# The High Luminosity LHC Project at CERN: Status, Perspectives, Plans

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On behalf of the HL-LHC Project

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# Outline

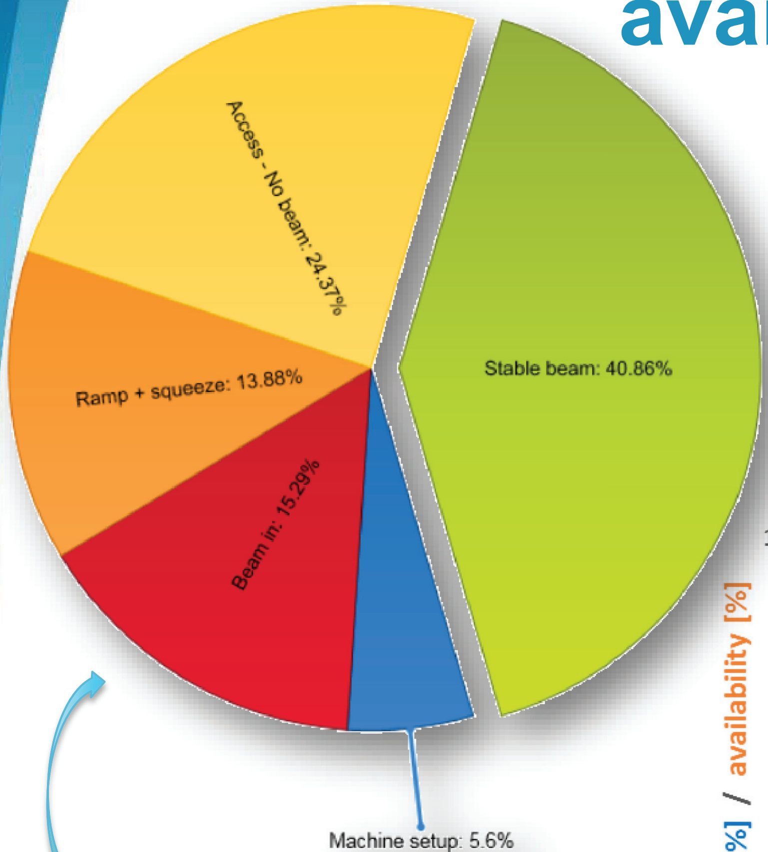
- The LHC achievements
- Looking beyond the LHC reach
- Motivation for the High Luminosity LHC
- A selection of the HL-LHC ingredients
- Perspectives and expectations: developments for the future
- Status at the edge of the construction
- Consolidated plans
- Conclusions


Large Hadron Collider
CMS
p
p
LHCb
ATLAS
ALICE

# The LHC achievements

- LHC has had a tremendous performance in the past years
- From 2008 with a quick recovery from the accident, a year 2009 with a short run and following years with long runs, through a break in 2013-2014
  - this year has reached and overcome the nominal instantaneous luminosity: **$1.4 \cdot 10^{34}$ cm$^{-2}$ s$^{-1}$**
- It is not only collecting records, but also demonstrating to be a very reliable machine

# Stable Beams time and machine availability 2016

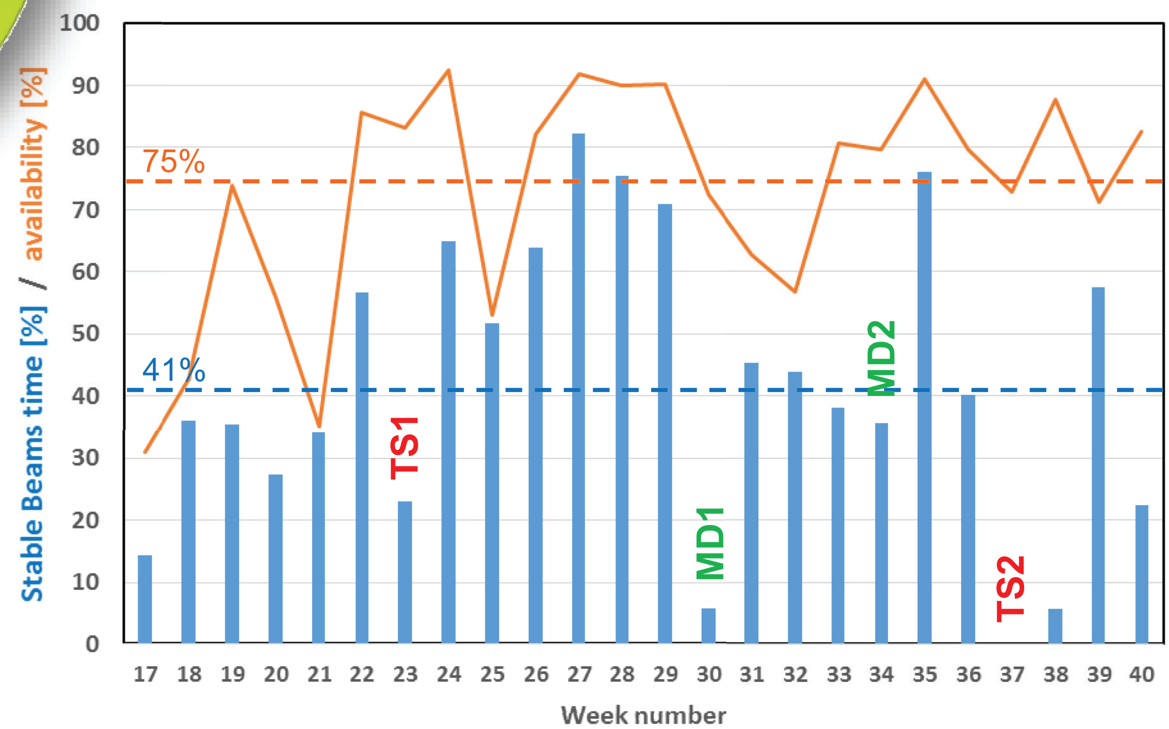



Time breakdown at the LHC
(April to October, <u>with TS and MDs included</u>)

HL-LHC challenge: machine efficiency

→ target time spent in Stable Beams around 50%

- Very encouraging results from LHC in June-July in view of reaching this target

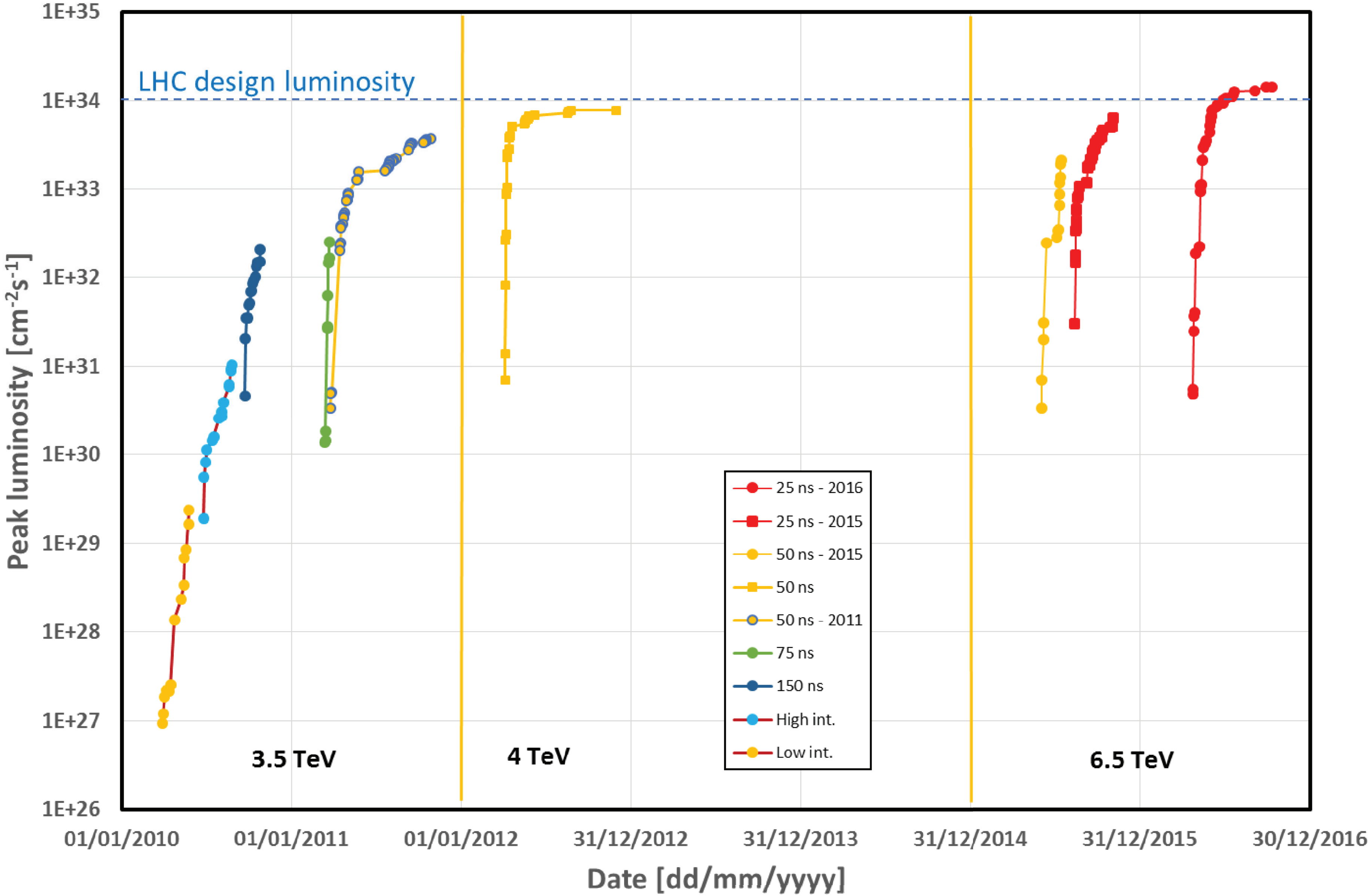


# Evolution of the machine parameters

$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot \gamma \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot F(\phi, \beta^*, \varepsilon, \sigma_s)$$

| Parameters | Design | Run I | 2015 | 2016 |
|---|---|---|---|---|
| Proton energy [TeV] | 7 | 3.5-4 | 6.5 | 6.5 |
| Bunch spacing [ns] | 25 | 50 | 25 | 25 |
| # proton per bunch [$10^{11}$] | 1.15 | 1.5-1.7 | 1.2 | **1.15** |
| Number of bunches | 2808 | 1374 | 2244 | **2220** |
| Transverse norm. emittance [mm mrad] | 3.75 | 2.5 | 3.5 | **2** |
| Stored energy per beam [MJ] | 362 | 140 | 270 | 260 |
| Crossing angle [mrad] | 142.5 | 145 | 145 | 185→**140** |
| β* in IP1and IP5 [cm] | 55 | 60 | 80 | **40** |
| Peak luminosity in IP1 and IP5 [$10^{34}$ $cm^{-2}s^{-1}$] | 1.0 | 0.77 | 0.5 | **1.4** |
| Pile-up IP1 and IP5 | 19 | 37 | 16 | 45 |

# Reached the nominal luminosity

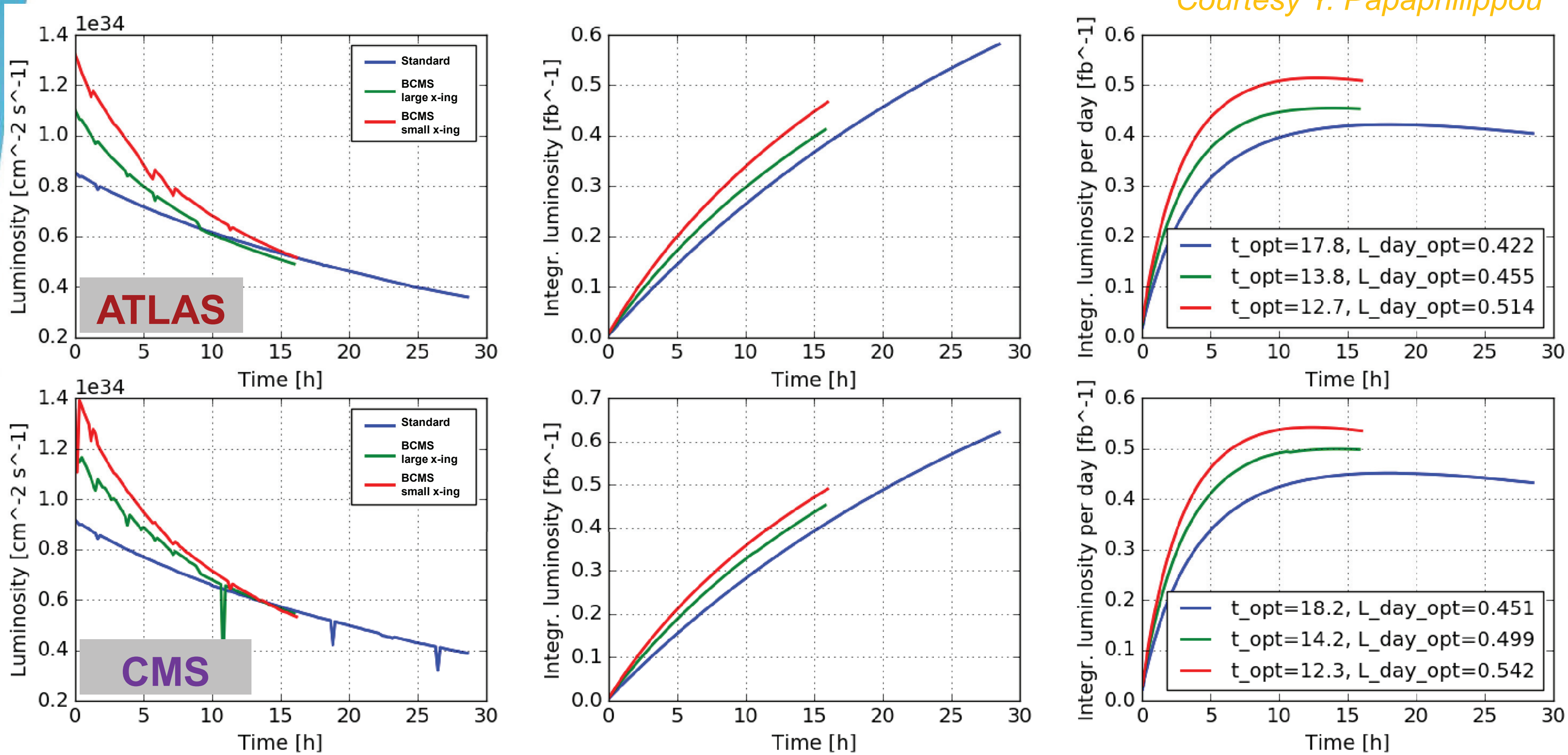


# Impressive fill length

For a turn-around time of 6h, the ideal fill length is between 12 and 15 hours

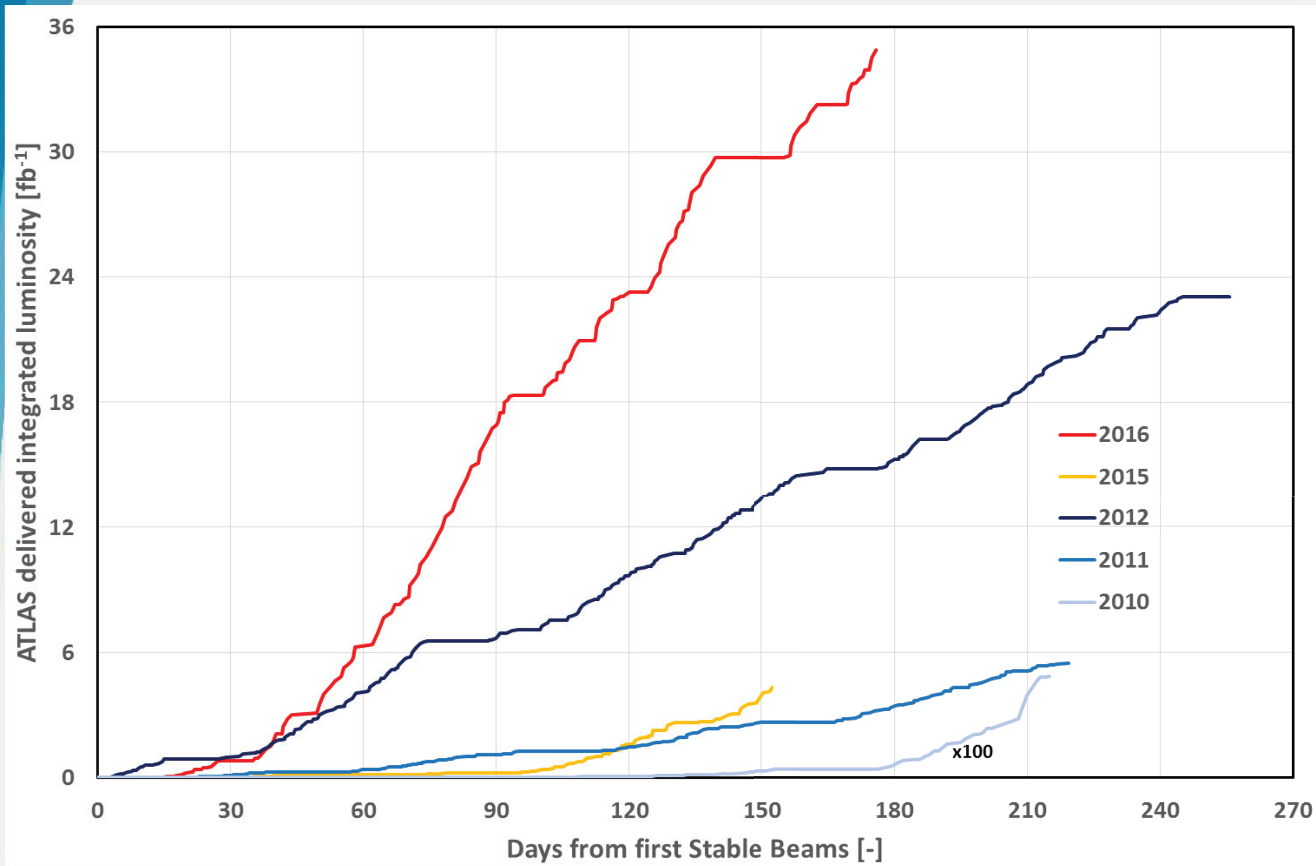
- ➢ HL-LHC considers an average fill length of ca10 hours

*Courtesy Y. Papaphilippou*



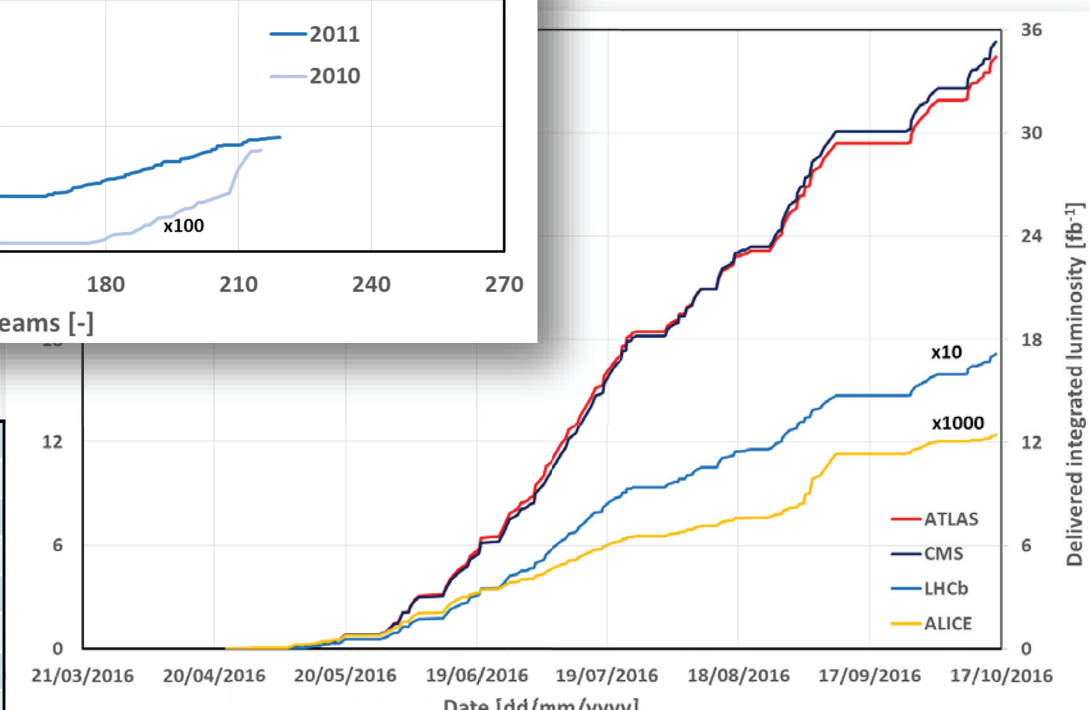

- Integrated luminosity gain of the order of **10%** from standard to BCMS
- An **extra 10%** for reduced crossing angle

# Integrated luminosity




**2016 delivered integrated Luminosities**
**(update 17/10)**

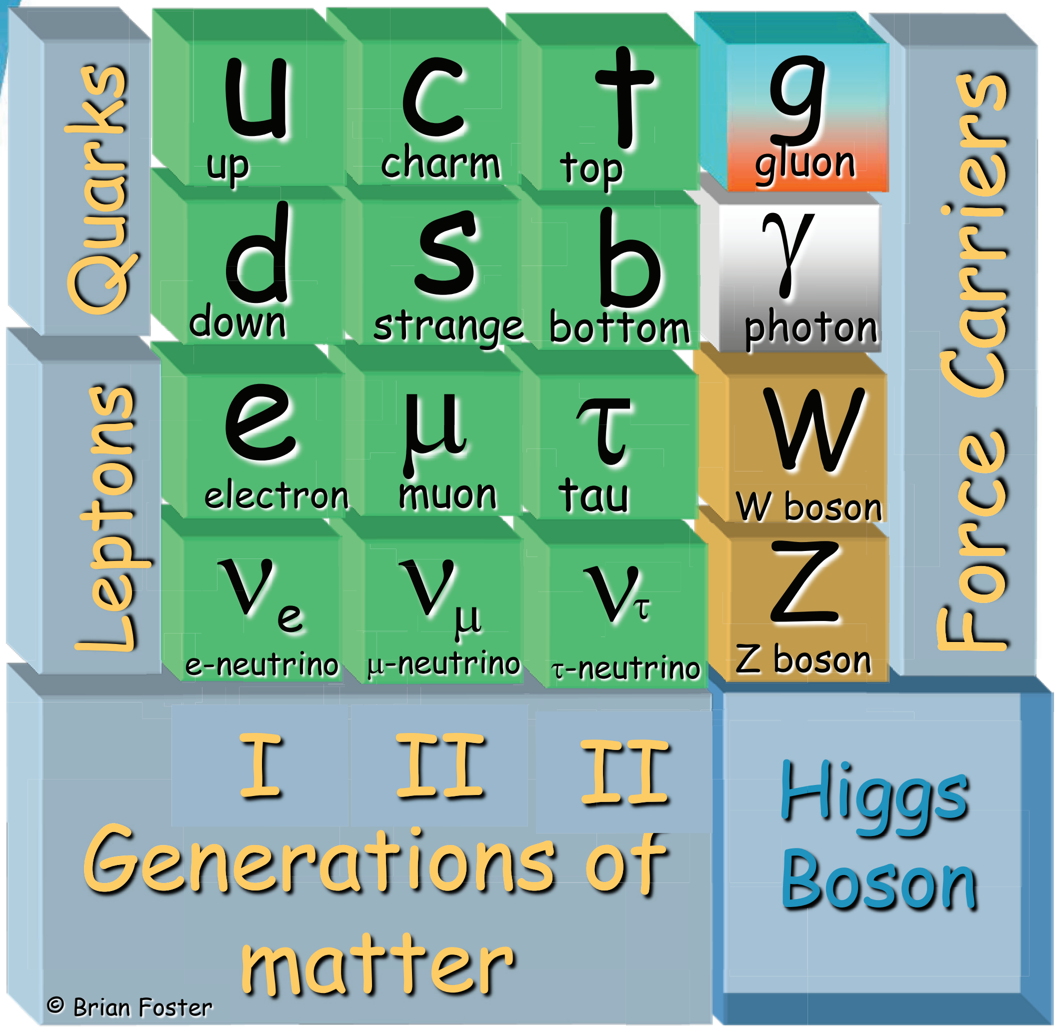
ATLAS: 34.1 $fb^{-1}$
ALICE: 12.4 $pb^{-1}$
CMS: 35.3 $fb^{-1}$
LHCb: 1.7 $fb^{-1}$




## 2016 parameters

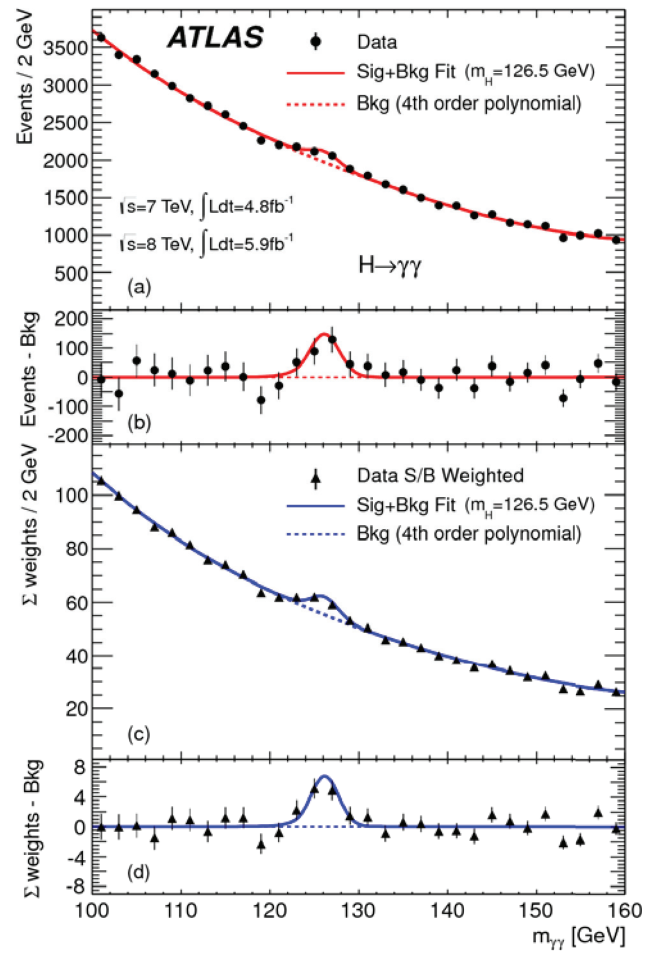
| | |
|---|---|
| Energy | 6.5 TeV |
| Bunch spacing | 25 ns |
| Bunch population | ~1.1-1.15e11 p/b |
| Max bunches/injection | 72-96 |
| Max. number bunches | 2220 |
| Nc GPDs | 2208 |
| Beta* GPDs | 40 cm |
| Crossing angle GPDs | 185→140 μrad |

# Achievements at LHC: the world of elementary particles after 4 July 2012




H

a spin-0 boson



# But…

- No evidence of New Physics so far…
- If New Physics at TeV scale its spectrum is heavy: need of high luminosity (3000 $fb^{-1}$) and a lot of energy
- Puzzle: LHC results indicate that the SM works up to scales much higher than TeV, but the limits found so far on new physics preclude attempts to fix its weaknesses. But SM needs new particles and/or interactions to address fundamental questions:
  - Why Higgs boson is so light? (naturalness or fine tuning?)
  - What is the origin of matter-antimatter asymmetry?
  - Why is Gravity so weak?
  - The 96% Dark Universe?
  - Other unknowns?

# If just looking at Higgs…

- The Higgs boson discovery is too young to say if it is the minimal mechanism predicted by the SM or something more complex (for example with multiple Higgs bosons)

Add Higgs potential to SM equations:

$$V(\phi^\dagger\phi) = \mu^2\phi^2 + \lambda\phi^4 \qquad \mu^2 < 0$$

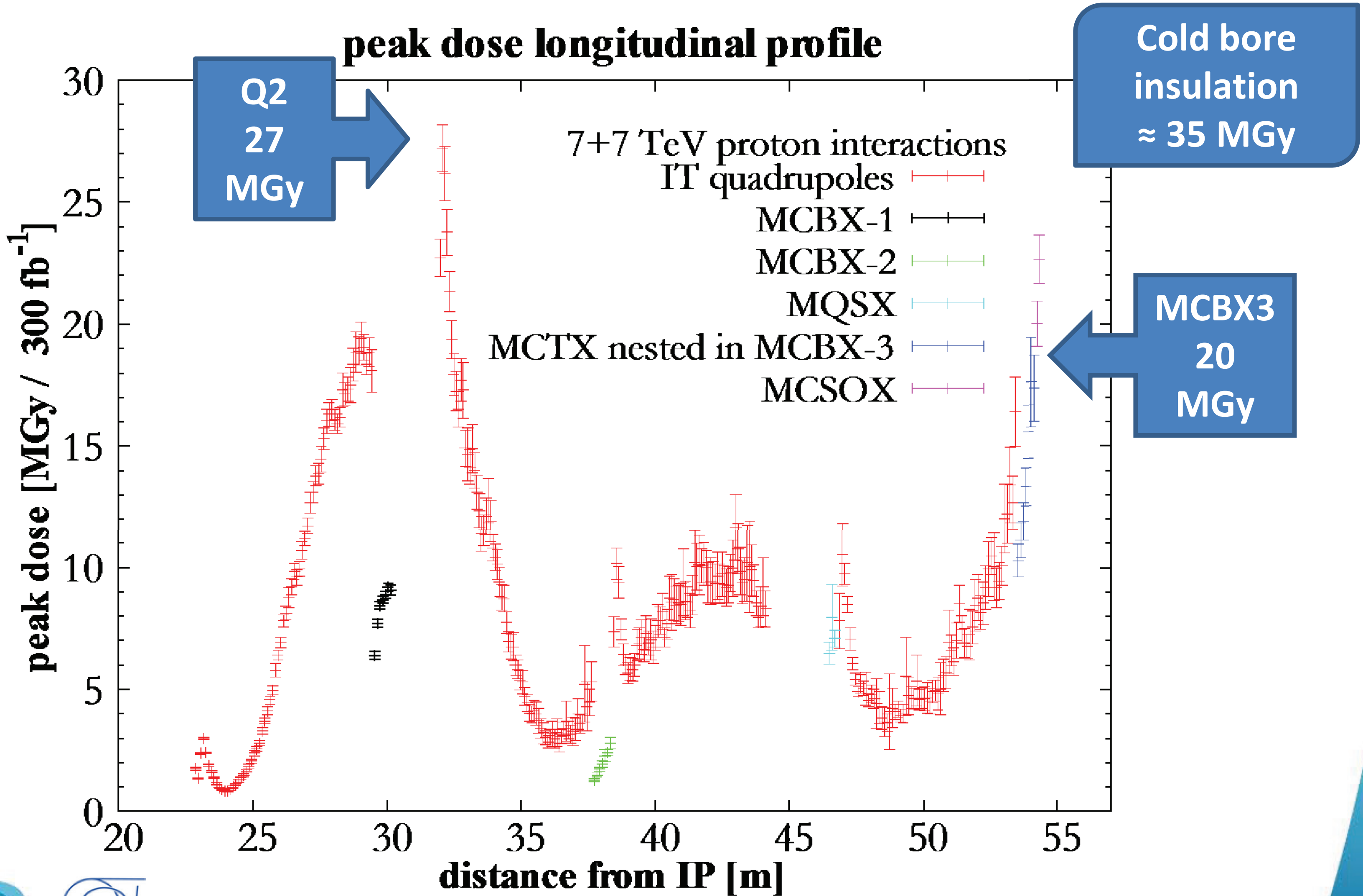
- ❑ Measure as many Higgs couplings to fermions and bosons as precisely as possible
- ❑ Measure Higgs self-couplings (give access to λ)
- ❑ Verify that the Higgs boson fixes the SM problems with W and Z scattering at high E

HL-LHC (3000 $fb^{-1}$): THE Higgs factory:
- ❑ > 170M Higgs events produced
- ❑ > 3M useful for precise measurements

more than (or similar to) ILC/CLIC/TLEP

Note: today ATLAS+CMS have thousands Higgs events

# The technical trigger of the upgrade: Radiation damage in low-beta triplet region



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

From FP7 HiLumi LHC Design Study application

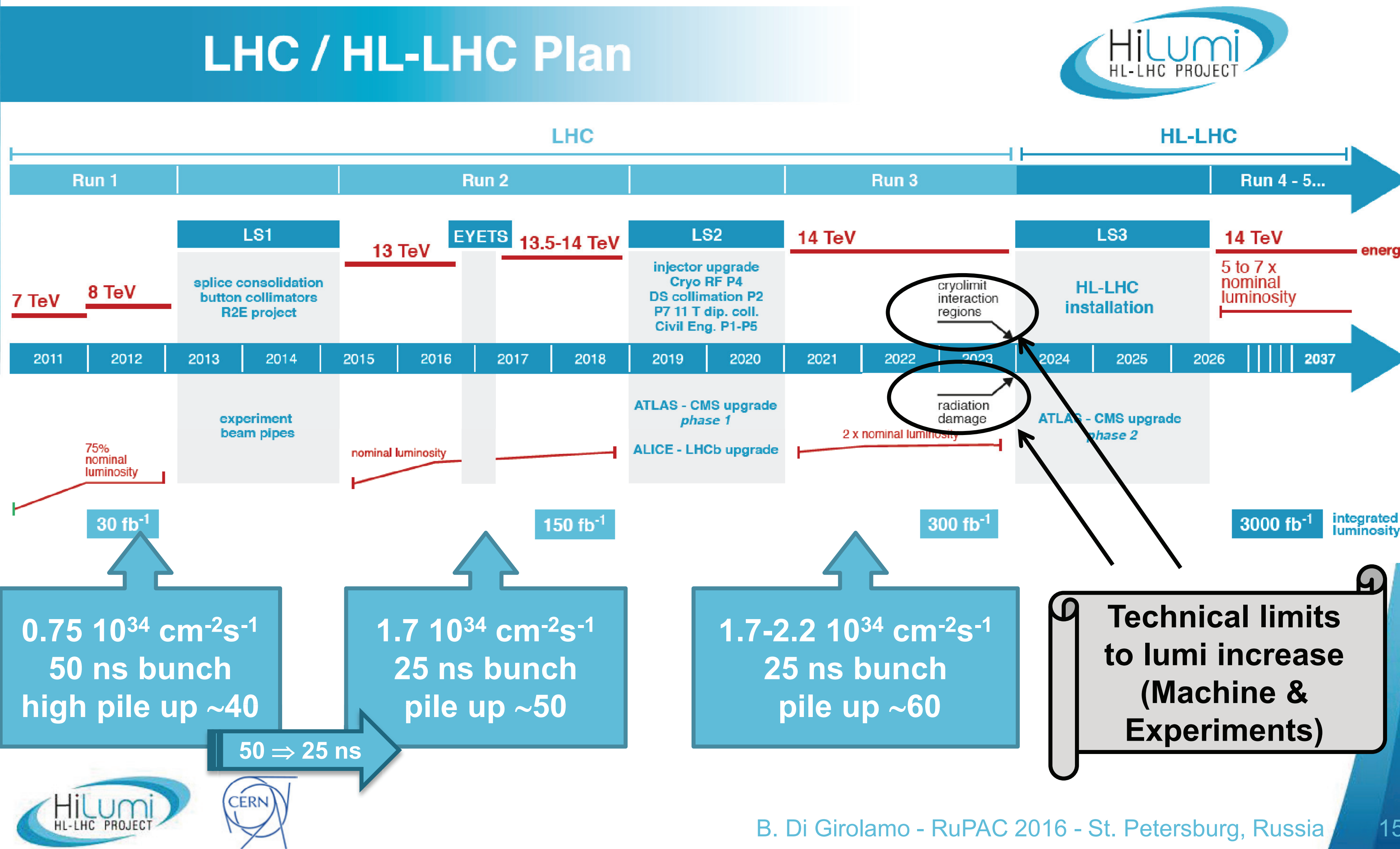
The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

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

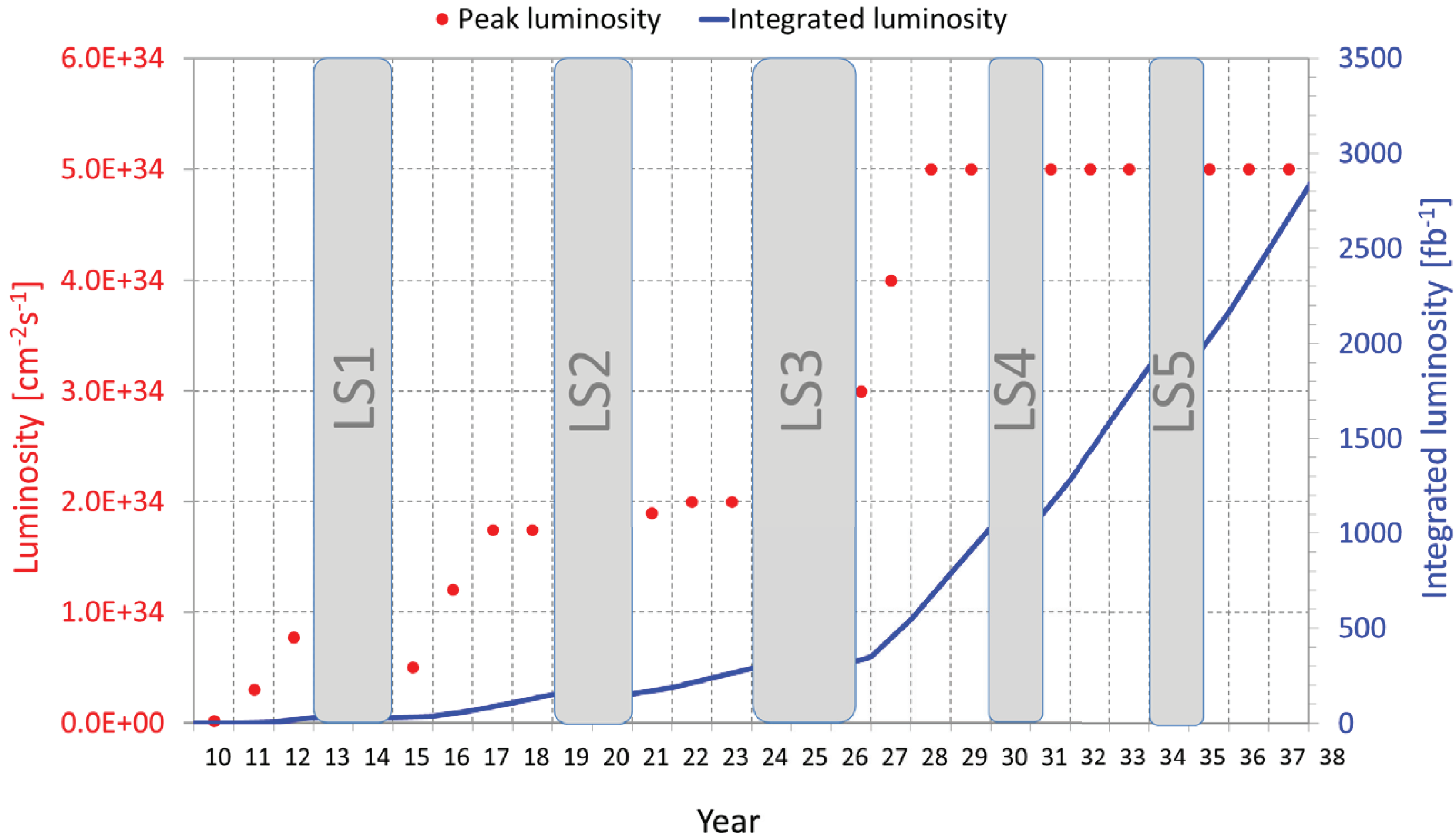
An integrated luminosity of **250 fb$^{-1}$ per year**, enabling the goal of **$L_{int}$ = 3000 fb$^{-1}$** twelve years after the upgrade.
This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

**Ultimate** performance established 2015-2016: with same hardware and same beam parameters: use of **engineering margins:**
**$L_{peak\ ult}$ ≅ 7.5 10$^{34}$ cm$^{-2}$s$^{-1}$** and **Ultimate Integrated $L_{int\ ult}$ ~ 4000 fb$^{-1}$**
LHC should not be the limit, would Physics require more…

# LHC and HL-LHC timeline

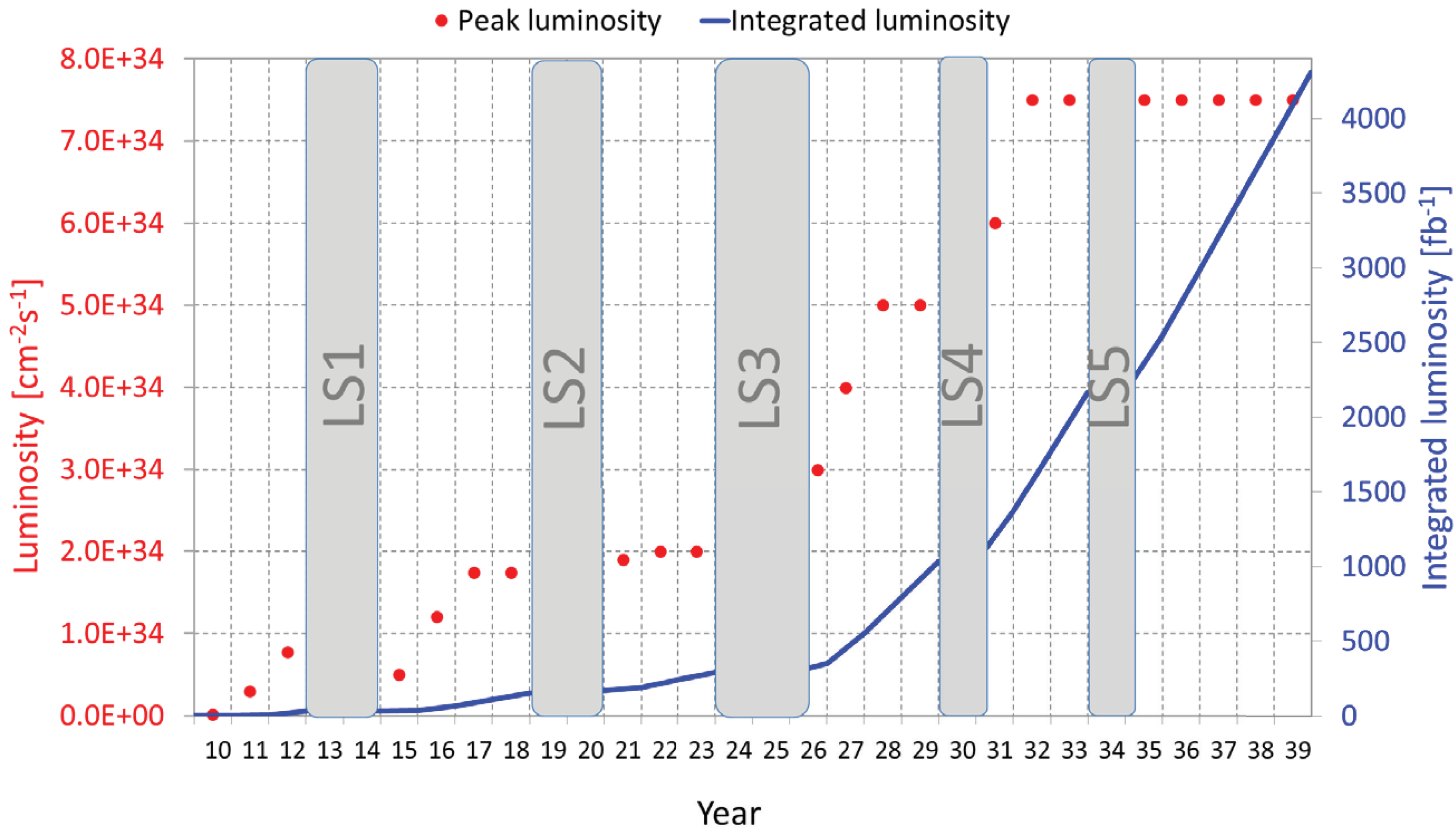


# Luminosity profile : NOMINAL




After LS4, proton physics days increase from standard 160 days to 200 and after LS5 to 220

# Luminosity profile : ULTIMATE

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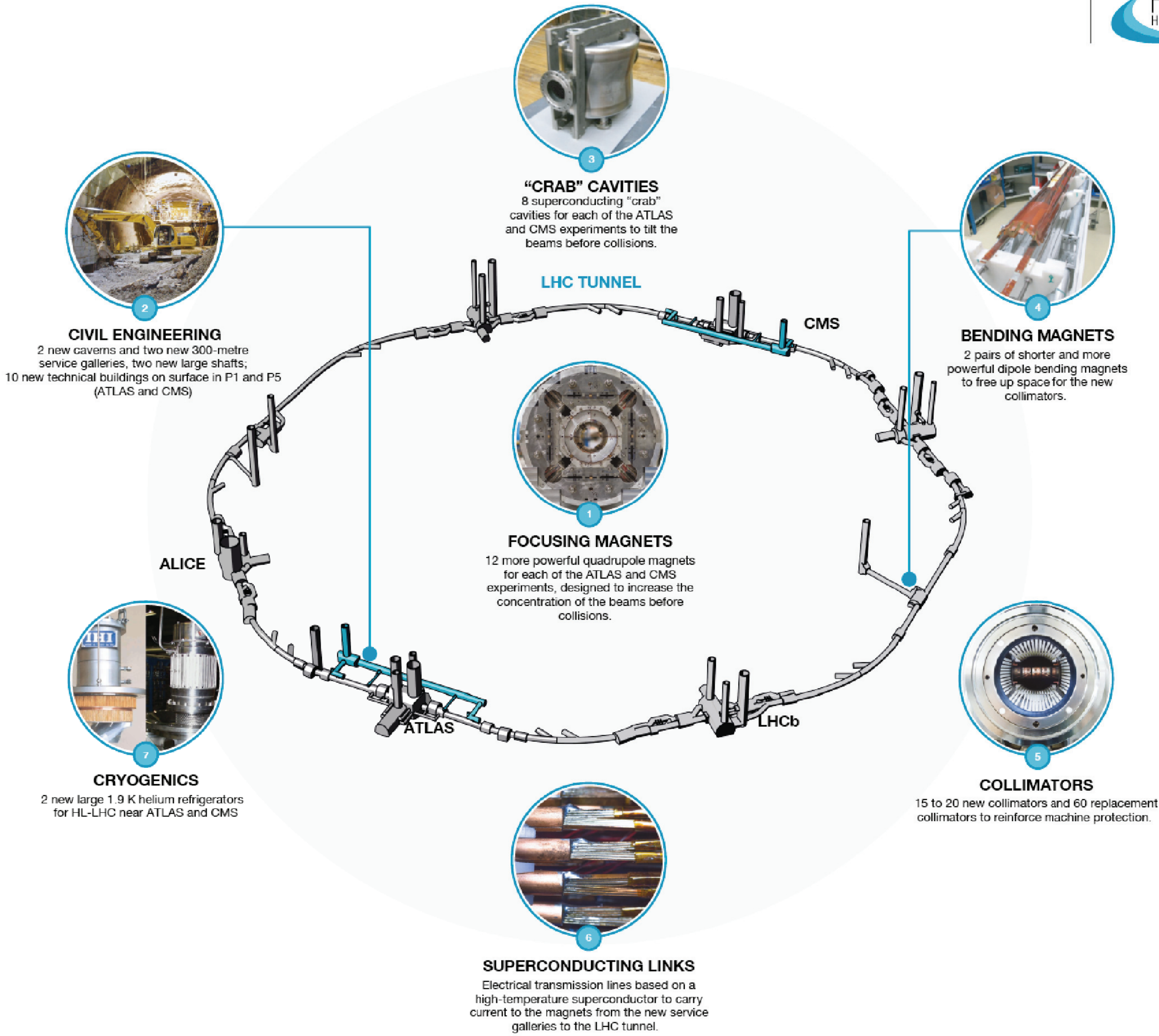
# HL-LHC landmarks

CERN May 2016



# Luminosity the main ingredients

$$\dot{N}_{evt} = L \times \sigma_{evt} ; N_{evt} = \int L dt \times \sigma_{evt} \qquad L_{int}$$

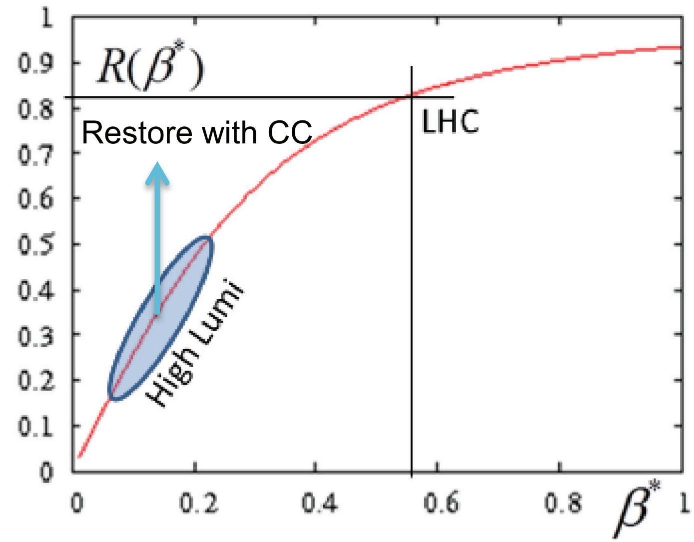
Beam current

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

energy

Beam size

$$R = \frac{1}{\sqrt{1 + \frac{\gamma(\theta_c \sigma_s)^2}{4\epsilon_n \beta^*}}}$$

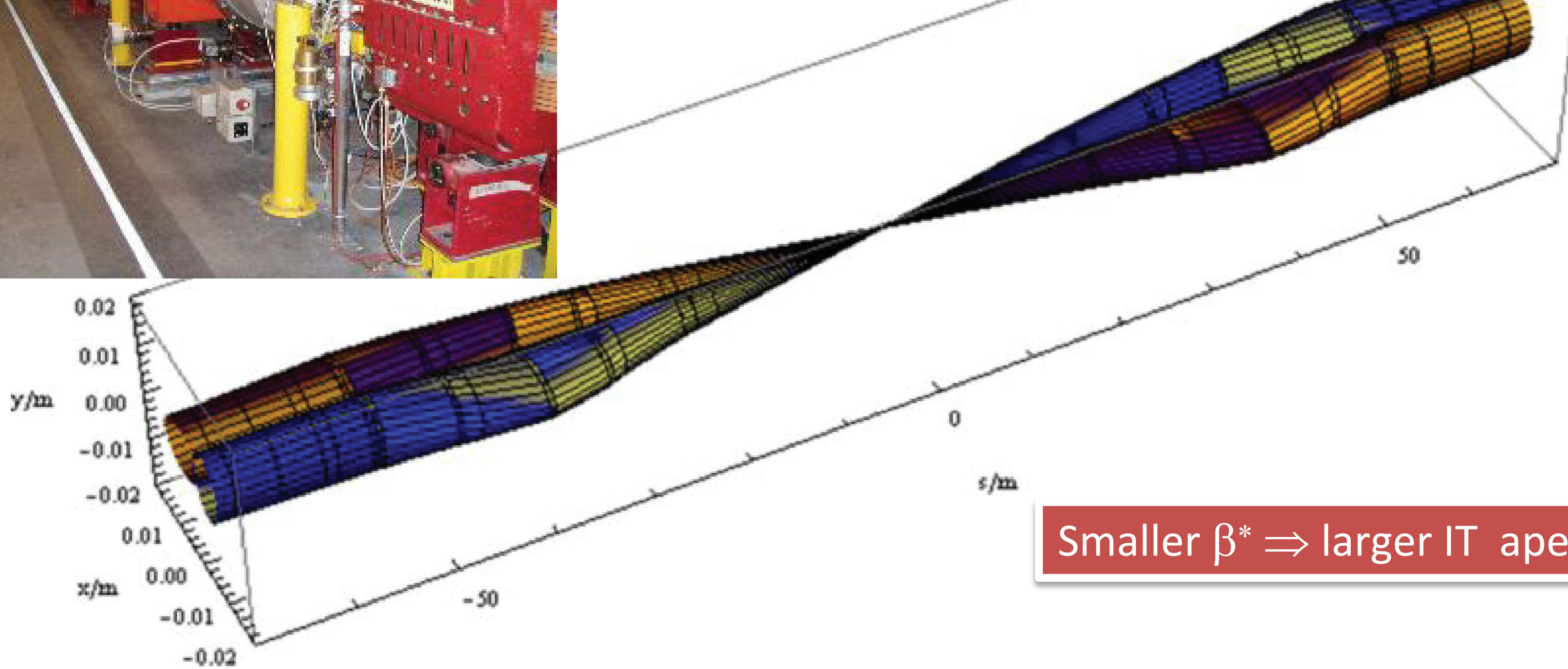



Beam current and emittance: involve injection chain and whole ring
$\beta^*$ involves «only» 2 IRs, 2x600 m

$$L_0 = 1 \cdot 10^{34}\ cm^{-2} s^{-1}$$

**All systems have ~ designed to withstand $2L_0$ (to be achieved by increasing $N_b$ x 1.5)**

# The most straightforward action to gain: reducing beam, size with a “local” action




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

LHC has better aperture than anticipated: now all margin can be used; however is not possible to have $\beta^*$ < 30-40 cm (55 cm being the nominal)

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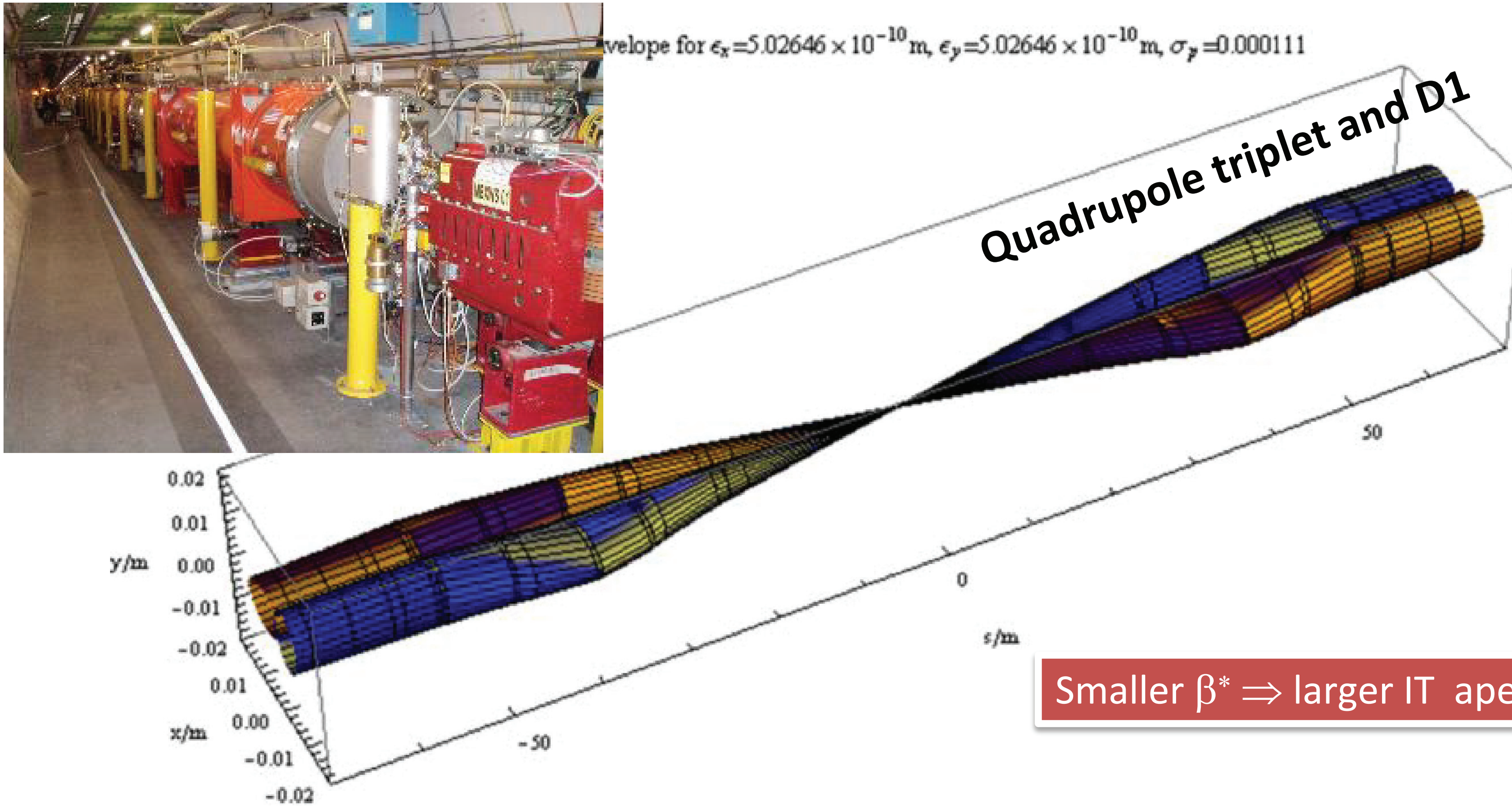


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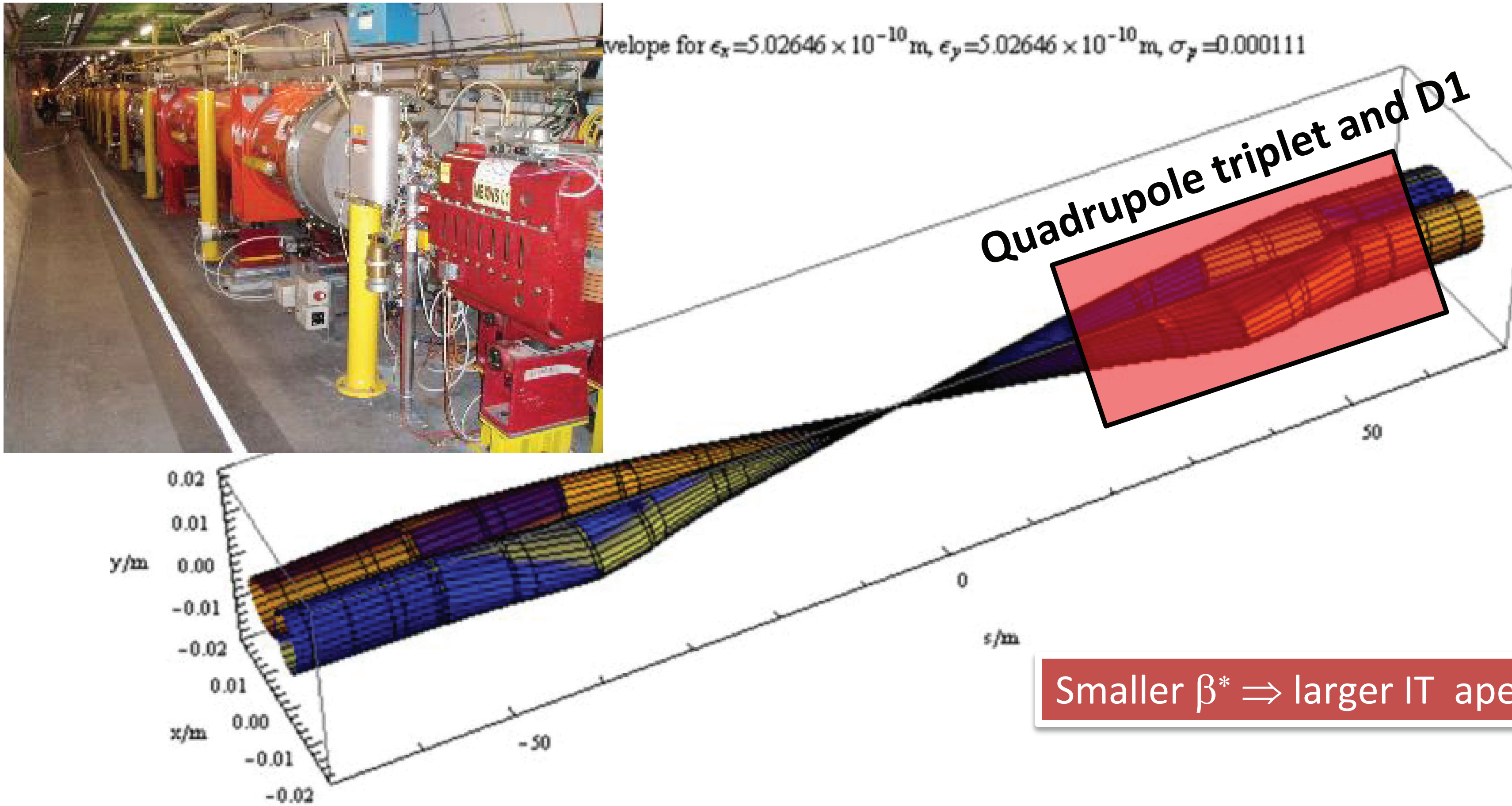


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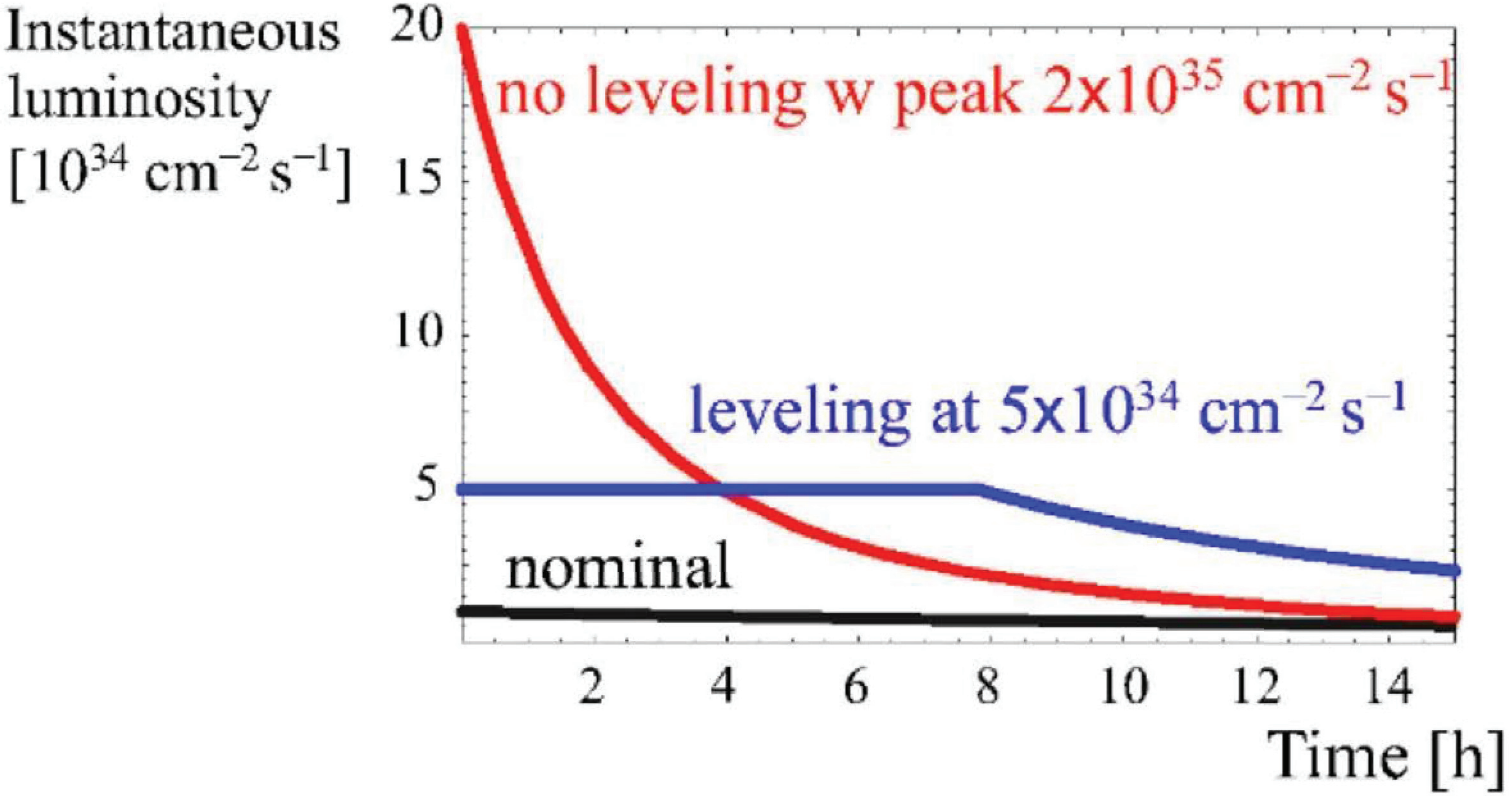
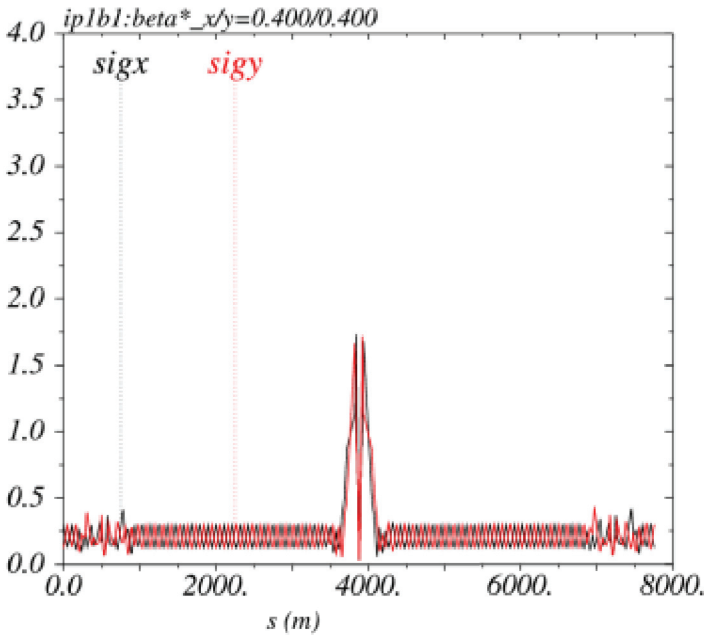
# The leveled luminosity

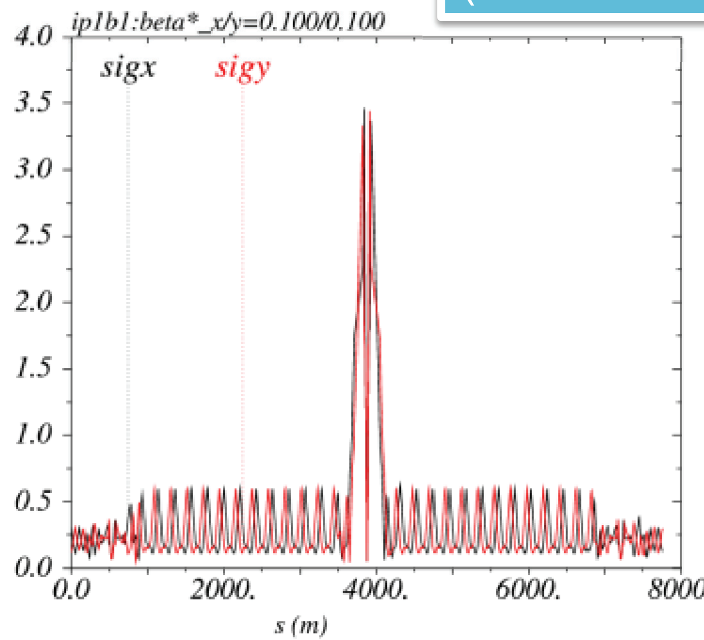


# Achromatic Telescopic Squeezing (ATS) scheme

- **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)



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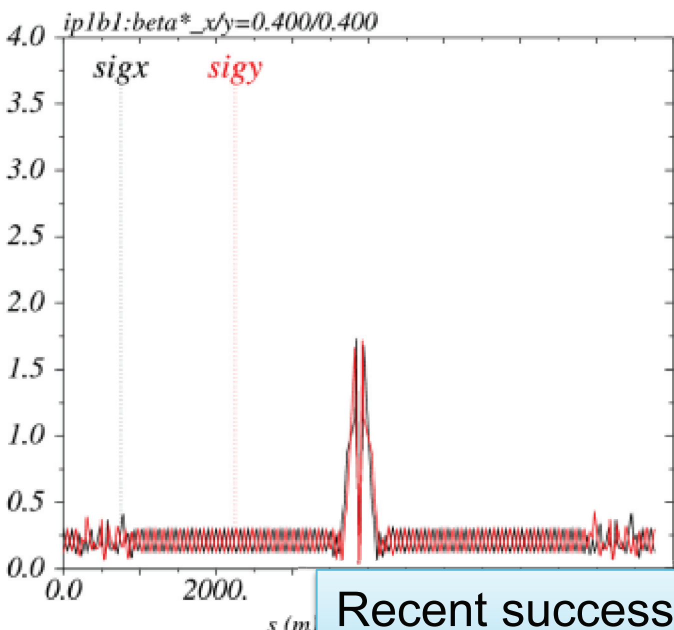


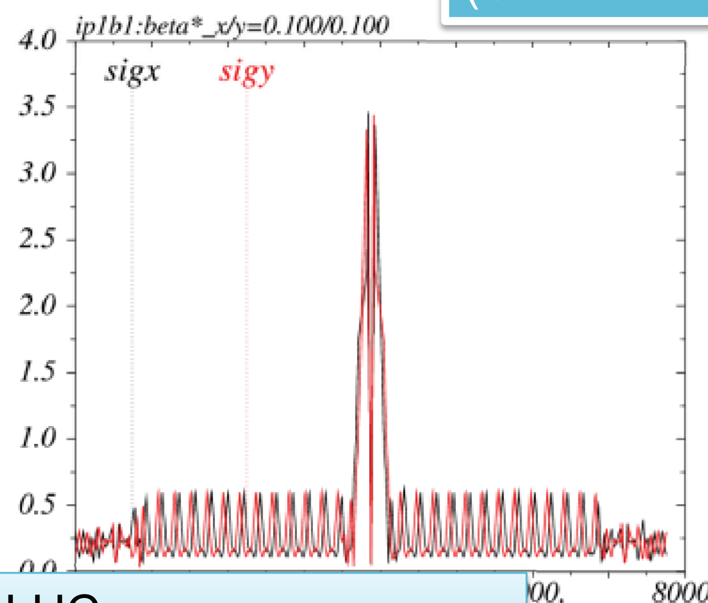


Recent successful MD in LHC.
We can push to $\beta* \sim$ 12 cm in HL-LHC (margins)

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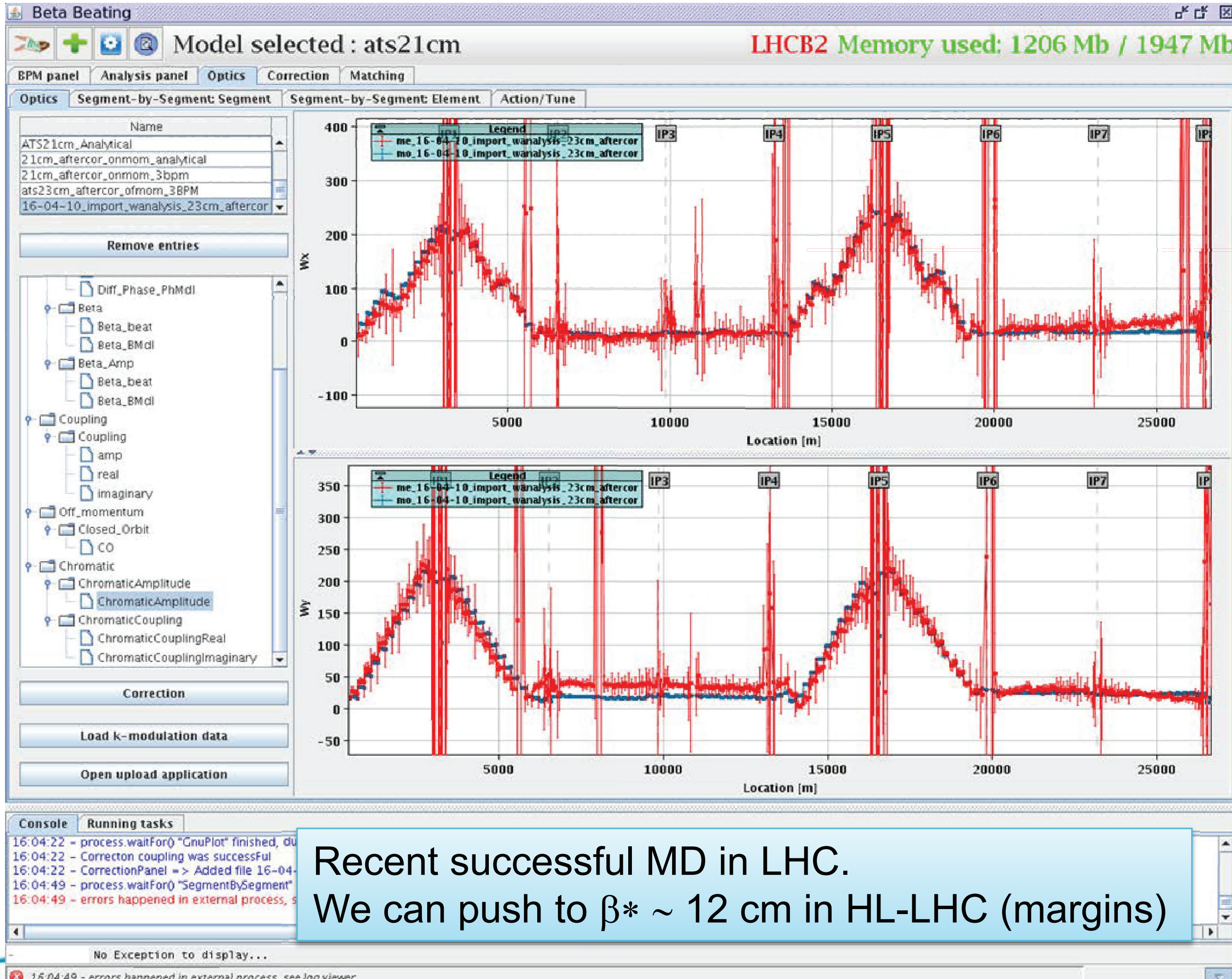


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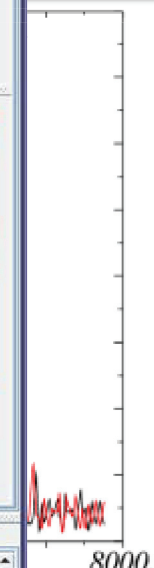


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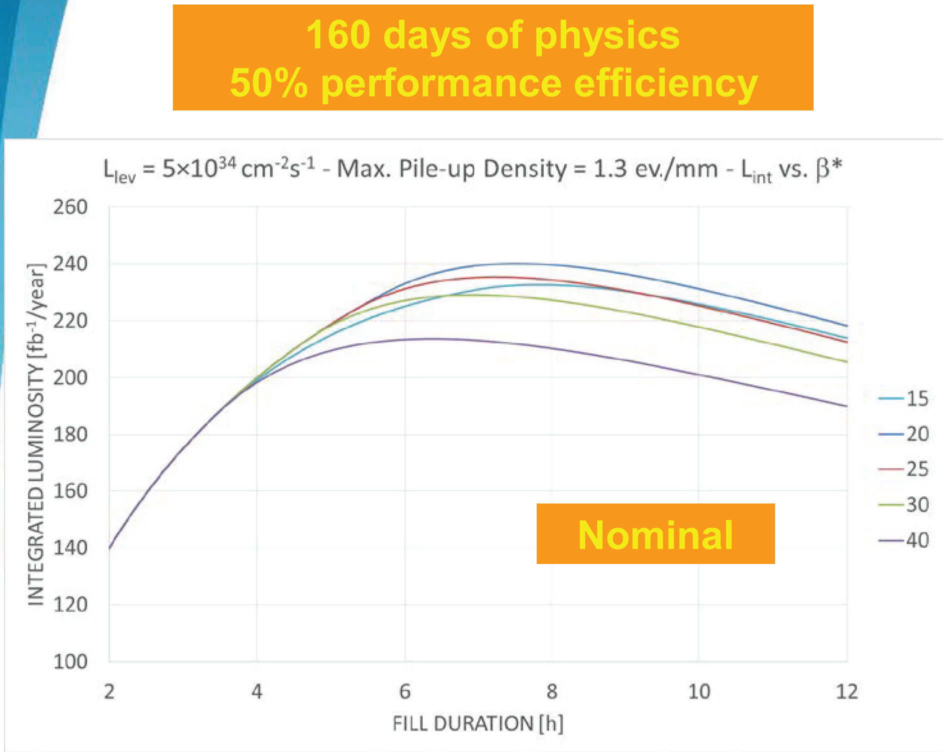
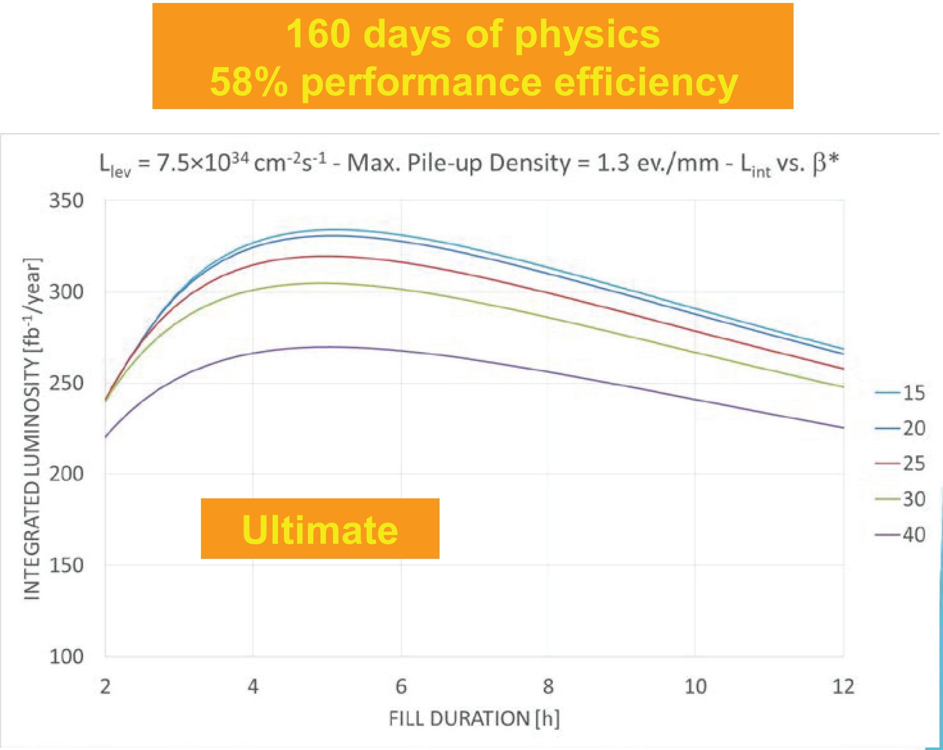
# Performance vs β*



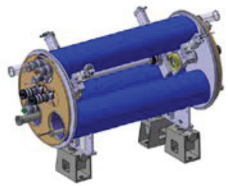



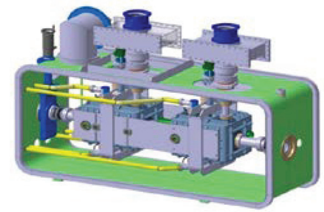

- Optimum at β*= 20 cm due to the reduced crab angle.
- Smaller β* ➔ larger crossing angles ➔ reduced crossing angle compensation ➔ increase of the pile-up density ➔ pile-up density levelling
- The reduction can be mitigated if larger pile-up densities (>1.3 ev./mm) are accepted during the fill

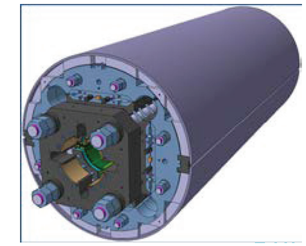
# Table of parameters: LHC and HL-LHC protons

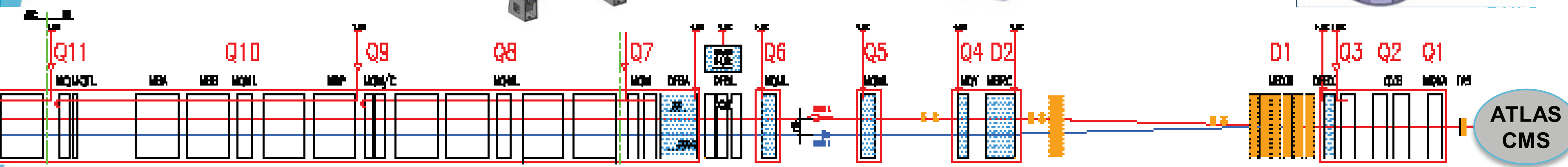
| Parameter | Nominal LHC (design report) | HL-LHC 25ns (standard) | HL-LHC 25ns (BCMS) | HL-LHC 8b+4e |
|---|---|---|---|---|
| Beam energy in collision [TeV] | 7 | 7 | 7 | 7 |
| $N_b$ | 1.15E+11 | 2.2E+11 | 2.2E+11 | 2.3E+11 |
| $n_b$ | 2808 | 2748 | 2604 | 1968 |
| $N_{tot}$ | 3.2E+14 | 6.0E+14 | 5.7E+14 | 4.5E+14 |
| beam current [A] | 0.58 | 1.09 | 1.03 | 0.82 |
| x-ing angle [μrad] | 285 | 510 | 510 | 480 [10] |
| $\beta^*$ [m] | 0.55 | 0.2 | 0.2 | 0.2 |
| $\varepsilon_n$ [μm] | 3.75 | 2.50 | 2.50 | 2.20 |
| Total loss factor R0 without crab-cavity | 0.836 | 0.369 | 0.369 | 0.369 |
| Total loss factor R1 with crab-cavity | (0.981) | 7.15E-01 | 7.15E-01 | 7.40E-01 |
| Peak Luminosity without crab-cavity [$cm^{-2}$ $s^{-1}$] | 1.00E+34 | 6.52E+34 | 6.18E+34 | 5.80E+34 |
| Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2}$ $s^{-1}$] | (1.18E+34) | 1.26E+35 | 1.19E+35 | 1.16E+35 |
| Levelled Luminosity [$cm^{-2}$ $s^{-1}$] | - | 5.32E+34 [5] | 5.02E+34 | 5.03E+34 |
| Events / crossing (with leveling and crab-cavities for HL-LHC) | 27 | 140 | 140 | 140 |
| Peak line density of pile up event [event/mm] (max over stable beams) | 0.21 | 1.3 | 1.3 | 1.3 |
| Leveling time [h] (assuming no emittance growth) | - | 5.23 | 5.23 | 6.20 |
| *$N_b$ at LHC injection* | *1.20E+11* | *2.30E+11* | *2.30E+11* | *2.40E+11* |
| *$n_b$ / injection* | *288* | *288* | *288* | *224* |
| *$N_{tot}$ / injection* | *3.46E+13* | *6.62E+13* | *6.62E+13* | *5.40E13* |
| *$\varepsilon_n$ at SPS extraction [μm] [3]* | *3.40* | *2.00* | *< 2.00 [6]* | *1.70* |

# The largest HEP accelerator in construction










**Dispersion Suppressor (DS) in P7**

**Modifications**

1. In IP2: new DS collim. in C.Cryost.
2. In IP7 new DS collimation with 11 T

**Cryogenics, Protection, Interface, Vacuum, Diagnostics, Inj/Extr… extension of infrastr.**

**Matching Section (MS)**

**Change/new lay-out**

1. TAXN
2. D2
3. CC
4. Q4
5. Correctors
6. Q5
7. Q5@1.9K in P6
8. New collimators

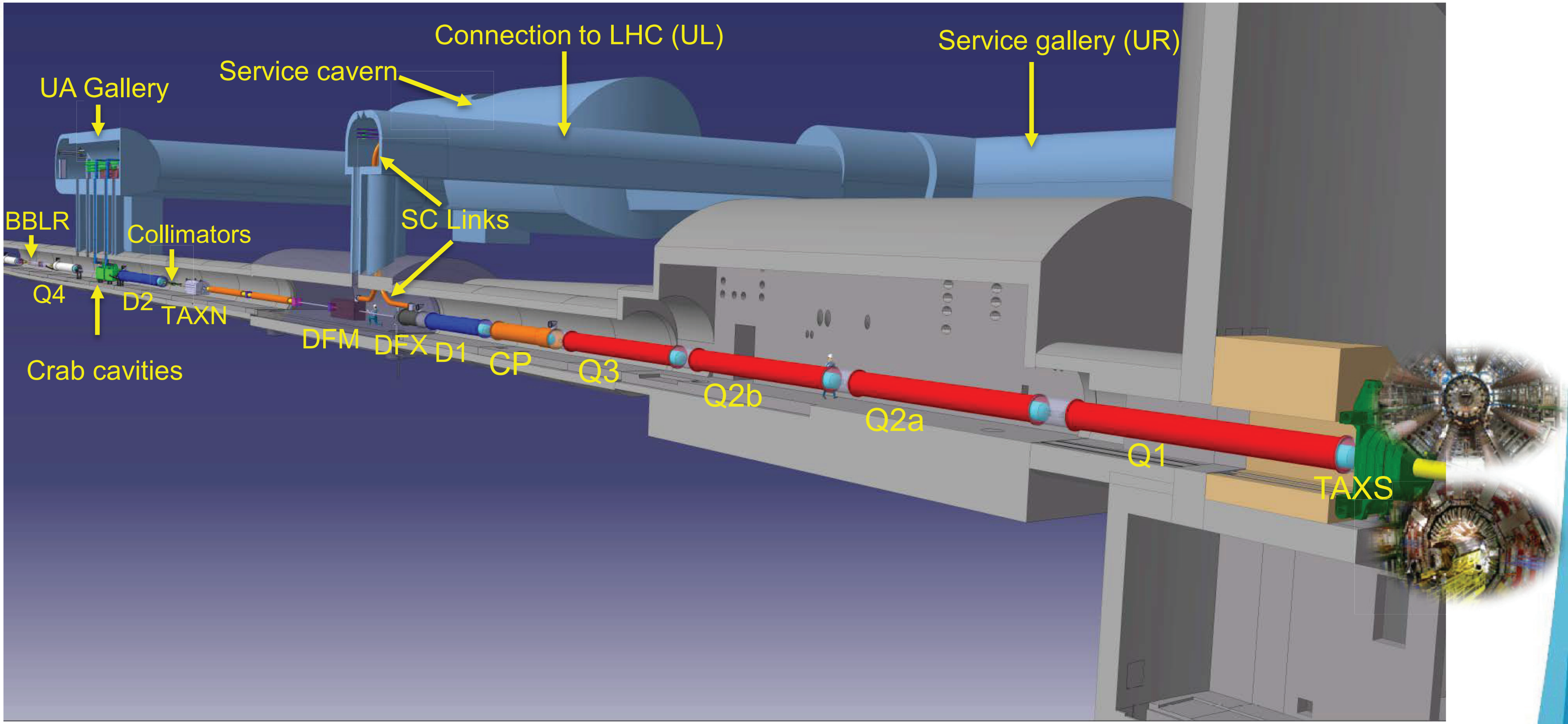
**Interaction Region (ITR)**

**Complete change and new lay-out**

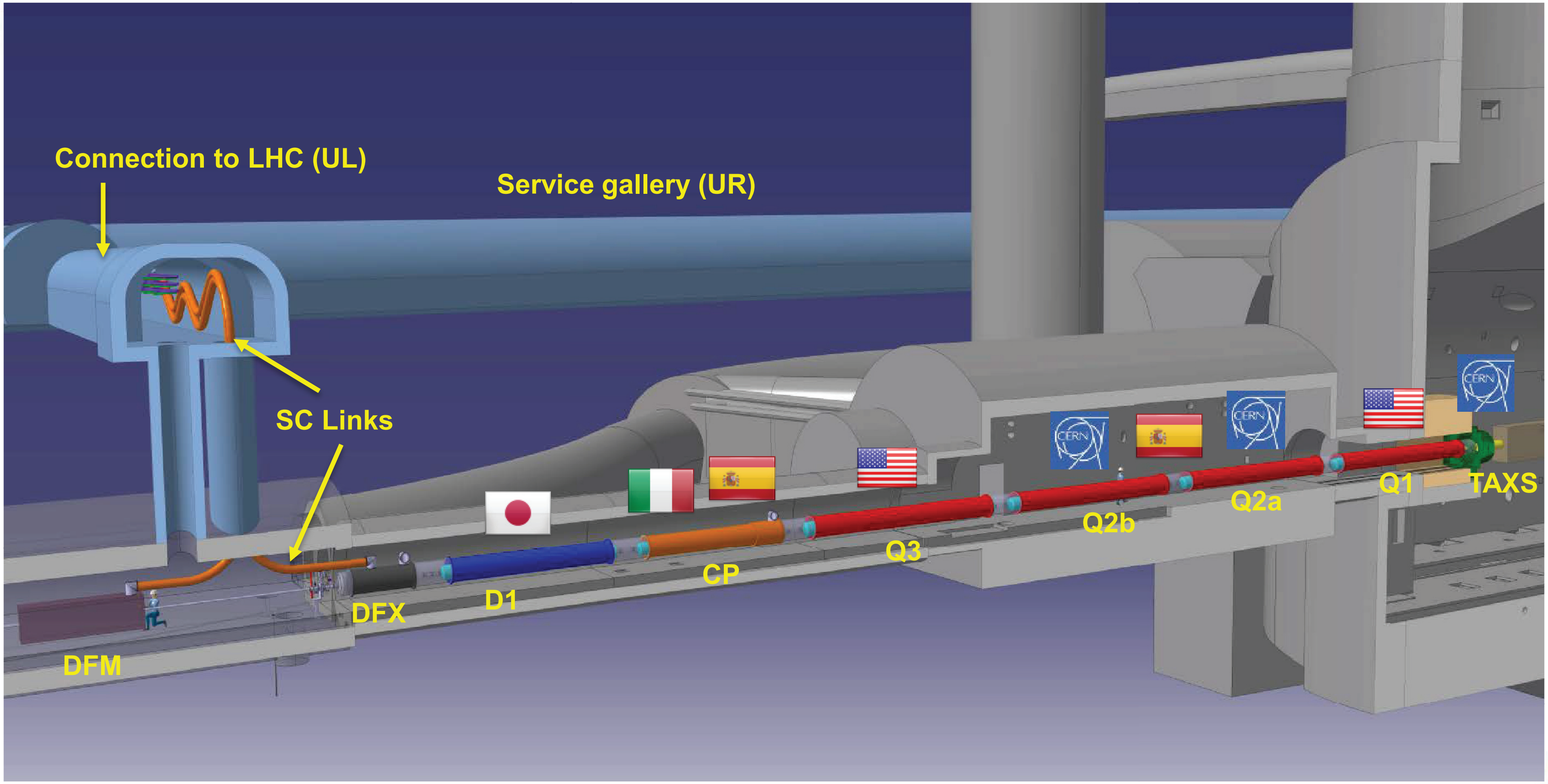
1. TAXS
2. Q1-Q2a-Q2b-Q3
3. D1
4. All correctors
5. Heavy shielding (W)

**> 1.2 km of LHC !!**

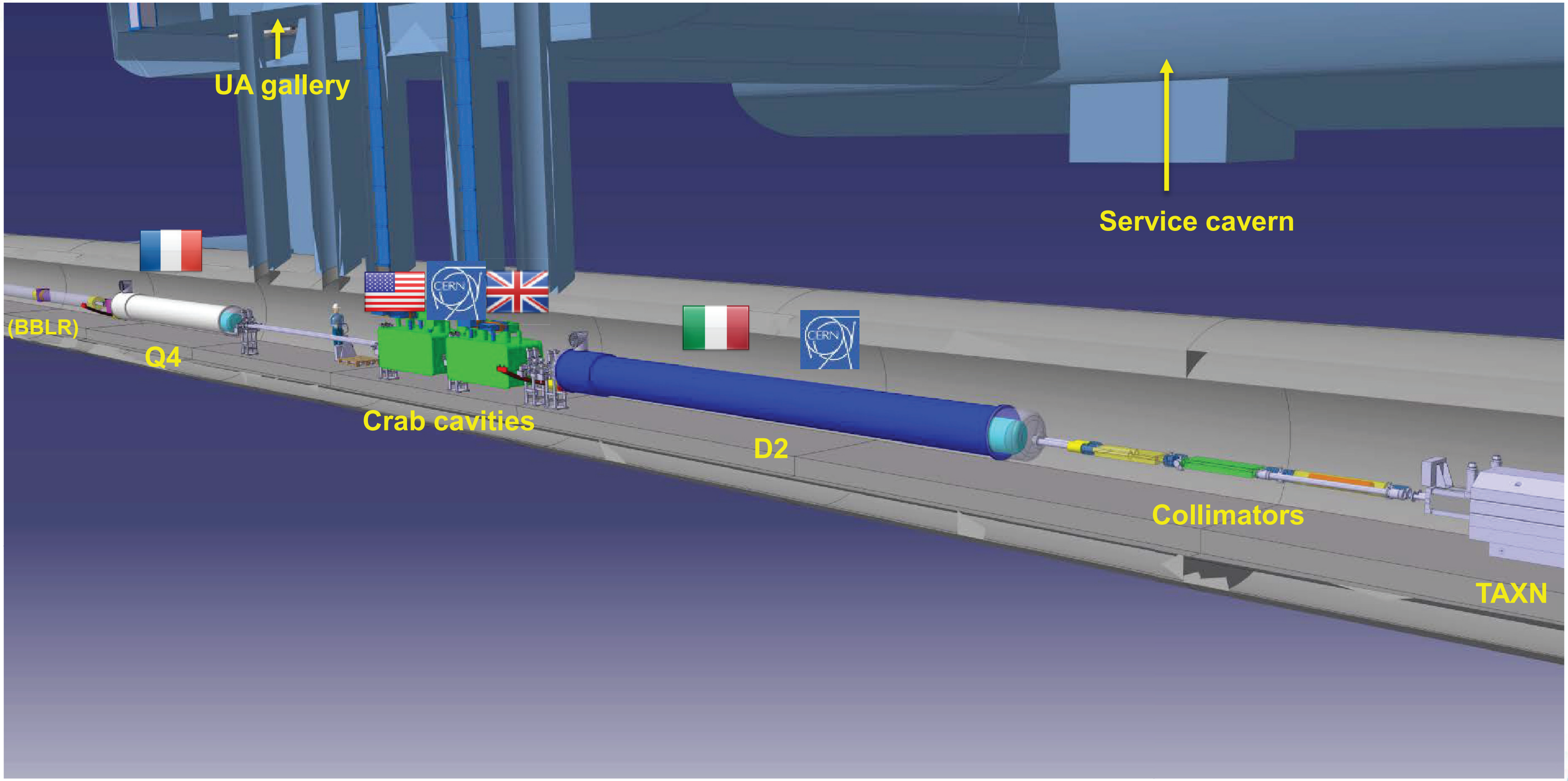
# The Insertion Region (till Q4)



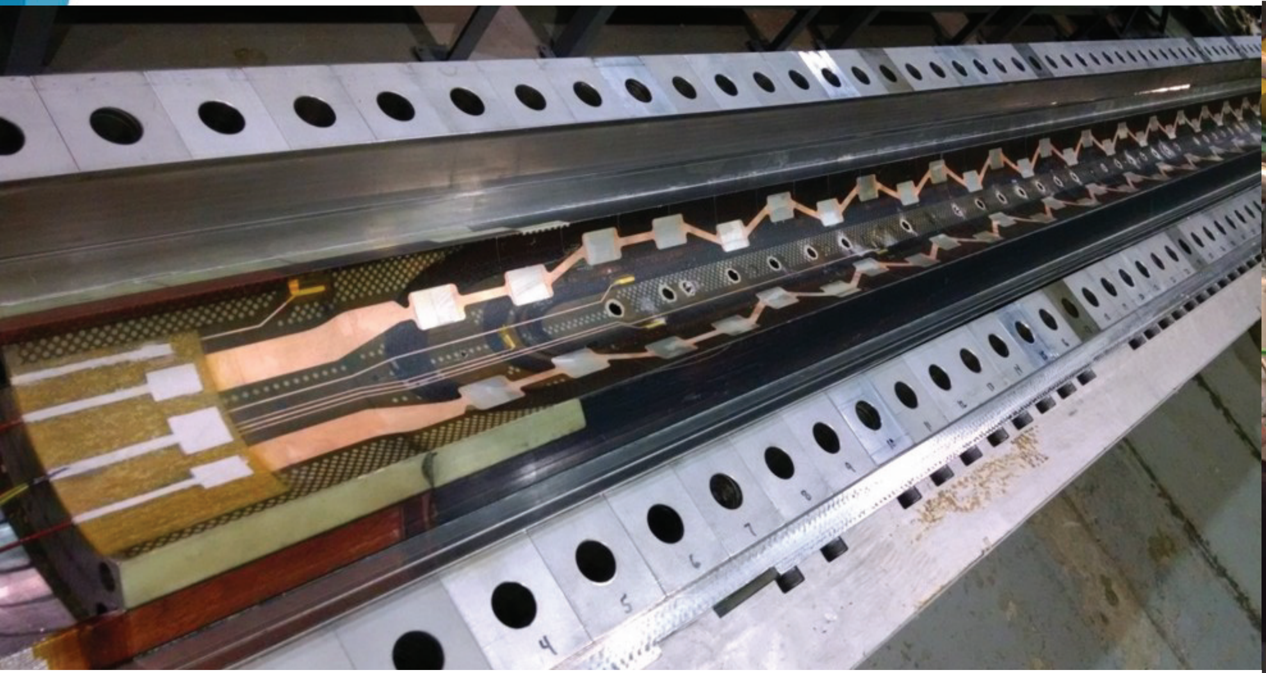
# The Inner Triplet region



# The MS region



# Main Hardware configuration: MQXF (triplet)



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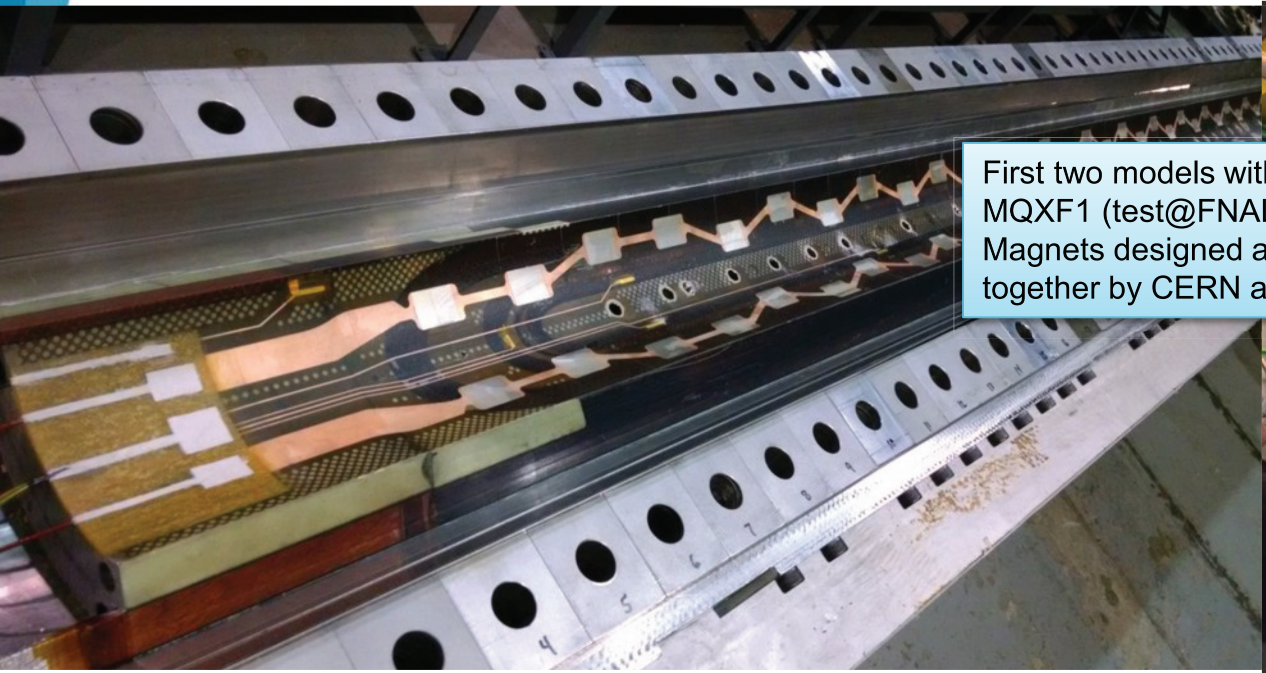

First two models with final X-section:
MQXF1 (test@FNAL, MQXF3 test@ CERN
Magnets designed and manufactured
together by CERN and US-LARP/AUP

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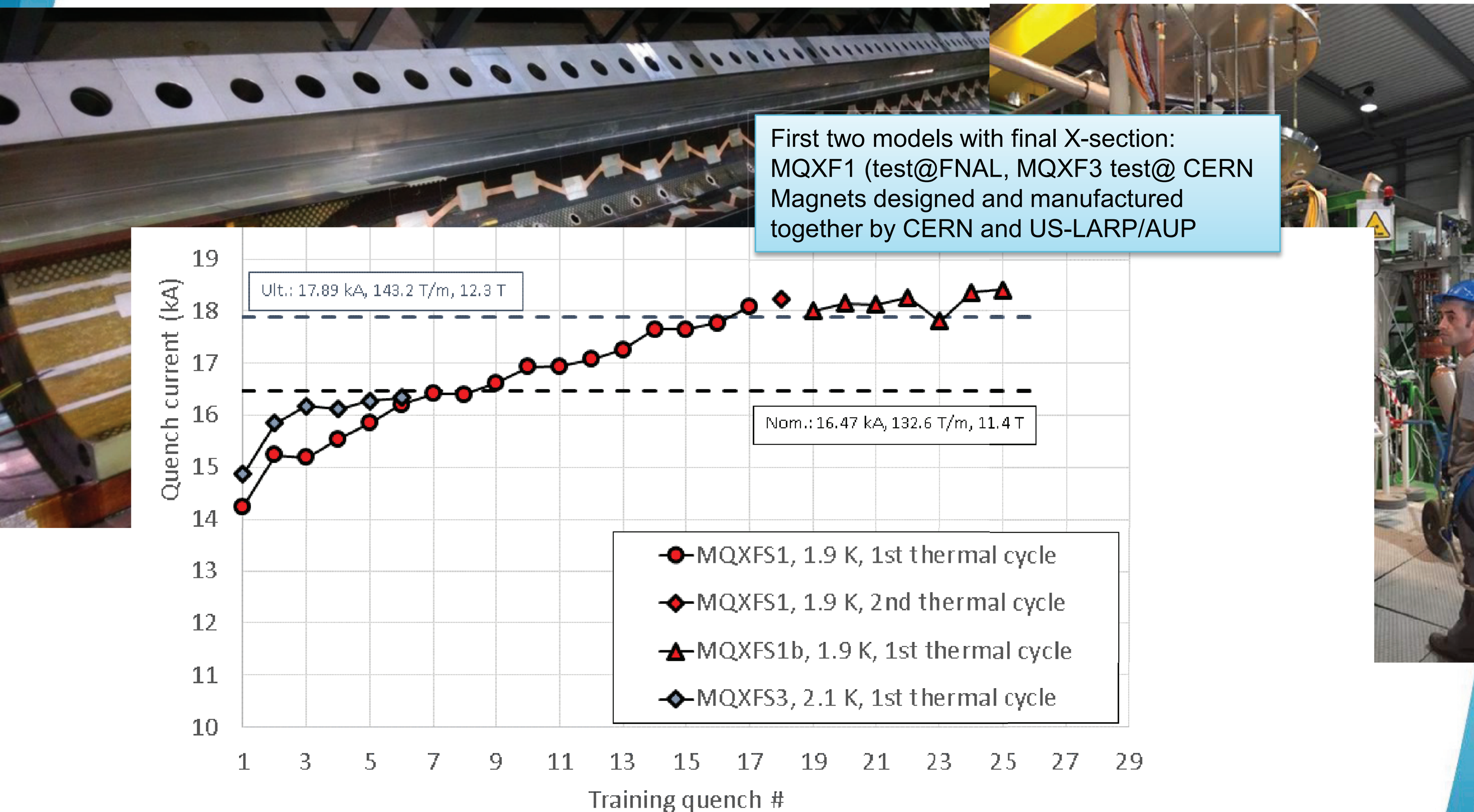
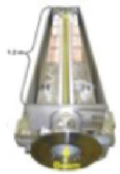


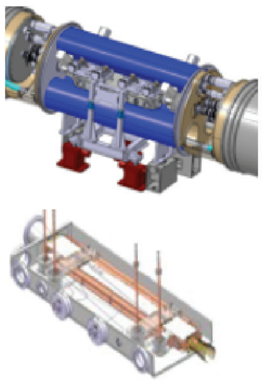
# Main Hardware configuration: collimators

## Baseline upgrade items

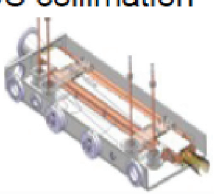


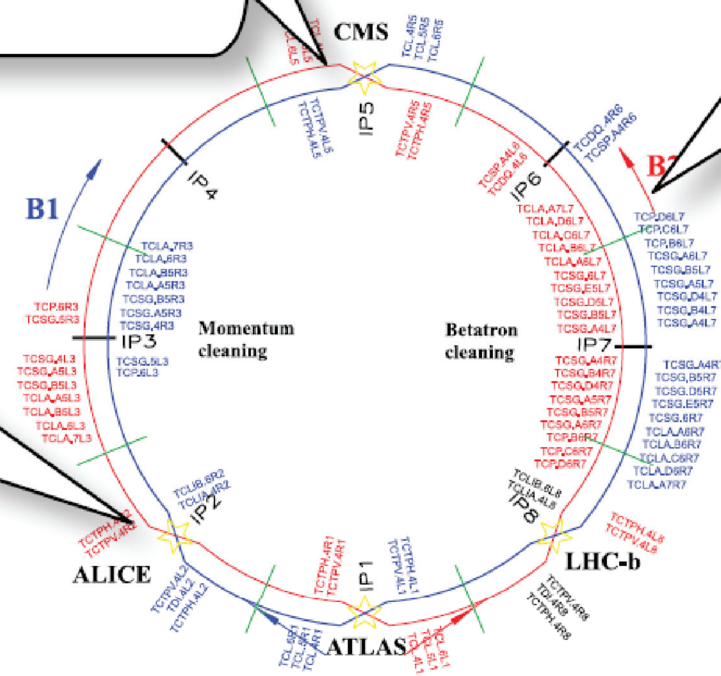
**Completely new layouts**
**Novel materials: TCTs in CuCD**
IR1+IR5, per beam:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks

Cleaning: DS coll. + 11T dipoles, 1 unit per beam

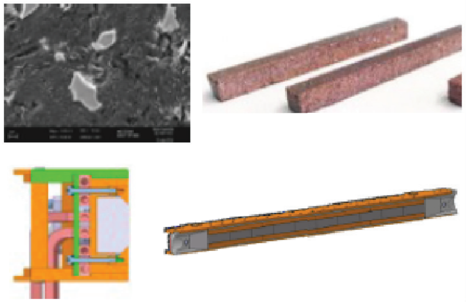


Ion physics debris: DS collimation



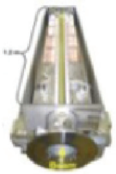



Low-impedance, high robustness secondary collimators: coated MoGr



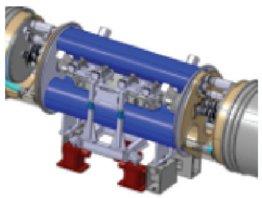
# Main Hardware configuration: collimators

## Baseline upgrade items



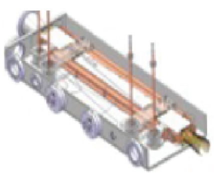
**Completely new layouts**
**Novel materials: TCTs in CuCD**
IR1+IR5, per beam:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks

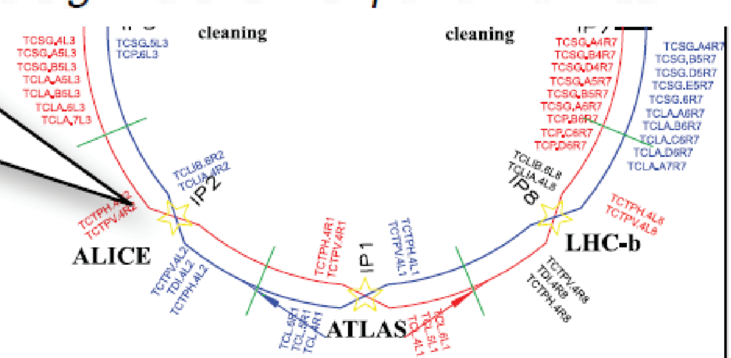
Cleaning: DS coll. + 11T dipoles, 1 unit per beam



☑ Increased beam stored energy: 362MJ → 700MJ at 7 TeV

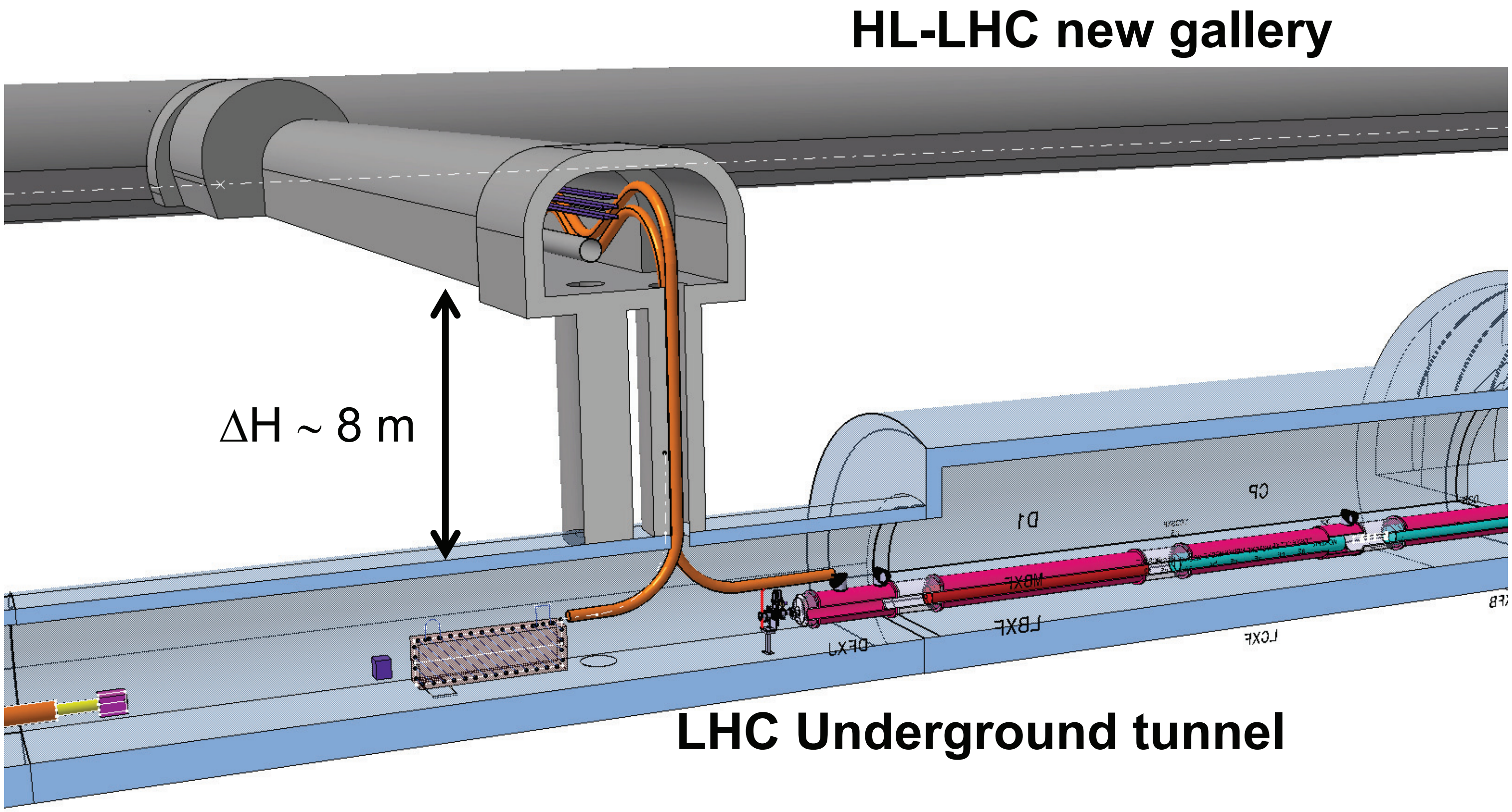
***Collimation cleaning** versus quench limits of superconducting magnets.*
*Machine protection constraints from **beam tail** population*
*(2 MJ above 3 sigmas even for perfect Gaussian tails!).*





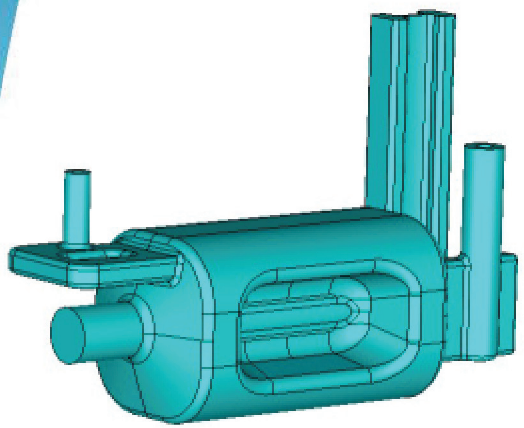

collimators: coated MoGr

# Main Hardware configuration – SC links & Cold Powering



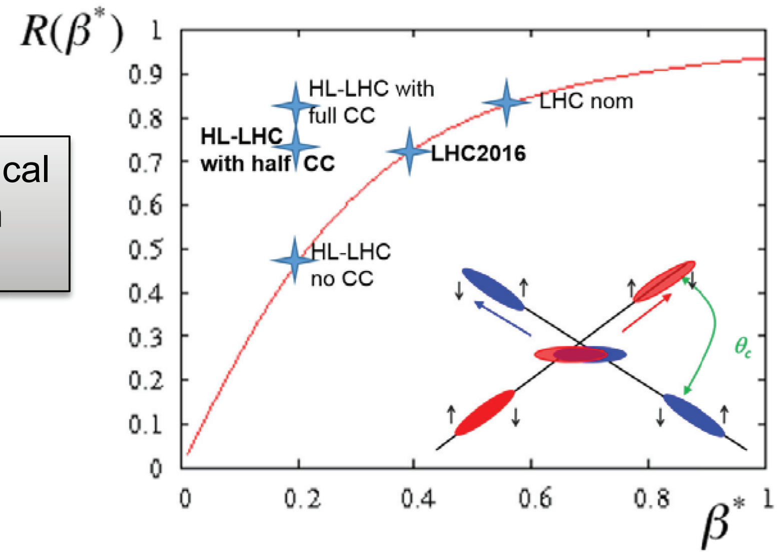

Length of DSHs for IR ~ **100 m**
Length of DSHs for MSs ~ **120 m**

# Main Hardware configuration: CC



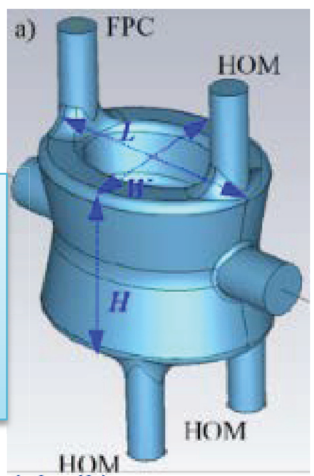
RF Dipole: Waveguide or waveguide-coax couplers

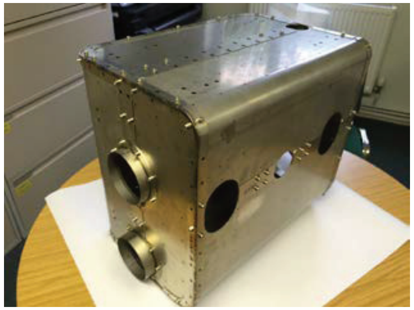
US-LARP/AUP critical for design and then for construction




~3.4 MV/cavity, 11-12 MV for complete bunch rotation

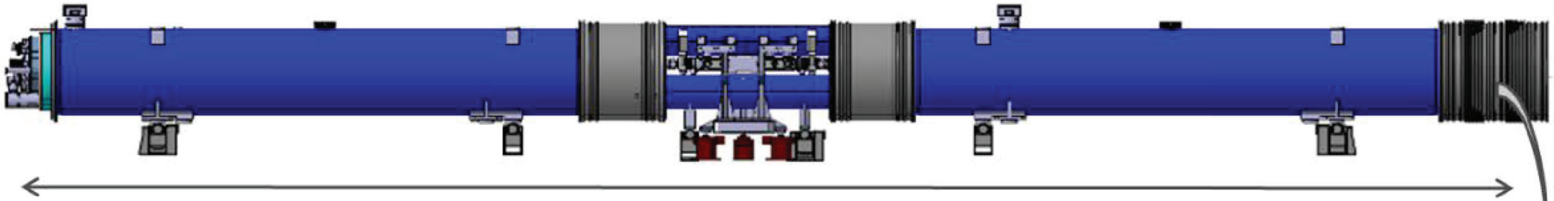
Double ¼-wave: Coaxial couplers with hook-type antenna



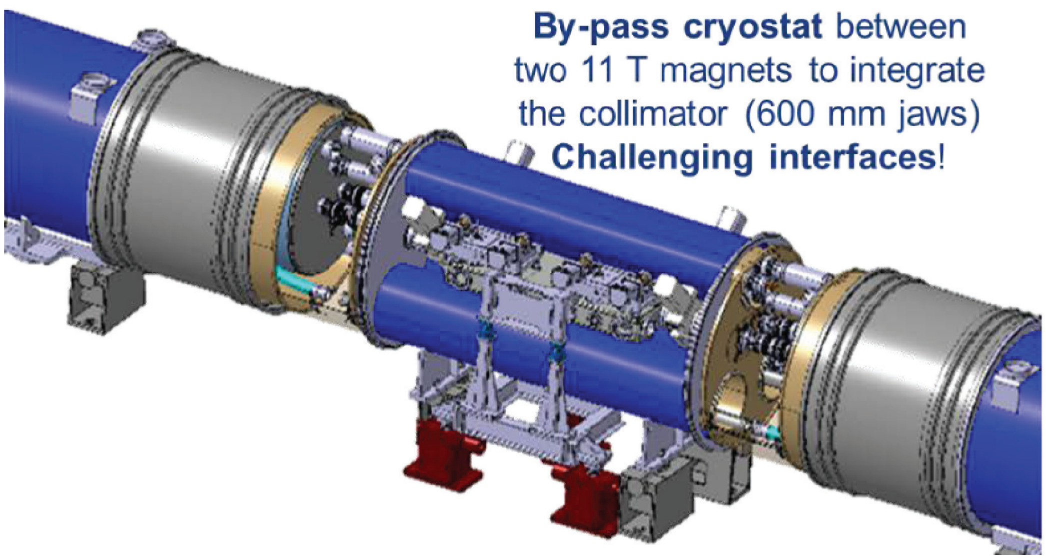



# Main Hardware configuration - 11 T dipole

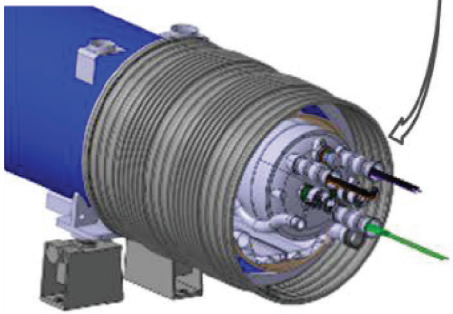
LHC MB cryostat replaced by **3 cryostats + collimator**, all independently supported and aligned



**Same 15660 mm length between the interconnect planes as an in the LHC Main Dipole**

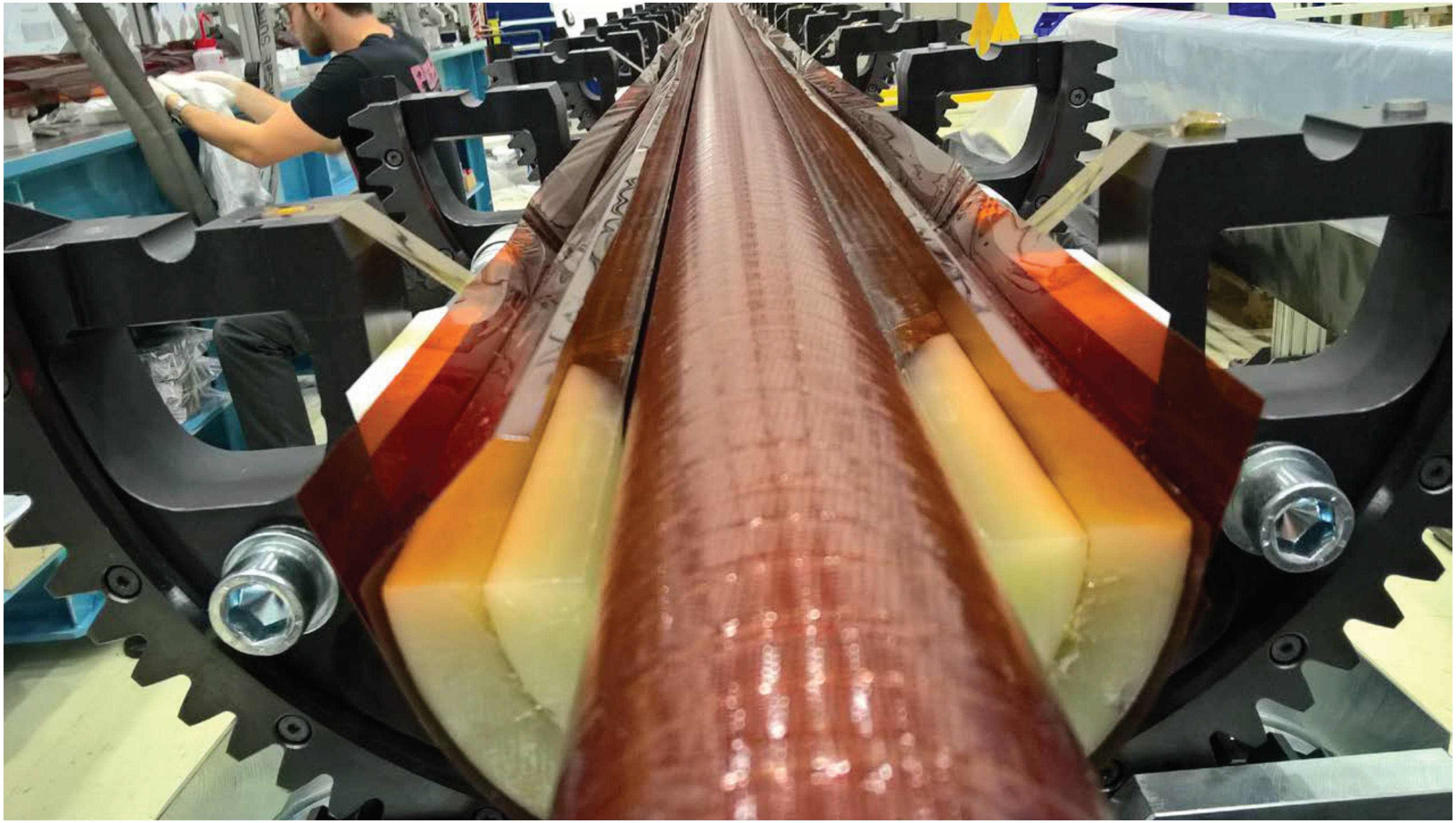


**By-pass cryostat** between two 11 T magnets to integrate the collimator (600 mm jaws)
**Challenging interfaces**!

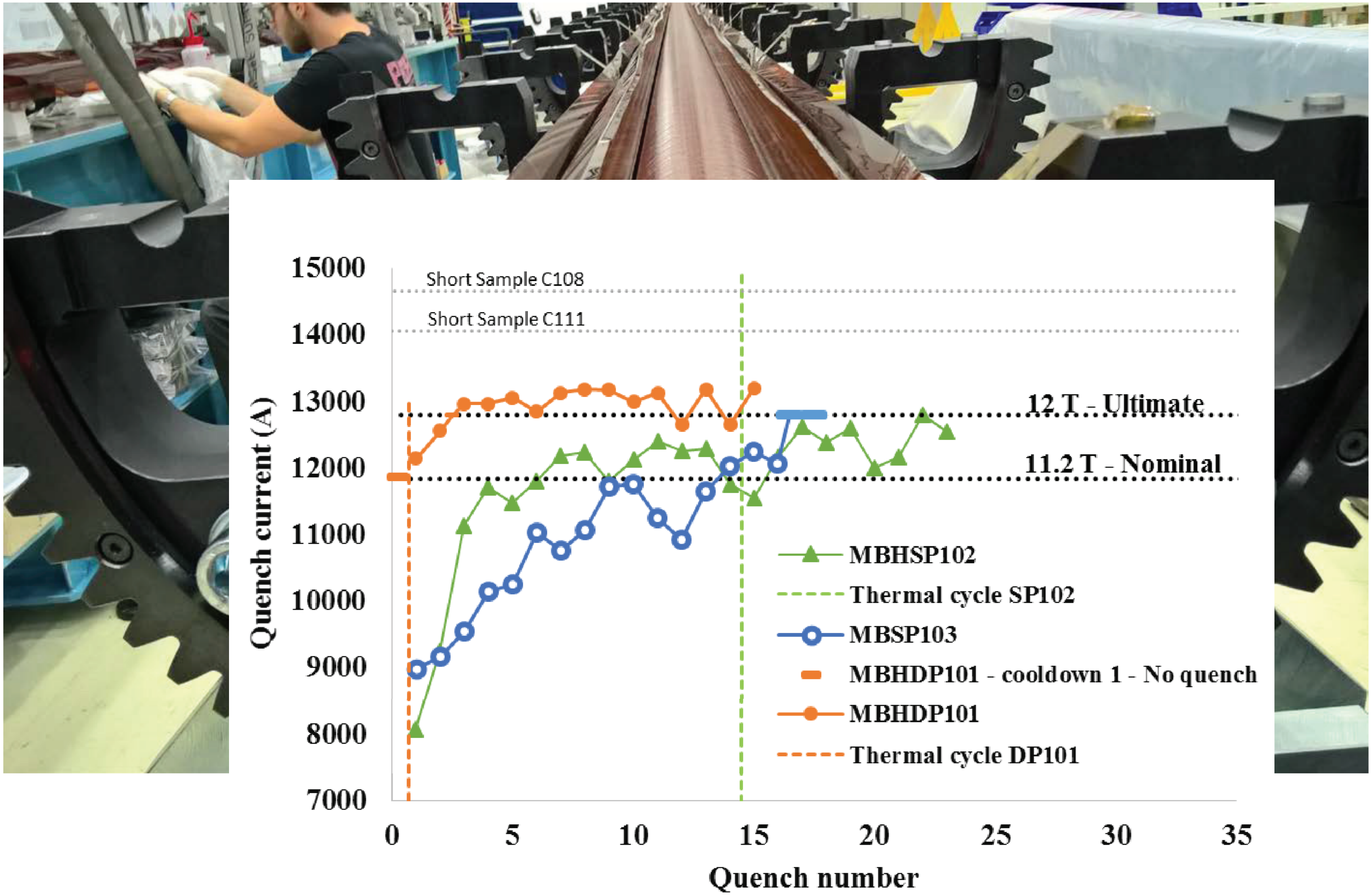


Same interfaces at the extremities: **no change to nearby magnets**, standard interconnection procedures & tooling

# Results: very good!
# R&D phase in collaboration with FNAL



# Results: very good!
# R&D phase in collaboration with FNAL



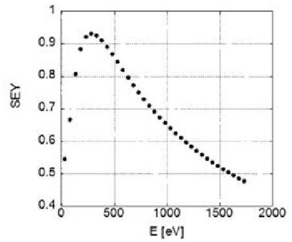
# Main Hardware configuration – Vacuum Beam Screen & coating (also IR2 and IR8!)

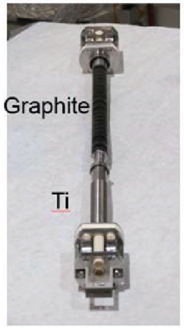
The beam screen with W-heavy shield is a pillar of the project

Prototype of Q1 beam screen.

System for a-carbon coating via sputtering in-situ for P2-P8 triplet during LS2 demonstrated! Also preliminary test with beam at cold very positive.

- Pulse magnetron sputtering under Ar with Ti under layer and permanent magnet



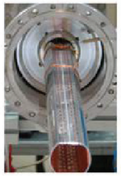


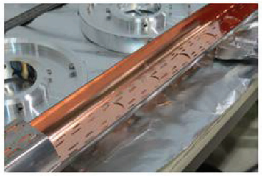
Achieved: SEY < 1 in a 1 m long beam screen + cold bore system

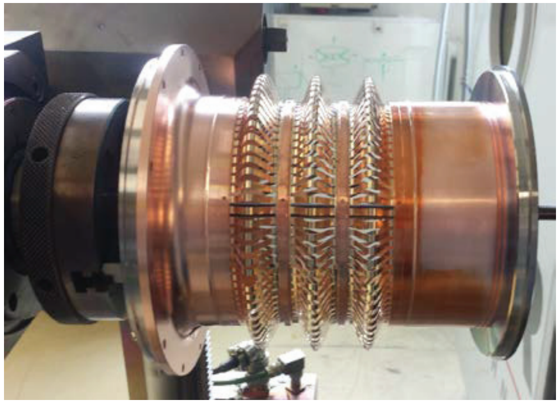
Optimisation of adhesion ongoing

Test in 10 meter mock up by the end of the year

P. Demolon
P. Costa Pinto







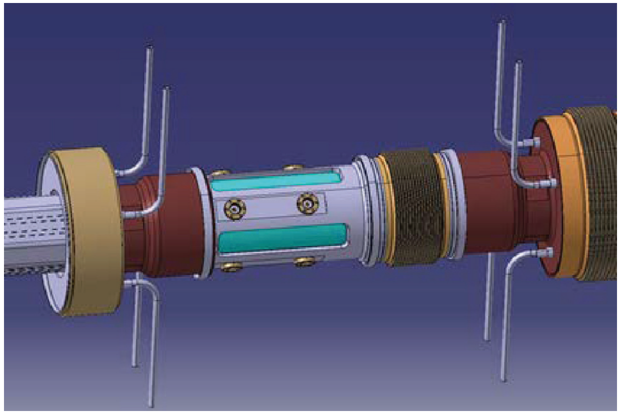
Prototype RF fingers for interconnections. Good results of mechanical and RF tests.

However this vacuum technique in situ remain a challenge, so an alterative LESS R&D via Collaboration with Univ. of Dundee and STFC (UK) launched and co-financed (TE dept., FCC)

# Main Hardware configuration – Beam Instrumentations

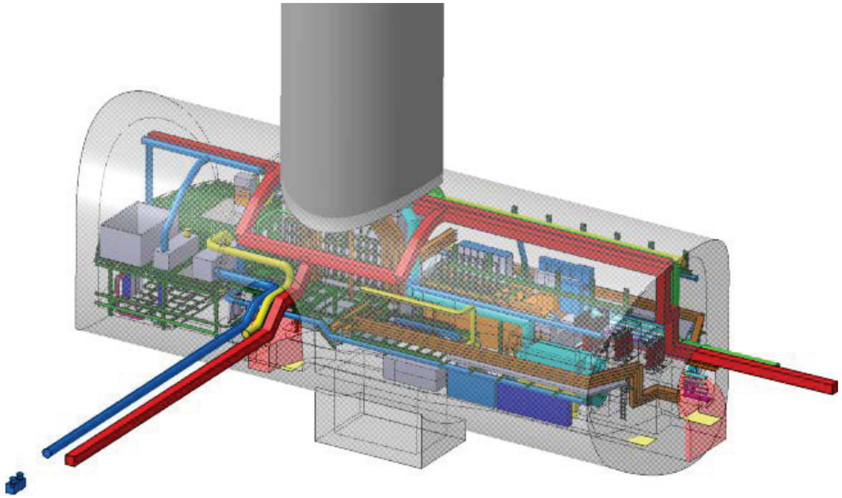
Important R&D supported: BBLR wire embedded in collimator for PoP in 2017/18

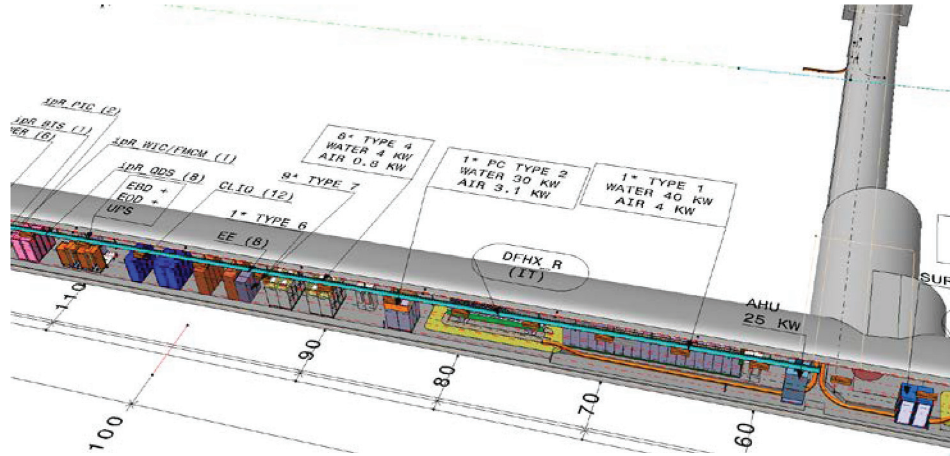
Cryogenic beam loss monitor
For all triplets
Installed already for test in LS1



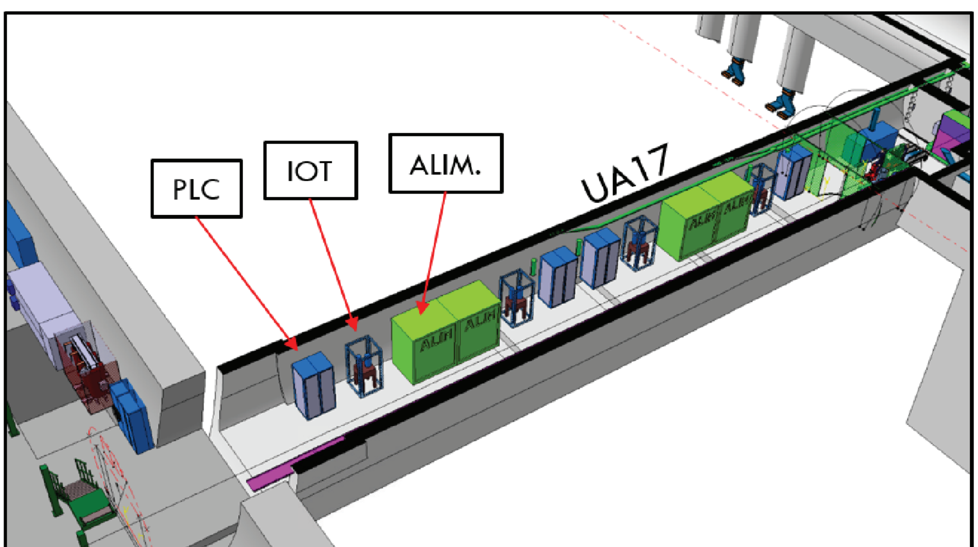
24 cold directional strip-line
BPMs for Q1-D1 regions
Further 20 in other regions
All W- shielded

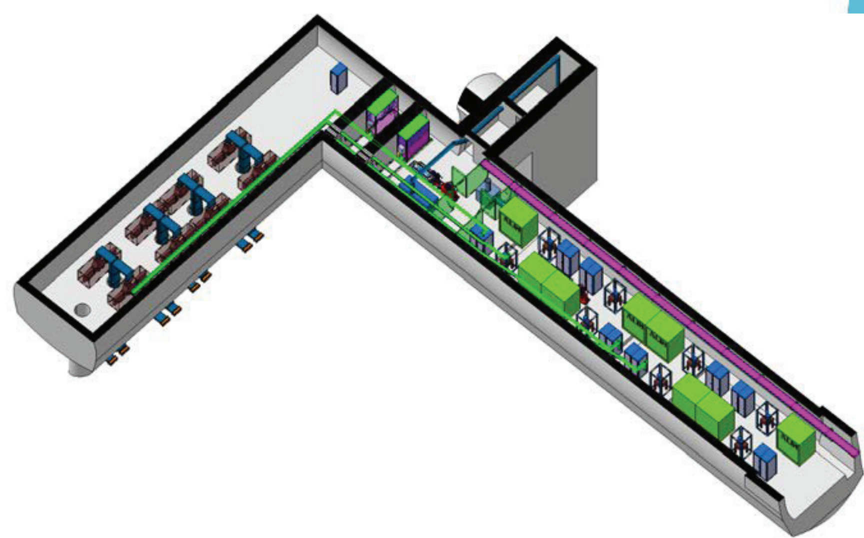
# Putting all together: Integration





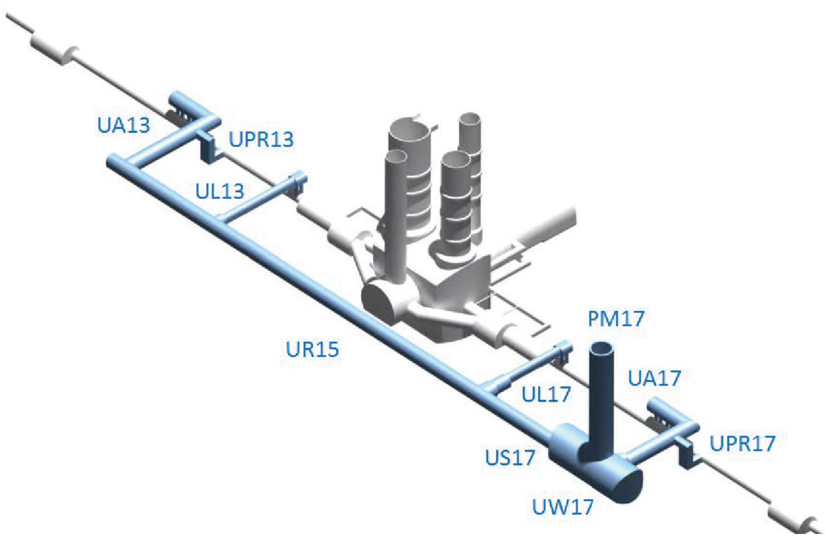

Complete underground integration was frozen in September 2015. This was followed by an optimised one in February 2016 and a new exploiting June re-baseline in September 2016. Standardization of components achieved

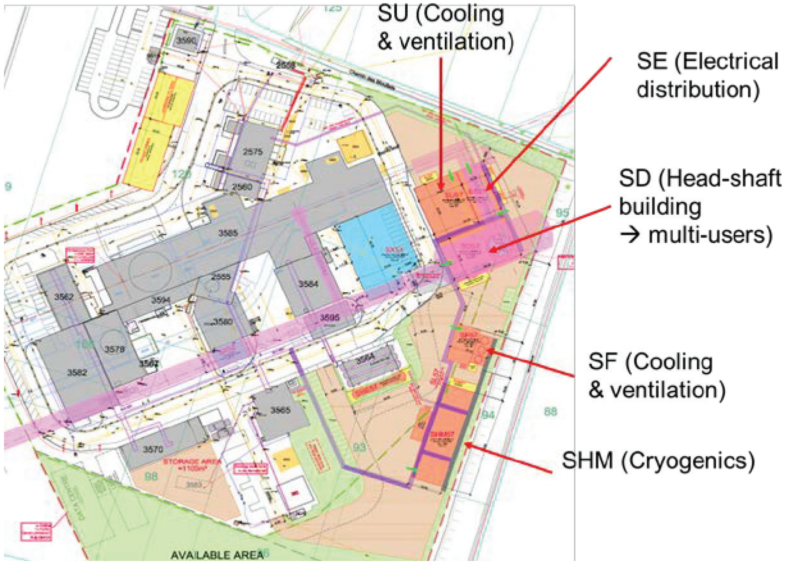


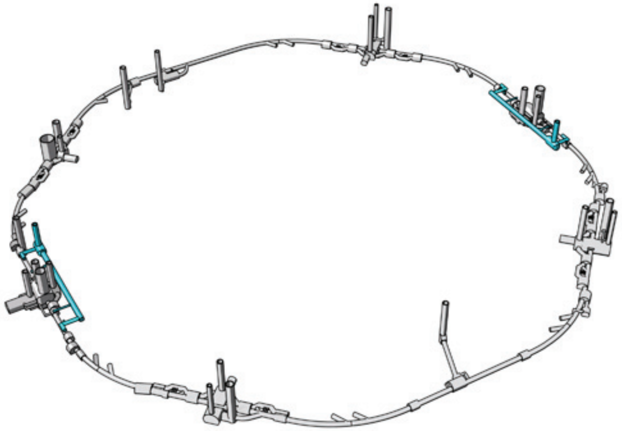



B.

# Starting construction with Civil Engineering



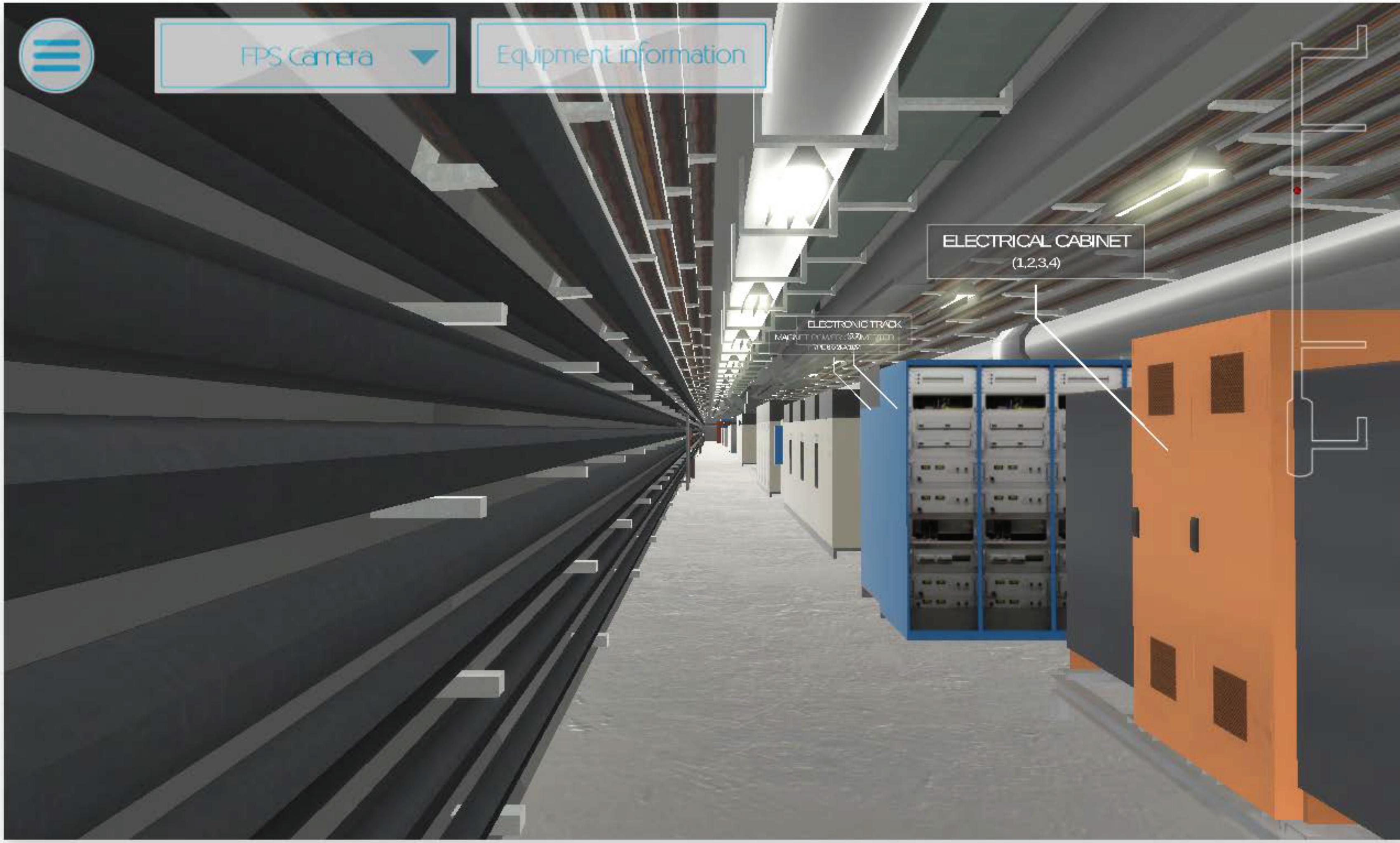



# How it could look like in point 5 (Before)

# How it could look like in point 5 (after)

# HL-LHC underground infrastructures




unity WebGL

HiLumi3D

# Critical points / concerns

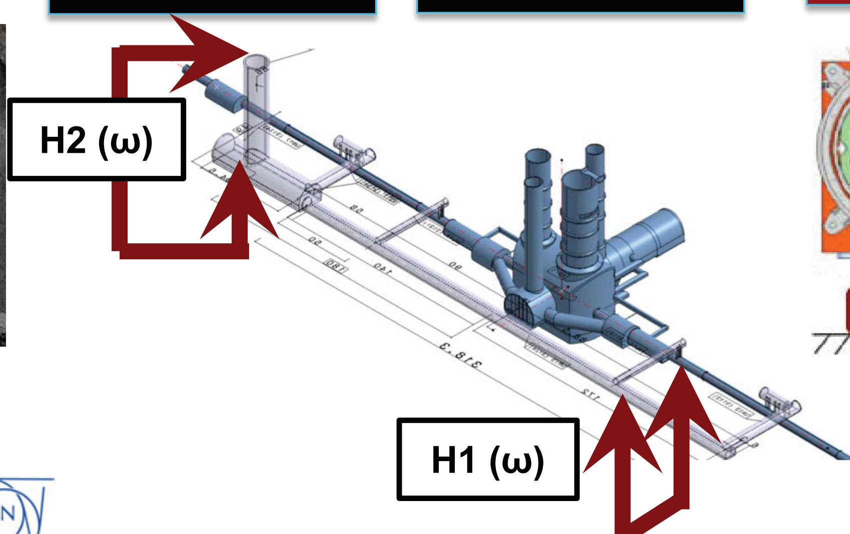
- Crab Cavity test in SPS
  - The plan is just on time no contingency;
  - If test is shifted (beginning 2021) the only alternative is just to lunch production (pre-series) even before the test: we do not have much time
  - We maintain that SPS test campaign must be done before installation in LHC.
- Timing and cost of Civil Engineering
- Secure in-kinds
- Still some construction items are available for collaboration (anybody interested?)
- Industrialization of new technology
- Massive use of MPA (staff is limited and HL-LHC competes with other projects for manpower…)

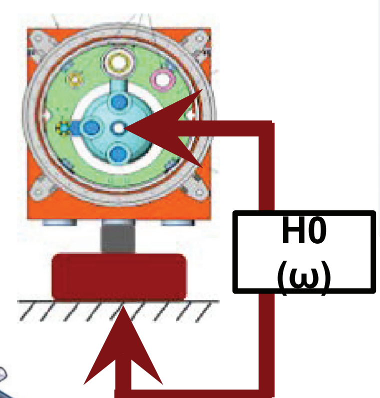
## Civil Engineering induced vibration: effect on LHC exploitation is a schedule rearrangement

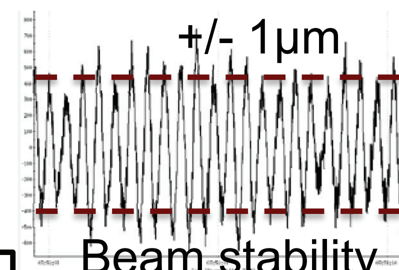
**See my talk on Thursday about vibration effects on High Luminosity colliders**

# Dividing the problem in smaller contribution

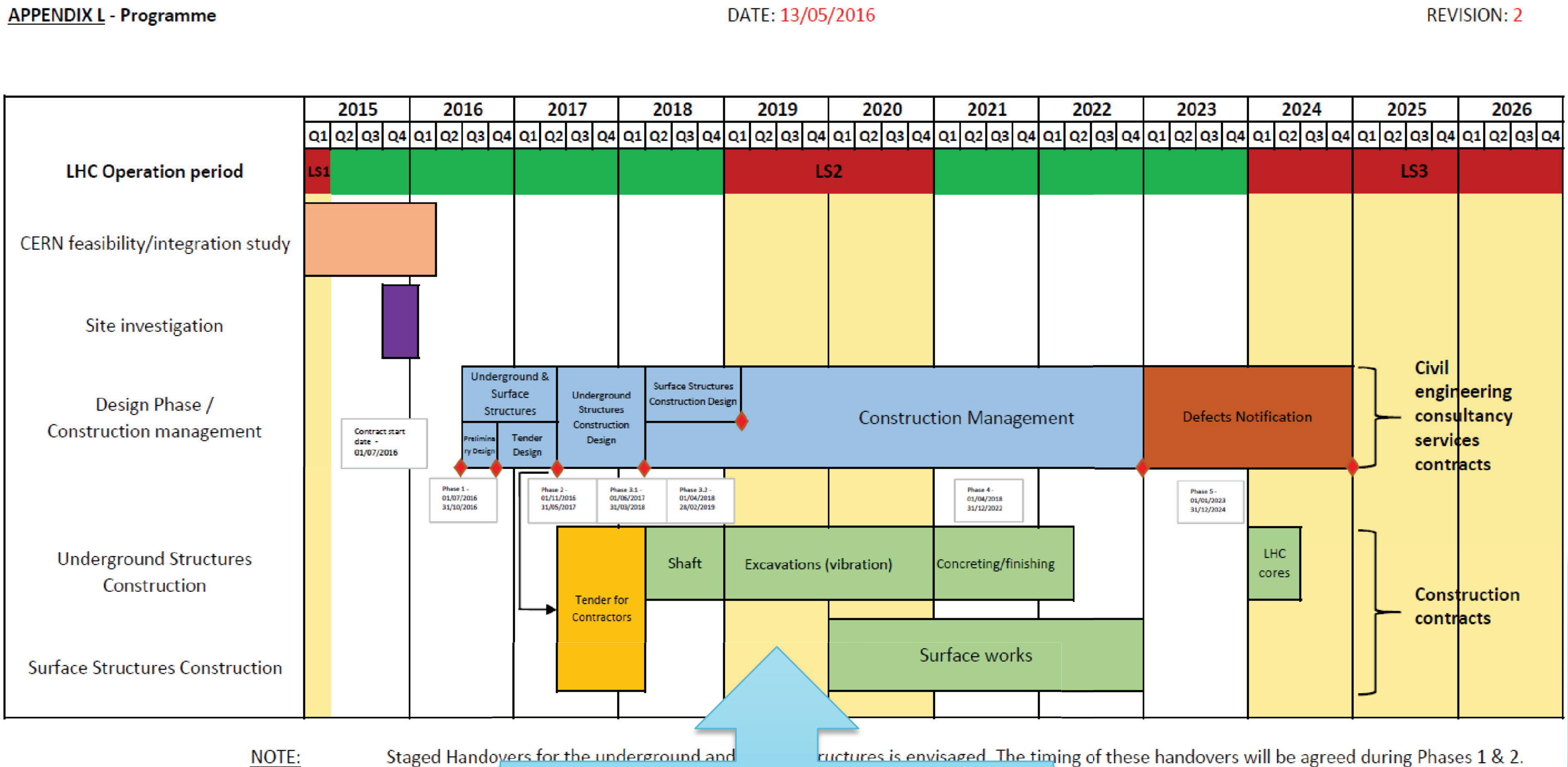
| Source term: the excavation technique | Transmission term: Vertical through the rock layers | Transmission term: Horizontal through rock | Transmission term: From the floor to the magnetic axis | Sensitivity: The beam stability |
|---|---|---|---|---|
| In (ω) | $H_2$ (ω) | $H_1$ (ω) | $H_0$ (ω) | Out (ω) |




# Minimize risk with appropriate planning approach




Maximum quantity of work out of beam time
Work in beam the furthest from critical point

# Conclusions

- The HL-LHC project is fully approved and the construction is beginning for infrastructure and accelerator elements. TDR ready.
- In less than 10 years the LHC luminosity will be 5 times its initial design one, ready for new discoveries and performing precision studies
- HL-LHC is an incubator of technologies that can be used for future accelerators for even higher reach in physics discovery
- Большое спасибо!