Corfu Summer Institute: Workshop on the Standard Model and Beyond,
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Accelerator physics and technology challenges for the HL-LHC

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Beams Department

CERN

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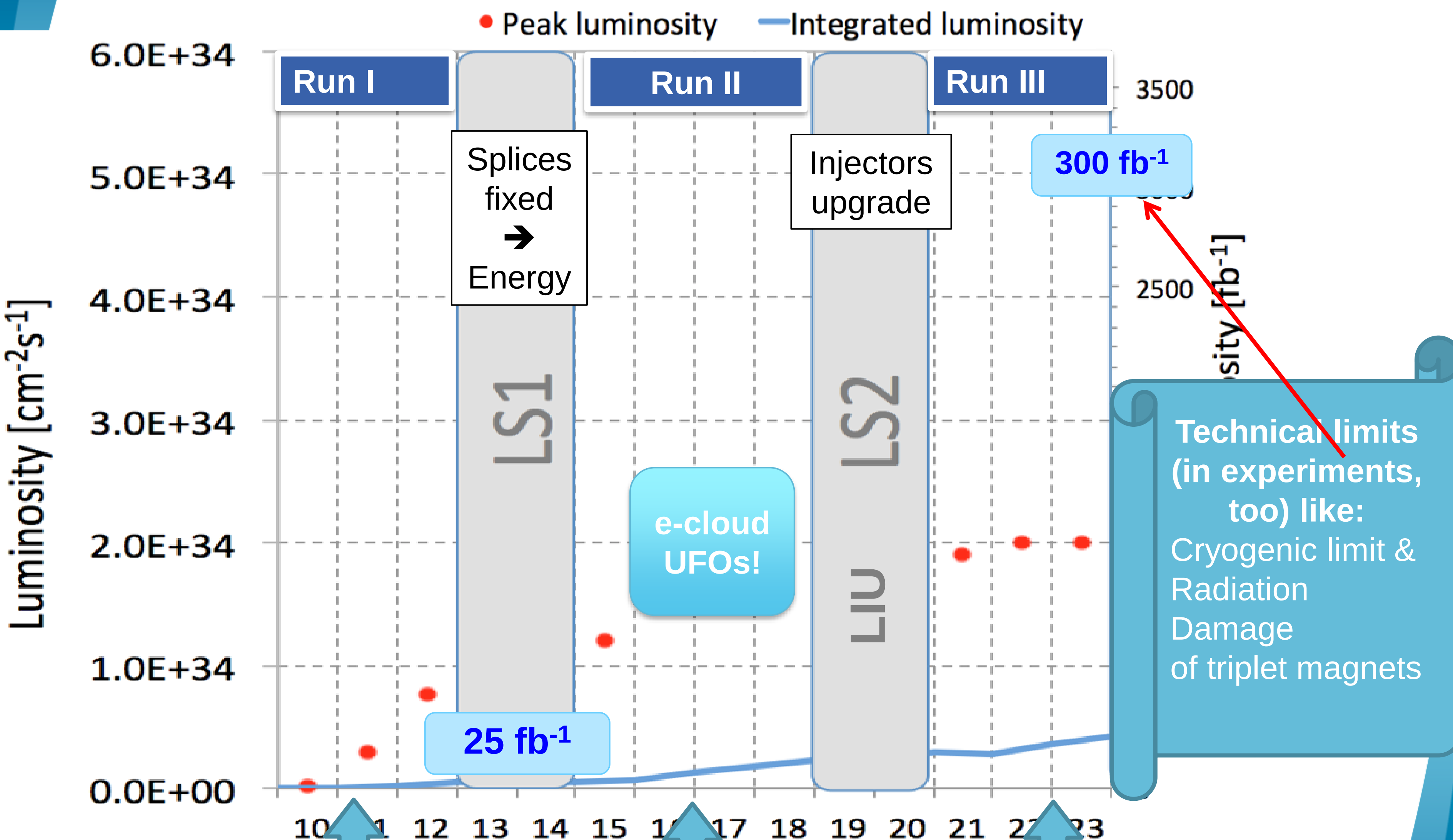
- From LHC to HL-LHC → HL-LHC goal
- HL-LHC project landmarks and collaboration
- HL-LHC challenges
  - Levelling
  - Triplet magnets
  - Optics challenges: the ATS
  - Beam-Beam aspects
  - Crab-cavities
  - Beam power
  - Civil engineering
- Performance projections

From LHC to HL-LHC



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
high pile up ~40

1.5 -2.2 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
very high pile up > 60

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:

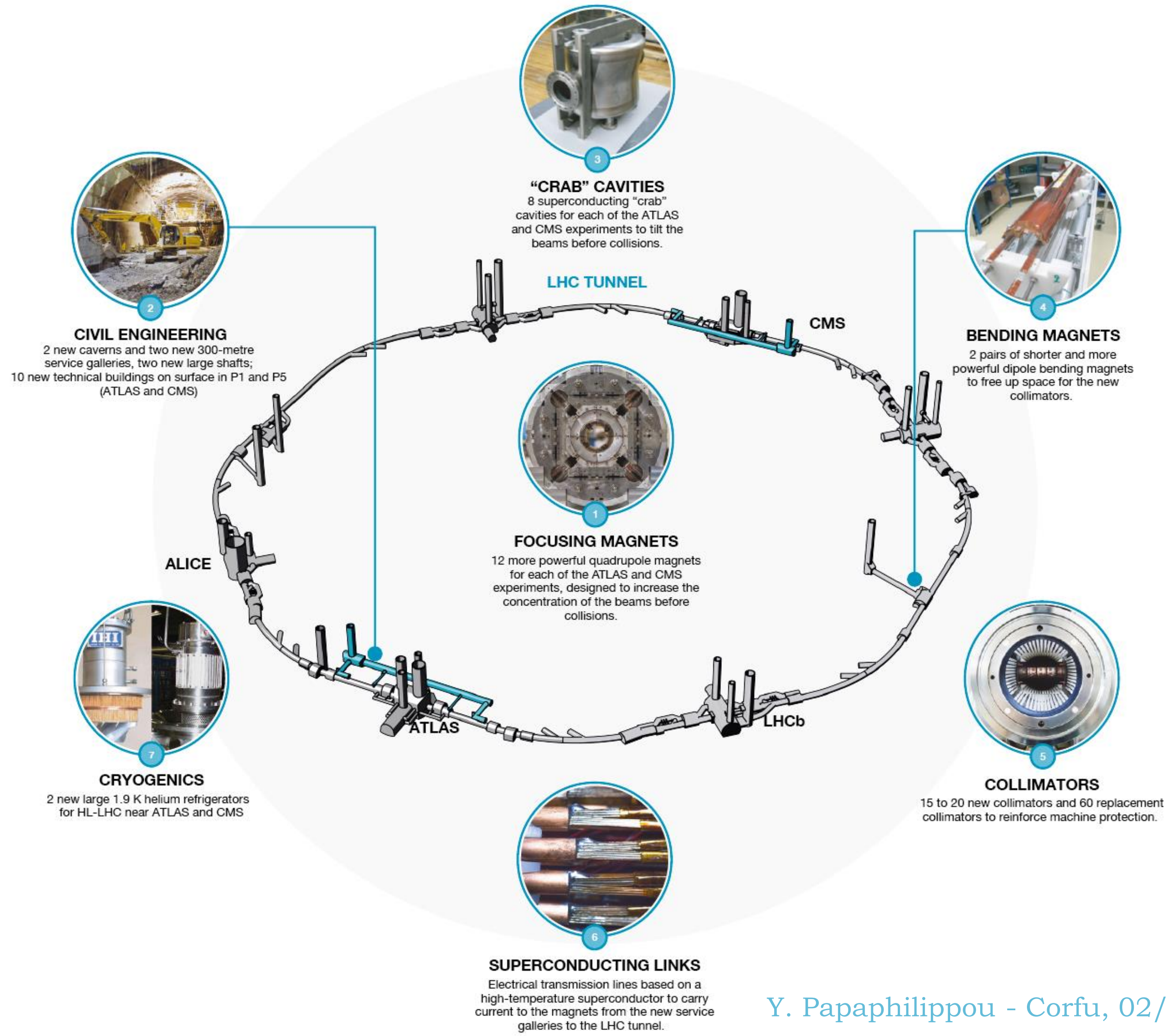
A peak luminosity of L_{peak} = **5×10^{34} $cm^{-2}s^{-1}$ with levelling**, allowing:

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:**
$L_{peak\ ult} \cong 7.5\ 10^{34}$ $cm^{-2}s^{-1}$ and **Ultimate Integrated $L_{int\ ult} \sim 4000$ fb^{-1}**
LHC should not be the limit, would Physics require more…

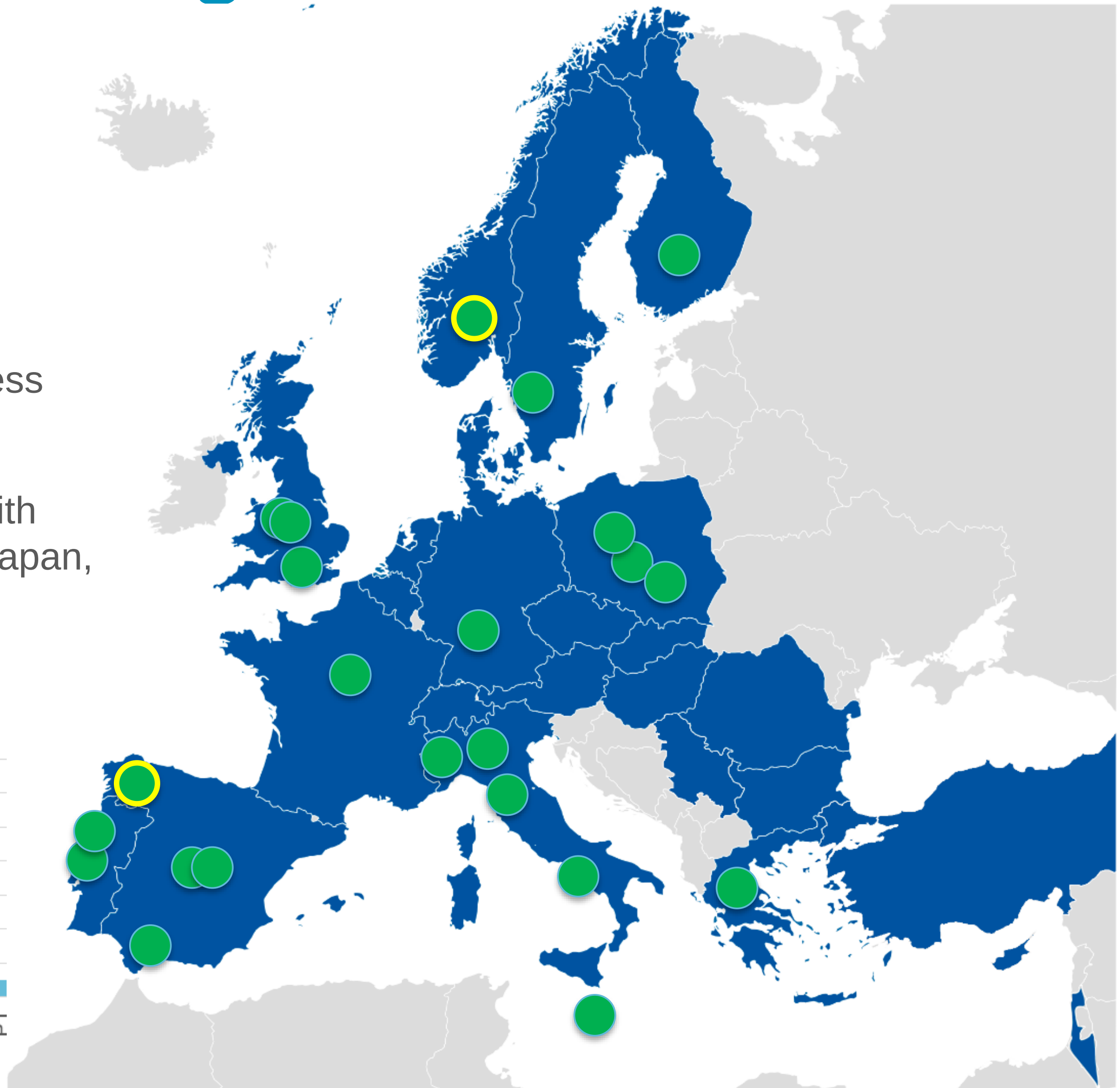
HiLumi HL-LHC PROJECT CERN

HiLumi LHC landmarks: a project for Physics and Technology jump



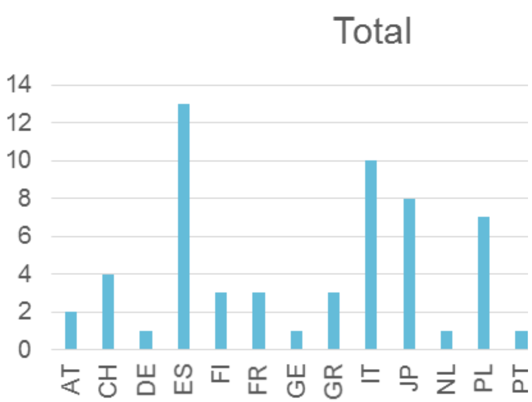
HL-LHC in-kind contri-butors

A global effort



- HL-LHC
- Negotiation in process

Under discussion with Canada, Georgia, Japan, Russia, USA



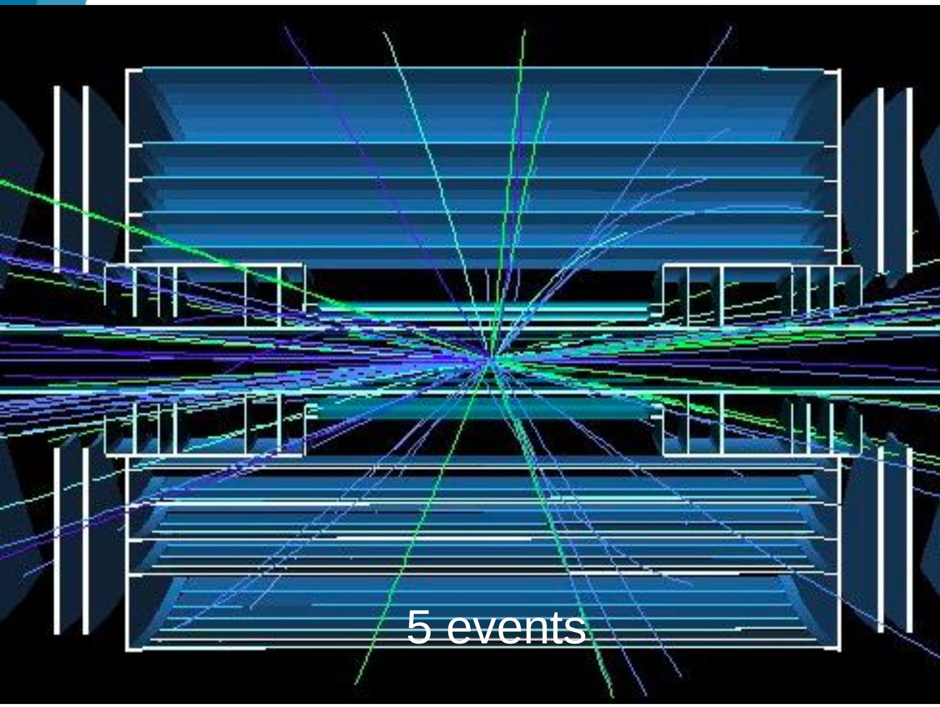
LHC upgrade goals: Performance optimisation

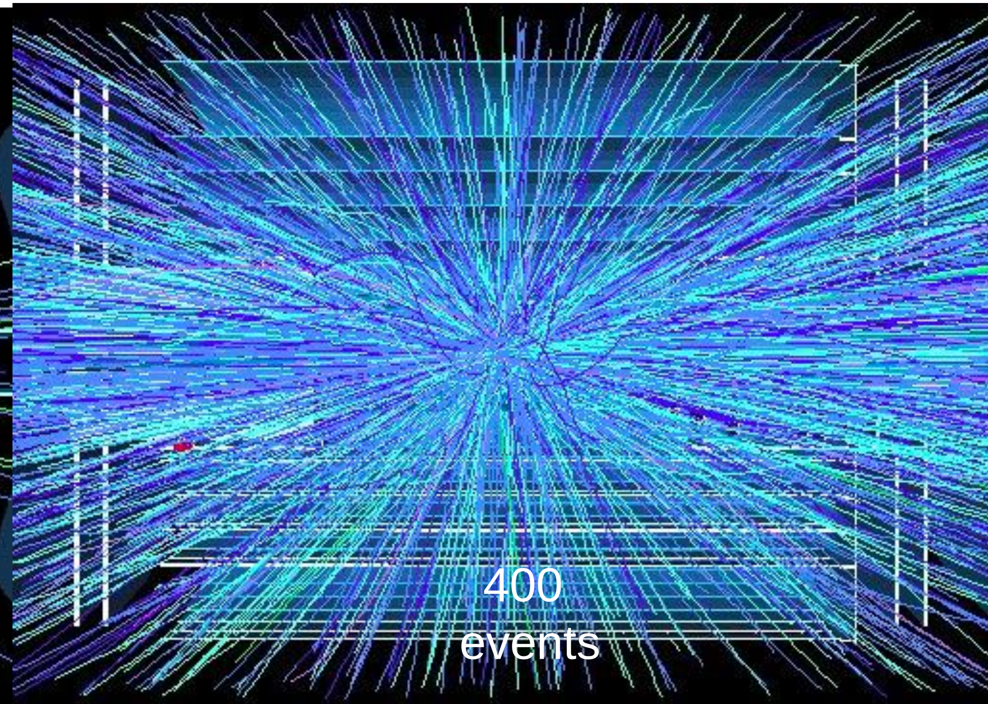
Luminosity recipe (round beams):

$$L = \frac{n_b \times N_1 \times N_2 \times g \times f_{rev}}{4p \times b^* \times e_n} \times F(f, b^*, e, s_s)$$

- ➔1) maximize bunch intensities ➔ Injector complex
- ➔2) minimize the beam emittance Upgrade LIU
- ➔3) minimize beam size (constant beam power); ➔ triplet aperture
- ➔4) maximize number of bunches (beam power); ➔ 25ns
- ➔5) compensate for ‘F’; ➔ Crab Cavities
- ➔6) Improve machine ‘Efficiency’ ➔ minimize number of unscheduled beam aborts

Goal of High-Luminosity LHC





implying an integrated luminosity of **250 fb^{-1} per year**,

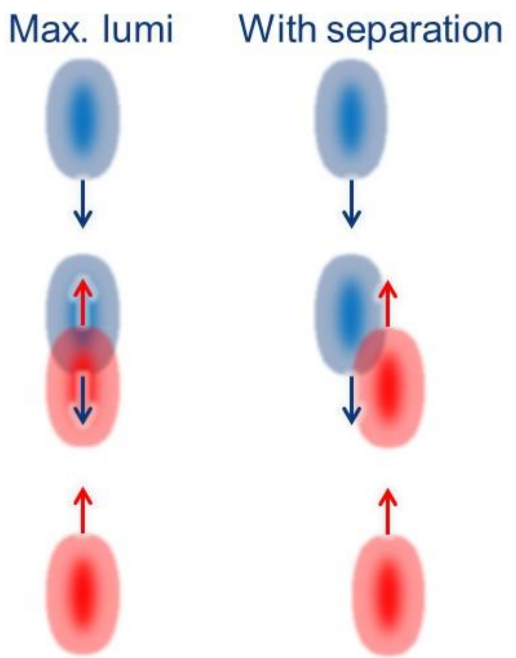
design oper. for μ δ **140** (➔ peak luminosity **5 10^{34} cm^{-2} s^{-1}**)

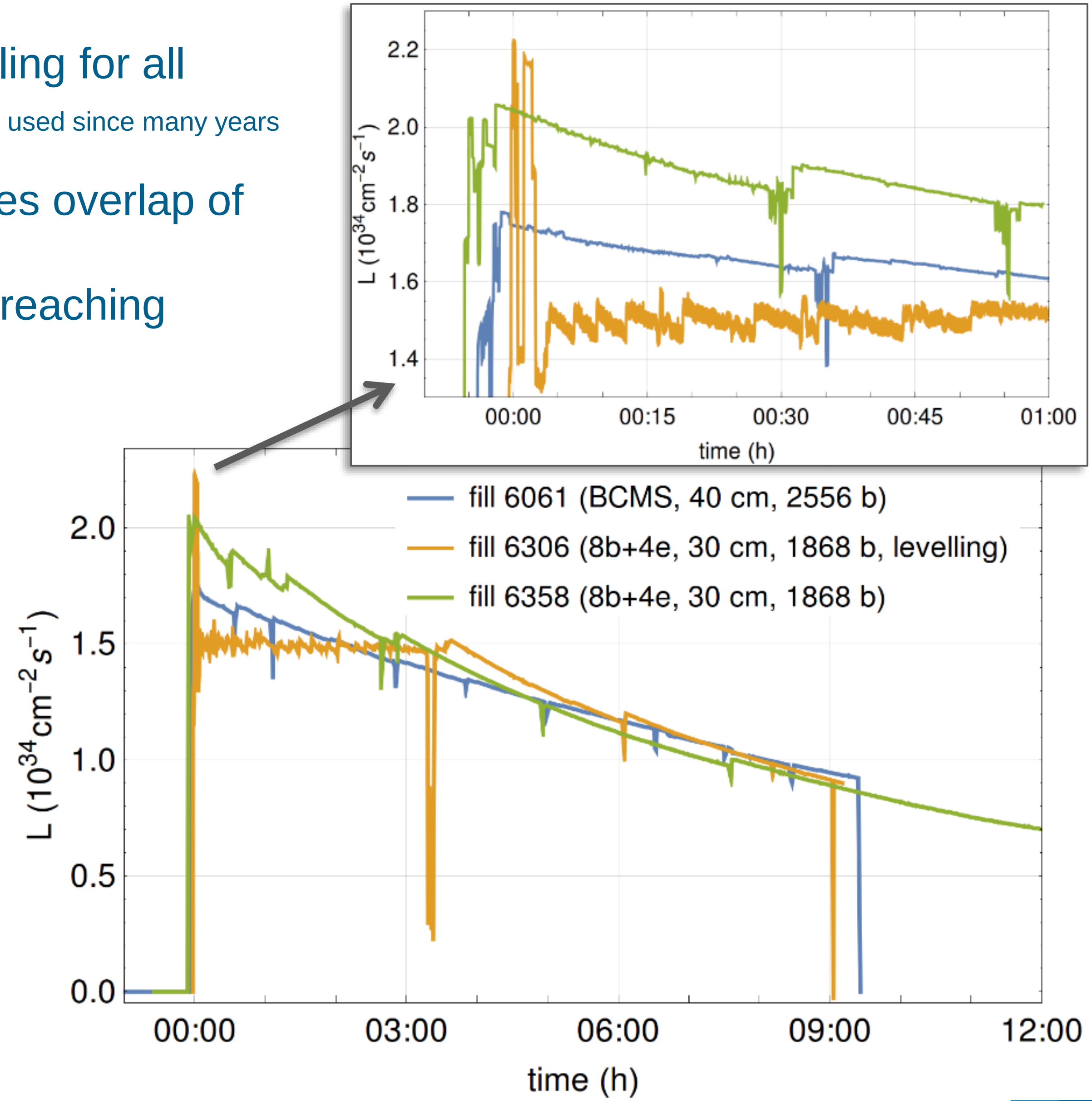
➔ Operation with levelled luminosity!

➔10 times the luminosity reach of first 10 years of LHC operation

LHC 2017 : separation levelling

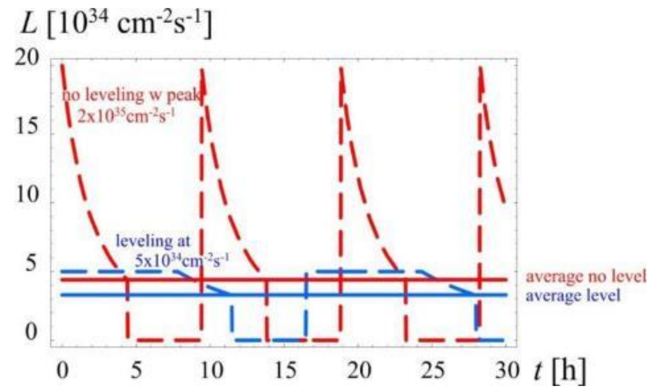
- Introduced separation levelling for all experiments (Separation levelling is used since many years for ALICE and LHCb)
- Dynamic orbit bump changes overlap of colliding bunches
- Initial spike before leveling reaching 2.2×10^{34} $cm^{-2}s^{-1}$





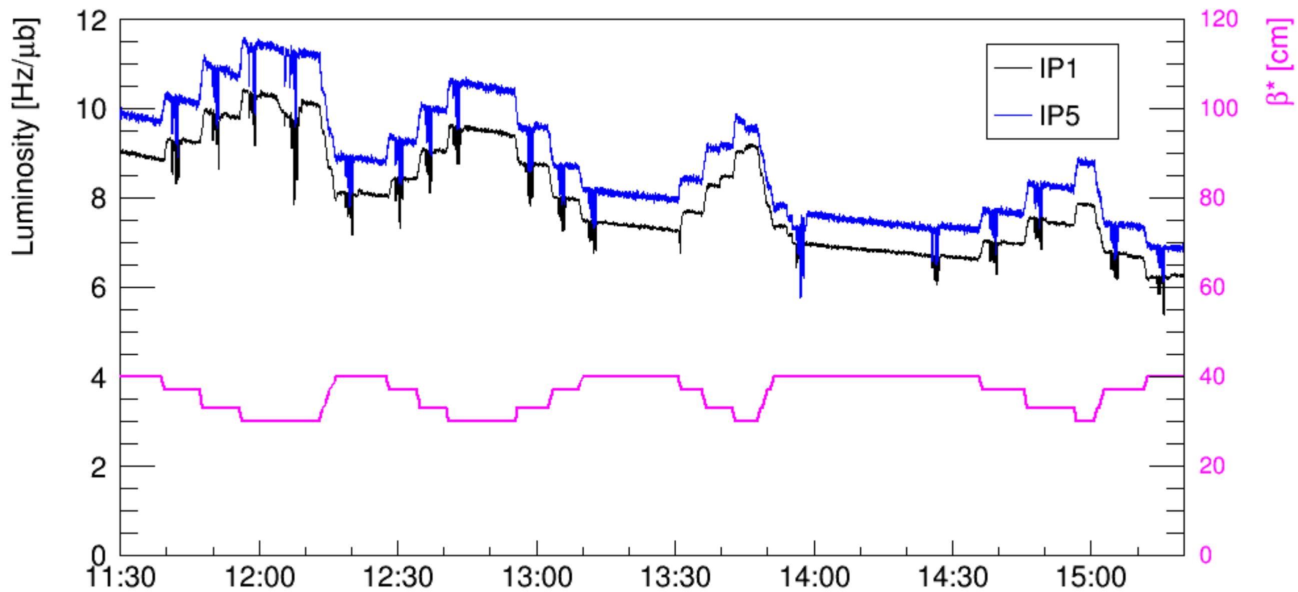
β* levelling

Levelling luminosity by β* should be the main levelling technique for HL-LHC



Succesfull β* levelling in **LHC MDs**

implementation of β* levelling steps during LHC **operation**



Luminosity evolution during β levelling, moving back and forth between 30 cm and 40 cm. The beams remained head-on* ***within ~ 2 μm*** *!*

LHC Limitations and HL-LHC Challenges

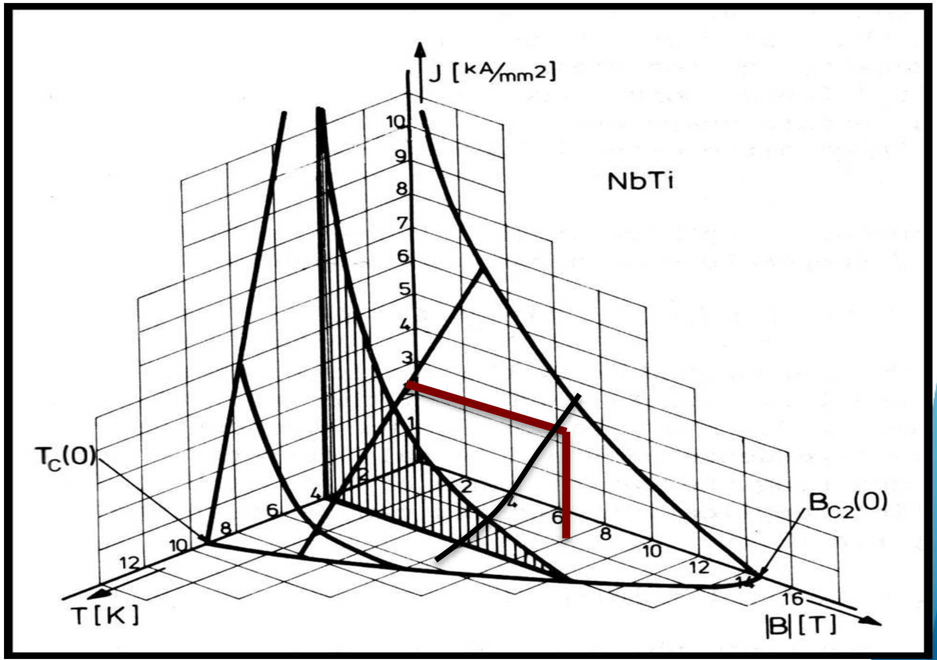
- Technical bottle necks (e.g. cryogenics) ➔ New addit. Equipment
- Insertion magnet lifetime and aperture:
  ➔ New insertion magnets and low-β with increased aperture
- Geometric Reduction Factor: ➔ SC Crab Cavities
  ➔ New technology and a first for a hadron storage ring!
- Performance Optimization: Pileup density ➔ Lumi levelling
  ➔ devise parameters for virtual luminosity >> target luminosity
- Beam power & losses ➔ additional collimators in DS region
- Machine effciency and availability:
  # R2E ➔ removal of all electronics from tunnel region
  # e-cloud ➔ beam scrubbing (conditioning of surface)
  # UFOs ➔ beam scrubbing (conditioning of surface)

HL-LHC Upgrade Ingredients: Triplet Magnets

- Nominal LHC triplet: 210 T/m, 70 mm coil aperture
  - ➔ ca. 8 T @ coil
  - ➔ 1.8 K cooling with superfluid He (thermal conductivity)
  - ➔ current density of 2.75 kA / mm^2
- At the limit of NbTi technology (HERA & Tevatron ca. 5 T @ 2kA/mm^2)!!!

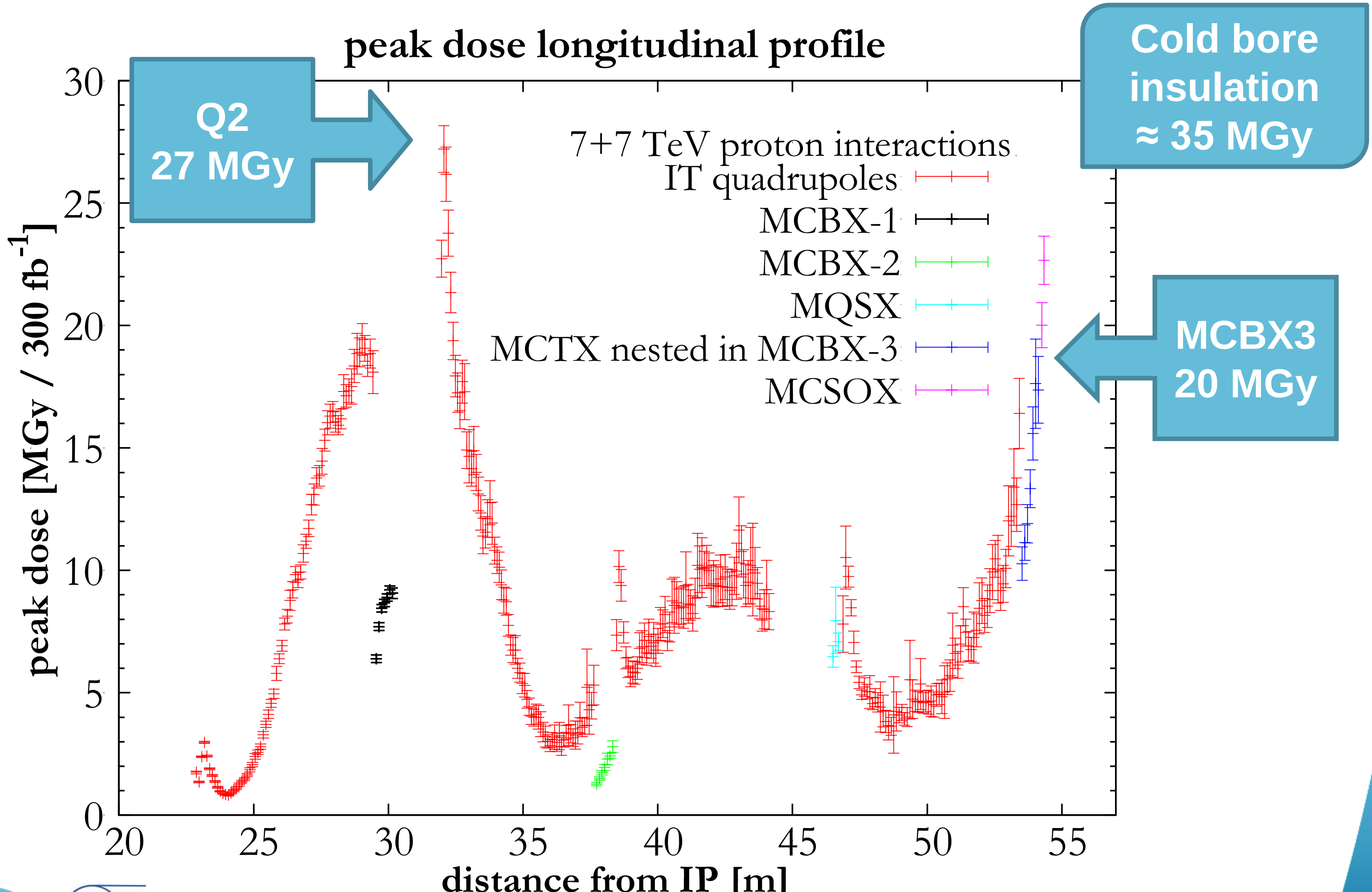
LHC Production in collaboration with USA and KEK

Critical Surface for NbTi



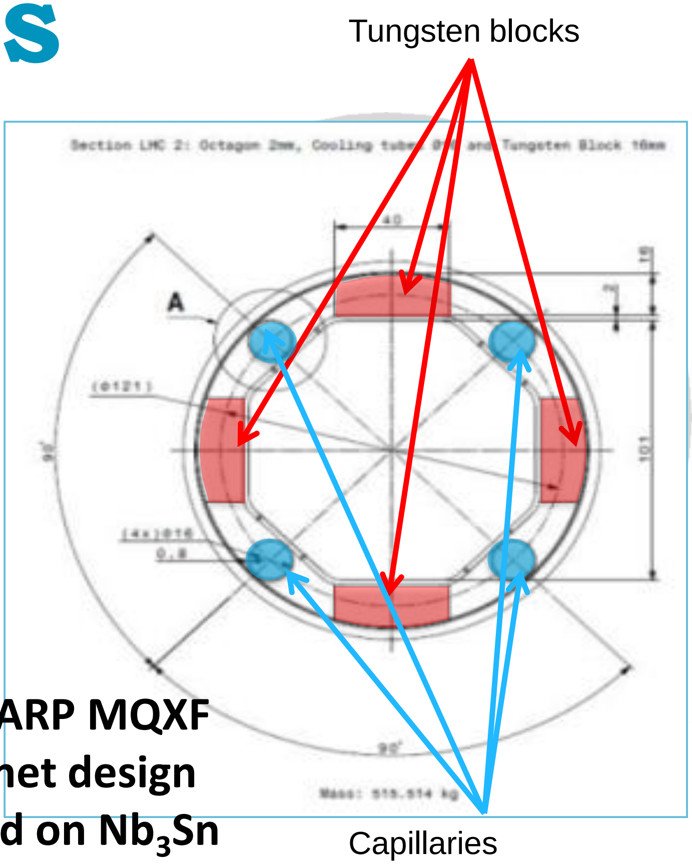
HL-LHC technical bottleneck

Radiation damage to triplet magnets at 300 fb-1



Radiation damage to triplet magnets

Need to replace existing triplet magnets with radiation hard system such that the new magnet coils receive a similar radiation dose @ 10 times higher integrated luminosity
➔ Shielding!



US-LARP MQXF magnet design Based on Nb_3Sn technology

- Requires larger aperture!
- New magnet technology
- 70 mm @ 210 T/m ➔150 mm diameter @ 140 T/m
  8 T peak field @ coils ➔ 12 T field at coils (Nb_3Sn)!!!

Optics Challenges & the ATS scheme

→ **Lowering β^* needs magnets of larger aperture**, but also new hardware or sophistication (crab-cavity, flat optics,…) to mitigate the luminosity loss due to the Piwinsky angle.

→ How to produce this β^* ???

This is the aim of the ATS scheme which solves many optics limitations coming from the overall LHC ring.

1. **Optics matchability to the arcs:**
   - Some IR quads going to 0 T/m, others to max. field (200T/m).
   - Simply the matching section becomes too short at some point.
2. **Correctability of the chromatic aberrations induced**, not only Q', but also Q'', Q''',…, and off-momentum b-beating:
   - limitations from the arc sextupole strength (<600A).

HiLumi HL-LHC PROJECT CERN

S. Fartoukh, PRSTAB 16, 111002, 2013

The ATS scheme

S. Fartoukh, PRSTAB 16, 111002, 2013

- **A new injection optics** (~π/2 FODO lattice → new integer tunes)
- **A squeeze in 2 steps**

1) An "almost" standard squeeze, **the Pre-squeeze**:

→ acting on the matching quads of IR1 and IR5,

→ with new matching constraints on the left/right IR phase

→ till reaching some limits (sextupoles, matching quadrupoles)

2) A further reduction of β^*, **the Squeeze**:

→ acting on IR2/8 for squeezing IR1 and IR4/6 for IR5,

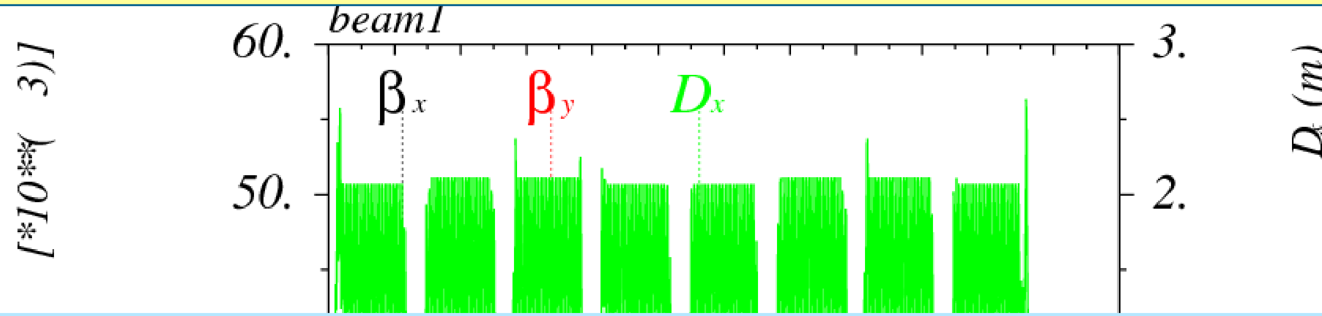
→ inducing **β-beating bumps in sectors 81/12/45/56 to boost the sextupole efficiency at constant strength.**

$$\rightarrow \quad \beta^*_{\text{Squeeze}} = \beta^*_{\text{Pre-Squeeze}} \times \frac{\left(\hat{\beta}_{\text{Arc}}\right)_{FODO}}{\left(\hat{\beta}_{\text{Arc}}\right)_{Mismatched}}$$

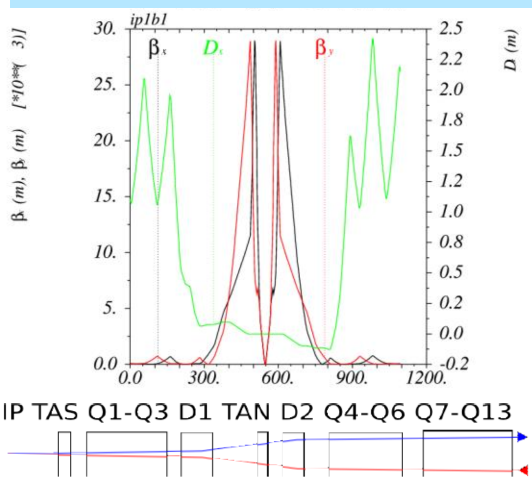
HL-LHC optics using the ATS

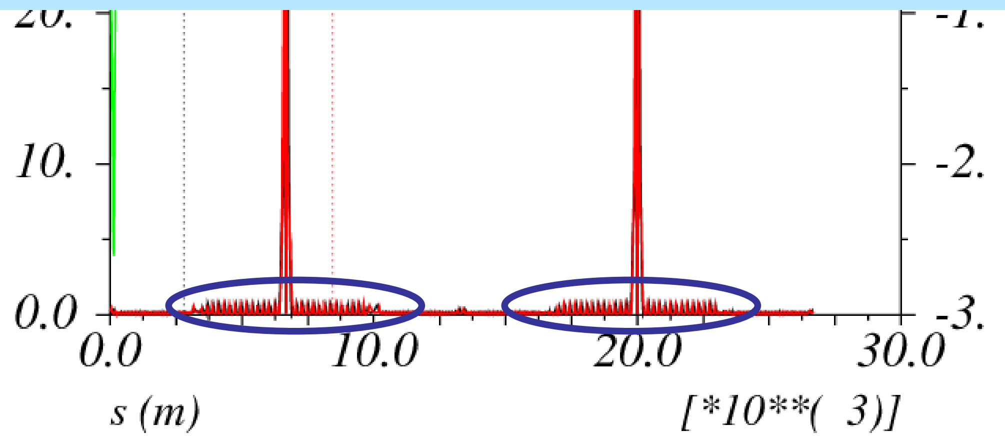
Round Squeezed optics β* = 10 cm at IP1 and IP5 (150 T/m IT gradient)

S. Fartoukh



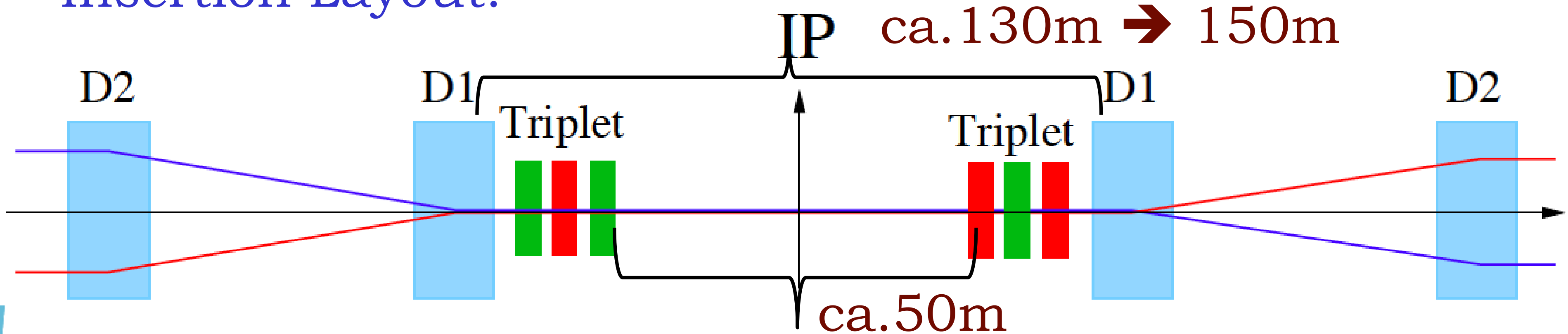
- ➔LHC operating **smoothly** with ATS optics since **2017**
- ➔Several **HL-LHC options** tested in MDs (flat optics, beam-beam long range compensation with DC wires and octupoles)





HL-LHC Challenges: Crossing Angle

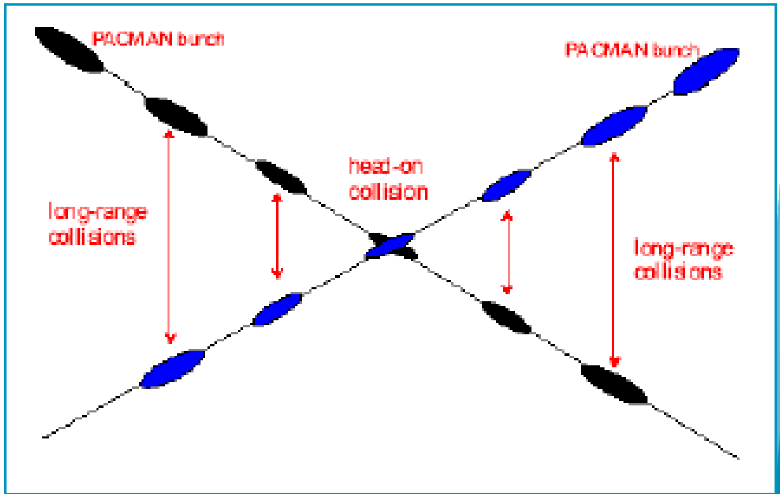
Insertion Layout:



Parasitic bunch encounters:

Operation with ca. 2800 bunches @ 25ns spacing ➔ approximately 30 unwanted collision per Interaction Region (IR).

➔ Operation requires crossing angle



Non-linear fields from long-range beam-beam interaction:

efficient operation requires large beam separation at unwanted collision points ➔ Separation of 10 -12 σ ➔ large triplet apertures for HL-LHC!!

HL-LHC Upgrade Ingredients: Crab Cavities

Geometric Luminosity Reduction Factor

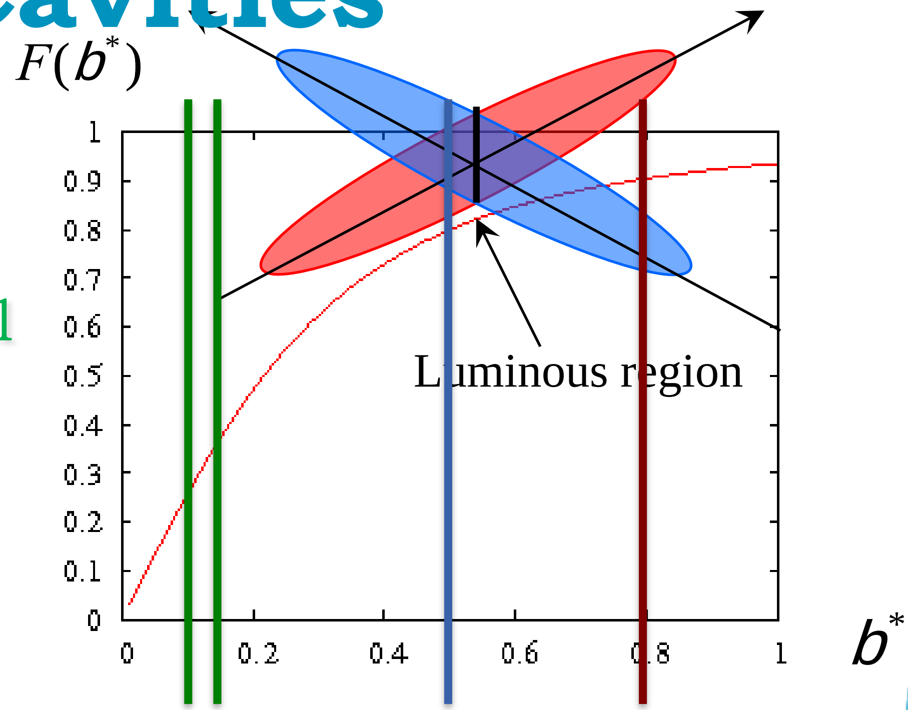
Crab Cavities

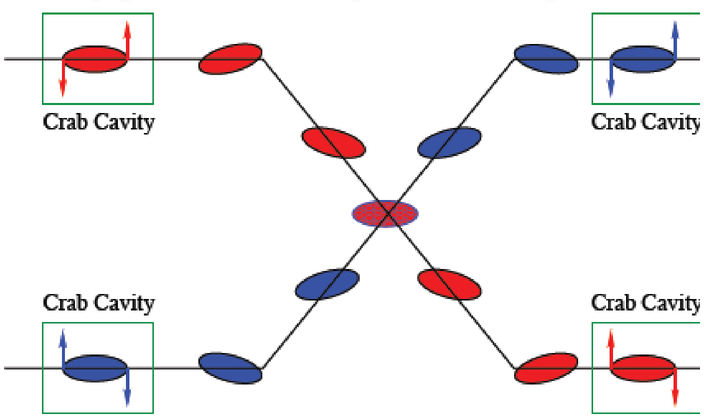
- Reduce the effect of geometrical reduction factor
- Independent for each IP

$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

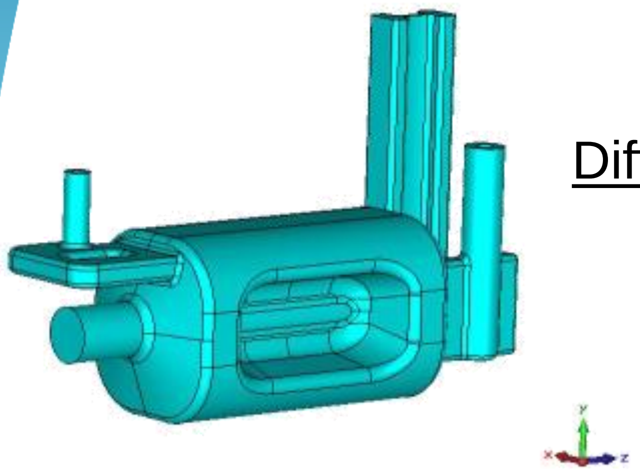
- Noise from cavities to beam???
- Challenging space constraints:

  ➔ requires novel compact cavity design



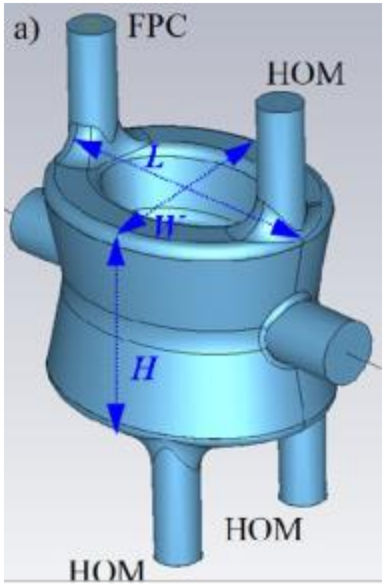


HL-LHC Crab Cavities designs



RF Dipole: Waveguide or
waveguide-coax couplers

2 Designs with
Different Coupler concepts and
Deflection planes



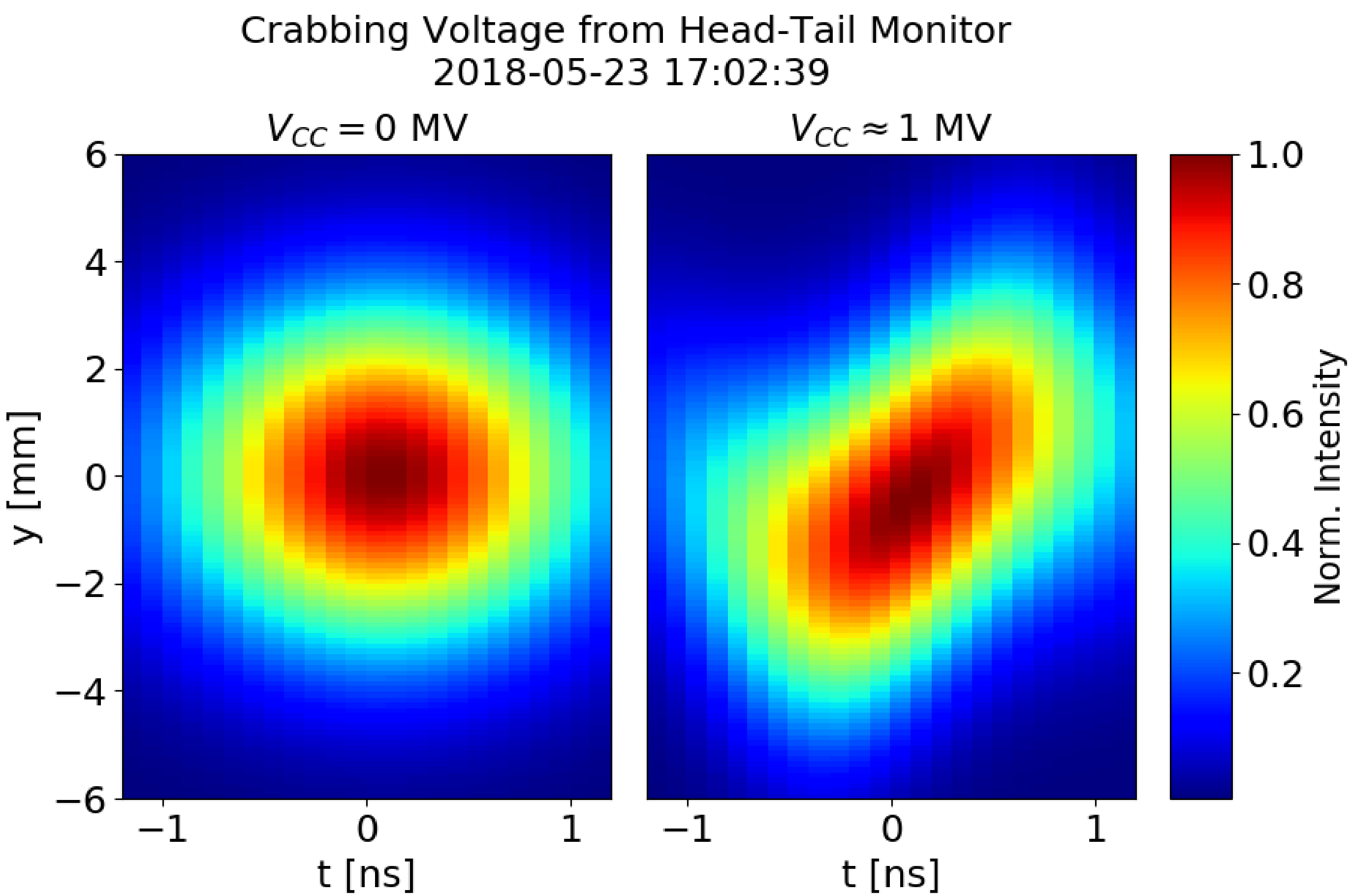
Double ¼-wave:
Coaxial couplers with
hook-type antenna

DQW crab-cavity
Cryomodule for
SPS tests

Present baseline: 4 cavities / IP / side → 16 total

First proton crabbing ever!

TEST in SPS ongoing since 2018



Study and R&D has been very useful to obtain this result

LHC Challenges: Beam Power

Unprecedented beam power:

Wo

Fail

Life

➔ New collimators and absorbers for the HL-LHC

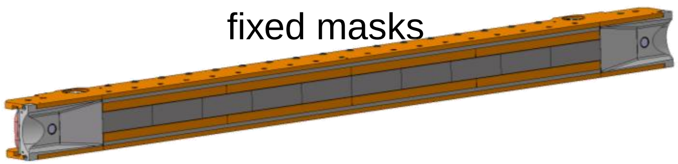
➔ Remove all active components from the LHC tunnel [requiring new space underground]

➔ R2E and SEU

➔ Machine efficiency

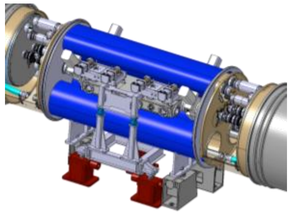
Baseline upgrades

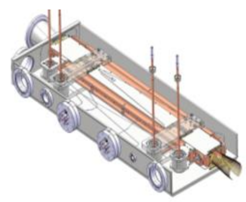
Completely new layouts
Novel materials.
IR1+IR5, per beam:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks

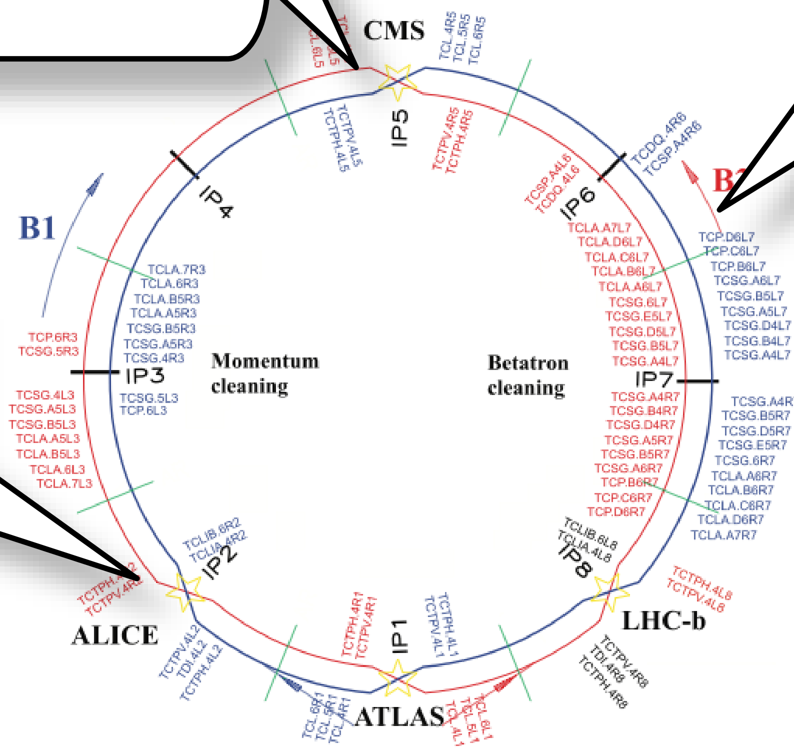


56 new collimators to be produced by LS3 in the present baseline!

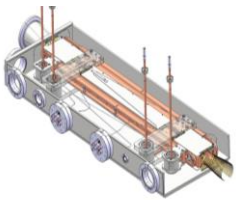
Cleaning: DS coll. + 11T dipoles, 2 units per beam



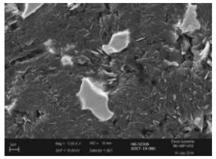


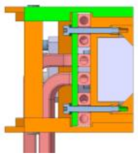


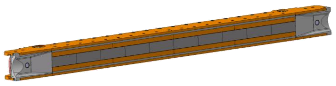
Ion pair production: DS collimation



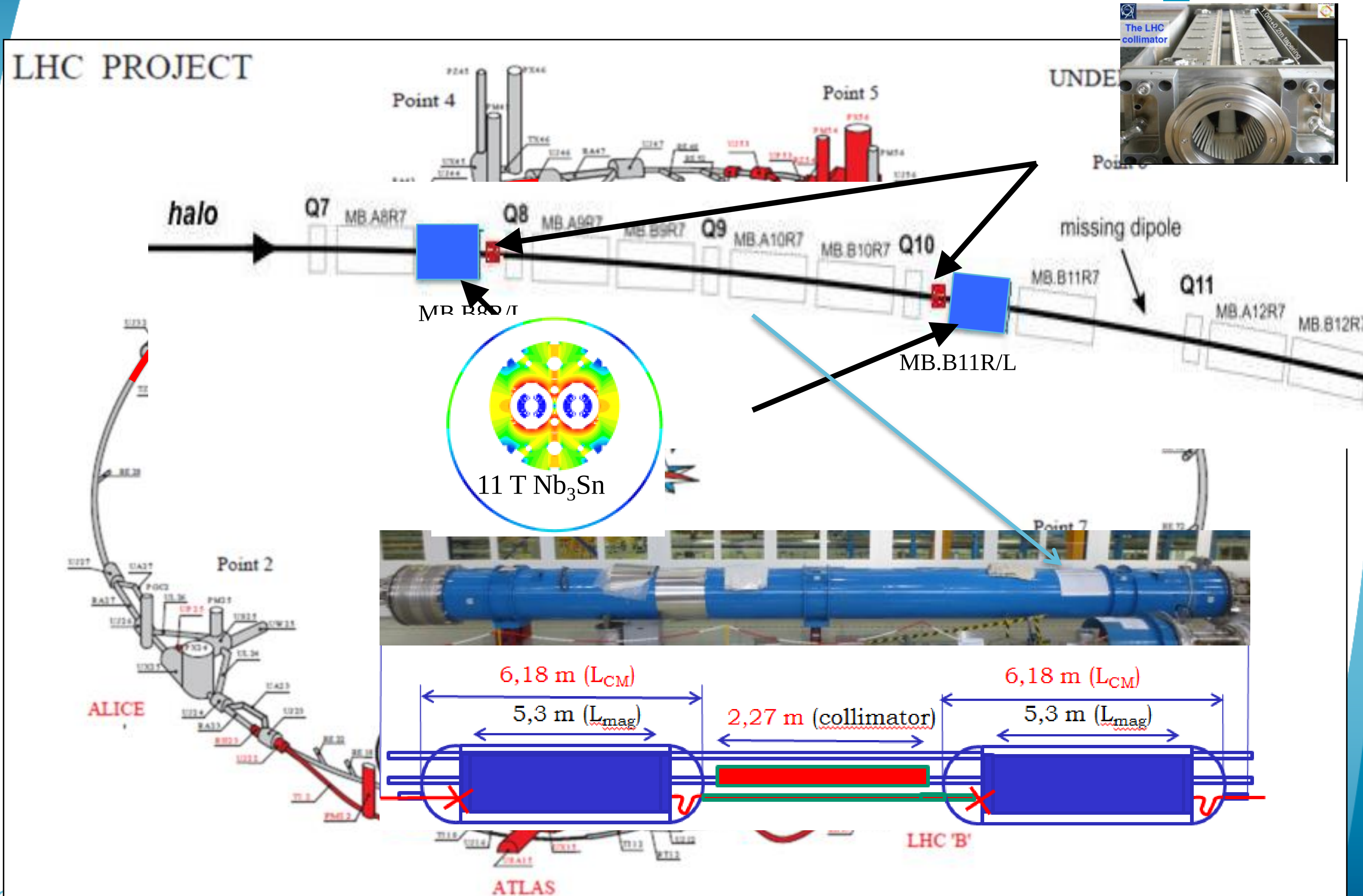
Low-impedance, high robustness secondary collimators



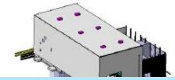




DS collimators – 11 T Dipole



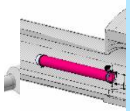
IR1 & IR5 Civil Engineering

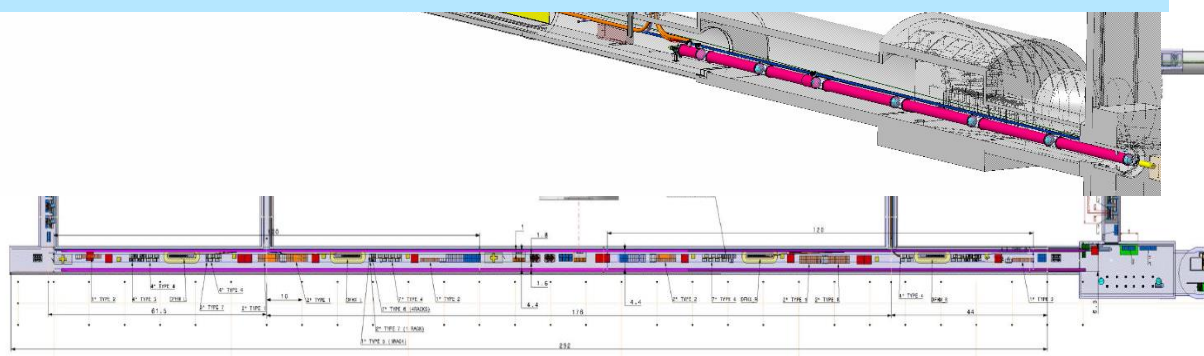


Vibrations of Civil Engineering Work affects operation!!!

➔ CE work needs to be done when LHC is not operating

➔ main work needs to be carried out during LS2 in order to finish work in time for LS3

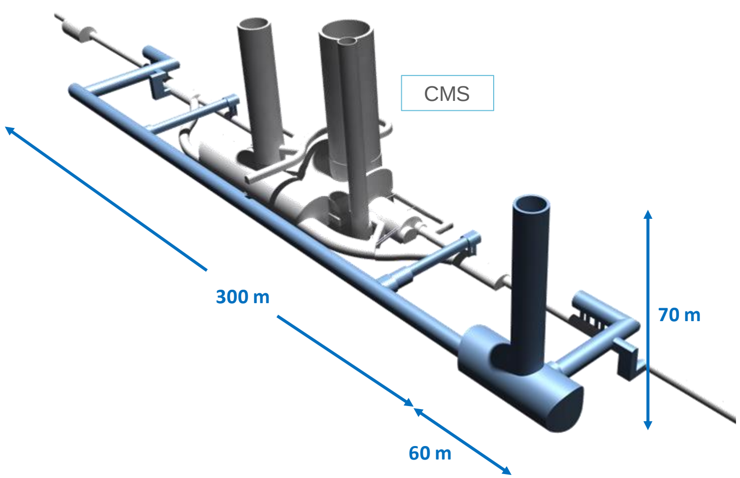




Underground Constructions

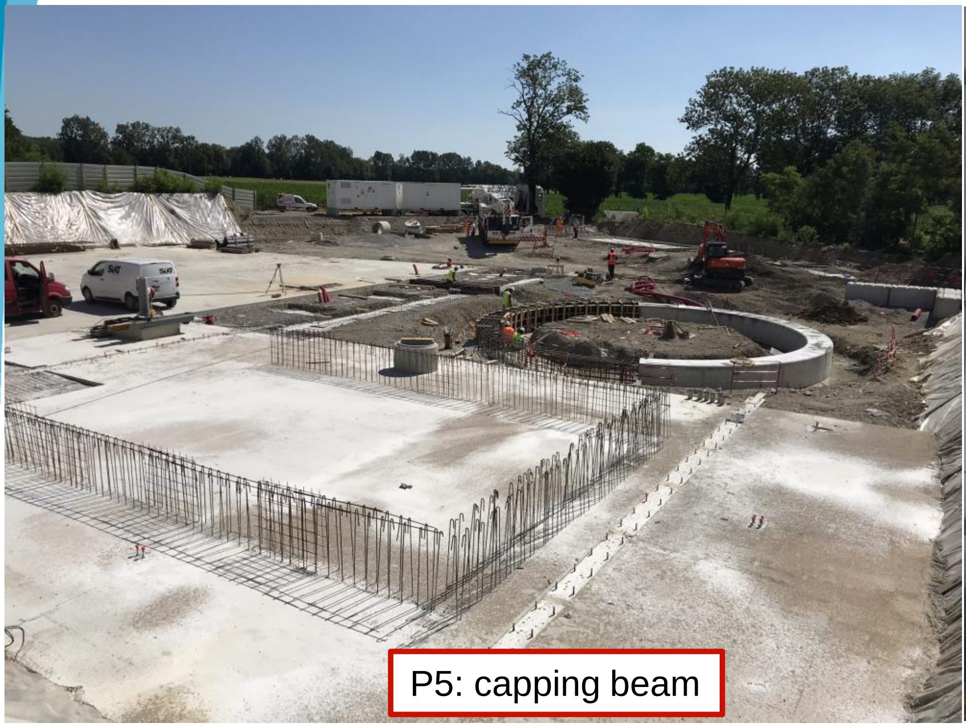
➔ HL-LHC CE work started in June

Point 5) Awarded and signed in March 2018!



15 June 2018 : Groundbreaking Ceremony

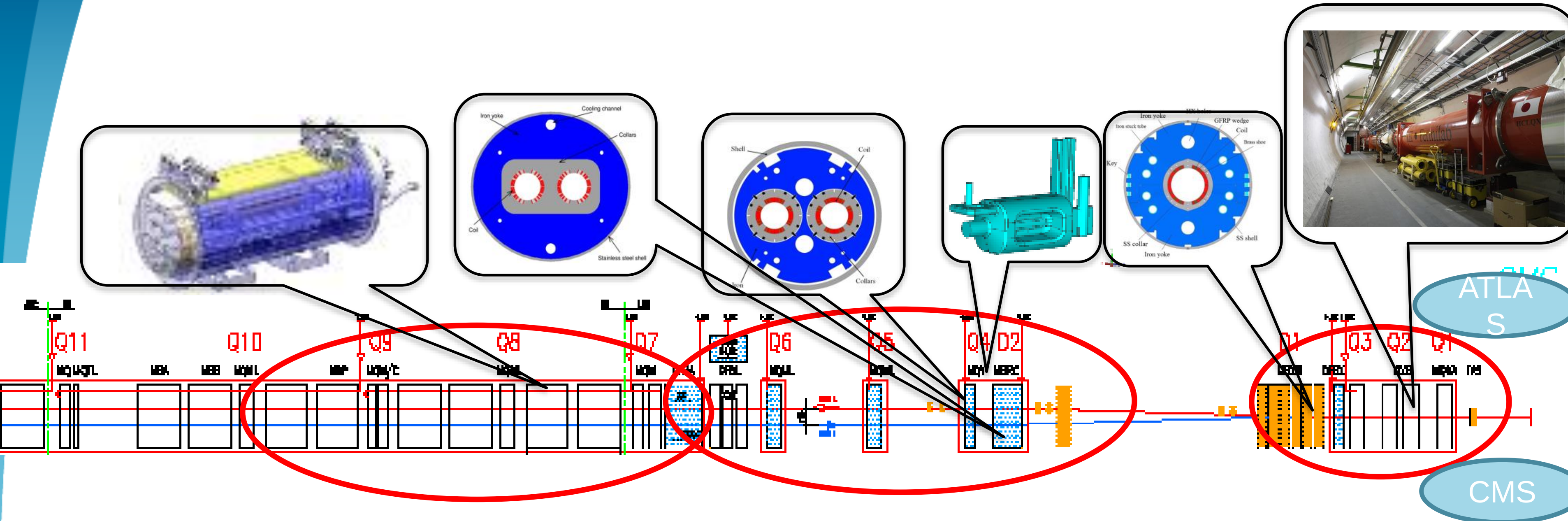
Work is progressing fast…



P5: capping beam

Temporary building above the shaft

Critical zones around IP1 and IP5



3. For collimation we also need to change the DS in the continuous cryostat: 11T Nb_3Sn dipole

2. We also need to modify a large part of the matching section e.g. Crab Cavities & D1, D2, Q4 & corrector

1. New triplet Nb_3Sn required due to:
-Radiation damage
-Need for more aperture

Changing the triplet region is not enough for reaching the HL-LHC goal!

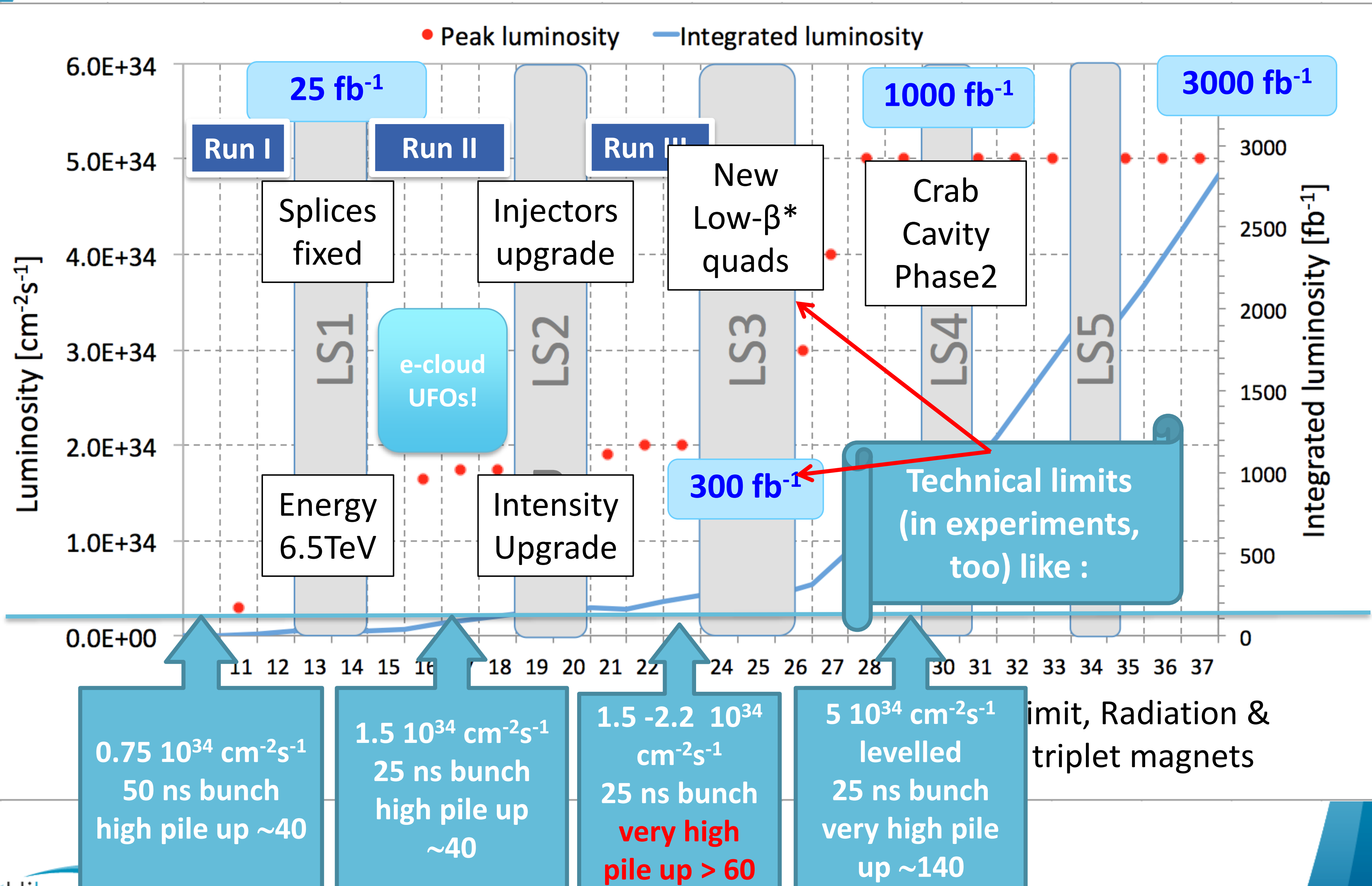
→ **More than 1.2 km of the LHC will be upgraded!!**
→ **Plus technical infrastructure (e.g. Cryo and Powering)!!**

HiLumi HL-LHC PROJECT CERN

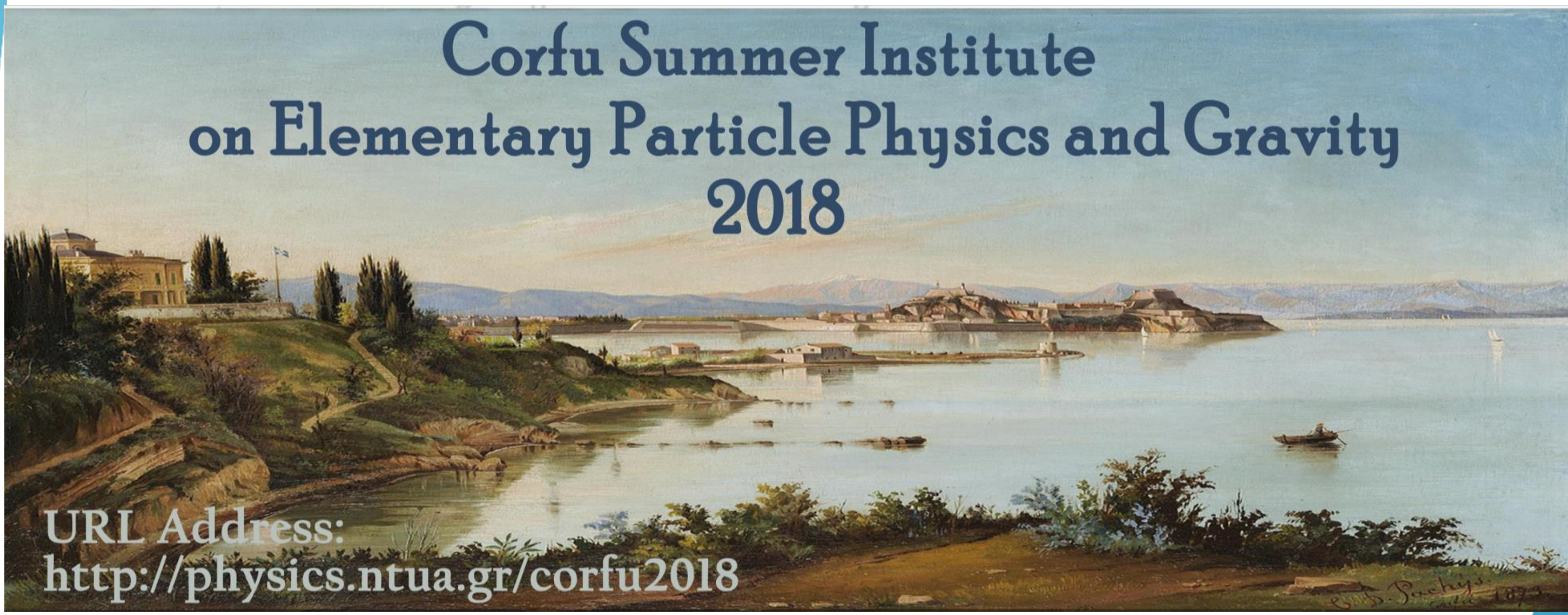
Schedule


2015
2016
2017
2018
2019
2020
2021
2022
2023
EYETS
LS2
Shutdown/Technical stop
Protons physics
Commissioning
Ions
2024
2025
2026
2027
2028
2029
2030
2031
2032
LS3
LS4
2033
2034
2035
2036
2037
LS5

Performance Projections up to HL-LHC

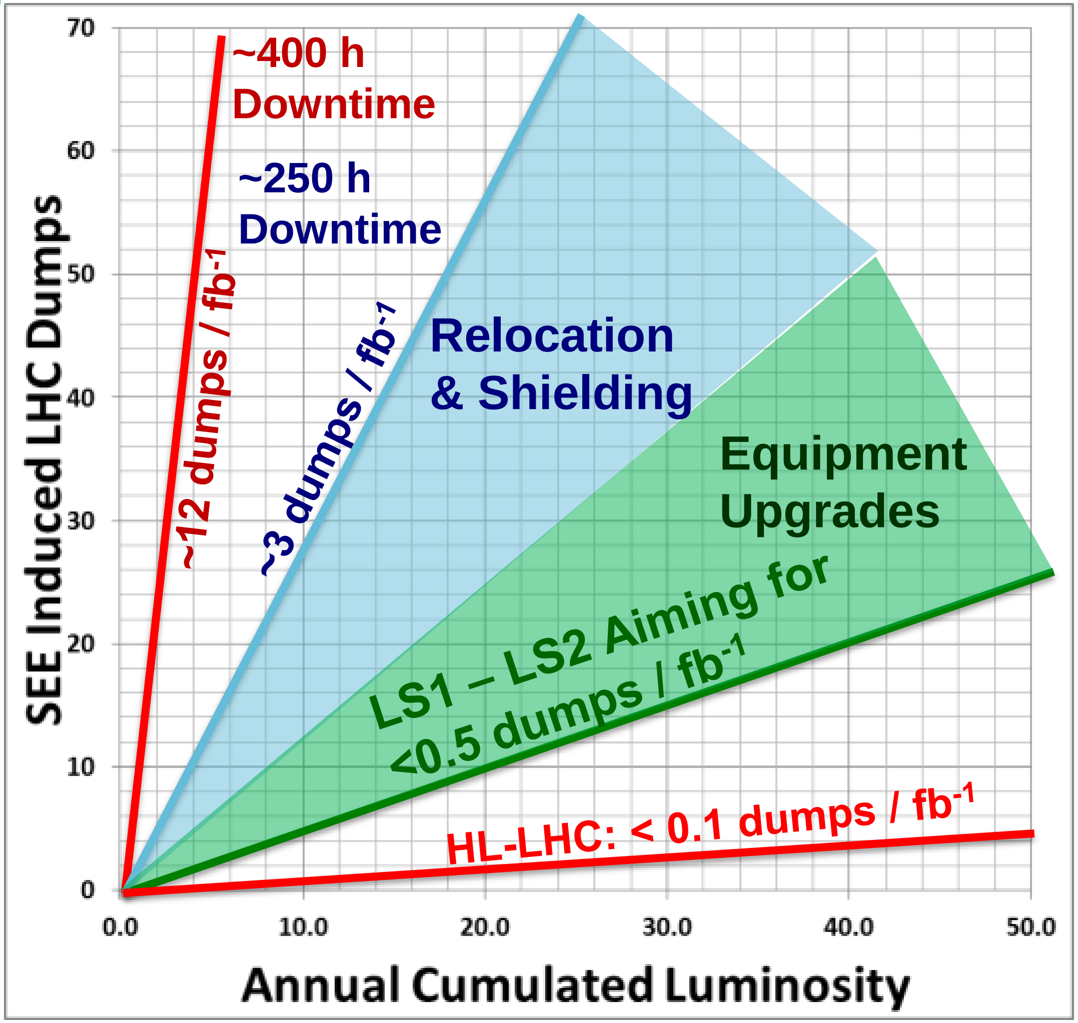


Ευχαριστώ για την προσοχή σας



Reserve slides

R2E SEU Failure Analysis - Actions



- **2008-2011**
  - Analyze and mitigate all safety relevant cases and limit global impact
- **2011-2012**
  - Focus on equipment with long downtimes; provide shielding
- **LS1 (2013/2014)**
  - Relocation of power converters
- **LS1 – LS2:**
  - Equipment Upgrades
- **LS3 -> HL-LHC**
  - Remove all sensitive equipment from underground installations

Prototyping of cryogenics bypass @ CERN

Prototyping of the by-pass crystostat (QTC) for the installation of a warm collimator in the cold dispersion

Magnet: prototypes reached 11 T field in March 2013!