Update of the HL-LHC Baseline Configuration, operation scenarios and performance projections

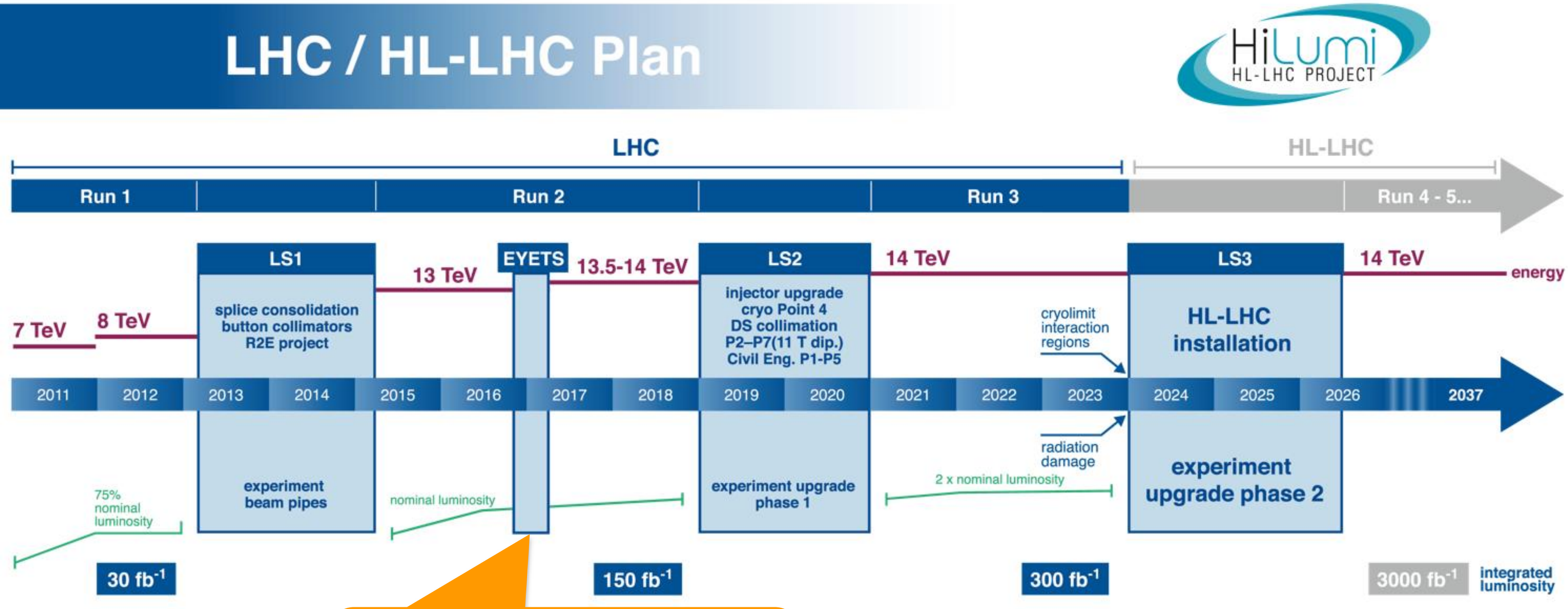
G. Arduini for the HL-LHC Project

ICHEP2016 – Chicago, USA – 04/08/2016

HL-LHC Goals

- Determine and implement a hardware configuration and a set of beam parameters allowing the LHC to reach the following targets:
  - Prepare machine for reliable operation beyond 2025 and up to ~2040 ➔ Remove LHC technical bottlenecks and limitations (triplet cooling power and radiation damage)
  - Enable the production of **3000 fb^{-1} ➔** ~**250 fb^{-1}/yr**,
    - operating at max. average pile-up **μ ~ 140** (➔ peak luminosity of ~**5×10^{34} cm^{-2} s^{-1}**) and pile-up density <**1.3 events/mm** compatibly with detector capabilities
    - Ultimate operation at higher pile-up up to **μ ~ 200** (➔ peak luminosity of ~**7.5×10^{34} cm^{-2} s^{-1}**) might be possible exploiting the engineering margins. Possibility to increase the integrated luminosity up to 4000 fb^{-1}.
- 10x luminosity reach of first 10 years of LHC operation!!

Timeline & Goals



Training of 2 sectors to 7 TeV before the end of EYETS – possibly before 2016 Christmas break

Recent Project Milestones

- Triplet Magnets Quadrupole Design Review (December 2014)
- Cost and Schedule Review (March 2015)
- Hi-Lumi Book (Summer 2015)
- Completion of the European Funded Study (October 2015)
- Publication of a Preliminary Technical Design Report (November 2015)
- Internal Review of the of the Civil Engineering and Technical Infrastructure costs (May 2016)
- Internal Review of the HL-LHC configuration/parameters (June 2016)
- Approval of the HL-LHC Project by the CERN Council (June 2016) for a total accelerator material cost of 950 MCHF

- The HL-LHC baseline configuration resulting from this work and consistent with the approved cost to completion is presented and the major changes highlighted

Ingredients for the Upgrade

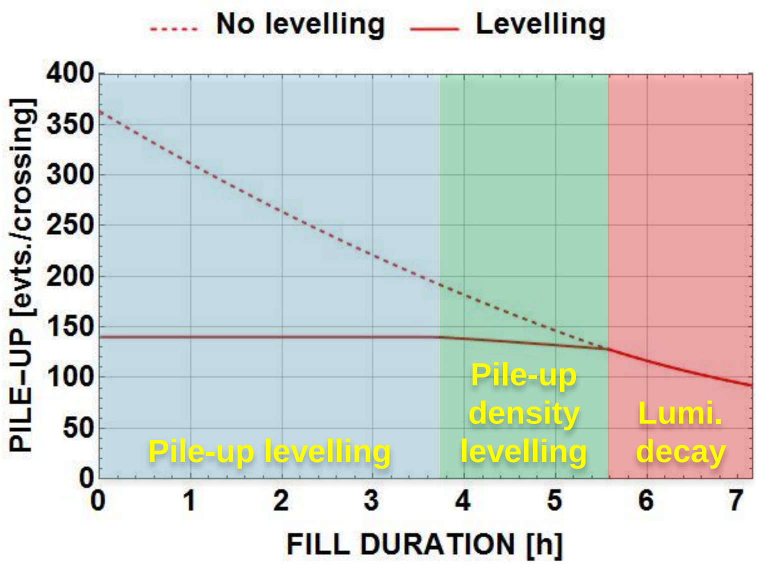
$$L = \frac{kN_b^{\,2} f \gamma}{4\pi \beta^* \varepsilon^*} F$$

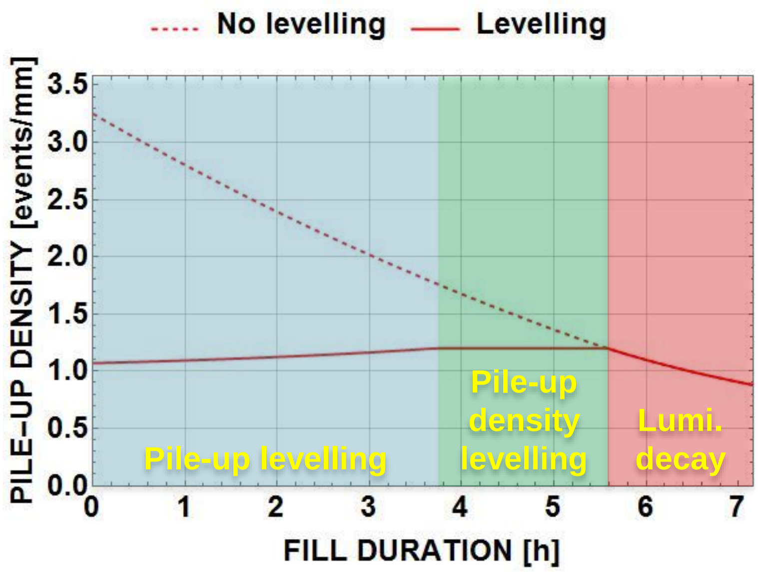
- Operation at pile-up/pile-up density limit (set by the experiments) by choosing parameters that allow higher than design pile-up (140 events) / pile-up density (1.2 events/mm):
  - Beam brightness and in particular bunch population to sustain burn-off over long periods ➔ LHC Injector Upgrade
  - Maximize number of bunches to minimize pile-up ➔ 25 ns
  - Low β^* optics
  - Large crossing angle to minimize the beam-beam effects
  - Fight the reduction factor F by crab crossing

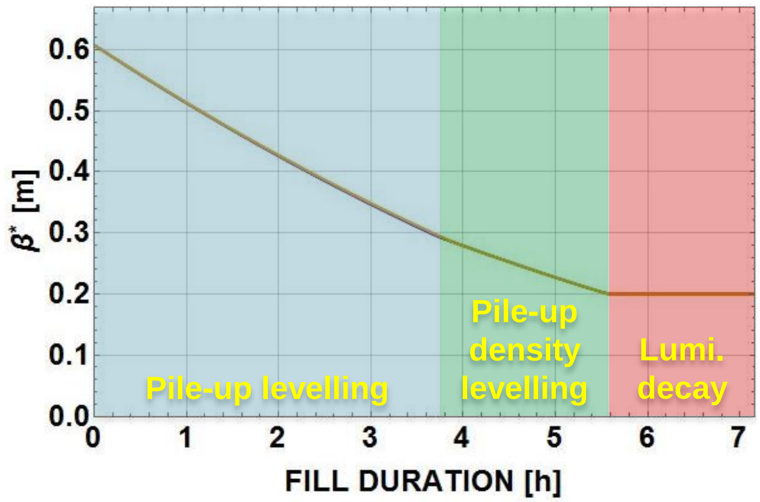
- Improve 'Machine Efficiency' ➔ minimize the number of unscheduled beam aborts

Ingredients for the Upgrade
β* levelling

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







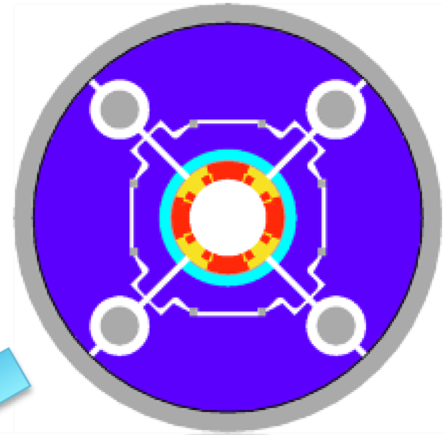
Challenges

- Low β* optics and large aperture triplets
- Operation of the crab cavities in a high intensity hadron machine
- Operation with large stored energy ➔ halo, losses ➔ collimation
- Beam stability and minimization of impedance
- Electron cloud mitigation with 25 ns beams
- Reliability!!

From LHC to HL-LHC triplets

Fermilab KEK

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

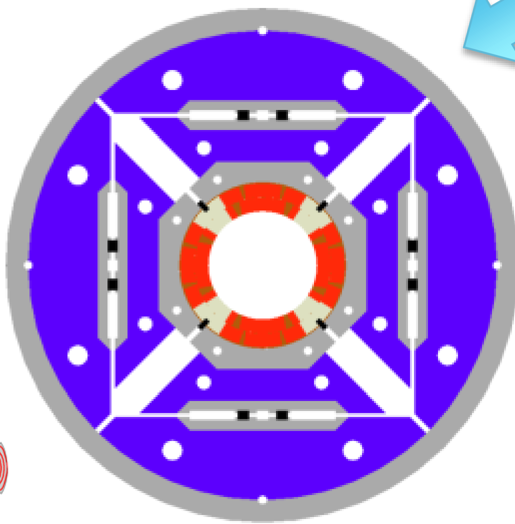


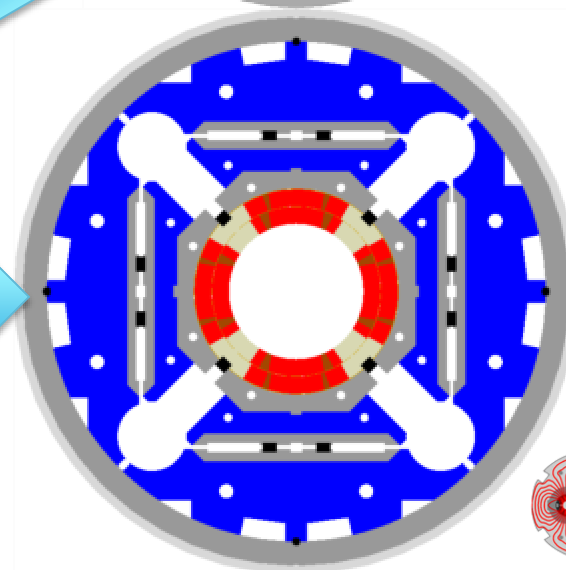
LARP

LARP TQS & LQ (4m)
∅90 mm, B_{peak}~ 11 T
Nb_3Sn
2004-2010

LARP HQ, ∅120 mm,
B_{peak}~ 12 T
Nb_3Sn
2008-2014

LARP



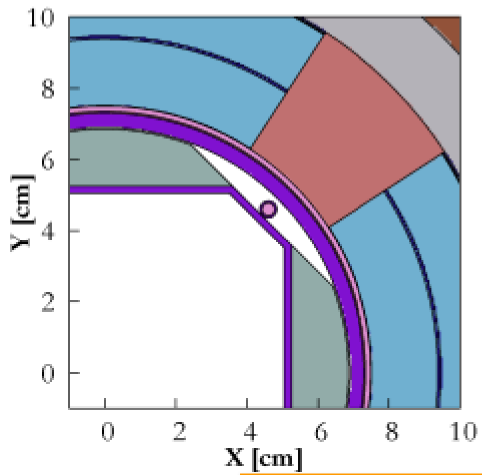


LARP & CERN
MQXF,∅150 mm,
B_{peak}~ 12.1 T
Nb_3Sn
2013-2020

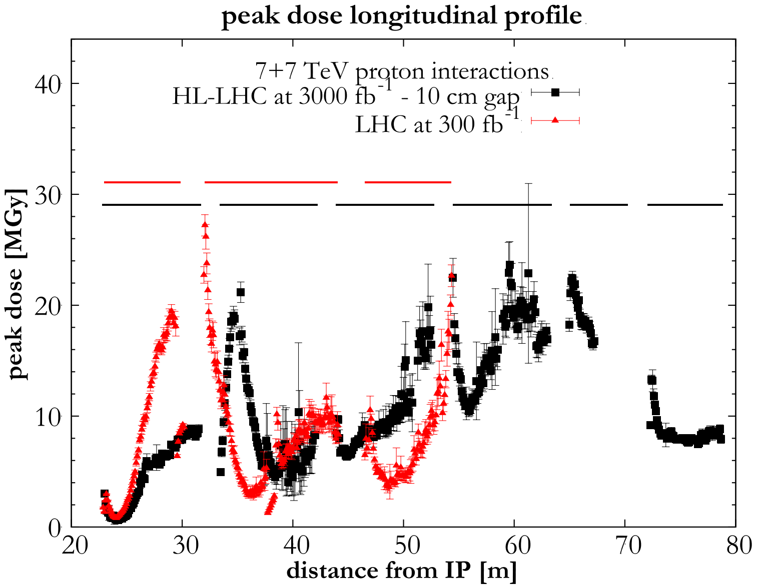
LARP CERN

Shielding against Radiation Damage

- Tungsten shielding on the beam screen 16 mm in Q1 and 6 mm elsewhere.
- More than 600 W in the cold masses as well as in the beam screen (i.e. 1.2-1.3 kW in total)!! ➔ New Cryogenics plants
- Expect same integrated radiation dose in HL-LHC after 3000 fb^{-1} as in LHC after 300 fb^{-1}!!
- Complex structure: update of the mechanical tolerances (and reduction of the triplet gradient led to an increase of β* from 15 to 20 cm) ➔ possibility of increasing performance by further improving tolerances



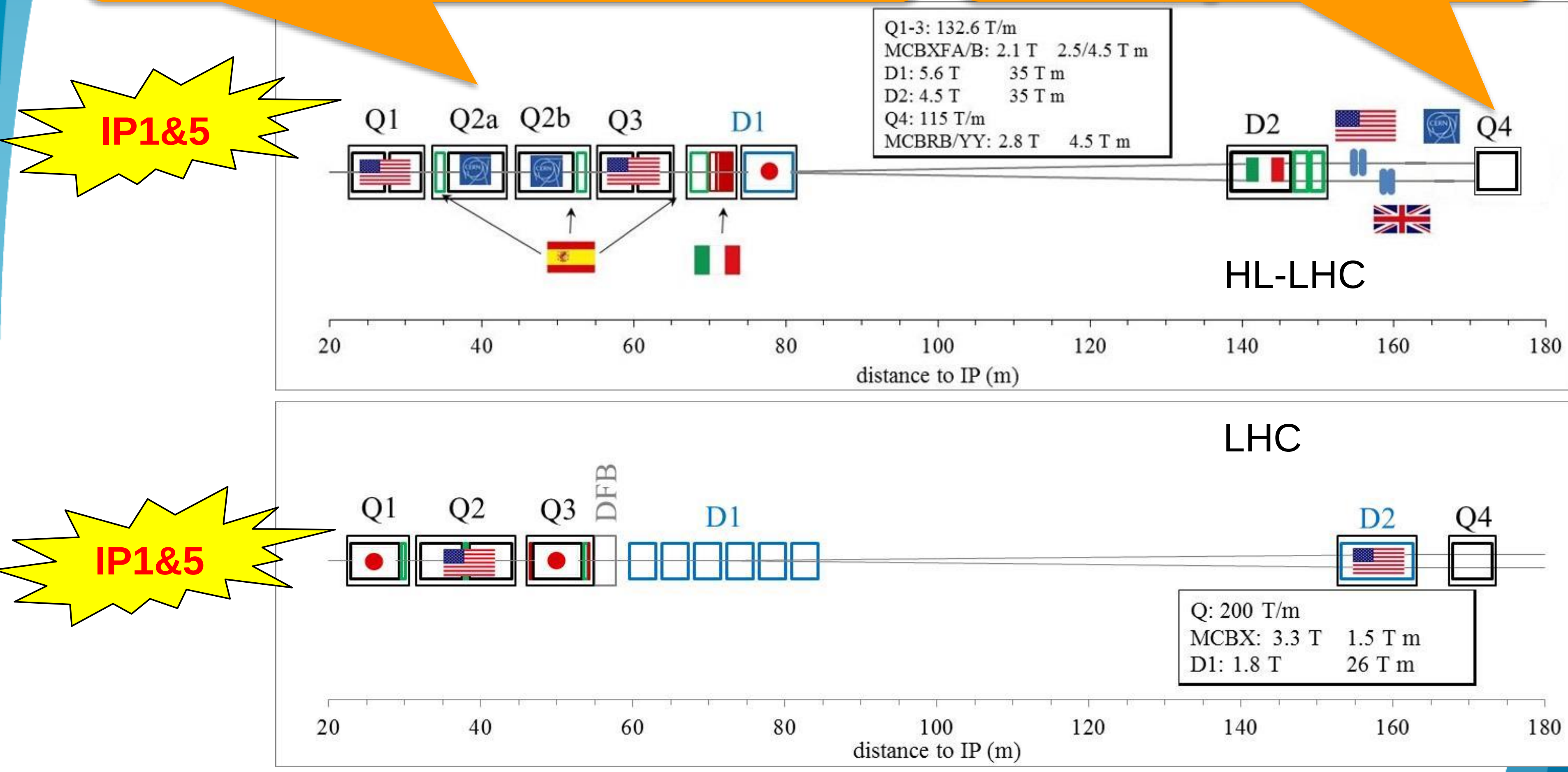
F. Cerutti, L. Esposito



The HL-LHC Interaction Region

Reduction of the triplet gradient from 140 T/m to 133 T/m. Additional safety margin taking into account of the completely new technology

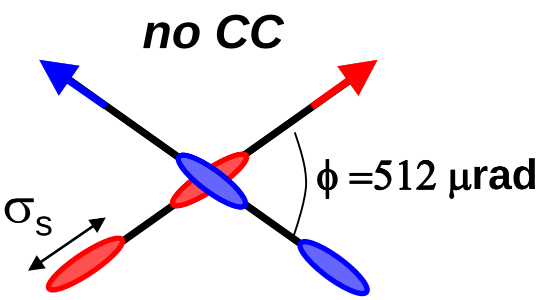
Staged installation of larger aperture quadrupole for other optics configurations (flat) following June review

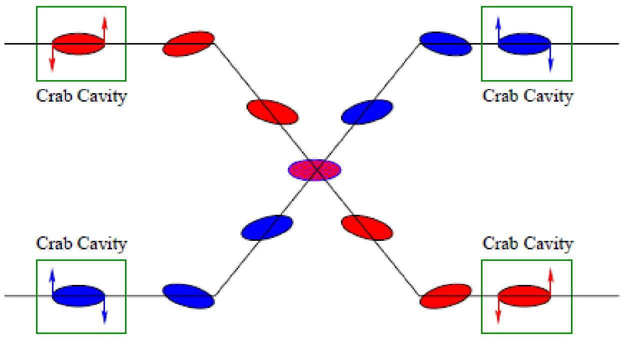


Crab cavities

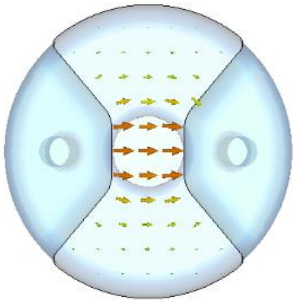
$$L = \frac{kN_b^2 f\gamma}{4\pi\beta^*\varepsilon^*}F$$

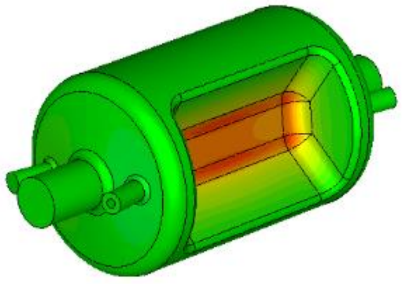
- Crab-cavities (CC) to deflect the bunch head and tail transversely to counteract the luminosity loss from the large crossing angles and small beam sizes at HL-LHC and to reduce pile-up density
  - On both sides of IP1 and IP5





Transverse Electric Field





- CCs have never been used in a hadron machine - there are many challenges: noise on the beam, machine protection etc. ➔ SPS tests in 2018
- Decided (June review) to limit the number of crab cavities per IP side/beam to 2 (3 required for full compensation)

Collimation Upgrade

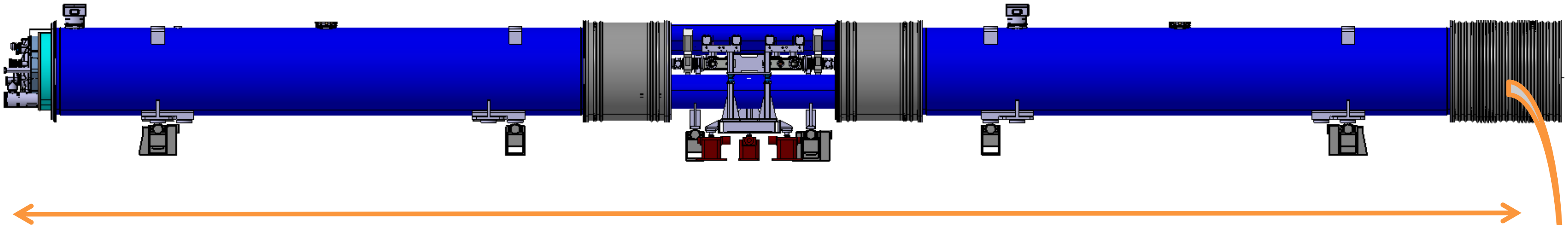
- Worry about beam losses:
  - Failure Scenarios ➔ Local beam Impact
    - Equipment damage
    - Machine Protection
  - Lifetime & Loss Spikes ➔ Distributed losses
    - Magnet Quench
    - Radiation to Electronics and Single Event Upsets
    - Machine efficiency

- New collimators (TCLD) with 11 T dipoles in the Dispersion Suppressors around the betatron collimation section (LSS7) only as machine studies in 2015 demonstrated alternatives solutions not requiring 11 T dipoles in IR2 (ion collimation). Two units should be sufficient (initially 4) according to recent simulation results

- Reduction of the impedance of the collimators by the choice of new materials to allow stable operation with higher intensity beams (needed only in the betatron collimation insertion in LSS7)

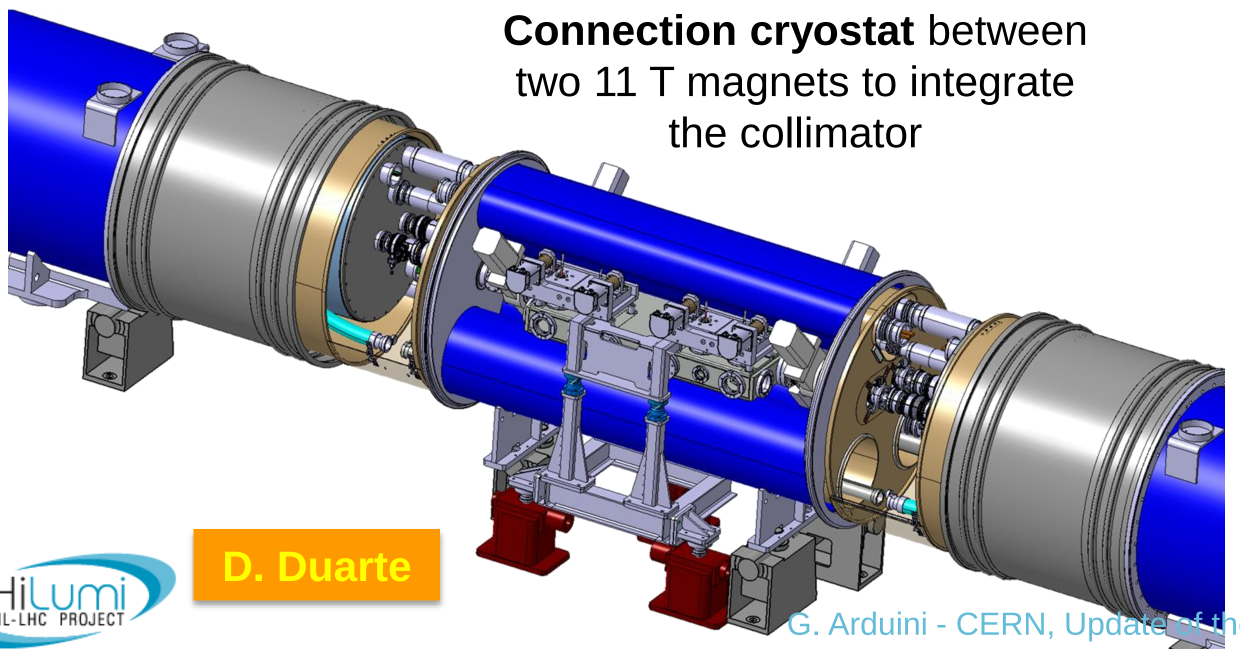
Dispersion Suppressor Collimators with 11 T Dipoles

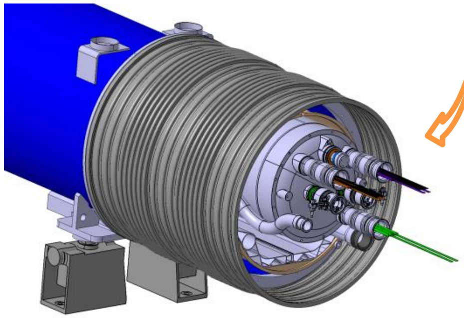
LHC MB replaced by **3 cryostats + collimator**, all independently supported and aligned:



Same 15660 mm length between interconnect planes as an LHC MB

Connection cryostat between two 11 T magnets to integrate the collimator

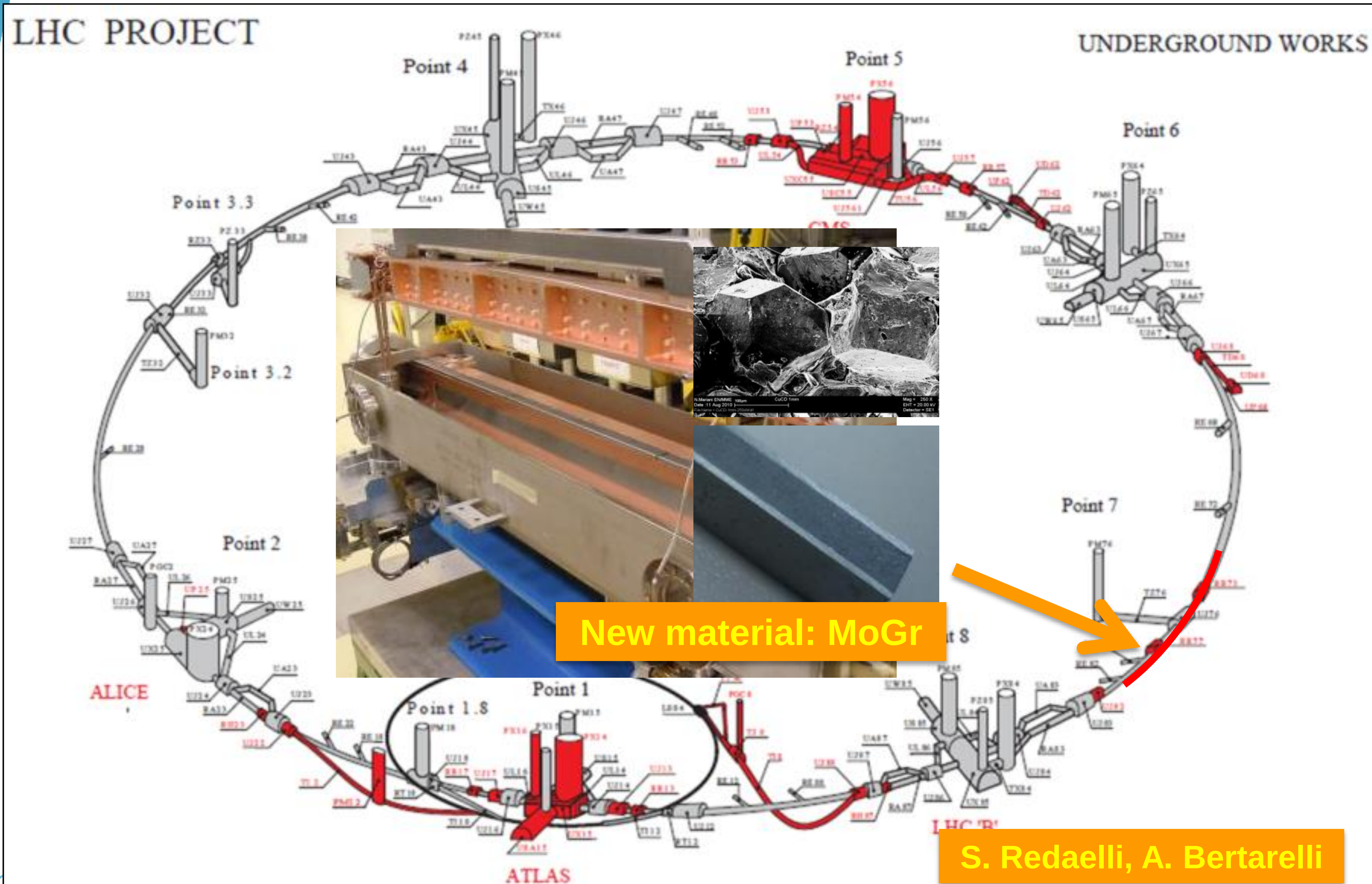




Same interfaces at the extremities: **no changes to nearby magnets**, standard interconnection procedures & tooling

D. Duarte

Low Impedance Collimators in LSS7



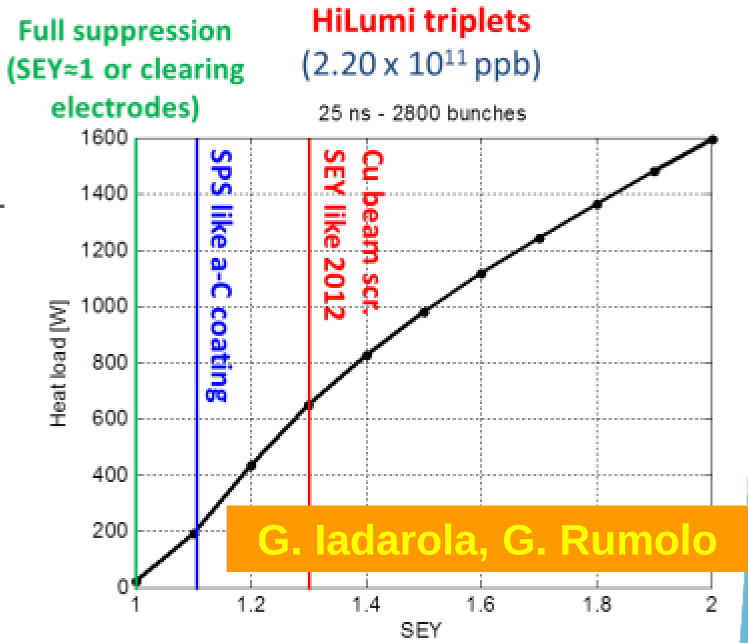
25 ns operation (e-cloud)

- Rely on scrubbing to suppress electron cloud in the main dipoles (conditioning observed but not yet full suppression ➔ Run 2 experience is vital! – *see also presentation on LHC status*)

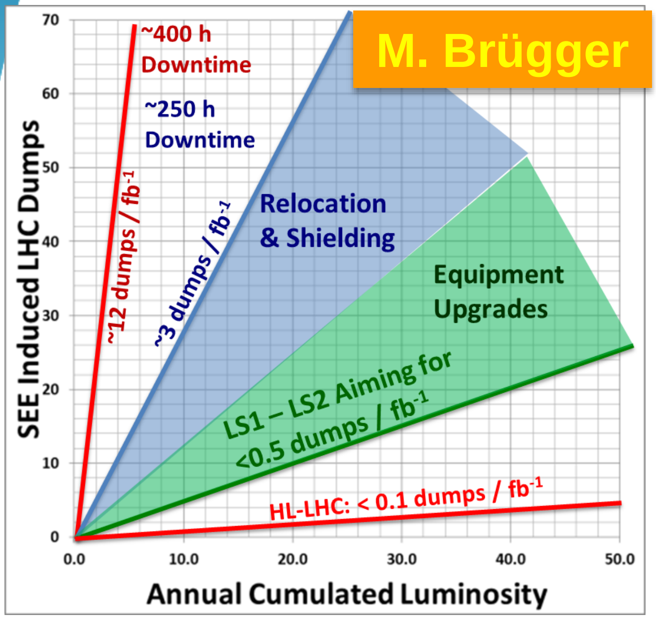
- Triplets/matching section in IP1 and 5 but also in IP2 and 8:
  - Expect no suppression of the electron cloud with scrubbing ➔ a-C coatings (SEY ~ 1.1) to minimize heat load on the beam screen.

- Laboratory and in-situ tests (SPS) ongoing to characterize the properties of these coatings at room and cryogenic temperatures

- Irradiation tests to evaluate aging effects.

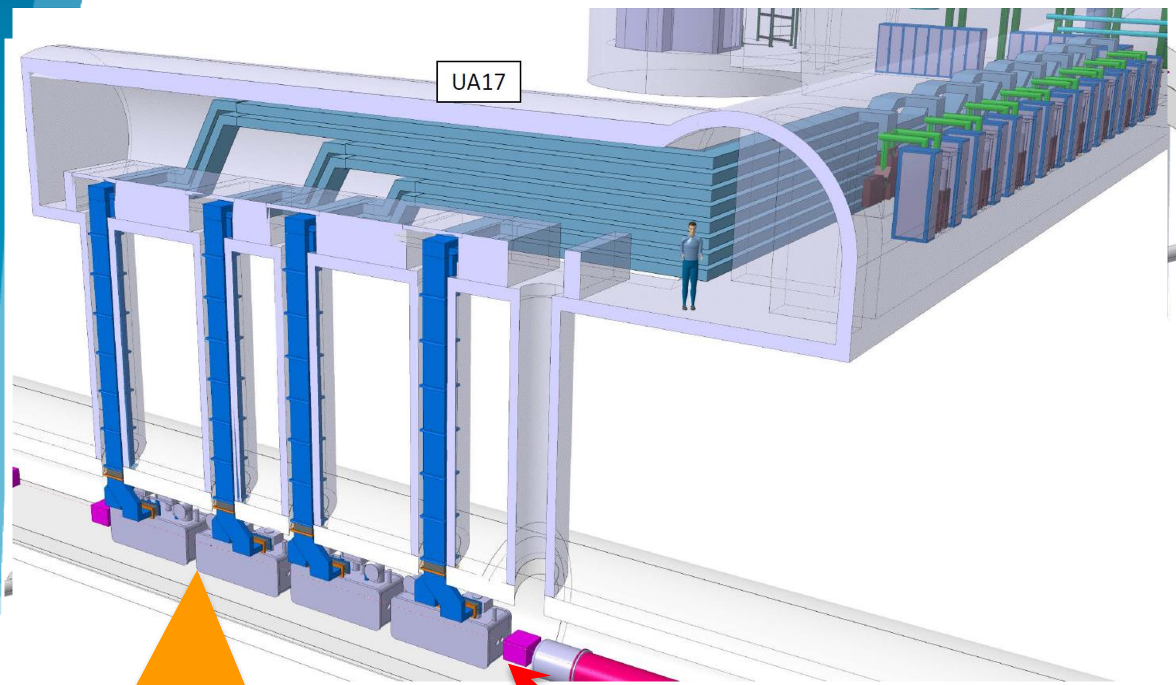


Reliability

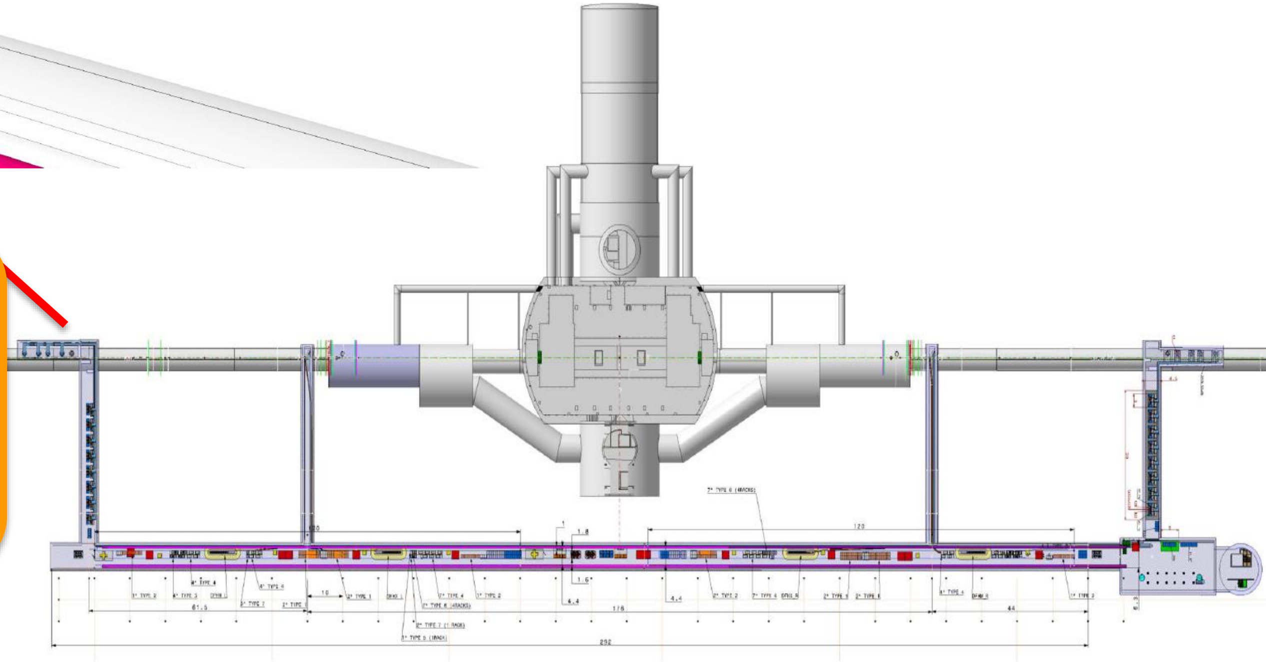


- Consolidation during LS1 (including measures to reduce radiation to electronics – R2E) is paying off
- LHC Efficiency for physics exceeded the HL-LHC target of 50 % at luminosities beyond nominal during the last month of operation before MD block 1 ➔ encouraging!
- Further measures are planned for HL-LHC operation:
  - PC far from tunnel ➔ SC links (HTS)
  - QPS systems out of the tunnel

Civil engineering



P. Fessia

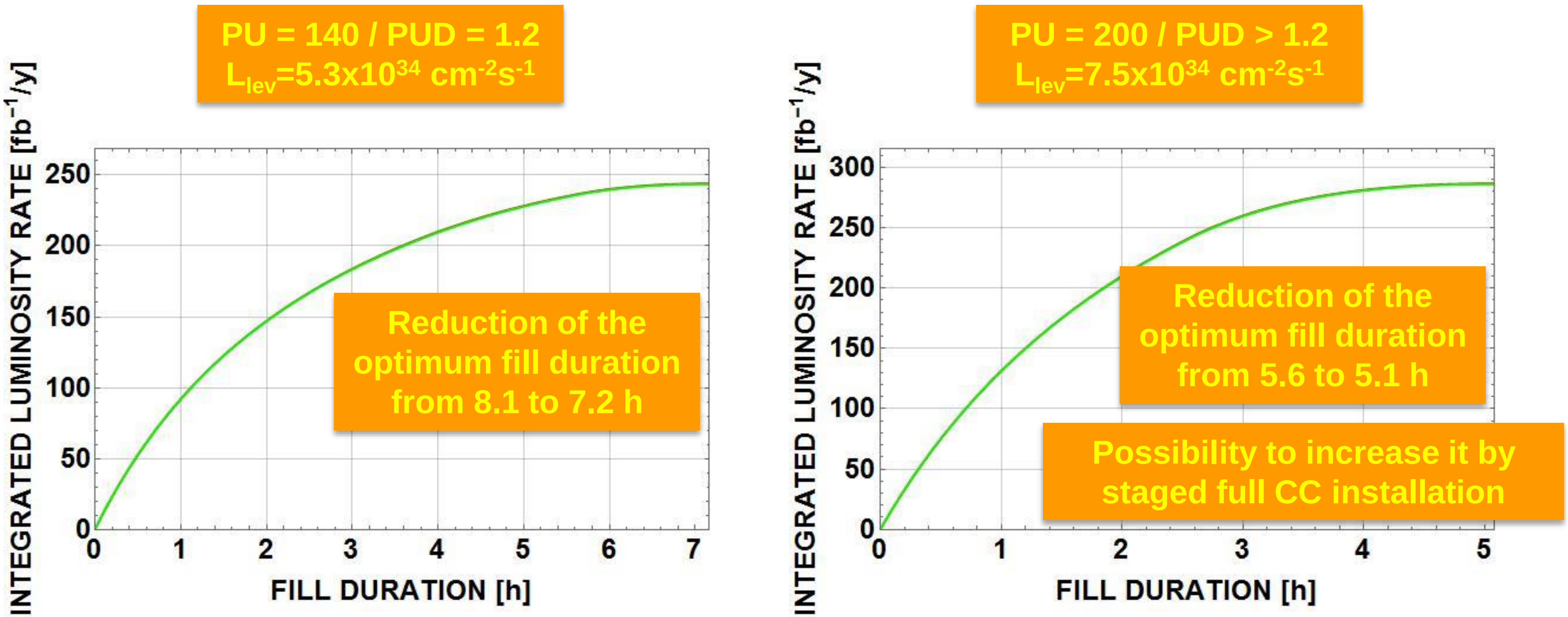


Extra cost of ~120 MCHF for civil engineering and technical infrastructure w.r.t. the initial estimates
Work ongoing to minimize the required volume

HL-LHC Parameters

Parameter	Nominal	HL-LHC	HL-LHC updated
Bunch population N_b [10^{11}]	1.15	2.2	2.2
Number of bunches	2808	2748	2748
Beam current [A]	0.58	1.12	1.12
Stored Beam Energy [MJ]	362	677	677
Full crossing angle [μrad]	285	590	512
Crossing angle with crab cavities [μrad]	285	0	150
Beam separation [σ]	9.9	12.5	12.5
Min β^* [m]	0.55	0.15	0.2
Normalized emittance ε_n [μm]	3.75	2.5	2.5
r.m.s. bunch length [m]	0.075	0.081	0.081
Virtual Luminosity (w/o CC) [10^{34} cm^{-2}s^{-1}]	1.2 (1.2)	21.3 (7.2)	13.8 (6.95)
Max. Luminosity [10^{34} cm^{-2}s^{-1}]	1	5.3	5.3
Levelled Pile-up|Pile-up density [evt. | evt./mm]	26/0.2	140/1.2	140/1.2

Expected Performance



- Integrated yearly performance within 5 % from the target of 250 fb^{-1} can be achieved with nominal parameters but with reduced margins due to the reduced levelling time
- Further gains could be obtained by improving beam screen tolerances, reducing crossing angle and with dedicated (flat) optics requiring staged upgrade of Q4 ➔ to be demonstrated.
- Levelled luminosity and total integrated luminosity values (3000 fb^{-1} and ultimately up to 4000 fb^{-1} with relaxed pile-up/pile-up density) are maintained by keeping engineering margins on cryogenics power and magnet radiation resistance

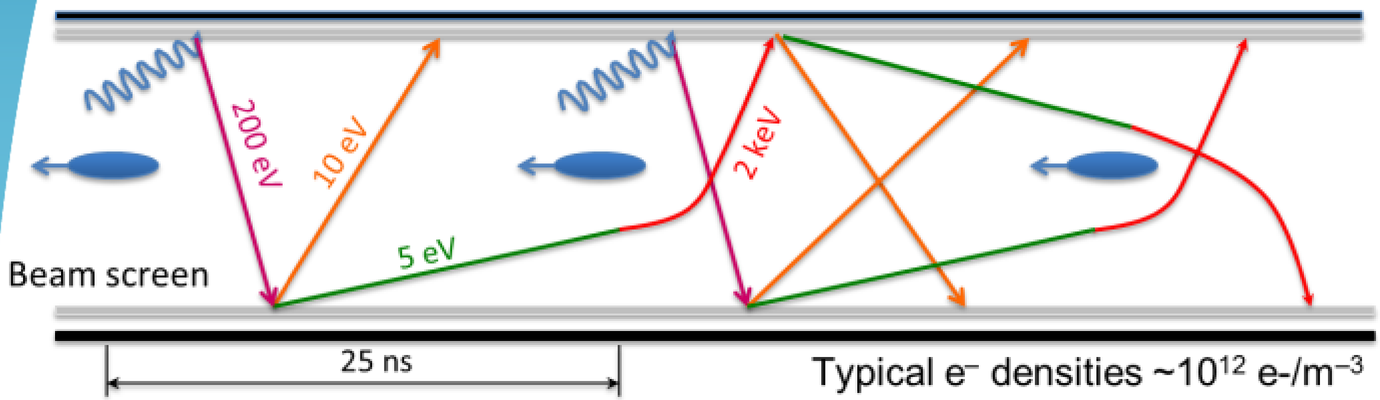
Summary and Conclusions

- A crucial milestone has been reached with the approval of the HL-LHC Project by the CERN Council with a total accelerator material cost of 950 MCHF
- The parameters and HW design choices have been optimized following the Cost and Schedule Review in 2015 and the publication of the Preliminary Technical Design Report
- More recently further cost savings and design optimizations have been identified to compensate the extra costs identified for the civil engineering and infrastructure
- The impact on the yearly performance has been minimized and engineering margins on cryogenics power and magnet radiation resistance have been maintained to keep the integrated luminosity goal of 3000 fb^{-1} (ultimate 4000 fb^{-1}) by the end of the HL-LHC programme

Thank you for your attention!

Acknowledgements: V. Baglin, A. Ballarino, N. Biancacci, M. Brugger, O. Brüning, R. Bruce, P. Chiggiato, S. Claudet, R. De Maria, S. Fartoukh, M. Giovannozzi, G. Iadarola, E. Métral, Y. Papaphilippou, T. Pieloni, S. Redaelli, L. Rossi, G. Rumolo, B. Salvant, E. Shaposhnikova, R. Tomas and many others...

Electron cloud effects



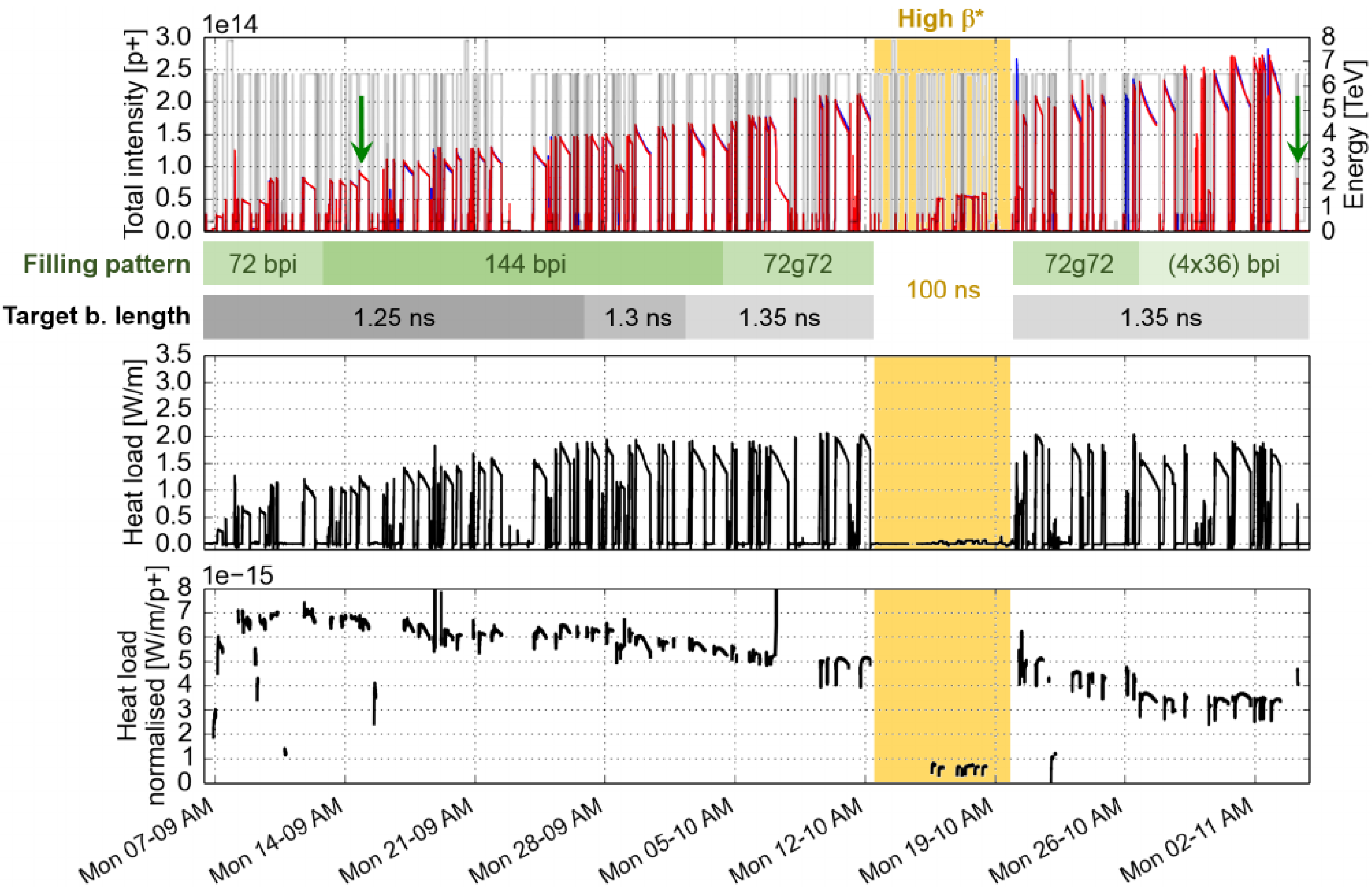
Secondary Emission Yield [SEY]
SEY>SEY$_{th}$ ➔ avalanche effect (multipacting)

Possible consequences:

- instabilities, emittance growth, desorption, vacuum degradation, background
- energy deposition in cryo surfaces

Electron bombardment of a surface has been proven to reduce **SEY** of a material as a function of the delivered electron dose. This technique, known as **scrubbing**, provides a means to suppress electron cloud build-up.

Electron cloud (3)

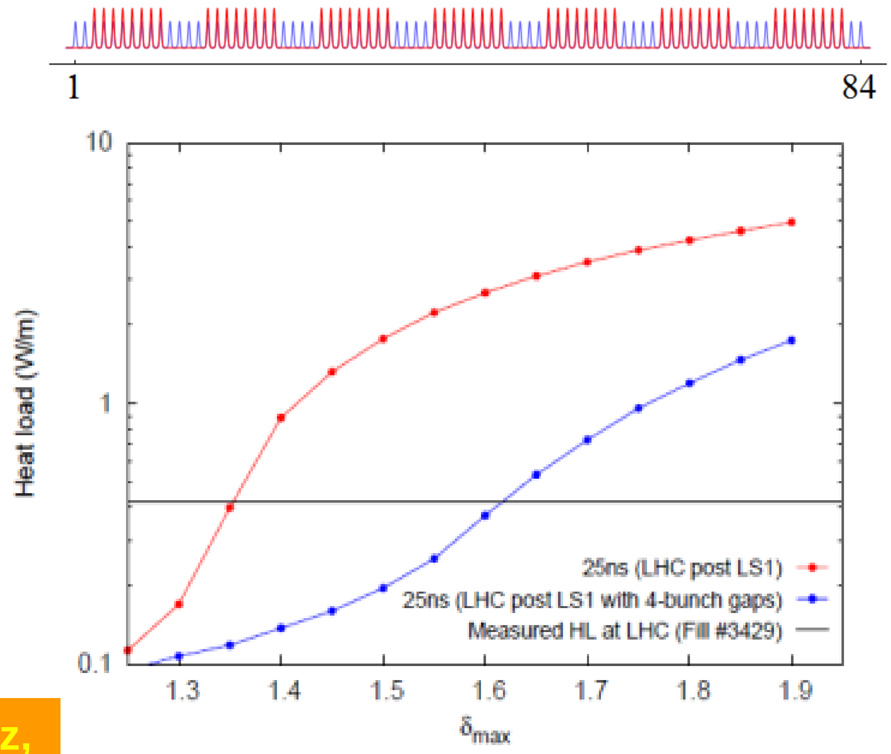


HiLumi HL-LHC PROJECT

25 ns operation (e-cloud)

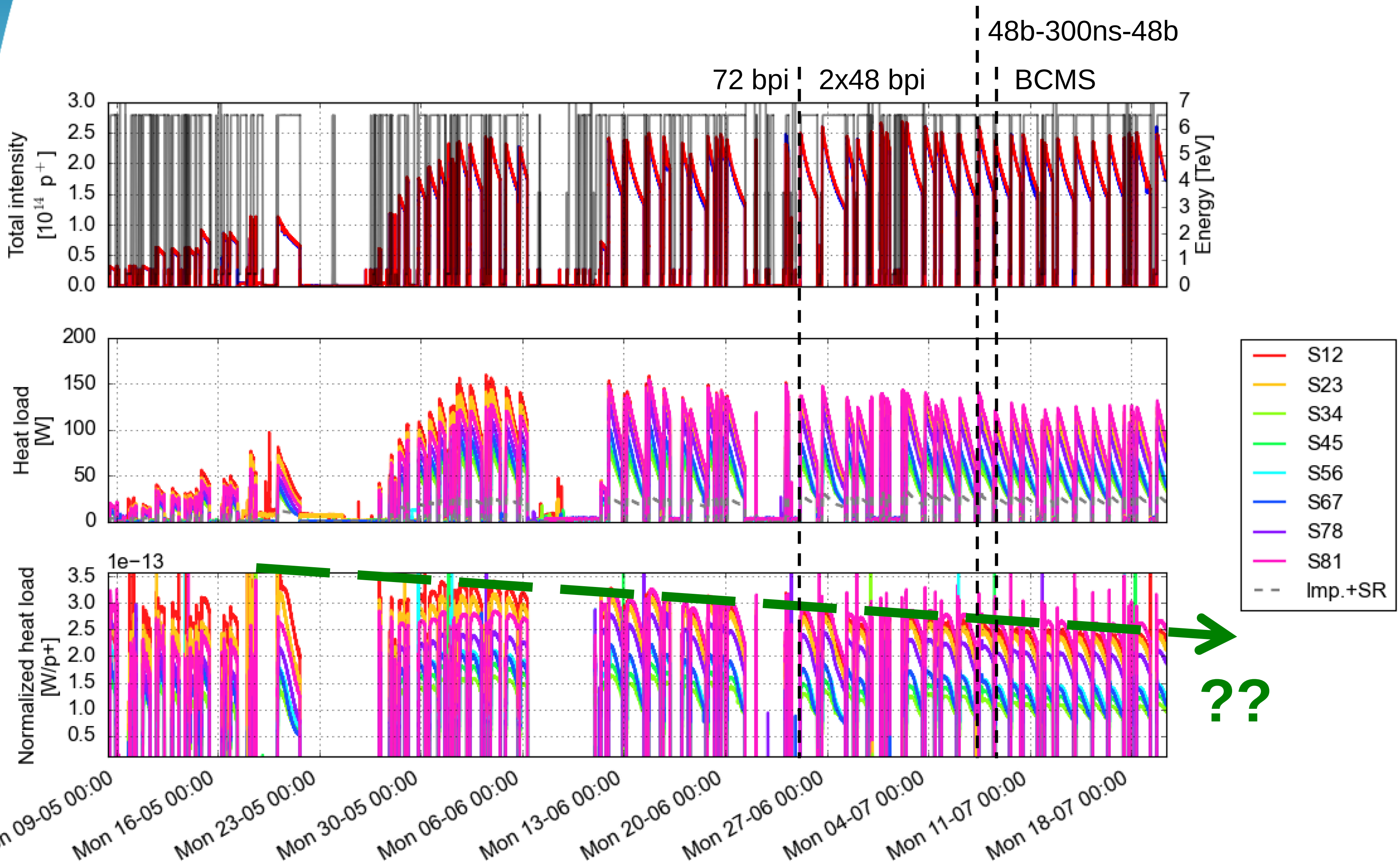
- Relies on scrubbing to suppress electron cloud in the dipoles (heat load and beam stability)

- Alternatives:
  - ‘ad-hoc’ 25 ns filling schemes to minimize electron cloud build-up (e.g. 8b+4e scheme) ➔ reduction of the integrated luminosity to 180 fb^{-1}/y (w.r.t. ~240 fb^{-1} for nominal scenario) but with longer fills (9 to 10 h)



H. Damerau, O. Dominguez, G. Iadarola, G. Rumolo

Intensity ramp up



HiLumi HL-LHC PROJECT