Superconducting Magnets R&D in the 10-20 T range for energy frontier machines

High Luminosity LHC

Lucio Rossi - CERN

AED seminar – Desy 23 May 2014

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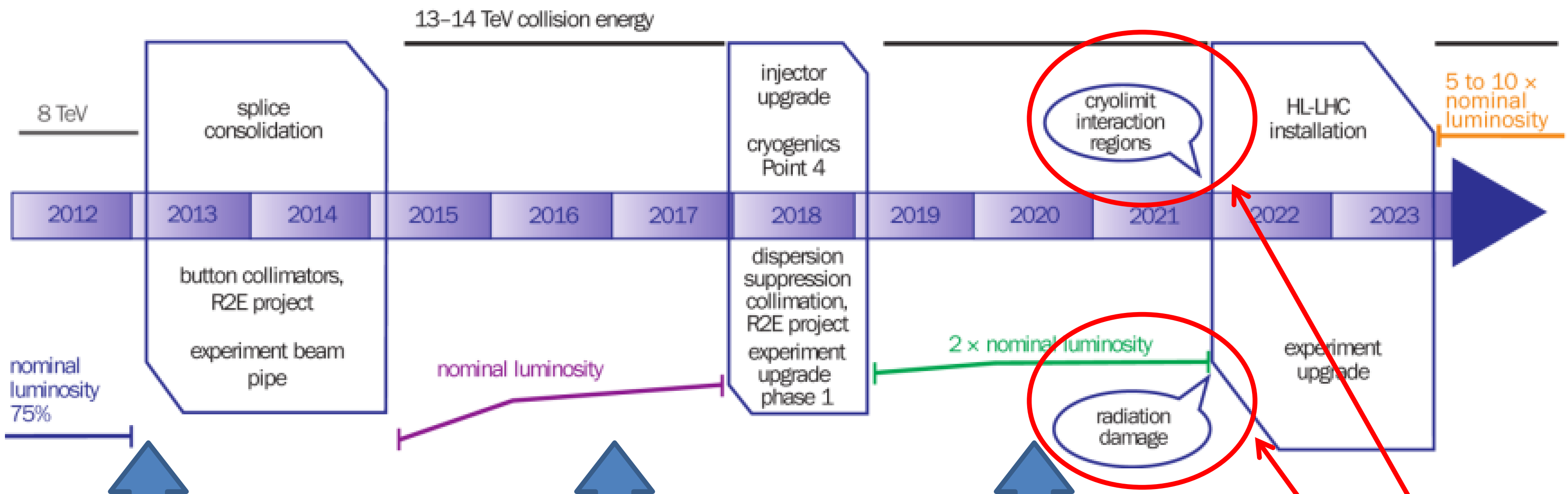
The CERN 10-year plan (approved early 2011)



0.75 10^{34} $cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

1.5 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~40

1.7-2.2 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~60

Technical limits (experiments, too) like :

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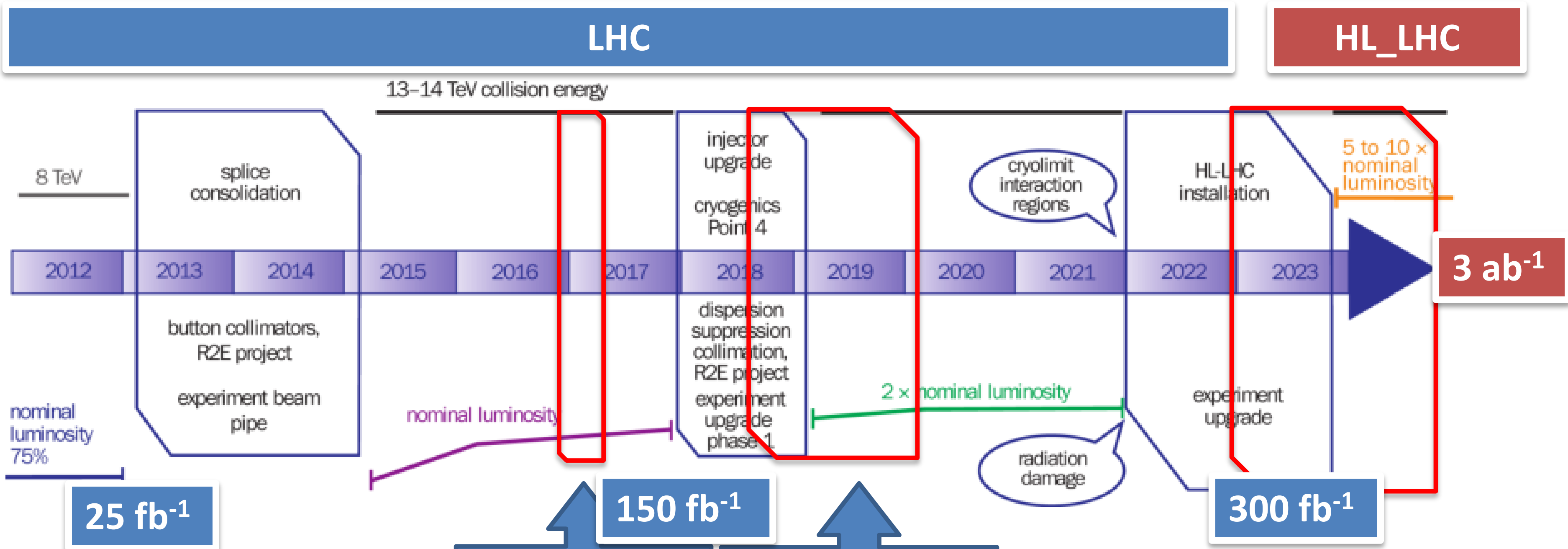
New LHC Plan since Dec. 2013 with HL-LHC approved



Big chance to install CC in SPS!

Install New Cryo in IP4, (install CC in IP4 _ NOT beasline) Preparation for CC in LS3

2.5 y beam-to-beam Is considered the minimum by experiments

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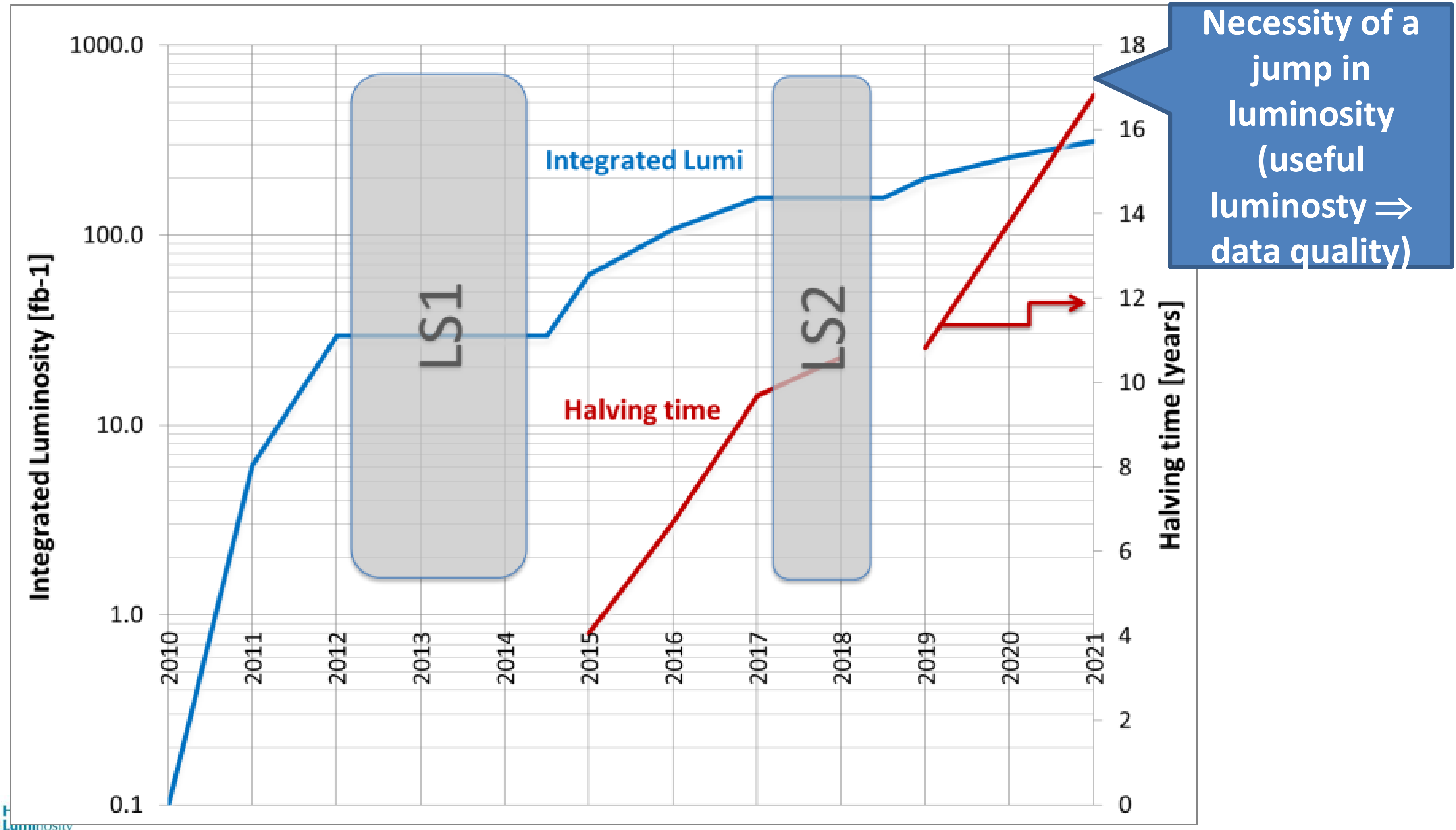
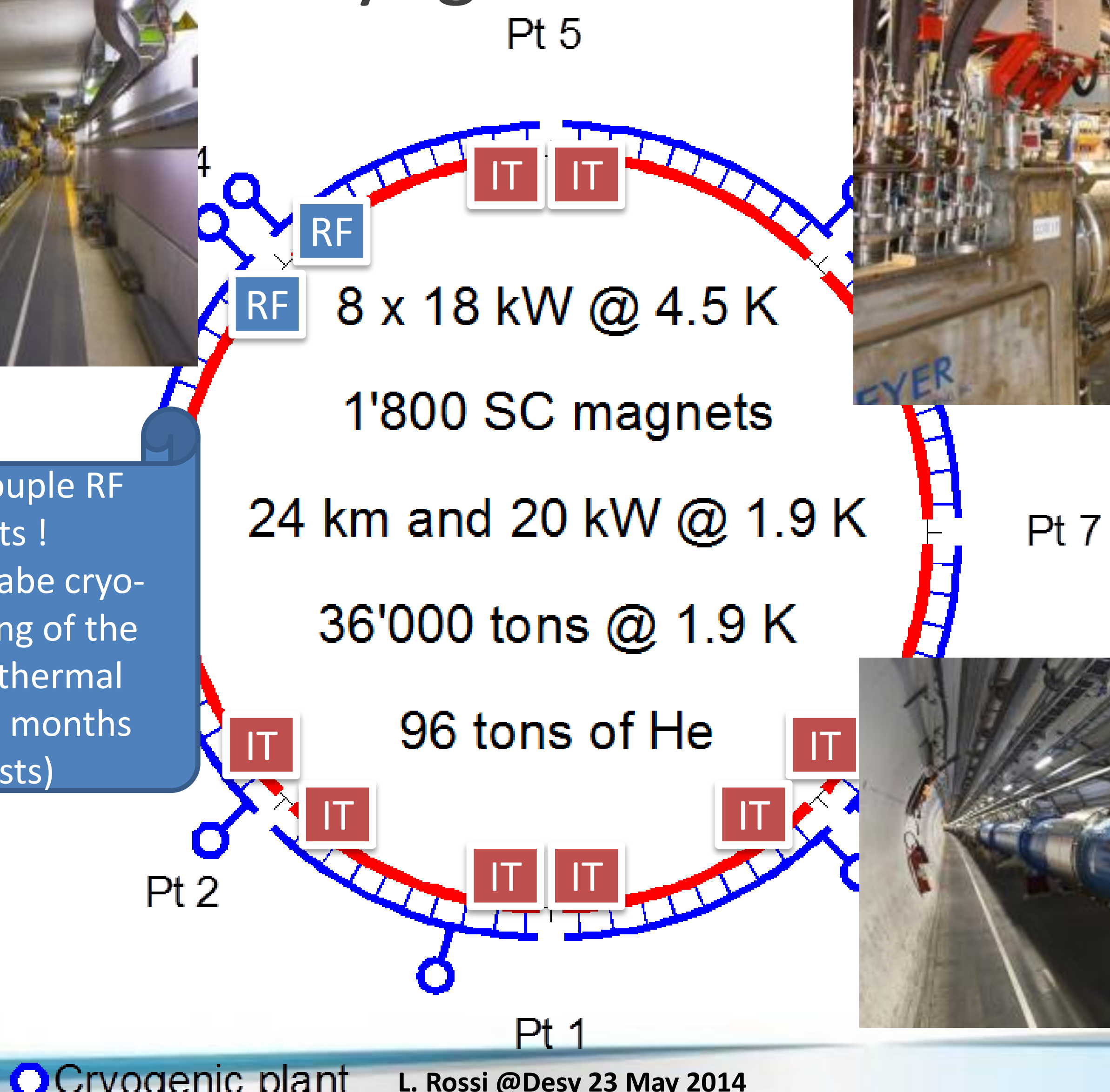
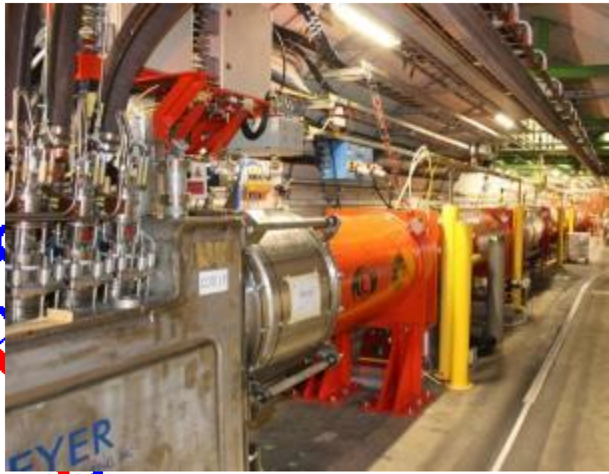
Mantain and increase physics reach



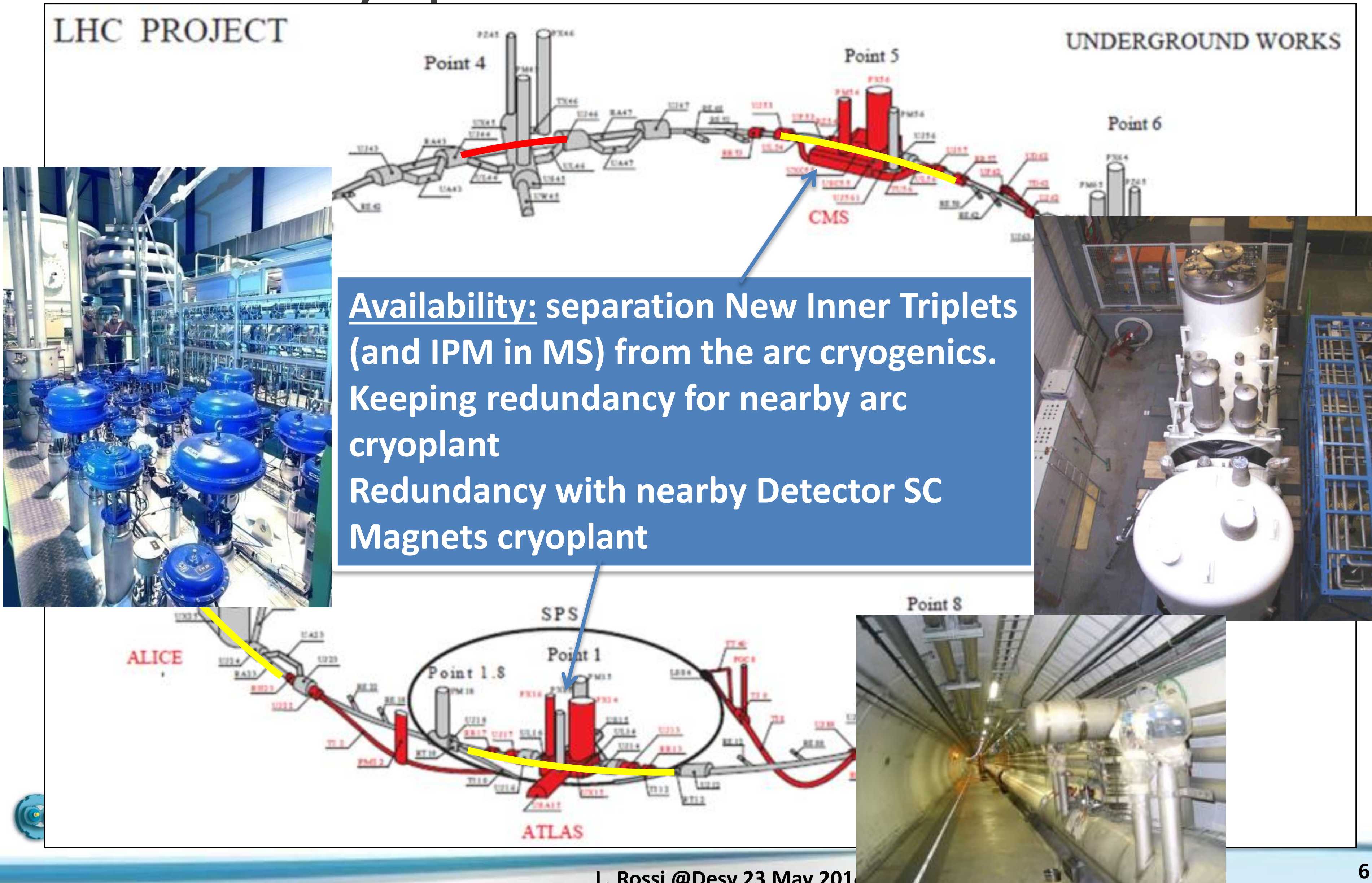
Technical bottlenecks
Cryogenics P4





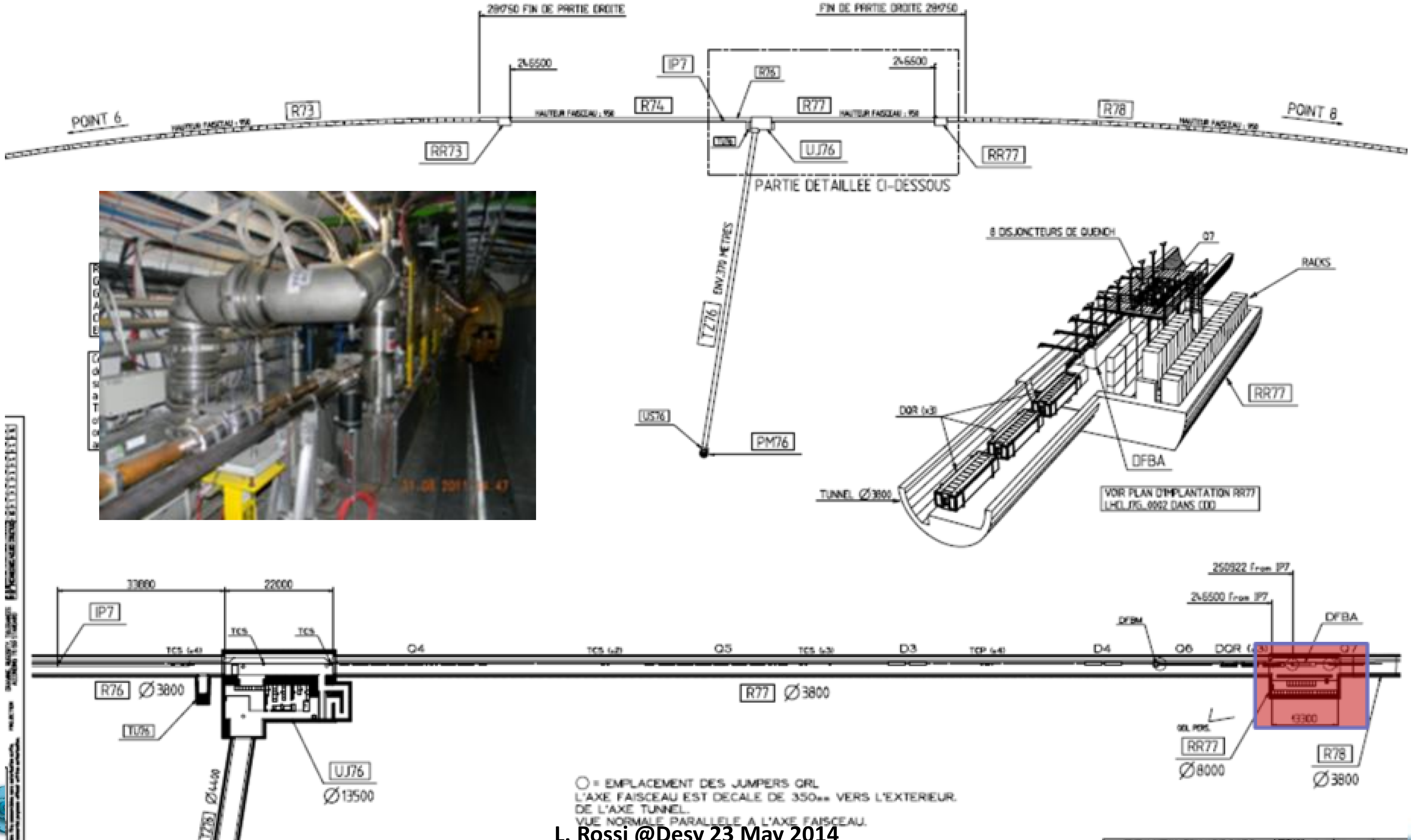
Never good to couple RF with Magnets !
Reduction of availabe cryo-power and coupling of the RF wiht the Arc (thermal cycle requires > 2 months and many tests)

IT cryoplants and new LSS QRL

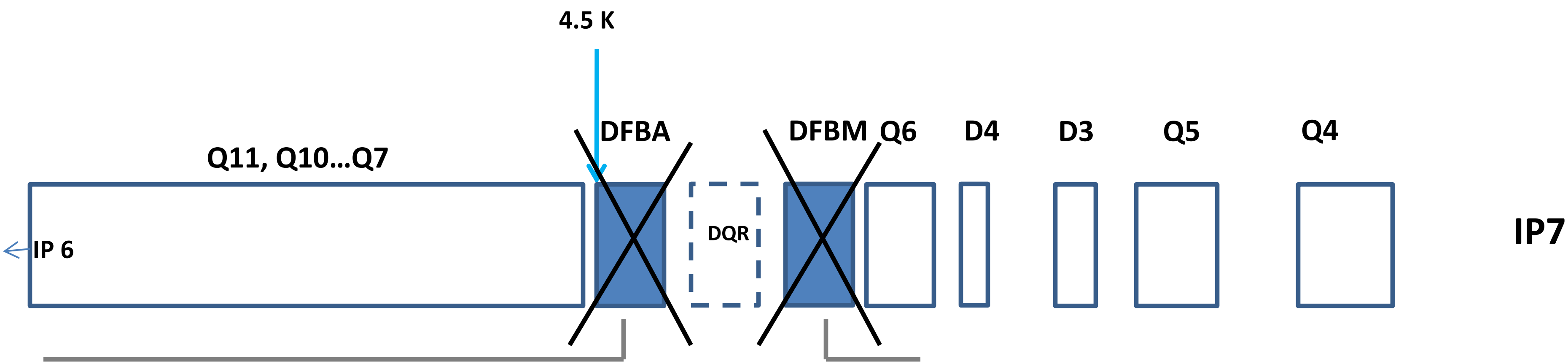


Availability: separation New Inner Triplets (and IPM in MS) from the arc cryogenics.
Keeping redundancy for nearby arc cryoplant
Redundancy with nearby Detector SC Magnets cryoplant

P7 : EPC and DFB near collimators

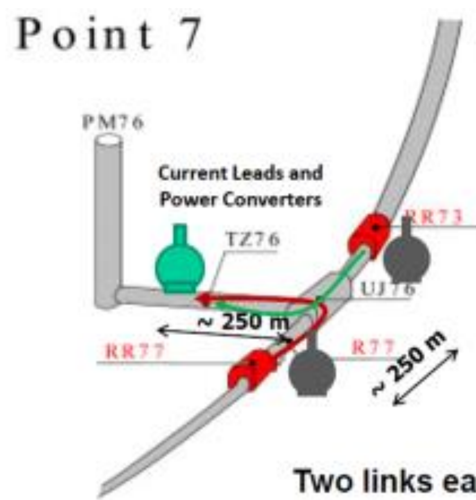


Displacing EPC and DFB in the adjacent TDZ tunnel (~ 500 m away) via SC links



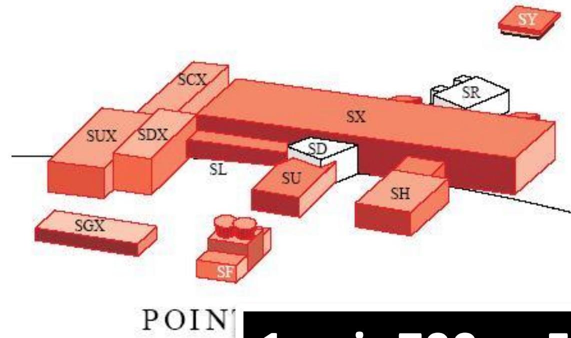
8.75 m

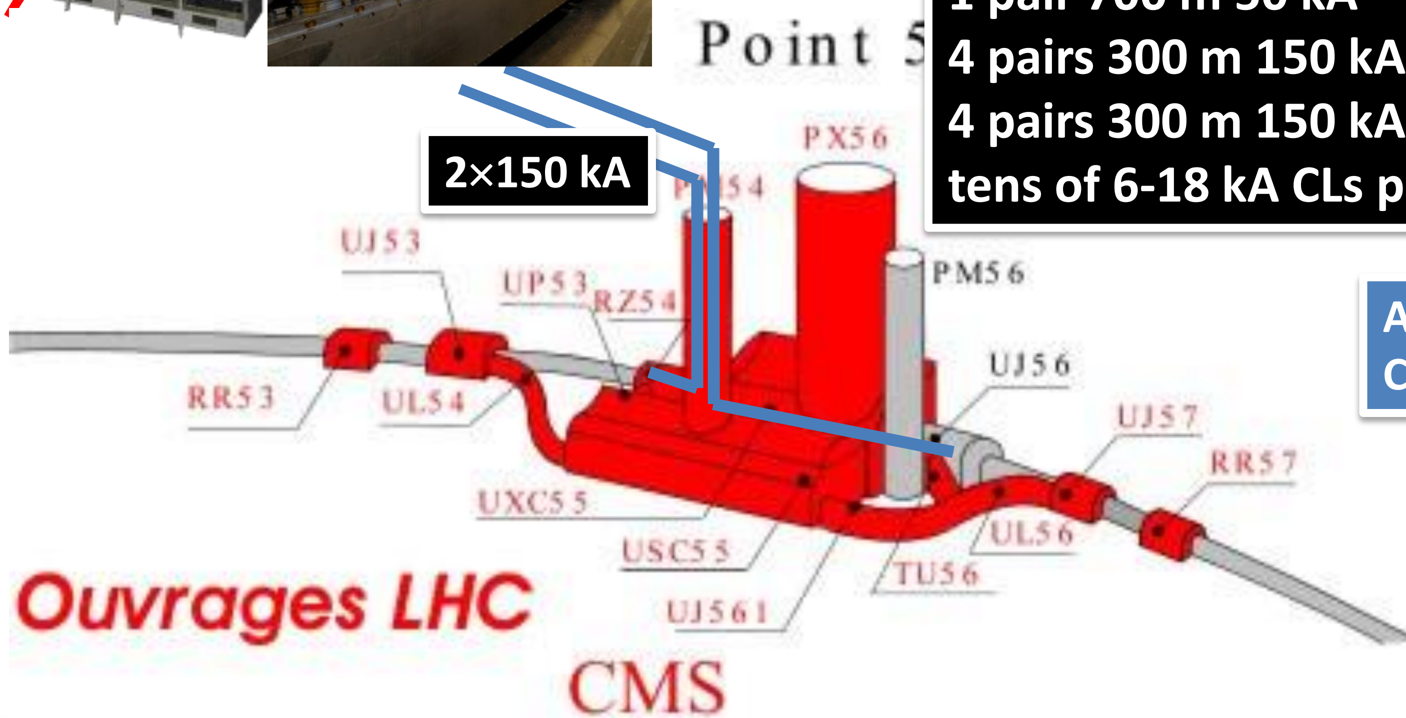
RR 73



Two links each about 500 m long
48 cables rated at 600 A per link

Availability: SC links ⇒removal of EPCs, DFBs from tunnel to surface





2×150 kA

1 pair 700 m 50 kA – LS2
4 pairs 300 m 150 kA (MS)– LS3
4 pairs 300 m 150 kA (IR) – LS3
tens of 6-18 kA CLs pairs in HTS

A. Ballarino, CERN

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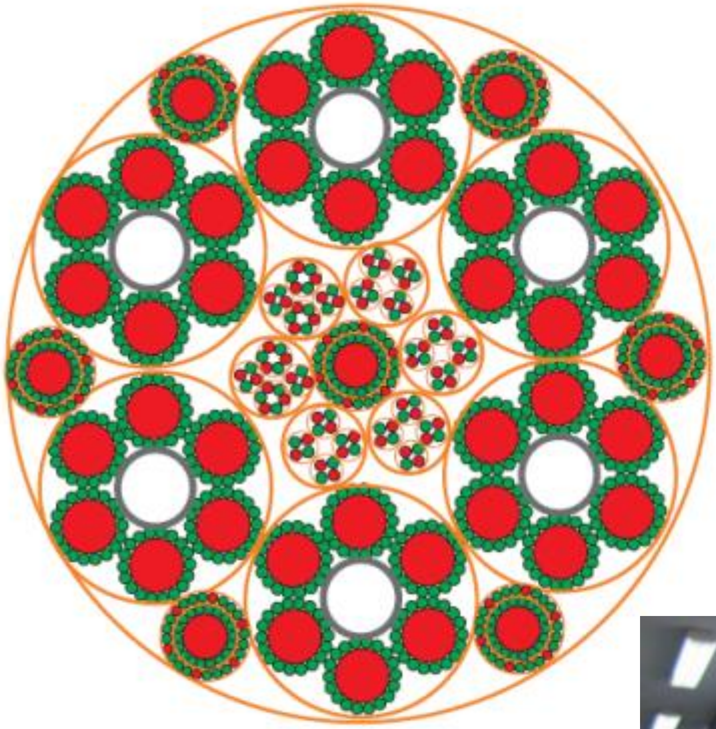
First test of high current high temperature



Tested March 2014
I = 20 kA
T = 24 K
Bpeak = 1 T
Length = 2×20 m

Φext ~ 65 mm

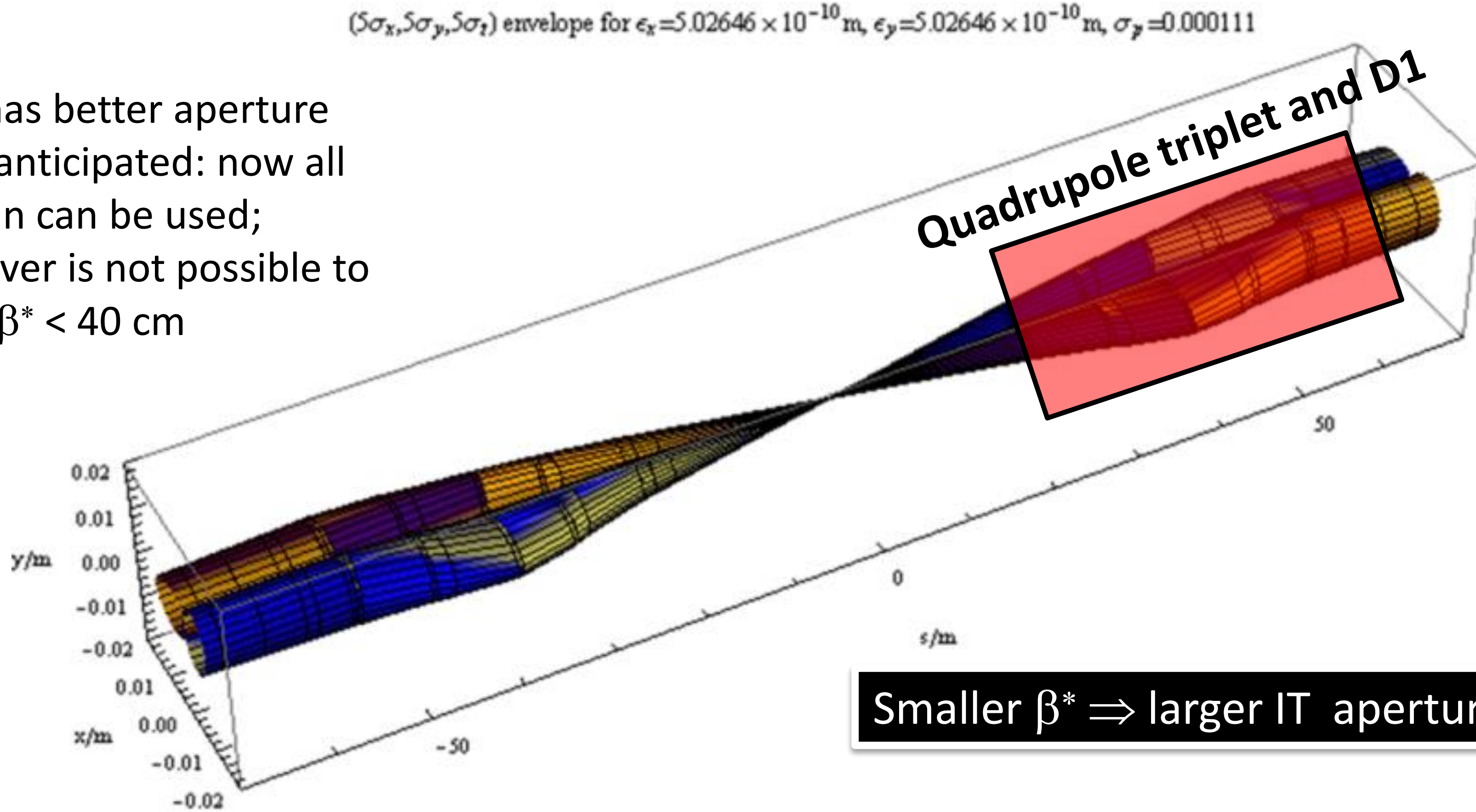
A. Ballarino, CERN

L = 20 m

(25×2) 1 kA @ 25 K, LHC Link P7

The most straight forward action for HL: reducing beam size with a «local» action

LHC has better aperture than anticipated: now all margin can be used; however is not possible to have $\beta^* < 40$ cm



Smaller $\beta^* \Rightarrow$ larger IT aperture

Not only β* ; more protons at low ε

$$L = \gamma \frac{f_{rev}\, n_b\, N_b^{\,2}}{4\pi \varepsilon_n \beta^*} R$$

Parameter	nominal	25ns	50ns
N_b	1.15E+11	2.2E+11	3.5E+11
n_b	2808	**2808**	1404
N_{tot}	3.2E+14	6.2E+14	4.9E+14
beam current [A]	0.58	**1.11**	0.89
x-ing angle [μrad]	300	590	590
beam separation [σ]	9.9	12.5	11.4
β^* [m]	0.55	**0.15**	0.15
ε_n [μm]	3.75	2.50	3
ε_L [eVs]	2.51	2.51	2.51
energy spread	1.20E-04	1.20E-04	1.20E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	18.5	17.2
IBS longitudinal [h]	61 -> 60	20.4	16.1
Piwinski parameter	0.68	3.12	2.85
Reduction factor 'R1*H1' at full crossing angle (no crabbing)	0.828	0.306	0.333
Reduction factor 'H0' at zero crossing angle (full crabbing)	0.991	**0.905**	0.905
beam-beam / IP without Crab Cavity	3.1E-03	3.3E-03	4.7E-03
beam-beam / IP with Crab cavity	3.8E-03	1.1E-02	1.4E-02
Peak Luminosity without levelling [$cm^{-2} s^{-1}$]	1.0E+34	7.4E+34	8.5E+34
Virtual Luminosity: Lpeak*H0/R1/H1 [$cm^{-2} s^{-1}$]	1.2E+34	**21.9E+34**	23.1E+34
Events / crossing without levelling	19 -> 28	210	475
Levelled Luminosity [$cm^{-2} s^{-1}$]	-	5E+34	2.50E+34
Events / crossing (with leveling for HL-LHC)	*19 -> 28	140	140
Leveling time [h] (assuming no emittance growth)	-	9.0	18.3

https://espace.cern.ch/HiLumi/PLC/default.aspx

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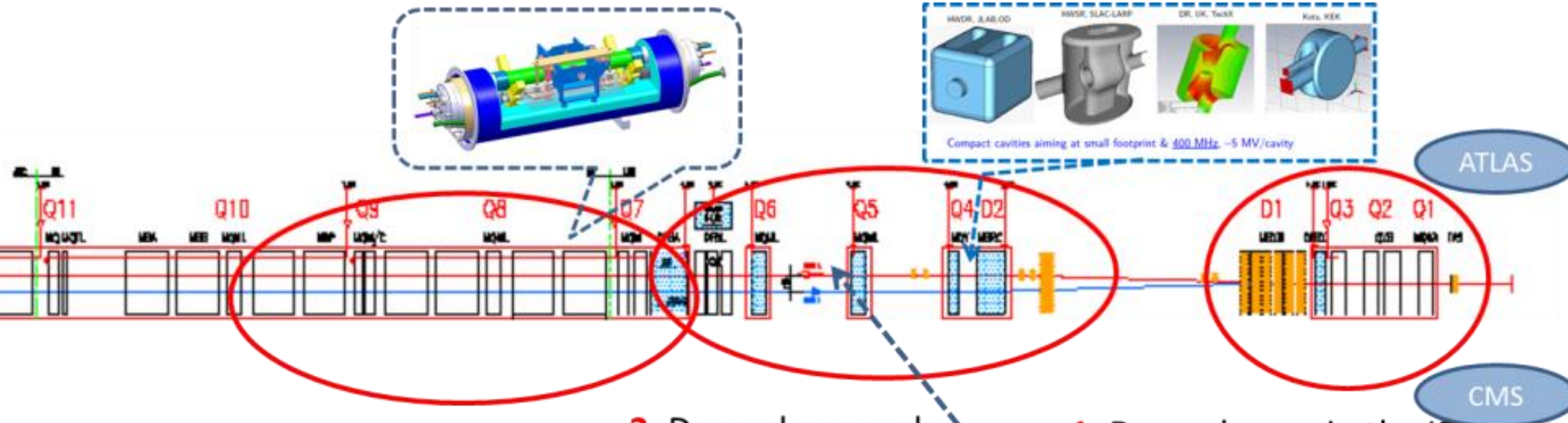
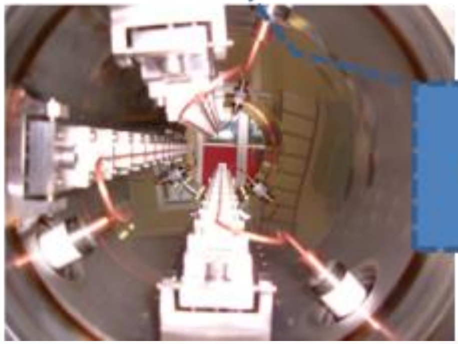
The critical zone around IP1 and IP5



3. For collimation we need to change also this part, DS in the continuous cryostat

2. Deep change also matching section: Magnets, collimators and CC

1. Deep change in the IRs and interface to detectors; relocation of Power Supply



4. LR BB compensation wires

1.2 km of LHC !!

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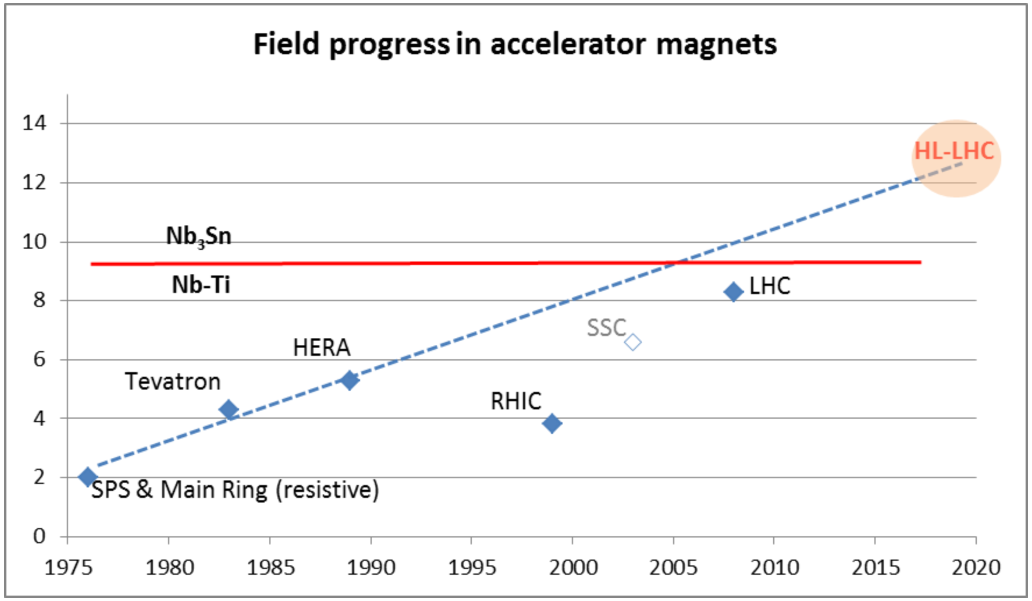
Magnet the progress

- LHC dipoles features 8.3 T in 56 mm (designed for 9.3 peak field)
- LHC IT Quads features 205 T/m in 70 mm with 8 T peak field
- HL-LHC
  - **11 T dipole (designed for 12.3 T peak field, 60 mm)**
  - **New IT Quads features 140 T/m in 150 mm > 12 T operational field, designed for 13.5 T).**



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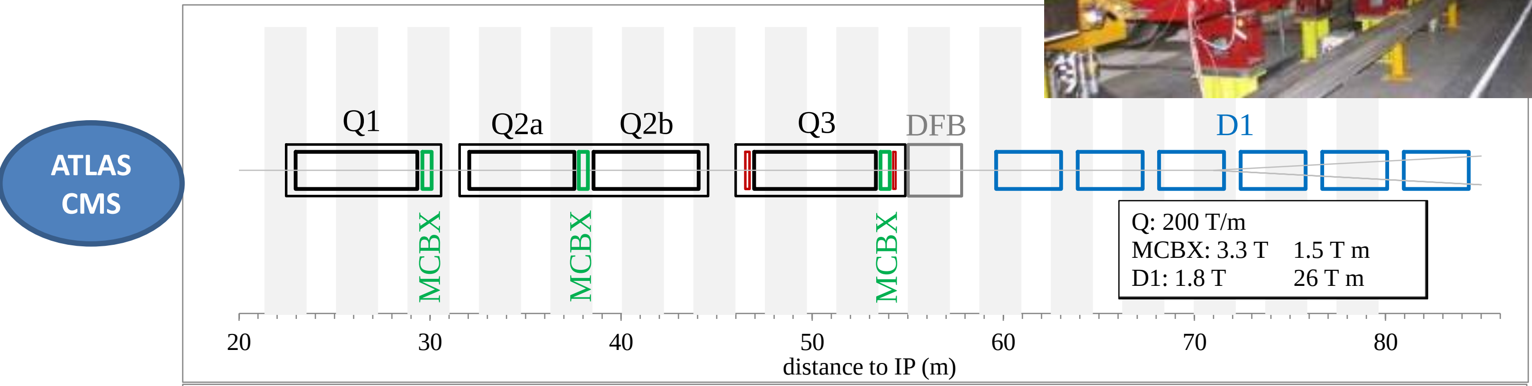
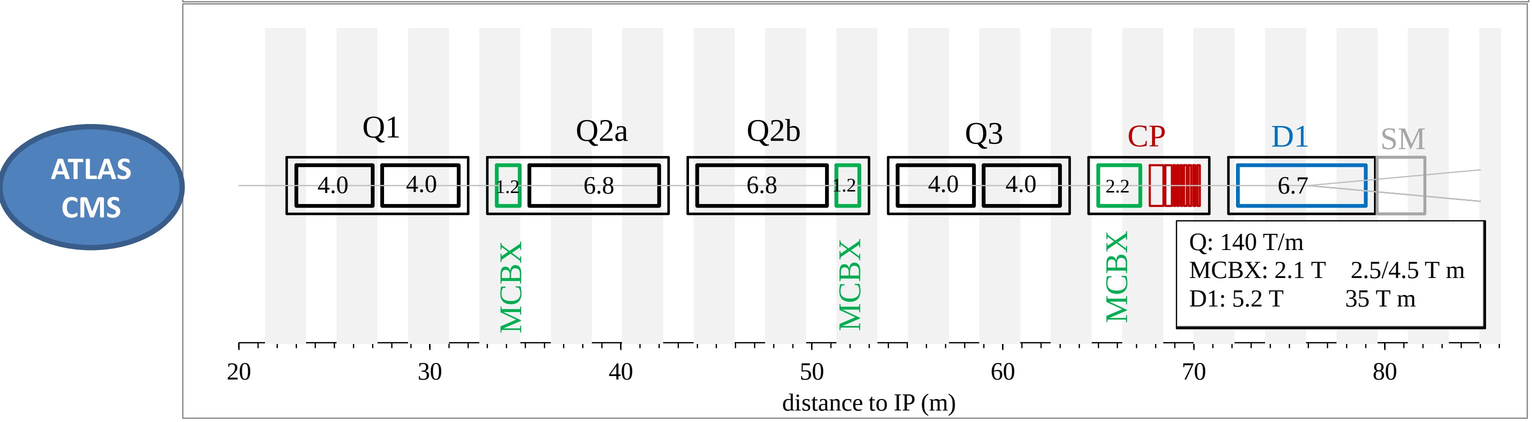
New Interaction Region lay out

Longer Quads; Shorter D1 (thanks to SC)



LHC



HL LHC

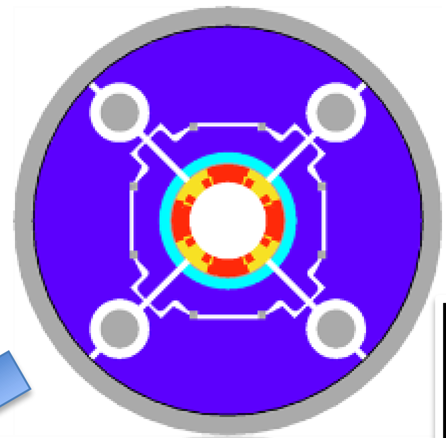
E. Todesco

Thick boxes are magnetic lengths -- Thin boxes are cryostats

LHC low-β quads: steps in magnet technology from LHC toward HL-LHC

Fermilab KEK

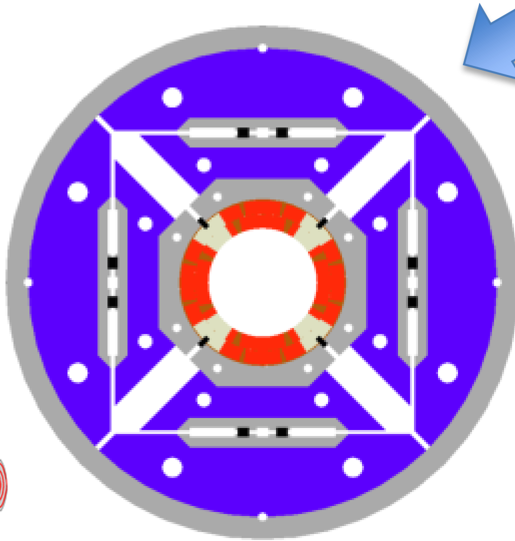
LHC (USA & JP, 5-6 m)
∅70 mm, B_{peak}~ 8 T
1992-2005



LARP

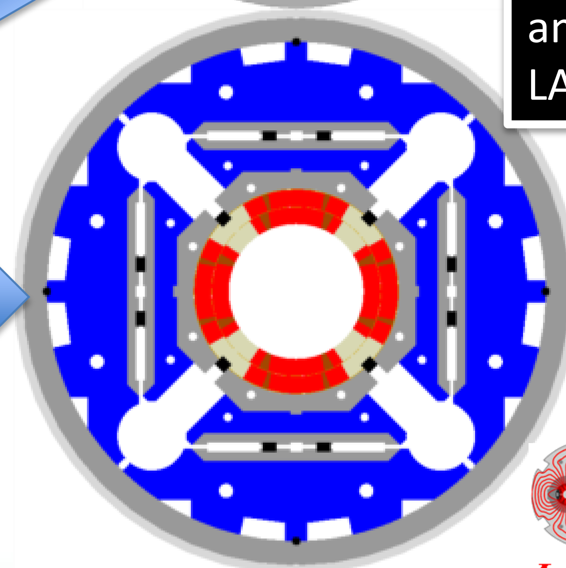
LARP TQS & LQ (4m)
∅90 mm, B_{peak}~ 11 T
2004-2010

New structure based on bladders and keys (LBNL, LARP)



LARP HQ
∅120 mm,
B_{peak}~ 12 T
2008-2014

LARP



LARP & CERN MQXF
∅150 mm,
B_{peak}~ 12.1 T
2013-2020

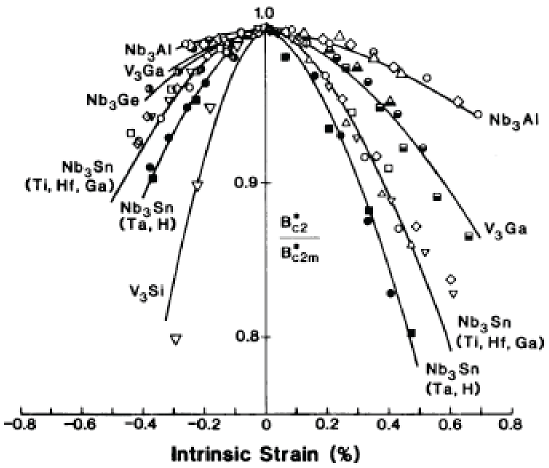
LARP

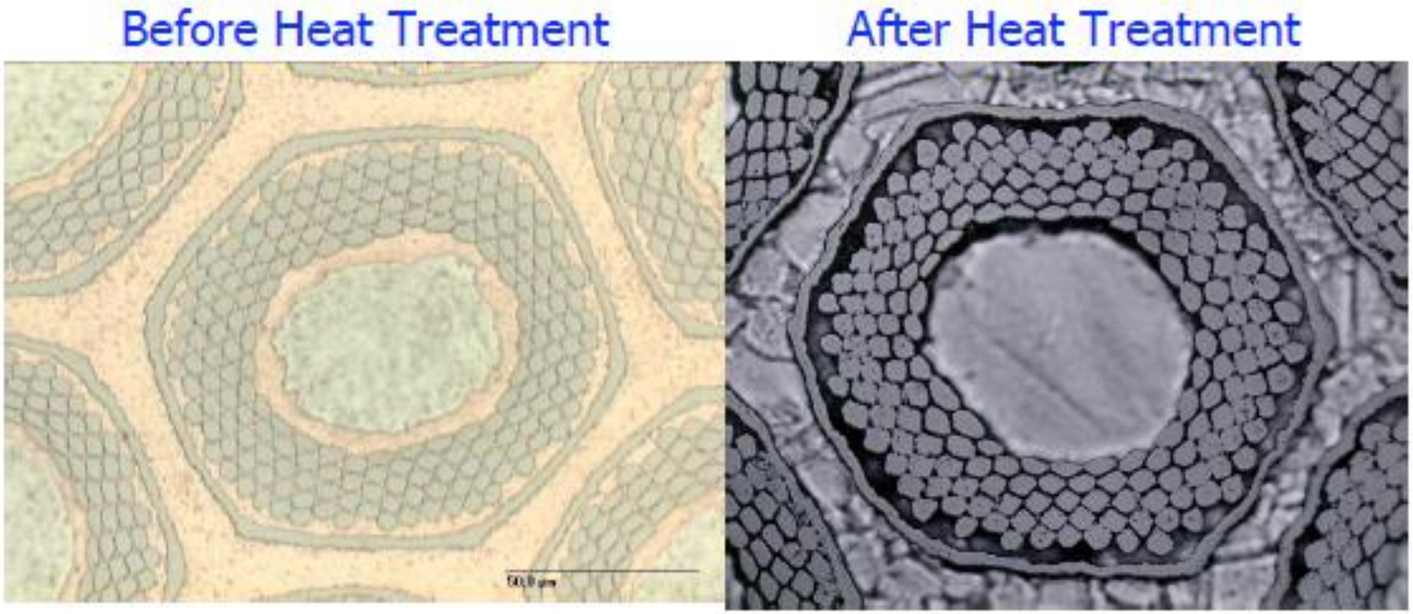
New development for HL magnets - 1

- Nb_3Sn superconductor
  - Fragile once formed

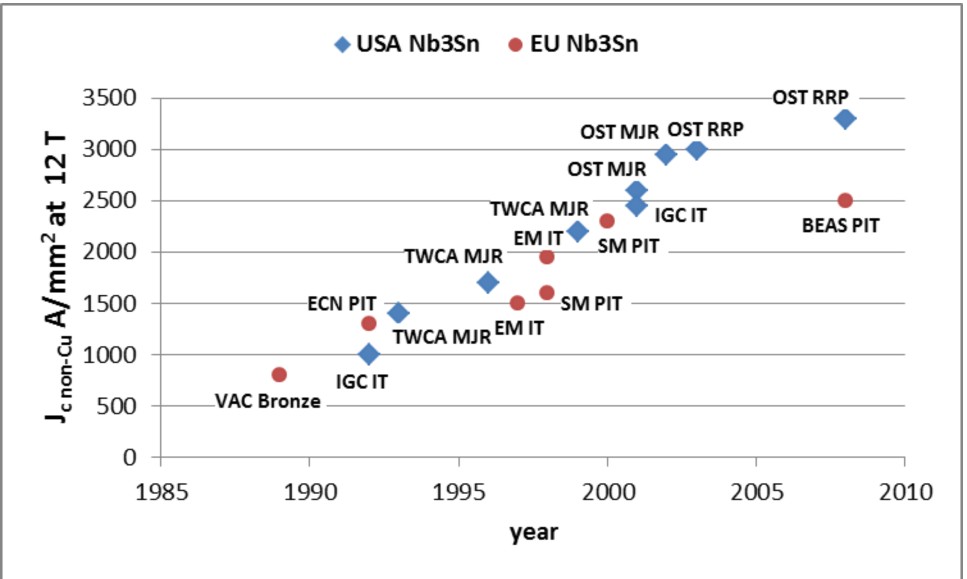
    For HEP magnets

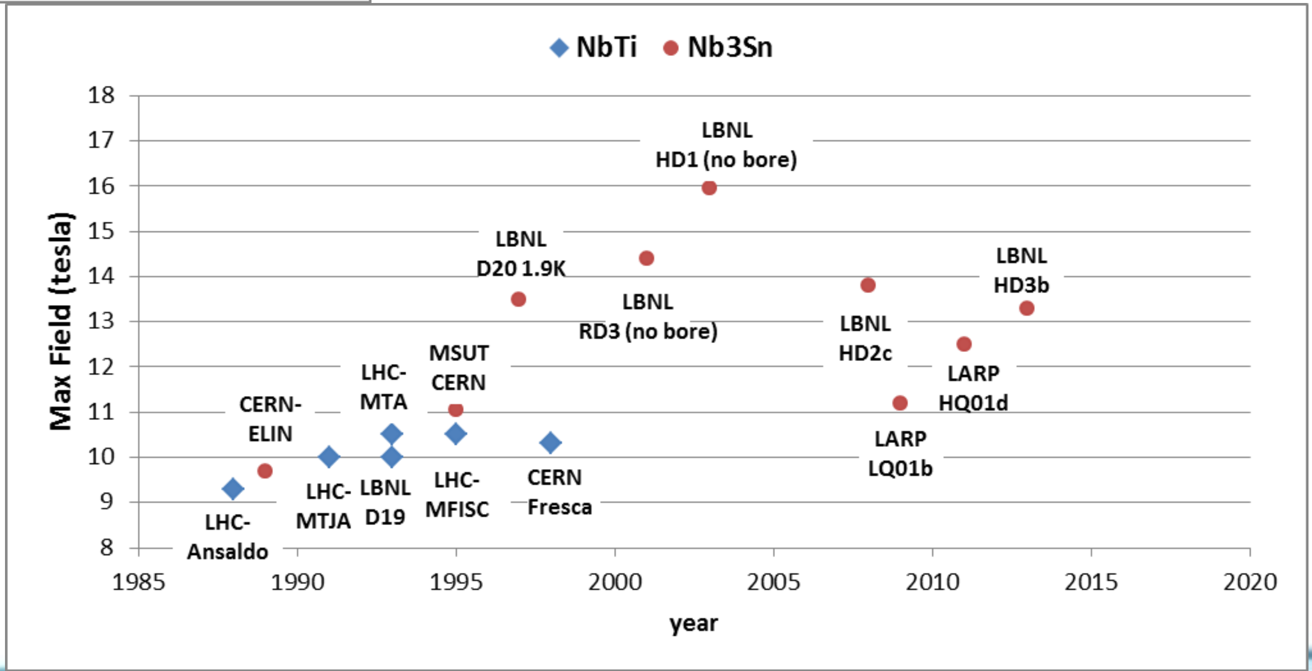
    R&W (~650 °C)





Magnets progress always follows SC progress





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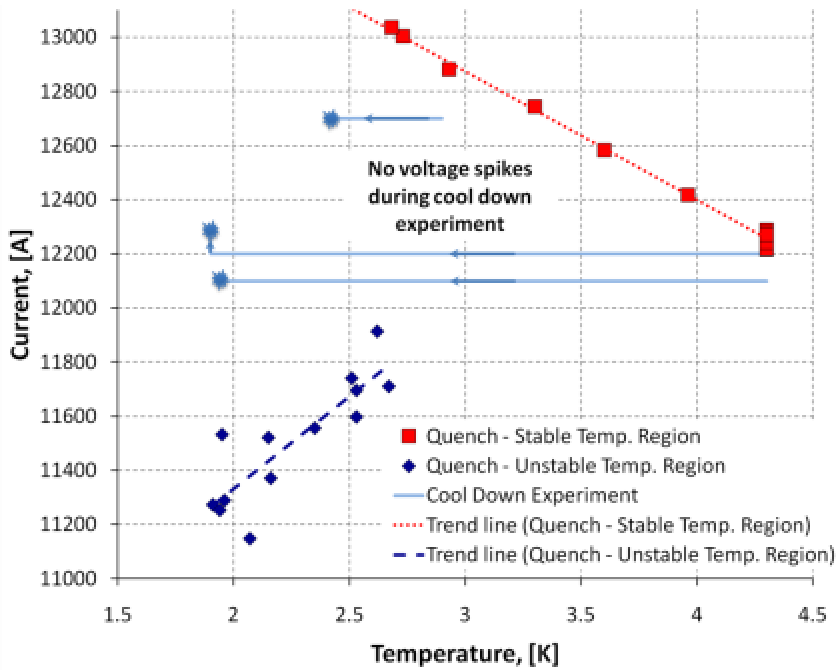
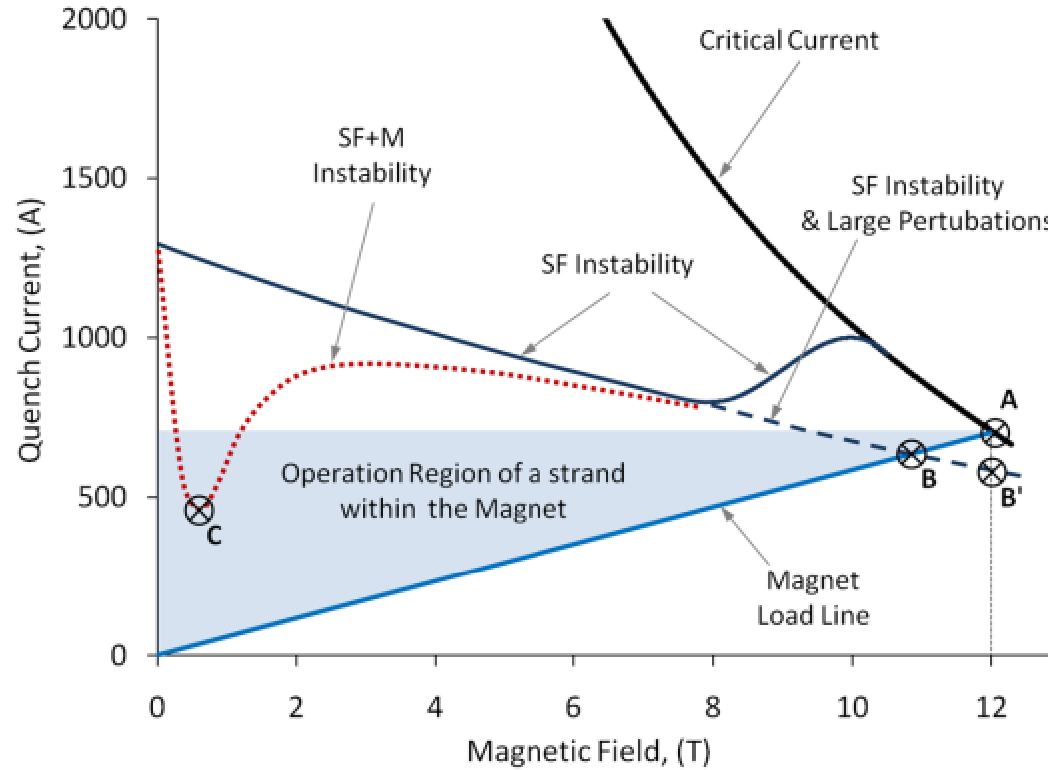
Re-discovering old gost: instability



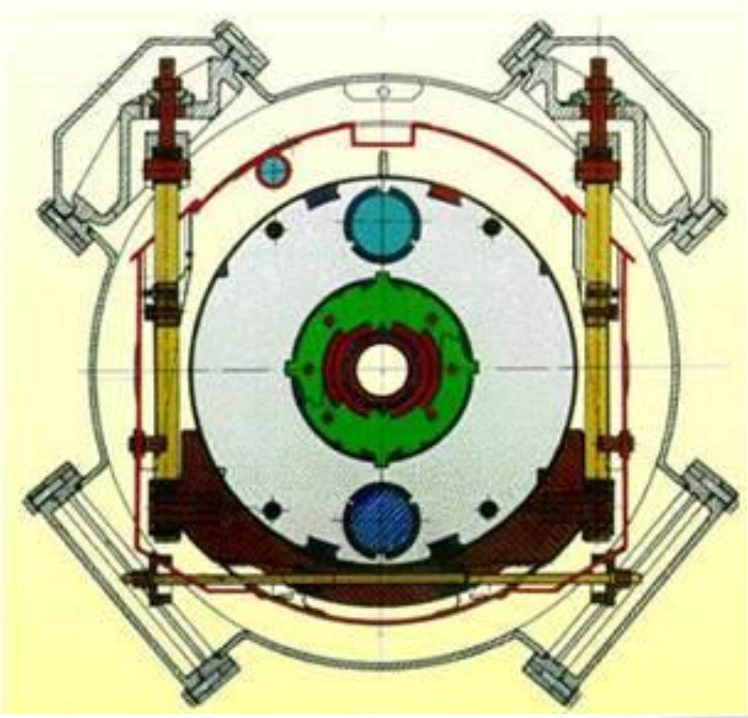


New development for HL magnets - 2

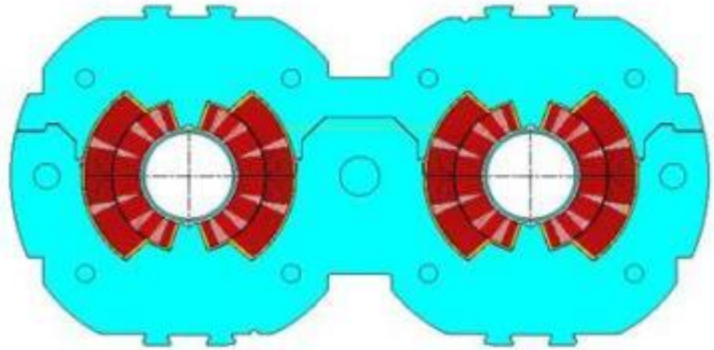
- Nb3Sn coils are less precise in size and more rigid than Nb-Ti coils. COLLARS are not ideal

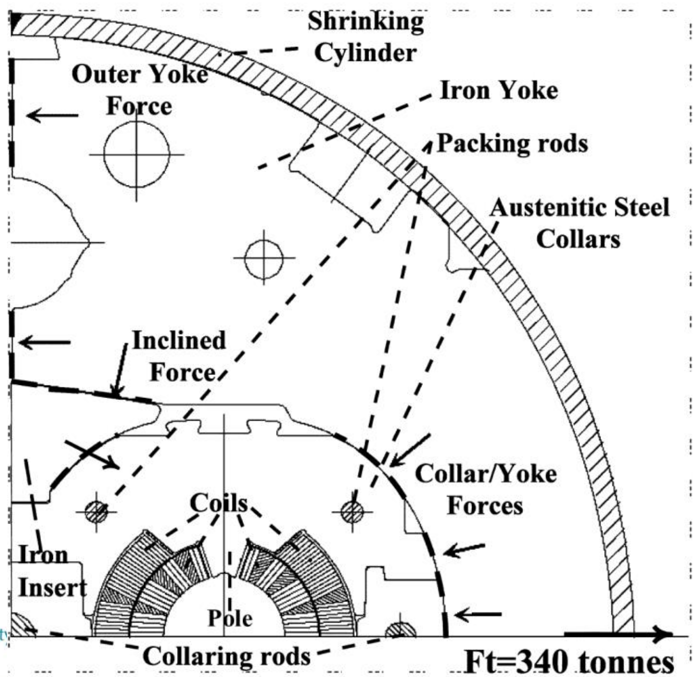
Tevatron

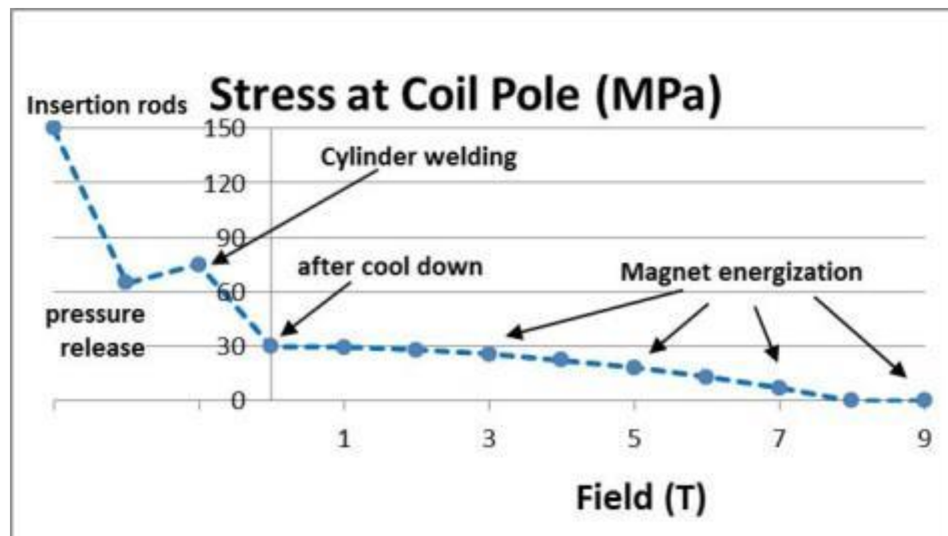
HERA



LHC case

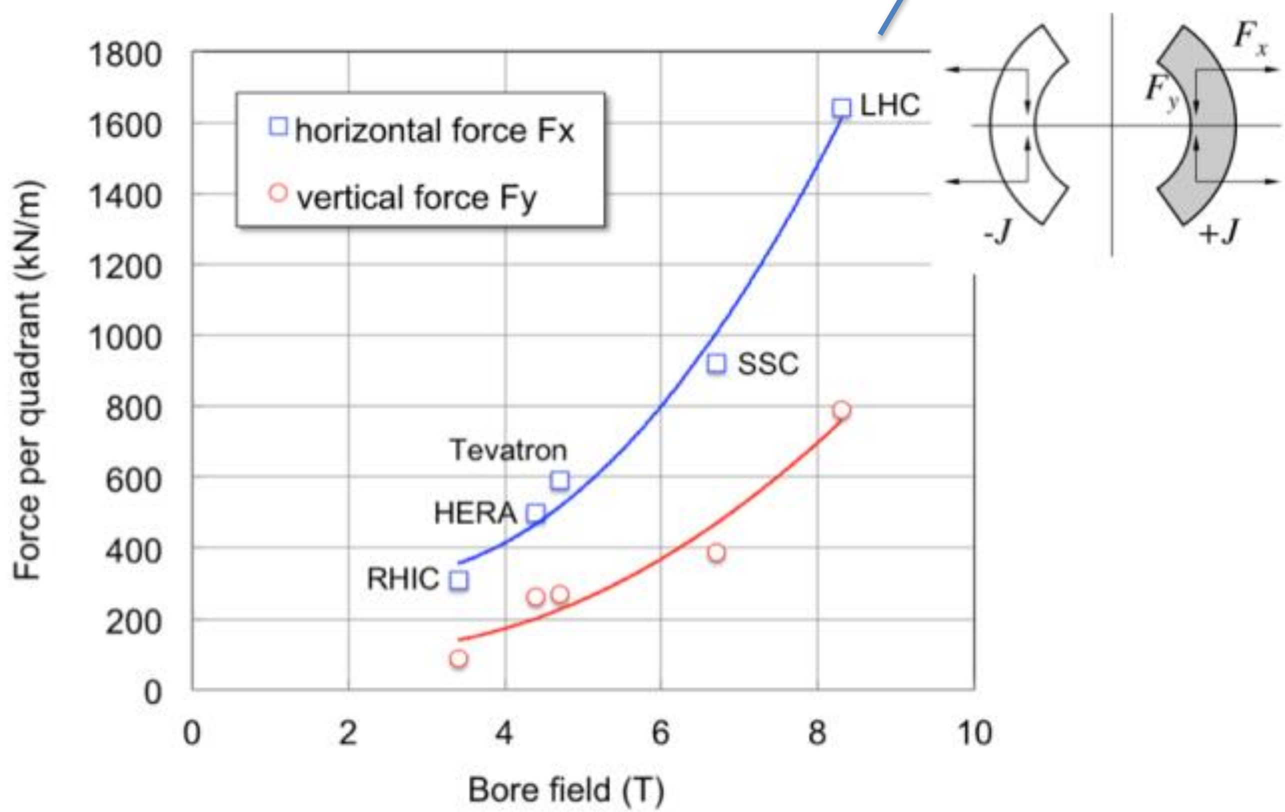



Shrinking Cylinder
Outer Yoke Force
Iron Yoke
Packing rods
Austenitic Steel Collars
Inclined Force
Collar/Yoke Forces
Coils
Iron Insert
Pole
Collaring rods
Ft=340 tonnes

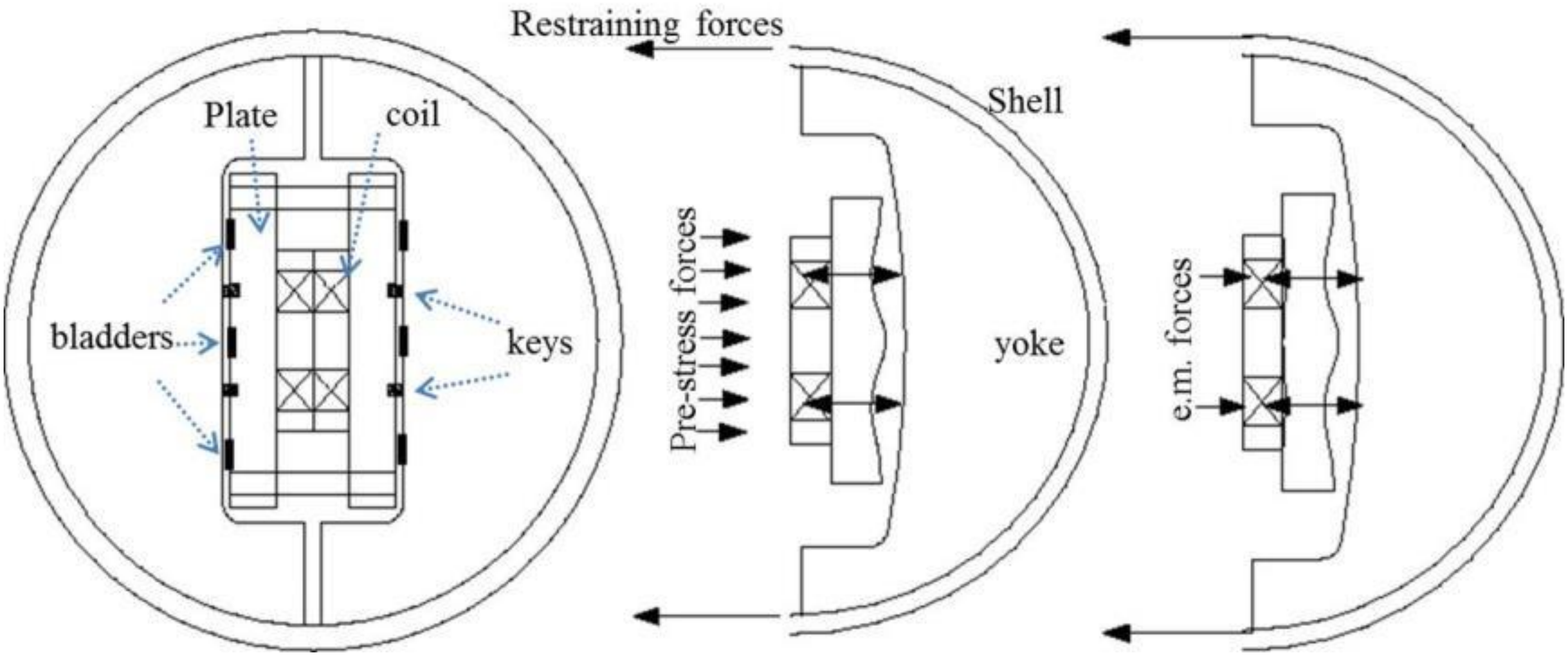

Stress at Coil Pole (MPa)
Insertion rods
Cylinder welding
pressure release
after cool down
Magnet energization
150
120
90
60
30
0
1
3
5
7
9
Field (T)

Going up to 11 or 12 T : forces doubles

HiLumi magnets!

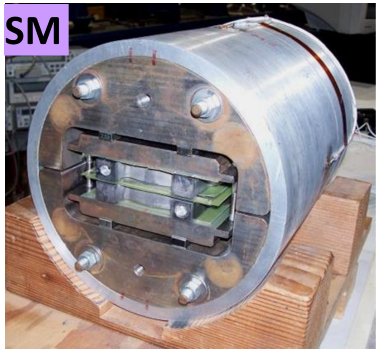


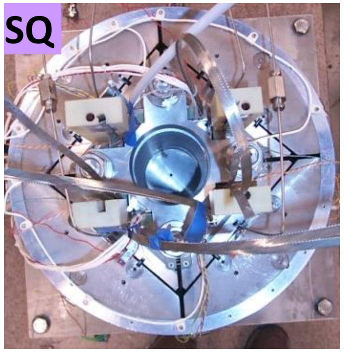
Pre-stress by bladder at high pressure then put solid keys and remove bladders

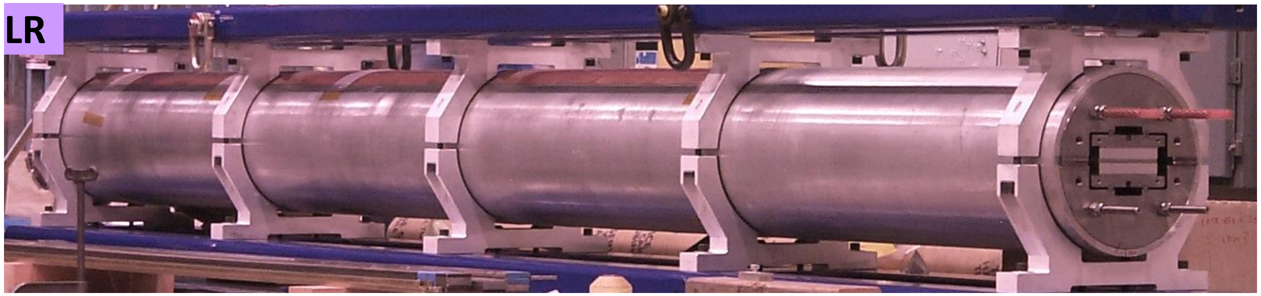


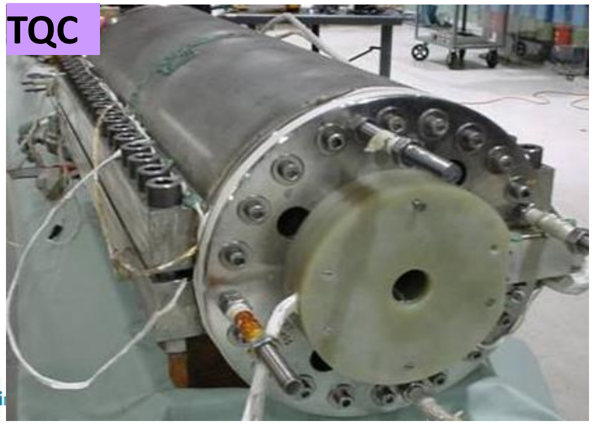
S. Caspi, LBNL, 1997 to 2007

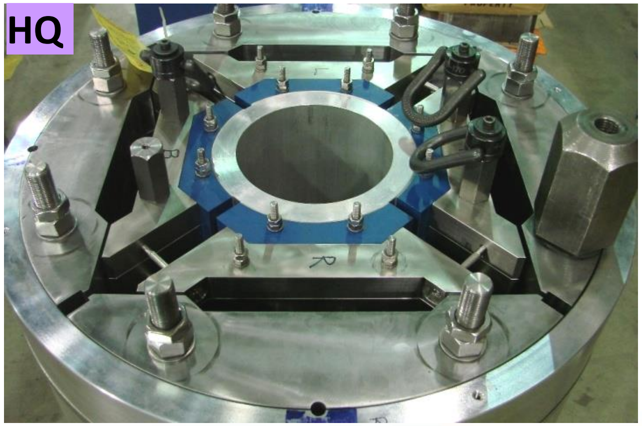
A line of 10 yers of development



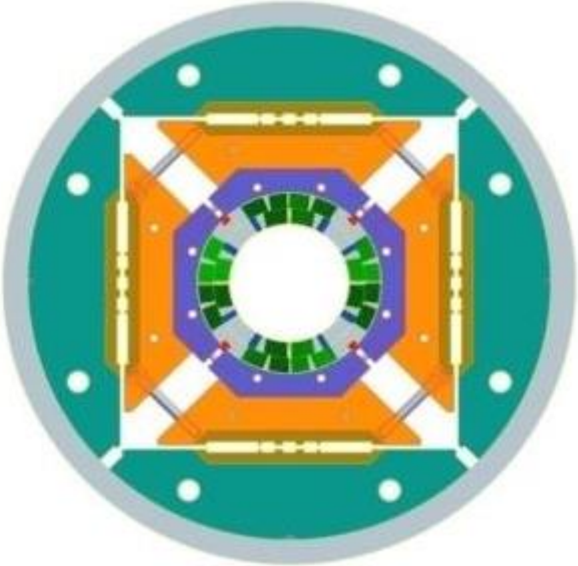


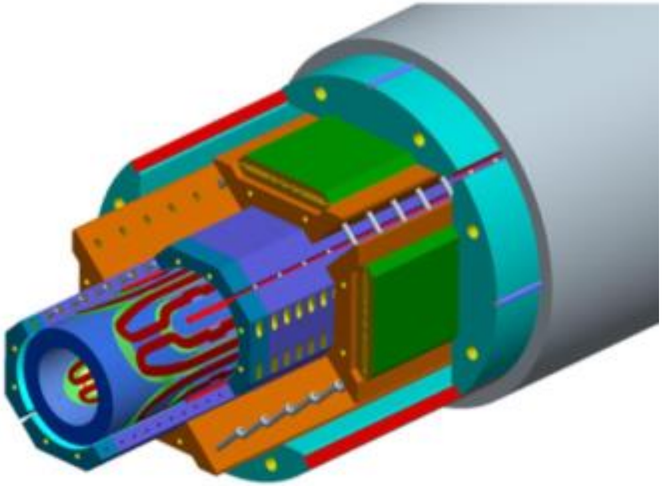


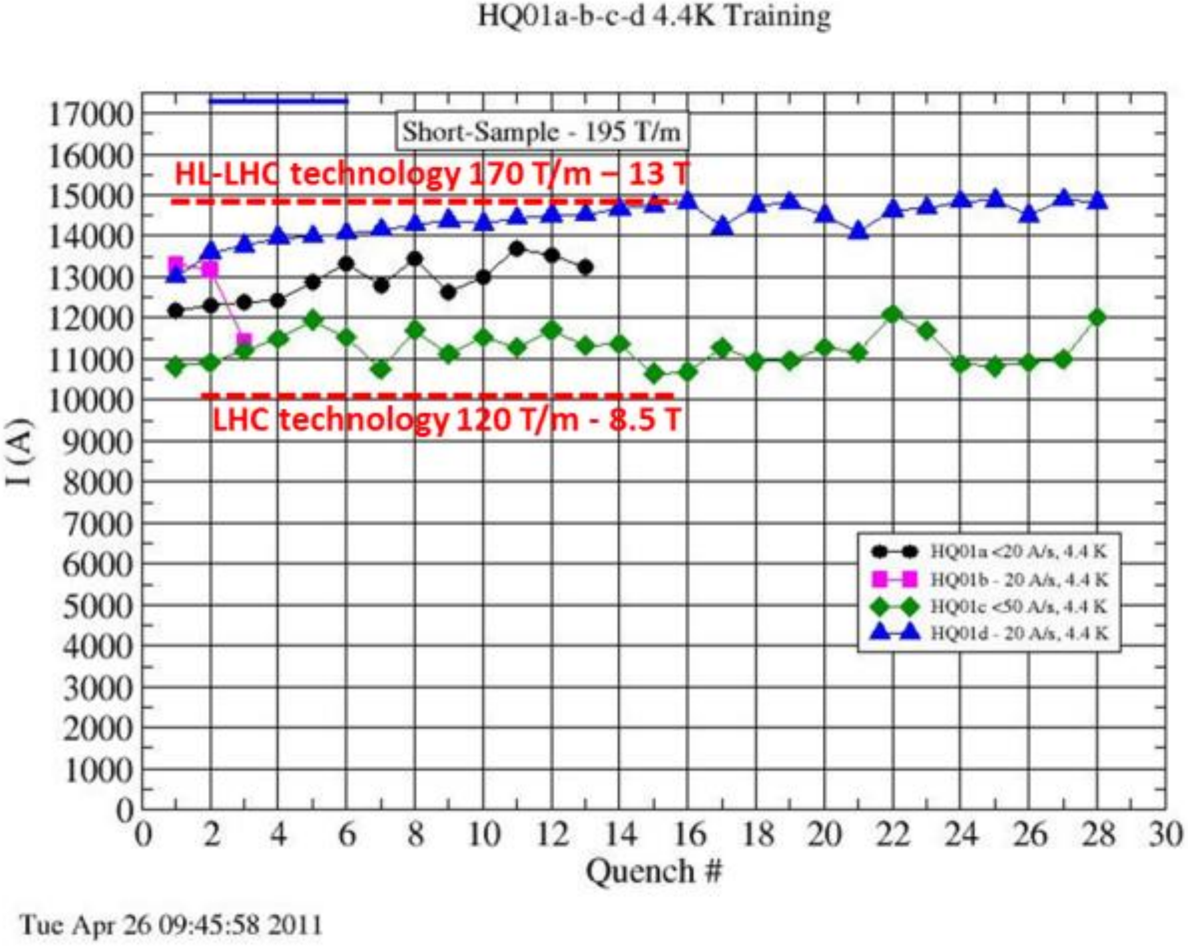




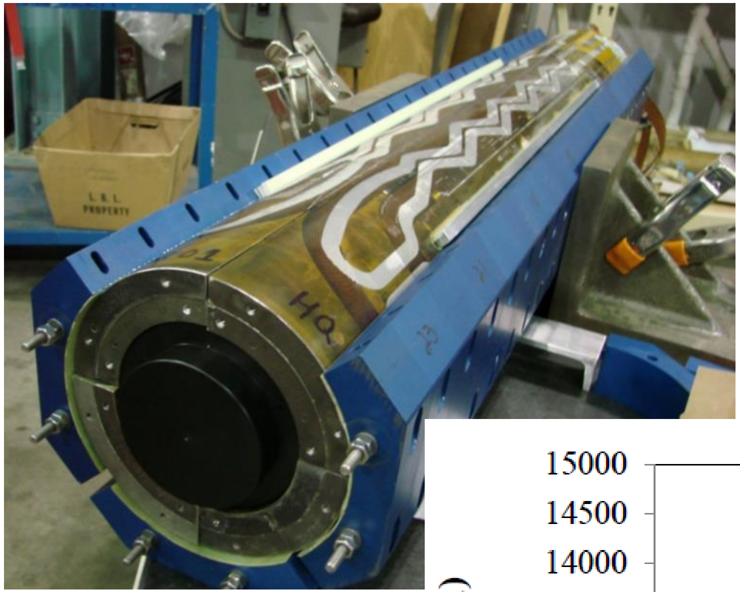
Results HQ01

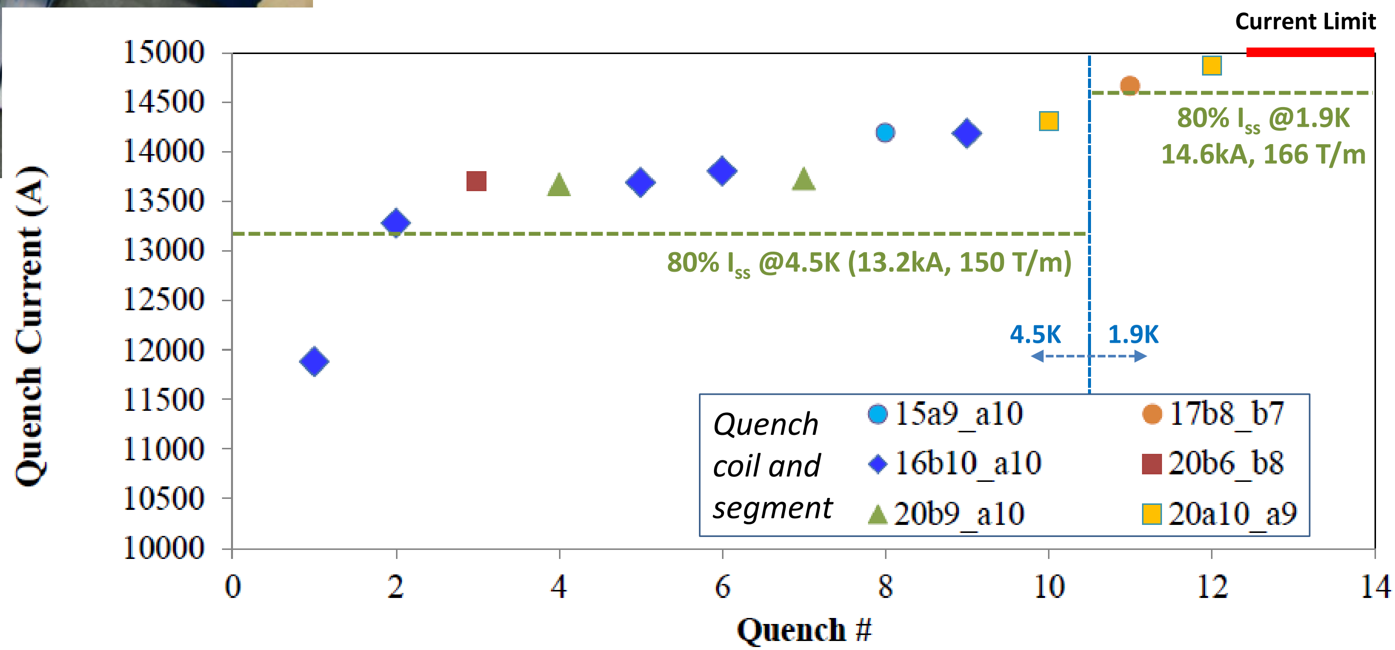




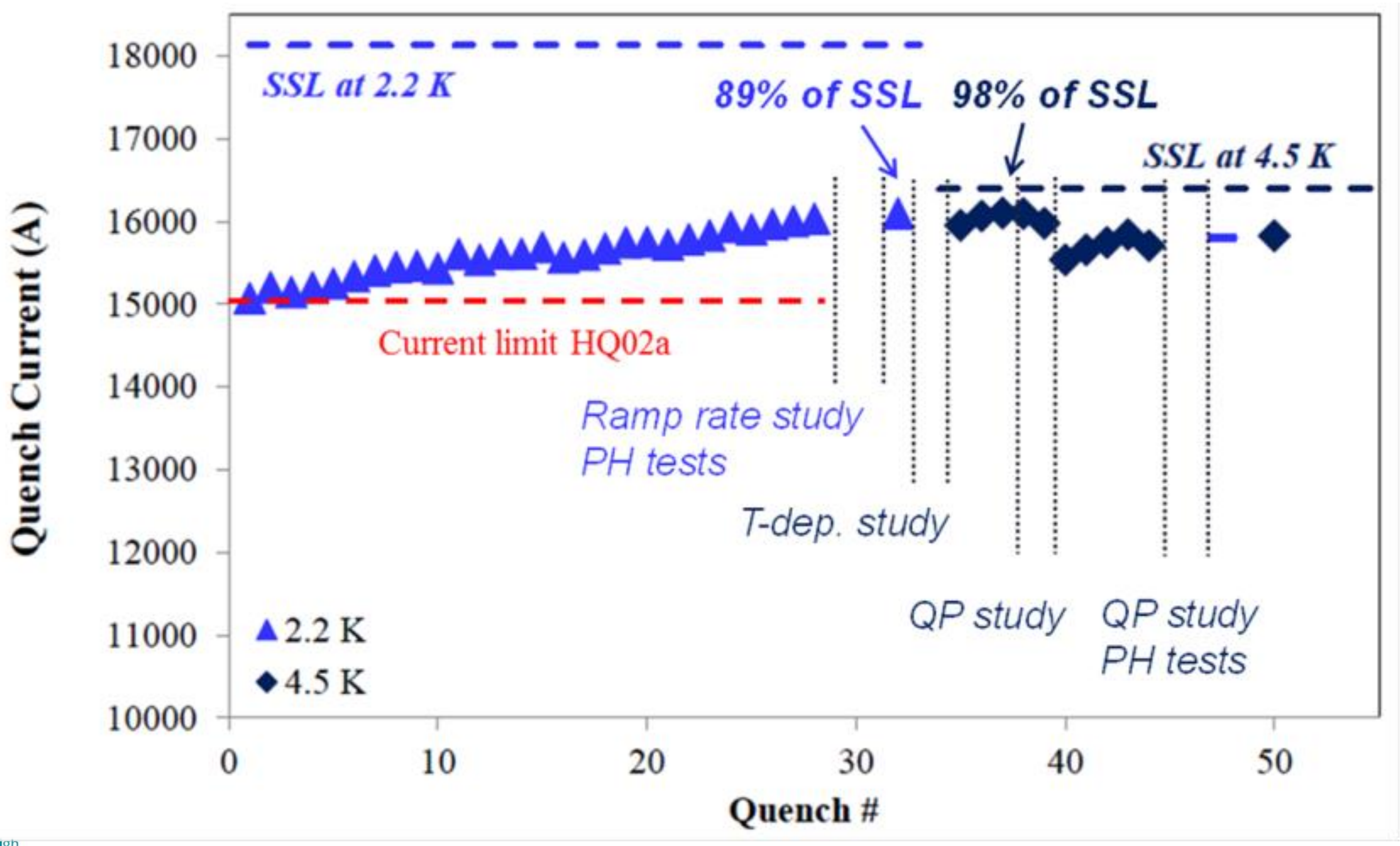


Recent results HQ02a-b ∅120 mm





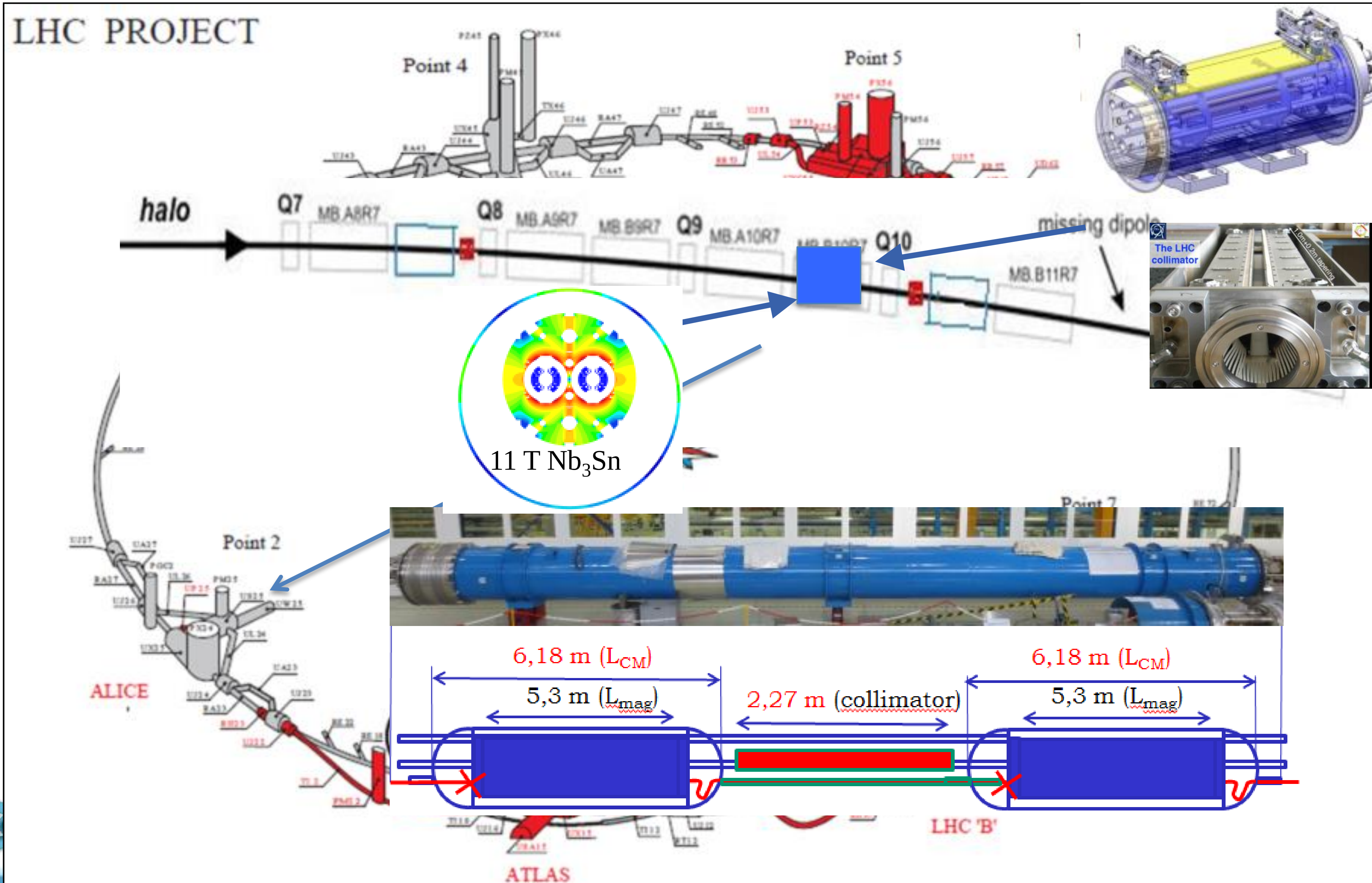
Recent results HQ02a-b ∅120 mm - cont.



Progress in MQXF (IT quads)

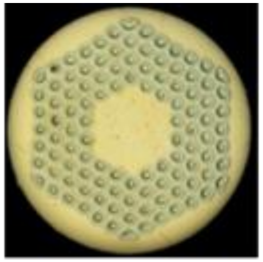
- First coil (1 m) : 2014!
- Magnet test 2015
- Long Magnets: 2016-17
- Many new technlogical developement:
  - Magnet Protection
  - Insulation
  - Precision mechanics

11 T dipole : why?



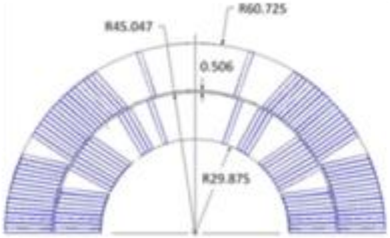
More classical collar chosen

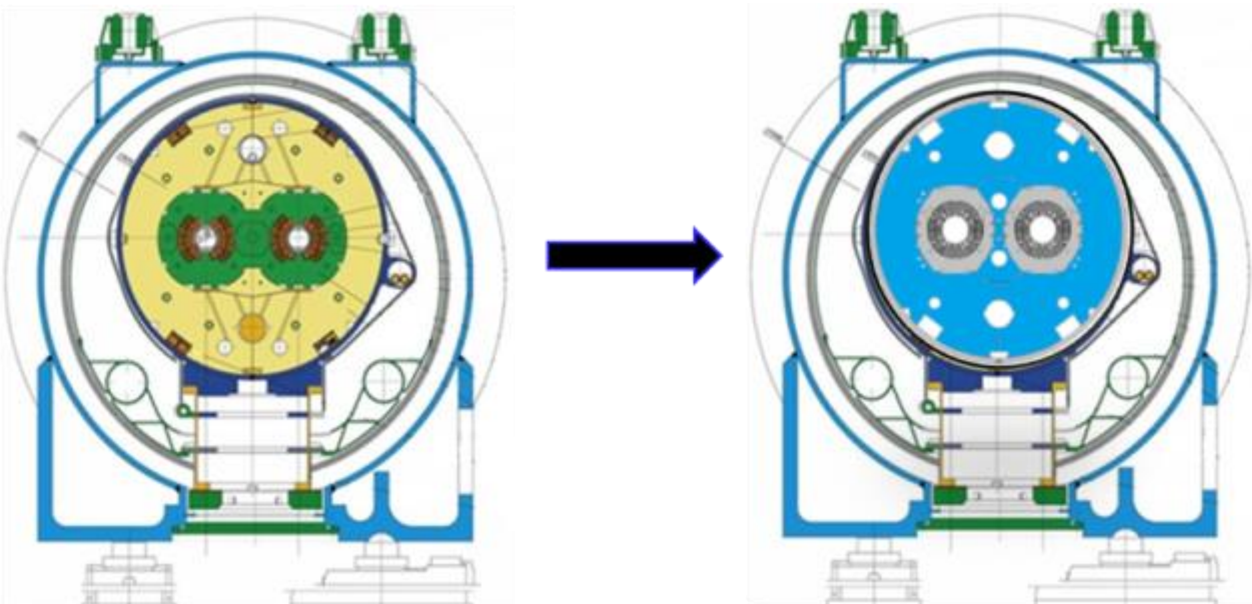
- Cosntrain: must be in series with LHC dipoles

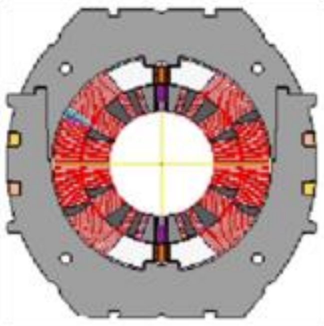


0.7 mm Nb_3Sn RRP strand

40-strand cable



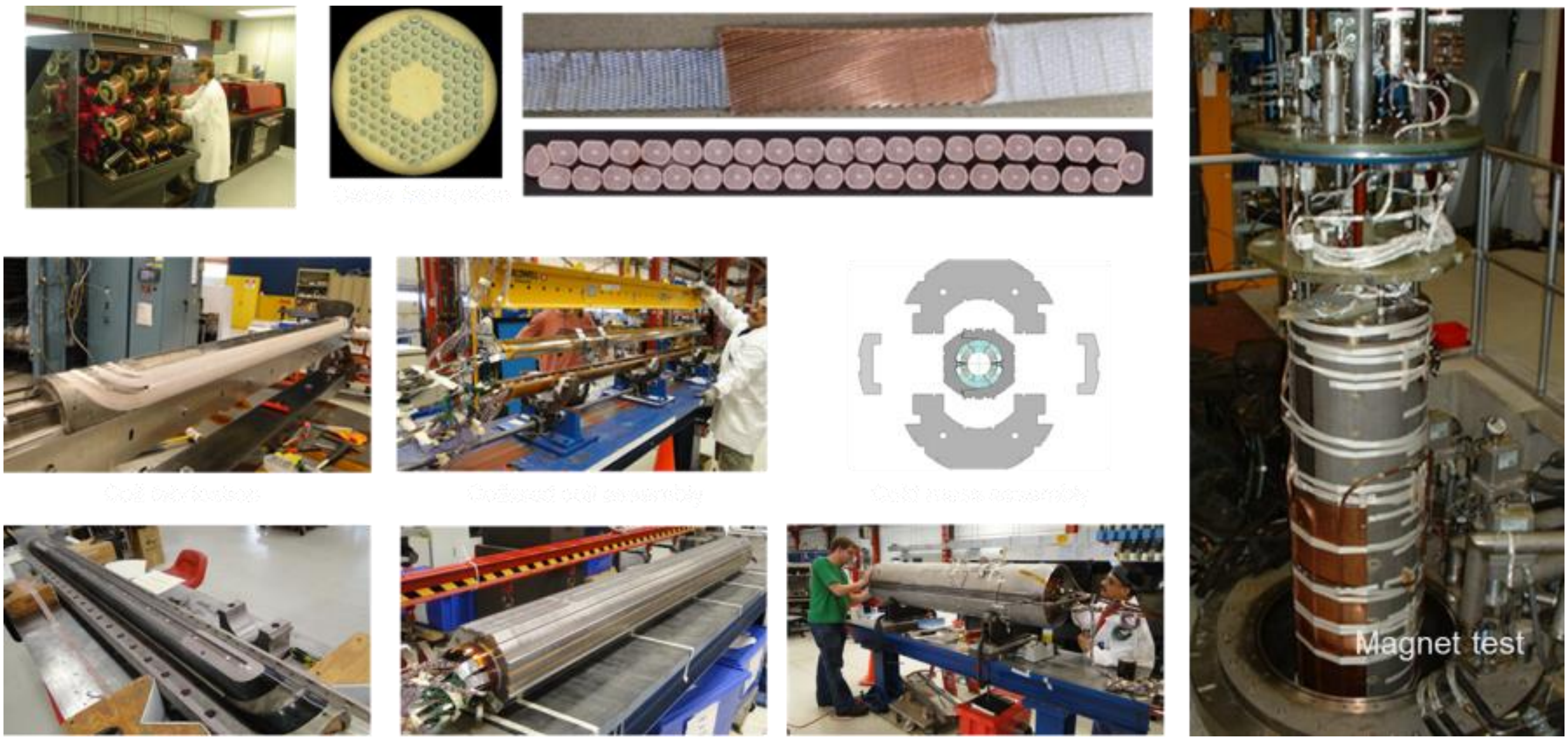




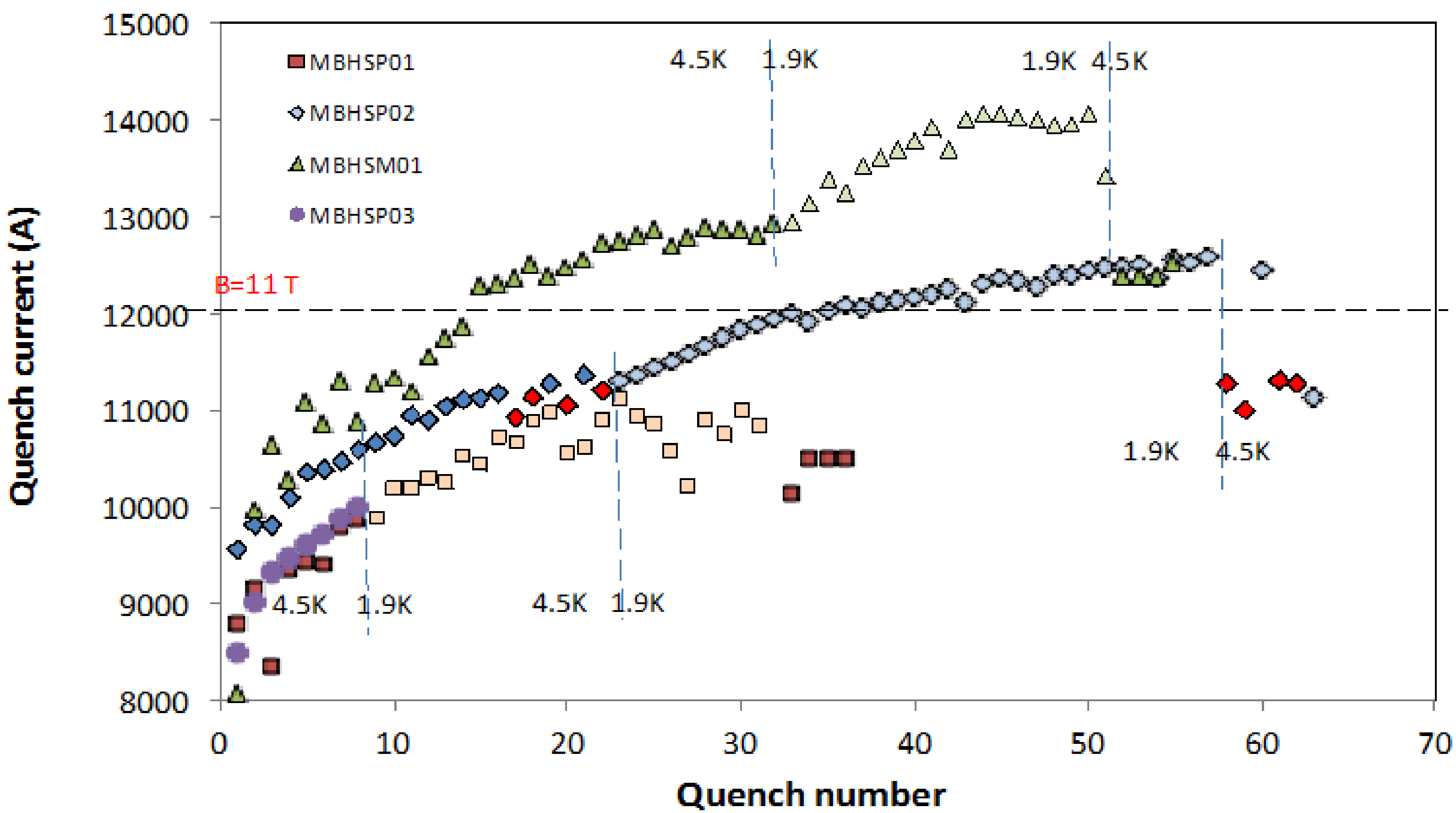
Stainless steel collar

High Luminosity LHC

11 T effort at FNAL

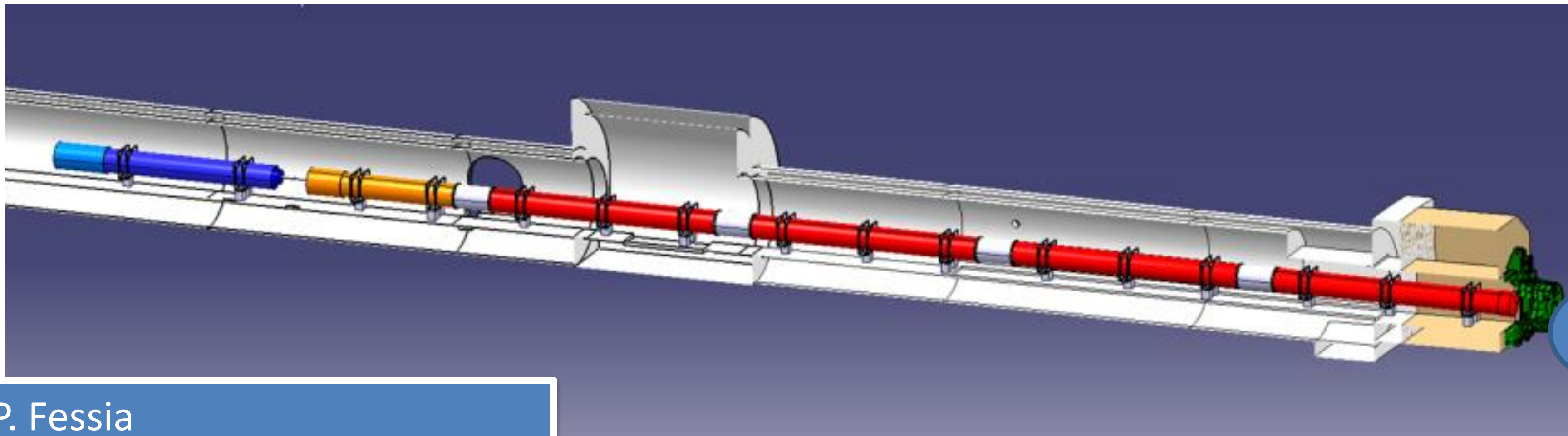


Result from 11 T
Potentially good but not yet A.Q.



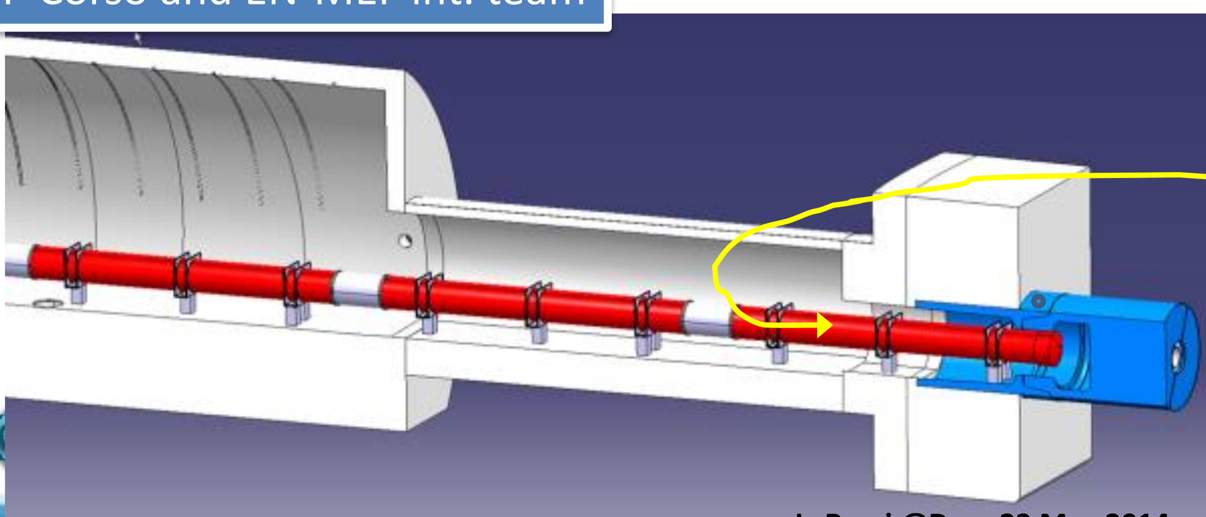
High Luminosity LHC

Integration view of IT zone

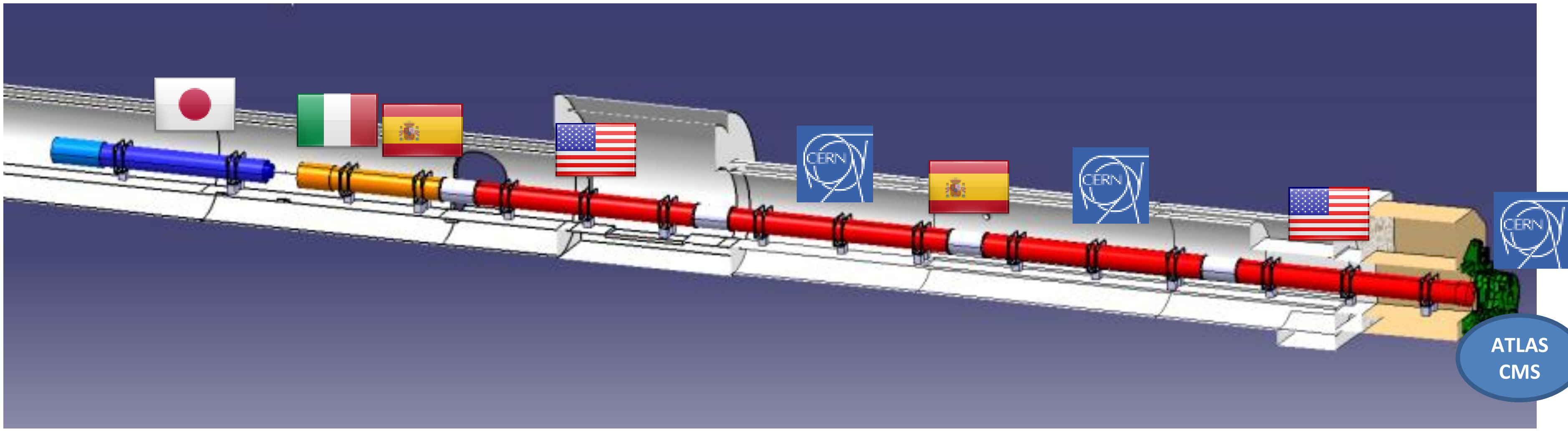


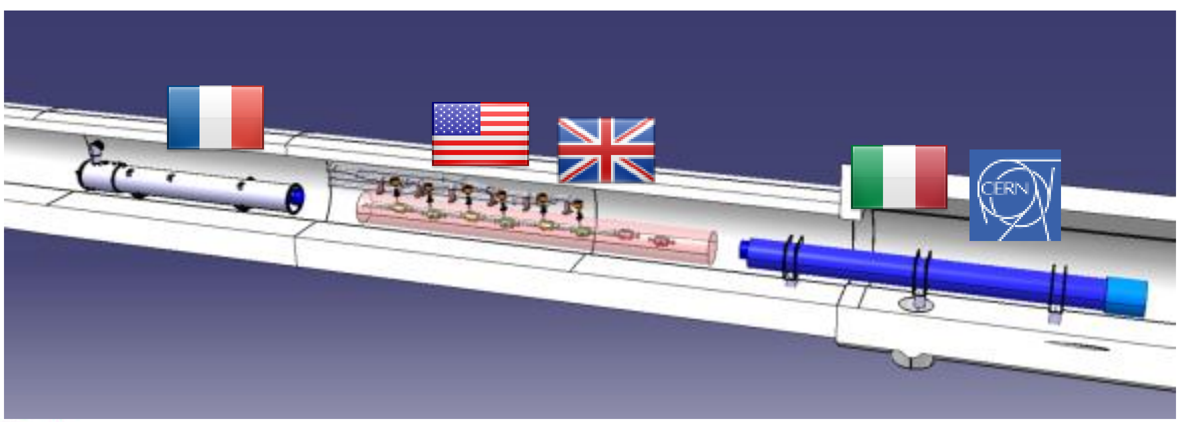
ATLAS
CMS

P. Fessia
JP Corso and EN-MEF int. team



In-kind contribution and Collaboration for HW design and prototypes





Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

CC : R&D, Design and in-kind **USA**

CC : R&D and Design **UK**

2025 is tomorrow: LHC timeline

First ideas
Twin Dipoles
Hell cooling

R&D for 8-10 T: 13 kA cables, short models, 10 m long prototypes, 1st string test

Final design, industrialization start pre-series

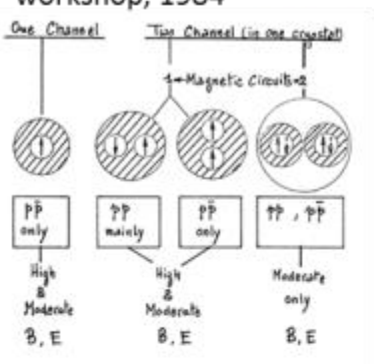
Magnet construction, performance test, tunnel preparation

Installation, LHC start
Incident

Re-start
4.2 T

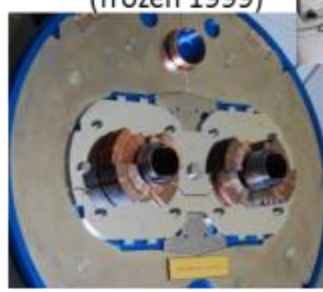
1985 — 1990 — 1995 — 2000 — 2005 — 2010 — 8 T

Magnet designs at first LHC workshop, 1984

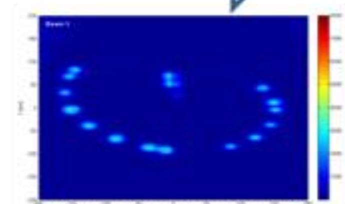


First LHC dipole prototype on the test bench (June1994)

Final dipole cross section (frozen 1999)



Assembly of 15 m long coils in industry, 2003



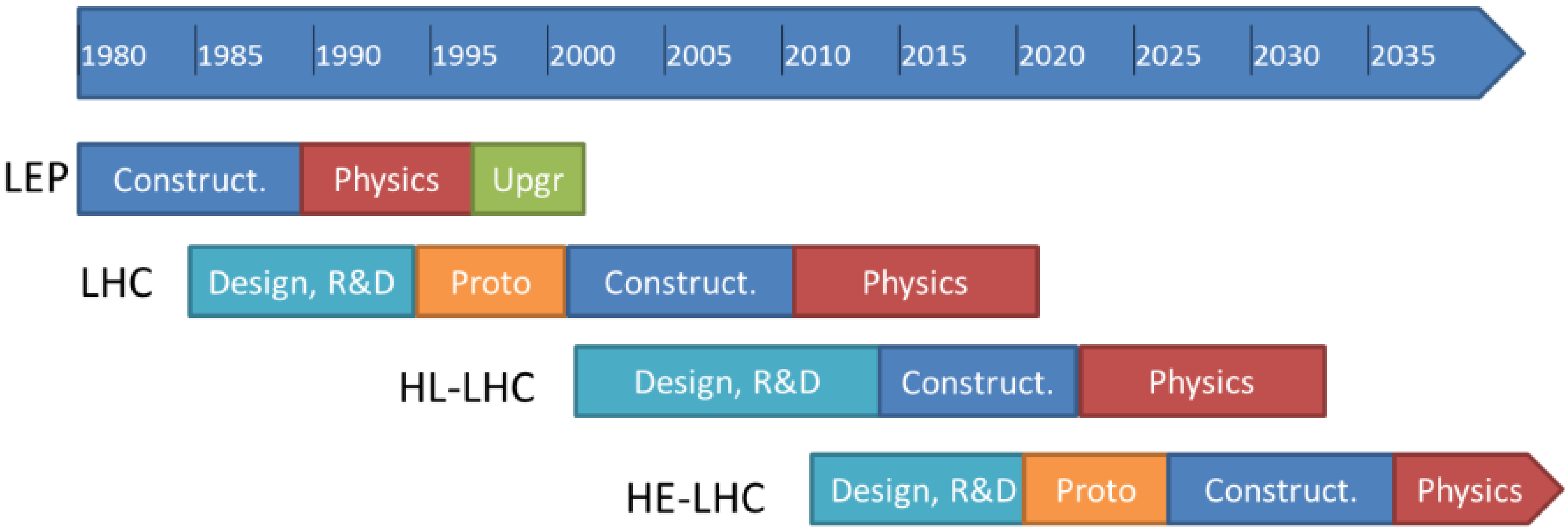
First energy record in the proton beam, December 2009

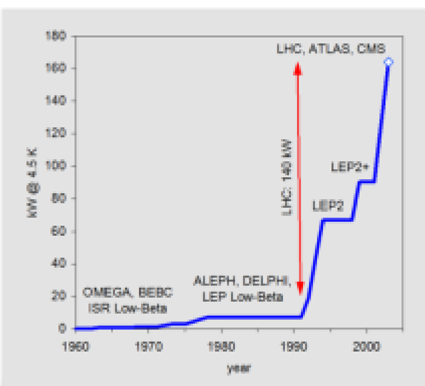
Continuous magnet line installed in the 27 km LHC tunnel, 2006

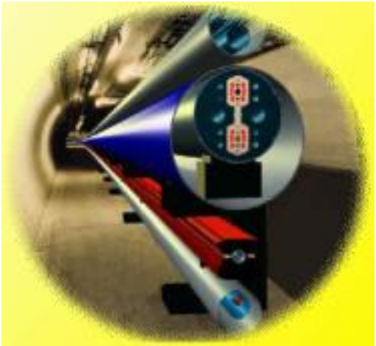
What HEP can do?

High Luminosity LHC

The super-exploitation of the CERN complex: Injectors, LEP/LHC tunnel, infrastructures





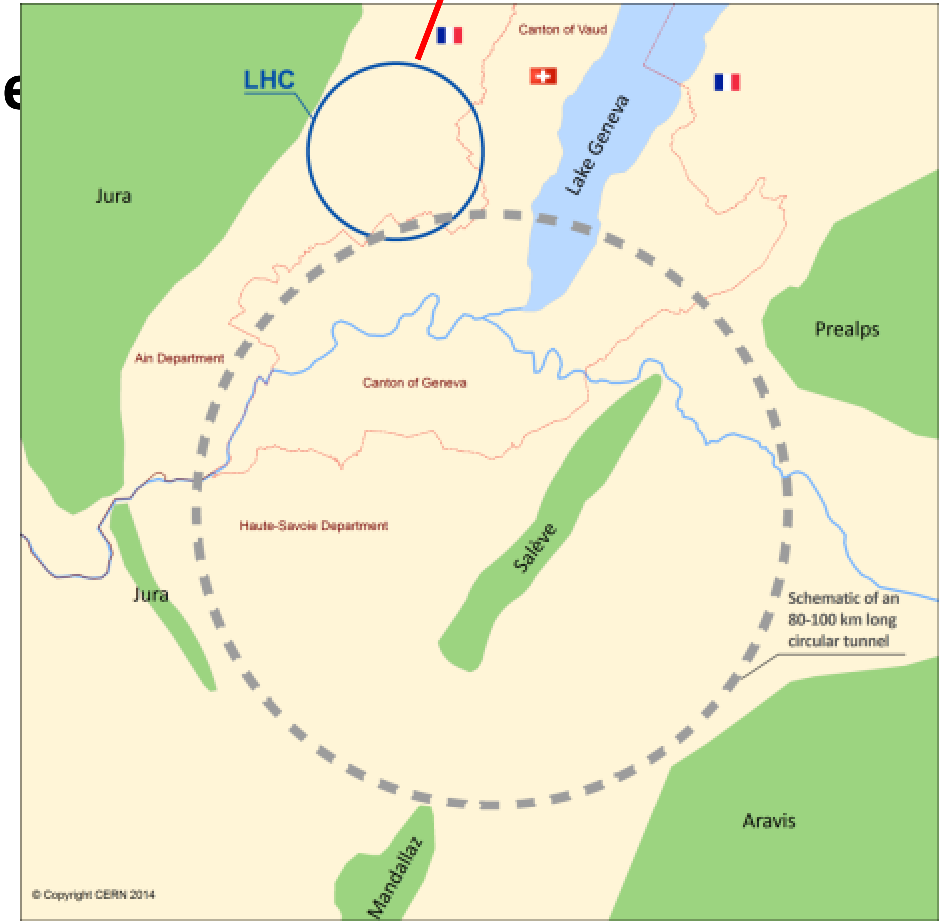


"High Energy LHC"

HE-LHC :33 TeV with 20T magnets

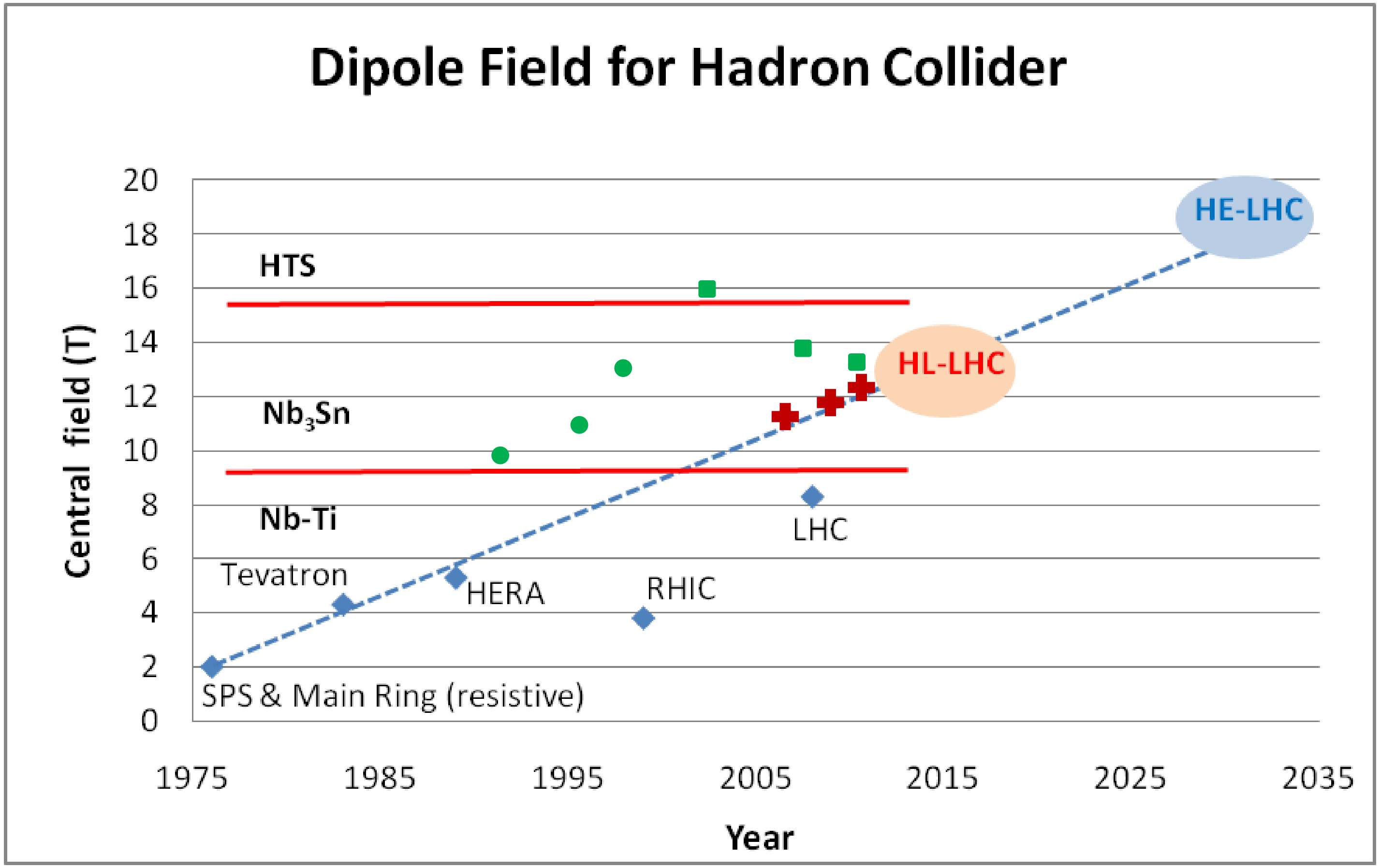
First studies on a new 80 km tunnel in the Geneva area

- **42 TeV with 8.3 T using prese LHC dipoles**
- **80 TeV with 16 T based on Nb_3Sn dipoles**
- **100 TeV with 20 T based on HTS dipoles**



High Luminosity LHC

Is it really possibile to go so high?



Looking at performance offered by practical SC, considering tunnel size and basic engineering (forces, stresses, energy) the practical limits is around 20 T. Such a challenge is similar to a 40 T solenoid (μ-C)

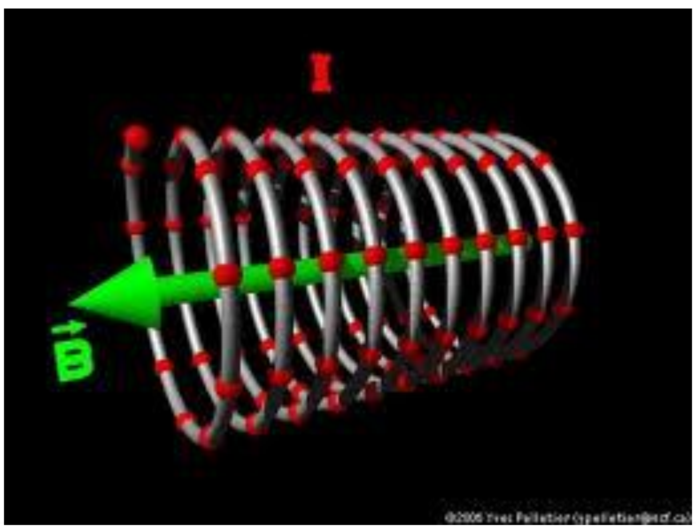
◆ Nb-Ti operating dipoles; ● Nb3Sn cosϑ test dipoles ■ Nb3Sn block test dipoles ✚ Nb3Sn cosϑ LARP QUADs

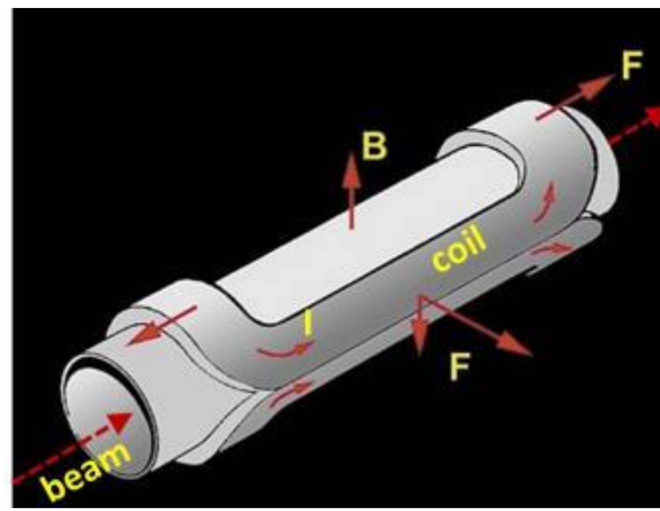
Intrinsic «inefficiency» of transverse field : $B_{dip} \sim 0.5\ J_{overall} \times t_{coil}$

F ~ JB

In solenoids, forces are self supported (till the limit of the winding!)

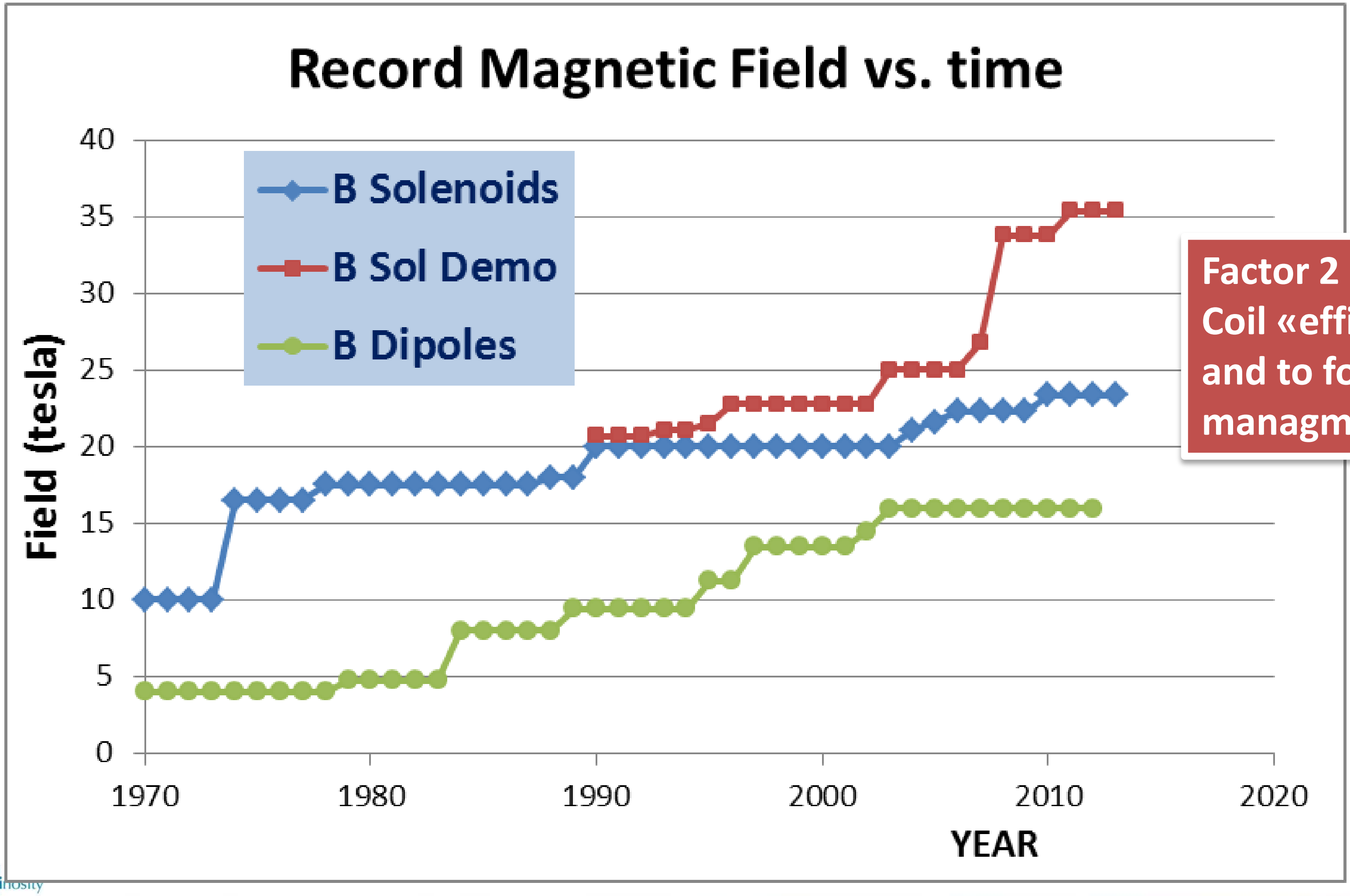
In transverse field the lateral forces are not supported at all
The longitudinal (along beam) forces are poorly supported



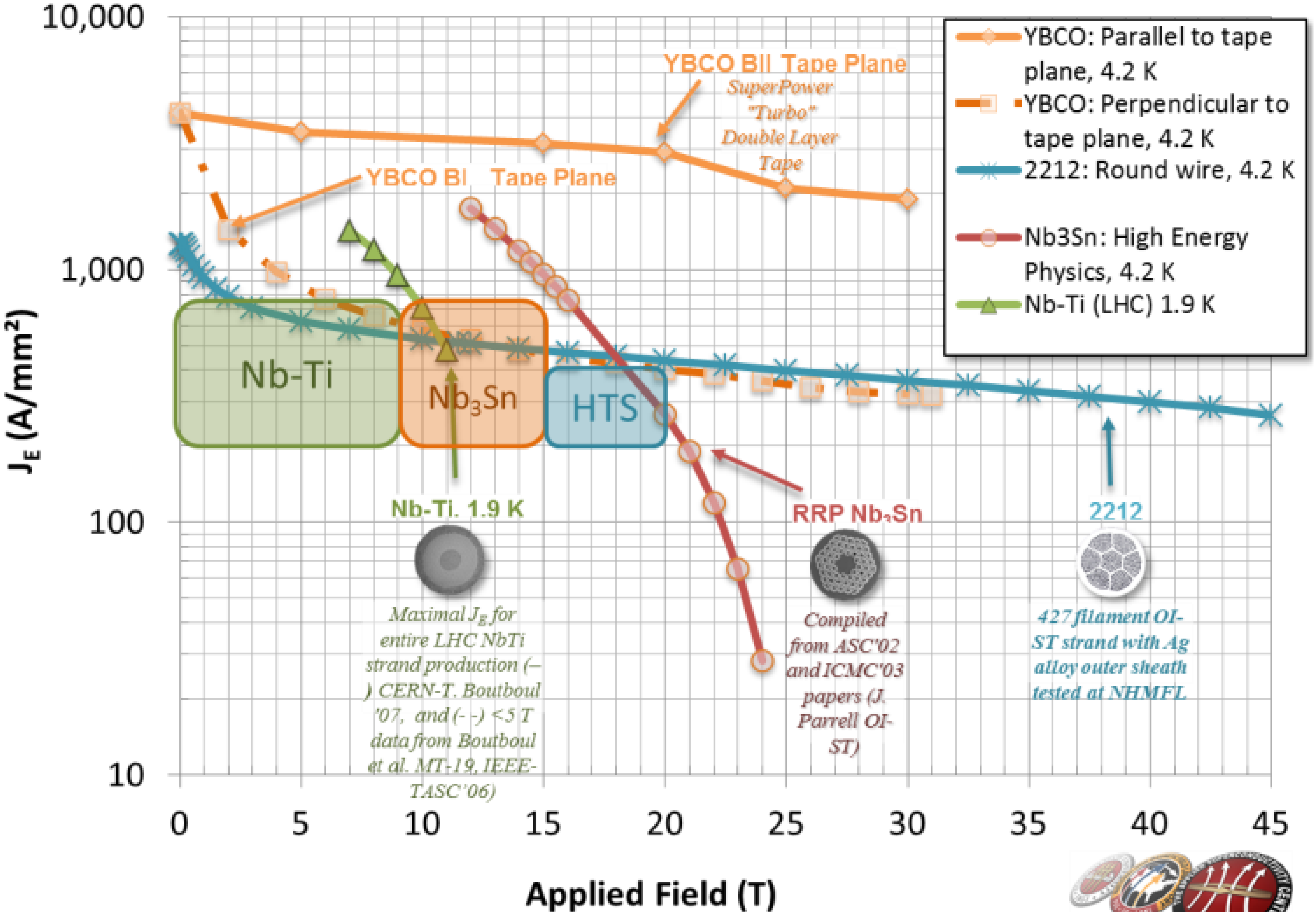


Large forces kept from outside means movements with –inevitably – friction (stick and slip, resin fracture, flux change, etc.). Thicker the coil and farther is restrain from JB_{peak}

Field timline



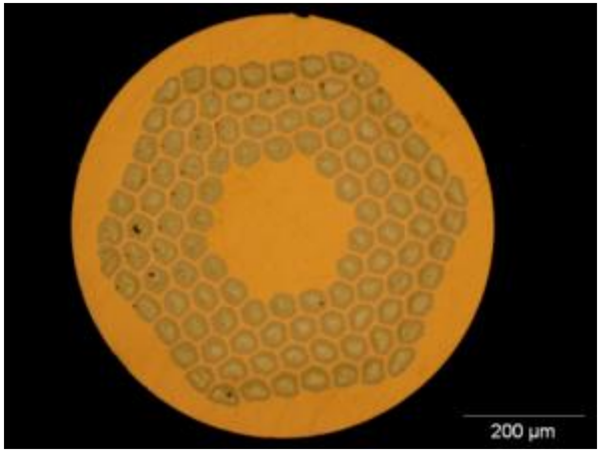
Factor 2 due to Coil «efficiency» and to force-stress managment



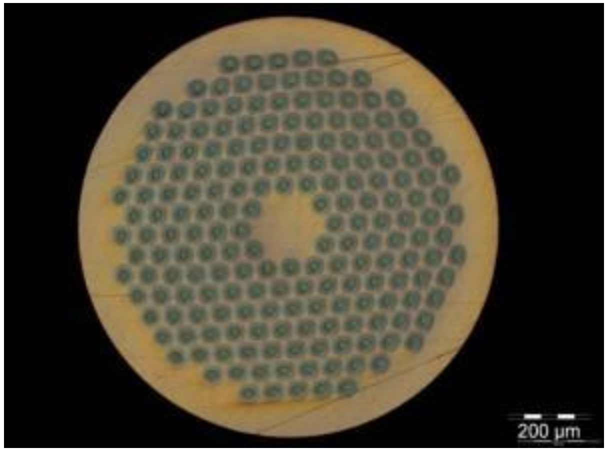
High Luminosity LHC

Nb_3Sn is becoming a «commodity»

- Recent 23.4 T (1 GHz) NMR Magnet for spectroscopy in Nb_3Sn (and Nb-Ti). 15-20 tons/year for NMR and HF solenoids. Experimental MRI is taking off
- ITER: 500 t in 2010-2015! It is comparable to LHC!
- HEP ITD (Internal Tin Diffusion):
  - High Jc., 3xJc ITER
  - Large filament (50 µm), large coupling current...
  - Cost is > 5 times LHC Nb-Ti



0.7 mm, 108/127 stack RRP from **Oxford OST**



1 mm, 192 tubes PIT from **Bruker EAS**

Nb3Sn

L. Bottura, CERN

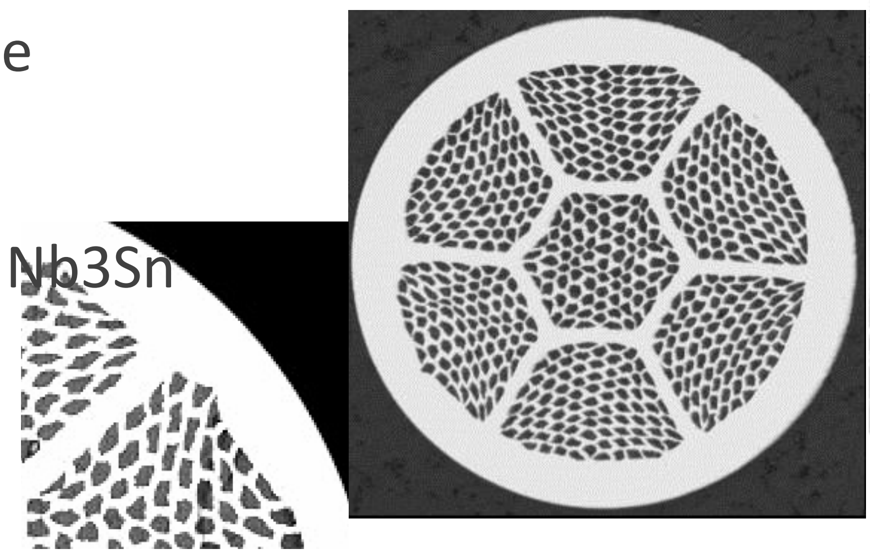
Controling filamente diameter & RRR (field quality and stabiility)
Increasign curent density at 15-18 T region

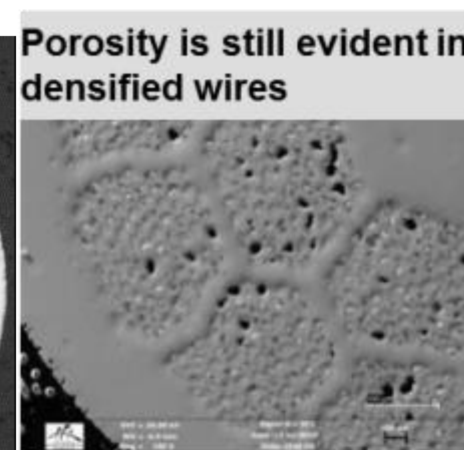
High Luminosity LHC

The « new » materials: HTS Bi-2212

- Round wire, isotropous and **suitable to cabling**!
- HEP only users (good < 20K and for compact cable)
- Big issue: very low strain resistance, brittle
- Production ~ 0,
- cost ~ 2-5 times Nb_3Sn (Ag stabilized)

- DOE program 2009-11 in USA let to a factor 2 gain. Another 50% and more uniformity is being gained now in USA…

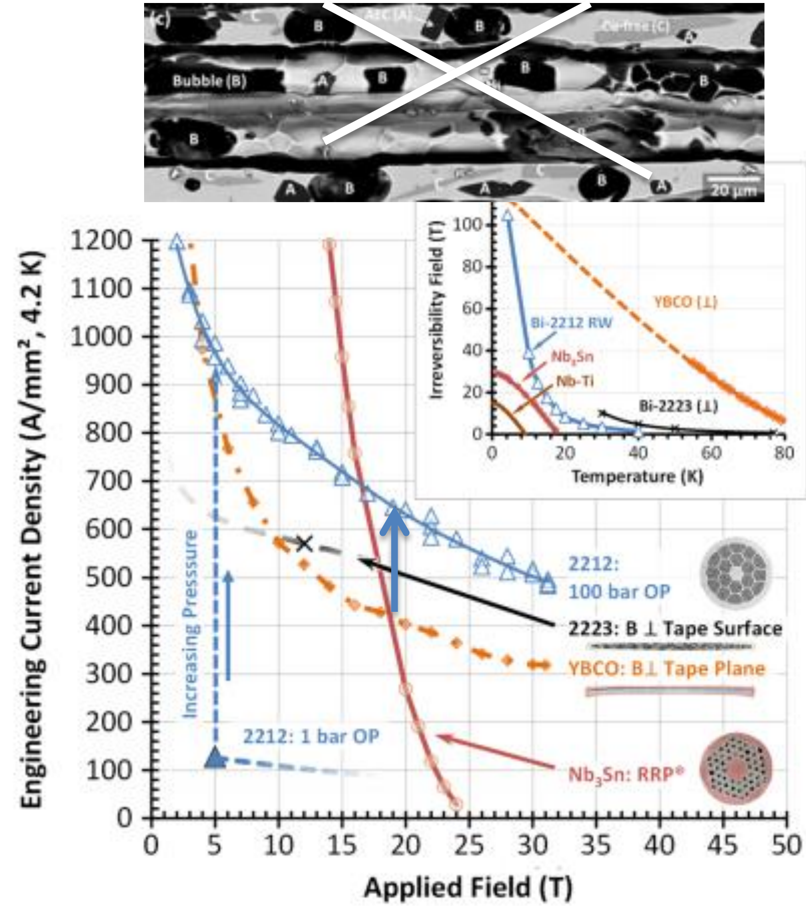




J. Jiang et al 2011

Bi-2212: example of guided R&D with partnership Labs/Industry

- Undestanding the reason for posrsity
- Finding the cure:
  - Better powder quality
  - OverPresssure treatment to densify and right O_2 content
  - Densification during fabrication (CIP, swaging)

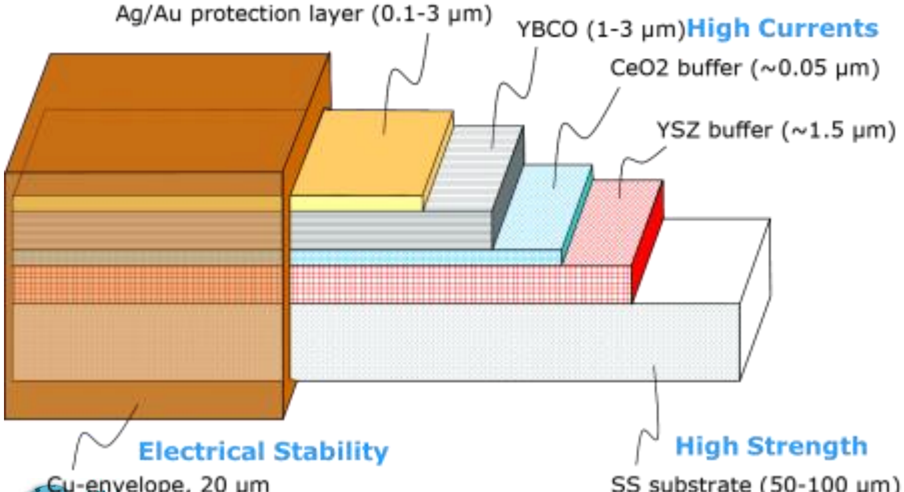


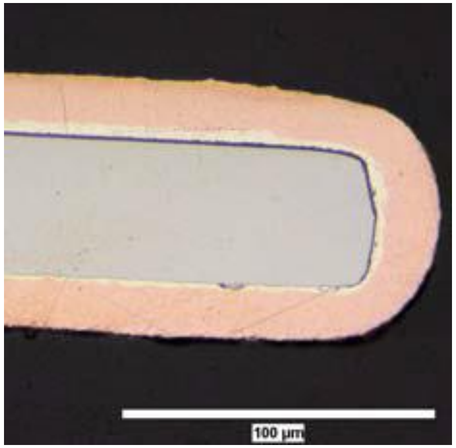
MAGNET LAB
NATIONAL HIGH MAGNETIC FIELD LABORATORY
FLORIDA STATE UNIVERSITY - LOS ALAMOS NATIONAL LABORATORY - UNIVERSITY OF FLORIDA

D. Larbalestier, ASC – FSU, Presentation at Eucad2 kickoff at CERN May 2013

The « new » materials: HTS YBCO

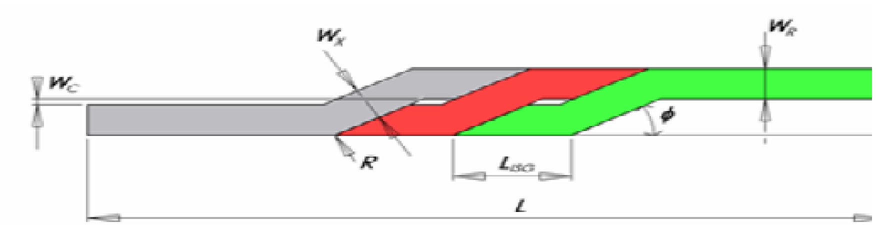
- Tape of 0.1-0.2 mm x 4-10 mm : difficult for compact (>85%) cables
- Current is EXCELENT but serious issue is the anisotropy;
- >90% of world effort on HTS are on YBCO! Great synergy with all community
- Cost : today is 10 times Nb_3Sn, target is same price: components not expensive, process difficult to be industrialize at low cost
- FP7 Eucard is developing EU Ybco

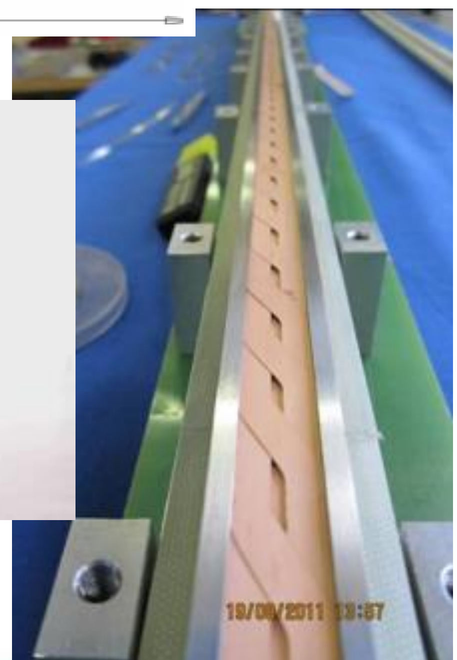




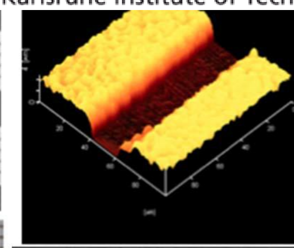
New (old) approach to cabling suitable for tapes: Roebel (full transposed cable)

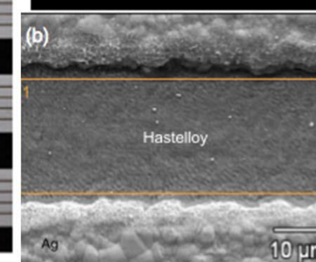
- An old type of cabling (Roebel) suitable for tapes has been recently rivisited (Karlsruhe, General Cable Superconductors NZ)

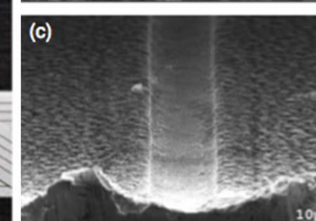




Karlsruhe Institute of Technology

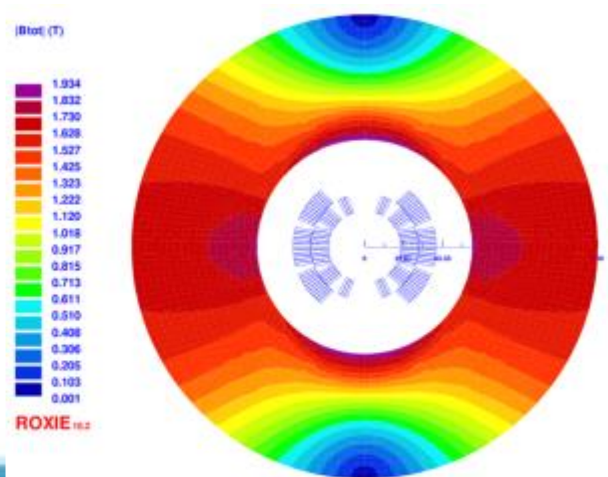


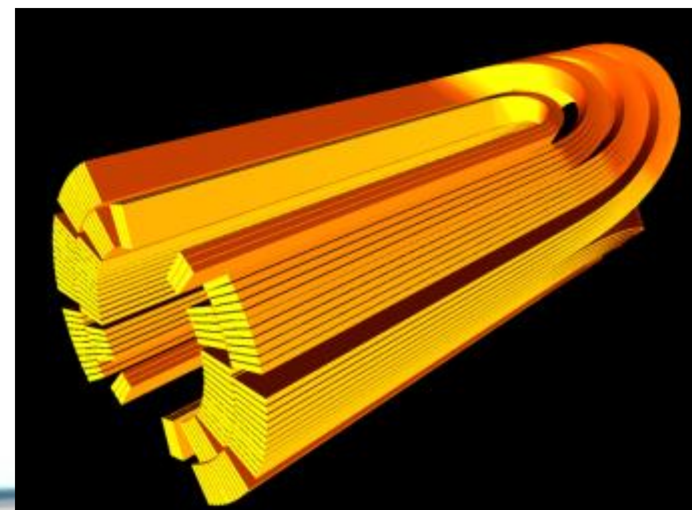




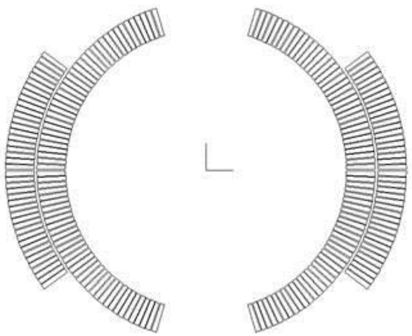
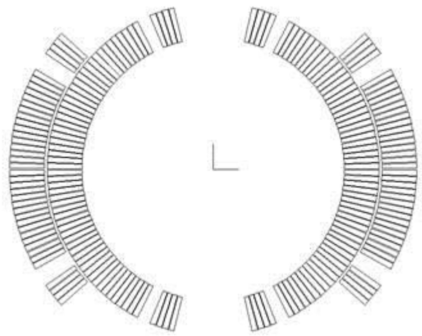
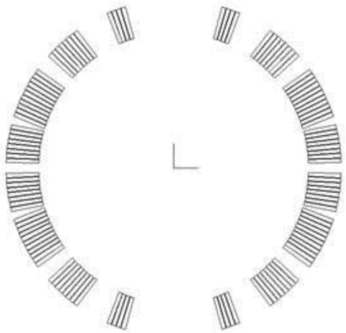
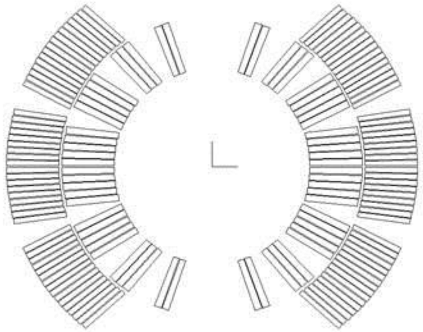
EU program FP7-Eucard2 (collab. with JP and USA)

- Develop 10 kA class HTS accelerator cables **both Bi-2212 and YBCO**
  - Stability, Magnetization, strain resistance
  - Uniformity and High $J_{overall}$
- Test in a 5 T <u>accelerator quality dipole</u>
- Then test in background field (10-12 T?)





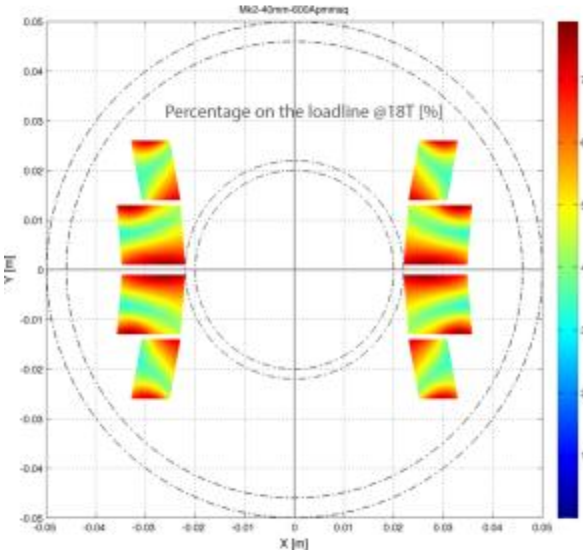
New coil design abandoning the perfection of cosϑ ?

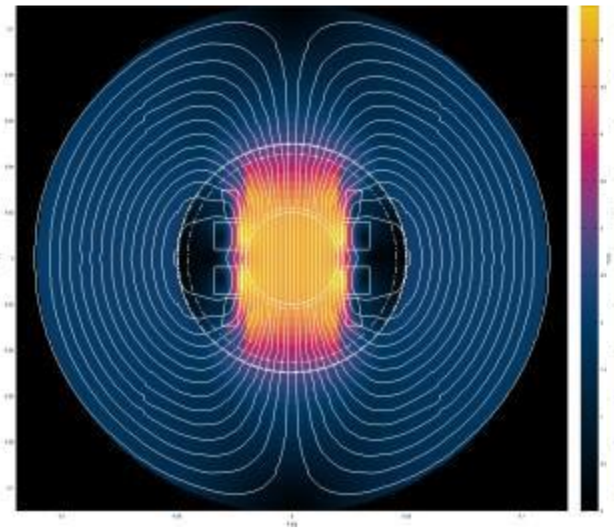





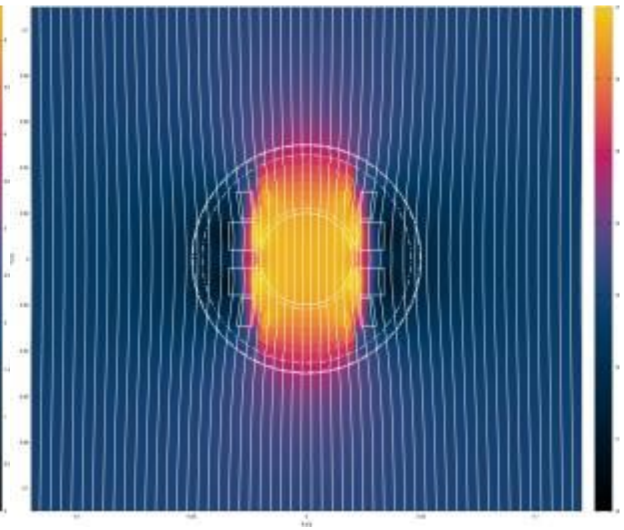


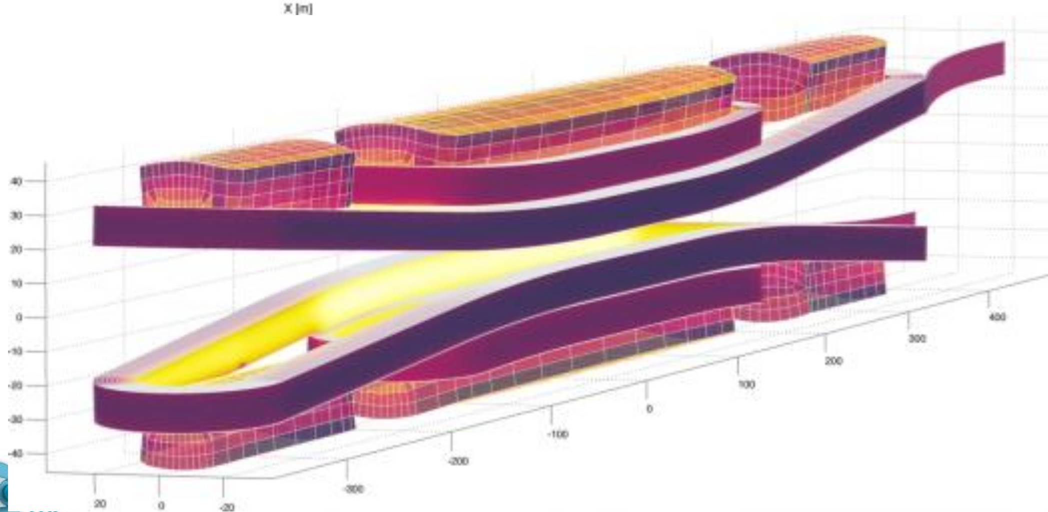

Tevatron **HERA** **RHIC** **LHC**

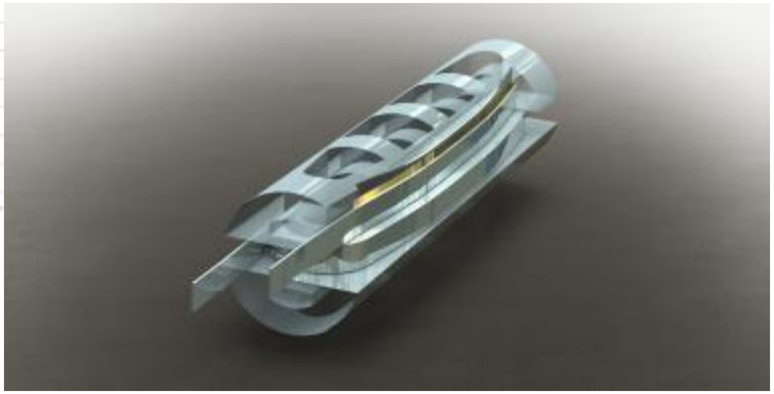
Explotring nerw ideas (J. van Nugteren) Aligned coil block dipole





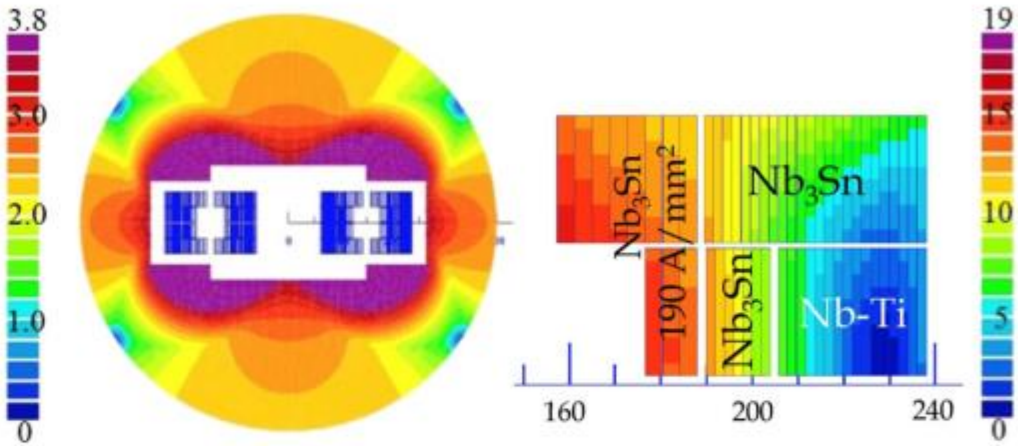






Strawman coil design for 20 T

From: E. Todesco, IEEE TAS, 24(3), 2014, 4004306

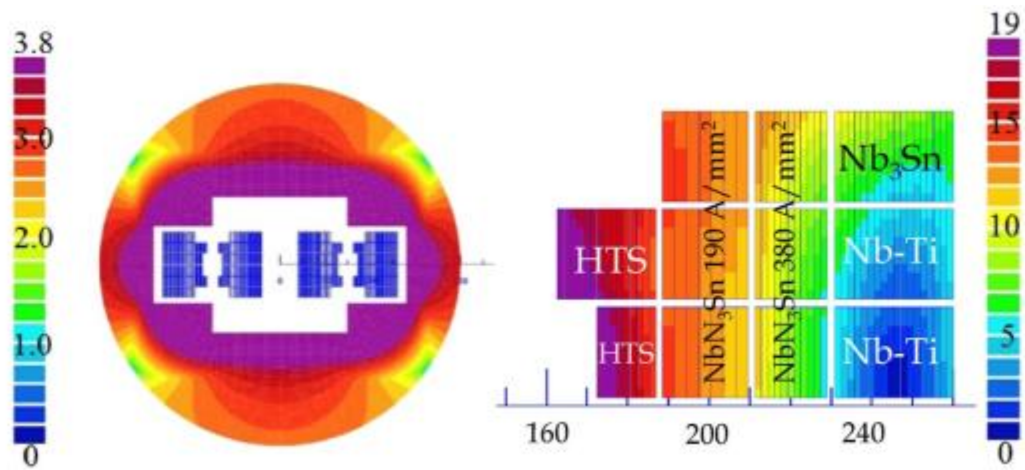


15 T "Snowmass" design
4578 units (+ 160 spares)

1000 tons of LHC-grade Nb-Ti
3500 tons of HEP-grade Nb_3Sn

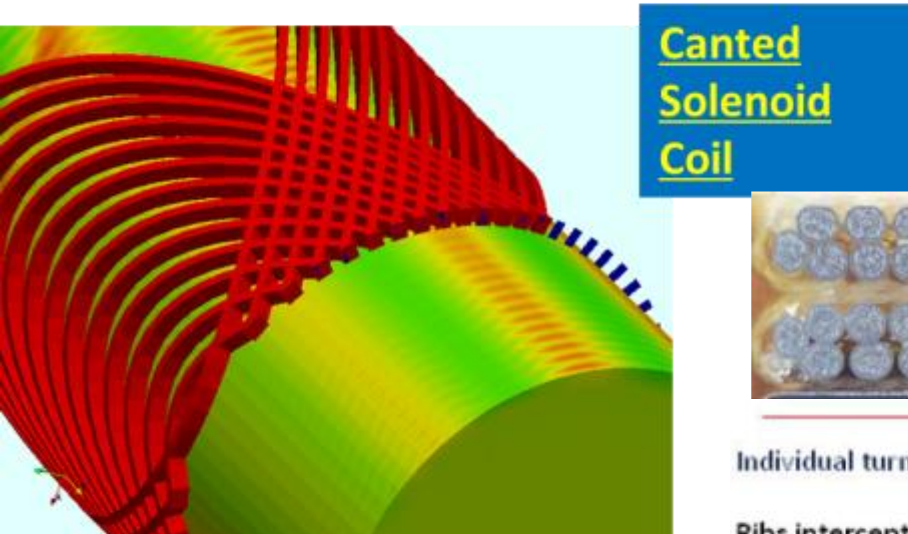
20 T "Malta revised" design
3662 units (+ 120 spares)

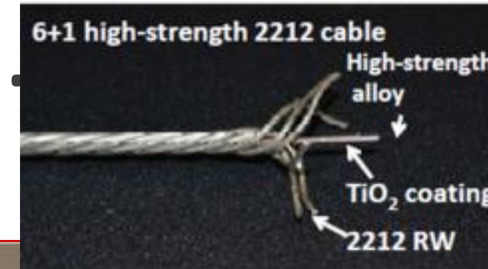
1000 tons of LHC-grade Nb-Ti
3000 tons of HEP-grade Nb_3Sn
750 tons of HTS

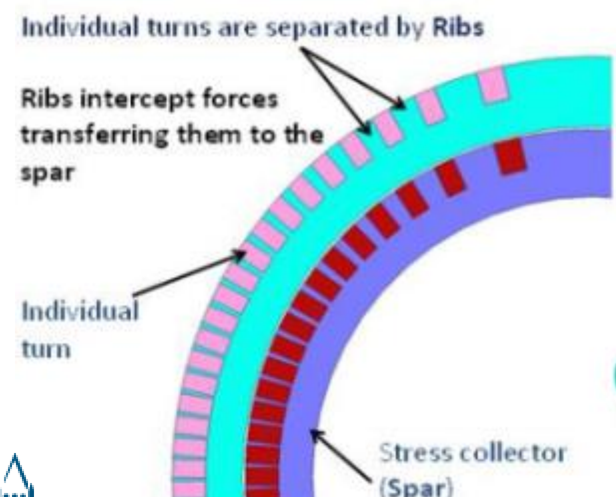


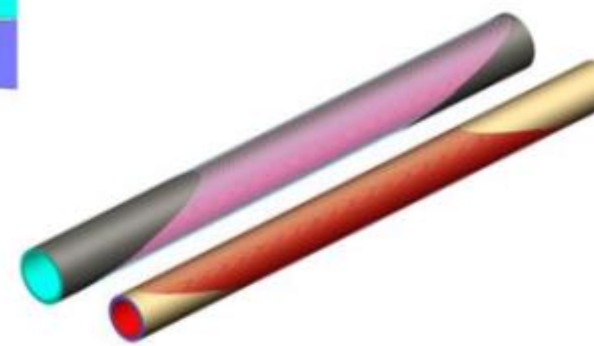
High Luminosity LHC

New (old) design very suitable for Bi-2212 (ASC, LBNL, FNAL…









…ique turns distribution

$J_z \sim \cos\vartheta$

*D.I. Meyer and R. Flasck "A new configuration for a dipole magnet for use in high energy physics application", Nucl. Instr.and Methods 80, pp. 339-341, 1970.)

57 attendants to a workshop intended only for HTS Accelerator Magnets (for high field)

EuCARD2

- Future - - Magnets -

WAM

THANKS!

High Luminosity LHC