Superconducting Magnets for HL-LHC and beyond

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SACM/LEAS

With contribution and material borrowed from: Clément Lorin, Franck Borgnolutti (SACM), Luca Bottura, Ezio Todesco, P. Ferracin, Juan Carlos Perez, Lucio Rossi (CERN)

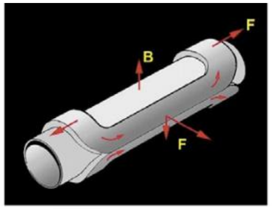
MAGNETS FOR PARTICLE ACCELERATOR: WHAT ARE WE AFTER?

DIPOLES

Beam energy — Bending radius

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

Dipole field



Design for the **largest feasible and economic B** to reduce the accelerator radius

QUADRUPOLES

Beam *size*

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

Emittance

Lorentz factor

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

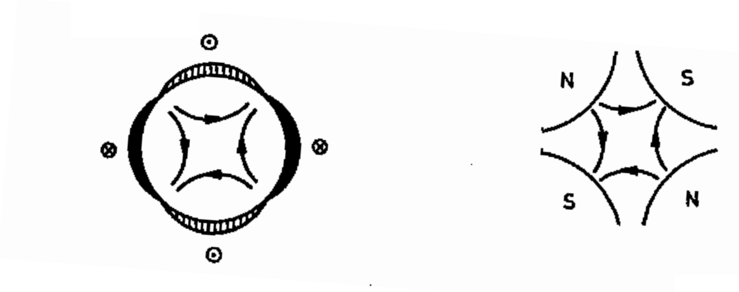
FODO cell length

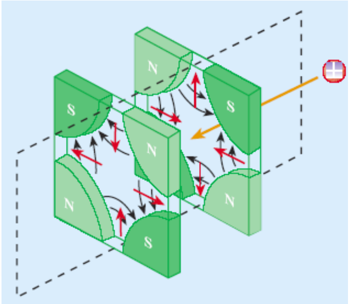
Beta function

Integrated quadrupole gradient

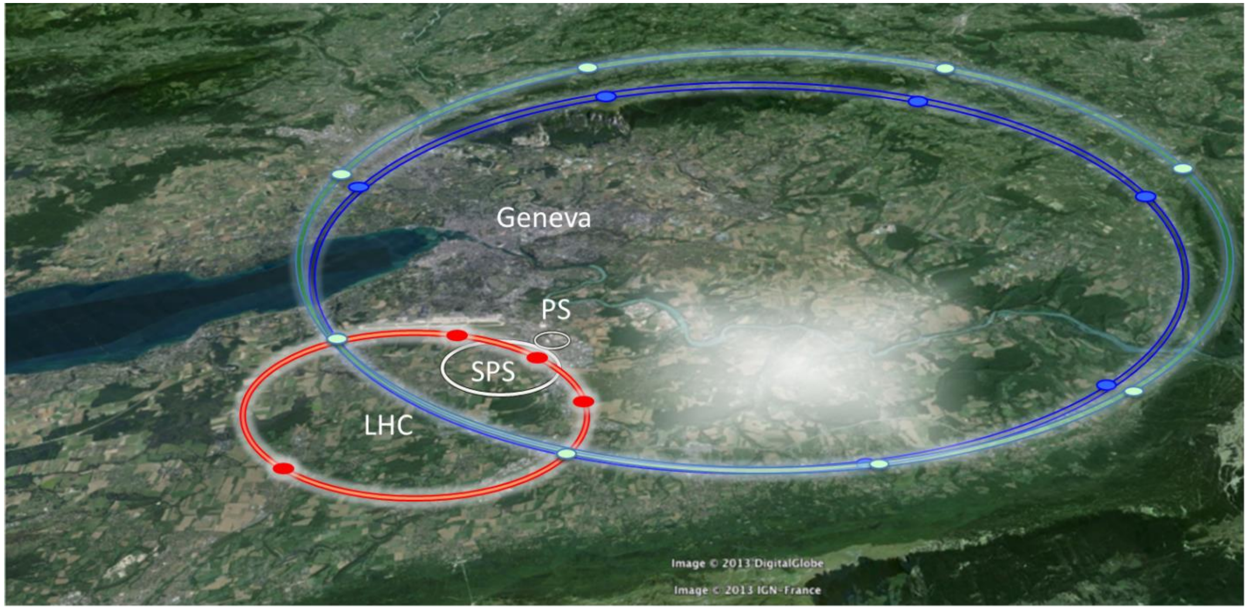
$$G\ell_q[T] = \frac{\sqrt{2}E[GeV]}{0.3L[m]}$$

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





FIELD TARGETS



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.)
1300 tons NbTi	3000 tons LTS	9000 tons LTS	6000 tons Nb_3Sn
	700 tons HTS	2000 tons HTS	3000 tons Nb-Ti

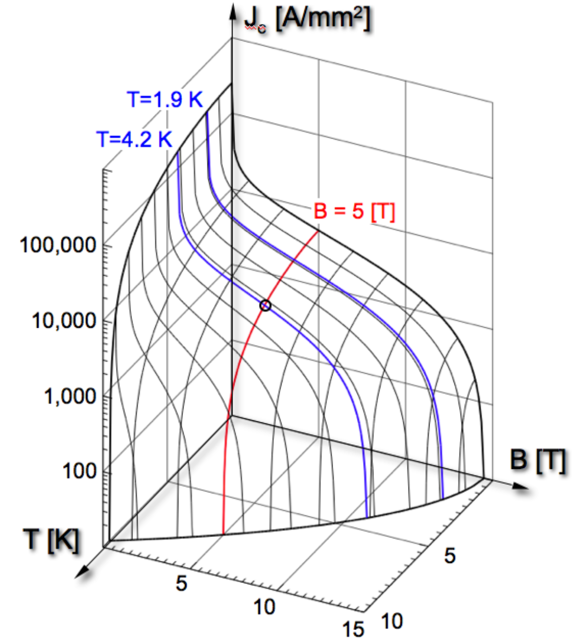
HiLumi HL-LHC PROJECT

12 T range

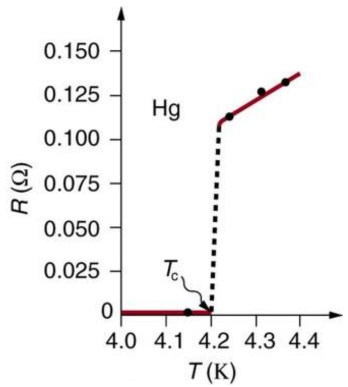
REACHING HIGH FIELD

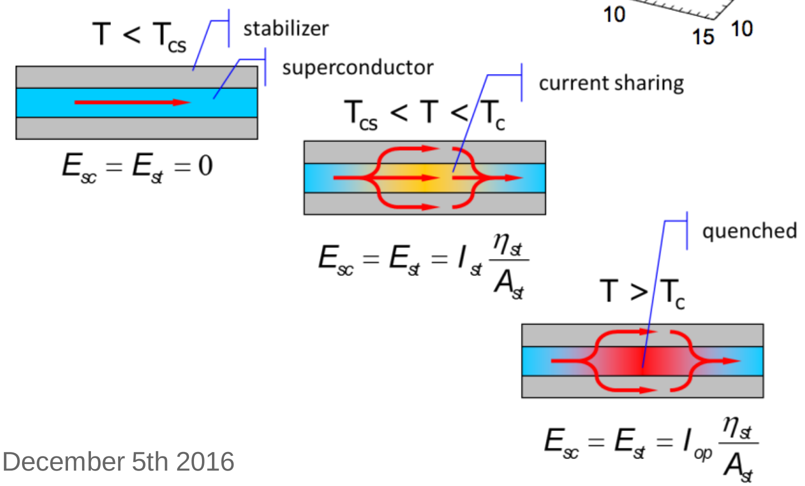
- Beyond 2 T => use of superconducting material
  - zero electrical resistance at cryogenic temperature
  - operate below a critical surface defined with 3 parameters: field, current and temperature.

LHC Nb-Ti critical surface
Courtesy of Luca Bottura, CERN



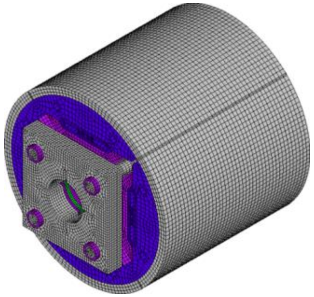
Beyond the critical surface, the superconductor quenches
= transition to a normal conducting state

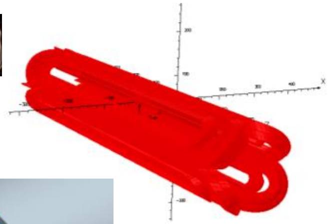


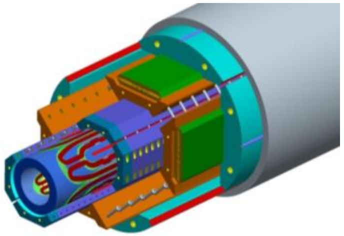


High Field reachable but high complexity

MAGNET TECHNOLOGY OVERVIEW







Material Science: *conductor*, *insulation*

Electrical Engineering

- Magnetic FEM analysis
- Field quality requirements = field purity
- Magnet testing
    - Magnetic measurements
    - Diagnostics…

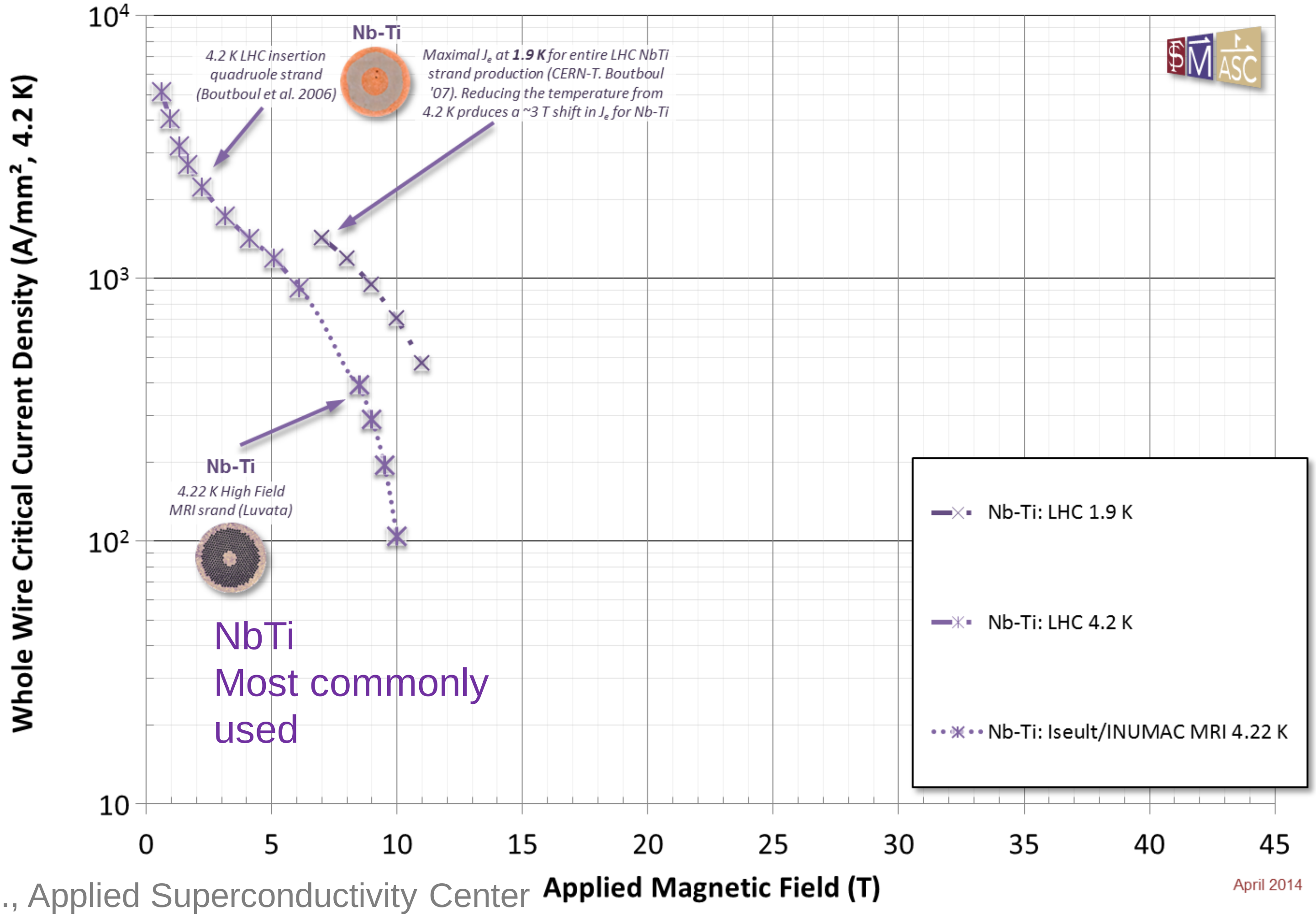
Mechanical Engineering

- Coil fabrication tooling
- Coil and magnet handling tooling
- ***Support structure***
- LHe containment…

Thermal analysis and Cryogenics

- Protection in case of quench
- Cryostating

~250$/kg



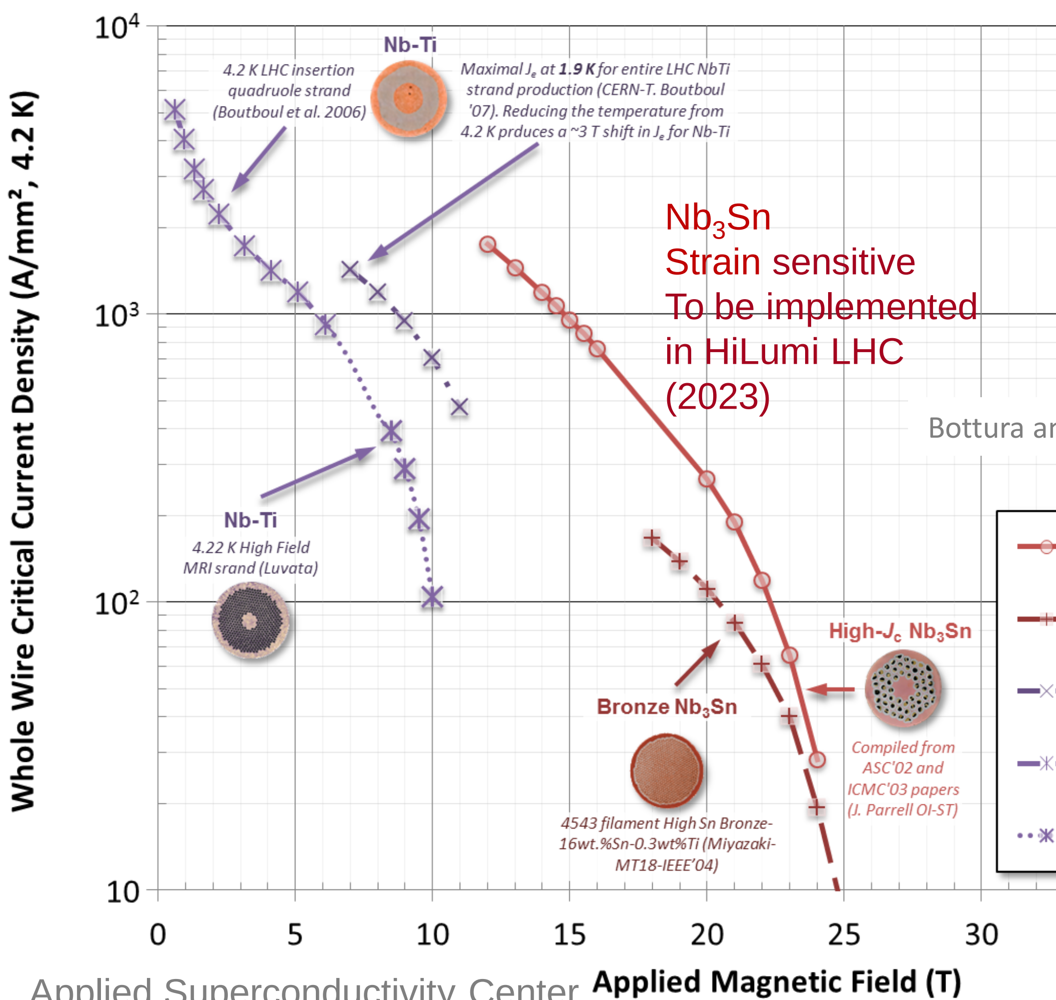
NbTi
Most commonly used

P. Lee et al., Applied Superconductivity Center

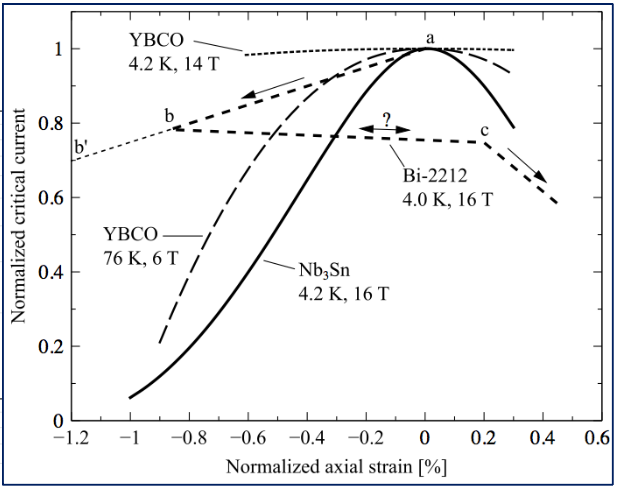
MATERIAL AVAILABLE TO MAGNET ENGINEER

250$/kg

x10



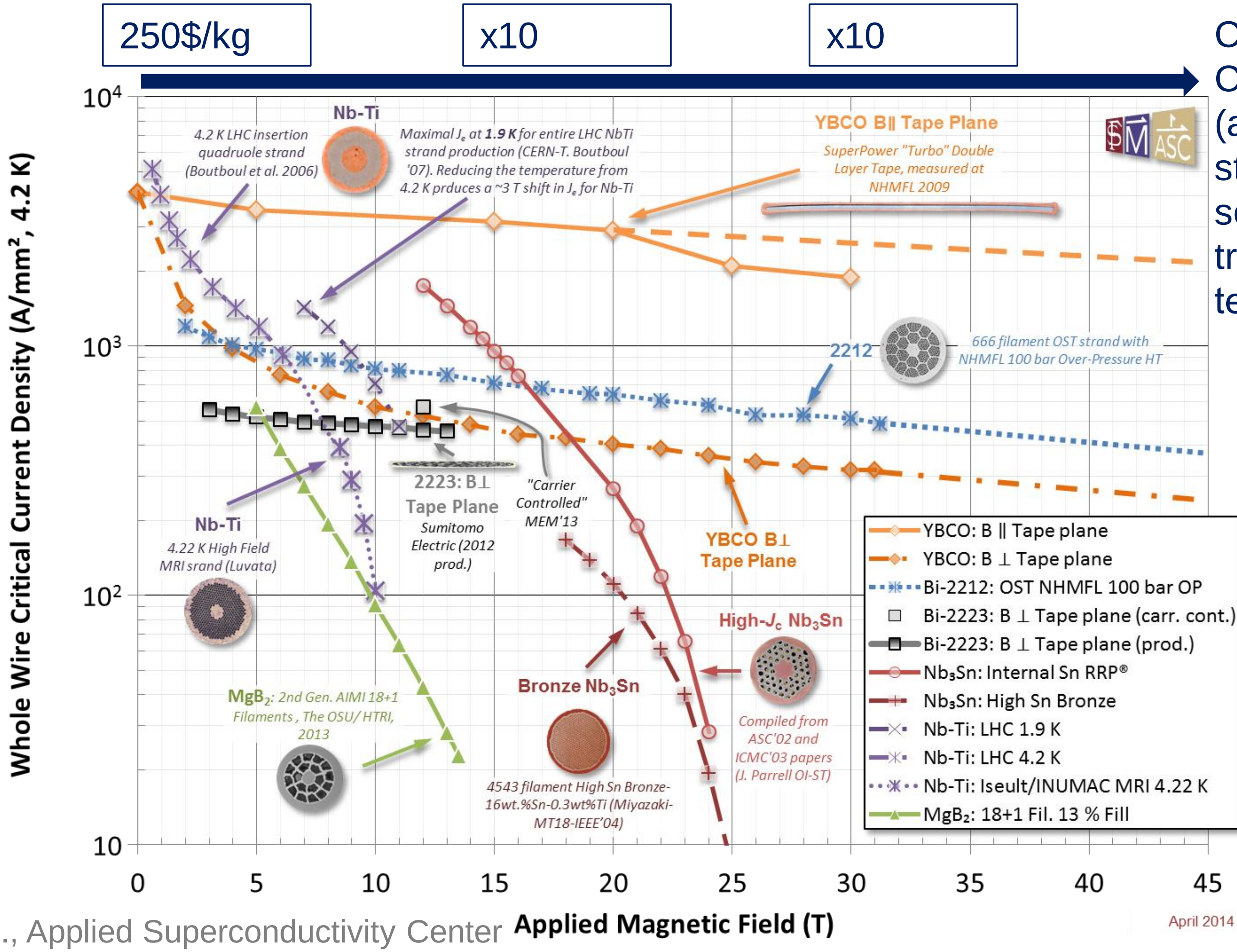
Nb_3Sn
Strain sensitive
To be implemented in HiLumi LHC (2023)



Bottura and Godeke, *Rev. Accel. Sci. Techn.* **5** 25 (2012)

P. Lee et al., Applied Superconductivity Center

MATERIAL AVAILABLE TO MAGNET ENGINEER



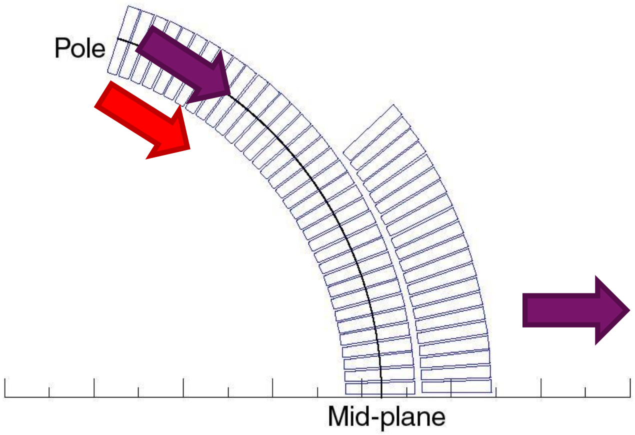
Cost
Complexity (anisotropy, strain sensitivity, heat treatment temperature…)

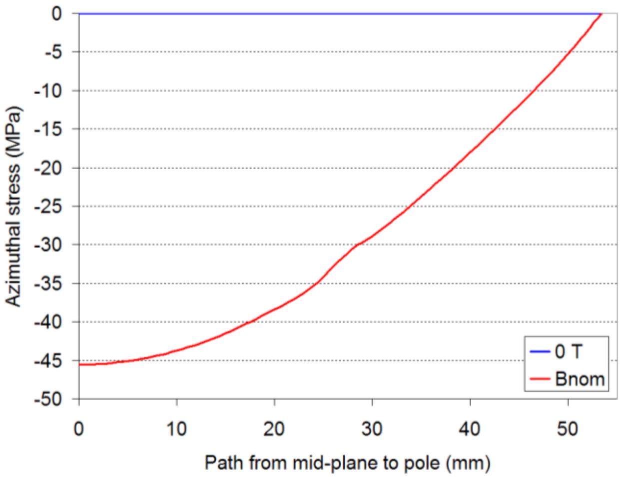
P. Lee et al., Applied Superconductivity Center

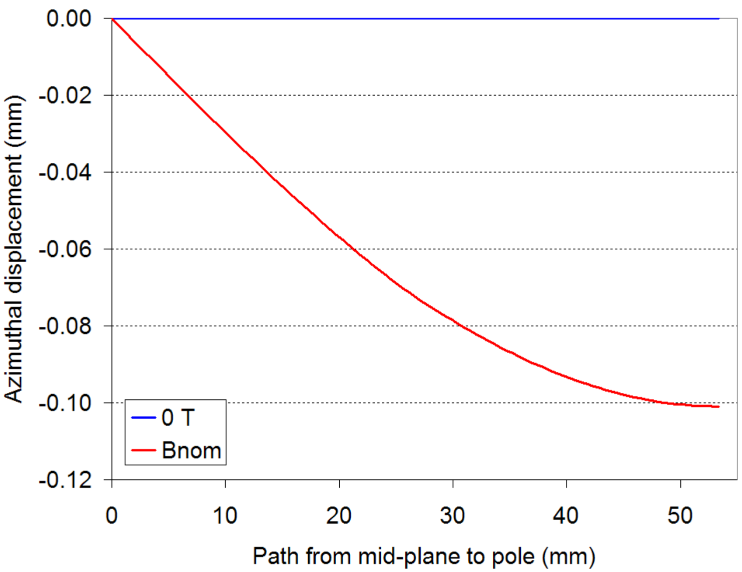
HANDLING THE MAGNETIC FORCES: THE PRESTRESS

Typical Lorentz forces in a cosθ or cos 2θ

- Azimuthal => accumulation of the forces at the midplance
- Radial => motion of the coil outward

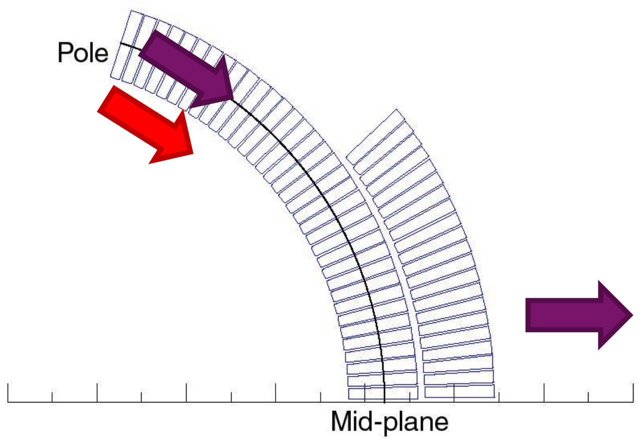






No pre-stress

Paolo Ferracin

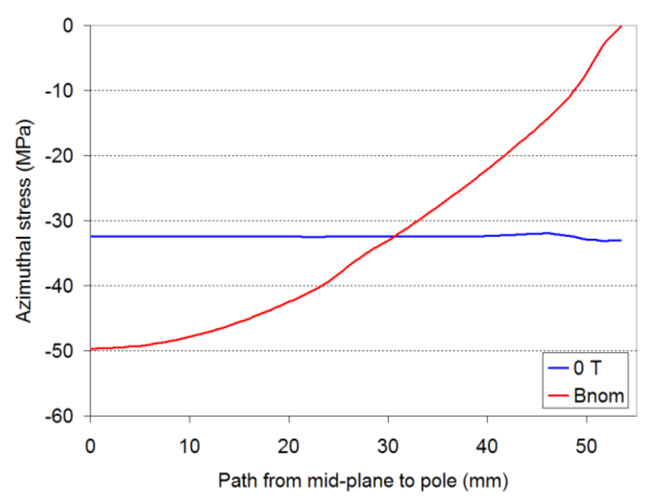


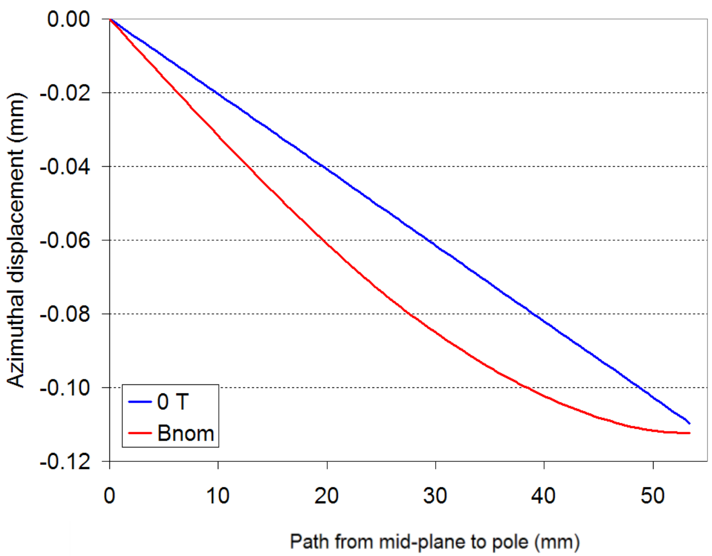
Typical Lorentz forces in a cosθ or cos 2θ

- Azimuthal => accumulation of the forces at the midplance
- Radial => motion of the coil outward

Pre-stress

- Application during assembly (and cool-down) of an azimuthal force on the coils to minimize motion during excitation



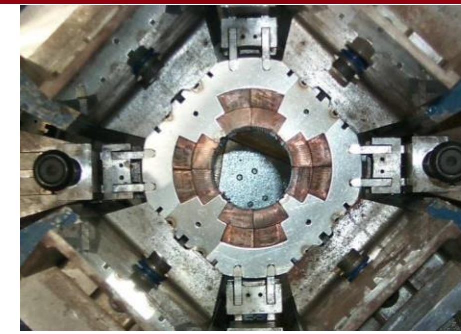


Pre-stress

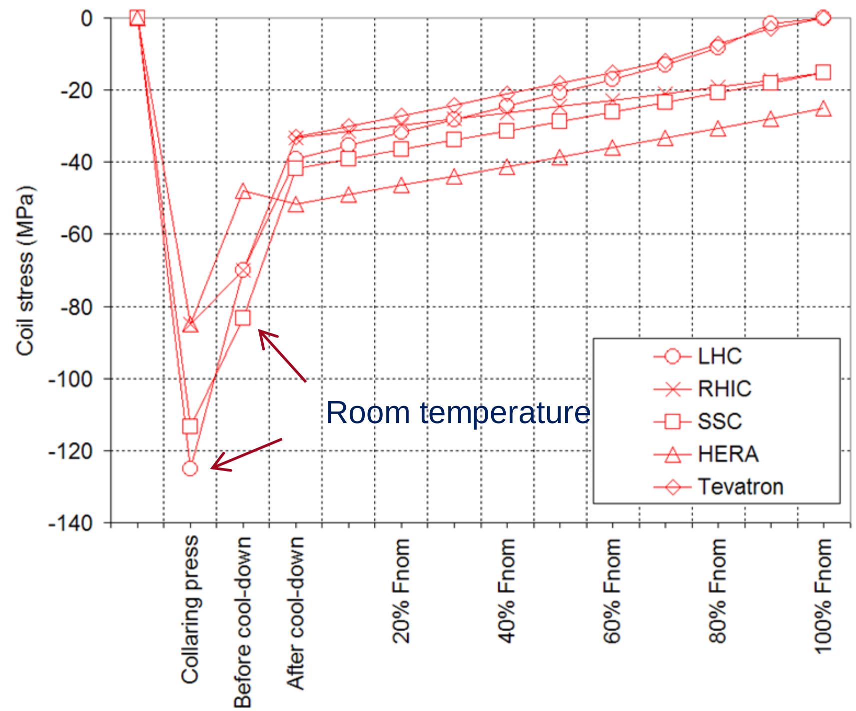
TRADITIONNAL APPROACH
LHC STATE OF THE ART

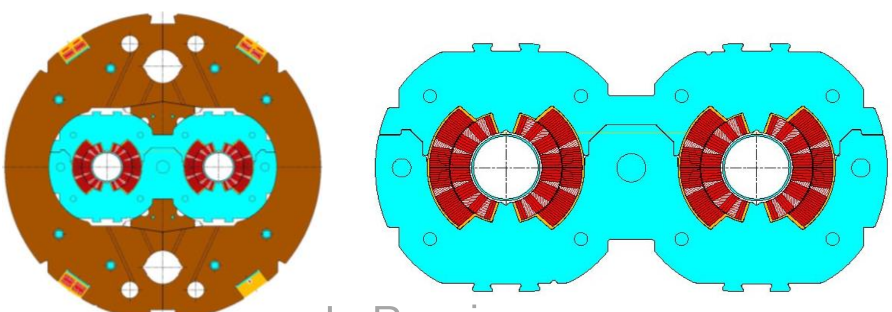
The collars are used:

- Since the Tevatron
- In most accelerator and R&D magnets
- They are composed by stainless-steel or aluminum laminations few mm thick and locked around the coils using a press



- By clamping the coils, the collars provide
  - coil pre-stressing;
  - rigid support against Lorentz forces (it can be self-supporting or not);
  - precise cavity (tolerance $\pm$ 20 μm).

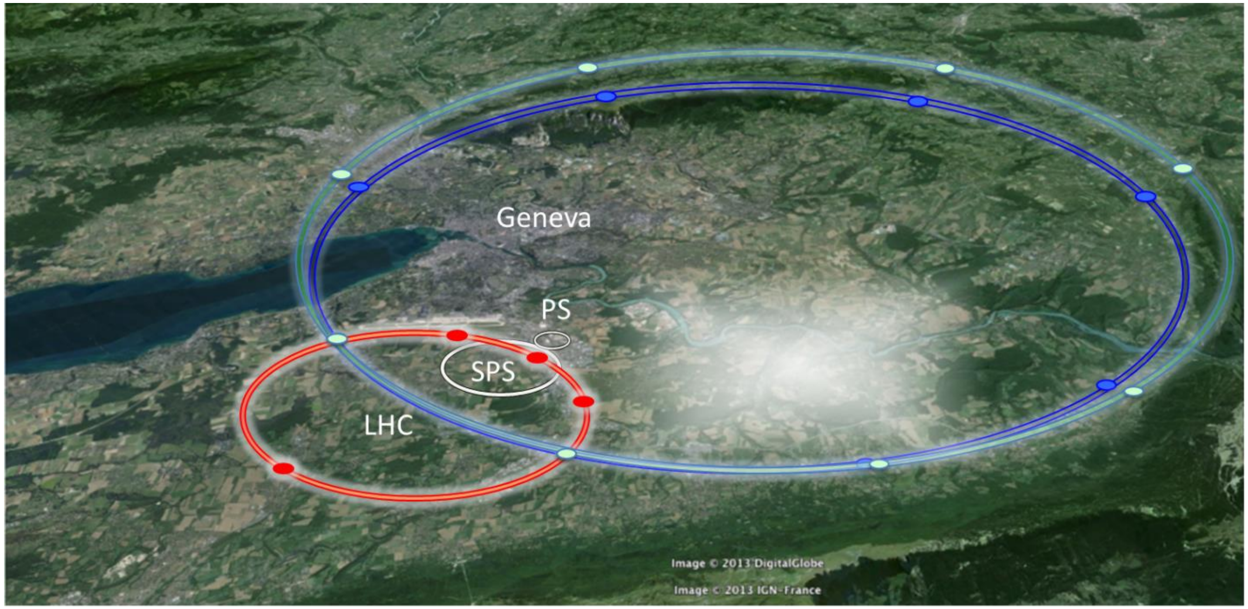




L. Rossi

Collaring process- Courtesy of Paolo Ferracin

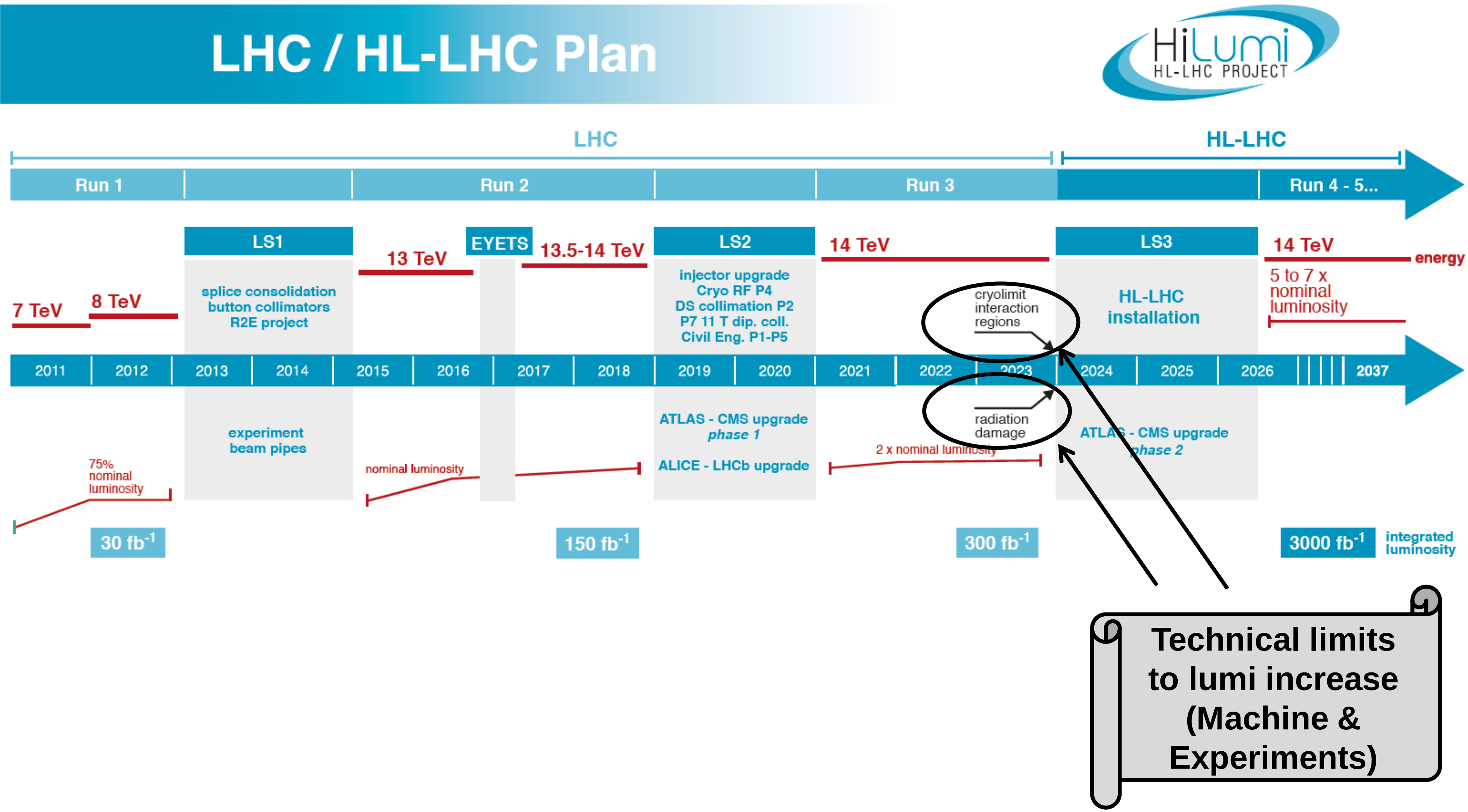
FIELD TARGETS



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.)

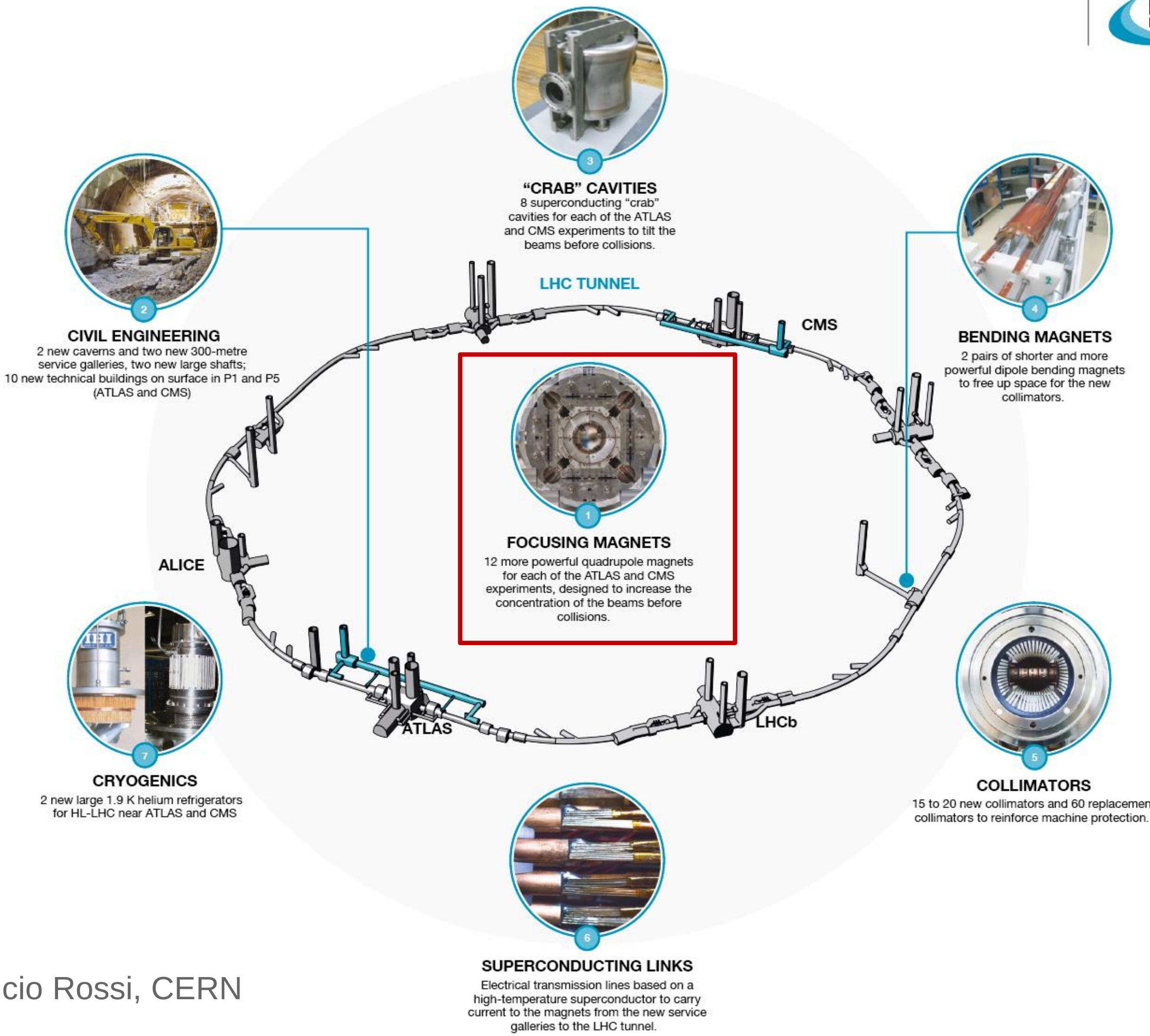
HiLumi HL-LHC PROJECT

CONTEXT OF THE UPGRADE



Courtesy of Lucio Rossi, CERN

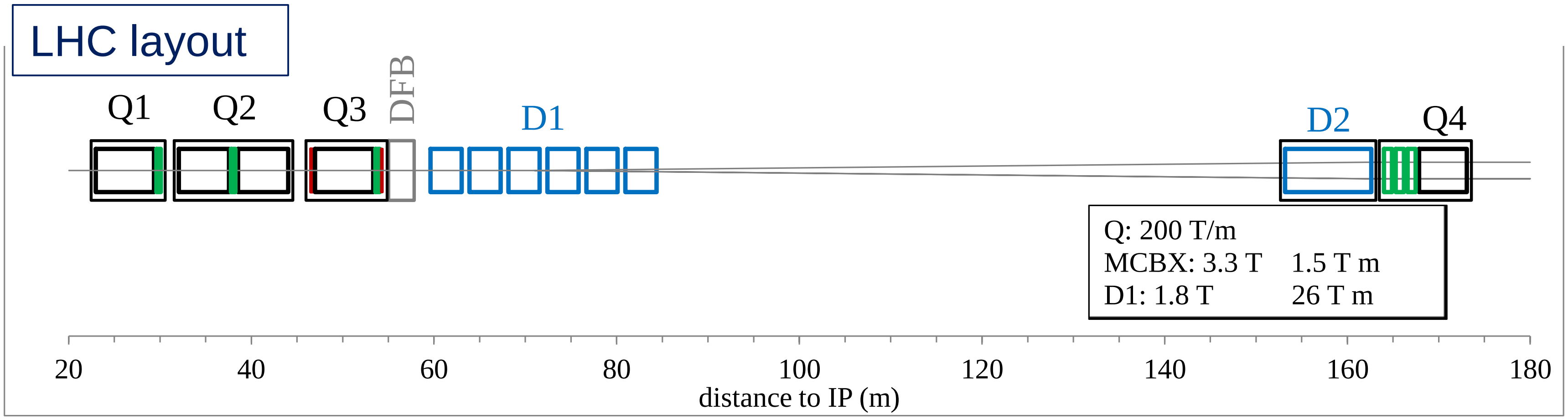
CONTENT OF THE UPGRADE

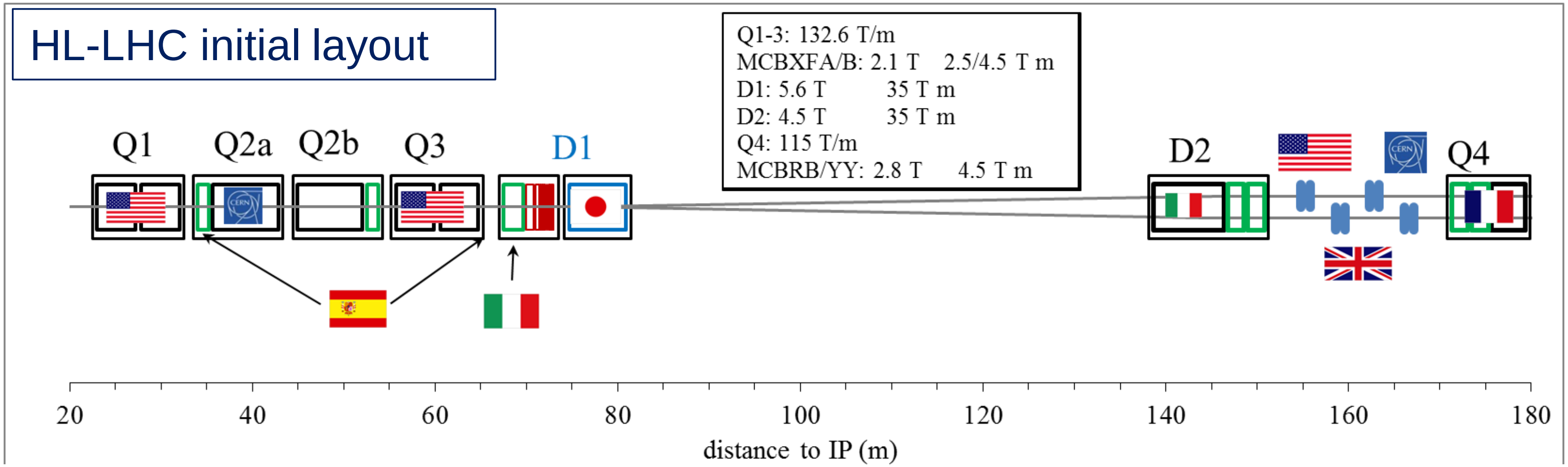


Courtesy of Lucio Rossi, CERN

ZOOM ON THE MAGNETS
FROM LHC TO HL-LHC (INITIAL BASELINE)

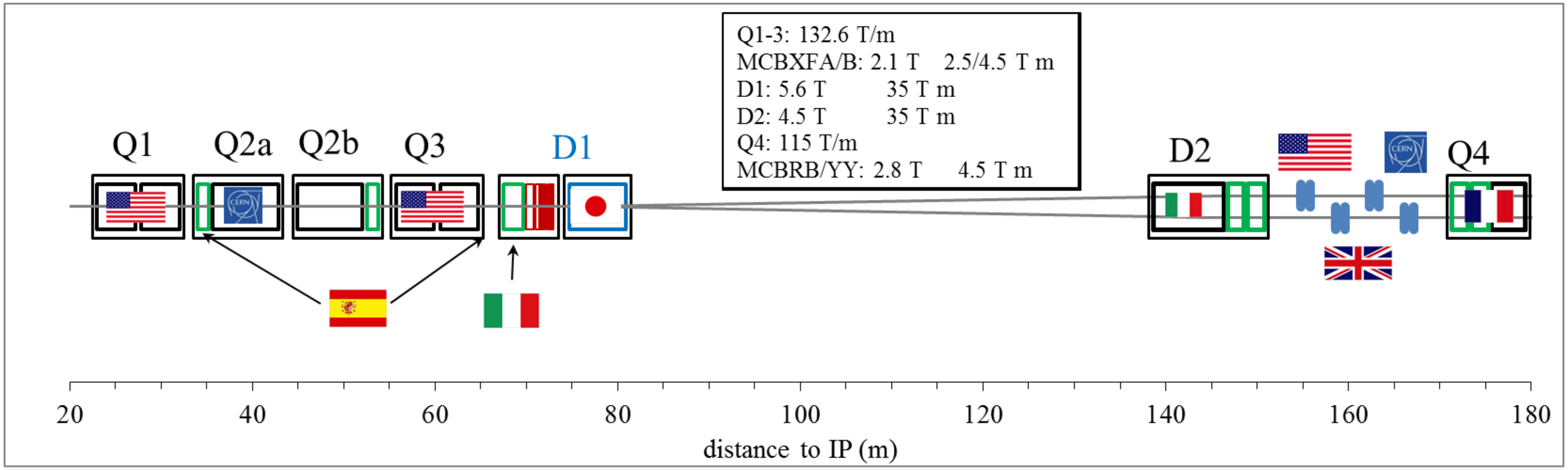
Replacement of IR magnets in IP1 and IP5 with larger aperture (~twice) to allow a β* reduction (~one fourth) therefore an increase in Luminosity

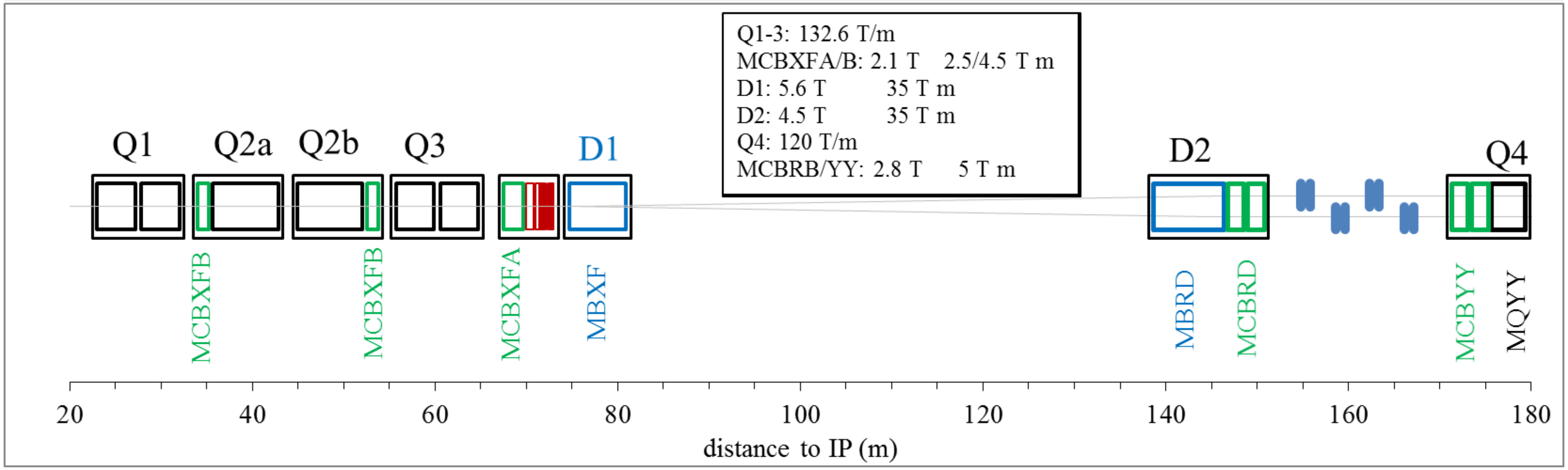




Courtesy of Ezio Todesco, CERN

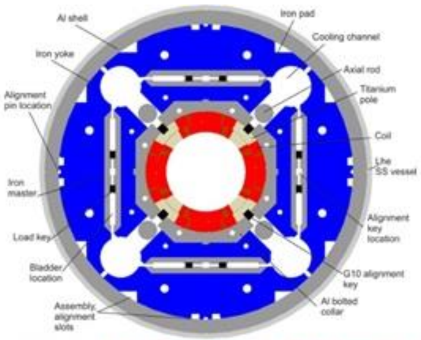
ZOOM ON THE MAGNETS INITIAL BASELINE



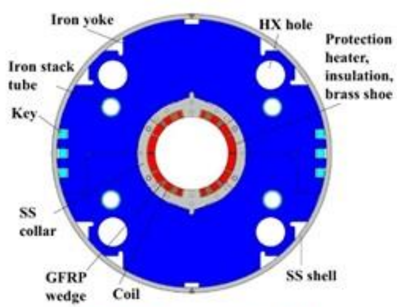


Courtesy of Ezio Todesco, CERN

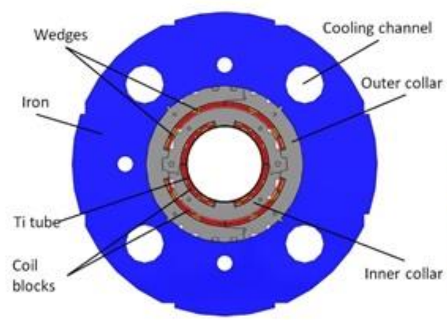
THE ZOO OF MAGNETS FOR HL-LHC



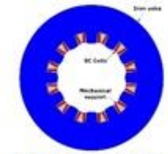
MQXF [G. Ambrosio, P. Ferracin et al.]



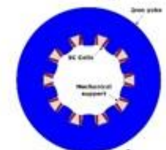
D1[T. Nakamoto et al.]



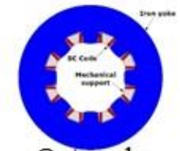
MCBXF [F. Toral, et al.]



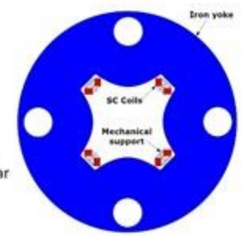
Dodecapole



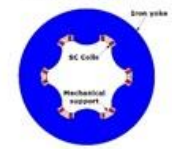
Decapole



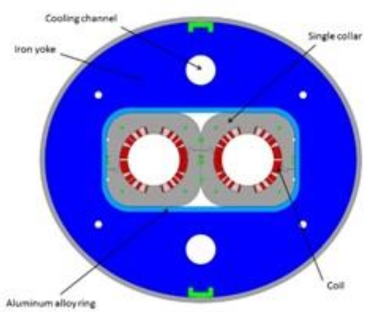
Octupole



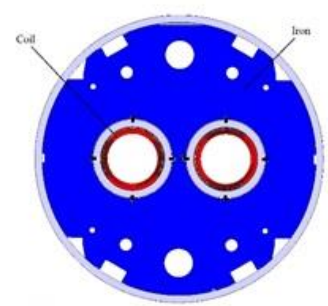
Skew quad



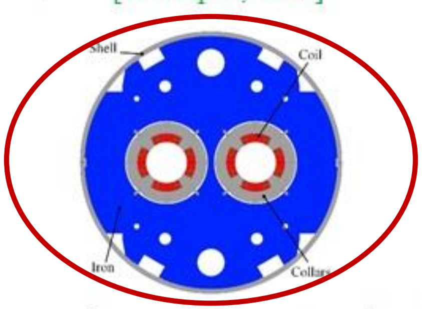
[G. Volpini, et al.]



D2 [P. Fabbricatore, S. Farinon]



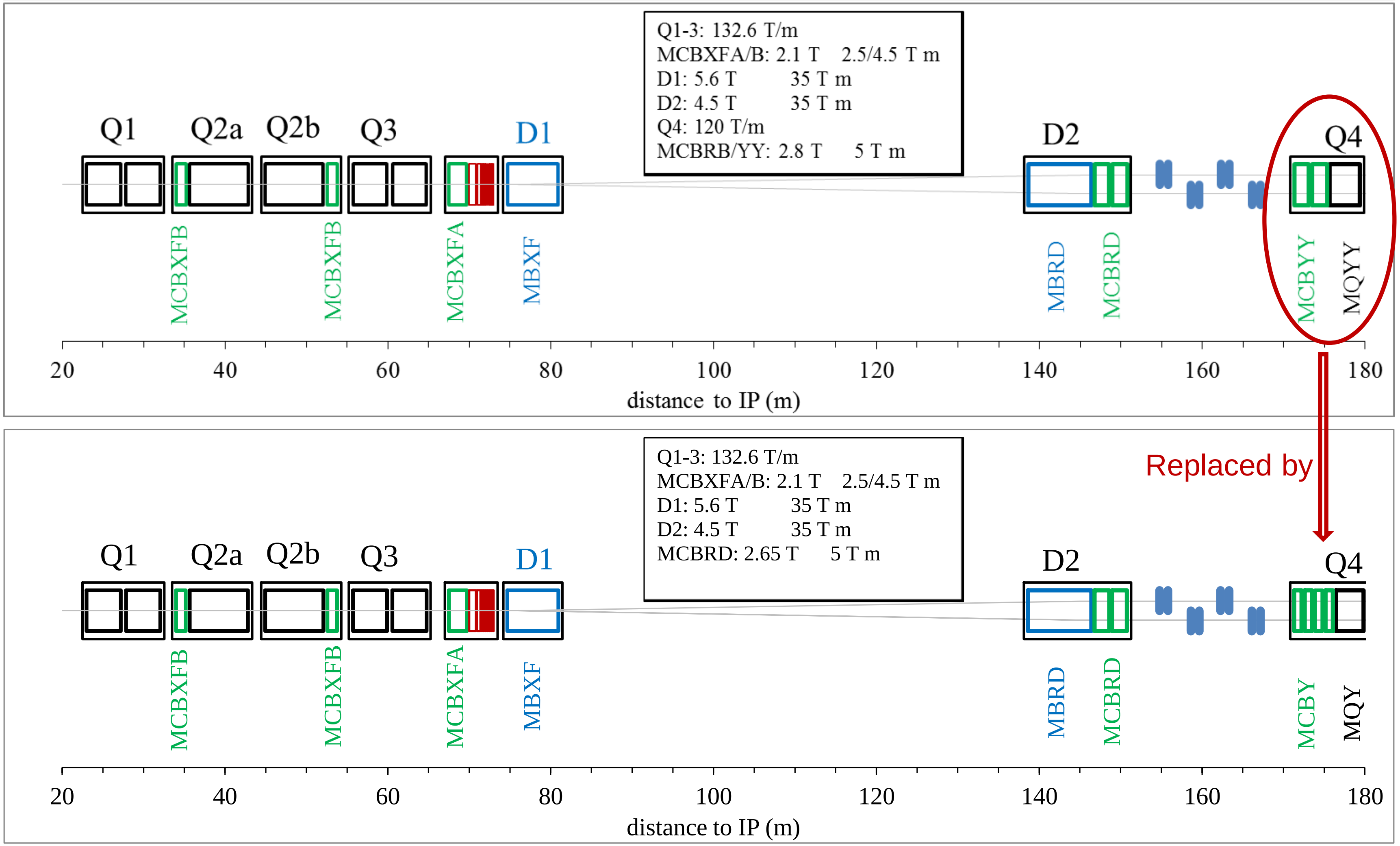
D2 correctors [G. Kirby, J. Rysti]



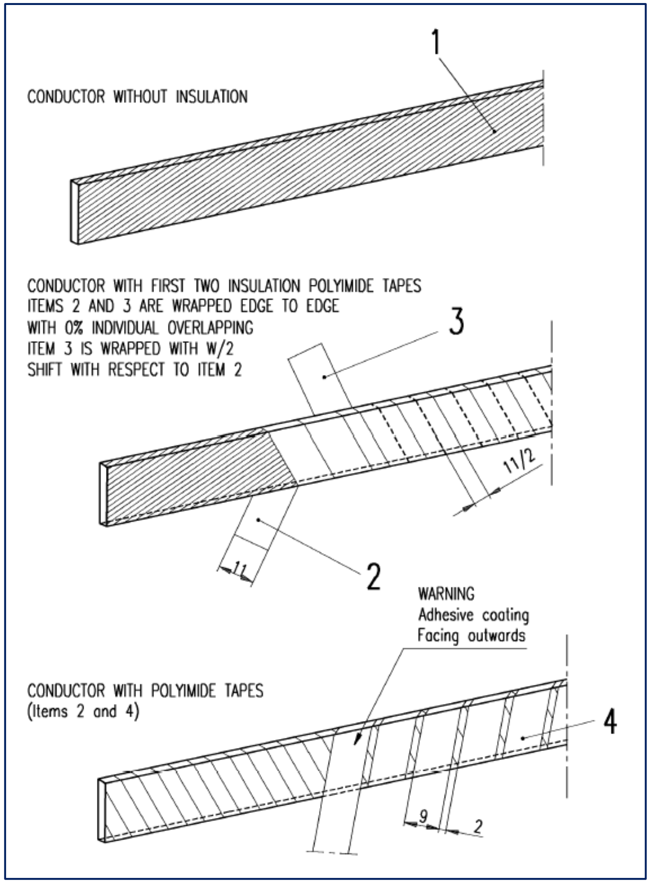
MQYY [J. M. Rifflet, M. Segreti, et al.]

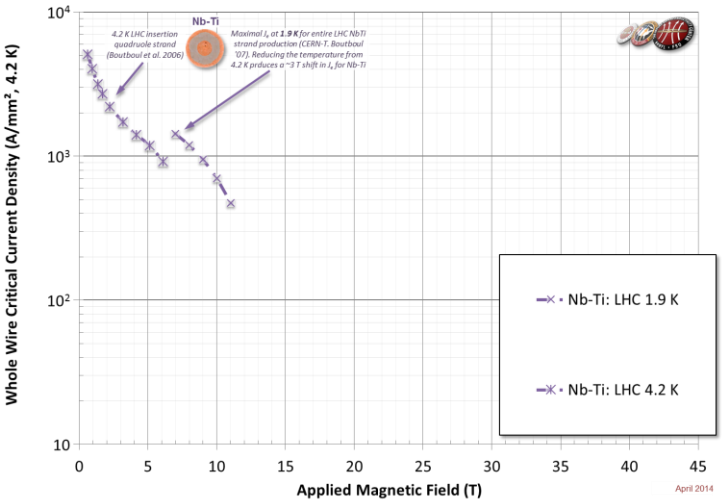
Courtesy of Ezio Todesco, CERN

ZOOM ON THE MAGNETS
NEW BASELINE: SUMMER 2016 => COST REDUCTION



Activities at CEA to design, manufacture and test MQYY short model and prototypes are maintained





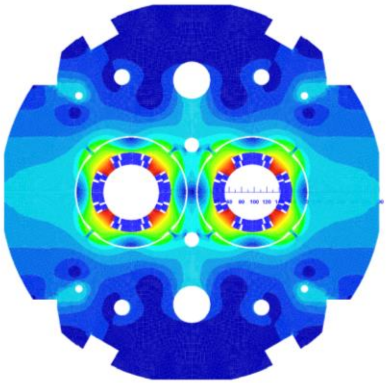
NbTi conductor

- 36 Strands cabled together
- Insultation is 0.105 microns of polyimide
- Provided by CERN

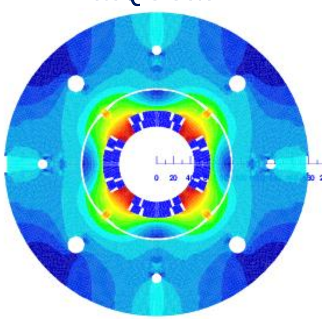
- Objective
  - Integrated gradient of 440 T.m
  - Double aperture magnet

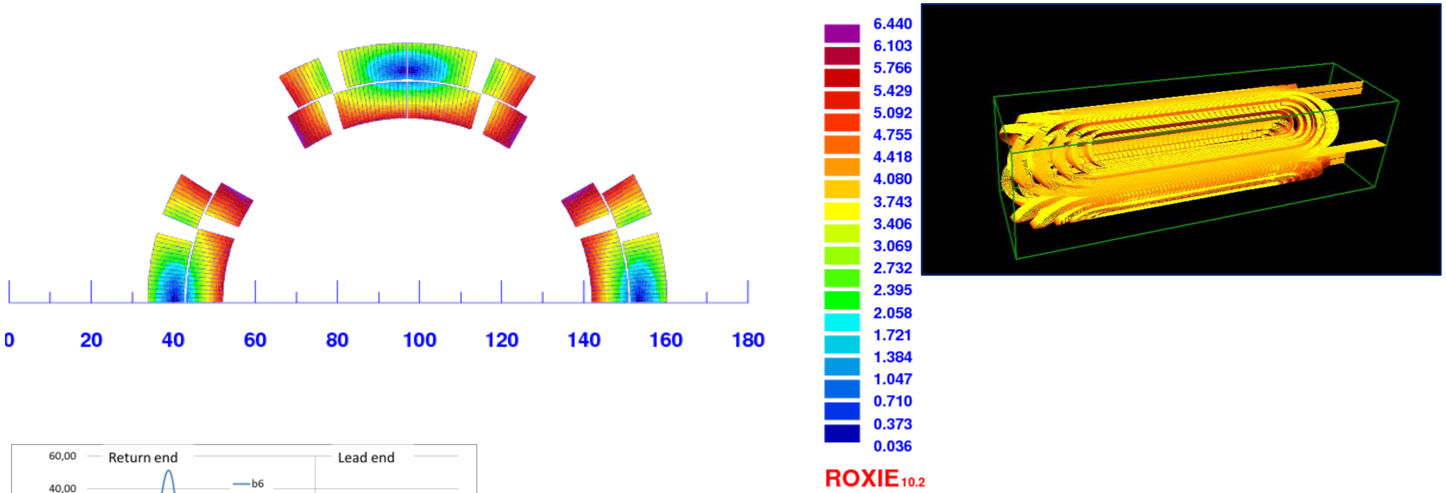
MAGNETIC DESIGN

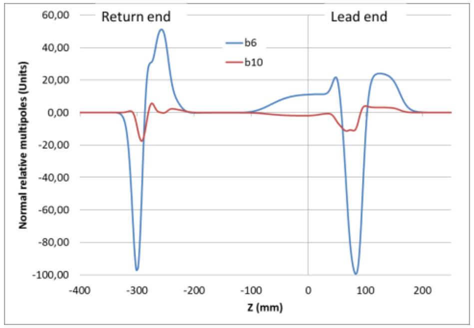
MQYY

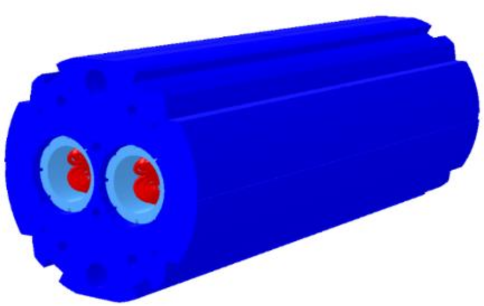


MQYYM

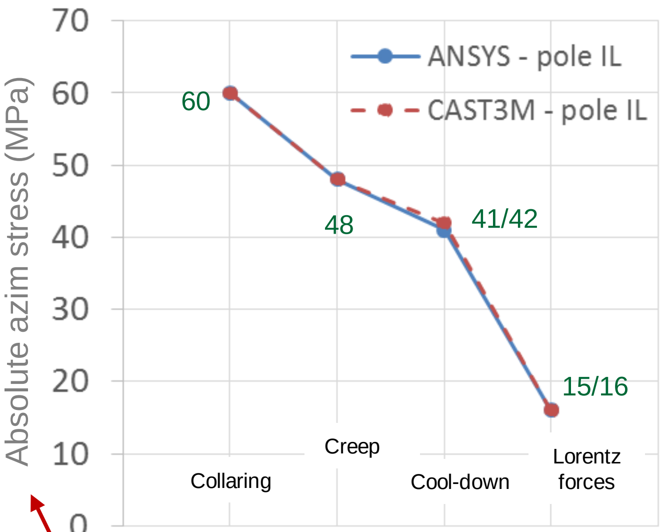


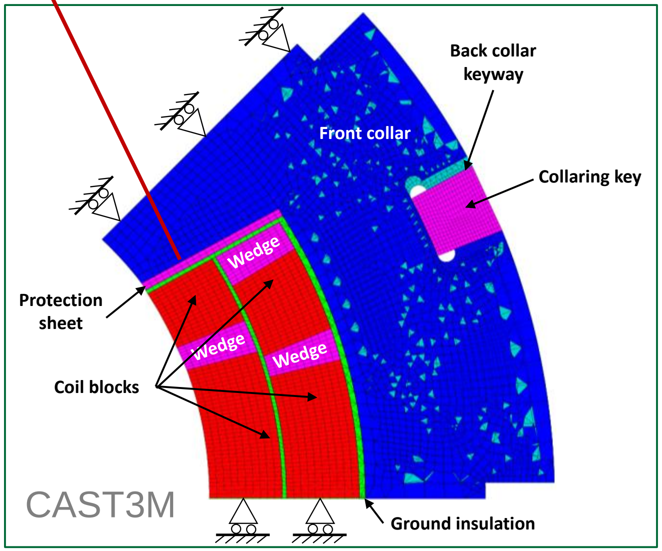


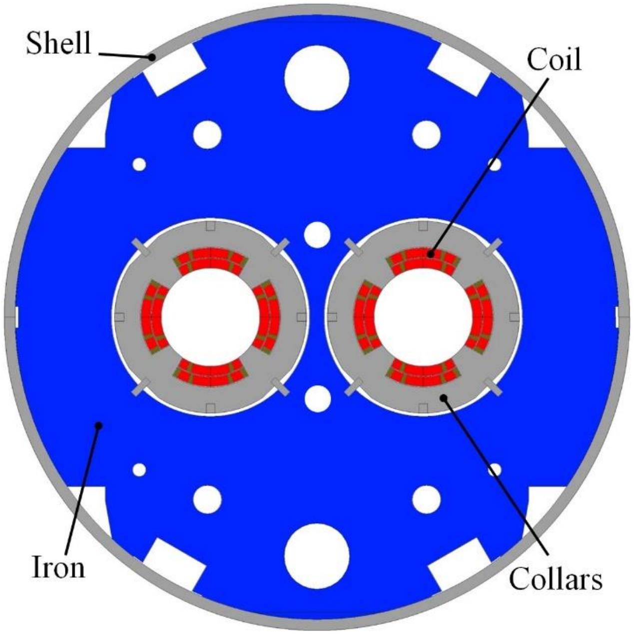




Aperture	90 mm
Nominal Gradient	120 T/m
MQYY Magn. length at 1,9 K (MQYYM)	3,7 m (1,2 m)
MQYY Nominal Current (MQYYM)	**4590 A (4550)**
Peak field	6,4 T
Margin on the loadline	23 %
Differential inductance	2 x 37,5 mH
Cable type	MQM
MQYYM / MQYY outer diameter	360 / 614 mm

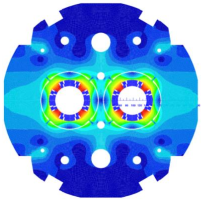




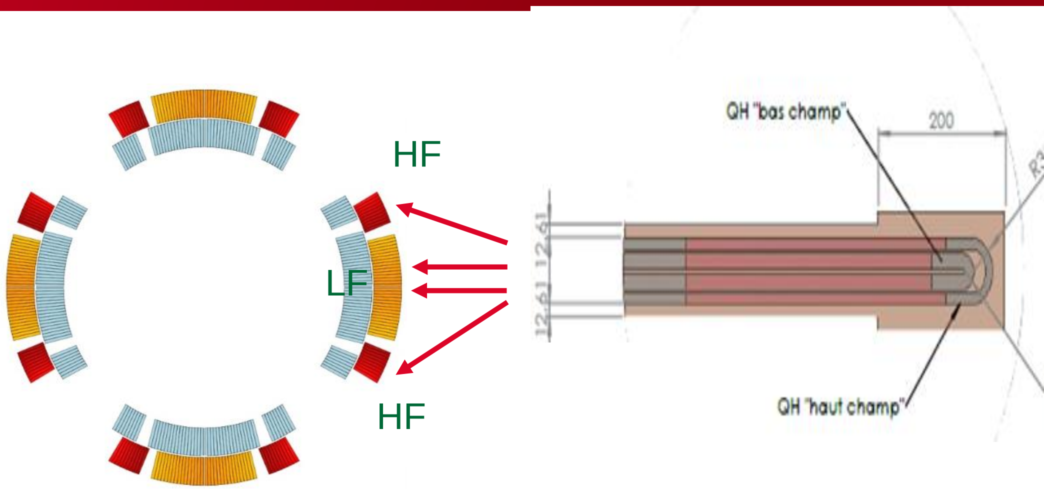


- Support structure to contain the Lorentz forces an minimize motion
  - to avoid quench
  - To avoid field distorsion
- Self standing collar structure applying prestress to the coil

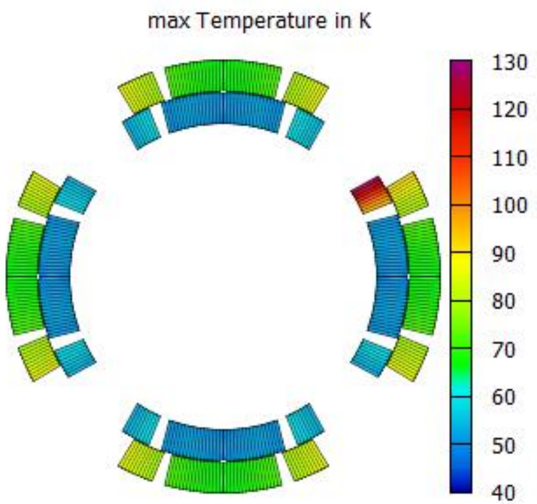
QUENCH PROTECTION



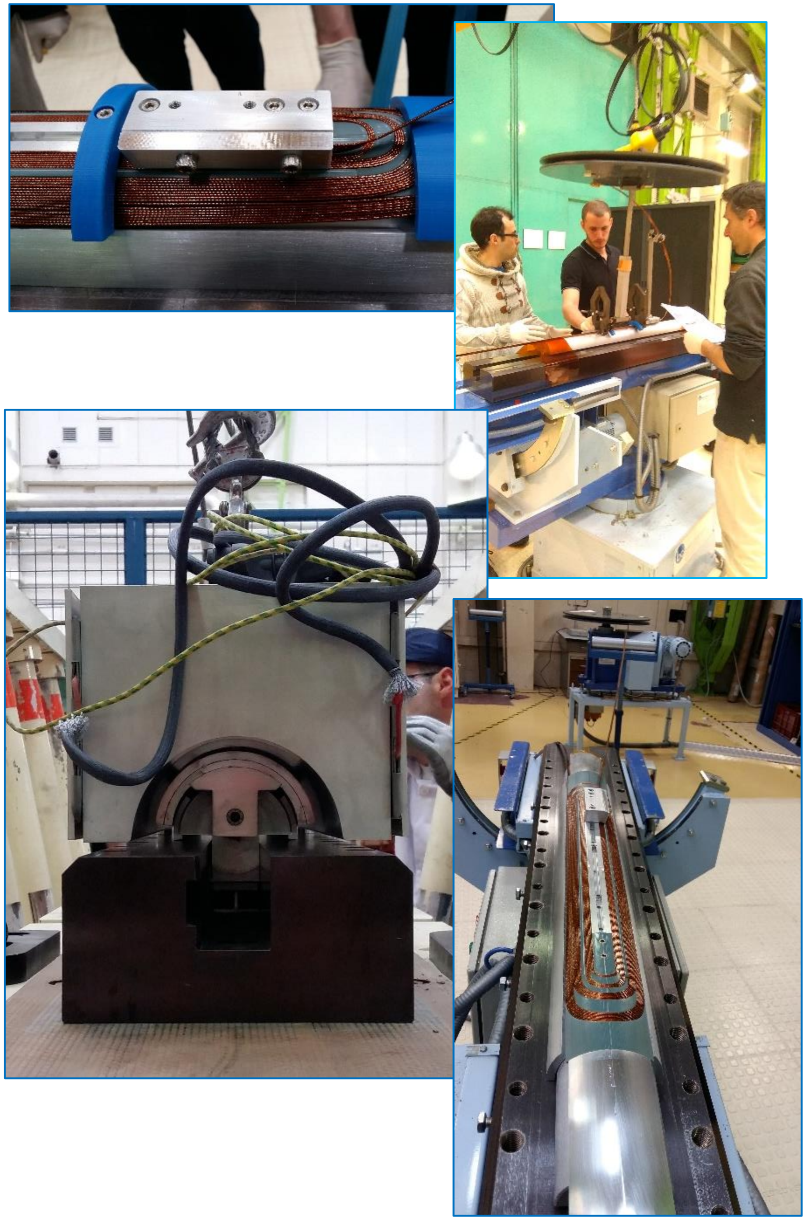
- Importance to protect the magnet in case of quench
- Large stored energy: 0.4 MJ per aperture
- Objective: to spread the energy during quench
  - to minimize the temperature increase in the winding
  - To minimize the peak voltage



Simulation Results	
With protection heaters	
Hot Spot	≈130K
Voltage to ground	≈135V



COIL FABRICATION STEPS



Winding of the 1st layer

↓

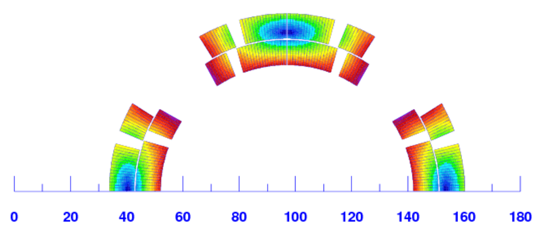
Curing of the 1st layer
Cycle thermique (185°C) sous compression

↓

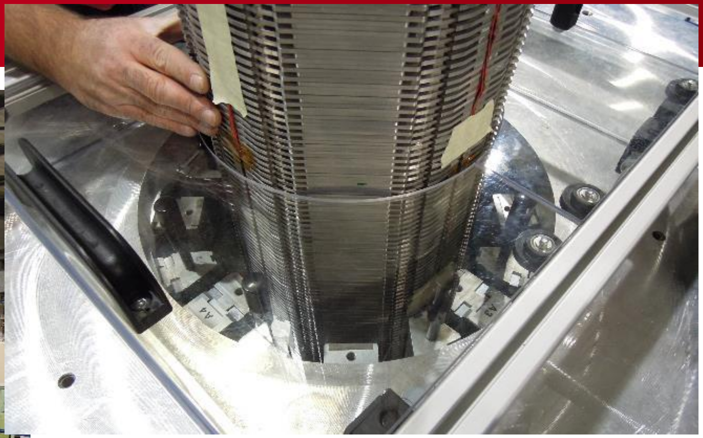
Winding of the second layer

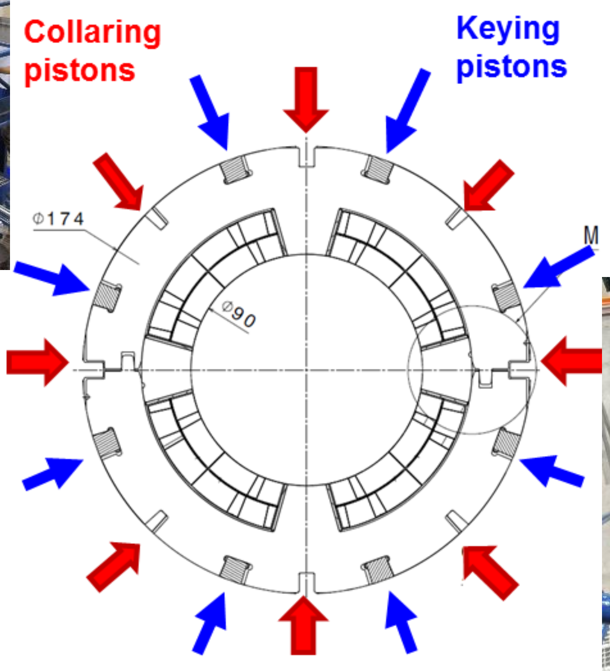
↓

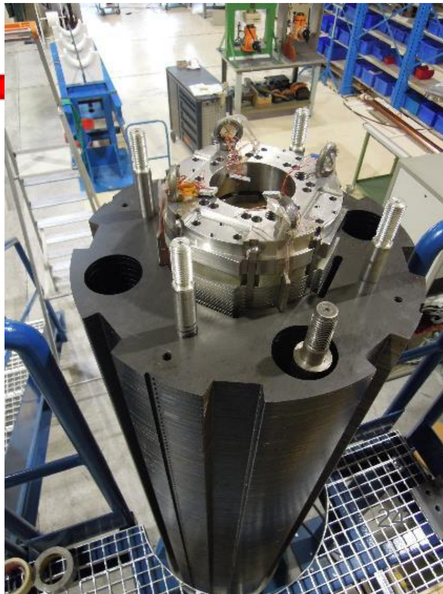
Curing of the second layer



ASSEMBLY PLAN FOR THE MQYYM







- ⇒ Collaring at CERN by a CEA team assisted by CERN
- ⇒ Yoking at CERN by a CEA team assisted by CERN

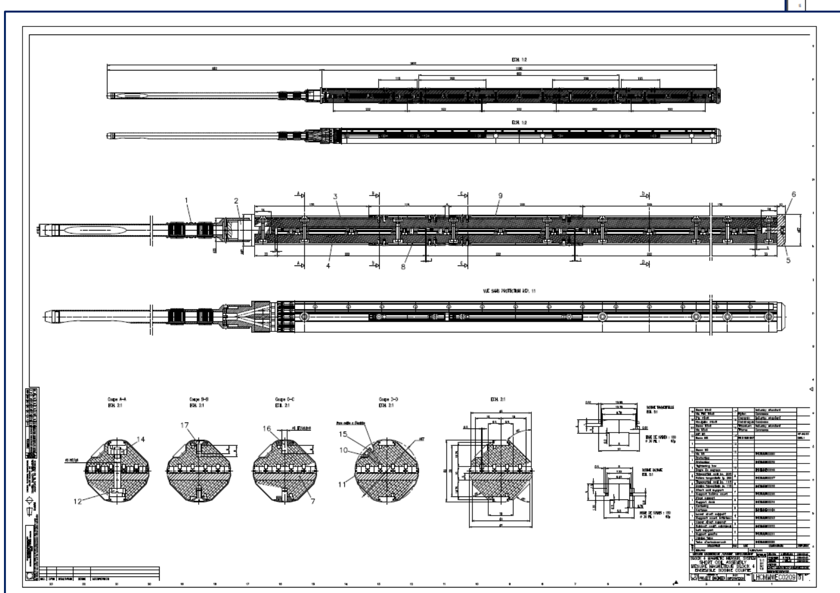
Courtesy of Juan Carlos Perez, CERN

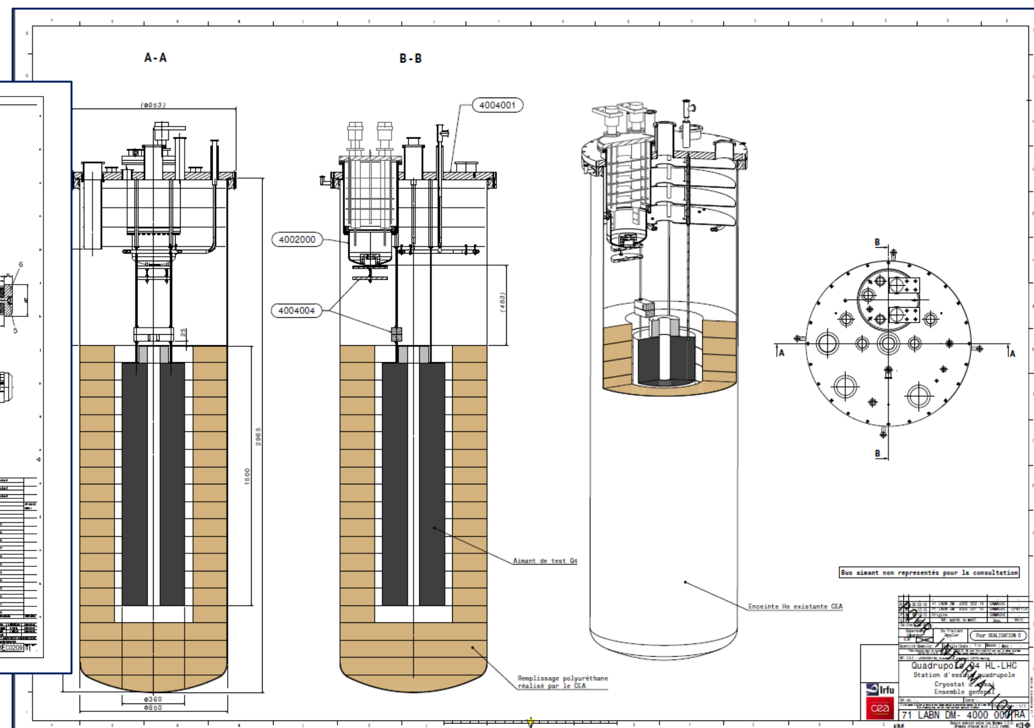
MQYYM TEST

- ***Test of MQYYM in the vertical cryostat at CEA-Saclay (Bld 198)***

⇒ 8 m cryostat equipped with a 3 m long « sock » (tank)
⇒ Adaptation of an existing top plate
⇒ Saturated LHe bath at 1,9 K 23 mbar

⇒ Magnetic measurements
  ⇒ Cold system provided by CERN
  ⇒ Adaptation on CEA test station under development





TOWARDS THE PROTOTYPE: QUACO

In 2015: a program to build two prototypes in the industry using EU funds has been launched (M. Losasso, I. Bejar Alonso)

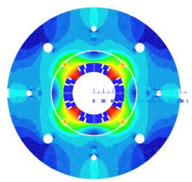
QUACO is a **PreCommercial Procurement** (PCP)

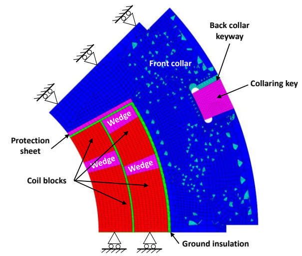
Principle:

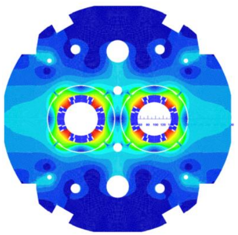
- R&D project in industry lead by a consortium of EU labs: CEA, CIEMAT, NCBJ and CERN
- Industries are in competition in 3 phases. At each end of phase, a company is eliminated.
- In Spring 2020, two companies will have produced two prototypes (one per company)
- The magnetic design and protection are given, mechanical structure and tooling have to be proposed by the company

QUACO INITIATIVE

MQYYM Expected to be completed by end of 2017 – early 2018

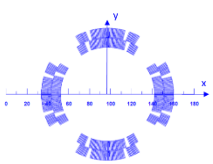






11/2016 03/2018 05/2020

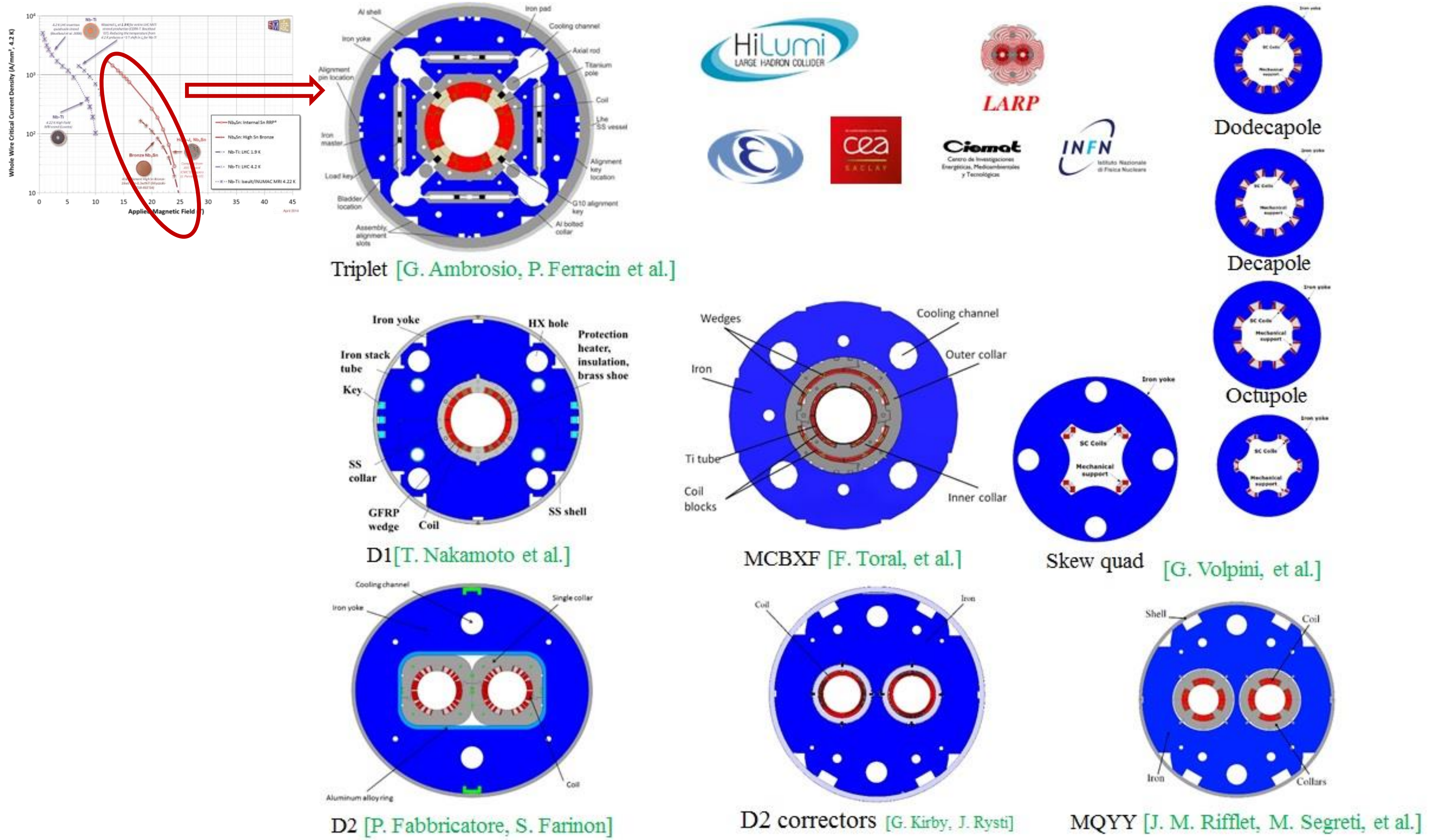
Concept. Design PHASE 1 4 months 11/2016 to 03/2017	Engineering Design PHASE 2 13 months 07/2017 to 08/2018	Manufacturing PHASE 3 18 months 11/2018 to 05/2020



- Baseline magnetic design **provided but not imposed**
- ROXIE provided without the BEM FEM module
- Mechanical support structure design **up to companies**

Narodowe Centrum Badań Jądrowych
National Centre for Nuclear Research
Świerk

MAGNET INNOVATION IN HL-LHC



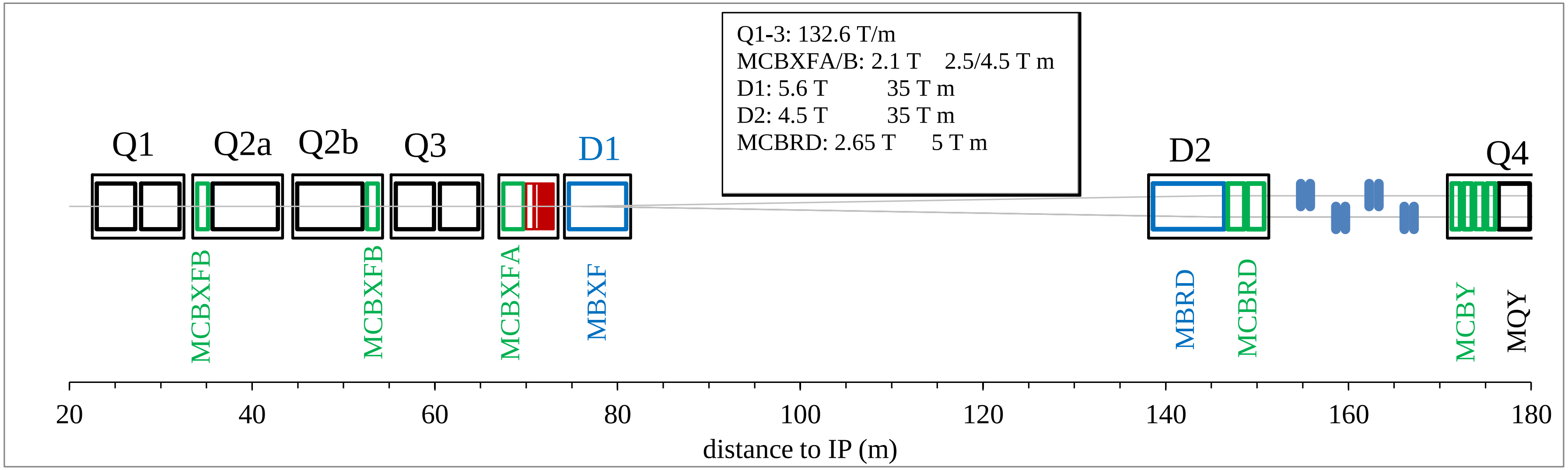
Courtesy of Ezio Todesco, CERN

MAGNET INNOVATION IN HL-LHC

Q1/Q3 : ~4 meter magnets provided by US labs

Q2a/Q2b : ~7 meter magnets provided by CERN

Large R&D program started around 2004 in the US: **LHC Accelerator Research Program** in order to prove Nb_3Sn technology was a viable solution for high field magnets



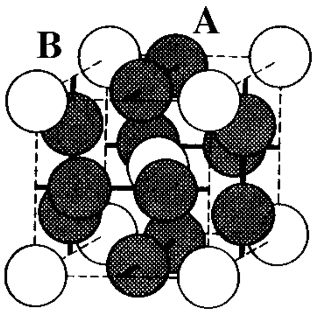
Courtesy of Ezio Todesco, CERN

U.S. LARP

CERN

DIFFICULTIES RELATED TO NB_3SN CONDUCTOR IN A NUTSHELL

Intermetallic compound



Winding of the cable

↓

heat treatment at 650°C to form the SC phase

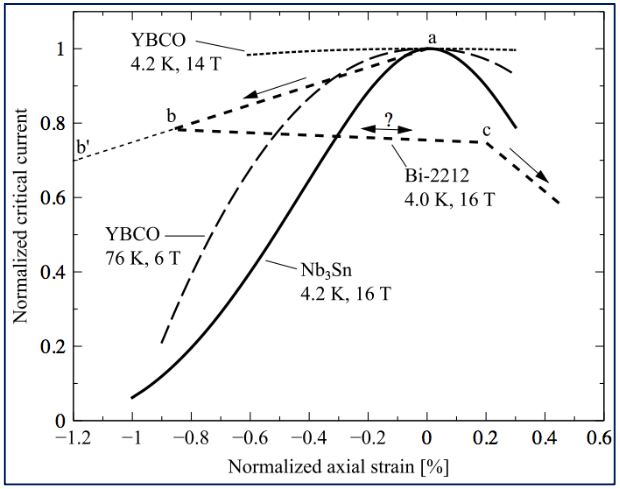
↓

- BRITTLE after heat treatment
- Dimensional changes

↓

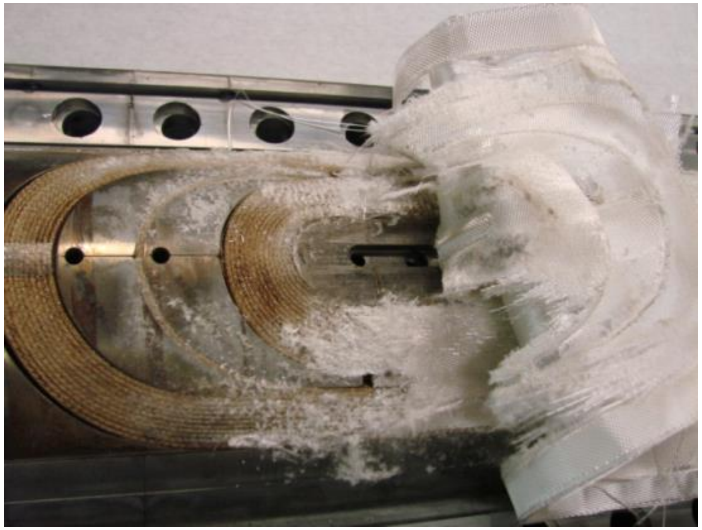
Vacuum impregnation

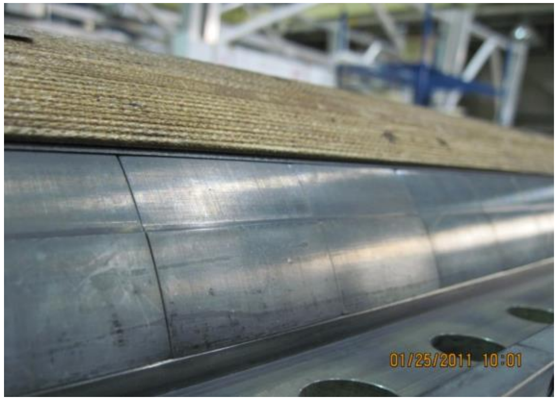
- Sensitivity to mechanical strain
- Preload application becomes critical to minimize the peak mechanical stress in the winding



Bottura and Godeke, *Rev. Accel. Sci. Techn.* **5** 25 (2012)

1ST CHALLENGE: NB_3SN COIL FABRICATION





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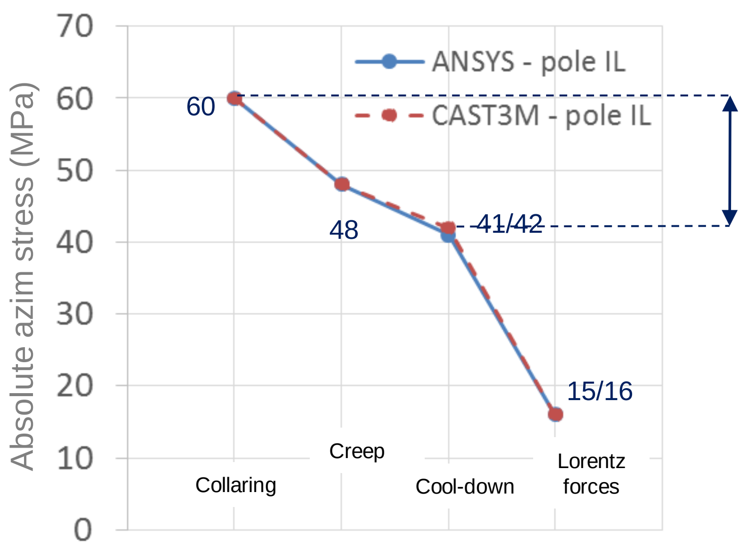
2[ND] CHALLENGE: APPLYING THE PRELOAD WITHOUT DEGRADING THE CONDUCTOR

Classical collar approach:

- Preload overshoot

Objectives of a new concept

- Prevent any overshoot of the pre-stress on the conductor
- Apply a gradual and tunable preload to the coil
- Allow magnet disassembly

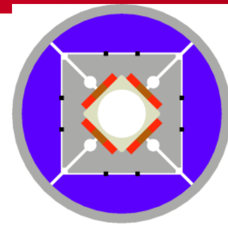


BERKELEY LAB
Lawrence Berkeley National Laboratory
U.S. LARP
HiLumi HL-LHC PROJECT

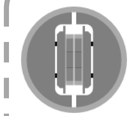
- A new concept developped at LBNL (~2000), implemented in the LHC accelerator Research Program (2003-2014)and now chosen as baseline for the low beta quad of the LHC High Luminosity upgrade

FAMILY TREE TOWARD MQXF FOR HL-LHC

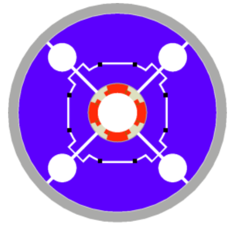
Subscale Quadrupole SQ
0.3 m long
110 mm bore

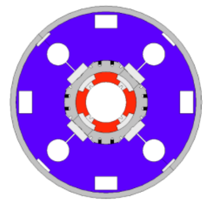


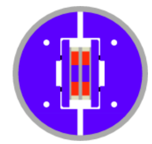
LBNL Subscale Magnet SM
0.3 m long
No bore



Technology Quadrupole TQS - TQC
1 m long
90 mm bore





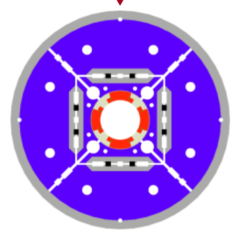


Long Racetrack LRS
3.6 m long
No bore

Technology selection:
Shell based support structure for LARP

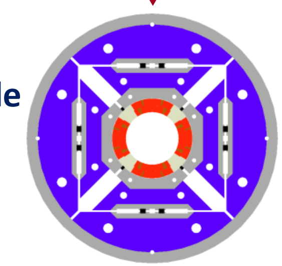
1st assembly: 2009
Last assembly: 2012

Long Quadrupole LQS
3.7 m long
90 mm bore



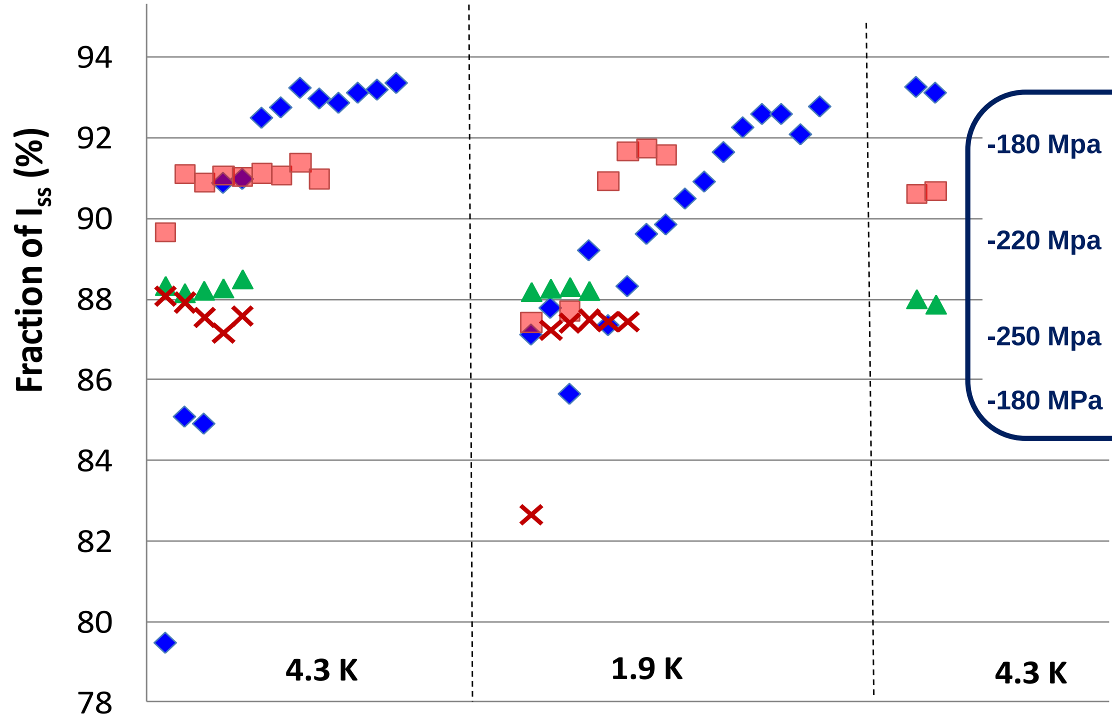
1st assembly: 2010
Most recent: 2013

High Field Quadrupole
1 m long
120 mm bore

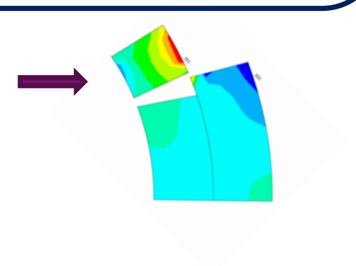


BERKELEY LAB
Lawrence Berkeley National Laboratory
U.S. LARP

IMPACT OF MECHANICAL STRESS ON MAGNET PERFORMANCE



-180 Mpa	TQS03a	93 %	~ 12.3 T / 13.5 kA
-220 Mpa	TQS03b	91 %	~ 12 T / 13.2 kA
-250 Mpa	TQS03c	88 %	~ 11.6 T / 12.8 kA
-180 MPa	TQS03d	88 %	

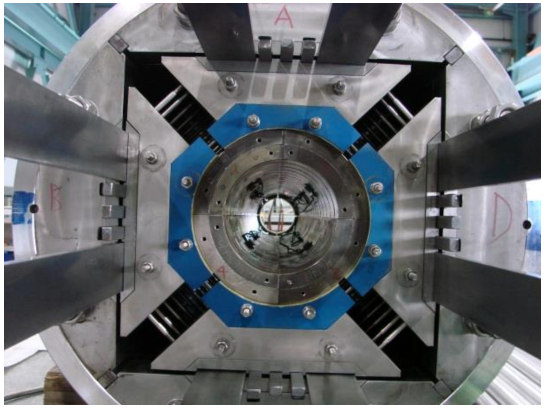


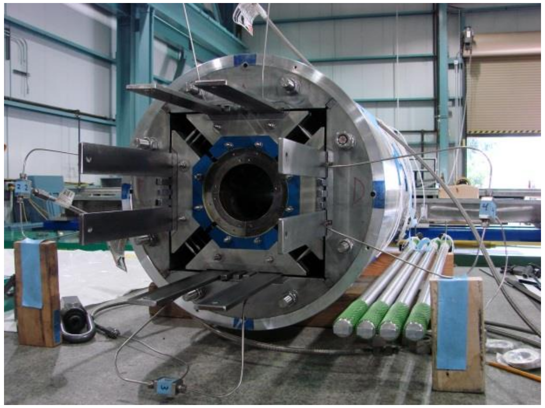
- Only 5 % degradation from TQS03a to TQS03c
- TQS03d did not recover => Permanent degradation

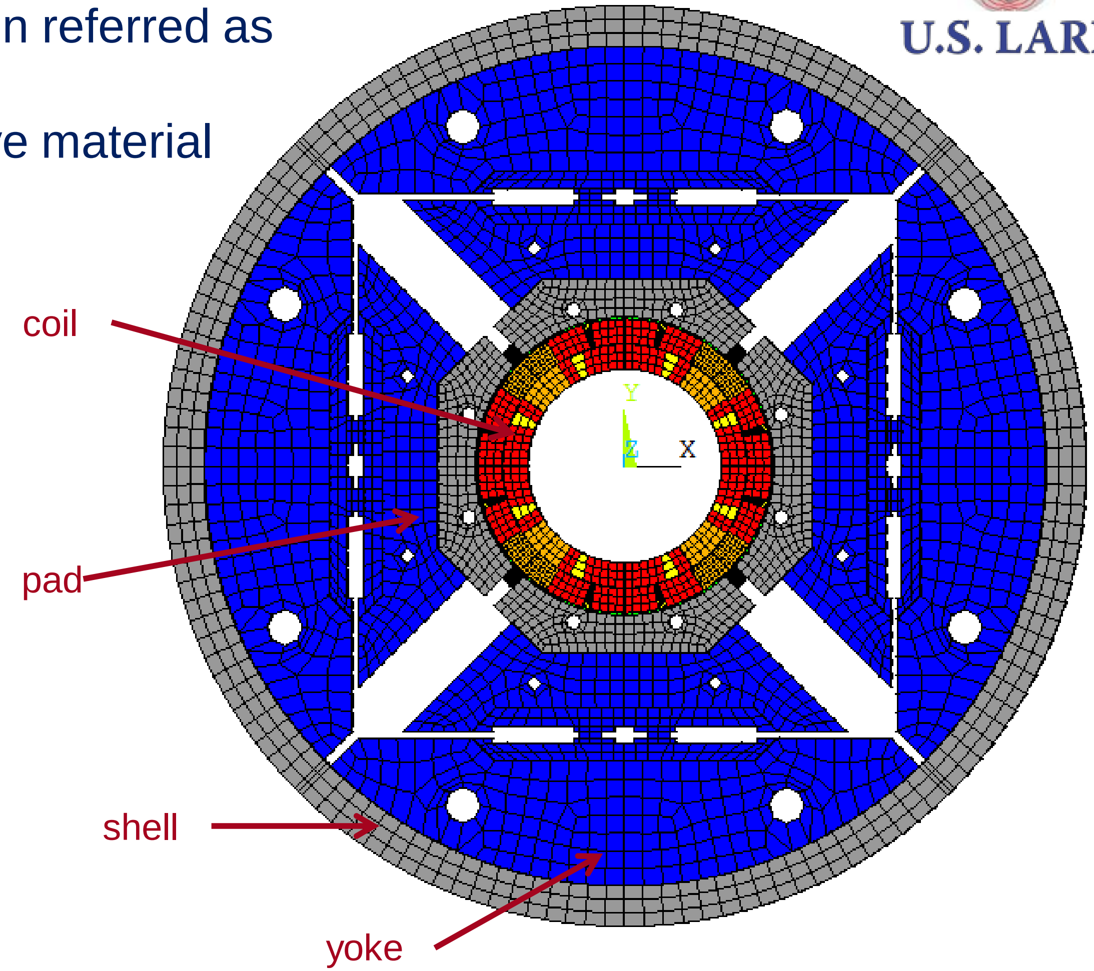
Performance above 90% reached with 220-250 MPa of estimated compressive azimuthal stress in the high field region
A limit has been set for maximum stress in the conductor

SHELL-BASED SUPPORT STRUCTURE MOTIVATION AND CONCEPT

- Shell-based support structure often referred as "bladder and keys" structure developed at LBNL for strain sensitive material

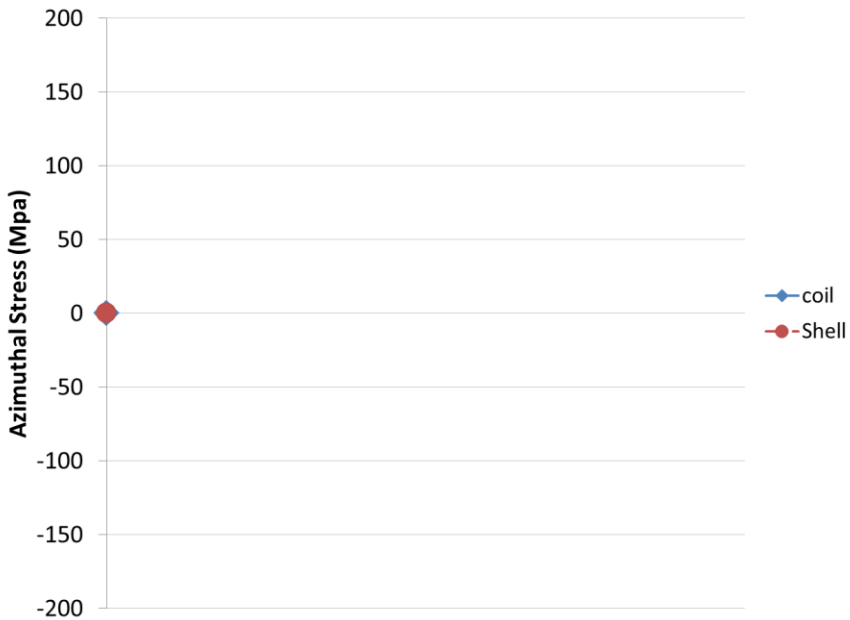


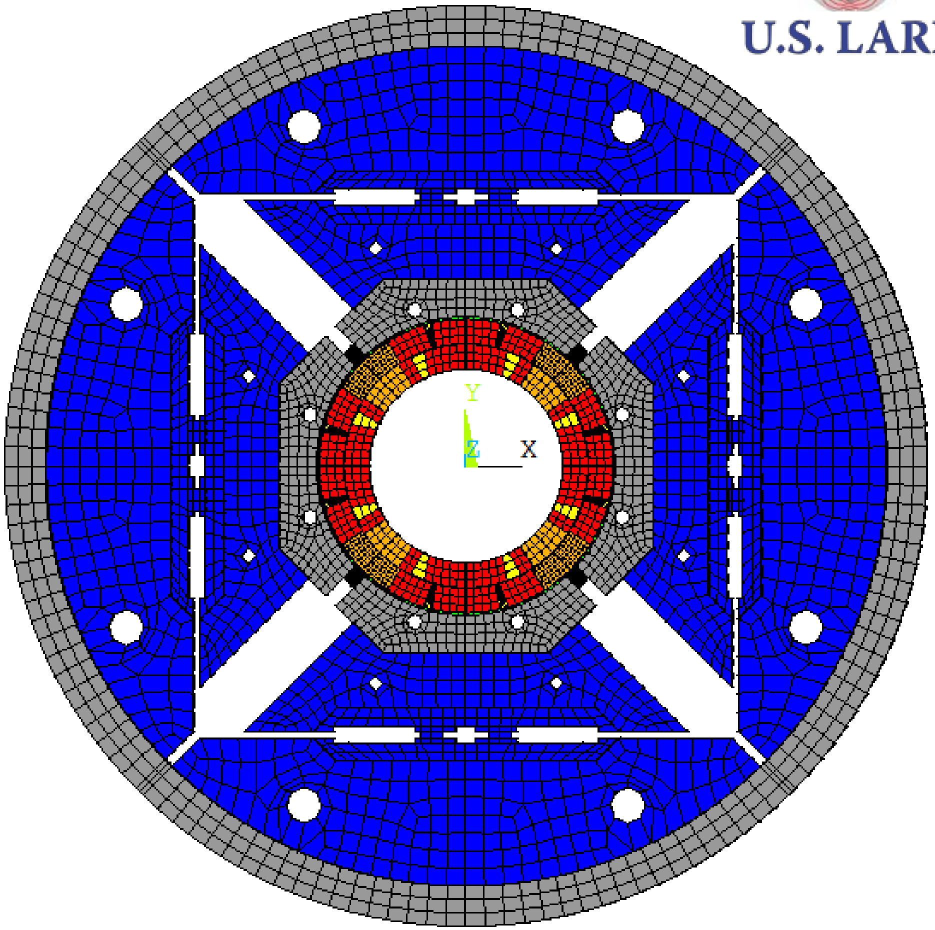




U.S. LARP

- Shell-based support structure also called "bladder and keys" structure developed at LBNL
for strain sensitive material





SHELL-BASED SUPPORT STRUCTURE CONCEPT

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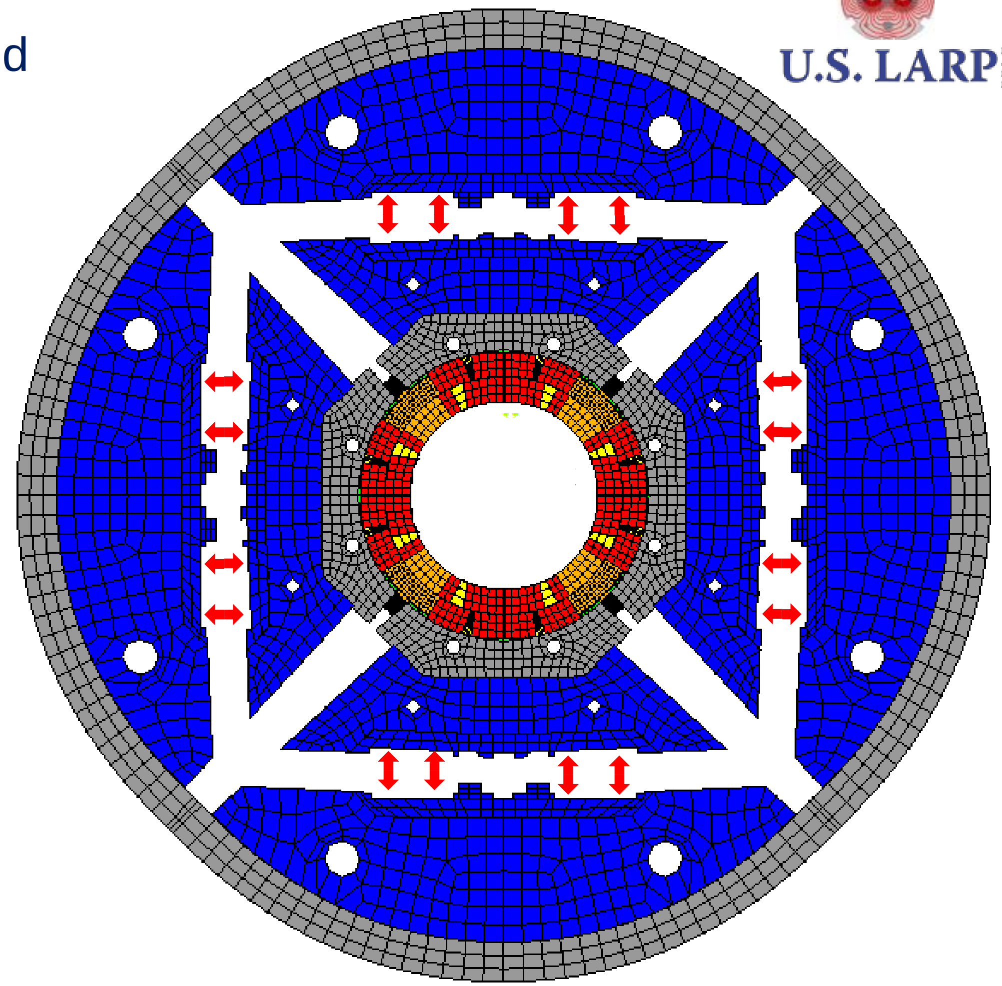
Inflated Bladders



Displacement scaling 30

SHELL-BASED SUPPORT STRUCTURE CONCEPT

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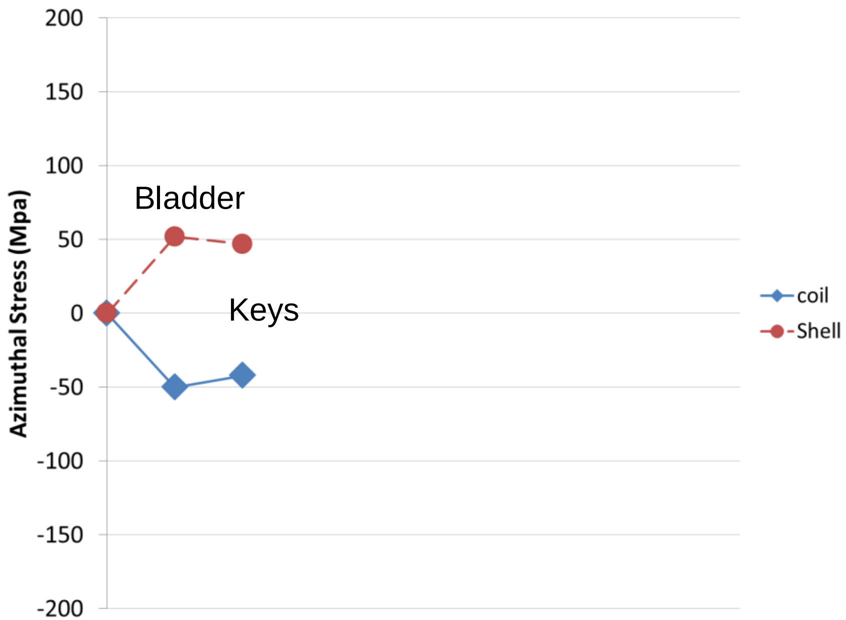
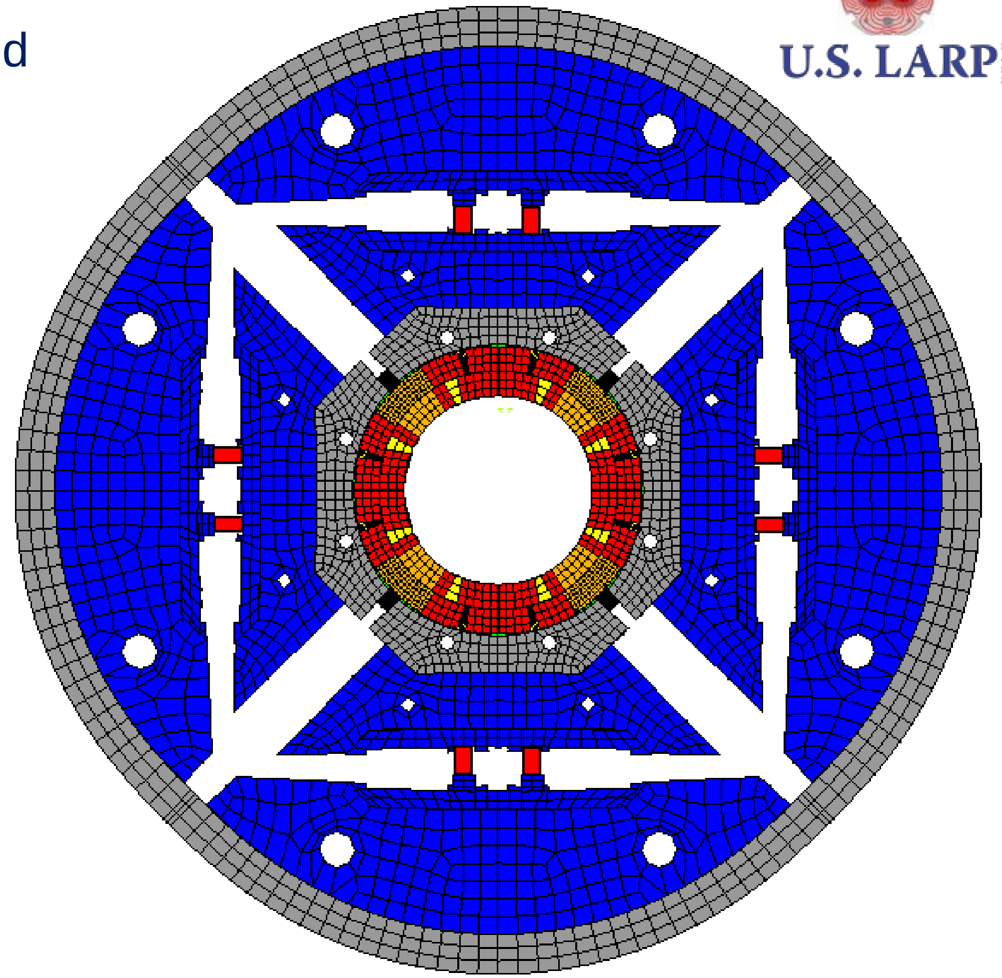
for strain sensitive material



Shimming of the load leys



Displacement scaling 30

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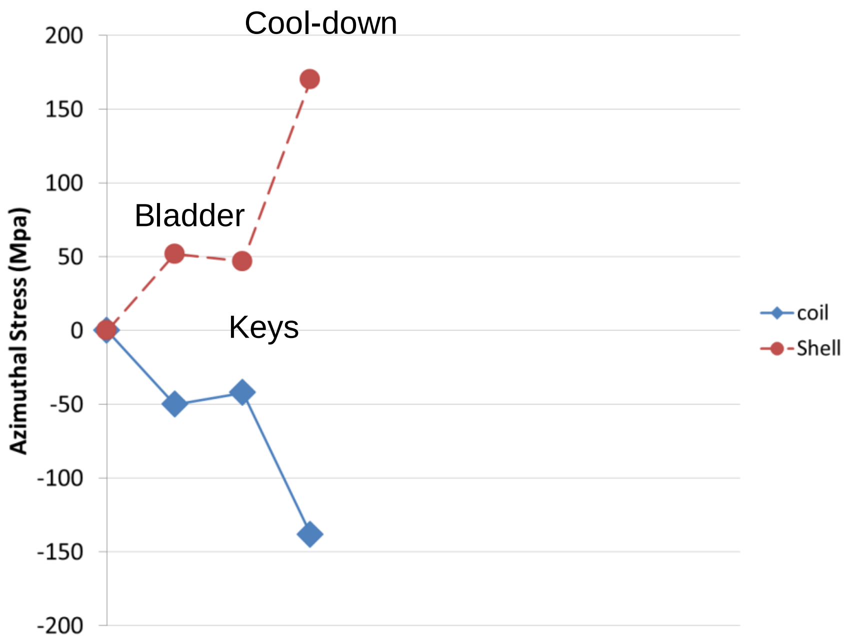

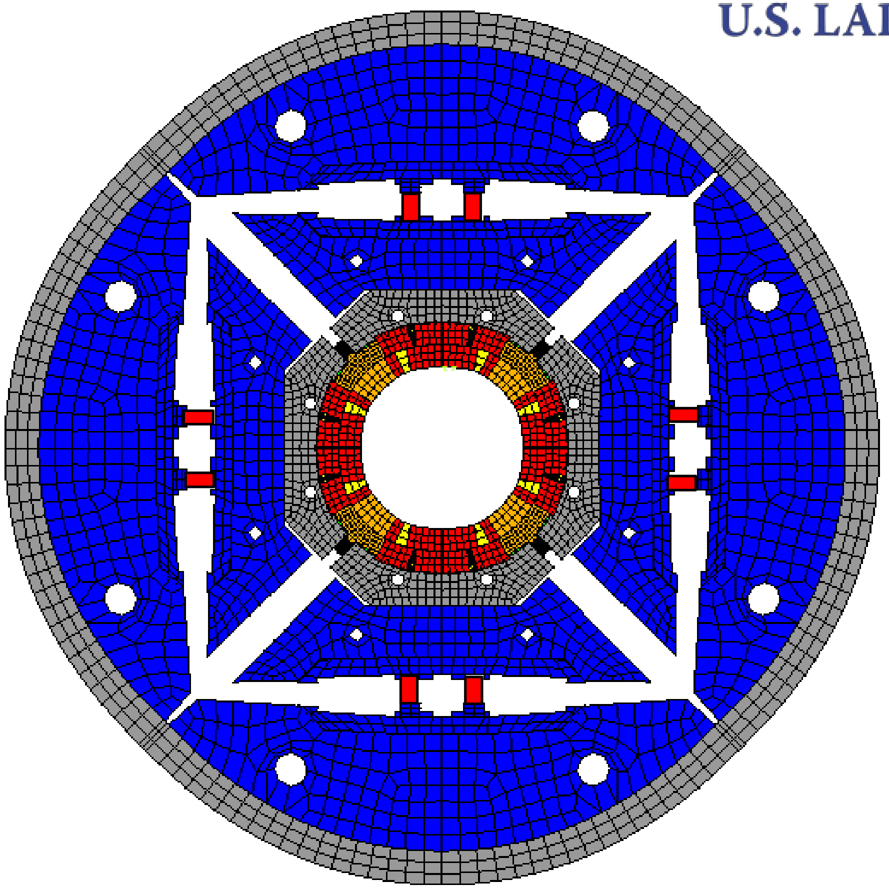

Displacement scaling 30

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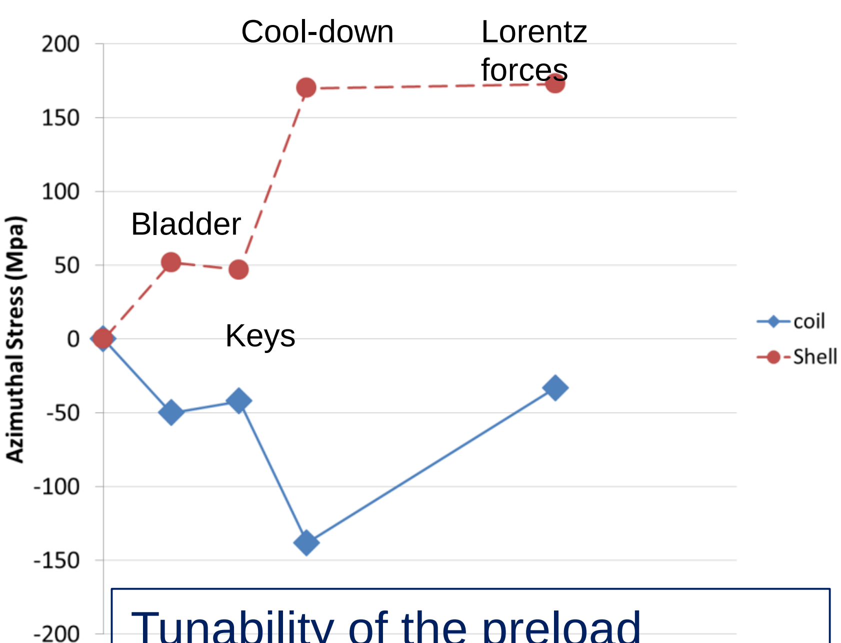
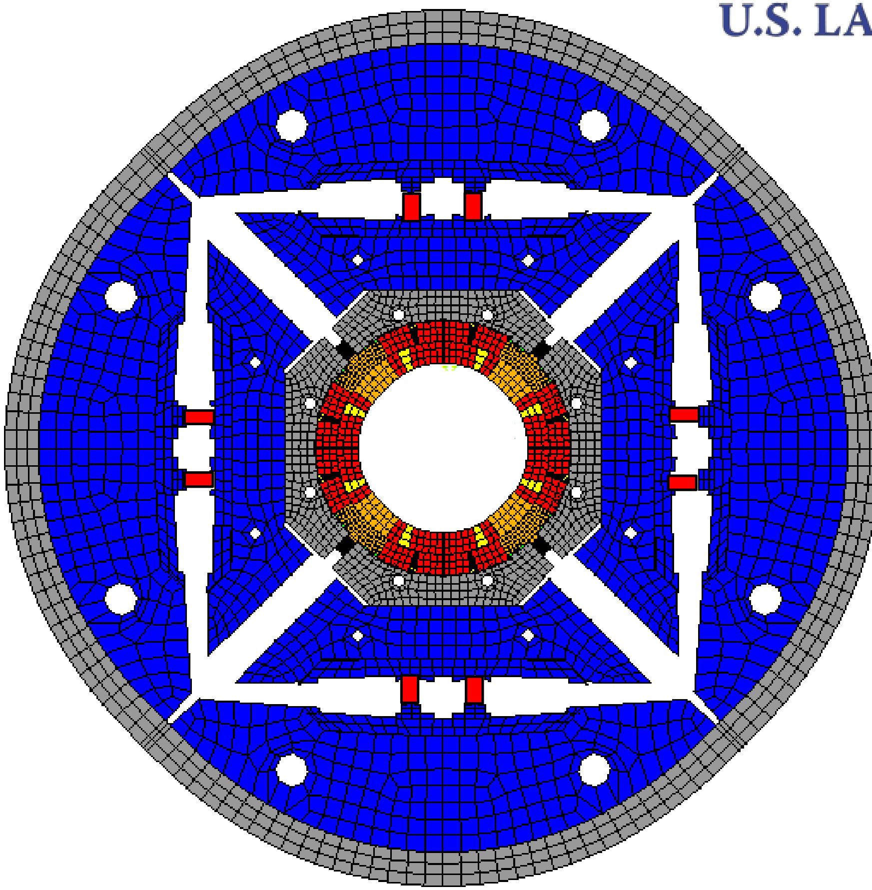


Tunability of the preload

Energized



Displacement scaling 30

SHELL-BASED SUPPORT STRUCTURE CONCEPT

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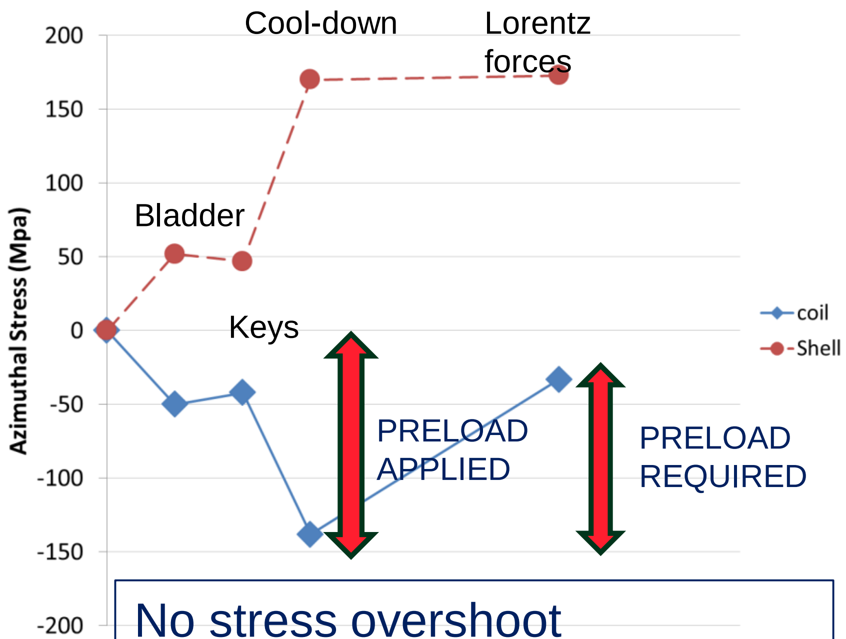
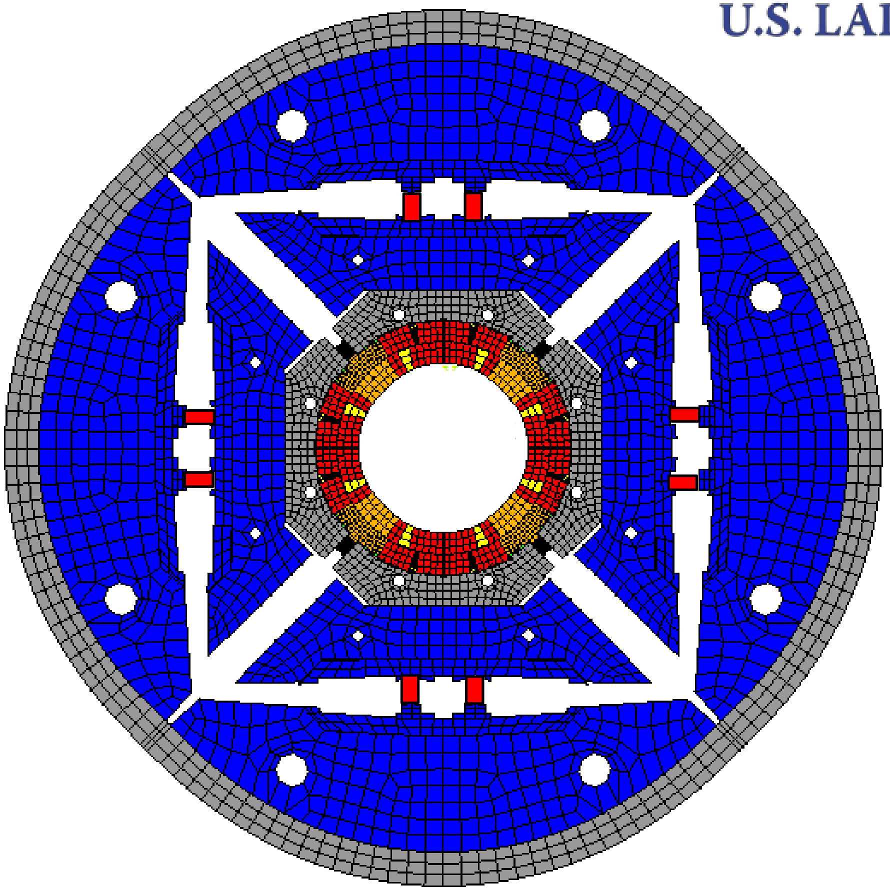


No stress overshoot

Energized



Displacement scaling 30

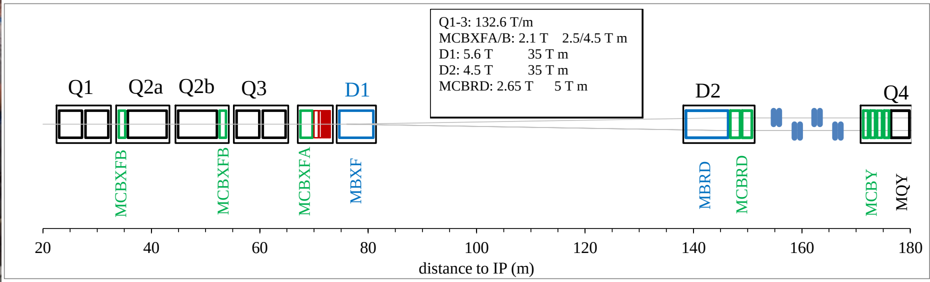
NB_3SN MAGNET IN HL-LHC: SUMMARY

Q1/Q3 : 4 meter magnets provided by US labs

Q2a/Q2b : 7 meter magnets provided by CERN

KEY CHALLENGES
- Coil technology
- Quench performance

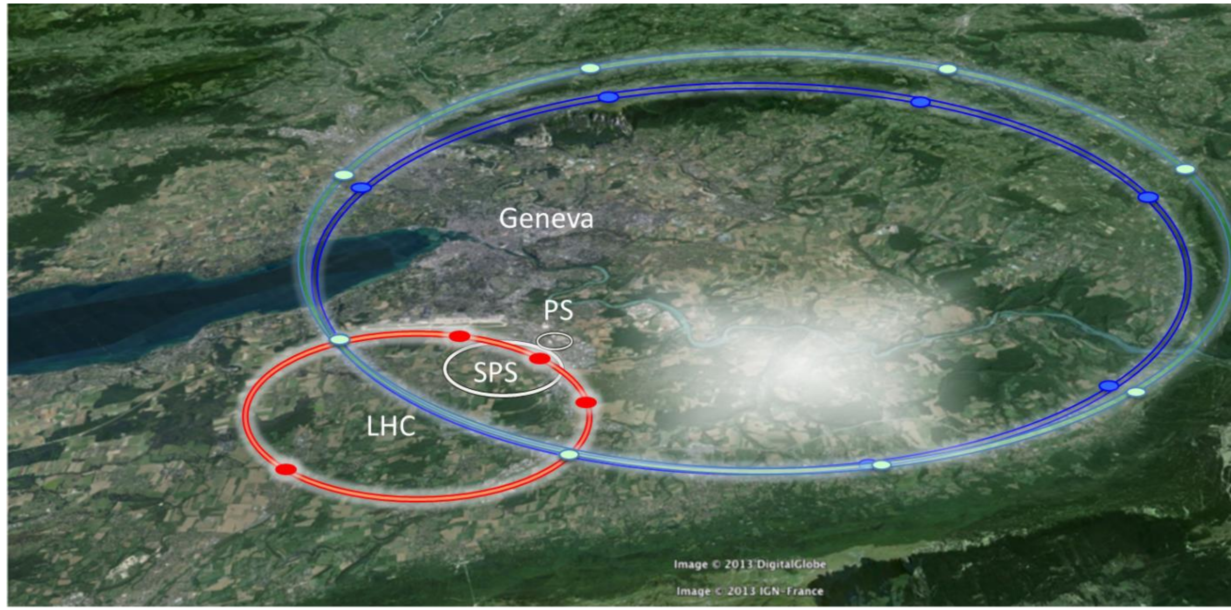
L. Rossi
E. Todesco



The success of MQXF is a major milestones in magnet development toward higher energy machine

Future Circular Collider

More beam energy…
=> More field, more forces
=> More magnets



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.)
1300 tons NbTi	3000 tons LTS	9000 tons LTS	6000 tons Nb_3Sn
	700 tons HTS	2000 tons HTS	3000 tons Nb-Ti

Example of questions among the magnet community :

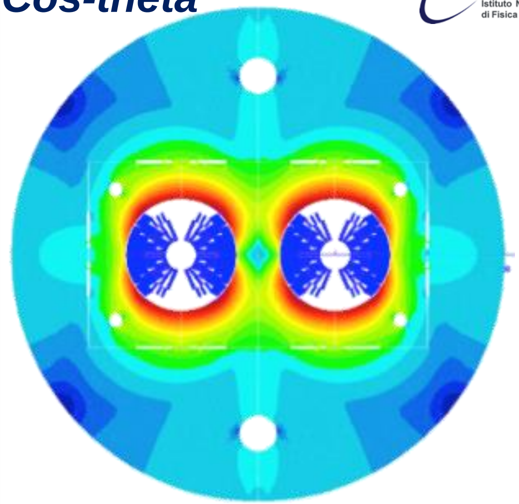
Is there a "stress wall"?
Making high field magnets out of reach?

How can we reduce the cost?

⇒ Need for a change of approach?
⇒ Innovative design?

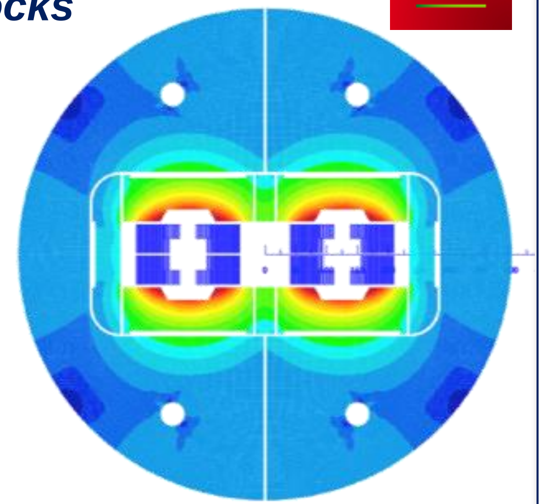
16 T TARGET: A WORLWIDE EFFORT
NON EXHAUSTIVE EXAMPLES

Cos-theta



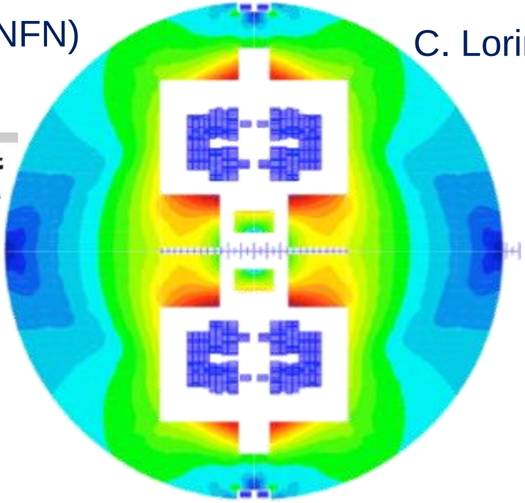
S. Farinon, M. Sorbi (INFN)

Blocks



C. Lorin, M. Durante (CEA)

Common coils



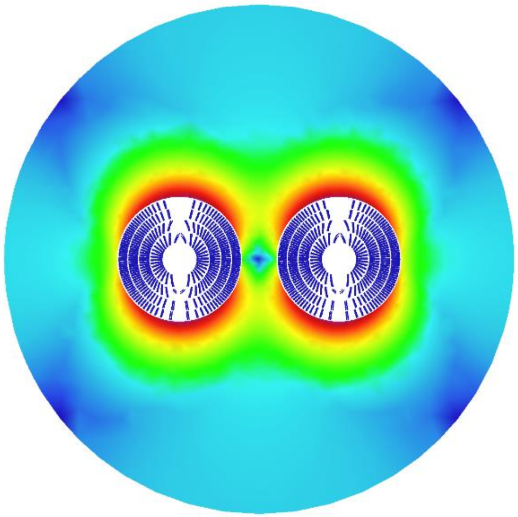
F. Toral (CIEMAT)

- **Relying on Nb_3Sn only**
- **Wide-range** study, based on the **same design assumptions**

16 T TARGET: A WORLWIDE EFFORT
NON EXHAUSTIVE EXAMPLES

PAUL SCHERRER INSTITUT PSI
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Canted Cos-theta



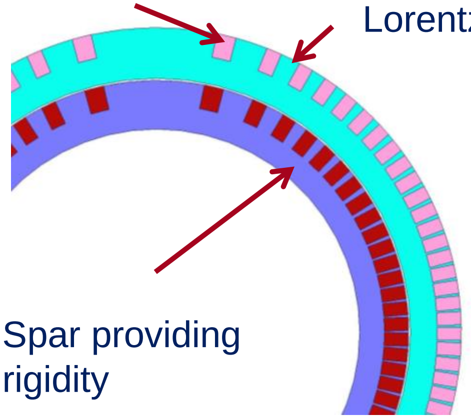
B. Auchmann (CERN/PSI)

CCT at LBNL

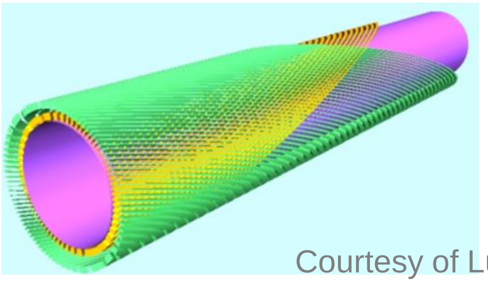
Two superimposed coils, oppositely skewed, achieve a pure cosine-theta field and eliminate axial field.

Turns

Ribs intercepting Lorentz forces



Spar providing rigidity



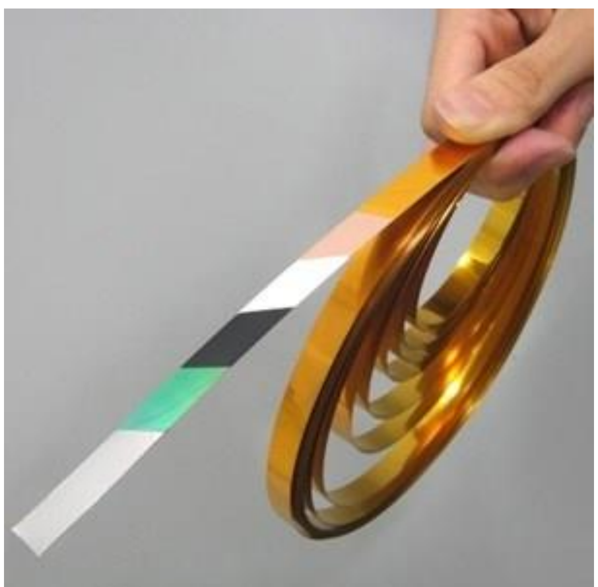
Structure "embedded" in the coil
- ⇒ Avoid azimuthal force accumulation
- ⇒ Minimize number of components

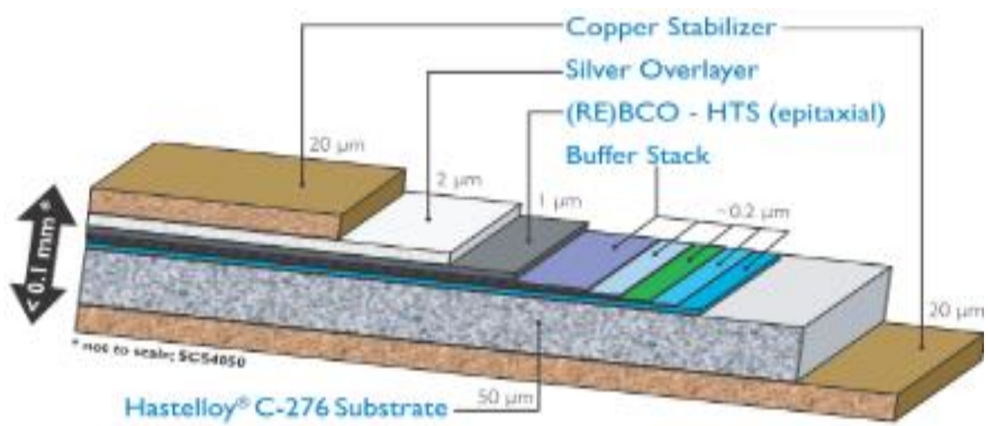
Ongoing development program at LBNL

Courtesy of Lucas Brouwer and Shlomo Caspi (LBNL)

- CEA is involved in 2 R&D projects on HTS magnets for accelerators:
  - **Insert EuCARD: Dipolar HTC** insert decoupling technological topics.
  - **Insert EuCARD 2:** Dipolar HTC insert with Accelerator quality features (aperture+ field quality)

- Same conductor technology: REBCO(Rare-earth Barym copper oxide):



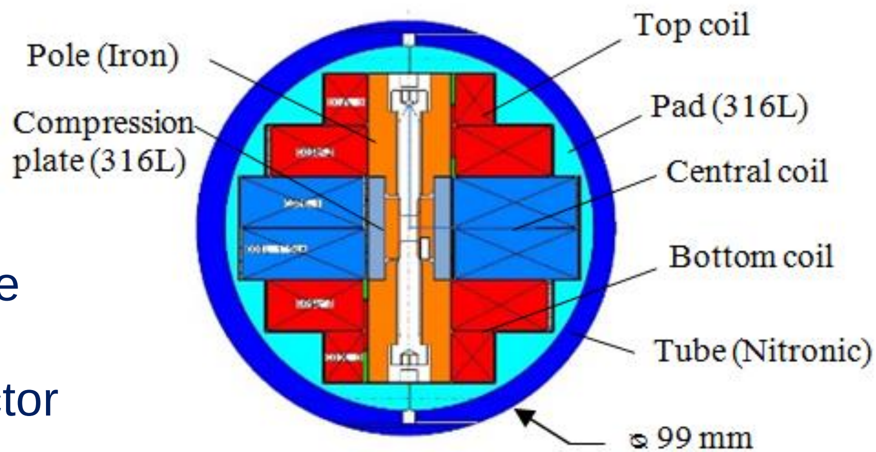


Ruban YBaCuO (SP)

Courtesy of F. Borgnolutti, M. Durante, CEA

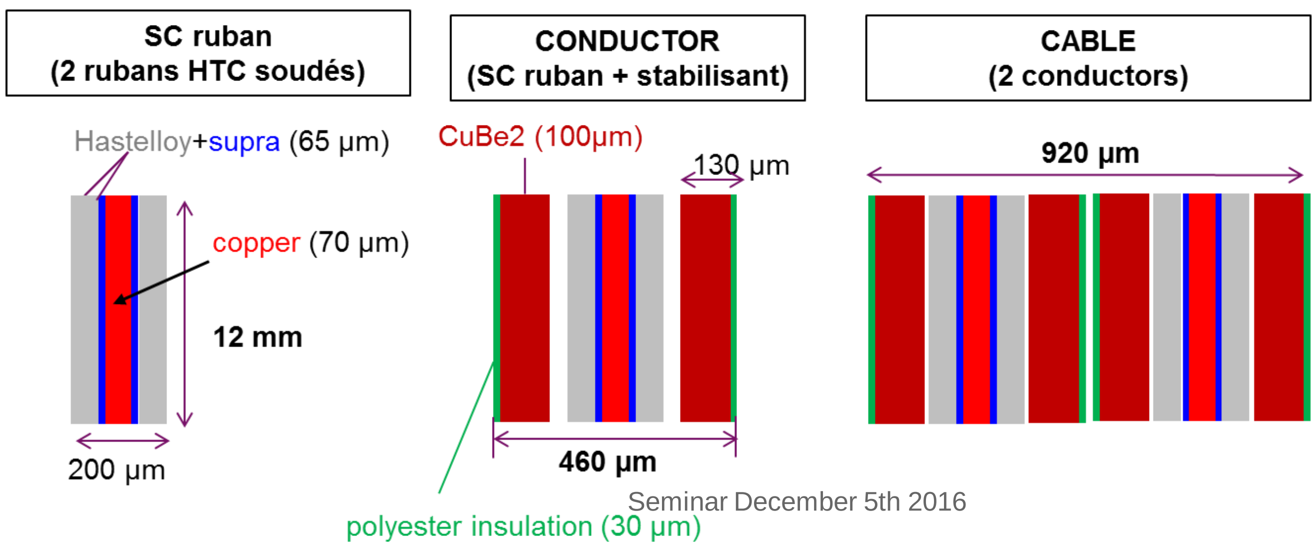
THE 20 T FRONTIER: EUCARD INITIATIVE AND CERN-CEA COLLABORATION

Courtesy of F. Borgnolutti, M. Durante, CEA



- Racetrack coil => no aperture
- 5.4 T in the center (2.8 kA)
- 12 mm wide REBCO conductor
- No impregnation
- No requirements on field quality

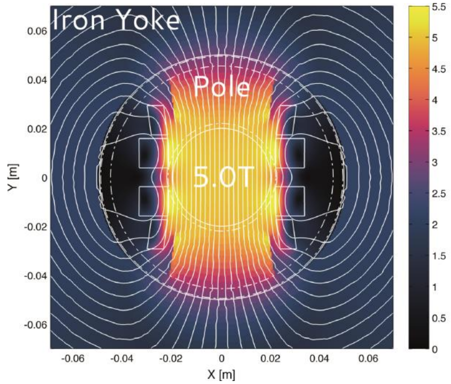
=> Test in preparation at Saclay – foreseen early 2017



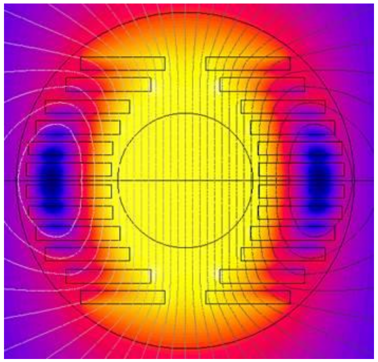
20 T TARGET : EUCARD 2 INITIATIVE

FP7 EuCARD2 WP10
Collaboration with CERN, INPG, INFN, TUT, DTI

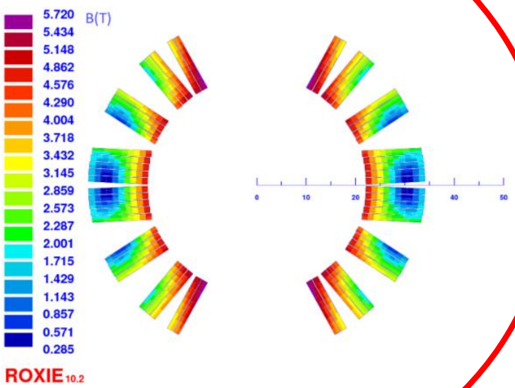
Design fabrication and test of a small accelerator dipole in **REBCO**
Objective : 5 T (self field) in a 40 mm aperture, 4.2 K, with accelerator field quality.



Aligned block Design (CERN)

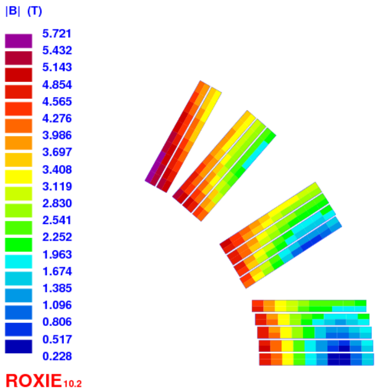


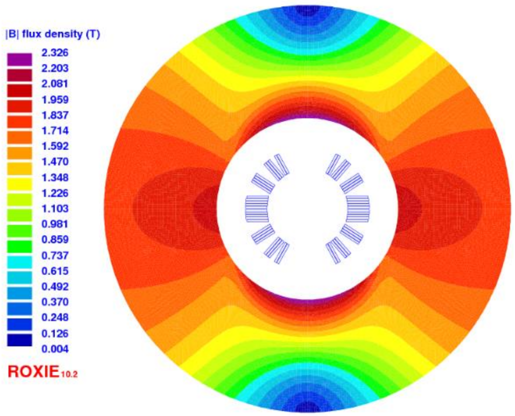
Stacked tapes Block Design (INPG)



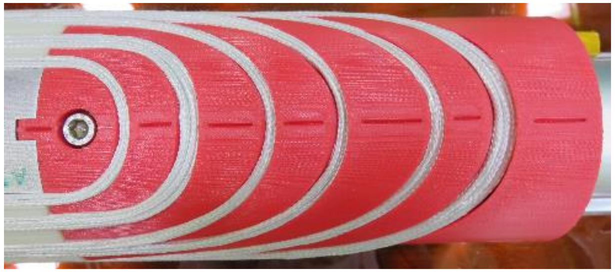
Costheta Design (CEA)

20 T TARGET : COS THETA - CEA APPROACH

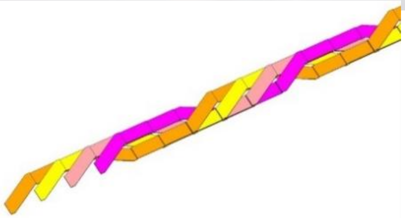


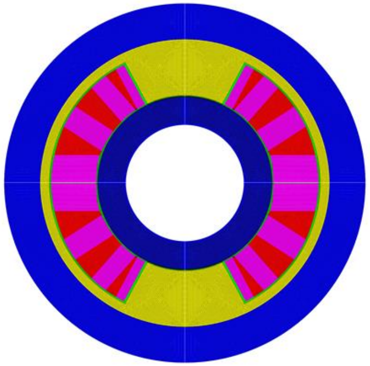


Layout	Unit	Cosϑ A
Iop	kA	**11.68**
Bop	T	**5**
Bpeak	T	**5.7**
Ic	kA	**14.4**
LL margin	(%)	**20**
T margin	K	**20**



- ○ Roebel Cable
- ○ Coil impregnation
- ⇒ **Coil fabrication in 2017**





Courtesy of C. Lorin, M. Durante, CEA

IN SUMMARY

- Looking for new physics calls for new magnet technology

- Moving from R&D magnets (even successful ones) to accelerator-ready magnets takes times and money and world-wide effort

- At CEA, we are presently covering
  - NbTi technology
  - Some Nb_3Sn technology: more to come with a CEA/CERN collaboration under finalization
  - HTS technology