Digesting the LIU high brightness beam: is this an issue for HL-LHC?

Asked to cover:

- Beam stability
- Electron cloud effects
- Emittance preservation

Here most of the messages and material, I still need to:

- Organize
- Compress
- Remove "technicalities"
- Acknowledge!

Beam stability

[Introductory slide with overview of the work done and some references]

Main points reported in the following…

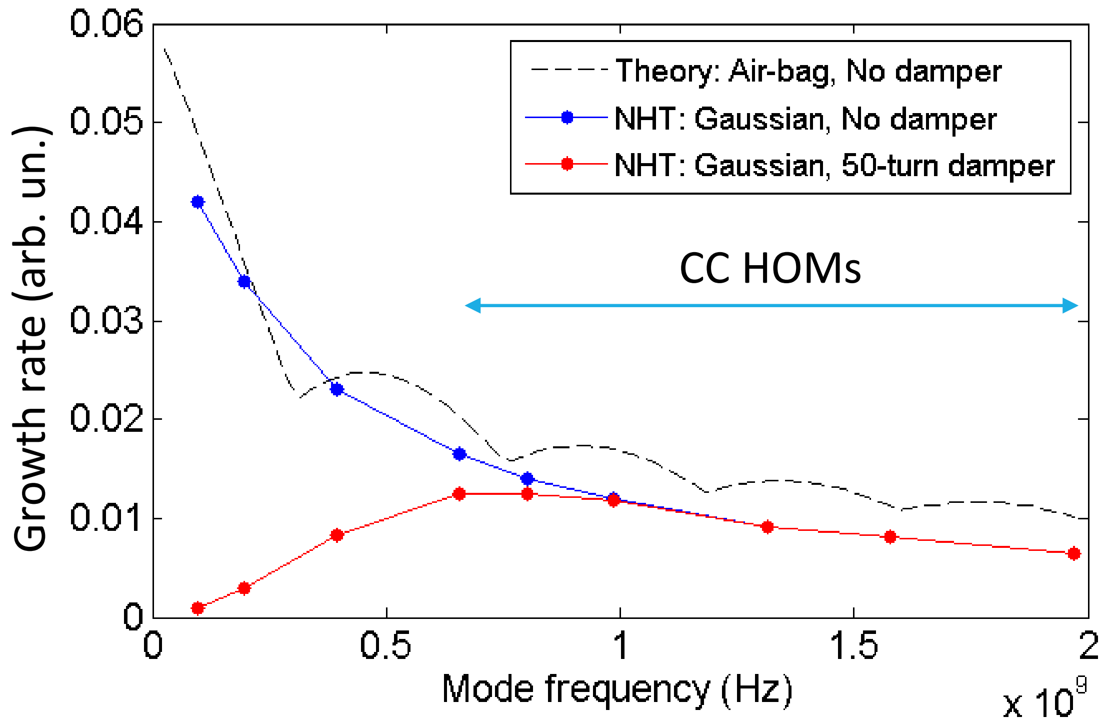
Coupled bunch instabilities

- Presently driven mainly by resistive-wall impedance
- The beam is stabilized using the transverse damper → no problem expected for HL-LHC (there is room to increase damper gain)

- **Crab cavity High Order Modes** (large beta) identified as additional source for CB instabilities and **damper ineffective for high frequency HOM**
  → Impedance carefully optimized by the design team in collaboration with the impedance team

Picture illustrating HOM optimization

Growth rate of the most critical CB mode
1 HOM, Q' = 10, d = 100 turns



Part of today's LHC life:

Single-bunch (head-tail) instabilities controlled by **damper** and a large enough **tune spread** (Landau damping) relying on:

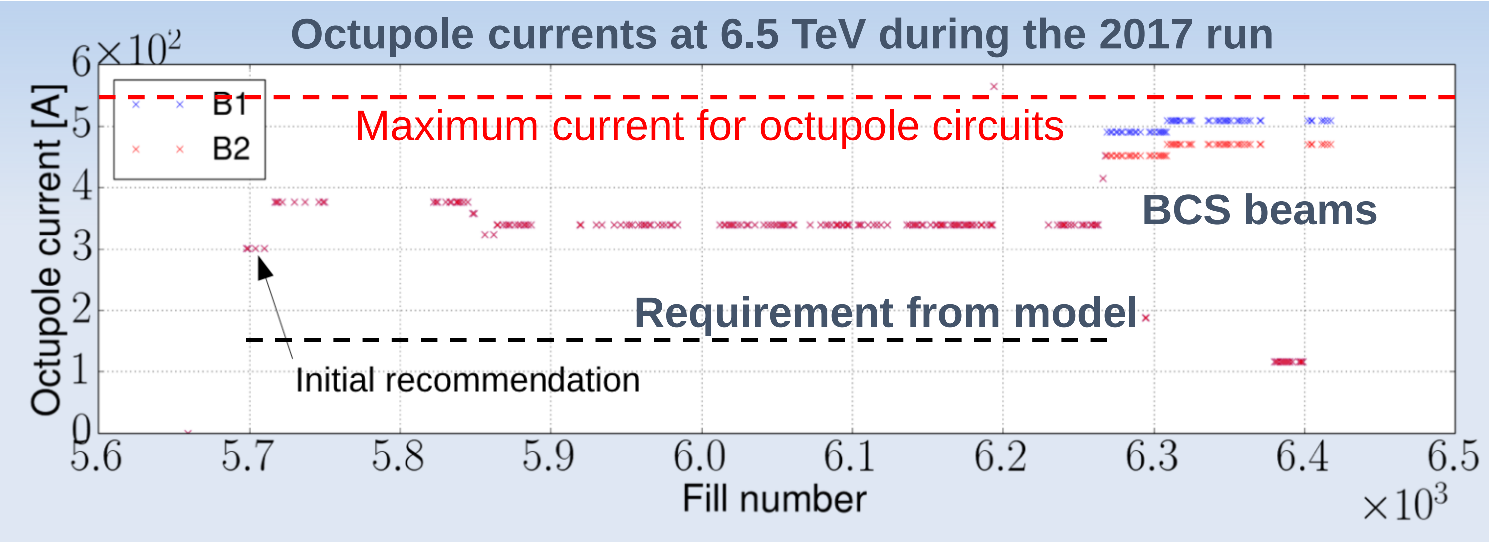
- **Octupole** magnets in the arcs
- **Beam-beam** effects (when in collision)

Octupole current required to operate reliably (i.e. also in real-life non ideal conditions) is significantly larger than expected from model

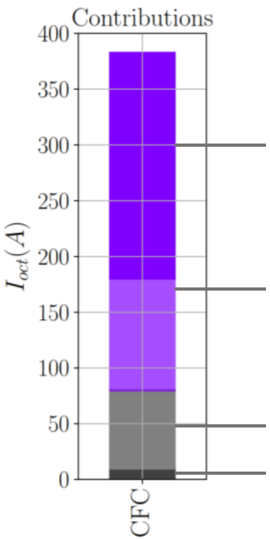
→ we should keep these margins!

Main instability source is the impedance from collimators:

→ Impedance reduction is part of the HL-LHC baseline



Impedance reduction for the collimators is part of the LHC baseline

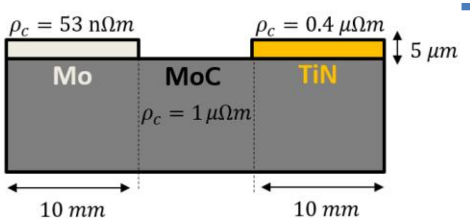


11 secondaries in IR-7 - 200 A

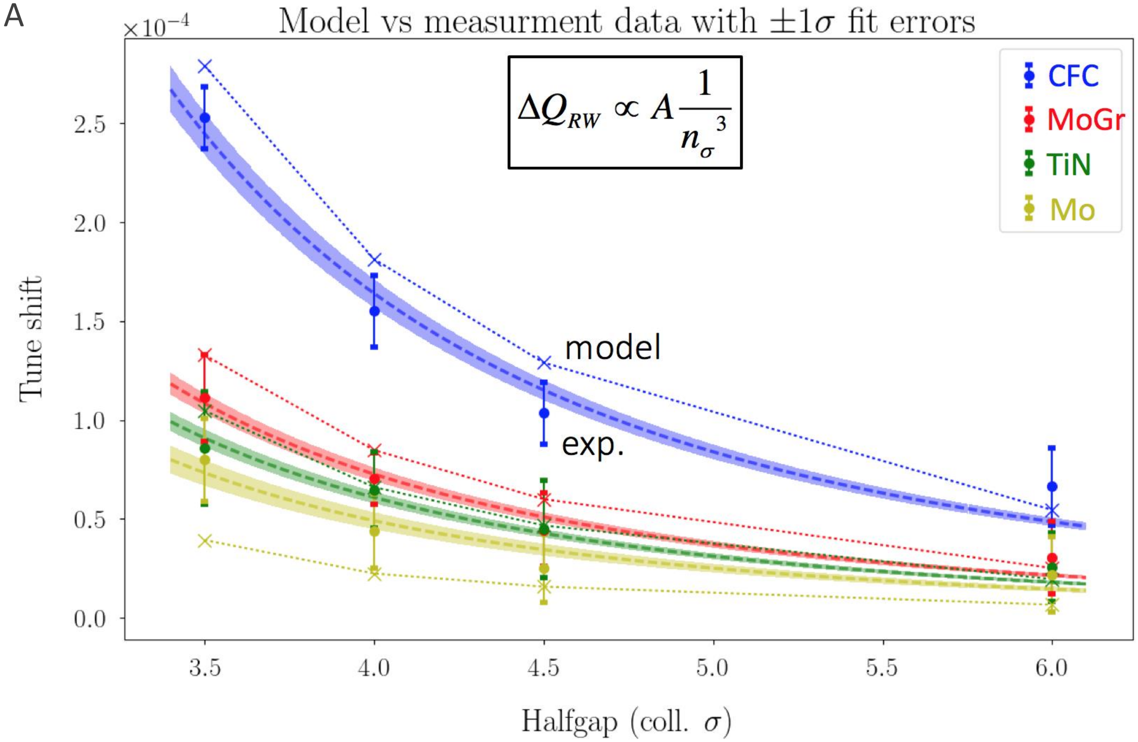
4 primaries - 100 A

All other collimators - 70 A

Everything else - < 10 A



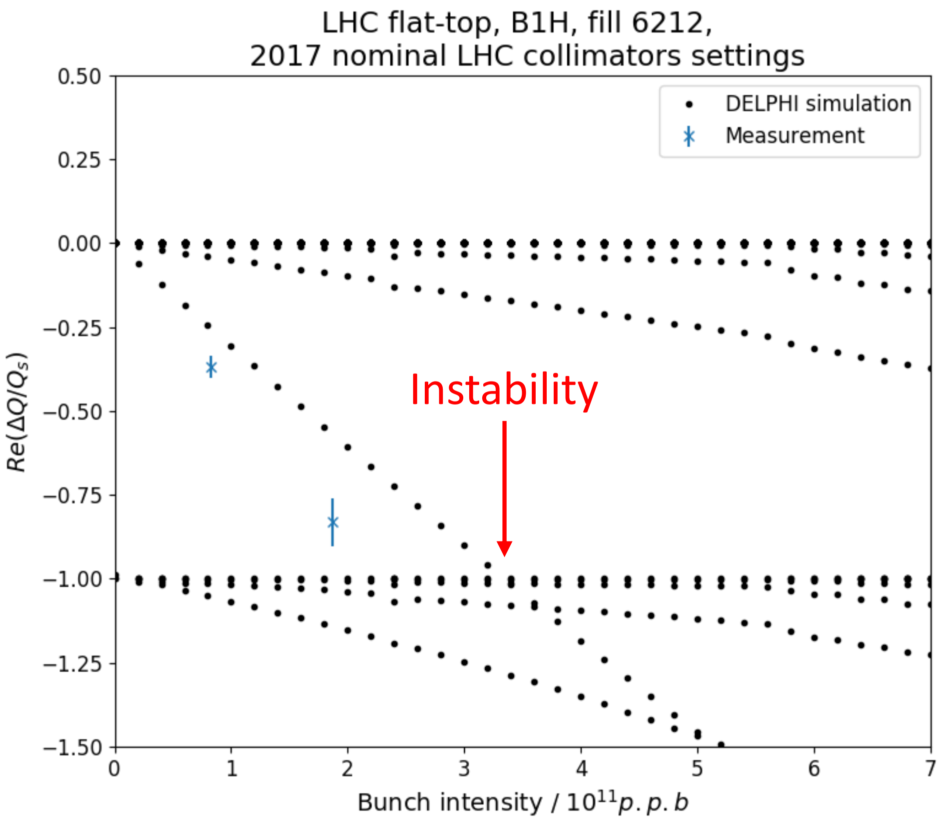
Low impedance design confirmed experimentally by prototype installed in the LHC in 2017



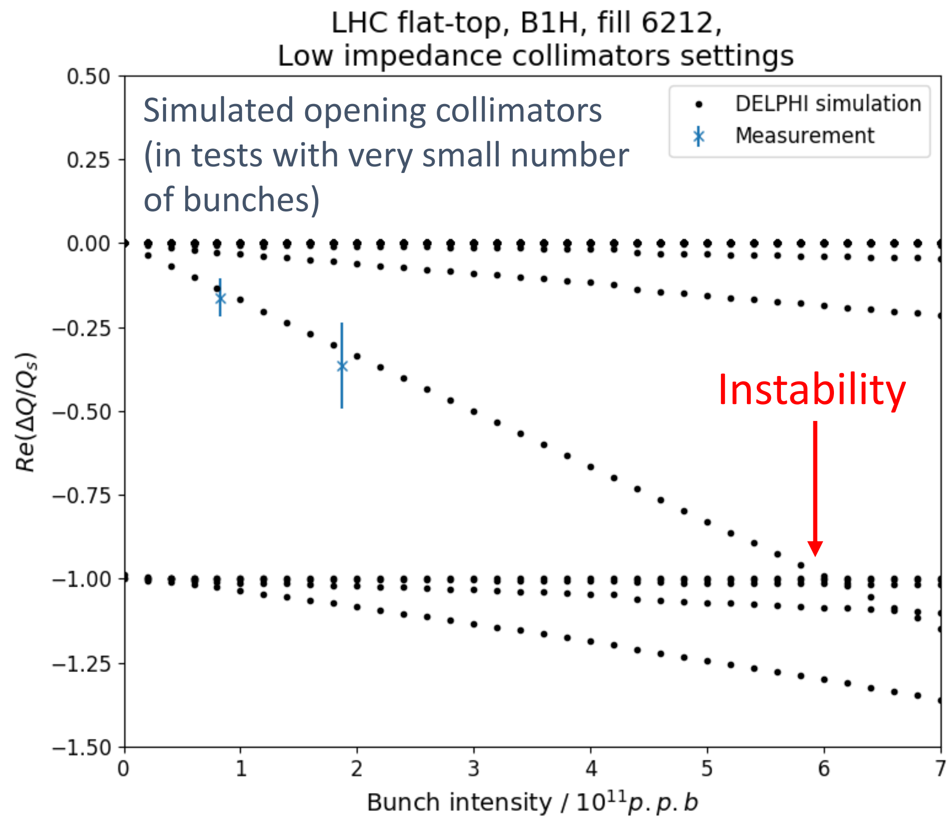
Transverse Mode Coupling instability (TMCI)

- More critical at high energy due to tighter collimator gaps
- Coupling between mode 0 and mode -1 is the most critical
- No instability observed up to 1.9e11 p/bunch (with no margins we hand 2e11 ~1.5um in collision)
- TMCI threshold can be inferred from mode-0 tune shift (instab. thresh: $\Delta Q = Q_s$)

Present LHC impedance



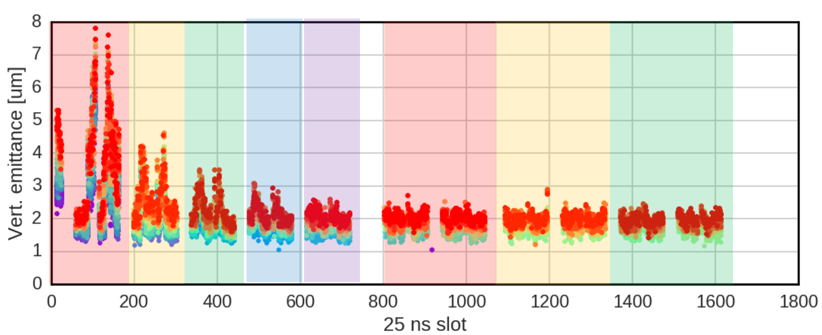
HL-LHC impedance (after collimator impedance reduction)



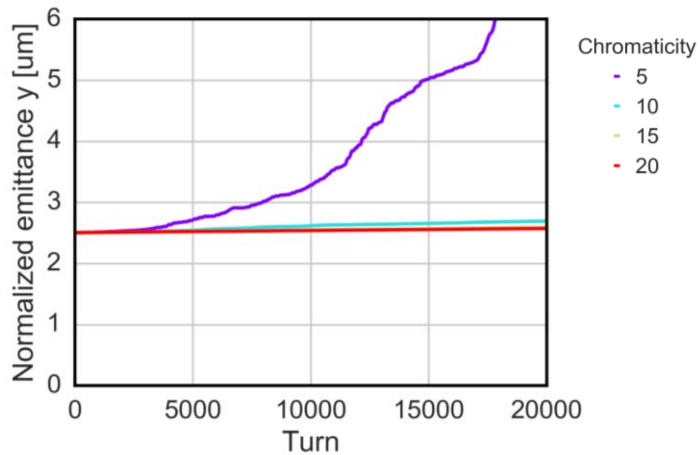
- EC in **quadrupoles** (7% of the machine) alone is a key driver of instabilities at the LHC **injection** energy
  - ➢ Simulations allowed explaining instabilities observations → large chromaticity values, relatively high octupoles current and a fully functional feedback system were needed to reach a satisfactory emittance preservation
  - ➢ instability suppressed when increasing the beam energy up to 6.5 TeV due to the increased beam rigidity

Bunch-by bunch emittance measurements

Oct [A] Chromaticity	6.5 5/5	13 5/5	13 10/10	13 15/15	26 15/15	52 15/15	52 10/15	52 20/15



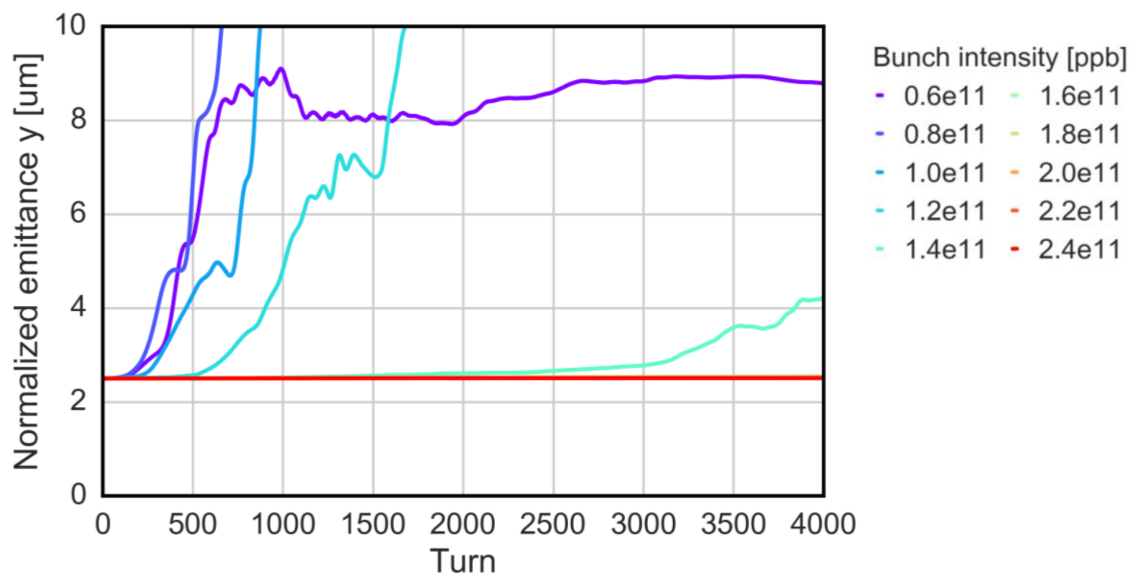
PyECLOUD-PyHEADTAIL simulation studies



(1) A. Romano et al., "Electron cloud induced instabilities in the LHC", presentation at the Joint Ecloud-PyHEADTAIL Meeting

Electron cloud instabilities

- Simulation results show that the beam intensity increase foreseen by the HL-LHC has a beneficial impact on the beam stability
- Unlike LHC, the EC in quadrupoles in HL-LHC is not expected to drive the beam unstable both at injection and flattop energy after conditioning → **provided that intensity dependence from build-up simulations is confirmed experimentally**
  - Psotential mitigation strategies have been investigated → strong stabilizing effect from large chromaticity values and mild effect from octupoles and damper



Impact of optics control on transverse stability

Importance of controlling:

- Tunes
- Linear coupling
- Amplitude detuning
- “a4 wall”
- Linear and non-linear chromaticity

[Add some example]

More challenging with low β^* and can be impacted in non-trivial ways by beam-beam, e-cloud, etc…

More in rogelio’s talk…

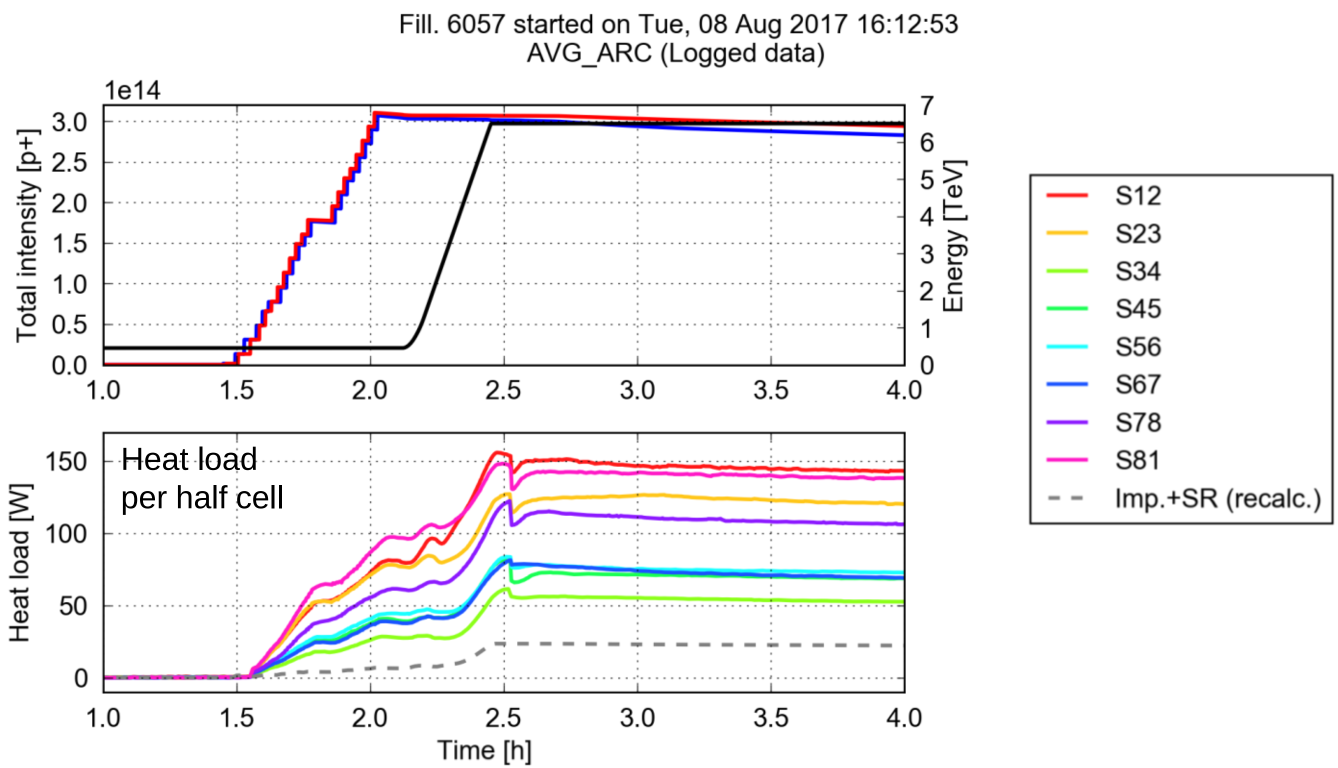
Electron cloud effects

[Introductory slide with overview of the work done and some references]

Main points reported in the following…

A **challenge for LHC operation with 25 ns in Run 2**: total load on the cryo-plants dominated by beam induced heating on arc beam screens

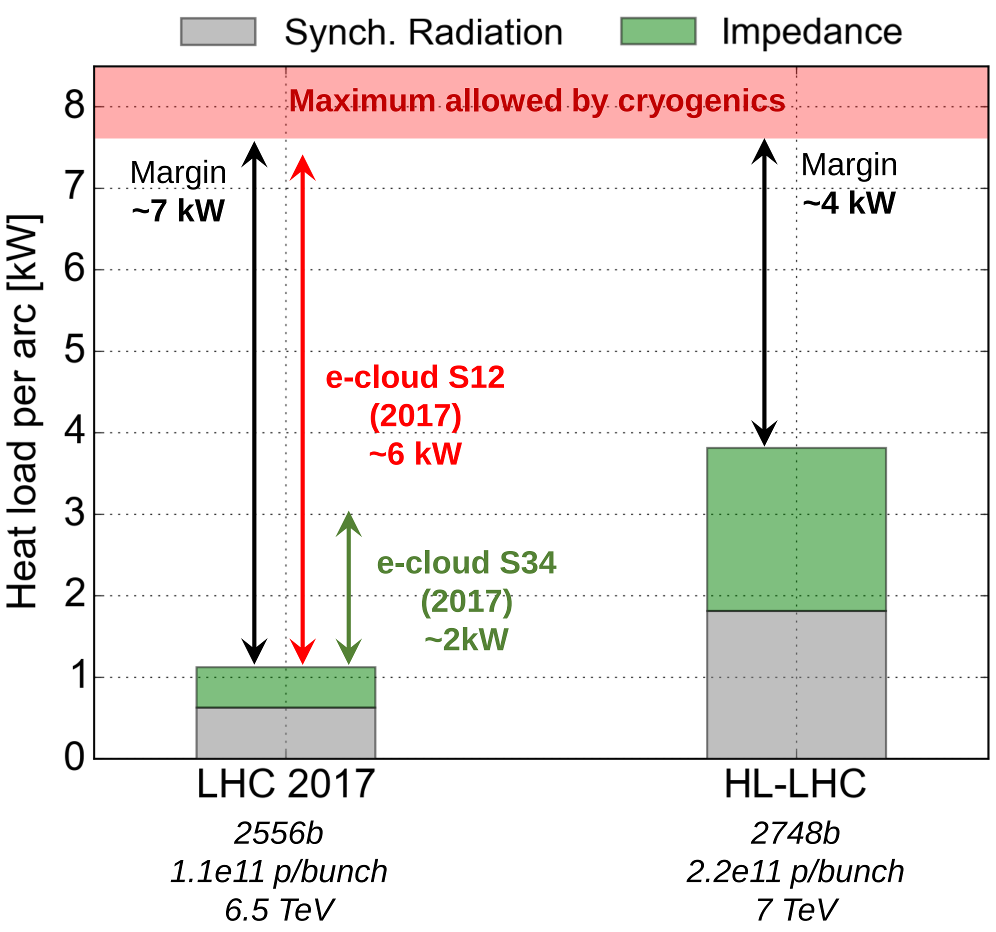
- Much **larger** than expected from **impedance and synchrotron radiation**
- Large **differences observed between sectors**
- Several observed features compatible with **e-cloud effects**
- Being followed-up by dedicated **Task Force** led by L. Tavian



More info can be found here

Arc heat loads from impedance and synchrotron radiation

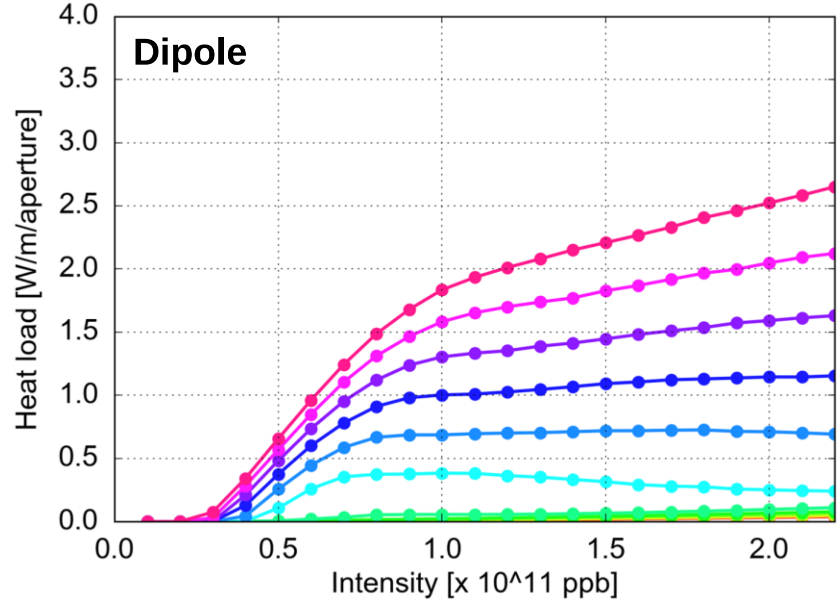
- In **Run 2** configuration: small contributions from **impedance and synchrotron radiation** → used large available **margins to cope with e-cloud**
- When moving to **larger beam intensities** (and to 7 TeV) the **margin reduces strongly**

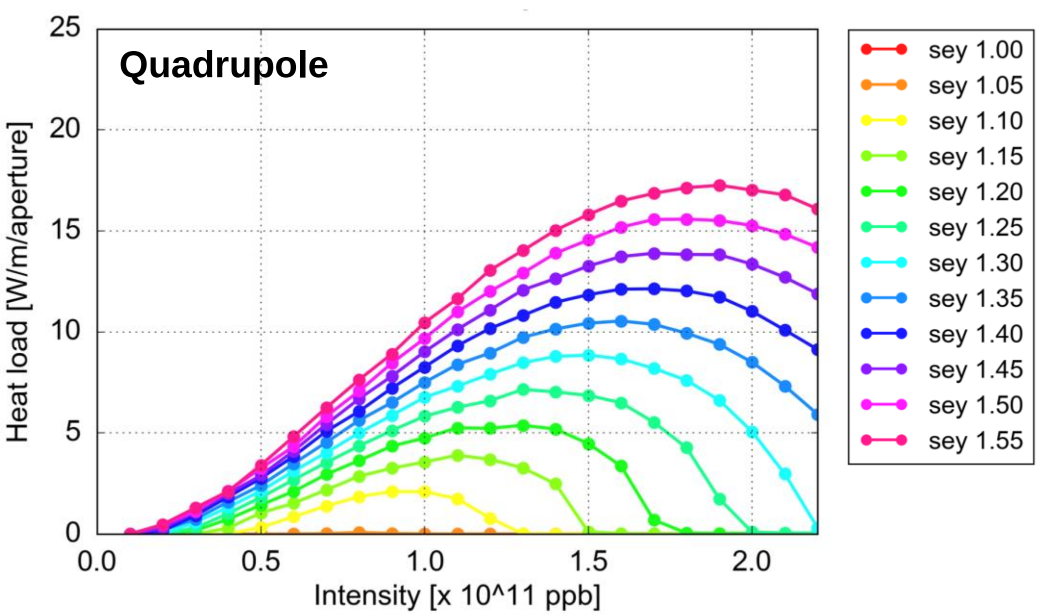


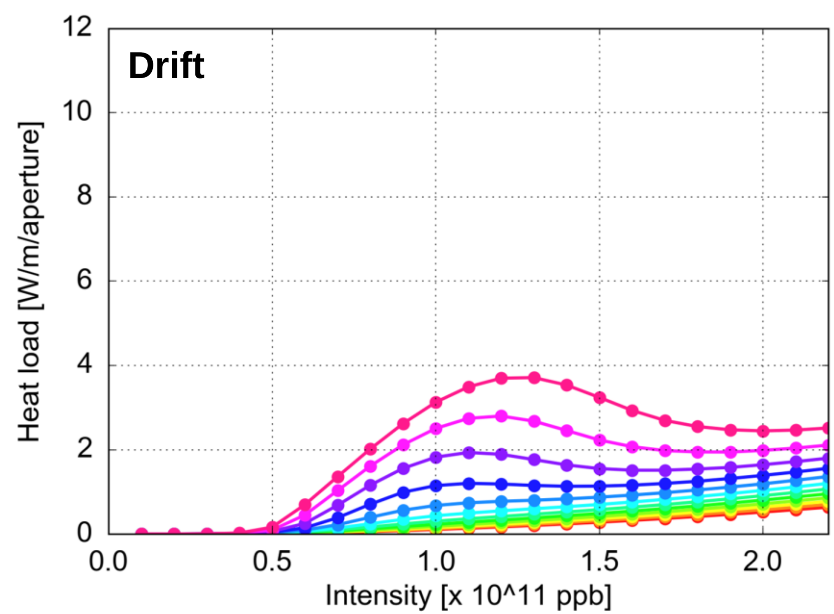
Arc heat loads – effect of bunch intensity

Assessed with PyECLOUD simulations:

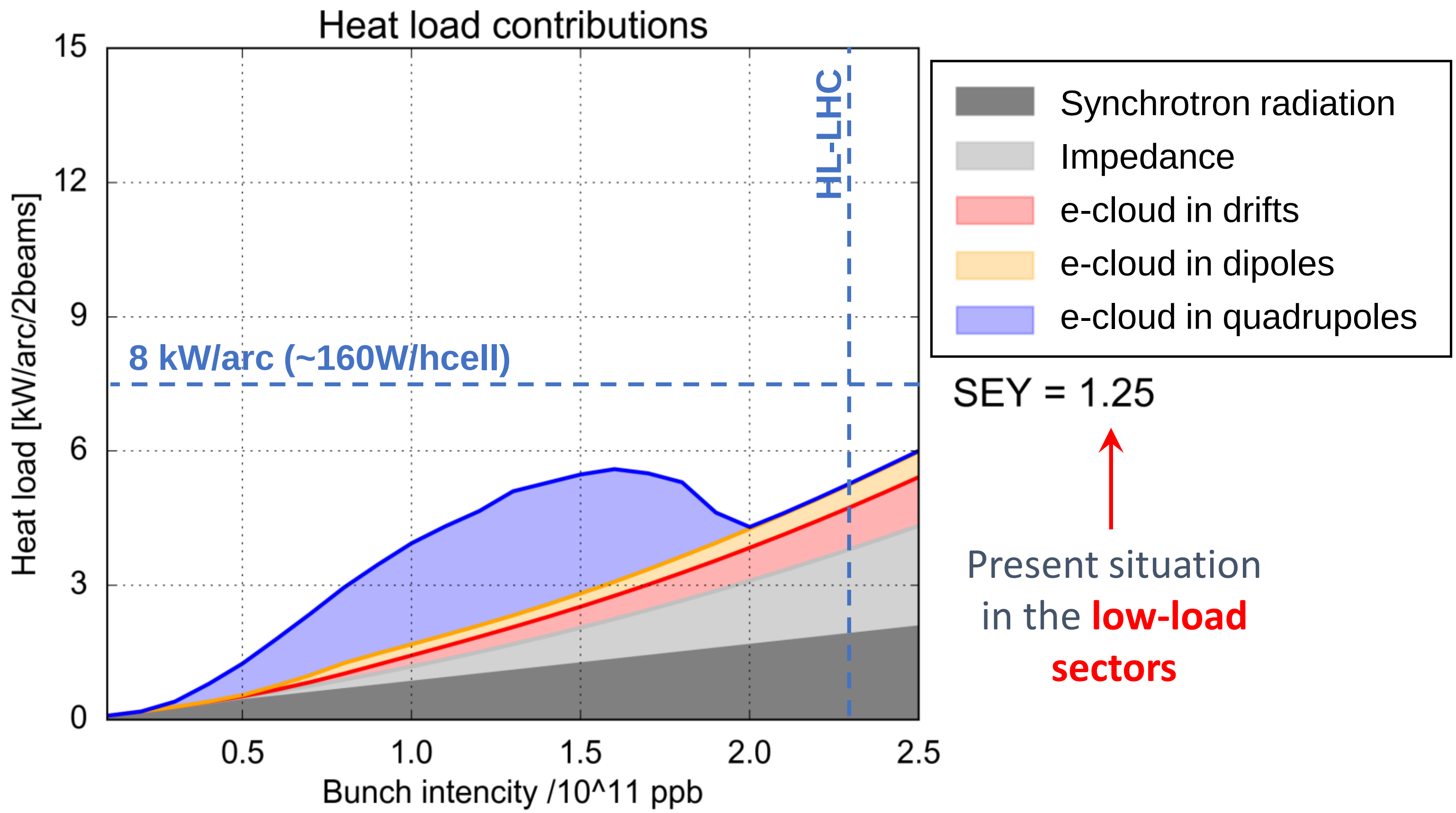
- The **dependence** of the heat load **on the bunch intensity** strongly depends on the **surface properties** (SEY parameter)
- The expected dependence on the bunch intensity is **strongly non linear**
- Full **experimental validation** of these curves **possible only after LS2**





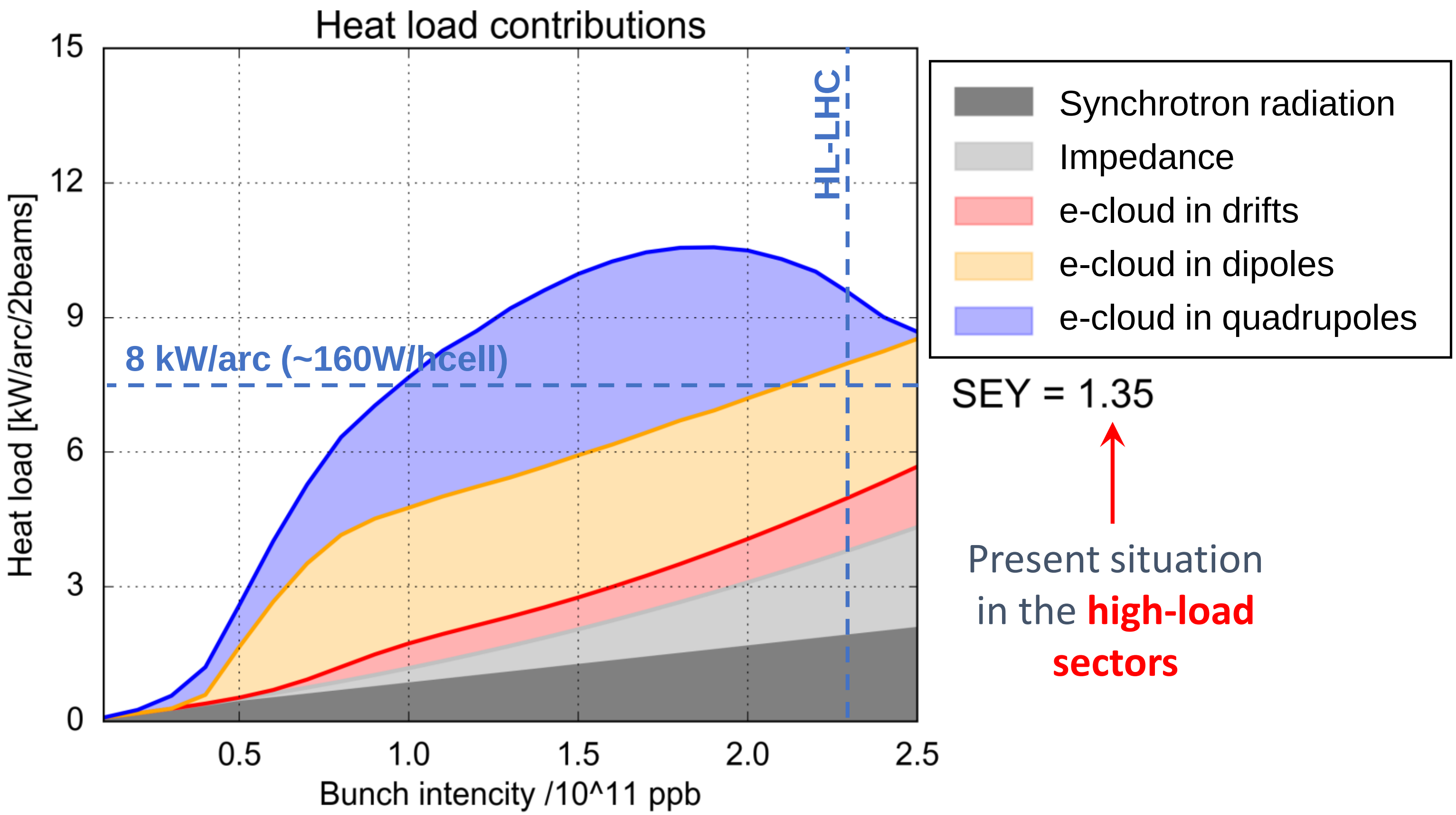


Arc heat loads: simulations for HL-LHC



- For high bunch intensity **significant heat load is observed already for low SEY** (from impedance, synchrotron radiation, photoelectrons in the drifts)
- Present conditioning achieved in the **low-load sectors** is **compatible with HL-LHC**

Arc heat loads: simulations for HL-LHC

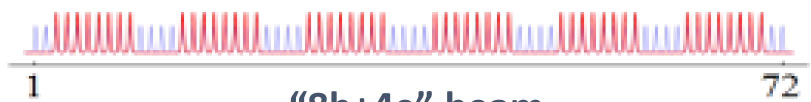


- For high bunch intensity **significant heat load is observed already for low SEY** (from impedance, synchrotron radiation, photoelectrons in the drifts)
- Present conditioning achieved in the **low-load sectors** is **compatible with HL-LHC**
- Expected heat load for the **high-load sectors** is **~10 kW/arc → not acceptable for HL-LHC**
  - → Ongoing work to identify and suppress the source of differences among arcs is very important for HL-LHC

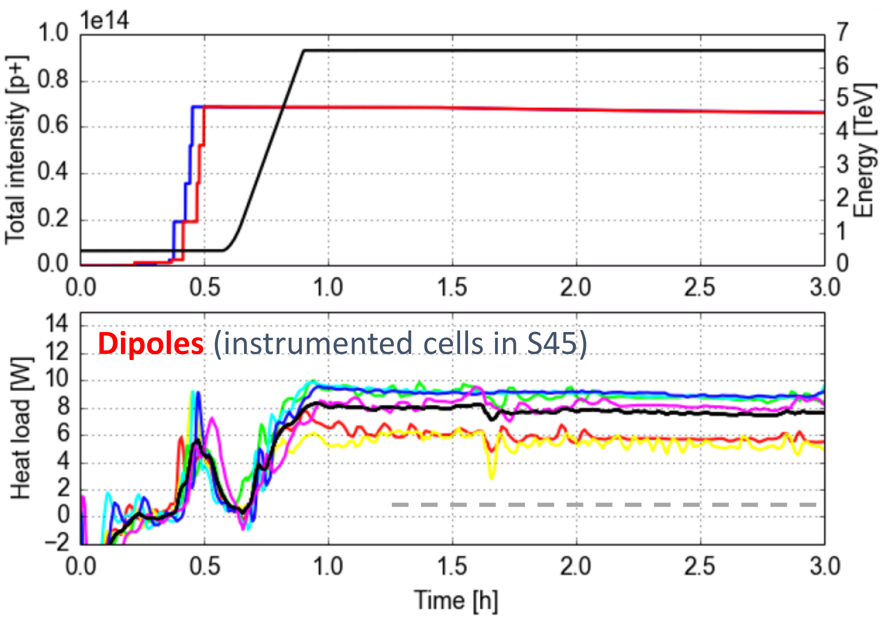
[Mention also importance of coatings in ITs and SAMs]

Filling pattern designed to **suppress the e-cloud build-up (~30 % less bunches w.r.t. nominal)**

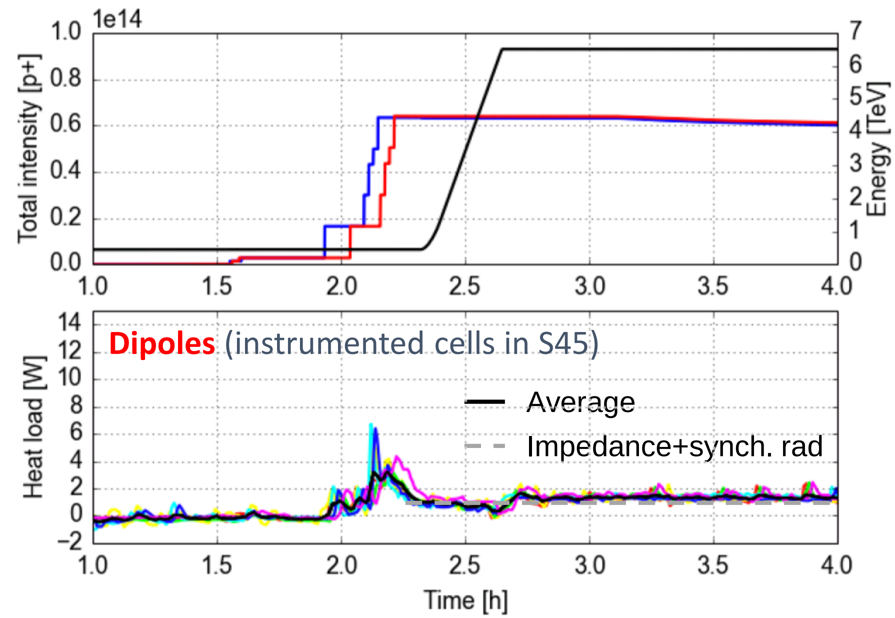
- **Confirmed experimentally in the LHC** in 2015 (for 1.1e11 p/bunch)
  - **Tests with ~1.7e11 p/bunch should be conducted in 2018**
- Included in the **HL-LHC TDR as backup scenario** in case issues with e-cloud



Standard 25 ns beam



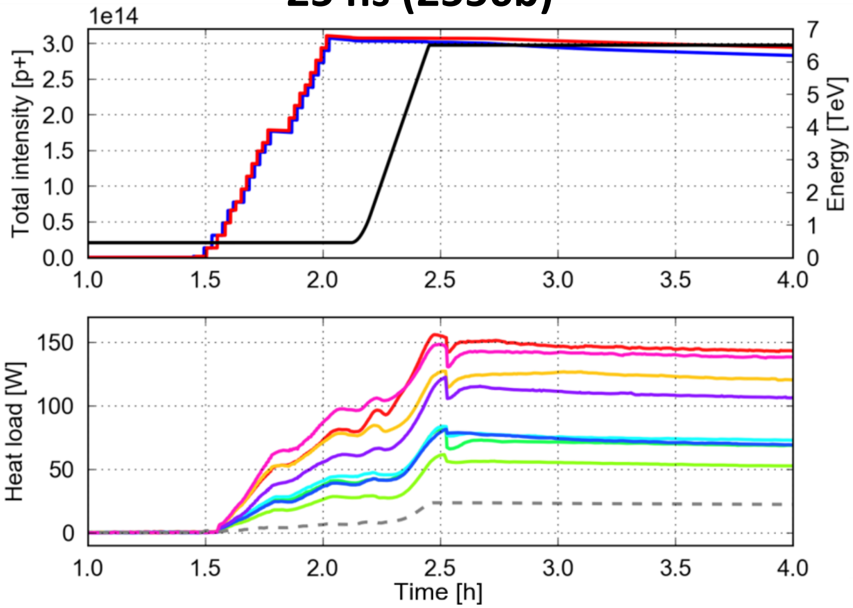
“8b+4e” beam



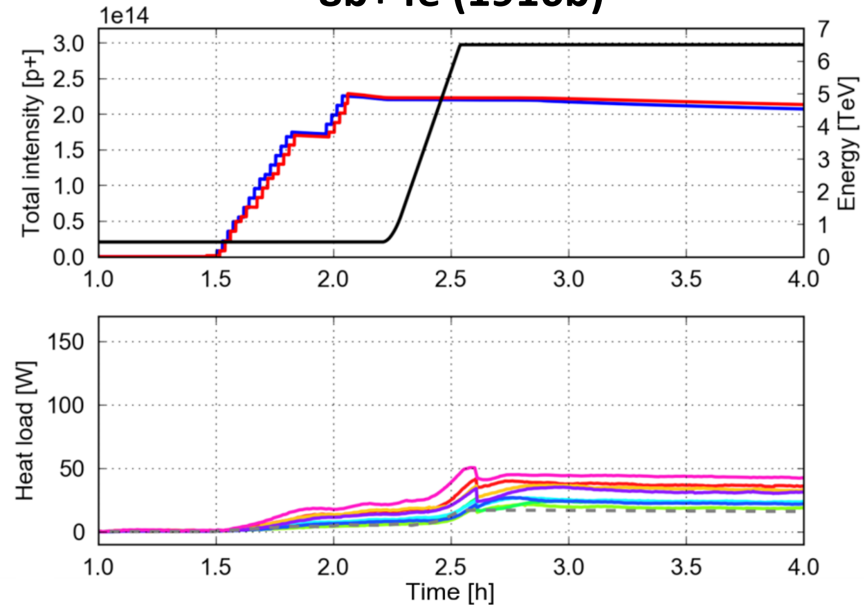
8b+4e scheme

- Used in **operation** in the last part of the **2017 Run** (to mitigate fast losses in 16L2)

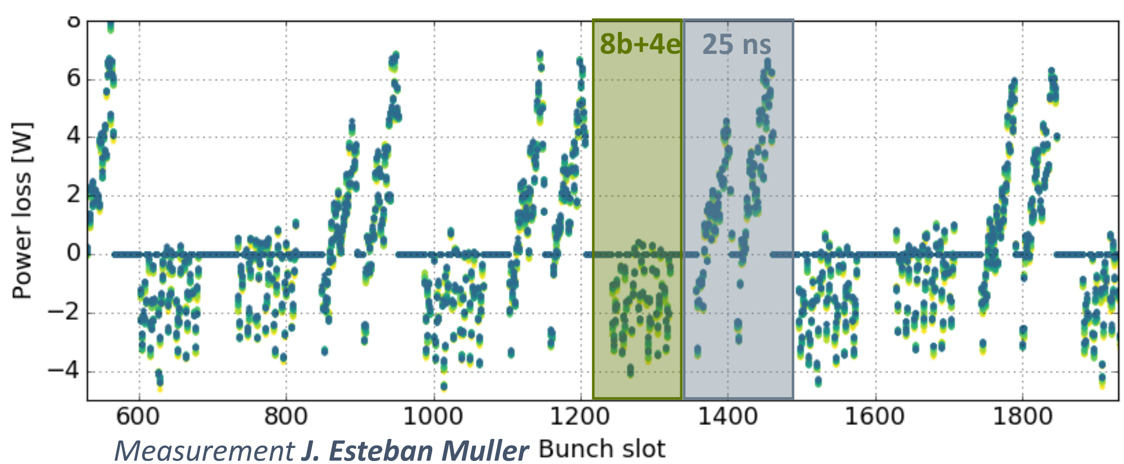
25 ns (2556b)



8b+4e (1916b)



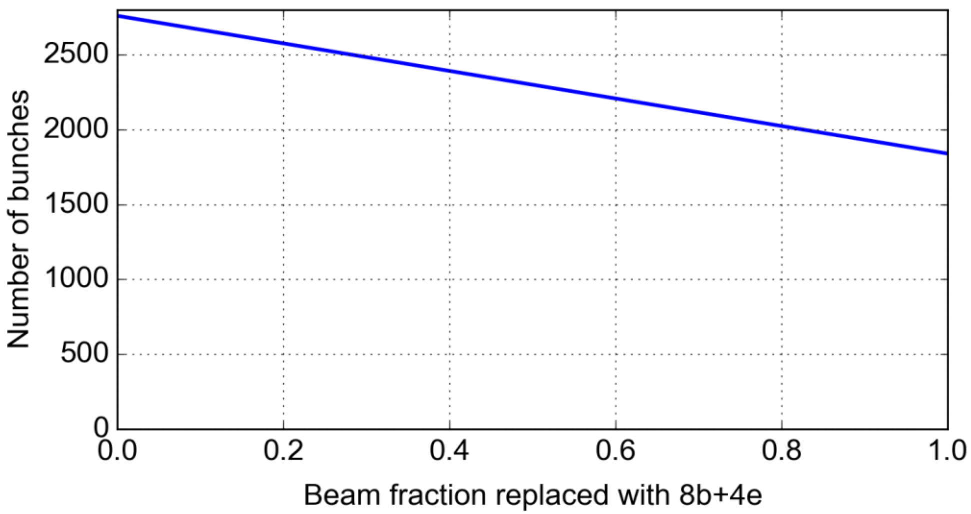
- Standard 25 ns trains and 8b4e trains can be **combined in the same filling scheme** in order to adapt the heat load to the available cooling capacity (tested in MD in 2016)

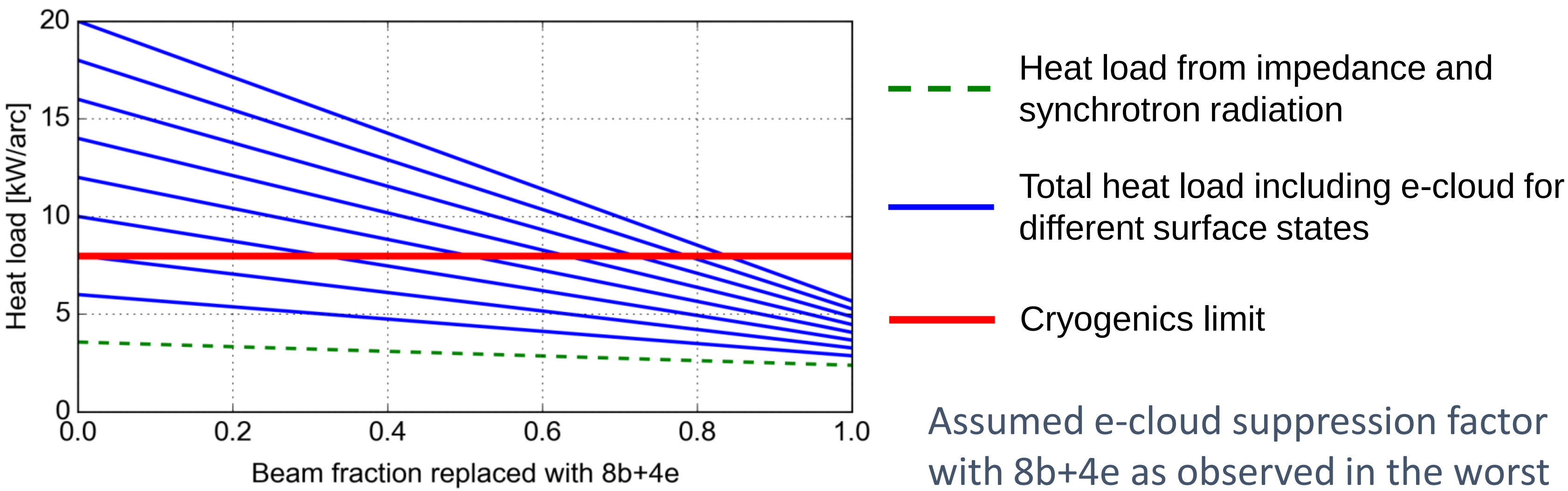


Measurement ***J. Esteban Muller***

Mixed filling schemes

Built a simple model to optimize the “mixed scheme” to the available cooling capacity

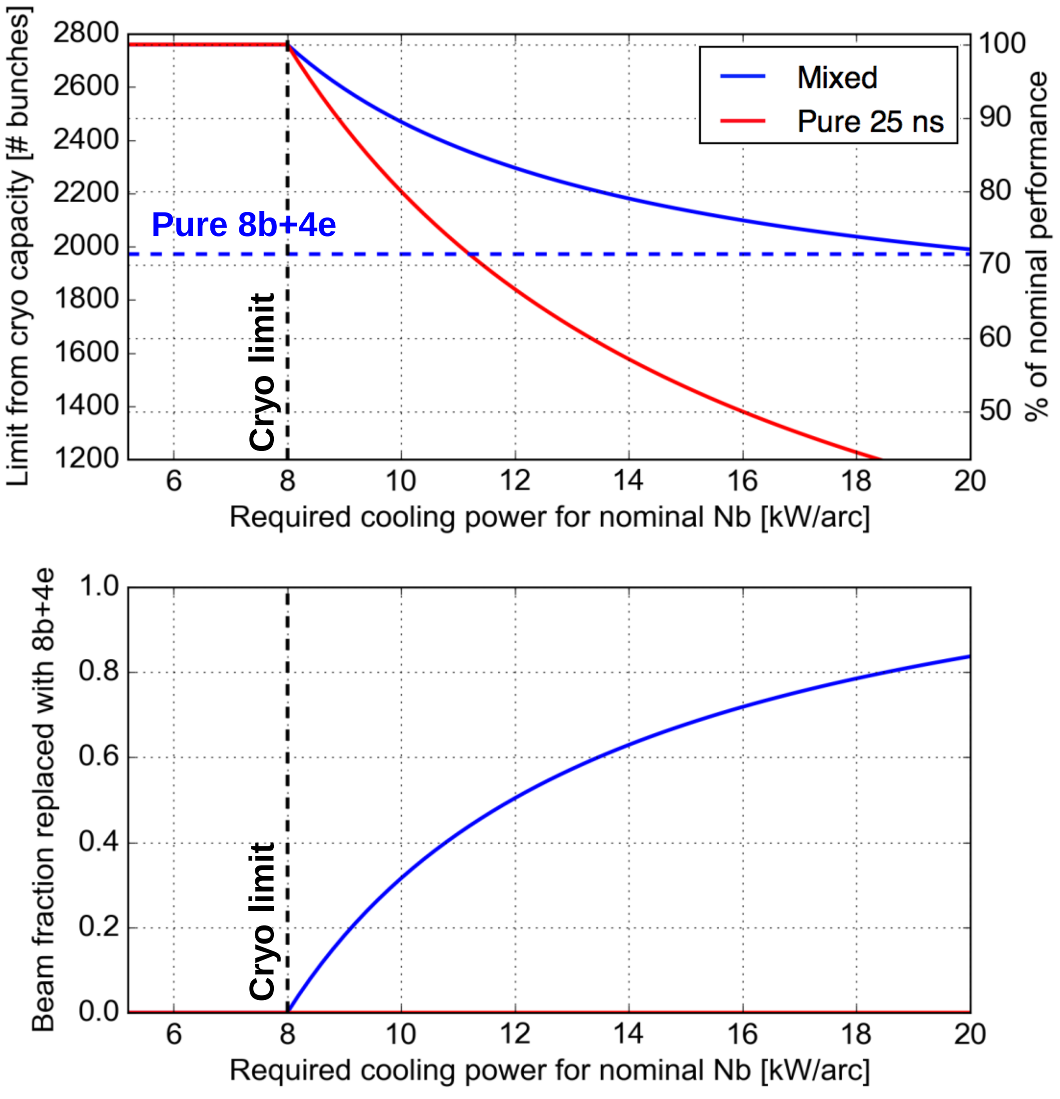




Assumed e-cloud suppression factor with 8b+4e as observed in the worst sector (S81) in 2017

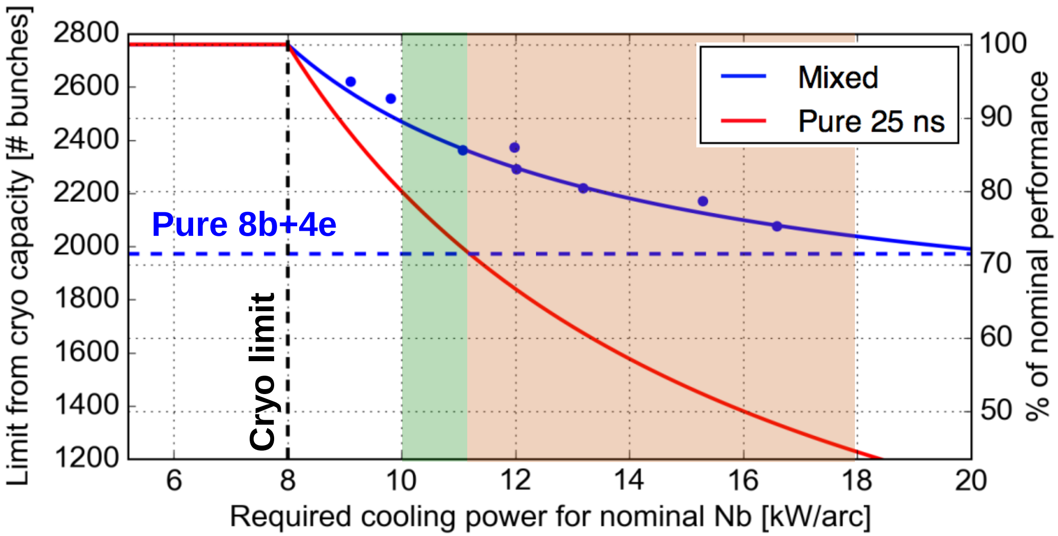
Mixed filling schemes

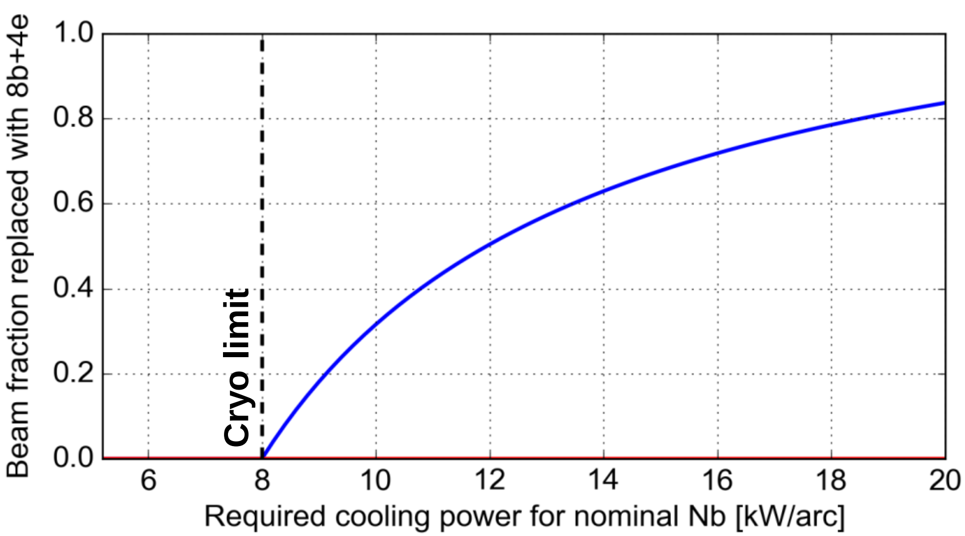
Built a simple model to optimize the “mixed scheme” to the available cooling capacity



Mixed filling schemes

Built a simple model to optimize the "mixed scheme" to the available cooling capacity





Failure scenario A:

- e-cloud scaling with intensity is confirmed by experiment
- Present LHC conditioning state cannot be improved

Perf. loss with pure 25ns: **~25 %**

Perf. loss with mixed: **~12 %**

Failure scenario B

- e-cloud scaling with intensity is found to be worse than expected
- Present LHC conditioning state cannot be improved

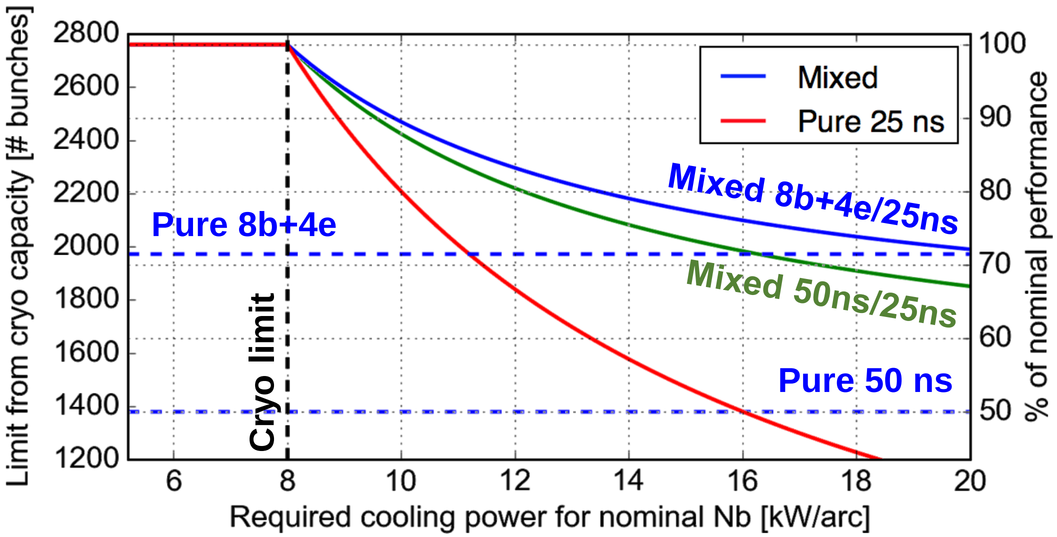
Perf. loss with pure 25ns:

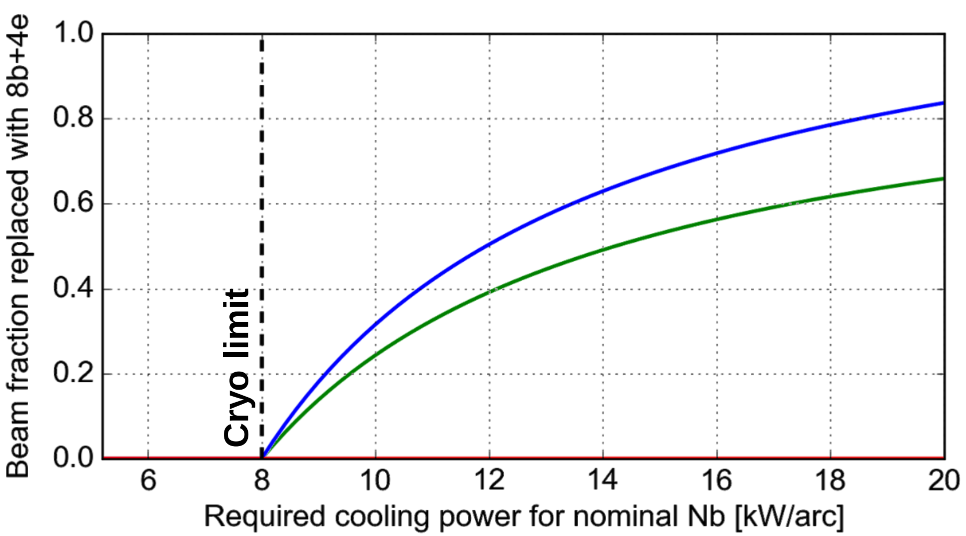
from ~**25%** to **very bad**

Perf. loss with mixed:

from **~12% to 28%**

Built a simple model to optimize the “mixed scheme” to the available cooling capacity





Considered also **50ns/25ns mixed scheme:**

- Assumed ideal e-cloud suppression for 50 ns
- We know from Run1 that e-cloud is suppressed with 50 ns for I_b<=1.7e11 p/bun (but at 4 TeV…)
- Performance is only slightly worse than 25ns/8b+4e
- Can be considered as **backup for a “Failure scenario C”** in which e-cloud suppression with 8b+4e is found to degrade with bunch charge

Emittance preservation

[Introductory slide with overview of the work done and some references]

Main points reported in the following…

Assumptions made for HL-LHC performance estimates:

- Blow-up from Intra-Beam Scattering (IBS) is included in the model
- 10% additional blow-up (0.3 μm) is assumed from end-of-injection to collisions

These are significantly better than presently achieved in the LHC (for nominal intensity):

- Observed increase from injection to collisions ~0.8 μm
- Additional blow-up in collisions (on top of IBS) ~0.07 μm/h

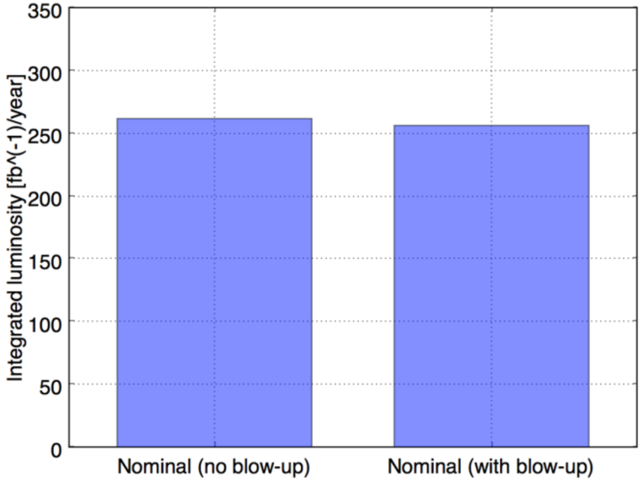
- These figures are observed to be practically independent on the injected intensity/brightness
- Studies to be conducted in 2018 to better identify the sources and device possible mitigations

To assess possible performance degradation applied LHC observed blow-up to HL-LHC cases:

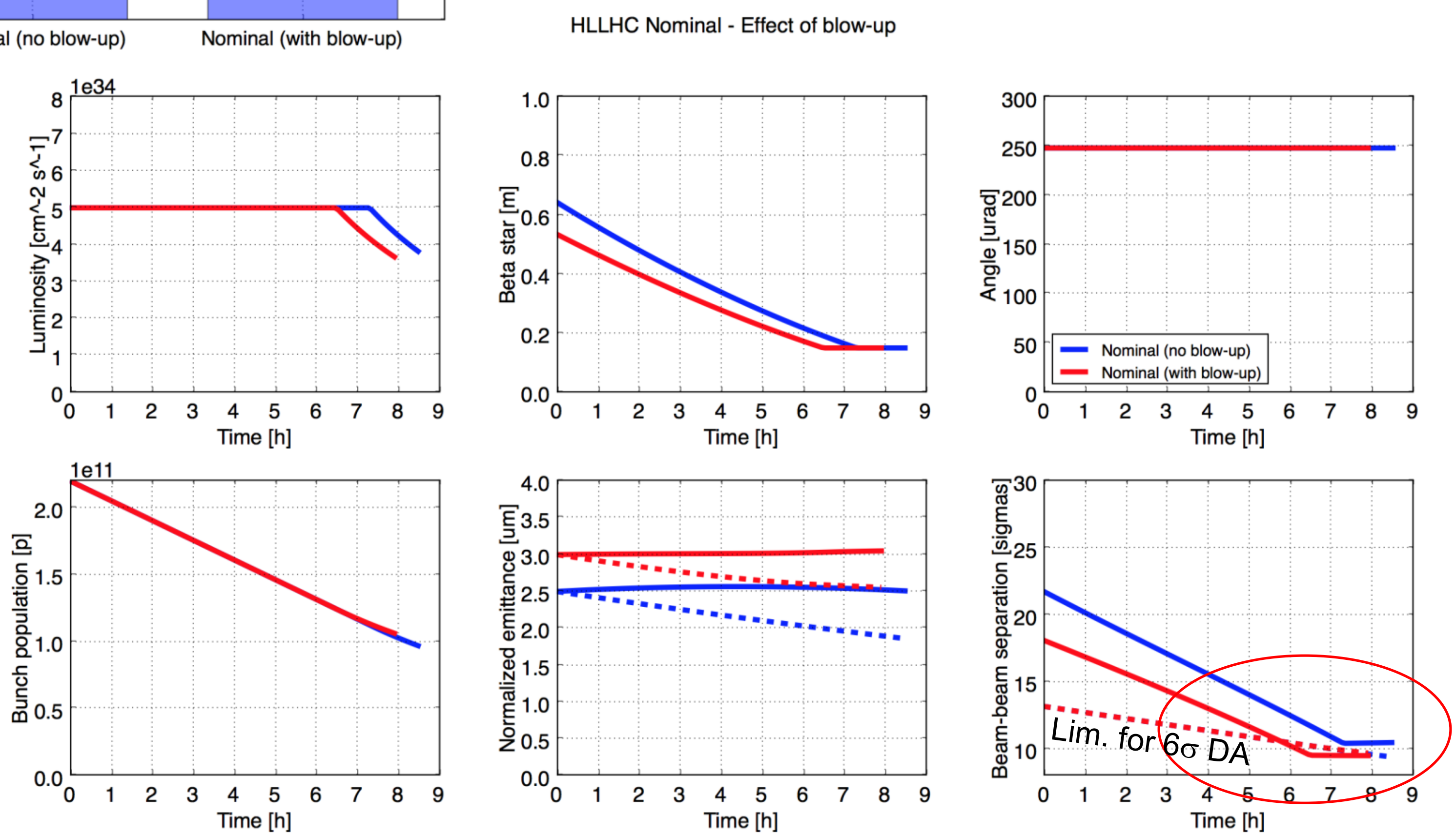
Blowup start ramp to SB	
Ideal	0.3
LHC like	0.8

	Intensity	Injected		Start ramp		**Start SB ideal**		**Start SB with blowup**		**Intensity start SB**
		H	V	H	V	**H**	**V**	**H**	**V**	
Nominal	2.30E+11	2.1	2.1	2.3	2.1	**2.5**	**2.5**	**3**	**3**	**2.20E+11**

Emittance preservation: impact on performance



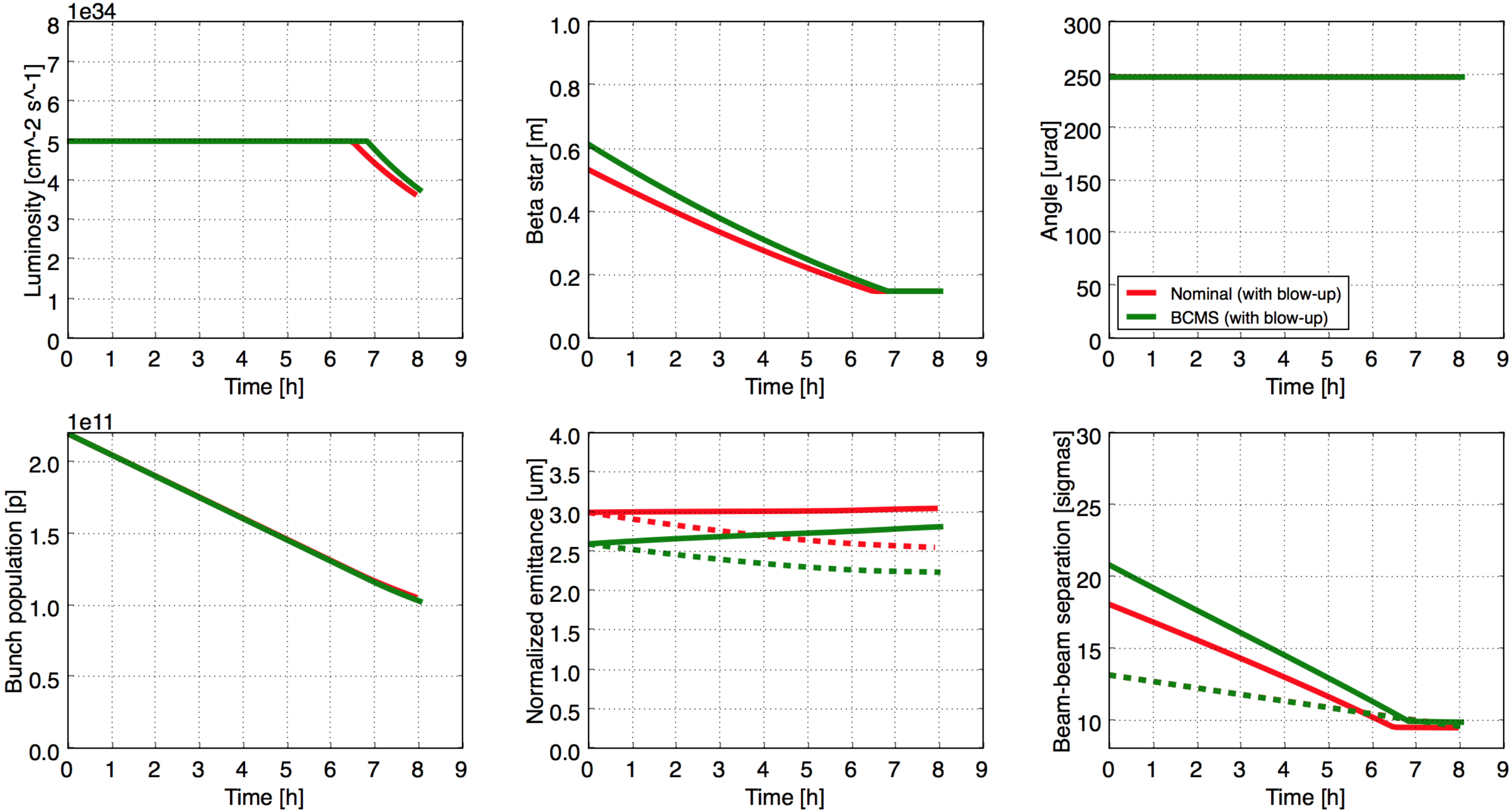
- The impact of the extra blow-up on the expected performance is very small, as during a large fraction of the fill we can use β^* to compensate
- But with large emittances it can become tricky to ensure the **required beam-beam separation**…



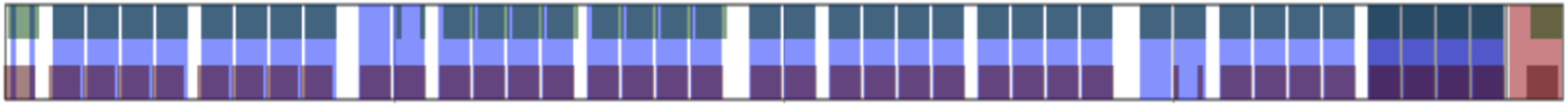
Emittance preservation: backup scheme (BCMS)

- **Low emittance beams from the injectors (BCMS)** can be used to restore the required beam-beam separation

	Intensity	Injected		Start ramp		**Start SB ideal**		**Start SB with blowup**		**Intensity start SB**
		H	V	H	V	**H**	**V**	**H**	**V**	
Nominal	2.30E+11	2.1	2.1	2.3	2.1	**2.5**	**2.5**	**3**	**3**	**2.20E+11**
BCMS	2.30E+11	1.7	1.7	1.9	1.7	**2.1**	**2.1**	**2.6**	**2.6**	**2.20E+11**

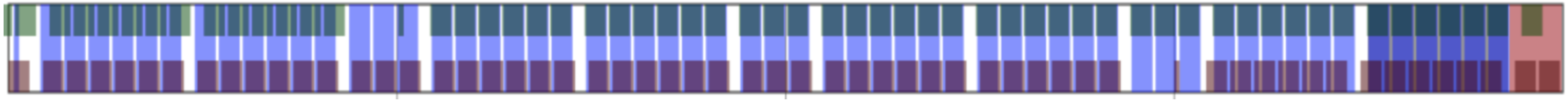


Standard (288b./inj.)



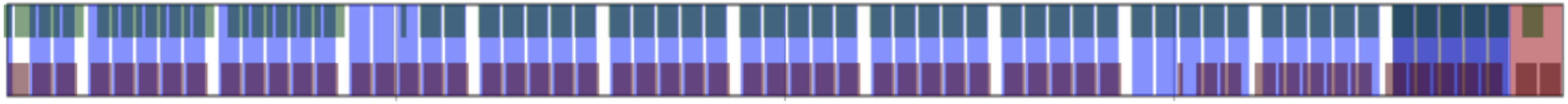
25ns_2760b_2748_2494_2572_288bpi_13inj_800ns_bs200ns

BCMS (288b./inj.)



25ns_2748b_2736_2251_2375_288bpi_12inj_800ns_bs200ns

BCMS (240b./inj.)



25ns_2748b_2740_2250_2376_240bpi_13inj_800ns_bs200ns

Easier for the injectors: less time at SPS flat-bottom, less demanding for protection devices

- **With 200 ns and 800 ns kicker gaps the three schemes are practically equivalent**

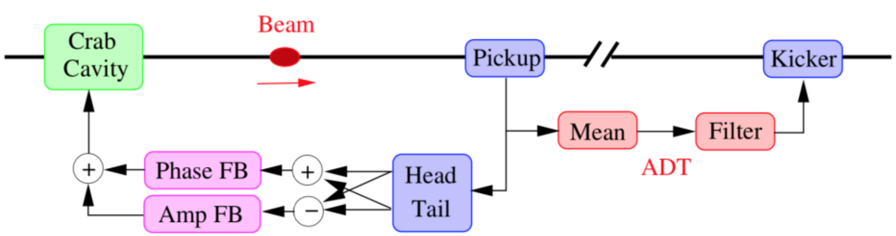
Emittance preservation in collisions

Stronger head-on beam-beam interactions (**larger tune spread**) will enhance the **emittance growth due to coherent excitations** → wen need to be careful with:

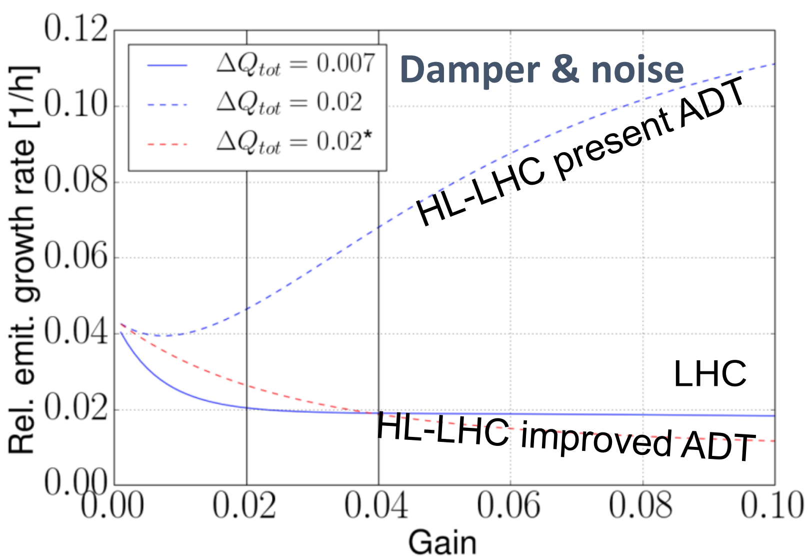
- Noise from **Power Converters** → part of design specs for the new ones
- Noise introduced by **Crab Cavities**
  → A dedicated feedback is being designed
- Noise introduced by the **Transverse Damper**
  → Improvements are under study: use of a larger number of pickups and improved electronics

If needed, further mitigation can be obtained by introducing a **small separation** (~1σ) at the main IPs in the first part of the fill (no impact on lumi as it is during β* leveling)

Crab Cavity noise feedback

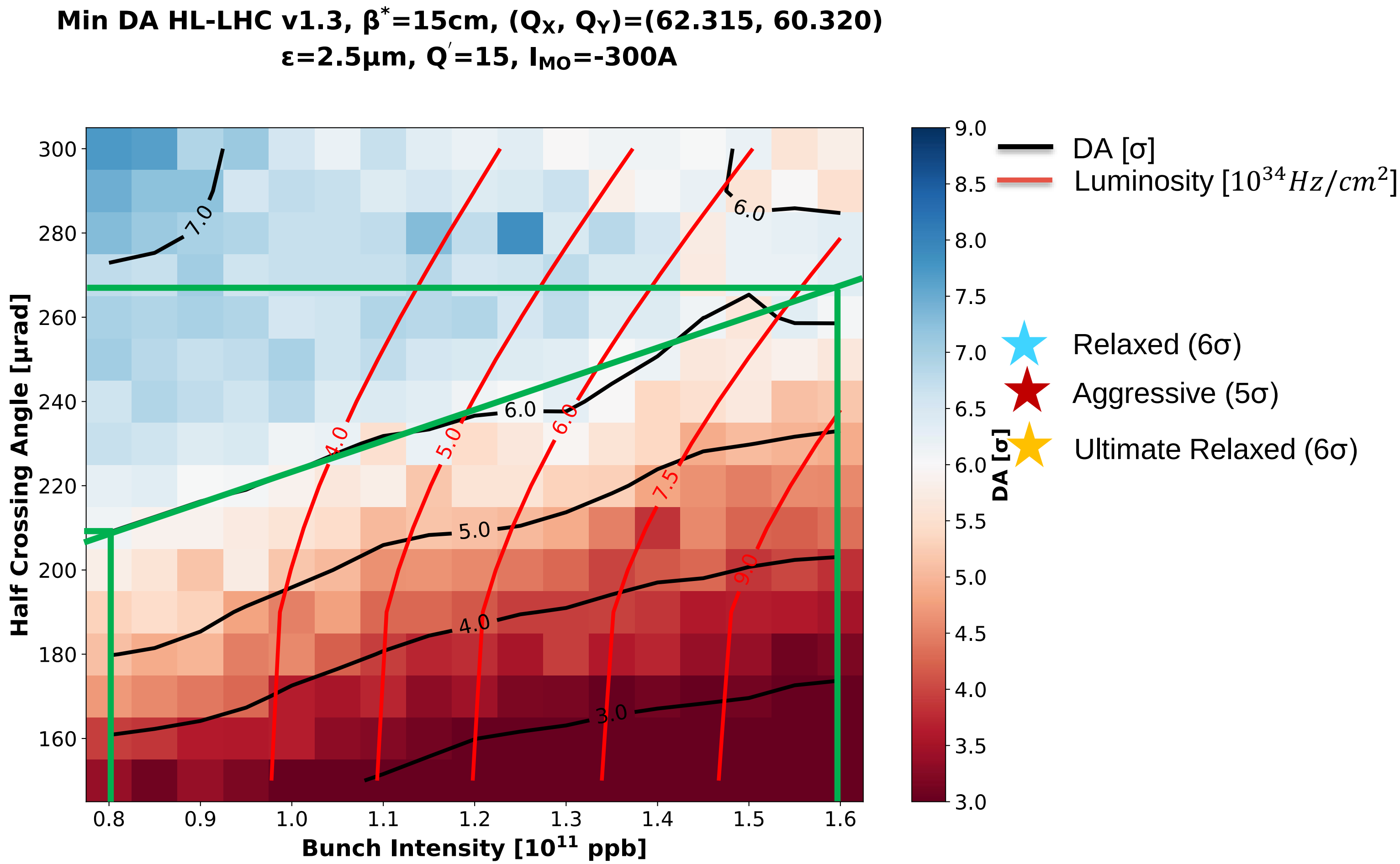


For more info: T. Mastoridis, "Crab cavity RF noise mitigation", HL-LHC WP2 meeting, 22 Aug 2017

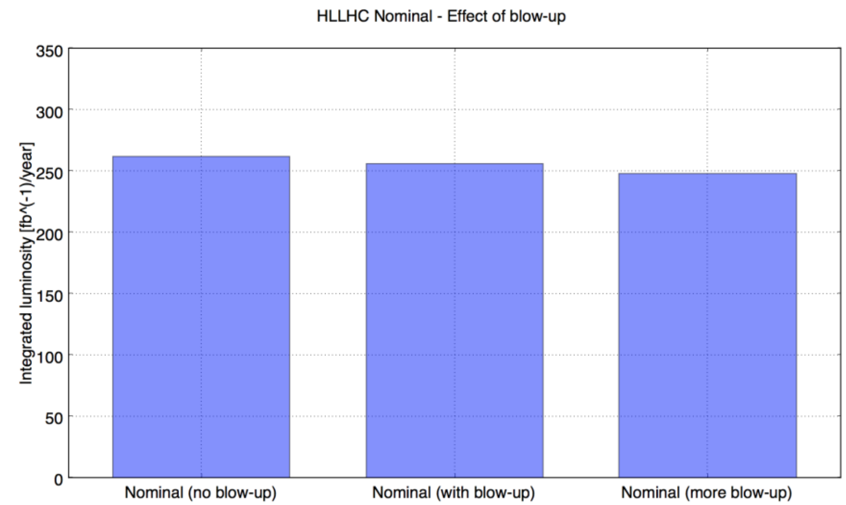


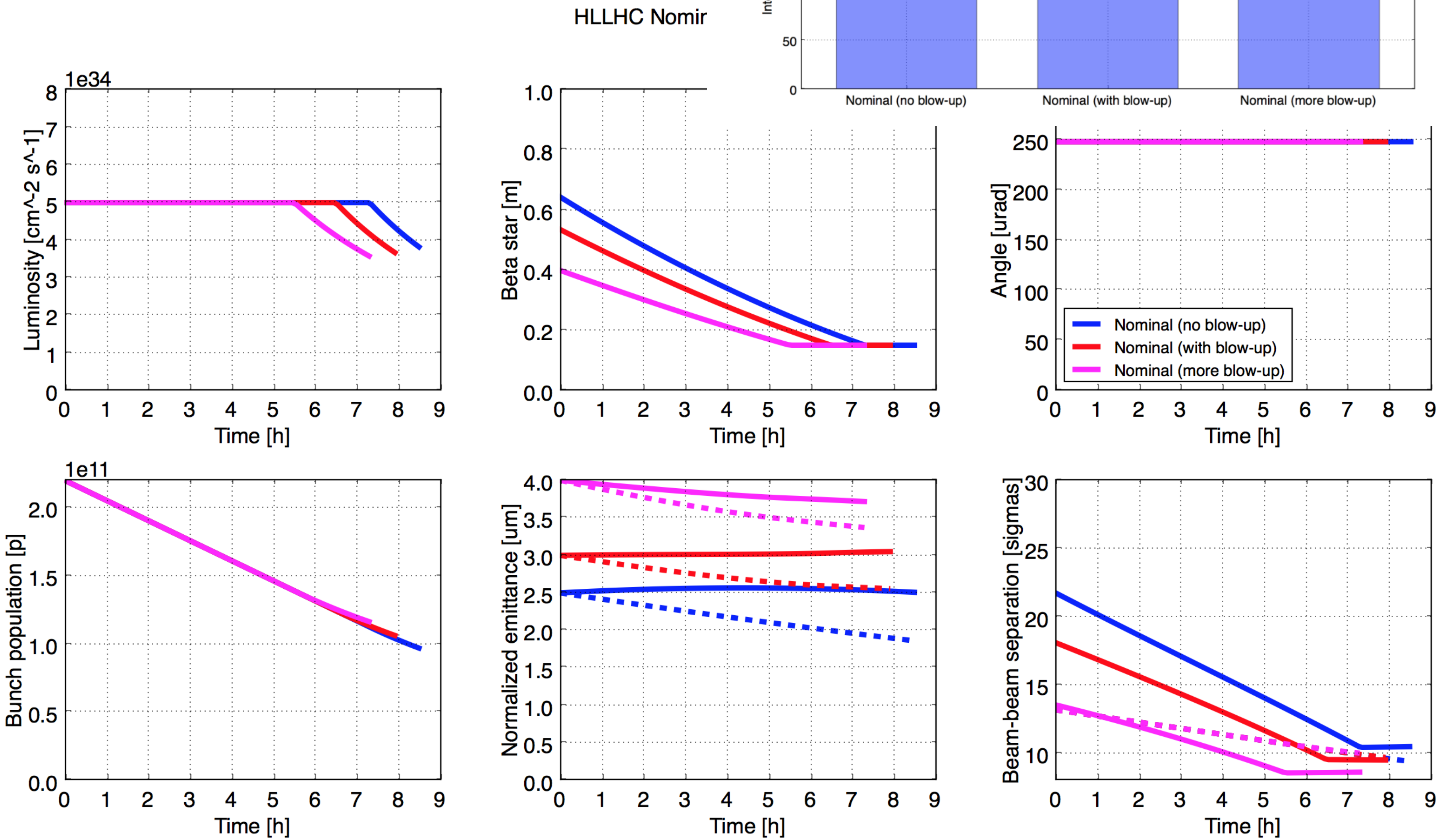
For more info: X. Buffat, "Beam stability and quality in the presence of beam beam and transverse damper", HL-LHC Annual Meeting, Madrid, 15 Nov 2017

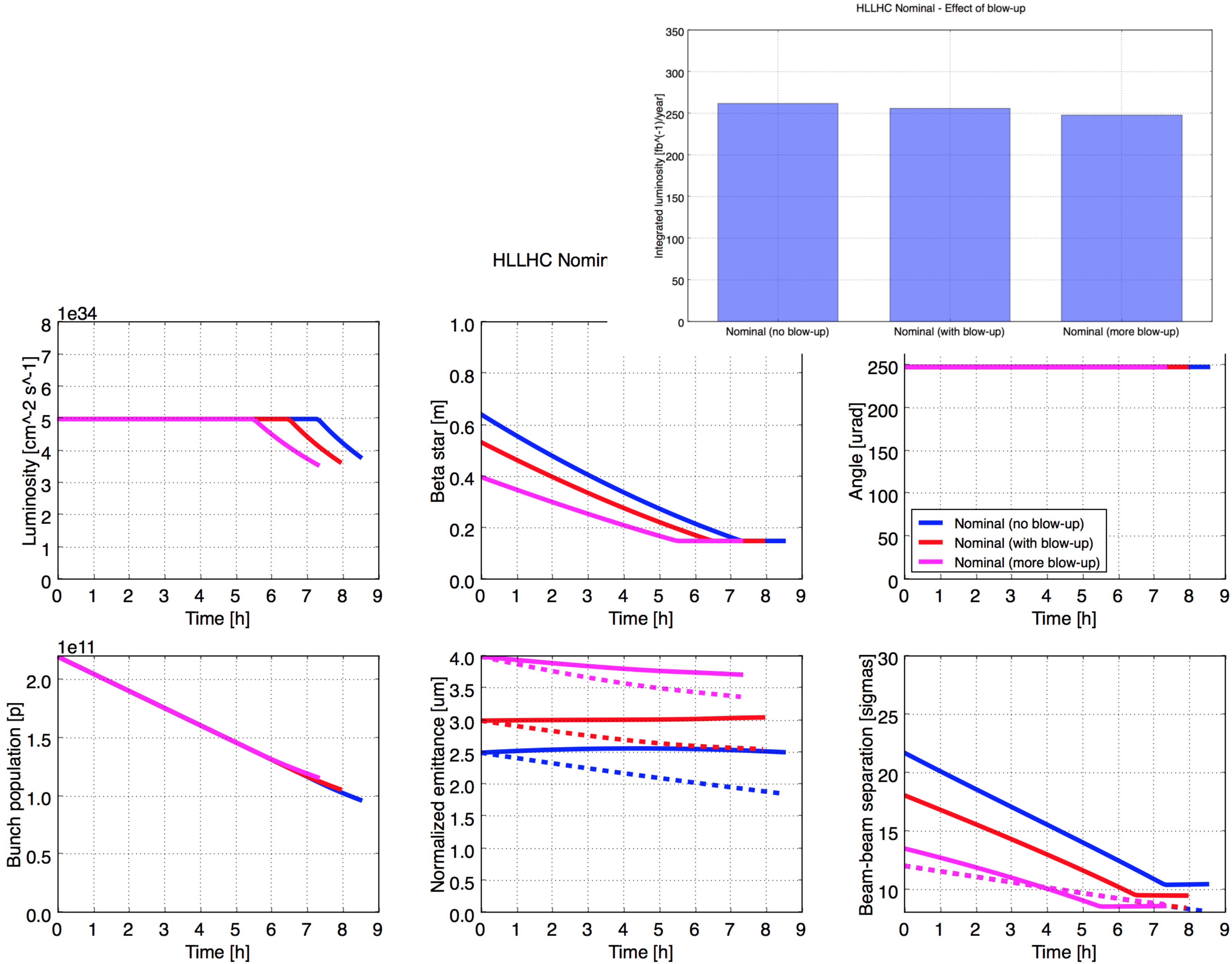
Thanks for your attention!



Min DA HL-LHC v1.3, β*=15cm, (QX, QY)=(62.315, 60.320)
ε=2.5μm, Q′=15, IMO=-300A
Half Crossing Angle [μrad]
300
280
260
240
220
200
180
160
Bunch Intensity [10^11 ppb]
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
7.0
6.0
6.0
5.0
4.0
3.0
4.0
5.0
6.0
7.5
9.0
DA [σ]
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
DA [σ]
Luminosity [10^34 Hz/cm^2]
Relaxed (6σ)
Aggressive (5σ)
Ultimate Relaxed (6σ)


HLLHC Nominal - Effect of blow-up
Integrated luminosity [fb^(-1)/year]
350
300
250
200
150
100
50
0
Nominal (no blow-up)
Nominal (with blow-up)
Nominal (more blow-up)


HLLHC Nomir
1e34
Luminosity [cm^-2 s^-1]
Time [h]
Beta star [m]
Time [h]
Angle [urad]
Nominal (no blow-up)
Nominal (with blow-up)
Nominal (more blow-up)
Time [h]
1e11
Bunch population [p]
Time [h]
Normalized emittance [um]
Time [h]
Beam-beam separation [sigmas]
Time [h]


HLLHC Nominal - Effect of blow-up
Integrated luminosity [fb^(-1)/year]
Nominal (no blow-up)
Nominal (with blow-up)
Nominal (more blow-up)
HLLHC Nomir
1e34
Luminosity [cm^-2 s^-1]
Time [h]
Beta star [m]
Angle [urad]
1e11
Bunch population [p]
Normalized emittance [um]
Beam-beam separation [sigmas]