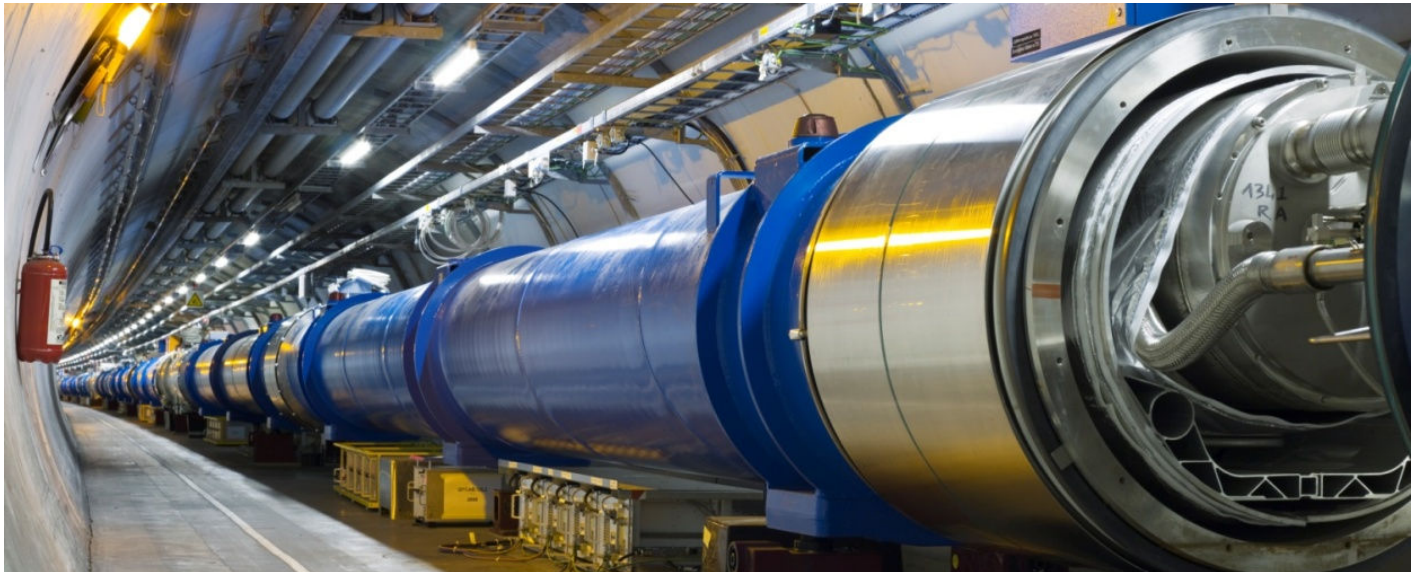


The CERN plan for the LHC upgrade

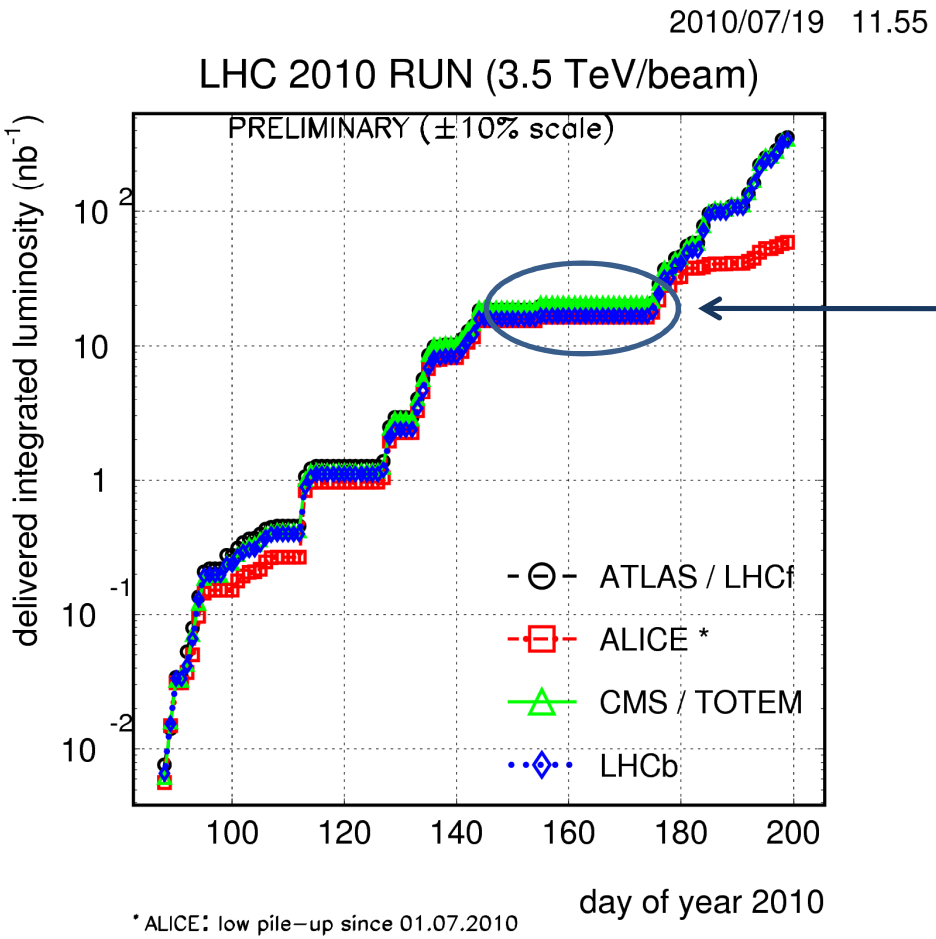
Lucio Rossi
CERN – TE dept

Accelerator seminar @ Fermilab 29Jul2010

Content

- LHC today, performances and consolidation plan
- LHC upgrade:
  - overview of the past work
  - Phase 1 (+ Phase 2 ?)
- LHC-INJ upgrade
- The new plan HL-LHC
  - Concept
  - Hardware
  - Preliminary plan
- The « definitive » upgrade: HE-LHC

Luminosity today
scope 0.1 fb^{-1} by 2010 – 1 fb^{-1} by 2011



ca. 70 nb-1 in last fill!

Work to have nominal bunch intensity of 1.1 e11 ppb

- ➔ Approach with high bunch intensity paid off (investment of commissioning time)
- ➔ **9e10 p per bunch**
- ➔ **up to 13 bunches (8 crossing pairs/IP)**

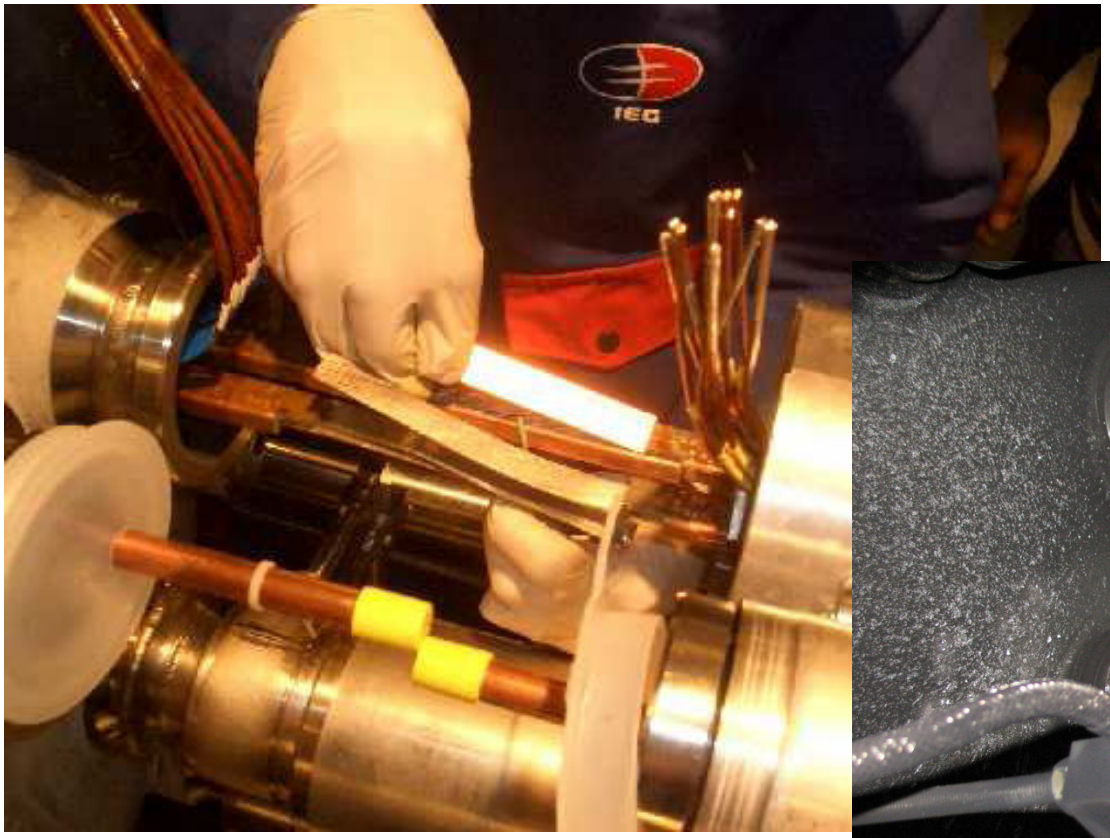
- ➔ **Record L_{peak}= 1.6 1030**
- ➔ Trying to resume the ramp at 10A/s (today working at 2 A/s because of n-QPS/PS interaction
- ➔ Yesterday first multibuch injection (4 b/fill)
- ➔ Today first attempt to 25 b (16 Xing pairs/IP)

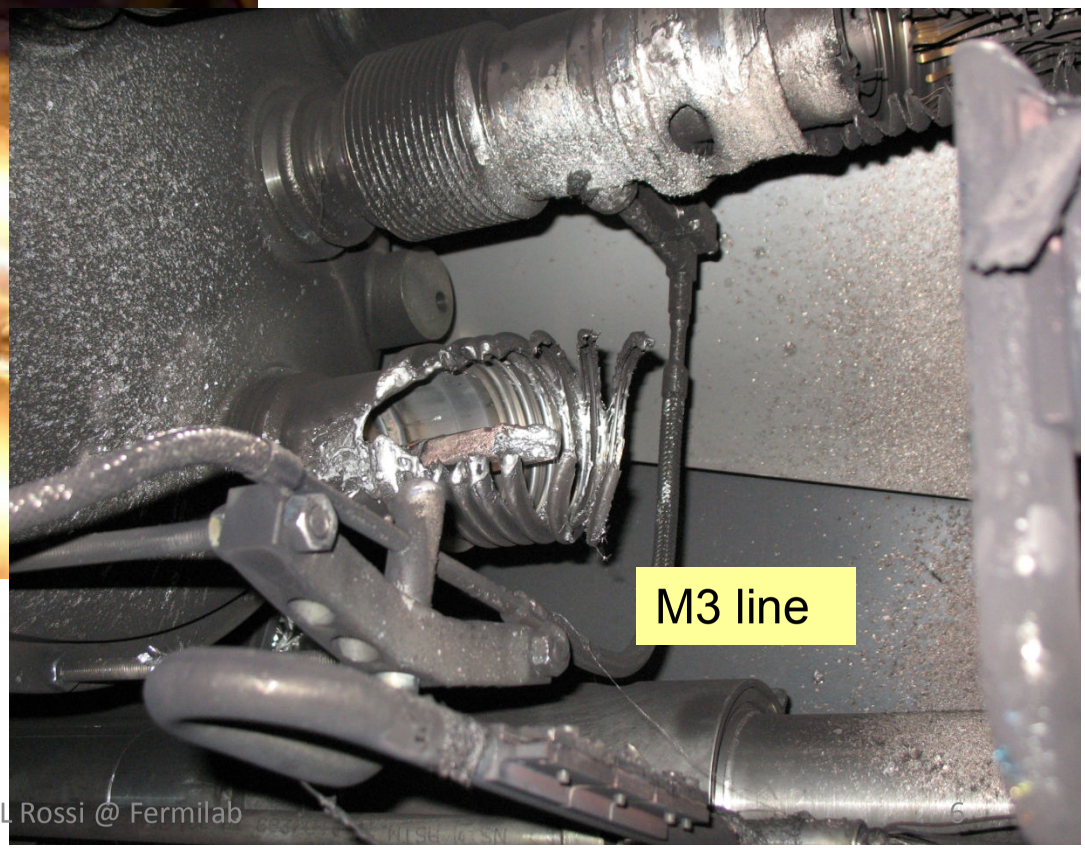
Also thanks to your magnets…

The two problems of LHC for reaching nominal performance

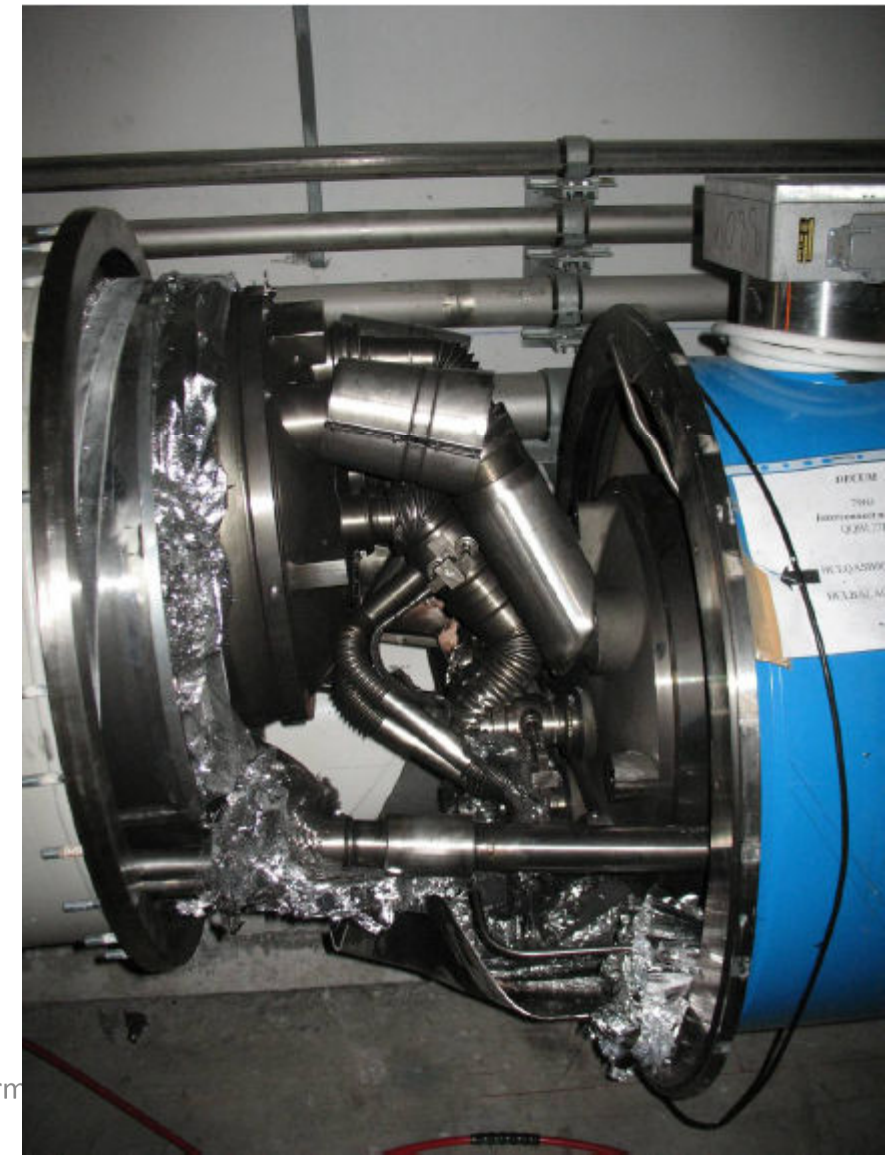
- Beam Energy: **IC joints limits to 3.5 TeV/beam**
  - We do not have anymore bad SC splice: the worst is 3 nΩ (specs is 0.6 nΩ, the one that melt away was 220 nΩ)
  - However we have left behind us many unstabilized joints…
- Beam Intensity: **collimation limits lumi to 0.05-0.2 10^{34}**
  - Today all so called phase 1 collimation is installed
  - Phase 2 collimation has changed **dramatically 1 years ago**: studies pointed to the need of collimators in the COLD regions (DS).

We recovers from here…



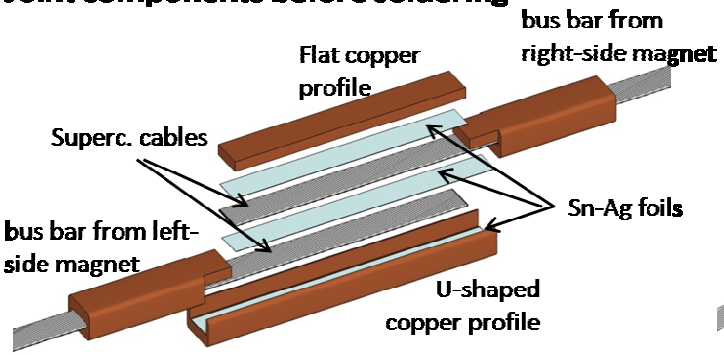


And here…

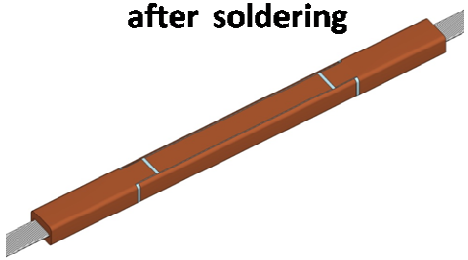


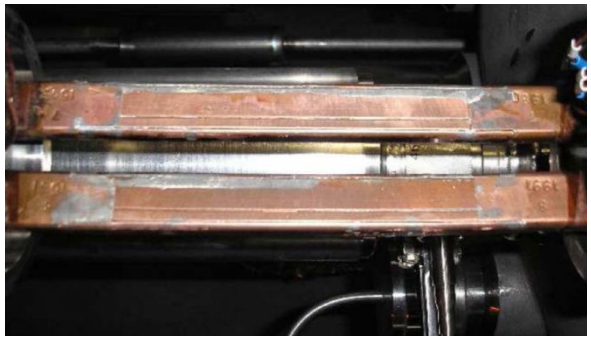
Looking back…
LHC Interconnection joints

Joint components before soldering

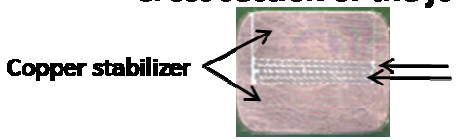


Bus bar well reconstituted after soldering

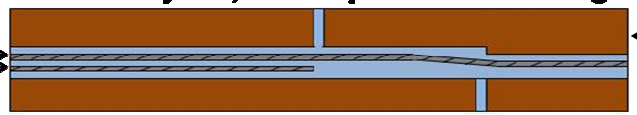




Cross section of the joint



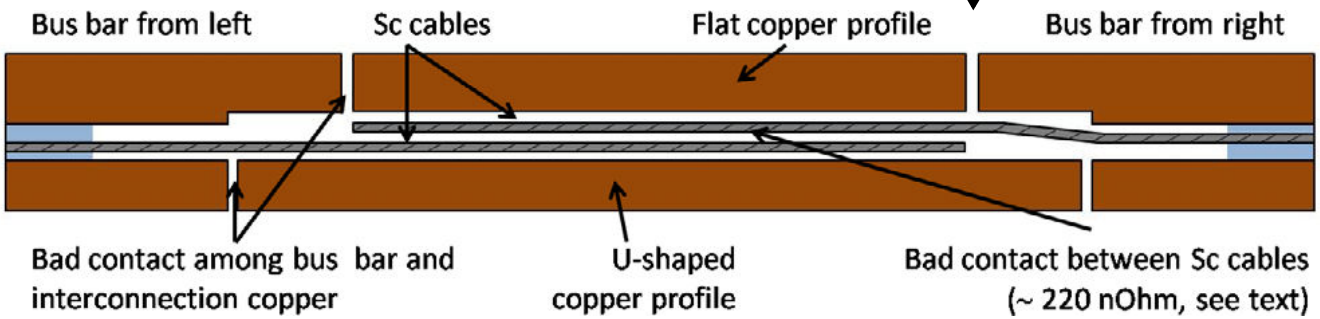
Longitudinal section of the joint, entirely filled with Sn-Ag



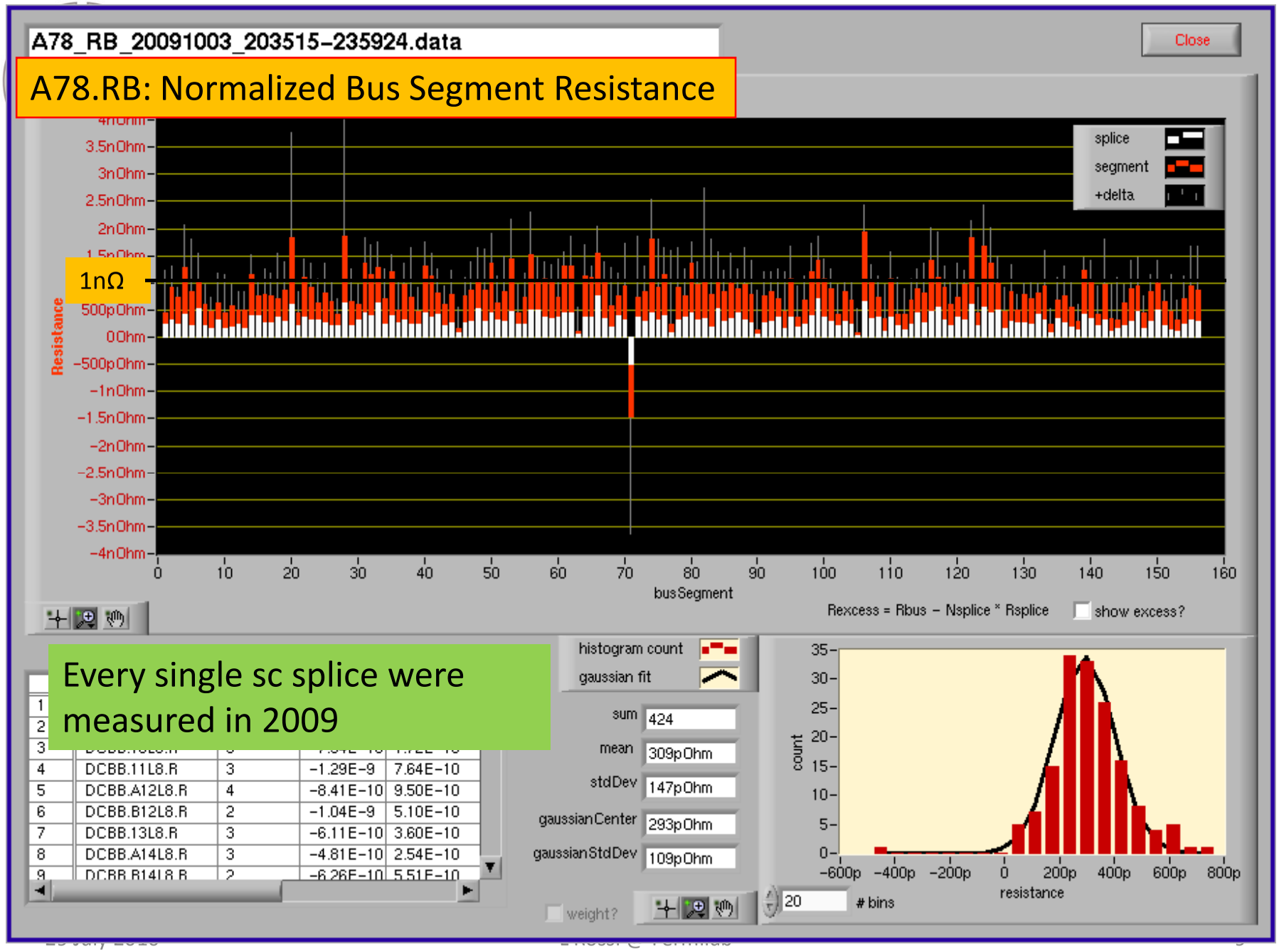
0.2 nOhm

220 nOhm

Most likely reconstruction of the one that melted away

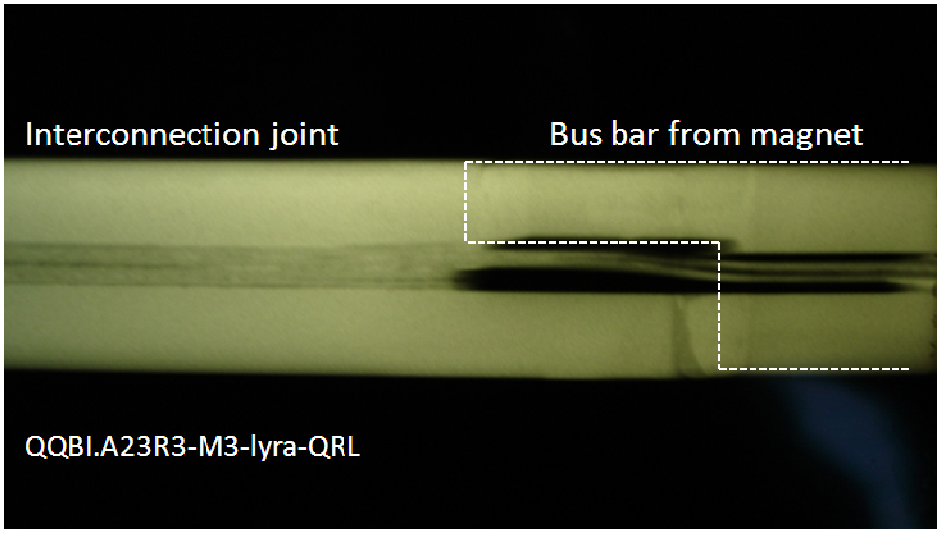


A78.RB: Normalized Bus Segment Resistance

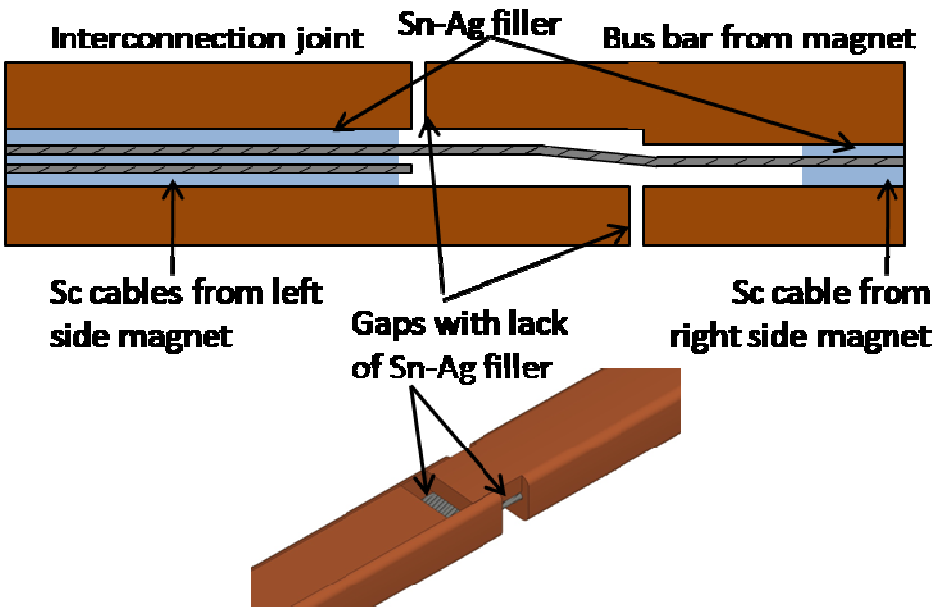


Every single sc splice were measured in 2009

The problem still left
Unstabilized joint (silent killer)

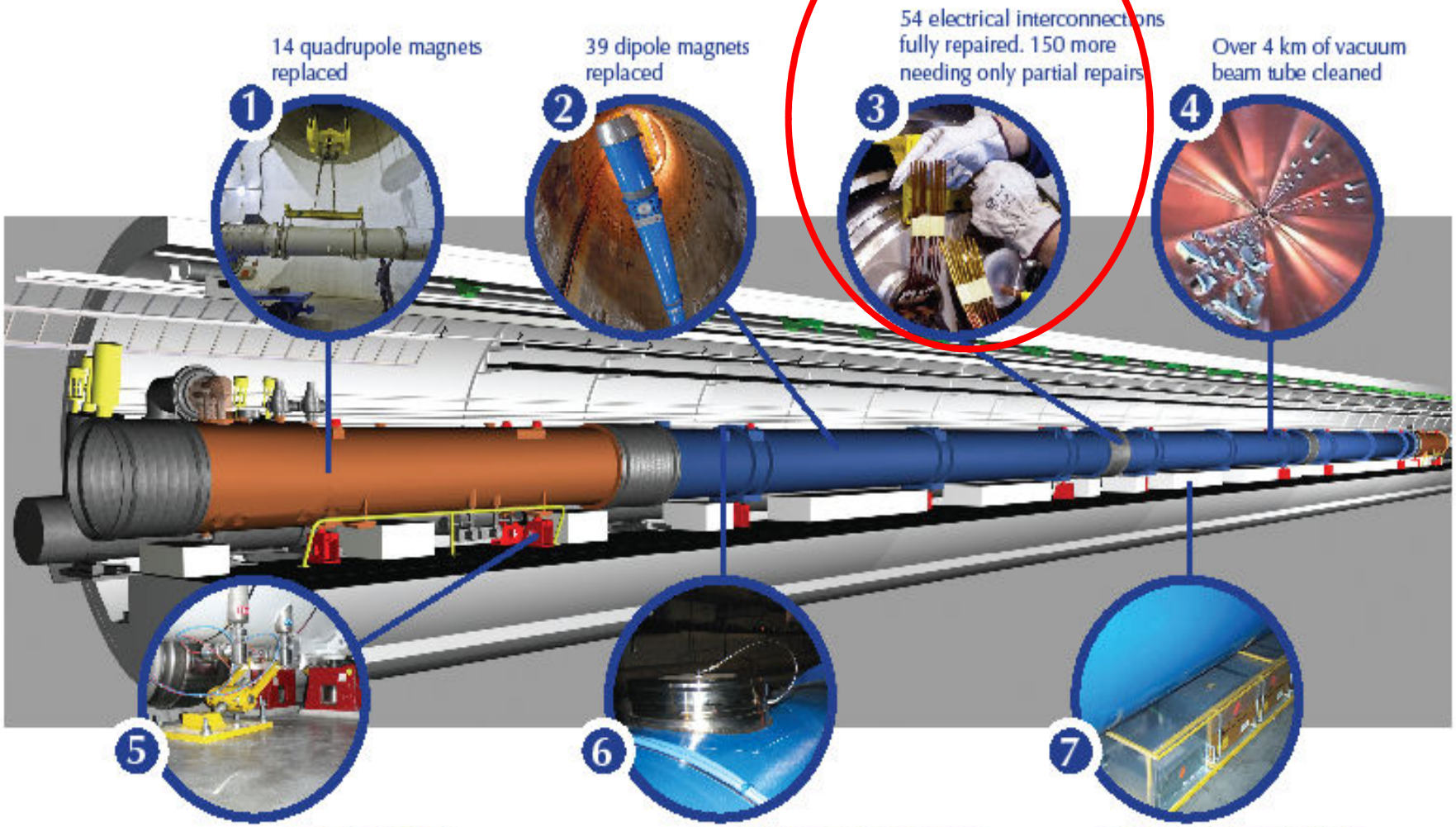


Defective interconnetion-bus bar transition γ-ray picture (left) and scheme (right)



Existance of unfilled gap was known during IC work in 2006 and reported. No problem for 1-2 mm gap…
End february 2009 an empty bus bar (20 m or more) discovered in a spare quadrupole through γ-ray
The picture above discovered in the tunnel in sector 3-4 in April 2009. It is 30 cnm long and it shows an extra resistance at room temperature of about 35 μΩ

The LHC repairs in detail



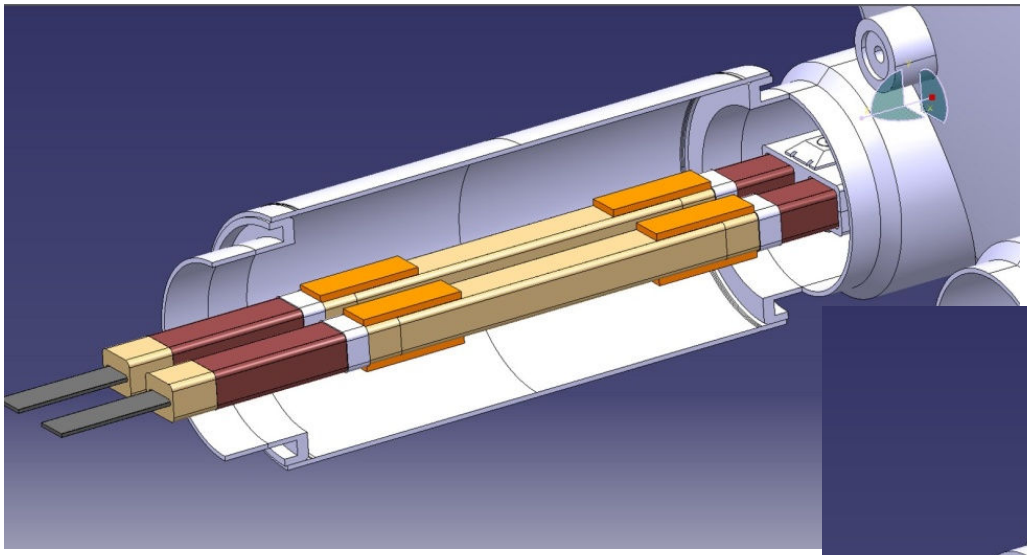
situation

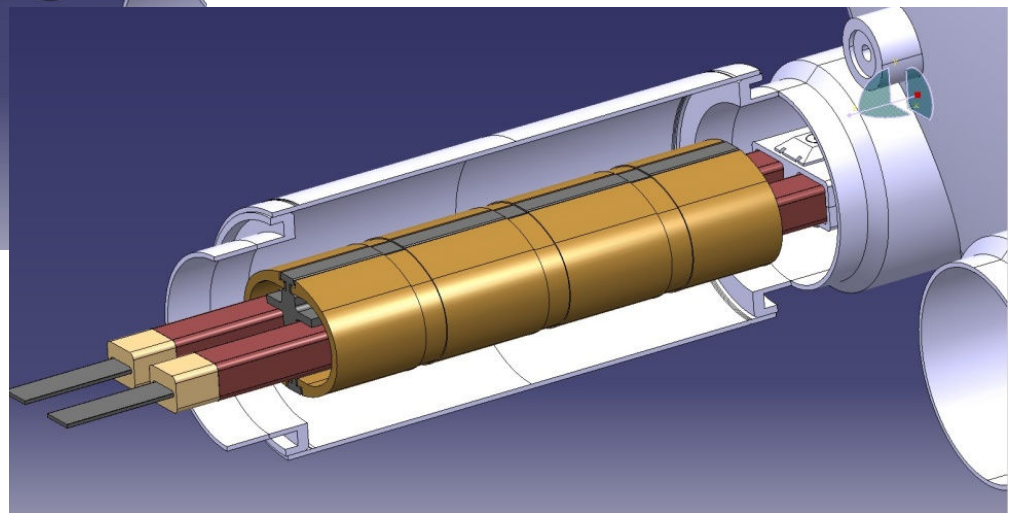
- We know we left behing unstabilzed length of 40 mm (50 microOhm)
- We measured well only 4 sector warm
- On the 4 sectors left cold (100 K) measurements are noisy. A statistical analysis showed that a 90 microOhm (70 mm lenght unstabilized) could not be excluded
- $\Rightarrow$ **run at 3.5 TeV/beam**
- Plan 2012 – 2013 (April):
  - open all 3 M lines/IC containing bus bars;
  - re-solder the 10-15% defective joint ones (experience)
  - **fix the stability on ALL IC joint by means of a copper shunt**

The fix to cure unstability

Making the shunt (reduntant!)

Making a box for lateral restraint and vertical containment)

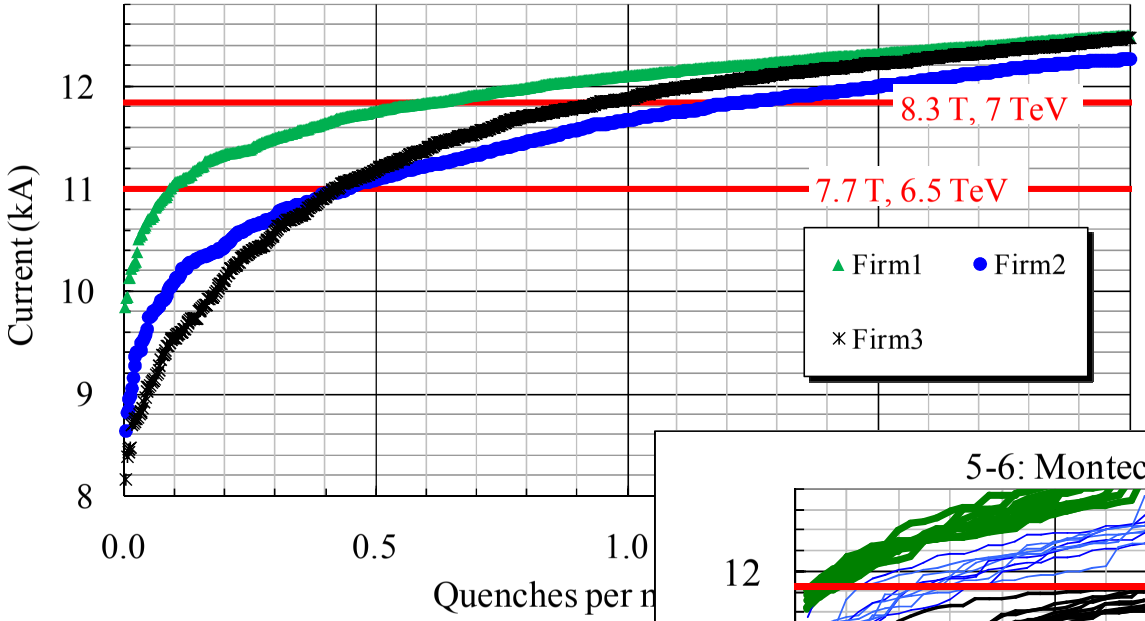


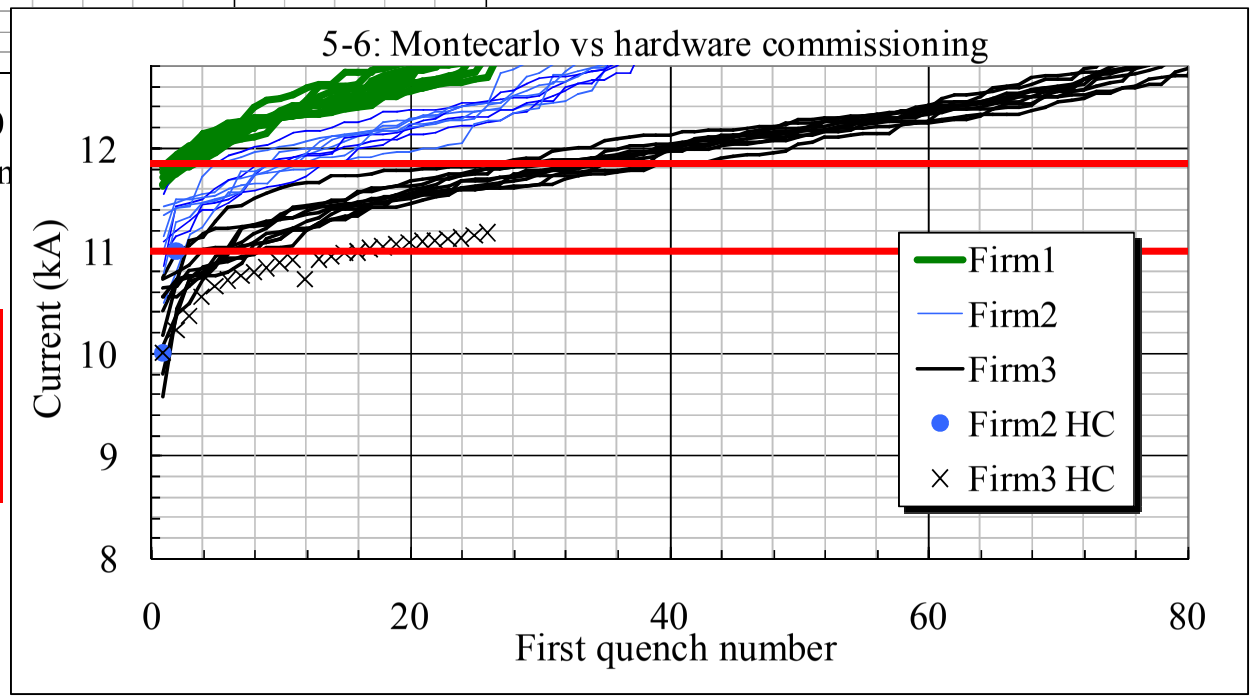


Will we reach 7 TeV ? Dipole training…

- In principle 4 quenches/day with 2-4 sectors going in parallel was foreseen for training in the design: say at least 10 quench/day for HWC.
- We might have expected less than 100 quenches to reach nominal based on best prototypes + preseries dipoles (2000-2002)
- Analysis done experience7 TeV based on analysis of 2005-07 indicated that we should have expected 250
- Re-analysis (see (E. Todesco at Chamonx 2010), of the same acceptance test data, points to 400: **about 40 days of HWC.**
- However HWC data, extrapolated from one sector only indicates about 800 !

Actual resutls in single test (all) and in the LHC HWC for sector 5-6 only





- 100 quenches to 6.5 TeV
- 250 quenches to 6.75 TeV
- 500-800 to 7 TeV !

Interim Collimation 2013

1. **Collimation upgrade in IR3 dispersion suppressors** to capture p losses due to single-diffractive scattering and to capture ion losses (removes highest predicted and highest measured loss).
2. **Collimation upgrade in IR3 warm insertion** (10 vertical collimators added) to add flexibility for relocating losses from IR7 to IR3 (SEE limitations).
3. Prepare work for 2015/16 collimation upgrades.

Gain: Hope to reach nominal intensity and up to half nominal luminosity. Lower complexity. Smaller horizontal impedance. Higher cleaning efficiency.

Price to pay: Twice larger vertical impedance, additional loss spike in IR5 and higher losses at tertiary collimators.

IR3 upgrade is an excellent step forward but no miracle solution.

Full Collimation 2016

1. **Collimation upgrade in IR7 and IR2 dispersion suppressors** to capture p losses due to SD scattering and to capture ion losses.
2. **Installation of advanced collimators** (mostly into prepared empty slots) to allow non-destructive and very fast collimator setup, compatible with LHC stability and small β^* (

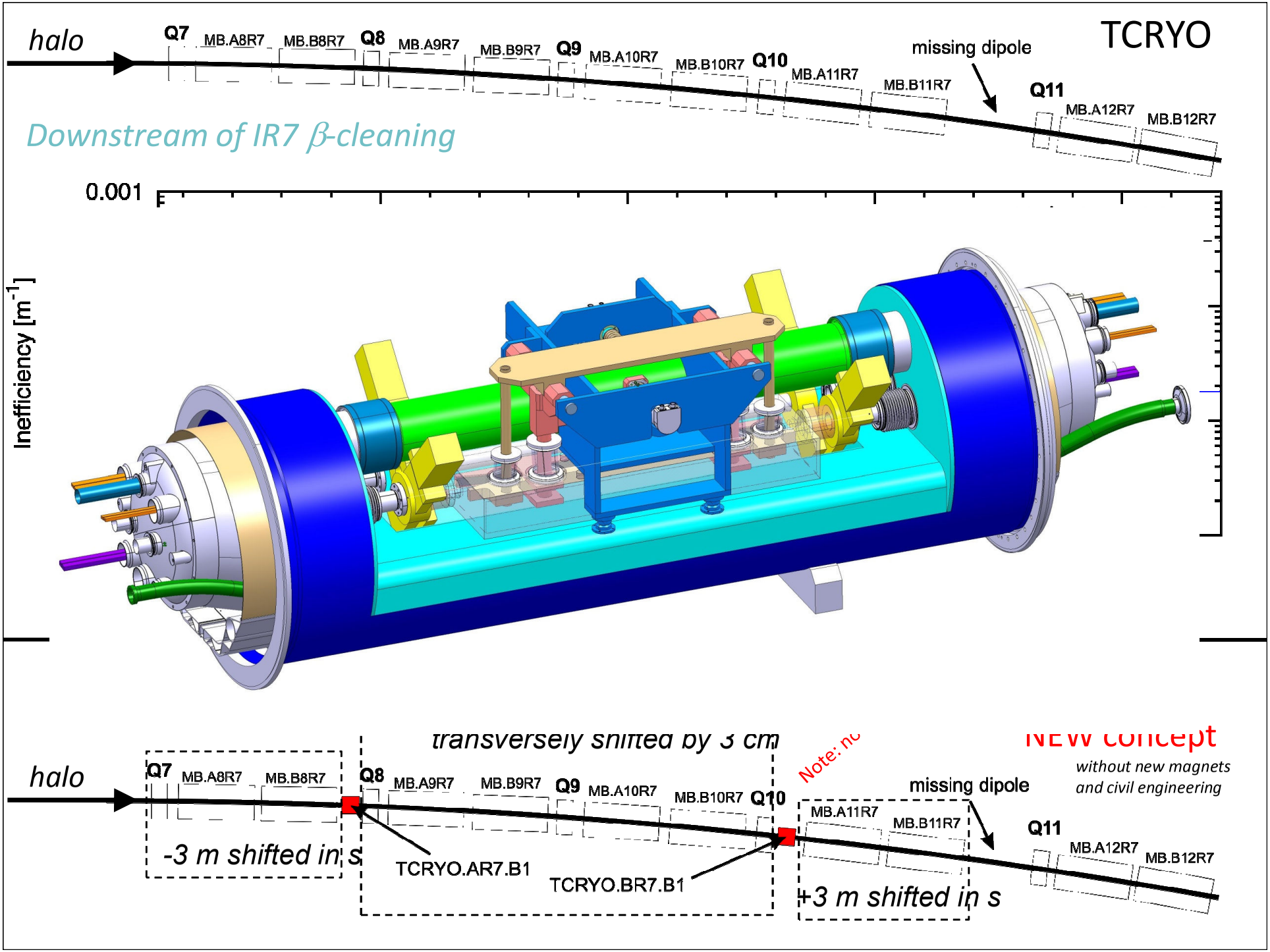
   SLAC very motivated to *r the secondary collimators to*

   Not discussed today!
3. **Collimati** **IR1 and IR5** for luminosity-induced losses from collisions (install 4 already produced Cu collimators).
4. **Collimation upgrade in IR2** for ZDC acceptance issue. EARLIER???
5. **Remote handling and air bypass** operational in IR7.
6. **Additional tungsten absorbers in IR6** dump protection system to improve local cleaning.

Dispersion Suppressor Work

- Addresses a very **basic limitation of the LHC collimation** system: protons lose energy when hitting matter, ions dissociate and fragment!
- Could not be addressed before: collimation started very late in the game and SC areas of LHC were frozen.
- Note that this is nothing exotic: other accelerators had this (e.g. LEP2 added collimators into dispersion suppressors).
- **A solution without new SC magnets was proposed:** allows collimation readiness for nominal and ultimate beams by 2015/6 at latest (if we start).
- Other solutions are nice but would come much later (e.g. shorter magnets with collimator in front).

➔ What – Where – Why


halo
Q7
MB.A8R7
MB.B8R7
Q8
MB.A9R7
MB.B9R7
Q9
MB.A10R7
MB.B10R7
Q10
MB.A11R7
MB.B11R7
missing dipole
Q11
MB.A12R7
MB.B12R7
TCRYO
Downstream of IR7 β-cleaning
0.001
Inefficiency [m-1]
transversely shifted by 3 cm
Note: no
New concept
without new magnets
and civil engineering
-3 m shifted in s
TCRYO.AR7.B1
TCRYO.BR7.B1
+3 m shifted in s

The LHC upgrade:
LHC and EU Particle Physics - Lisbona 2006

The European strategy for particle physics

…

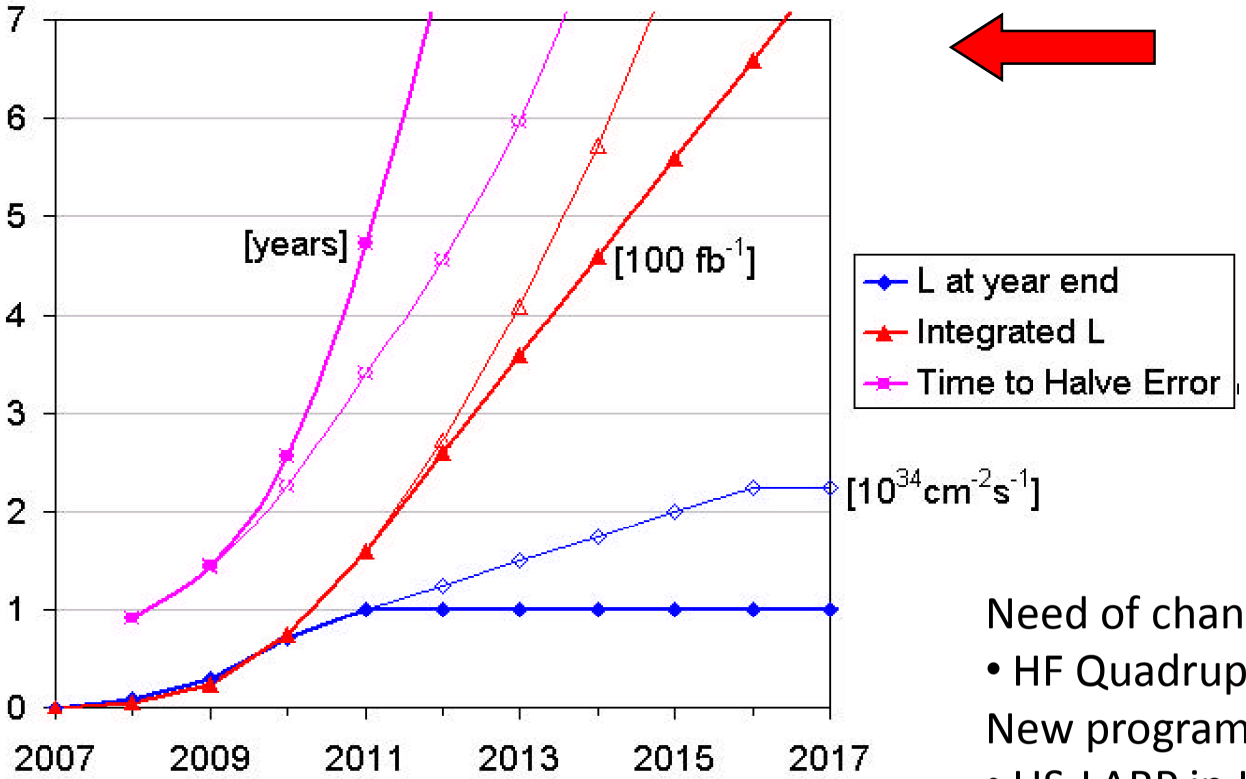
Scientific activities

3. The LHC will be the energy frontier machine for the foreseeable future, maintaining European leadership in the field; *the highest priority is to fully exploit the physics potential of the LHC, resources for completion of the initial programme have to be secured such that machine and experiments can operate optimally at their design performance. A subsequent major* luminosity upgrade (SLHC), motivated by physics results and operation experience, will be enabled by focussed R&D; *to this end, R&D for machine and detectors has to be vigorously pursued now and centrally organized towards a luminosity upgrade by around 2015.*

Statement is perfectly actual and valid
However the date must be shifted 5 years

- **1 y of delay in LHC and detector commissioning**
- **2 y for the incident and for next splice consolidation**
- **2 y more of operation to reach ~500 fb^{-1} (Int. Lumi per year ~ 50 fb-1, not 100 !)**

The baseline in 2003-2006



Radiation damage limit ~700 fb^{-1}

Paper of J. Strait et al. PAC2003

In 2007 new – anticipated – scenario :

- Nb_3Sn not ready before 2015-17
- Decision to target a first upgrade in 2012-13

⇒ Phase 1 based on Nb-Ti Ø=120 mm

⇒FP7 SLHC-PP launched for 2008-2010

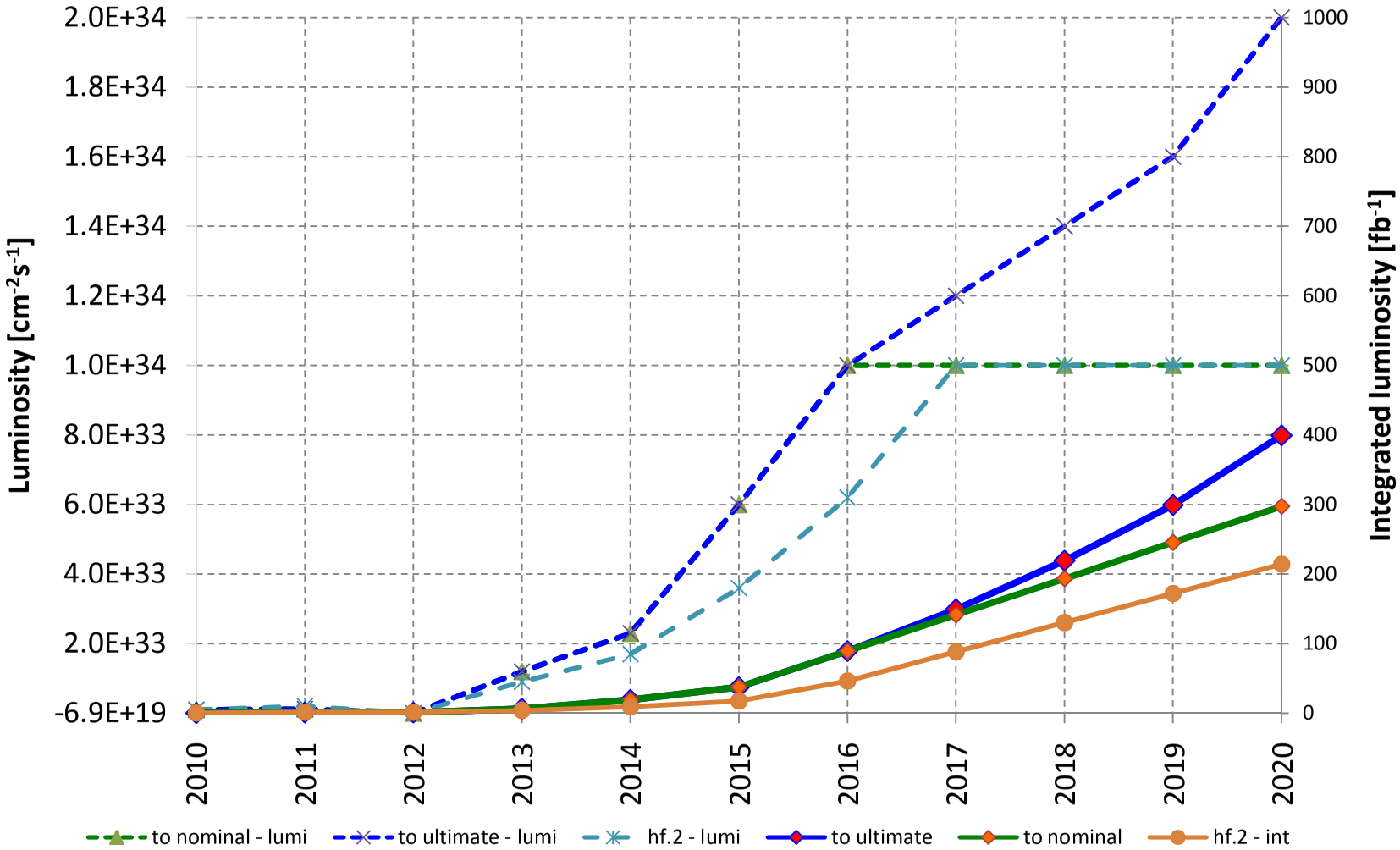
Need of change in 2013 -15. Main hardware:

- HF Quadrupole magnets for 13-15 T

New program (in // to LHC construction)

- US-LARP in US in 2003 (6 MCHF/y 2006-13) – based on a Nb_3Sn DOE program 1998-2010
- FP6-CARE : NED JRA to develop EU Nb3Sn in 2004-08 . **Its positive effects NOW!**
- FP7 EuCard IA: WP on HFM 2009-2012

Updated LHC lumi vs. (end of) year



Courtesy of M. Lamont, spring 2010

Intensity Limits

Intensity Limitations (10^{11} protons per bunch)

Reminder design = 1.15 (for 10^{34}); Ultimate = 1.7 (for 2.3×10^{34})

	Present	SPL-PS2	2GeV in PS
Linac2/LINAC4	4.0	4.0	4.0
PSB or SPL	3.6	4.0	3.6
PS or PS2	1.7	4.0	3.0
SPS	1.2	>1.7?	>1.7?
LHC	1.7-2.3?	1.7-2.3?	1.7-2.3?

From S. Myers

Conclusion:
We continue (as planned) and terminate the study for LP-SPL/PS2 and study in parallel the PS Booster energy upgrade
Decision can be taken when we have the results of these studies and experience with the LHC operation

MTP "Observations from the DG"

- **Thus, the MTP assumes the feasibility of the energy upgrade of the PS Booster and does not include the start of the LP-SPL and PS2 construction as of 2013**
- In order to optimize the strategy towards the HL-LHC, with the goal of maximizing the integrated luminosity useful for physics, Management has set up a task force. A preliminary recommendation from this task force is to delay the inner triplet replacement to a single HL-LHC upgrade around 2020.

From S. Myers

Phase 1 assessment: summary from taskforce @ LMC-10Mar2010 - 2a

- Disadvantage of the Phase 1.
  - Optics much more rigid;
    - requires special scheme. Aberration sat the limit of LHC correction capability. Longer magnets (same technology) does not help.
    - 30 cm β^* is more difficult than 55 cm of the present LHC. Better solution found with β^* = 40 cm offering a 3 sigma margin per beam (which was part of the initial goal) but only 1.2 gain in lumi over nominal. Today we are limited by a single element. IR upgrade will use all the margins in the whole ring.
  - To change this:
    - modification in MS positions and replacement of a few magnets,
    - additional IR collimators to catch higher losses in IR matching section (lower aperture due to higher beta* in the not-changed magnets
    - Use ultimate strength in the sextupoles, NEW powering scheme of MQT corrector families.
  - Logistics is hard: The logistic for ancillary equipment is hard.
    - A solution NOT fully satisfactory has been found for IP1; more difficult for IP5.
    - A real long term solution devised (see S. Weisz in Chamonix and SC links by A. Ballarino).
      This solution should be integrated in a more global study for **R2E** radiation protection of electronics

Phase 1 assessment: summary from taskforce @ LMC-10Mar2010 - 2b

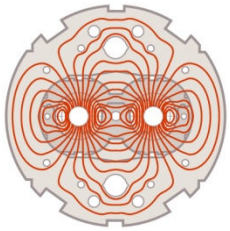
- Disadvantage of the Phase 1
  - The use of the same refrigerator for RF and Arc-IT in 4-5 makes 5L (CMS) weaker in term of cryo-power for high luminosity.
  - The new schedule of LHC: we will not be at nominal before 2014-15 at the very best, and the 300-400 fb-1 are foreseen well beyond 2020.
  - Because of past and future delay (splice consolidation) the IT phase 1 cannot be installed anyway before 2016/17.
  - 1 year optimistic installation time + needed time for a new commissioning of the machine
  - The fairly long stop, and the relatively low gain factor: 2 at max, 1.2 at min) require 2.5 to 5 years just to catch up. Then other long stops will be required for L > 2-3 10^{34}.

Phase 1 assessment: summary from taskforce @ LMC-10Mar2010 – 3

- Recommendation about Phase 1
  - Stop the phase 1 project
  - Keep going on the R&D of Phase 1 that is necessary because of long lead time development;
  - **Decision in 2013/2014**, after LHC behaviour near nominal will be known, the best technology for upgrade. We can't start construction before half 2013. Decision in 2014 to have it by 2018-2020.
  - Put the IT upgrade in a global pictures, preceded by all consolidation or improvement needed to make it most effective and compatible with other equipment.

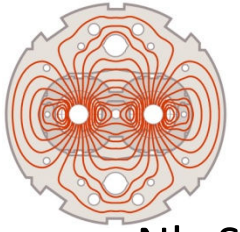
What needs for average lumi 5x10^{34} New lay-out of some part of LHC

- Improve some correctors
  - Commissioning @ 600-650 A the lattice sextupoles
  - New MQT corrector scheme using existing spare 600 A bus bars
- Re-commissioning DS quads at higher gradient
- Review MSs
  - Change of New Q5/Q4 (larger aperture), with new stronger corrector orbit, displacements of few magnets
  - Larger aperture D2
- (may be other actions, more quads in points 6 and 7)
- Displacement of Power Converters & DFBs at least of Inner Triplets but also of OTHER equipment on **surface** by means of SC links.
- Cryo-plant for RF in point 4 : 5-7 kW @ 4.5 K



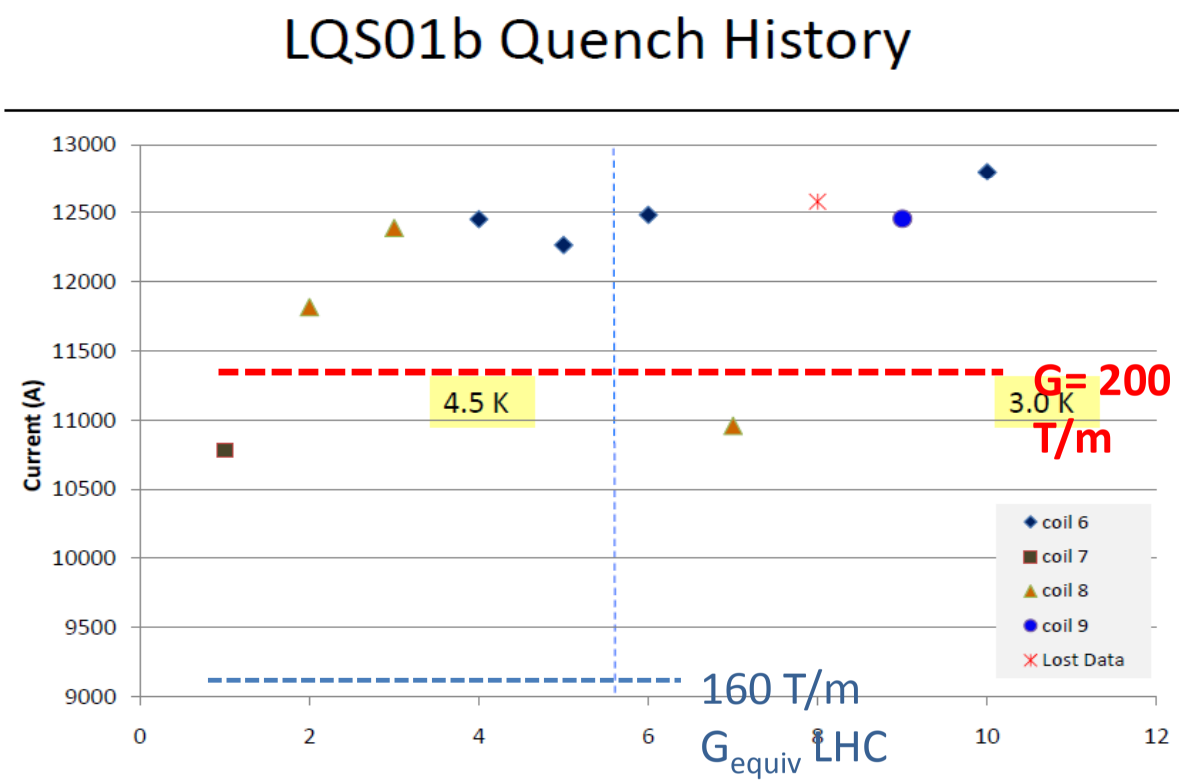
The main ingredient of the upgrade -1 IR Quads

- **High Gradient/Large Aperture Quads, with B_{peak} 13-15 T.** Higher field quadrupoles translate in **higher gradient/shorter length** or larger aperture/same length or a mix . **US-LARP engaged to produce proof by 2013. Construction is 1 year more than Nb-Ti : by 2018** is a prudent assumption. β^* as small as 22 cm are possible with a **factor ~2.5** in luminosity by itself, **if coupled with a mechanism to compensate the geometrical reduction.** If a new way of correcting chromatic aberration could be found, β^* **as small as 10-12 cm can be eventually envisaged.**

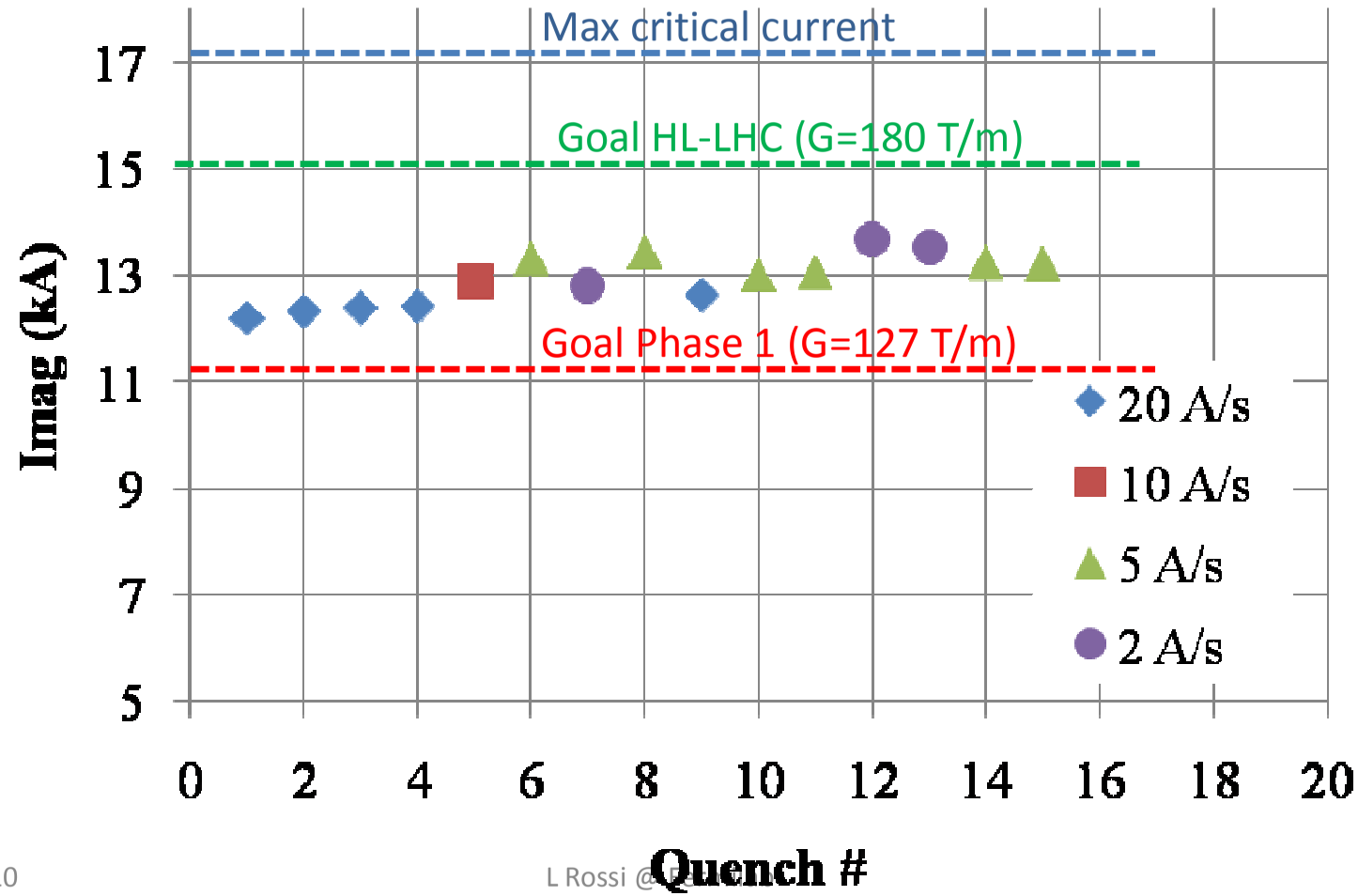


HF Nb_3Sn Quad

- Nb_3Sn is becoming a reality (first LQ long -3.6 m – quad 90 mm)
- This year we expect a second LQ **and a 1 m long - 120 mm** aperture model
- In 3 years: 4-6 m long magnets, 120 mm ap., G=180-200 T/m



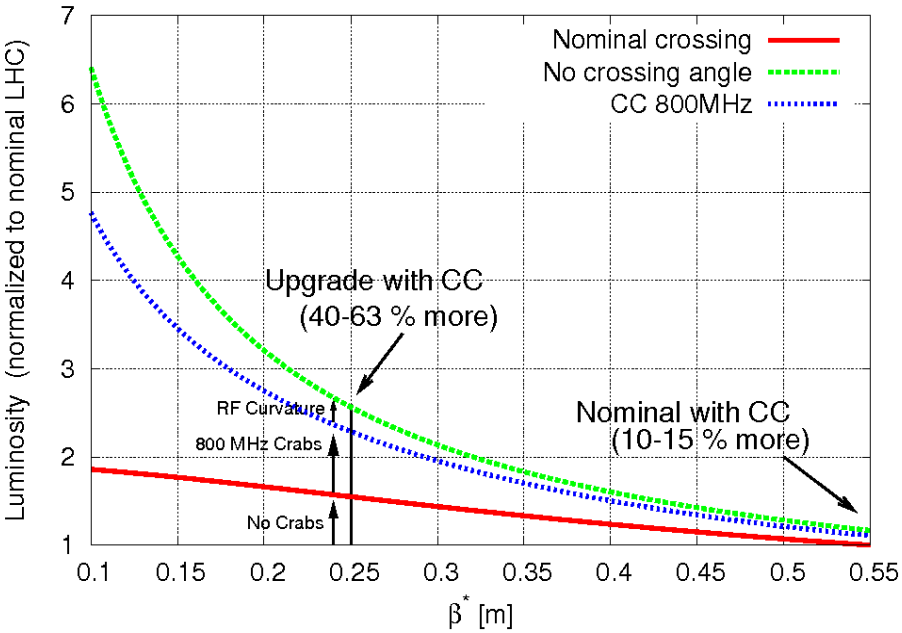
We are near…
Test of LARP HQ – 120 mm

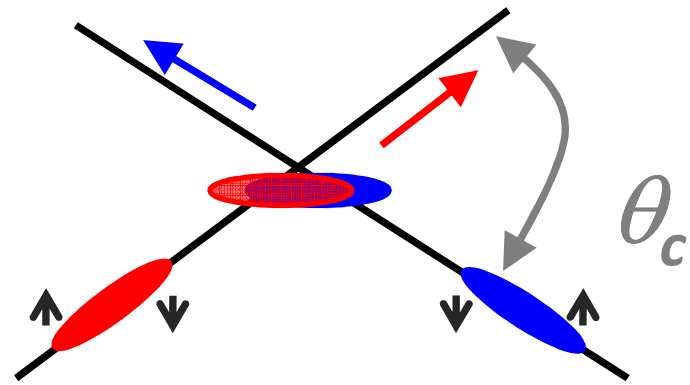


The main ingredient of the upgrade - 2 RF Crab cavities

- **Crab Cavities**: this is the best candidate for exploiting small β^* (for β^* around nominal only +15%). However it should be underlined that today Crab Cavities are not validated for LHC , not even conceptually: **the issue of machine protection should be addressed with priority.**
    - Global Scheme. 1 cavity in IP4, Proof on LHC, good for 1 X-ing.
    - Semi-global; it may work!(JP Koutchouck)
    - Local scheme; 1 cavity per IP side. **Maybe local doglegs needed.**
  - **Early Separation Scheme** could be an alternative (or a complement)
- Both scheme, Crab Cavities and ESS provide a simple mean to do levelling

Crab Cavities

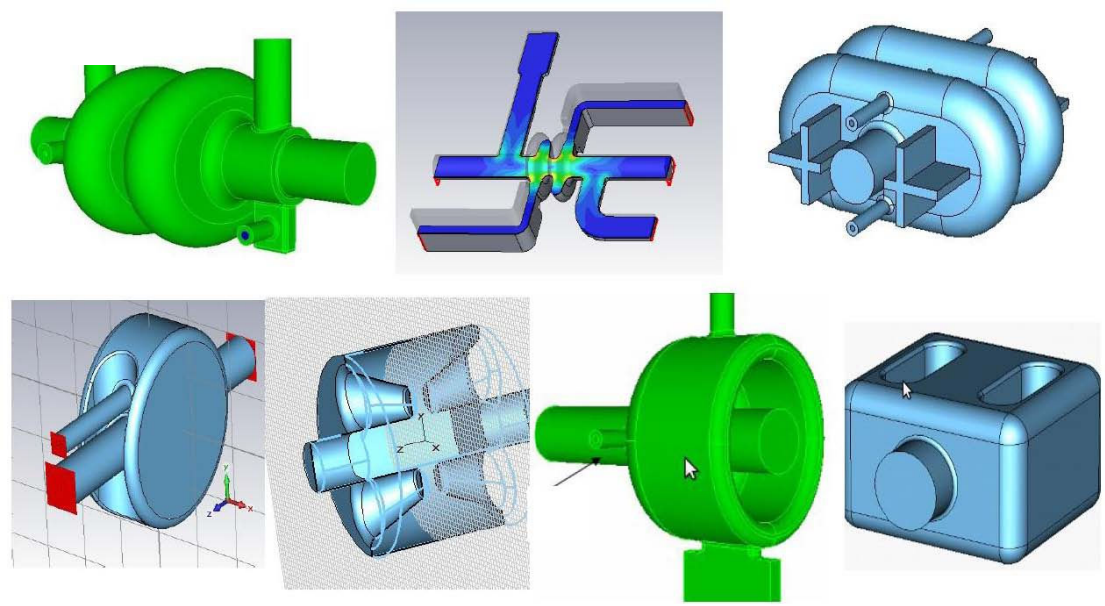


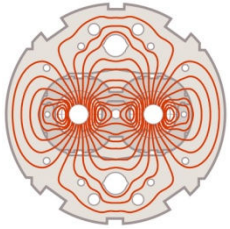


Elliptical 800 MHz not far from being designed. Require 400 mm beam-beam

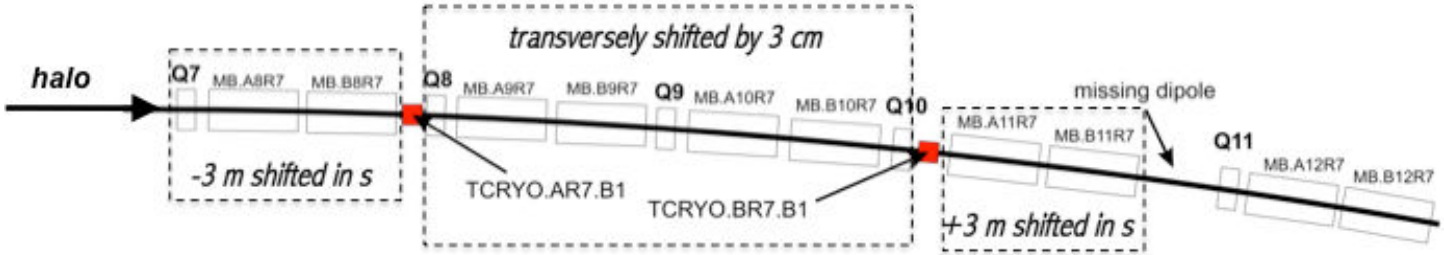
400 MHz small cavity under conceptual study, they can (?) fit in 194 mm beam-beam. Required for final solution

Ref. : F. Zimmermann, Ed Ciapala

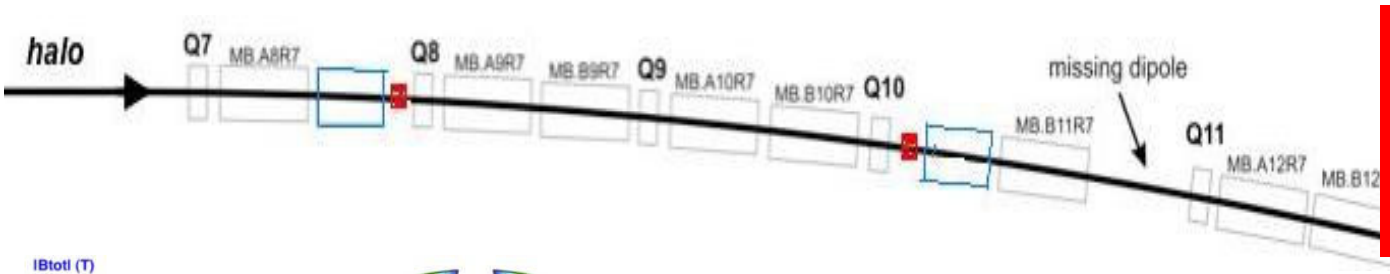




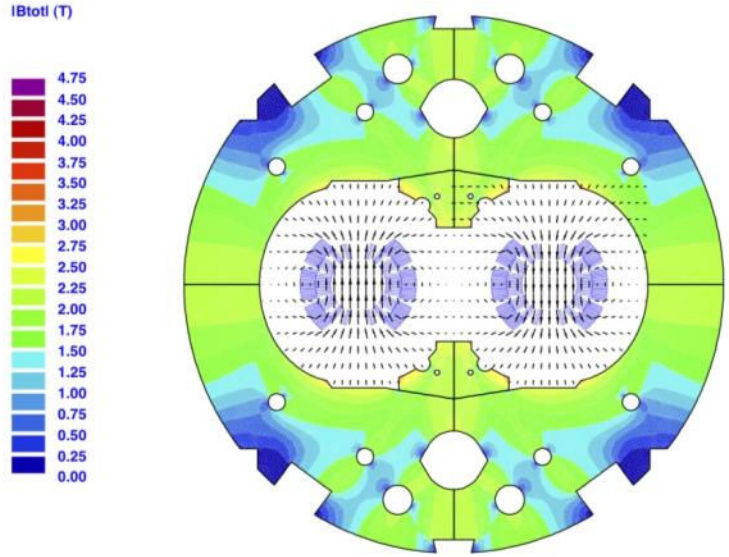
Collimation: need of room in DS of P7, P2… 11 T–11 m Twin Dipole for DS

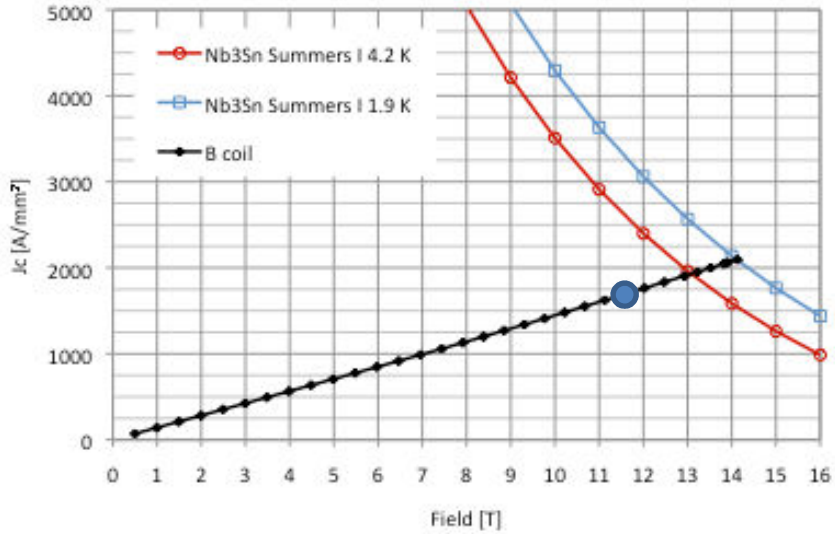


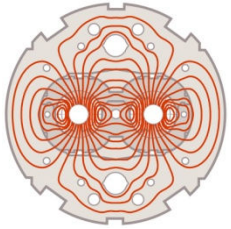
Shift in the magnet position requires to make room for collimators (red squares).



Alternative option based on stronger and shorter magnets (blue rectangles). 2 dips/Point



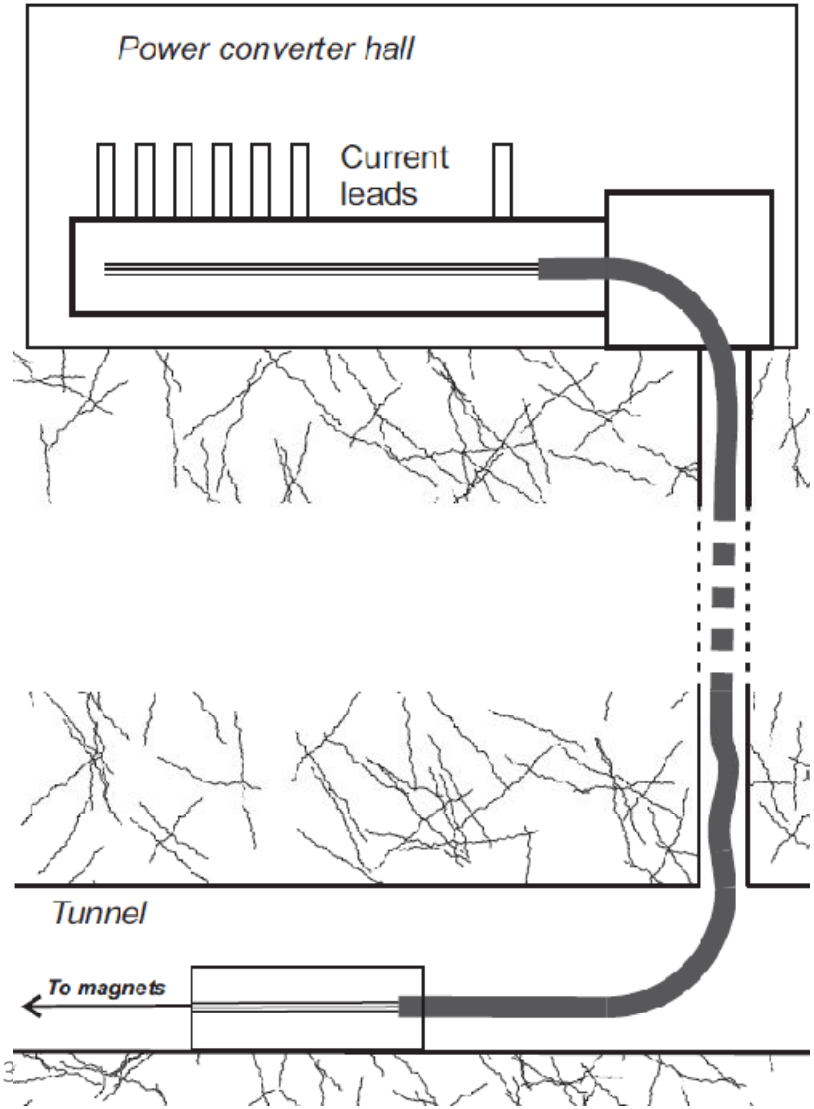


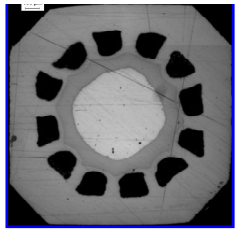


Addressing R2E (upgrade +consolidation)

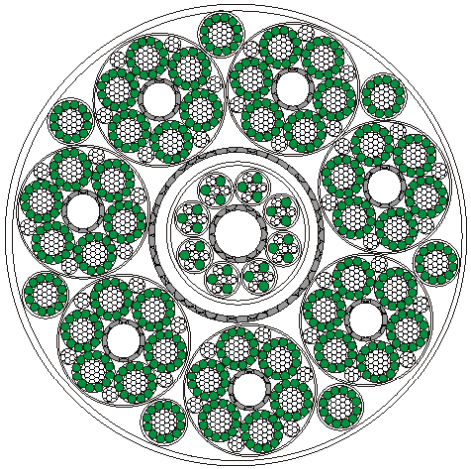
120 kA were already assembled at CERN last year.

Sub-cables were tested at CERN at currents of up to 18 kA (@ 4.5 K and in self-field)





1.1 mm
MgB_2 wire



$\Phi = 62$ mm

And more …

- **New Cryoplants** in IP1 & IP5: for power AND **to make independent Arc- IR:**
  2.8 kW @ 1.8 K scales as 5.2 kW @ 2 K (for 1 set of cold compressor)
- Working at 4.2 K will be a plus (for IR magnets)
- **Special dedicated collimation system (also for background) and Machine protection**
- Robotics for remote manipulation
  - Dismantling present Triplet
  - Installation HL-LHC
  - Maintenance
  - Dismounting HL-LHC ???

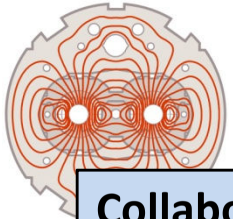
It is new entire project
⇒ we need a Design Study

- We will try to get a EU funded DS (design Study) in the FP7

- The work of SLHC-PP (Phase 1) has been essential to arrive to thsi point and most of it will be used
- Scope of the HL-LHC DS:
- **Carry out the study to produce a consistent design to reach 5 10^{34} with levelling, allow LHC to reach the goal of 3000 fb^{-1} by 2030(s)**
  - Exploring in details all solutions and paths for the upgrade, both in terms of LHC operational mode and hardware changes
  - Producing by end 2013 a **PDR** (Preliminary Design Report) **enabling the CERN management**, to make a choice about the configuration of LHC upgrade in 2014.
  - Producing by end of 2014/half 2015 a **TDR** (Technical Design Report) of the selected path for the upgrade defining the maximum goal for the LHC luminosity

Resources for the program

- 10 M€ total cost over 4 years: July 2011-2015
- Reimbursment by EU
  - 30-40% may be reimbursed by EU to EU Institution
- Total cost of the LHC upgrade : 500 M
  - Cost of the R&D & Study : at least 50 M (teh contribution of EU is marginal…
- … However si important to get a structured organization in which project is governed by a collaboration…
- Possibility for US labs (and/or DOE , LARP) and KEK to be full partner of the governing board of the EU DS.
- **Would the EU Ds not be approved we intend to promote the collaboration with MoUs very much like detectors.**
  - A first step for Design and R&D
  - A second step for actual construction



CERN Council & DG

Collaboration Board

Advisory Committee

FP7 Design Study framework

Project Coordinator

Project Office:
Resource manager
Technical coordinators

Steering Committee

R&D on enabling technologies

Design Studies

Technical Design

EuCARD

USLARP

WP1

WP2

WPn

I see the 11T dipoles as part of HL-LHC but outside the EU DS

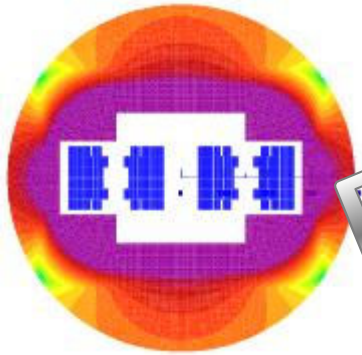
Organization model for HL-LHC

Jpk 27/4/2010

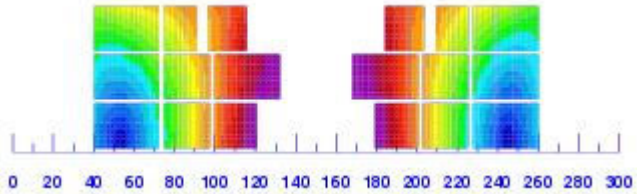
HE-LHC

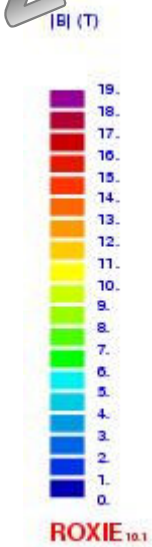
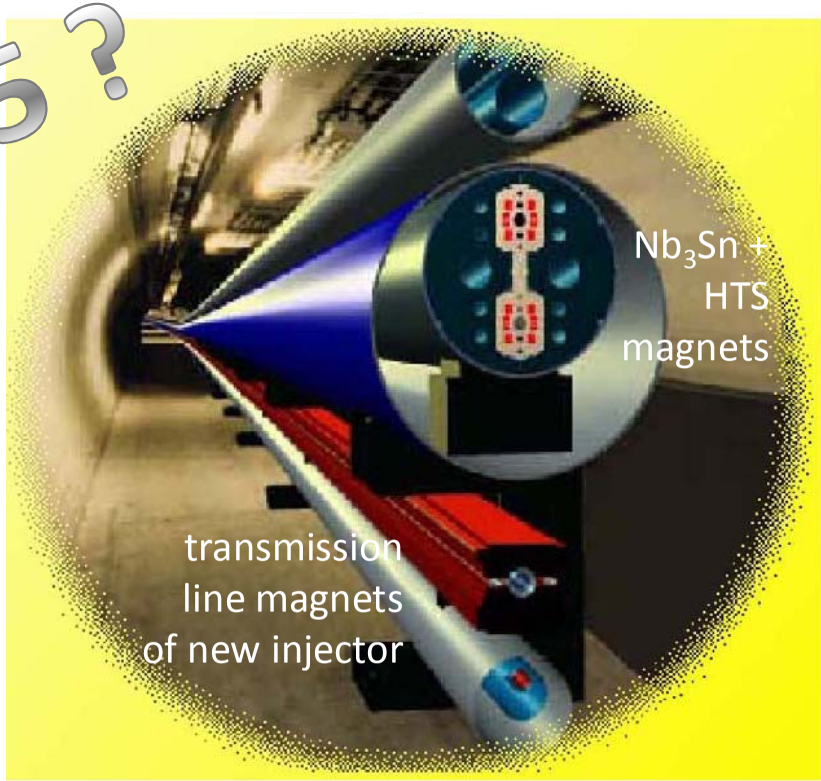
- The High Luminosity LHC or HL-LHC is the route that will enable the way to the Farthest Energy Frontier : an HE-LHC based on 20 T magnets for a 33 TeV c.o.m. collider
- HE-LHC Workshop 14-16 October in Malta

By 2035 ?



Sketch of the double aperture magnet with the iron yoke – Coils are in blue





Field in the coil (one pole shown) at 20 T operational field