LHC: from construction to upgrade

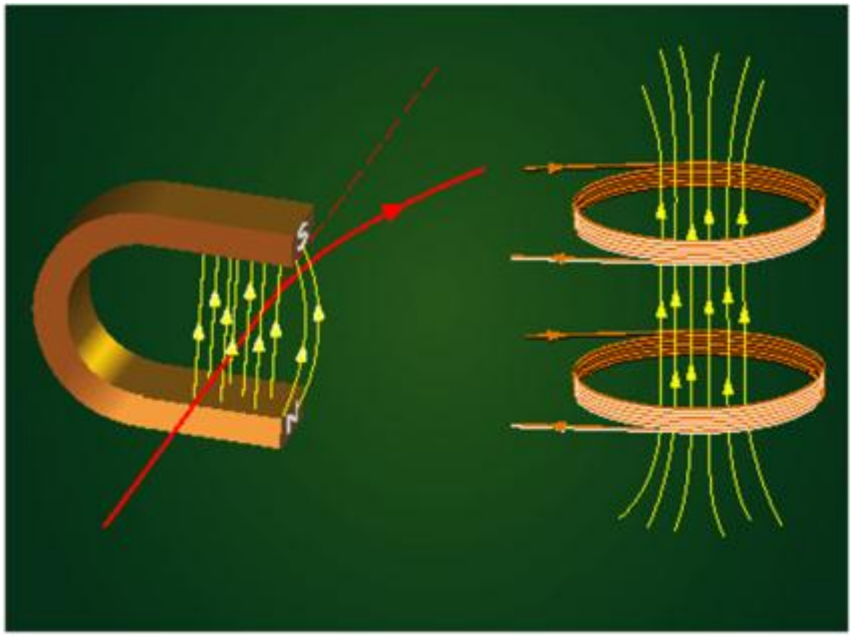
Lucio Rossi – CERN

Seminar at ITER – Cadarache
24 June 2014

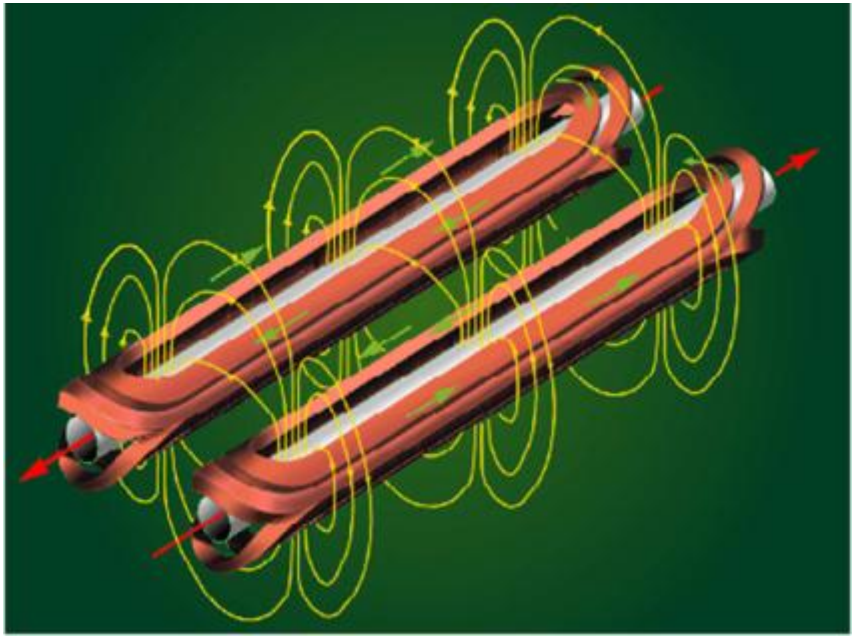
The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

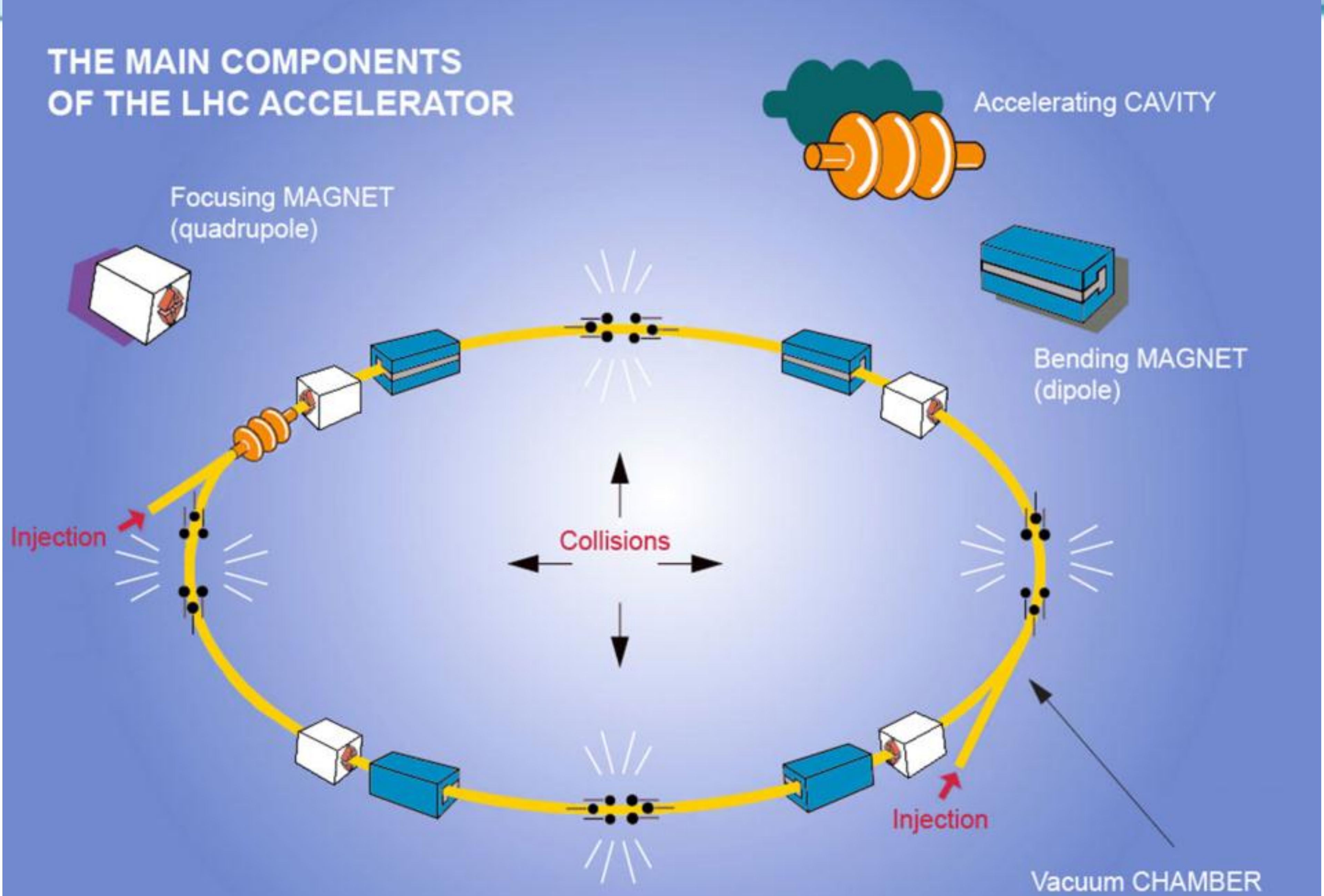
Particle bending in Accelerators for Nuclear and Particle Physics

Low Energy Physics (Cyclotrons, Synchrocyclotrons): fill the magnetic volume with particle orbits



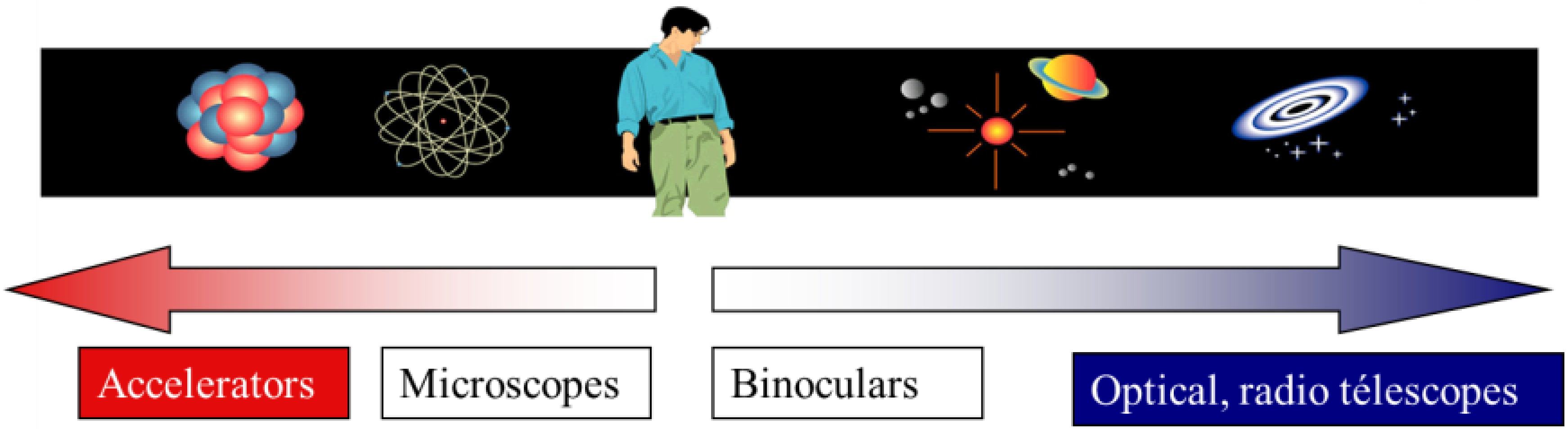
High Energy Physics (synchrotrons, colliders): minimum field volume along the beam path





Large size and high field : $E_{beam} \cong 0.3BR$

Accelerators, powerful microscopes



Accelerators are the finest microscopes:

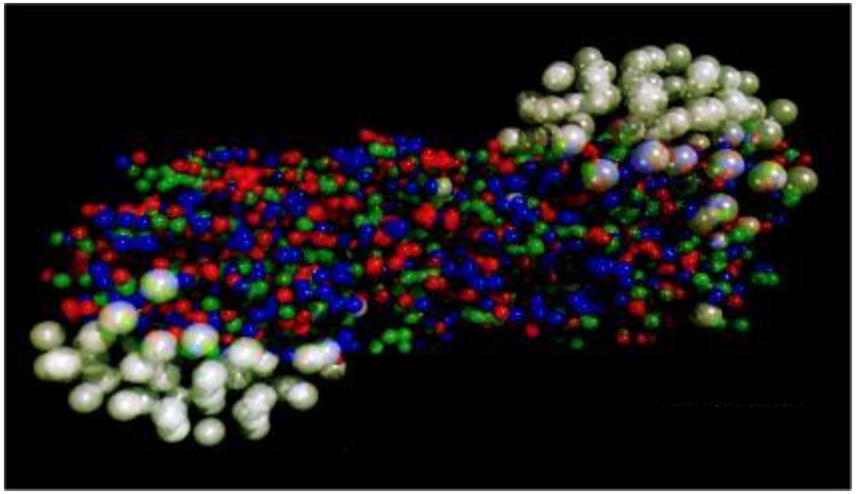
acto-scope or zepto-scope

λ = h/p ; @LHC: T = 1 TeV $\Rightarrow \lambda \cong 10^{-18}$ m

(reached : $50 \cdot 10^{-21}$ m)

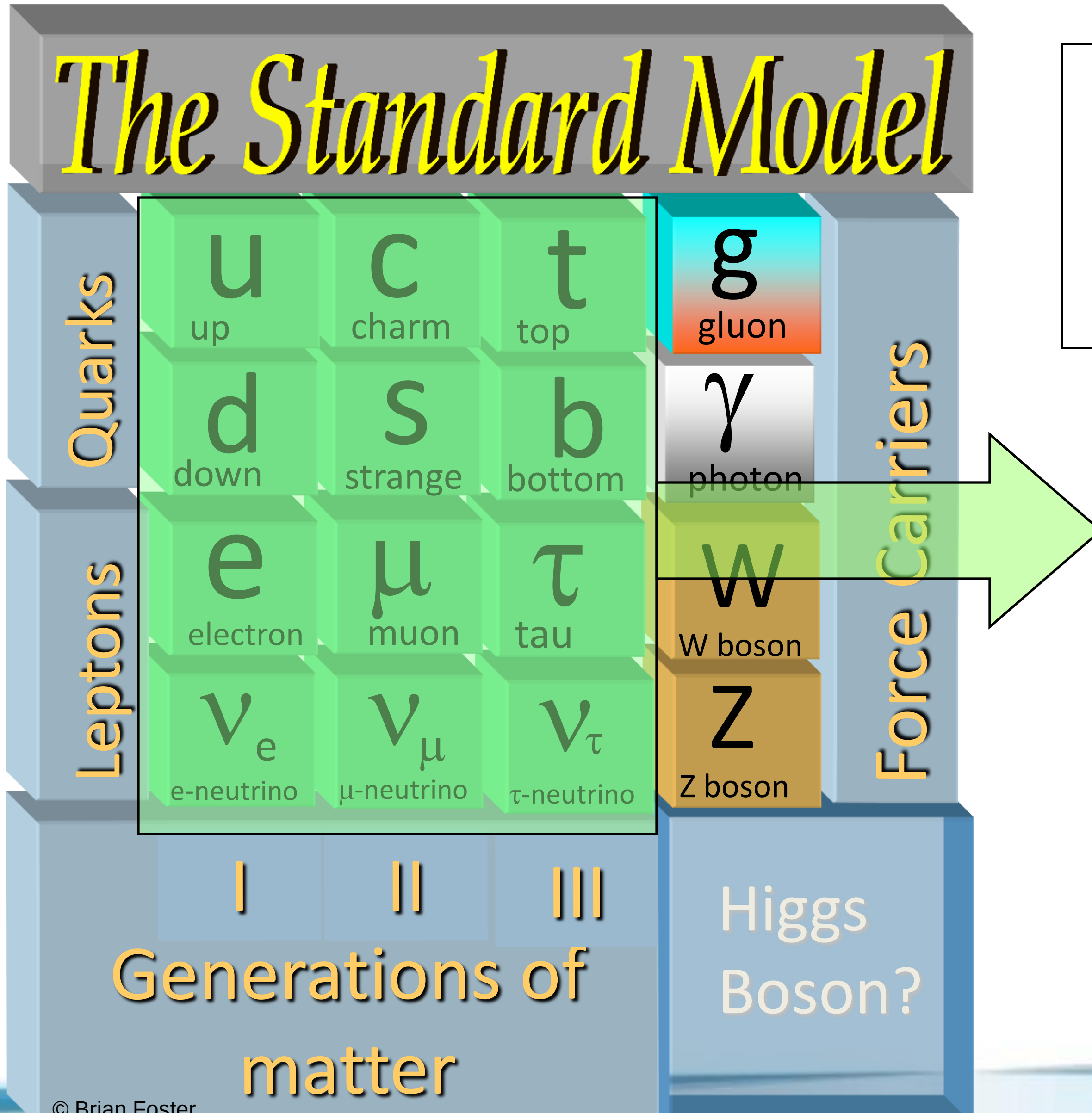
…bringing us back to Big Bang

- Trip back toward the Big Bang: $t_{\mu s} \cong 1/E^2_{Gev}$
- $T \cong 1$ ps for single particle creation
- $T \cong 1$ μs for collective phenomena QGS (Quark-Gluon Soup)



But we are left with the task of explaining how the rich complexity that developed in the ensuing 13.7 billion years came about…

Which is a much more complex task!



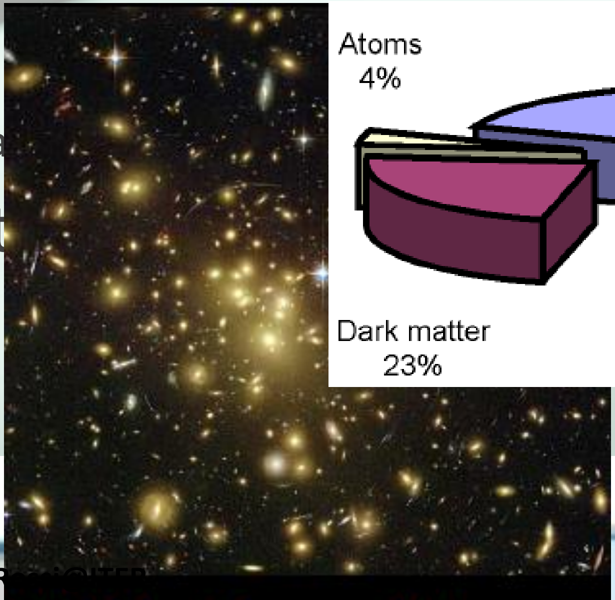
Particles and Forces

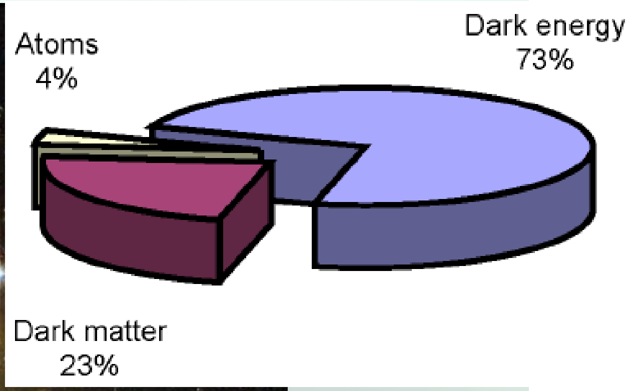
Each with its own 'antiparticle'

What remains to be done?

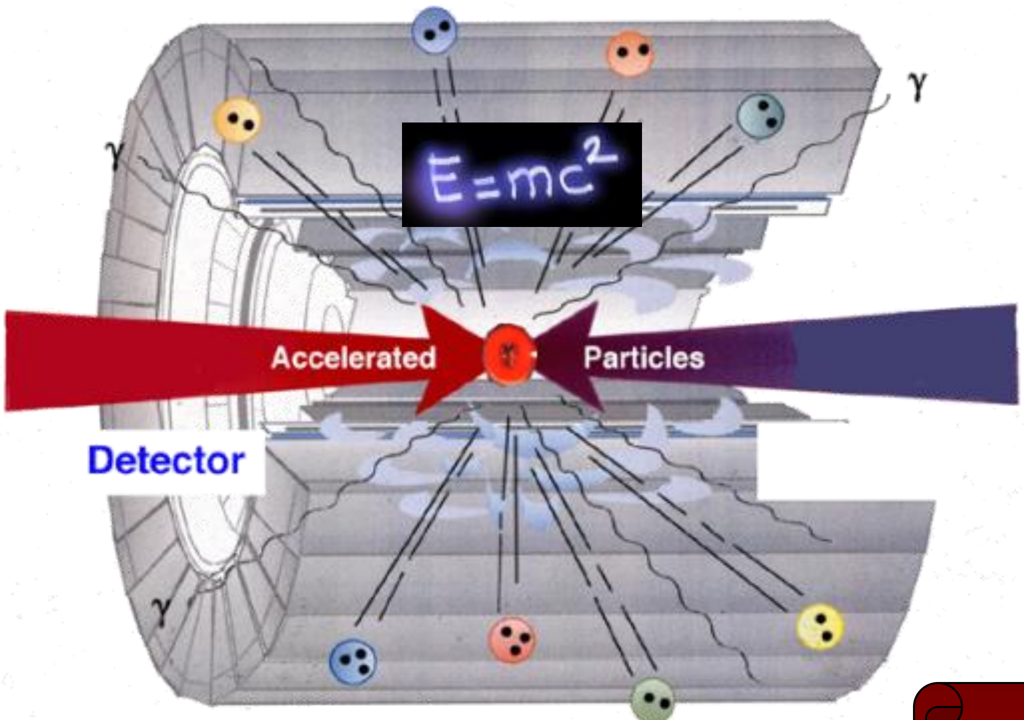
- The Standard Model is a very good *description* of the Universe at the particle scale (~2M_W)
  - But does not *explain* many things
    - Why so many particles?
    - Why so many forces?
    - What is mass?
      - Why do particles have the masses they have?
    - Why is matter different from antima
      - (Where did all the ant
    - What is Dark Matter? Dark Energy?
    - Where does gravity fit in?

LHC !





The method of high energy physics



1) Concentrate energy on particles (**accelerator**)

2) **Collide** particles (recreate conditions after Big Bang)

3) Identify created particles in **Detector** (search for new clues)

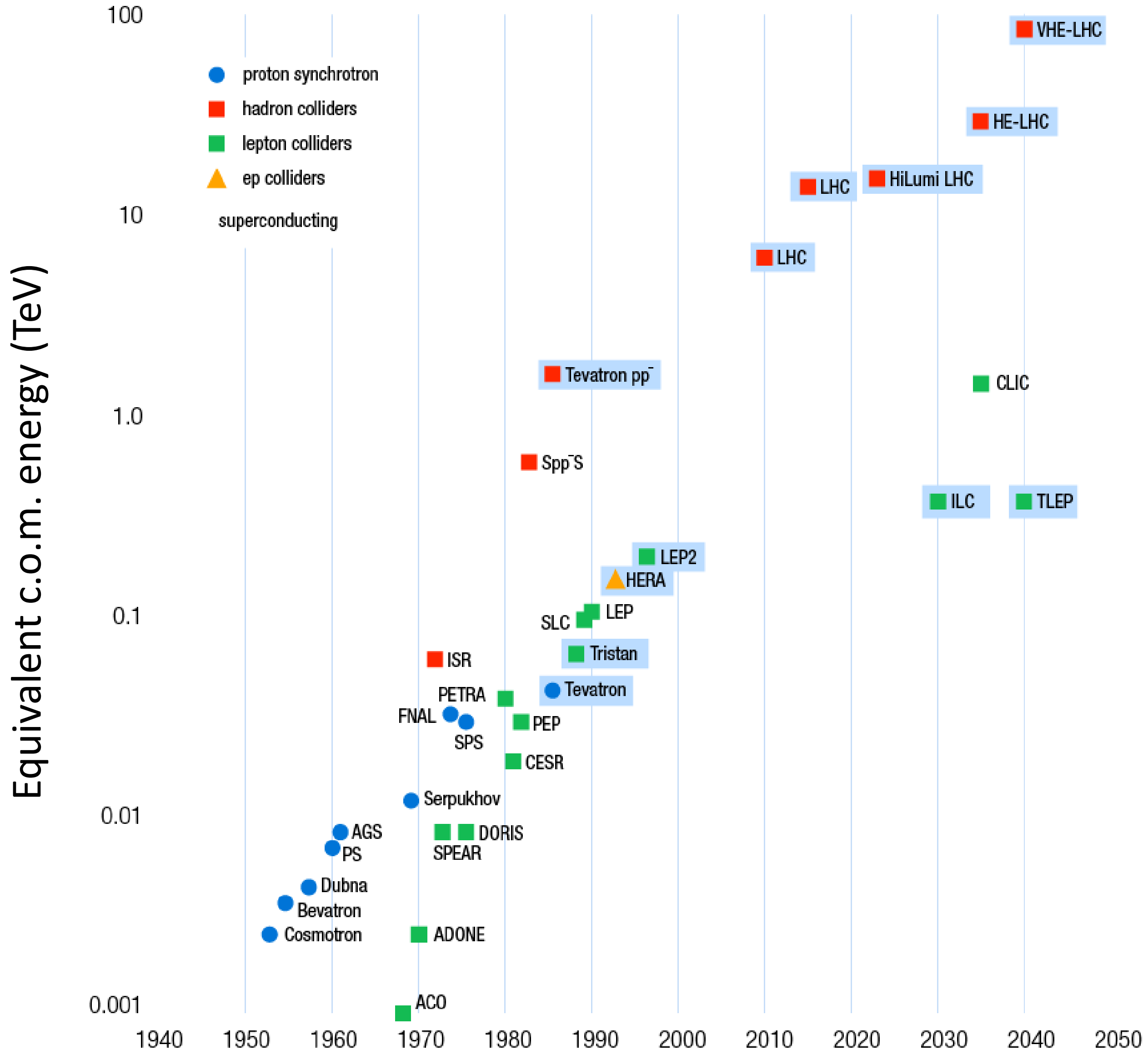
And the good news is that both of them need SC and other HiTech!

CERN

European Organization for Nuclear Research

- Founded in 1954 by 12 countries
- Today: 20 member states
- More than 10,000 users from all over the world
- ~750 M€ / Year budget
- 2400 permanent staff

2004: The 20 member states



SC has dominated the scene of HEP accelerators since at least 30 years

SC : an enabling technology

Better vacuum in the beam pipe (1.9 K) is a big plus

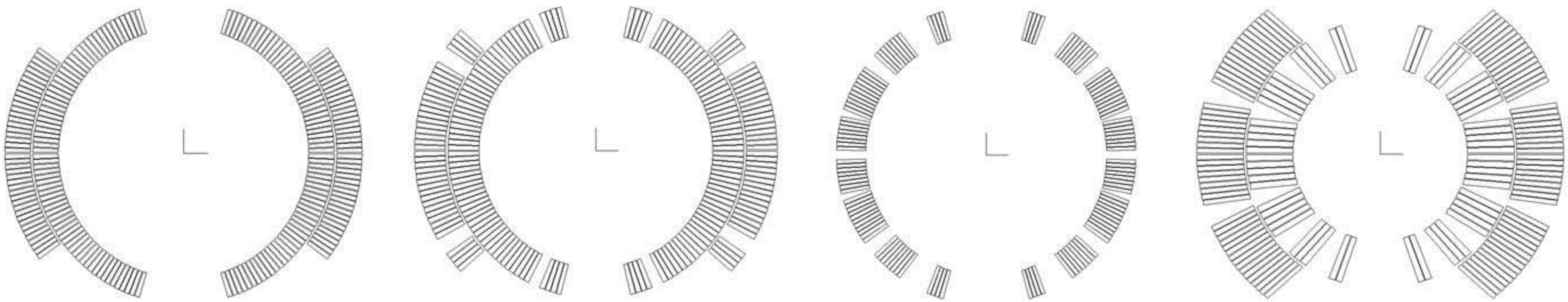
Superconducting LHC

- Tunnel : 27 km
- Field : 8.3 T
- Cryoplant power at the plug: 40 MW
- Average power (cryo always on: 1 x 40 = 40 MW

Normalconducting LHC

- Tunnel 120 km
- Field : [illegible]
- Dissipated power at collision: ~ 2,2[illegible] MW
- Average power (0.4 coefficient): 900 MW

Acc. SC Magnets: basic shape
Main dipoles of existing machines



Tevatron

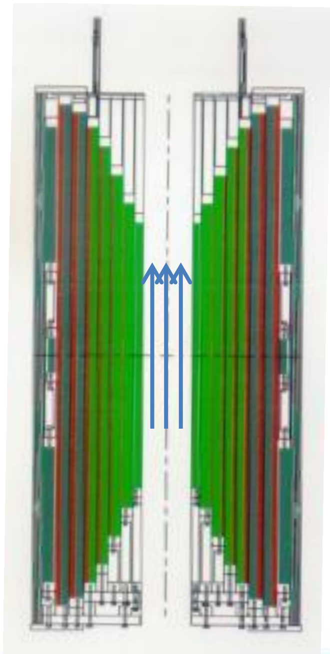
HERA

RHIC

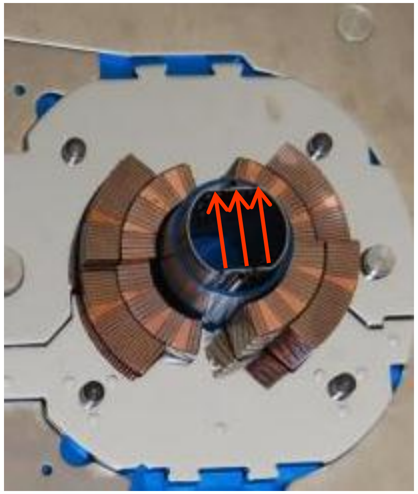
LHC

Transverse field and Magnetic efficiency

- In ideal solenoids the field goes as : $\boldsymbol{B = \mu_0 J t}$ where ***t*** is the coil thickness



- In trasverse field the field is less with the same coil thickness:
- $\boldsymbol{B = \frac{1}{2} \mu_0 J t}$ (geom cosϑ)
- $\boldsymbol{B = (\sqrt{3}/\pi) J t}$ (60° shell)



HEP Accelerator : current density

Magnetic system (only dc)	Current density $J_{overall}$ (A/mm^2)	Operating current (kA)	Typical field range (T)	System stored energy (MJ)
Resisitive – air cooled	1 - 5	1-2	< 1	0.01
Resistive – water cooled	10-15	1-10	2	0.05
SC magnets for particle detectors	20-40	2-20	2-6	5-2500
SC Tokamaks for fusion†	25-50	5-70	8-13	5-40,000
SC magnets for MRI	50-200	1	1-10	1-50
SC laboratory solenoids	100-250	0.1-2	5-20	1-20
SC Accelerators	200-500	1-12	4-10	1-10,000

†Top figures refer to ITER, under construction

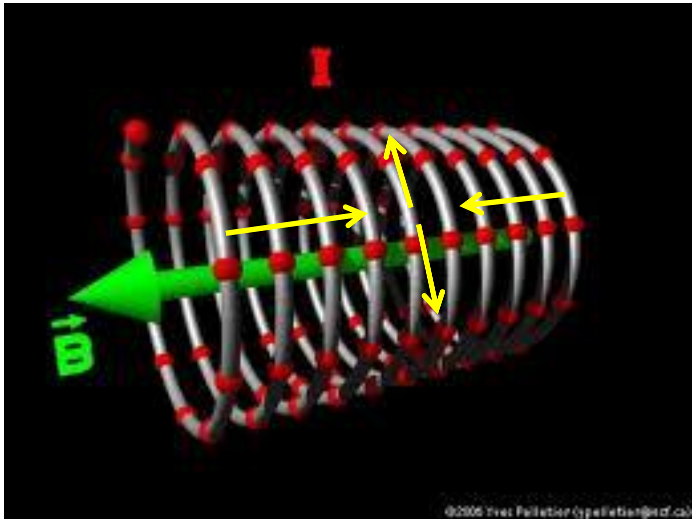
Why not more?

Huge force density: J B
Huge stresses : J B R
Huge energy : protection needs time…

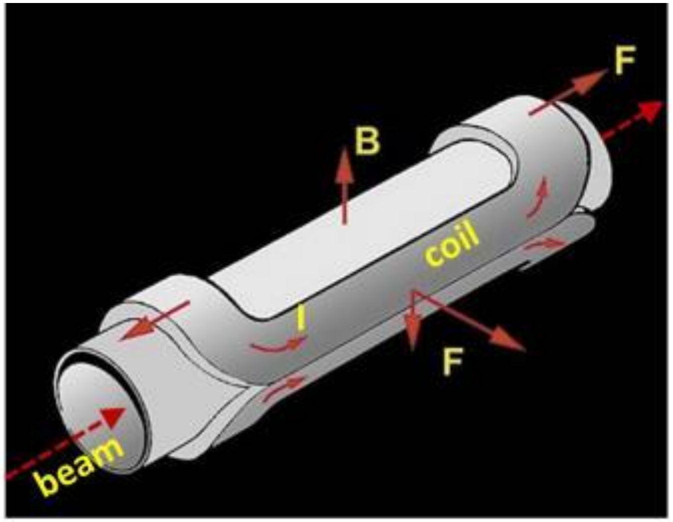
Transverse field: Forces

F ~ JB

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

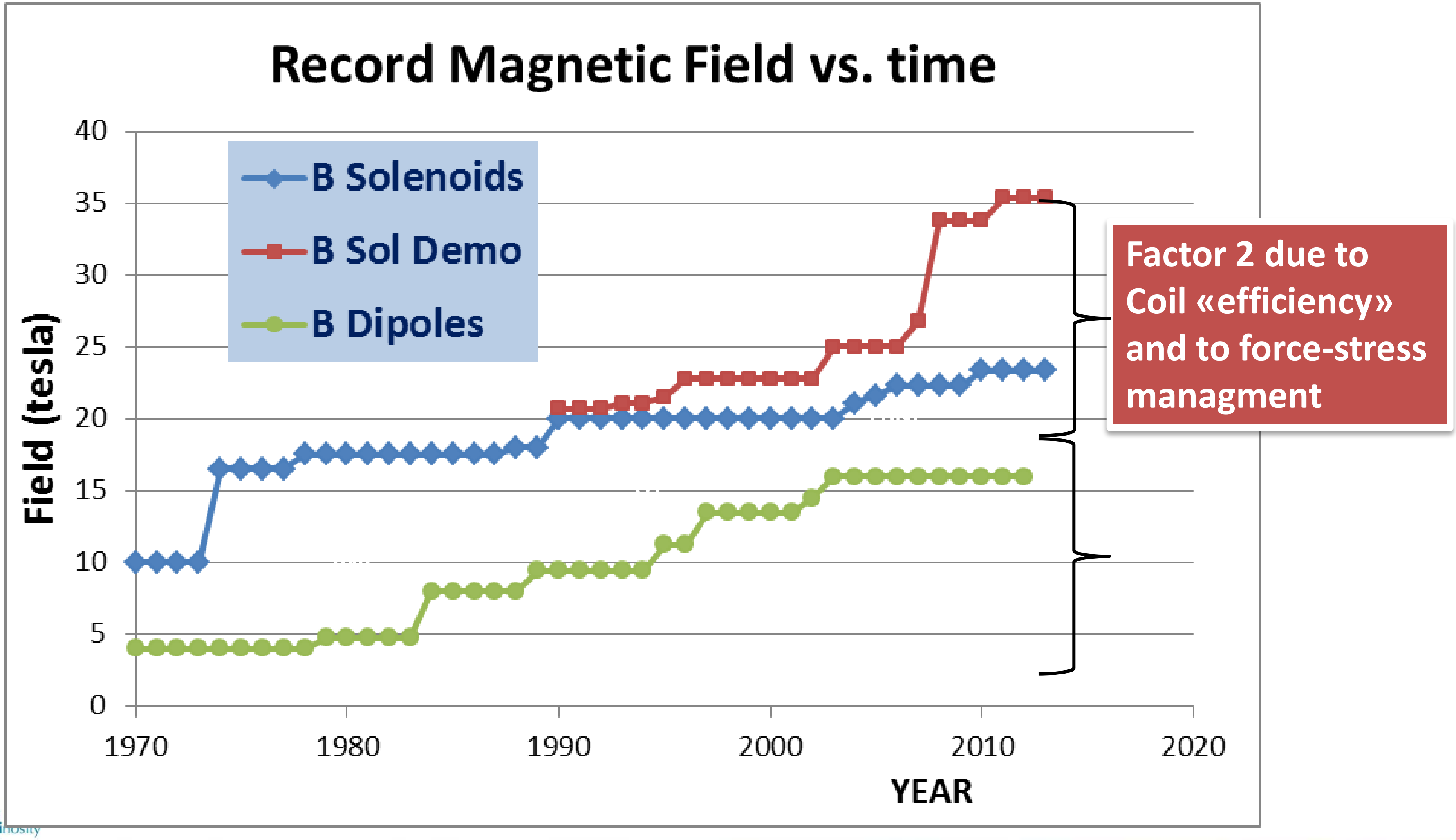


In transverse field the lateral forces are not supported at all
The longitudinal (along beam) forces are poorly supported



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}

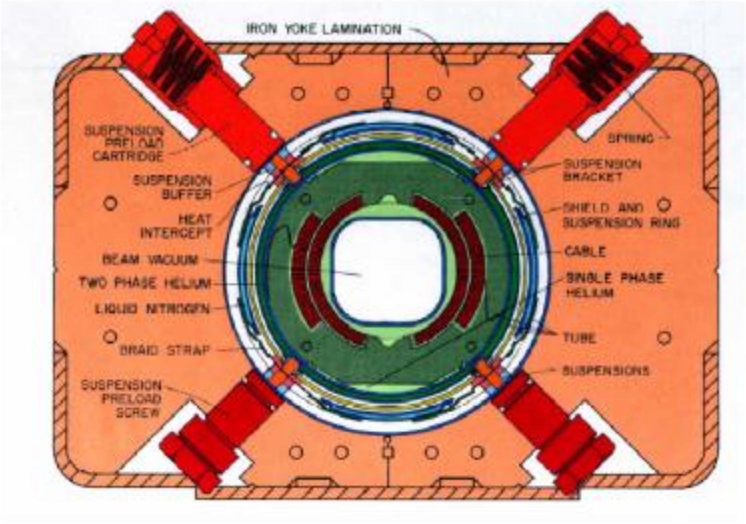
Dipoles vs solenoids in time : a comparison



Tevatron: the «grand father of large SC projects» : R R Wilson

LAB DIRECTOR WINDING A 1 FOOT MODEL MAGNET

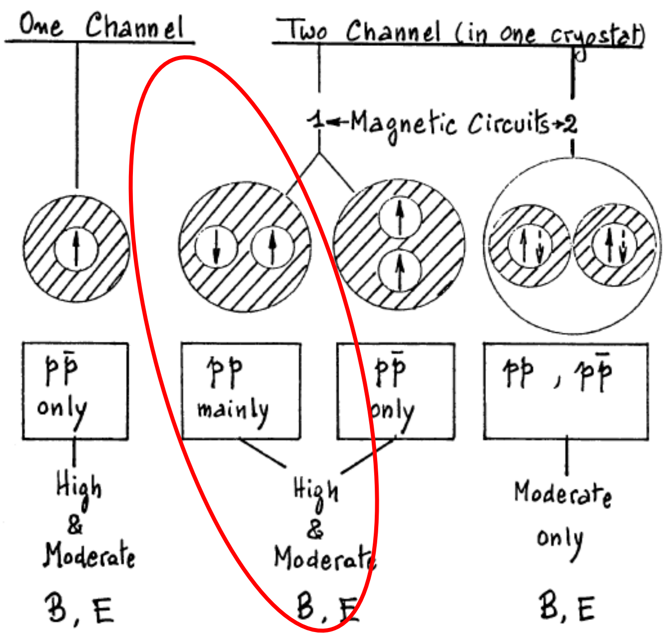
THIS ONE DIDN'T WORK! BUT WE LEARNED!

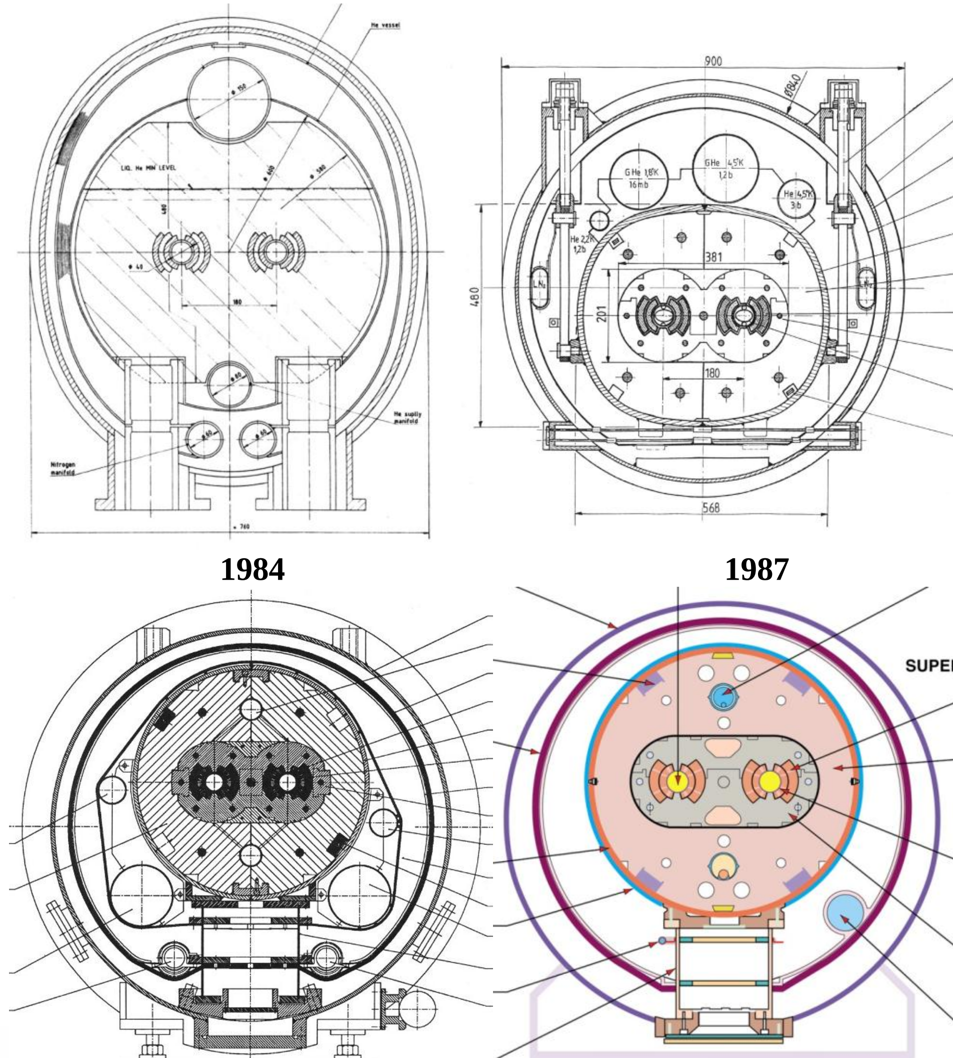


Lab director winding a protype (however this it didn't work…). Courtesy A. Tollenstrup

LHC inception: 1983
Evolution of X-section in time

J. Adams & G. Brianti (right)



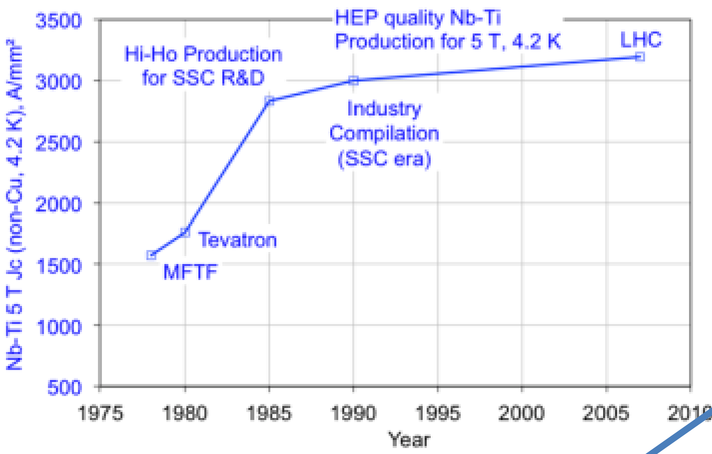


Two routes : Nb-Ti and Nb_3Sn

- High field dipole in Nb-Ti (HERA strands). CERN (Perin &Leroy) Ansaldo (Spigo)
- 8. 55 T first quench, reached 9.3 T at 1.6 K

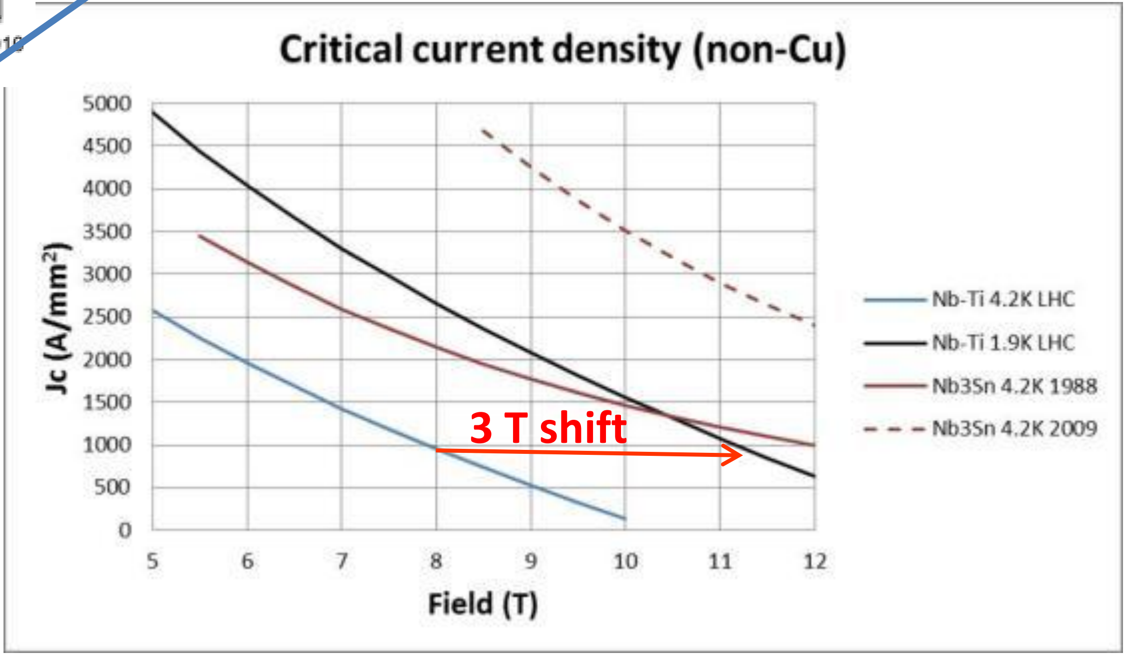
- Nb_3Sn CERN-Elin dipole (Asner-Wenger & Zerobin)
- Reached 9.7 T, : Previously a coil in mirror configursation broke first the 10 T barrier

But the route was signed…



Continous progress in Jc of fine filaments Nb-Ti
Definitive step achieved by SSC

Nb_3Sn 5 to 10 time more expensive
HE II Cryogenics was working in Tore Supra!

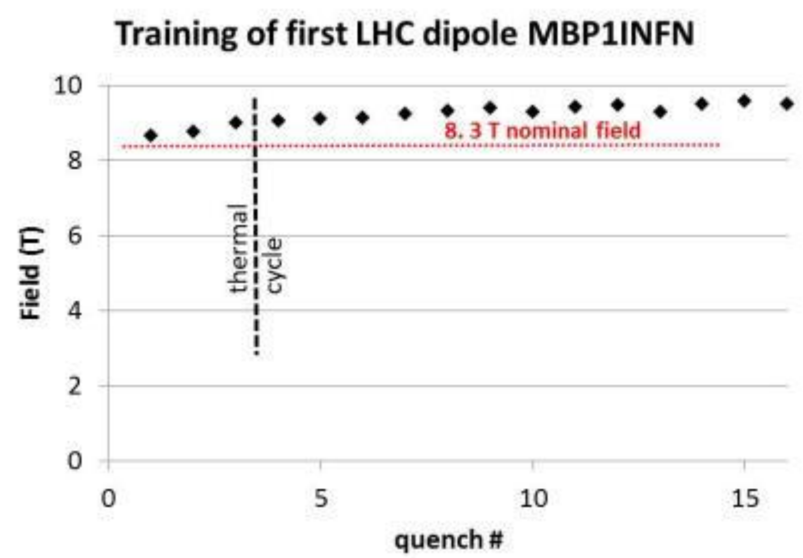


High Luminosity LHC

Putting all together 1989-94
First LHC prototypes (CERN-INFN-CEA)

First LHC coils arriving!

SSC stop on October 21, 1993
Cost was escalating to 14 B$
(from 4.4 B$ intial).
Spent 2 B$ for civil and tech.



Test INFN-1: June 1994: incredibly good!
String1 : 3 dipoles 1 Quads by end of year
Approval by Council of LHC : December 1994

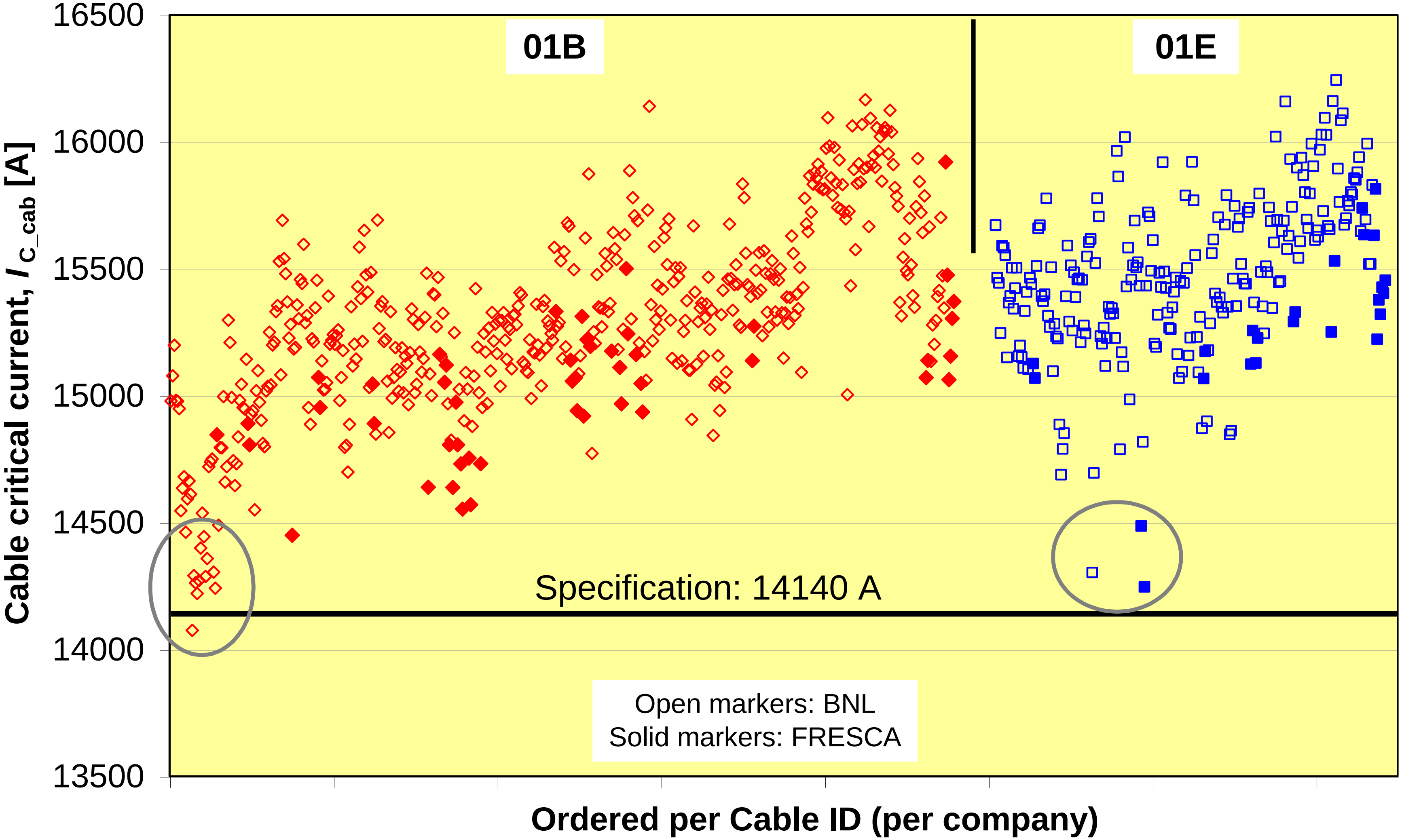
The «hole»

- In 1994 three 10 m long dipoles were successfully tested
- However tenders:
- for all Sc and for first 90 dipoles pre-series only in 1999 (contract in 2000)
  - Tender for the remaining 1158 dipoles only in 2001 (contract 2002)…
- Why? Redesigning, «optimization» etc… other components and integration… Money as well!

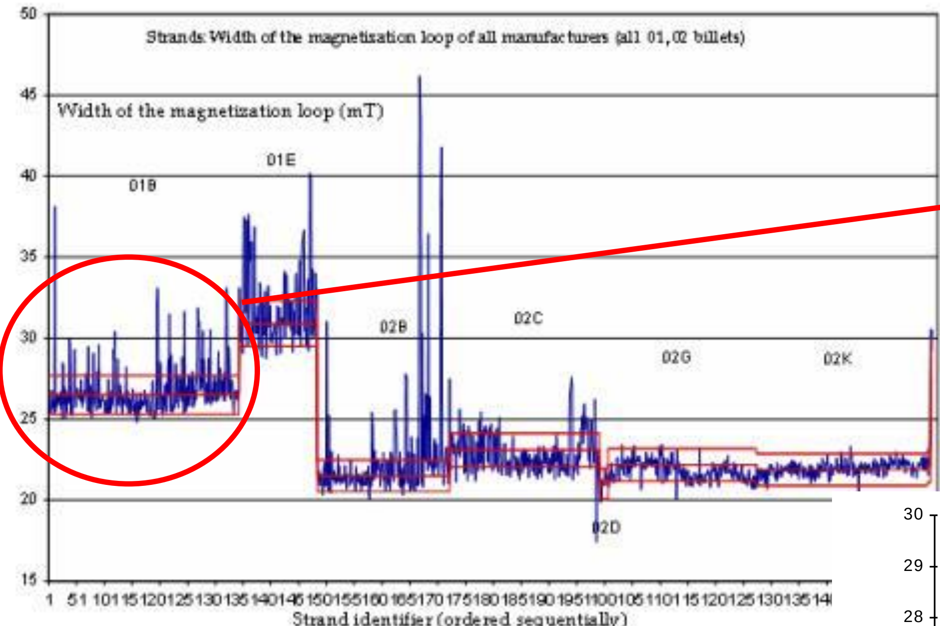
The LHC superconductor
7000 km of Cu/Nb-Ti cable

STRAND	Type 01	Type 02
Diameter (mm)	1.065	0.825
Cu/NbTi ratio	1.6-1.7 ± 0.03	1.9-2.0 ± 0.03
Filament diameter (μm)	7	6
Number of filaments	8800	6425
Jc (A/mm^2) @1.9 K	1530 @ 10 T	2100 @ 7 T
μ_0M (mT) @1.9 K, 0.5 T	30 ±4.5	23 ±4.5
CABLE	**Type 01**	**Type 02**
Number of strands	28	36
Width (mm)	15.1	15.1
Mid-thickness (mm)	1.900 ±0.006	1.480 ±0.006
Keystone angle (degrees)	1.25 ±0.05	0.90 ±0.05
Cable Ic (A) @ 1.9 K	13750 @ 10T	12960 @ 7T
Interstrand resistance (μΩ)	10-50	20-80

Critical Current of LHC inner cable



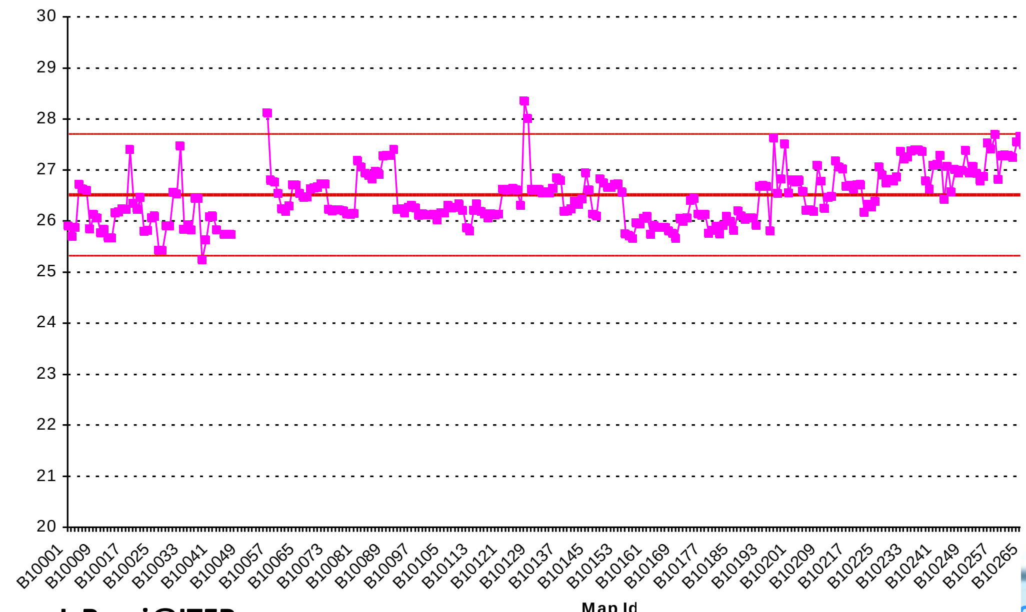
Magnetization for LHC NbTi

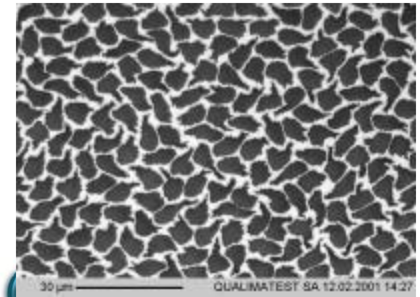


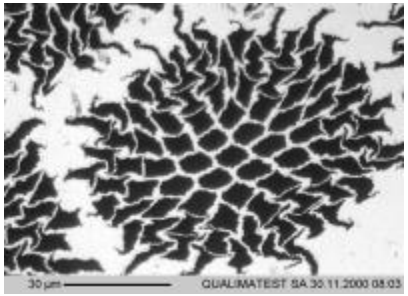
Rejection of conductor (few)

Limit in the dynamic range of the magnets

Cable 01B







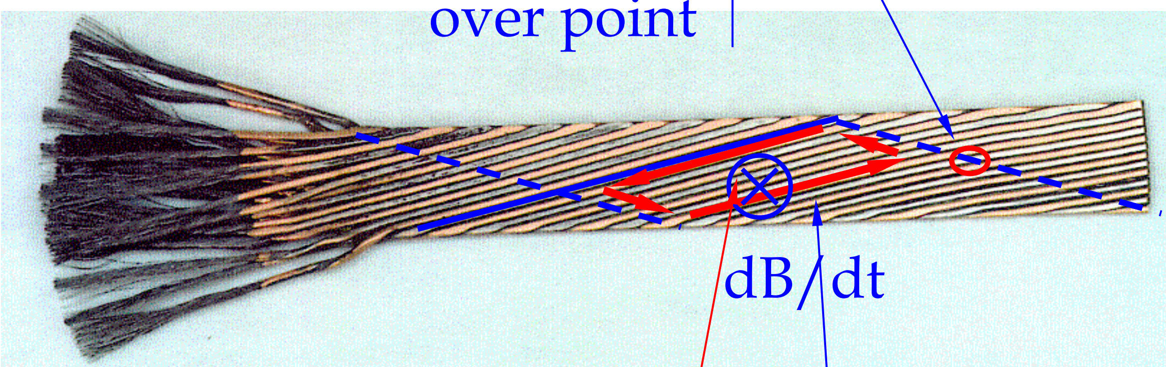
Courtesy of S. LeNaour

Needs for 10-20 kA cable for protection

Needs very high packing factor: 90% !!

Needs a system simple that keep strands

resistive contact R_c at cross-over point



dB/dt

induced eddy currents in the loop $I \propto -dB/dt$ and $I \propto 1/R_c$

superconducting path in the strands

The strand are fully transposed

BUT field changes over a period !

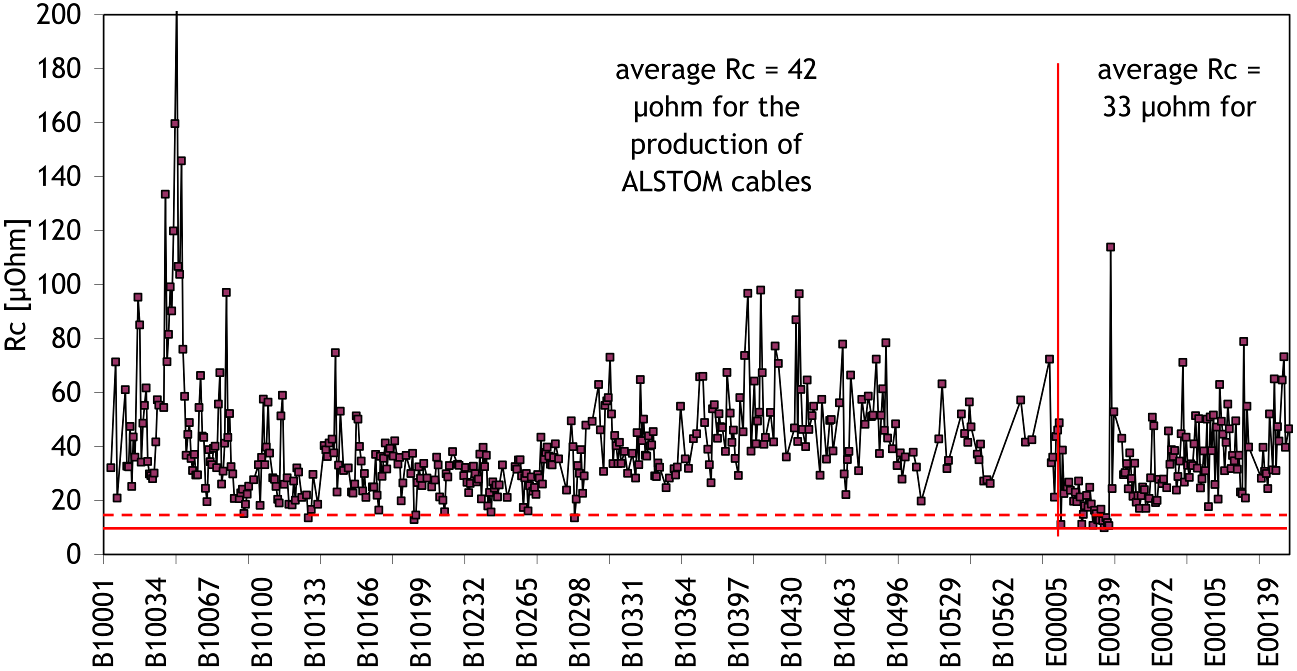
Ends problems

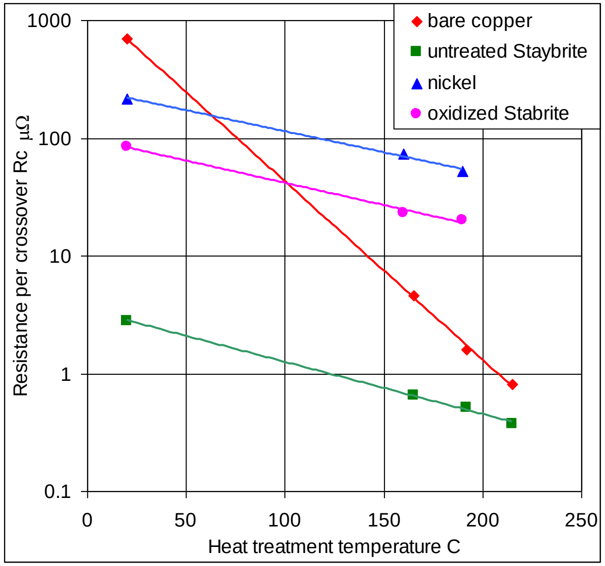
Junctions

BICC

Controlling the contact resistance

Rc measured by CERN on the cables for the inner dipole layer





CERN has developed the controlled oxidation method

Value too low gives field errors

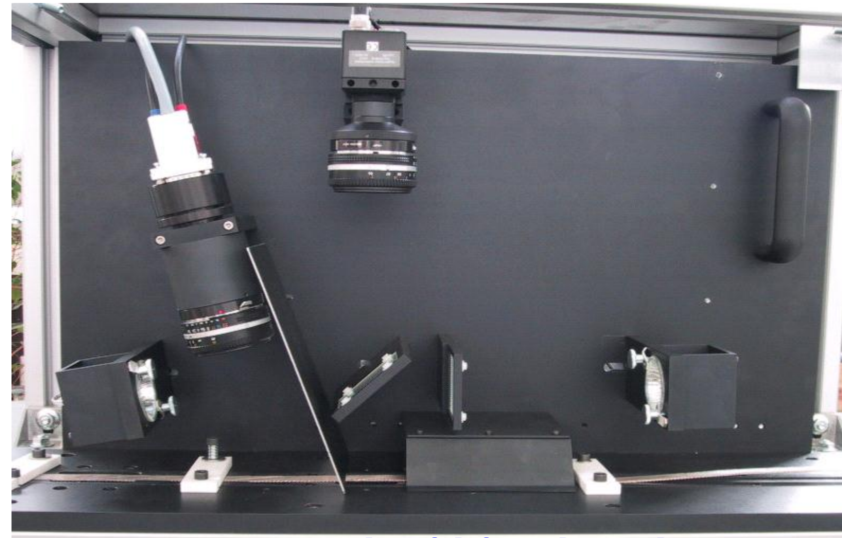
Too high may give instability

High Luminosity LHC

Number of tests in 2003 at CERN

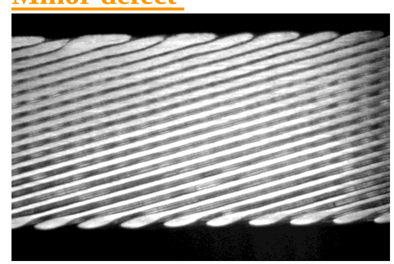
Number of billets approved in 2003 :	**1578**		
Number of UL received in 2003 :	**2818**		
Wire		**Cable**	
◆ Ic	462 /month	◆ Ic (BNL)	54 /month
◆ RRR	482 /month	◆ Rc	120 /month
◆ Magnetisation	137 / month		
		◆ Bend test	88 /month
◆ Bend test	311 /month	◆ Residuel Twist	83 /month
◆ Spring back	235 /month		
		◆ CMM	88 /month
◆Diameter	251 /month	◆ 10-stack	111 /month
◆ Cu/Sc	850 /month	◆ Sharp edges	93 /month
◆ Coating	454 /month		
◆ Twist pitch	175 /month		

QA: Laboratory Equipment

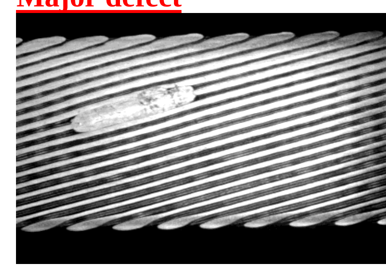


Examples of defects detected **C. I. S.**

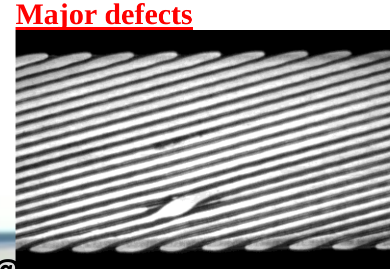
Minor defect



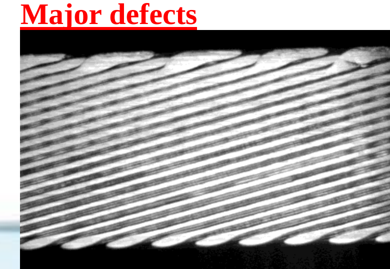
Major defect



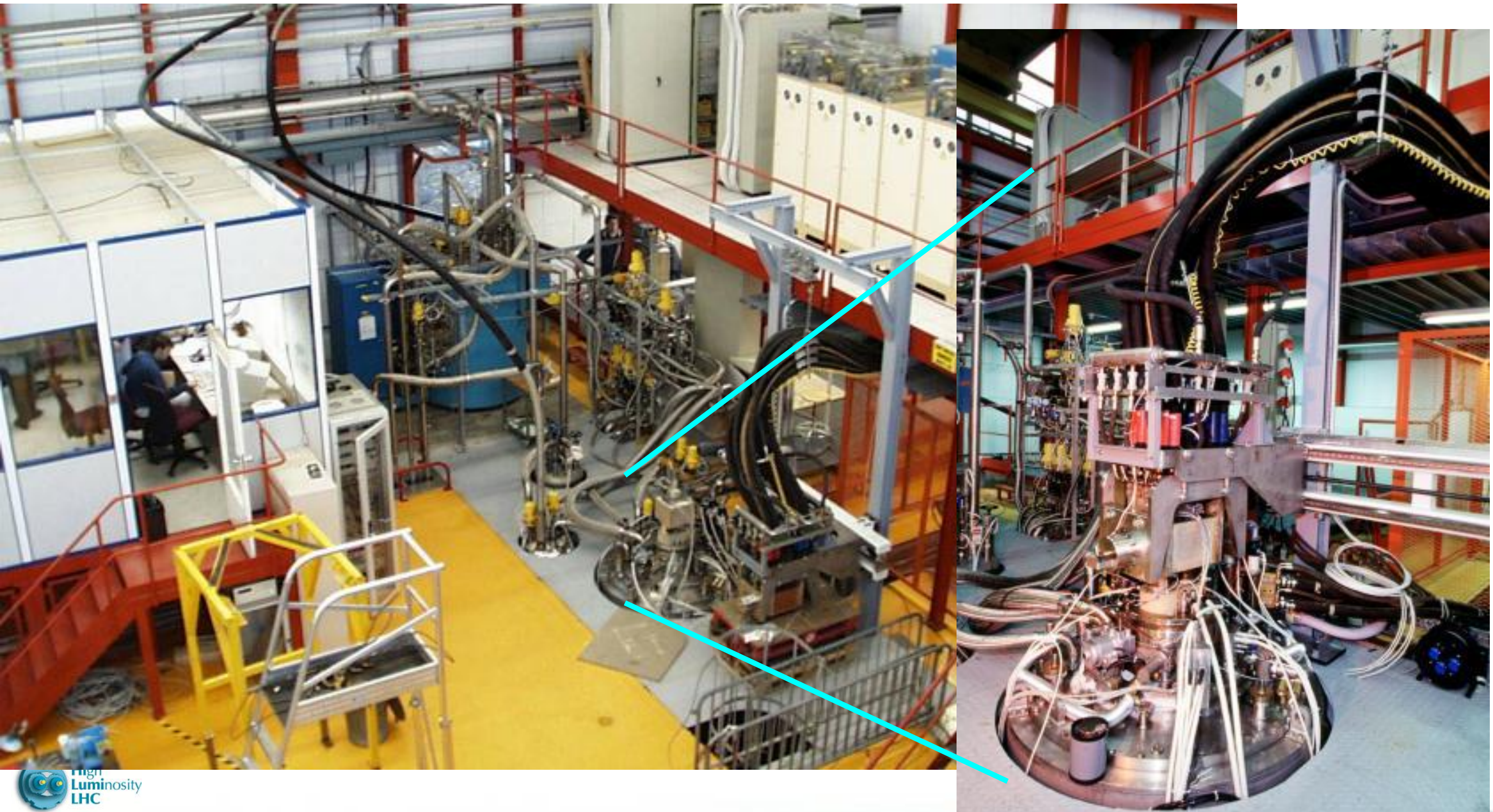
Major defects



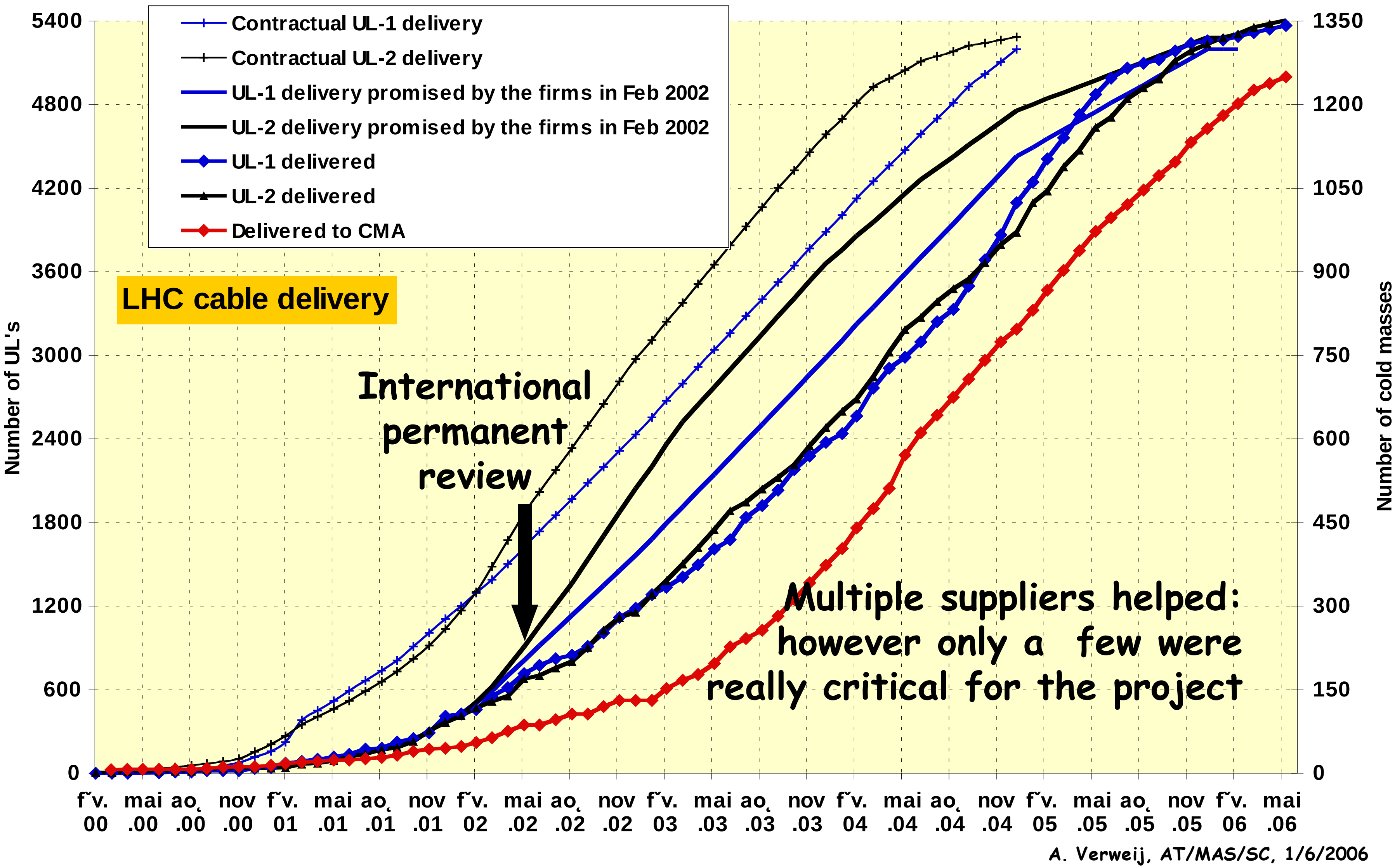
Major defects



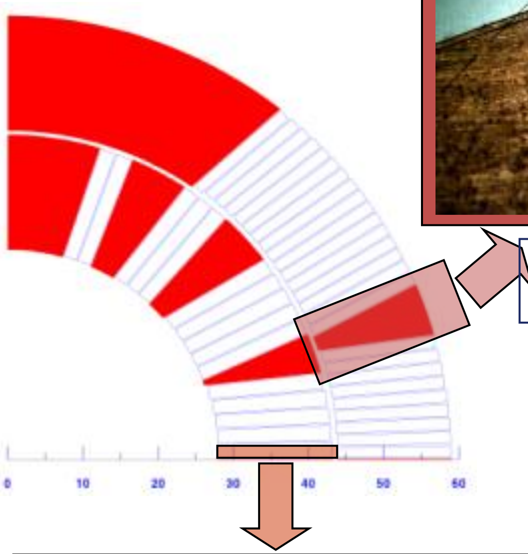
QA : Cable Ic measurements on thousands samples (BNL, CERN)



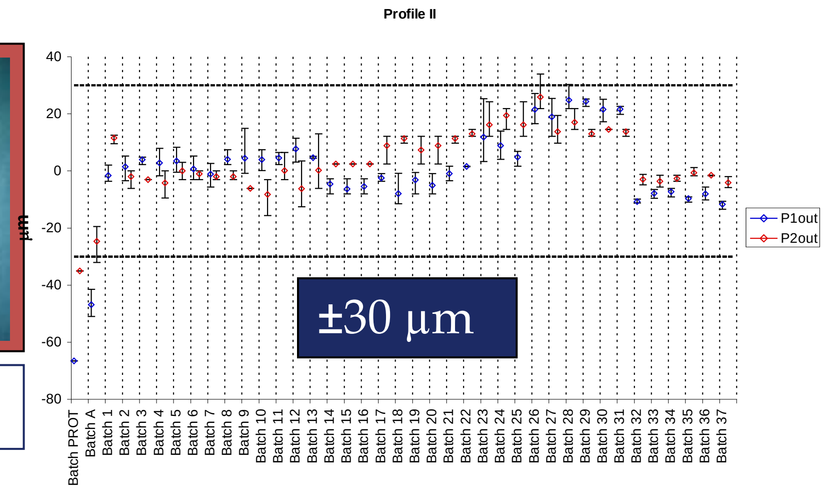
Cable for main dipoles : delivery

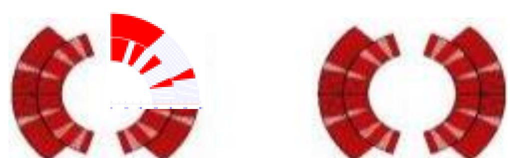


Dipole cross section: cable and copper wedges

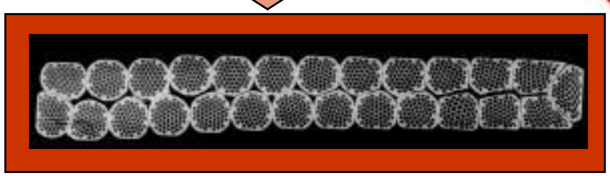


Cu wedges





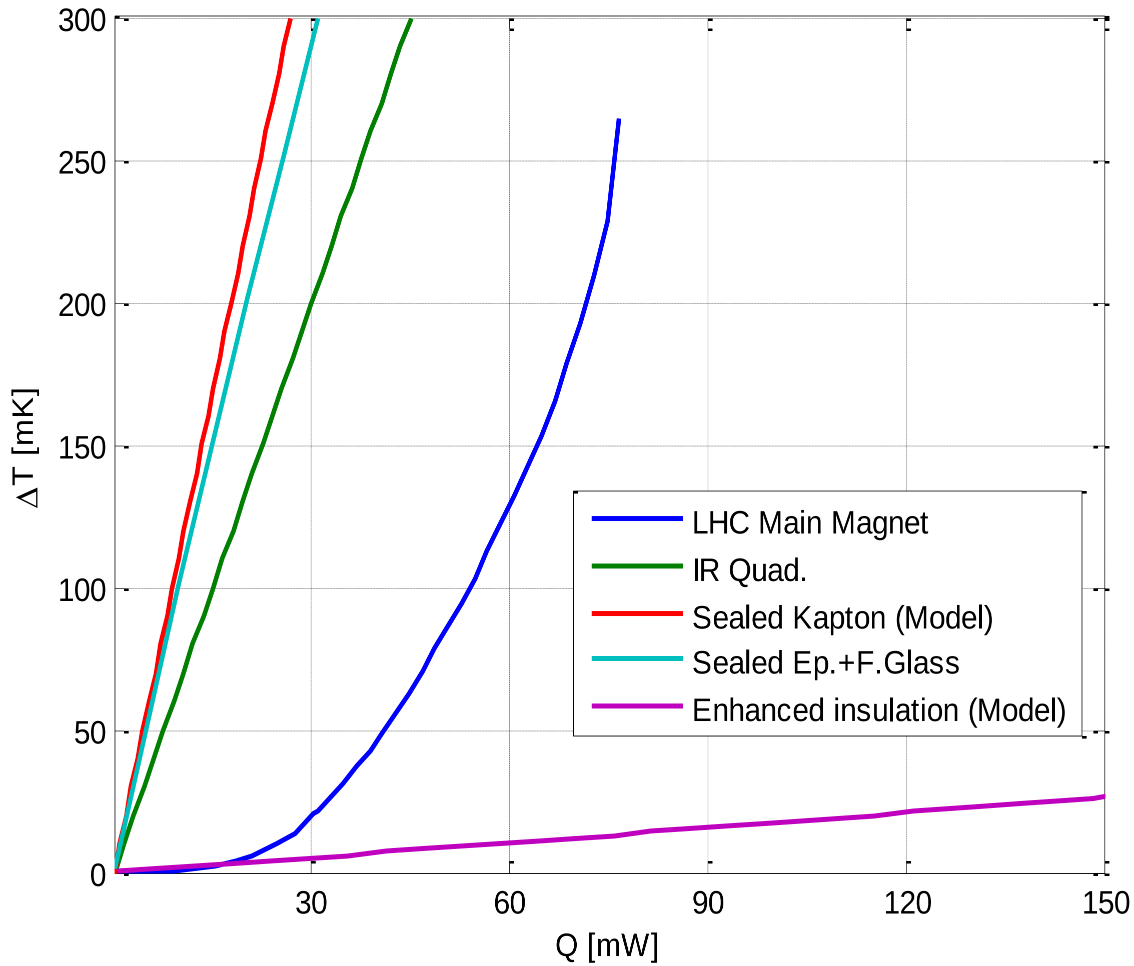
Dipole X-Section

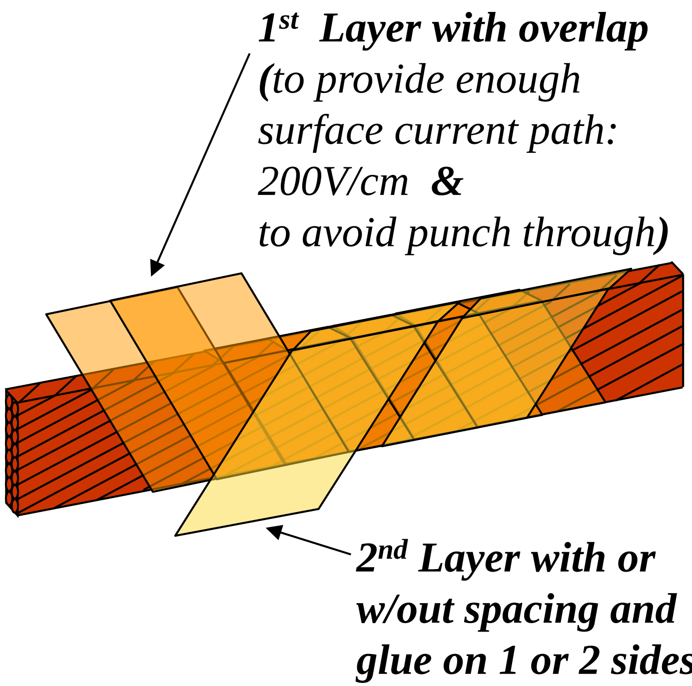


Rutherford cable

Mid-thickness ±6 µm
Key-stone angle ±0.05 deg
Width 0/+80 µm

Insulation and heat removal

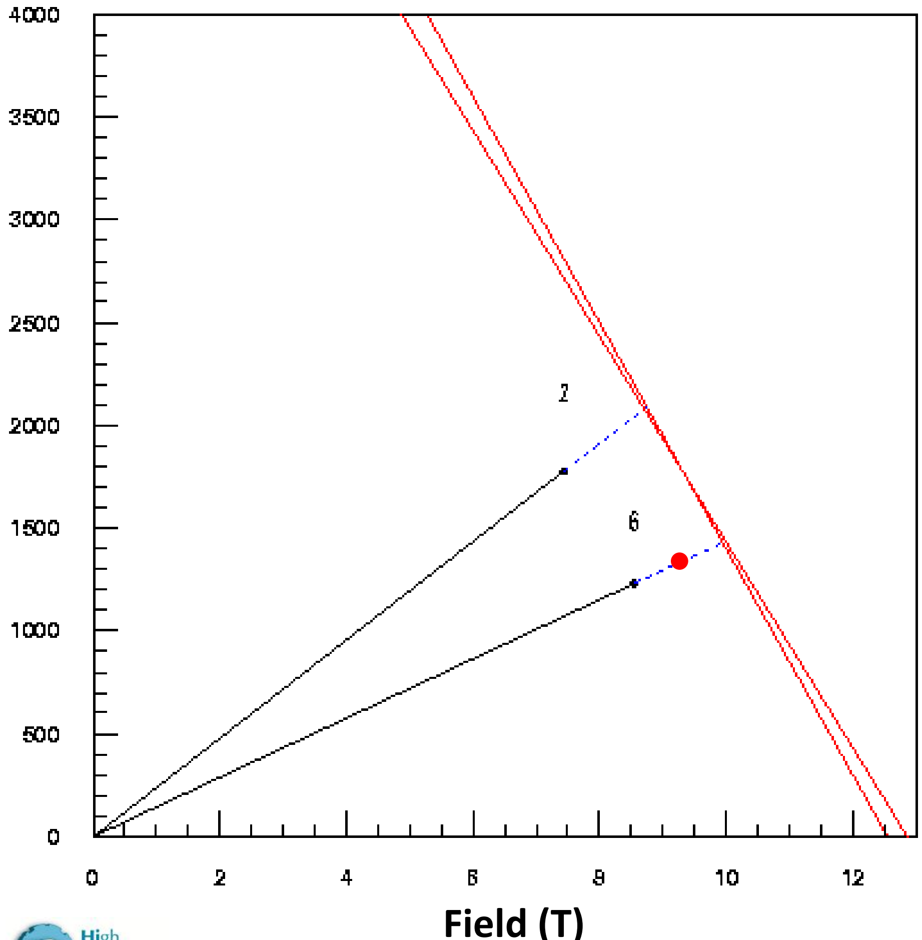


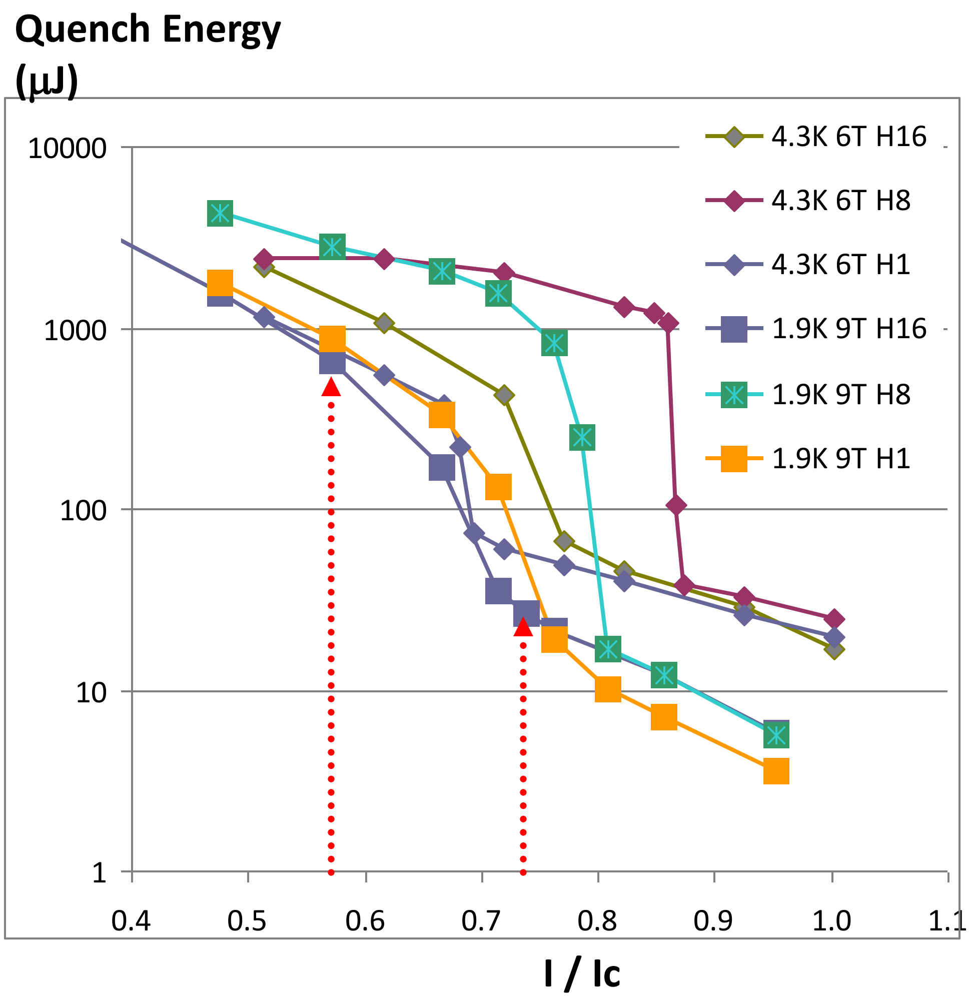


This translate in about 10 W/m of heat tr. from coil to the bath

High Luminosity LHC

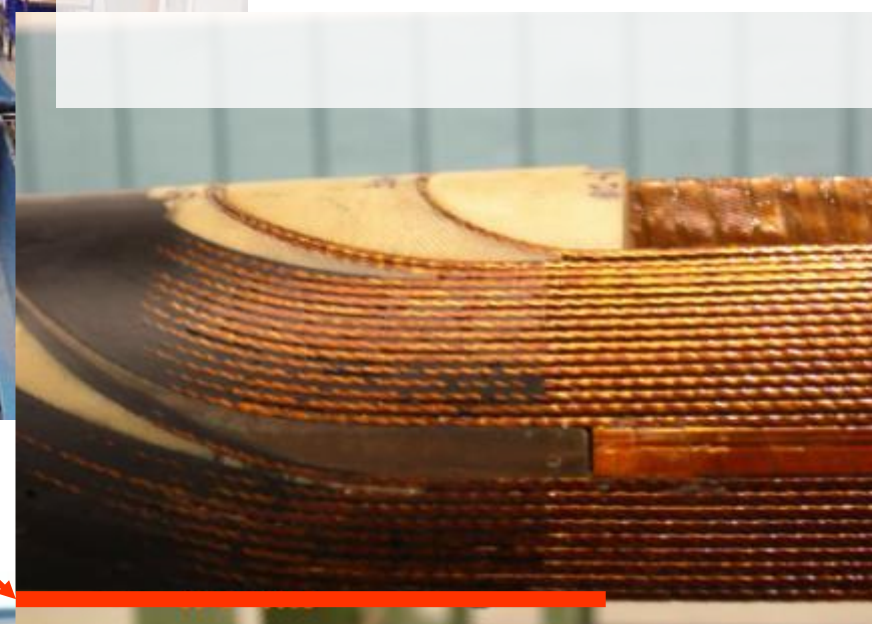
Operating point and stability



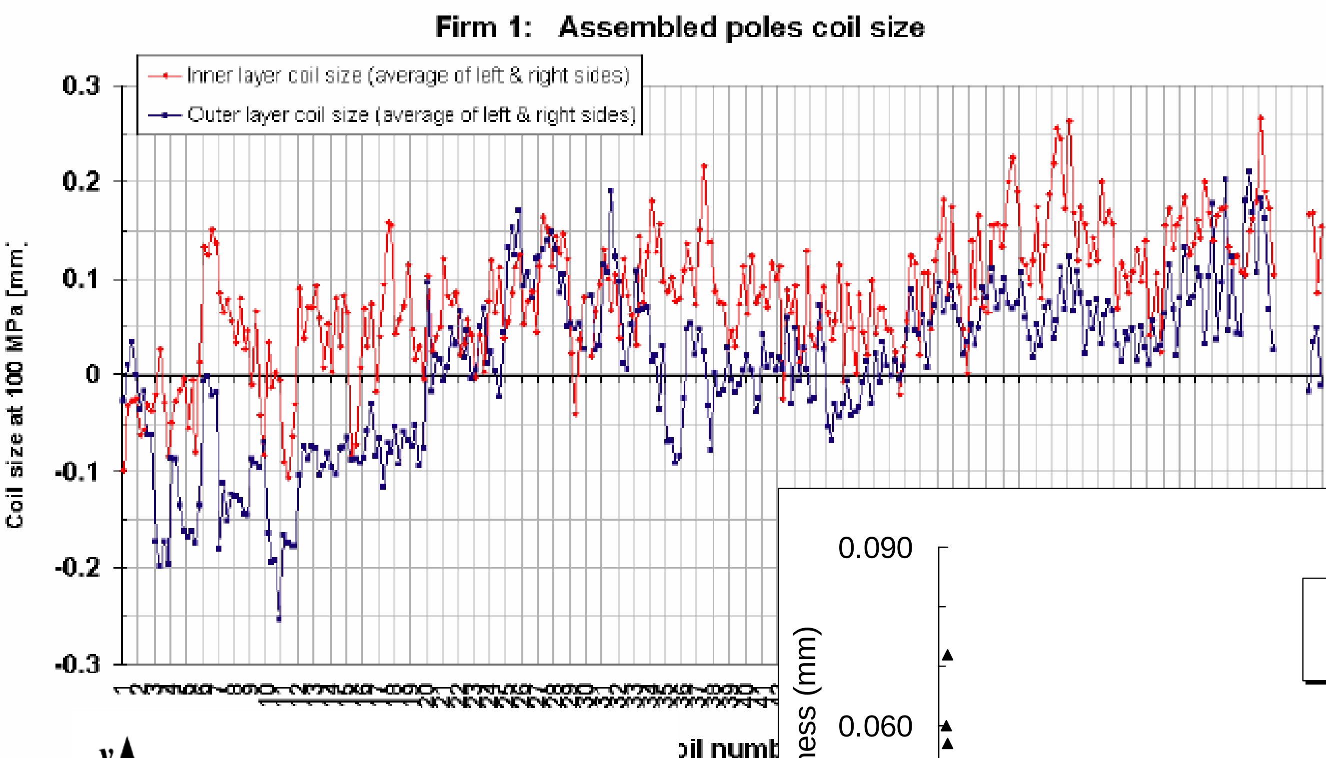


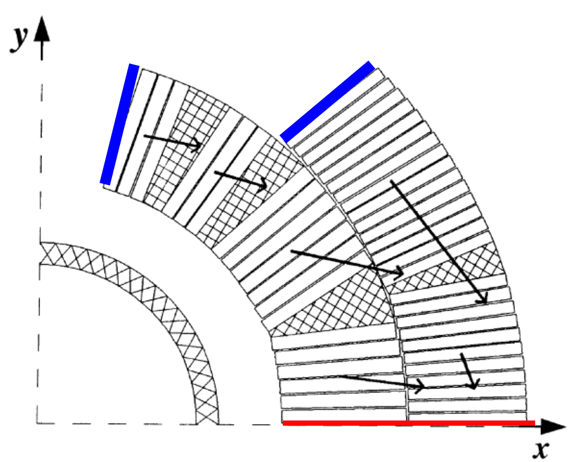
Coils - Winding

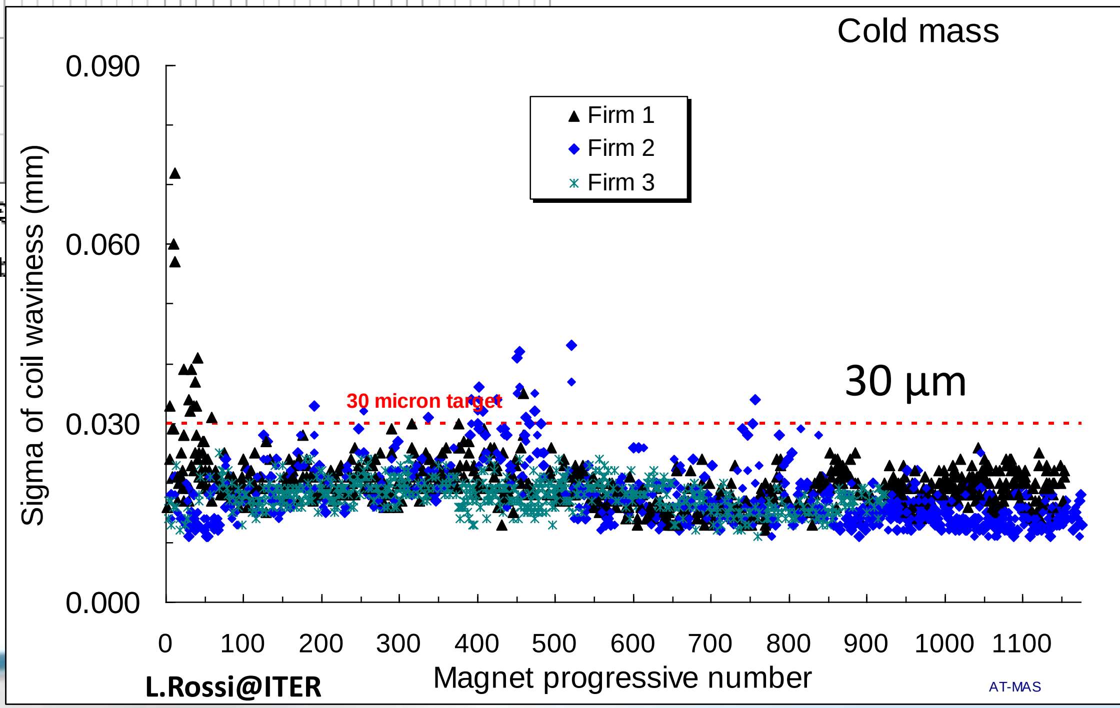
- Accurate positioning
  ⇒for quench
  ⇒for field accuracy
- Winding
- Curing at 185 °C
- 3-D: ends. Quasi-impregnation



Critical Process
Winding-Curing-Coil

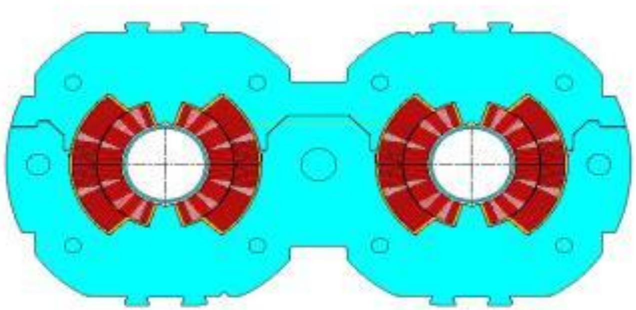


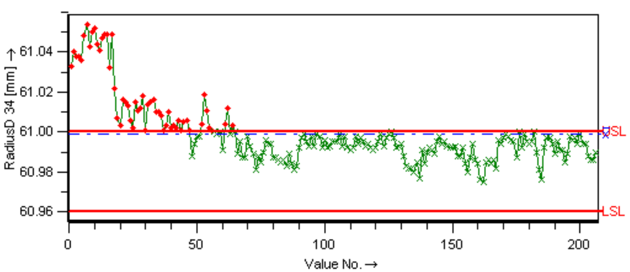


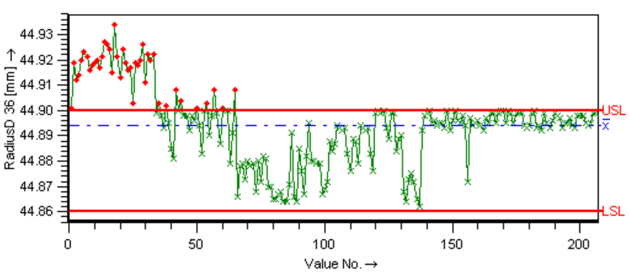


Dipole cross section : Collars

Collars and collaring are the main controllers of the final coil shape Fine blanking of special austenitic strips (μ_r<1.005).

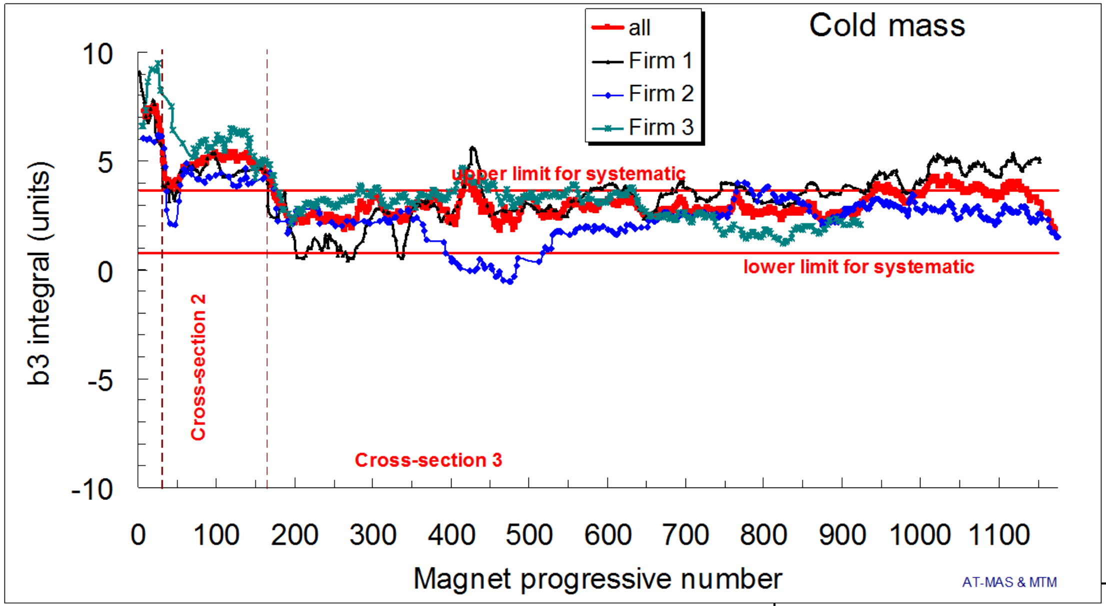






- Collaring press
- > 20 MN/m
- 700 mm wide
- 450 mm high
- Beam accuracy 20 μm

Ultimate QA: Magnetic Measurements

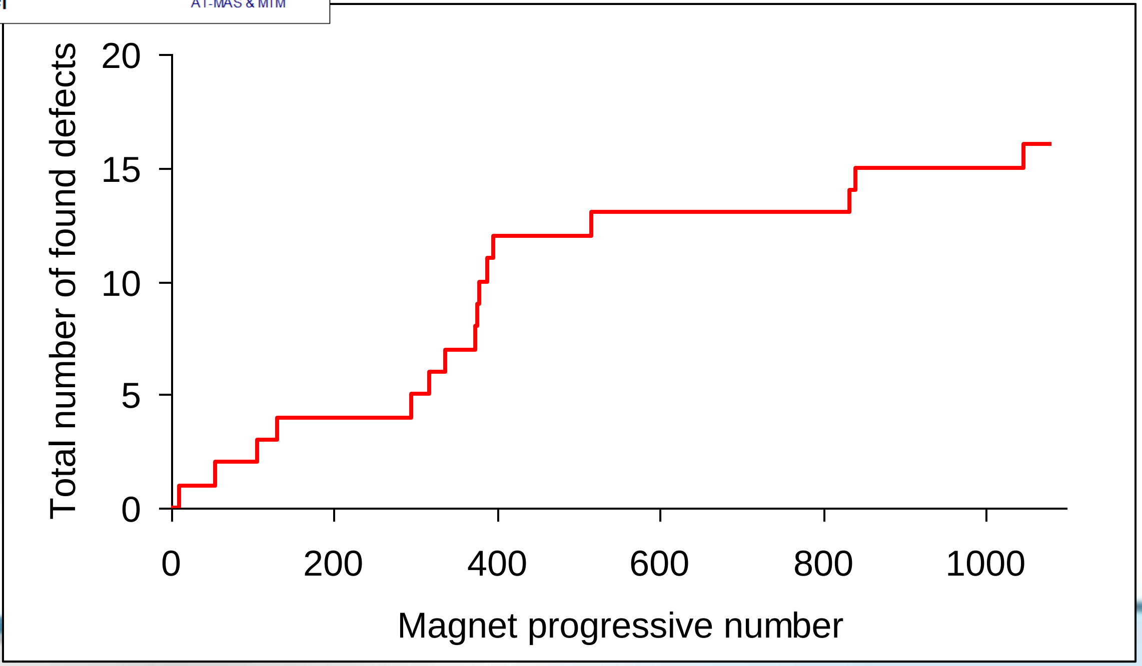


Introduced first to steer the FQ toward beam dynamics targets.

To get it right we need model that predict position and deformation at the level of 10-20 micron

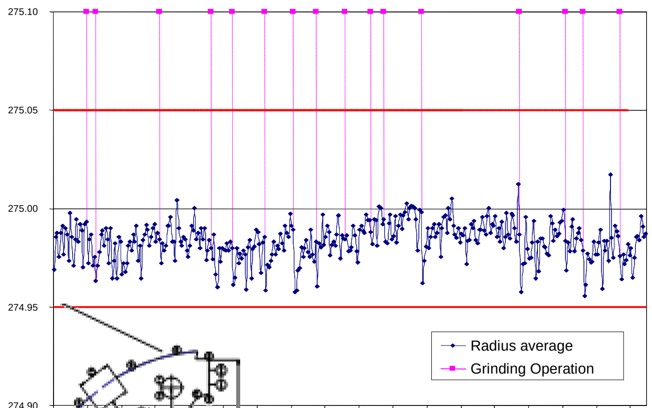
It has also helped to detect a number of defects.

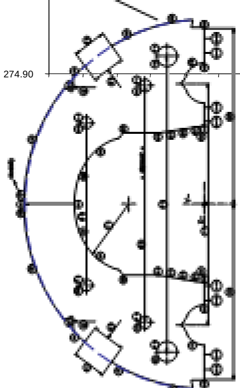
It has also been used to detect subtle electrical shorts



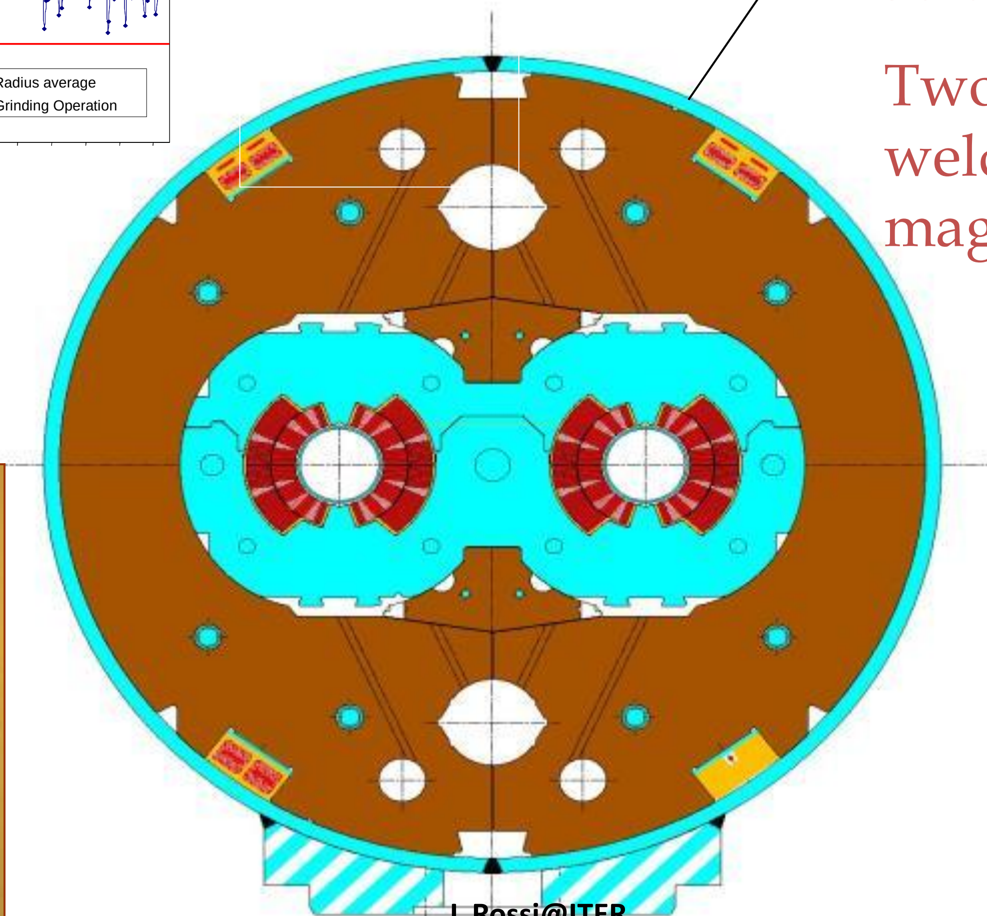
High Luminosity LHC

Dipole cross section: yoke & shrinking cylinder





Also MQ
(Only the steel)

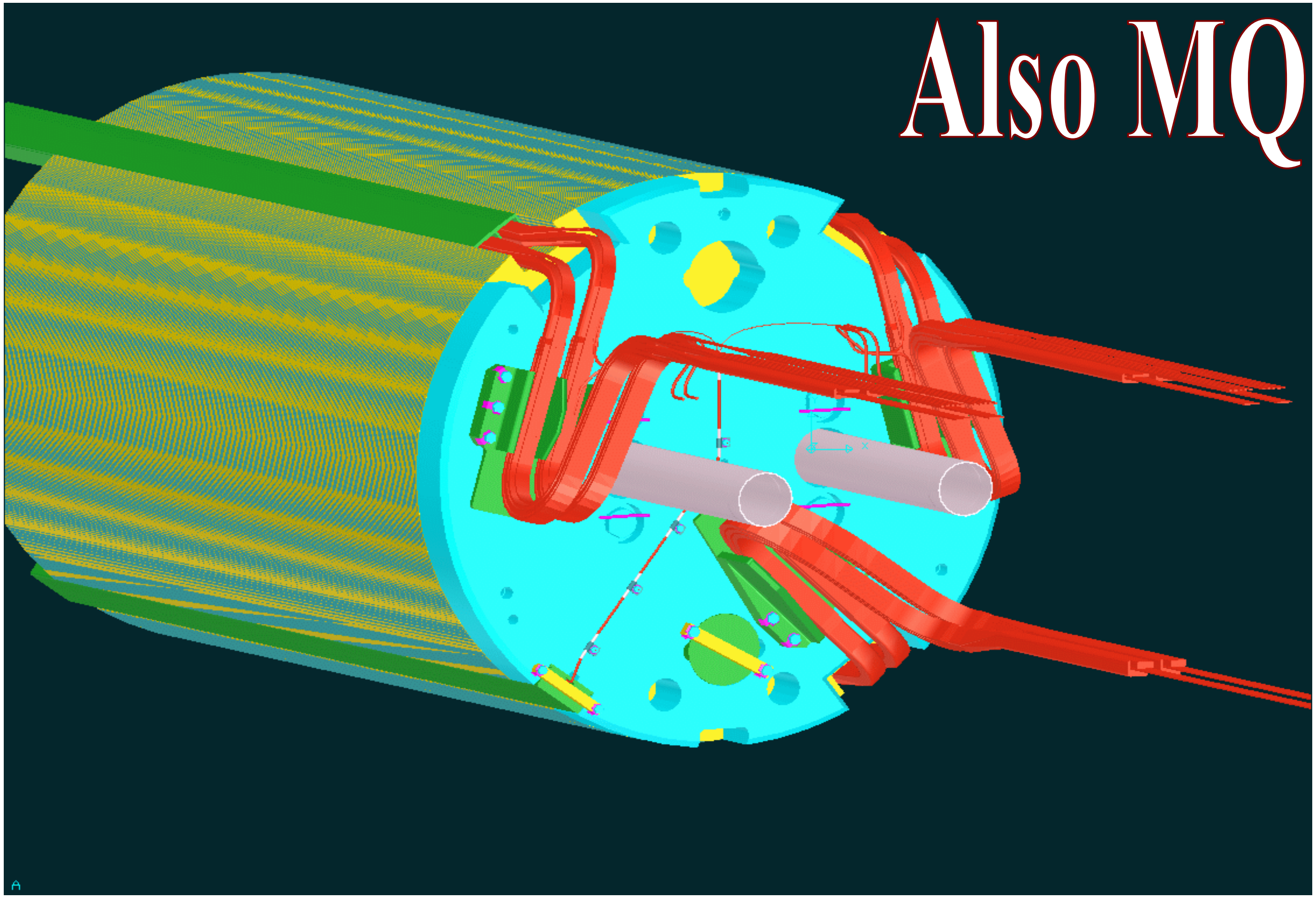


Curvature released from ± 1 to ± 2.5 mm:

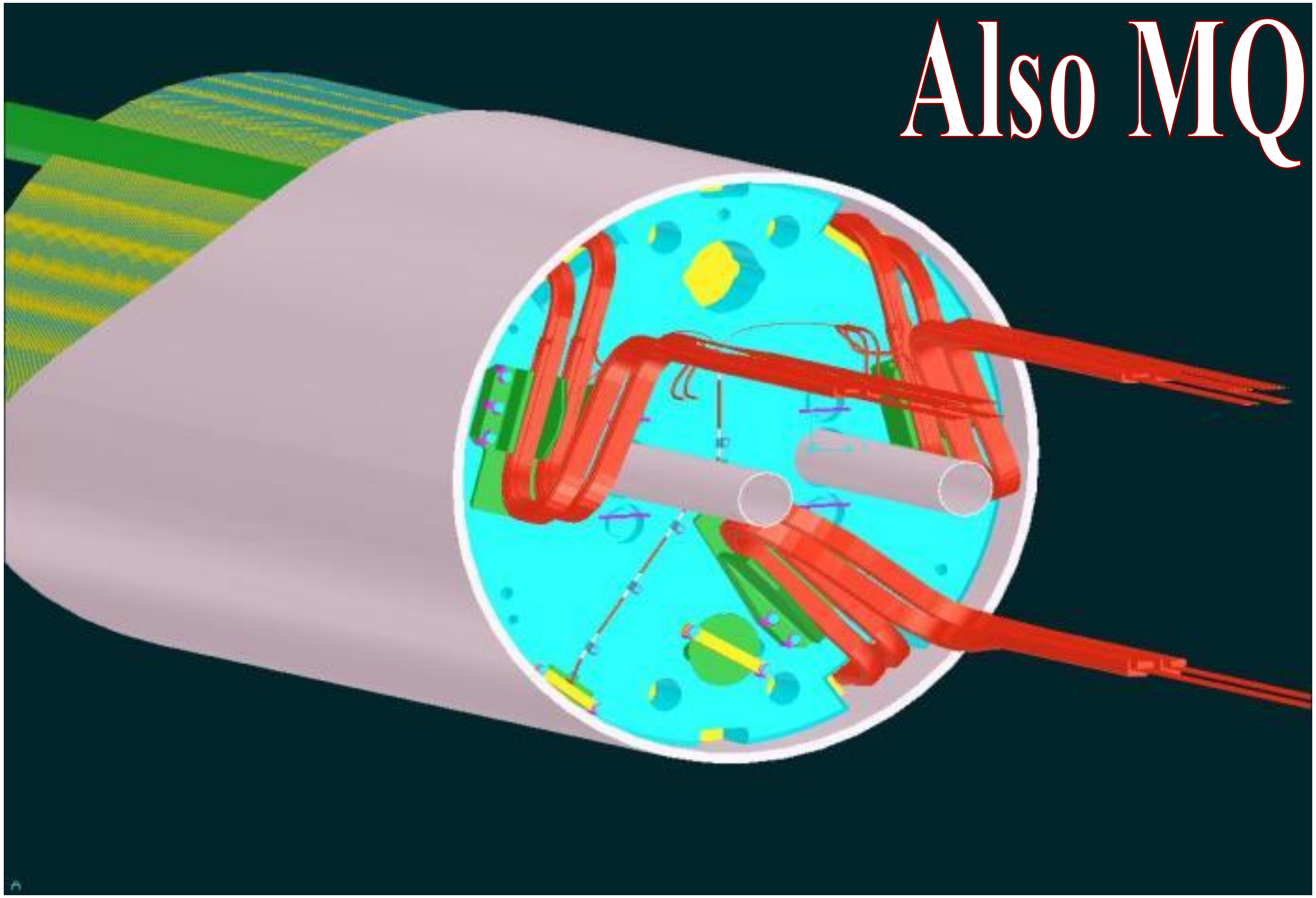
Solution: pairing

Two half shells, welded on the magnet

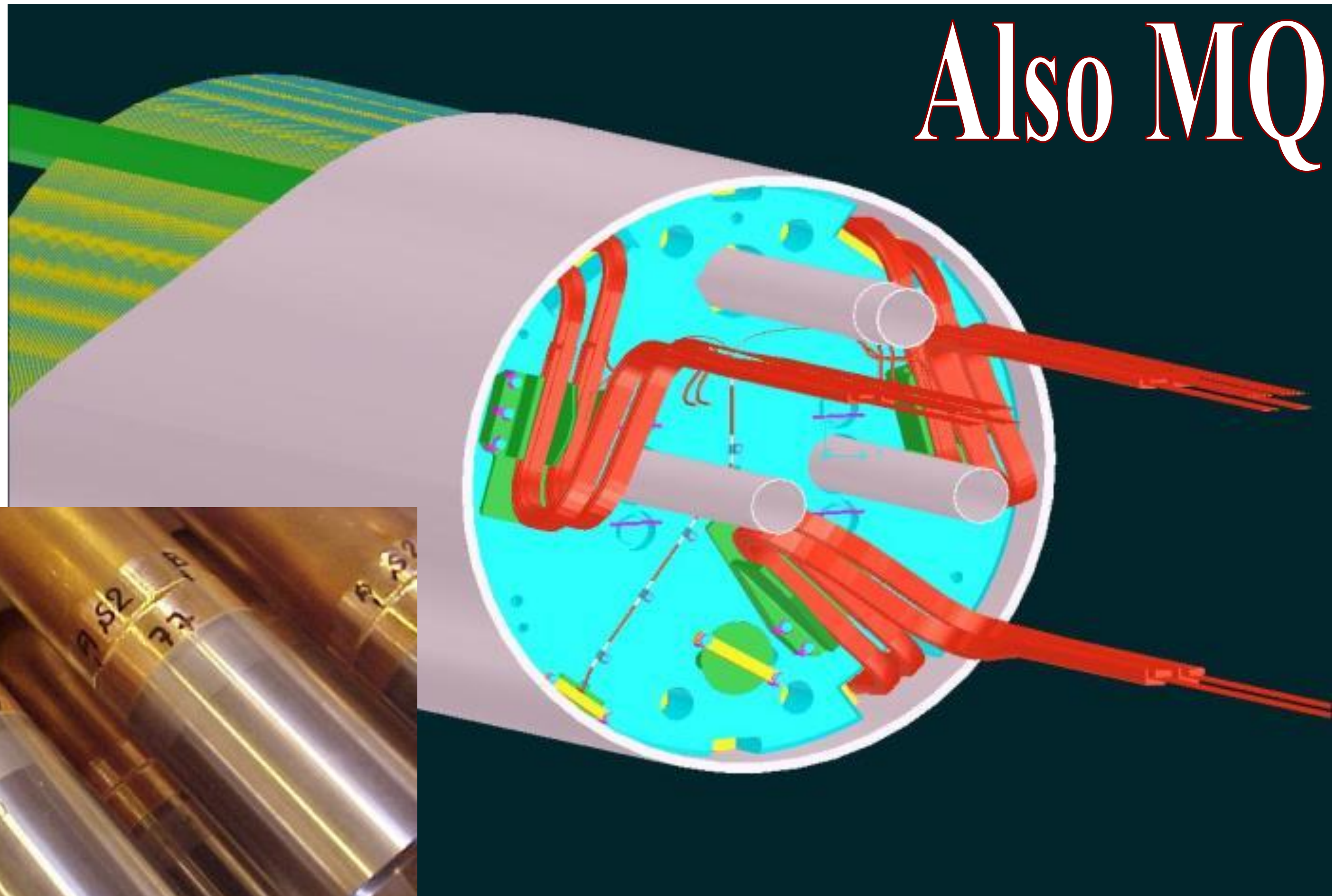
Dipole-end part
Bus Bars



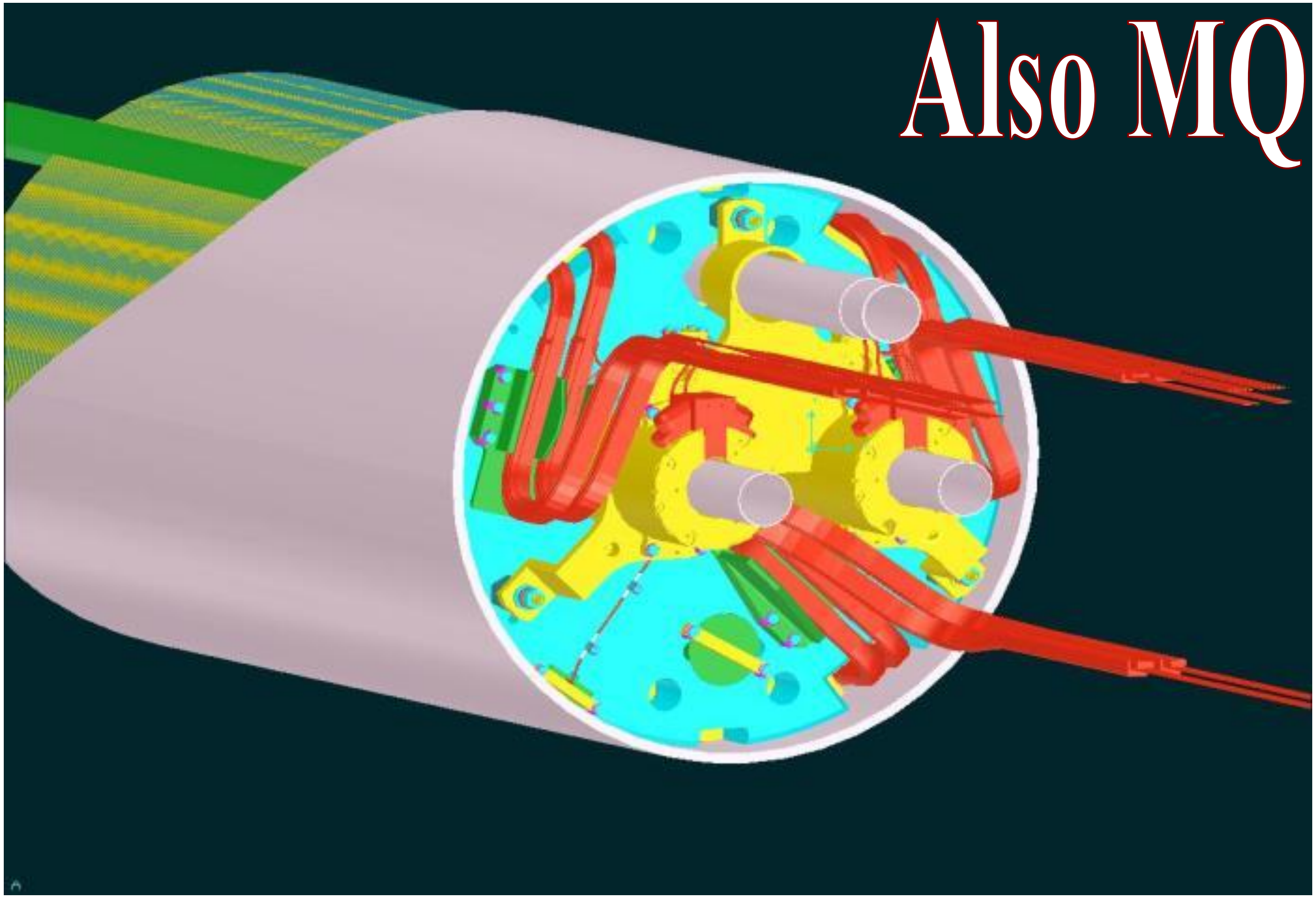
Dipole -end part
Shrinking cylinder



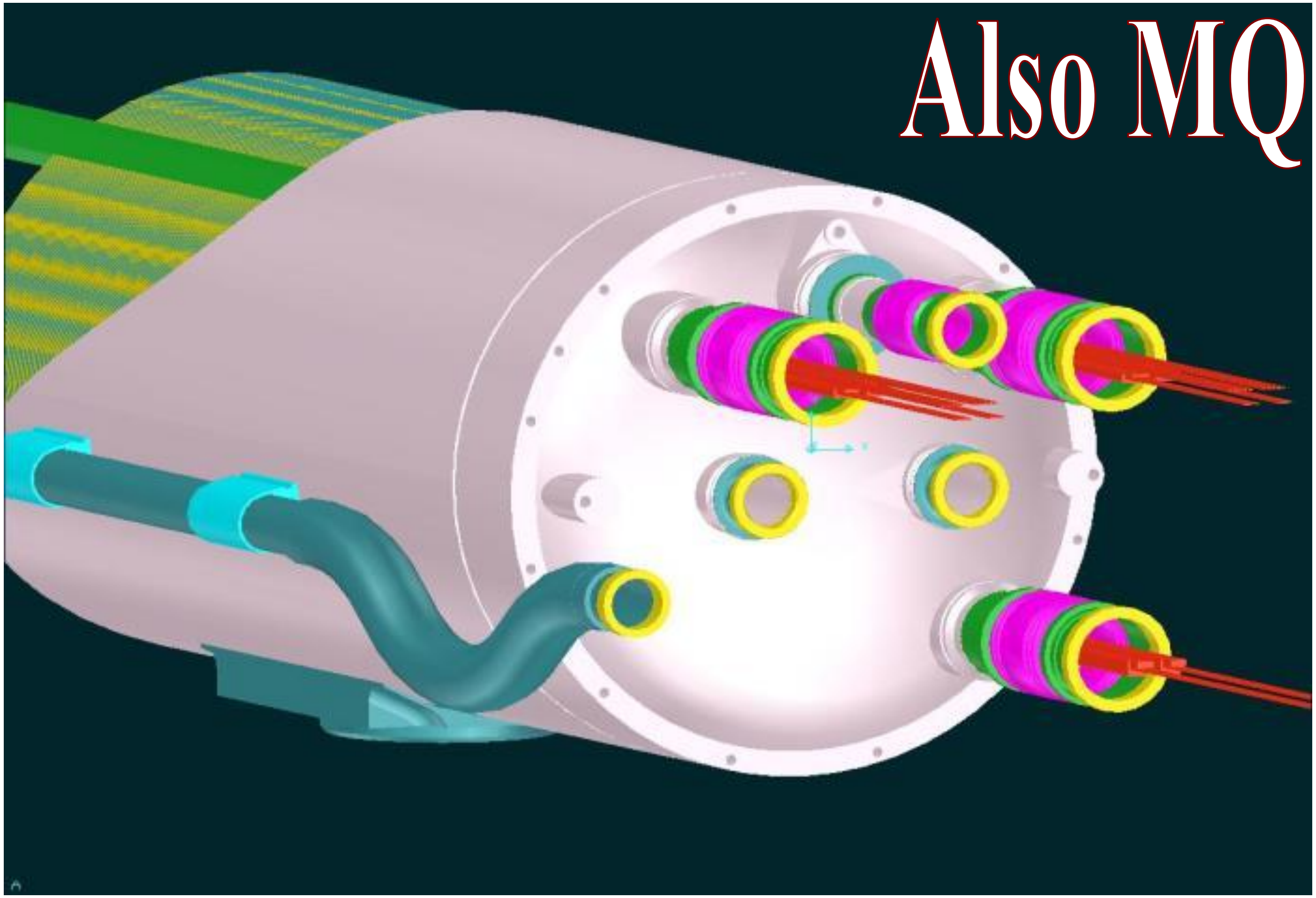
Dipole -end part
Cu HXT

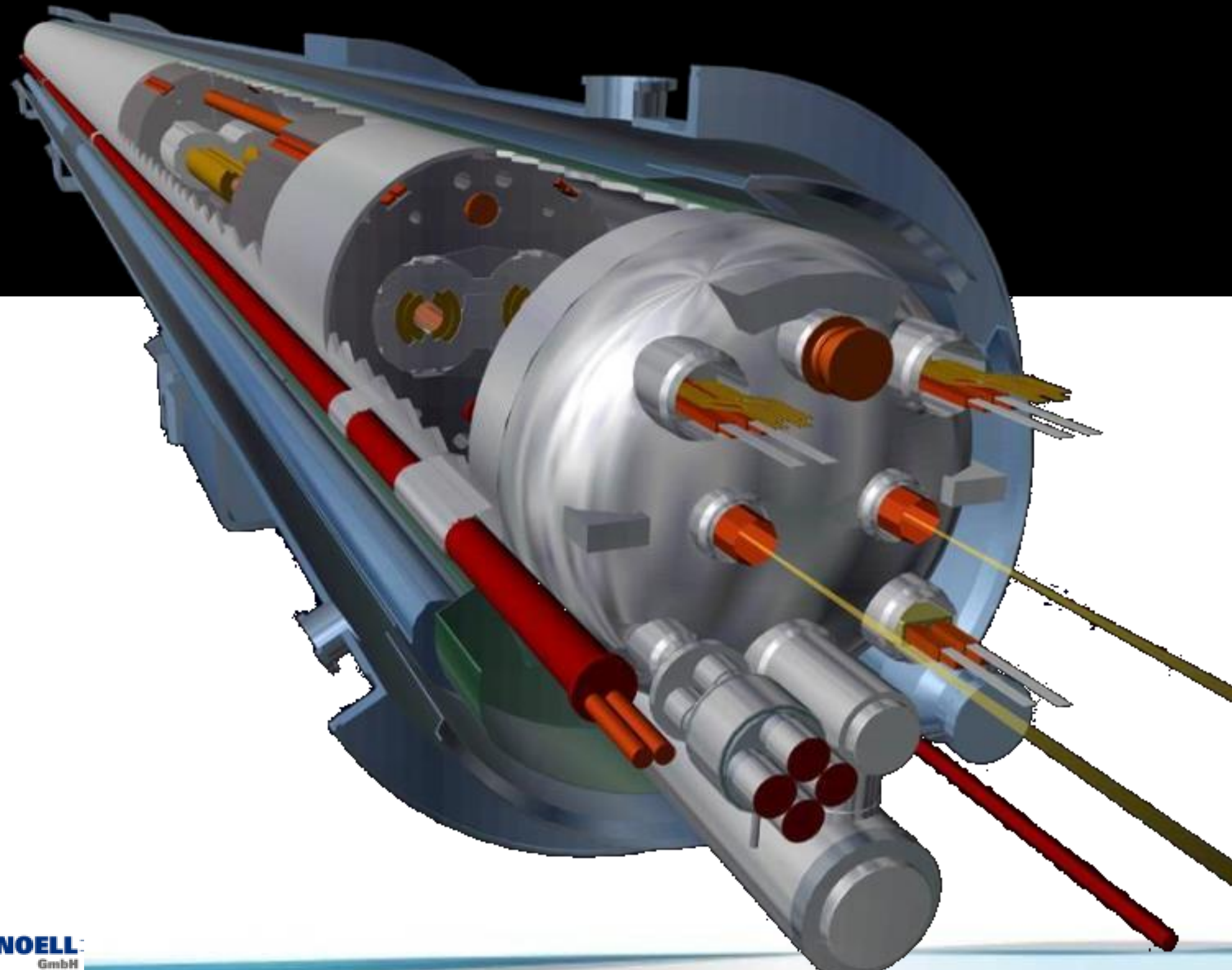


Dipole -end part
Corrector Magnets



Dipole -end part
Cold foot, Bellows and N-line





CERN

ALSTOM

FRAMATOME ANP
JEUMONT S.A.

ASG Superconductors

BABCOCK NOELL GmbH

Snapshot at Industry: Superconducting poles

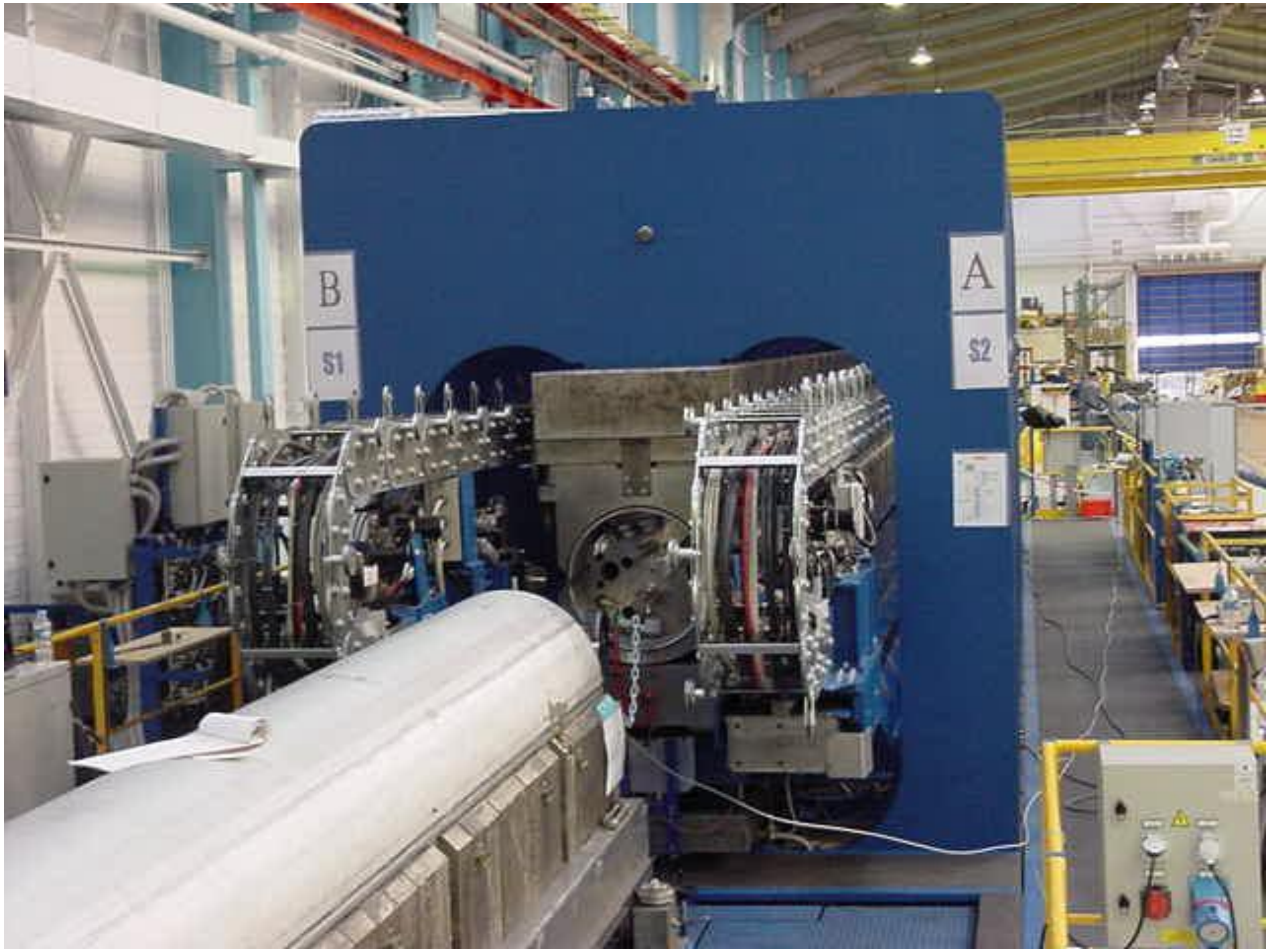
High Luminosity LHC

Snapshot at Industry: Aperture assembly

Snapshot at Industry: collaring process

Snapshot at Industry: The Welding Press

- 3 welding presses, 12 MN/m, aperture (mm) : 2000W x 1500H, 15 m long, beam accuracy 50 mm !!
- equipped with **new welding technique (STT)** for the route pass
- With calibrated curved half shells, and proper shaping under press the geometry is obtained in one go



Snapshot at Industry: Cold Mass

Laser Tracking measurements

Leica Geosystems

High Luminosity LHC

Snapshot at Industry: Cold Mass waiting

ACCEL

More than 7600 of various corrector magnets

Superconducting LHC dipoles: the long route

1988-98 short models and six prototypes for each of the three generation design were built by industry/CERN

1999: 3x30 pre-series magnets were ordered from three firms.

Three contracts for the fabrication of 1146 (+30 spares) magnets have been signed March 2002

Integrated supply chain management

CERN took care of most components

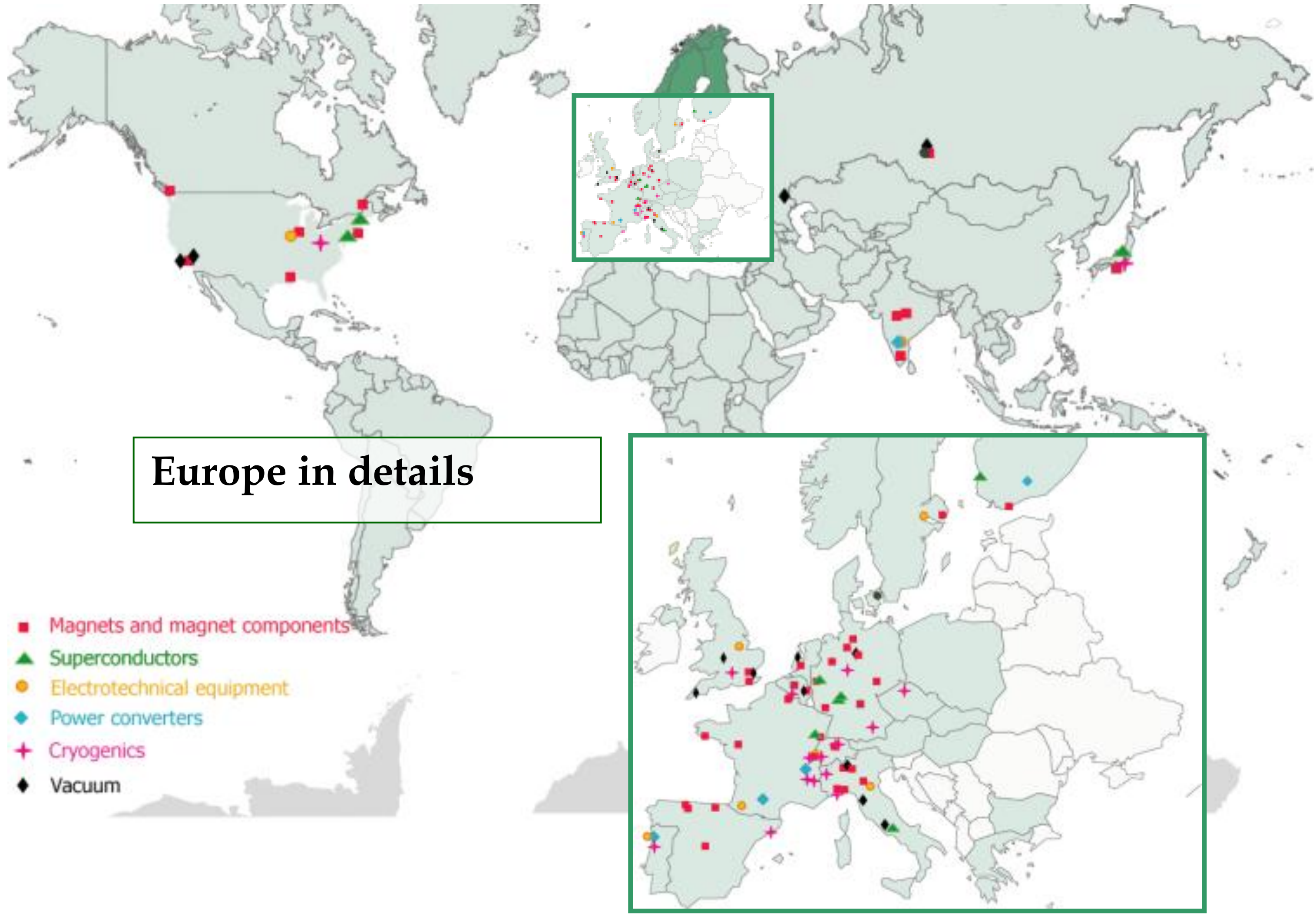
Benefits

- Technical homogeneity
- Quality assurance
- Economy of scale
- Security of supply
- Balanced industrial return

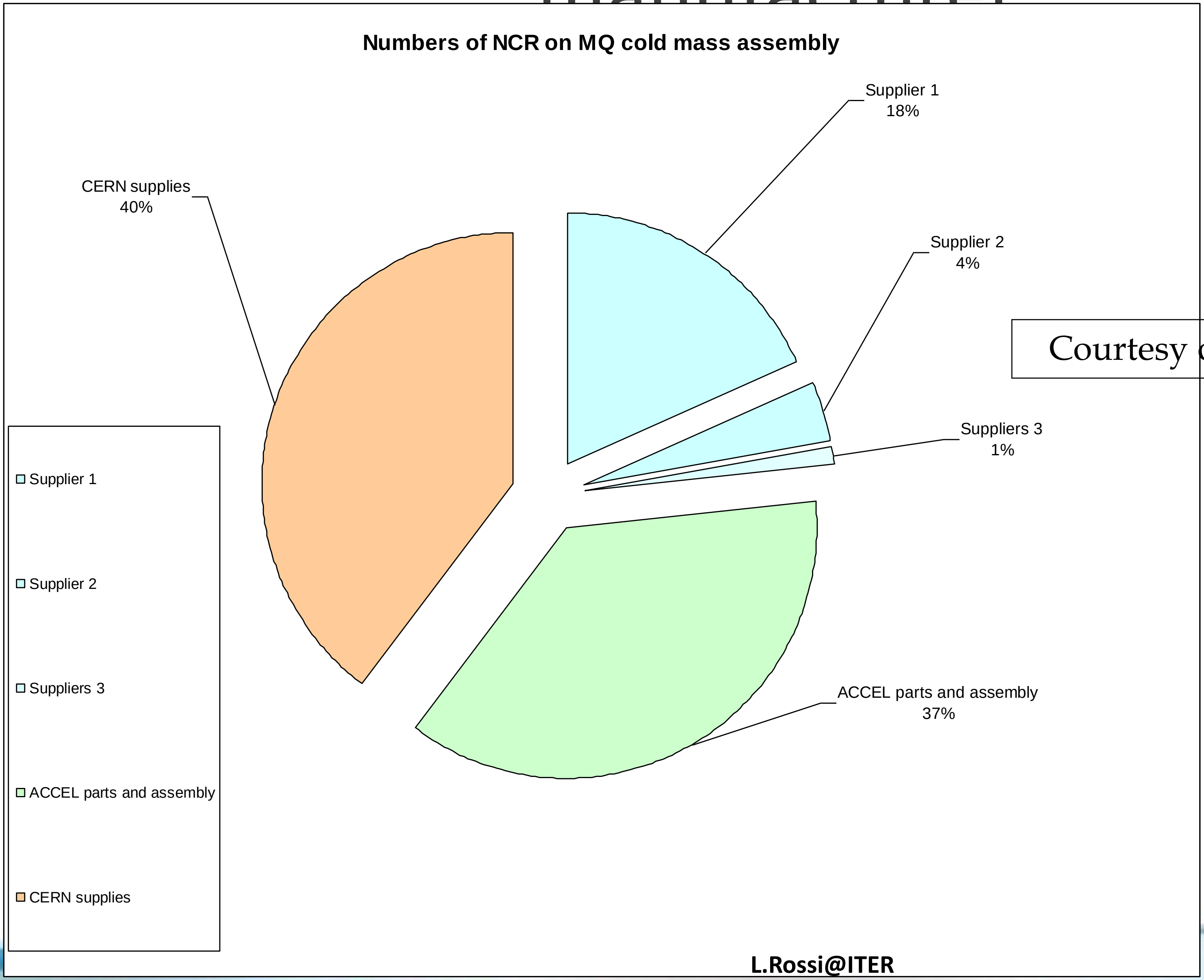
Risks & drawbacks

- Responsibility interface
- Additional workload
- Liability for delays (just in time!)
- Transport, storage & logistics: we have moved 120,000 tonnes around Europe (5 TIRs a day for 5 years)

90 main supply contracts worldwide



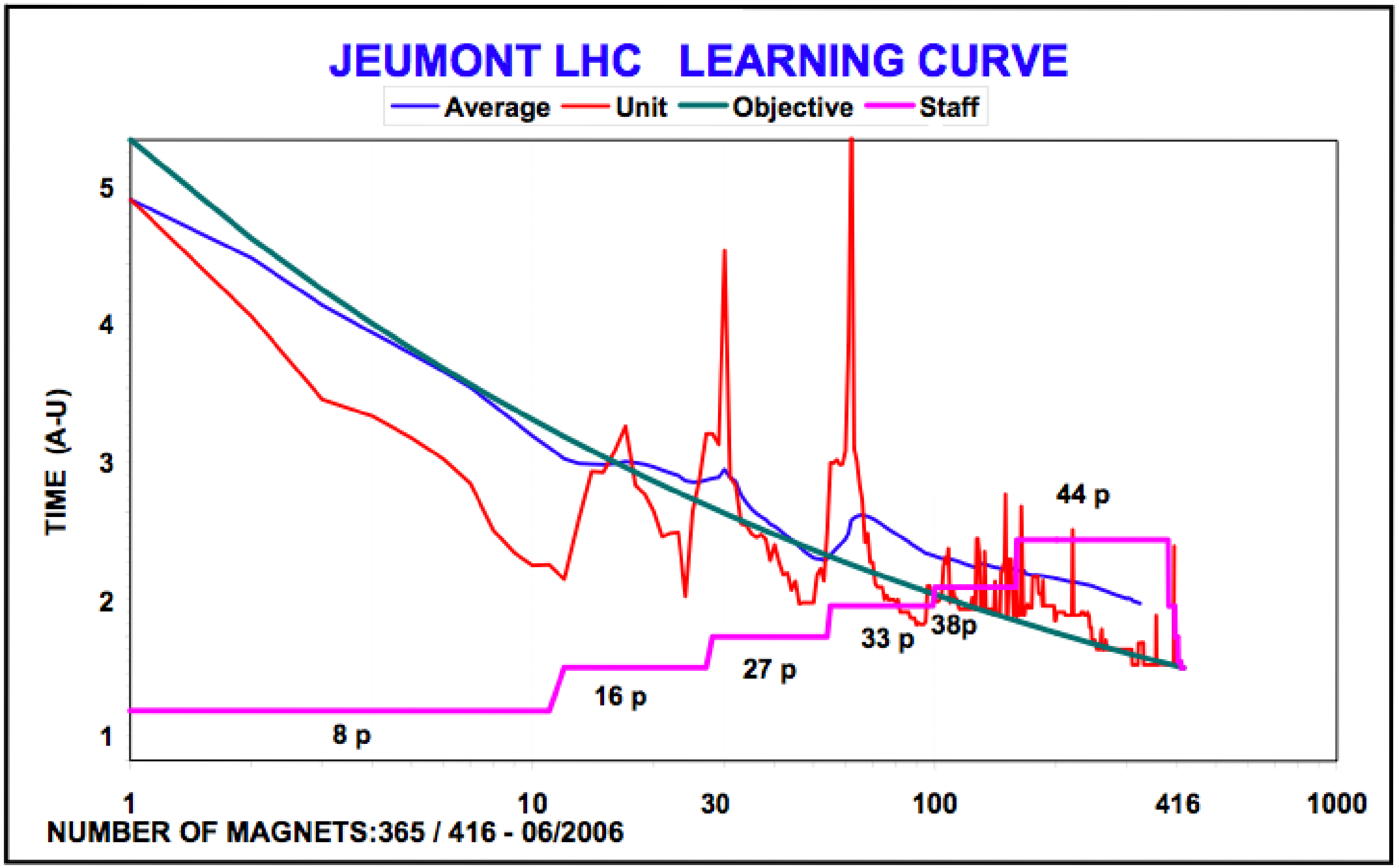
Statistics of Non-conform. At one manufacturer



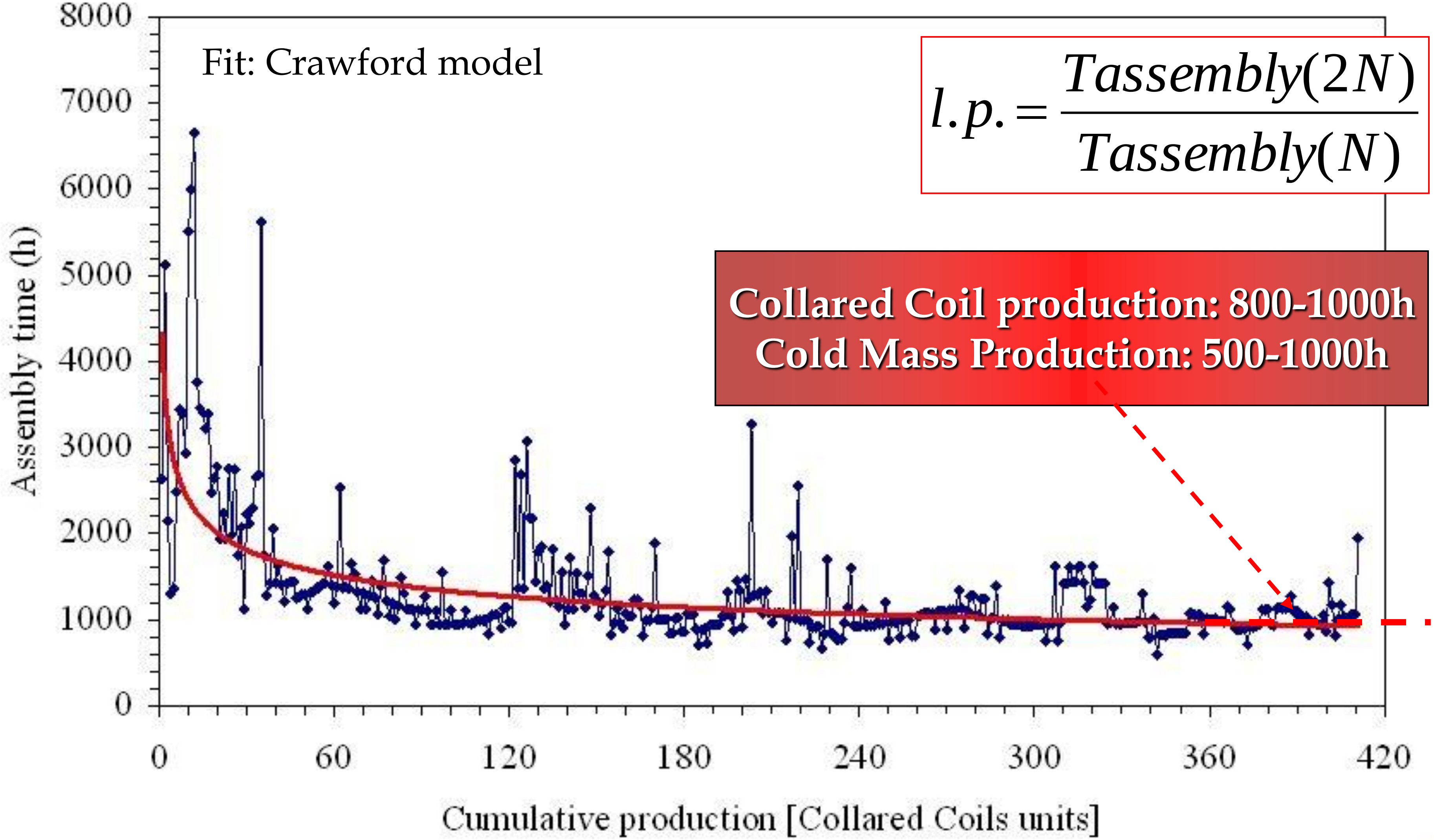
Courtesy of Accel, Germany

Personnel training in Coil production

Courtesy of Jeumont, France



Log Linear model learning curves: Firm 3



Courtesy of P. Fessia and F. Regis

Comparison with other industries

Industry	ρ
Complex machine tools for new models	75%-85%
Repetitive electrical operations	75%-85%
Shipbuilding	80%-85%
LHC magnets	80%-85%
RHIC	85%
Aerospace	85%
Purchased Parts	85%-88%
Repetitive welding operations	90%
Repetitive electronics manufacturing	90%-95%
Repetitive machining or punch-press operations	90%-95%
Raw materials	93%-96%

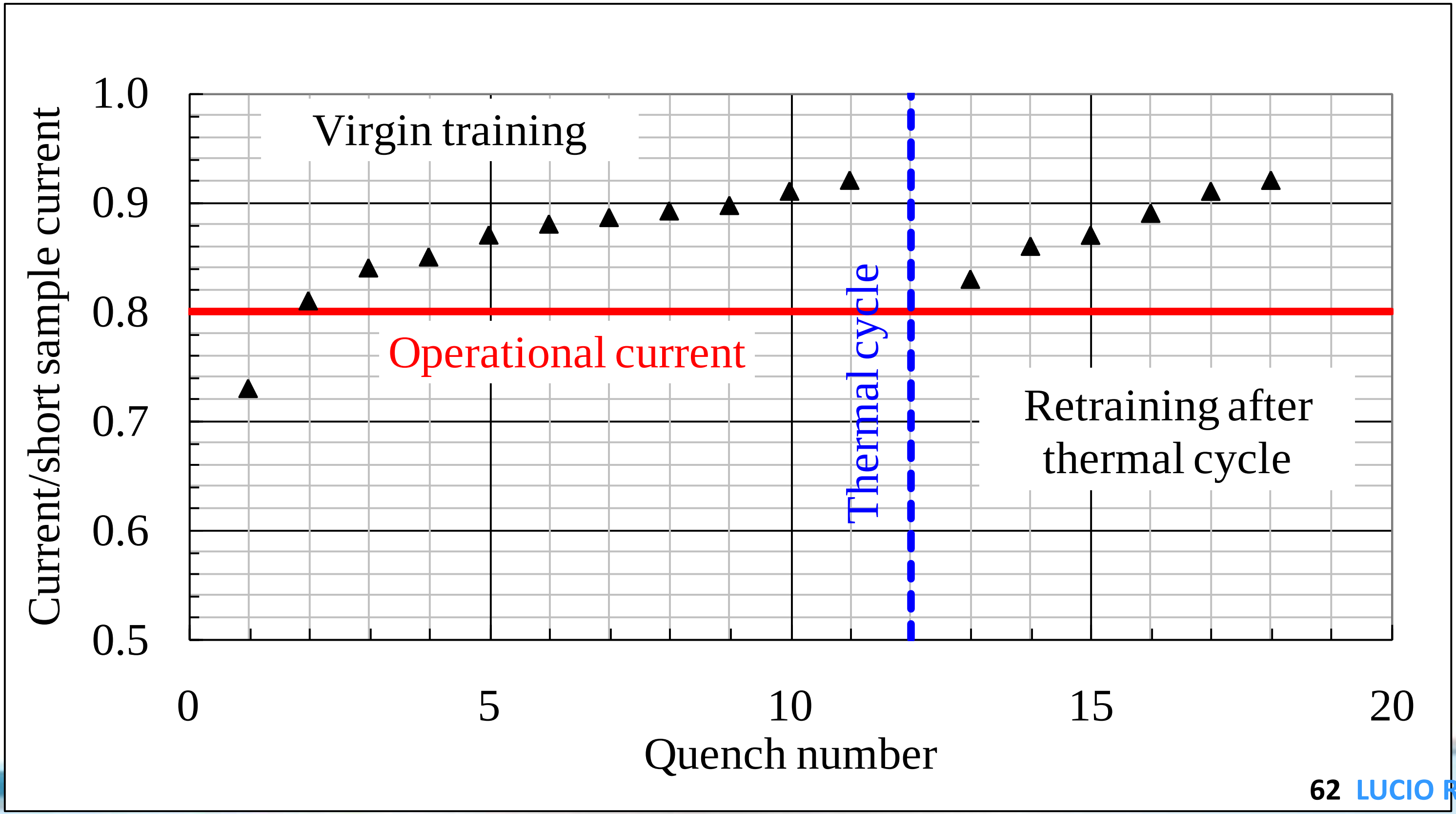
LHC Main Dipoles

High Luminosity LHC

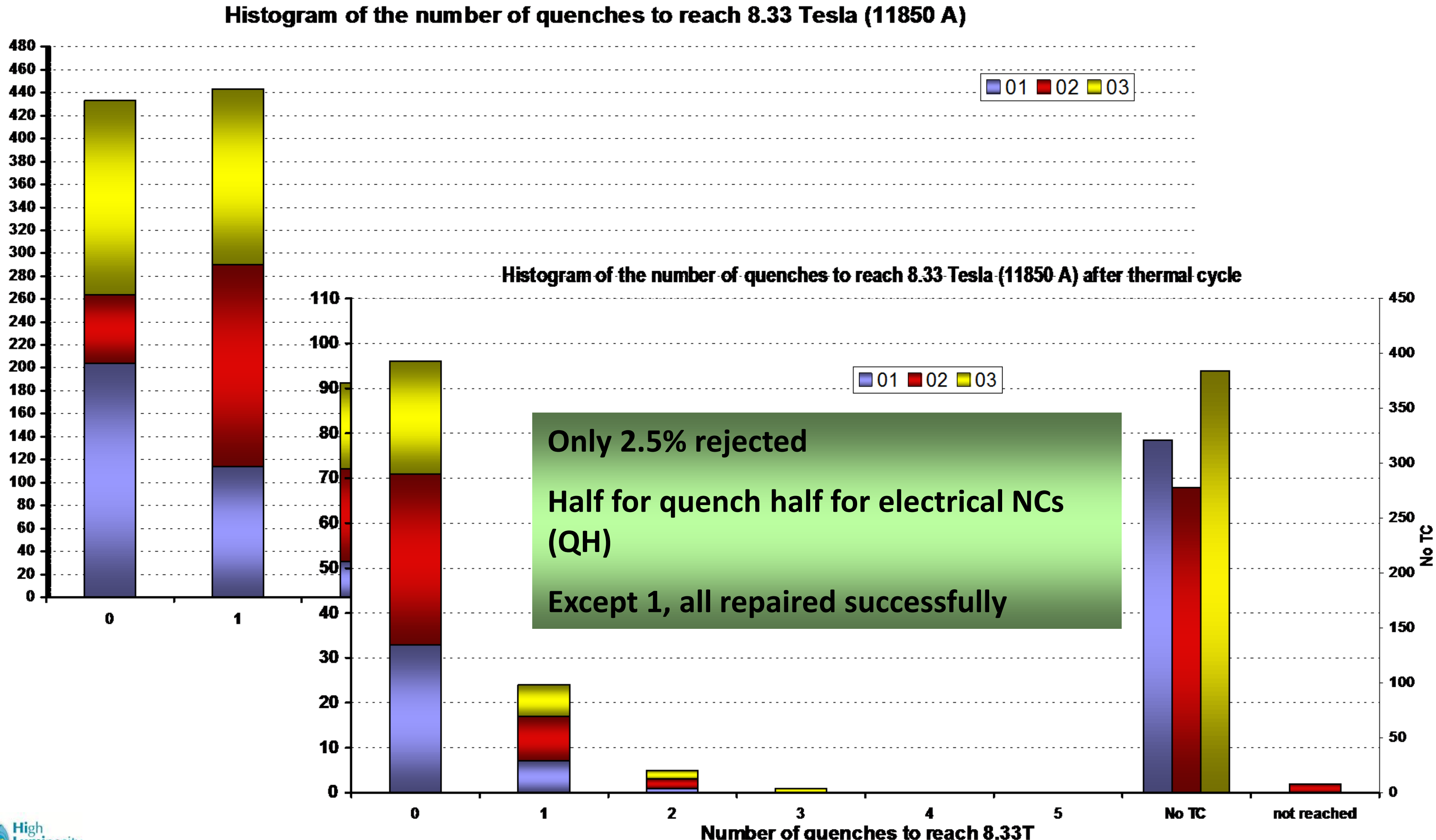
A happy end of industrial production

LHC Dipole : typical quench performance

- **1-2 quench to pass nominal field (8.3 3 T, 0.86 of I_{quench}**
- **Further 4-5 quenches to reach ultimate design field of 9 T at 0.93 I_{quench} : actually half of the dipole reached 9 T with 0-2 quenches (bonus magnets)**
- **For first 30 magnets and then for the 10% worst magnets of the 1200 remaining dipoles we did a thermal cycle**
- **Almost all the re-tested dipole went over the nominal current with no quench**



Dipoles : quench performance -results



Only 2.5% rejected

Half for quench half for electrical NCs (QH)

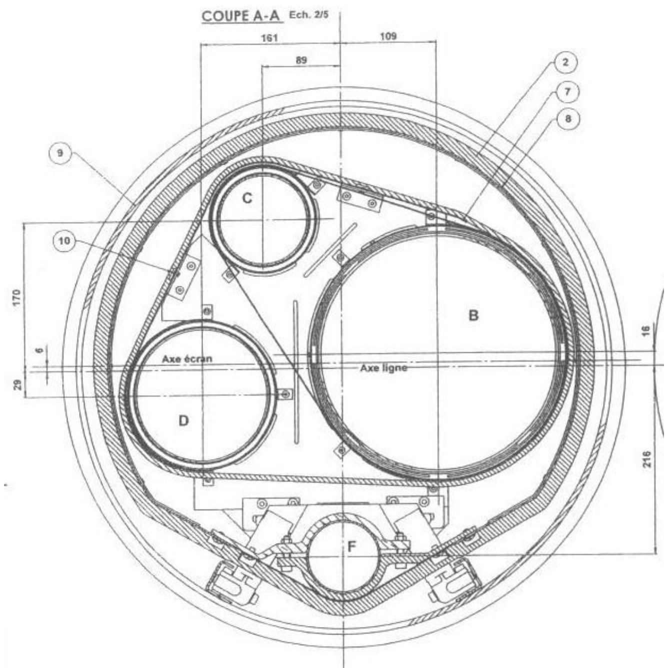
Except 1, all repaired successfully

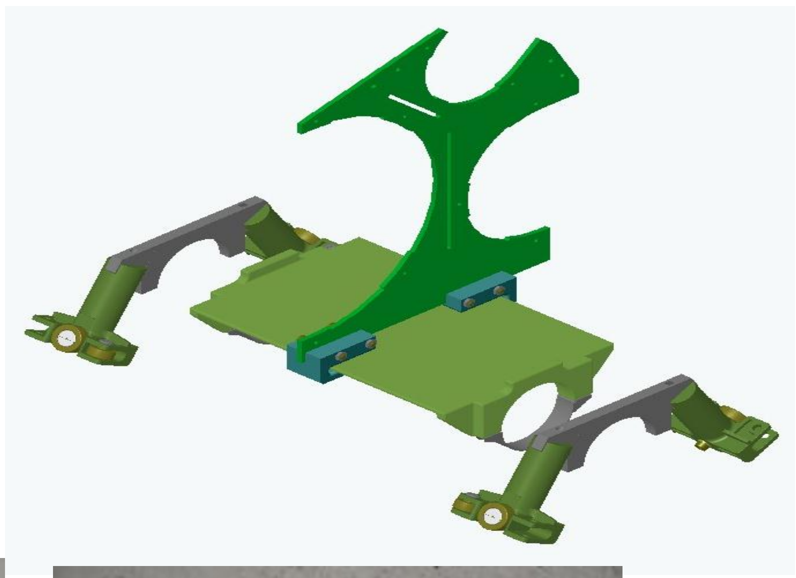
Magnet work flow at CERN (schedule 2006)

1st dipole lowered : 7th March 2005

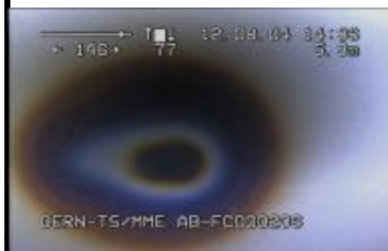
Serious problem: Cryoline QRL

Sliding table





Welding defects – inspection of 18 service modules in August 2004

	Temper colour 100 %		Scaled surface 100 %
	End crater pipe 100 %		Root concavity 30 %
	Root porosity 50 %		Incomplete root penetration 45 %

Further cause of deay: Cryofeedboxes

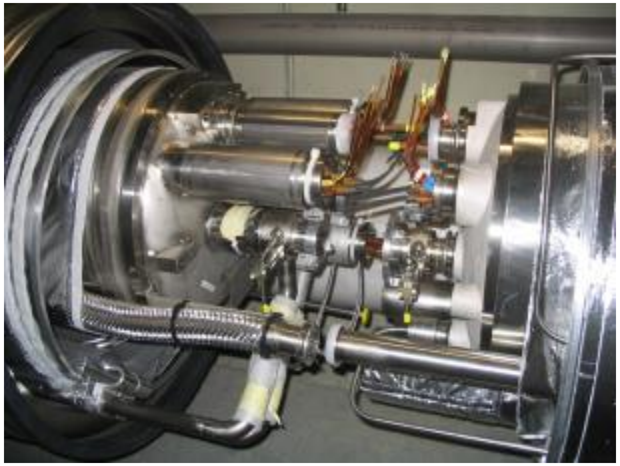
Production in Protvino & CERN

CERN re-insourced activty ended in May 2007

High Luminosity LHC

Main tunnel work : IC
Effort IC recovered part of delay

- Late start, accelerated rate
- > 200 people in the tunnel at peak
  - > 100 contractor
  - 100 CERN+associated for managing, QA, repair, in-sourcing of special WPs

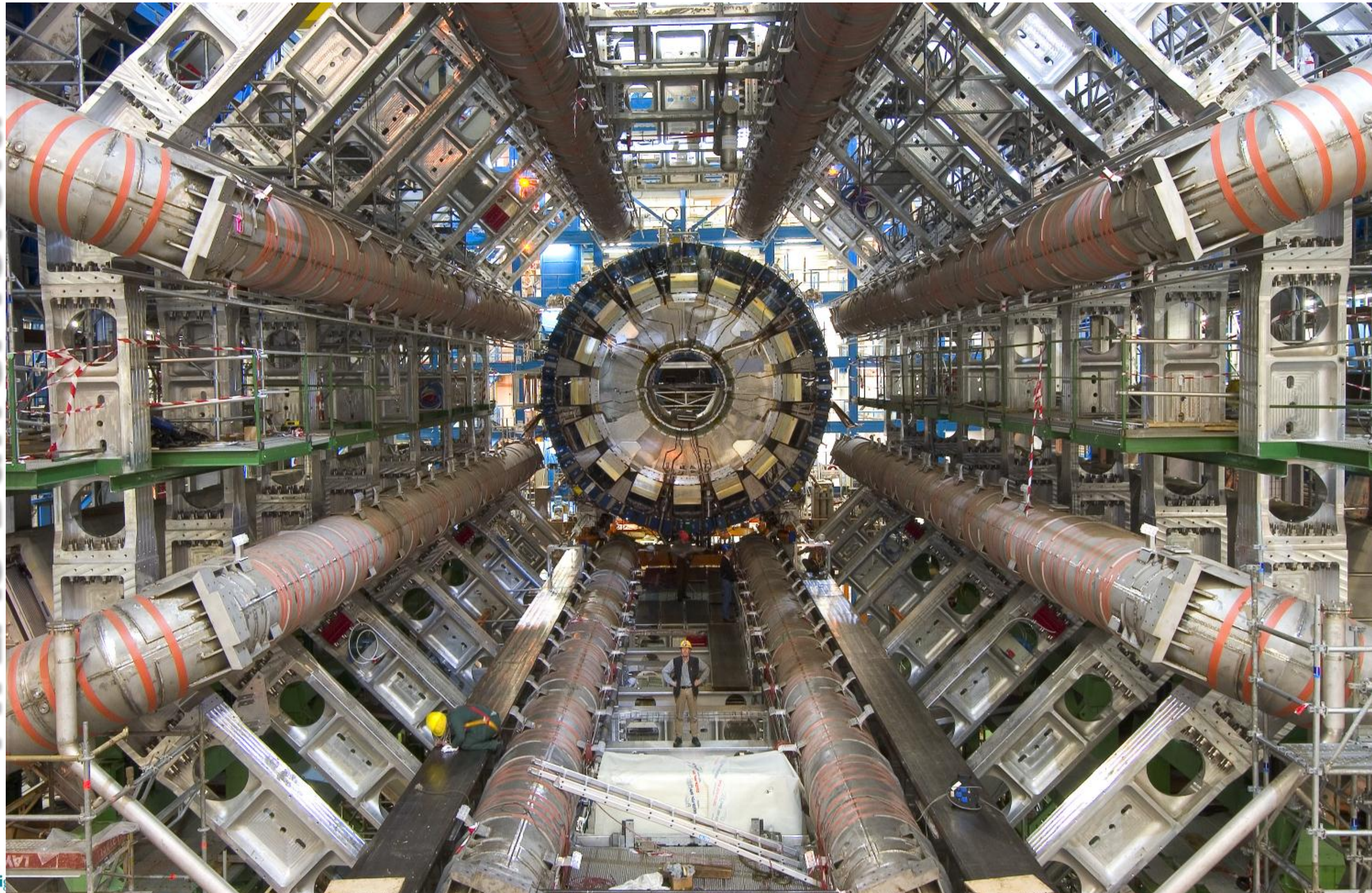


High Luminosity LHC

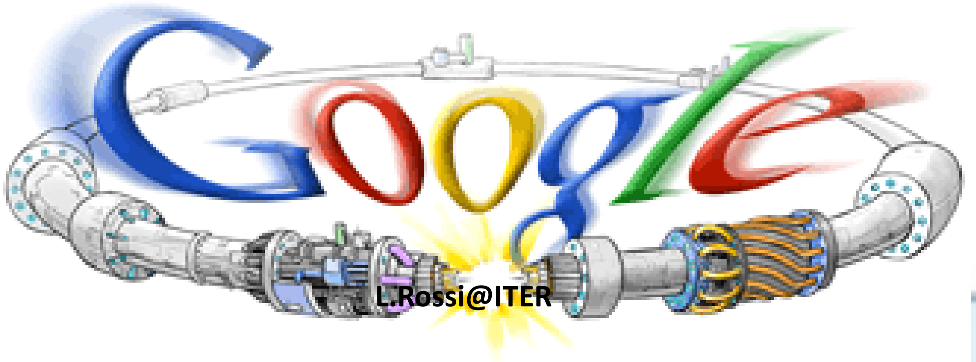
Large SC Magnets at 1-4 T for detectors

Scope: momentum spettroscopy ($\propto 1/BL^2$)

ATLAS Barrel Toroid



10th Set.08: the success



Protection in a chain: bypass diode-busbar

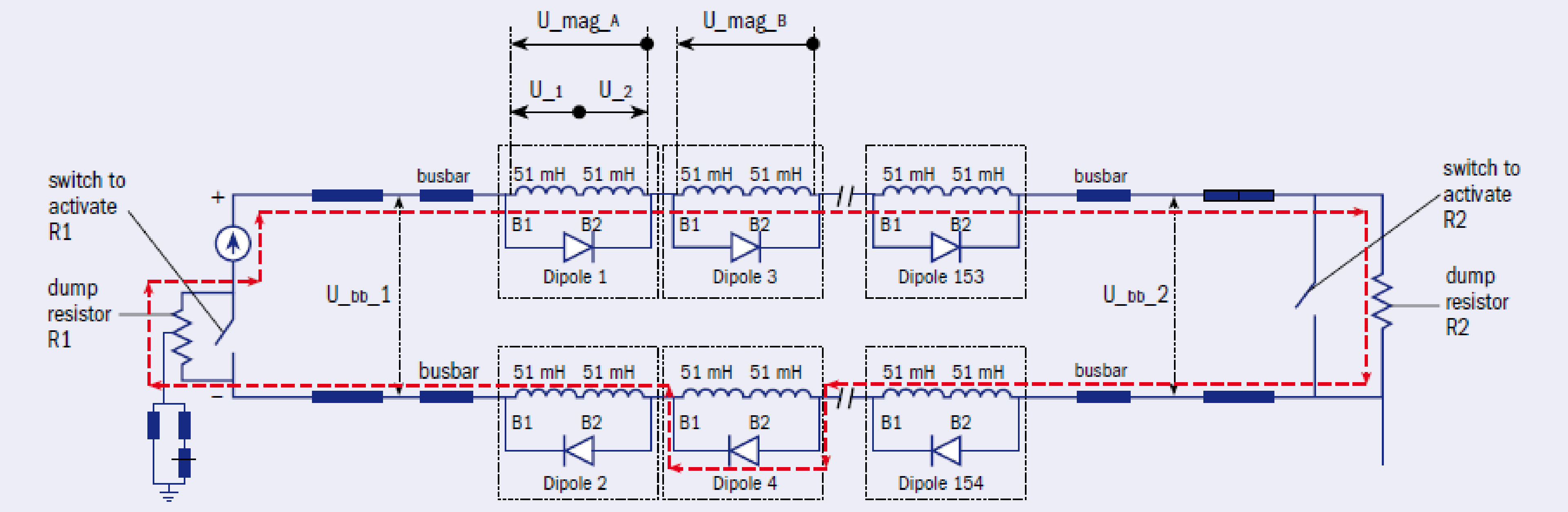


Fig. 1. The protection scheme of the LHC magnets. Magnet coils are connected in series and bypassed by a diode if there is a voltage rise. The path of the current is shown for the case of one quench (dipole 4 in this picture) after about 1 s, when all current has bypassed the quenched coil. At this stage the current passes through the dump resistors (R1 and R2), but in the circuit as a whole it is still very close to its initial high value.

We have about 10,000 12 kA connection between magnets (and 10,000 inside magnets), about 1000 6 kA, about 60,000 600 A between magnets and 60,000 inside magnets)

The incident (connection not executed) and problem left (not stabilized)

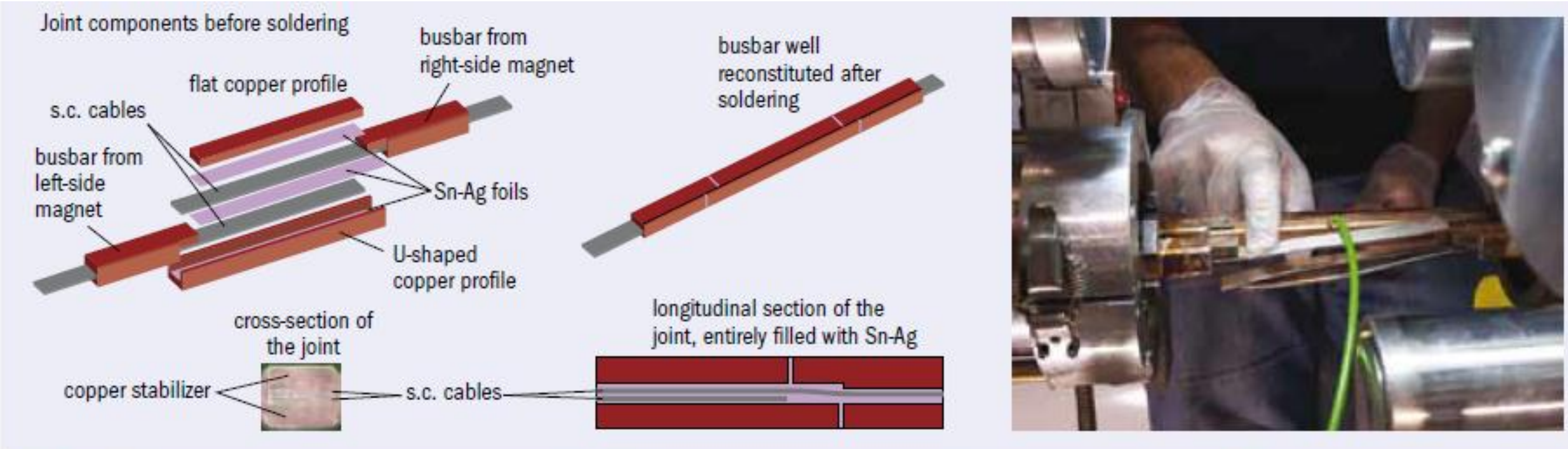
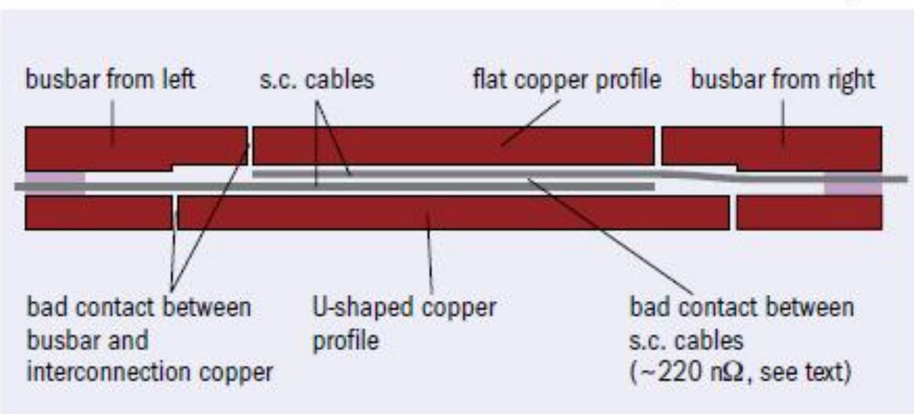
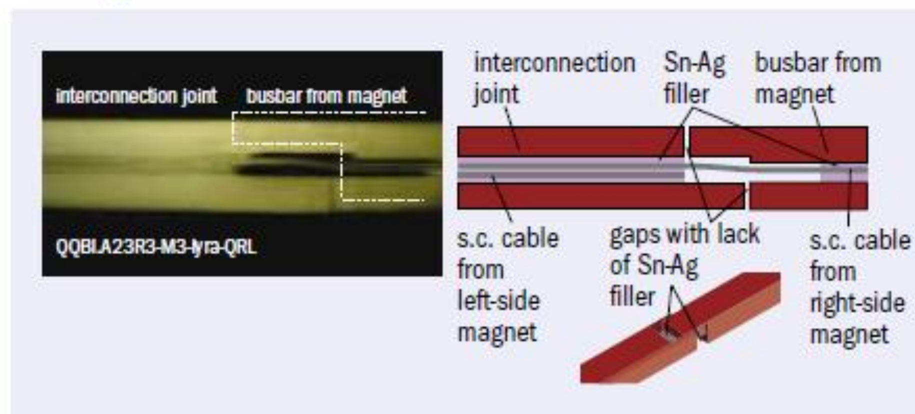


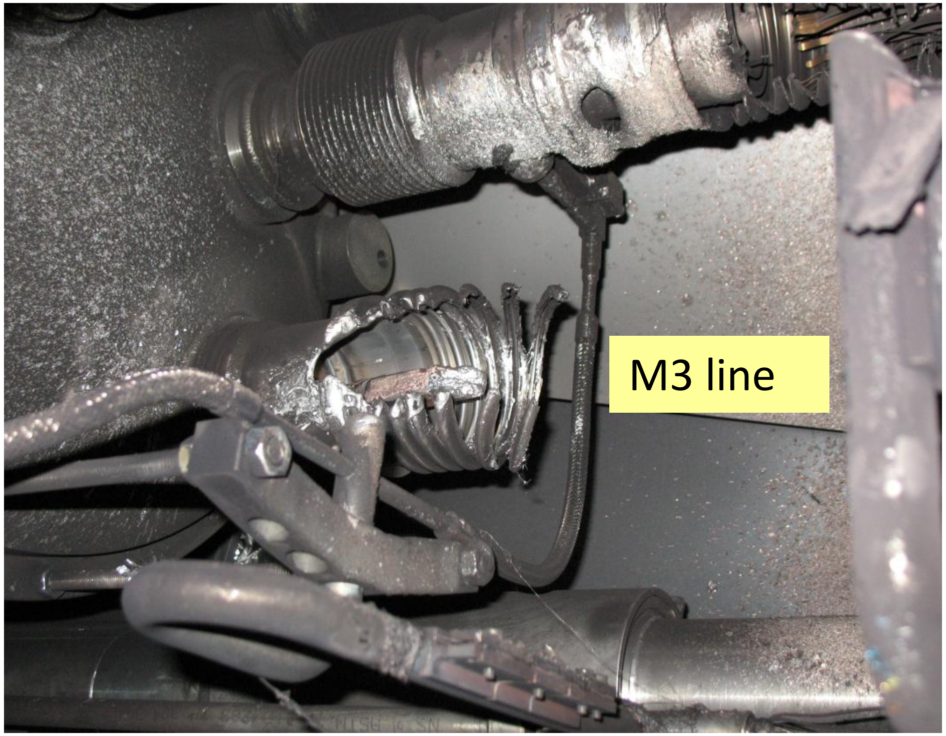
Fig. 2. Left: The various components of an interconnection. Right: A real interconnection, with as yet unconnected cables in the foreground. Note, there are two busbars in each interconnection sleeve, i.e. six 13 kA joints for each magnet interconnection.

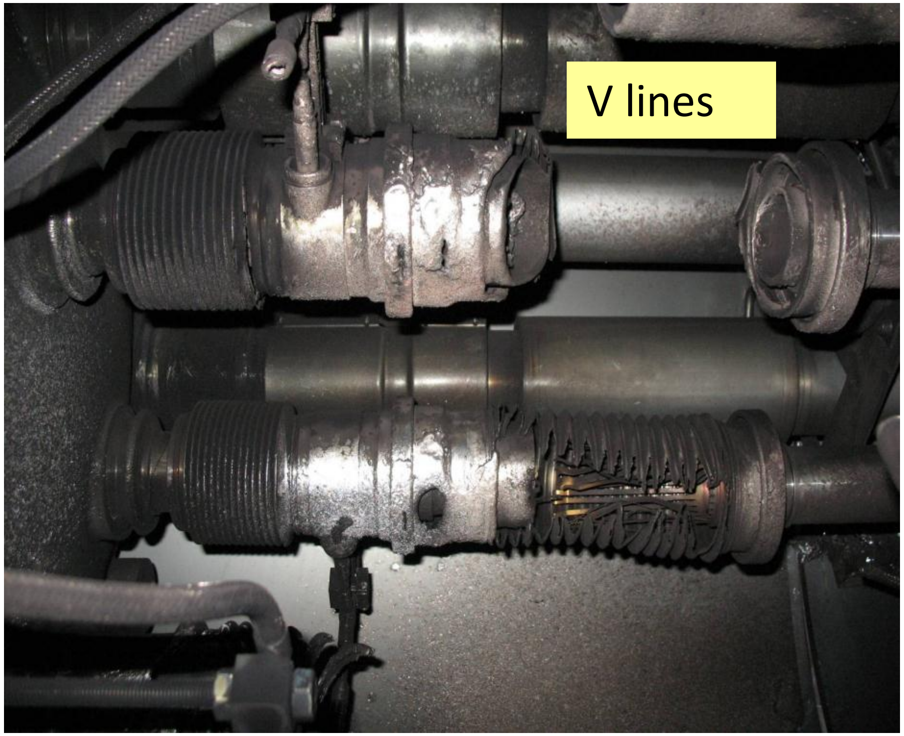




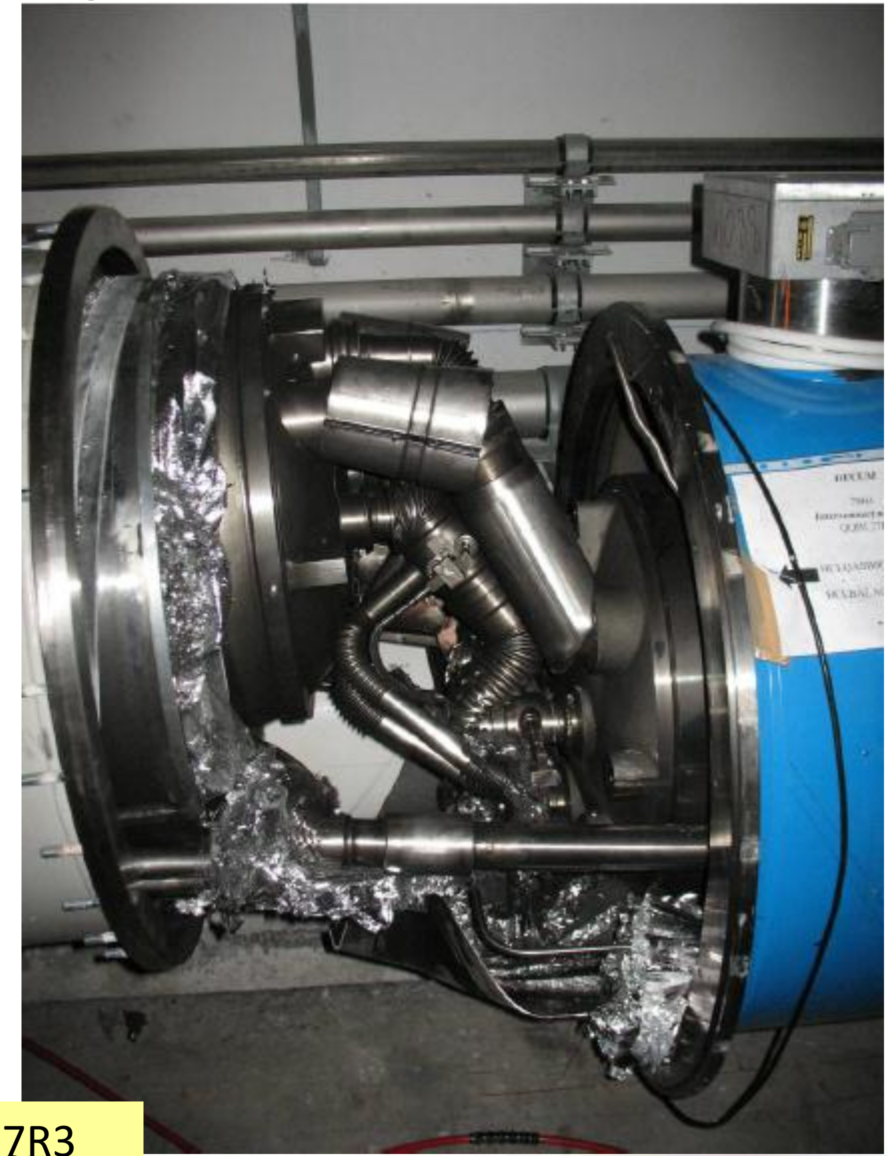
Left: Fig. 3. Schematic of the defective joint assumed to have caused the incident in September 2008. Right: Fig. 4. A defective interconnection, with the superconducting cable detached from the stabilizer. In the gamma-ray photo, left, the two vertical gaps appear to be filled, but electrical measurement and visual inspection showed that they are in fact open, as indicated in the diagram. There is therefore no continuity in the stabilizer and current must flow in the isolated cable.

Electrical arc between C24 and Q24



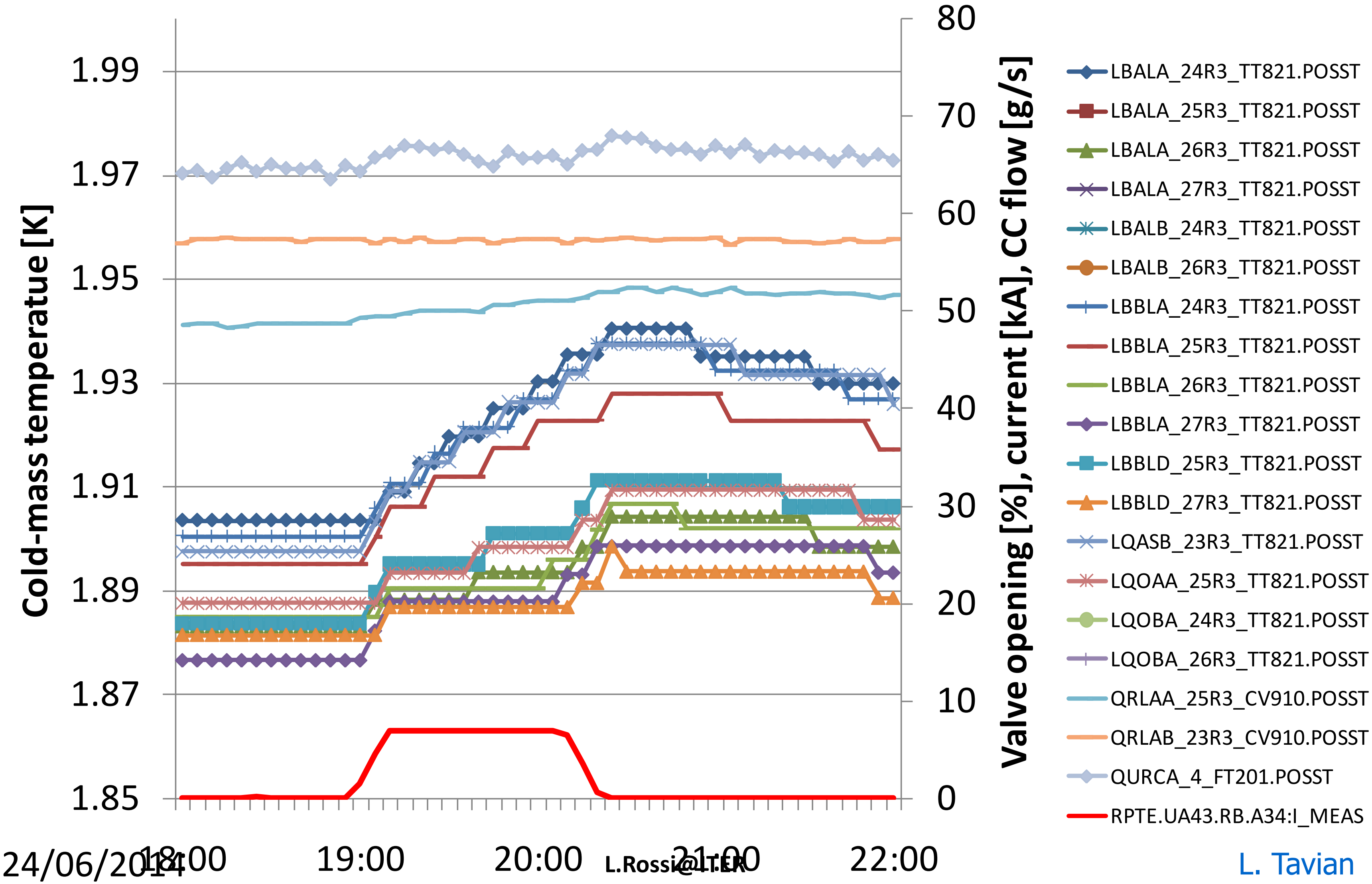


Collateral damage: magnet displacements



QQBI.27R3

@ 7 kA current flat top (15.09.08)



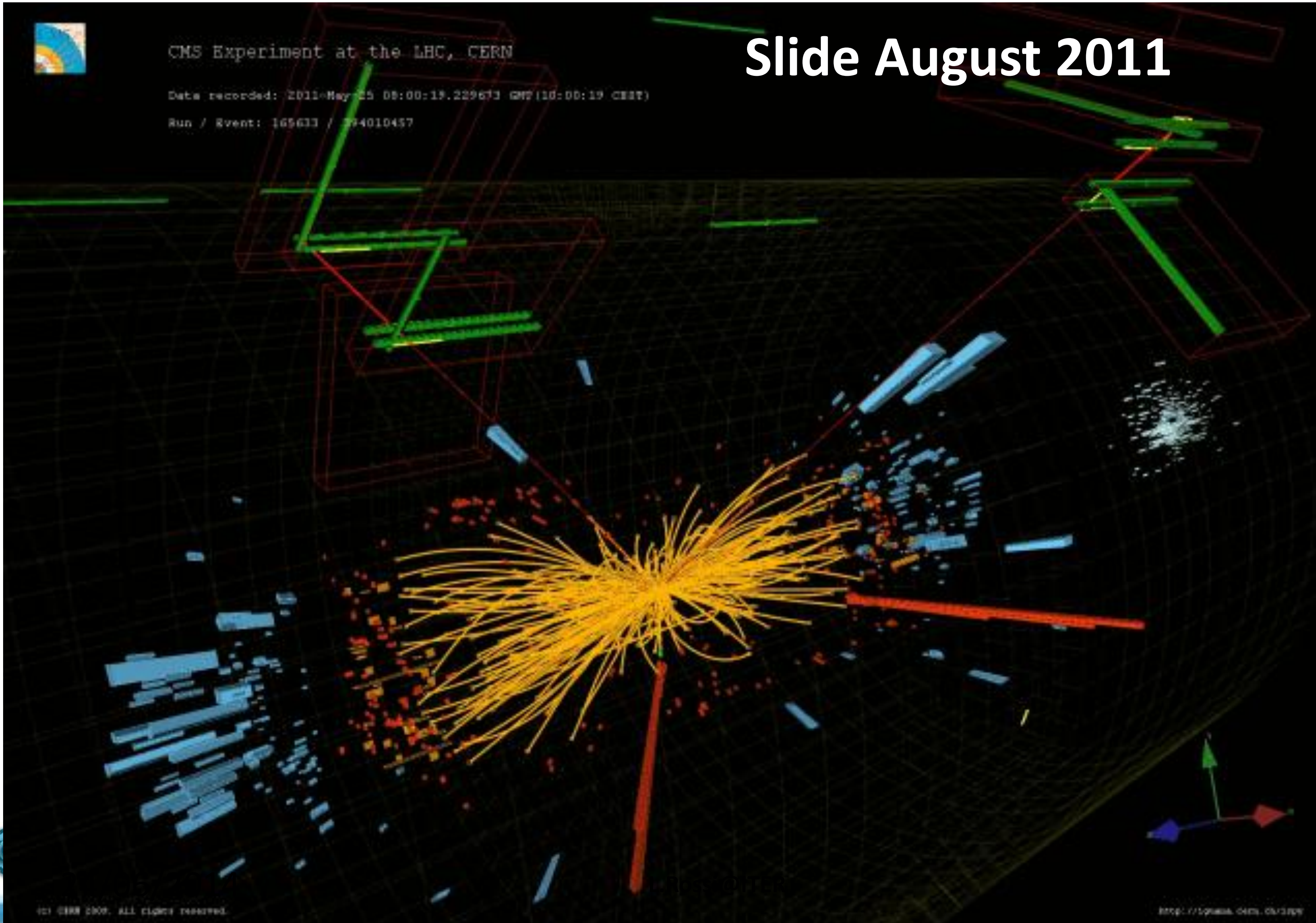
L. Tavian

Spare magnets

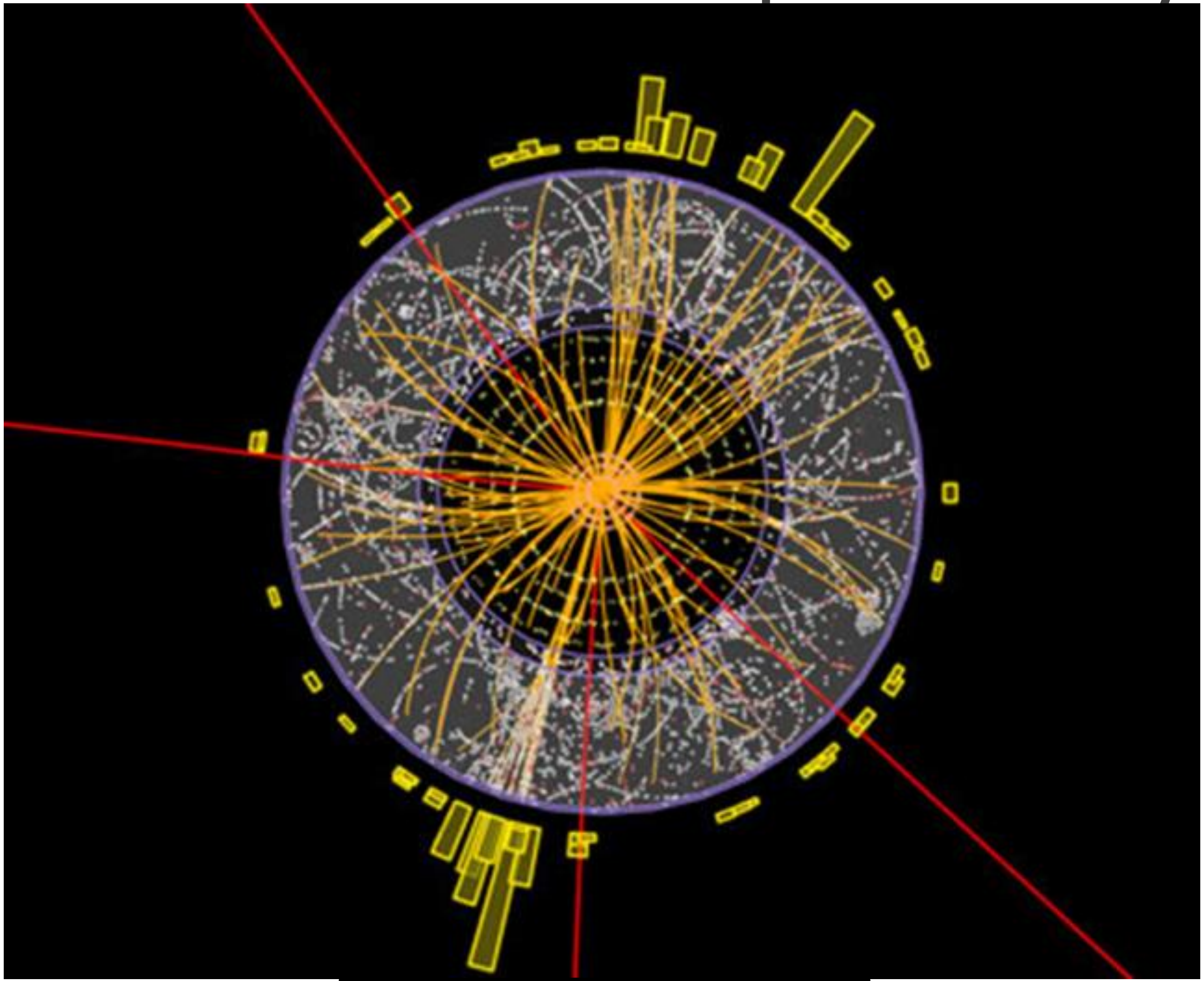
53 magnets replaced in sect.3-4:

- 39 dipoles:
  - 30 new spares
  - 9 recovered from sect.3-4 and refurbished
- 14 Short Straight Sections:
  - 7 new spares
  - 7 recovered from sect.3-4 and refurbished
- All cold tested (or re-tested)
- Spares available, but just enough!

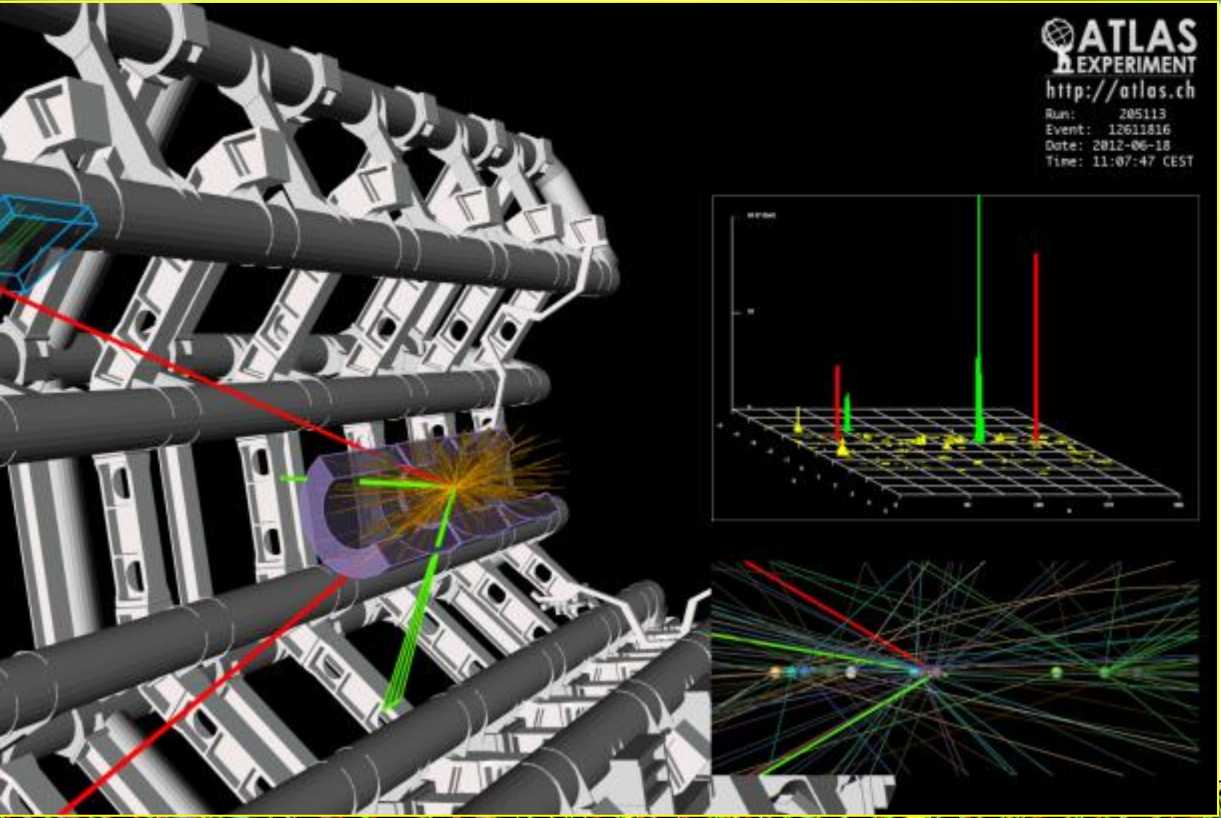
First hints of the Higgs



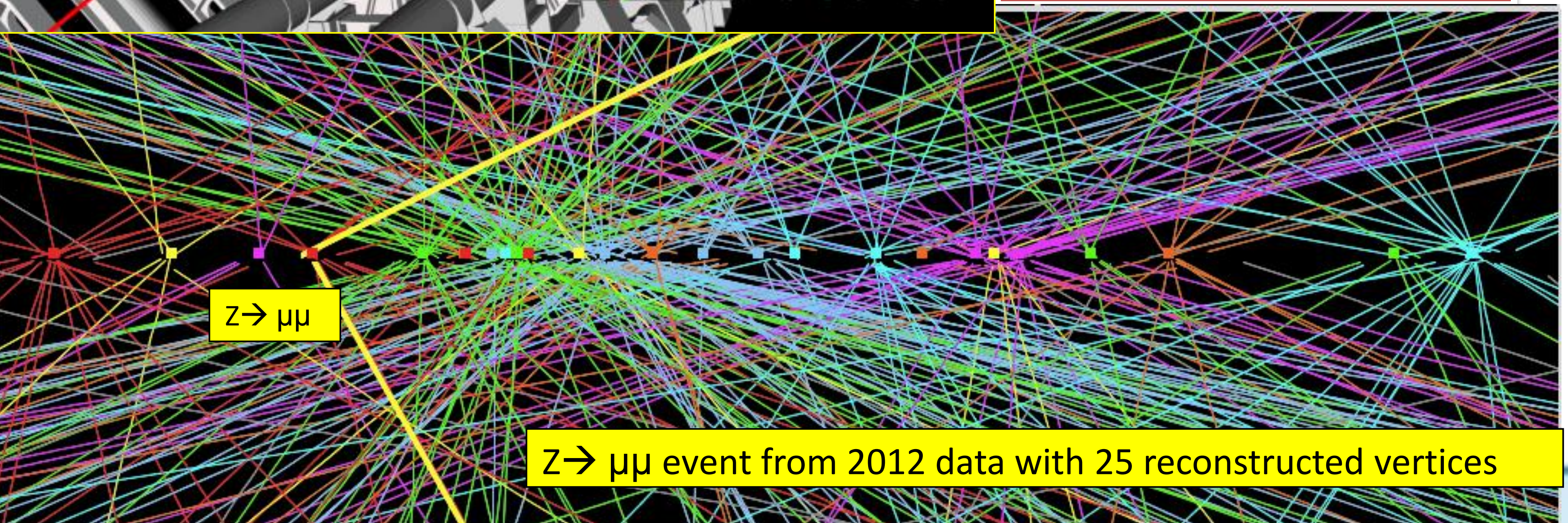
Hints indicating a possibility
December 2011: 99% probability



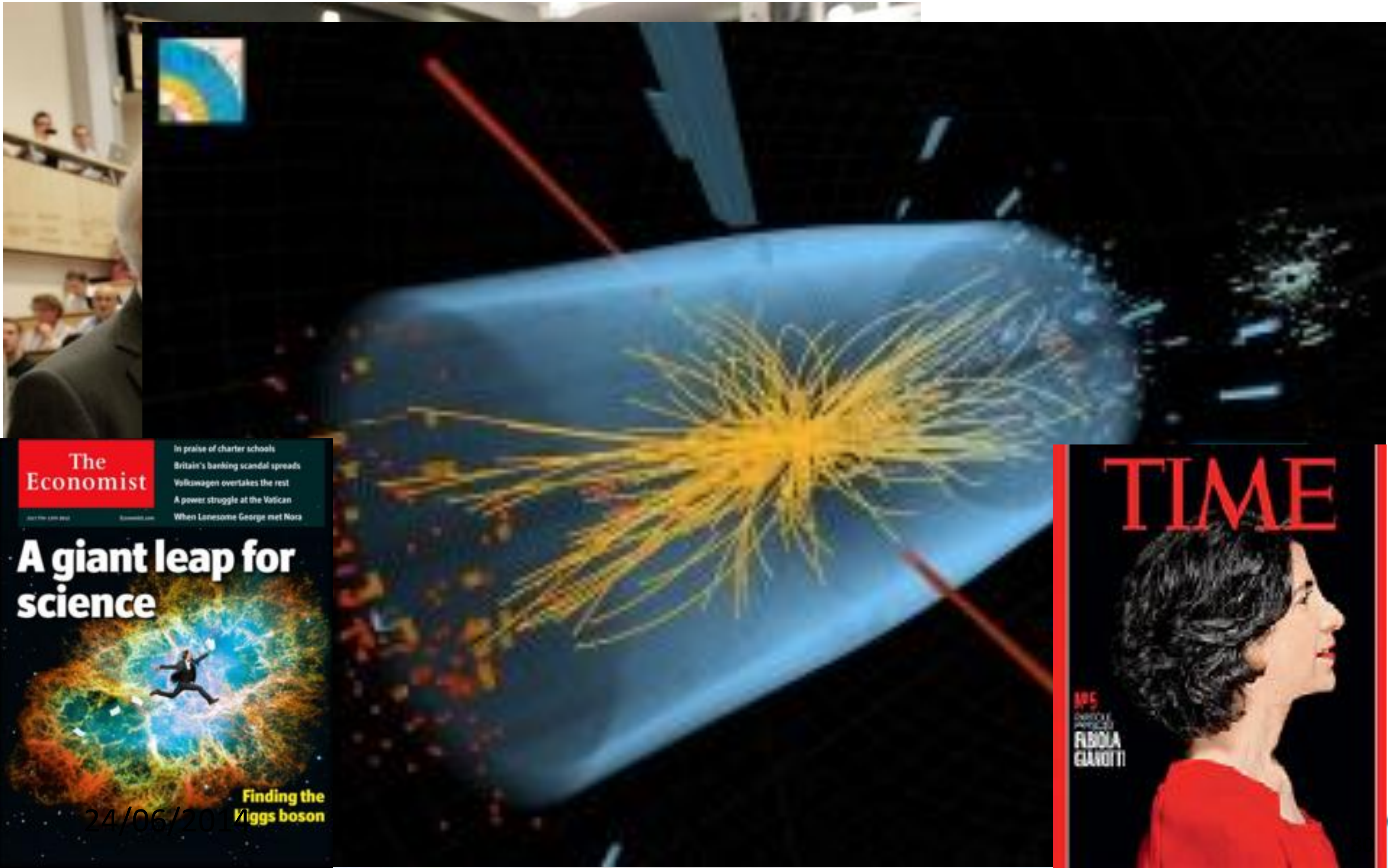
Higgs $\rightarrow$2 Z$\rightarrow$ 4 μ



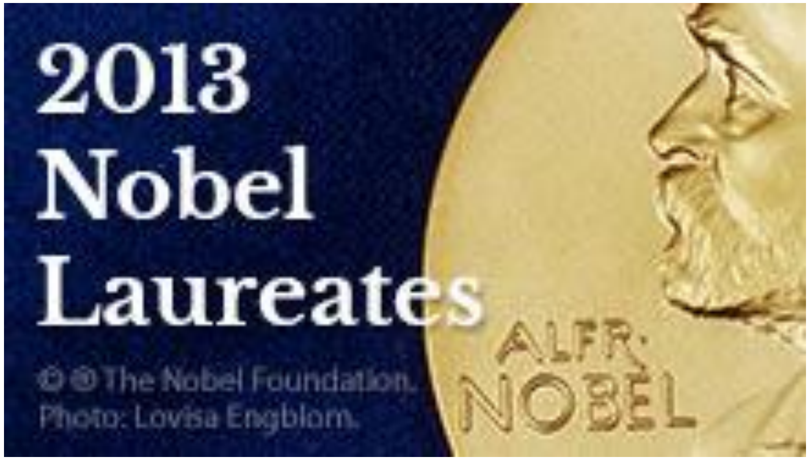
The Higgs: the needle in a haystack



4 July 2012 : Boson got!

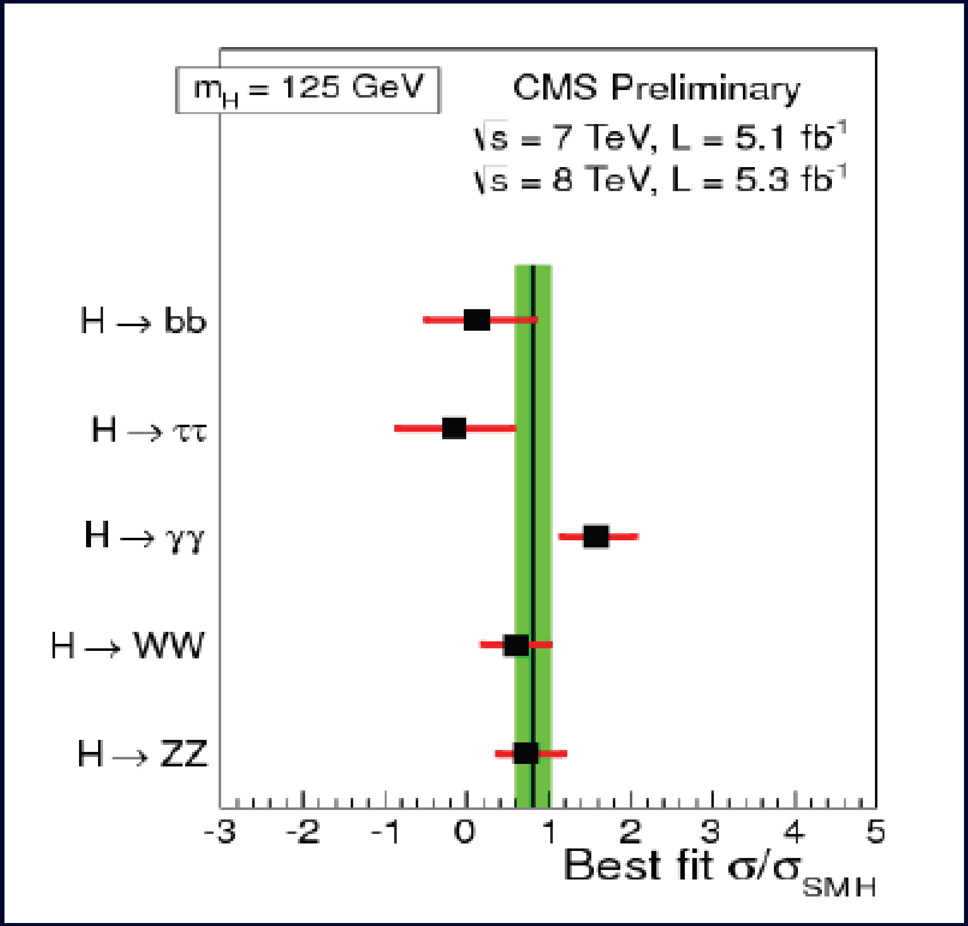


Brout – Englert – Higgs mechanism 2013 Nobel Prize



…for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider

… but that's only the beginning !
What's next ?



Measure properties of Higgs with high precision:
we have more questiono now than before the Higgs!

Higgs got: completion of 100 years of quantum mechanics (Standard Model)

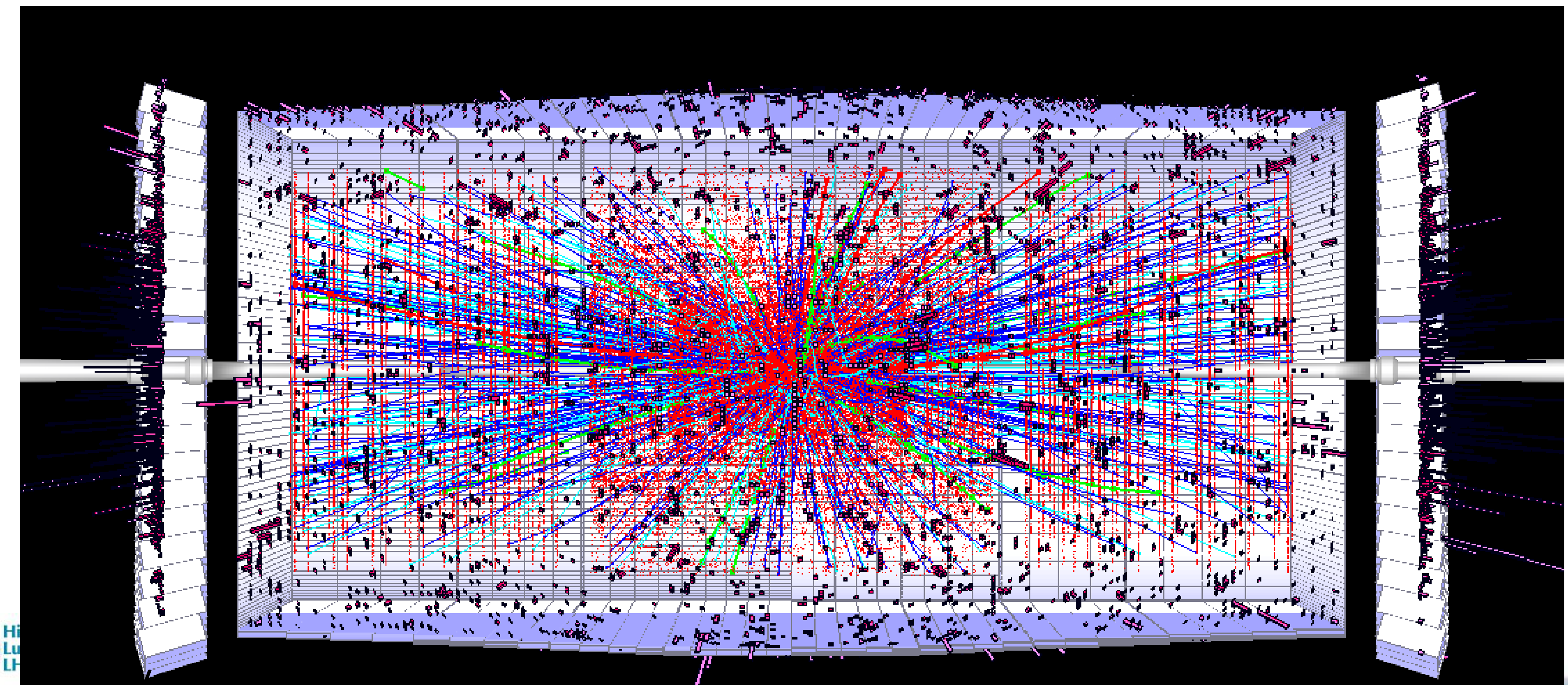
- This is not enough
- Higgs is not «stable» alone
- Why Higgs boson is so light?
- We think is probably that above 1 TeV there are particle stabilizing the Higgs mass…
- Matter-Antimatter broken symmetry
- Why we see only 4% of the matter-energy contnet of the universe?
- Much more statistics will open new doors extending the physics reach of LHC

High Luminosity LHC

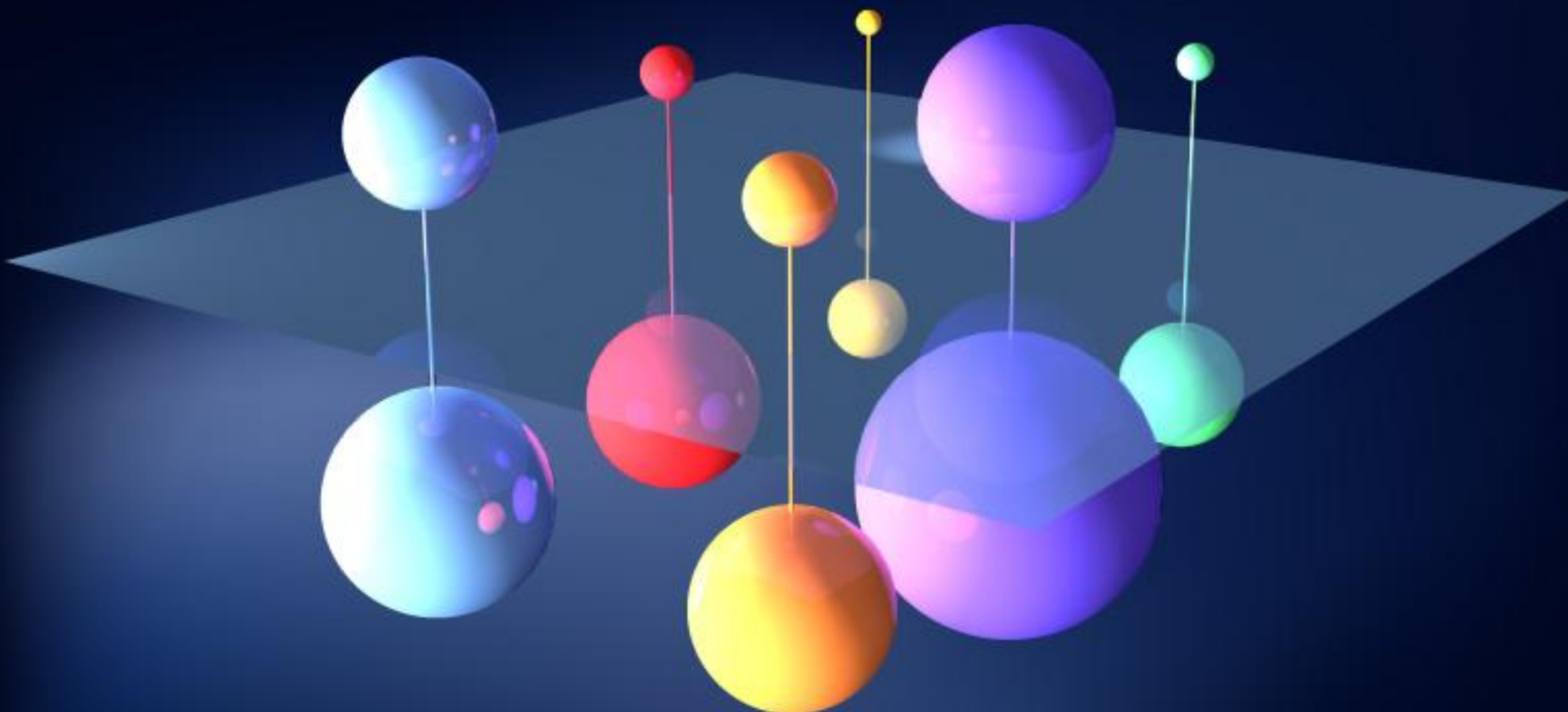
High Luminosity LHC

The HiLumi LHC Design Study (a sub-system of HL-LHC) is cofunded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404

CAPACITIES

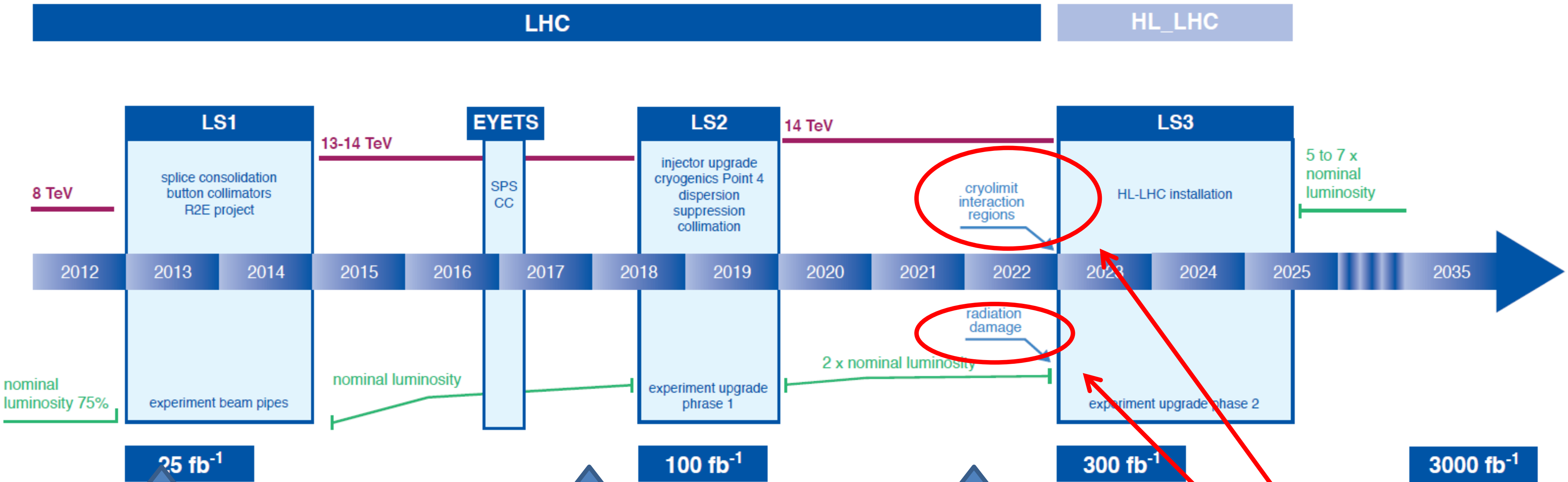


A superworld ahead of us?



Light on dark matter?

New LHC / HL-LHC Plan



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

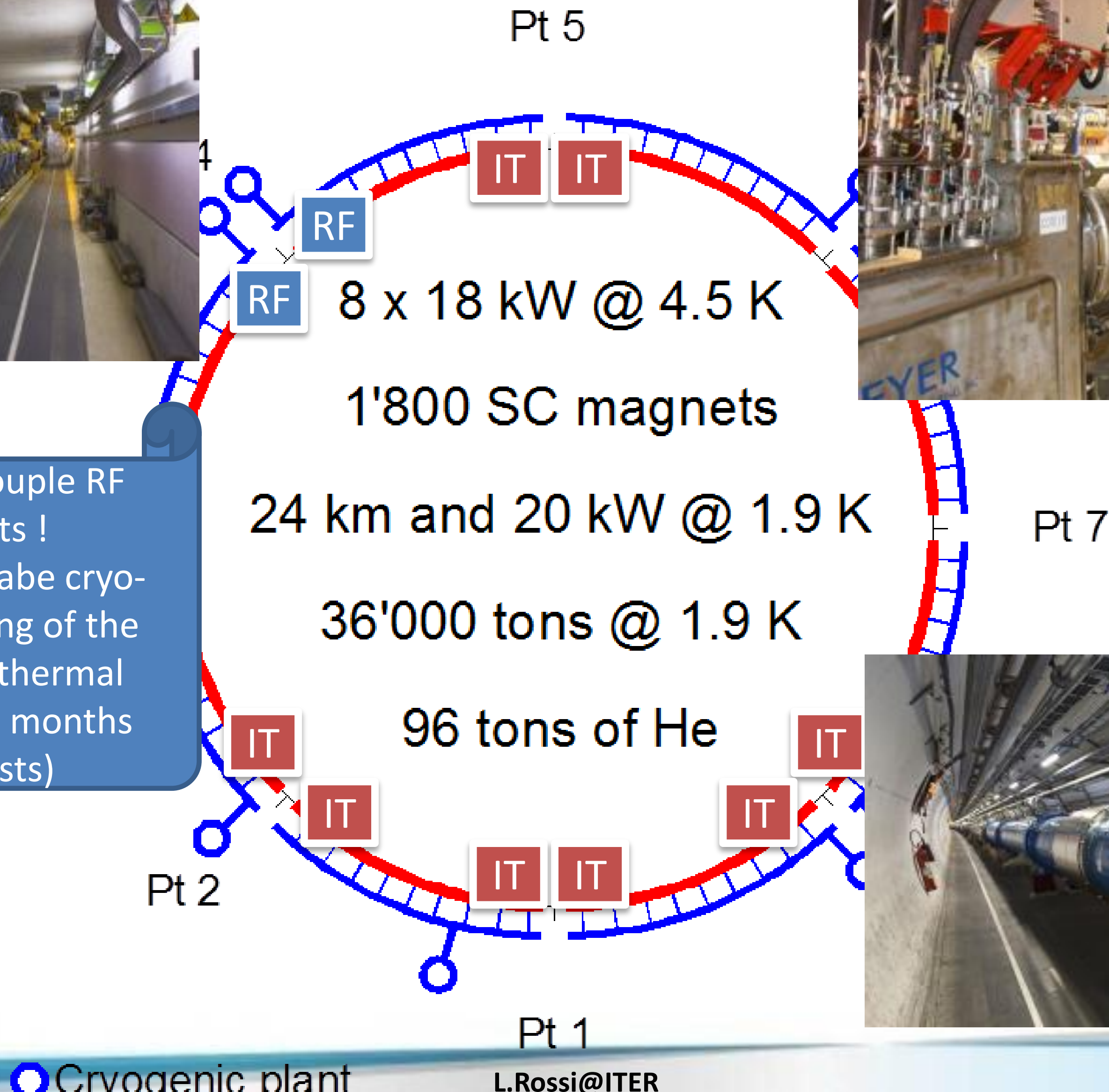
$1.5\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
pile up ~40

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

Technical limits (experiments, too) like :

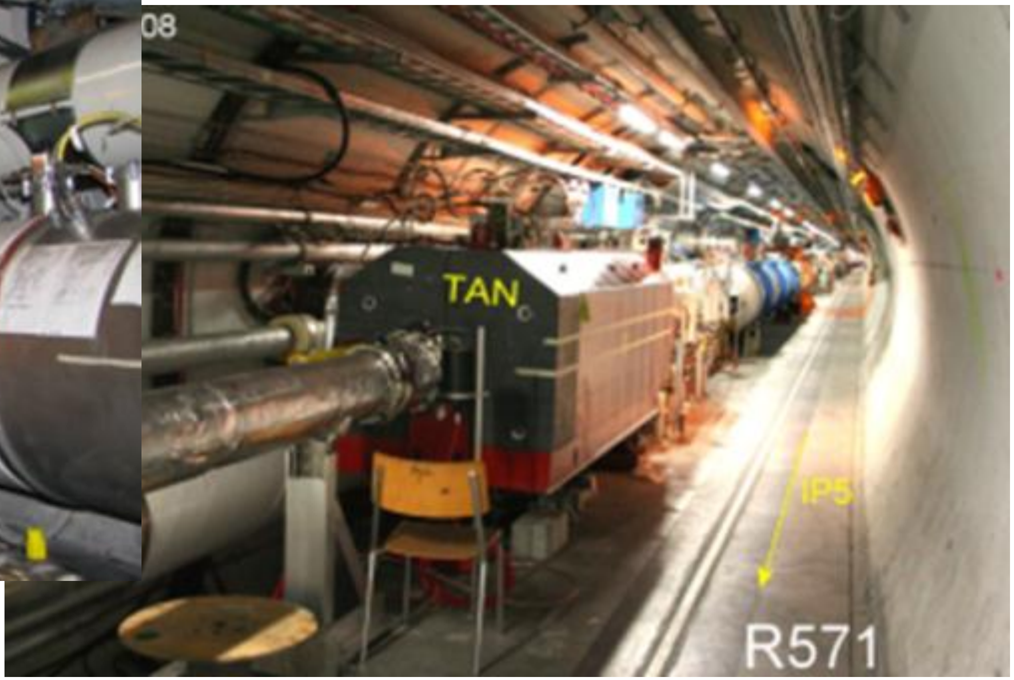
High Luminosity LHC

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)

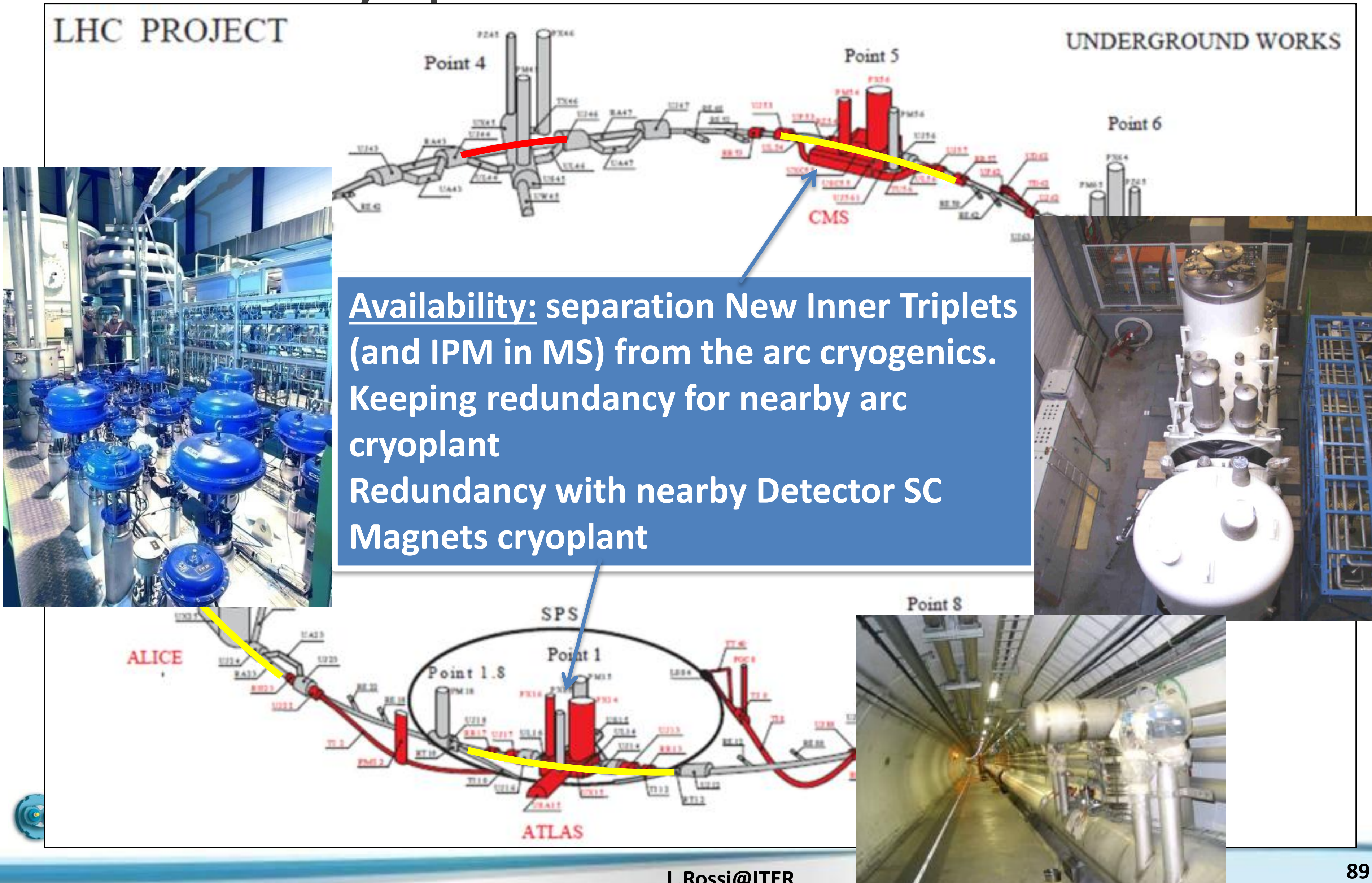
Triplet and MS connection to main arc



The cryoline is continous between the Continuous cryostat (Regular lattice Arc and DS Arc) and the MS-IT zones. This connections have consequences:

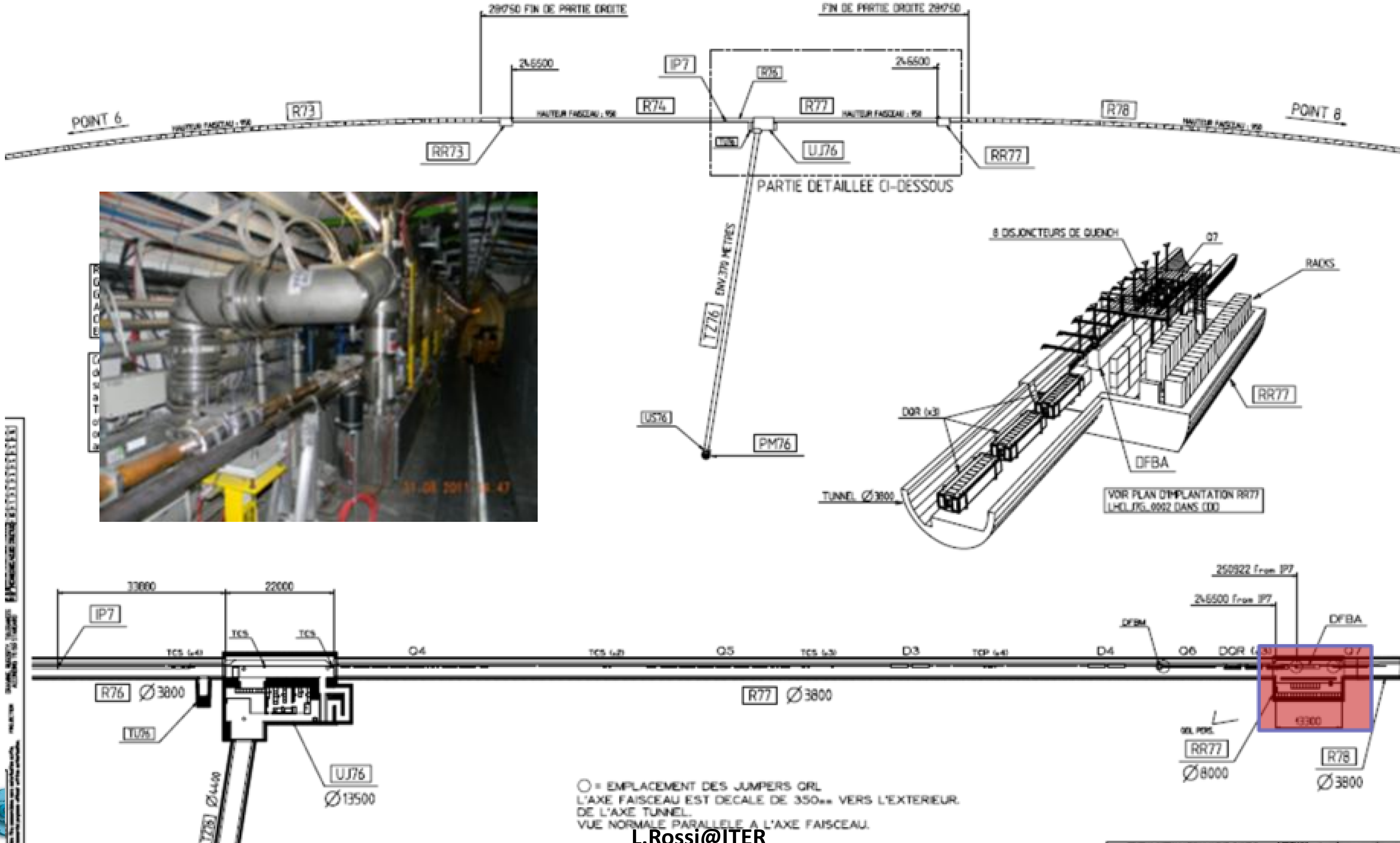
- Makes a limitation in cryopower since the IT zone will increase the power deposited with the lumi increase
- A stop in the MS or IT zone would entail a thermal cycle on the entire Sector

IT cryoplants and new LSS QRL

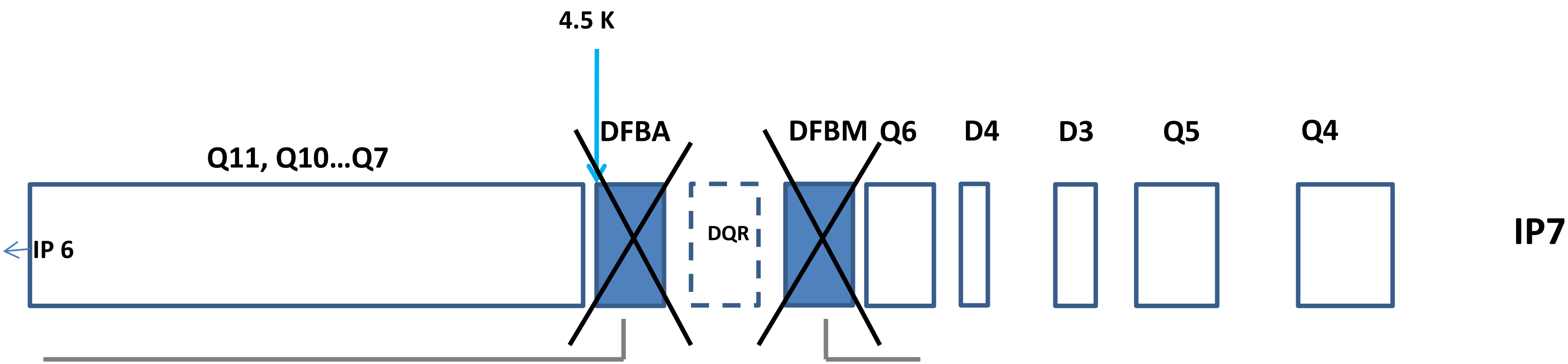


<u>Availability:</u> **separation New Inner Triplets (and IPM in MS) from the arc cryogenics.**
Keeping redundancy for nearby arc cryoplant
Redundancy with nearby Detector SC Magnets cryoplant

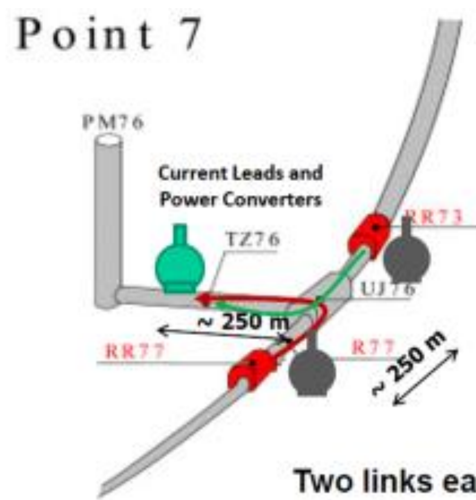
P7 : EPC and DFB near collimators



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



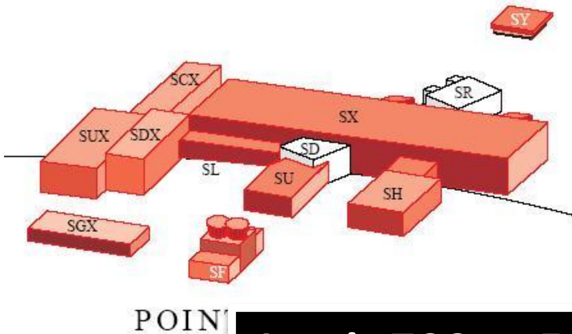
RR 73

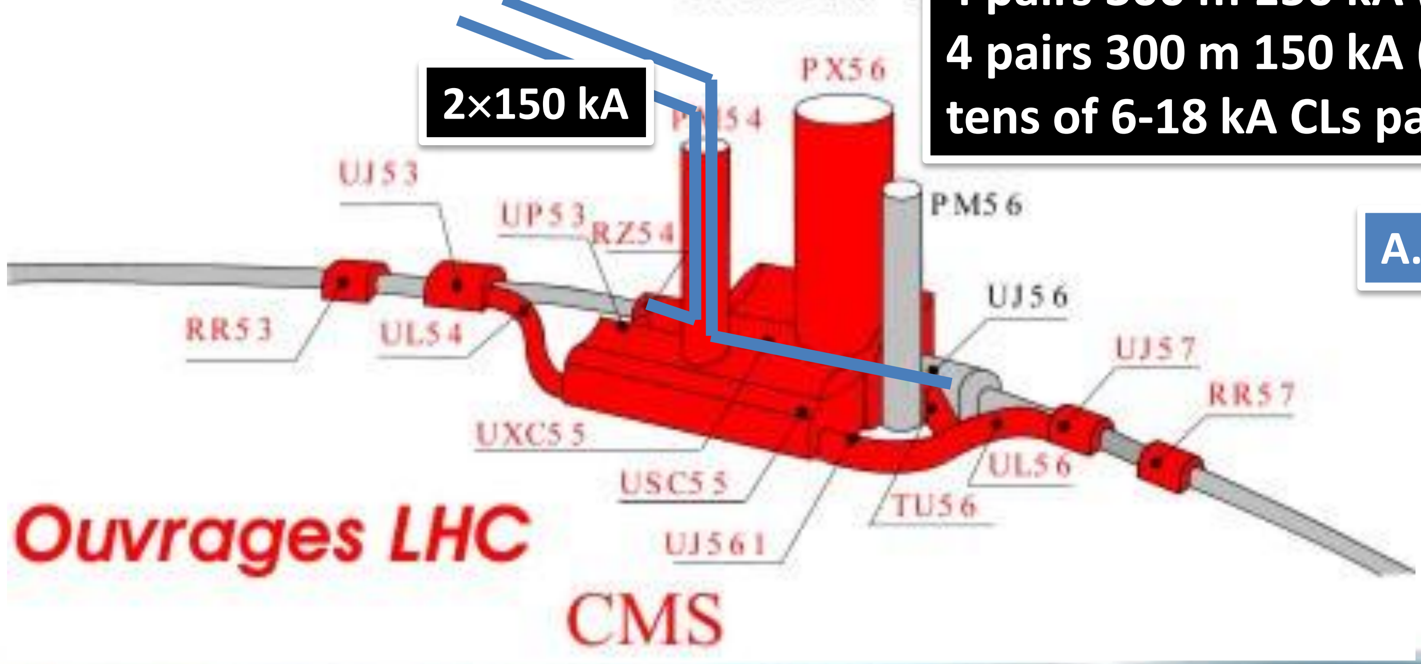


Two links each about 500 m long
48 cables rated at 600 A per link

High Luminosity LHC

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

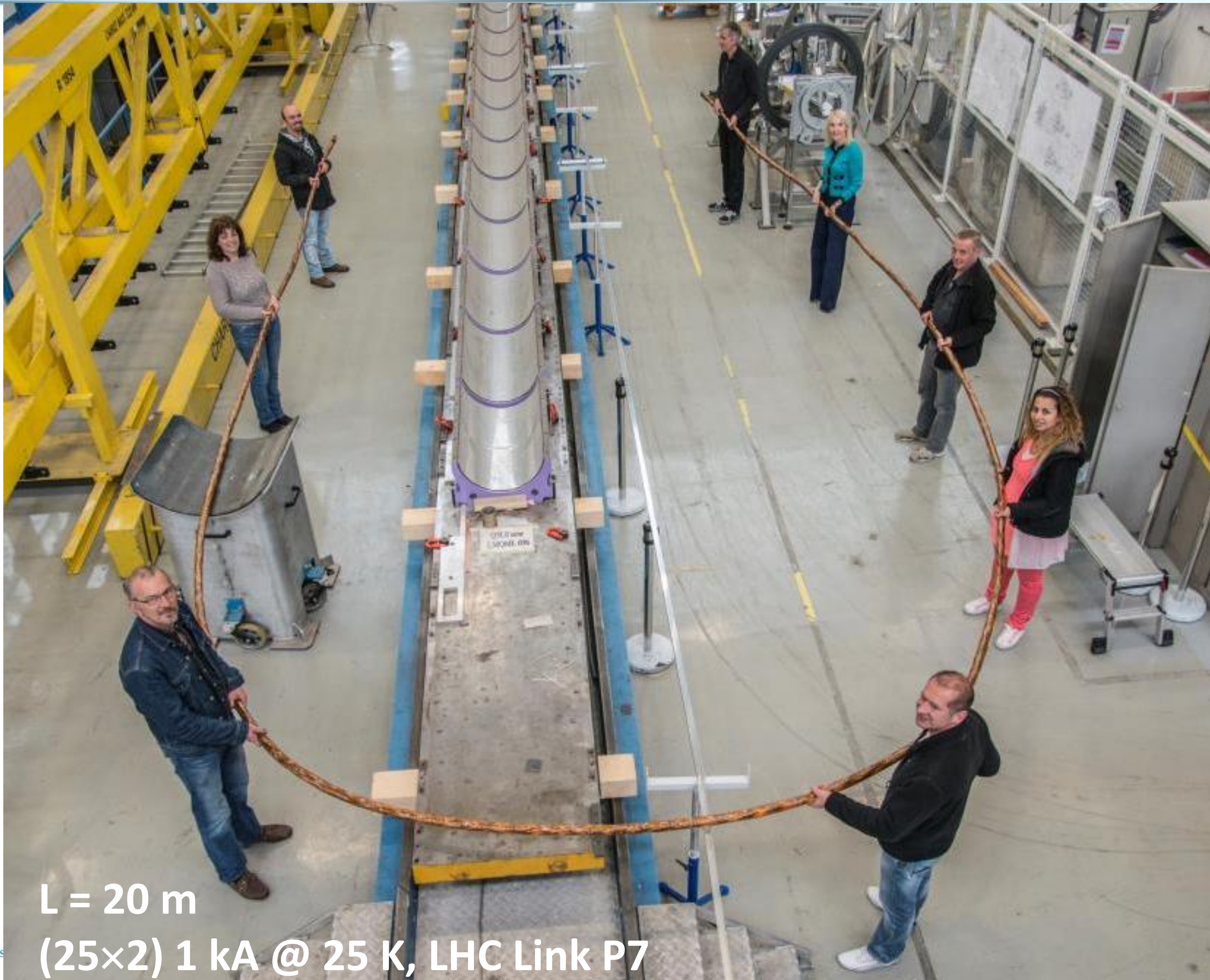




2×150 kA

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



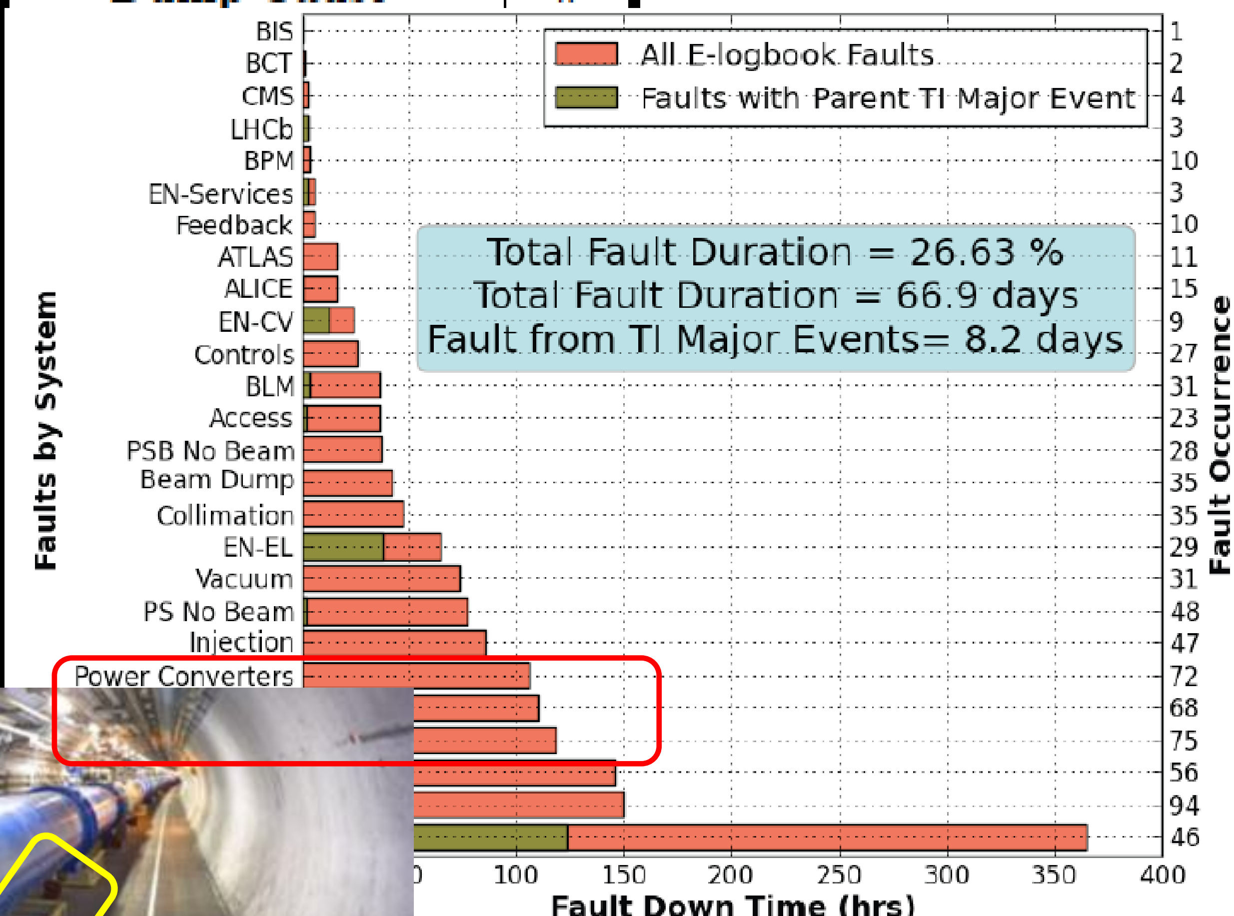
L = 20 m

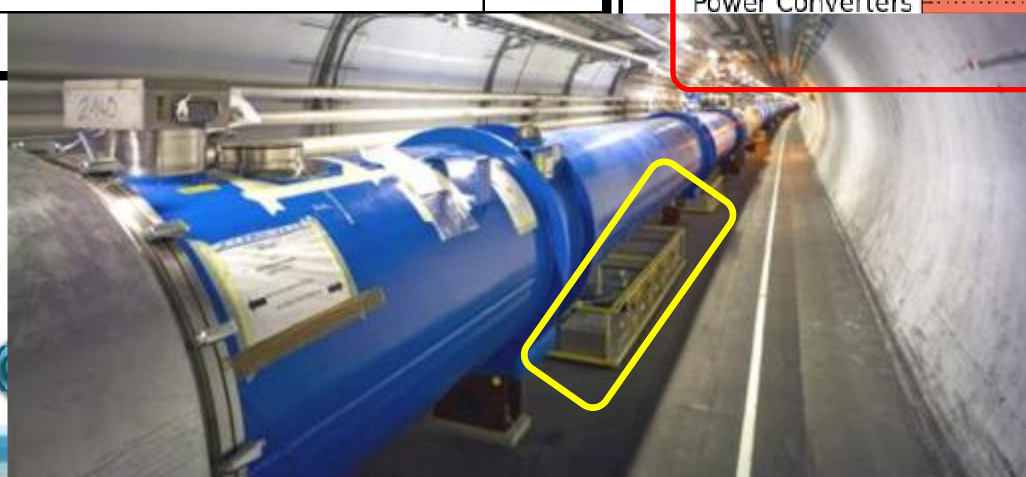
(25×2) 1 kA @ 25 K, LHC Link P7

QPS boxes and intervention time

Dump Cause	#
Beam: Losses	58
Quench Protection	56
Power Converter	35
Electrical Supply	26
RF + Damper	23
Feedback	19
BLM	18
Vacuum	17
Beam: Losses (UFO)	15
Cryogenics	14
Collimation	12

Dump Cause	#

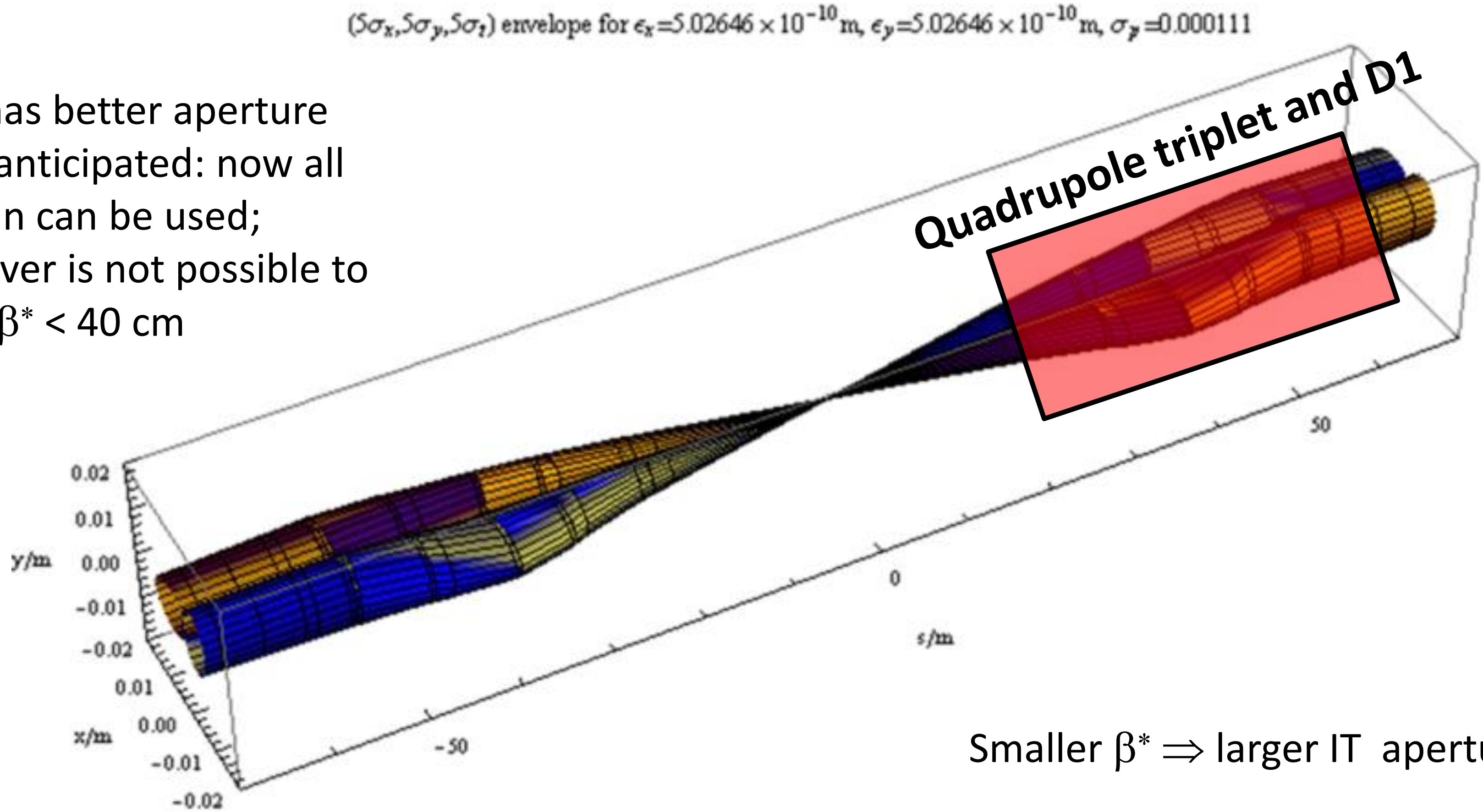




Consolidation of infrastructure !
But also new paradigma: remove from tunnel of QPS (as much as possible)

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

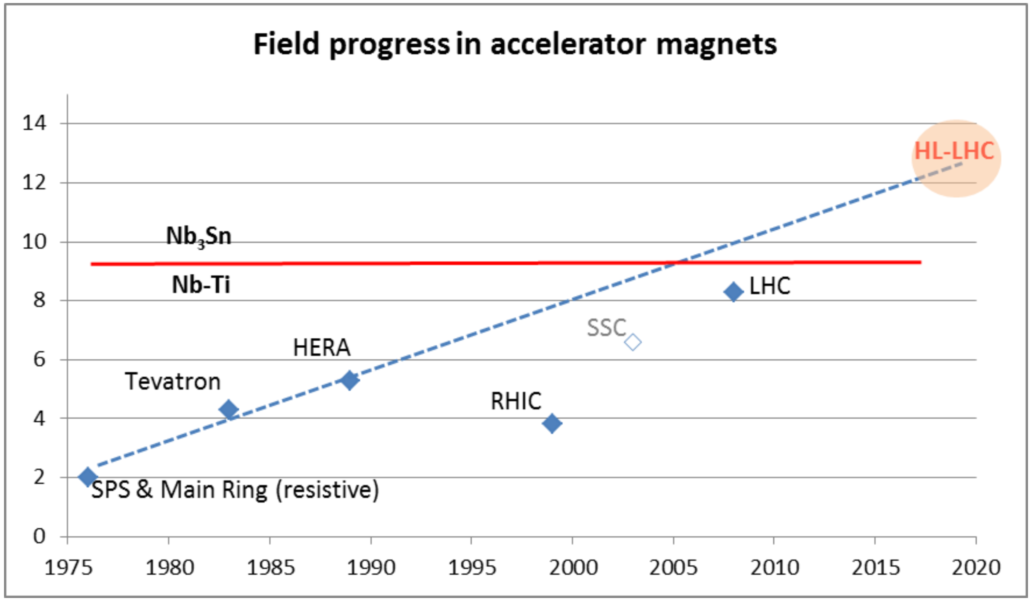
LHC has better aperture than anticipated: now all margin can be used; however is not possible to have $\beta^* < 40$ cm



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

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).

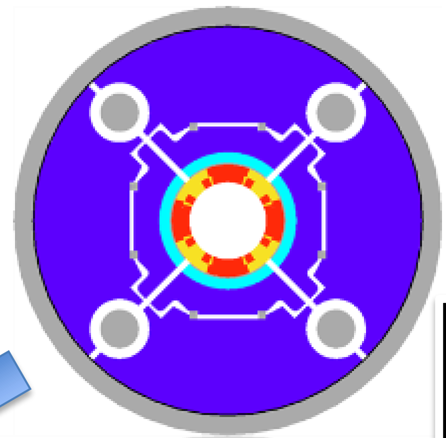


High Luminosity LHC

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

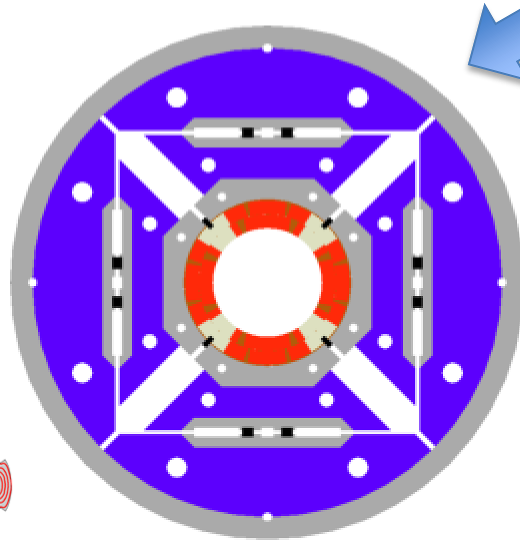
LHC (USA & JP, 5-6 m)
Ø70 mm, B_{peak}~ 8 T
1992-2005

LARP TQS & LQ (4m)
Ø90 mm, B_{peak}~ 11 T
2004-2010

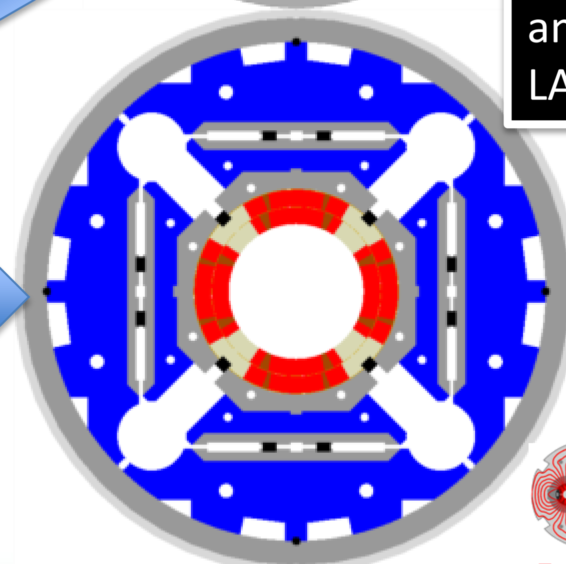


New structure based on bladders and keys (LBNL, LARP)

LARP HQ
Ø120 mm,
B_{peak}~ 12 T
2008-2014



LARP & CERN
MQXF
Ø150 mm,
B_{peak}~ 12.1 T
2013-2020



Progress in MQXF (IT quads)

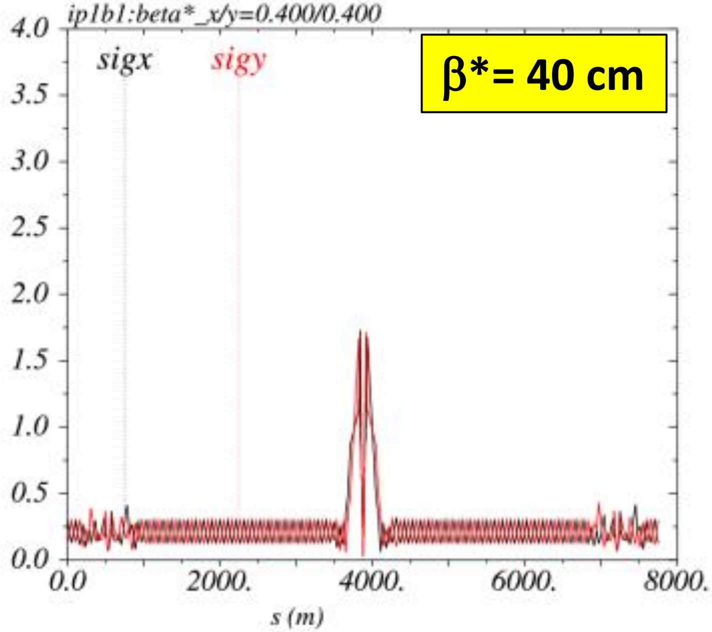
- First short coils for practice winding fabricated with plastic part completed
- Cu cable by CERN
- Both layer wound and cured
- Nb3Sn cable by LARP
- External review of spacer design in 10/13
- 2 additional short coils planned in Nov/Dec, 2013
- End spacers version v3
- Fabrication of metal end-spacers for first coil early 2014

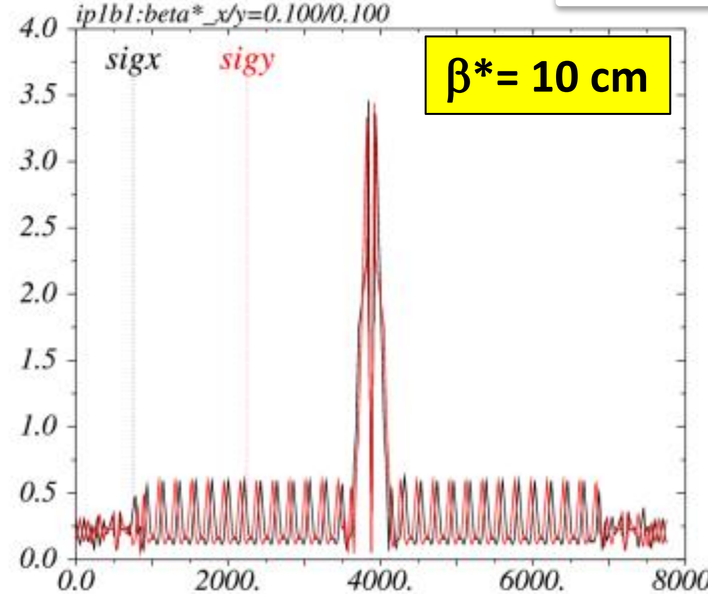
G. Ambrosio – LARP & P. Ferracin - CERN

The **Achromatic Telescopic Squeezing** (ATS) scheme

Small β* is limited by aperture but not only: optics matching & flexibility (round and flat optics), chromatic effects (not only Q'), spurious dispersion from X-angle,..

A novel optics scheme was developed to reach un-precedent β^* w/o chromatic limit based on a kind of generalized squeeze involving 50% of the ring **(S. Fartoukh)**

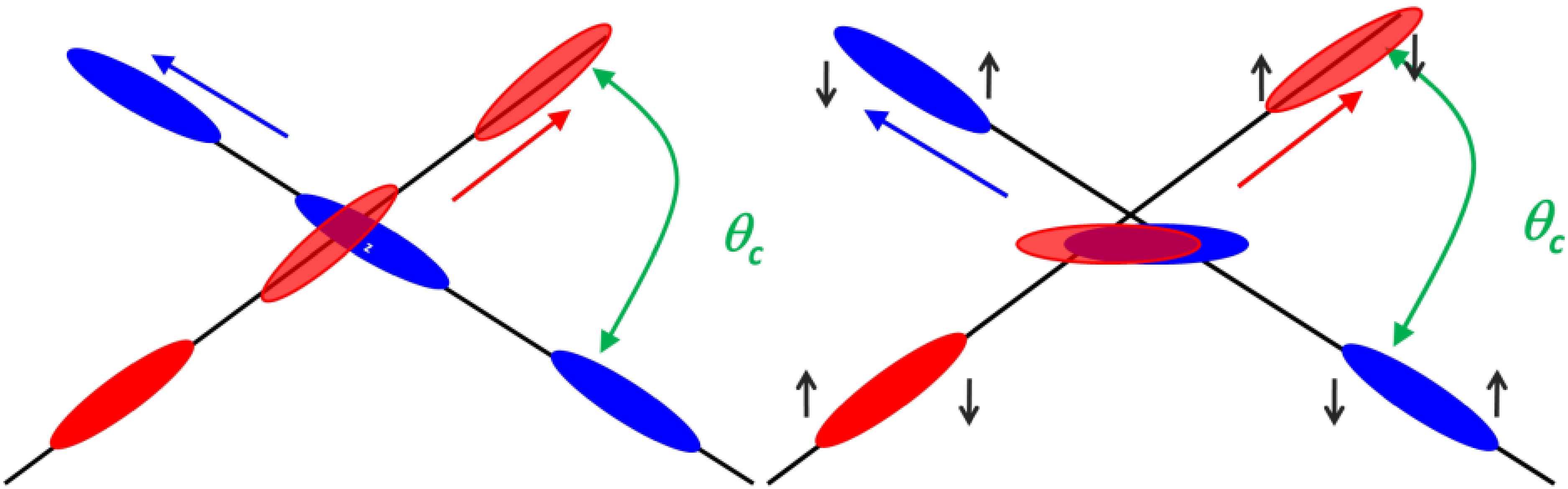




The new IR is sort of 8 km long !

Beam sizes [mm] @ 7 TeV from IR8 to IR2 for typical ATS "pre-squeezed" optics (left) and "telescopic" collision optics (right)

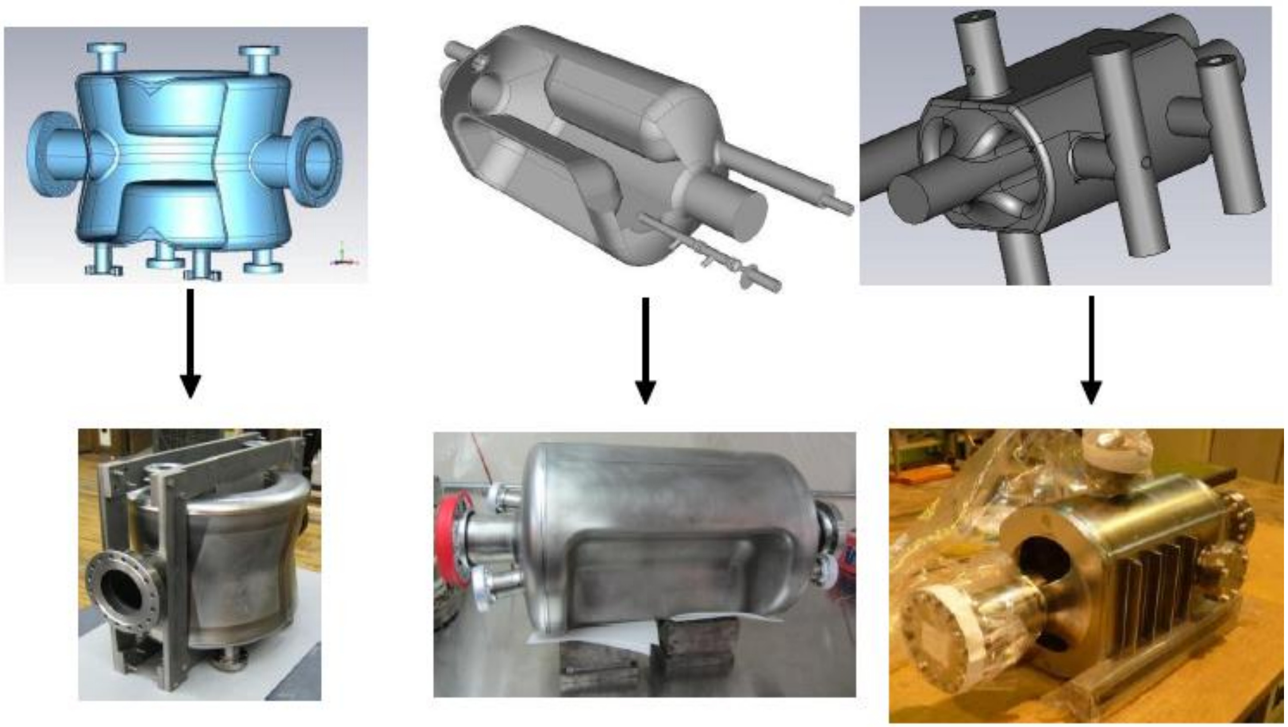
Effect of the crab cavities



- **RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" and then luminosity is maximized**
- ***Crab cavity maximizes the lumi and can be used also for luminosity levelling: if the lumi is too high, initially you don't use it, so lumi is reduced by the geometrical factor. Then they are slowly turned on to compensate the proton burning***

Situation: from drawings to reality…

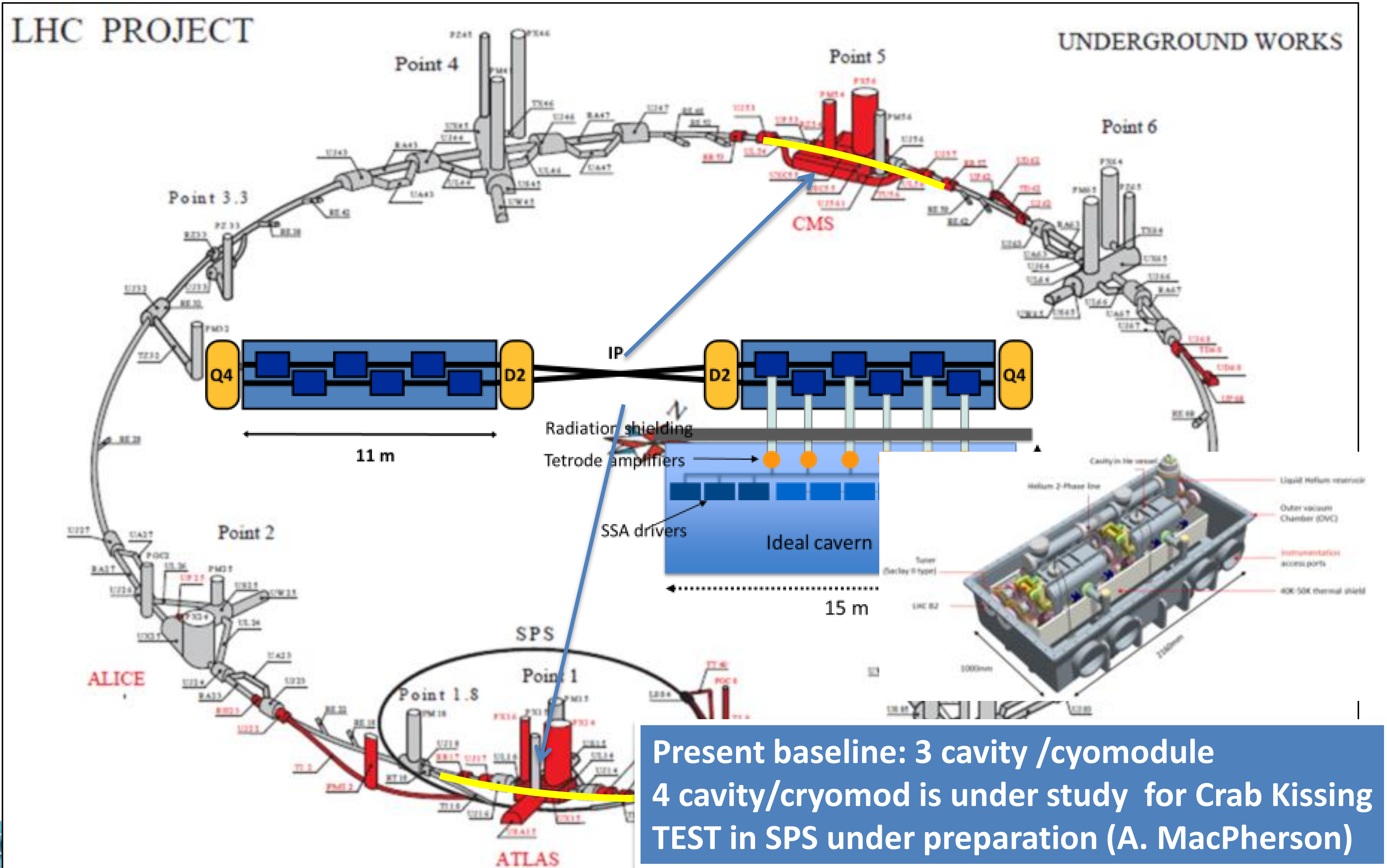
All Prototypes in Bulk Niobium (2011-12)



LARP-BNL LARP-ODU-JLAB UniLancaster-CI-CERN

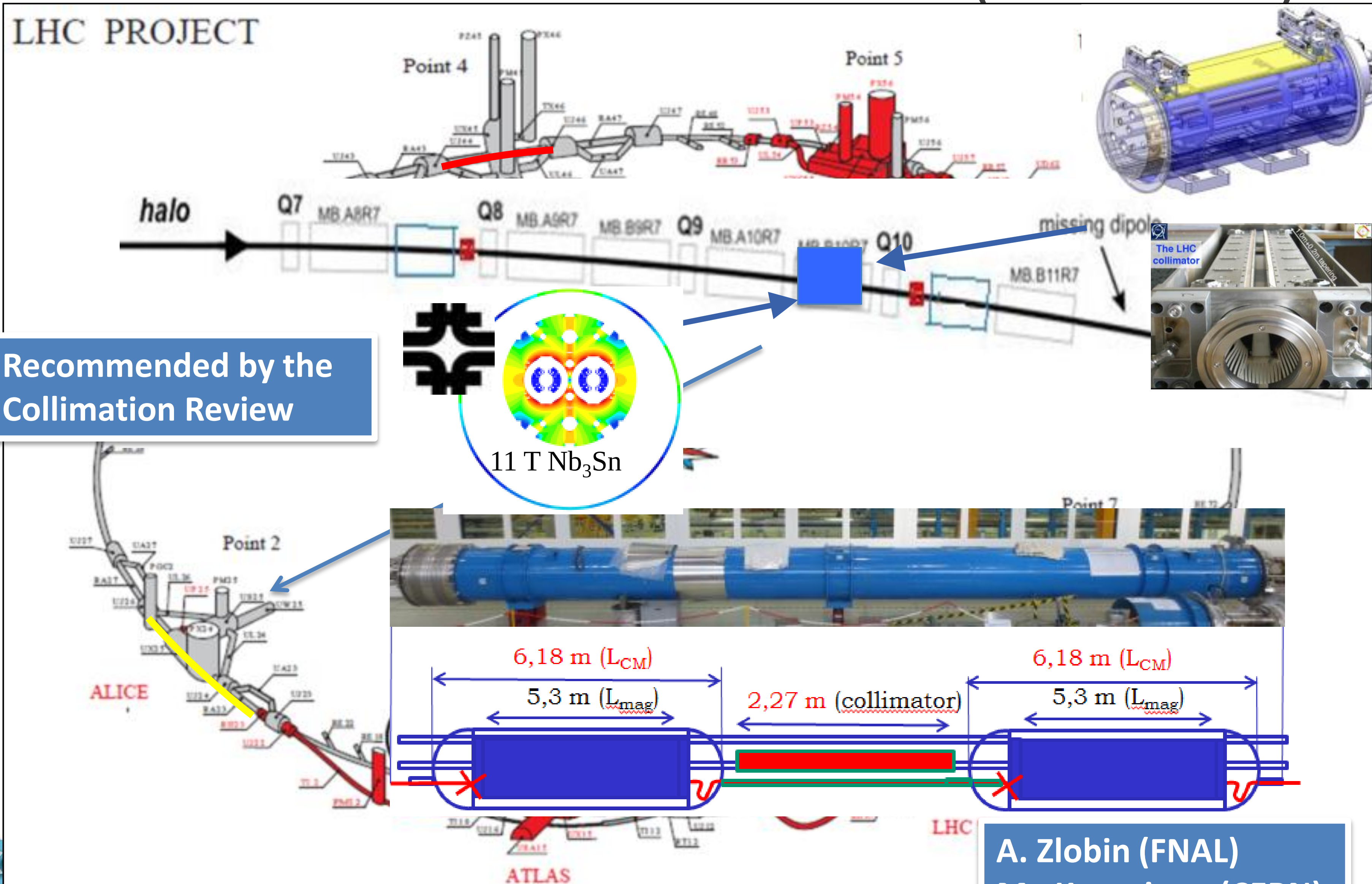
High Luminosity LHC

Crab Cavities for fast beam rotation



Present baseline: 3 cavity /cyomodule
4 cavity/cryomod is under study for Crab Kissing
TEST in SPS under preparation (A. MacPherson)

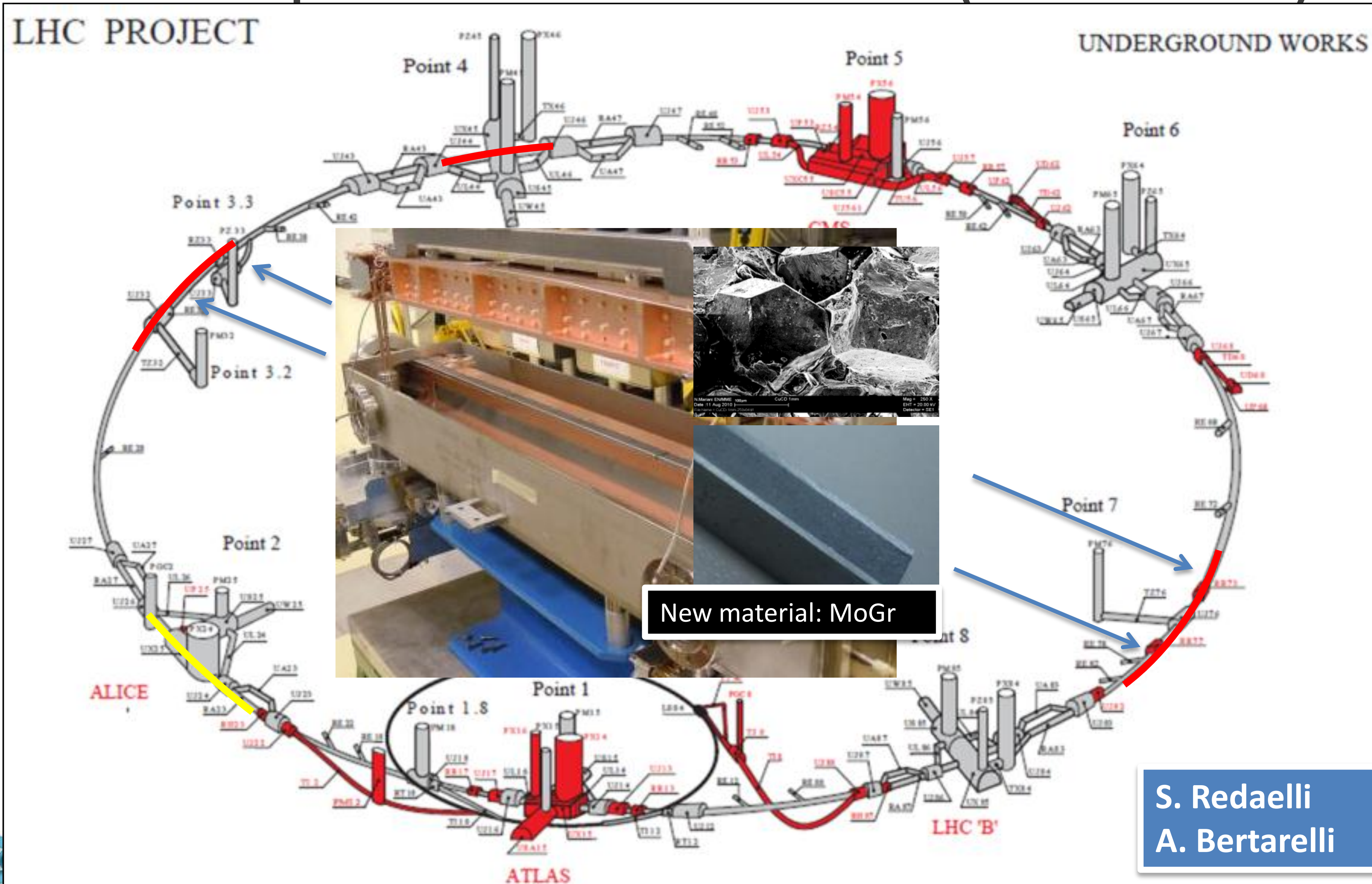
P2 - DS collimators ions – 11 T (LS2 -2018)



Recommended by the Collimation Review

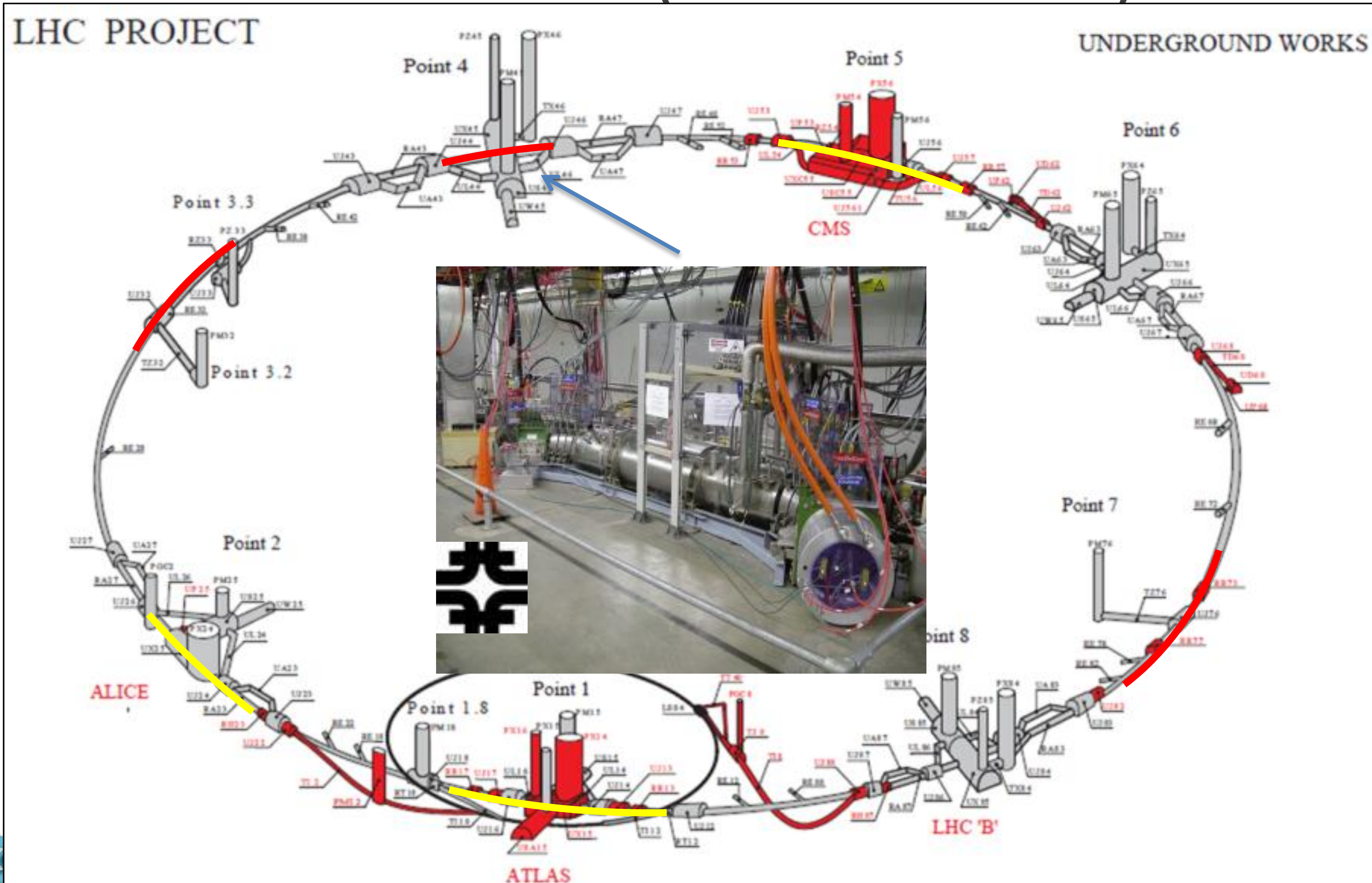
A. Zlobin (FNAL)
M . Karppinen (CERN)

Low impedence collimators(LS2 & LS3)

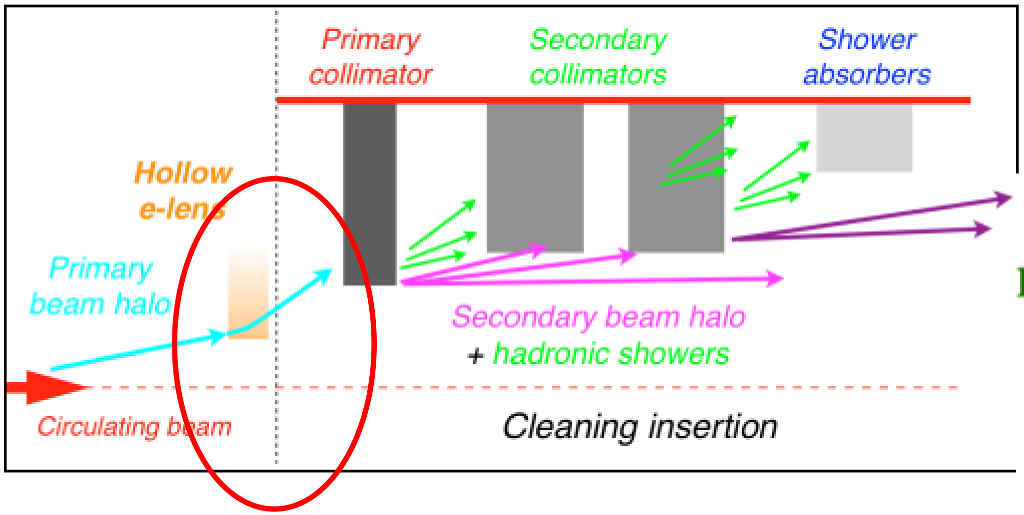


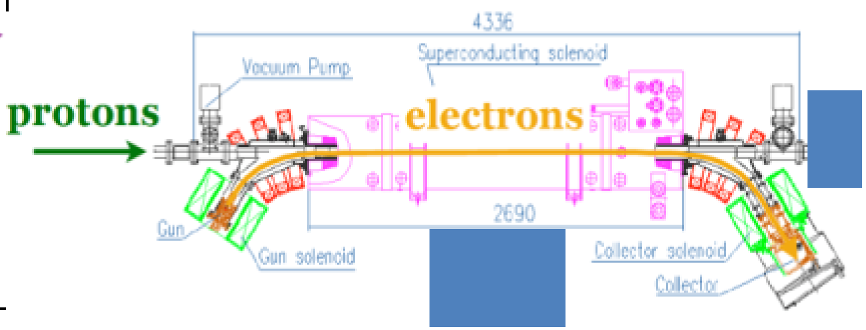
S. Redaelli
A. Bertarelli

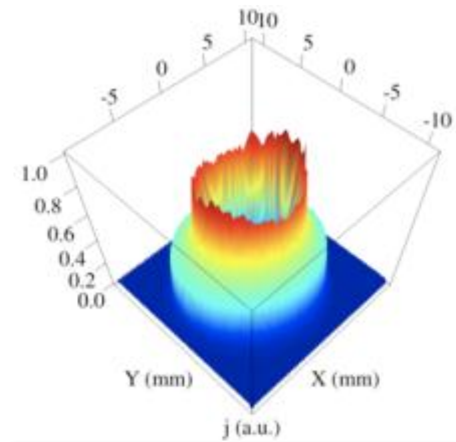
Halo control (hollow e-lens)



Controlling diffusion rate: hollow e-lens





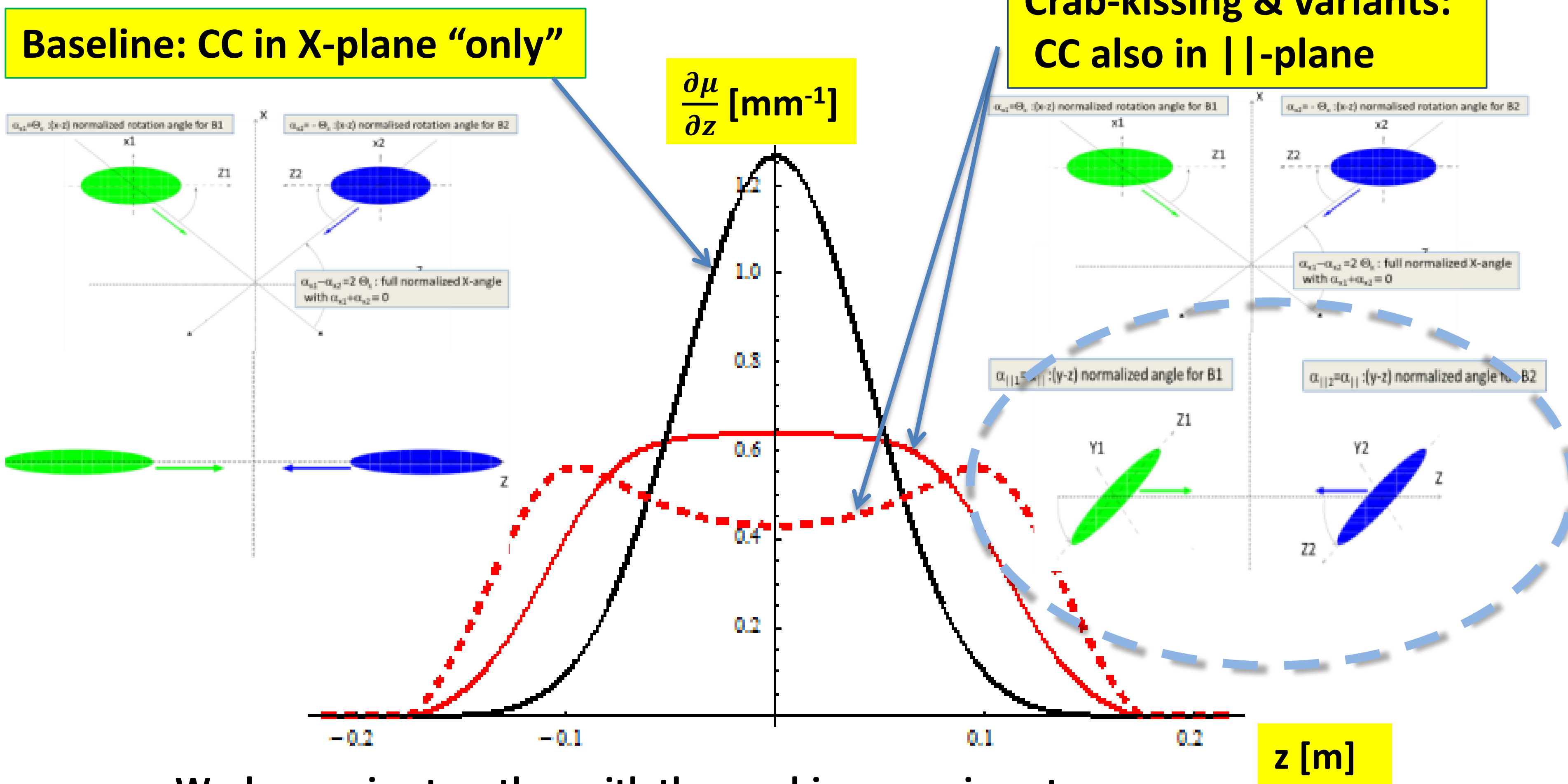


Promises of hollow e-lens:
1. Control the halo dynamics without affecting the beam core;
2. Control the time-profile of beam losses (avoid loss spikes);
3. Control the steady halo population (crucial in case of CC fast failures).

Remarks:
- very convincing experimental experience in other machines!
- full potential can be exploited if appropriate halo monitoring is available.

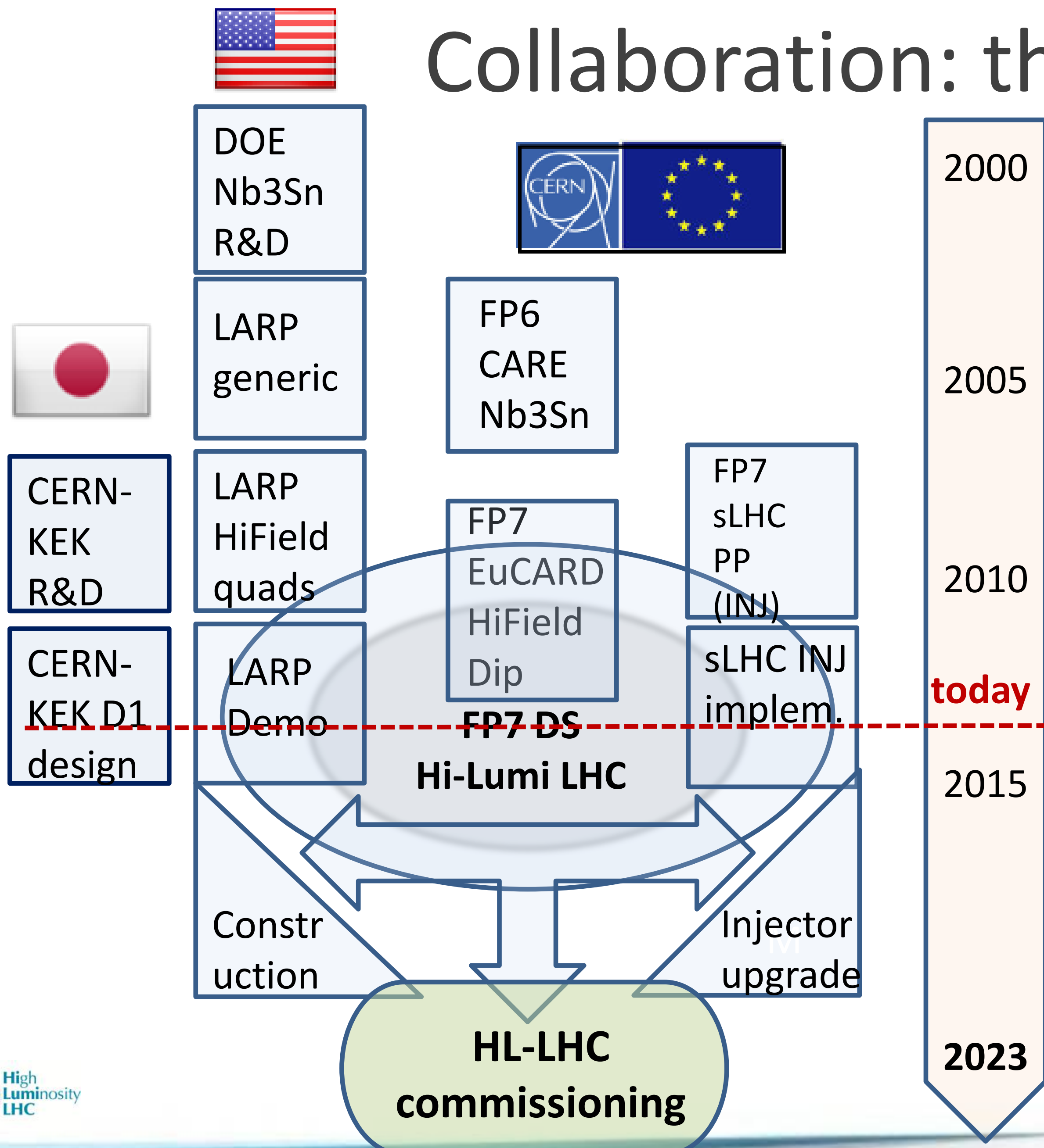
S. Redaelli
Developed by Fermilab

The **Crab-kissing** (CK) scheme for **pile-up density** shaping and leveling (S. Fartoukh)



... Work on-going together with the machine experiments (S. Fartoukh, A. Valishev, A. Ball, B. Di Girolamo, *et al.*)

Collaboration: the long way

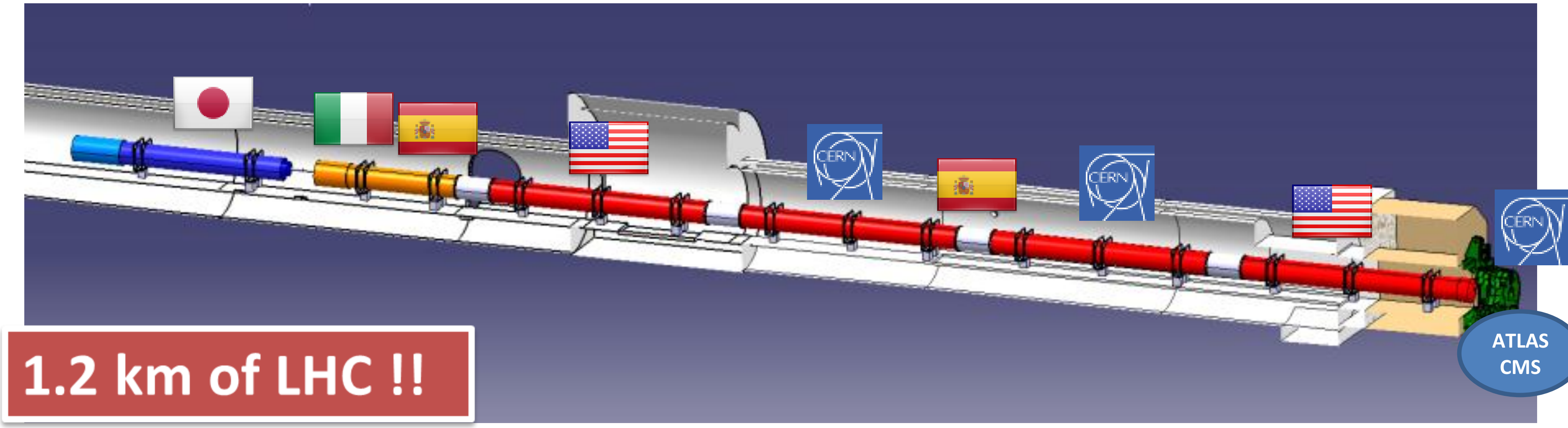


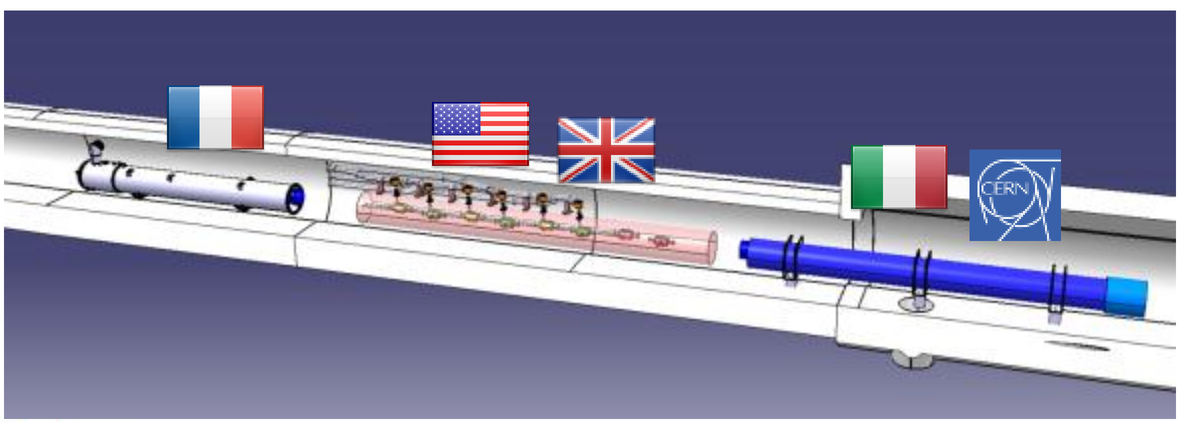
The HL-LHC project formally started in 2010; however it is the focal point of 20 years of <u>converging</u> International Collaboration

High Luminosity LHC

High Luminosity LHC Participants

In-kind contribution and Collaboration for HW design and prototypes



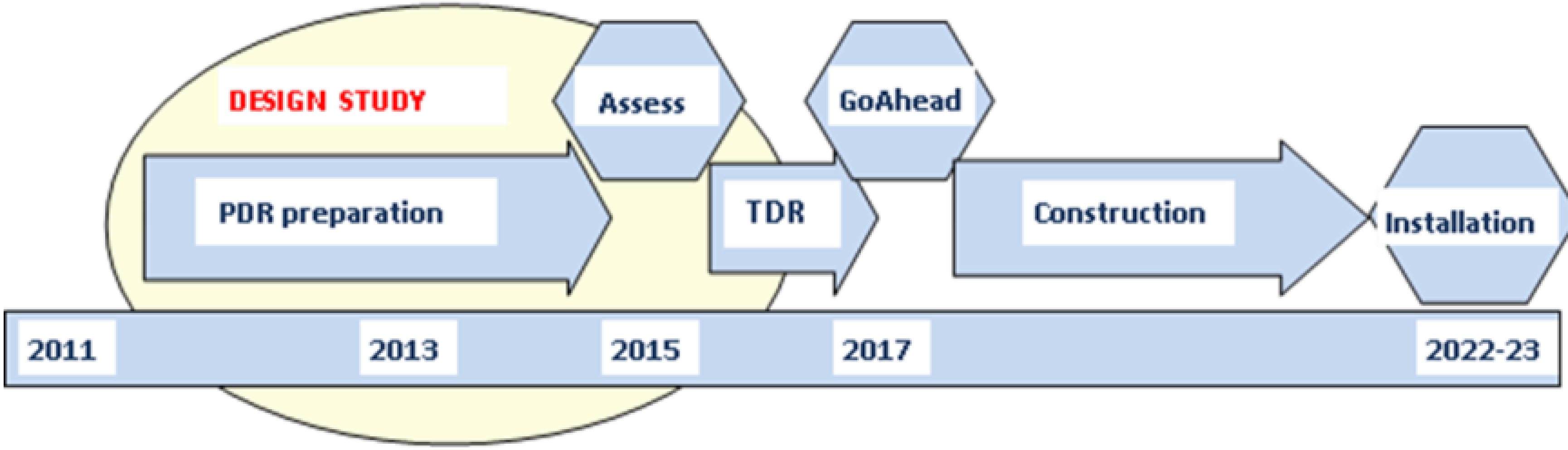


Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

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

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

Implementation plan

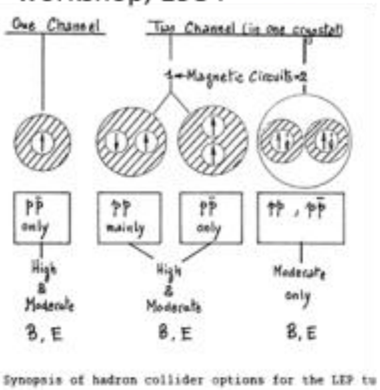


- All WP active, from diagnostics to Machine Protection;
- Integration started with vigour as well as QA (workshop soon)
- Cryo, SC links, Collimators, Diagnostics, etc. starts in LS2 (2018)
- Proof of main hardware by 2016; Prototypes by 2017
- Start construction 2017/18 from IT, CC, other main hardware
- IT String test (integration) in 2019-20; Main Installation 2022-23
- Though but – based on LHC experience – feasible
- Cost: 810 MCHF (Material, CERN accounting)

2025 is tomorrow: what we can do for after 2025? Look at LHC timeline

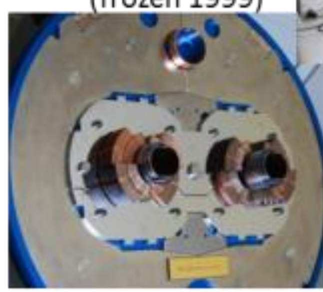
- **1985** — First ideas, Twin Dipoles, HeII cooling
- **1990** — R&D for 8-10 T: 13 kA cables, short models, 10 m long prototypes, 1st string test
- **1995 – 2000** — Final design, industrialization, start pre-series
- **2000 – 2005** — Magnet construction, performance test, tunnel preparation
- **2005 – 2010** — Installation, LHC start, Incident
- **2010** — Re-start 4.2 T
- **8 T**

Magnet designs at first LHC workshop, 1984

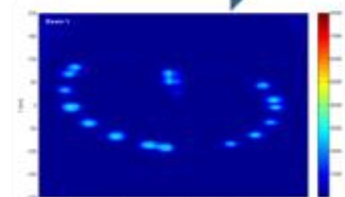


First LHC dipole prototype on the test bench (June1994)

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

High Luminosity LHC

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

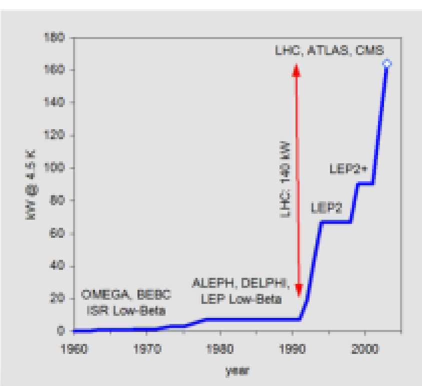
1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035

LEP: Construct. → Physics → Upgr

LHC: Design, R&D → Proto → Construct. → Physics

HL-LHC: Design, R&D → Construct. → Physics

HE-LHC: Design, R&D → Proto → Construct. → Physics

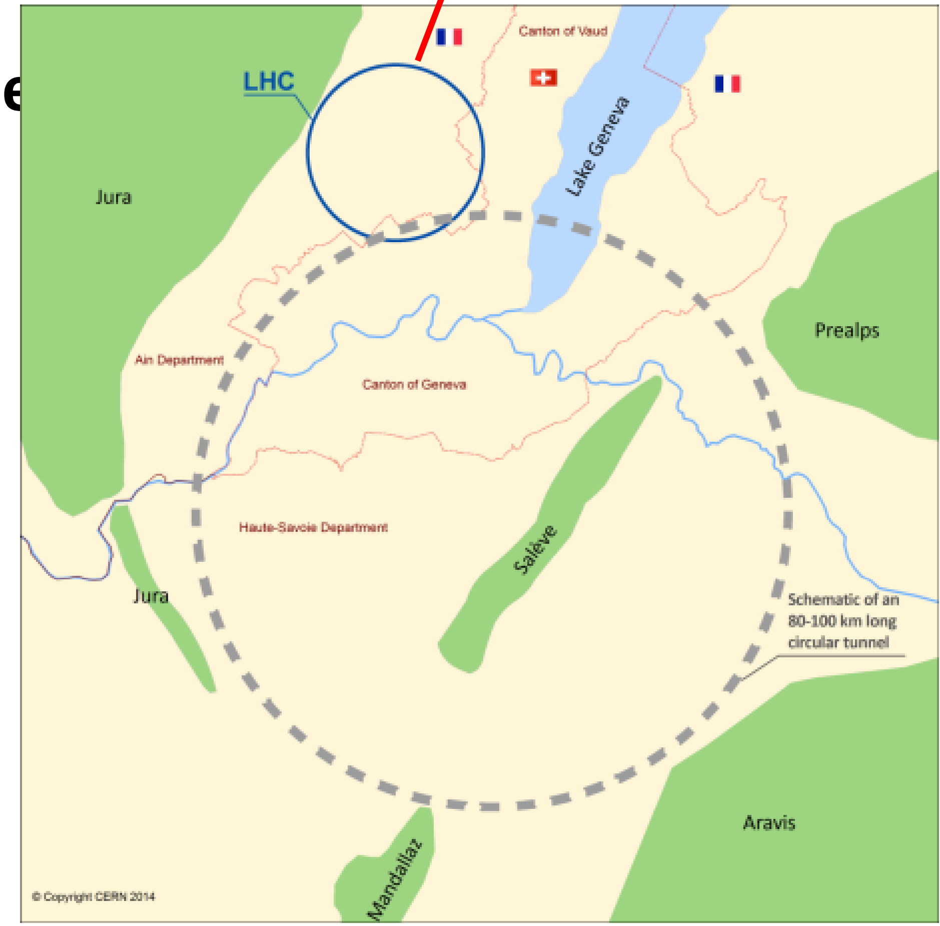


FCC-Future Circular Colliders

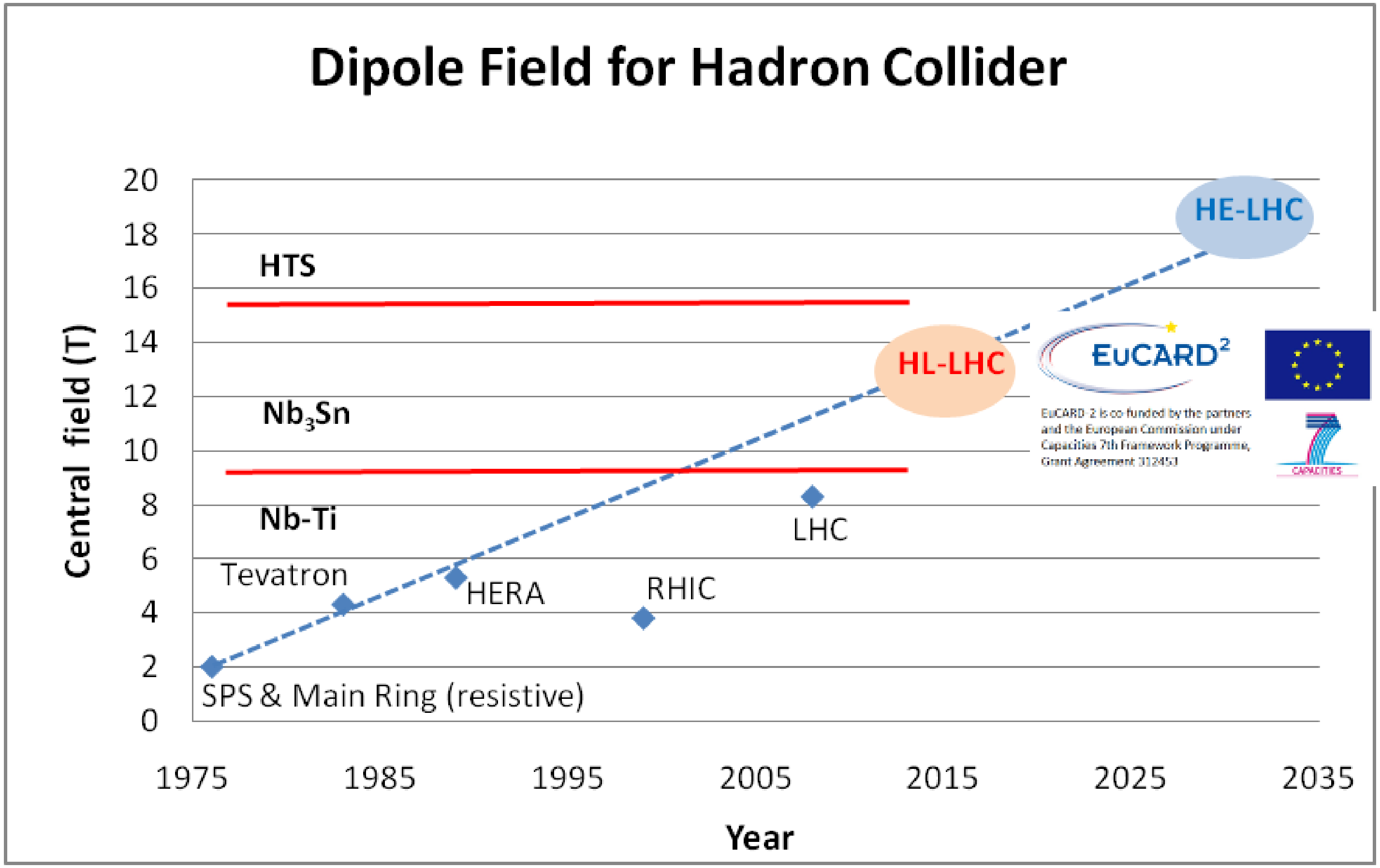
HE-LHC :33 TeV with 20T magnets

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**



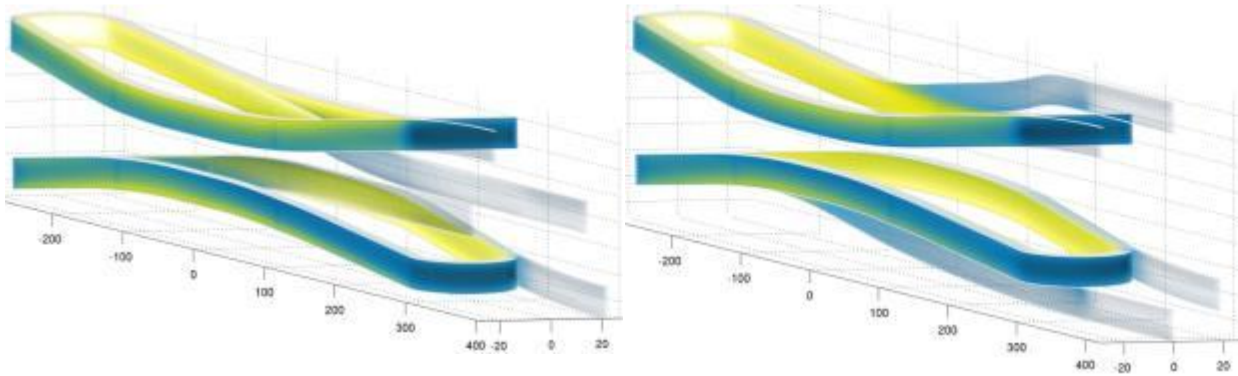
The long route toward a new machine: R&D !!!

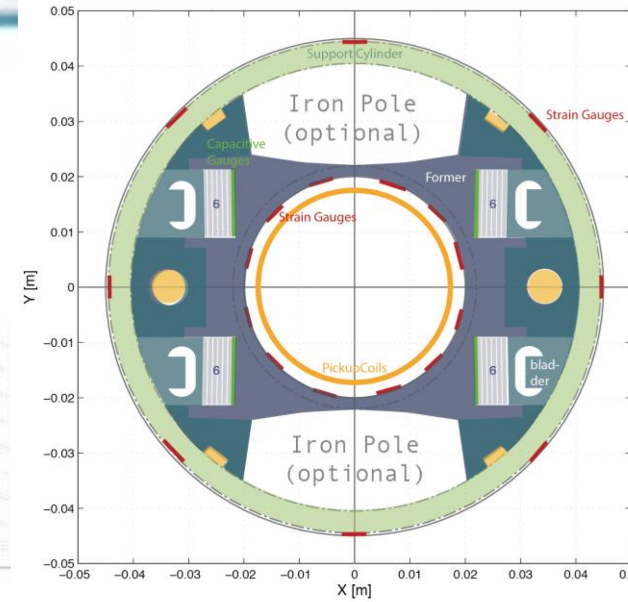


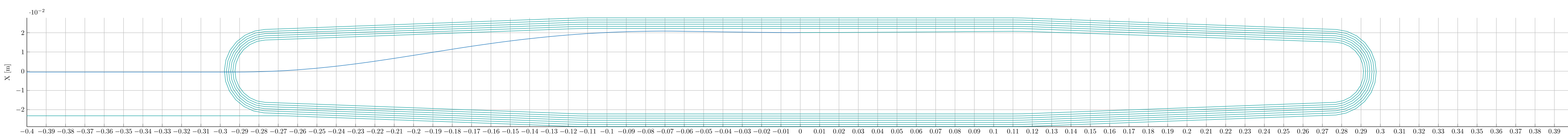
Looking at performance offered by practical SC, considering tunnel size and basic engineering (forces, stresses, energy) the practical limits is around 20 T. Such a challenge is similar to a 40 T solenoid (μ-C)

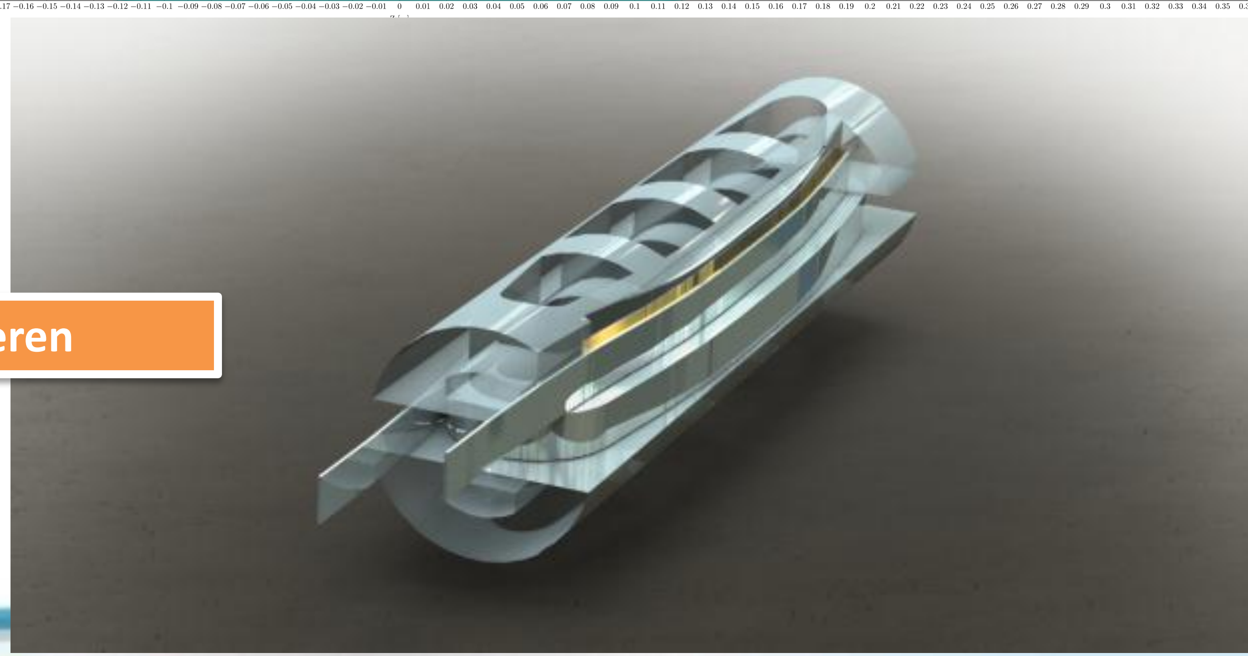
High Luminosity LHC

New design, cont.





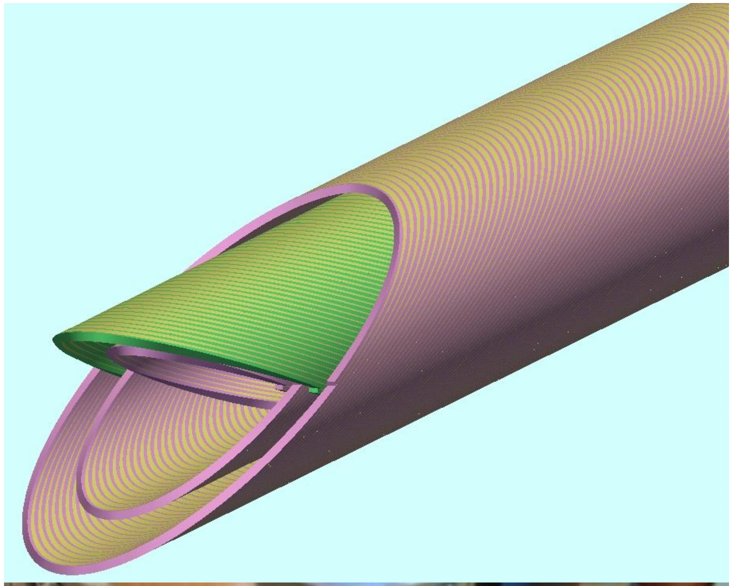


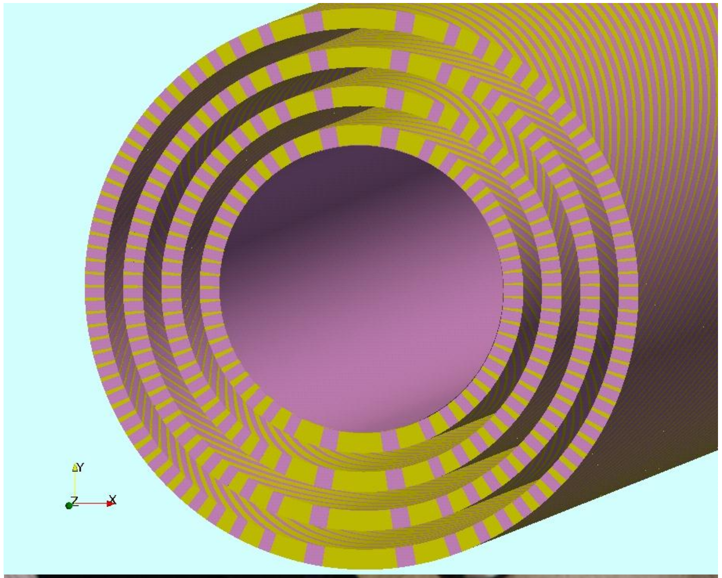


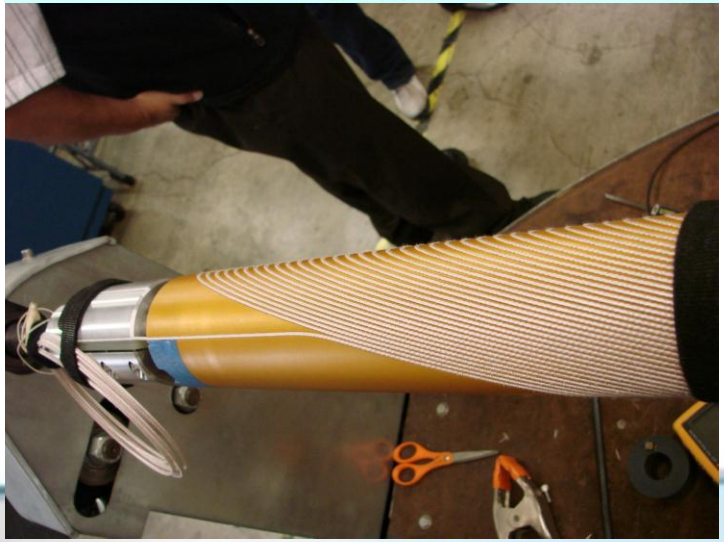
Courtesy J. Van Nugteren

Canted Cosϑ (CCT);

successfull test at LBNL (2.7 T in a first Nb-Ti)







High Lumino LHC