Nb_3Sn Accelerator Magnet Development in Europe

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Workshop on Nb_3Sn Rutherford cable
characterization for accelerator magnets
CIEMAT
16th November 2017

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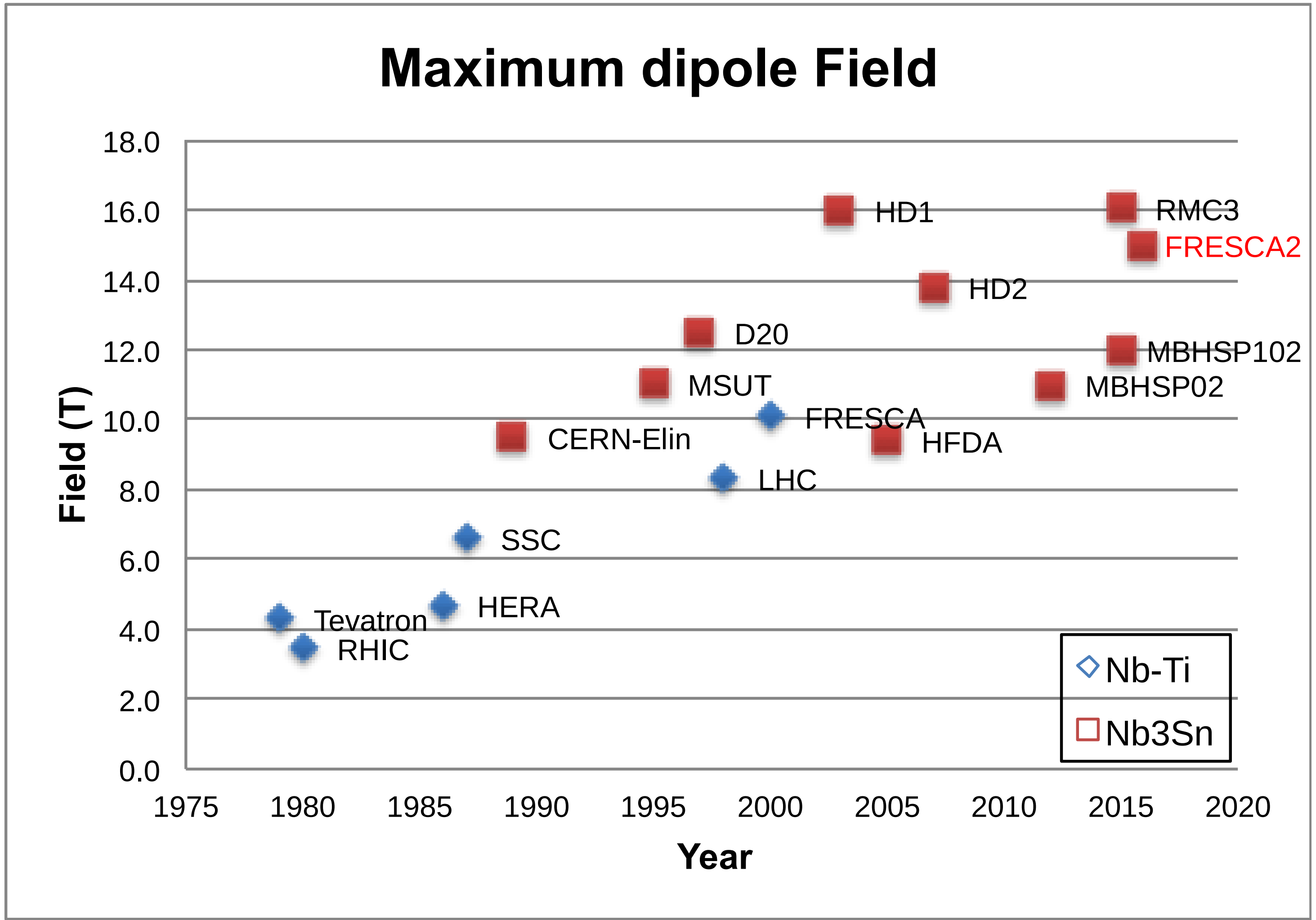
Collaboration and exchange

- Nb_3Sn technology for accelerator magnets was and is being developed in steps at different places
- Some steps have been or are being taken in the US
- Some steps have been or are being taken in Europe
- It would be scientifically wrong to talk about the European programs and results as if done in pure isolation
- Collaboration and exchange have in fact allowed us to move to magnets usable in accelerators

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

The early Nb_3Sn era 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

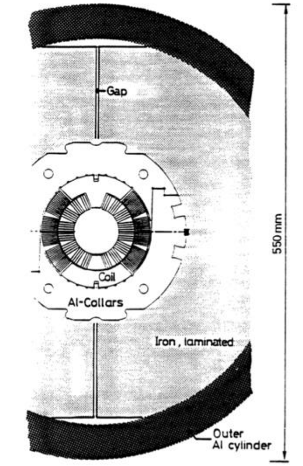
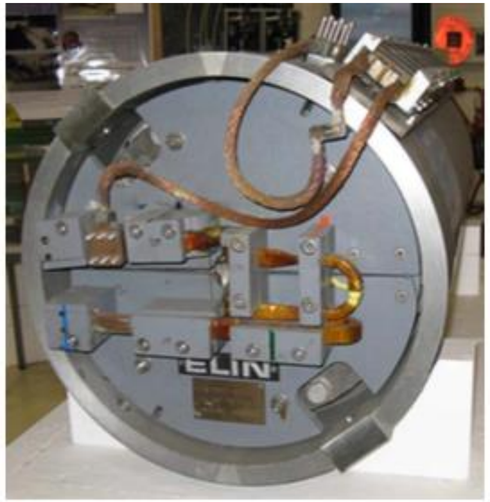


Fig.1: Schematic cross-section of the 1m long full aperture dipole magnet



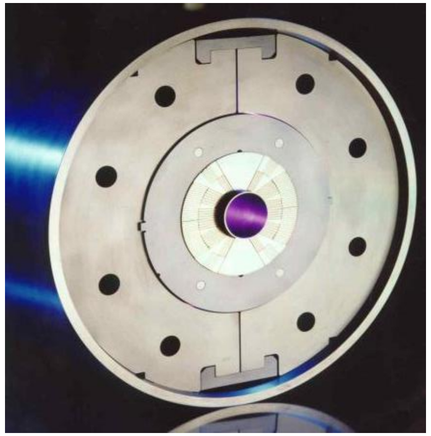
S. Wenger, A. Asner, F. Zerobin, IEEE Trans. Mag, 25(2) 1989

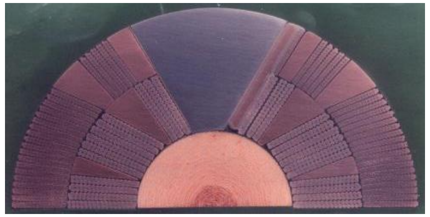
Twente

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 ıl Conference on Magnet Technology, Eds. Beijing, China: Science Press, pp. 137-140, 1998.

The early Nb_3Sn era 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.

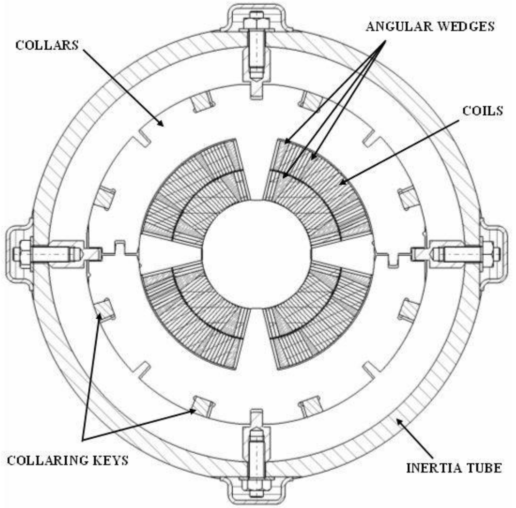
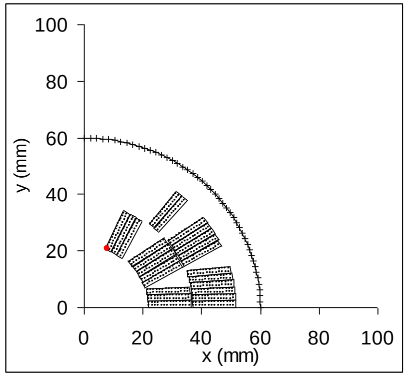
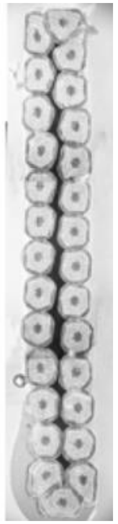


Fig. 4. Cross-sectional view of 56-mm-aperture, 210-T/m Nb_3Sn quadrupole magnet model under development at CEA/Saclay.

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 Nb_3Sn era 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(Θ) 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

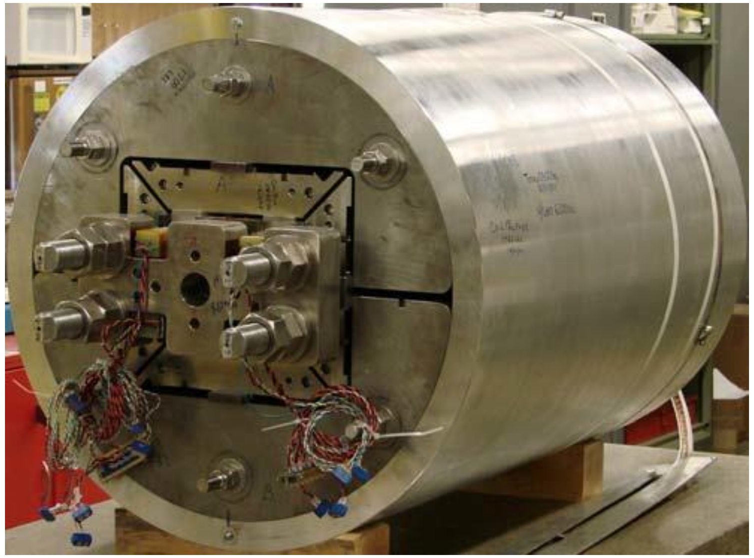


Fig. 1. HD2 assembled and pre-loaded.

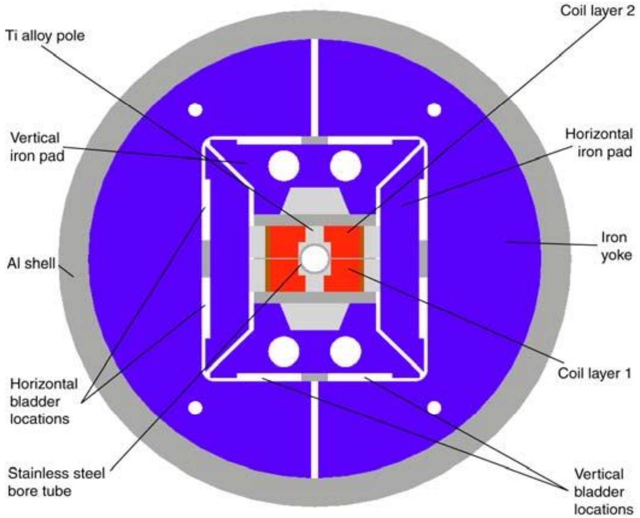
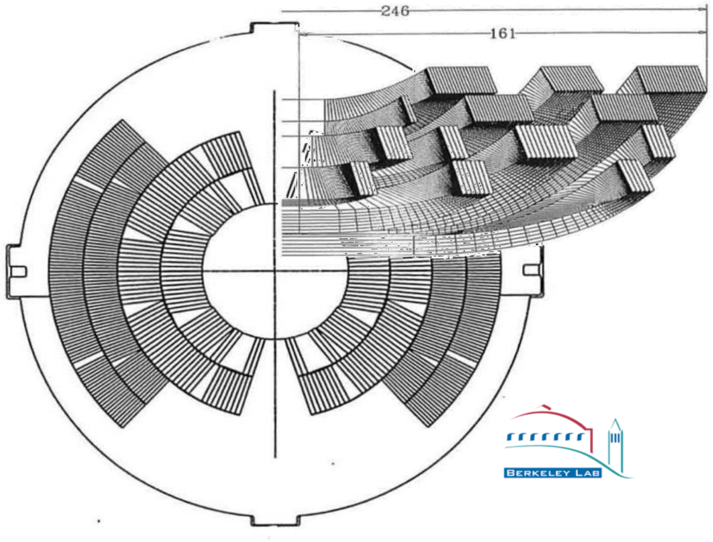


Fig. 2. HD2 cross-section.

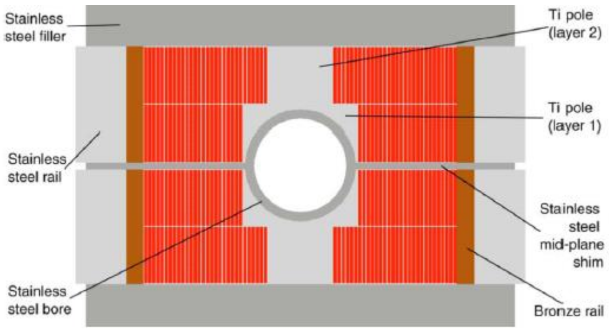


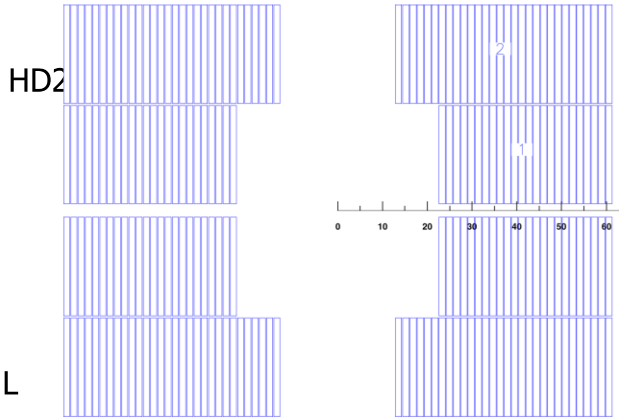
A.D. McInturff, et al., Proc. of PAC 1997, 3212

The early Nb_3Sn era IV, New geometry: Block coils

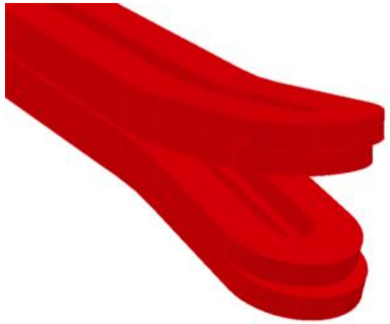
LBNL block coil designs

- 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 Nb_3Sn era V, Realizing what the challenges are

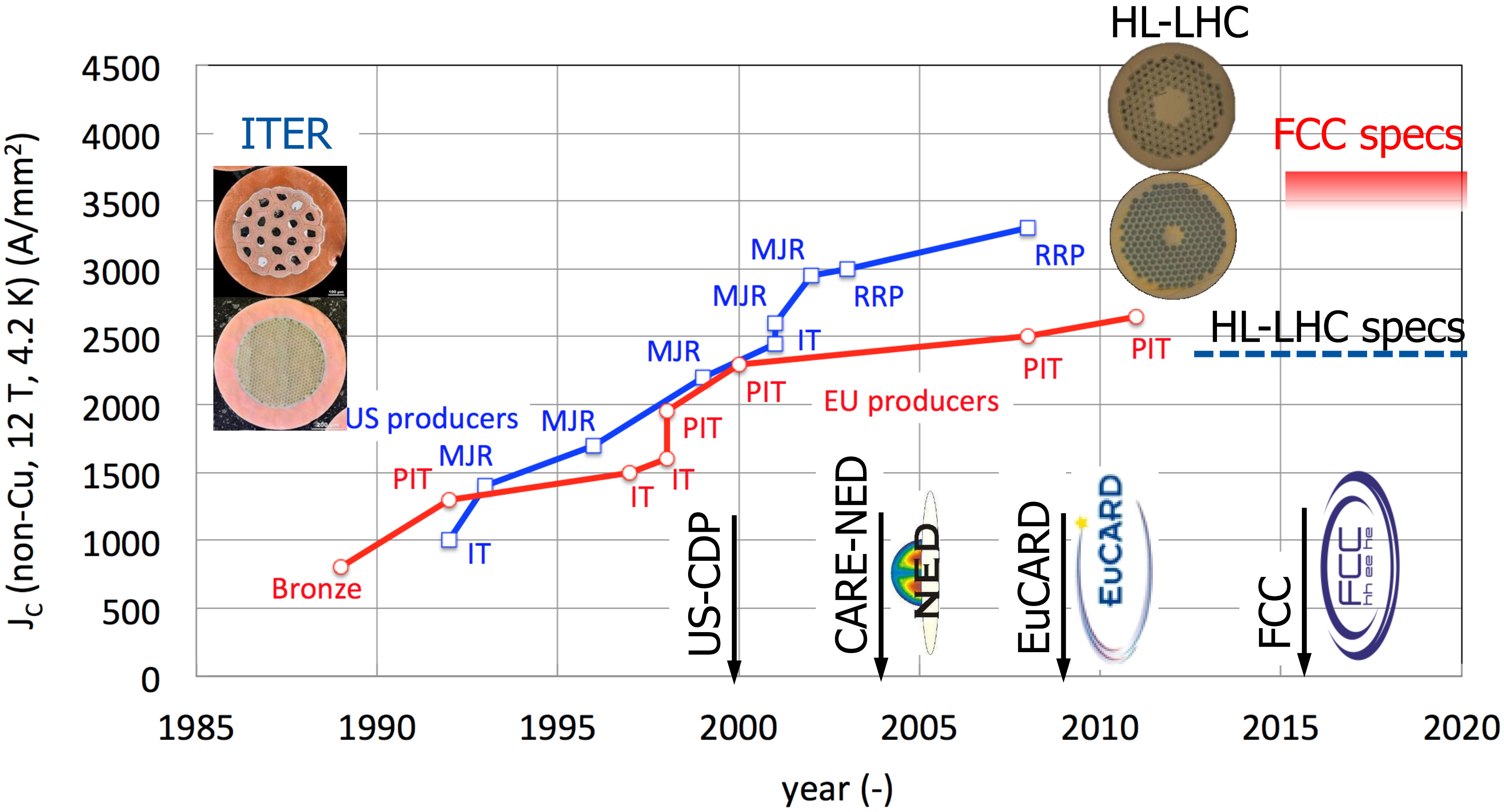
=== It should in principle be possible to go up to 16T with Nb_3Sn===

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
- The coils are very sensitive and fragile
- 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
- To get up to high fields other coil geometries and force containment / pre-stress structures will be needed

Conductor development (1998-2008)

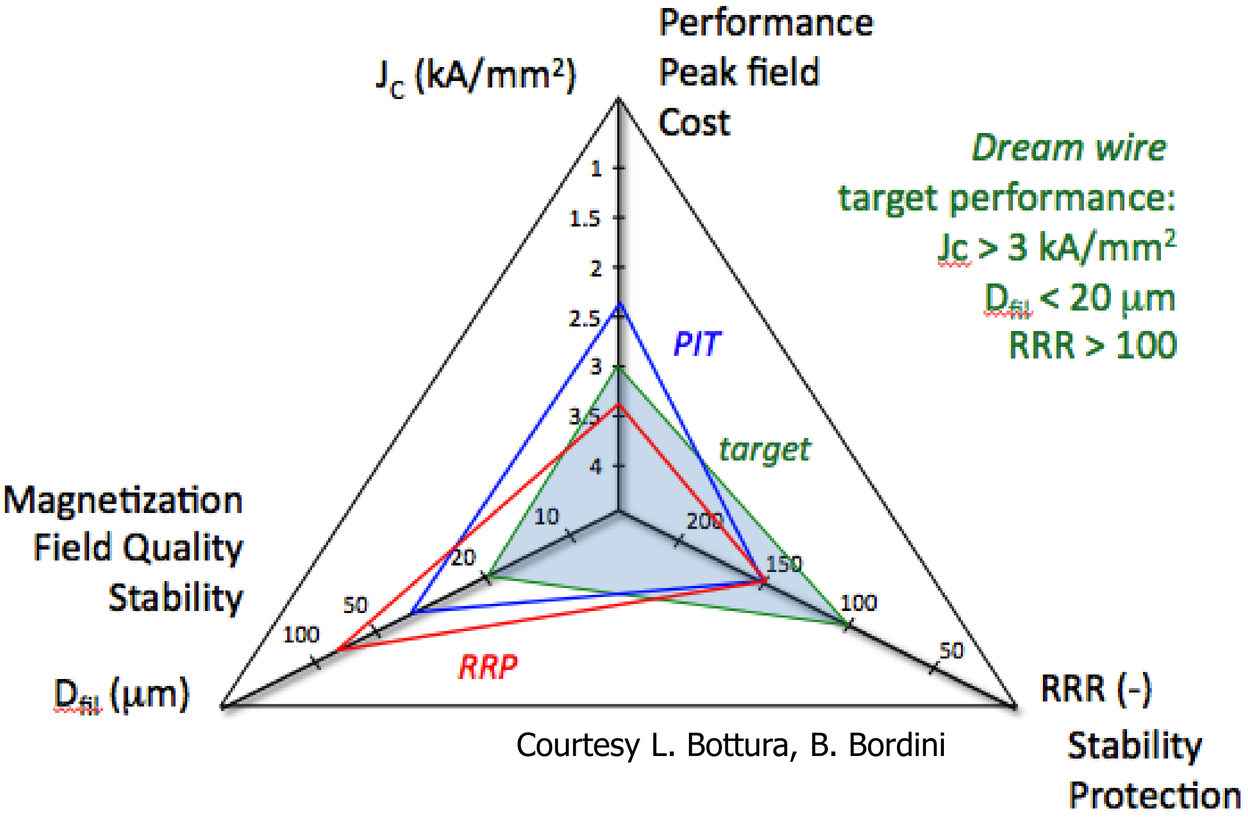


after 10 years of development the US and EU development gave us the Nb_3Sn conductor for HILUMI.

Nb_3Sn Acc. Magnet Dev. in Europe, 16th Nov. 2017, GdR

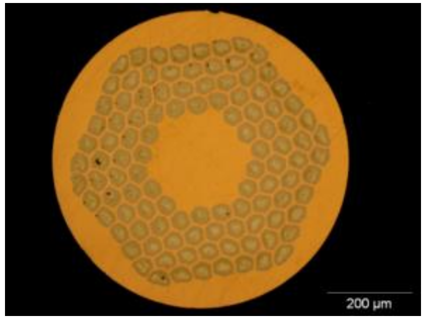
Nb$_3$Sn Conductor specification for HEP

A Nb$_3$Sn dream wire for the LHC

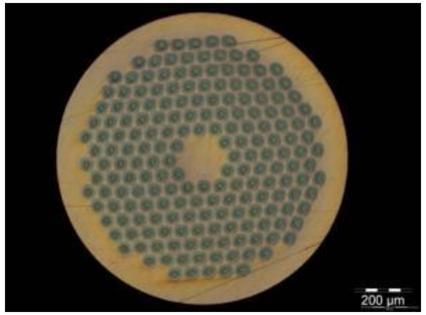


Dream wire
target performance:
Jc > 3 kA/mm^2
D_{fil} < 20 µm
RRR > 100

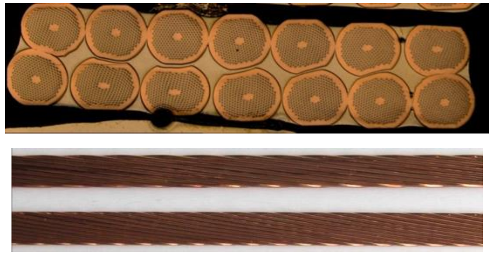
Courtesy L. Bottura, B. Bordini



0.7 mm, 108/127 stack
RRP from Oxford OST

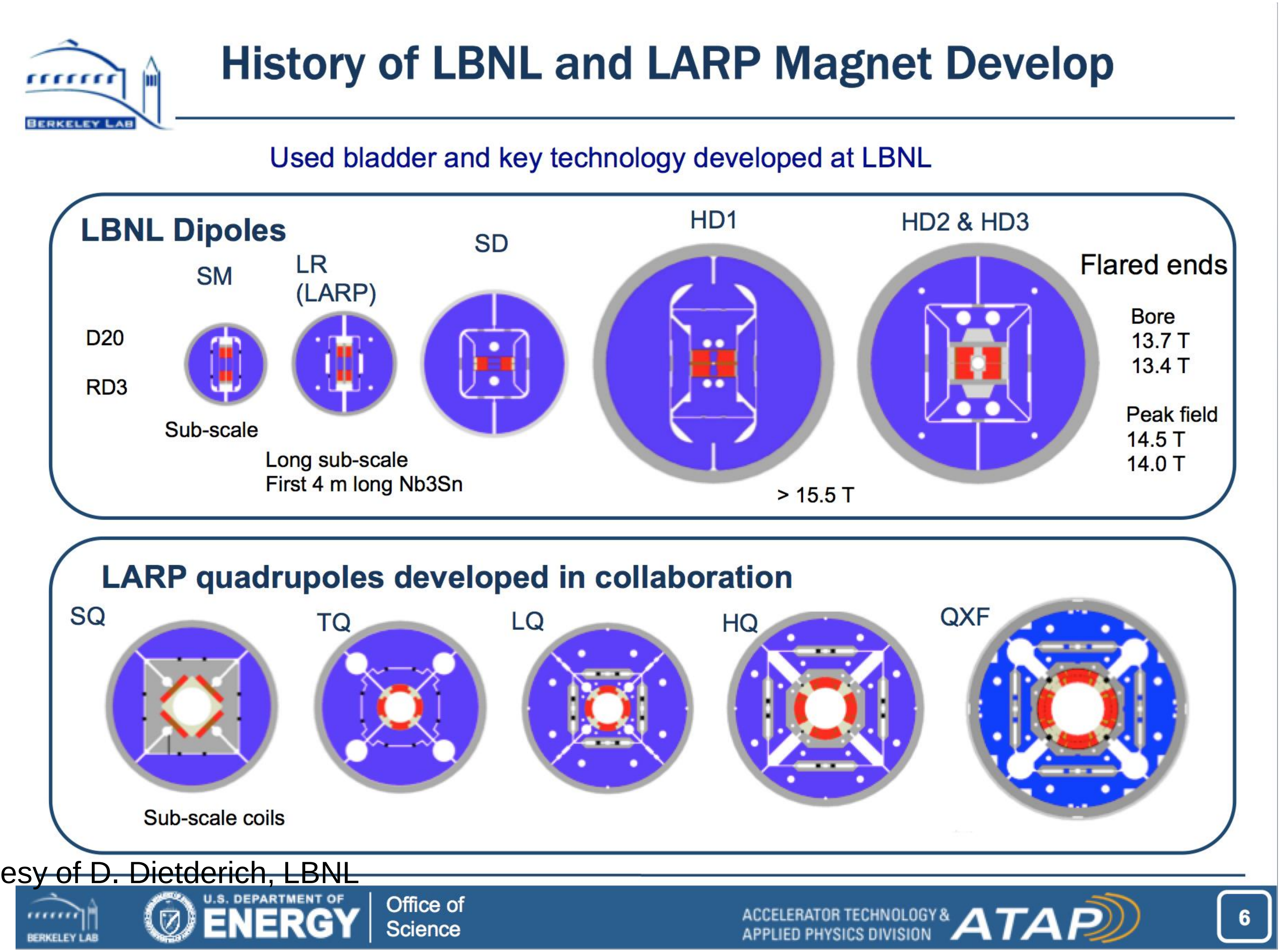


1 mm, 192 tubes
PIT from Bruker EAS



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

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

BERKELEY LAB

U.S. DEPARTMENT OF ENERGY | Office of Science

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

6

By courtesy of D. Dietderich, LBNL

Basic magnet technology development for HILUMI and beyond (2004-2013/4) ; Europe

European programs

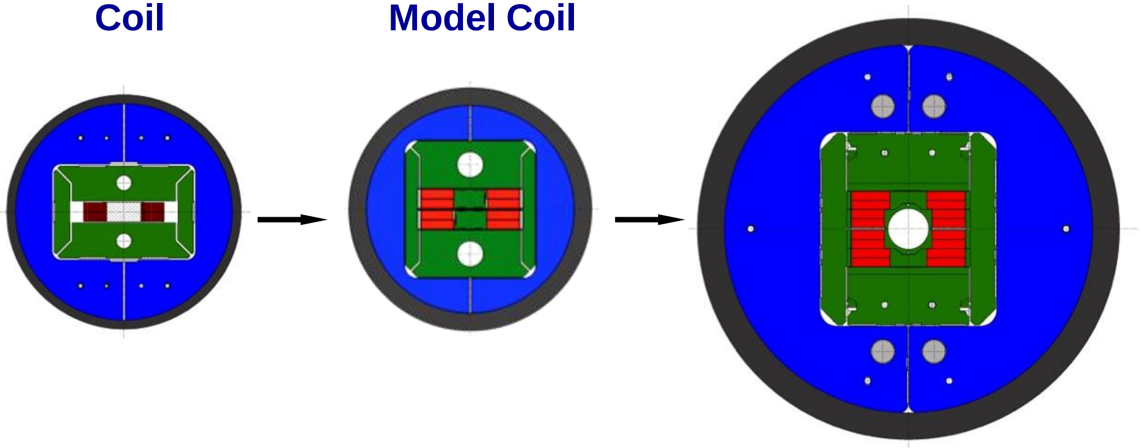
- 2004-2008 FP7-CARE-NED project (Next European dipole)
  - European accelerator grade Nb_3Sn conductor ➔ Powder In Tube (PIT) conductor now available from Brucker
  - Various studies on design options and materials

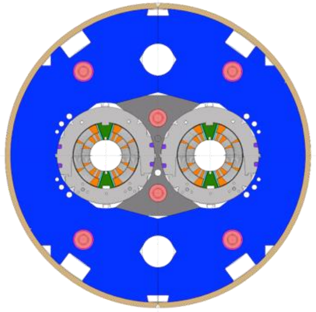
- 2009-2013 PF7-EuCARD-HFM project (High Field Magnets)
  - 100mm aperture 13 – 15 T Nb_3Sn dipole “Fresca2”
  - HTS insert with $\Delta B = 6$ T (inside Fresca2)
  - HTS current link
  - Nb_3Sn helical undulator

- 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

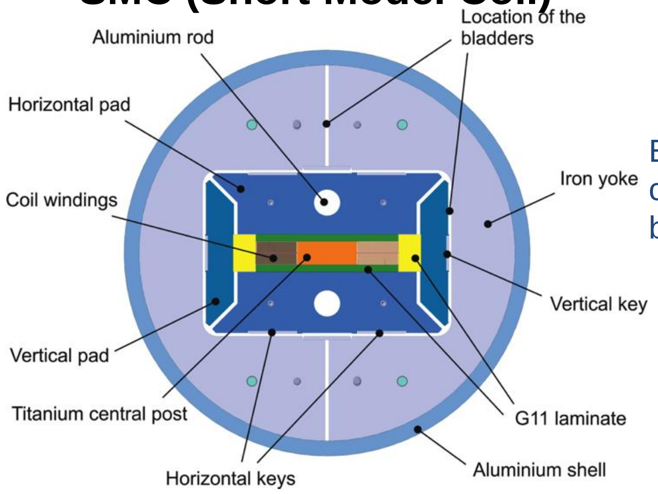
Short Model Coil → **Race-track Model Coil** → **FReSCa2 Nb_3Sn Dipole**



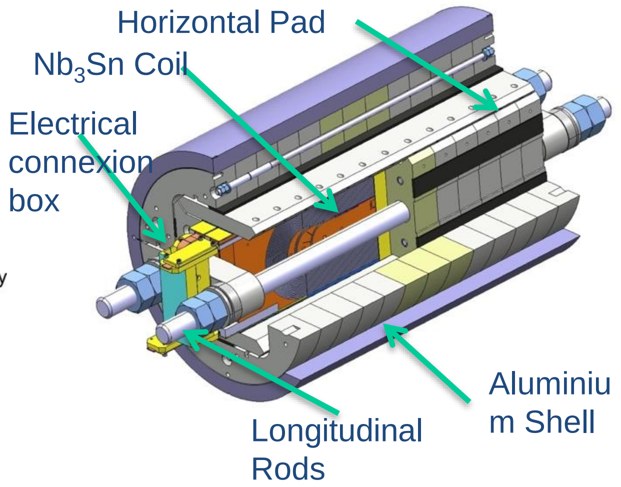


11 T dipole (CERN)

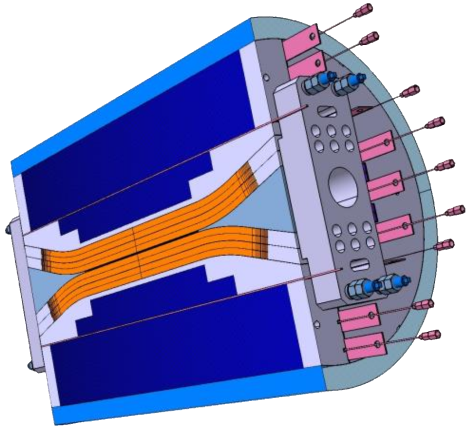
SMC (Short Model Coil)



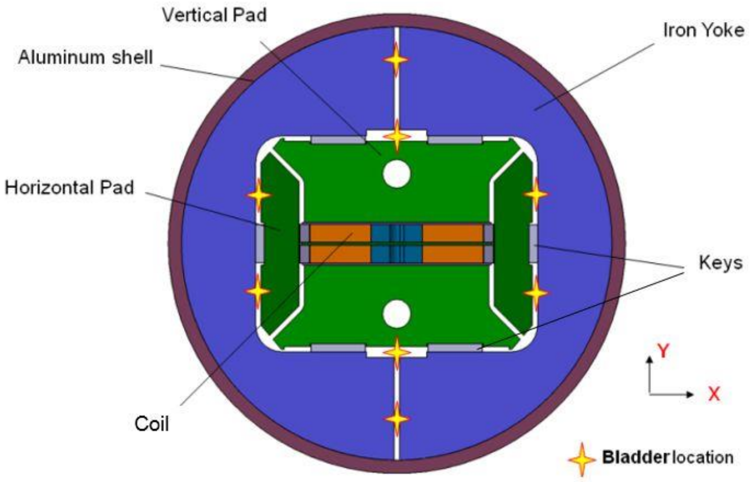
RMC (Racetrack Model Coil)

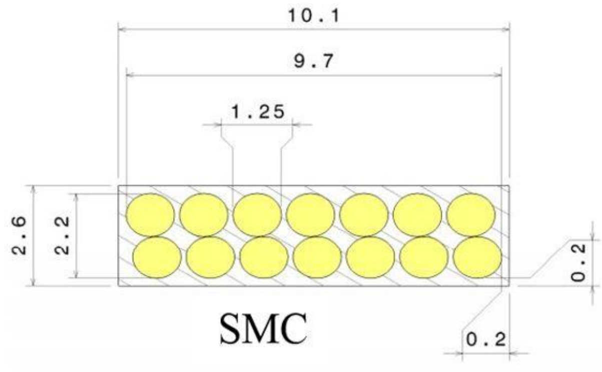


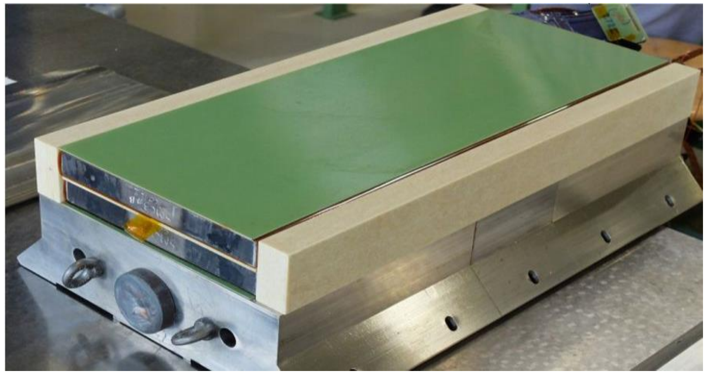
FReSCa2

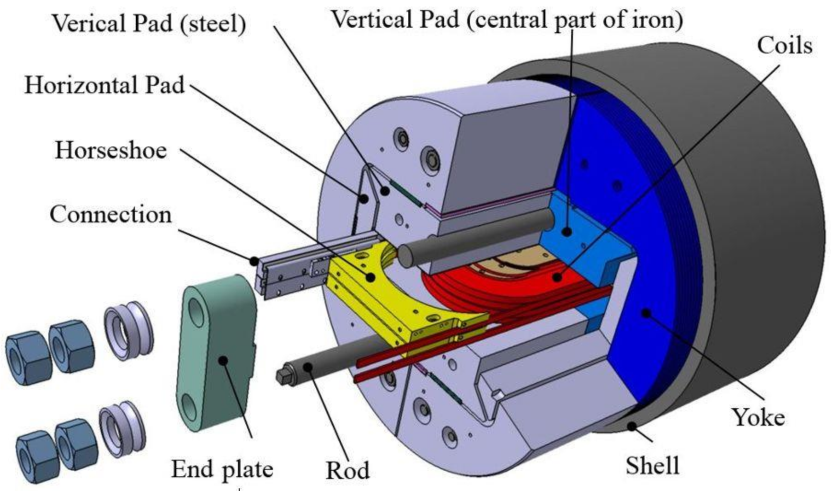


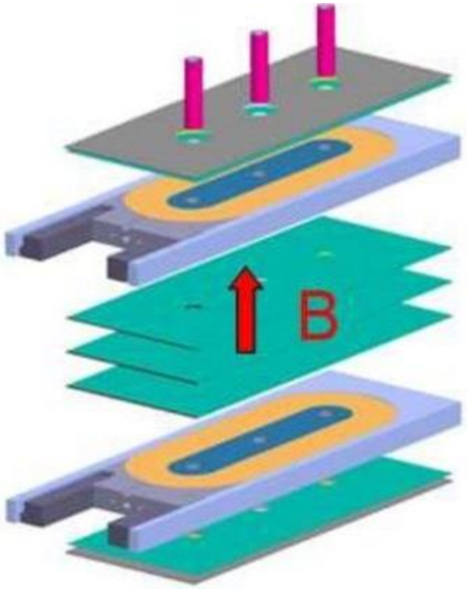
Short Model Coil, SMC

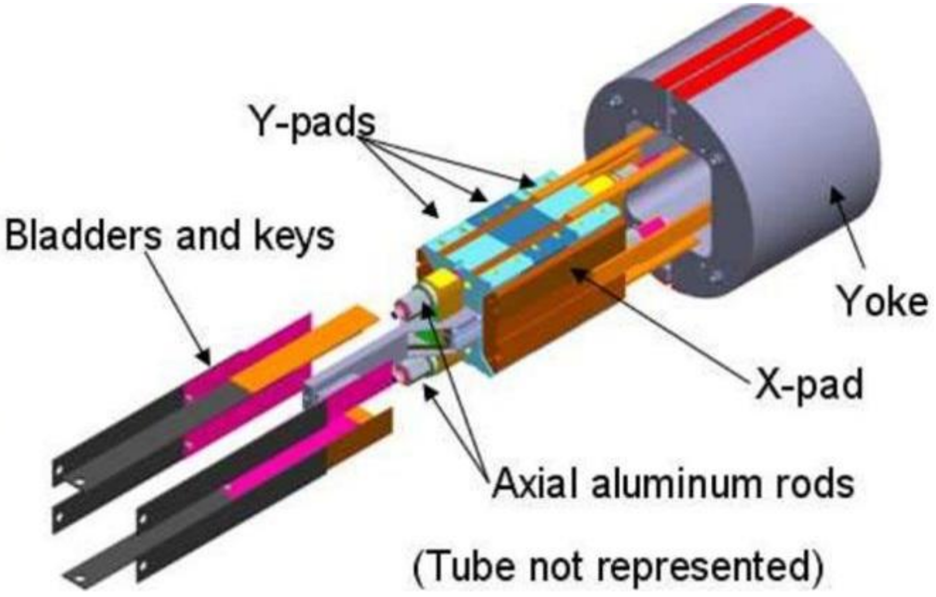












Courtesy: J-C Perez

SMC (2)

Number	Name	Number of DP	Coil names	Conductor type
1	SMC#1	2	SMC#1_c_1	IT
			SMC#1_c_2	IT
2	SMC#2	2	SMC#2_c_201	PIT
			SMC#2_c_202 (not produced)	PIT
3	SMC#3a	2	SMC#3a_c_201	PIT
			SMC#3a_c_202	PIT
4	SMC#3b	2	SMC#3b_c_201	PIT
			SMC#3b_c_202	PIT
5	SMC#4	2	SMC#4_c_201	PIT
			SMC#4_c_202	PIT
6	SMC#5	2	SMC#5_c_101	RRP
			SMC#5_c_102	RRP
7	SMC11T#1	1	SMC11T#1_c_101	RRP
8	SMC11T#2	1	SMC11T#2_c_101	RRP
9	SMC11T#3	1	SMC11T#3_c_101	RRP
10	SMC11T#4 201	1	SMC11T#4a_c_201	PIT
11	SMC11T#4 202	1	SMC11T#4b_c_202	PIT

- 16 SMC coils produced up to now
- Used to learn how to make Nb_3Sb coils
  - braiding, reaction, impregnation, traces
- Learn how to design, build and use shell-bladder-keys structure
- Cold tested to study:
  - Mechanics
  - Quench behaviour
  - Training behaviour
  - Cable performance
  - Stress sensitivity

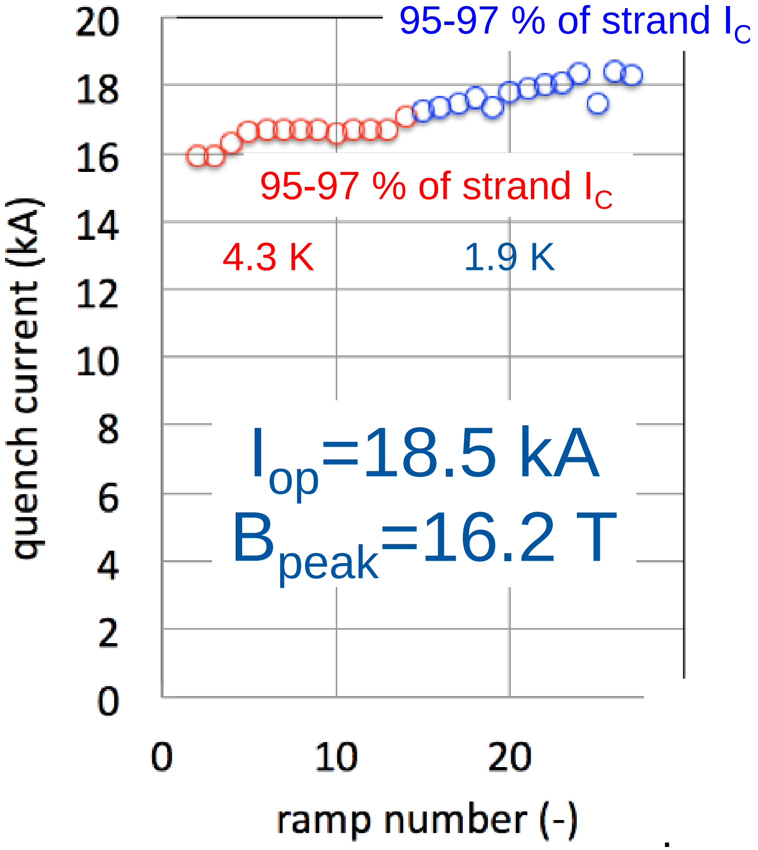
RMC3 16T: first milestone for FCC 16T !

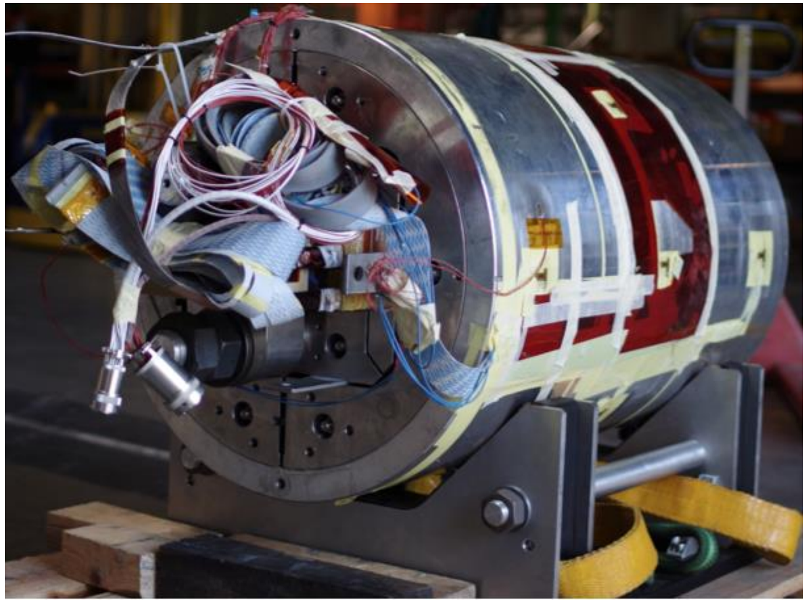
RMC:

Intermediate step towards Fresca2: “scaled up SMC”

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

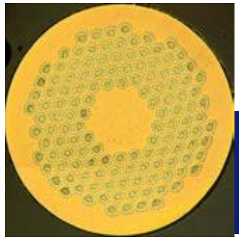
Joining LBNL at the 16T record level





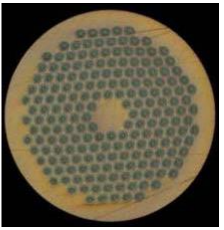
Fresca 2 Dipole cable

40 Strands, Width = 20.9 mm



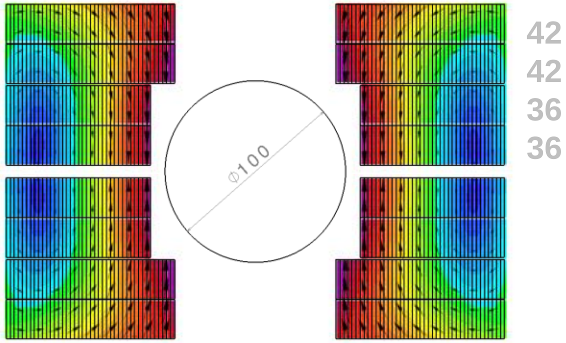
RRP 132/169

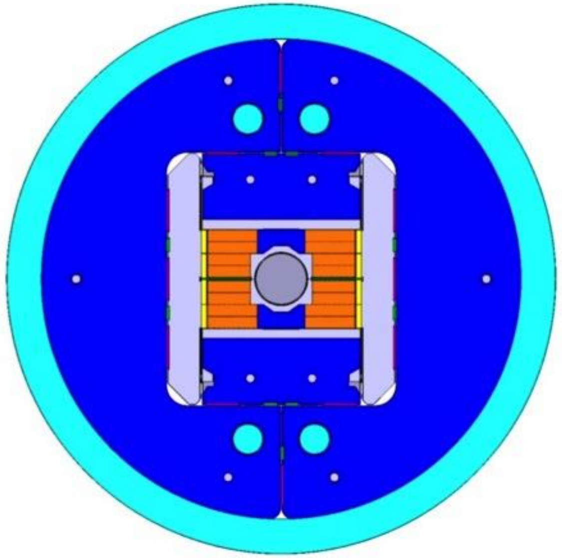
PIT 192



EuCARD high field dipole (FRESCA2)

- FRESCA2 : a CERN, CEA EuCARD collaboration

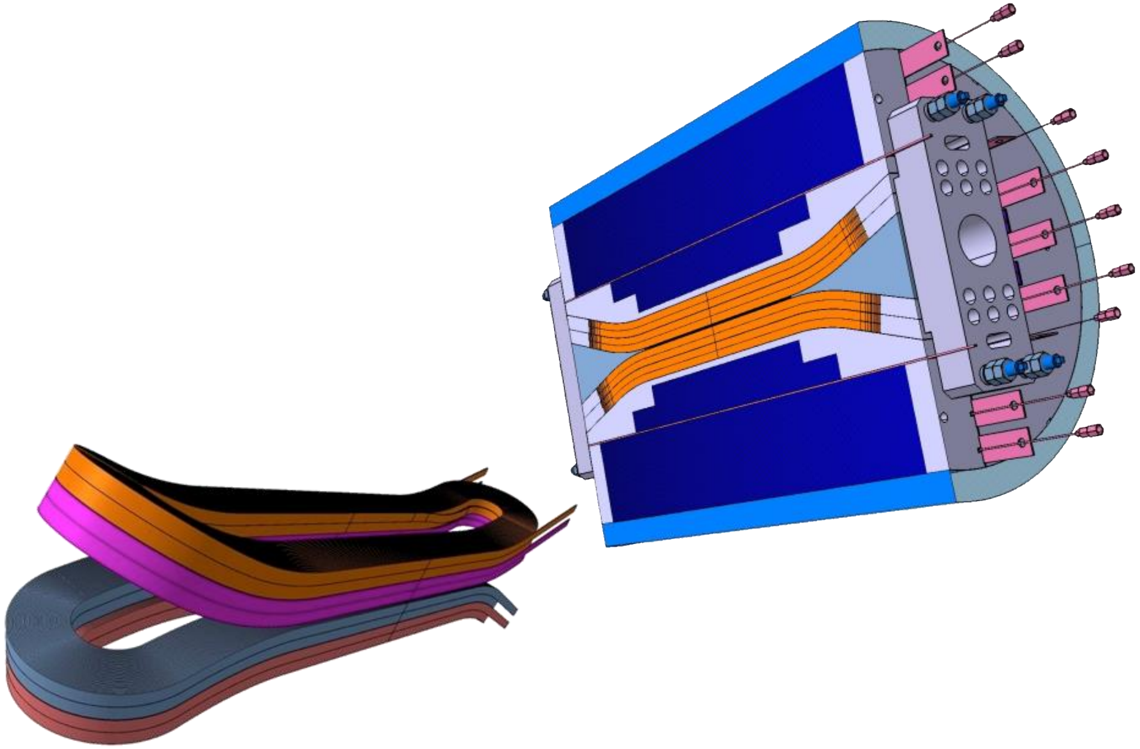




- 156 turns per pole
- Iron post
- B_{center} = 13.0 T
- I_{13T} = 10.7 kA
- B_{peak} = 13.2 T
- E_{mag} = 3.6 MJ/m
- L = 47mH/m

- 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

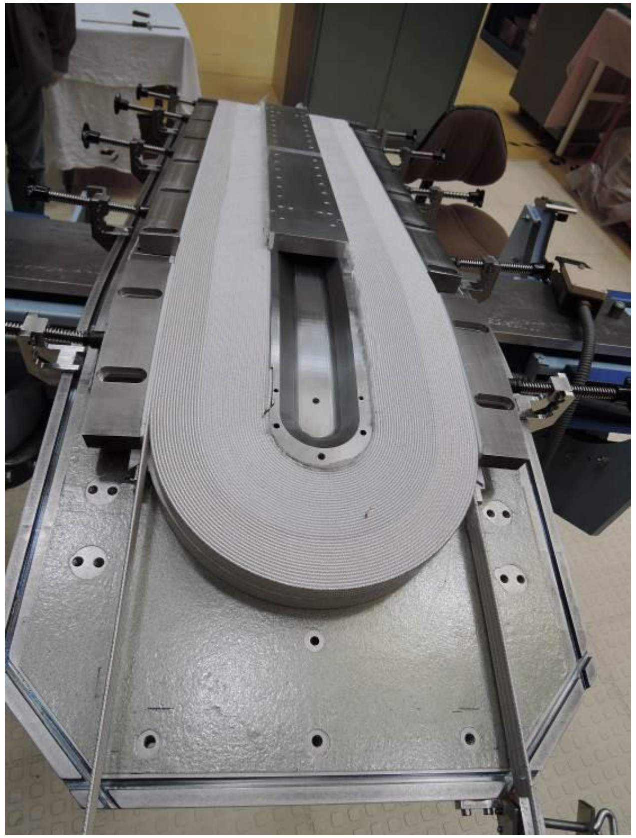


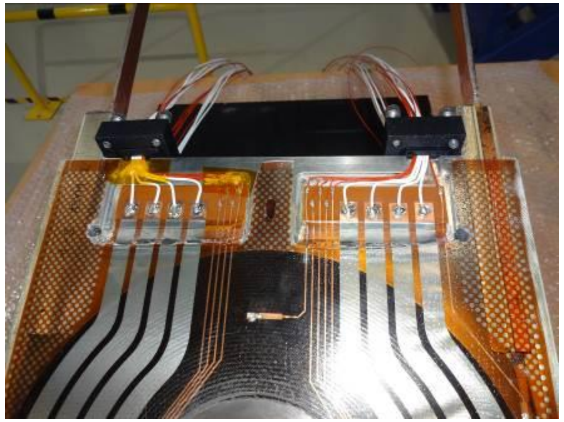
Courtesy: Paolo Ferracin, J-C. Perez, Attilio Milanese, Pierre Manil

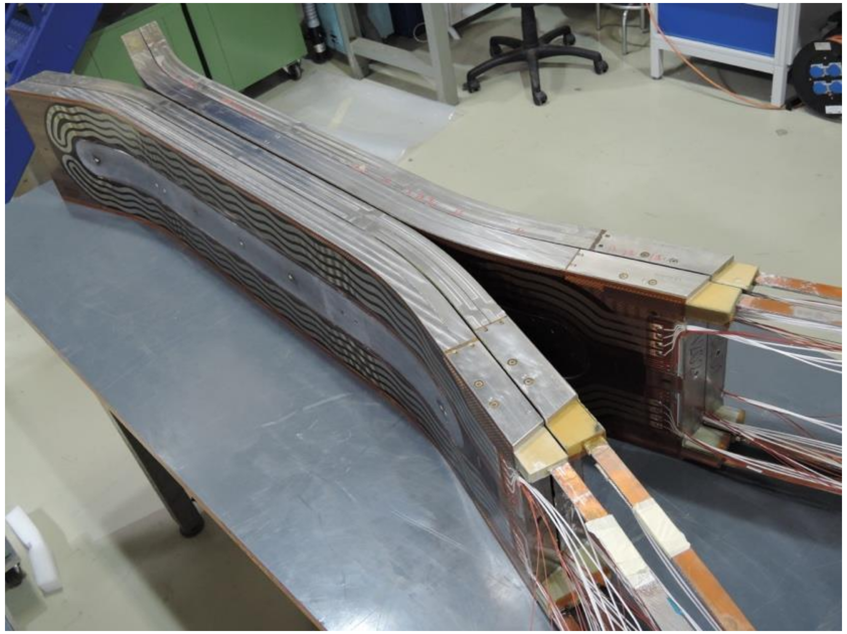
Fabrication of Fresca2 coils

Straightforward technology to wind block coils with flared ends:

This is a lesson for FCC magnets !

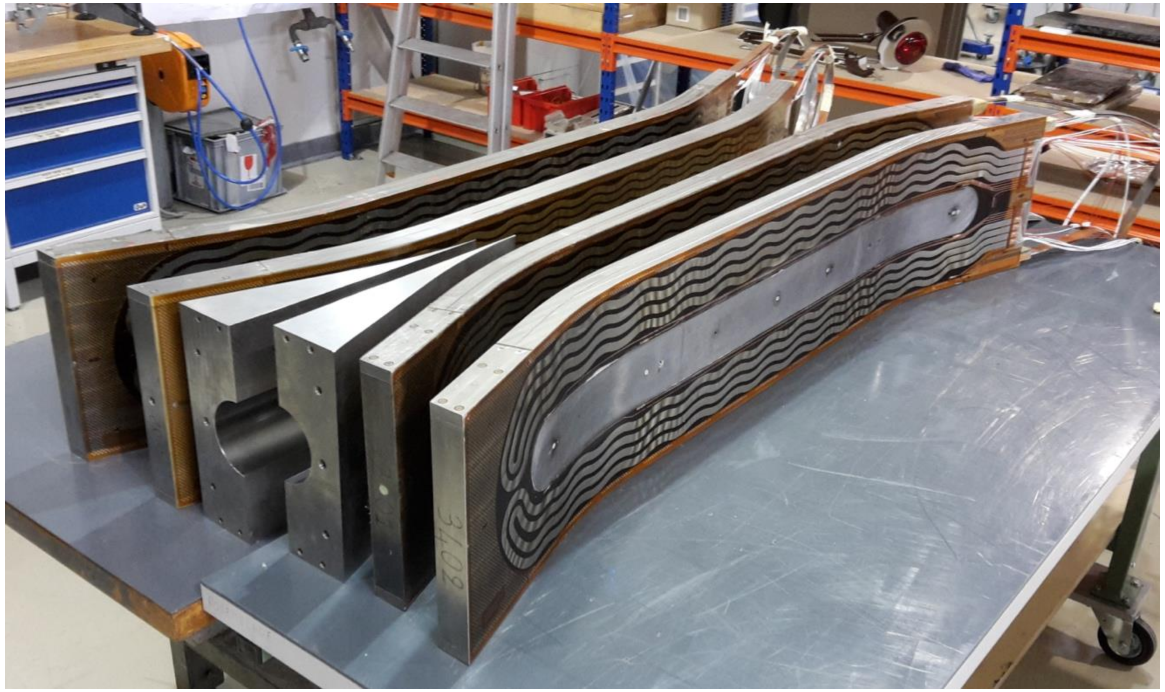






Courtesy: F. Rondeaux, J-C. Perez

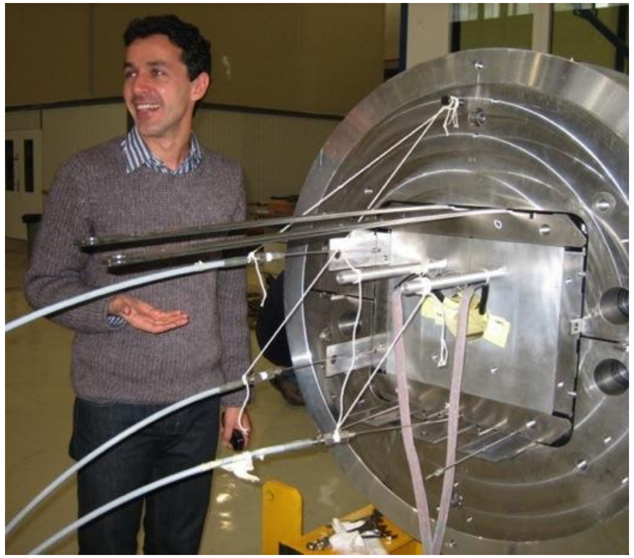
Fresca2 : get the 13T FCC milestone in 2017 and then move to 15 T



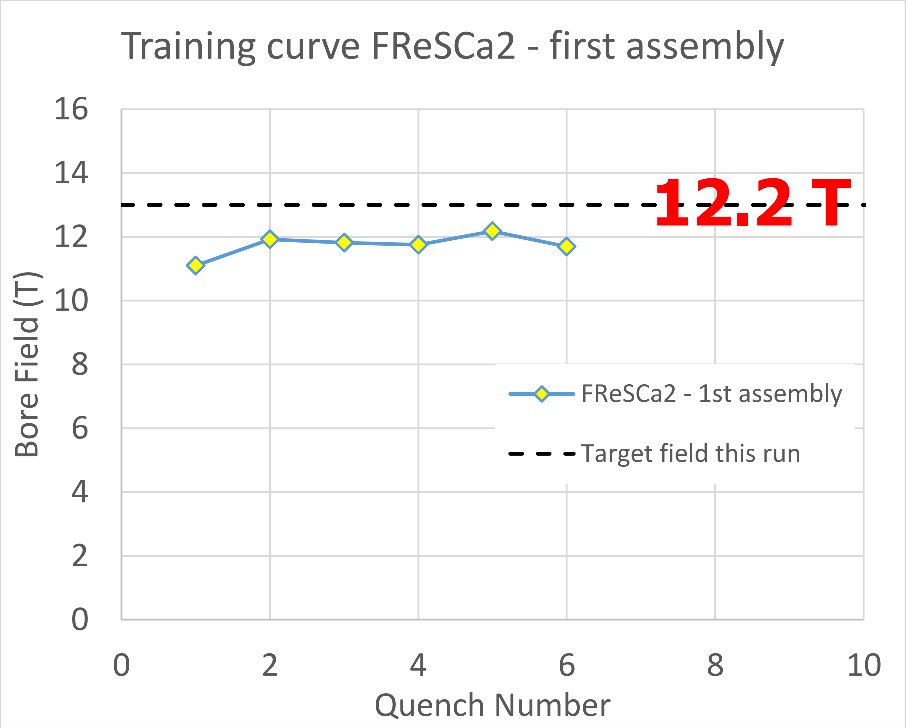
First test: 13T loading,

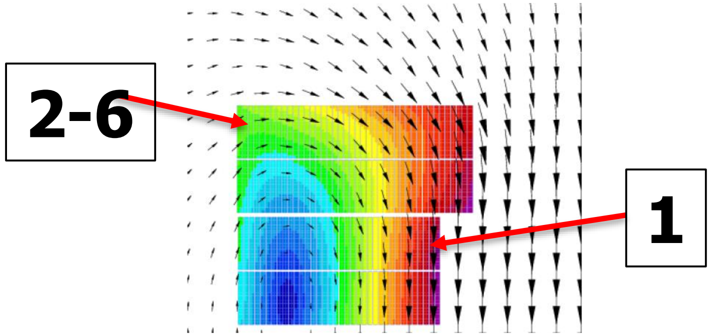
then warm up and loading for 15T,

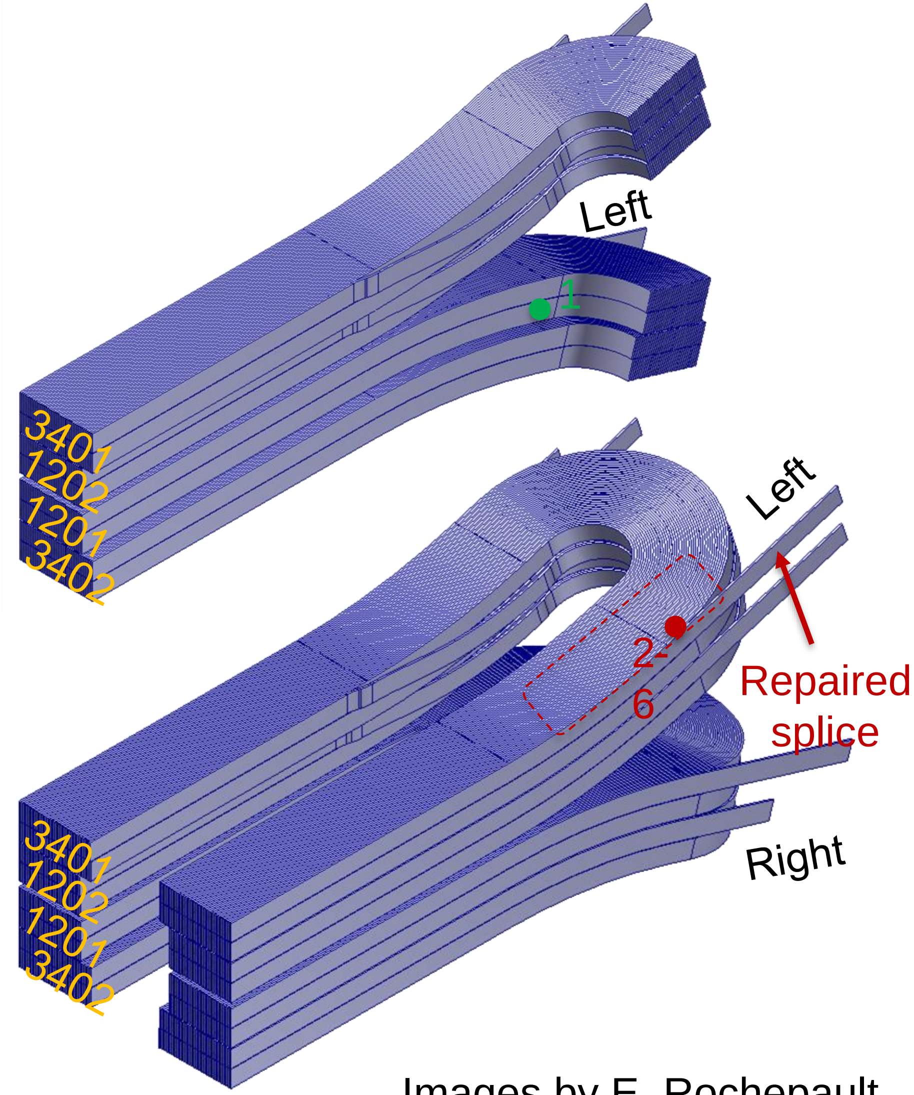
Second test: go up to 15T



FRESCA2 – first assembly - training





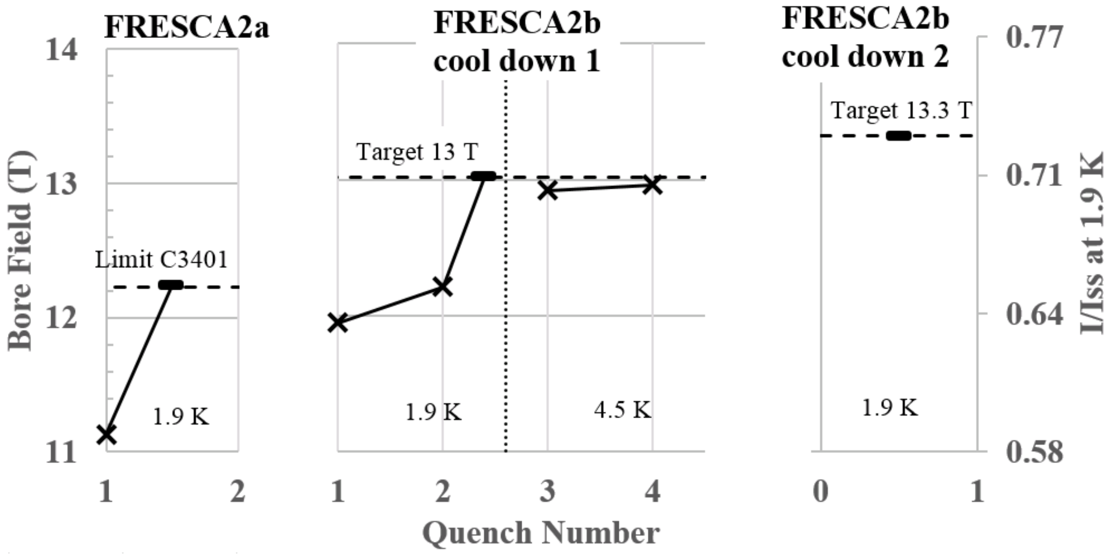


Images by E. Rochepault

FRESCA2 – second assembly - training (Aug 2017)

With Pre-stress for 13T

- @1.9K in 2 quenches to 13.0 T
- @4.2K in 2 quenches to 13.0 T
- Warm-up cooldown cycle : @1.9K to 13.3T
- Why limit to 13.3T ?
  - Not to damage the coils by pole detachment due to lack of pre-stress



Increased pre-stress for 15T

- After a water leak from the bladders a coil-ground short circuit developed (and stayed)

Plan: disassemble coil pack from the structure and redo the ground insulation, then put the pre-stress back (for 15T ops)

Basic magnet technology development for HILUMI and beyond: Results

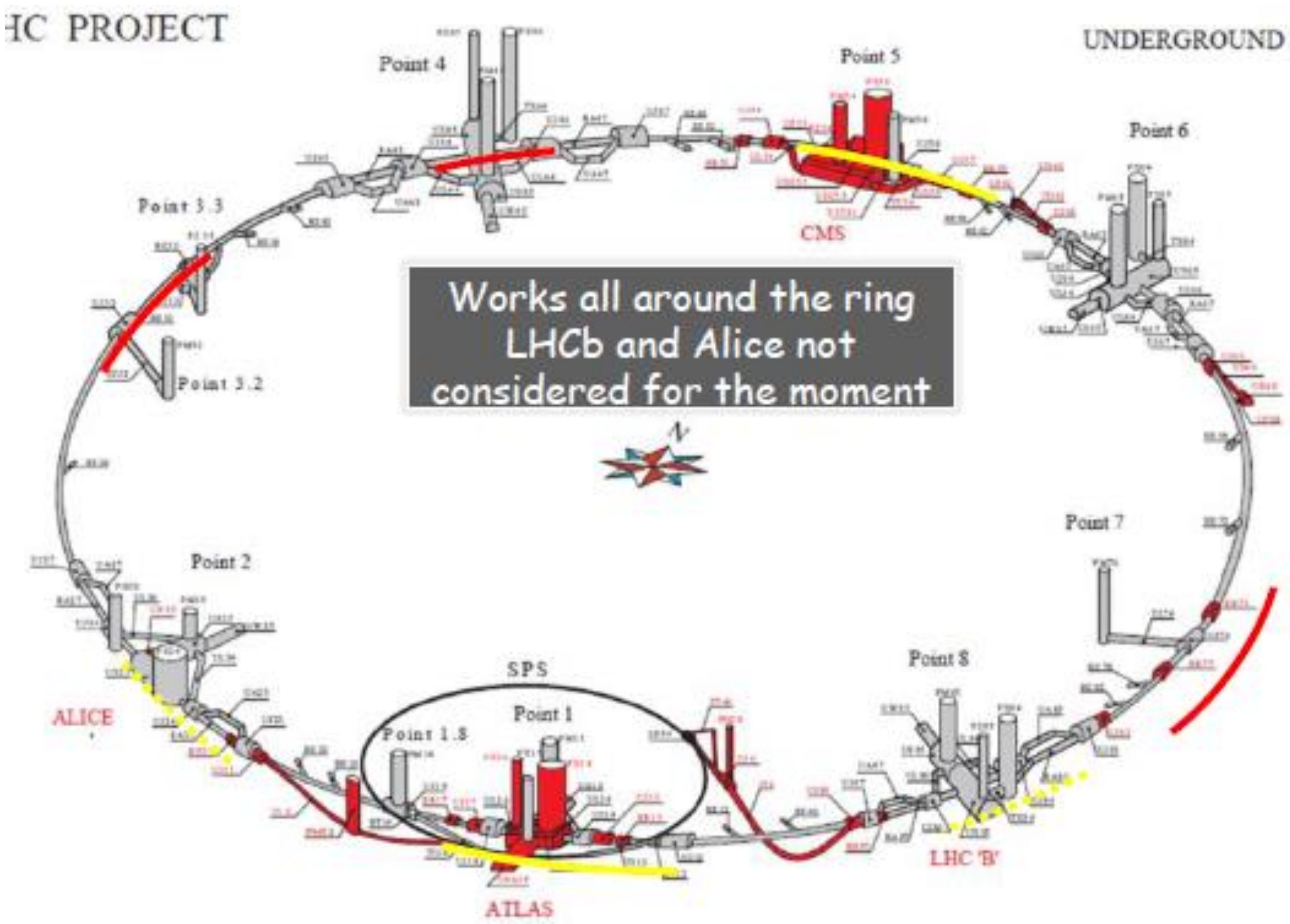
- This phase of development gave us
  - Conductor pre-FCC grade in both US and EU
  - Basic coil manufacturing technology close to FCC standard
  - New coil and structure geometries

- 3 milestones
  - HD1 & RMC 16T on the coil (no aperture) Achieved mid 2015
  - Fresca2 13.3T in a large aperture Achieved mid 2017,

    15T in a large aperture : after short circuit repair : Q1 2018

HILUMI magnet development (2013-2016)

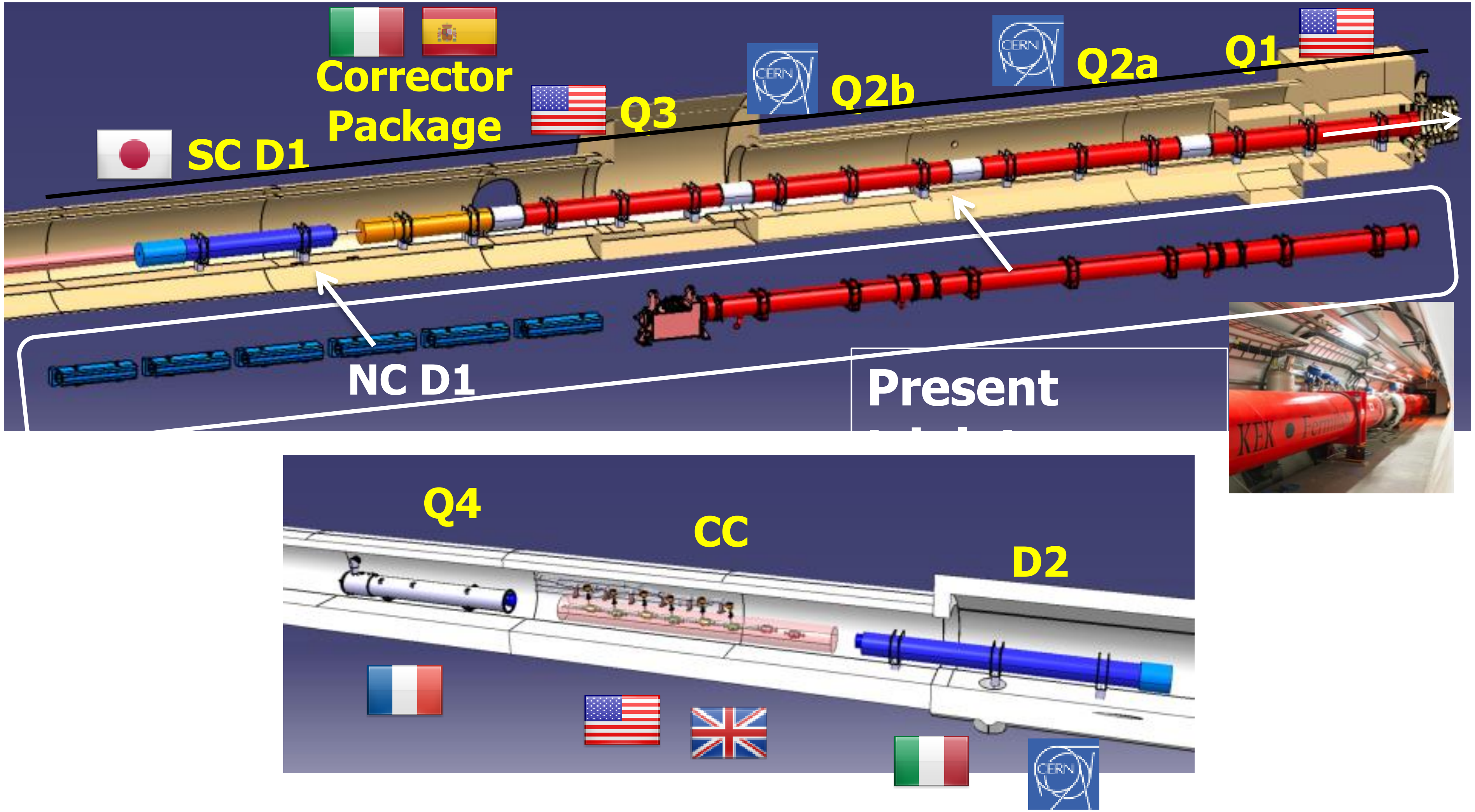
- HILUMI means new magnets in ~1 km of the the LHC main ring
- The ultimate test-bed for the feasibility of Nb_3Sn magnets in accelerators!



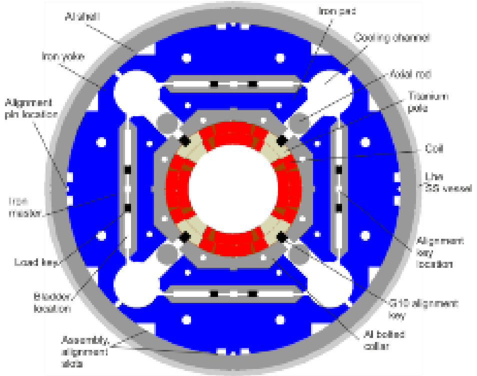
Works all around the ring
LHCb and Alice not
considered for the moment

New triplet for HHILUMI

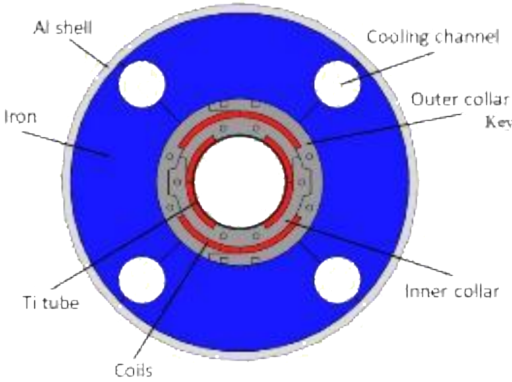
Lower β value in the interaction points : larger apertures needed in the triplet of the machine (from 70 mm to 150 mm)



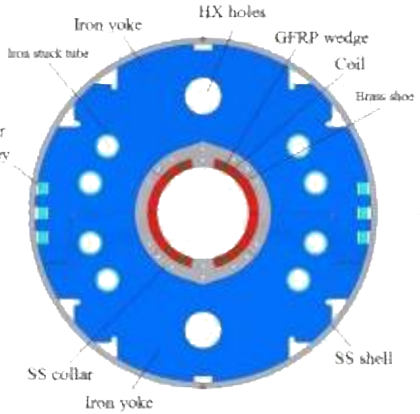
HILUMI IT magnet zoo



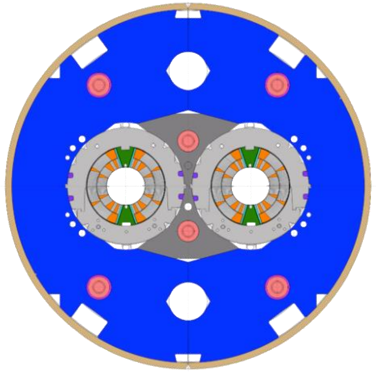
Triplet QXF (LARP and CERN)



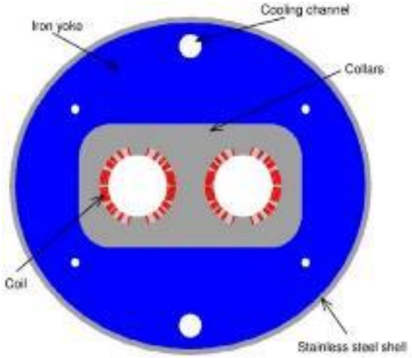
Orbit corrector (CIEMAT)



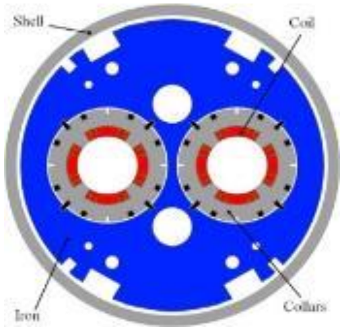
Separation dipole D1 (KEK)



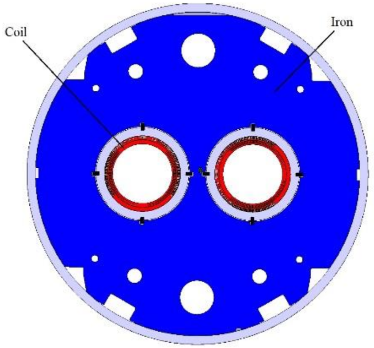
11 T dipole (CERN)



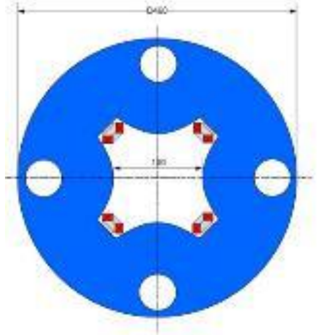
Recombination dipole D2 (INFN)



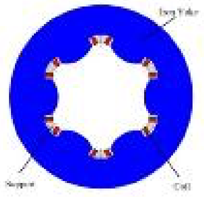
Q4 (CEA)



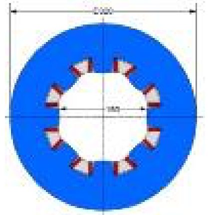
D2/Q4 orbit corrector (CERN)



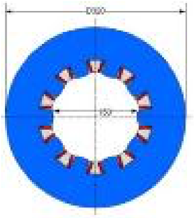
Skew quadrupole (INFN)



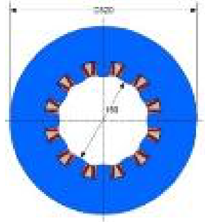
Sextupole (INFN)



Octupole (INFN)



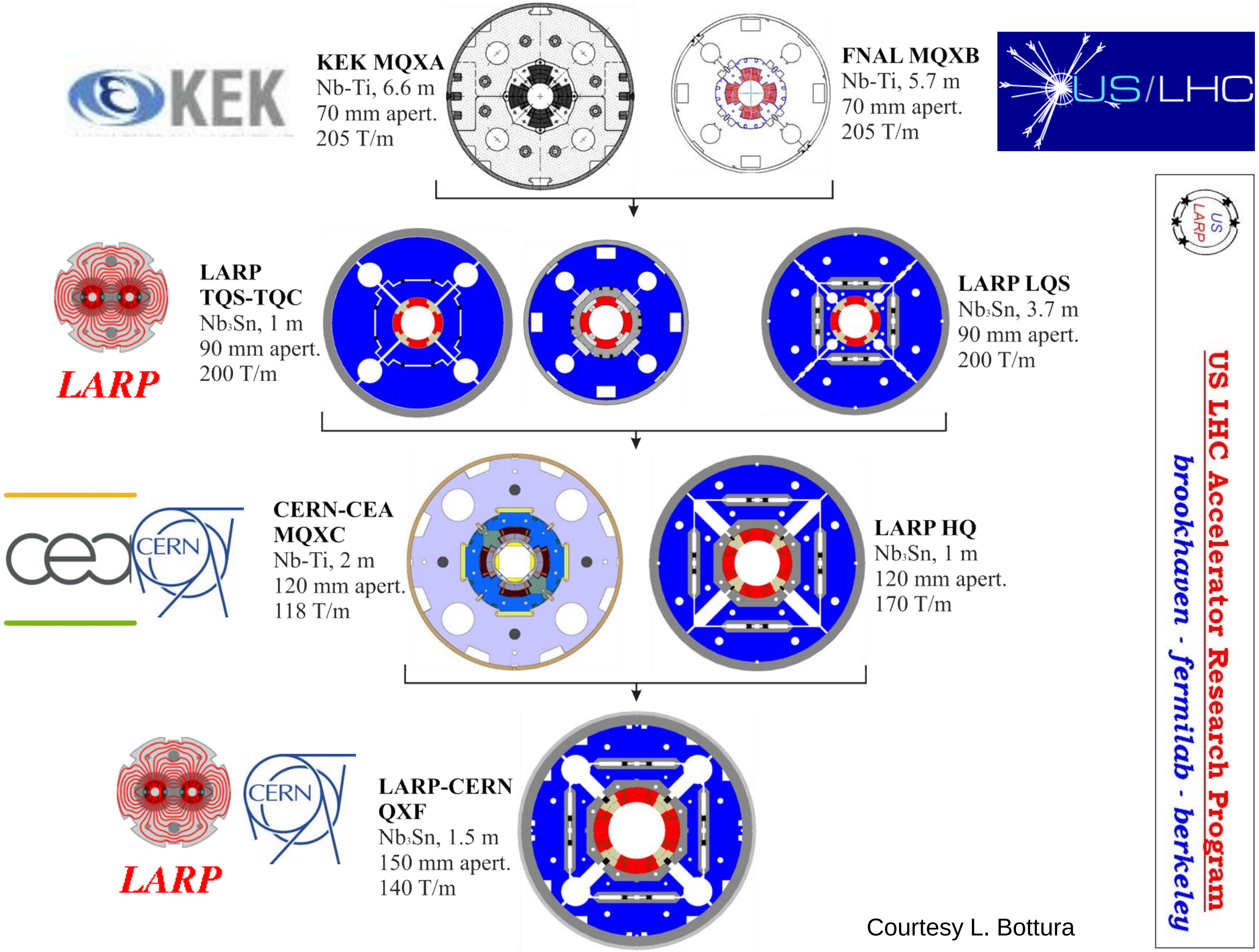
Decapole (INFN)



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

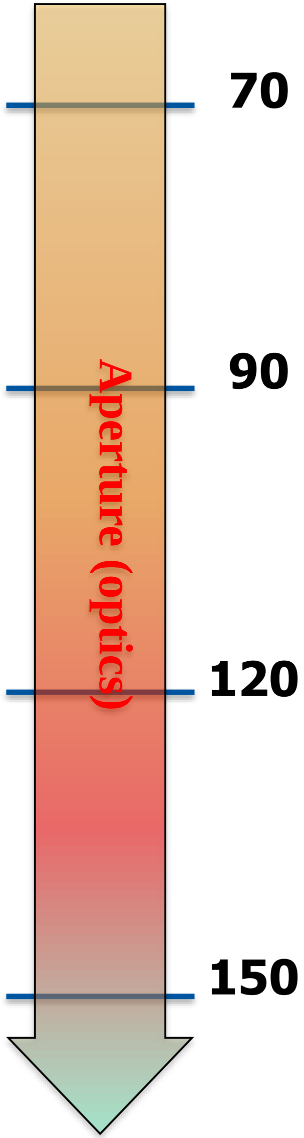
LARP TQS-TQC
Nb$_3$Sn, 1 m
90 mm apert.
200 T/m

LARP LQS
Nb$_3$Sn, 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$_3$Sn, 1 m
120 mm apert.
170 T/m

LARP-CERN QXF
Nb$_3$Sn, 1.5 m
150 mm apert.
140 T/m



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 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

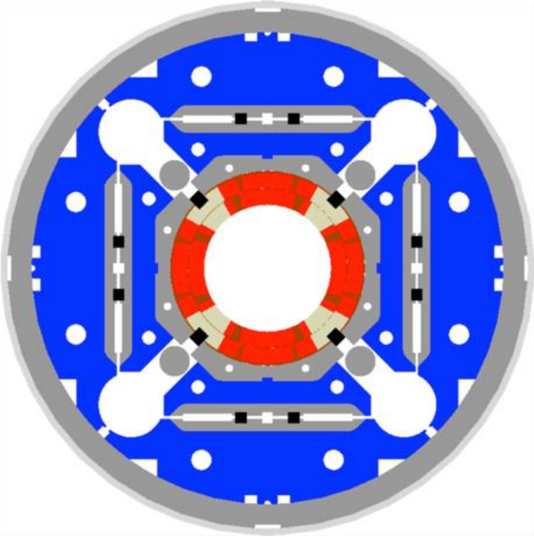
Aperture diameter 150 mm

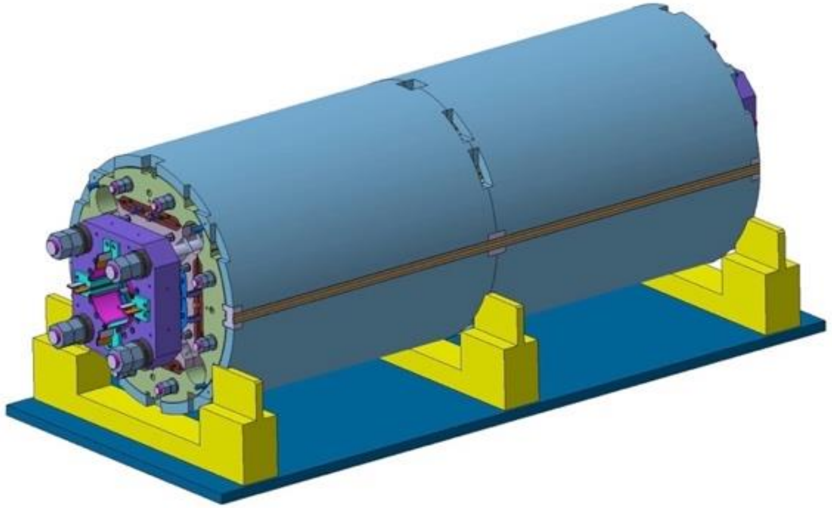
Peak Field 12.1 T

Current 17.5 A

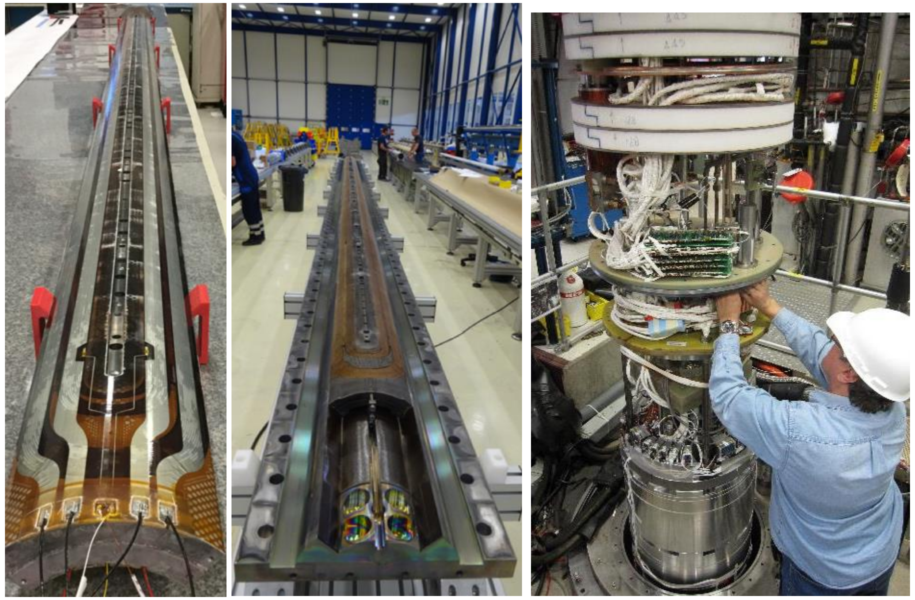
Loadline Margin 20% @ 1.9 K

Stored Energy 1.32 MJ/m

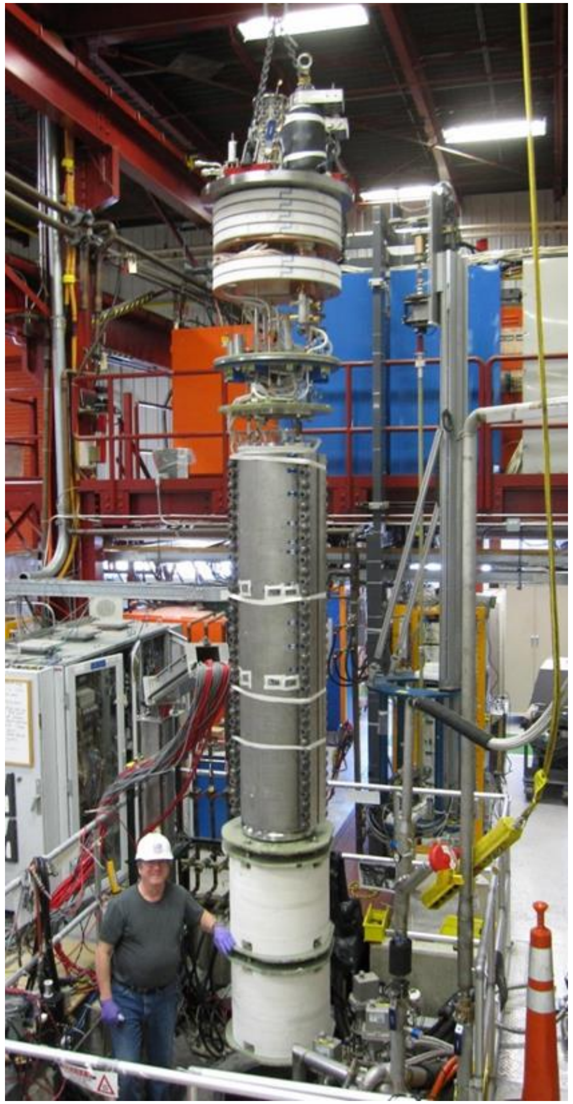


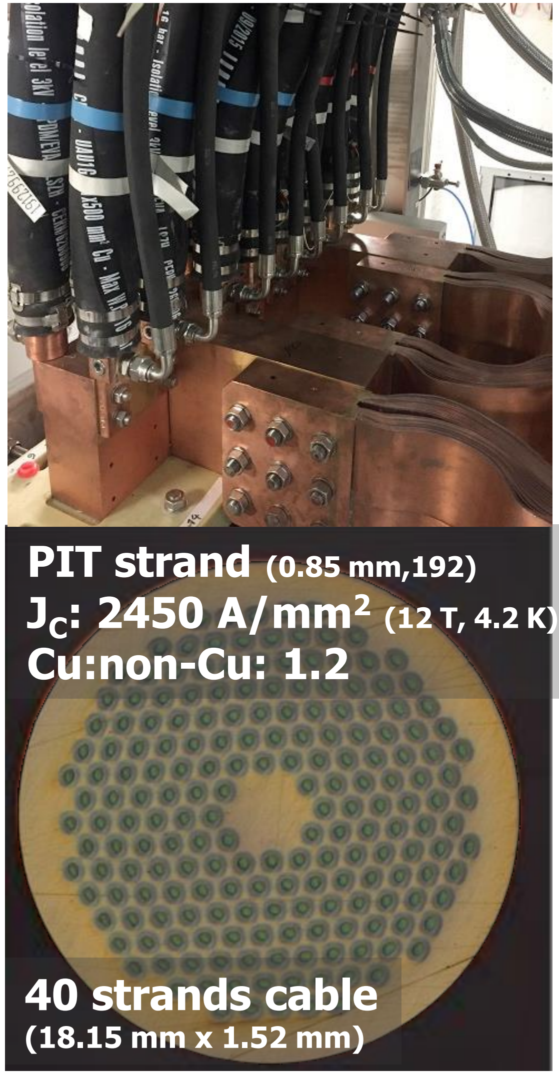


By courtesy of G. Ambrosio (FNAL), P. Ferracin (CERN)



Test of MQXFS models 1 & 3





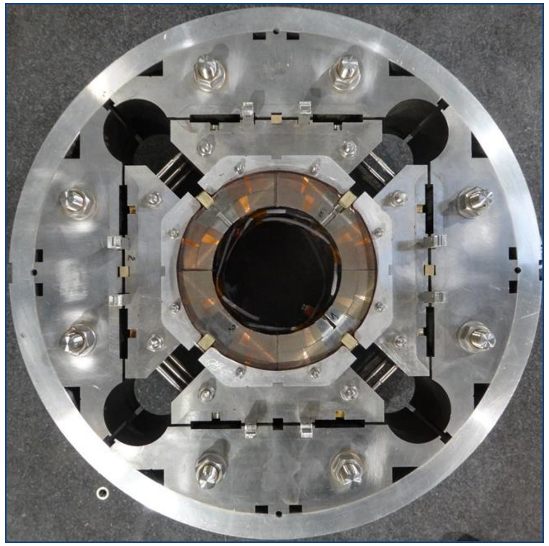
PIT strand (0.85 mm,192)

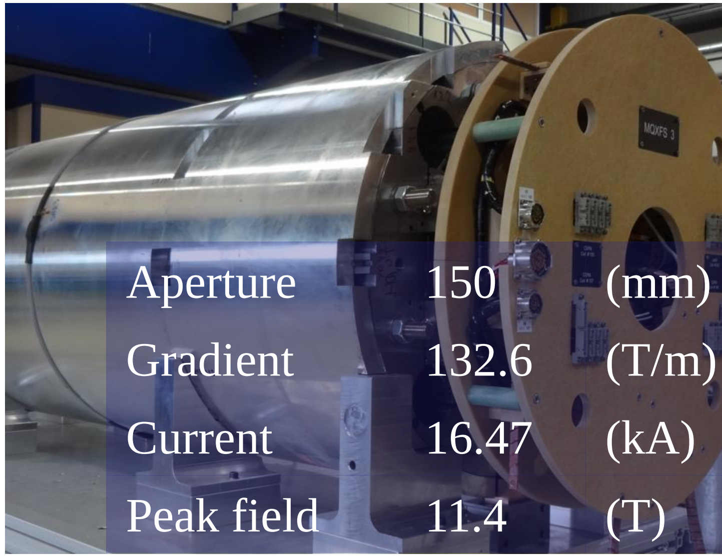
J_C: 2450 A/mm^2 (12 T, 4.2 K)

Cu:non-Cu: 1.2

40 strands cable

(18.15 mm x 1.52 mm)

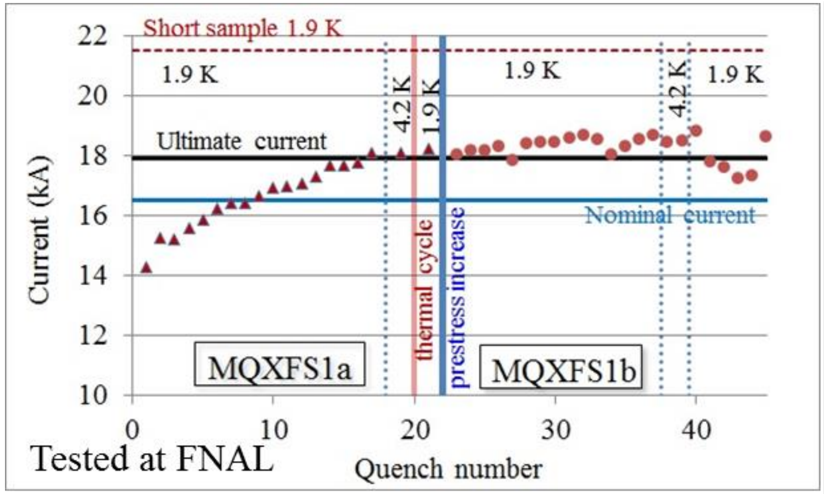




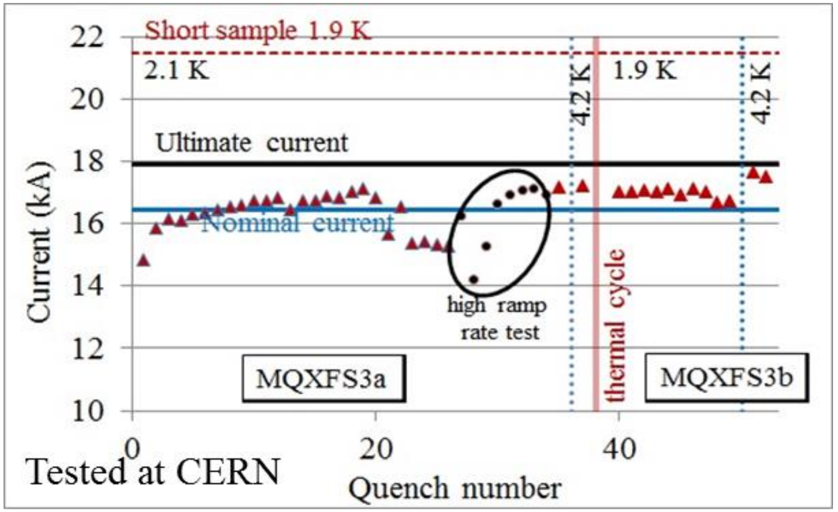
Aperture	150	(mm)
Gradient	132.6	(T/m)
Current	16.47	(kA)
Peak field	11.4	(T)

Short Model Tests: Quench History

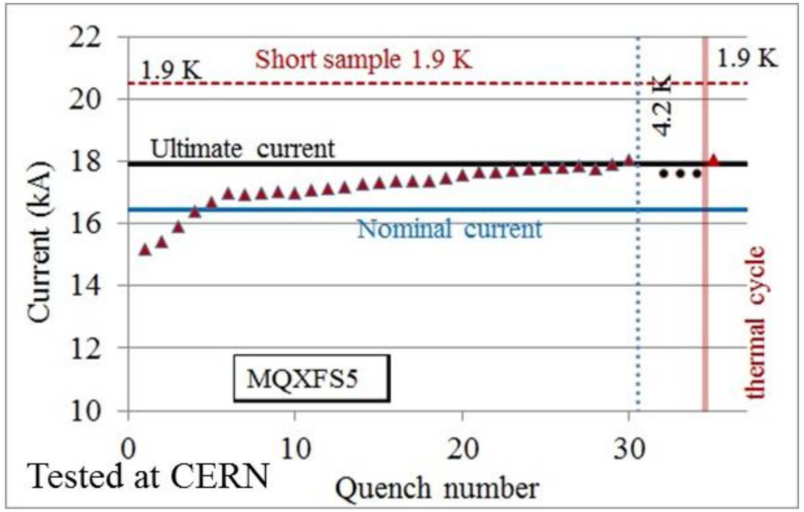
MQXFS1: ultimate current, temperature margin and excellent memory



MQXFS3a: Reached nominal, but slower than MQXFS1 and detraining in coil 7 (recovered)



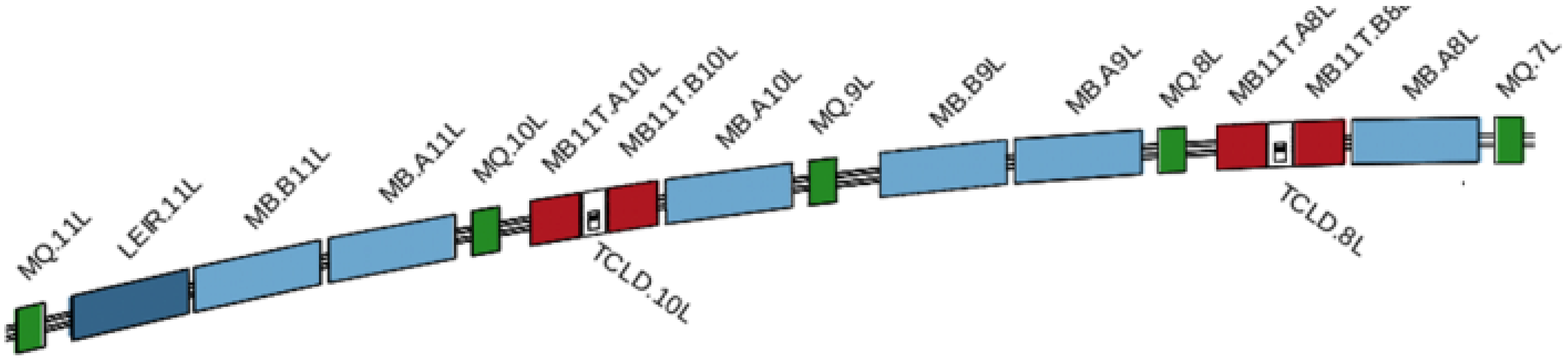
MQXFS5: Reached ultimate

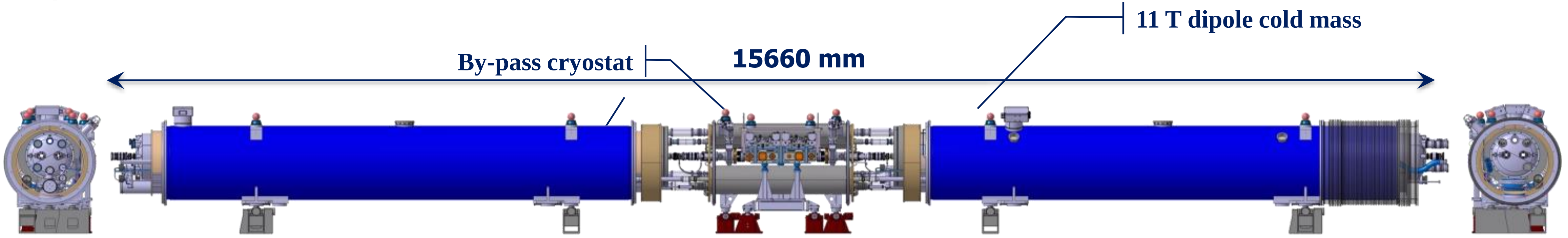


- MQXF magnets can meet gradient & memory requirements
- Understanding safe pre-stress range & application

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

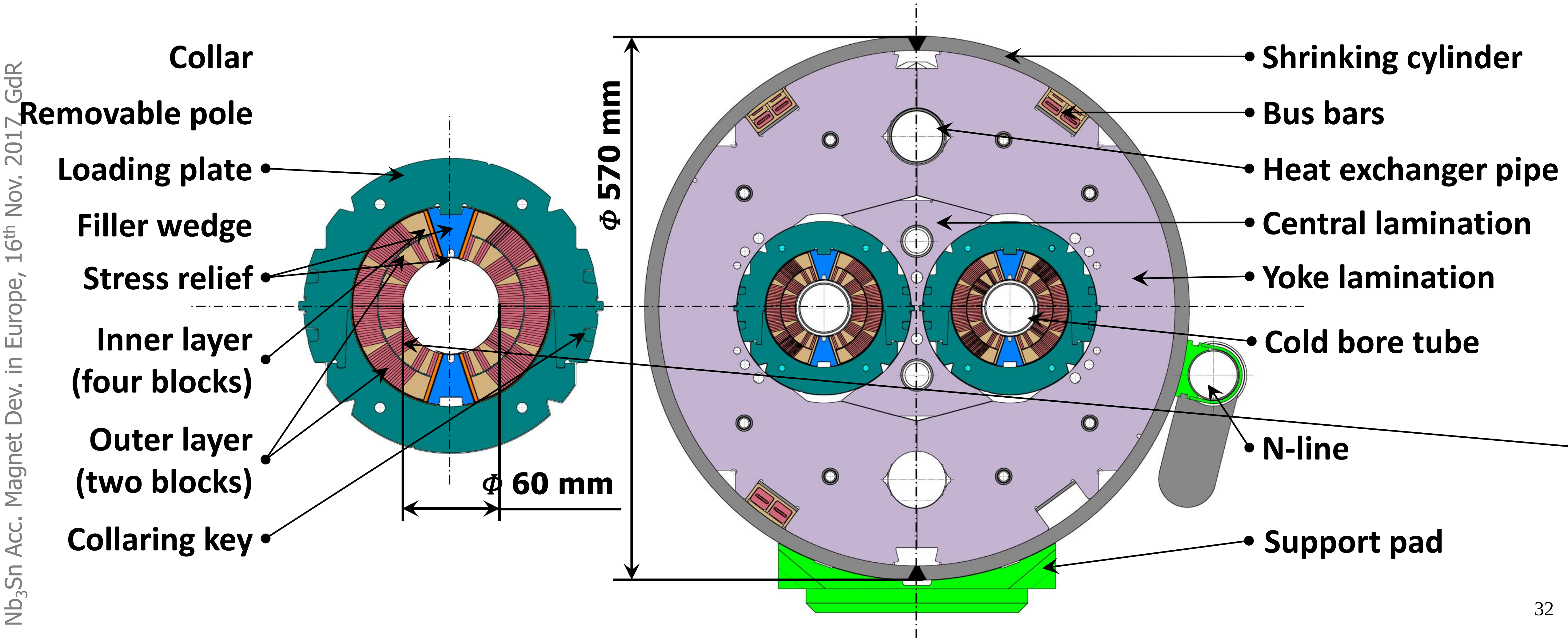
- Create space in the dispersion suppressor regions of LHC, i.e. a room temperature beam vacuum sector, to install additional collimators (TCLD), (needed to cope with beam intensities that are larger than nominal, such as in the HL LHC)
- Replace a standard MB by a pair of 11T dipoles (MBH)





11T Dipole – Main design features

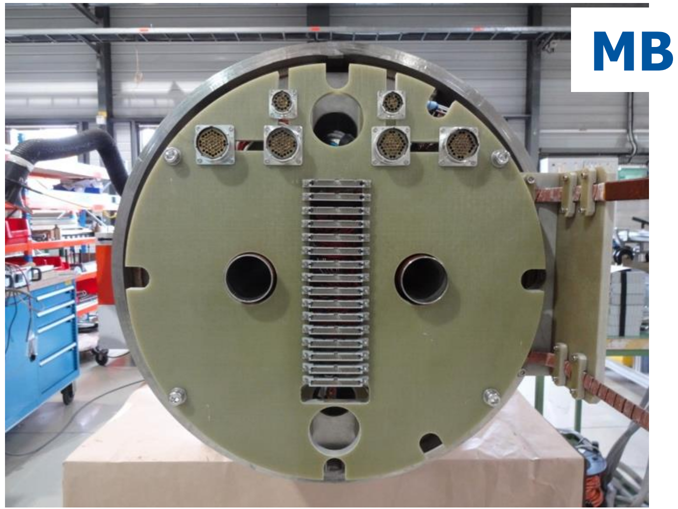
- Like the LHC main dipole, the 11 T dipole has a **two-in-one** structure
- Cold mass length: 6.252 m, weight ≅ 8 t, magnetic length = 5.307 m



Ongoing work and results

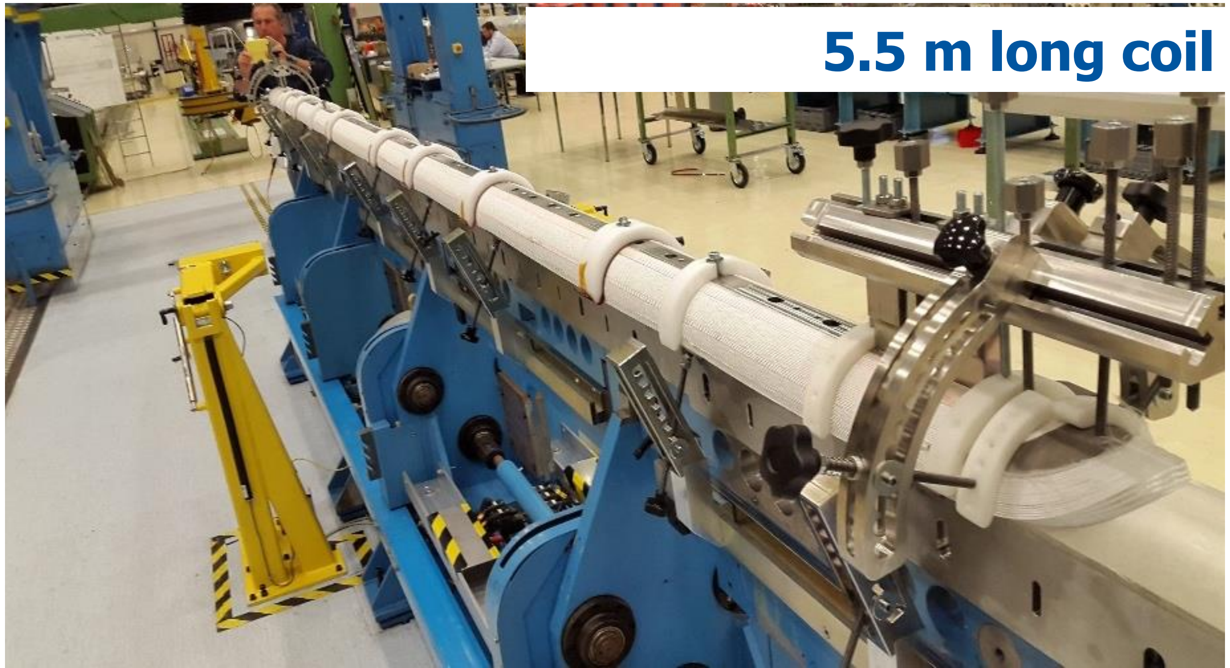
MBHDP102

MBHDP101



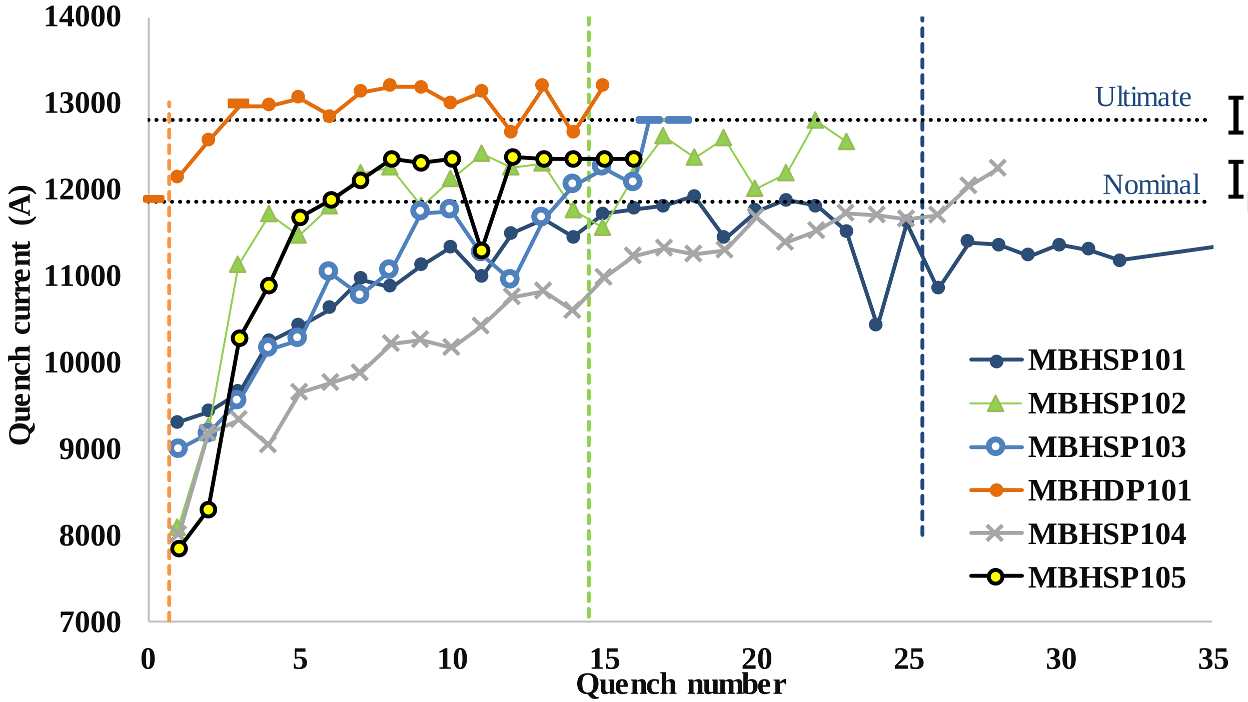
5.5 m long collared coils

5.5 m long coil



Summary cold power results

[Willering et al., MT25 2017]



$I_{ultimate}$ = 12.8 kA

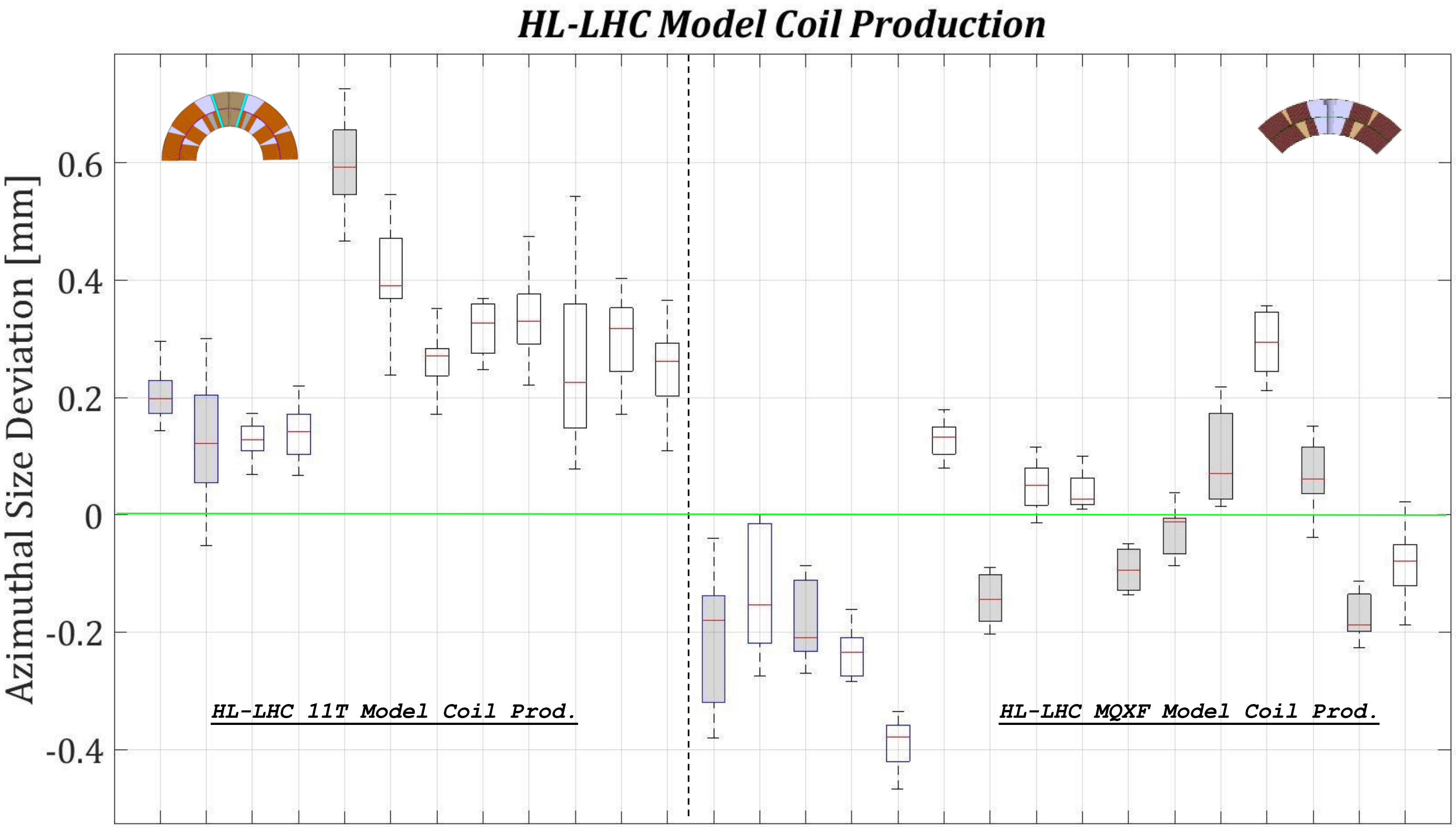
$I_{nominal}$ = 11.85 kA

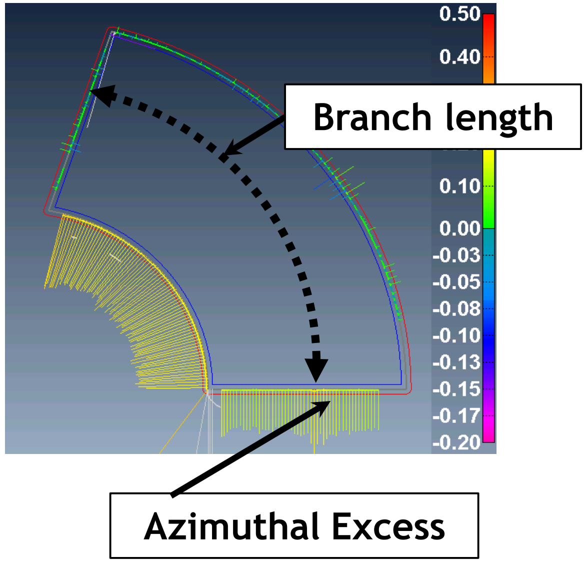
Model	I_{max} (kA)
SP101	11.92
SP102	12.8
SP103	12.8
DP101	13.3
SP104	12.3
DP105	12.4

- All reach nominal current.
- Excellent performance of DP102.
  - Coils pre-trained in 1in1 (SP102 and SP103) → Straight to nominal.
  - Exceed ultimate current.
- SP104 slow training to nominal current.
- SP105 fast training to nominal current.
- SP104 and SP105 did not reach ultimate current. Limited at midplane!

Azimuthal size of coils for 11T and MQXF

- 11 T are consequently over sized, whereas MQXF (aperture about 3 times larger) can be both too small and too large.
- Main issue when the coil size varies over the length of the straight section.


HL-LHC Model Coil Production


Branch length

Azimuthal Excess

[J. Ferradas MT25]

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)
• We showed that 13T is possible in a large aperture	(CEA and CERN)

But we still have some issues:

- A bit too large coil azimuthal size variation
- Pre-stress for collared structures is not (yet) completely under control
- Inhomogeneity of the (pre)stress over cable width
- Cable insulation fragility
- Training: Epoxy cracking, sliding surfaces, non-binding poles, etc
- The margin issue: do we need 10 or 20% on the loadline ?

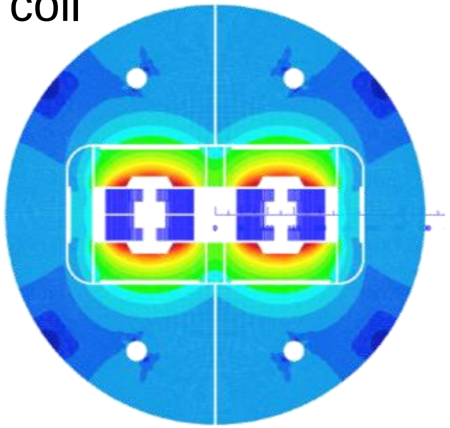
Towards FCC

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

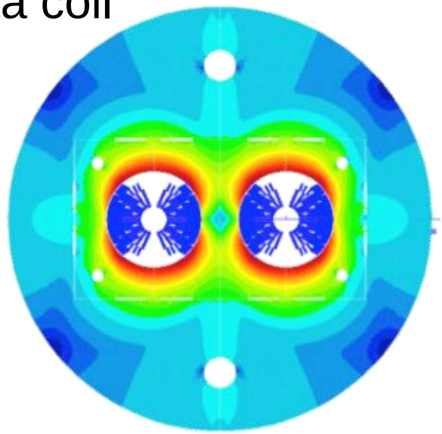
FCC: 16T dipole options

Block coil



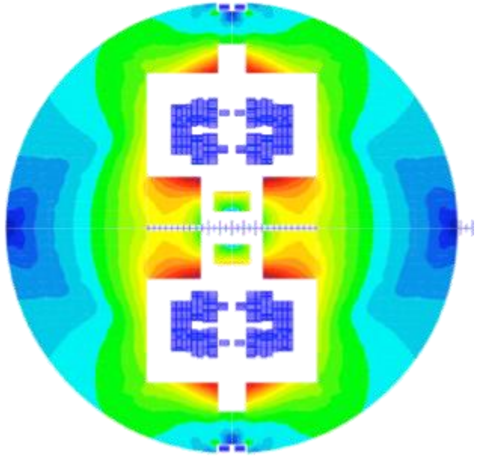
C. Lorin, M. Durante (CEA)

Cos-theta coil



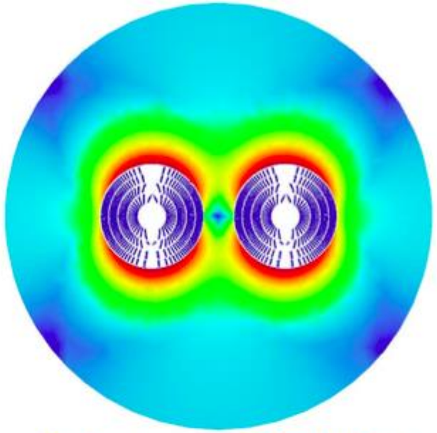
S. Farinon, P. Fabbricatore (INFN)

Common coils



F. Toral (CIEMAT)

Canted Cos-theta



B. Auchmann (CERN/PSI)

FCC Magnet Designs

$T_{op} \approx 1.9$ K

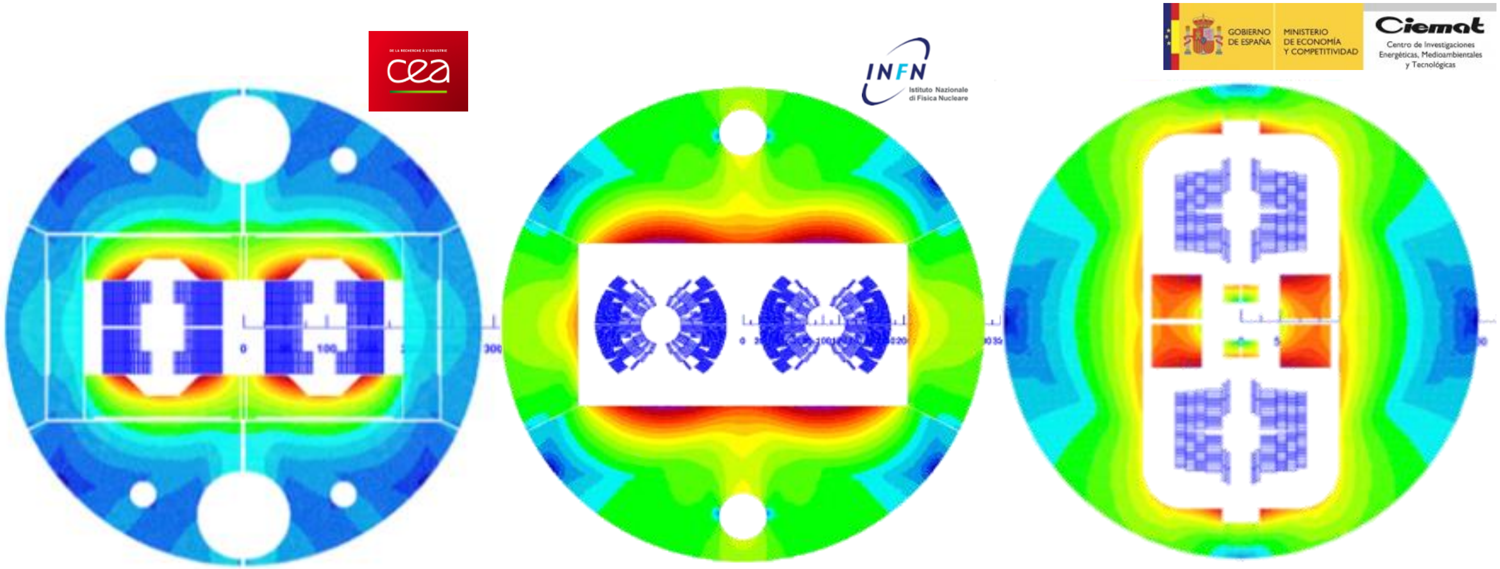
I_{op}/I_C(loadline) ≈ 86 %

$V_{dump} < 2.5$ kV

$\sigma_{max} < 200$ MPa

$T_{hot} < 350$ K

$D_{out} \approx 600$ mm



		blocks		cos(θ)		common coil
Current	(A)	11230		10000		16100
Inductance	(mH/m)	40		50		19.2
Stored energy	(kJ/m)	2520		2500		2490
Coil mass	(tons)	7400		7400		9200

Very efficient use of superconductor

Simplified mechanics
and manufacturing ?

Courtesy of D. Tommasini, CERN

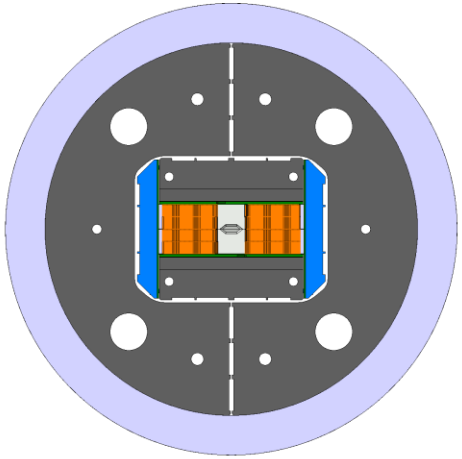
The ERMC and RMM program

ERMC

Enhanced Racetrack Model Coil

16 T midplane field

- Demonstrate field on the conductor
- Coil technology development

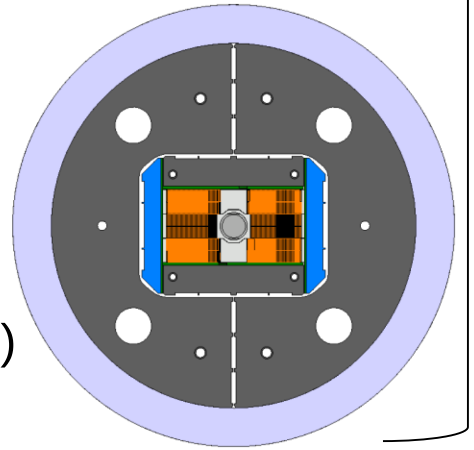


RMM

Racetrack Model Magnet

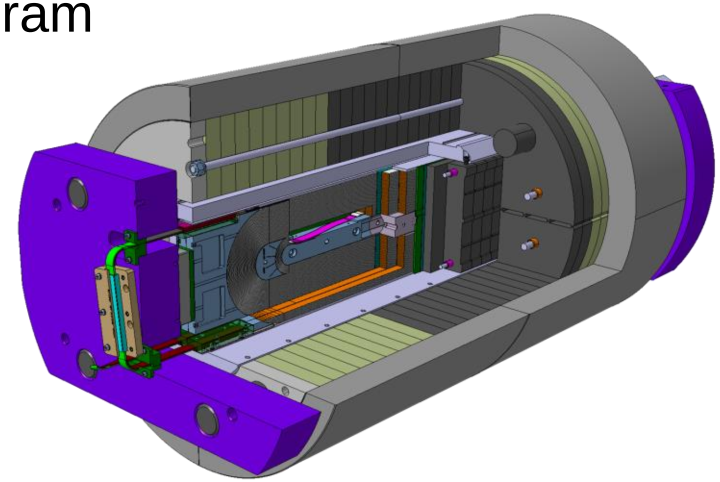
16 T in a 50 mm cavity

- Demonstrate field on the aperture
- Mechanics (including inner coil support)



Method: go step by step towards a 16T block coil dipole

Base for the development of the technology needed for the 16 T dipole program



First eRMC coil to be wound in the next weeks

Conclusions

- We have working models of 12T ‘grade’ dipoles and quadrupoles
- The technology allows us to advance with the HILUMI prototypes and then series production for the LHC ring
- We have 2 racetrack models that went to 16T
- Fresca2 has shown us 13.3T in a large aperture, in Q1 of 2018 to continue prospecting to 15T

Nevertheless we still need to do some ‘homework’ to move to higher fields reliably, use the conductor more efficiently and abolish training www.cern.ch