High Luminosity LHC

PICs: what do we gain in beam performance?

G. Arduini

with input from: D. Banfi, J. Barranco, O. Brüning, R. De Maria, O. Dominguez, S. Fartoukh, P. Fessia, S. Gilardoni, B. Gorini, G. Iadarola, V. Kain, M. Kuhn, E. Métral, N. Mounet, T. Pieloni, S. Redaelli, L. Rossi, G. Rumolo, R. Tomàs, A. Valishev, J. Wenninger and in general LIU and HL-LHC teams

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.

Outline

- Beam parameters:
  - Injectors
  - LHC
- Beam Parameter Evolution during the fill
- Yearly performance
- Key questions and studies
- Conclusions

Beam Parameters

- 5% intensity loss assumed during the cycle
  - ➔ Average lifetime along the cycle before collision of ~22 hours
  - ➔ But minimum lifetime > 0.2 hours (assuming tight collimator settings) limited by power deposited on the collimators

- Emittance blow-up of 20% from SPS extraction to LHC collision when compatible with inevitable sources of blow-up ➔ IBS
  - Margin of ~10-15 % on the average emittance blow-up on top of IBS
  - IBS calculations including injection/ramp and squeeze assuming controlled-longitudinal blow-up to keep bunch length at 10 cm up to flat-top

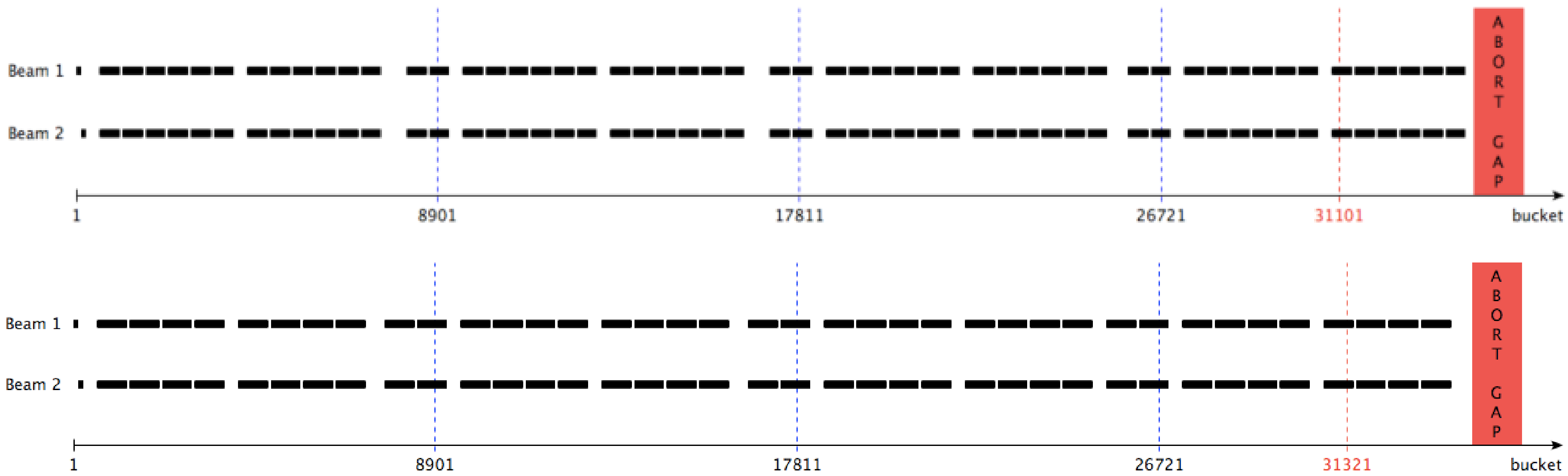
	SPS Extraction		LHC collision (min. value – IBS)	LHC collision		
	Bunch population [10^{11}]	ε_n (H/V) [μm]	ε_n (H/V) [μm]	Bunch population [10^{11}]	$\varepsilon_{n\ coll}$ (H/V) [μm]	Blow-up [%]
BCMS	1.45	1.45/1.45	1.74/1.45	1.38	1.85/1.85	27
Standard	1.45	1.85/1.85	2.09/1.85	1.38	2.25/2.25	21

AGREED - LIU

R. Tomàs, O. Dominguez

Beam parameters (Filling schemes - 25 ns)

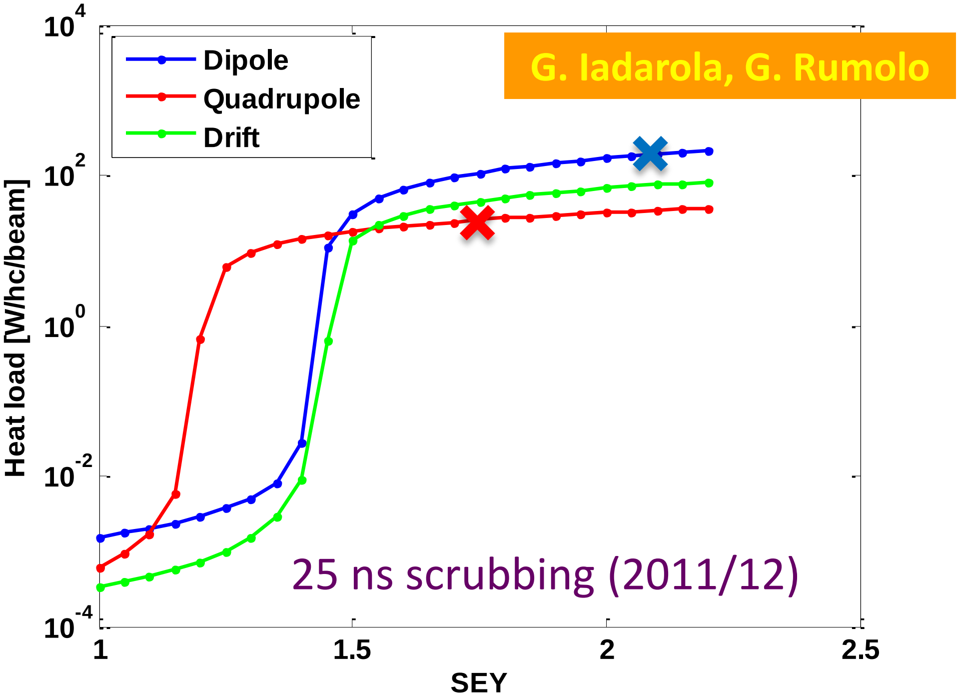
Filling scheme	Total	IP1-5	IP2	IP8
BCMS: 48b 6 PS inj, 12 SPS inj	2604	2592	2288	2396
Standard: 72b 4 PS inj, 12 SPS inj	2748	2736	2452	2524



B. Gorini

Implications & Assumptions (e-cloud)

- Control of the blow-up due to e-cloud via scrubbing at 450 GeV
  - Emittance blow-up occurs when electron cloud activity in the dipoles
  - SEY reduction in the dipoles at 450 GeV with 25 ns scrubbing run. Need margin for small emittance/shorter bunch ➔ doublet beams being considered and LS1 interventions to increase cryo-margin at injection (SAM and Sector 34)

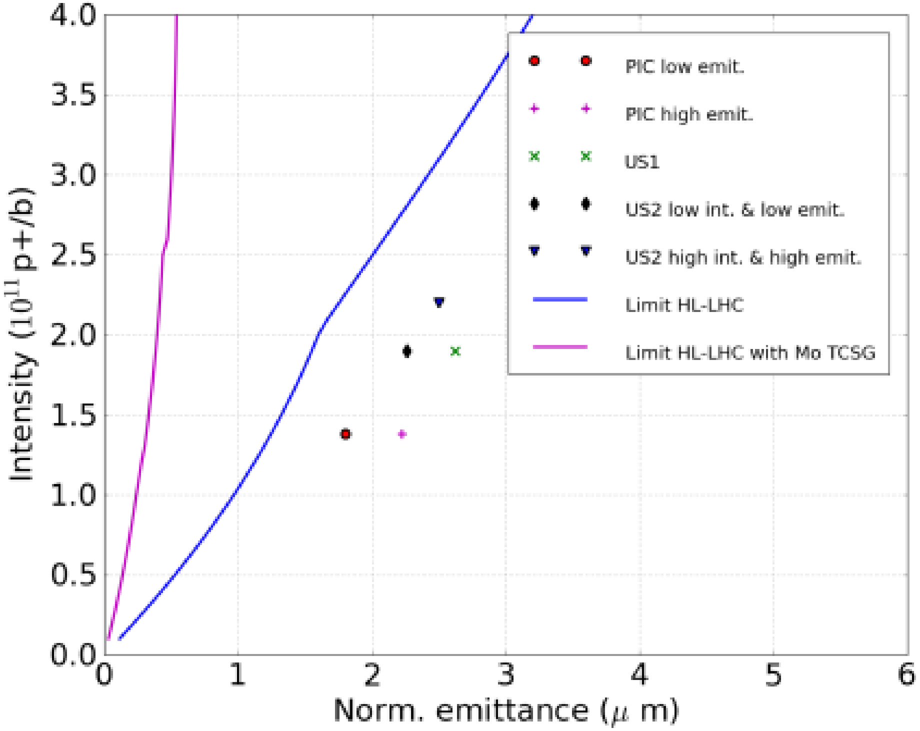


- Expect heat load in the quadrupoles due to the lower threshold SEY ➔ cryo upgrade (c/o P. Fessia)
- HL-LHC triplets/D1 will have e-cloud countermeasures implemented (aC coatings and possibly clearing electrodes)

Implications & Assumptions (impedance)

- Collimators are the largest source of impedance in the LHC.
- Possible limitation in minimum opening and β^* reach
- Interplay between impedance and beam-beam possible origin of the instabilities observed in 2012 (not fully understood yet)
- Limited margin for all the scenarios based on extrapolations from 2012 (with positive octupole polarity)
- Impedance reduction with metallic collimators (Mo-C) to provide safe margin

EFFECT OF CHROMATICITY, DAMPER, OCTUPOLES INCLUDED



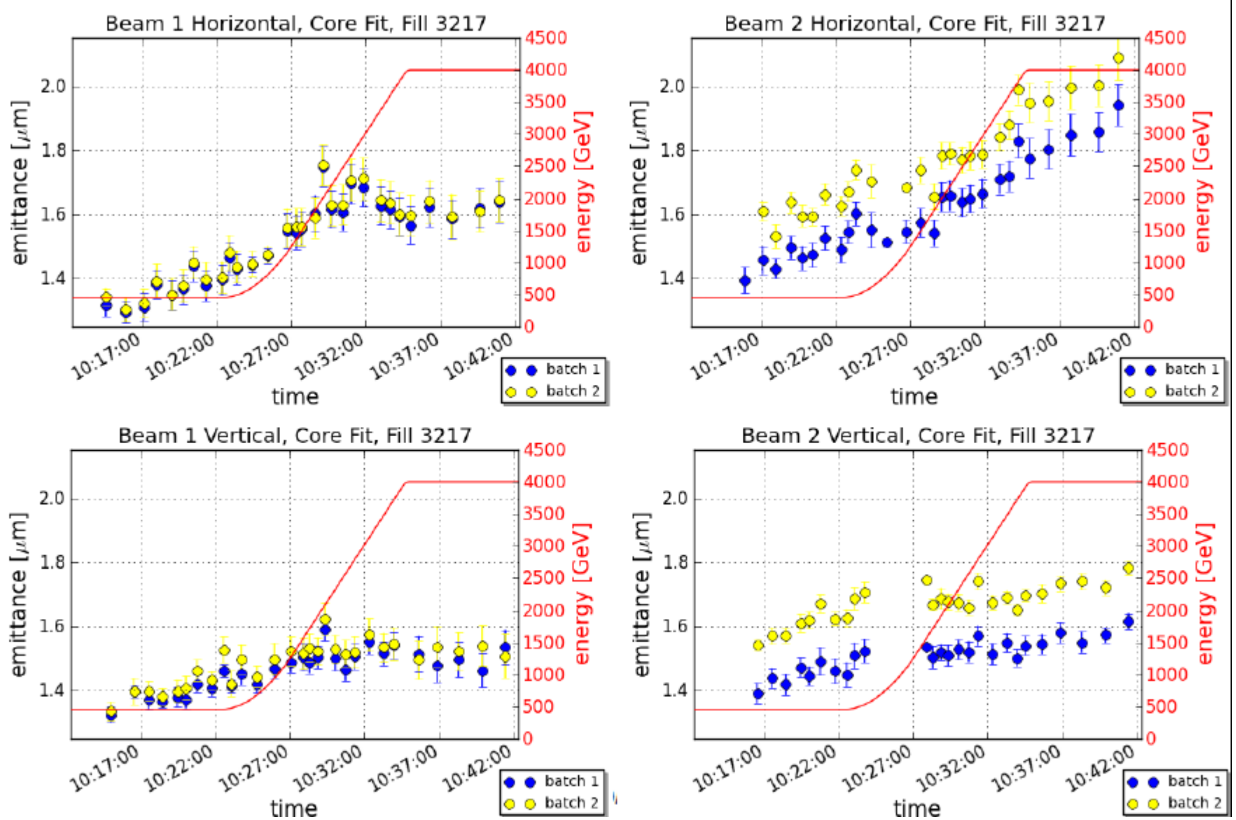
E. Métral, N. Mounet

Implications & Assumptions

- Control of the additive sources of blow-up (injection errors, noise, etc.)
  - Contributions at injection and first part of the ramp in H-plane consistent with IBS

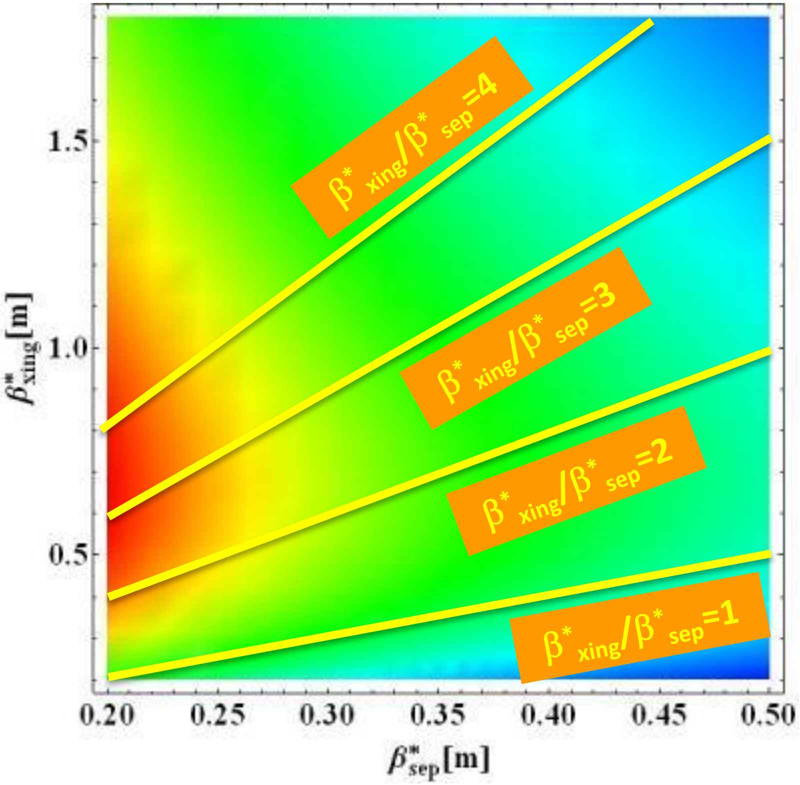
V. Kain, M. Kuhn

- Asymmetry between the two beams and planes
- Not yet managed in reducing observed blow-up
- Assume progress in the understanding and solutions. Had a similar process in the injectors.



Optics

- Minimum β^* in IR1 and 5 limited by aperture in the matching section
- TAN,Q5,Q4,D2 become aperture bottlenecks ➔ need to install new TCTs in IR1-5 for D2-Q5 for protection
- Two flat optics considered with maximum β^* ratio = 2 (S. Fartoukh):
  - β^*_{xing}= 40 cm / β^*_{sep} =20 cm
  - β^*_{xing}= 50 cm / β^*_{sep} =25 cm
- The latter providing more margin in aperture and possibly better behaved in the absence of MS in Q10
- Flat beams likely require larger beam-beam separations as compared to round. Larger β^* ratios (>2) might imply larger B-B separations ➔ being further investigated



Peak luminosity (Max=2.6x10^{34} – Min=1.2x10^{34}) at constant beam-beam separation (14 σ)

Peak Performance at 6.5 TeV

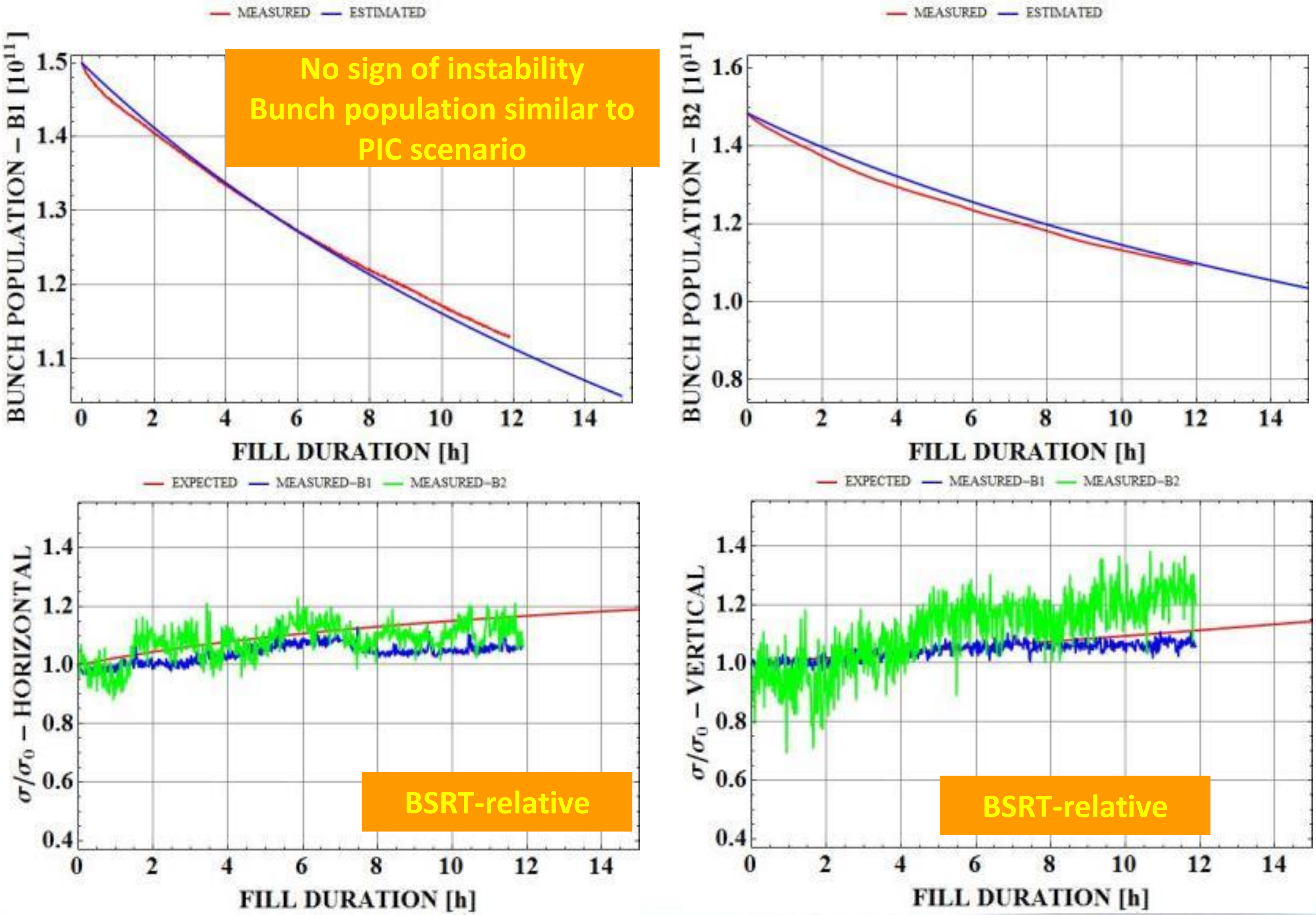
Momentum [TeV/c]	6.5
Bunch population in collision [10^{11} p]	1.38
Total RF Voltage [MV]	16
ε_L*[eV.s] at start of fill	3.6
Bunch length (4 σ)[ns]/ (r.m.s.) [cm]	1.33/10
Beam-beam separation [σ]	14

	$\varepsilon^*_{n\ coll}$ [μm]	# Coll. Bunches IP1,5	Xing angle [μrad]	BB separation [σ]	L_{peak} [10^{34} cm^{-2}s^{-1}]
BCMS – 40/20	1.85	2592	364	14	2.9
Standard - 40/20	2.25	2736	400	14	2.5
BCMS – 50/25	1.85	2592	326	14	2.7
Standard – 50/25	2.25	2736	360	14	2.3

Performance estimate during collisions

- Evolution of beam parameters based on:
  - Burn-off
    - Total cross-section: 100-110 mb (assumed worst case 110 mb for E_{cm}=13-14 TeV)
- Emittance evolution (no coupling assumed) including:
  - IBS
  - Radiation damping
- Additional (unknown) sources of loss/blow-up from comparison with 2012 fills with similar bunch populations with no sign of instability
  - Intensity loss (τ ~ 200 hours)
  - Vertical emittance blow-up (τ ~ 40 hours)
- Finite difference method (5 mins step)

Comparison with 2012 (Fill 2728)



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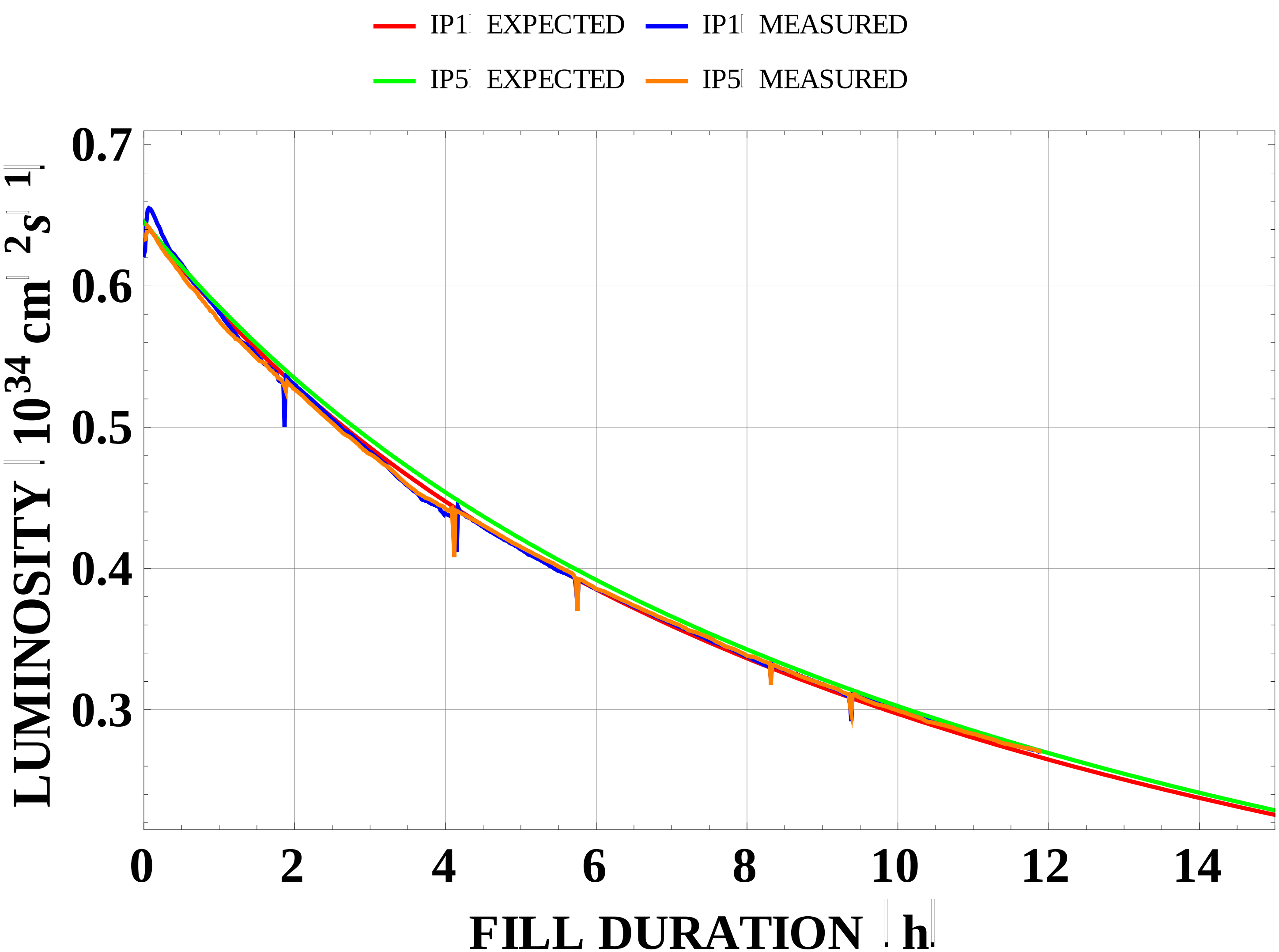
Comparison with 2012 (Fill 2728)



Integrated luminosity targets

- Assumptions:
  - Luminosity in 2015=30 fb^{-1}
  - 310 fb^{-1} by the end of 2021. (M. Lamont 6th HL-LHC Coordination Group meeting 26/07/13).

	PIC	US1	US2
Integrated luminosity by end 2021/ end 2035	310/1000	310/2000	310/3000
Number of years of operation after 2021	10	10	10
Target luminosity/year	70	170	270

Yearly Performance

- Performance efficiency (η) required to achieve the target yearly integrated luminosity L_{target} is evaluated for every scenario. This is the percentage of scheduled physics time spent for successful fills (including minimum turn-around)

 # successful physics fills/year

$$\eta = \frac{L_{target}}{L_{fill}} \frac{T_{around\_min} + T_{fill}}{T_{spt}} \times 100$$

  - L_{fill} = luminosity integrated during one fill of duration T_{fill}
  - $T_{around-min}$ = minimum turn-around time
  - T_{spt}=time spent in physics for luminosity production

- The performance efficiency for T_{fill}=6 h (η_{6h}) and for the optimum fill length based on the luminosity evolution and on the considered turn-around time (η_{opt}) have been evaluated for every scenario

Yearly Performance

- Physics efficiency (ϕ) is evaluated for every scenario:

$$\phi = \frac{L_{target}}{L_{fill}} \frac{T_{fill}}{T_{spt}} \times 100$$

- This is the percentage of time spent in physics. Particularly important for ALICE and LHCb constantly running in levelling mode

- The physics efficiency for T_{fill}=6 h (ϕ_{6h}) and for the optimum fill length based on the luminosity evolution and on the considered turn-around time (ϕ_{opt}) have been evaluated for every scenario

Yearly Performance

2012 data	
Scheduled Physics Time for p-p luminosity production/year (T_{spt}) [days]	190.5
Minimum Turn-Around Time ($T_{around-min}$) [h]	2.2
Average Fill length T_{fill}[h]	6.1
Integrated Luminosity (L_{int}) [fb^{-1}]	23.3
Physics efficiency ϕ [%]	**36**
Fills that made it to physics (N_{fill})	295
Performance efficiency $\eta = N_{fill}*(T_{around-min}+T_{fill})/T_{spt}*100$ [%]	**53.5**

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Yearly Performance

HL-LHC Assumptions	
Scheduled Physics Time for p-p luminosity production/year (T_{phys}) [days]	160
Minimum Turn-Around Time [h]	3
Average Fill length [h]	6 or optimum
Performance Efficiency – goal [%]	**50**
Pile-up limit [events/crossing]	**140**
Pile-up Density limit – baseline (stretched) **[events/mm/crossing]**	**1.3** (0.7)

PIC @ 6.5 TeV (Pile-up limit at 140)

	Lev. time [h]	Opt. Fill length 2012 6h	η_{6h}/η_{opt} [%] Goal <50%	ϕ_{6h}/ϕ_{opt} [%] 2012 36%	Int. Lumi for η=50% for 6h /opt. fill length Goal > 70 fb^{-1}	Max. Mean Pile-up density/Pile-up [ev./mm]/[ev./xing] <1.3/<140
BCMS – 40/20	-	6.5	37/37	25/26	93/94	0.97/84
Standard - 40/20	-	7.3	40/40	27/28	87/88	0.79/69
BCMS – 50/25	-	6.8	39/39	26/27	89/89	0.77/78
Standard – 50/25	-	7.6	43/42	28/30	82/83	0.63/64

- All the configurations allow to achieve the target integrated luminosity per year with performance efficiency and physics efficiency compatible with 2012 values
- Fill lengths are comparable (although slightly longer) to 2012 average ➔ Importance of consolidation to increase reliability
- 50/25 optics provides reduced pile-up density for small reduction of the integrated luminosity and it relaxes constraints on aperture/optics
- Standard filling scheme provides slightly lower performance but it is more tolerant to additive sources of blow-up

PIC @ 6.5 TeV (Pile-up limit at 45)

	Lev. time [h]	Opt. Fill length [h]	η_{6h}/η_{opt} [%]	ϕ_{6h}/ϕ_{opt} [%]	Int. Lumi for η=50% for 6h /opt. fill length [fb^{-1} /y]	Max. Avg. Pile-up density/Pile-up [ev./mm]/[ev./xing]
BCMS – 40/20	6.8	10.2	49/45	33/34	71/79	0.53/45
Standard - 40/20	5.3	9.6	47/44	31/33	75/80	0.53/45
BCMS – 50/25	6.2	9.8	49/45	33/35	71/77	0.45/45
Standard – 50/25	4.5	9.2	47/45	32/34	74/78	0.46/45

- With a reduced pile-up limit the target luminosity is still achievable but with reduced margin and longer fills (by >50 %)
- BCMS and standard filling schemes provide the same performance with a slight advantage for the standard scheme due to larger number of bunches and therefore larger levelling luminosity for the same pile-up limit.

Yearly Performance

- Assumed distribution (delta at T_{fill} - see J. Wenninger) is likely optimistic (10-20%) but:
  - Improvement in reliability could be expected as a result of PICs and in particular:
    - SC links in 1/5/7 ➔ R2E
    - Cryogenics upgrade in point 4 and additional IR1-5 cryoplants providing more margin for operation

Key questions and studies required in Run 2

- Confirmation of the feasibility of scrubbing the dipoles down to SEY=1.3-1.4 possibly with dedicated beams
- Full understanding of the stability limits for single and two-beams
- Study of the beam-beam effects with flat beams and large tune spread. Round beams with 30/30 cm and 12 σ separation as a back-up ➔ same pile-up density for smaller integrated luminosity (-12 %).
- Understanding and Control of the additive sources of blow-up
- Confirmation of the feasibility of β^*-levelling as a possible solution for IP8

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Conclusions

- The luminosity target can be reached with 40/20 optics
  - Comfortably, provided pile-up limit is increased above present values
- BCMS production scheme gives slightly higher performance as compared to Standard filling scheme although the latter is less sensitive to additive sources of emittance blow-up
- 50/25 optics provides margin in aperture and offers a reduction of the pile-up density below 0.7 events/mm for a small reduction of the integrated luminosity but still within the target
- Key questions and studies required in Run 2 have been sketched

High Luminosity LHC

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Main Hardware Modifications (c/o P. Fessia)

PIC

- New TAS, New IT, D1 with 150 mm aperture and correctors
- New collimators with buttons:
  - new materials (Mo-C) for robustness and impedance (should be required already at this stage)
  - new TCTs in IR1-5 for D2-Q5 for protection
- SC links in IR1-5, QRL
- New powering with SC links at P7 (RR)
- New Cryoplant P4 for SCRF
- Cryoplants in P1, 5

Peak Performance at 7 TeV

Momentum [TeV/c]	7
Bunch population in collision [10^{11} p]	1.38
Total RF Voltage	16
ε_L*[eV.s] at start of fill	3.8
Bunch length (4 σ)[ns]/ (r.m.s.) [cm]	1.33/10
Beam-beam separation [σ]	14

	$\varepsilon^*_{n\ coll}$ [μm]	# Coll. Bunches IP1,5	Xing angle [μrad]	L_{peak} [10^{34} cm^{-2}s^{-1}]
BCMS – 40/20	1.85	2592	351	3.1
Standard - 40/20	2.25	2736	387	2.7
BCMS – 50/25	1.85	2592	315	2.9
Standard – 50/25	2.25	2736	347	2.5

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PIC @ 7 TeV (Pile-up limit at 140)

“Visible” cross-section IP1-5 [mb] for pile-up estimation	85
“Visible” cross-section IP8 [mb] for pile-up estimation	75
Pile-up limit IP1	140
Pile-up limit IP5	140
Pile-up limit IP8	4.5
Luminosity limit IP2 [10^{34} cm^{-2} s^{-1}]	0.002

	Lev. time [h]	Opt. Fill length [h]	η_{6h}/η_{opt} [%]	ϕ_{6h}/ϕ_{opt} [%]	Int. Lumi for η=50% for 6h /opt. fill length [fb^{-1} /y]	Max. Avg. Pile-up density/Pile-up [ev./mm]/[ev./xing]
BCMS – 40/20	-	6.6	34/34	23/24	102/102	1.0/90
Standard - 40/20	-	7.4	37/37	25/26	95/95	0.85/74
BCMS – 50/25	-	6.8	36/36	24/25	97/97	0.83/84
Standard – 50/25	-	7.6	39/39	26/28	90/91	0.68/69

- 50/25 optics reduced pile-up density for small reduction of the integrated luminosity)

Break-down of Turn-Around (HL-LHC)

Phase	**Duration [min]**
Ramp down/pre-cycle	60
Pre-injection checks and preparation	15
Checks with set-up beam	15
Nominal injection sequence	20 (=2*12 injections*48.8s)
Ramp preparation	5
Ramp	25
Squeeze/Adjust	40
Total	**180**

M. Lamont

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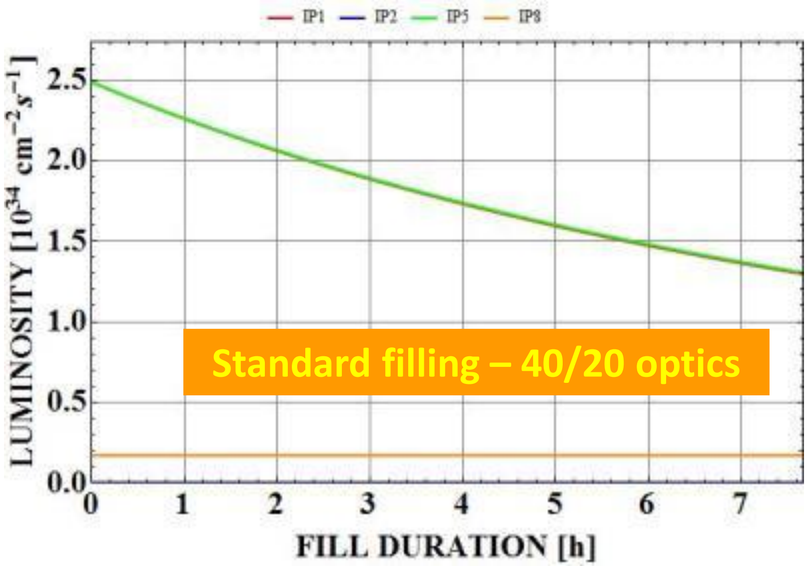
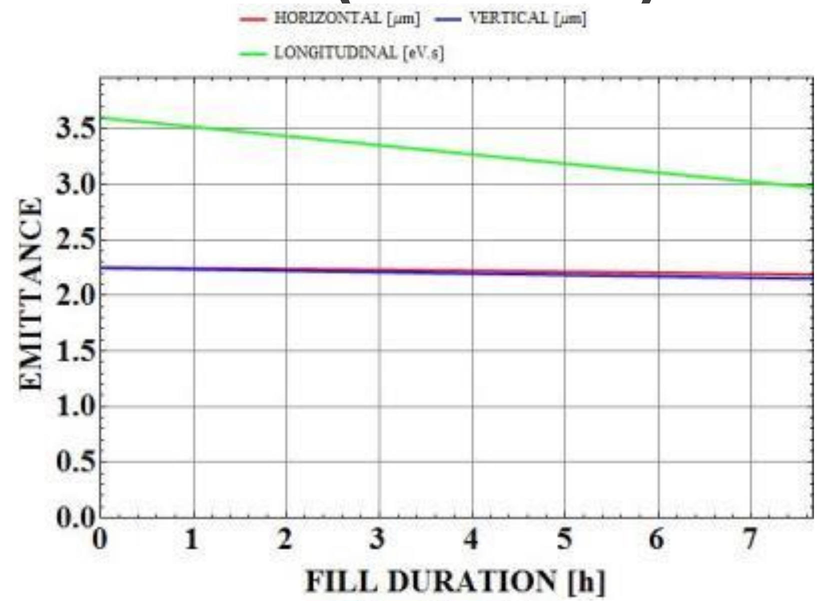
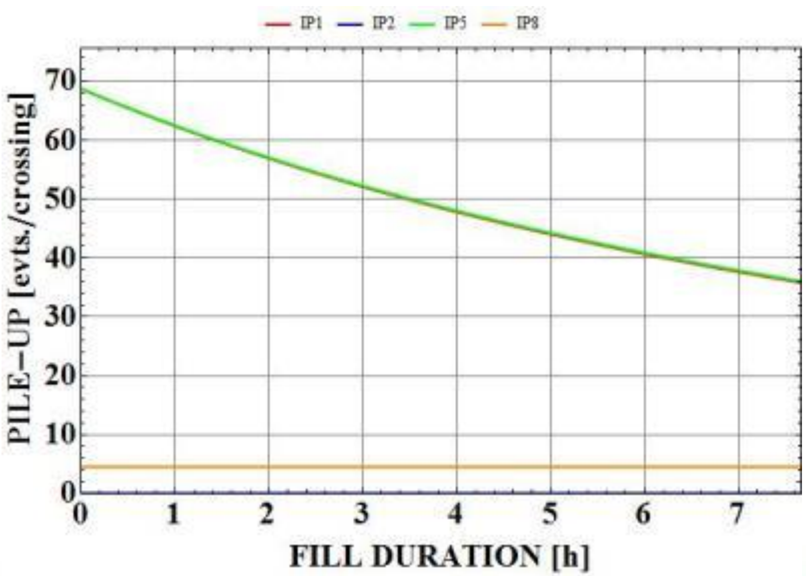
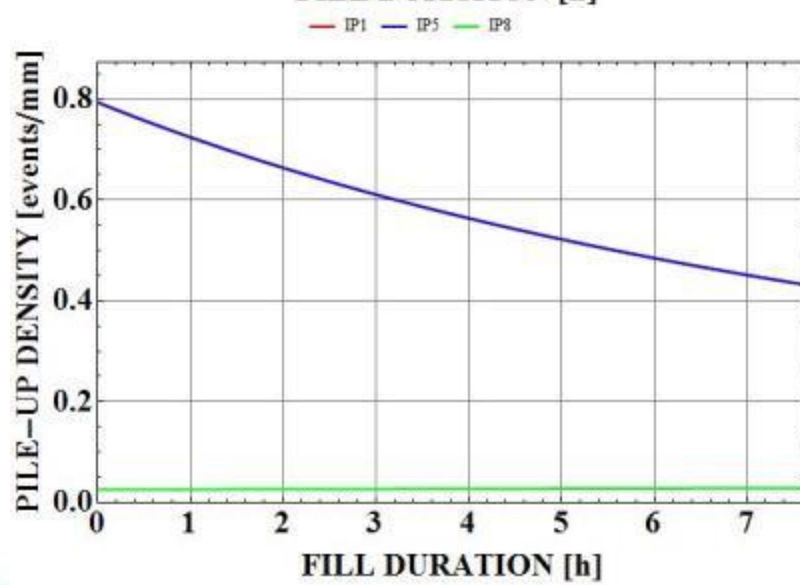
Parameter evolution at 6.5 TeV (model)









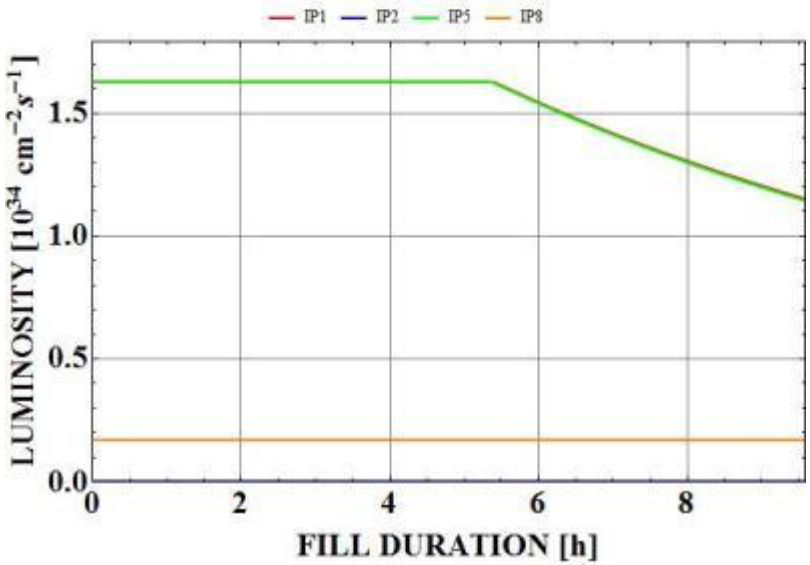
PIC @ 6.5 TeV (Pile-up limit at 140) – 30/30

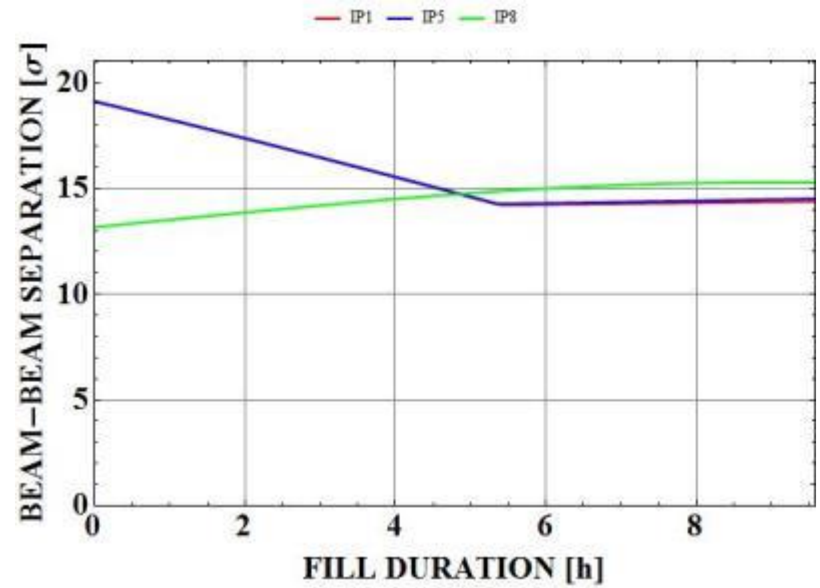
	$\varepsilon^*_{n\ coll}$ [μm]	# Coll. Bunches IP1,5	Xing angle [μrad]	BB separation [σ]	L_{peak} [10^{34} $cm^{-2}s^{-1}$]
BCMS – 30/30	1.85	2592	360	12	2.5
Standard - 30/30	2.25	2736	396	12	2.1

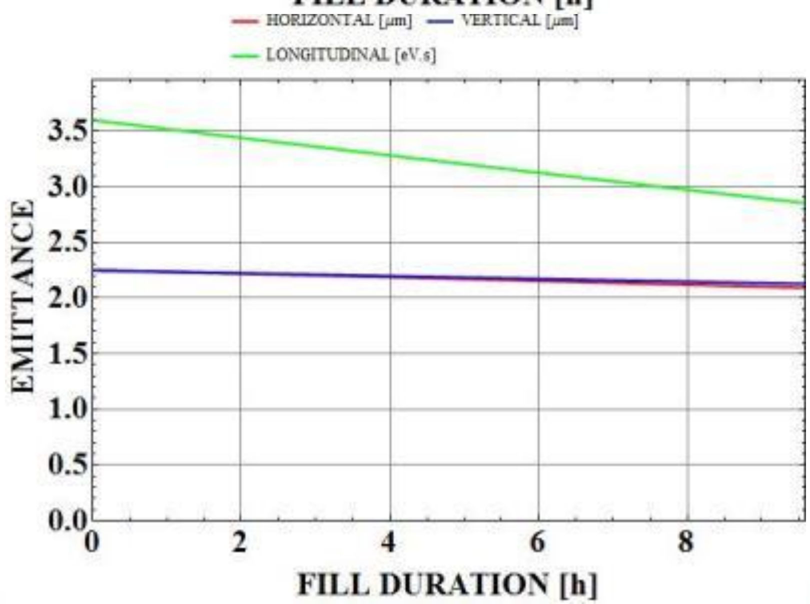
	Lev. time [h]	Opt. Fill length [h]	η_{6h}/η_{opt} [%]	ϕ_{6h}/ϕ_{opt} [%]	Int. Lumi for η=50% for 6h /opt. fill length [fb^{-1} /y]	Max. Avg. Pile-up density/Pile-up [ev./mm]/[ev./xing]
BCMS – 30/30	-	7	41.7/41.5	27.8/29.1	83.8/84.3	0.9/72
Standard - 30/30	-	7.9	45.1/44.4	30.1/32.2	77.6/78.8	0.75/59

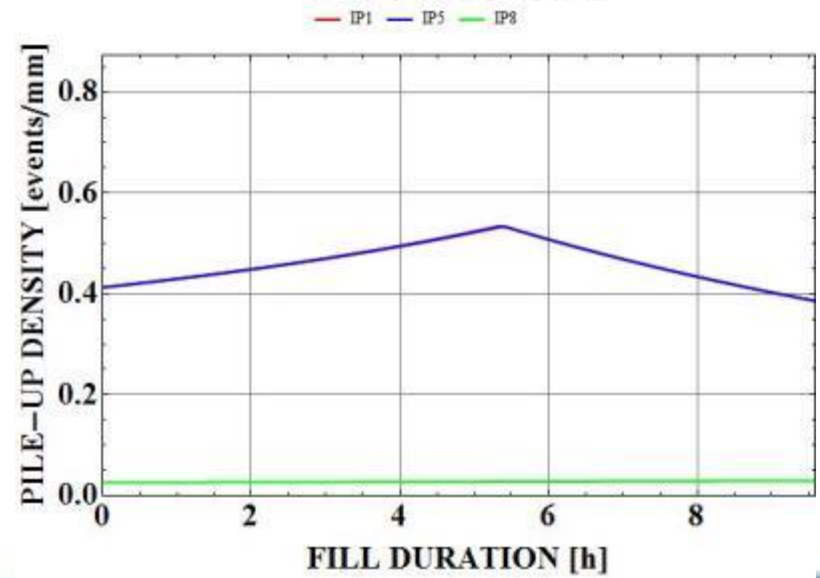
Parameters evolution

Standard beam – 40/20 optics



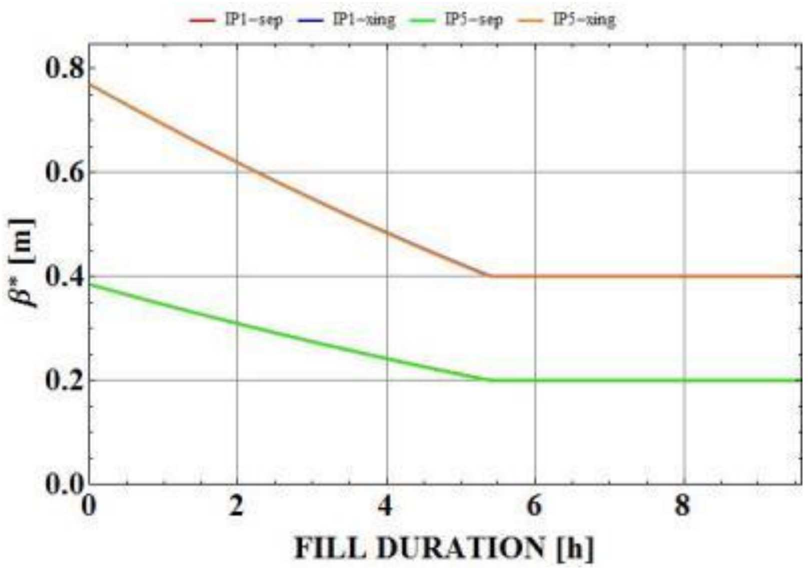


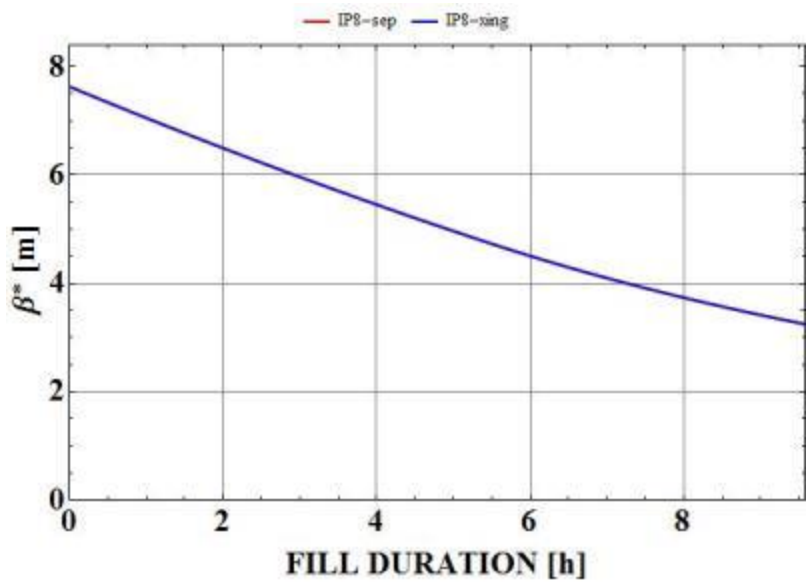




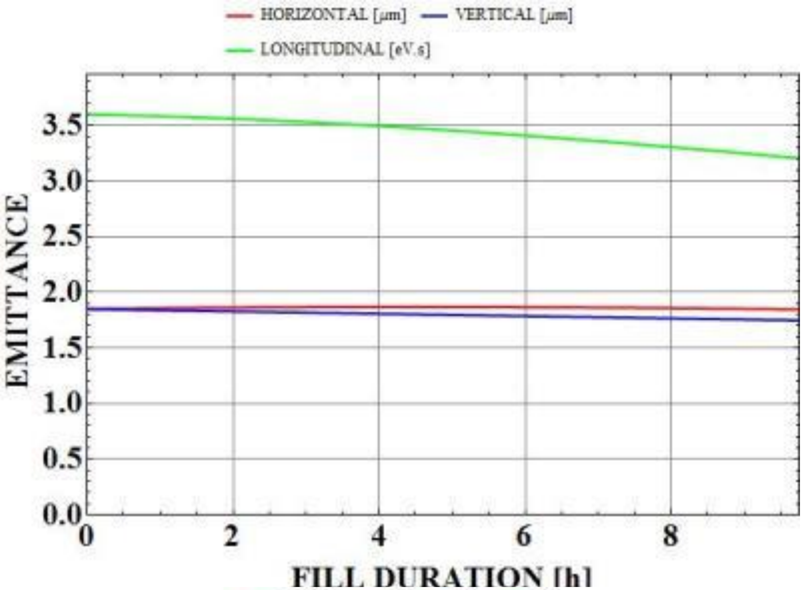
Parameters evolution

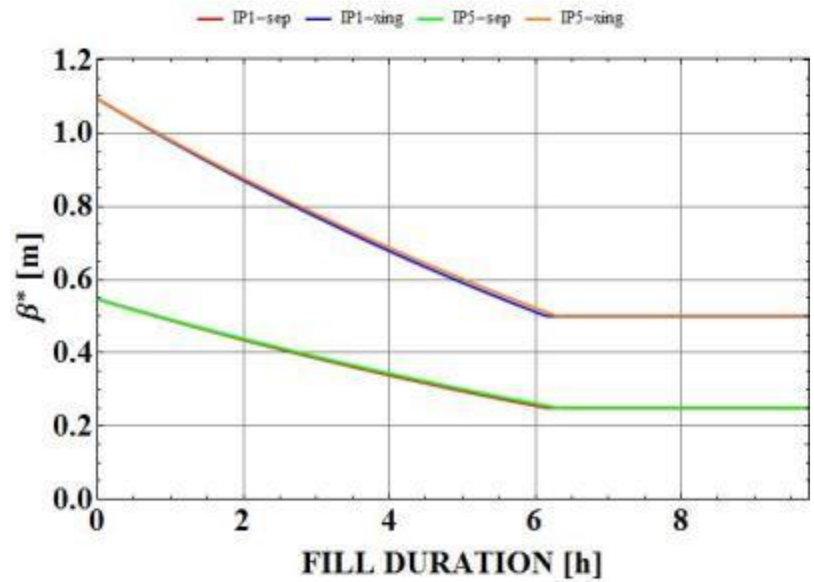
Standard beam – 40/20 optics

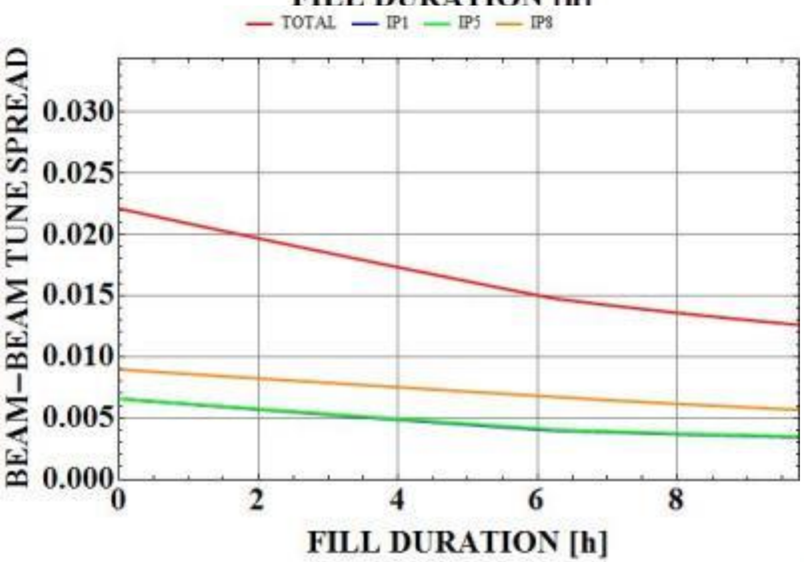


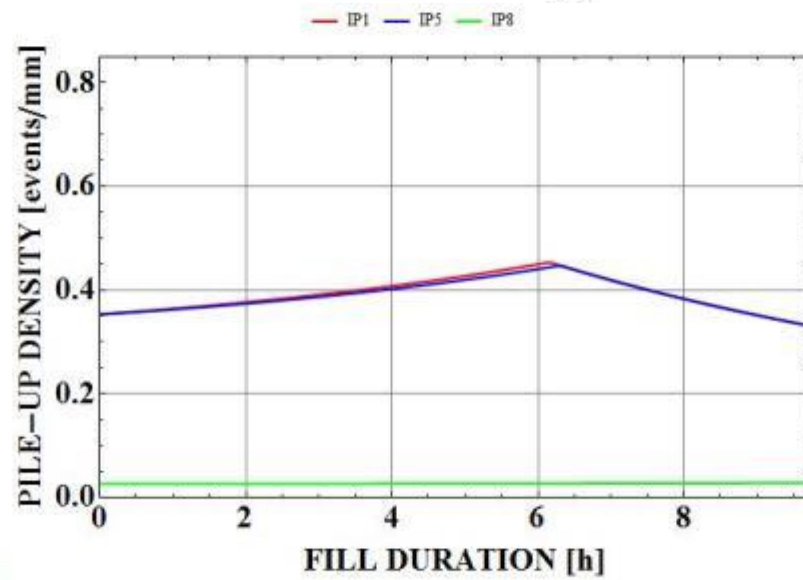


BCMS (50/25)

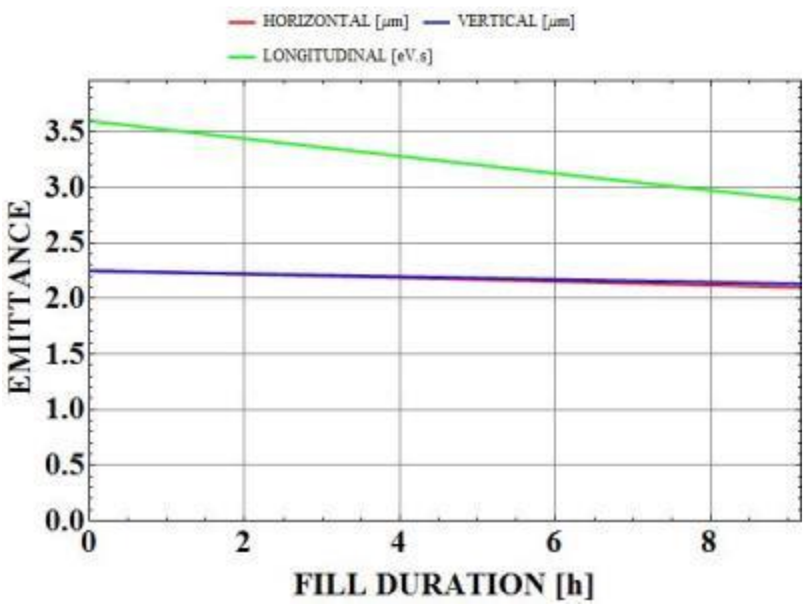

HORIZONTAL [μm]
VERTICAL [μm]
LONGITUDINAL [eV.s]
EMITTANCE
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
2
4
6
8
FILL DURATION [h]

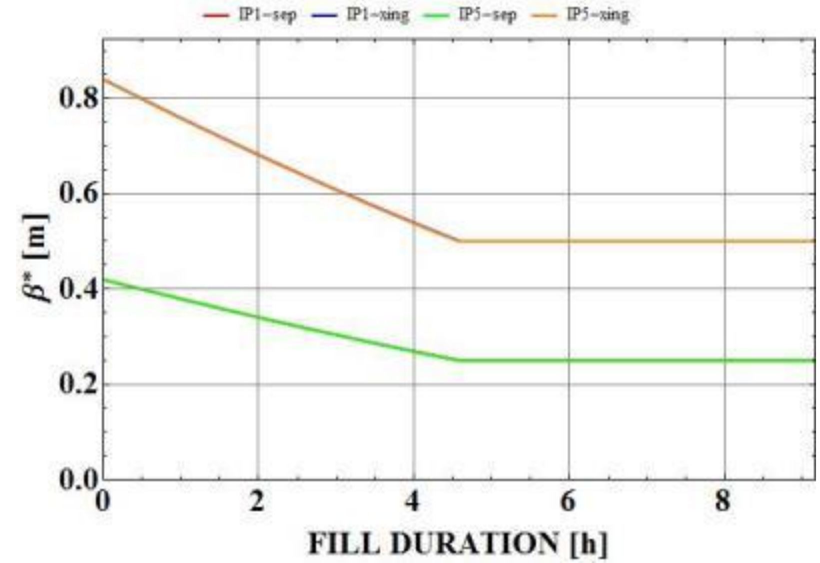

IP1−sep
IP1−xing
IP5−sep
IP5−xing
β* [m]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
2
4
6
8
FILL DURATION [h]

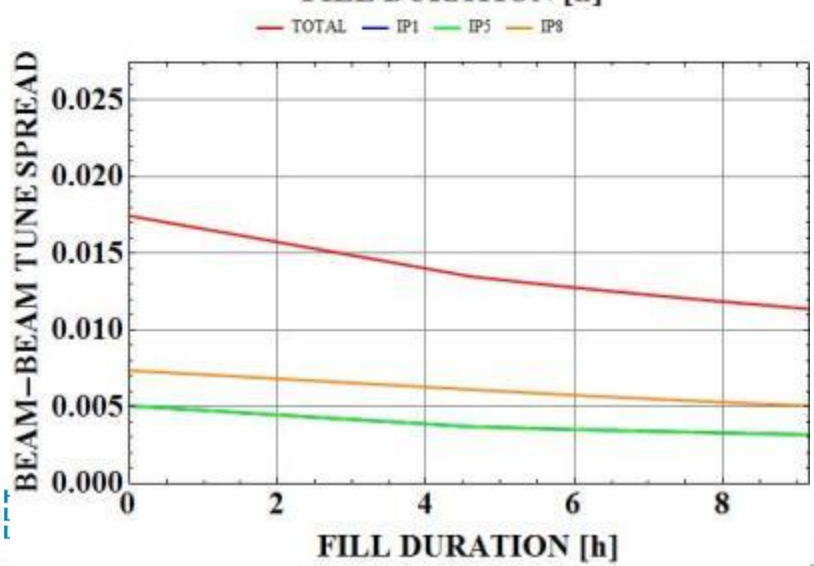

TOTAL
IP1
IP5
IP8
BEAM−BEAM TUNE SPREAD
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0
2
4
6
8
FILL DURATION [h]

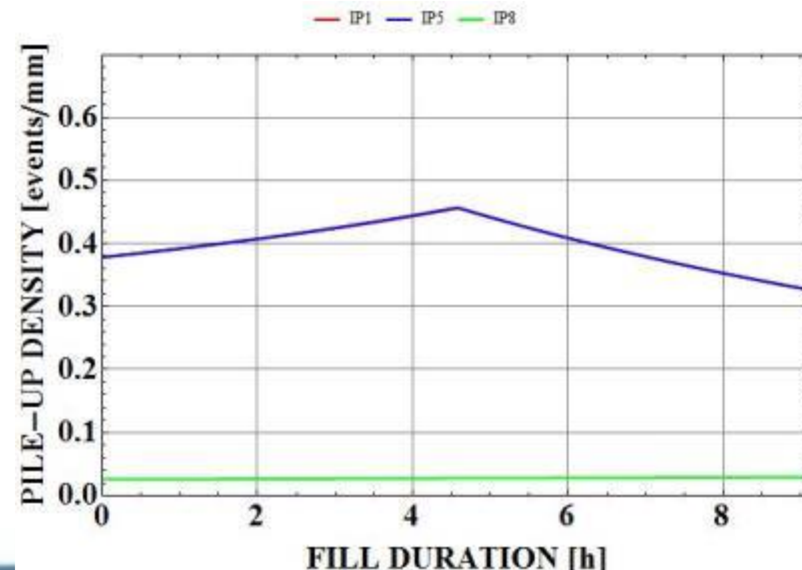

IP1
IP5
IP8
PILE−UP DENSITY [events/mm]
0.0
0.2
0.4
0.6
0.8
0
2
4
6
8
FILL DURATION [h]

Standard (50/25)





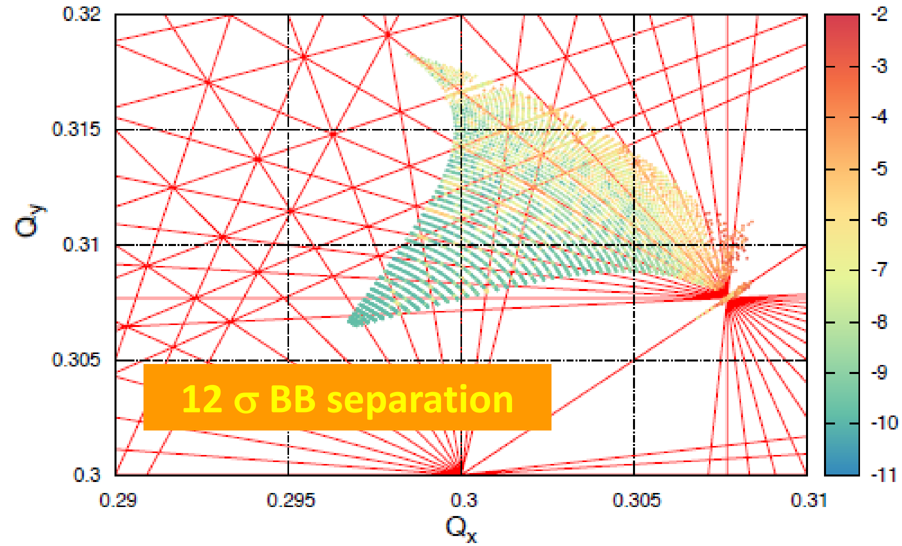


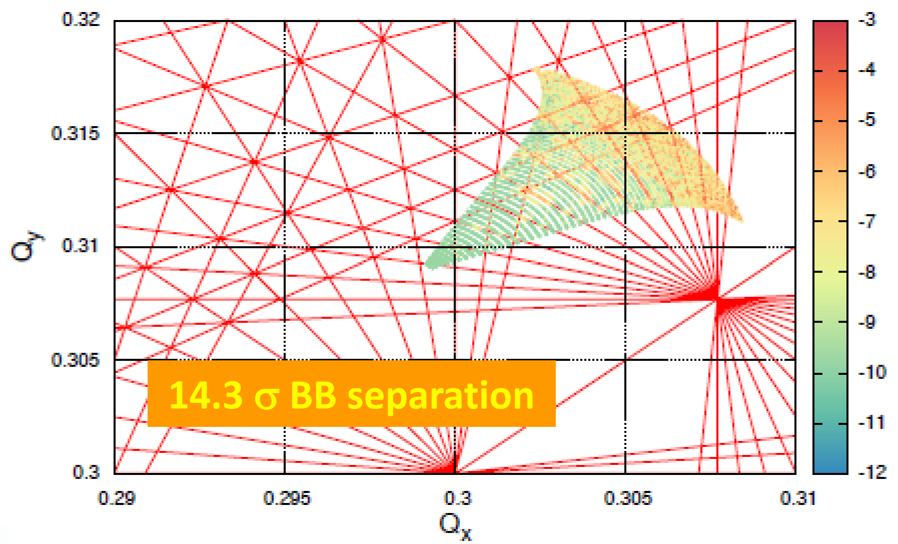


Beam-beam separation

- Frequency map analysis show the importance of increasing beam beam-separation for flat beams (no optimization of working point done yet) at least in the absence of Beam-Beam Compensator and no levelling (all the fill with minimum β*)

Standard filling – 40/20 optics





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PRELIMINARY