Baseline parameters, feedback from MDs and outcome from the HL-LHC/LIU day

G. Arduini – CERN – BE/ABP

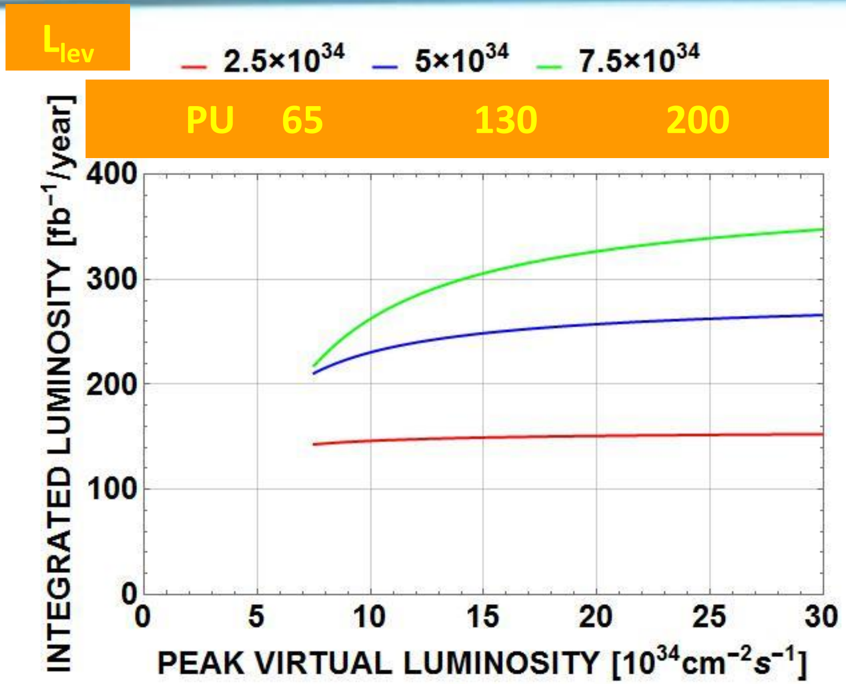
Acknowledgements: N. Biancacci, O. Brüning, H. Damerau, R. De Maria, S. Fartoukh, S. Gilardoni, M. Giovannozzi, B. Goddard, A. Gorzawski, G. Iadarola, E. Métral, Y. Papaphilippou, T. Pieloni, L. Rossi, G. Rumolo, E. Shaposhnikova, R. Tomás, A. Valishev, J. Wenninger, A. Wolski & all WP2 collaborators

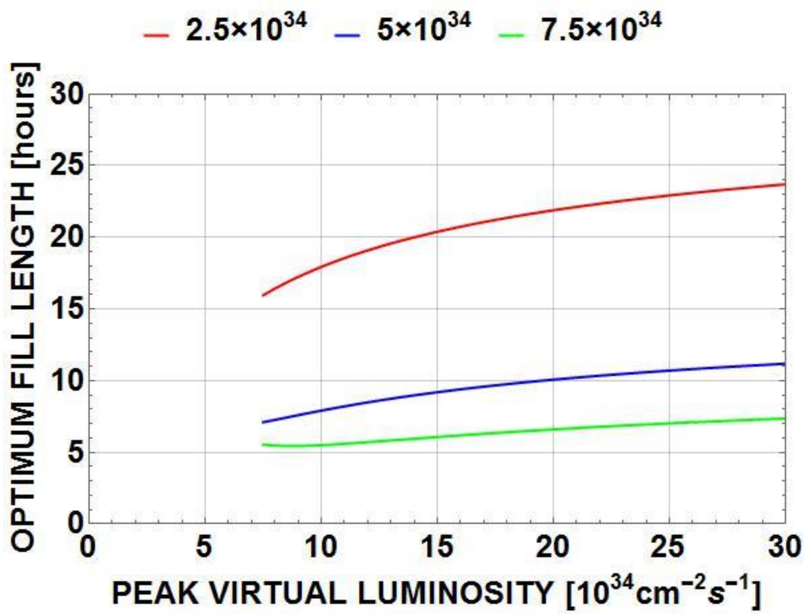
The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Main ingredients

- Goal: > 250 (300) fb^{-1}/year by:
  - 'virtual' peak luminosity higher than max. compatible with pile-up (140 ←→ 200 events/xing) and pile-up density (1.3 events/mm)
  - 'luminosity levelling' over longer periods (6 to 8 hours – average was 6 h in 2012)
  - Realistic performance efficiency (i.e. percentage of time spent for successful physics fills including turn around time): 50 % (50.6 % in 2012)

Burn-off only – 50 % performance efficiency – 3 h turn-around





Main ingredients

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

- Beam brightness and in particular bunch population to sustain burn-off over long periods ➔ LIU Upgrade
- Low β* optics with well behaved chromatic properties ➔ ATS optics
- β* levelling
- Large number of bunches to minimize pile-up ➔ 25 ns
- Large crossing angle to minimize the beam-beam long range effects
- Compensation of the crossing angle by crab crossing

Beam parameters in collision

Back-up scenario

Parameter	Nominal	25ns HL-LHC	8b+4e
Bunch population N_b [10^{11}]	1.15	2.2	2.3
Number of bunches	2808	2748/2604	1968
Beam current [A]	0.58	1.09/1.03	0.82
Crossing angle [μrad]	285	590	554
Beam separation [σ]	9.9	12.5	12.5
Minimum β^* [m]	0.55	0.15	0.15
Normalized emittance ε_n [μm]	3.75	2.5	2.2
ε_L [eVs]	2.5	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)	18.9 (6.73)	16.8 (6.0)
Max. Luminosity [10^{34} cm^{-2}s^{-1}]	1	5.30	3.6
Levelled Pile-up/Pile-up density [evt. / evt./mm]	27/0.2	140/1.2	140/1.2
Integrated luminosity [fb^{-1}/year]	45	260	190

Higher brightness beam (BCMS) as mitigation in case of difficulties with emittance preservation in LHC but potential limitations (e.g. injection protection) need to be evaluated

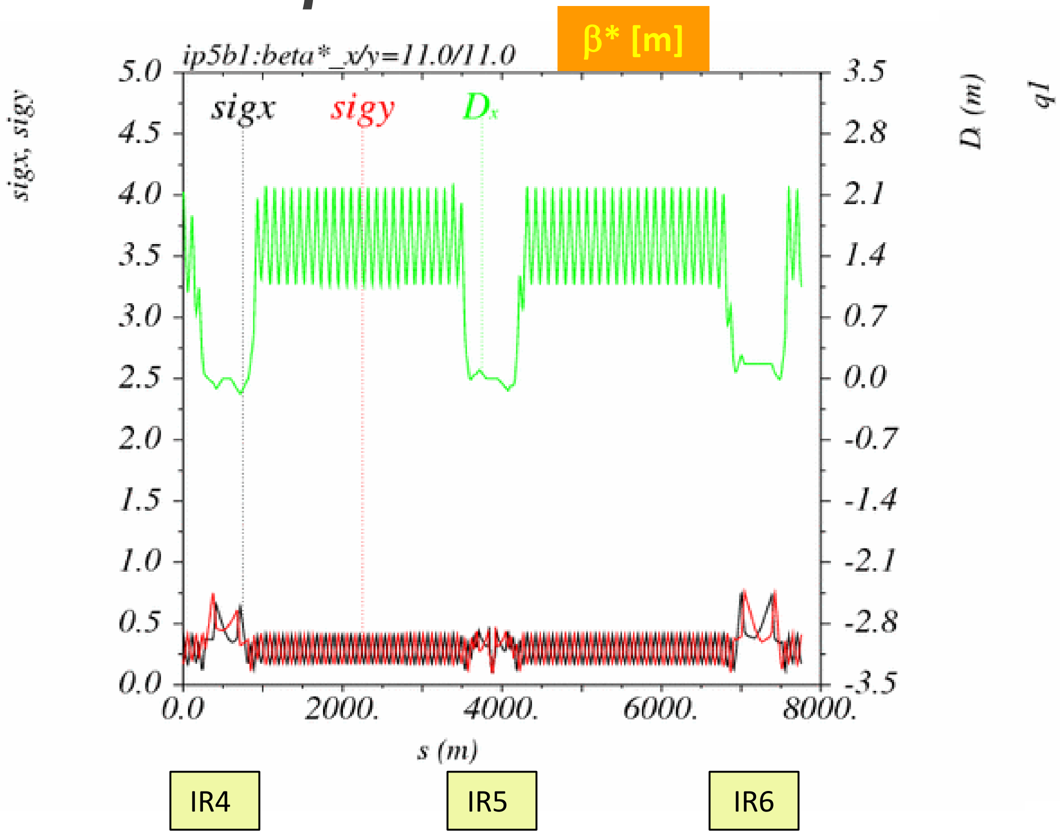
Challenges

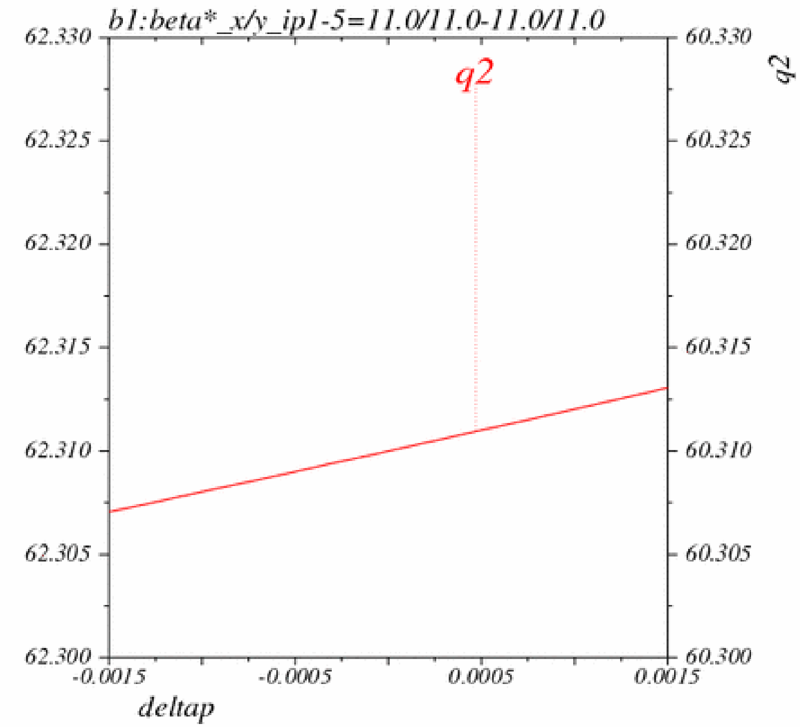
- Some of the challenges:
  - Operation with low β^* optics
  - Beam intensity, brightness in the injectors
  - Electron cloud effects with 25 ns beams
  - β^* levelling
  - Beam-beam effects ➔ Large crossing angles
  - Crab Crossing to minimize the geometric reduction factor and pile-up density
  - Stability and Minimization of impedance
  - Reliability!!

Low β*

ATS=Achromatic Telescopic Squeeze

S. Fartoukh

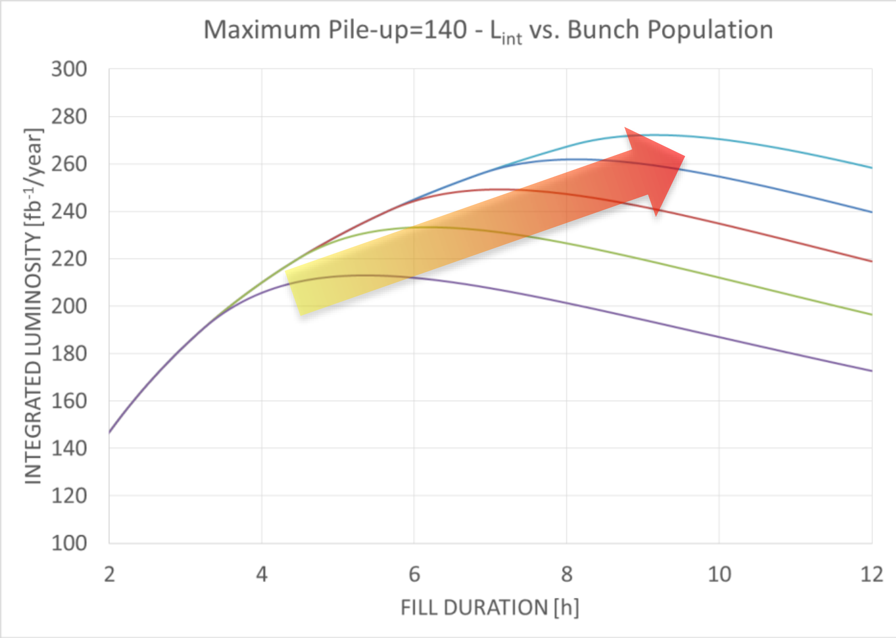




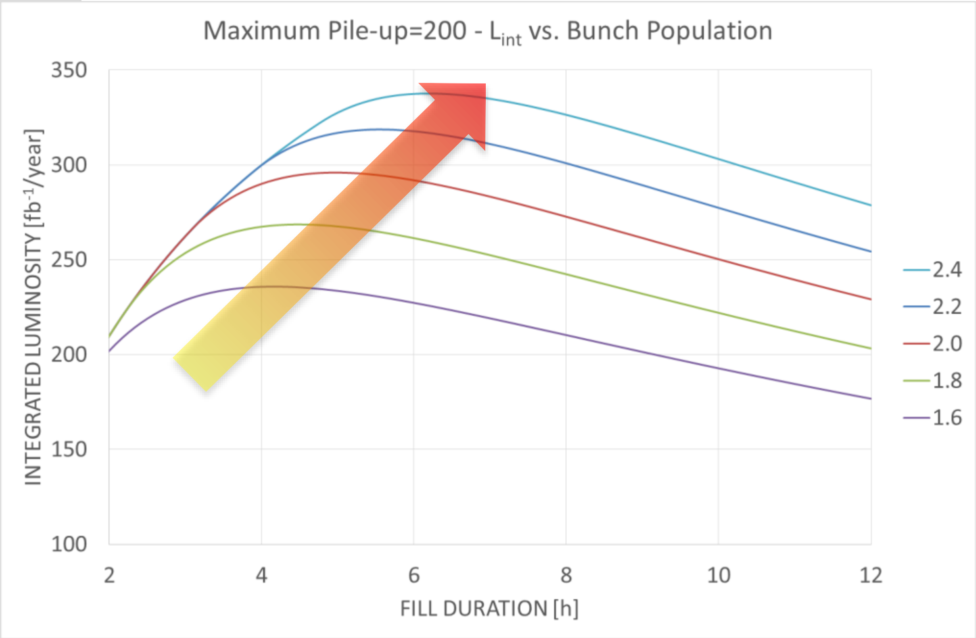
- An "almost" standard squeeze (local to IP1/5), **the Pre-squeeze**
- A further reduction of β^*, **the Squeeze**: acting on IR2/8 for squeezing IR1 and IR4/6 for IR5, inducing **β-beating bumps in sectors 81/12/45/56 to boost the sextupole efficiency at constant strength.**
- **Aim to test it in operation during run 2**

Sensitivity to beam parameters

Nominal

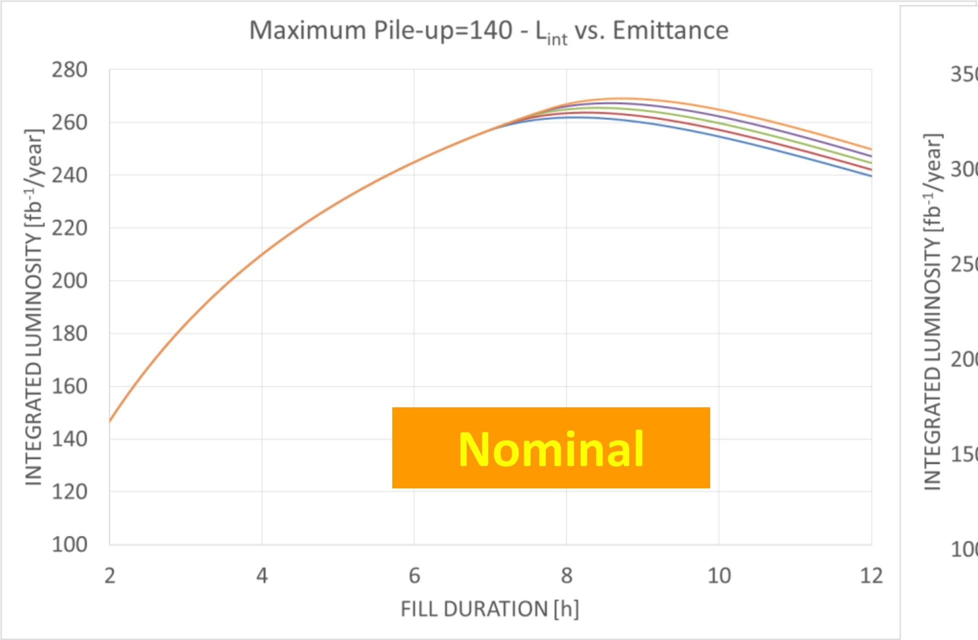


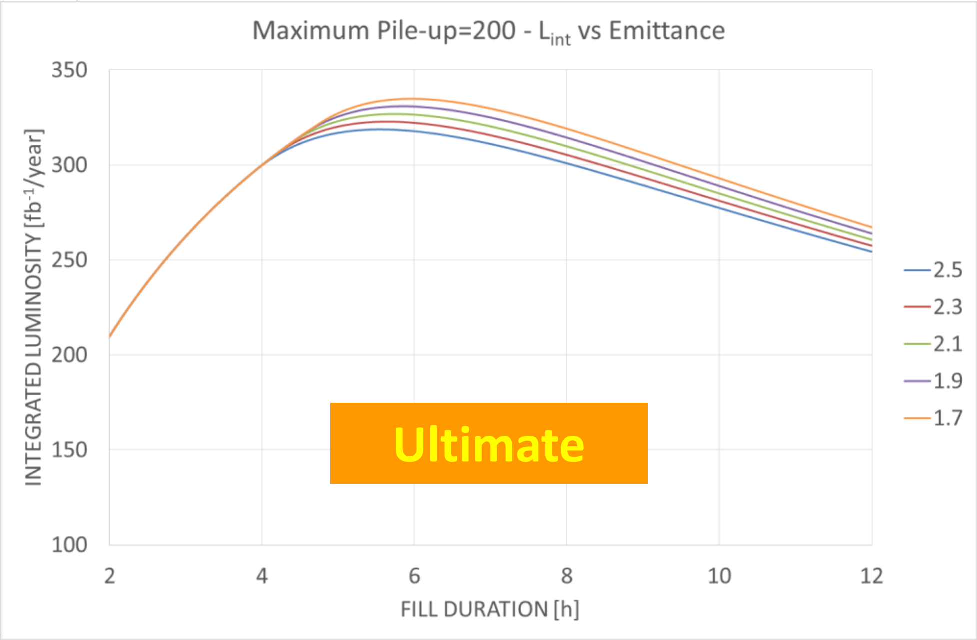
Ultimate



50 % performance efficiency (50.6 % in 2012)
160 days of physics – 3 hours turnaround time
Average fill length = 6 h in 2012

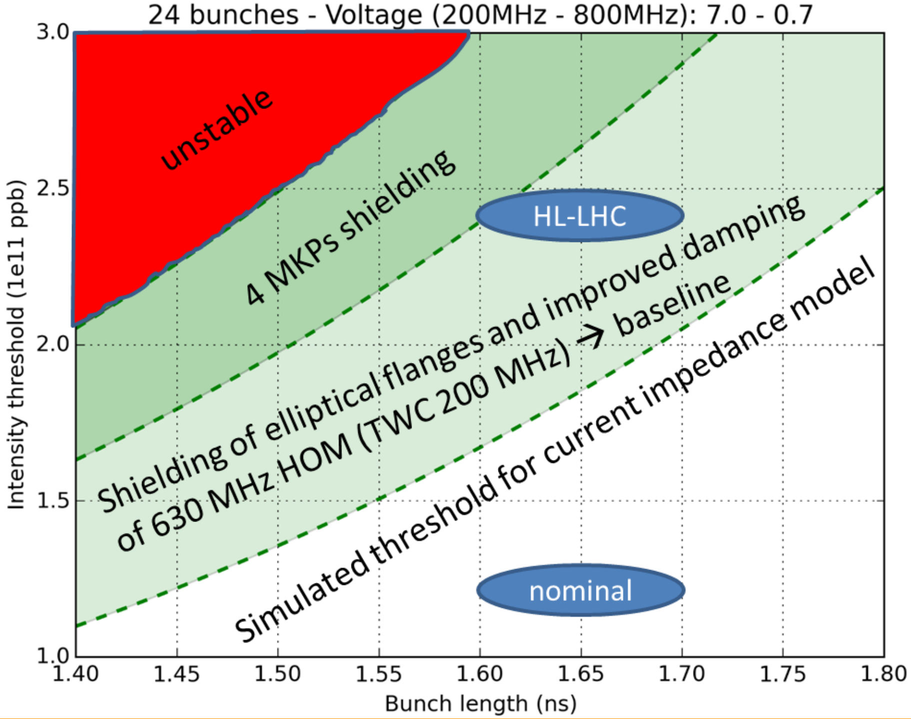
Sensitivity to beam parameters

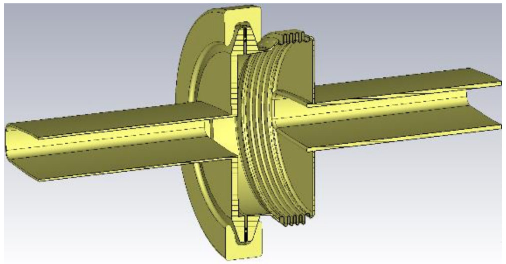


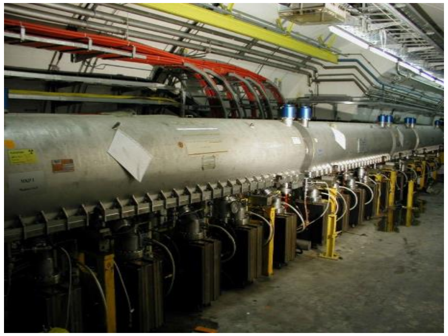


- No important sensitivity. But upper limit given by BBLR effects.

Filling the gap between HL-LHC and LIU







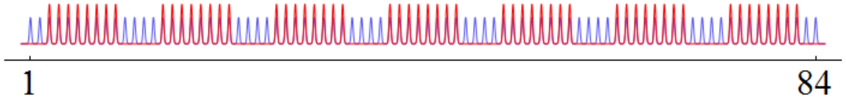
T. Argyropoulos, A. Lasheen, E. Shaposhnikova, B. Salvant, J. Varela, C. Zannini et al.

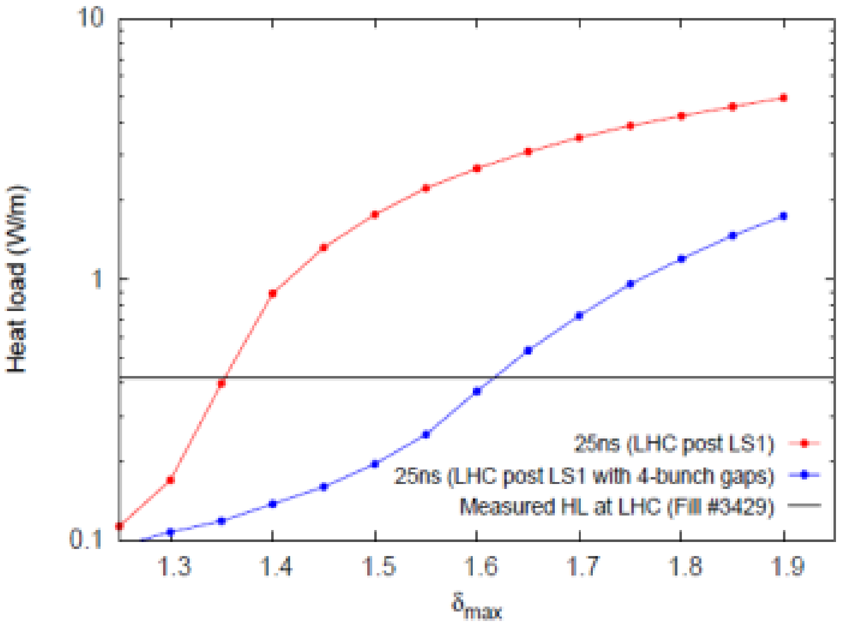
- Impressive progress of the SPS impedance model and in particular localization of the sources of longitudinal instability
- SPS Impedance reduction campaign will allow achieving the HL-LHC bunch population within the required longitudinal parameters

25 ns operation (e-cloud)

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

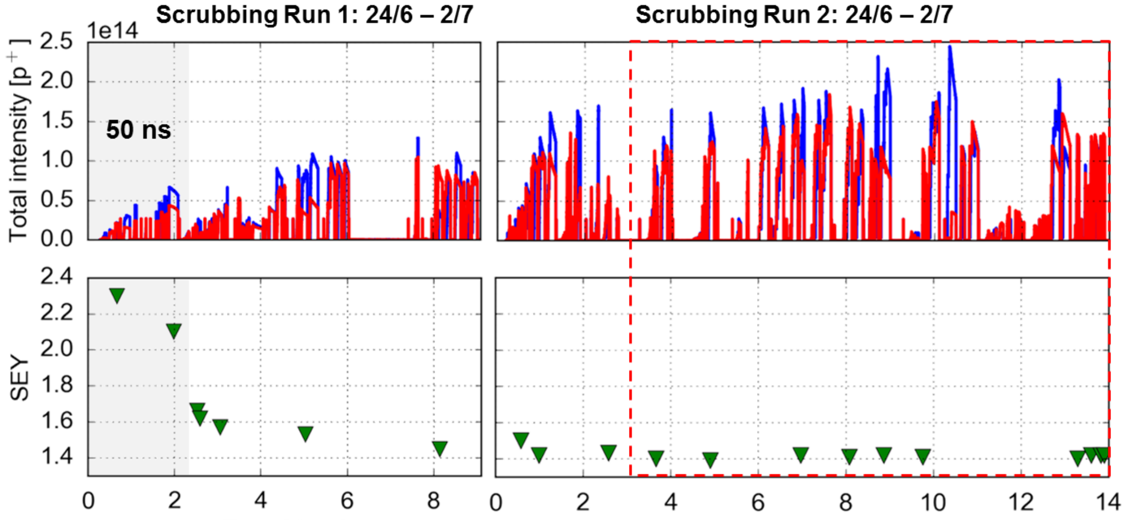
- Alternatives:
  - 'ad-hoc' 25 ns filling schemes to minimize electron cloud build-up (e.g. 8b+4e scheme) ➔ reduction of the integrated luminosity to 190 fb^{-1}/y (w.r.t. ~260 fb^{-1} for nominal scenario) but with longer fills (9 to 10 h)

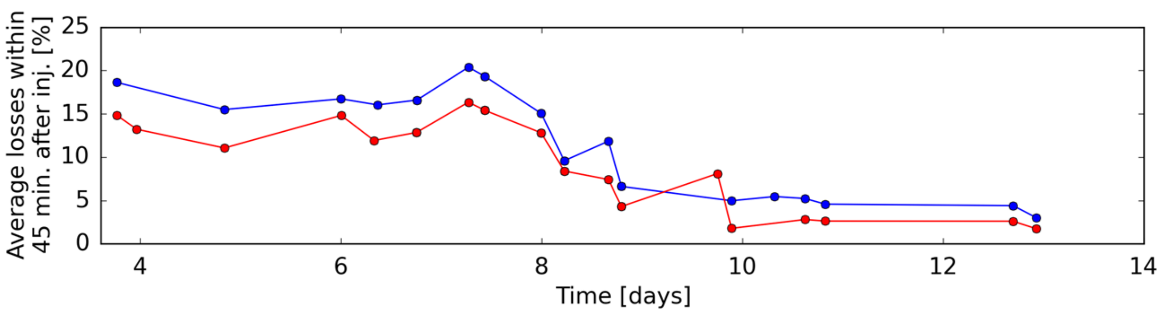




H. Damerau, O. Dominguez, G. Iadarola, G. Rumolo, R. Tomás

Scrubbing for 25 ns operation (2015)



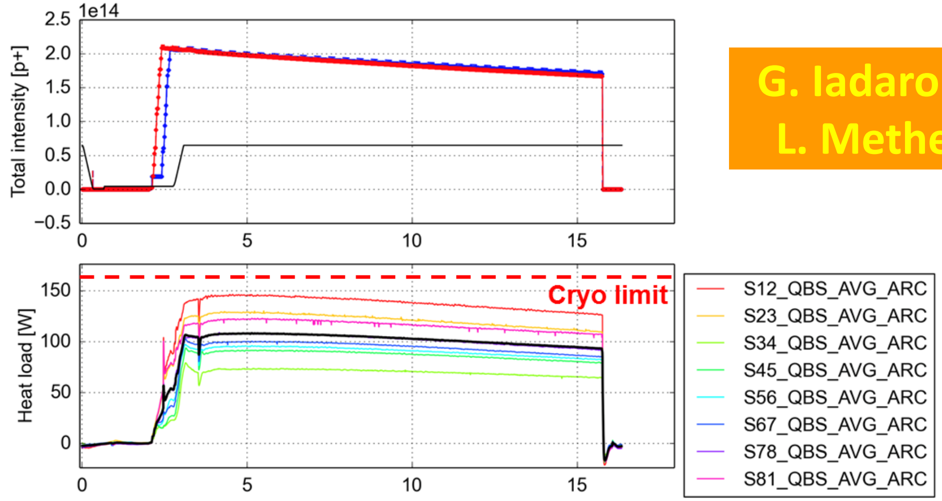


G. Iadarola, G. Rumolo, L. Mether

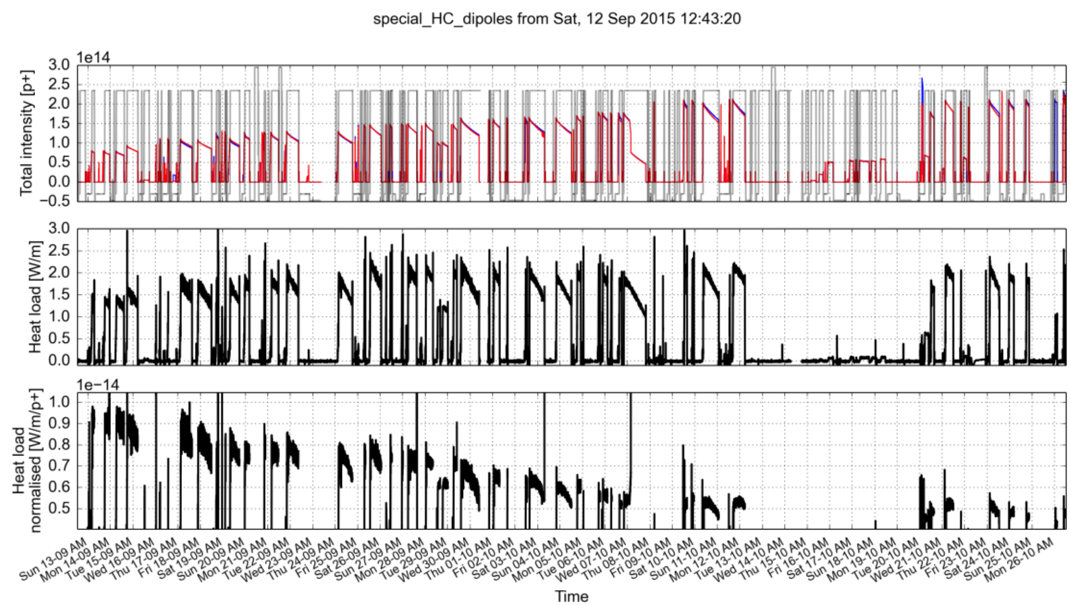
- Lost memory of previous scrubbing after venting the machine (LS1)
- Achieved SEY of ~1.4 in about 10 days
- Improvement of the beam quality observed later but with no significant reduction of the heat load/SEY

25 ns operation: LHC

- After Scrubbing Run beam quality allowing physics at 6.5 TeV but no full suppression of the e-cloud
- Scrubbing continued with physics fills at 6.5 TeV running always at cryo limit
- Slower than expected from laboratory measurements
- Significant difference among sectors observed: need to understand origin.

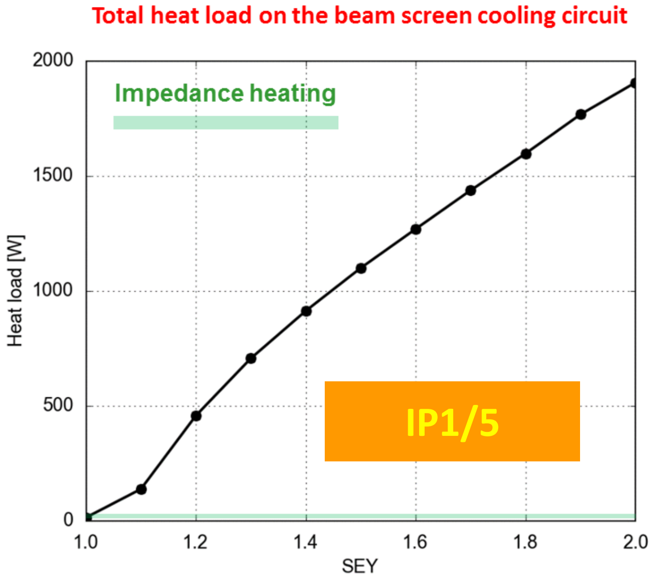


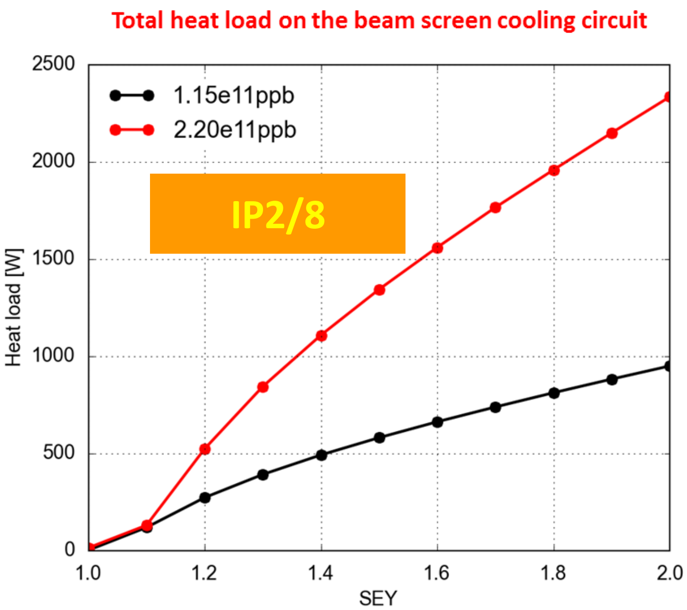
G. Iadarola, L. Mether



Heat loads (HL-LHC)

- We rely on scrubbing of the main dipoles to suppress electron cloud
- Complete analysis of the zoo of vacuum chambers and magnets in the TAS-Q7 area for heat loads:
  - Electron cloud
  - Image currents
  - Synchrotron Radiation (at first view negligible)
- Confirmed the need for e-cloud suppression measures (coating and possibly clearing electrodes) for the triplets/D1 in IP1/5 and IP2/8

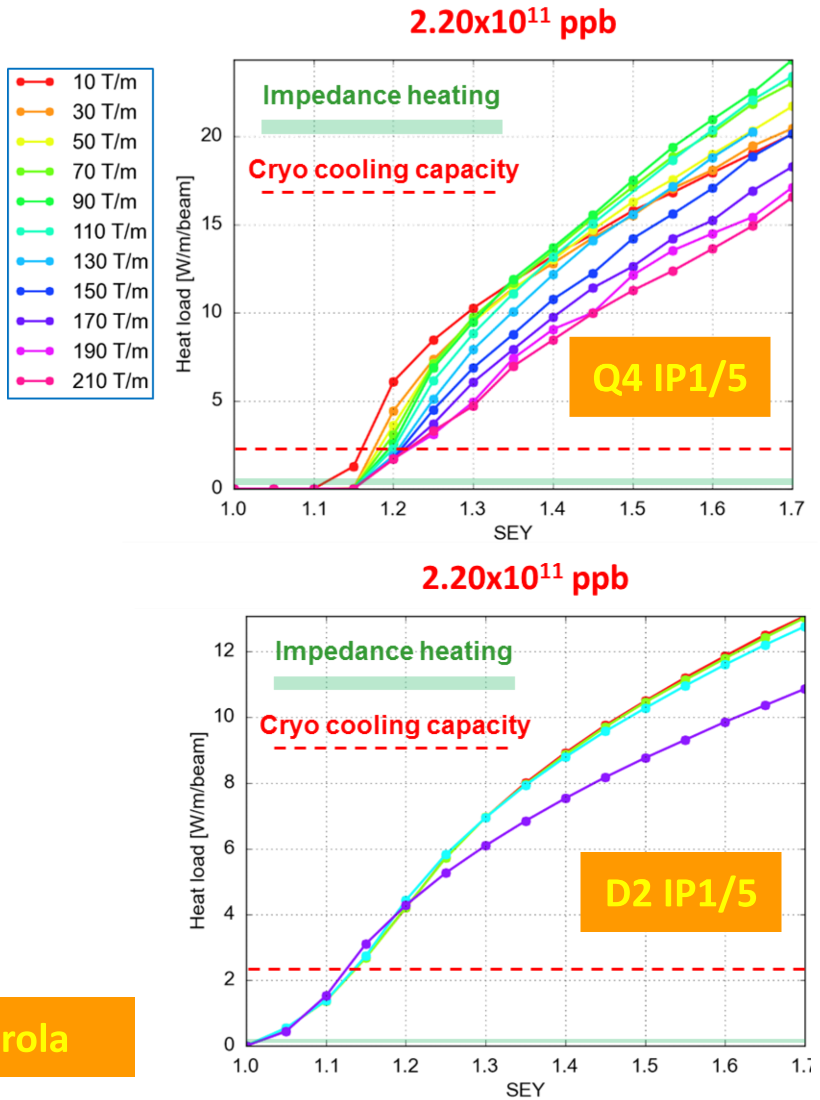




G. Iadarola

Heat loads (HL-LHC)

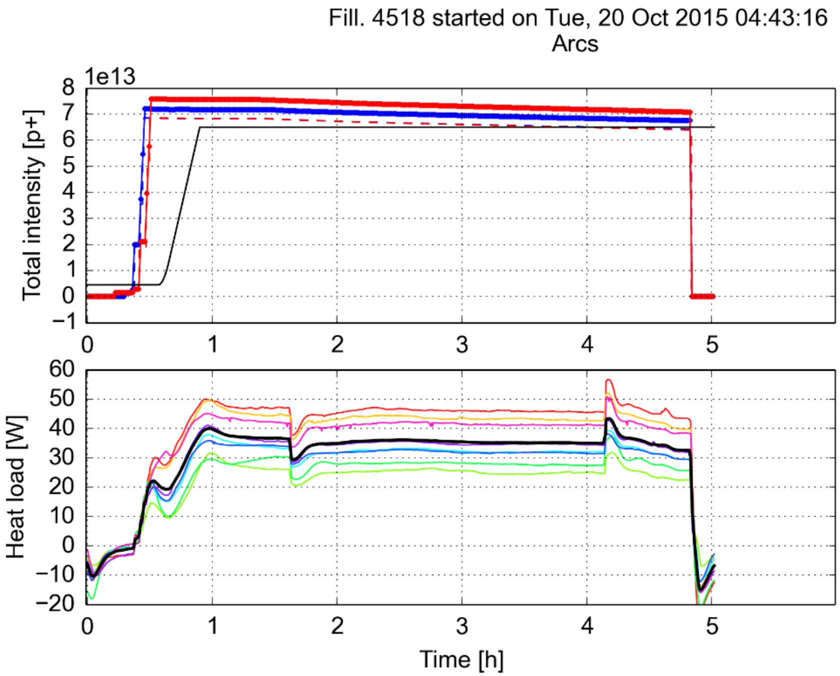
- Matching sections:
  - New Q4/D2 in IP1/5 will require aC coating.
  - Based on the analysis of 2015/2016 SEY evolution a proposal will be made for D2 IP2/8 and other Quadrupoles of the IP1/5 Matching Sections



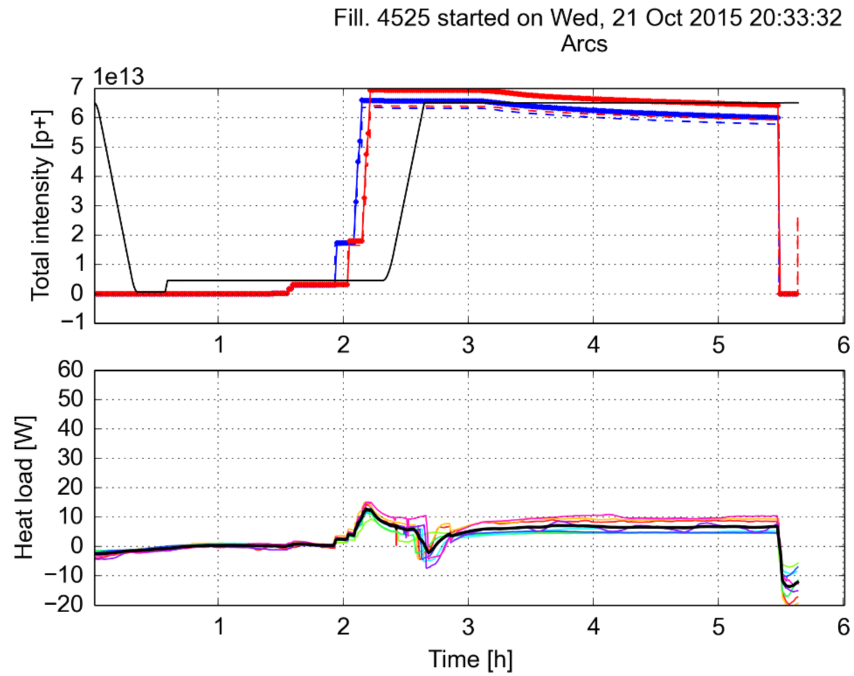
G. Iadarola

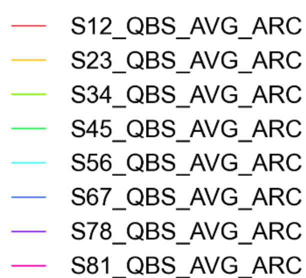
8b+4e: a validated alternative

Standard 25 ns



8b+4e



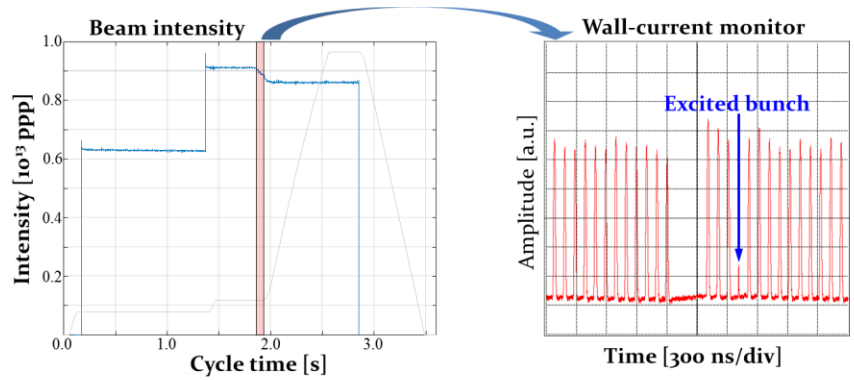


G. Iadarola, G. Rumolo

Alternative filling patterns

G. Sterbini, H. Damerau, S. Gilardoni, B. Goddard

- 80 bunch scheme obtained by selective removal of one bunch after triple splitting in PS: 20b in h=21 ➔ 80b in h=84
- 8 bunches more per PS batch

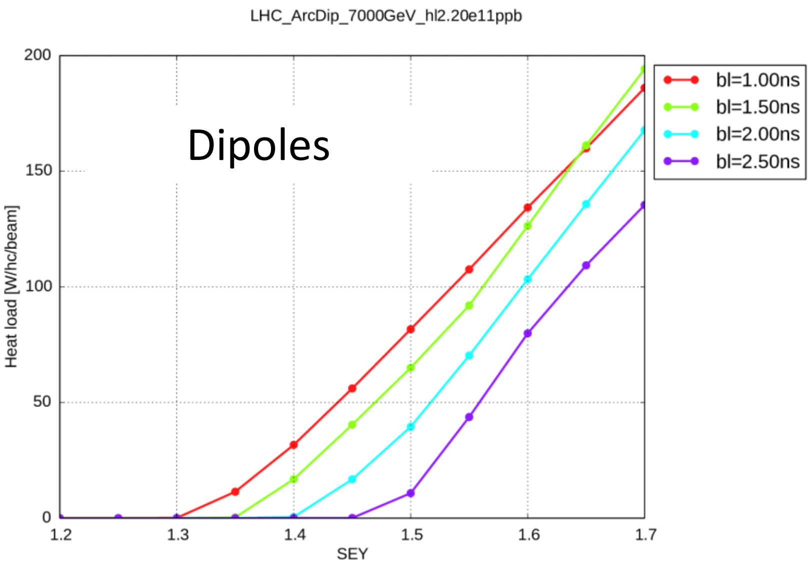


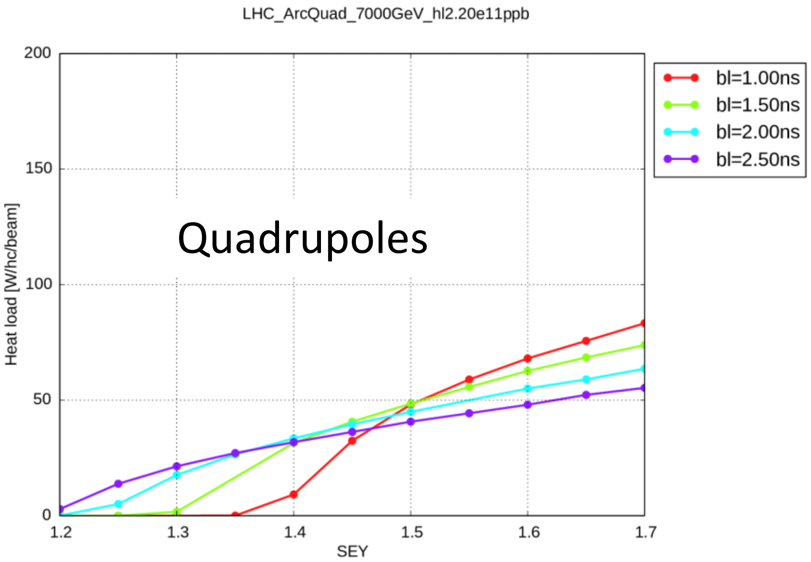
- Increase luminosity in LHC/Recover baseline performance with 17 % less intensity in SPS
- Anti electron cloud filling pattern in SPS and LHC creating multiple 4-bunch gaps (e.g. filling with 2×(24b+4e)+24b batches)

Scheme	n_b at SPS ejection	Colliding bunches in LHC	Gain [%]
Baseline LIU	4 × 72 = 288	2736	
80b, 4 PS batches per SPS cycle	4 × 80 = 320	2800/2880	2.3/5.3
80b, 3 PS batches per SPS cycle	3 × 80 = 240	2732	±0

200 MHz

- Longer bunches captured on a 200 MHz system could significantly reduce electron cloud effects:
  - Strong beneficial effect on dipoles (main limitation)
  - Weak effect on quadrupoles, even detrimental for low SEY
- Negligible reduction of the integrated luminosity
- Beam-beam effects studied and did not show any show-stopper
- Expected reduction of the TMCI threshold to 2.6×10^{11} p/bunch
- Need to take a decision by 2018 in order to be ready for LS3



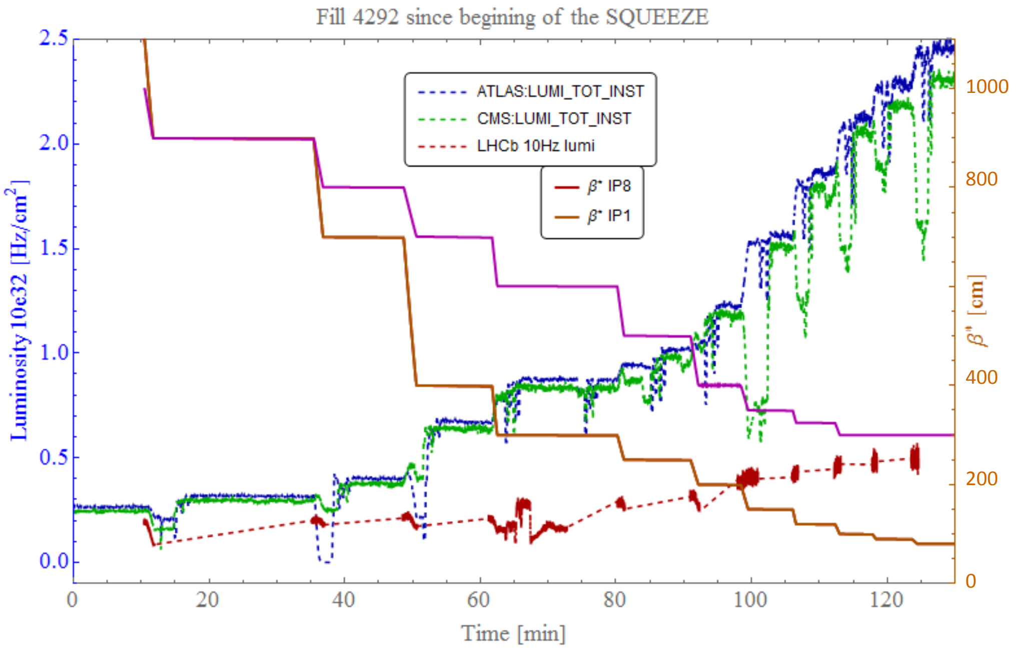


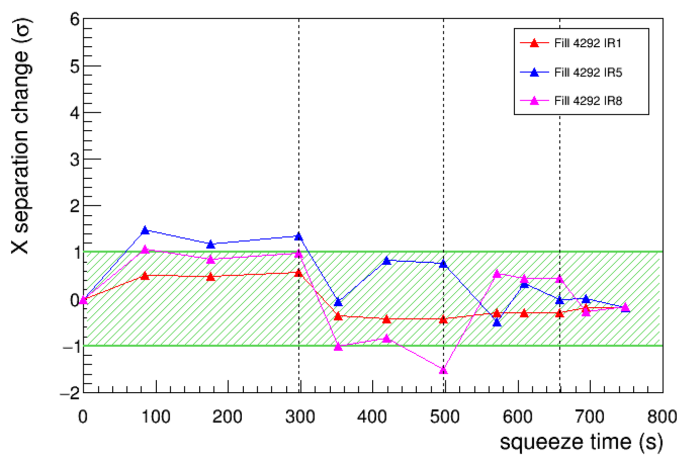
G. Iadarola, G. Rumolo, R. Tomas

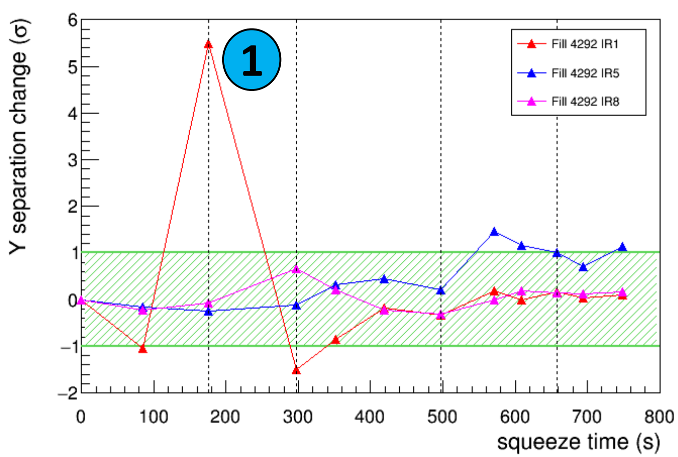
β* levelling

A. Gorzawski, J. Wenninger

- Successful test (at low intensity) with 3 points collided and squeezed at the same time:
  - Reproducible
  - Change in beam separation below **1 sigma** (green band) in most cases.



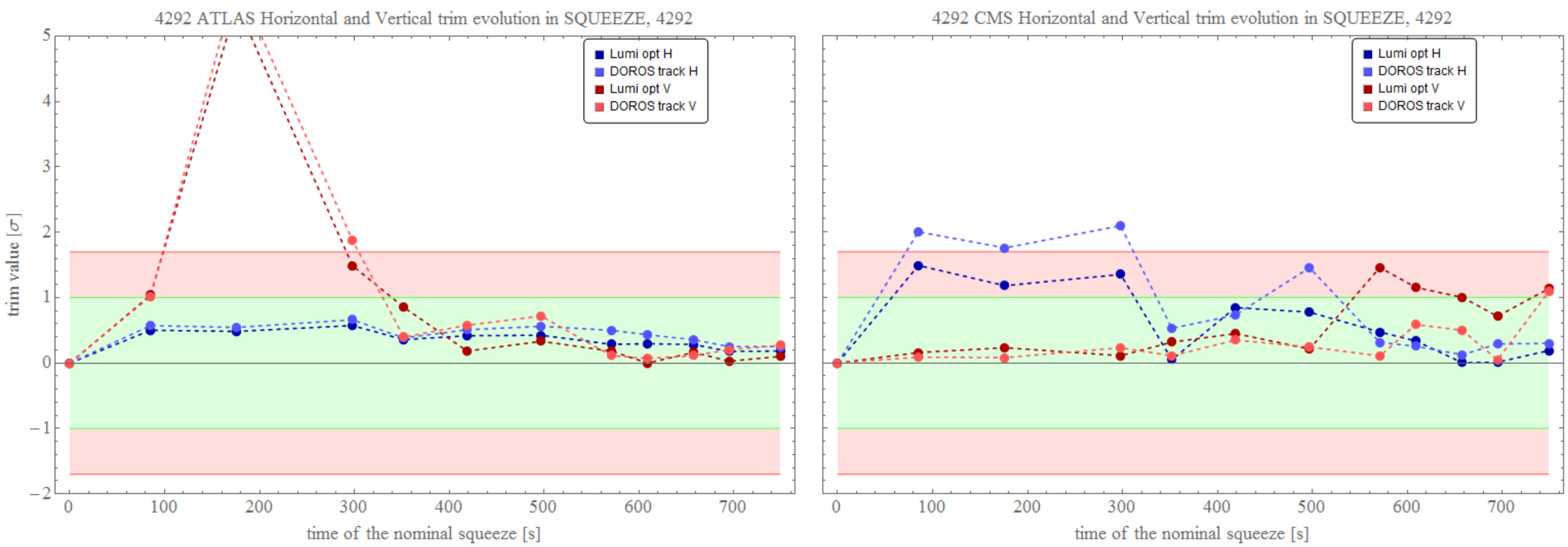




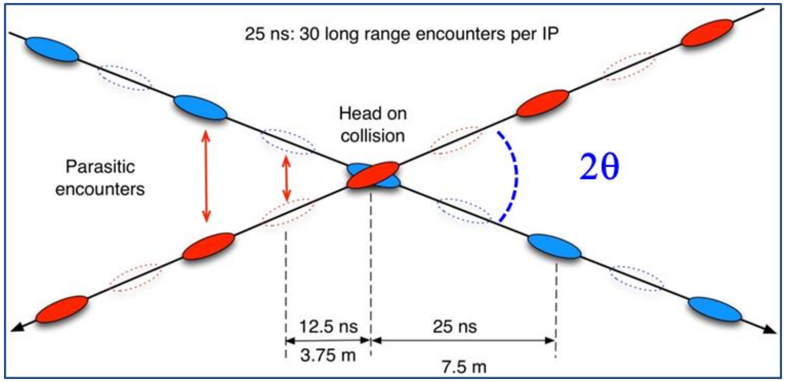
β* levelling

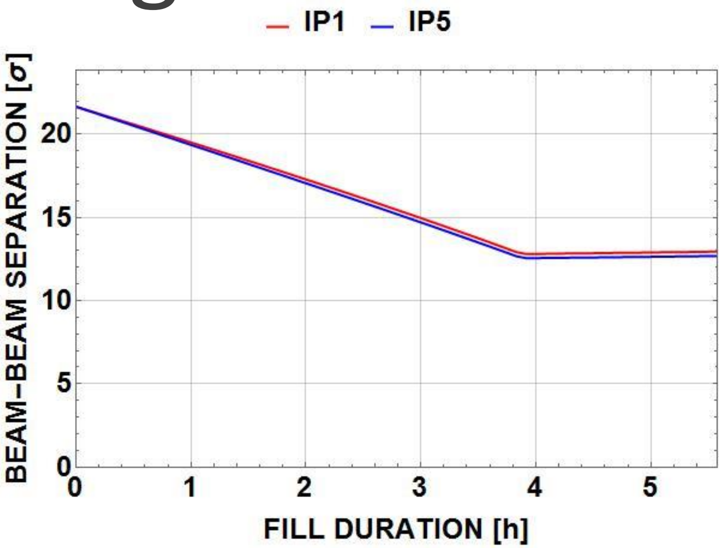
- Good agreement between the applied luminosity trims and separation values (at the end of each step) tracked by the BPMs (IP1/IP5) ➔ can be used for active feedback (next step)

A. Gorzawski, J. Wenninger



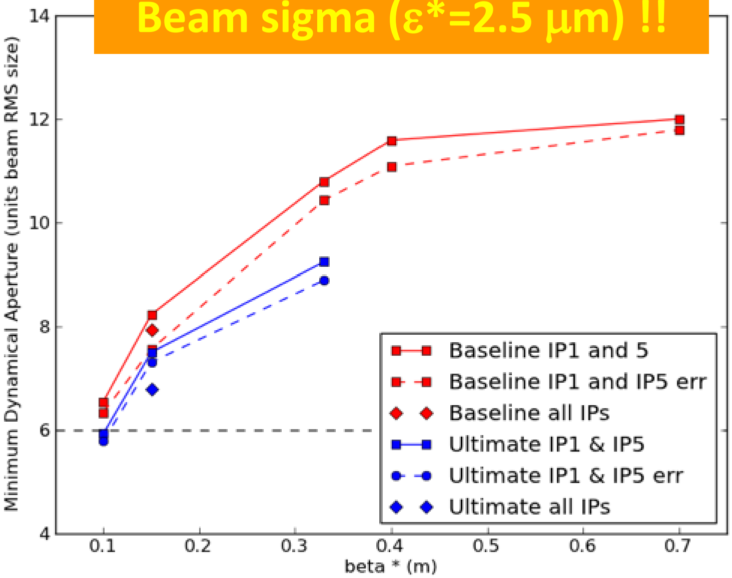
Beam-beam and β* levelling





- β* levelling allows operating with larger long range beam-beam separation over a fraction of the fill also for the ultimate scenario
- need to guarantee sufficient DA (>6 σ) down to low β*

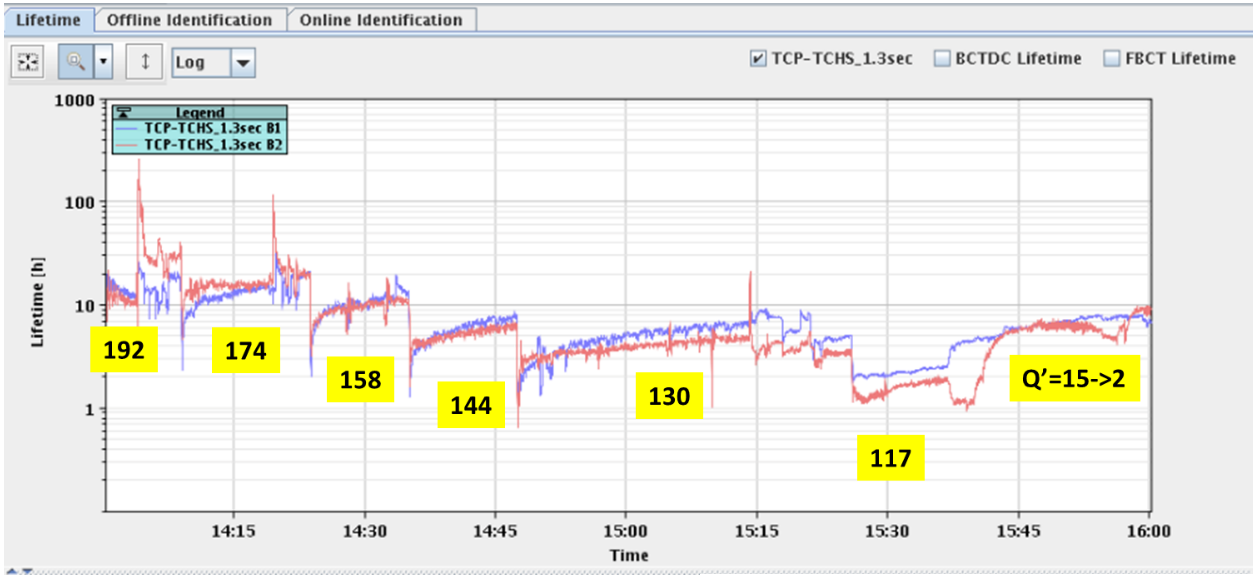
Beam sigma (ε*=2.5 μm) !!



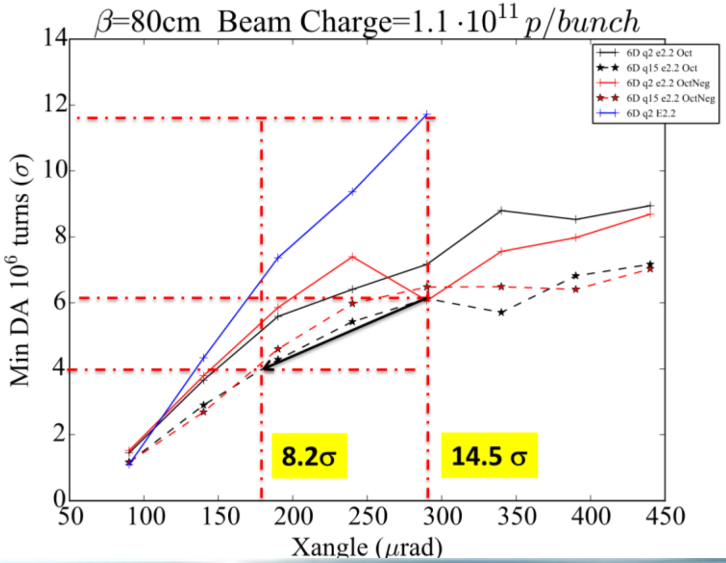
D. Banfi, J. Barranco, T. Pieloni, A. Valishev

Beam-beam

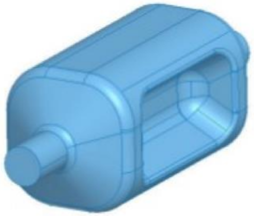
J. Barranco, T. Pieloni, B. Salvachua, C. Tambasco

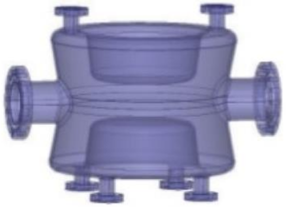


- Preliminary MD results with 25 ns beam (and those of previous MD with 25 ns) seem to validate the choice of 6 σ as minimum DA acceptable in collision



Crab crossing

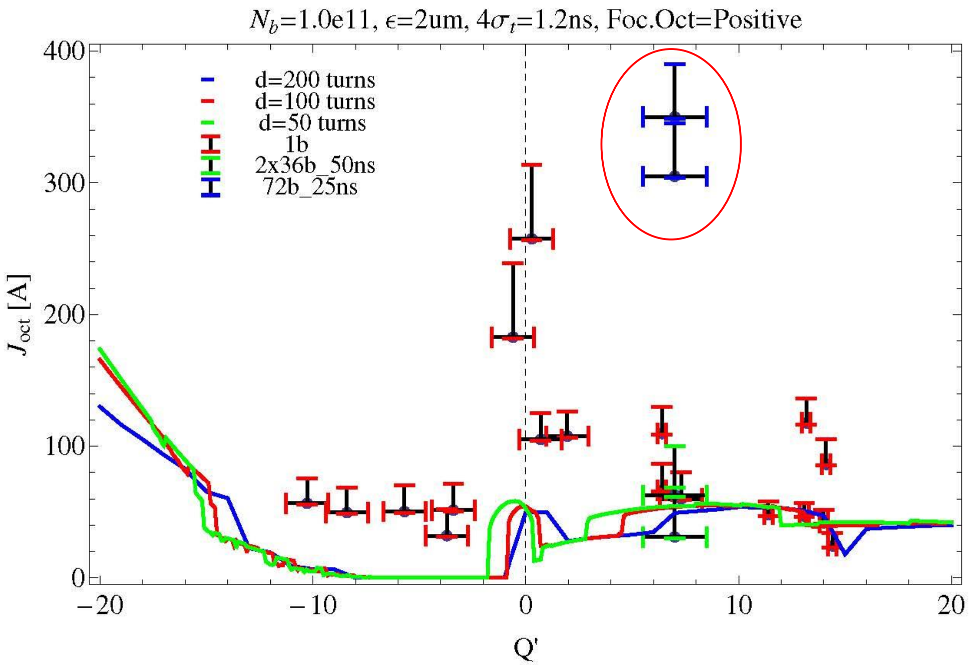




- Crab crossing to fight the luminosity reduction factor due to the crossing angle
- A First in a high intensity proton machine:
  - Performance with high intensity beams
  - Transverse Stability and HOM power
  - Cavity control (tight frequency control when detuned to avoid instabilities)
  - Validation of operation modes
  - Failure scenarios
  - Effect of noise: transverse blow-up, halo?
- SPS tests in 2018
- Staged Installation (2 crab cavities/IP side/beam)

Impedance and transverse stability (LHC)

- In 2015 Systematic scan of the stability parameter space with single bunches to fully characterize the effect of impedance
- Some discrepancies w.r.t. model (within a factor 2 in the operational range) being closely evaluated
- 50 ns beams behave as single bunches as expected
- 25 ns-beams beam dynamics strongly affected by electron cloud → need of scrubbing of the arcs (and coating of the new elements for HL-LHC)

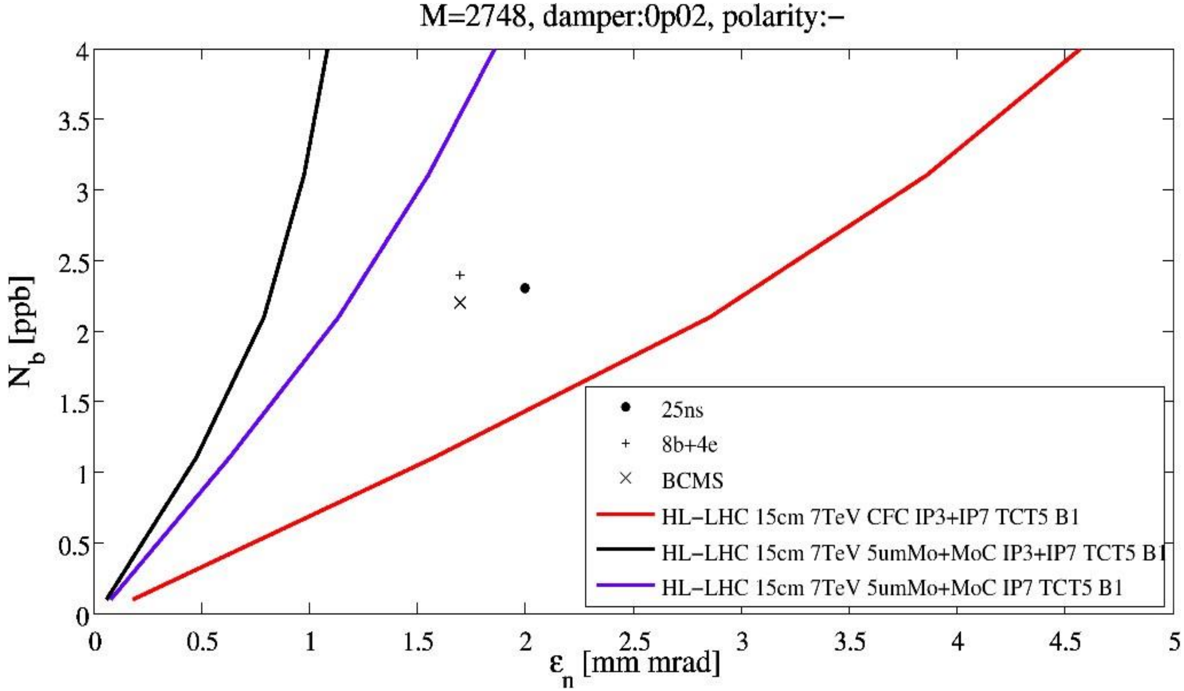


25 ns beams: stability thresholds **5x larger** w.r.t. to single bunches → e-cloud effect

N. Biancacci, L. Carver, E. Métral

Impedance and transverse stability (HL-LHC)

N. Biancacci, E. Métral

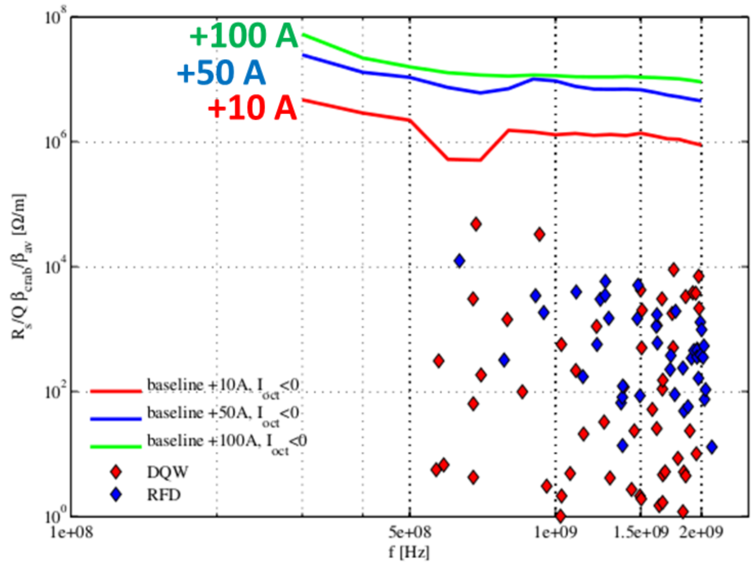


- Low-impedance secondary collimators are necessary (at least in IR7) in order to guarantee beam stability
- A wide*(er)*-band feedback could help increasing the stability parameter space:
  - For scrubbing
  - At injection and at flat-top in the presence of electron cloud

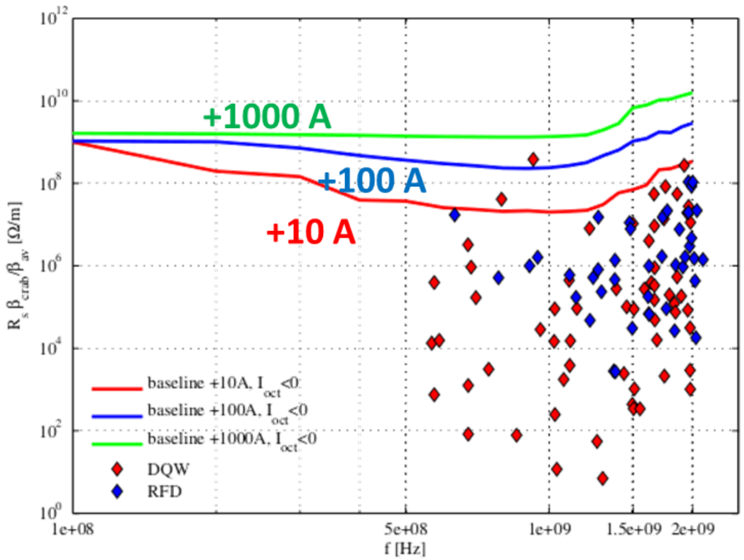
Impedance and transverse stability (HL-LHC)

- Crab cavities HOMs spectrum critical for beam stability
- Involved studies both from **RF design** and **beam dynamics**.
- Limited increase of the octupole current beyond that required to stabilize the beam with known impedances and low impedance collimators in IR7
- Significant progress in the control of HOM modes. Most of HOM modes within the required specifications. Statistical analysis made.

Single bunch limits



Coupled bunch limits

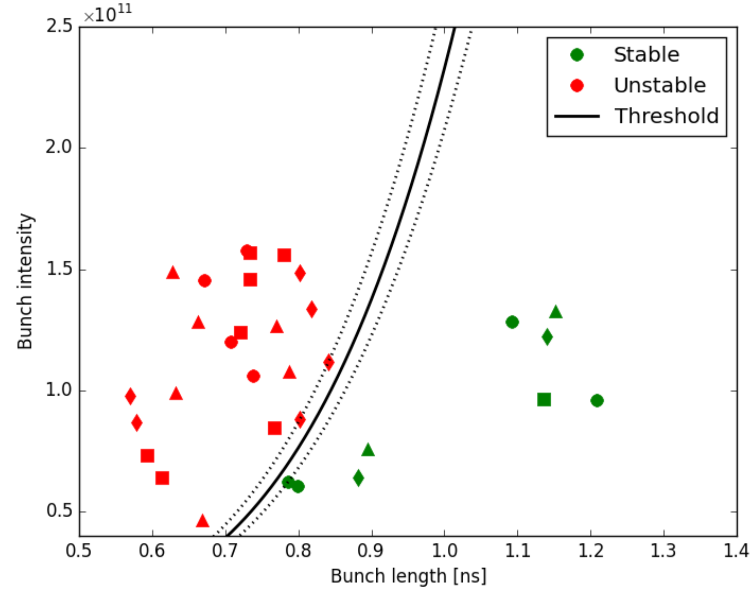


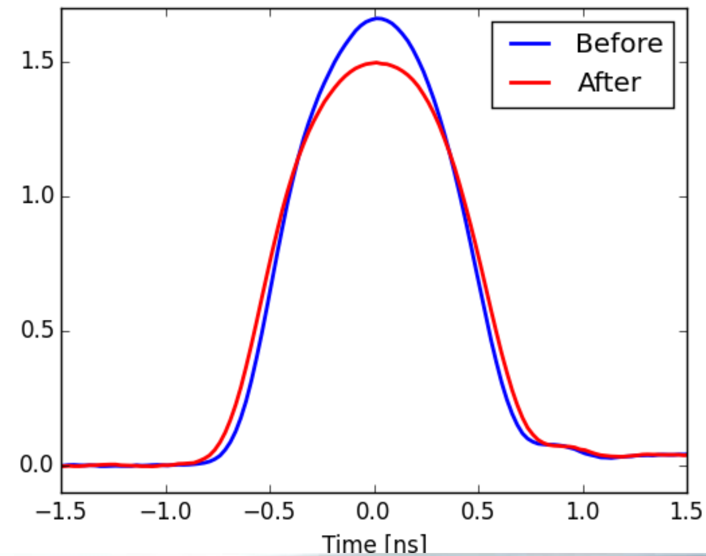
N. Biancacci, R. Calaga – x 8 cavities –β*=15 cm

Longitudinal stability

- Recent MDs confirmed:
  - single bunch stability limits
  - Possibility to shape the longitudinal distribution (flat bunches) with RF phase modulation
- 800 MHz RF system operated in Bunch Shortening Mode (BSM) needed only in case of longitudinal coupled bunch instabilities
- Estimate of the instability threshold with the future impedance model (including the effect of crab cavities) needed.
- Decision must be taken before 2018

Single bunch
E. Shaposhnikova - J.E. Müller





Ph. Baudrenghien, H. Timko

Conclusions

- Integrated luminosity goal within reach for nominal operational scenario:
  - Nominal bunch population
  - Average fill length of ~8 hours ➔ Machine Availability

- Ultimate scenario provides additional flexibility towards integrated performance
  - But:
    - more strain on detector and machine performance
    - relies even more on (HL-LHC) nominal bunch population from the injectors and on nominal HL-LHC machine parameters (e.g. β^*)

- Recent progress in the understanding of the sources of longitudinal instabilities and corresponding impedance reduction in the SPS should allow filling the performance gap between LIU and HL-LHC
  - New 80 bunch scheme could help in further enhancing performance

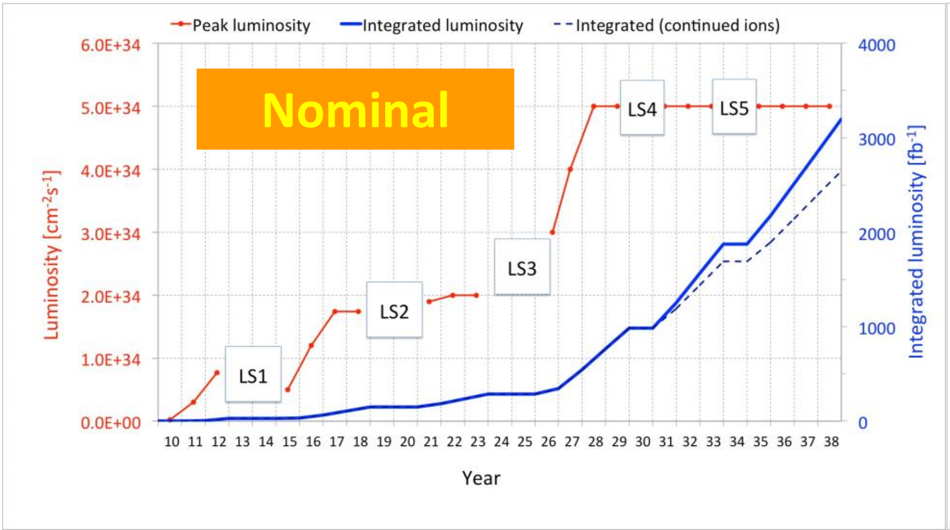
Conclusions

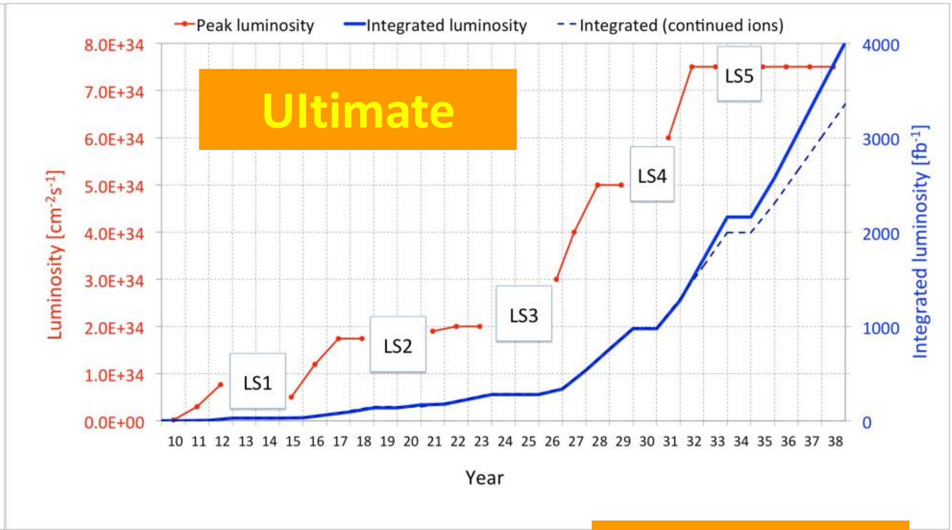
- Promising experience with 25 ns beams but adequate time must be allocated for scrubbing following major interventions on the vacuum system (e.g. after a long shut-down)
- Alternative fall-back schemes for electron cloud suppression exist (8b+4e)
- Recent MD results are contributing to the validation of the main scenarios for HL-LHC:
  - β^* levelling
  - Beam-beam
  - Longitudinal and transverse stability
- Important progress has been done with the evaluation of the impact of impedance on beam stability and in the minimization of the impedance (in particular crab cavities)

High
Luminosity
LHC

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.

Operational Scenario



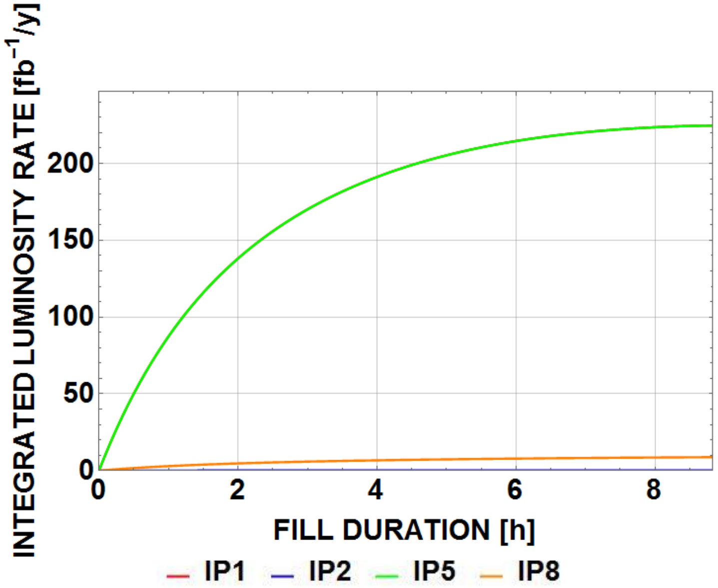


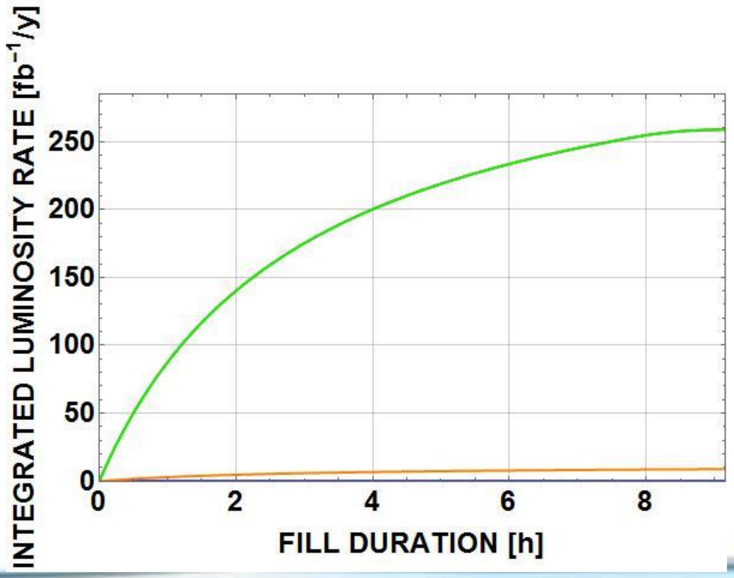
M. Lamont

- Pre LS4:
  - 30 days ion physics (set-up incl.), 10 days special physics runs, 160 days of p physics at high luminosity (ramp-up incl.)
- Post LS4:
  - No ion physics, no special physics runs: 160 ➔ 200 days of proton physics at high luminosity
- Post LS5:
  - No more MDs either (feasible?) 220 days of proton physics at high luminosity

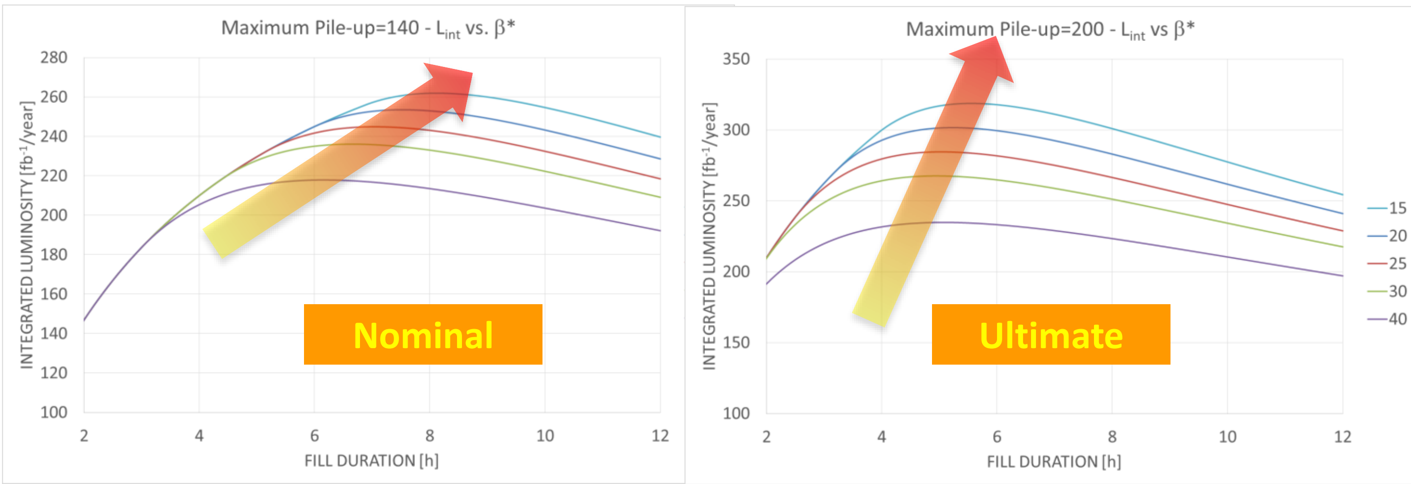
Staged Crab Cavity Installation

- Half of CC installed in LS3 (6.8 MV/beam/IP side) and the rest in the following YETS/LS
- Visible (~20 %) reduction of the integrated luminosity if we limit the maximum pile-up density to 1.2 events/mm by levelling.
- Recover performance with flat beams for the nominal levelling luminosity/pile-up (provided that a crossing angle of 400 μrad could be reached) or by accepting higher peak pile-up density (up to 1.7 events/mm)





Sensitivity to machine parameters



- Ultimate performance requires the capability of operating down to 15 cm with average fill lengths already achieved in 2012
- Large values of β* imply optimum fills of 4 to 6 hours in particular for the ultimate luminosity, which might be suboptimal for reliability