LHC, HL-LHC and future upgrades

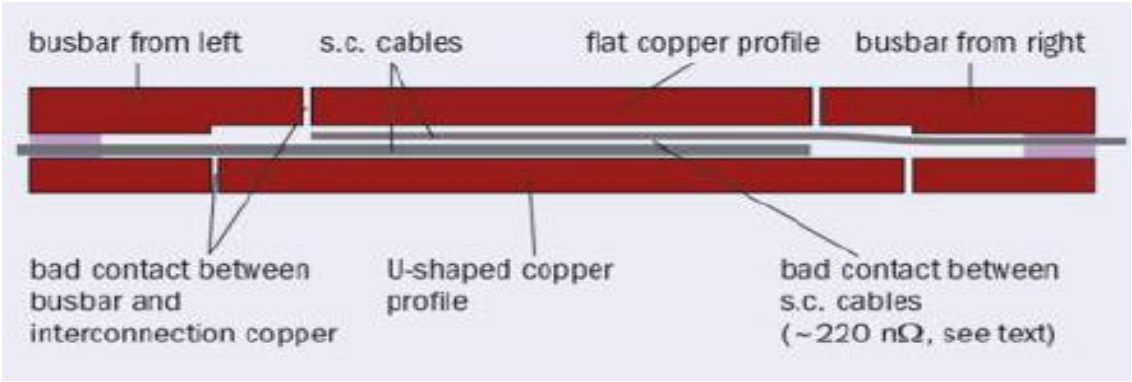
Lucio Rossi - CERN

MAP Collab. Meeting

28 May 2014 (via readytlak)

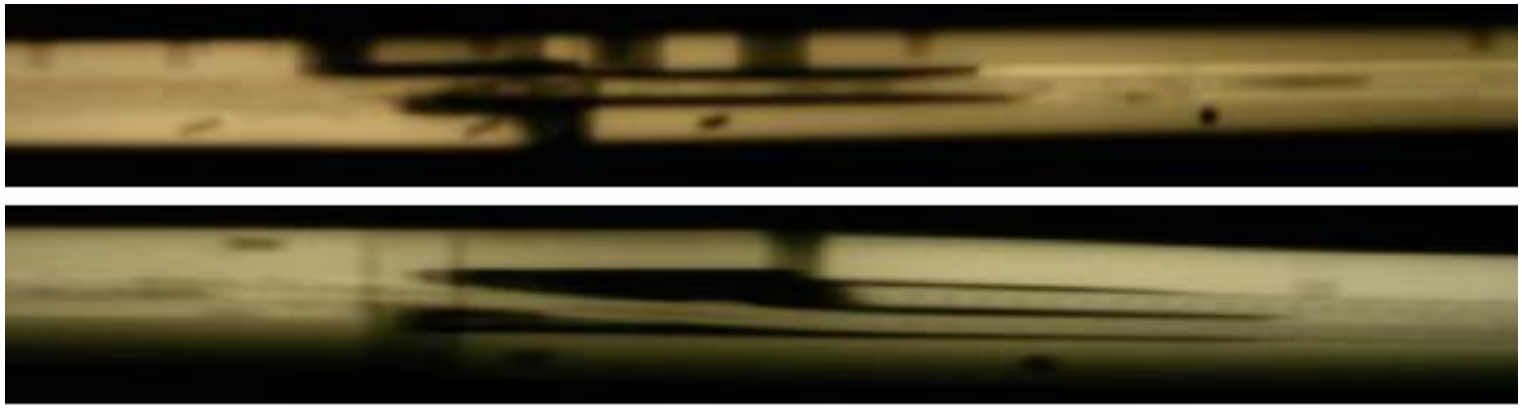
The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Splice consolidation: why?



The splice components

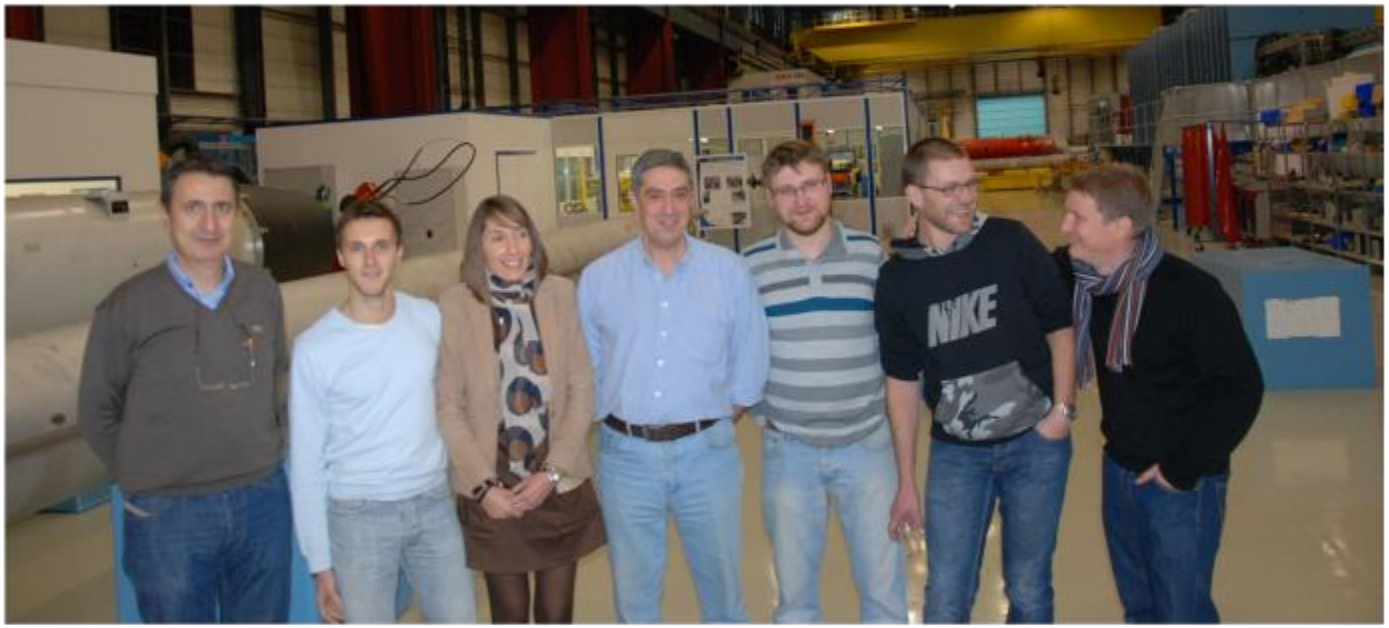
X-rays of splices, presenting bad contacts



Wor ahead of uis (2 years ago)

High Luminosity LHC

Quality



FINISH

SMACC PROJECT

Other works : R2E

- Point 1
  - All equipment are reinstalled and reconnected
  - Commissioning in progress
- Point 5 & Point 7
  - Major cabling campaign in progress

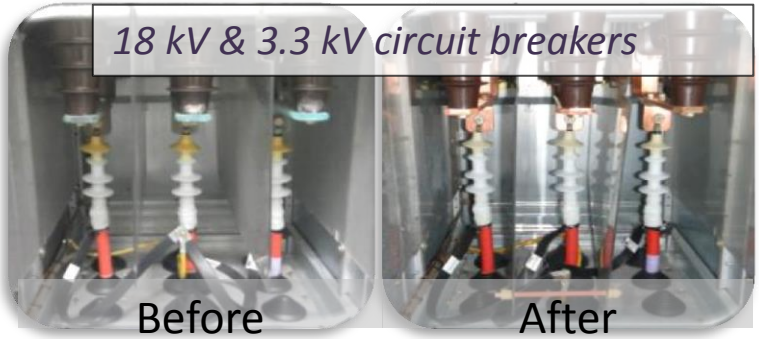
UL16 power converters

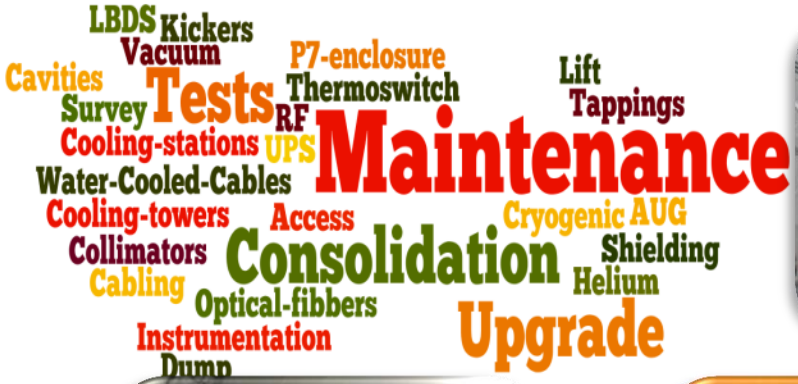
UL55 safe-room

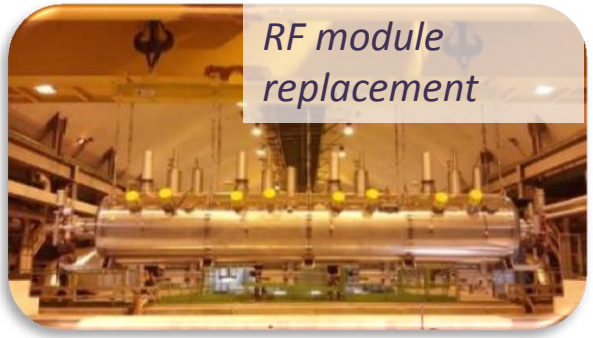
Warm Cable installation @ P5

TZ76

And many others







Key points

- We are on time for restarting Physics in LHC
- In April 2015
- Start at 50 ns, then 25 ns as son possible (test of scrubbing to reduce e-clouds)
- Chamonix Workshop on 22-25 September

$$L = \frac{k N_b^{\,2} f \gamma}{4\pi \beta^* \varepsilon^*} F$$

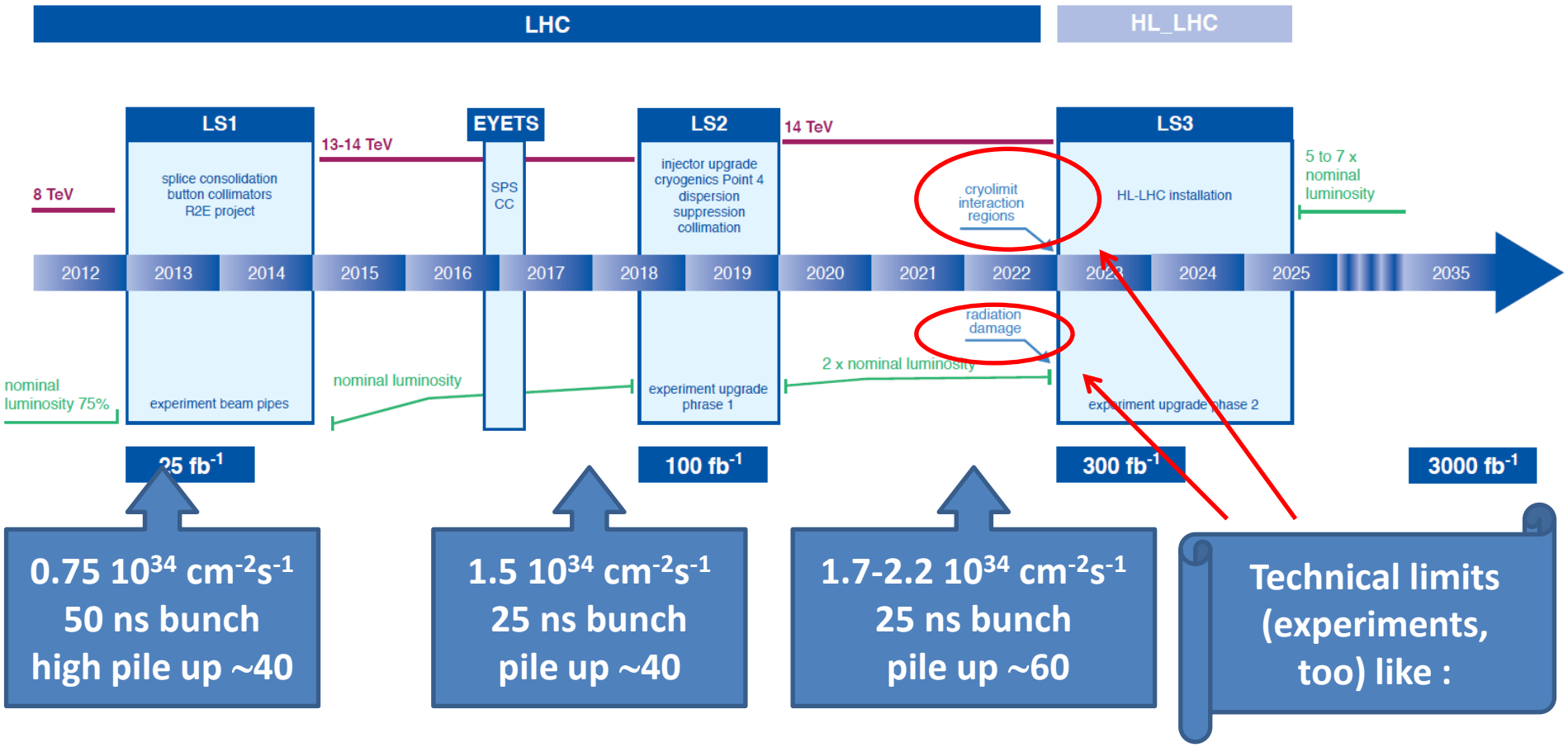
	N_{bcoll} [10^{11}]	ε^*_{coll} [μm]	# Coll. pairs IP1,5	B-B Sep [σ]	Full Xing angle [μrad]	L_{peak} [10^{34} $cm^{-2}s^{-1}$]	Max. Avg. Peak-pile-up density/Pile-up [ev./mm]/[ev./xing]
BCMS	1.24	1.65	2592	12	295	2.1	0.46/45
Standard	1.24	2.0	2736	12	320	1.8	0.46/45

	L_{lev} [10^{34} $cm^{-2}s^{-1}$]	Lev. time [h]	Opt. Fill length [h]
BCMS	1.5	2.9	8
Standard	1.6	1.7	8.1

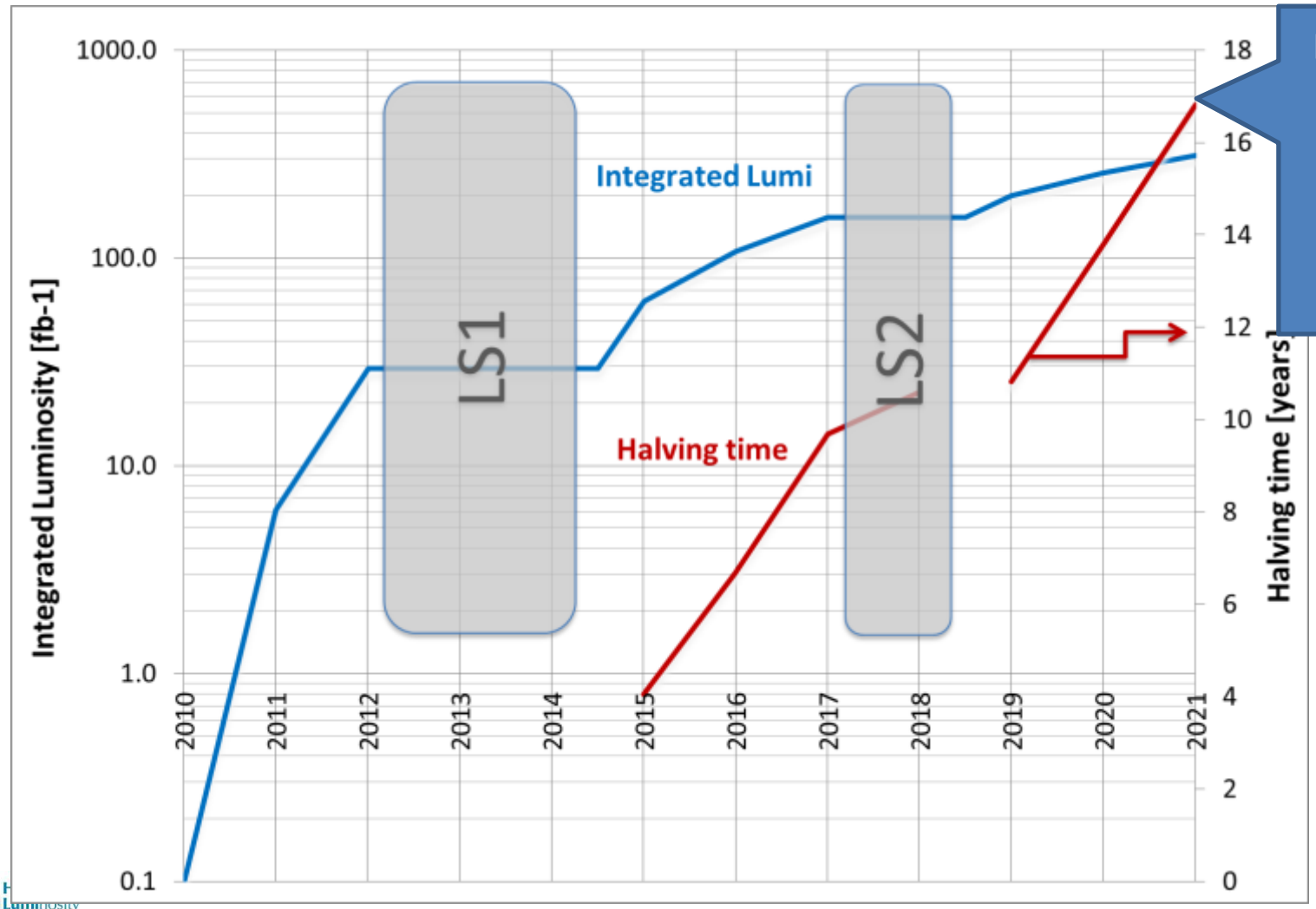
- Limited by:
  - Inner triplet heat due to collisions debris (**1.7 x 10^{34} cm^{-2} s^{-1}** ± 20%)
  - Pile-up (here assumed to be 45 events/crossing)
  - ➔ Will need levelling

High Luminosity LHC

New LHC / HL-LHC Plan



Mantain and increase physics reach



Necessity of a jump in luminosity (useful luminosty ⇒ data quality)

Goal of High Luminosity LHC (HL-LHC) as fixed in November 2010

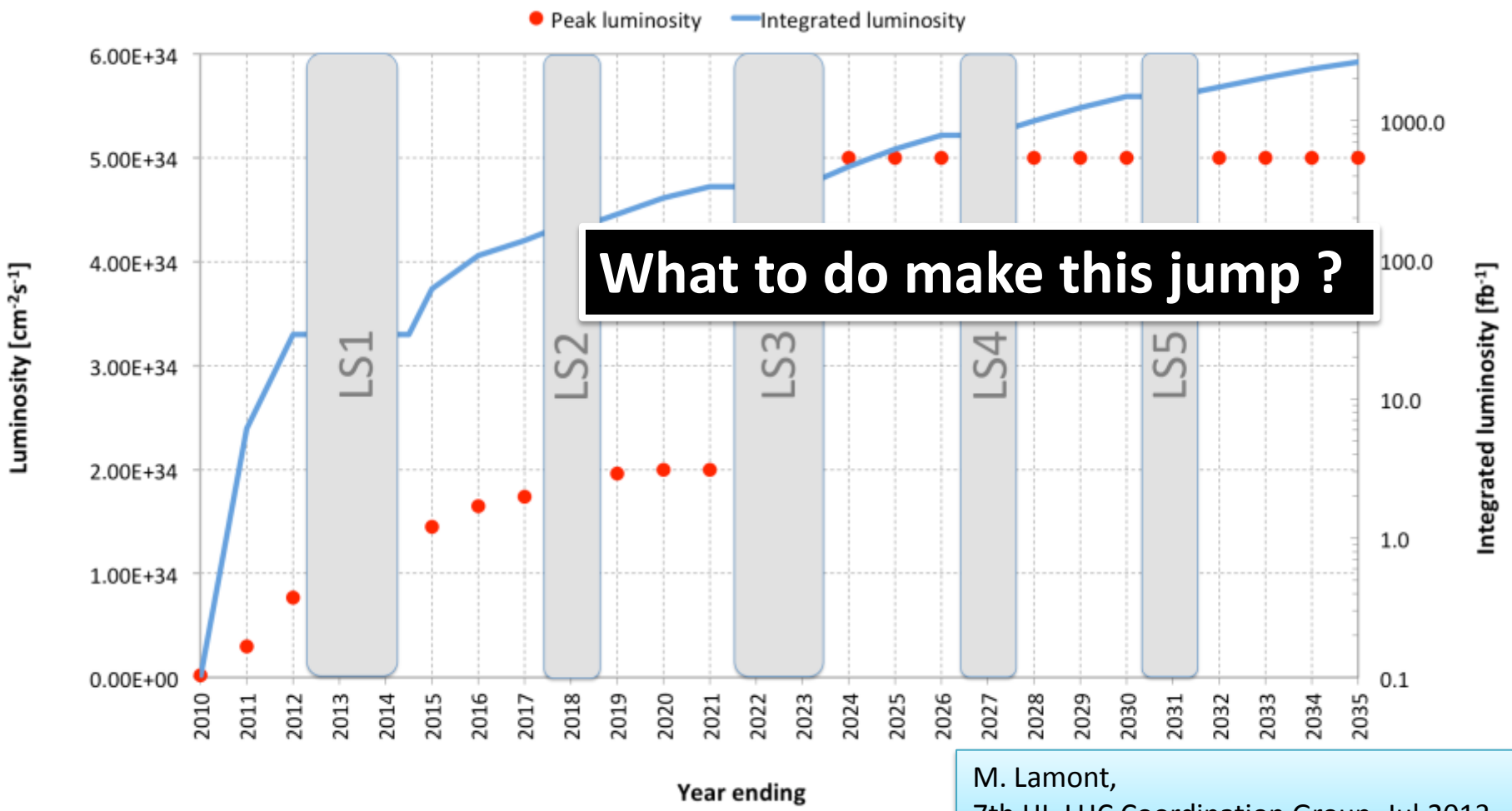
The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of **5×10^{34} cm^{-2}s^{-1} with levelling,** allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **3000 fb^{-1}** twelve years after the upgrade.
This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

High Luminosity LHC

This goal would be reached in 2036

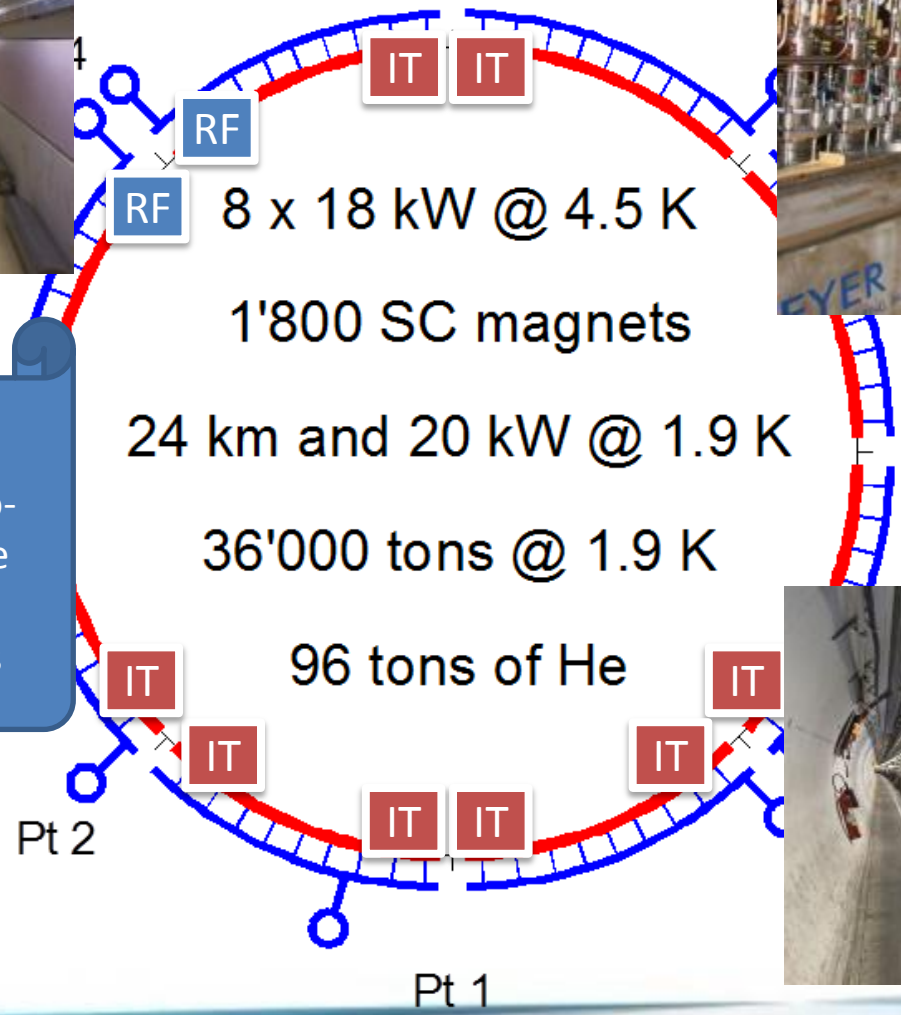


What to do make this jump ?

M. Lamont,
7th HL-LHC Coordination Group, Jul.2013

Technical bottlenecks

Cryogenics P4

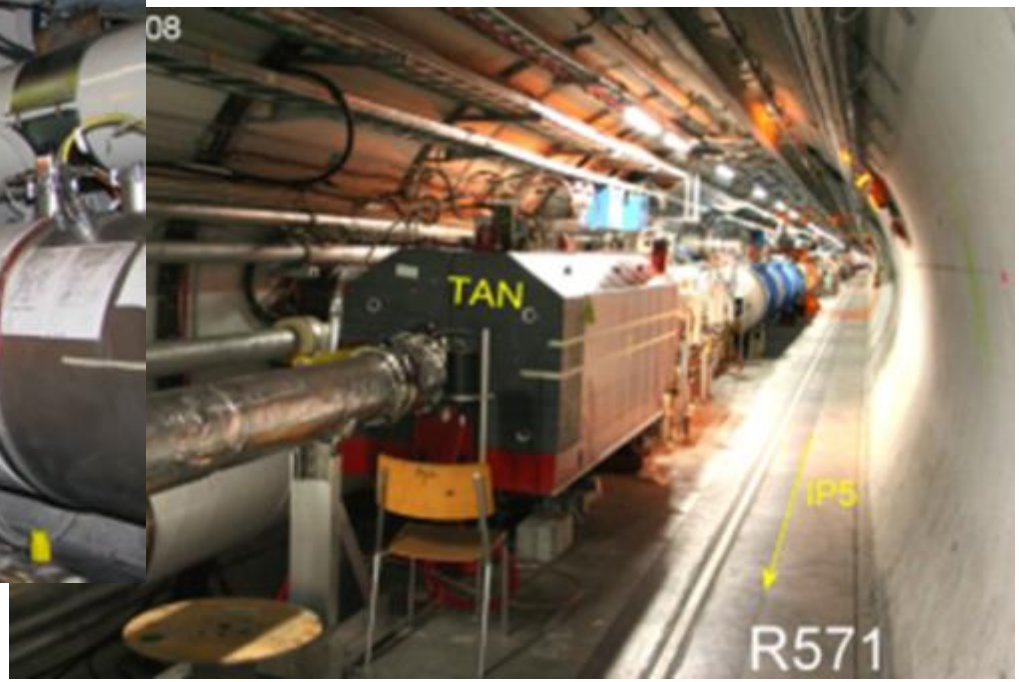


Pt 7

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)

High Luminosity LHC

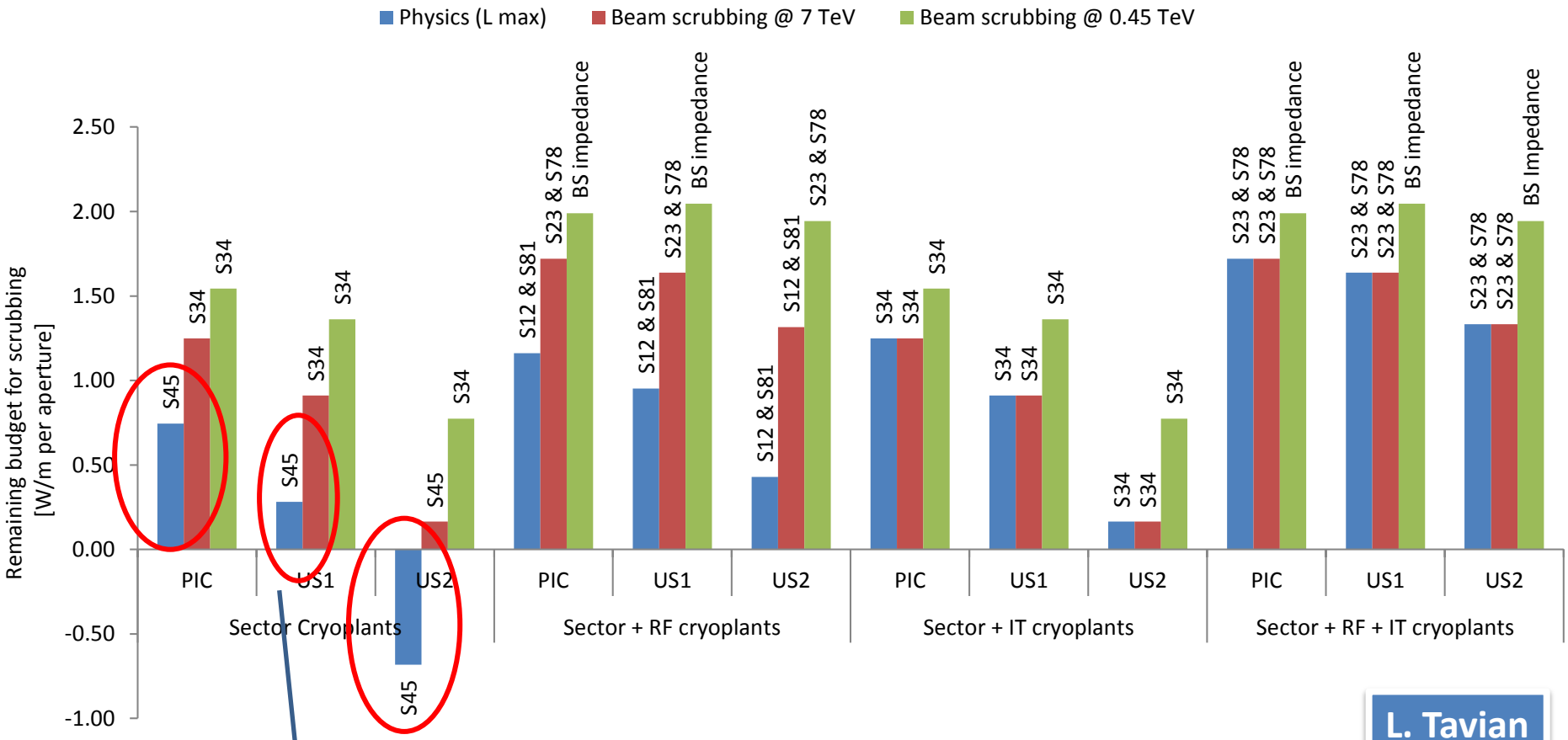
Triplet and MS connection to main arc



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

Cryogenic load: sector 4

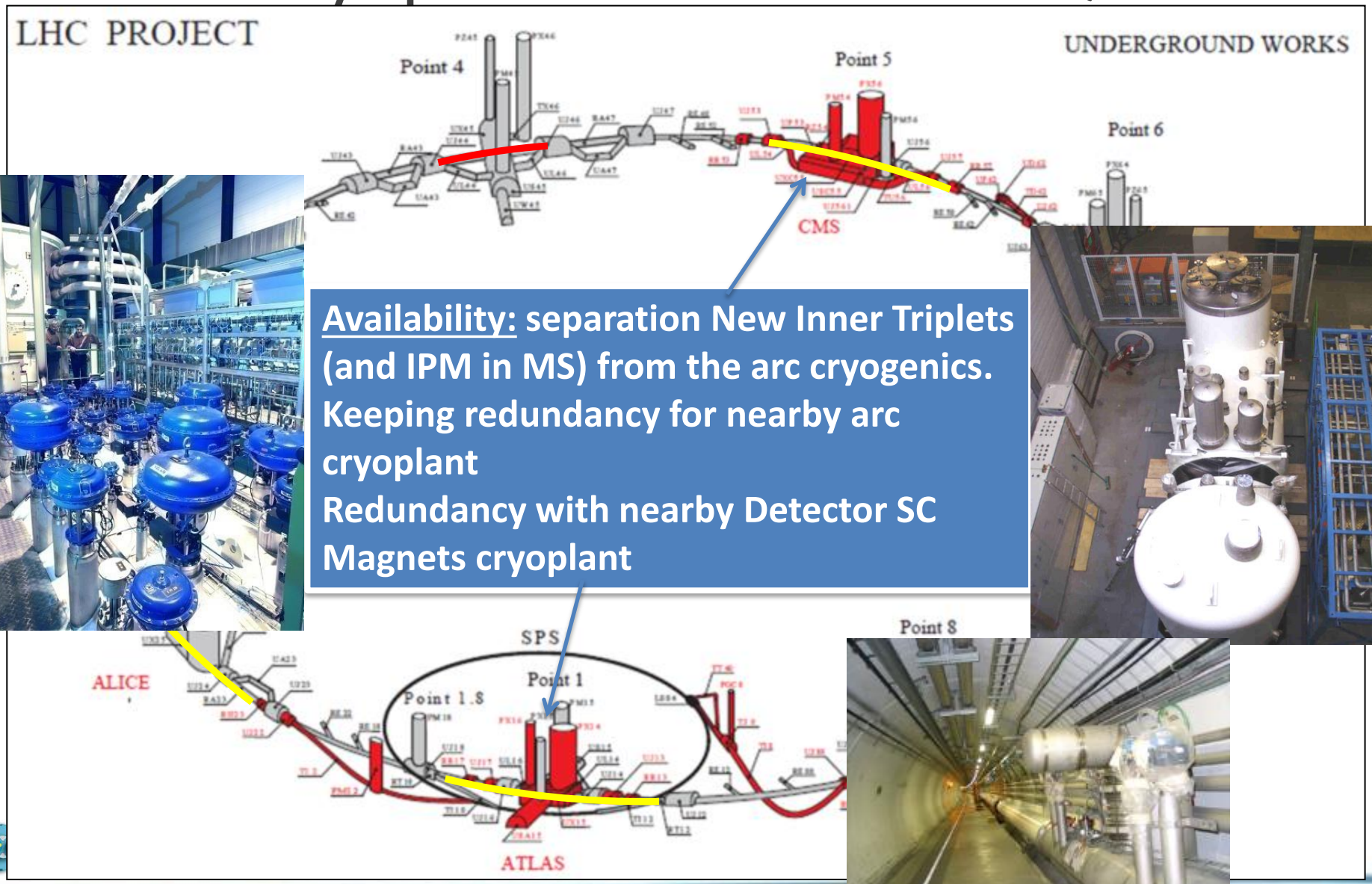


L. Tavian

All existing margins already «used» at around 2 10^{34} (like cryostat consumption 30% less than design)

High Luminosity LHC

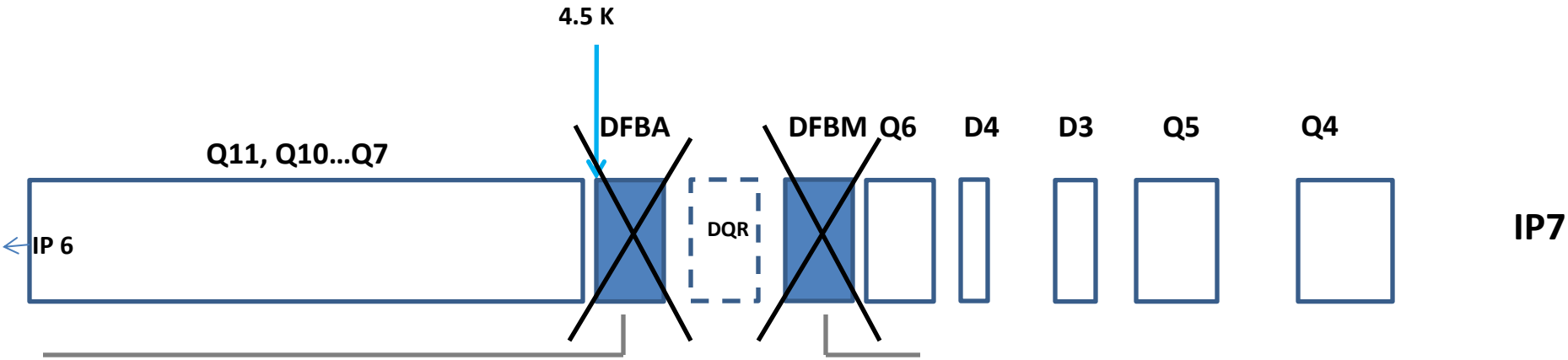
IT cryoplants and new LSS QRL



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

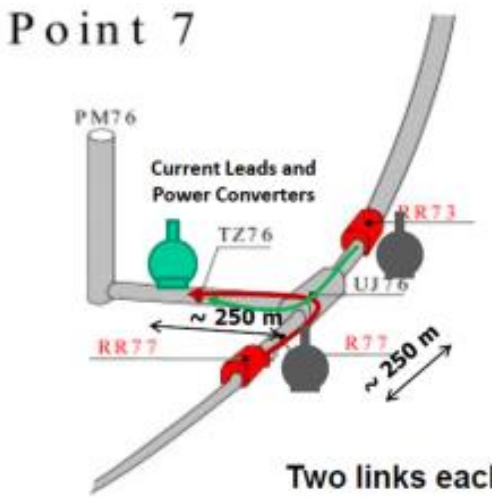
Redundancy with nearby Detector SC Magnets cryoplant

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



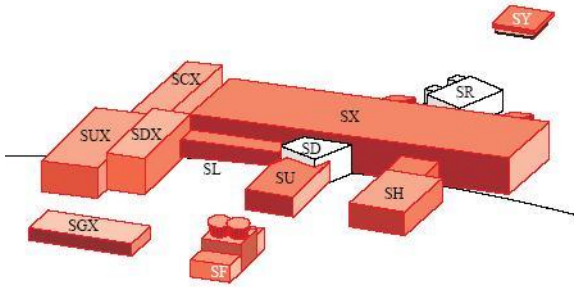
8.75 m

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

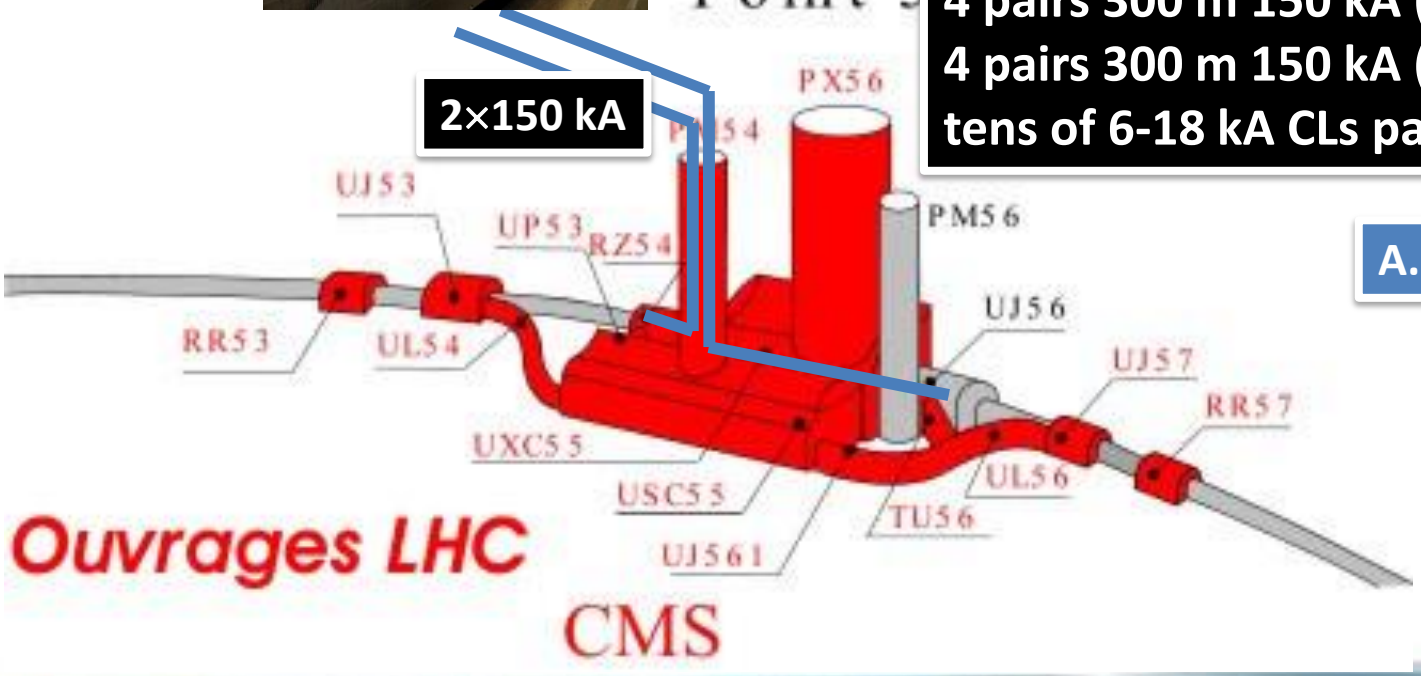


POIN

Point 5

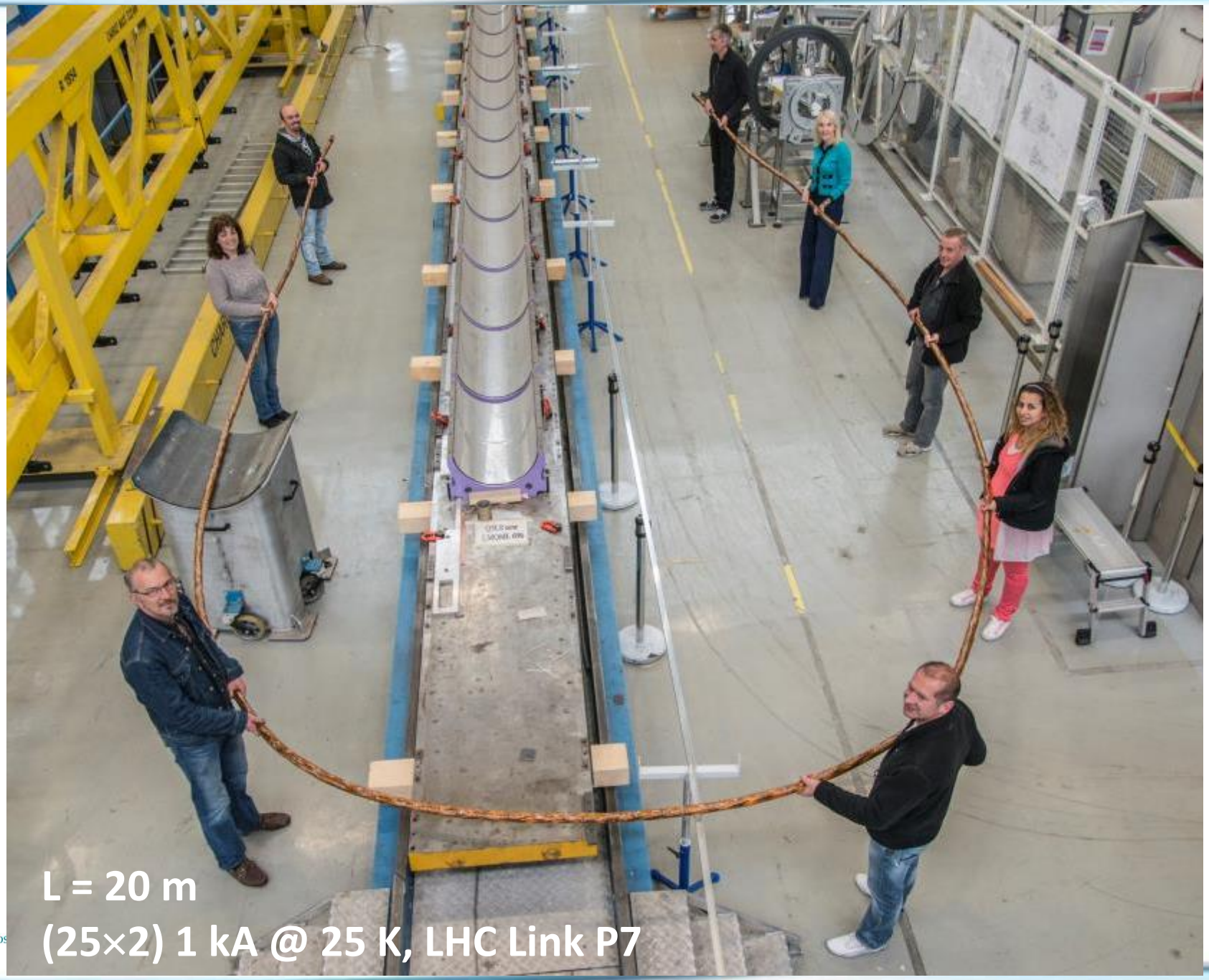
1 pair 700 m 50 kA – LS2
4 pairs 300 m 150 kA (MS)– LS3
4 pairs 300 m 150 kA (IR) – LS3
tens of 6-18 kA CLs pairs in HTS

2×150 kA



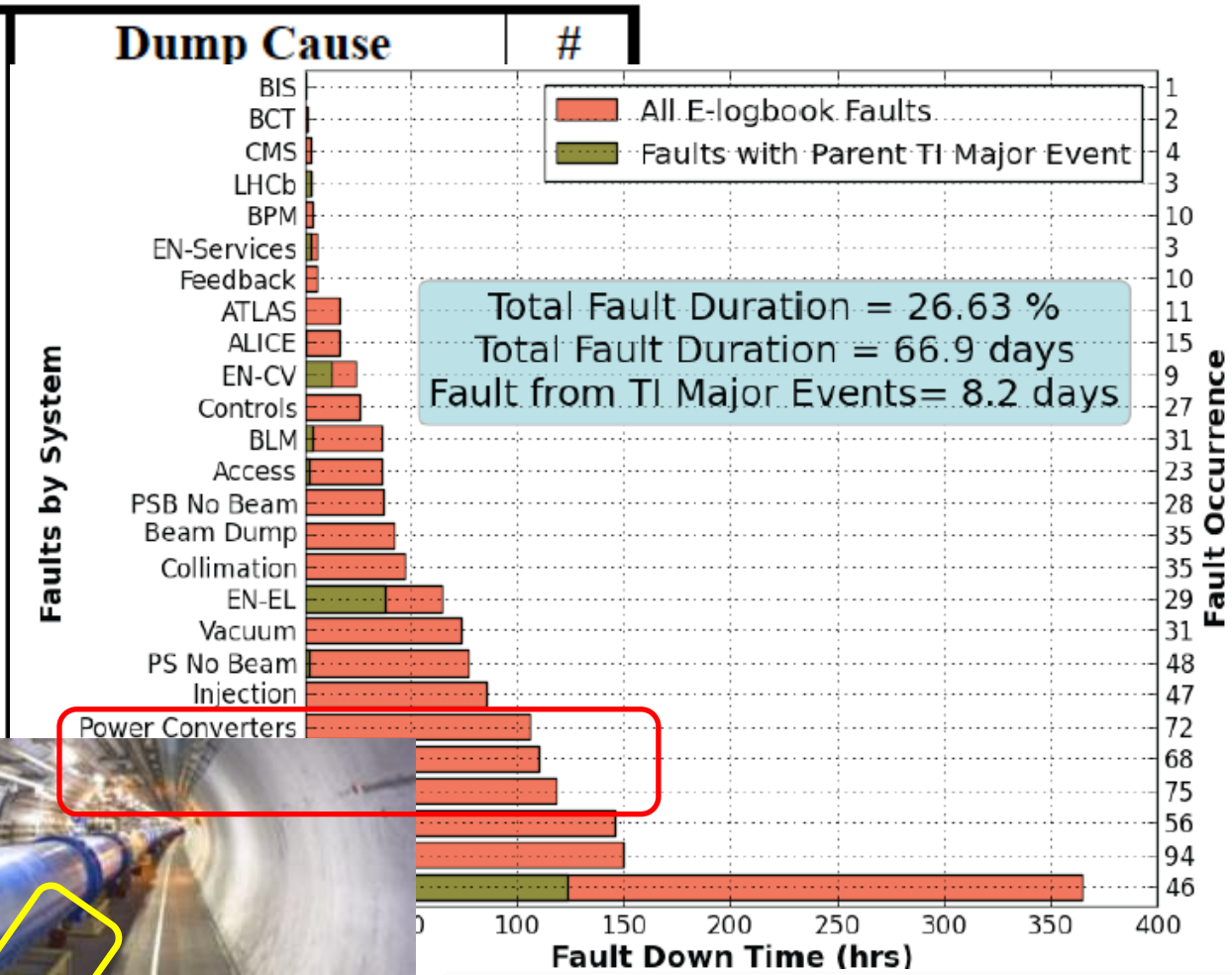
A. Ballarino

High Luminosity LHC


L = 20 m
(25×2) 1 kA @ 25 K, LHC Link P7

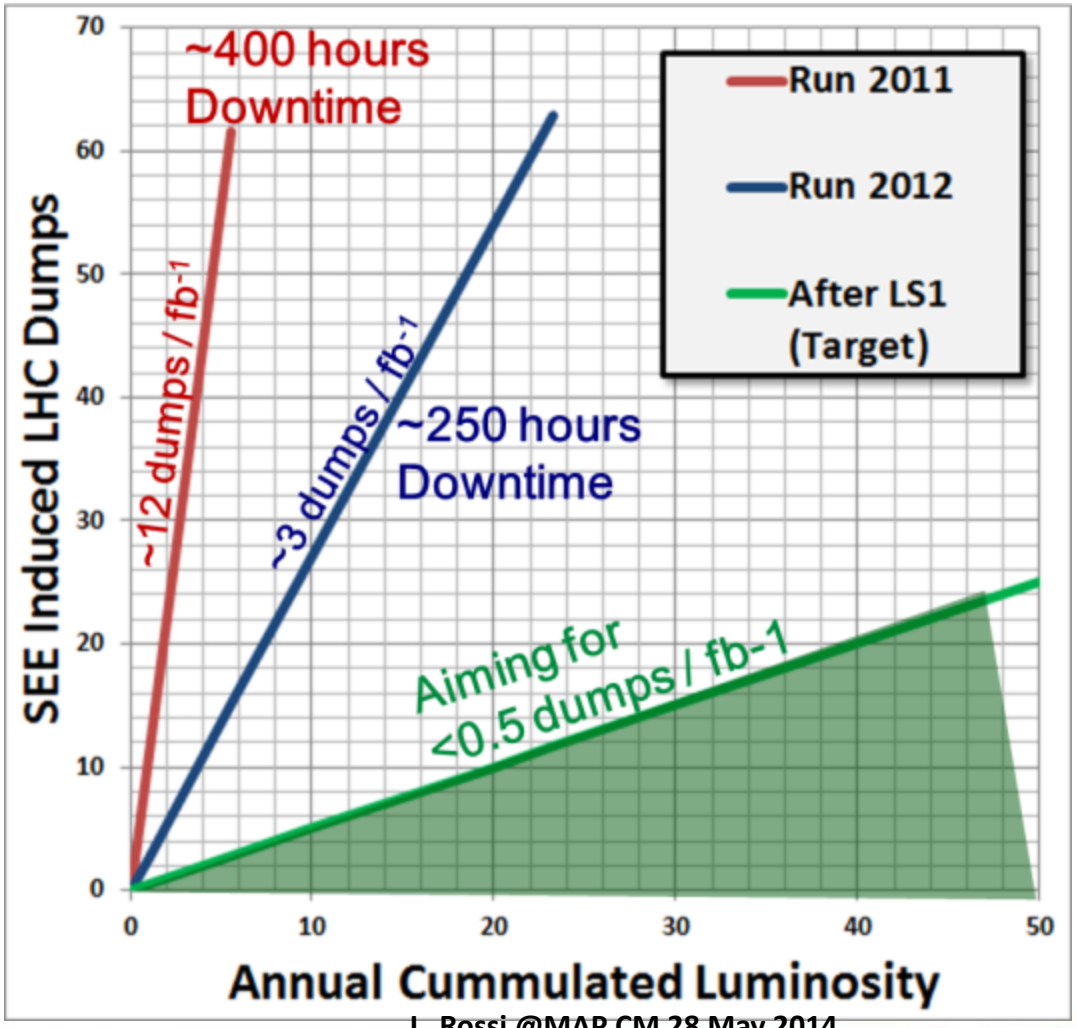
QPS boxes and intervention time

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



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

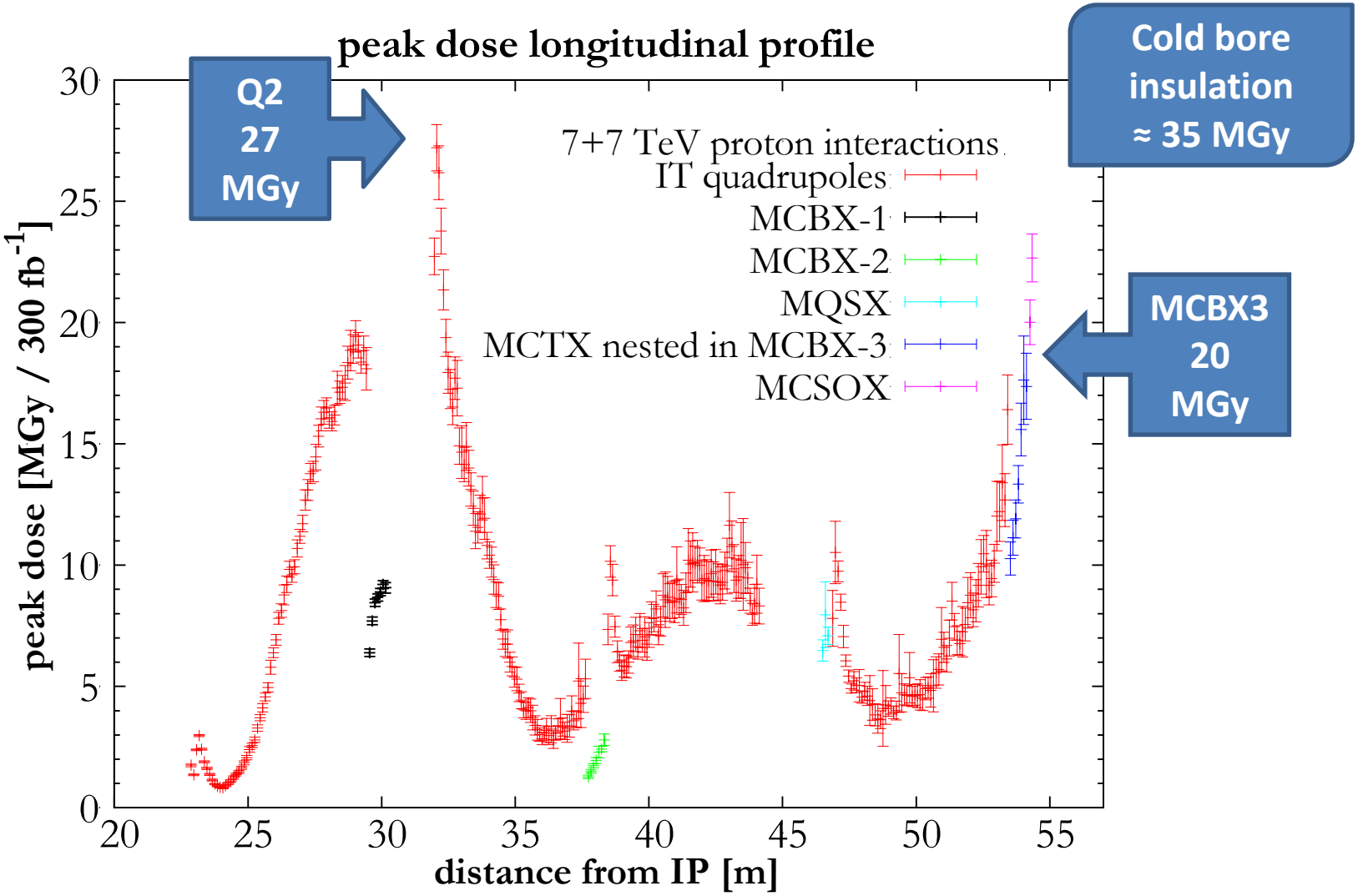
R2E improvement.
Need further for 1-3 fb^{-1}/day!



M. Brugger

L. Rossi @MAP CM 28 May 2014

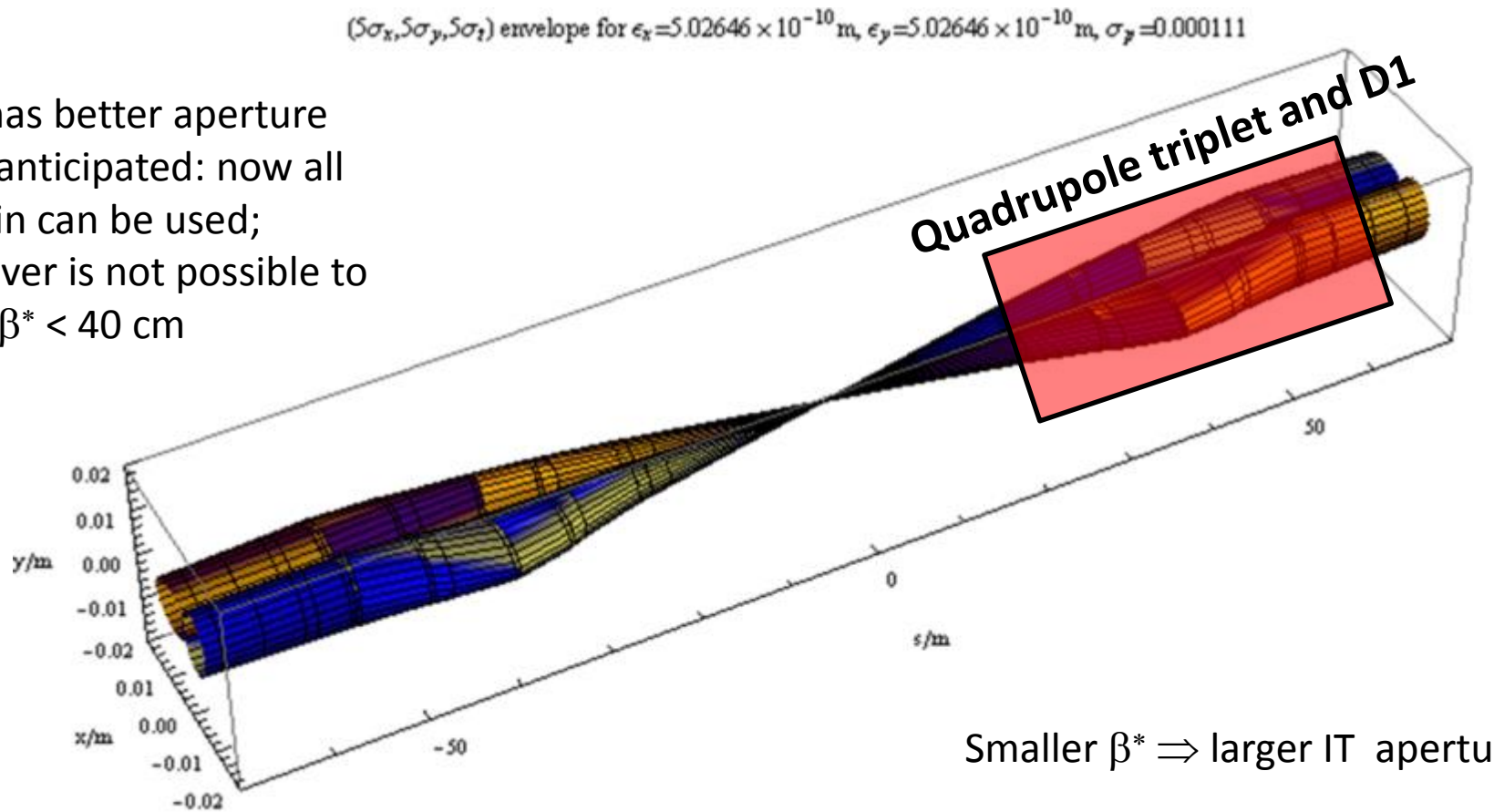
The big technical bottleneck: Radiation damage to triplet



L. Rossi @MAP CM 28 May 2014

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

High Luminosity LHC

Parameters (PLC web page)

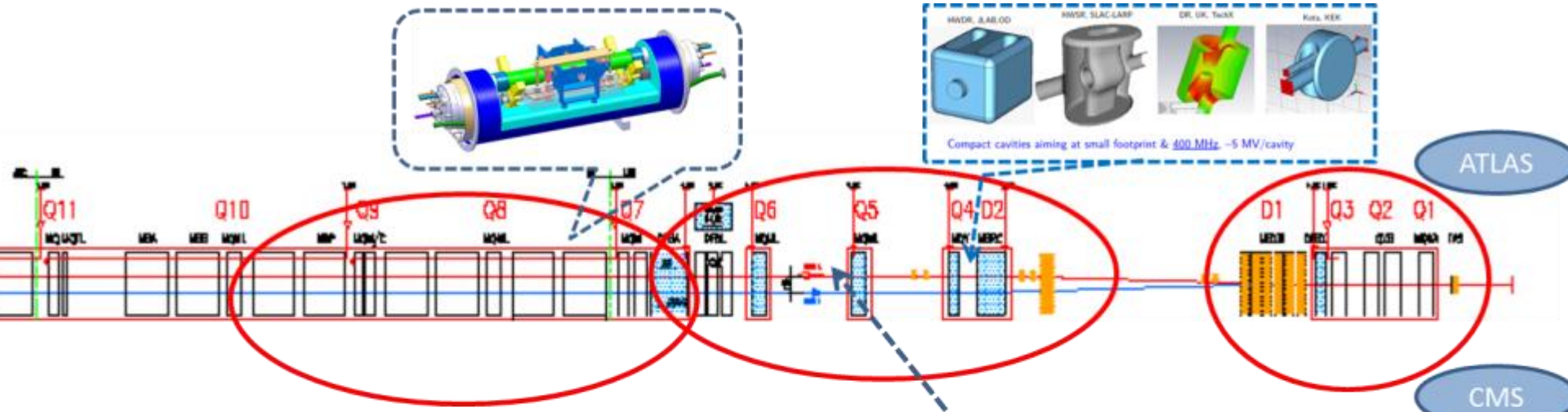
https://espace.cern.ch/HiLumi/PLC/default.aspx

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

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

High Luminosity LHC

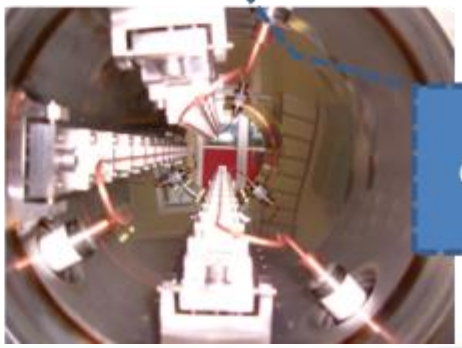
The critical zone around IP1 and IP5



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



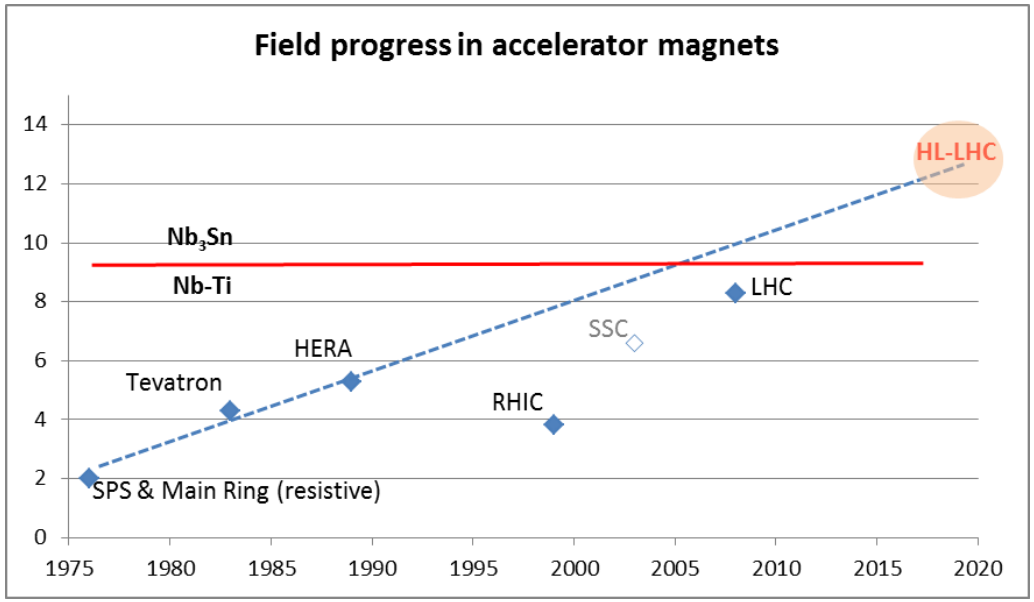
4. LR BB compensation wires

1.2 km of LHC !!

High Luminosity LHC

Magnet the progress

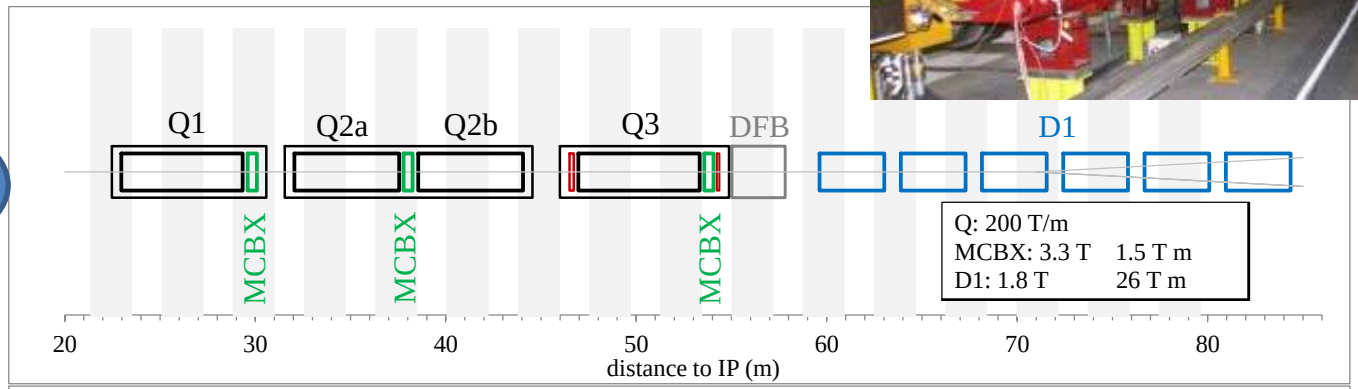
- LHC dipoles features 8.3 T in 56 mm (designed for 9.3 peak field)
- LHC IT Quads features 205 T/m in 70 mm with 8 T peak field
- HL-LHC
  - 11 T dipole (designed for 12.3 T peak field, 60 mm)
  - New IT Quads features 140 T/m in 150 mm > 12 T operational field, designed for 13.5 T).



New Interaction Region lay out

Longer Quads; Shorter D1 (thanks to SC)

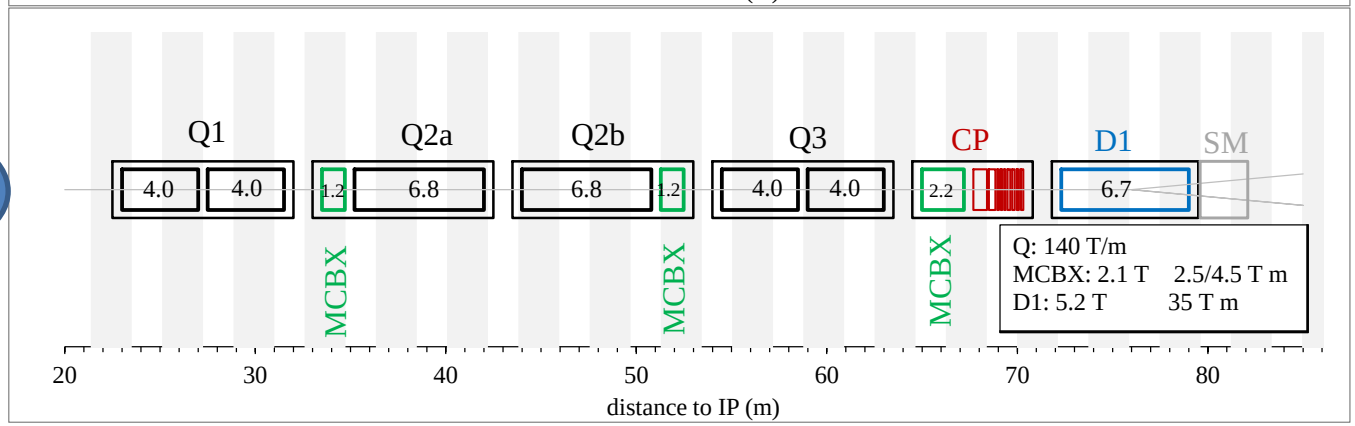
ATLAS
CMS



LHC

E. Todesco

ATLAS
CMS



HL LHC

Thick boxes are magnetic lengths -- Thin boxes are cryostats

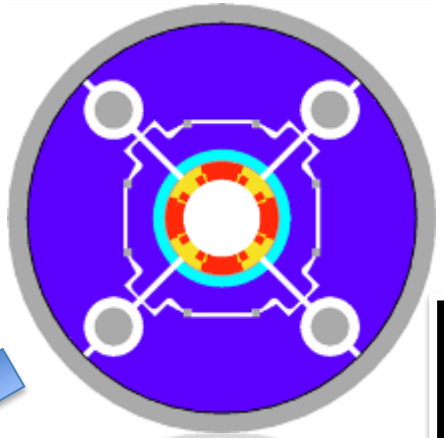
LHC low-β quads: steps in magnet technology from LHC toward HL-LHC

Fermilab KEK

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

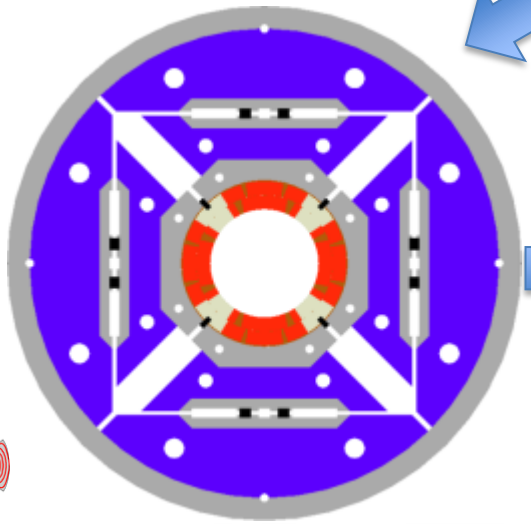
LARP

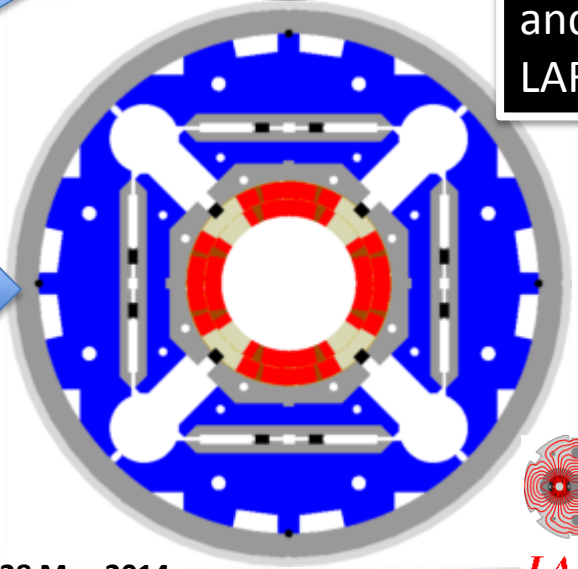
LARP TQS & LQ (4m)
∅90 mm, B_{peak}~ 11 T
2004-2010



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

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





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

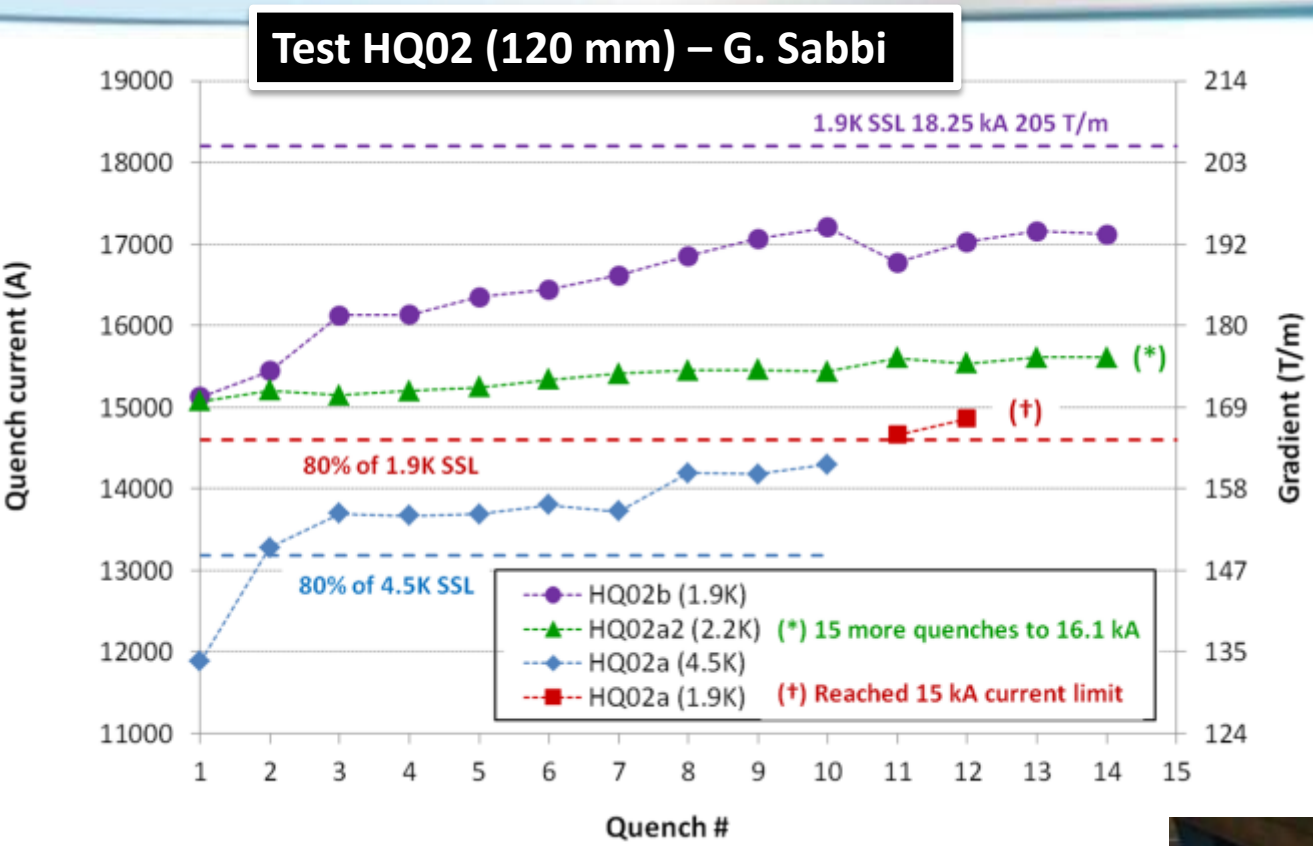
LARP

High Luminosity LHC

LARP

CERN

MQXF (IT quads)

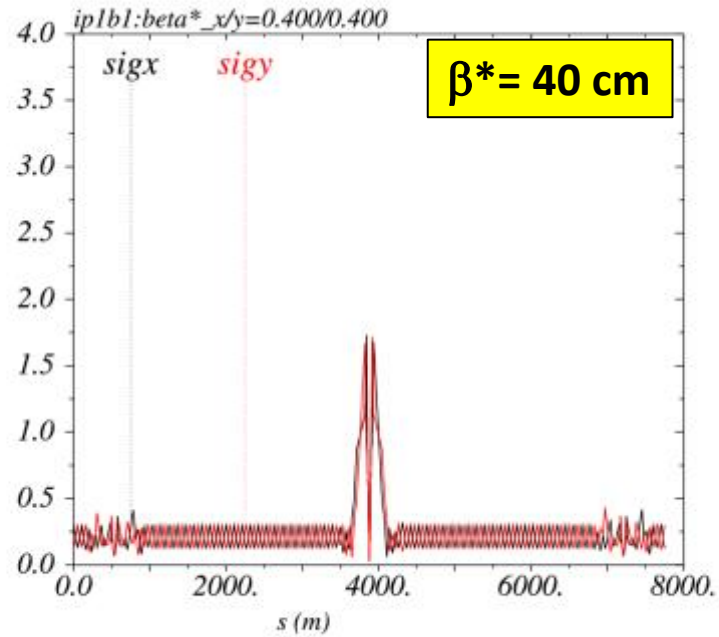


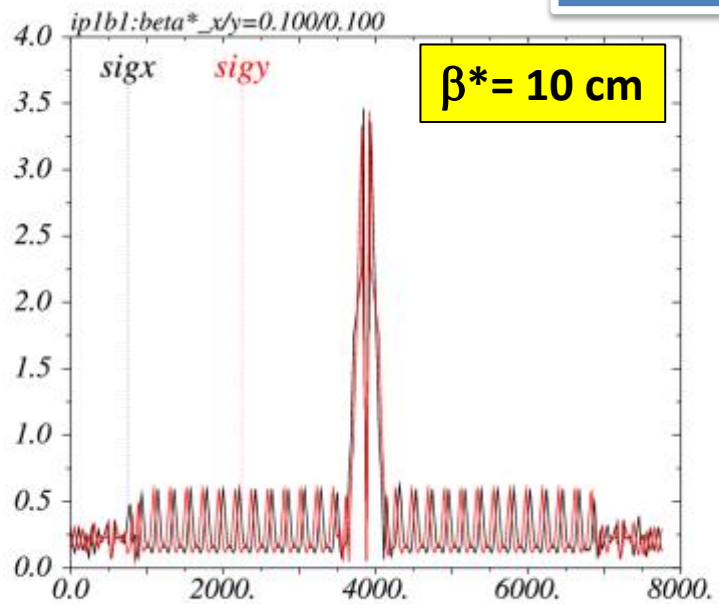
The **Achromatic Telescopic Squeezing** (ATS) scheme

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)



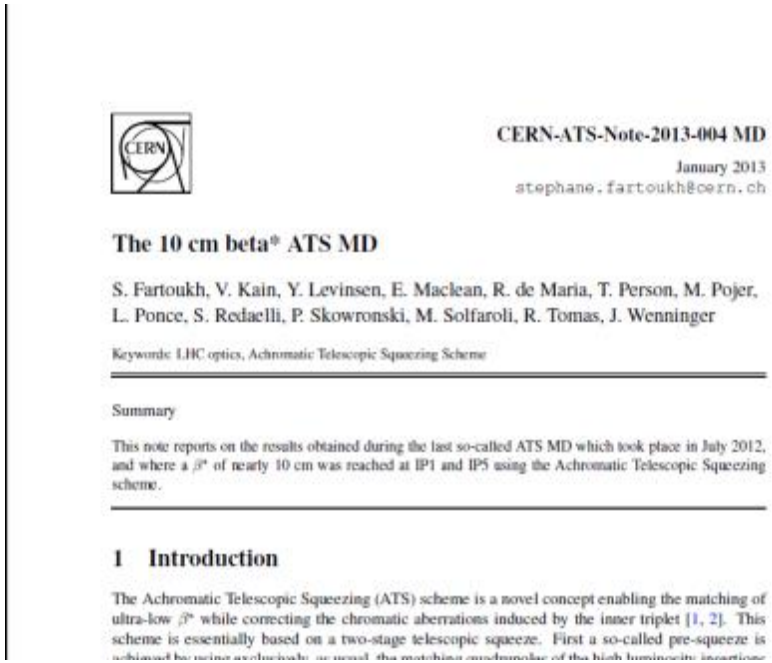


The new IR is sort of 8 km long !

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

*The **Achromatic Telescopic Squeezing** (ATS) scheme (2/2)*

→ Proof of principle demonstrated in the LHC down to a **β* of 10-15 cm at IP1 and IP5**



CERN-ATS-Note-2013-004 MD

January 2013

stephane.fartoukh@cern.ch

The 10 cm beta* ATS MD

S. Fartoukh, V. Kain, Y. Levinsen, E. Maclean, R. de Maria, T. Person, M. Pojer, L. Ponce, S. Redaelli, P. Skowronski, M. Solfaroli, R. Tomas, J. Wenninger

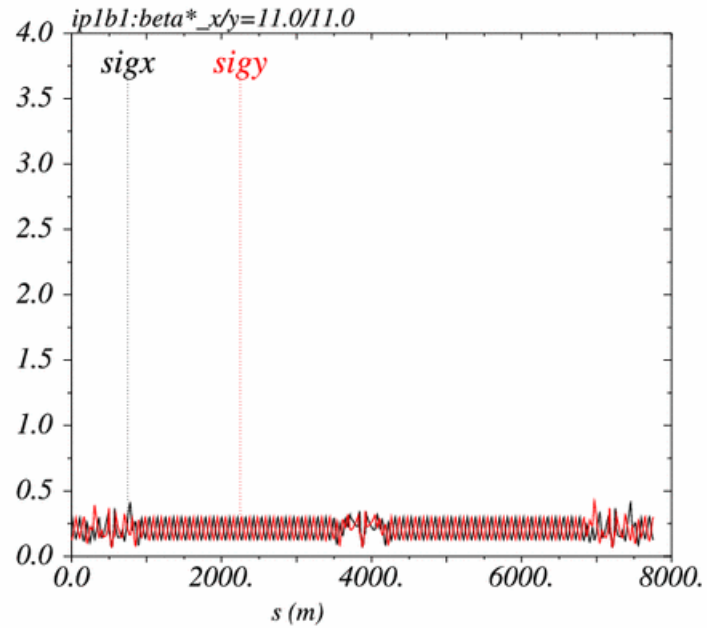
Keywords: LHC optics, Achromatic Telescopic Squeezing Scheme

Summary

This note reports on the results obtained during the last so-called ATS MD which took place in July 2012, and where a β^* of nearly 10 cm was reached at IP1 and IP5 using the Achromatic Telescopic Squeezing scheme.

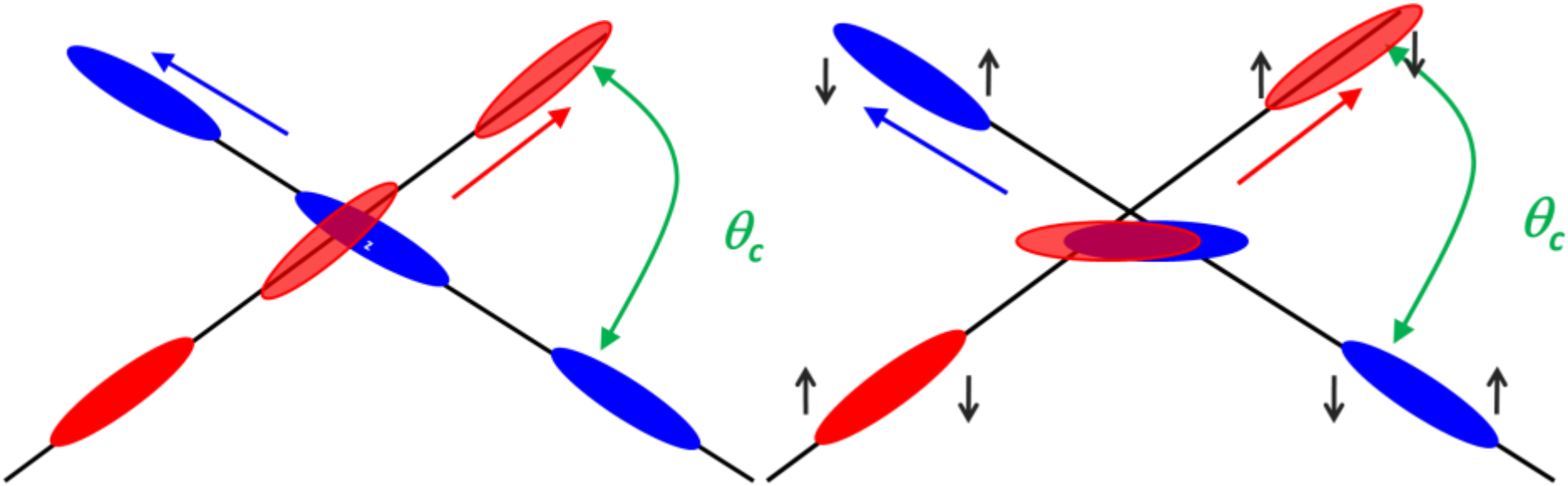
1 Introduction

The Achromatic Telescopic Squeezing (ATS) scheme is a novel concept enabling the matching of ultra-low β^* while correcting the chromatic aberrations induced by the inner triplet [1, 2]. This scheme is essentially based on a two-stage telescopic squeeze. First a so-called pre-squeeze is



S-. Fartoukh

Effect of the crab cavities

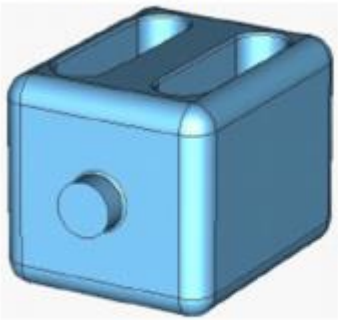


- **RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" and then luminosity is maximized**
- ***Crab cavity maximizes the lumi and can be used also for luminosity levelling: if the lumi is too high, initially you don't use it, so lumi is reduced by the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

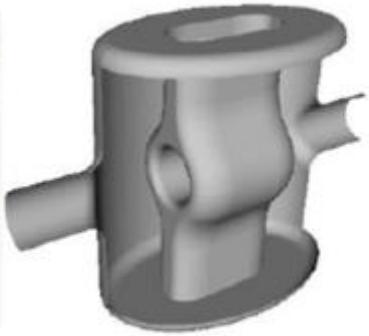
Crab Cavity, for p-beam rotation

at 10 fs level!

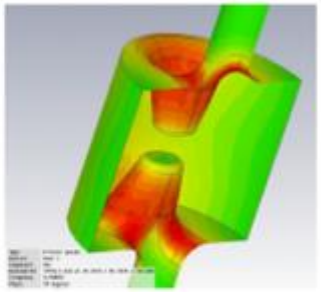
HWDR, JLAB,OD



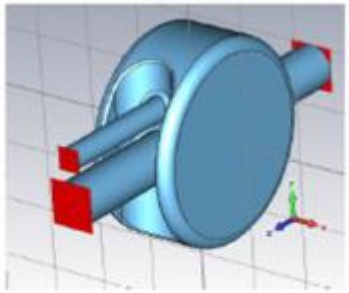
HWSR, SLAC-LARP



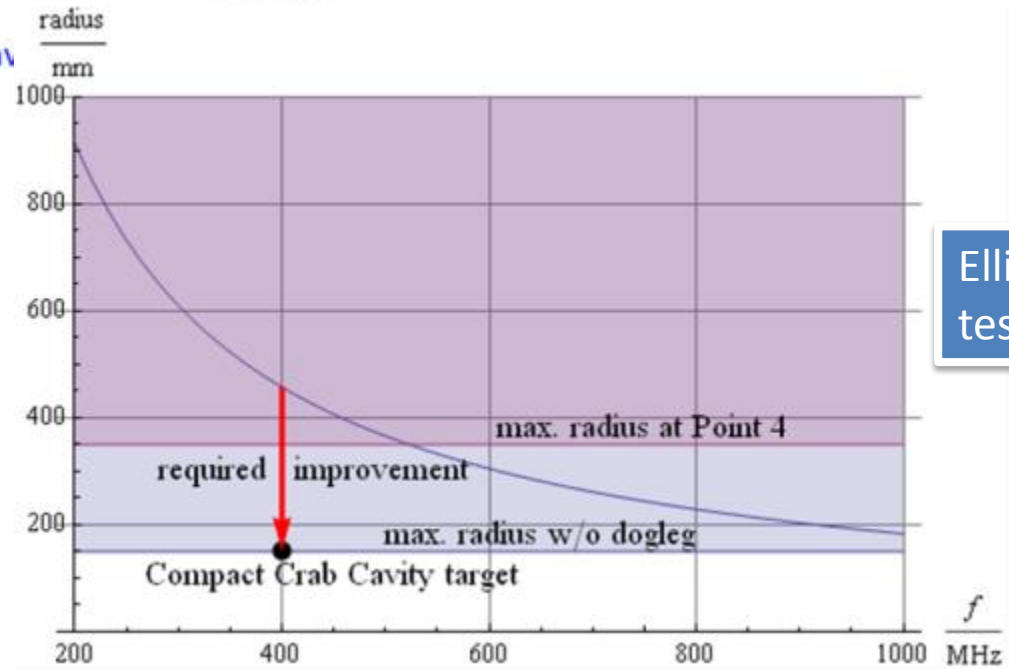
DR, UK, TechX



Kota, KEK



Compact cav

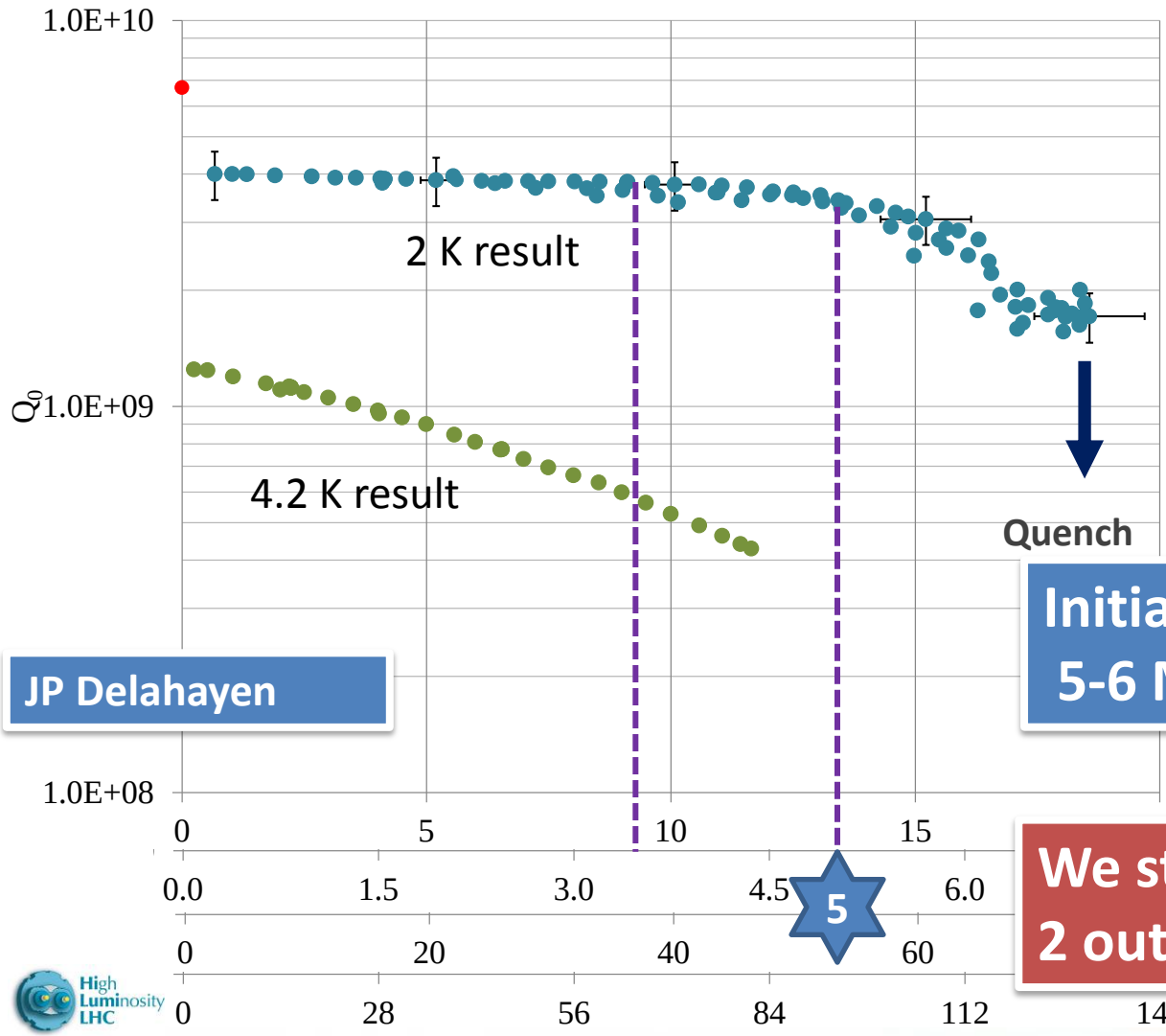


Elliptical type CC has been tested first in KEK 2008

And excellent results: RF dipole > 5 MV

¼ w and 4-rods also tested (1.5 MV)

cleaning & vacuum issues: new test under way

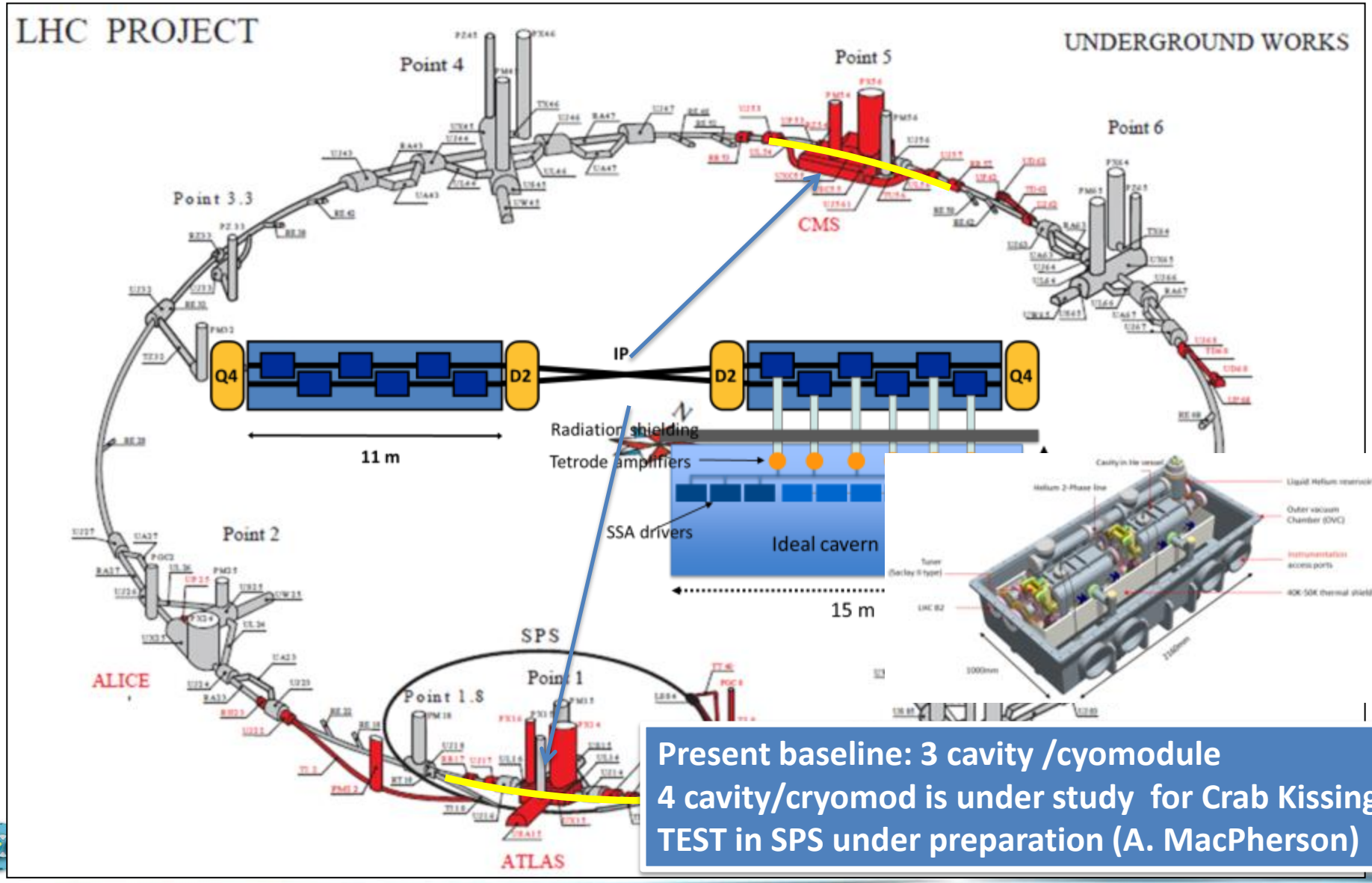


Initial goal was 3.5 MV
5-6 MV may be at hand

JP Delahayen

We started downselection,
2 out of 3 design kept for test

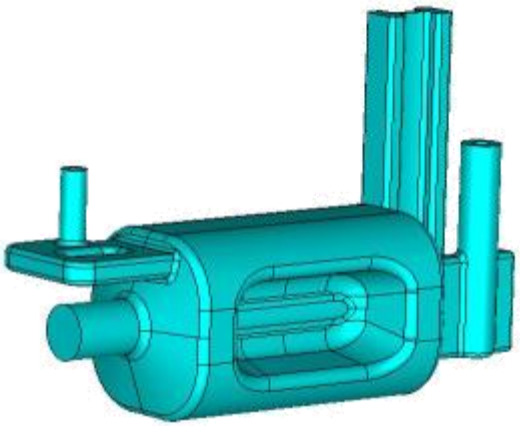
Crab Cavities for fast beam rotation



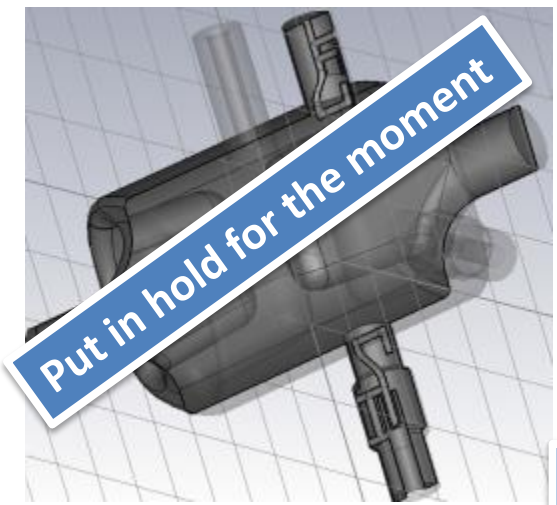
Present baseline: 3 cavity /cyomodule
4 cavity/cryomod is under study for Crab Kissing
TEST in SPS under preparation (A. MacPherson)

Latest cavity designs toward accelerator

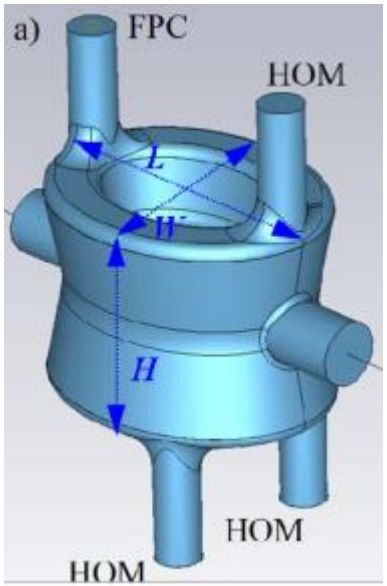
Coupler concepts



RF Dipole: Waveguide or waveguide-coax couplers



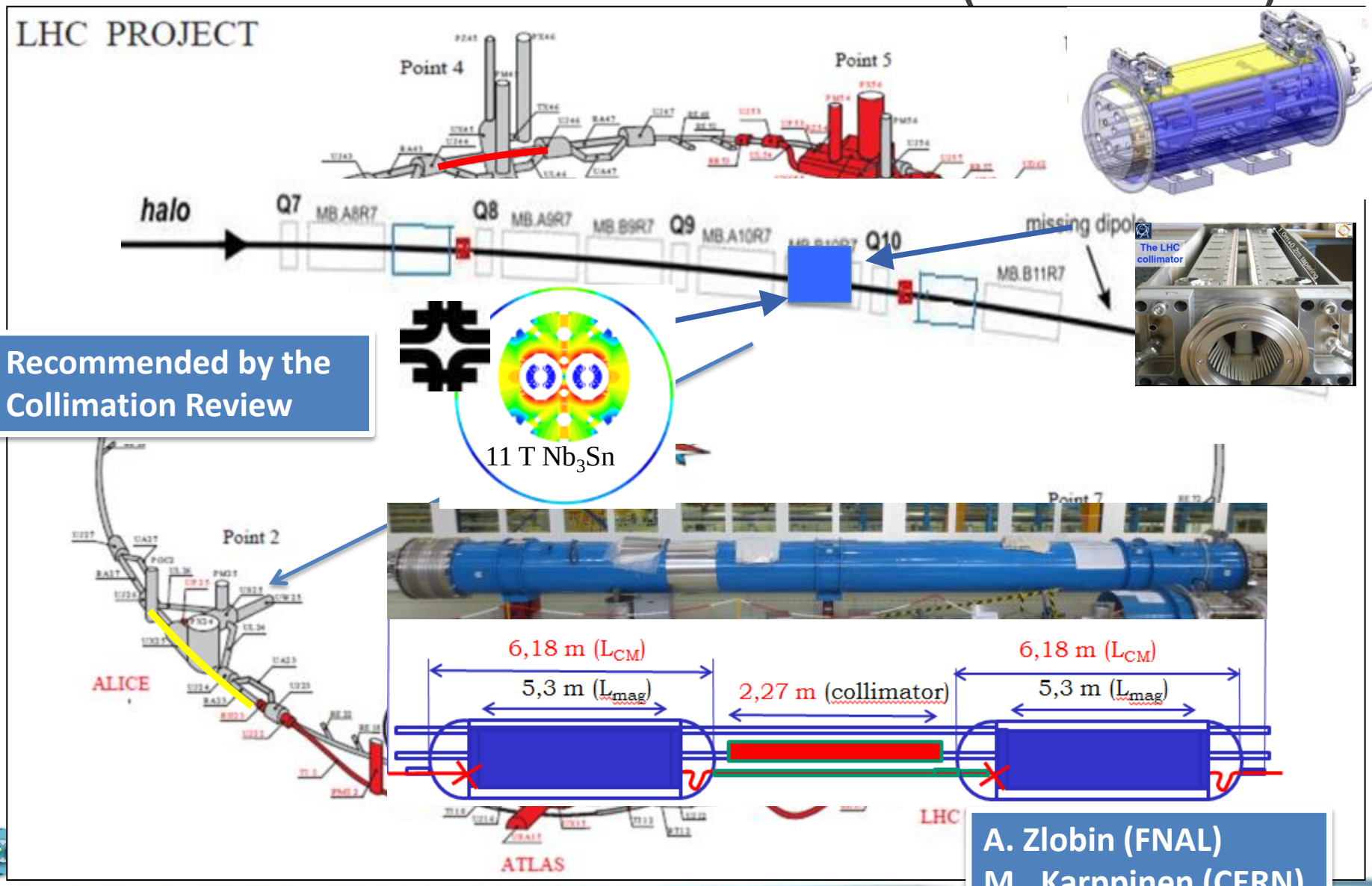
4-rod: Coaxial couplers with different antenna types



Double ¼-wave: Coaxial couplers with hook-type antenna

E. Jensen (CERN)
G. Burt (U.Lancaster, CI
R. Calaga (CERN, former LARP)
A. Ratti (LBNL, LARP)

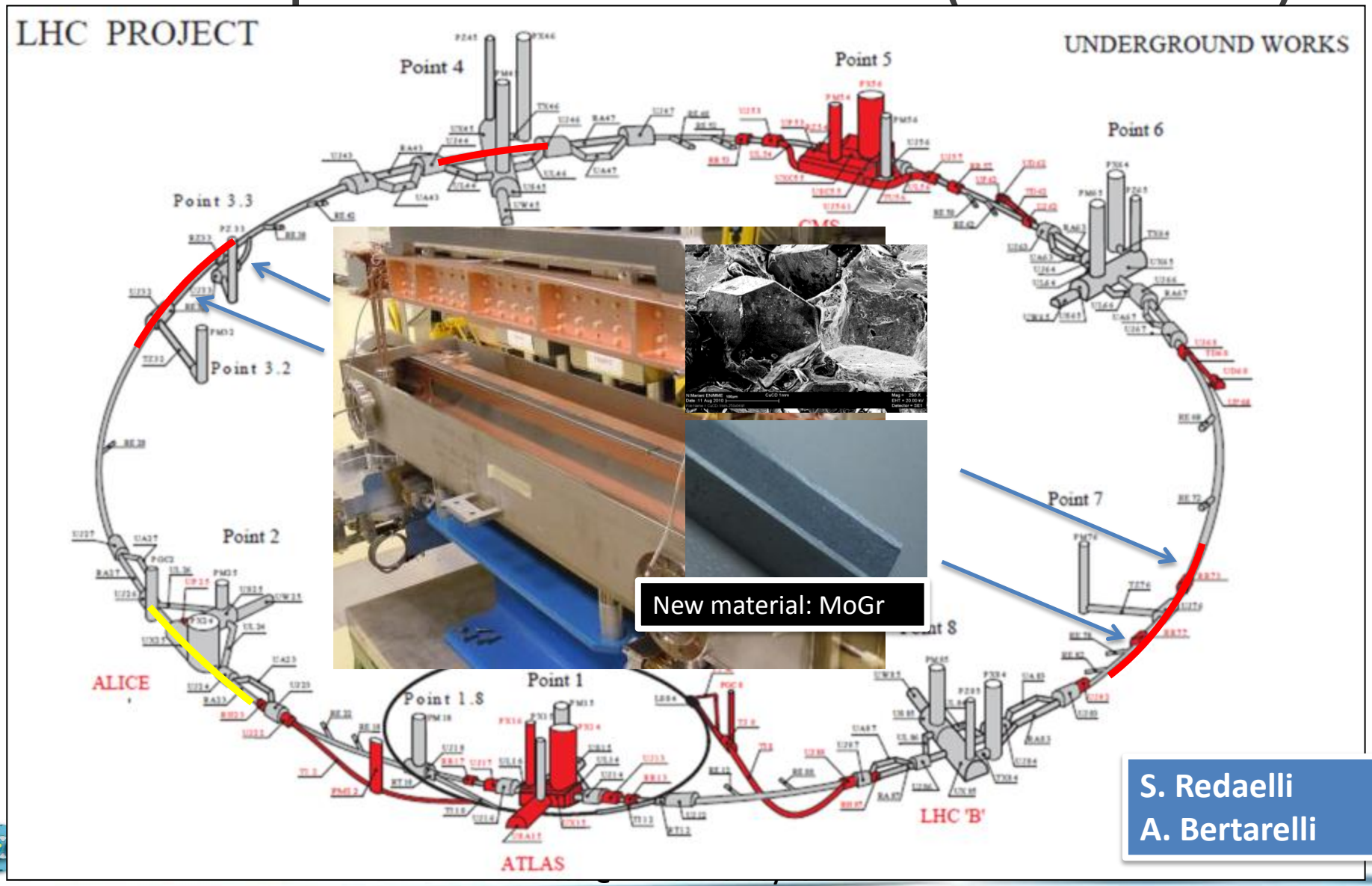
P2 - DS collimators ions – 11 T (LS2 -2018)



Recommended by the Collimation Review

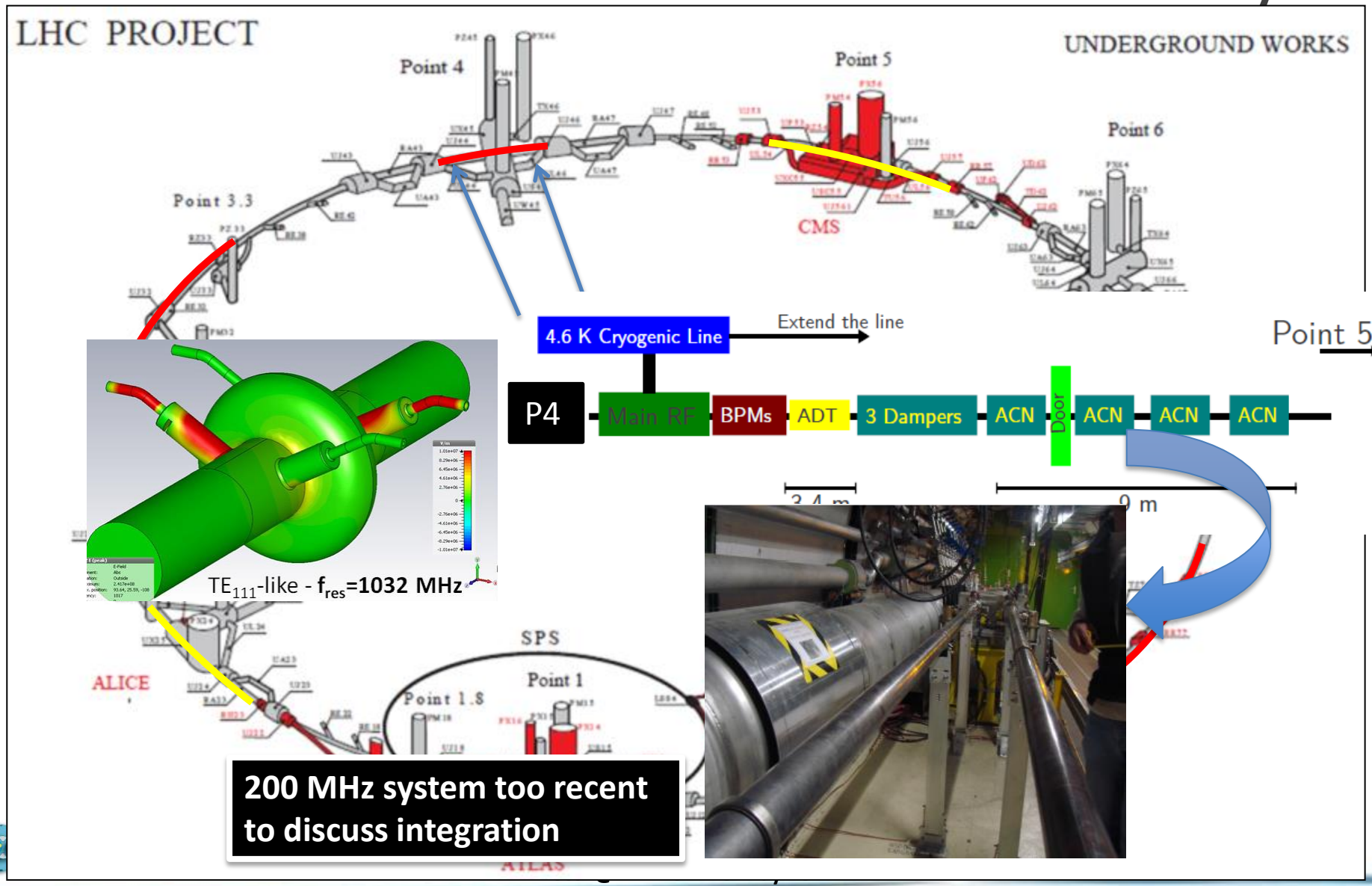
A. Zlobin (FNAL)
M . Karppinen (CERN)

Low impedence collimators(LS2 & LS3)

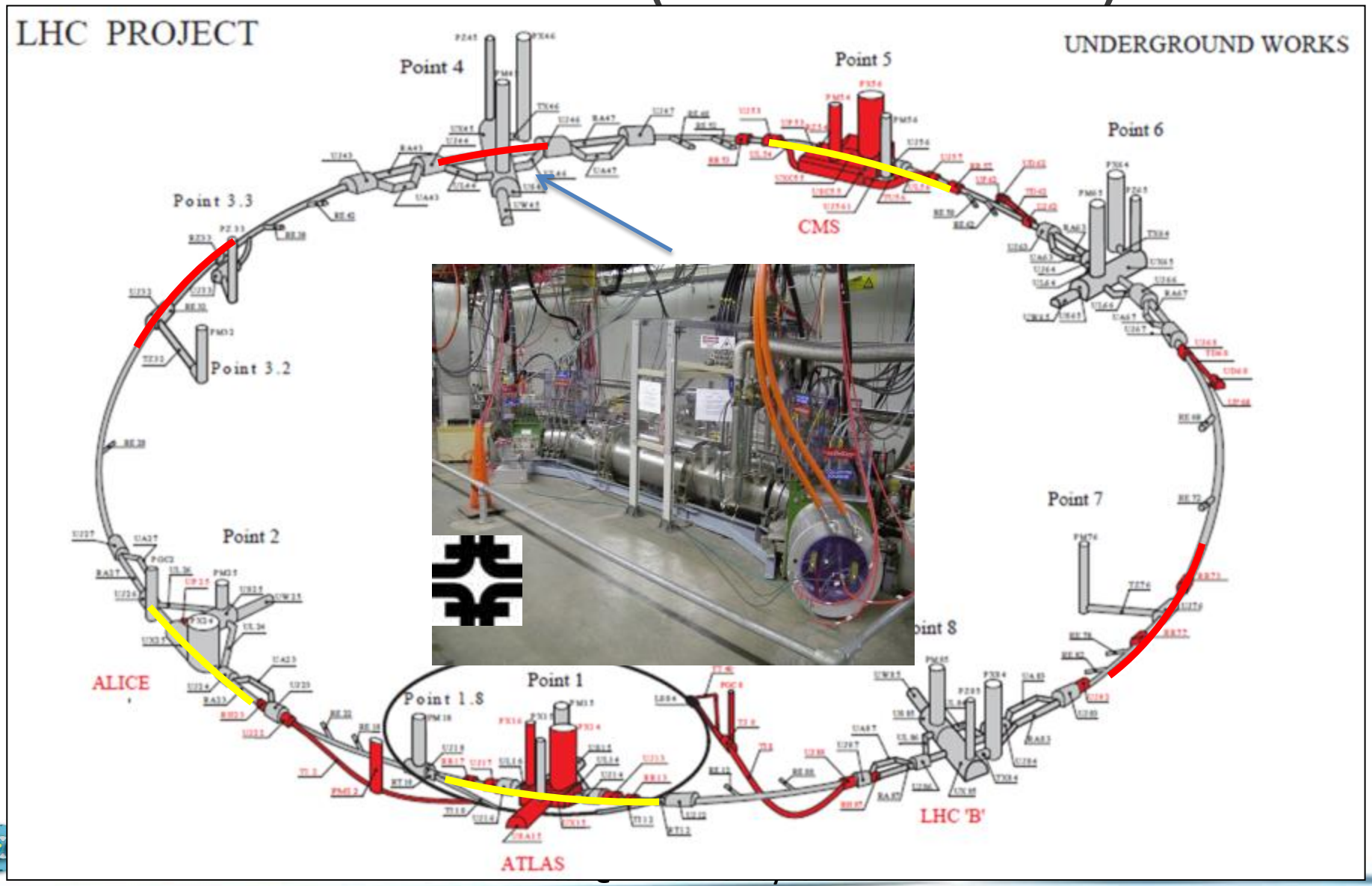


S. Redaelli
A. Bertarelli

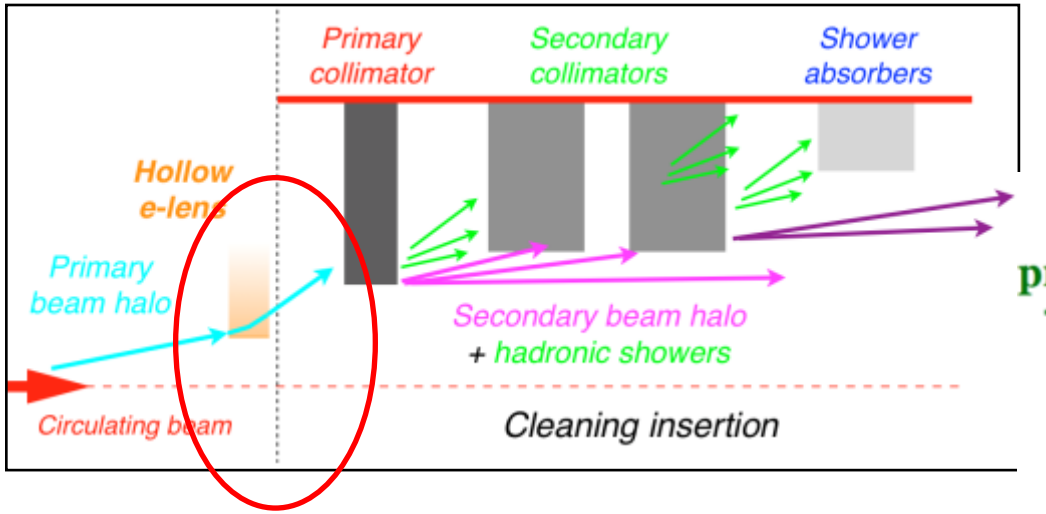
SCRF 800 MHz harmonic: under study

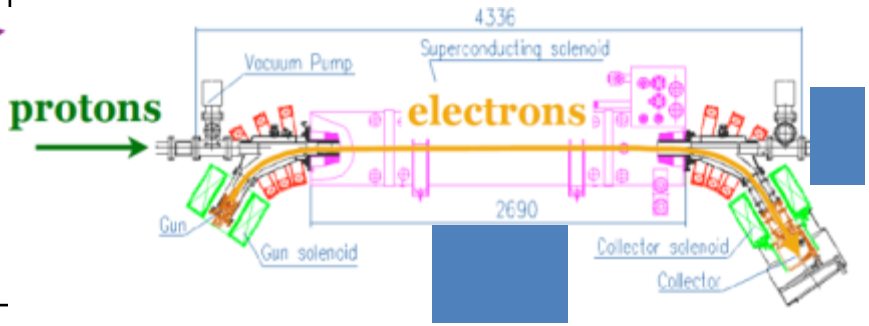


Halo control (hollow e-lens)



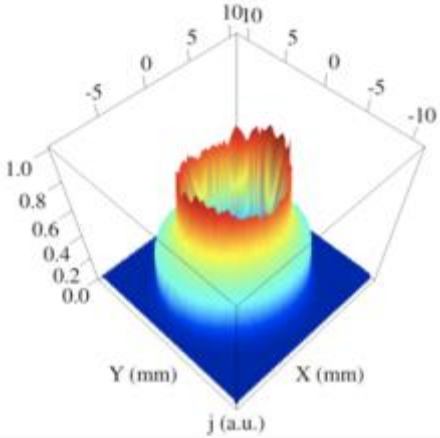
Controlling diffusion rate: hollow e-lens





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.

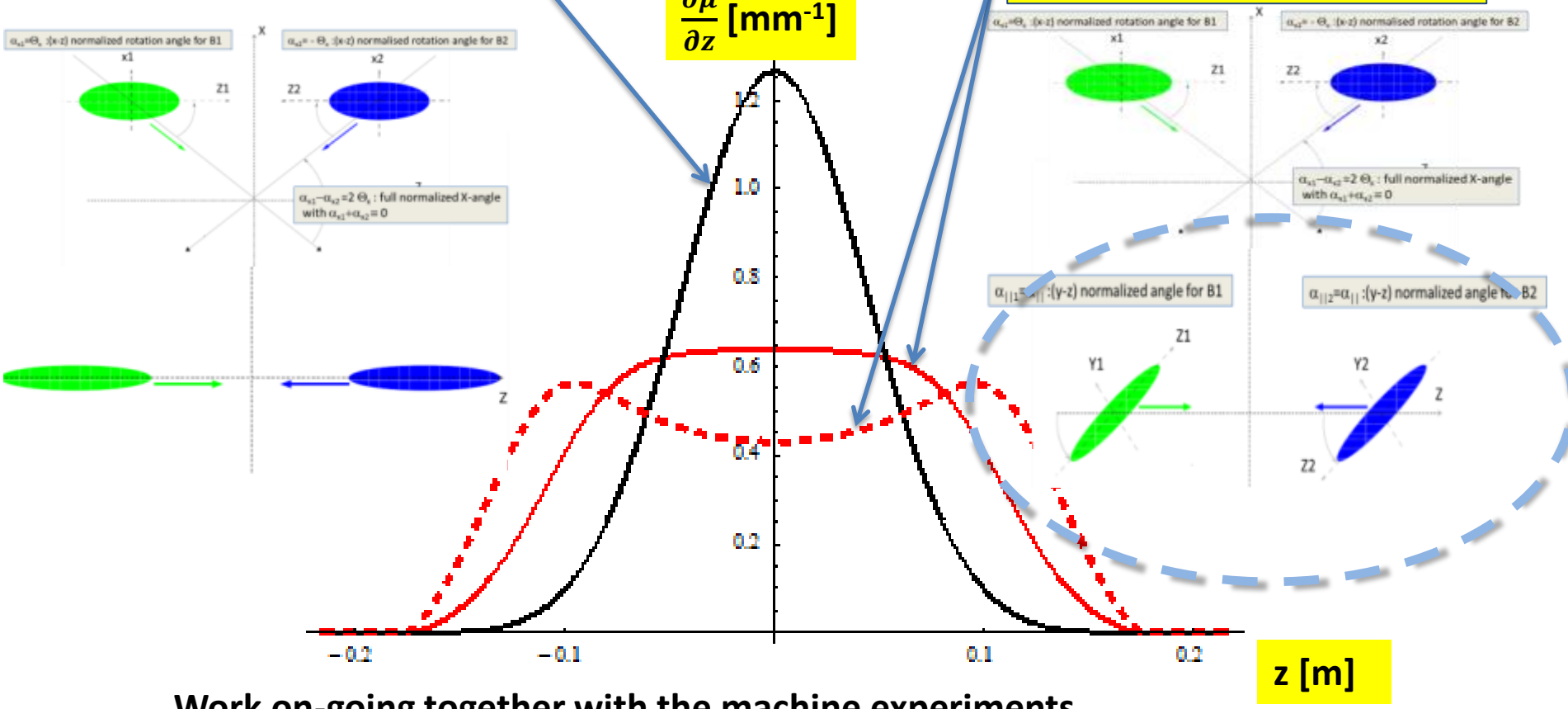


S. Redaelli
Developed by Fermilab

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

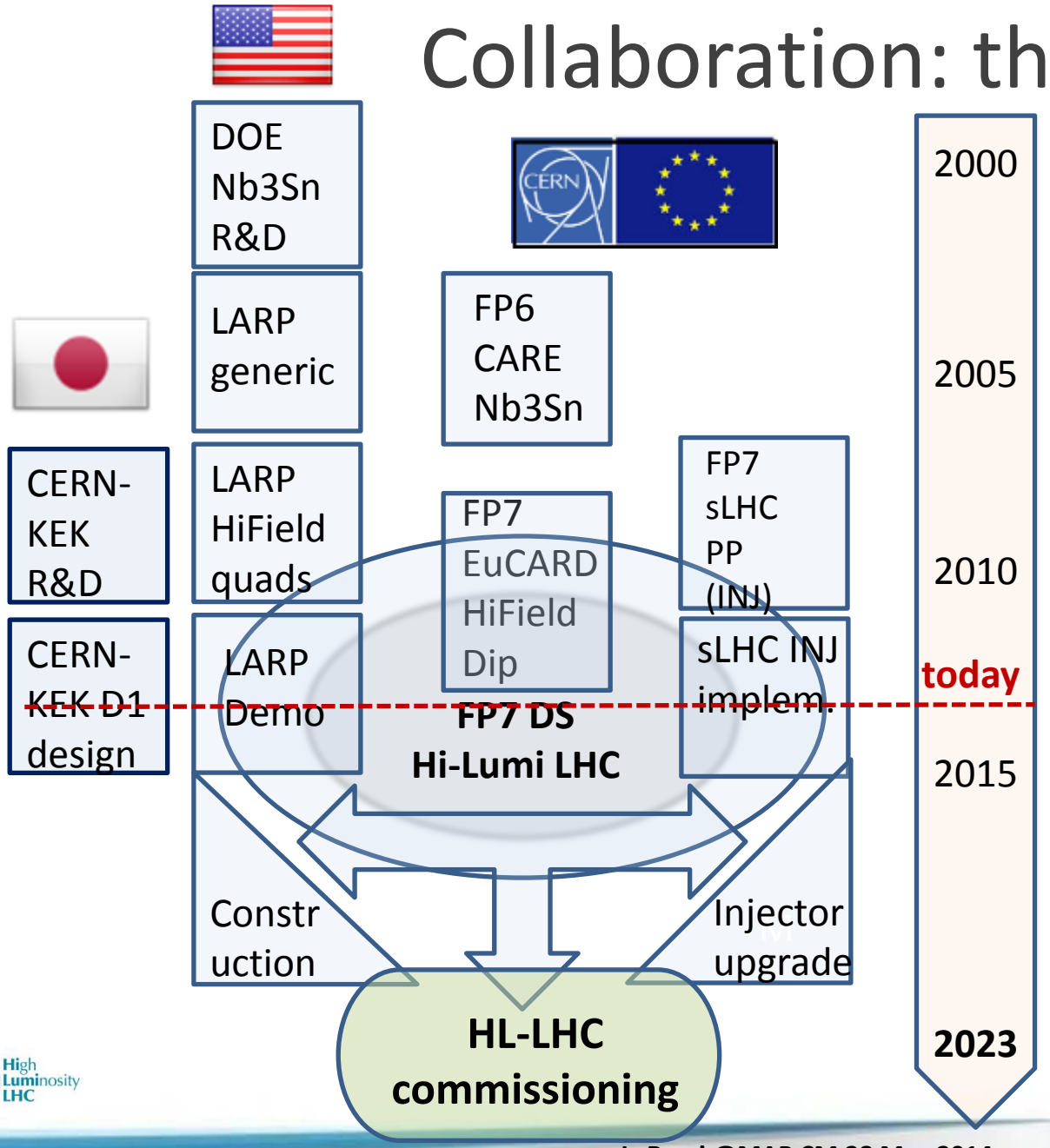
Baseline: CC in X-plane "only"

Crab-kissing & variants: CC also in ||-plane



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

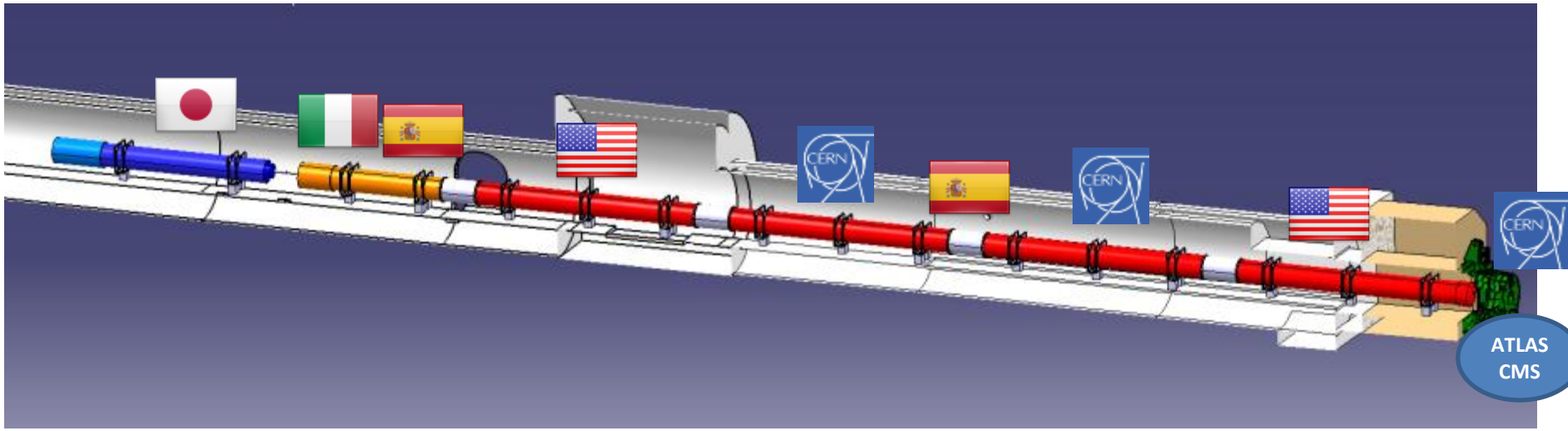
Collaboration: the long way

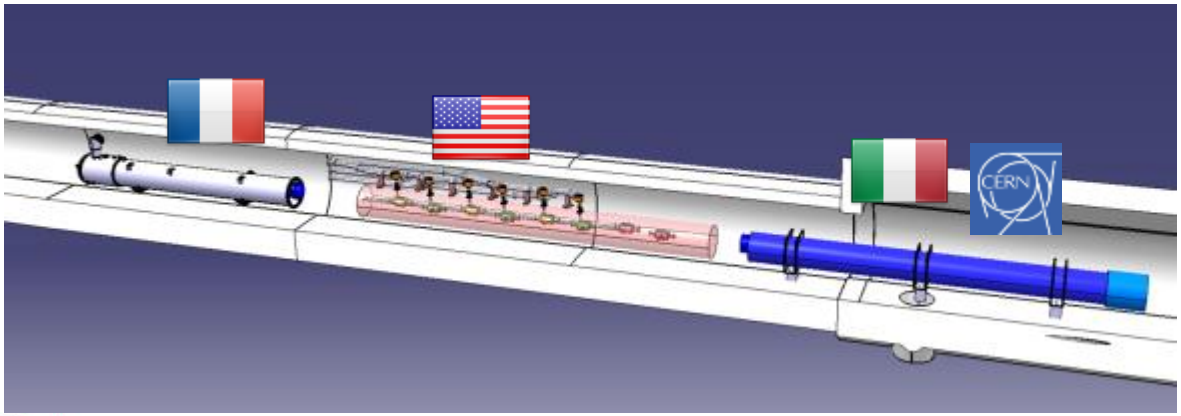


The HL-LHC project formally started in 2010; however it is the focal point of 20 years of <u>converging</u> International Collaboration

High Luminosity LHC Participants

In-kind contribution and Collaboration for HW design and prototypes

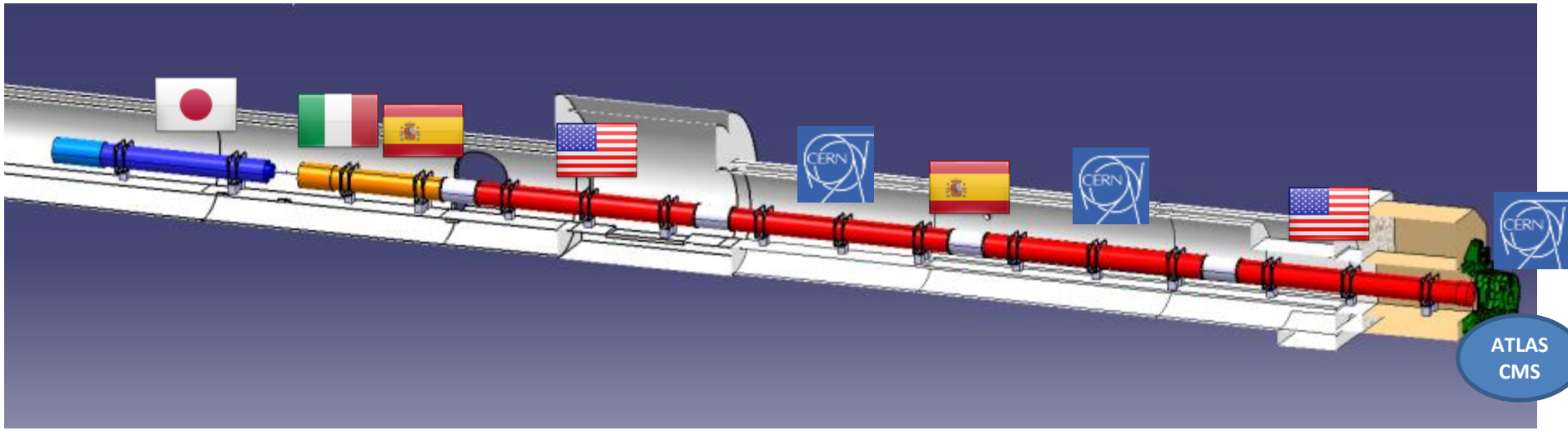


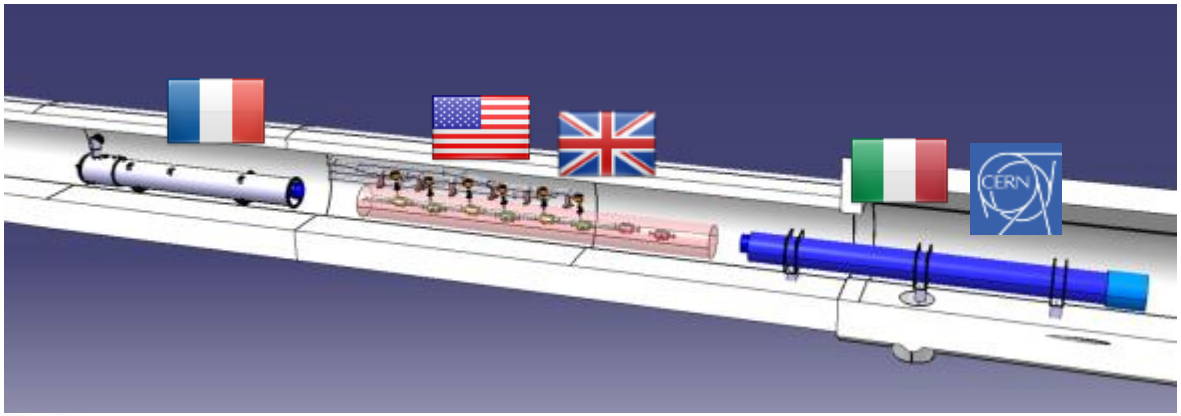


CC : R&D, Design and in-kind **USA**

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**

In-kind contribution and Collaboration for HW design and prototypes



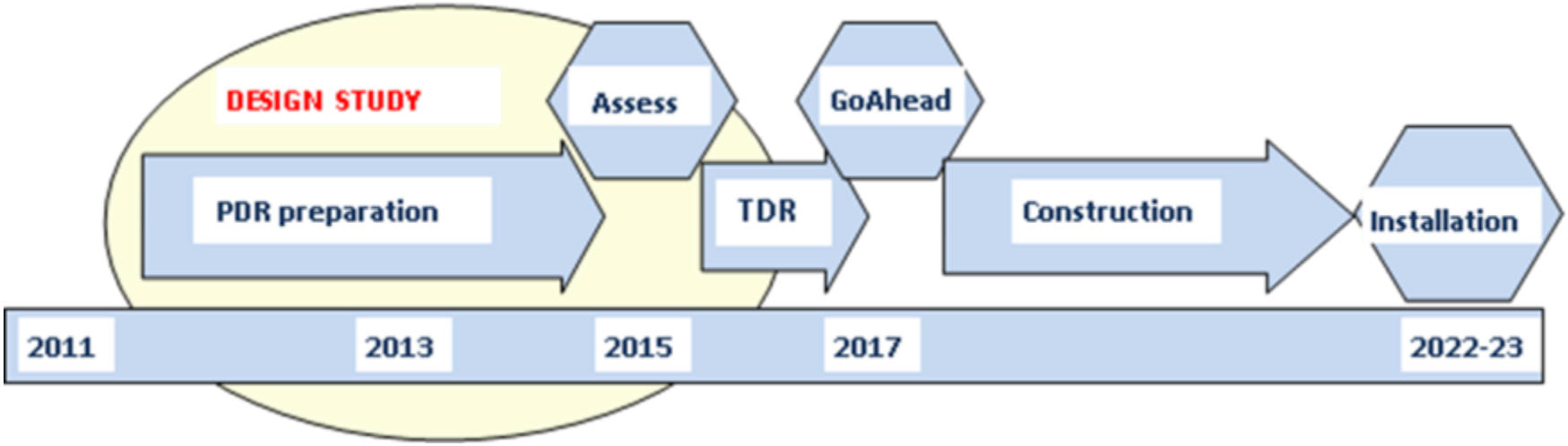


CC : R&D, Design and in-kind **USA**

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

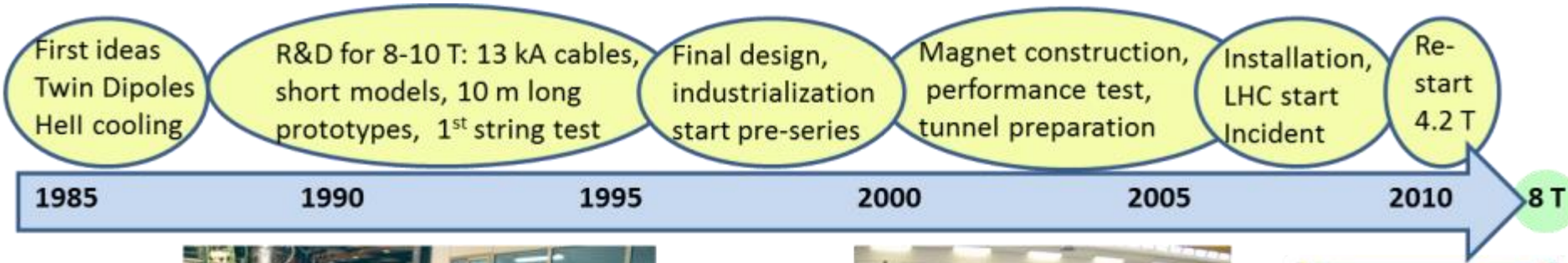
Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

Implementation plan

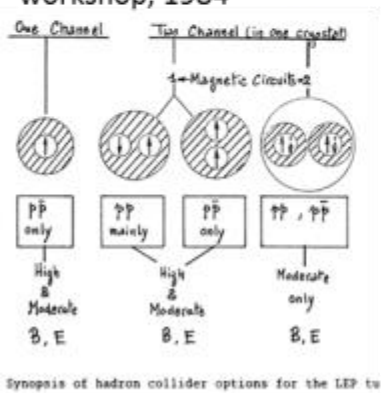


- All WP active, from diagnostics to Machine Protection;
- Integration started with vigour as well as QA (workshop soon)
- Cryo, SC links, Collimators, Diagnostics, etc. starts in LS2 (2018)
- Proof of main hardware by 2016; Prototypes by 2017
- Start construction 2017/18 from IT, CC, other main hardware
- 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

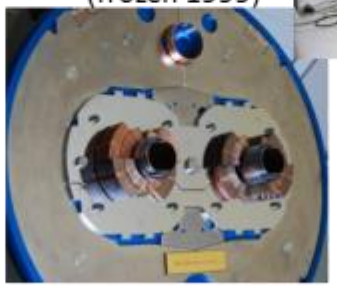


Magnet designs at first LHC workshop, 1984

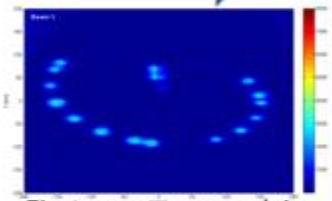


First LHC dipole prototype on the test bench (June1994)

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

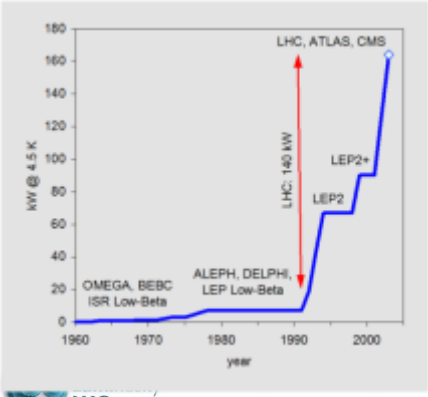
1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035

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

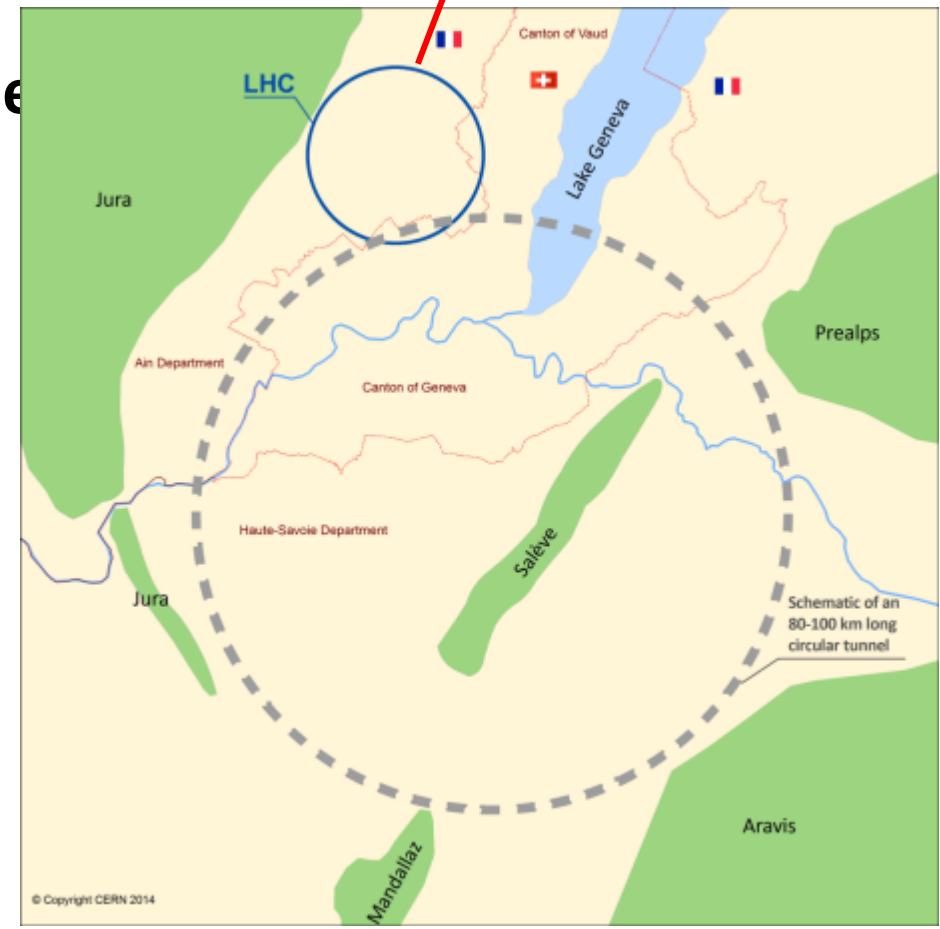


FCC-Future Circular Coliders

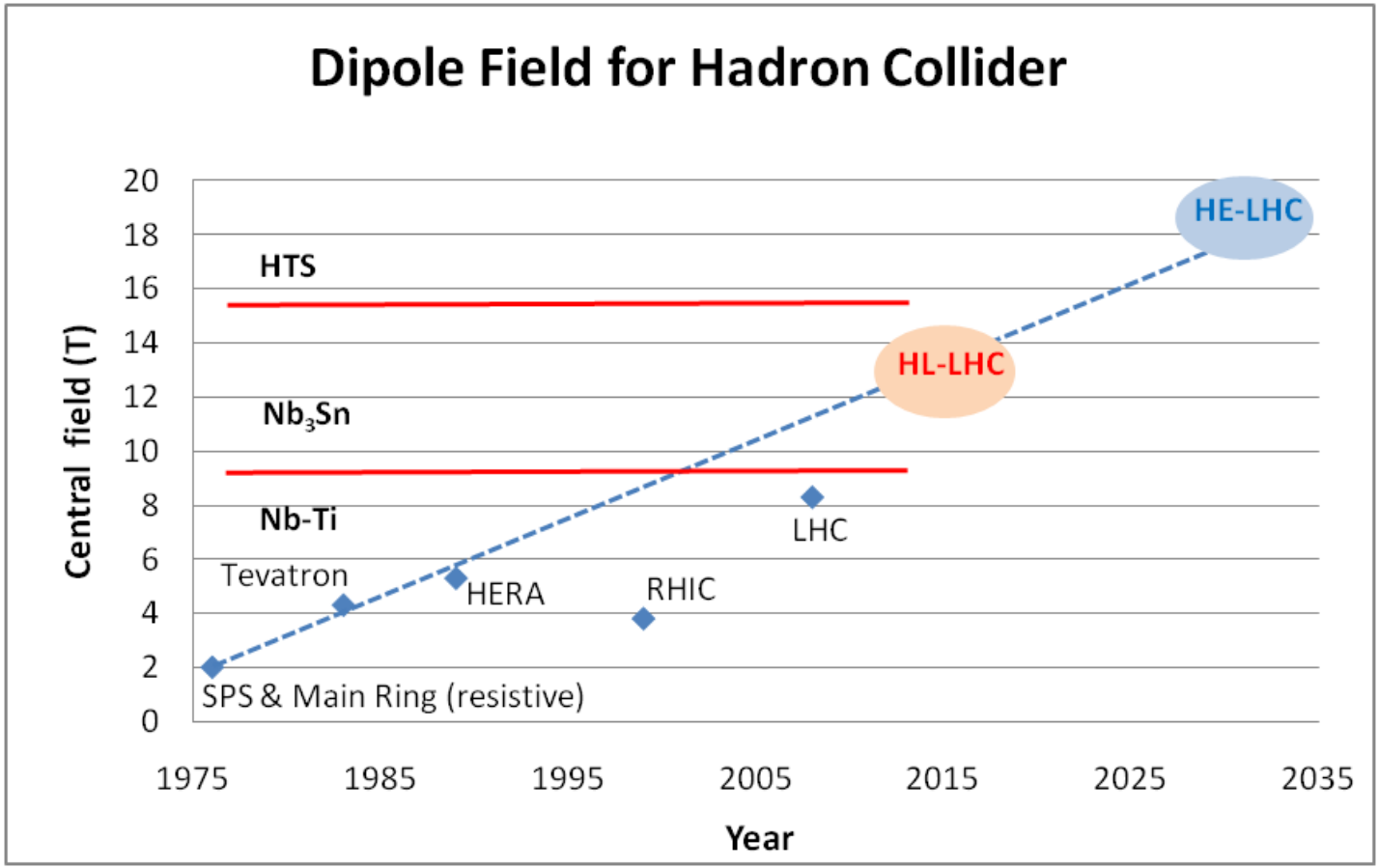
HE-LHC :33 TeV with 20T magnets

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 main (but not unique) 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)