	01.01.2017	30.06.2019																
Design$20T$dipole$model	01.06.2019	30.06.2021																
EuCARD/EuCARD2$demonstrators	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																

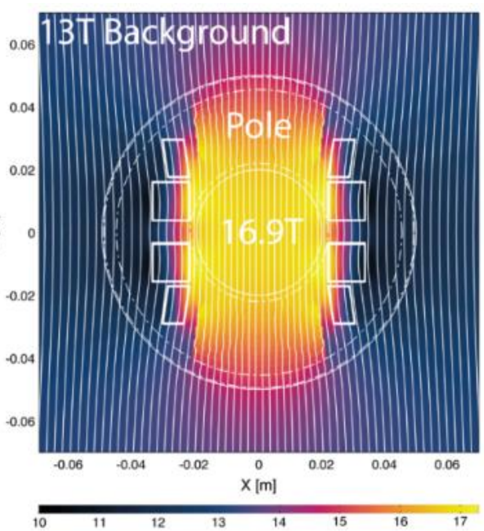


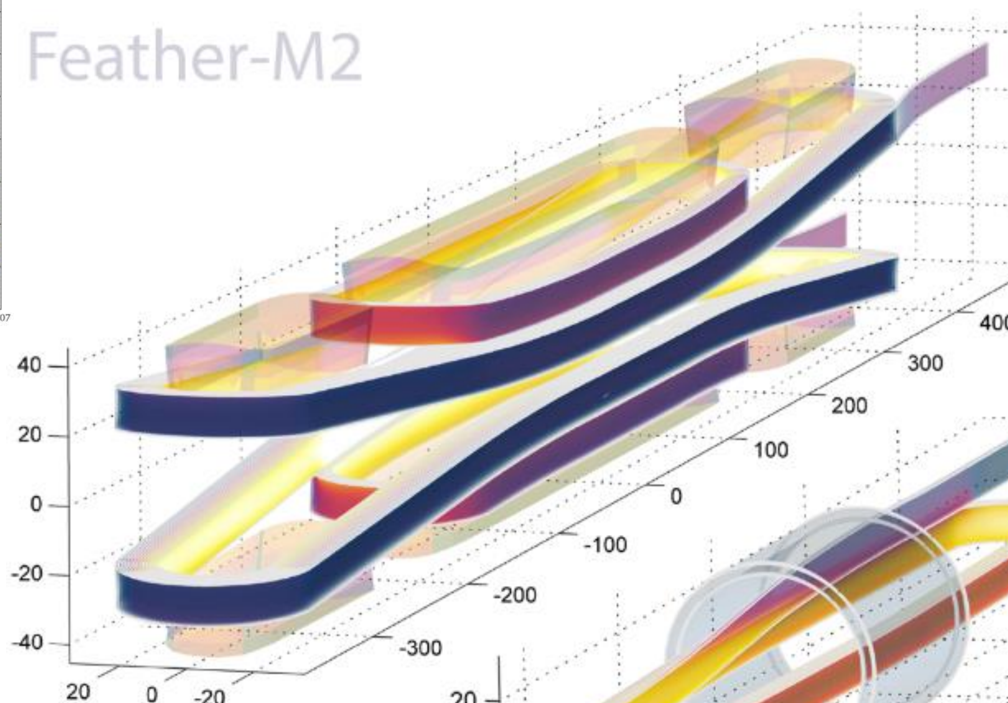
Courtesy , J. van Nugteren, CERN

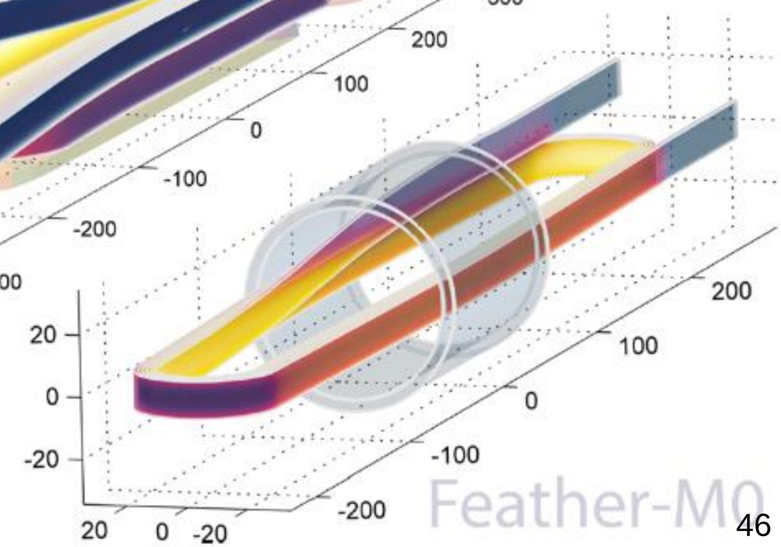
EuCARD2 5T accelerator quality ReBCO magnet

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





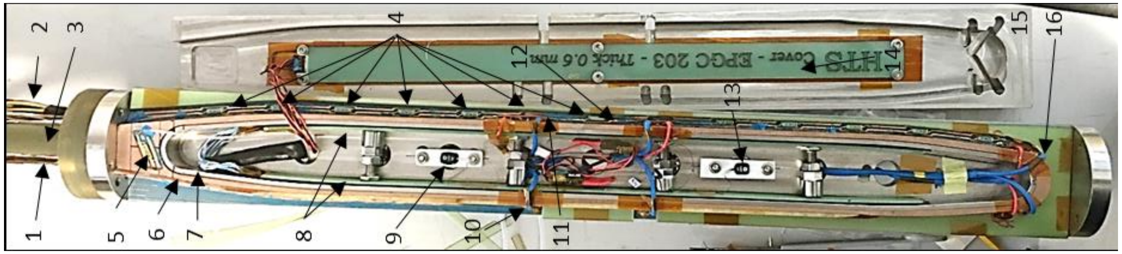


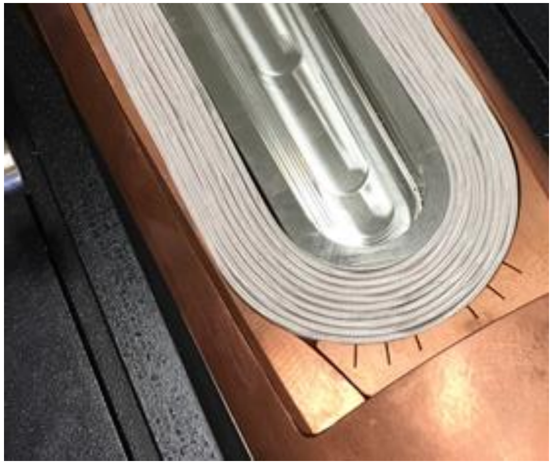


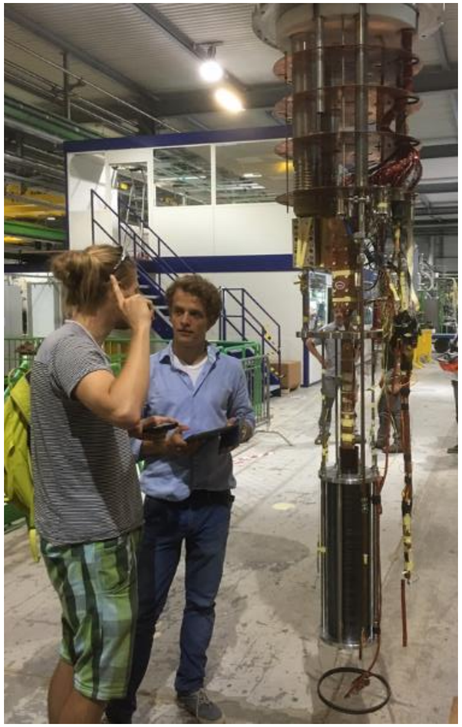
http://eucard2.web.cern.ch/

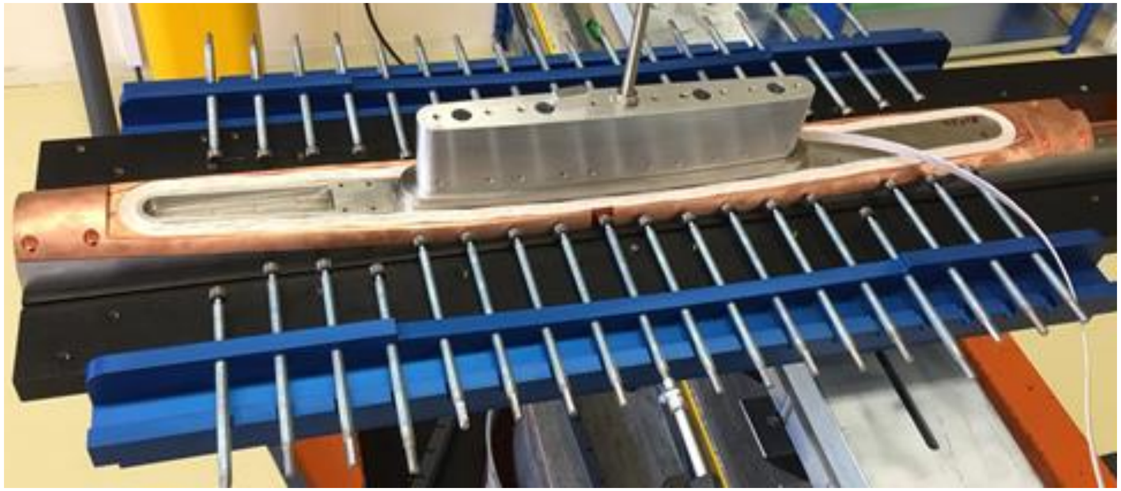
Feather0 - Feather-M2.0

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



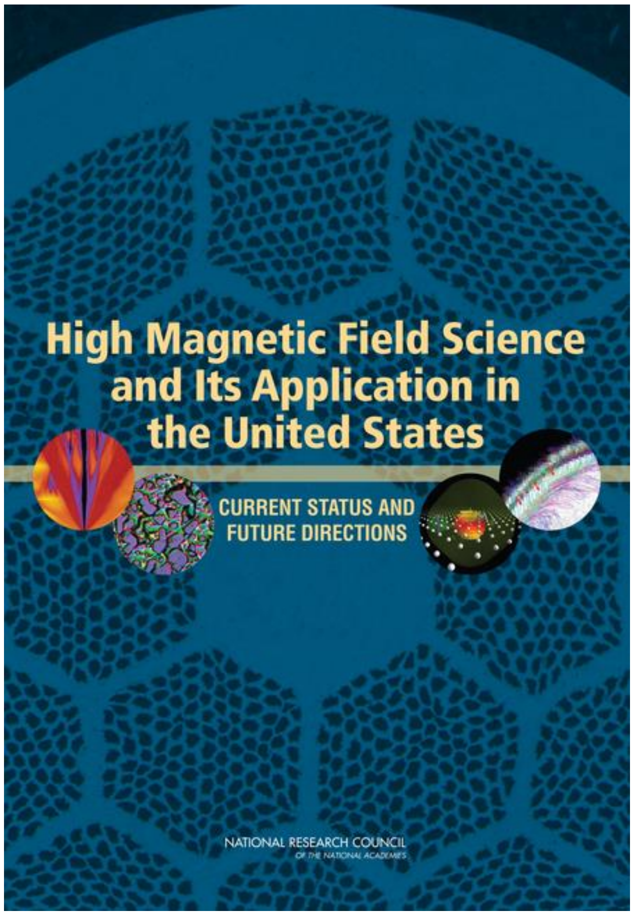






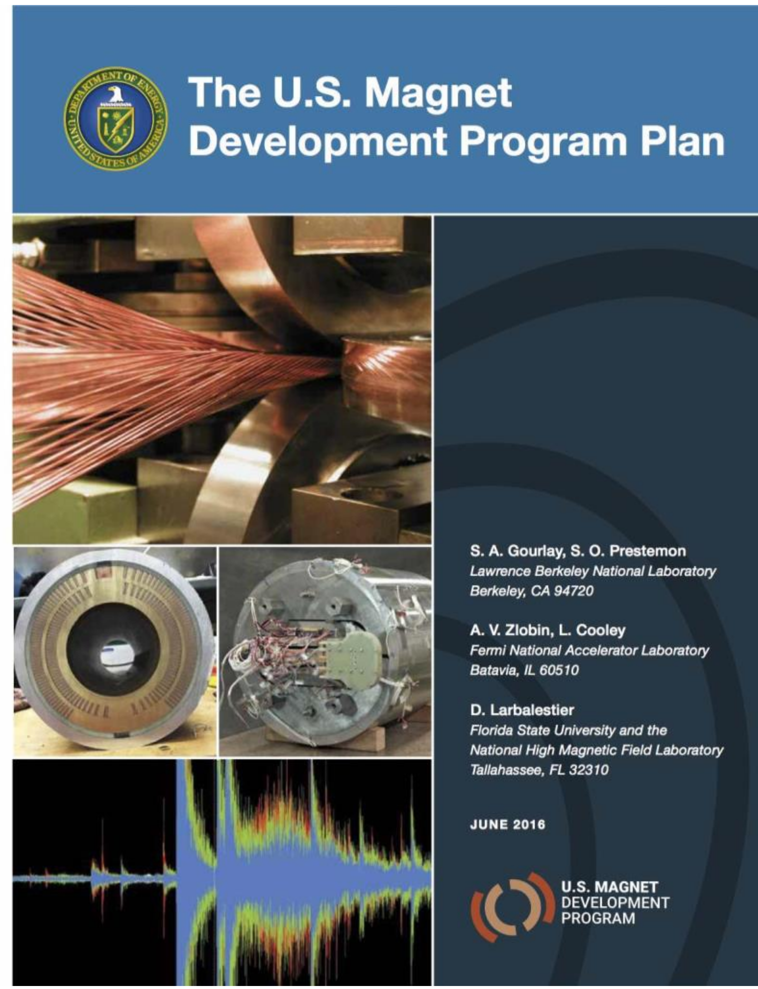
Synergy programs

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



ISBN: 978-0-309-28634-3

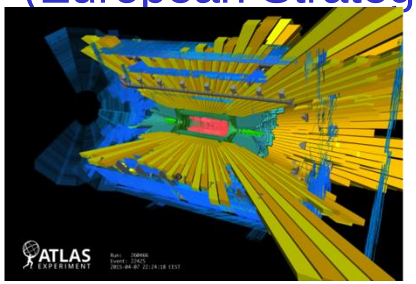
30 T (NMR) to 60 T (user facilities)
HTS solenoids

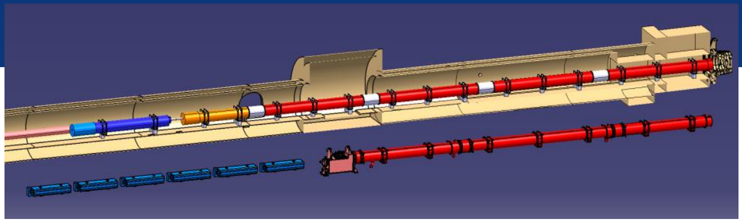


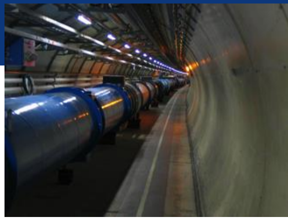
By courtesy of S. Gourlay (LBNL)

Conclusions

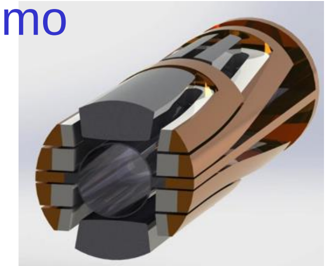
LHC Run-II provides results to define future HEP roadmap (European Strategy 2018)







Accelerator-grade HTS 5 T demo

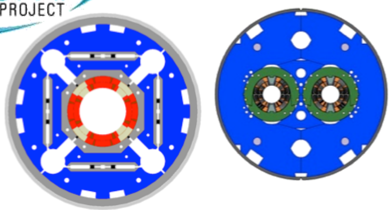


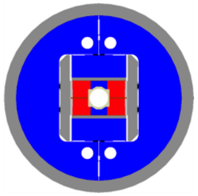
HL-LHC demonstrates large-scale use of Nb_3Sn

End of LHC useful life

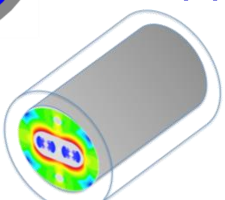
2015 2016 2017 2018 2019 2020 2025 2030 2035 2040

12 T accelerator technology



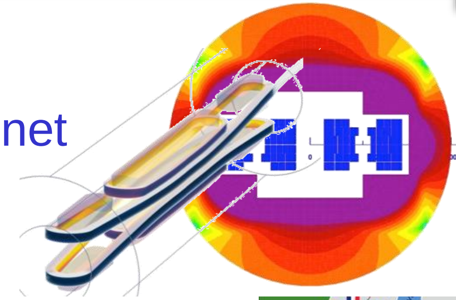


16 T magnet model(s)



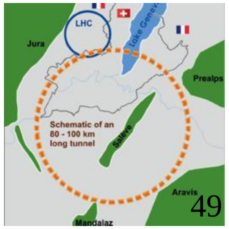
16 T accelerator technology

20 T magnet model(s)



FCC CDR (EuroCirCol) propose a new energy frontier accelerator

FCC construction decision



CERN

FCC-hh magnet parameters

	B / G (T) / (T/m)	B_{peak} (T)	Bore (mm)	Length (units x m)
MB	**16**	16.4	**50**	≈4500 x 14.3
MQ	450 (> 350)	13	**50**	≈800 x 6
MQX	225	13	100 (<150)	
MQY	300	13	70	
MBX	12	12.5	*60*	(4x2) x 12
MBR	10	10.5	*60*	(4x3) x 10

Inter-aperture distance ≈ 250 mm
Yoke diameter ≤ 700 mm
Stray field ≤ 100 mT