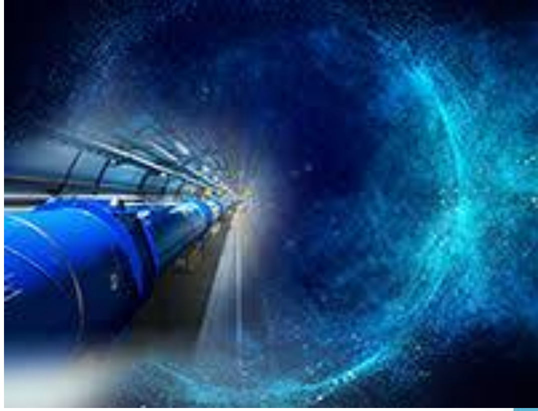
Accelerators Revealing the QCD Secrets,
3-5 September 2016, Thessaloniki, Greece



HiLumi
HL-LHC PROJECT

HL-LHC Accelerator Physics Challenges

Y. Papaphilippou

Accelerator and Beam Physics group

Beams Department

CERN

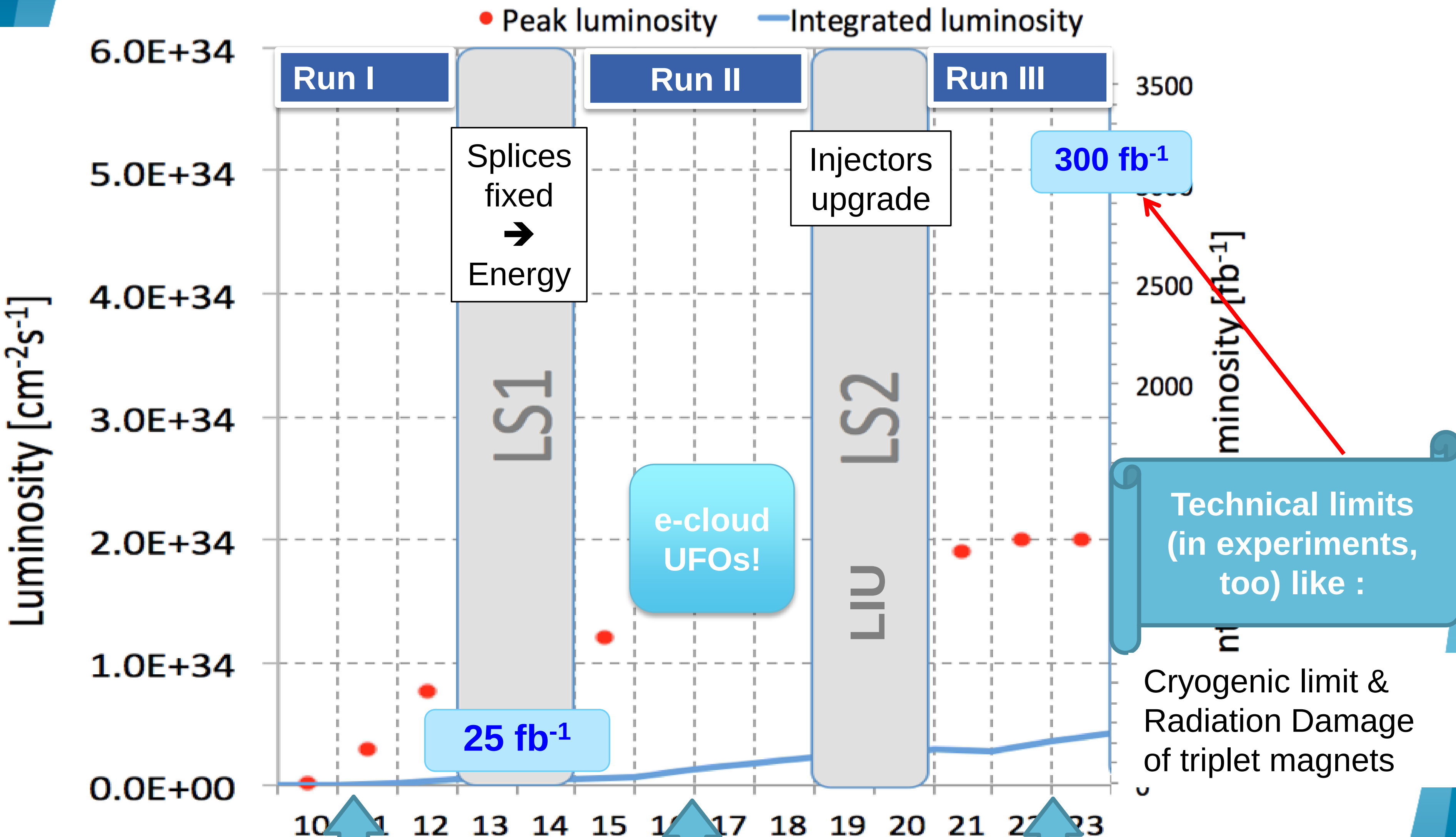
Thanks to G. Arduinig, O. Brüning and S. Fartoukh for the material provided

CERN

Content

- HL-LHC goal and performance optimisation
- HL-LHC challenges
  - Triplet magnets
  - Optics challenges: the ATS
  - Beam-Beam aspects
  - Crab-cavities
  - Collimation
  - Vibrations
- Performance projections

From LHC to HL-LHC

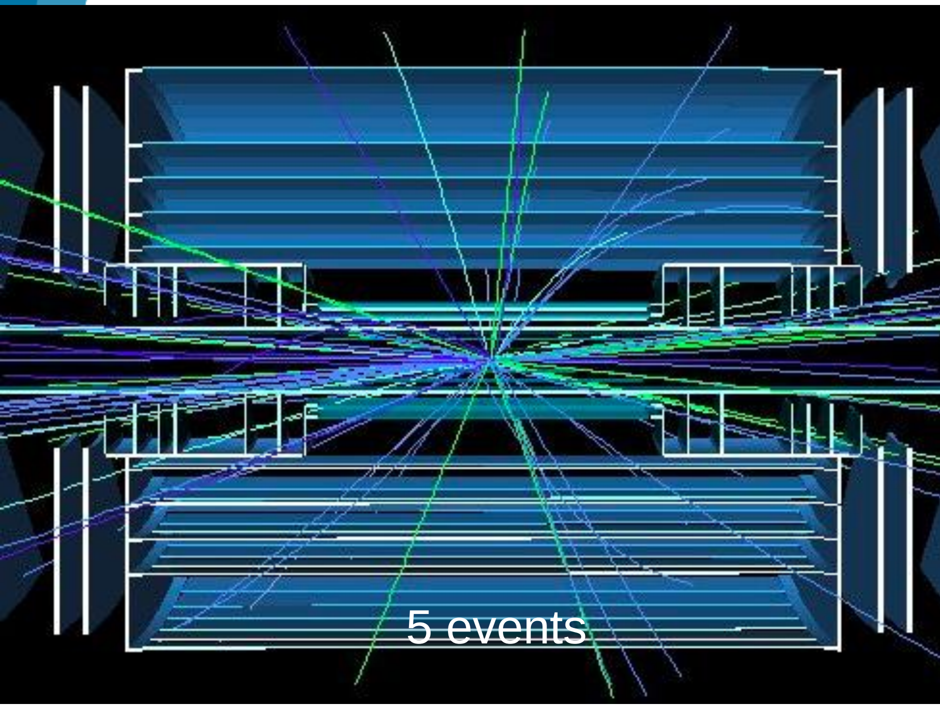


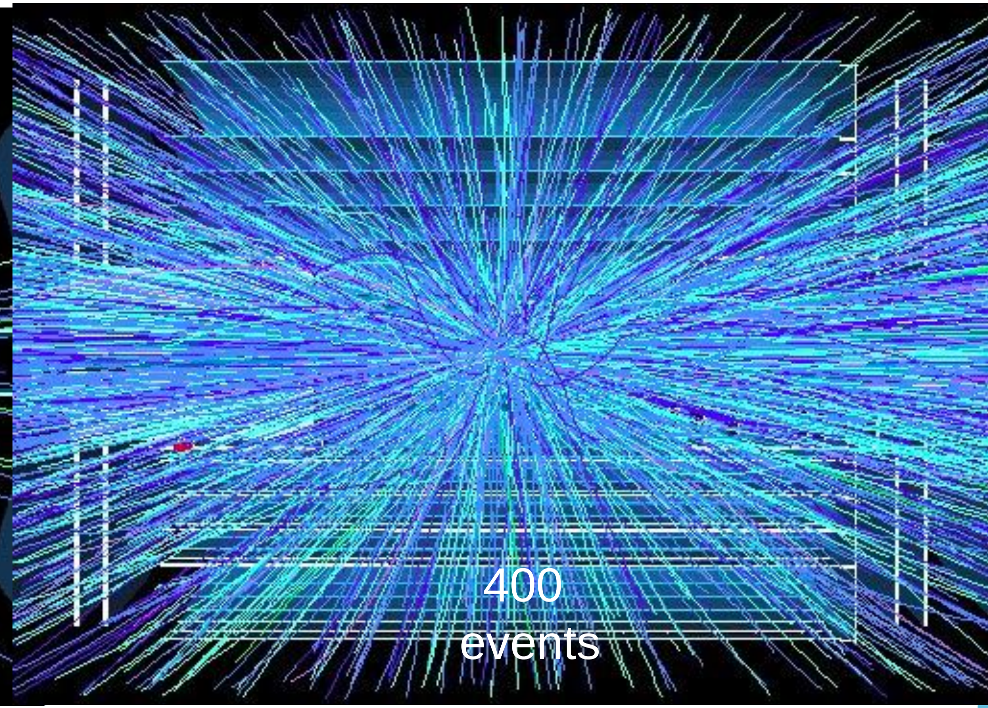
0.75 10^{34} $cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

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





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

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LHC upgrade goals: Performance optimisation

Luminosity recipe (round beams):

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

- ➔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

LHC Limitations and HL-LHC Challenges

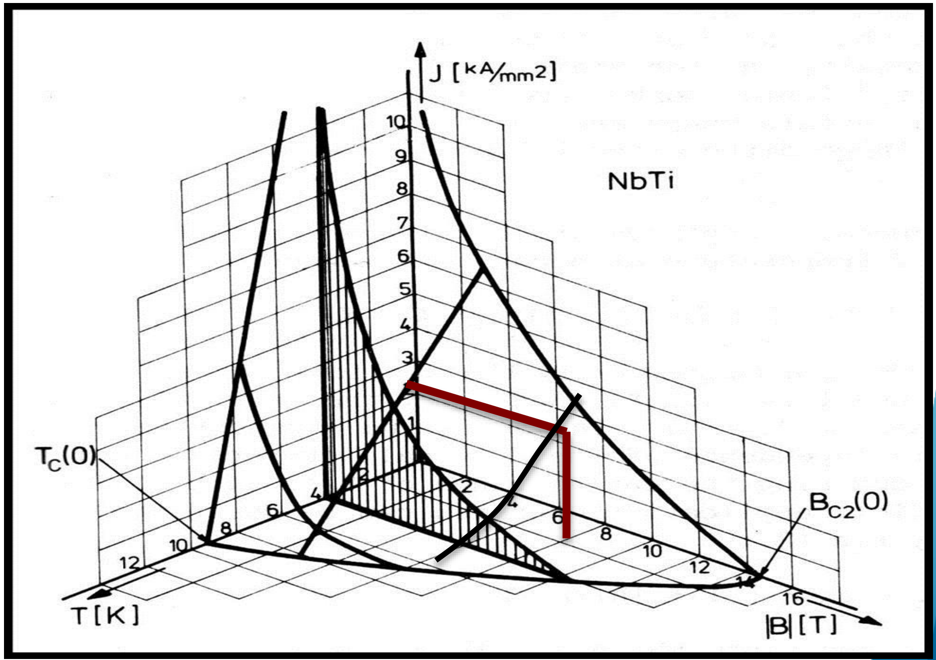
- Technical bottle necks (e.g. cryogenics) ➔ New addit. Equipment
- Insertion magnet lifetime and aperture:
  ➔ New insertion magnets and low-β with increased aperture
- Geometric Reduction Factor: ➔ SC Crab Cavities
  ➔ New technology and a first for a hadron storage ring!
- Performance Optimization: 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)!!!

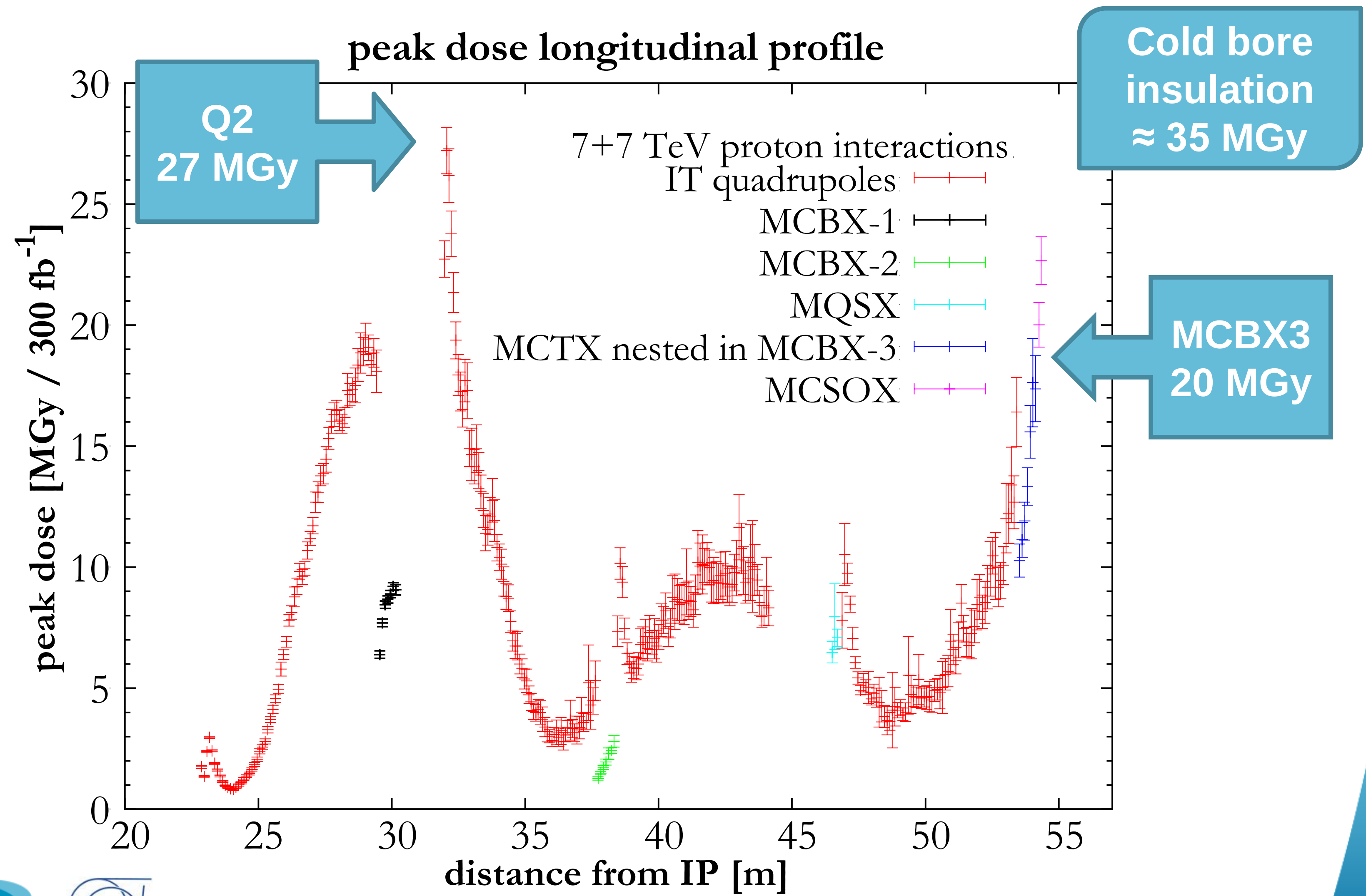
LHC Production in collaboration with USA and KEK

Critical Surface for NbTi



HL-LHC technical bottleneck

Radiation damage to triplet magnets at 300 fb-1



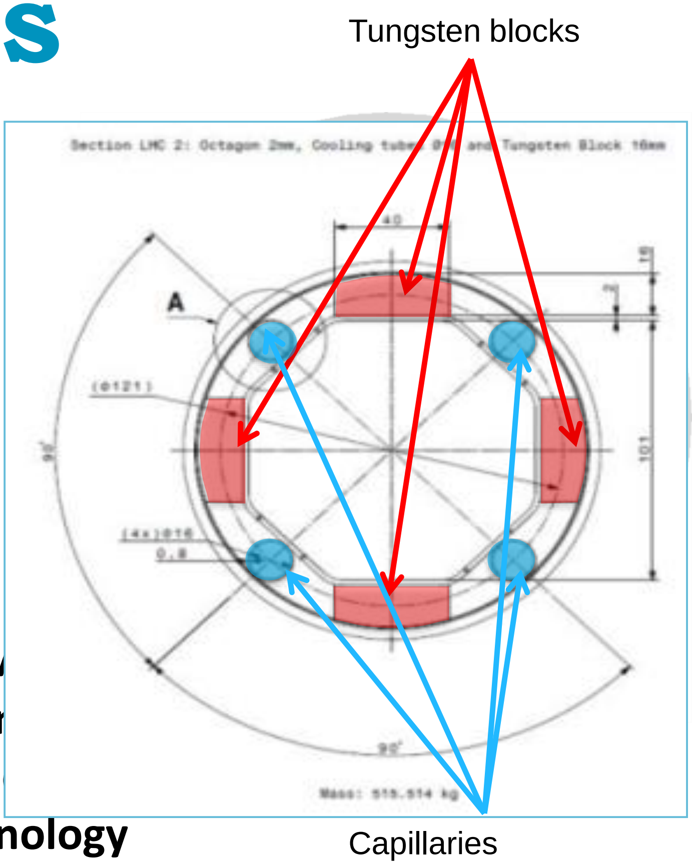
Radiation damage to triplet magnets

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

➔ Shielding!

- ➔ Requires larger aperture!

US-L
magr
Base
technology



- ➔ New magnet technology

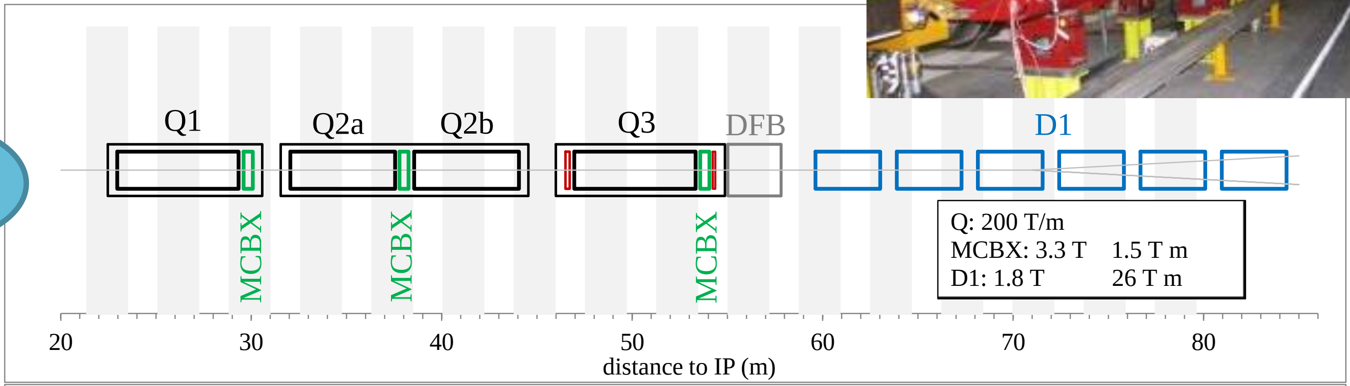
- ➔ 70mm at 210 T/m ➔150mm diameter 140 T/m

  8T peak field at coils ➔ 12T field at coils (Nb_3Sn)!!!

New Interaction Region layout

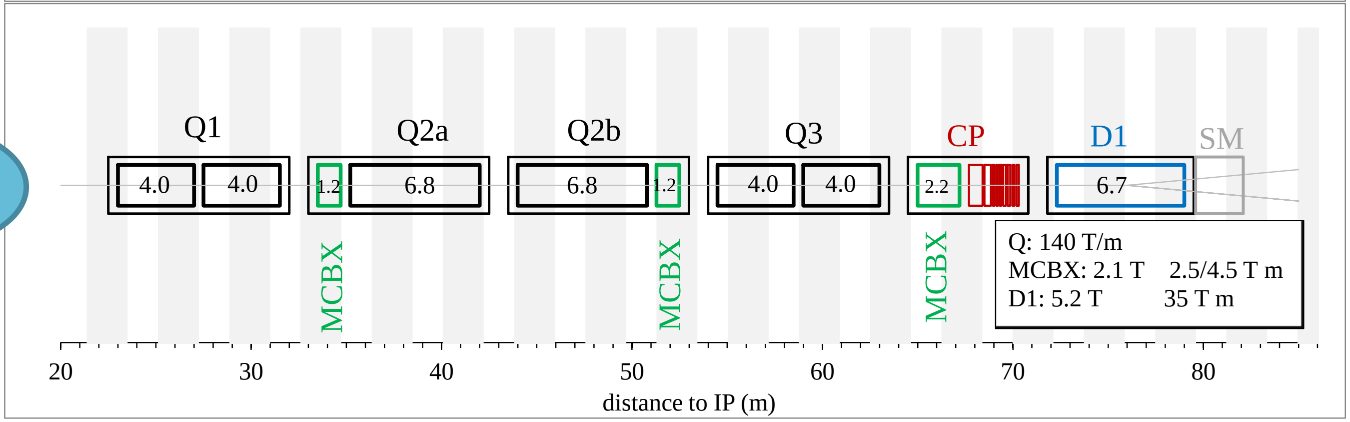
Longer Quads; Shorter D1 (thanks to SC)

ATLAS CMS



LHC

ATLAS CMS



HL LHC

Thick boxes are magnetic lengths -- Thin boxes are cryostats

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 β-beating:
   – limitations from the arc sextupole strength (<600A).

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,

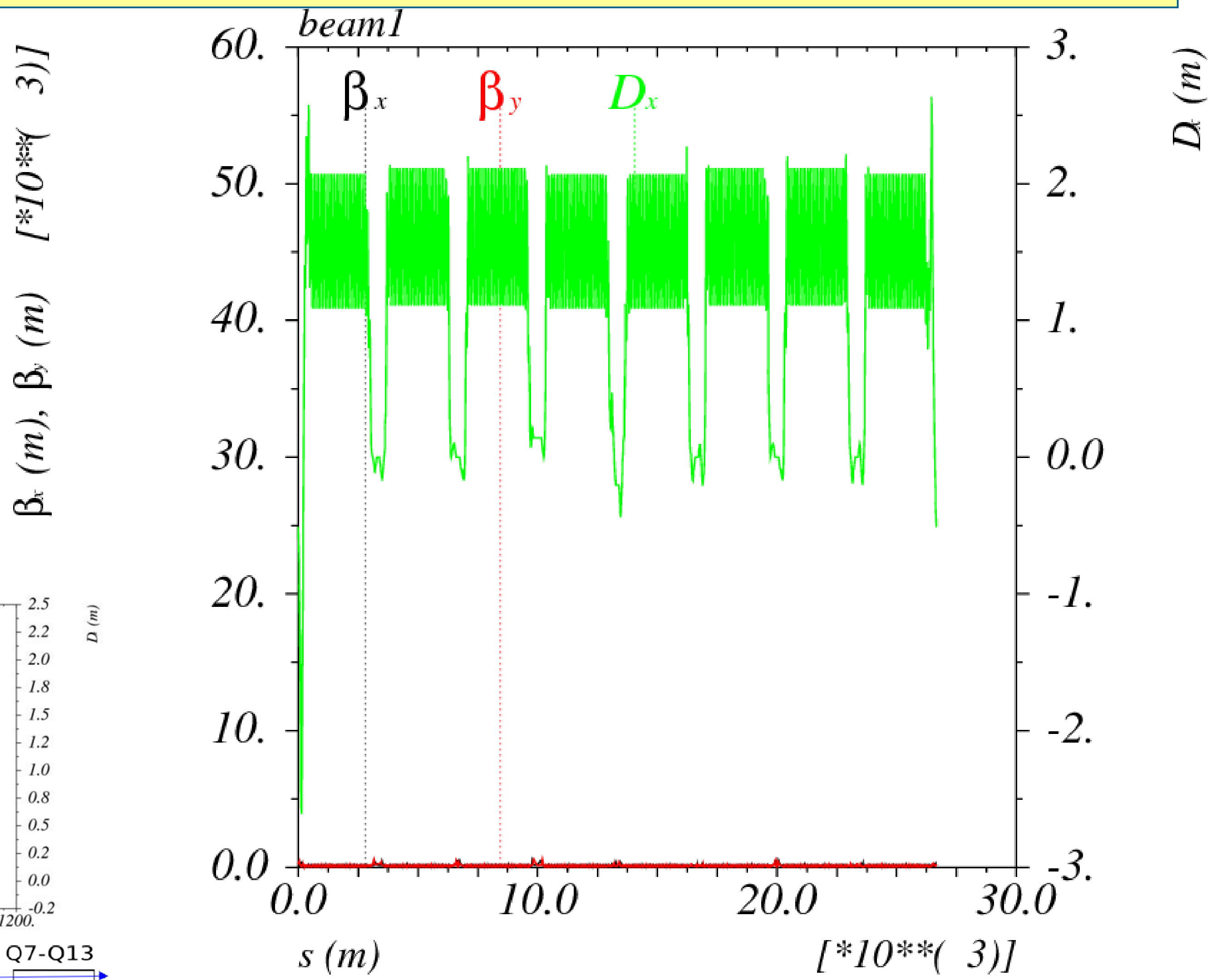
→ inducing **β-beating bumps in sectors 81/12/45/56 to boost the sextupole efficiency at constant strength.**

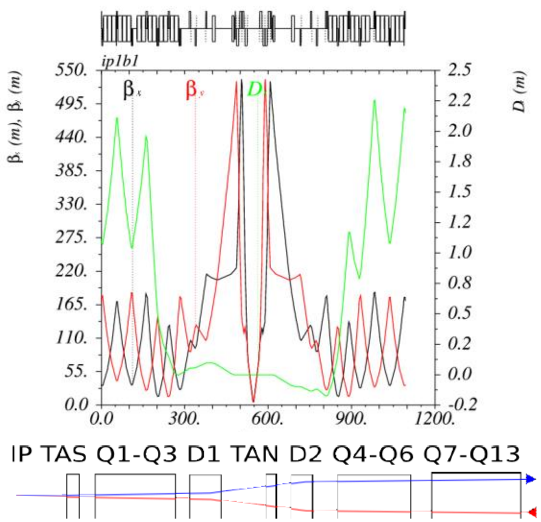
$$\rightarrow \quad \beta^*_{\mathrm{Squeeze}} = \beta^*_{\mathrm{Pre-Squeeze}} \times \frac{\left(\hat{\beta}_{\mathrm{Arc}}\right)_{FODO}}{\left(\hat{\beta}_{\mathrm{Arc}}\right)_{Mismatched}}$$

HL-LHC optics using the ATS

Injection optics $\beta^* = 5.5$ m at IP1 and IP5 (150 T/m IT gradient)

S. Fartoukh

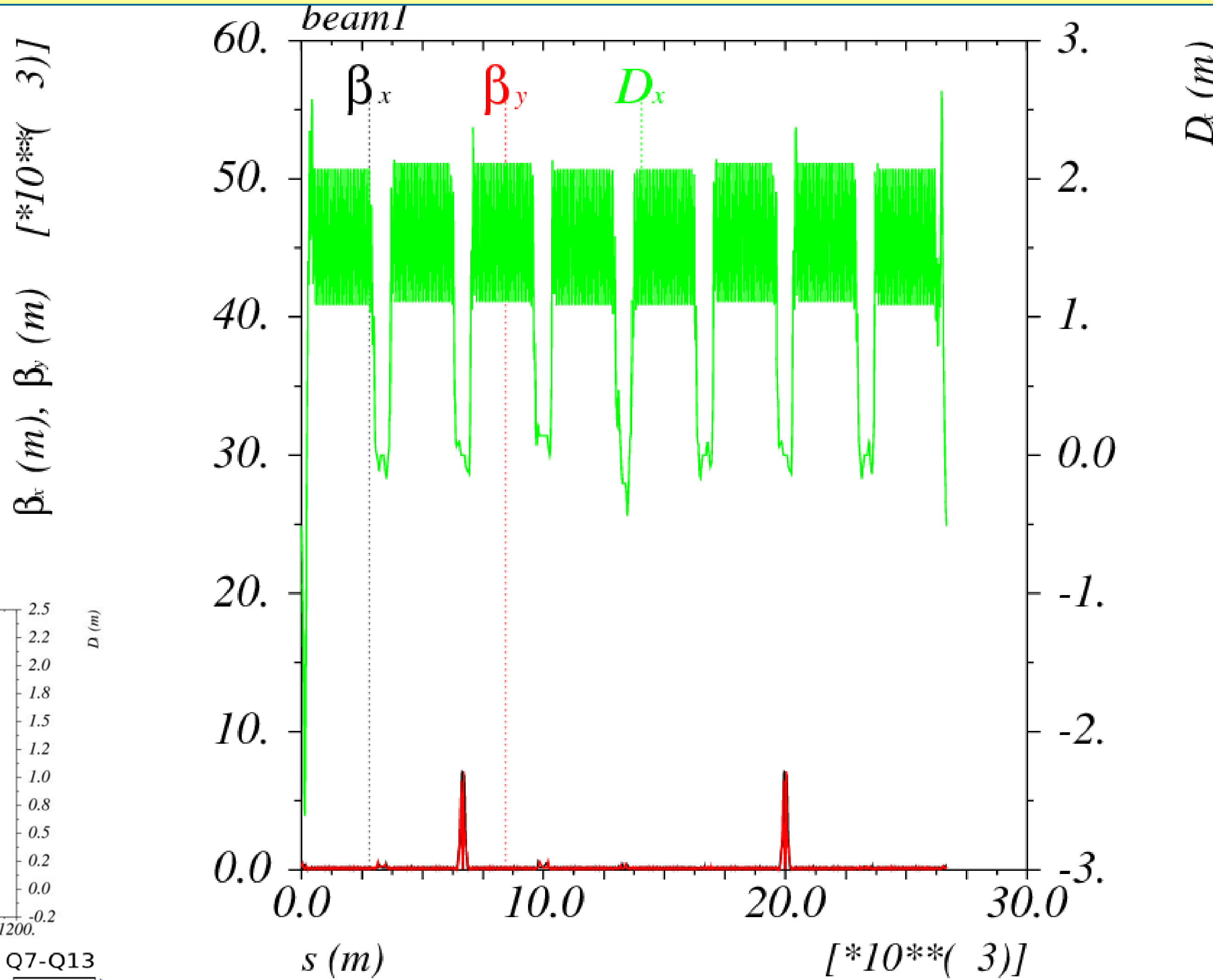


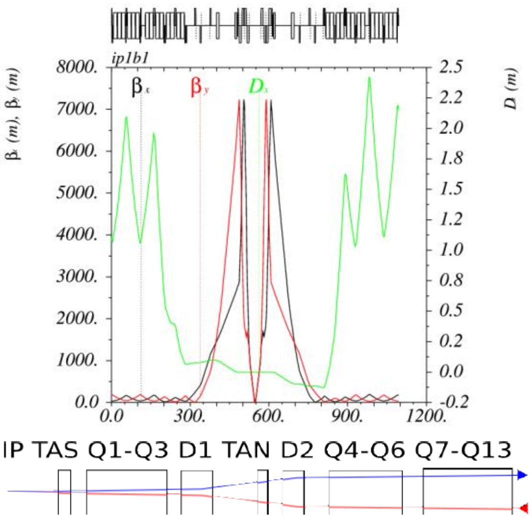


HL-LHC optics using the ATS

Pre-squeezed optics β* = 40 cm at IP1 and IP5 (150 T/m IT gradient)

S. Fartoukh

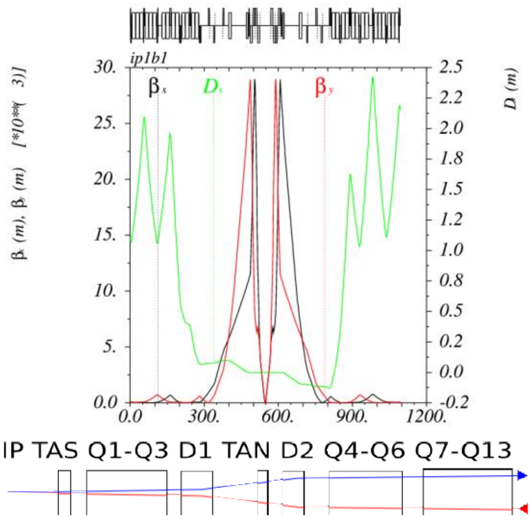


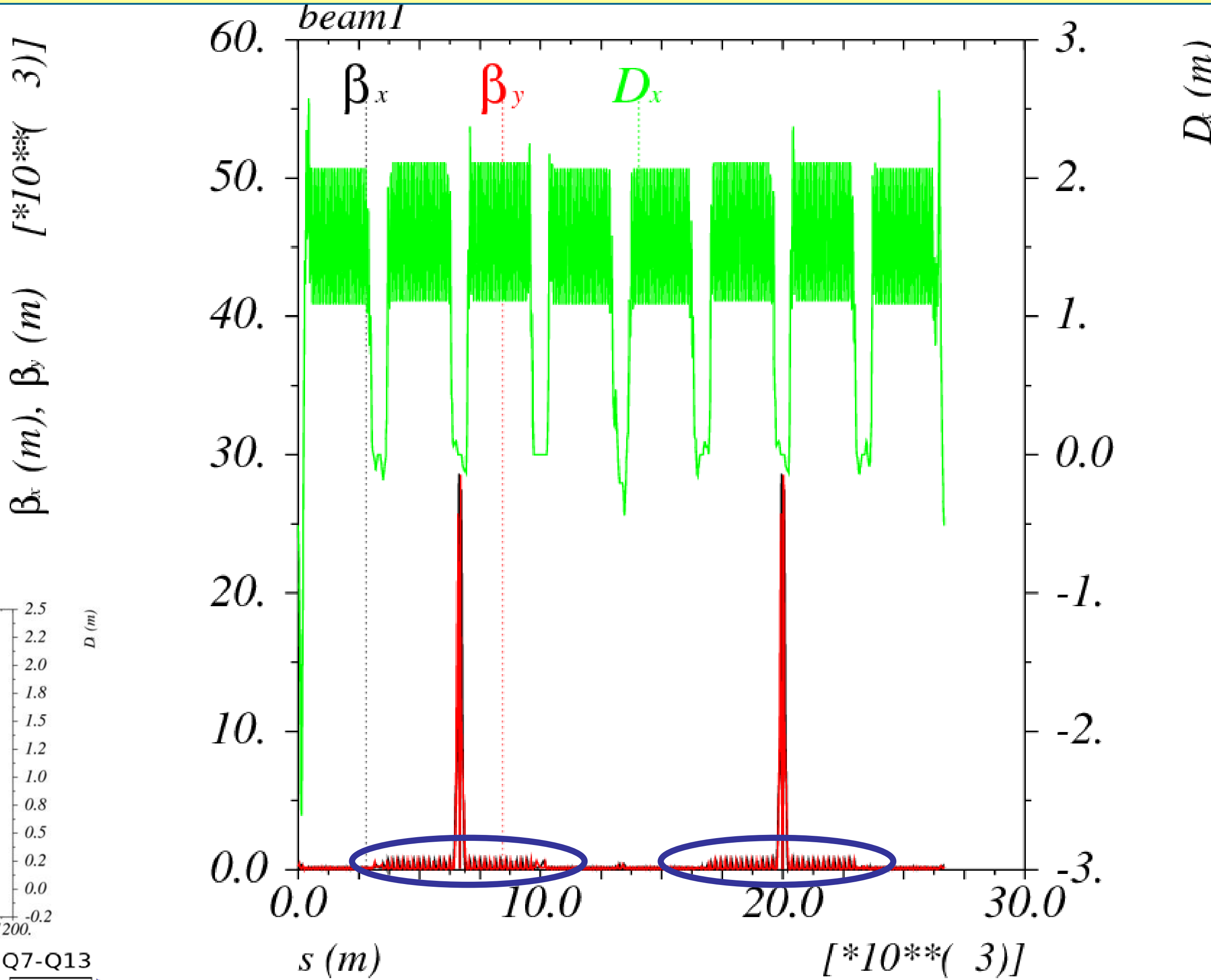


HL-LHC optics using the ATS

Round Squeezed optics $\beta^* = 10$ cm at IP1 and IP5 (150 T/m IT gradient)

S. Fartoukh

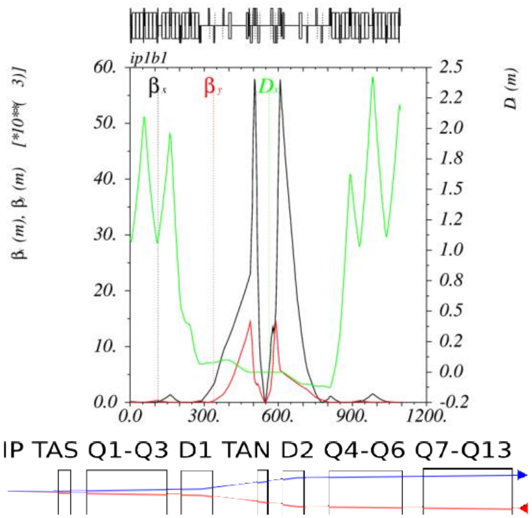


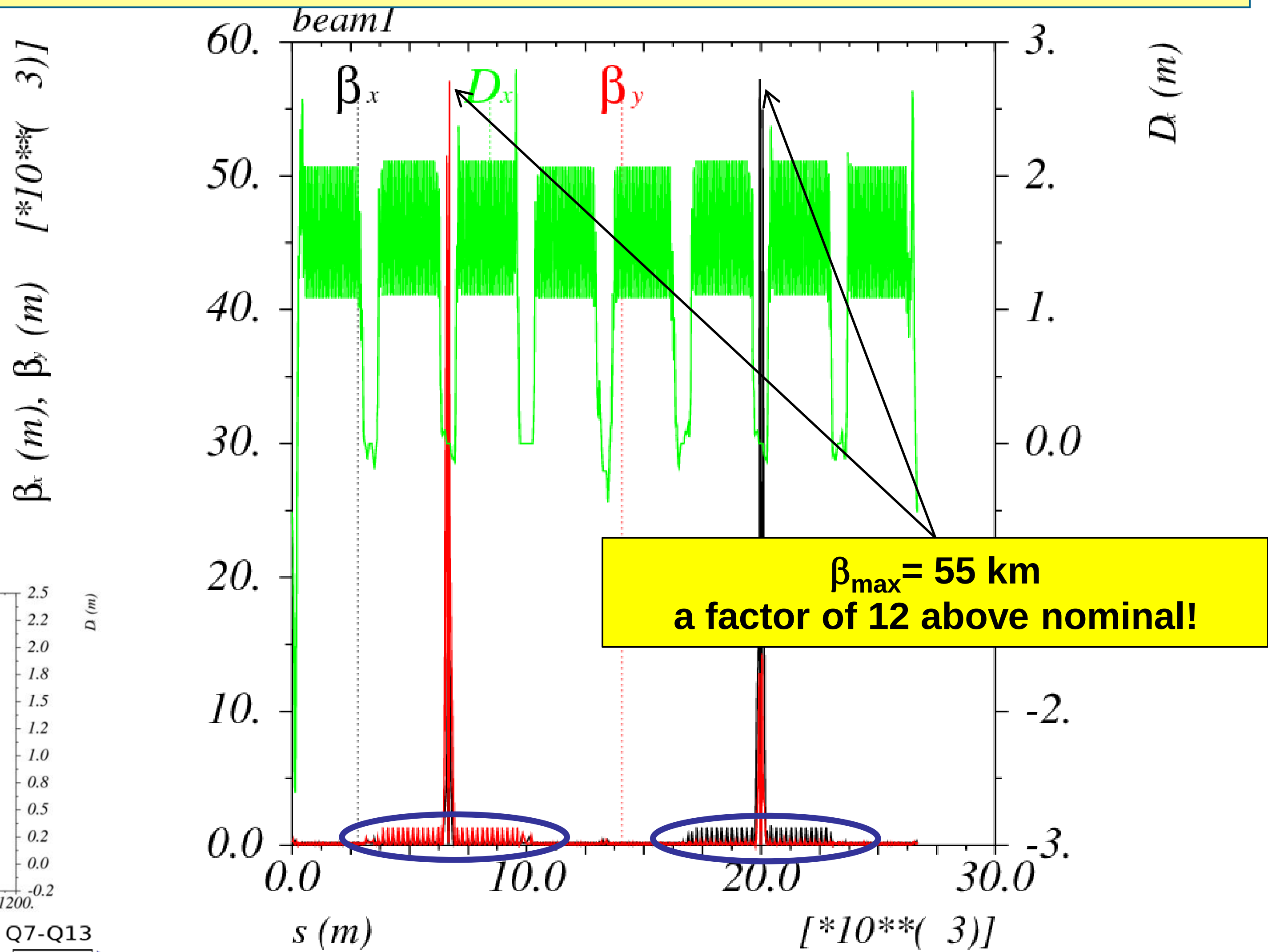


HL-LHC optics using the ATS

Flat Squeezed optics $\beta^* = 20/5$ cm at IP1 and IP5 (150 T/m IT gradient)

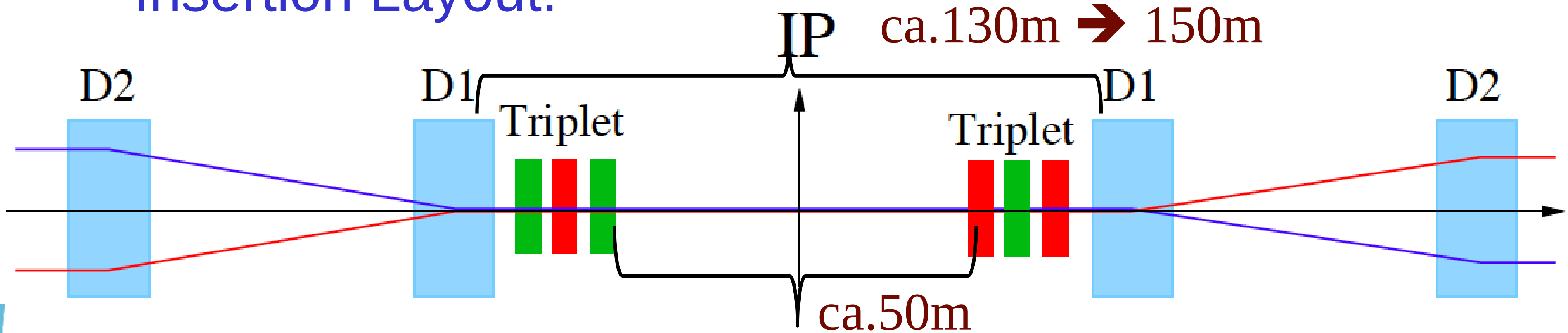
S. Fartoukh





HL-LHC Challenges: Crossing Angle I

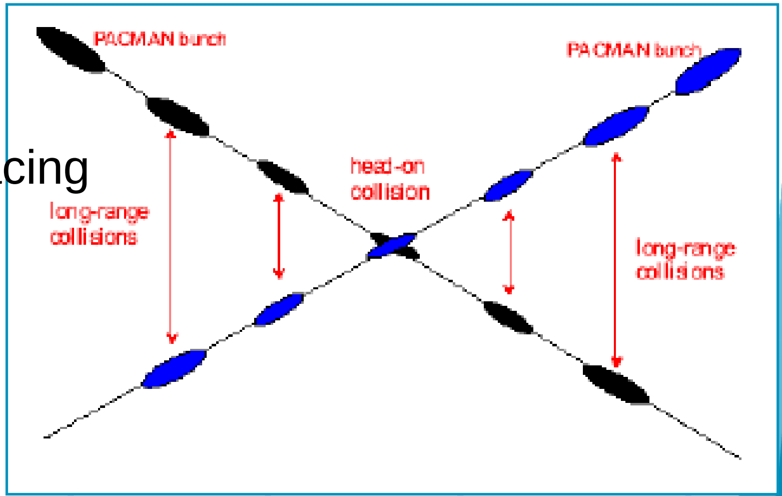
Insertion Layout:



Parasitic bunch encounters:

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

➔ Operation requires crossing angle

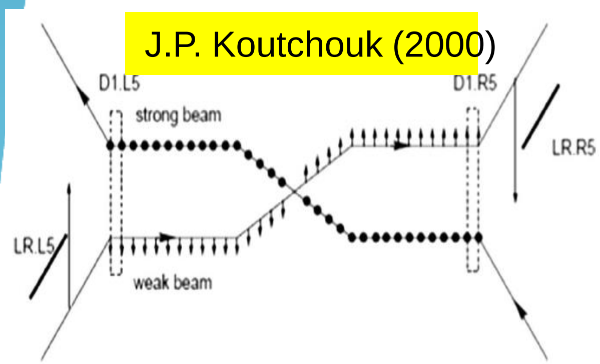


Non-linear fields from long-range beam-beam interaction:

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

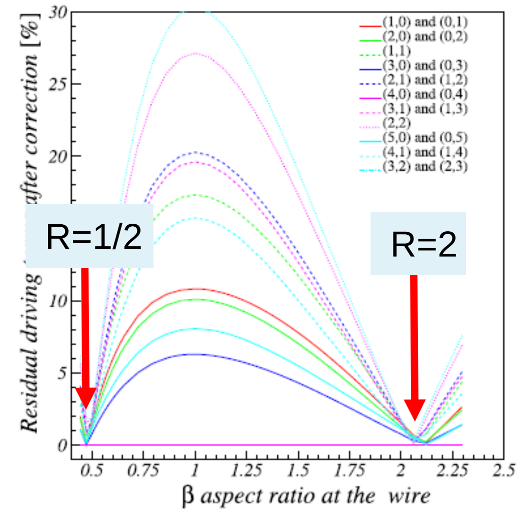
Long range beam-beam compensation option

S. Fartoukh et al, PRSTAB 18, 121001

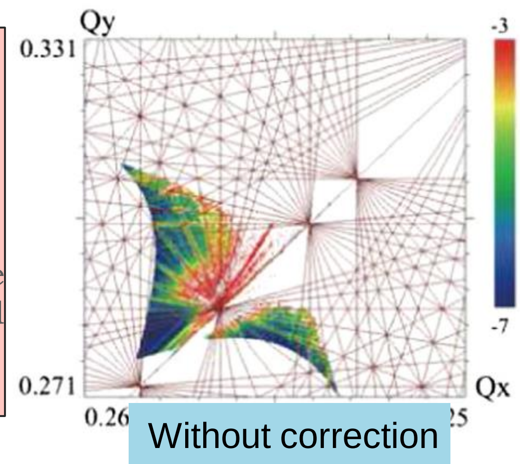


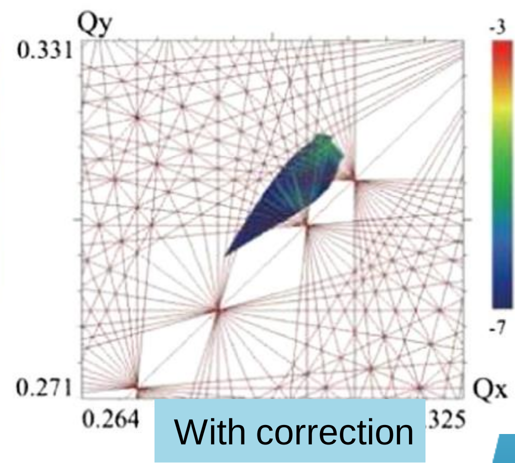
New tools and new theory

- The beta aspect ratio at the wire(s) is fundamental
- $\beta_x/\beta_y = 1$ is a poor compromise with 1 wire/IP
- **With 2 wires $\beta_x/\beta_y \sim 2$ and 1/2 is optimal for all driving terms !**



- **Provide new credit to the ``HL-LHC Plan B'' (back up w/o crab-cavity)**
- Based on flat optics and BBLR compensation, with similar(+/- 10 %) data quantity and quality w.r.t. the baseline
- Installing the wires between Q4 and Q5, where the optimal β aspect ratio can easily be realized and the integration are quite relaxed (if any!)





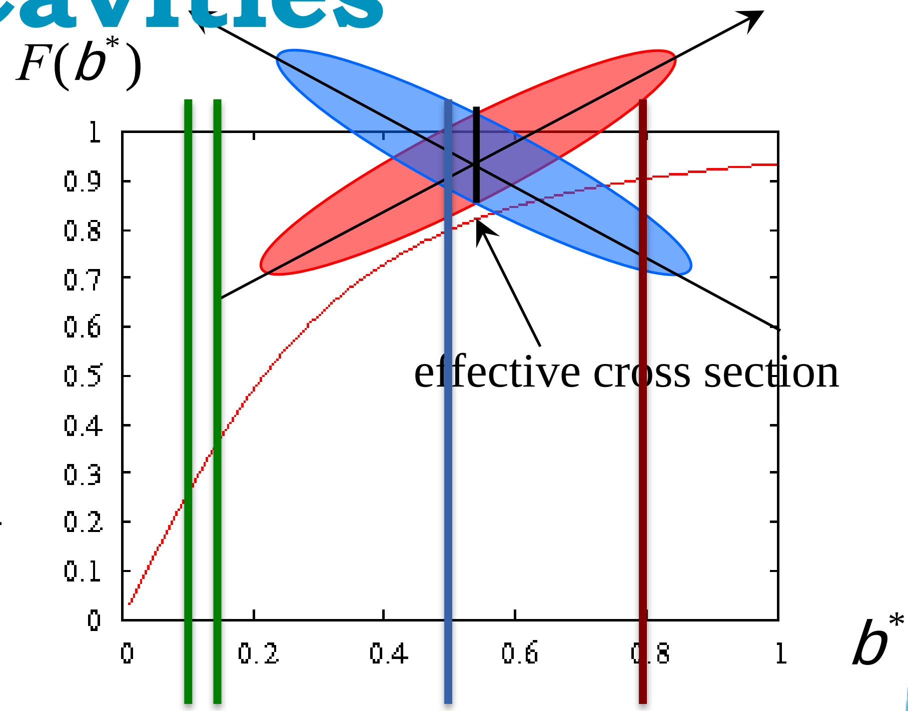
HL-LHC Upgrade Ingredients: Crab Cavities

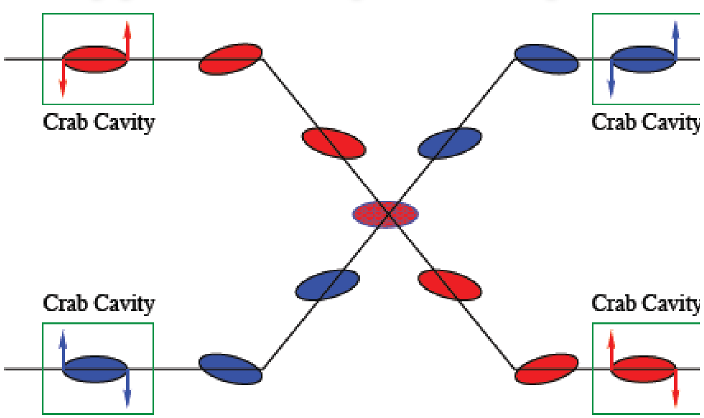
Crab Cavities:
Geometric Luminosity Reduction Factor:

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

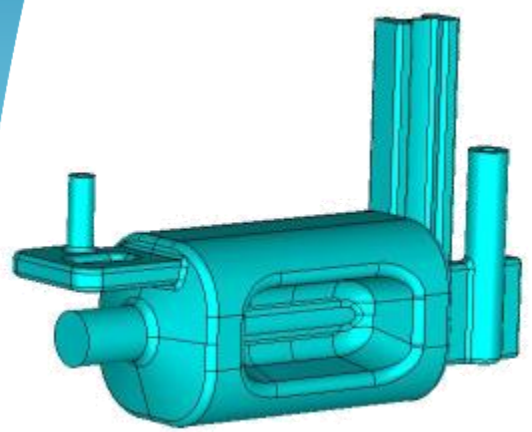
$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

- Noise from cavities to beam?!?
- Challenging space constraints:
  - ➔ requires novel compact cavity design



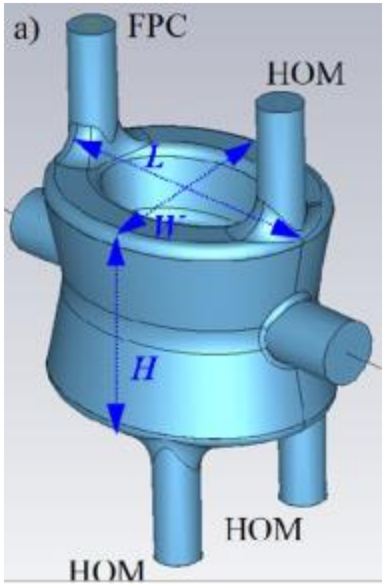


HL-LHC Crab Cavities designs



3 Advanced Design Studies with Different Coupler concepts

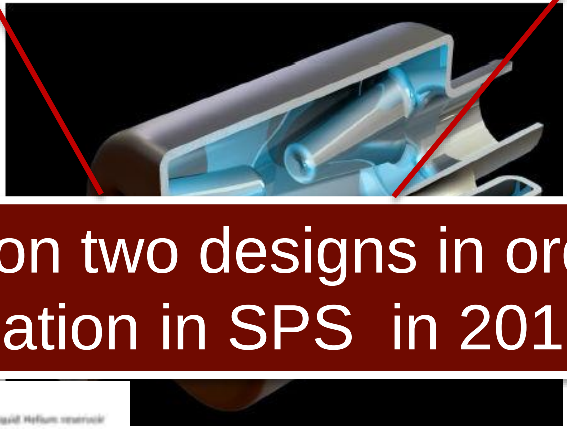
RF Dipole: Waveguide or waveguide-coax couplers



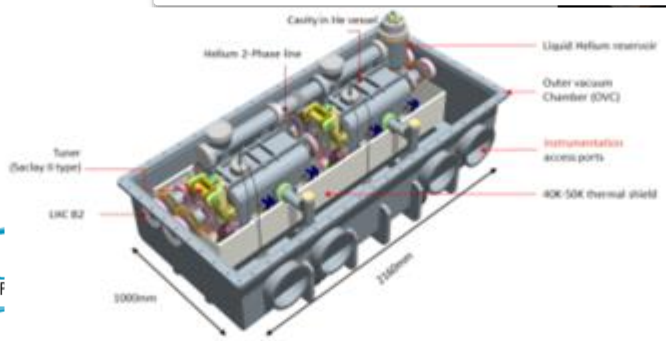
Double ¼-wave:

…with

…a



Concentrate on two designs in order to be ready for test installation in SPS in 2016/2017 TS

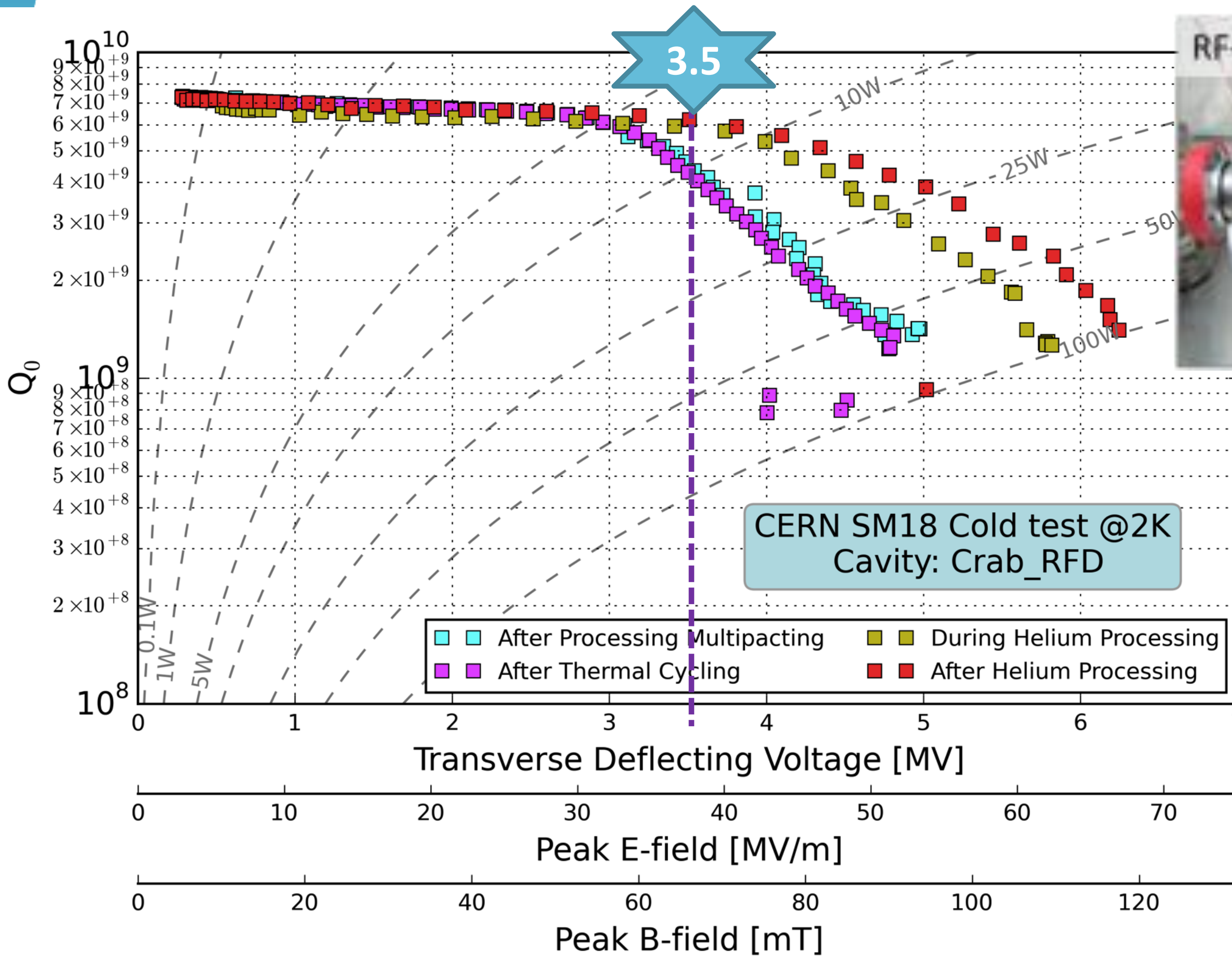


Present baseline: 4 cavity/cryomod

TEST in SPS under preparation for 2017

And excellent first results: RF Dipole

Recent results from Measurements @ CERN



Initial goal was 3.5 MV however ΔV > 5-6 MV would ease integration

Testing Crab Cavities with Beams

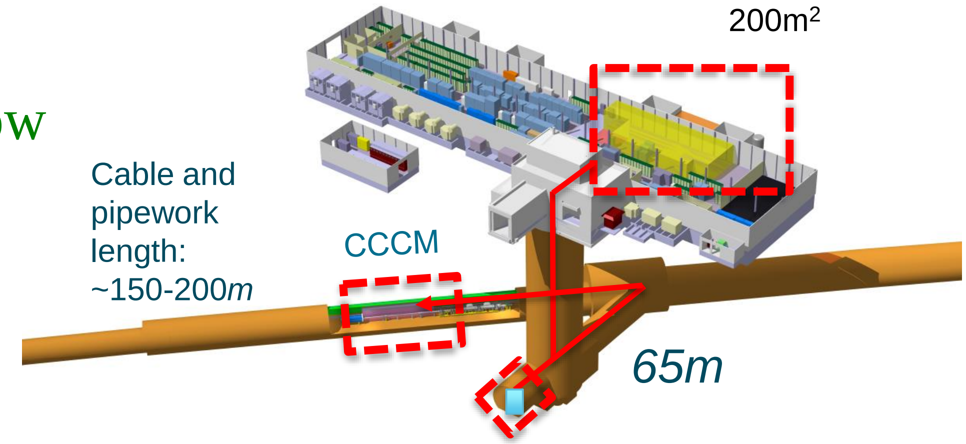
Crab Cavity Test Installation in the SPS:

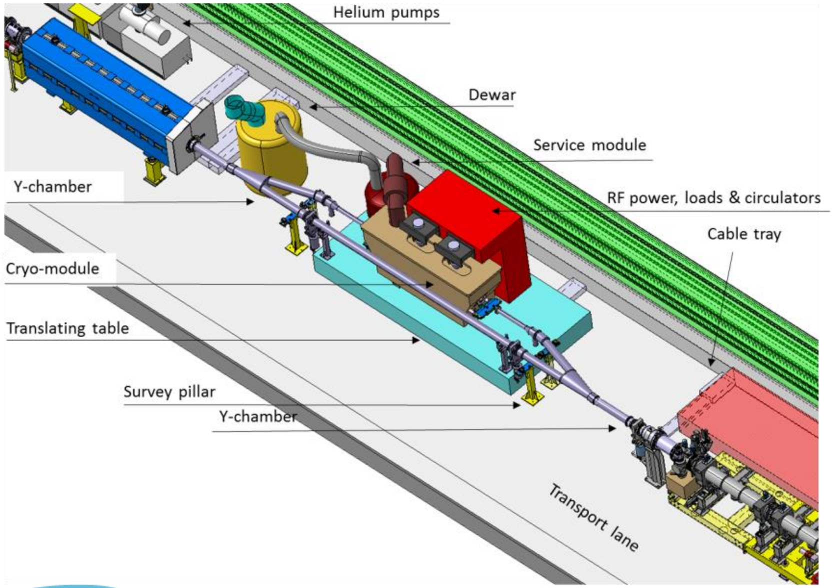
- Vital to gain feedback from operation with beam before launching of cavity production for HL-LHC ➔ need results before LS2!!!
- Tight and ambitious schedule but doable!

➔ Visualization and planning now

➔ Preparation in EYETS 16/17

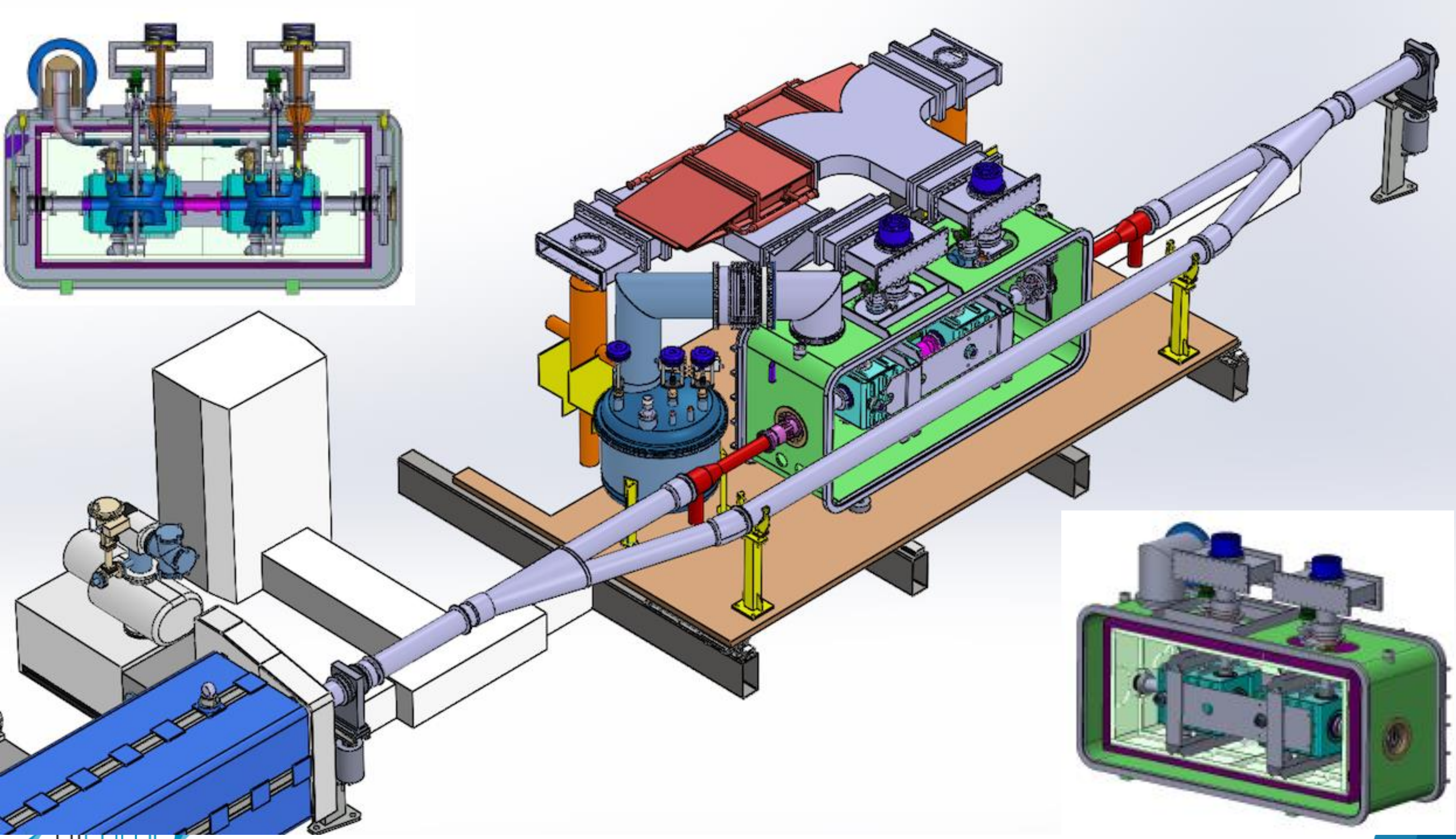
➔ Installation YETS 17/18





➔ vital for project to be able to launch Crab cavity production by LS2!!! (international partners!!!)

SPS beam test: a critical step for Crab Cavities



LHC Challenges: Beam Power

Unprecedented beam power:

Worry about beam losses:

Failure Scenarios ➔ Local beam Impact

➔ Equipment damage

➔ Machine Protection

Lifetime & Loss Spikes ➔ Distributed losses

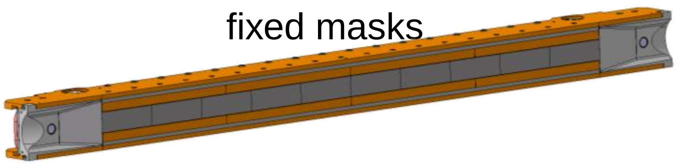
➔ Magnet Quench

➔ R2E and SEU

➔ Machine efficiency

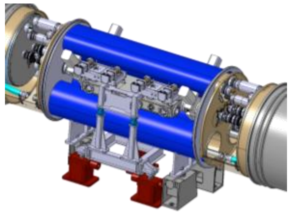
Baseline upgrades

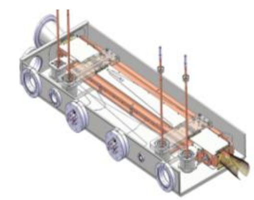
Completely new layouts
Novel materials.
IR1+IR5, <u>per beam</u>:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks



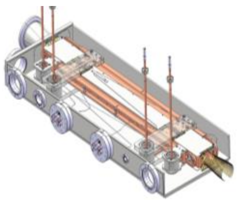
56 new collimators to be produced by LS3 in the present baseline!

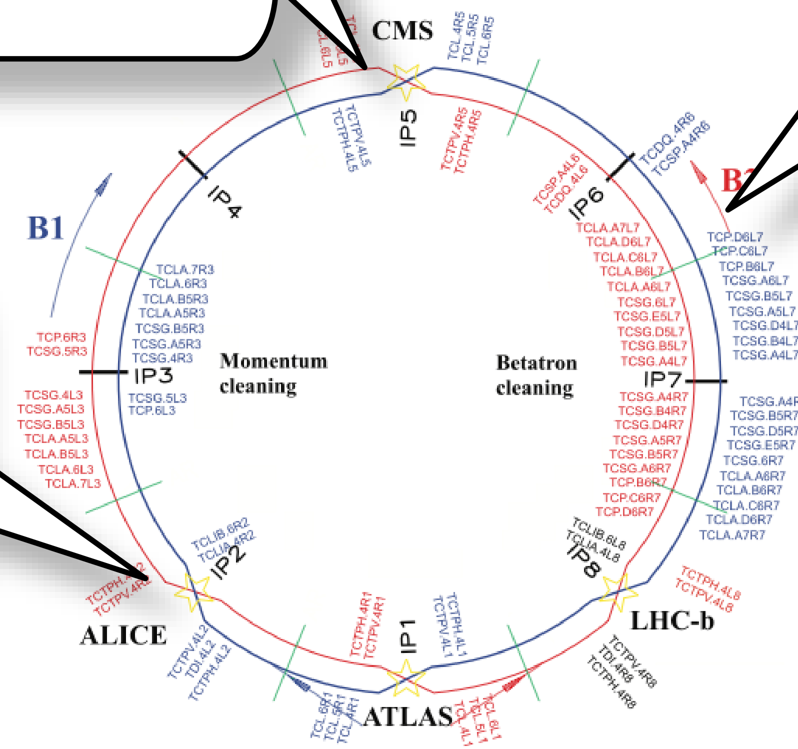
Cleaning: DS coll. + 11T dipoles, 2 units per beam



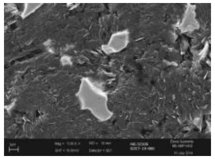


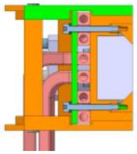
Ion physics debris: DS collimation

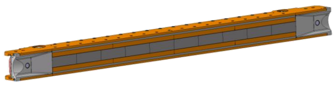




Low-impedance, high robustness secondary collimators

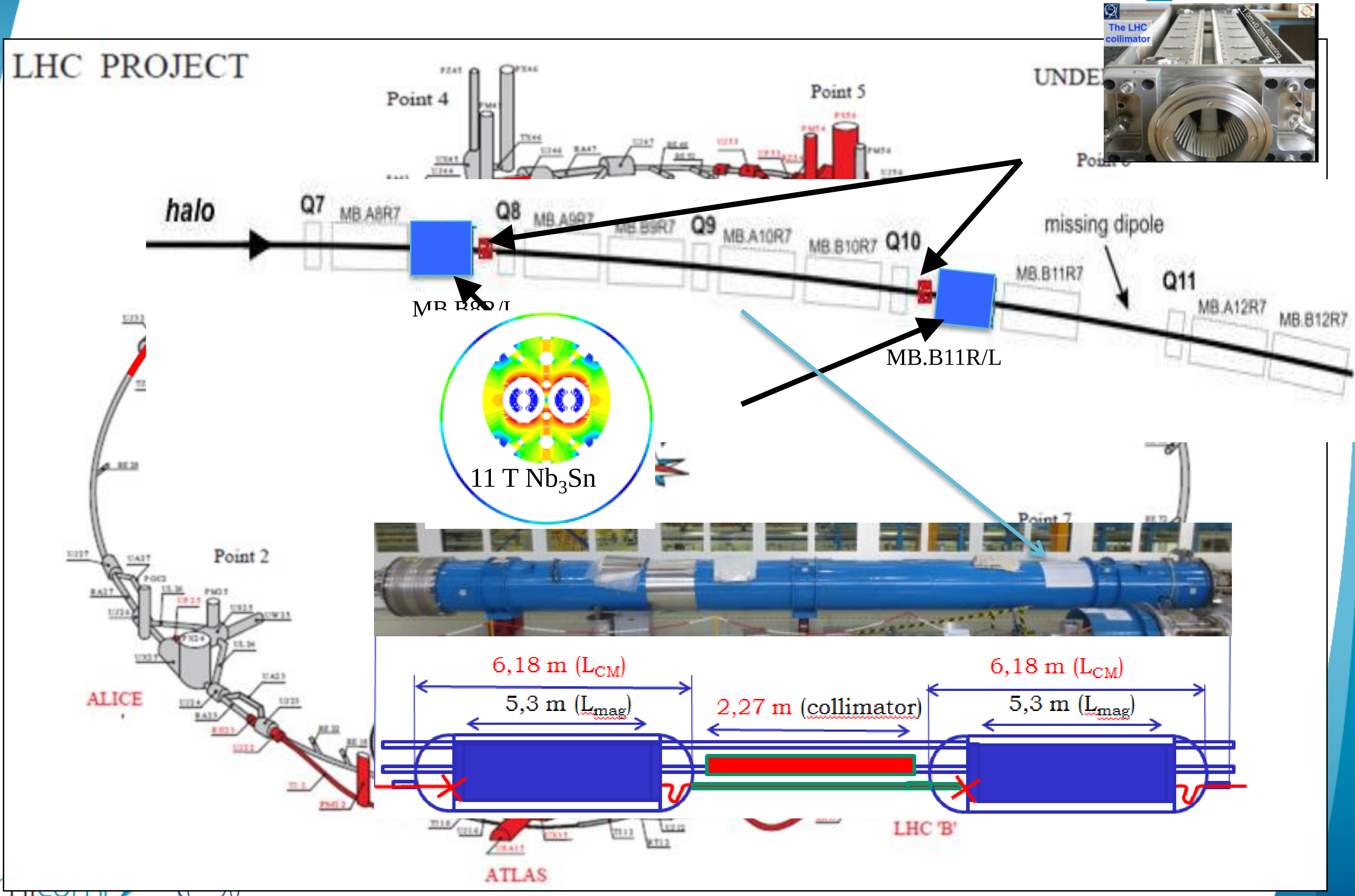






S. Redaelli,
Chamonix 2016, 28-01-2016

DS collimators – 11 T Dipole

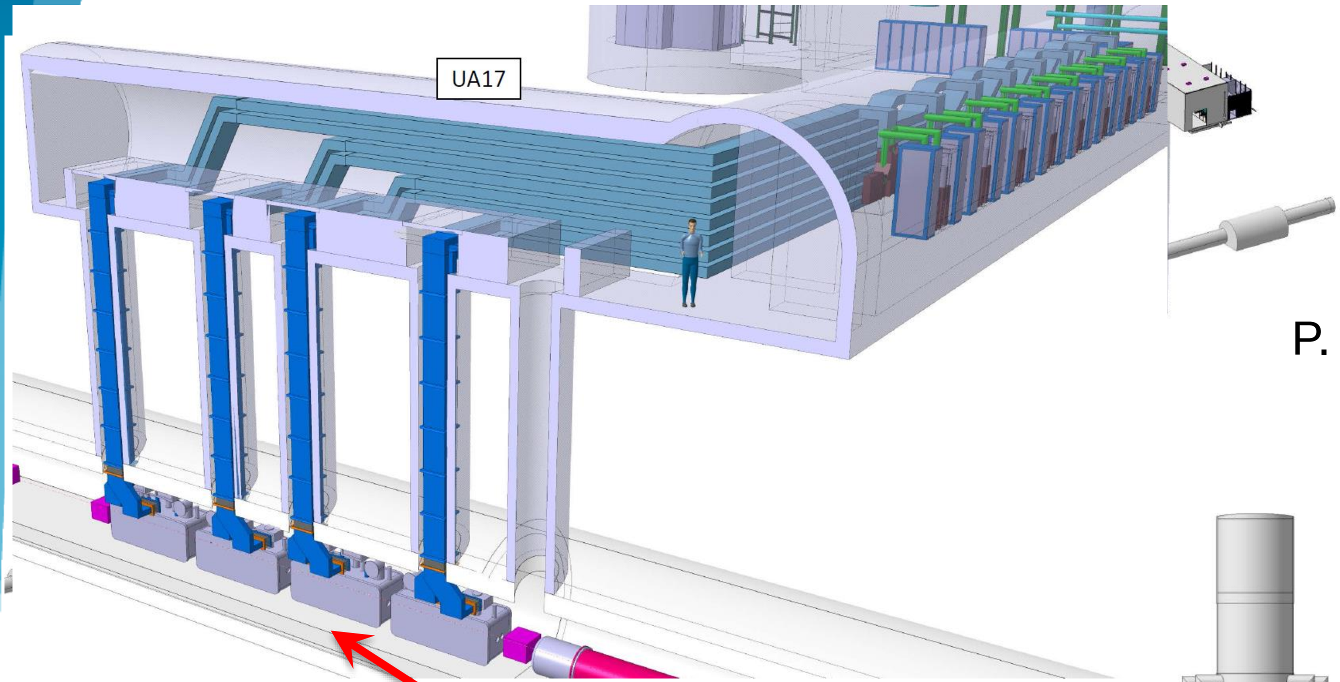


Prototyping of cryogenics bypass @ CERN

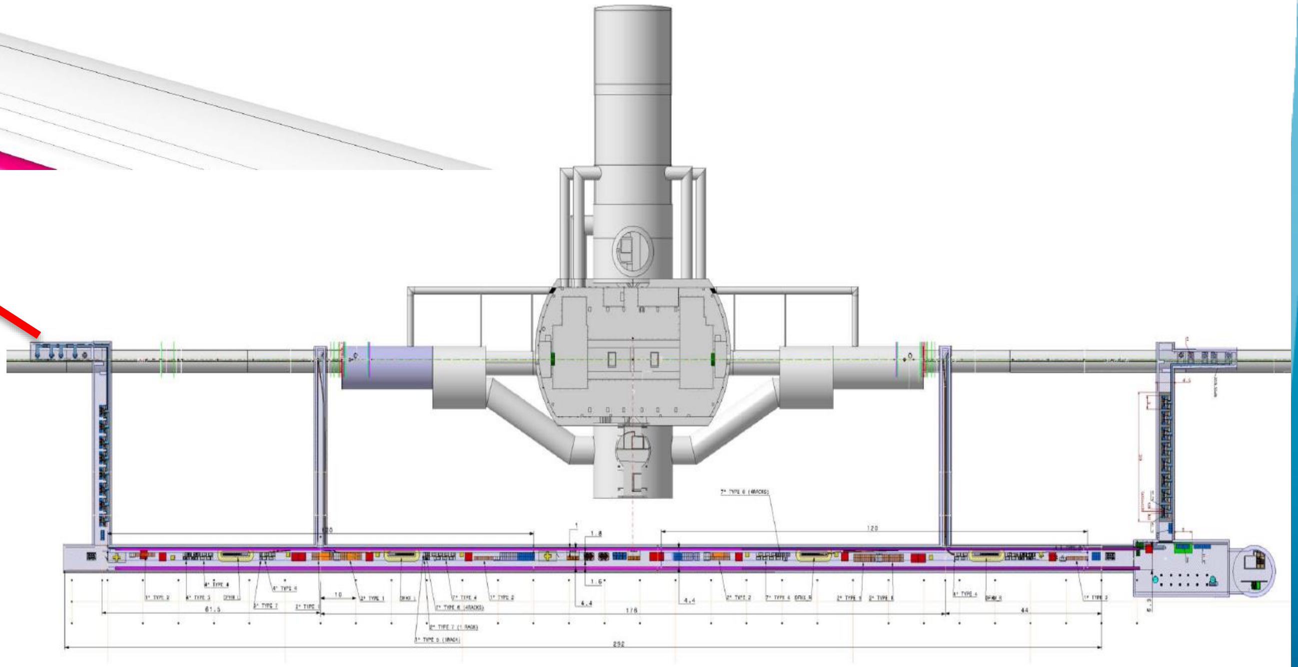
Prototyping of the by-pass crystostat (QTC) for the installation of a warm collimator in the cold dispersion

Magnet: prototypes reached 11 T field in March 2013!

IR1 & IR5 Underground Civil Engineering



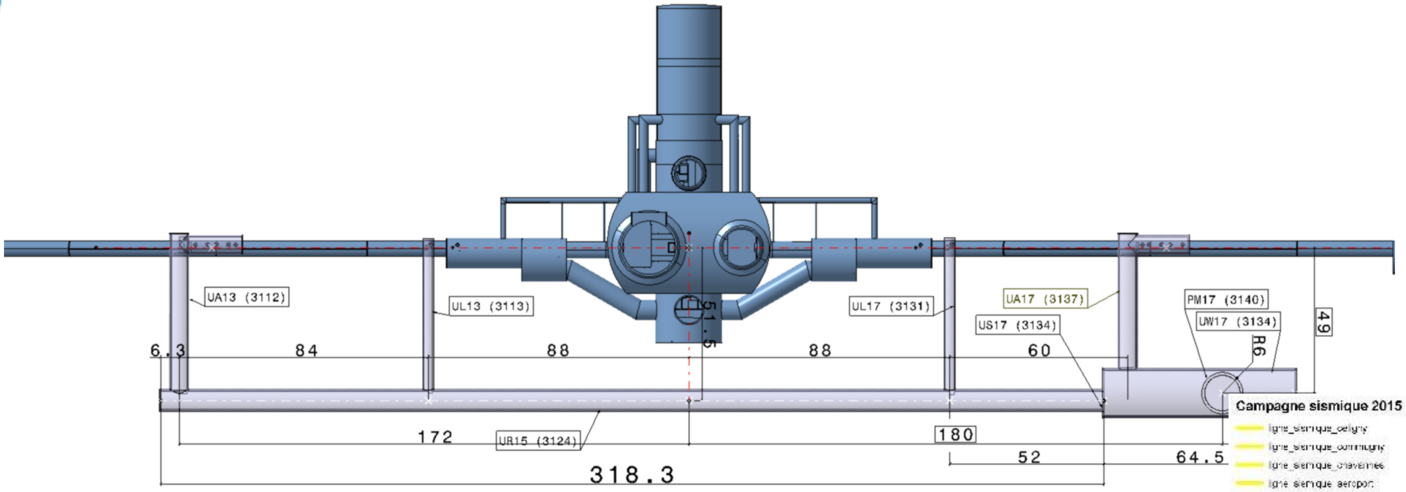
P. Fessia, HL-LHC TDR



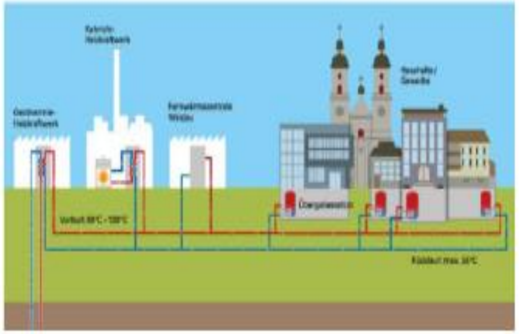
Vibration Tolerances for Operation

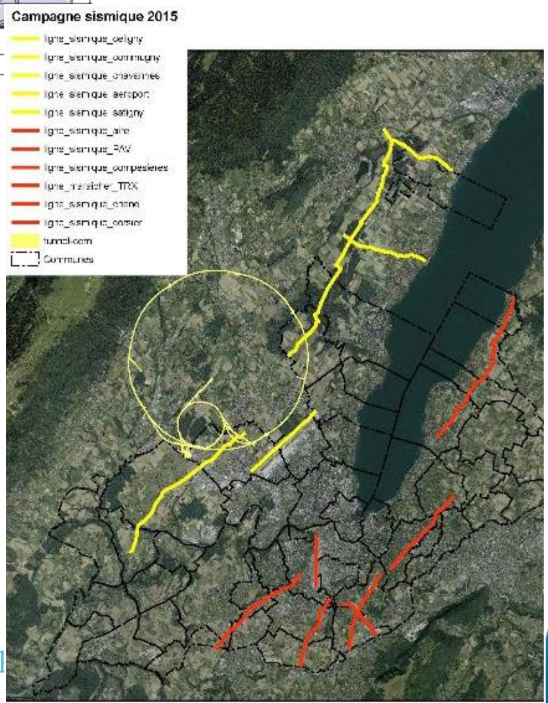
Lessons from Civil Engineering Test Drills and Earth Quakes On Vibration Tolerances:

- Driven by worries about vibrations from the HL-LHC civil engineering



- GEOTHERM2020
  a renewable energy production project by the Canton of Geneva



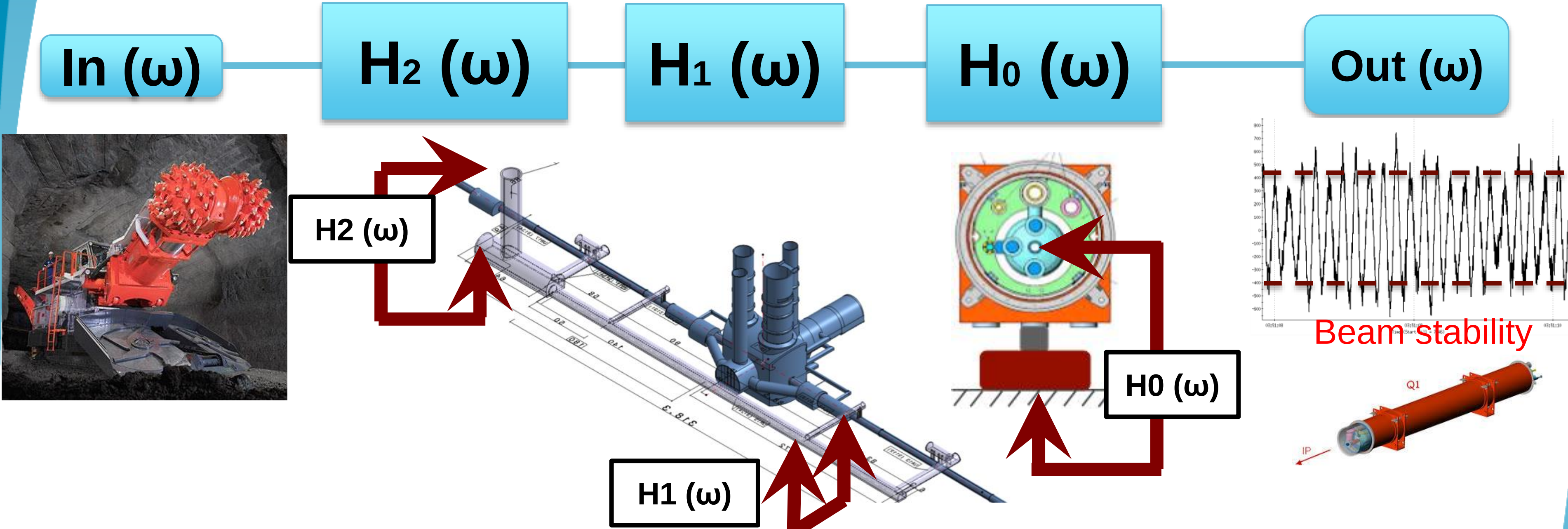


Vibration Tolerances for Operation

Lessons from Civil Engineering Test Drills and Earth Quakes

On Vibration Tolerances:

- From Noise to Beam



➔ O(100) amplification to cold-mass for certain modes (H_0)

➔ O(10-100) attenuation H_1 and H_2

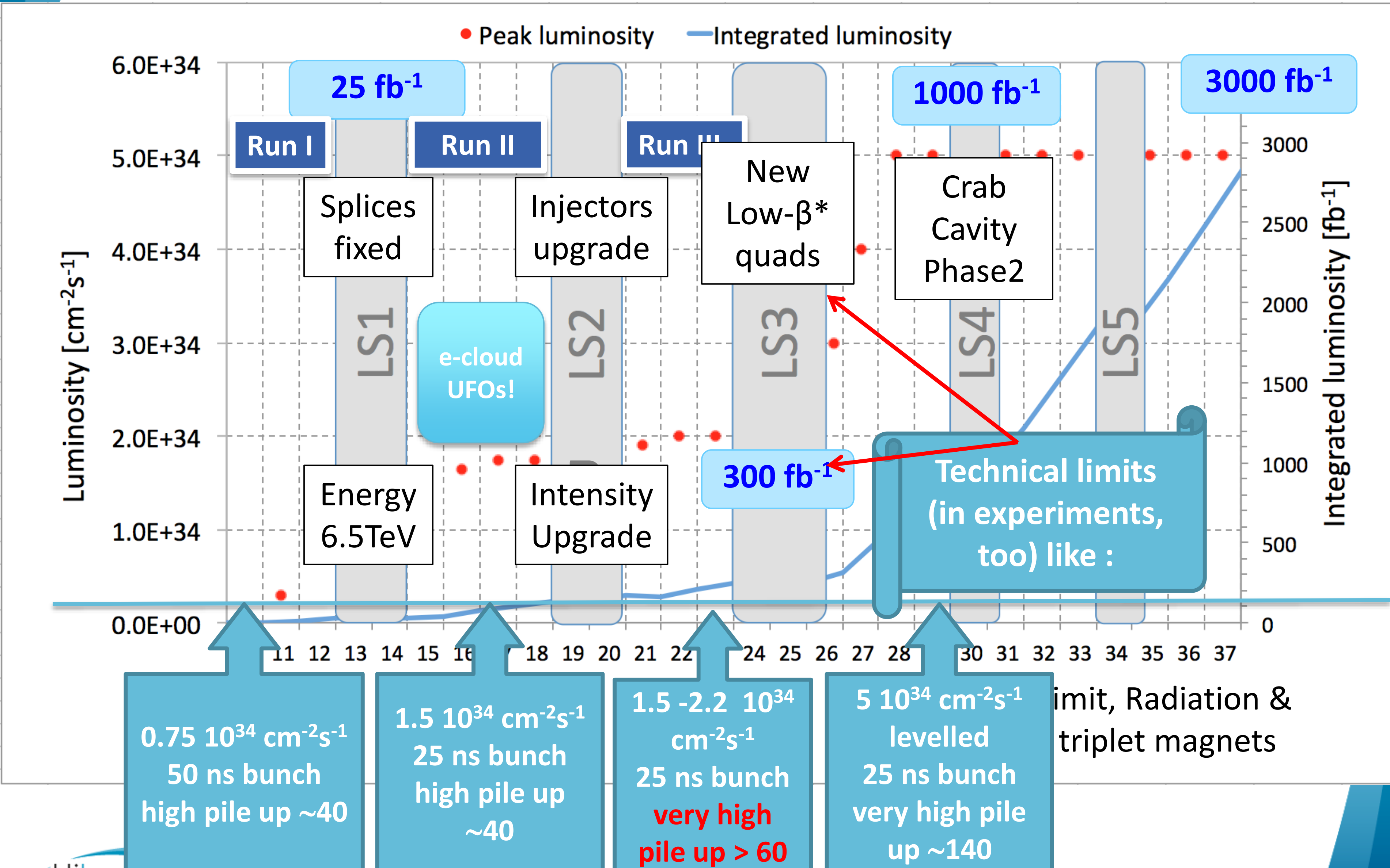
➔ order of micrometer tolerance for vibrations!

➔ Schedule that allows CE construction during LS2!!

➔ Hollow electron lens for halo depletion!

New Schedule: HL-LHC CE during LS2

Performance Projections up to HL-LHC



HL-LHC Baseline Parameters

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

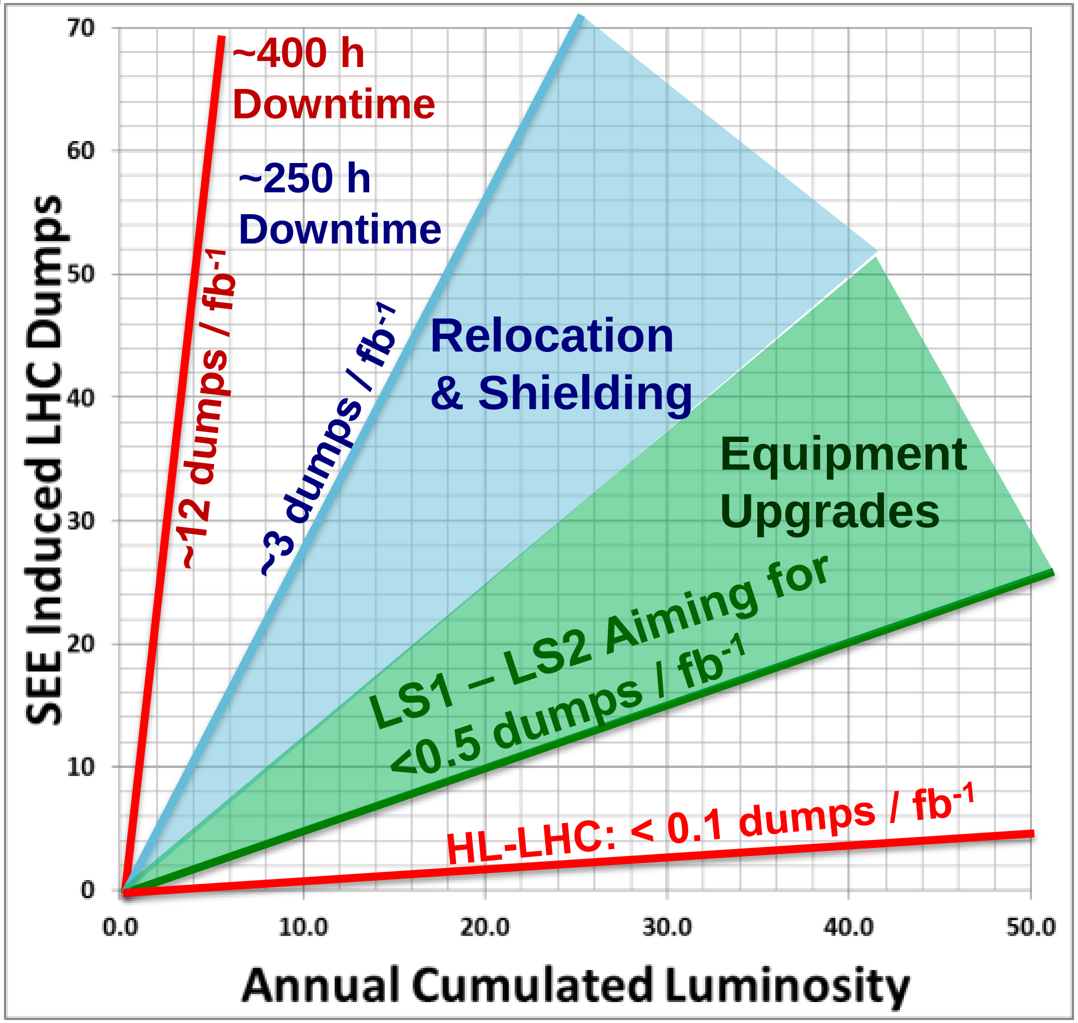
ATS required

Collision values

Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)	HL-LHC 25 ns (BCMS)	HL-LHC 50ns
Beam energy in collision [TeV]	7	**7**	7	7
N_b	1.15E+11	**2.2E+11**	2.2E11	3.5E+11
n_b	2808	**2748**[1]	2604	1404
Number of collisions at IP1 and IP5	2808	**2736**	2592	1404
N_{tot}	3.2E+14	**6.0E+14**	5.7E+14	4.9E+14
beam current [A]	0.58	**1.09**	1.03	0.89
x-ing angle [μrad]	285	**590**	590	590
beam separation [σ]	9.4	**12.5**	12.5	11.4
β^* [m]	0.55	**0.15**	0.15	0.15
ε_n [μm]	3.75	**2.50**	2.50	3
ε_L [eVs]	2.50	**2.50**	2.50	2.50
r.m.s. energy spread	1.13E-04	**1.13E-04**	1.13E-04	1.13E-04
r.m.s. bunch length [m]	7.55E-02	**7.55E-02**	7.55E-02	7.55E-02
IBS horizontal [h]	80 -> 106	**18.5**	18.5	17.2
IBS longitudinal [h]	61 -> 60	**20.4**	20.4	16.1
Piwinski angle	0.65	**3.14**	3.14	2.87
Geometric loss factor R0 without crab-cavity	0.836	**0.305**	0.305	0.331
Geometric loss factor R1 with crab-cavity	(0.981)	**0.829**	**0.829**	**0.838**
beam-beam / IP without Crab Cavity	3.1E-03	**3.3E-03**	3.3E-03	4.7E-03
beam-beam / IP with Crab cavity	3.8E-03	**1.1E-02**	1.1E-02	1.4E-02
Peak Luminosity without crab-cavity [$cm^{-2}\,s^{-1}$]	1.00E+34	**7.18E+34**	6.80E+34	8.44E+34
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2}\,s^{-1}$]	(1.18E+34)	**19.54E+34**	18.52E+34	21.38E+34
Events / crossing without levelling w/o crab-cavity	27	**198**	198	454
Levelled Luminosity [$cm^{-2}\,s^{-1}$]	-	**5.00E+34**	5.00E34	2.50E+34
Events / crossing (with levelling and crab-cavities for HL-LHC)	27	**138**	146	135
Peak line density of pile up event [evt/mm] (max over stable beam)	0.21	**1.25**	1.31	1.20
Levelling time [h] (assuming no emittance growth)	-	**8.3**	7.6	18.0

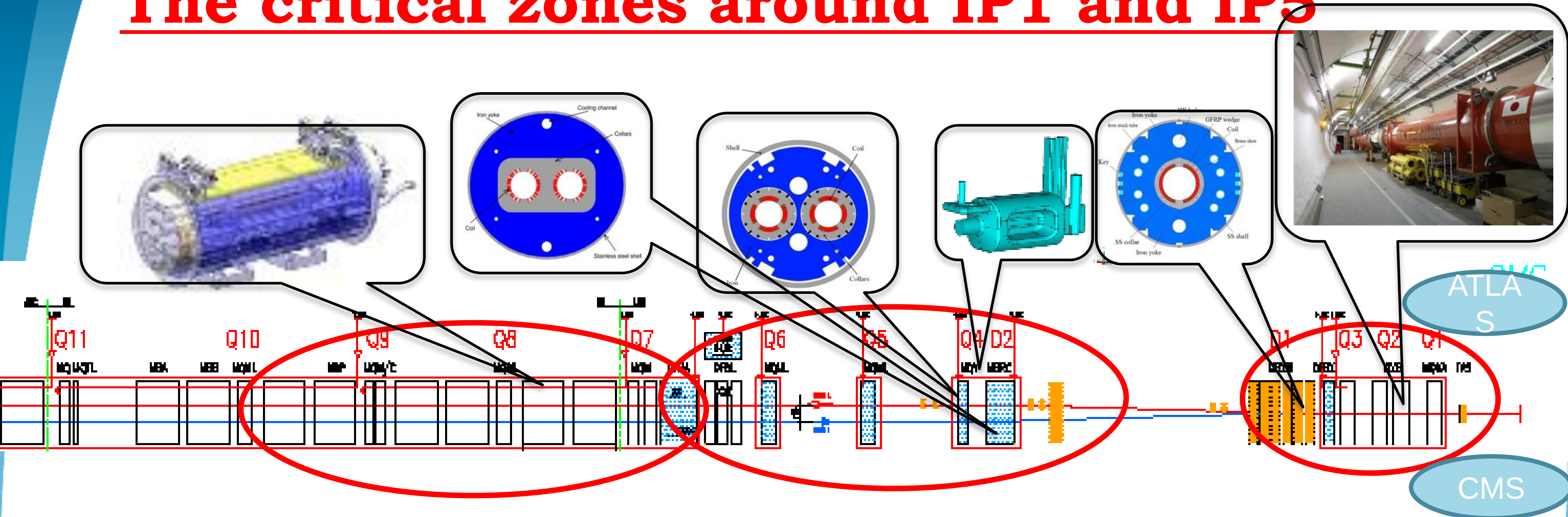
Reserve slides

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

The 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 LHC !!
→ Plus technical infrastructure (e.g. Cryo and Powering)!!