Optimization of the Filling Scheme for Ions in the LHC

Michaela Schaumann

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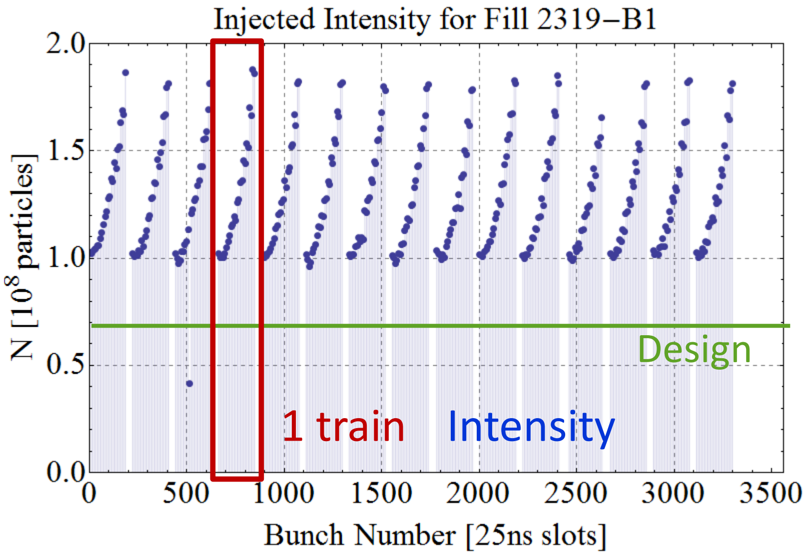
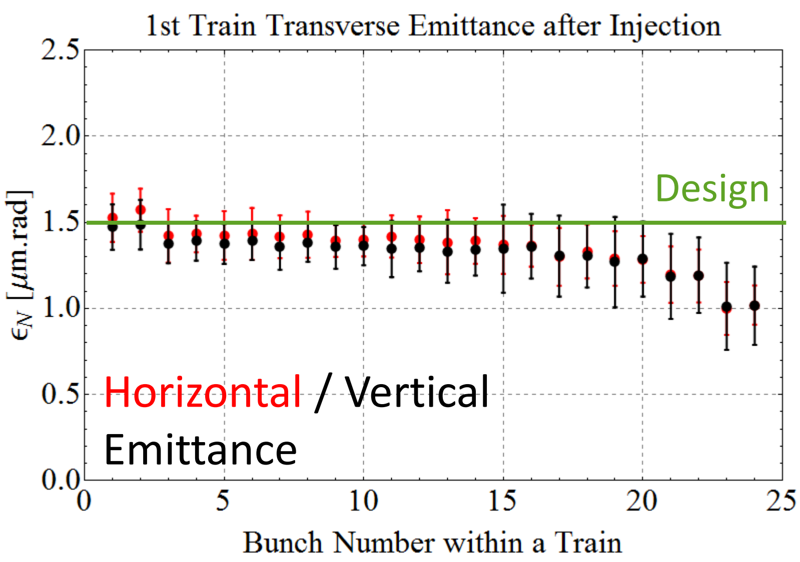
Outline

- Bunch-by-Bunch Differences in the LHC.
- Empirical Model to Predict Peak Luminosities per Bunch.
- Optimum Filling Schemes for after LS1 and LS2.
- Instantaneous and Integrated Luminosity Evolution for Selected Scenarios.

Bunch-by-Bunch Differences after Injection in the LHC

E = 450 Z GeV

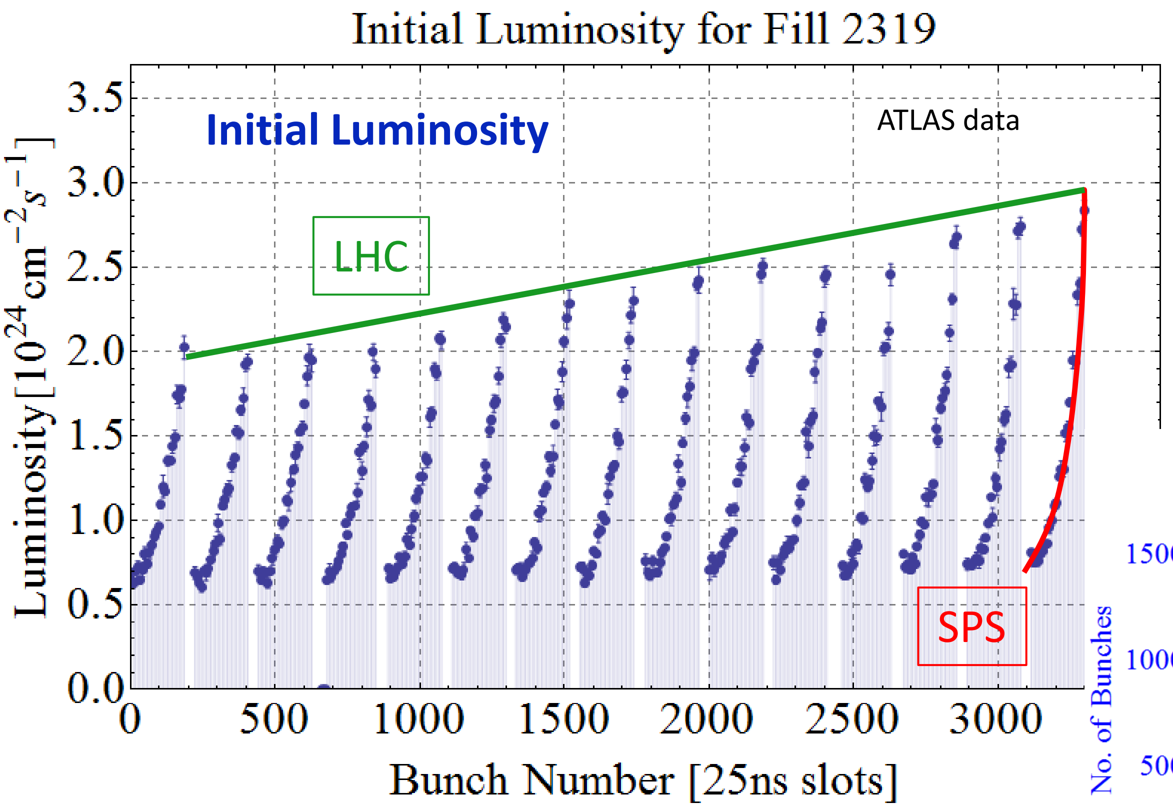


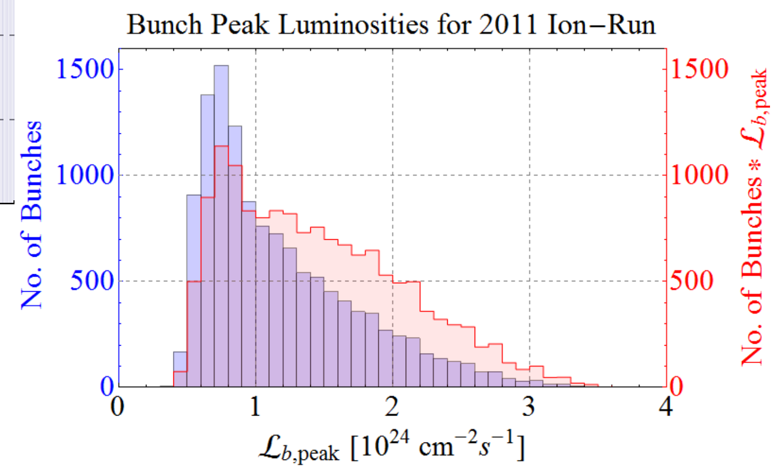


- Structure within a train (1st to last bunch):
  - increase: - intensity
    - bunch length
  - decrease: emittance.
- IBS, space charge, RF noise … at the injection plateau of the SPS:
  - while waiting for the 12 injections from the PS to construct a LHC train.
- First injections sit longer at low energy
  → strong IBS,
  → emittance growth and particle losses.

Bunch-by-Bunch Luminosity

E = 3.5Z TeV





Two effects:

Slope imprinted by SPS injection plateau.

Slope imprinted by LHC injection plateau.

→ Last train does not see degradation due to LHC injection plateau.

→ Cleanest picture of what happens "to the luminosity" in the SPS.

Parametrisation of Degradation in the SPS

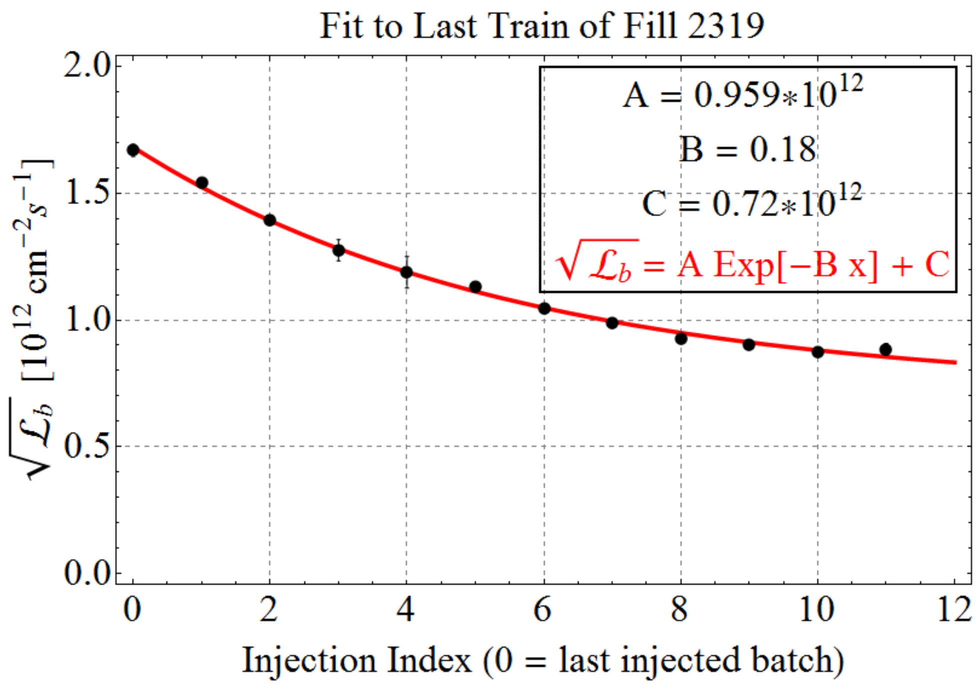
- Take ATLAS bunch-by-bunch luminosity data of last train injected into LHC.
- Invert order of the bunches. → time evolution
- Average over bunches of one PS batch.
- Take square root of the data, since: $\sqrt{\mathcal{L}} \propto N_b/\sqrt{\epsilon}$

  for equal colliding bunches (as is approx. the case in ATLAS):

$$N_b = N_{b1} = N_{b2}$$
$$\epsilon = \epsilon_1 = \epsilon_2$$

- Fit an exponential of the form:

$$\sqrt{\mathcal{L}} = A \exp[-B\, x] + C$$



Average over all proper fills of 2011

$$\sqrt{\mathcal{L}_{\mathrm{SPS}}} = \bar{a}\exp[-\bar{b}\,x] + \bar{c}$$
$$\bar{a} = 1.04 * 10^{12}\,\mathrm{cm}^{-1}\mathrm{s}^{-1/2}$$
$$\bar{b} = 0.19$$
$$\bar{c} = 0.71 * 10^{12}\,\mathrm{cm}^{-1}\mathrm{s}^{-1/2}$$

Parametrisation of Degradation in the LHC

- Group bunches of equivalent PS batches (n^th PS batch) from all trains, which saw the same SPS injection plateau length.
- Invert the order → time evolution.
- Fit an exponential of the same form as before: $\sqrt{\mathcal{L}} = A \exp[-B\, x] + C$

➢ Result: 12 fits with different decay speed due to different brightness's of the bunches.

➢ Simplification: 1 curve that describes all of them.

➢ Two possibilities:

1) Average fit parameters of all curves.
2) Take fit of average bunch.

➢ Number 2) is in better agreement with the data.

Average over all proper fills of 2011

$$
\begin{aligned}
\sqrt{\mathcal{L}_{\mathrm{LHC}}} &= \bar{A} \exp[-\bar{B}\, x] + \bar{C} \\
\bar{A} &= 7.74 * 10^{12}\, \mathrm{cm}^{-1}\mathrm{s}^{-1/2} \\
\bar{B} &= 0.0012 \\
\bar{C} &= -6.53 * 10^{12}\, \mathrm{cm}^{-1}\mathrm{s}^{-1/2}
\end{aligned}
$$

Complete Parametrisation

$$\sqrt{\mathcal{L}_{\mathrm{b}}} = F_{Nb}\, F_{norm} (\bar{a} \exp[-\bar{b}\, n_{\mathrm{PSbatch}}] + \bar{c})(\bar{A} \exp[-\bar{B}\, n_{\mathrm{LHCtrain}}] + \bar{C})$$

Intensity scaling factor

Normalisation factor

$$F_{norm} = 8.27 * 10^{-13}$$

$$\begin{aligned} \sqrt{\mathcal{L}_{\mathrm{SPS}}} &= \bar{a} \exp[-\bar{b}\, x] + \bar{c} \\ \bar{a} &= 1.04 * 10^{12}\, \mathrm{cm}^{-1}\mathrm{s}^{-1/2} \\ \bar{b} &= 0.19 \\ \bar{c} &= 0.71 * 10^{12}\, \mathrm{cm}^{-1}\mathrm{s}^{-1/2} \end{aligned}$$

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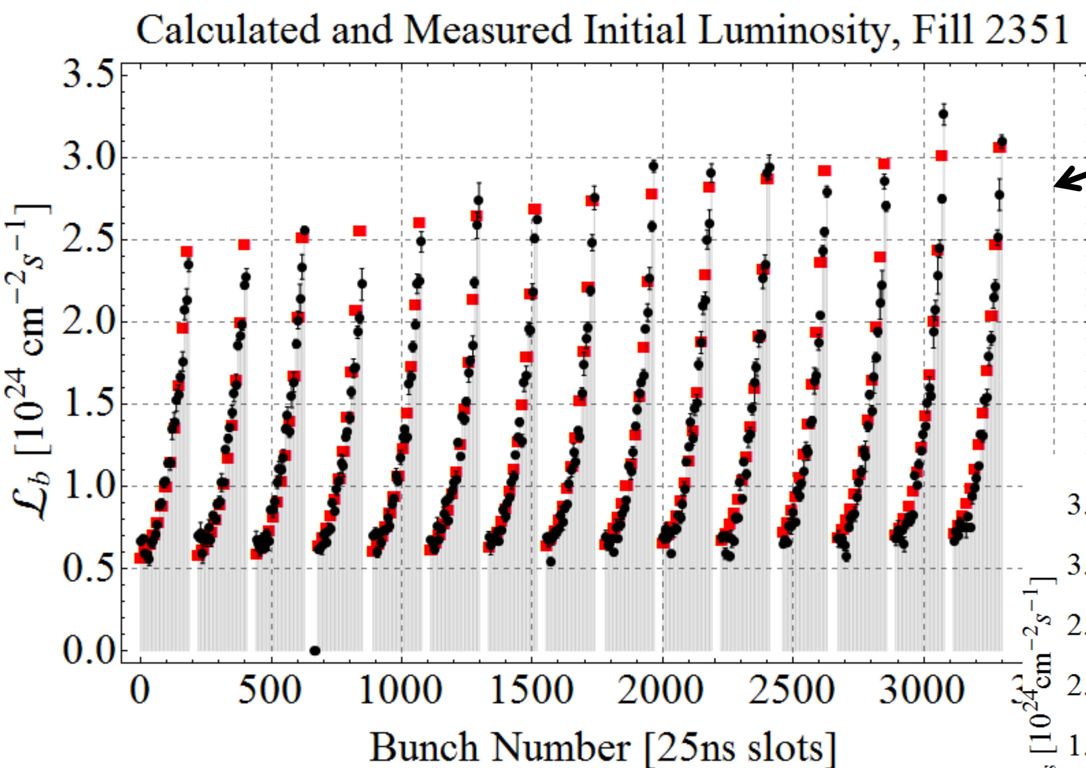
Only takes variations due to SPS and LHC into account.
LEIR, PS are assumed to have cycles similar as in 2011.

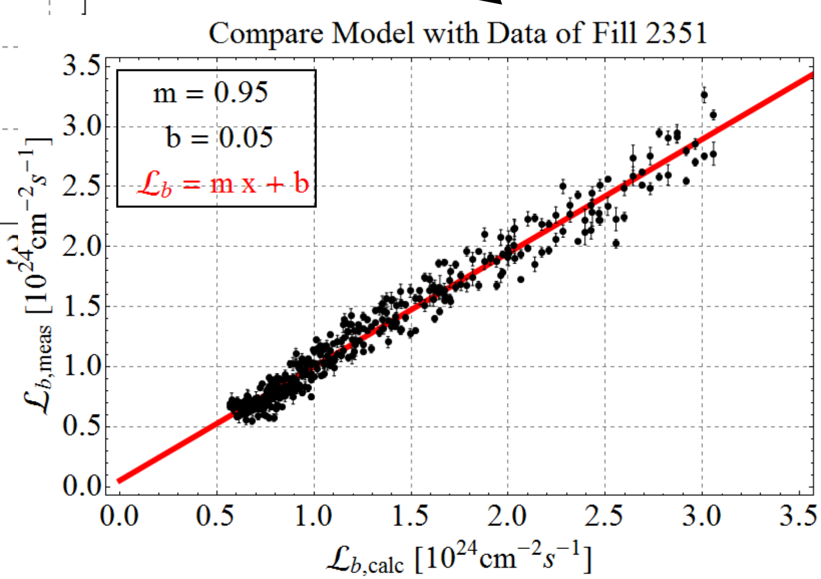
Validation of the Parametrisation

$$\sqrt{\mathcal{L}_\mathrm{b}} \;=\; F_{Nb}\, F_{norm} (\bar{a} \exp[-\bar{b}\, n_{\mathrm{PSbatch}}] + \bar{c})(\bar{A} \exp[-\bar{B}\, n_{\mathrm{LHCtrain}}] + \bar{C})$$



Calculation compared to data of the last fill from 2011.

Data vs. calculation



Estimates

Linear parameter scaling w.r.t. 2011 parameters:

1. Number of particles per bunch N_b
2. Energy E
3. β^*

Vary injection scheme:

Free parameters:

1. Number of bunches per PS batch. (*Constrain: 2011 PS cycle length*)
2. Spacing PS.
3. Spacing SPS.
4. *Spacing LHC: assumed to be 900ns.*

} Given by hardware constrains.

Parameters to be optimised:

1. Set number of PS batches per LHC train.
2. Set number of LHC trains.

} Optimise to achieve max. peak luminosity.

Intensity Scaling

Measured Bunch Intensities and Scaling

	2011	**2013**	**+40% out of LEIR**
LEIR pulse intensity [ions]	9×10^8	11×10^8	15.4×10^8
Number of bunches per batch	2	2	4
Intensity per future LHC bunch [ions]	4.5×10^8	5.5×10^8	3.9×10^8
Injected intensity per bunch into LHC [ions]	1.24×10^8 (27%)	1.6×10^8 (29%)	1.1×10^8 (29%)
Intensity in Stable Beams [ions]	1.2×10^8 (96%)	1.4×10^8 (87%)	1.0×10^8 (96%)
Transmission LEIR → LHC SB	26%	25%	27%
Intensity scaling factor for best transmission	1	1.28	0.88

Intensity scaling factor for best transmission means:
29% from LEIR to LHC injection,
96% from LHC injection to Stable Beams,
→ 27% from LEIR to LHC Stable Beams

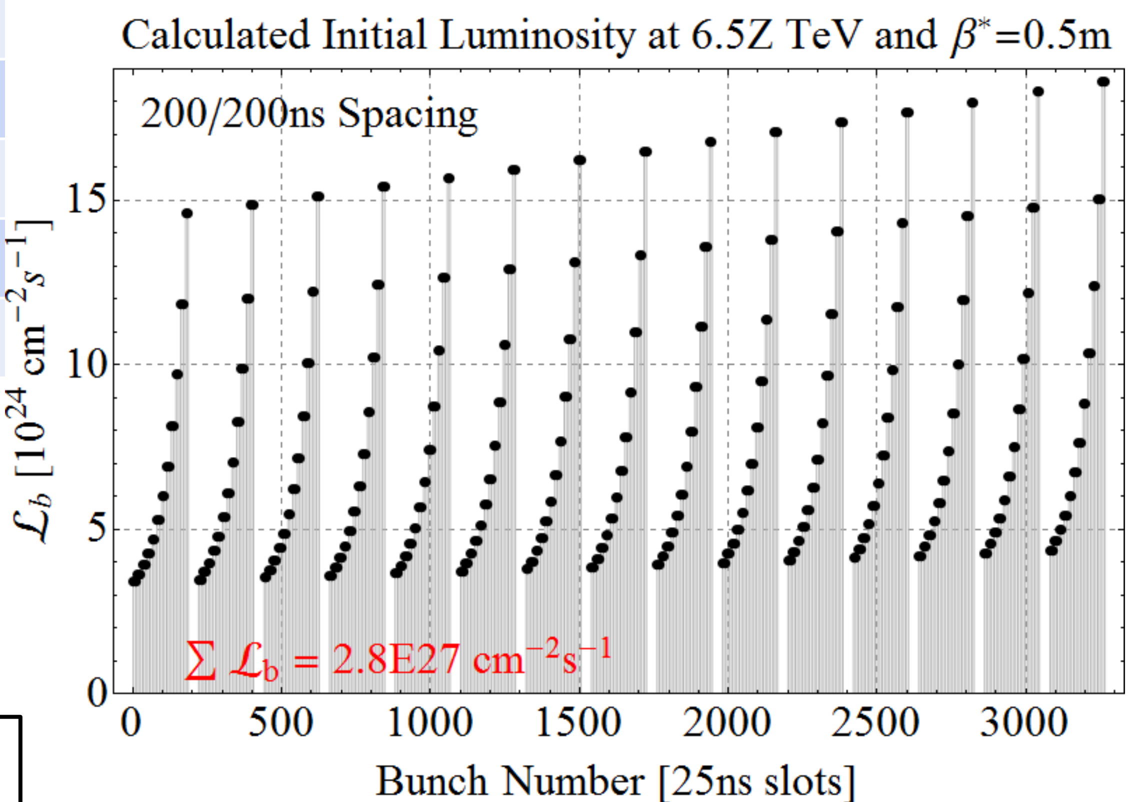
↑ 1.28: taken for all cases ladled with "*2013 performance*".

↑ 0.88: taken for all cases ladled with "*+40%*".

Estimates for after LS1 – 2011 Scheme, scaled Nb

E = 6.5 Z TeV

2011 Filling Scheme	@ E = 6.5Z TeV β^* = 0.5m F_{Nb} = 1.28
Spacing PS [ns]	200
Spacing SPS [ns]	200
No. bunches/PS batch	2
No. PS batches/train	12
No. LHC trains	15
No. bunches/beam	358



2011 filling scheme
2013 bunch performance
2011 injection→ stable beams

Max. peak luminosity (ATLAS/CMS)
$2.8 \times 10^{27} \mathrm{cm}^{-2} \mathrm{s}^{-2}$

Estimates for after LS1 – 100ns Batch Compression

Batch Compression	@ E = 6.5Z TeV β^*= 0.5m F_{Nb} = 1.28
Spacing PS [ns]	100
Spacing SPS [ns]	225
No. bunches/PS batch	2
No. PS batches/train	7 / 9
No. LHC trains	29 / 24
No. bunches/beam	406 / 432

max. Luminosity

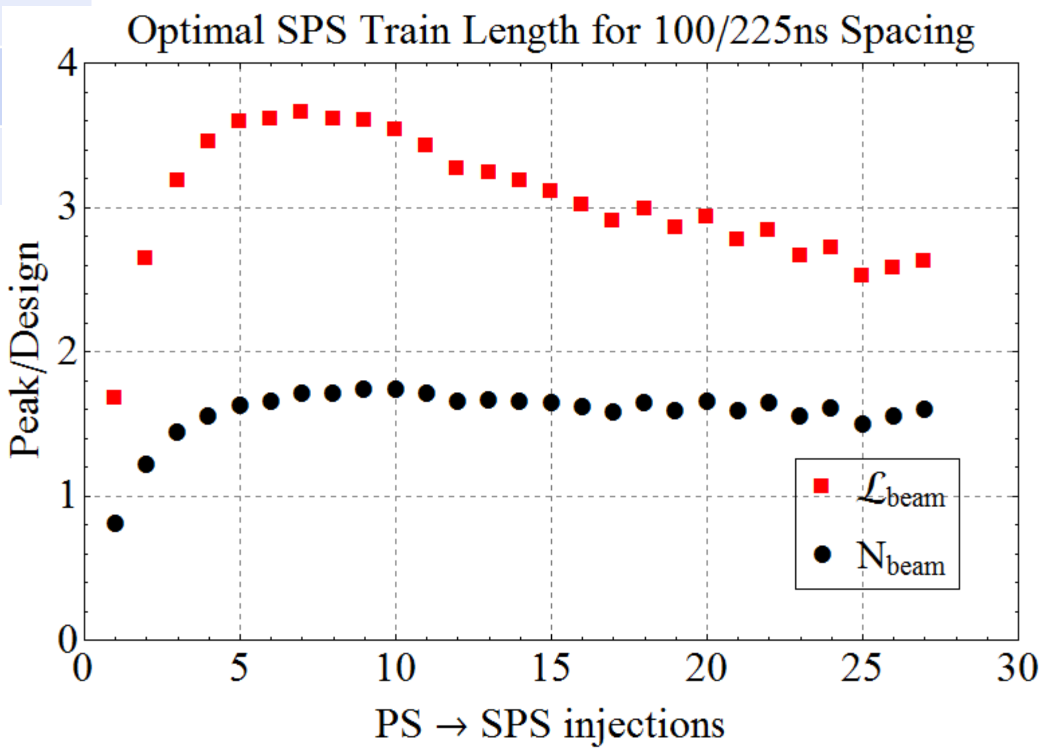
max. Intensity

2013 bunch performance
2011 injection→ stable beams

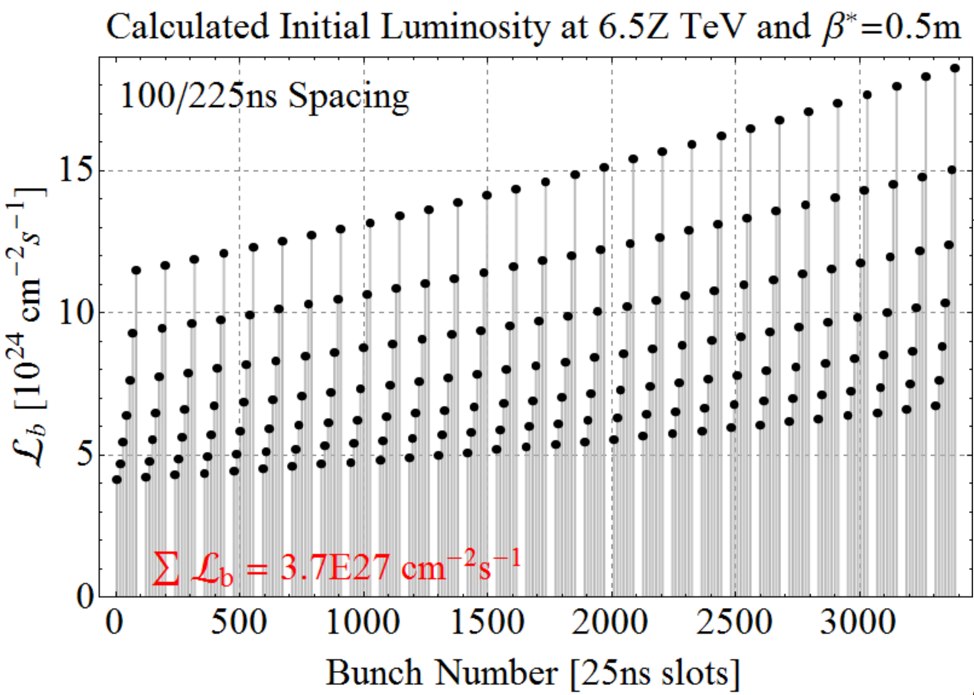
Max. peak luminosity
$3.7 \times 10^{27} \text{cm}^{-2}\text{s}^{-2}$

Filling schemes are not exact!
Takes into account:

- Not more than 40% of the SPS is filled.
- 3.3μs abort gap.
- 900ns LHC kicker gap.
- All bunches are colliding with an equal partner.

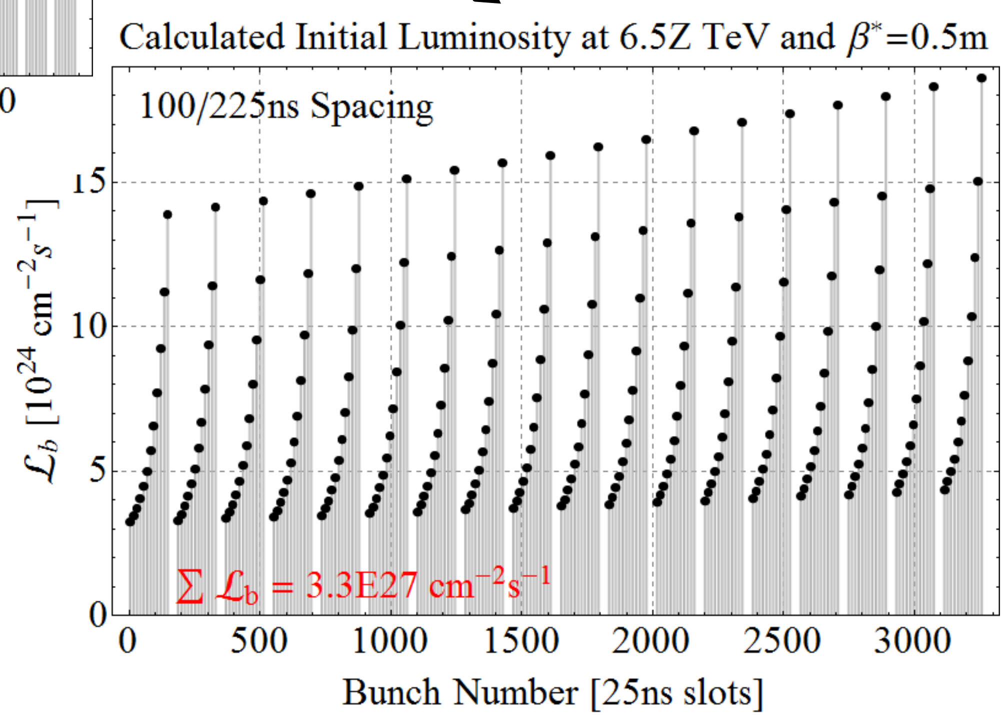


Estimates for after LS1 – Optimisation



Scheme with max. peak luminosity
7 batches & 29 trains = 406 bunches

Scheme similar to 2011
12 batches & 18 trains = 432 bunches



- ~15% improvement in peak luminosity due to batch compression in the PS.
- Another ~10% by shortening the trains.

→ 30% more than 2011 scheme.

Estimates for after LS2

E = 7 Z TeV

Increasing the Luminosity by increasing the total number of bunches.

1. Reduce bunch spacing within batches.
2. Decrease SPS kicker rise time to reduce batch spacing.
3. Increase intensity out of LEIR by 40% and perform bunch splitting in the PS.

PS Spacing [ns]	SPS Spacing [ns]	No. Bunches/PS Batch	
50 or 100	225	**2 (unsplit)** or 4 (split)	**Present** with batch compression (100ns)
50 or **100**	**100**	**2** or 4	1. **Baseline** 2. **Batch compression** (50ns) with split bunches
50 or 100	75	2 or 4	
50 or 100	50	2 or **4**	**Slip stacking** with split bunches

Estimates for after LS2 – 100/100ns Baseline Scheme

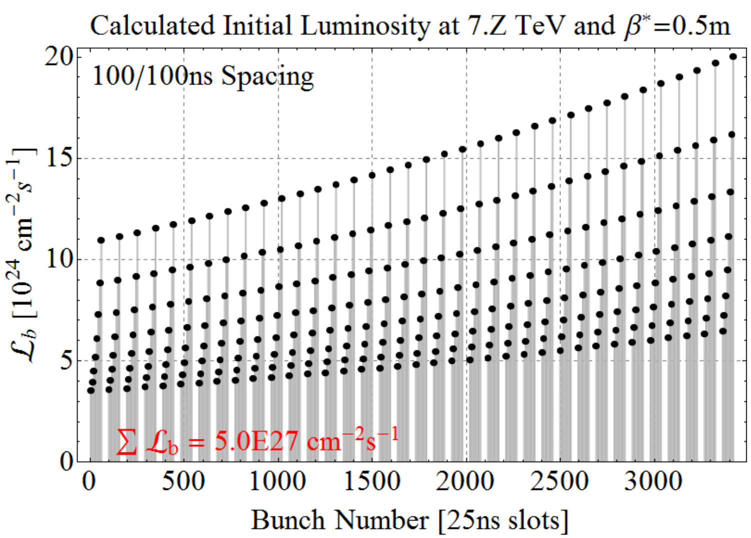
50/50ns Scheme PS Bunch Splitting	@ E = 7Z TeV β^*= 0.5m F_{Nb} = 1.28
Spacing PS [ns]	100
Spacing SPS [ns]	100
No. bunches/PS batch	2
No. PS batches/train	8
No. LHC trains	36
No. bunches/beam	576

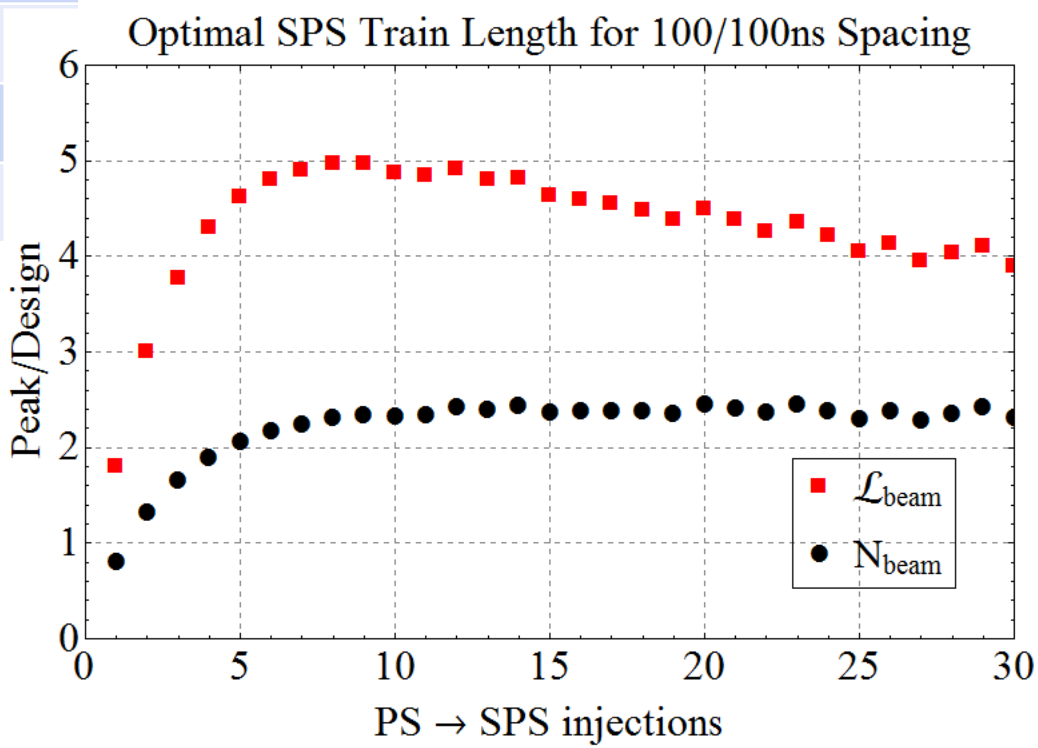
With 2013 transmission from Inj. to SB:

$$L_{peak} = 4 \times 10^{27}\,\mathrm{cm^{-2}s^{-2}}$$

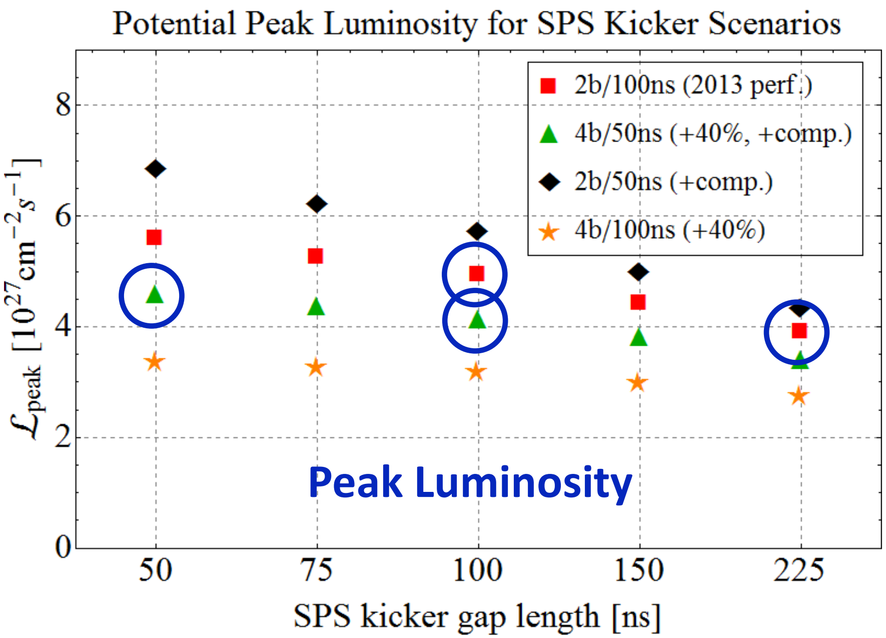
With 2011 transmission from Inj. to SB:

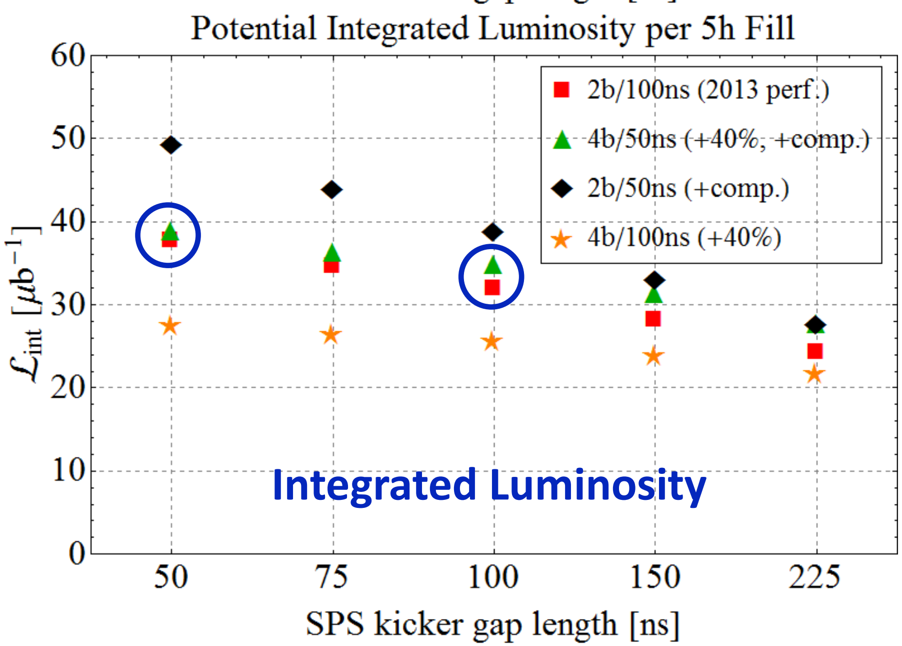
$$L_{peak} = 5 \times 10^{27}\,\mathrm{cm^{-2}s^{-2}}$$





Estimates for after LS2





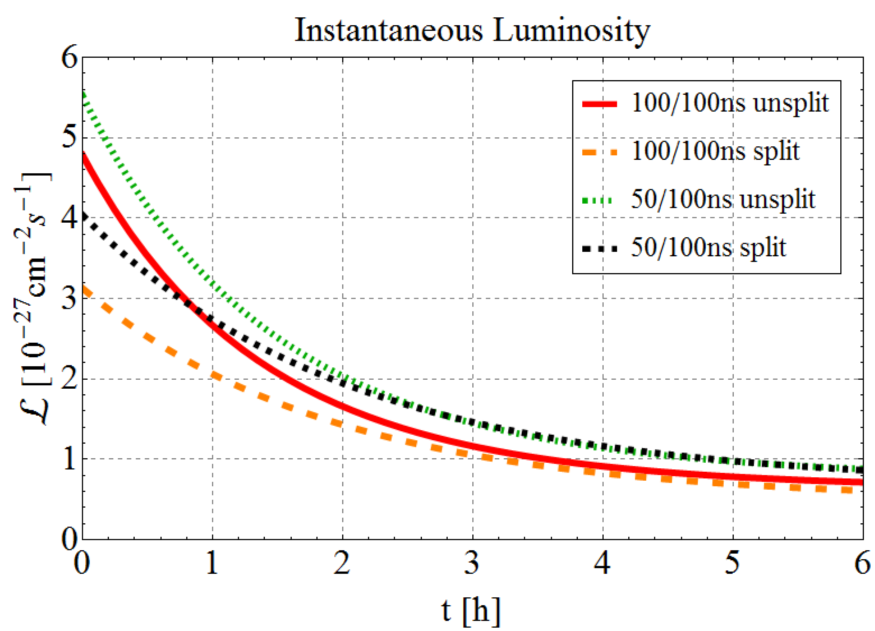
Peak luminosity higher for 100ns PS spacing with unsplit bunches.

→ Higher brightness bunches decay faster.

→ Higher integrated luminosity for 50ns PS spacing with split bunches.

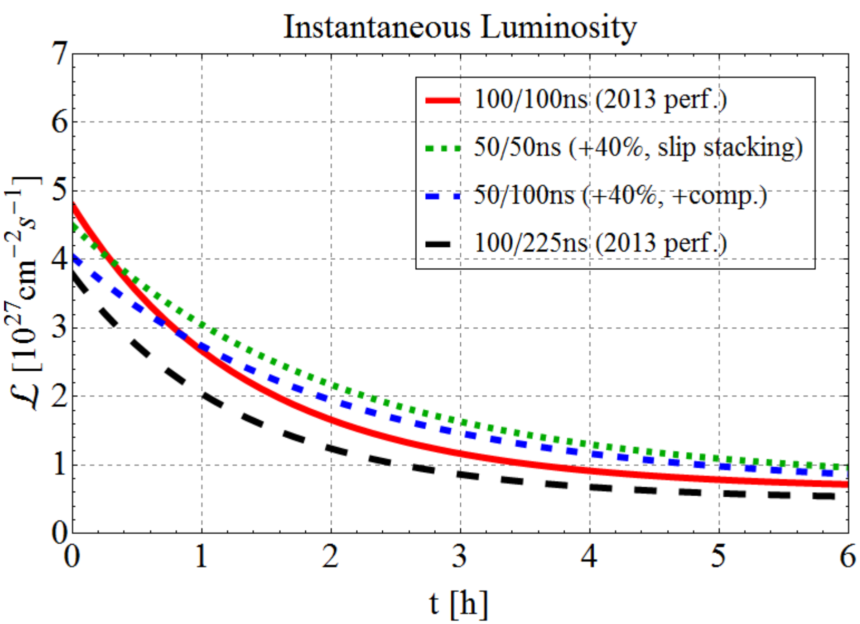
50/100ns split → ~1000 bunches/beam

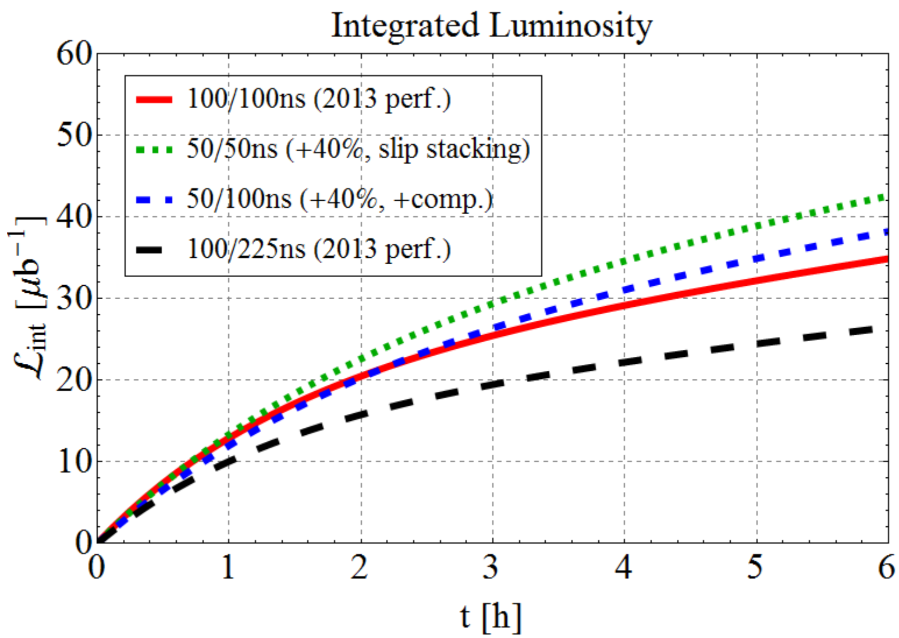
100/100ns unsplit → ~600 bunches/beam



Luminosity Evolution for main Upgrade Scenarios

Takes into account different initial bunch luminosities and bunch luminosity decay times.





Scenario	L_{int} after 3h [μb^{-1}]	L_{int} after 5h [μb^{-1}]	L_{int} in run with 30×5h	
100/225ns	19	25	0.8 nb^{-1}	Present
100/100ns	25	32	1.0 nb^{-1}	**Baseline**
50/50ns	29	39	1.2 nb^{-1}	Slip Stacking
50/100ns	26	35	1.1 nb^{-1}	Batch compression

Summary

- Strong bunch degradation in the SPS/LHC, due to accumulation process of the bunches/trains.
- Empirical model for the $L_{b,peak}$ depending on the bunch position inside the train/beam (i.e. SPS/LHC injection plateau length per bunch) was built based on 2011 ATLAS luminosity data.
- For final decision integrated luminosity has to be considered as well.

- Model can be refitted to SPS and LHC performance in the run-up to a given Pb-Pb run to re-optimise the length of the SPS trains.

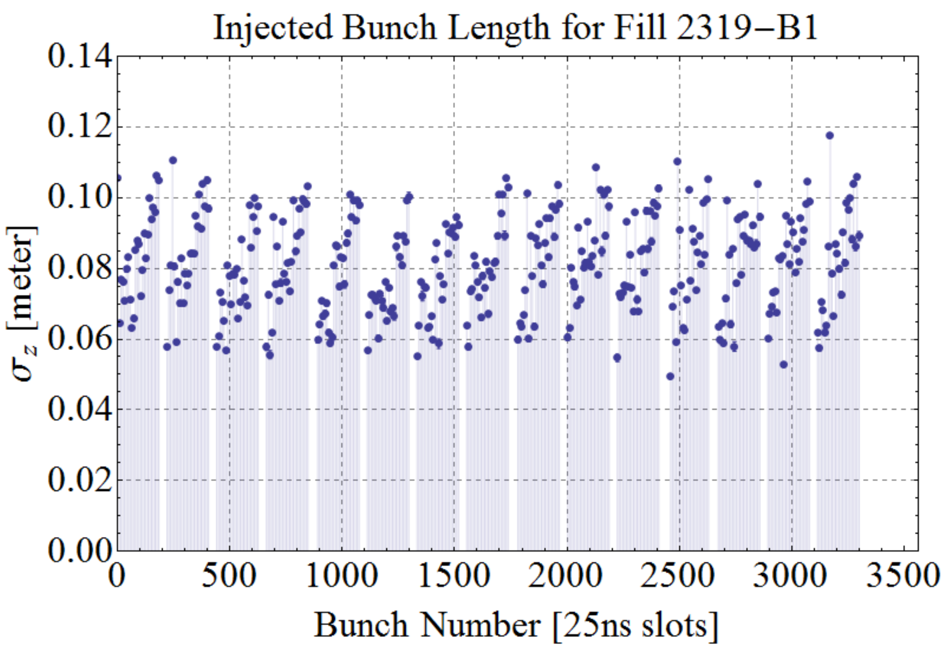
Scenario	L_{peak} [Hz/mb]	L_{int} after 3h [μb^{-1}]	L_{int} after 5h [μb^{-1}]	L_{int} in run with 30×5h	$L_{int,run}$ (Hubner Factor)	Years to integrate 10 nb^{-1}	
200/200ns	2	15	21	0.64 nb^{-1}	0.64nb^{-1}	15.6	2011 @ 7Z TeV
100/225ns	3.7	19	25	0.8 nb^{-1}	1.2 nb^{-1}	12.5	Present
100/100ns	5.0	25	32	1.0 nb^{-1}	1.6 nb^{-1}	10	**Baseline**
50/50ns	4.6	29	39	1.2 nb^{-1}	1.5 nb^{-1}	8.3	Slip Stacking
50/100ns	4.1	26	35	1.1 nb^{-1}	1.3 nb^{-1}	9.0	Batch Compression

THANK YOU
FOR YOUR ATTENTION

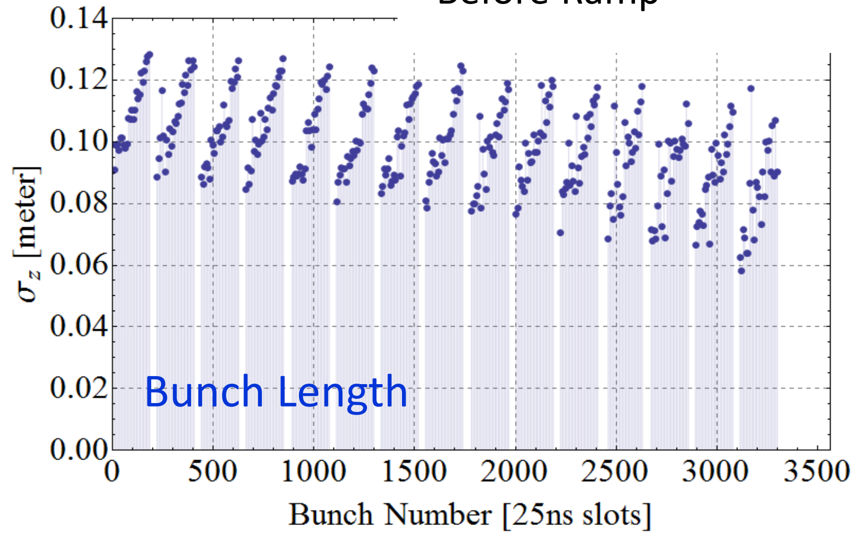
Design & Current Performance

	Collision (Design)	Injection (2011)	Collision (2011)	Injection (2013)	Collision (2013)
Beam Energy [Z GeV]	7000	450	3500	450	4000
No. Ions per bunch $[10^8]$	0.7	1.24 ± 0.30	1.20 ± 0.25	1.67 ± 0.29	$\mathbf{1.40 \pm 0.27}$
Transv. normalised emittance $[\mu\mathrm{m.rad}]$	1.5	---	1.7 ± 0.2	$\mathbf{1.3 \pm 0.2}$	---
RMS bunch length $[\mathrm{cm}]$	7.94	8.1 ± 1.4	9.8 ± 0.7	8.9 ± 0.2	9.8 ± 0.1
Peak Luminosity $[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1	---	$\mathbf{0.4 \pm 0.1}$	---	p-Pb

Bunch-by-Bunch Differences after Injection (450Z GeV)

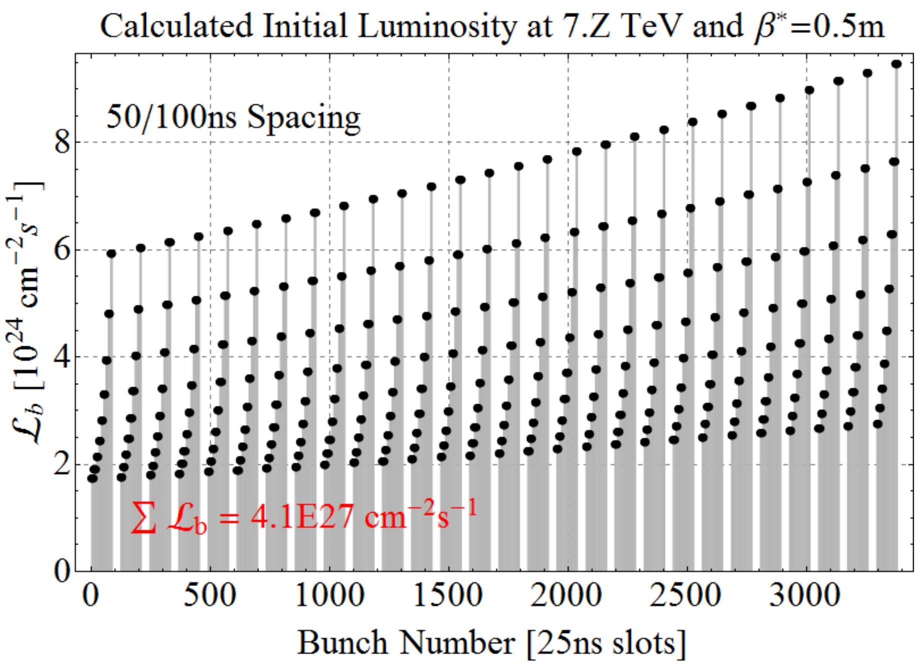


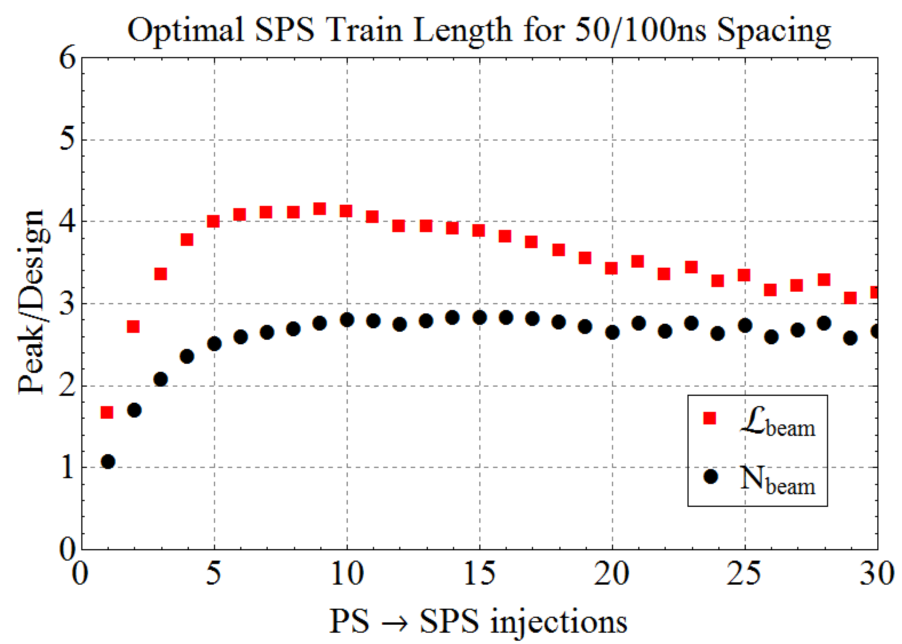
Before Ramp



50/100ns Scheme

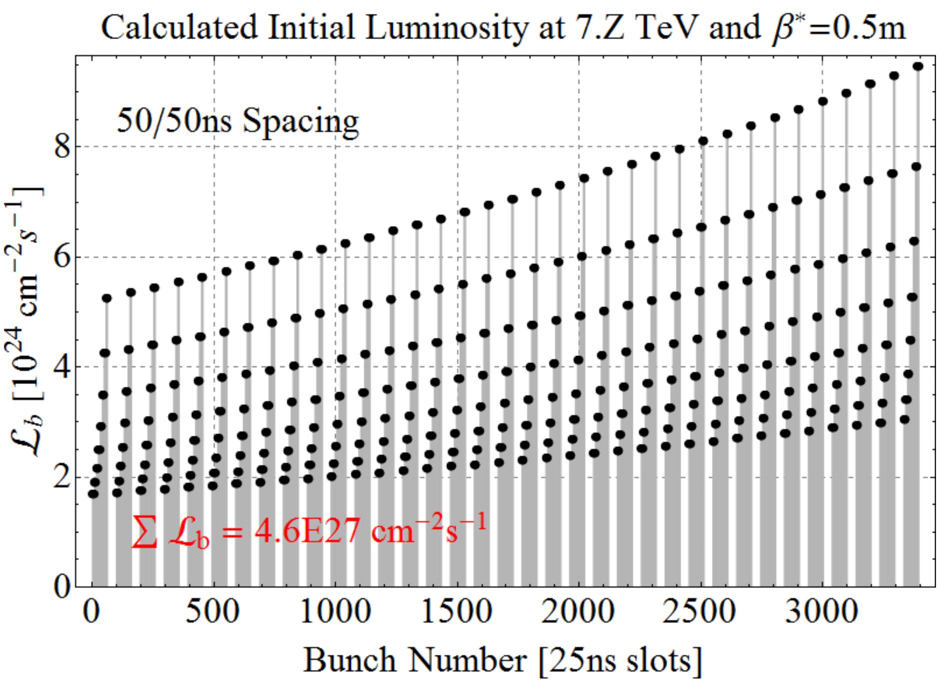
- 40% more out of LEIR
- Splitting into 4 Bunches /PS Batch
- Batch compression to 50ns

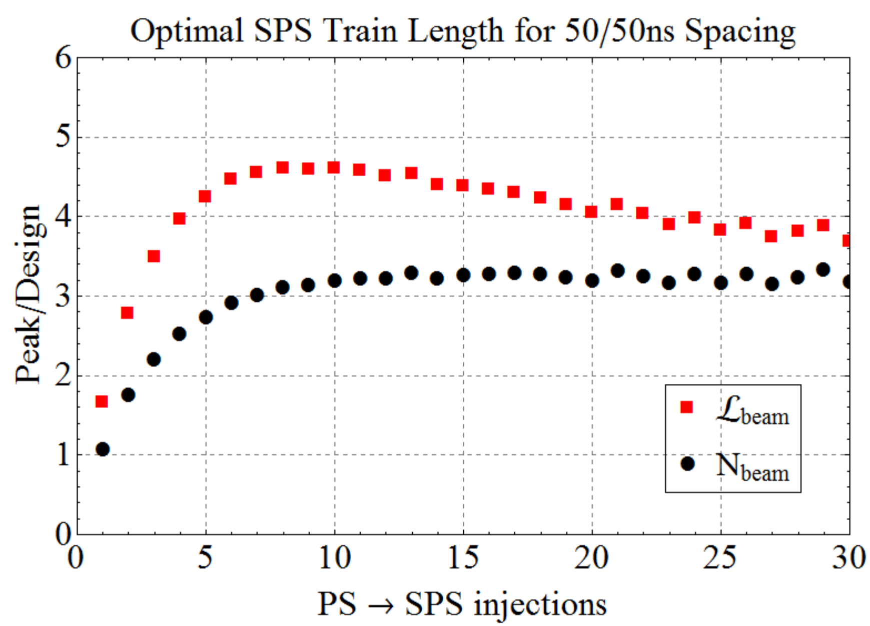




50/50ns Scheme

- 40% more out of LEIR
- Splitting into 4 Bunches /PS Batch spaced by 100ns
- Slip stacking in the SPS





Estimates for after LS2