Nuclear Beams at HL-LHC

Plans, requirements, solutions

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Thanks for input to:

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Physics Programme

- ***Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.***

- Pattern of 1 month heavy-ion run at the end of each year will continue through HL-LHC period.
- ALICE, ATLAS, CMS for full programme
- LHCb joins for p-Pb

Outline

- Pb-Pb and p-Pb collisions
  - LHC has already entered a high burn-off, high IBS, regime
  - Luminosity levelling will be required after LS1
  - Foretaste of p-p operation several years later after LS3
- Run 2 will already exceed design performance
- Future high-luminosity heavy ion operation of LHC depends on a somewhat different set of (more modest) upgrades to LHC and its injectors from p-p.
- The high-luminosity phase of the heavy-ion programme will start sooner, in Run 3, when necessary upgrades to detectors should be completed.
- It follows that the upgrades for HI operation need high priority in LS2
- How to make *really small* colliding beams

Design Baseline and Performance Achieved

"p-Pb not part of baseline"

	Pb-Pb				p-Pb	
	Baseline	Injection 2011	Collision 2011	Injection 2013	physics case paper	2013
Beam Energy [Z GeV]	7000	450	3500	450	7000	4000
No. Ions per bunch $[10^8]$	0.7	1.24 ± 0.30	1.20 ± 0.25	1.67 ± 0.29	0.7	$\mathbf{1.40 \pm 0.27}$
Transv. normalised emittance $[\mu m. \mathrm{rad}]$	1.5	---	1.7 ± 0.2	$\mathbf{1.3 \pm 0.2}$	1.5	---
RMS bunch length $[\mathrm{cm}]$	7.94	8.1 ± 1.4	9.8 ± 0.7	8.9 ± 0.2	7.94	9.8 ± 0.1
Peak Luminosity $[10^{27} \mathrm{cm}^{-2} \mathrm{s}^{-1}]$	1	---	$\mathbf{0.5}$	---	115	110

$= 2 \times$ design scaled with E^2

Future runs and species

Charges Z_1, Z_2 in rings with magnetic field set for protons of momentum p_p : colliding nucleon pairs have:

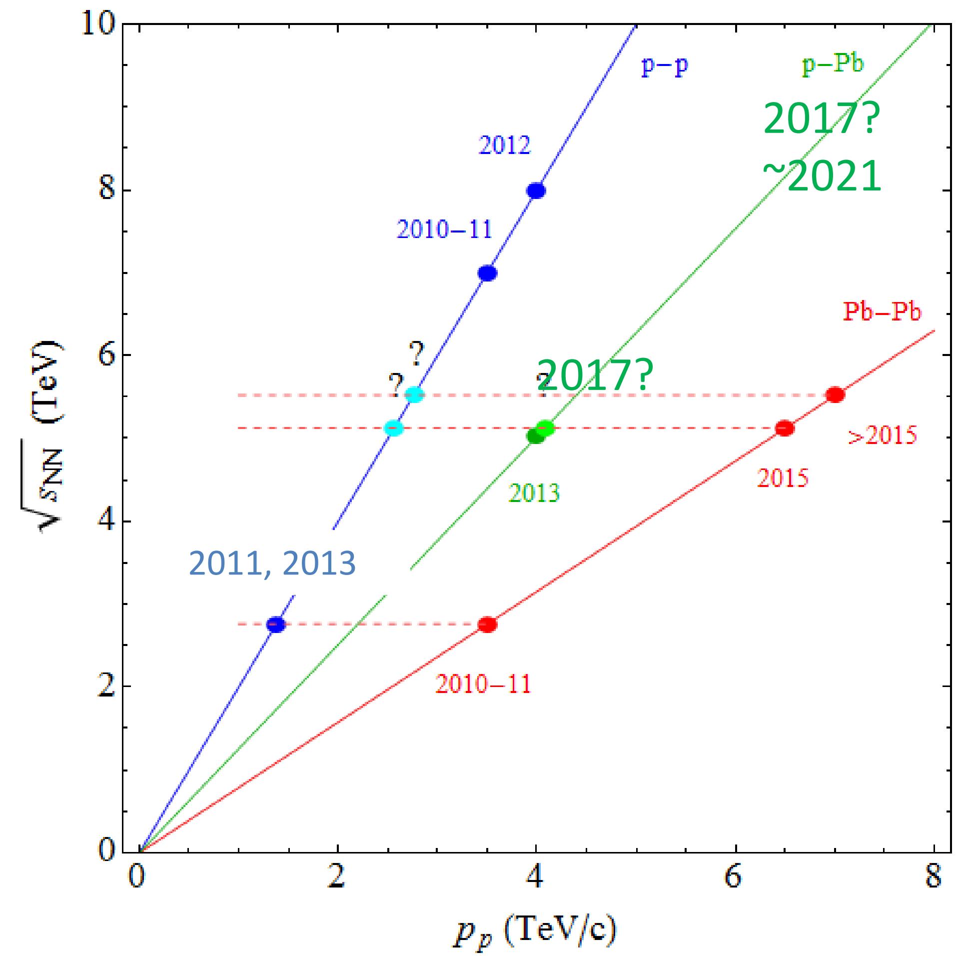
$$\sqrt{s_{NN}} \approx 2c\, p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}}, \qquad y_{NN} = \frac{1}{2}\log\frac{Z_1 A_2}{A_1 Z_2}$$

Mainly Pb-Pb operation with p-Pb roughly every 3rd year.

More efficient to do p-Pb at same p_p energy as preceding p-p but may need to lower it to an equivalent CM energy.

Reference data in p-p also required at equivalent CM energies, should ideally track integrated Pb-Pb luminosity.

Lighter species not considered for now.



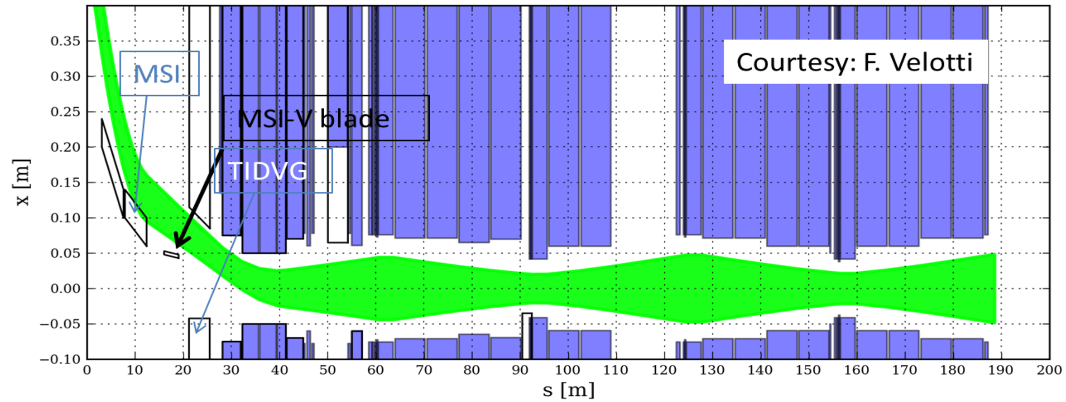
Possible injection schemes for Pb ions

- Reference: achieved performance of the ion injector chain
- Baseline upgrade scheme
  - 100ns batch compression in the PS
  - 100ns batch spacing into the SPS (kicker)
- Additional improvements, potential for 50 ns spacing in LHC
  - Intensity increases from source, Linac 3, LEIR
  - Splitting and/or additional batch compression in the PS
  - Momentum Slip Stacking in the SPS
- Expectations for 2015
  - Alternating 100ns/225ns

SPS injection system kicker upgrade 100 ns

Recent review https://indico.cern.ch/conferenceDisplay.py?confId=263338

- ❑ Install a faster pulser & switch on MKP-S system in parallel to the present one
- ❑ Supplement septum by new MSI-V

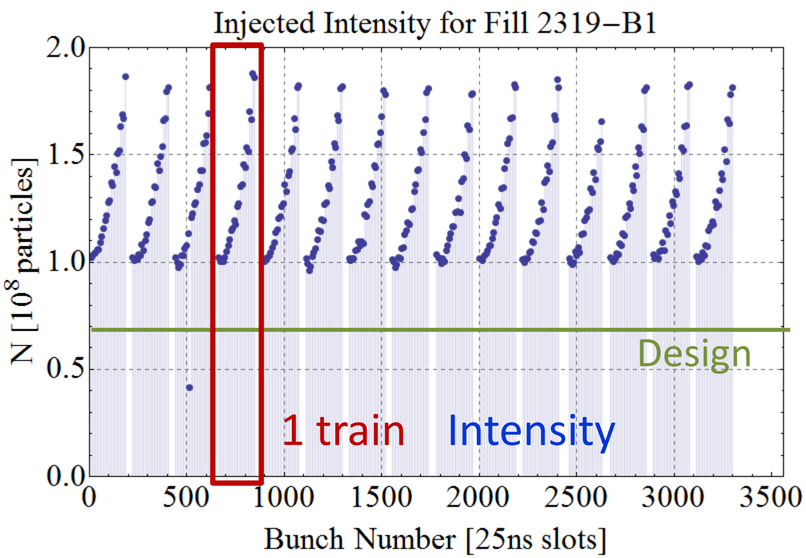


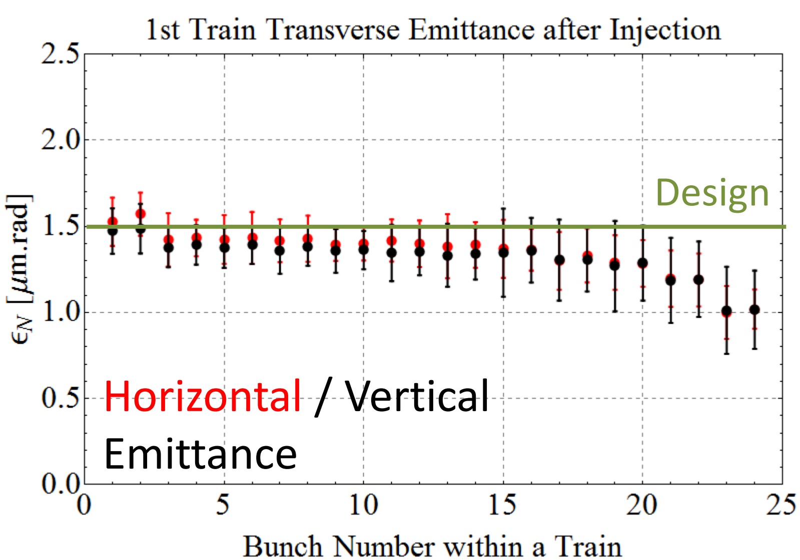
- No additional kicker magnets to be installed in the tunnel
- Maximum voltage of 40 kV
- Installation of MSI-V, recuperated from PSB recombination septa, one winter shutdown after LS2 (but spares can be used)
- With the MSI-V one can run at low voltages on the MKP-S and MSI-V, very comfortable, and no problems with Q20 optics
- Development time and lab tests needed

RUN 2 NUCLEUS-NUCLEUS PERFORMANCE PROJECTIONS

Bunch-by-Bunch Differences after Injection in the LHC

E = 450 Z GeV

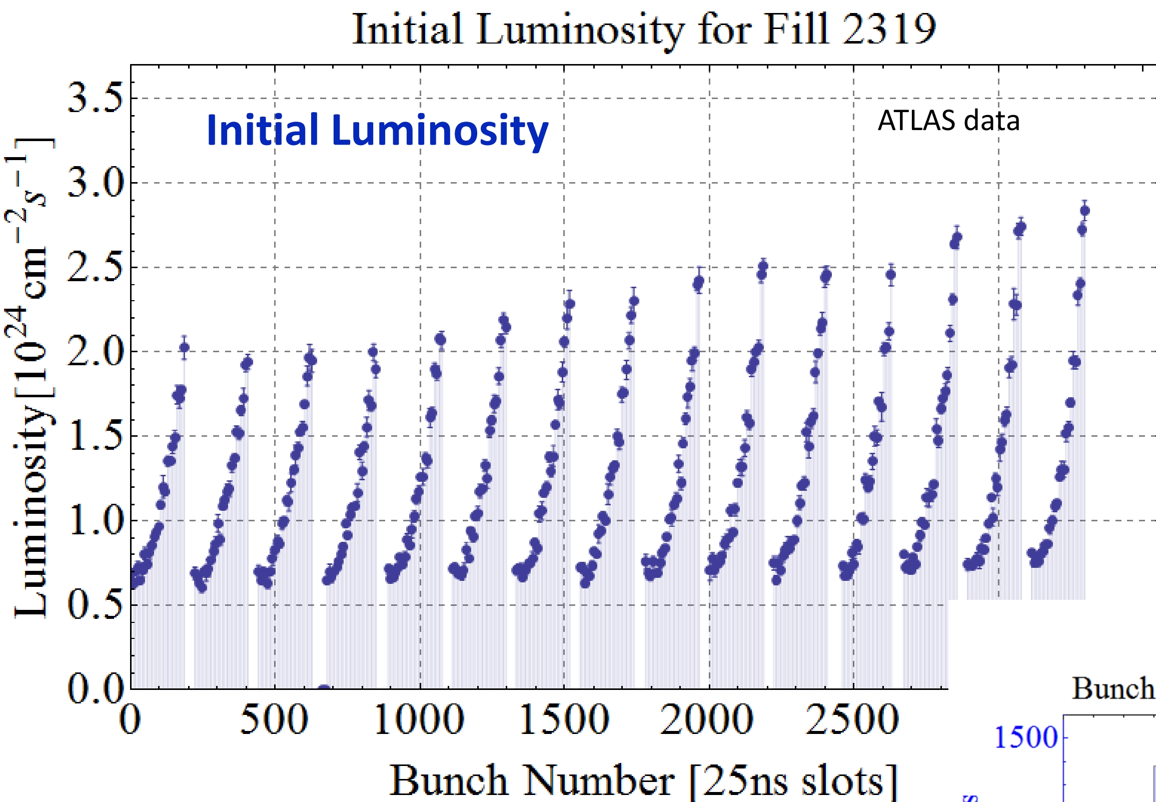


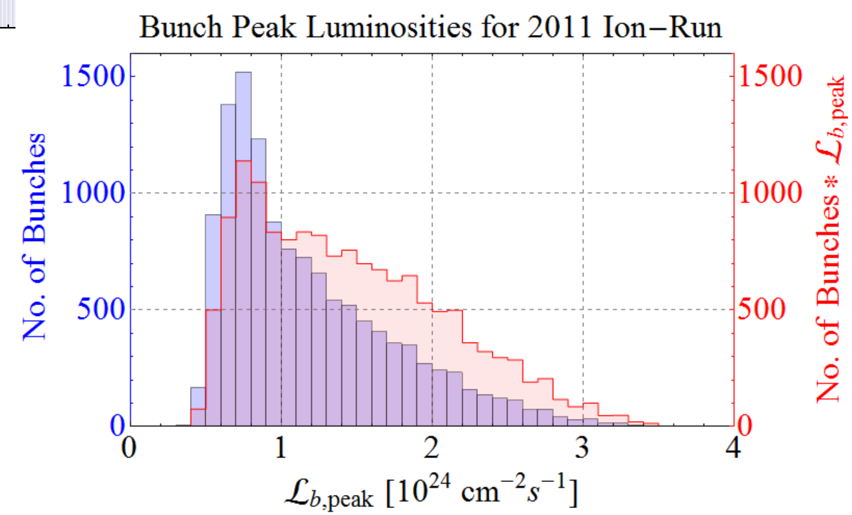


- Structure within a train (1st to last bunch):
  - increase: - intensity
    - bunch length
  - decrease: emittance.
- IBS, space charge, RF noise … at the injection plateau of the SPS:
  - while waiting for the 12 injections from the PS to construct a LHC train.
- First injections sit longer at low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

Bunch-by-Bunch Luminosity

E = 3.5Z TeV





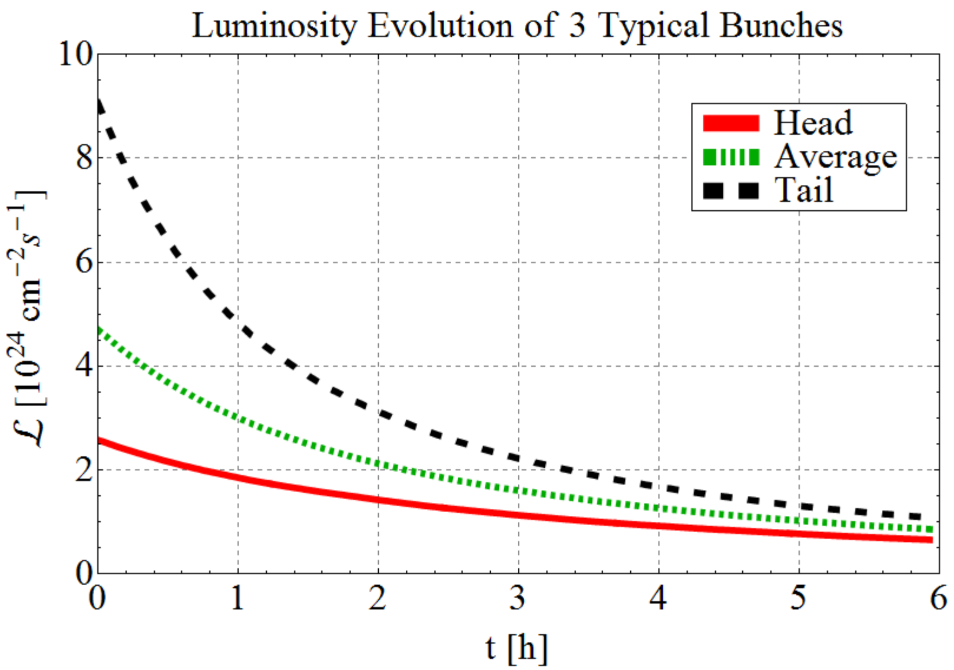
General features of Pb-Pb in Run 2 and HL-LHC

- Running 3 experiments at β^*=0.5 m (also for Run 3,…)
  - No ATS optics etc.
  - Generally, we should be able to take over most of ramp and squeeze from p-p run for fast commissioning
    - Additional squeeze and crossing angle configuration for ALICE
  - Usual run length each year
    - 2015 & 2016: Pb-Pb
    - 2017: p-Pb (with LHCb)
    - 2018: Pb-Pb

Spectrum of bunches in physics

In the following integrated luminosity estimates are made by summing over simulation results (CTE program) which includes effects of :

- Emittance growth and debunching from IBS (stronger for heavy ions) , model of non-gaussian longitudinal distribution
- Radiation damping (twice as strong for heavy ions)
- Luminosity burn-off (much stronger for heavy ions)

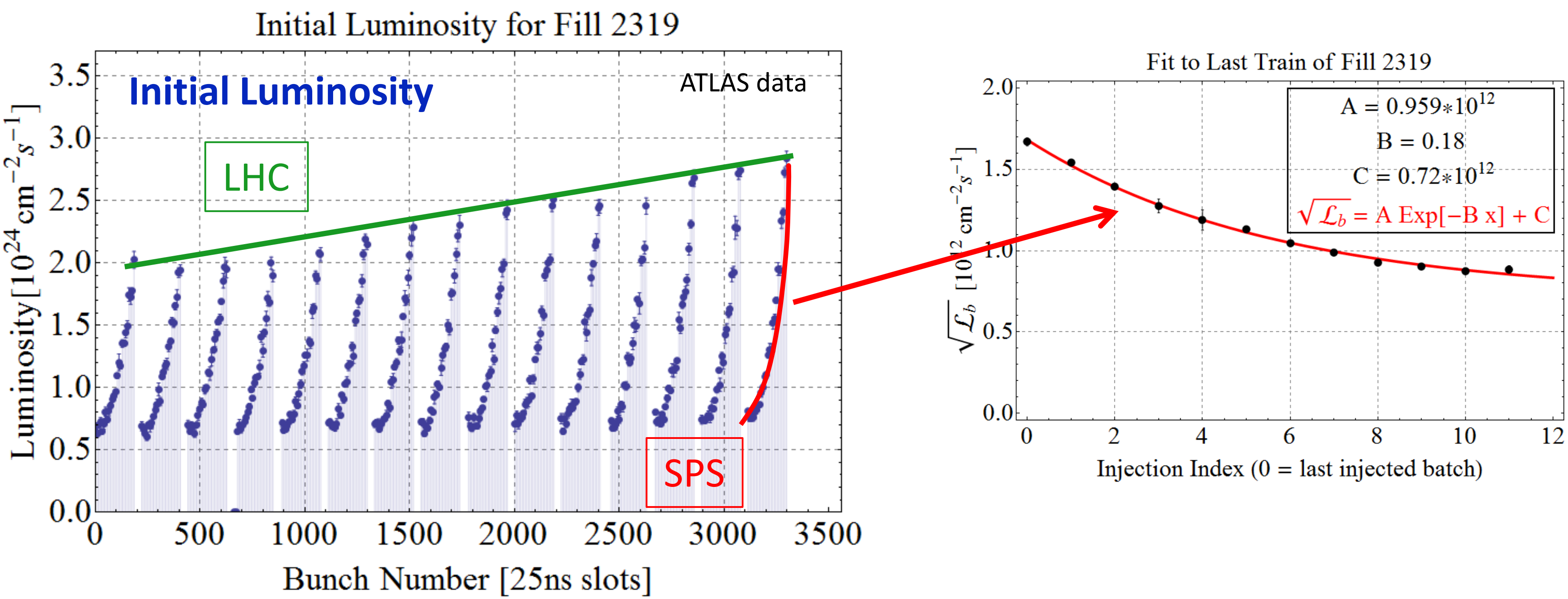


Spectrum of bunch intensities and emittances implies a spectrum of bunch luminosities and luminosity lifetimes.

Distribution over bunch train from phenomenological model based on ATLAS 2011 data – described in following slides.

Work by Michaela Schaumann

Bunch-by-Bunch Luminosity Model



SPS Effect:

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

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

LHC Effect:

→ Group bunches of equivalent PS batches from all trains, which saw the same SPS injection plateau length.

Fit to both effects:

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

Complete Parametrisation

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

Intensity scaling factor

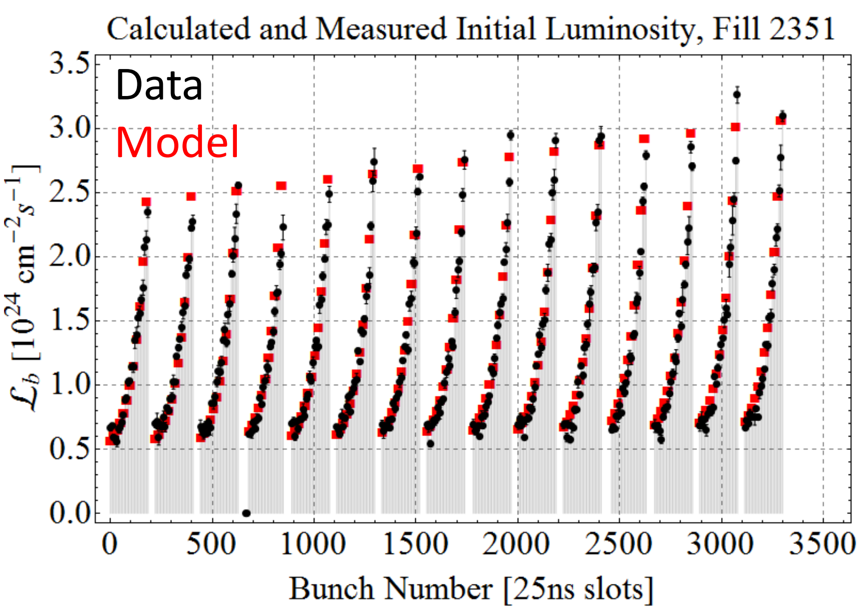
Normalisation factor

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

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

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

Average over all proper fills of 2011



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

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 labelled "*2013 performance*".

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

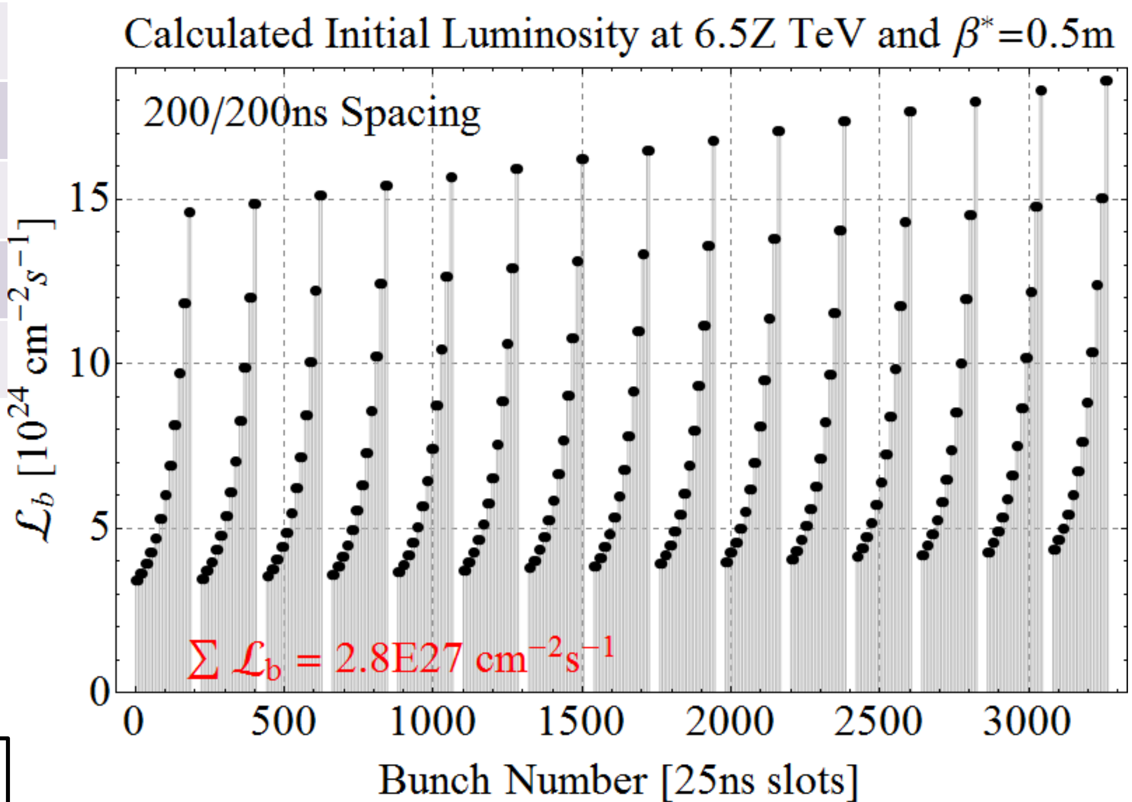
Estimates for after LS1 – 2011 Scheme, scaled N_b

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

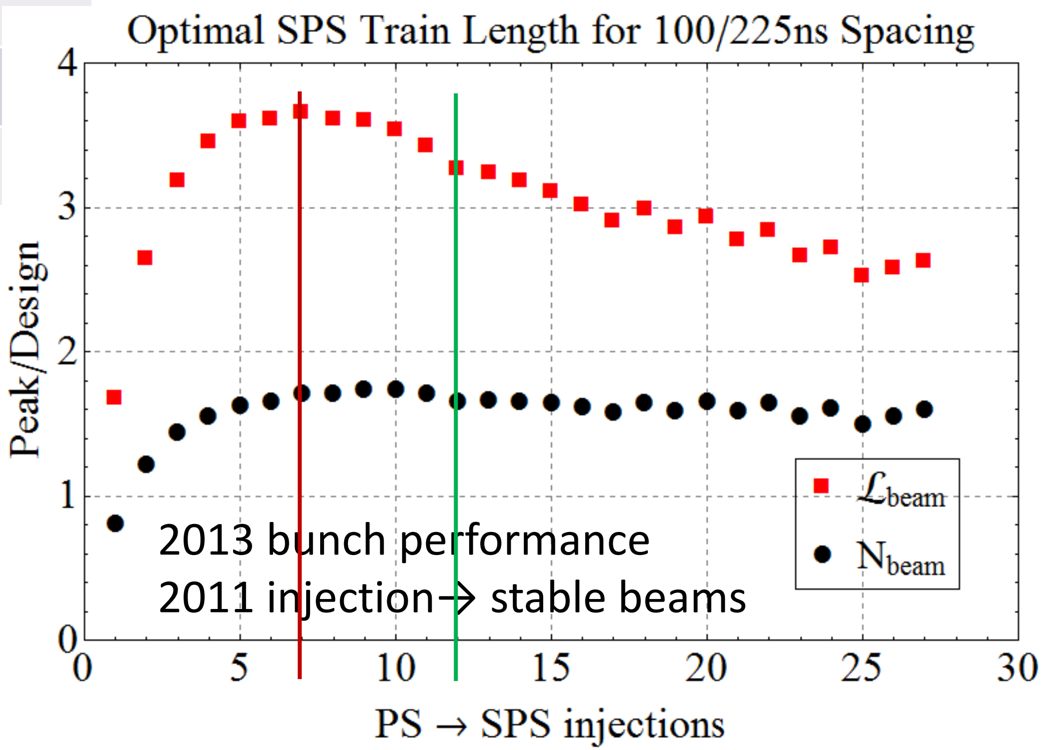
max. Luminosity

max. Intensity

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.



Max. peak luminosity:

$L = 3.7 \times 10^{27} cm^{-2} s^{-2}$

With 2011 like scheme:

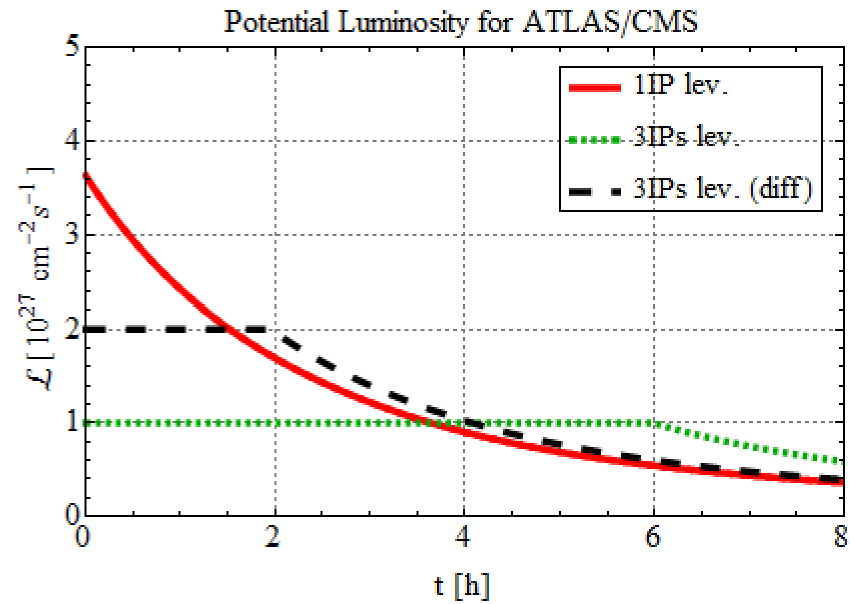
$L = 3.3 \times 10^{27} cm^{-2} s^{-2}$

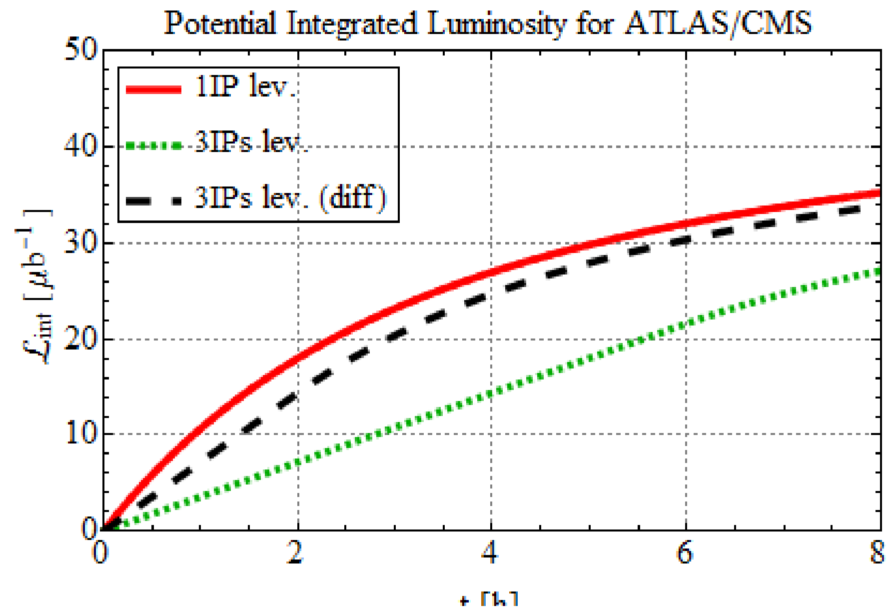
→ 30% improvement by optimising the filling scheme compared to 2011 scheme.

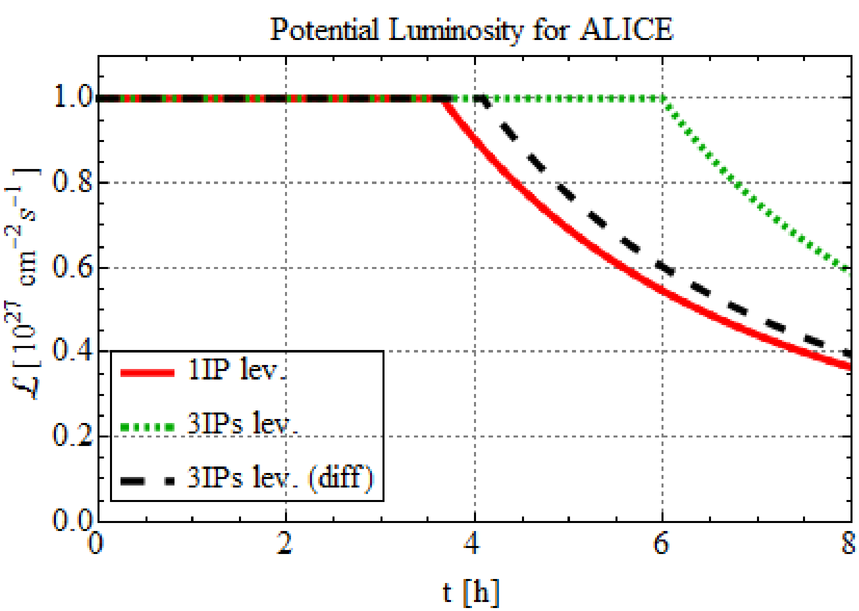
Levelling in Run 2

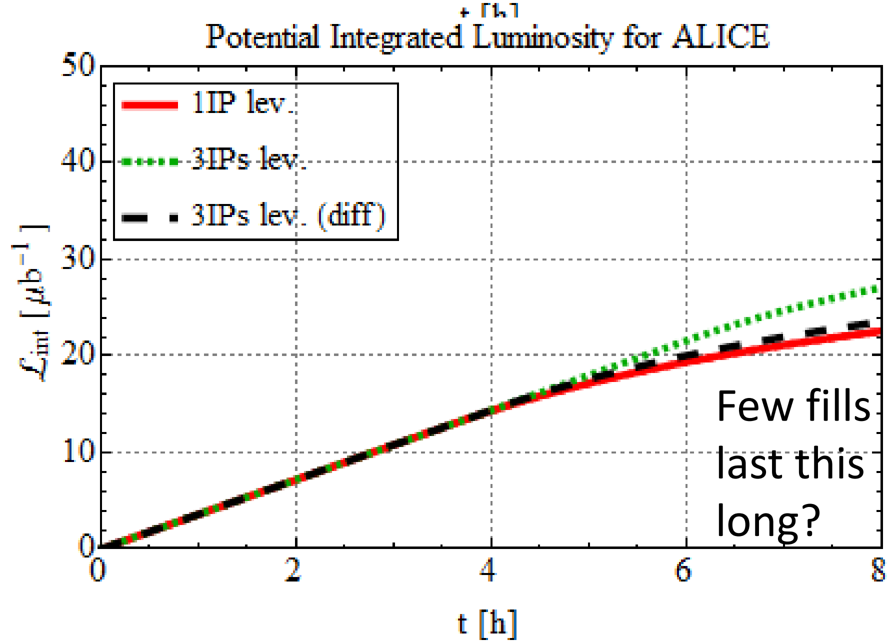
- Before the upgrade (LS2), ALICE luminosity must be levelled at $L = 1 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1}$
- ATLAS and CMS are not limited in peak *L.*
- Luminosity decay dominated by burn-off: largely a conversion of stored beam particles to events.
- Compare 3 possibilities
  - Levelling only in ALICE
  - Levelling all experiments to $L = 1 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1}$
  - Levelling ATLAS, CMS at $L = 2 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1}$

Comparison of levelling scenarios for Run 2









Remarks on levelling

- Some of the initial very high luminosity likely to be lost anyway during collision setup time (> 10 min)
  - Favours some level of levelling for all experiments – very similar to future high luminosity p-p
- Experience in 2013 p-Pb run was similar because of initial minimum-bias operation of ALICE
  - Solution was 2 catch-up fills with beam separated in ATLAS and CMS – this remains an option
- Optimum also depends on real turn-around times
- Levelling can be done by standard separation method (or β^*)

RUN 3 & BEYOND, NUCLEUS-NUCLEUS PERFORMANCE PROJECTIONS

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**	1. **Slip stacking** with split bunches

Estimates for after LS2 – 100/100ns Baseline Scheme

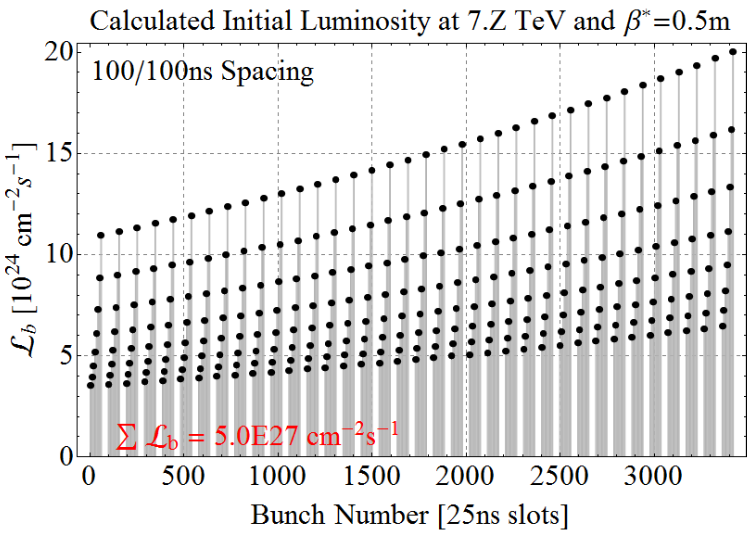
50/50ns Scheme PS Bunch Splitting	@ E = 7Z TeV β^*= 0.5m F_{Nb} = 1.28
Spacing PS [ns]	100
Spacing SPS [ns]	100
No. bunches/PS batch	2
No. PS batches/train	8
No. LHC trains	36
No. bunches/beam	576

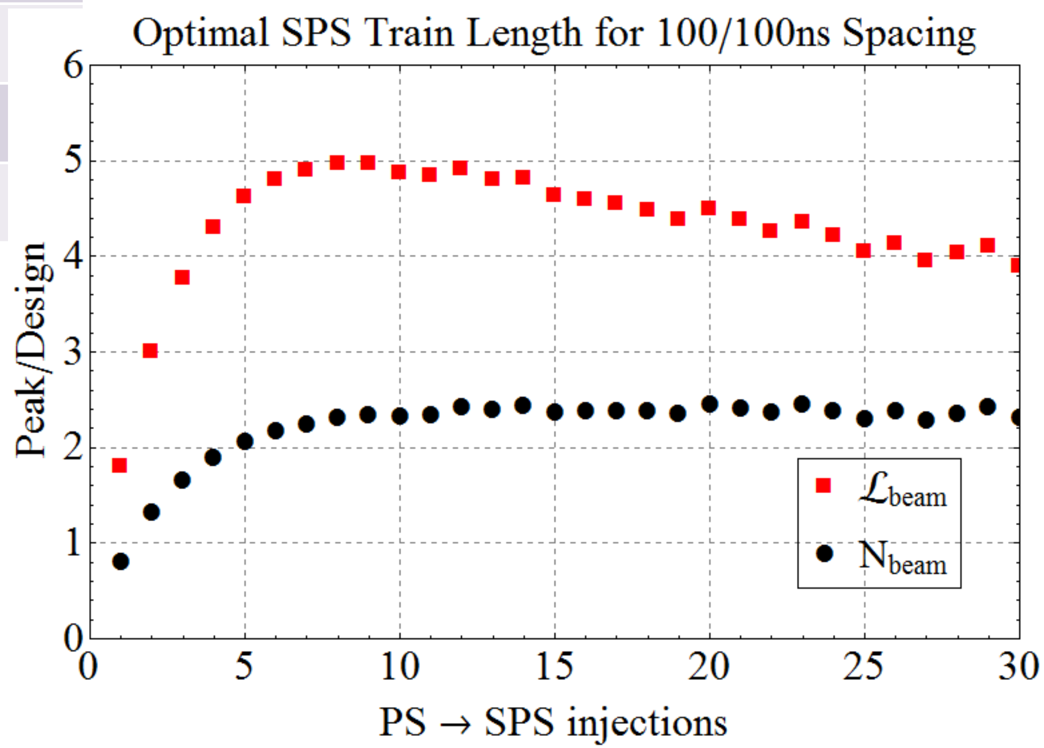
With 2013 transmission from Inj. to SB:

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

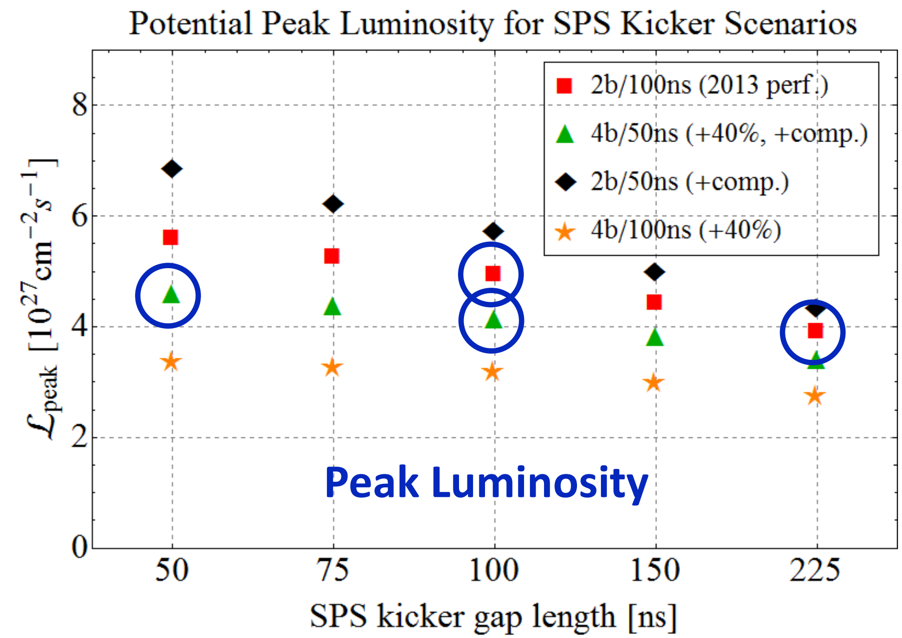
With 2011 transmission from Inj. to SB:

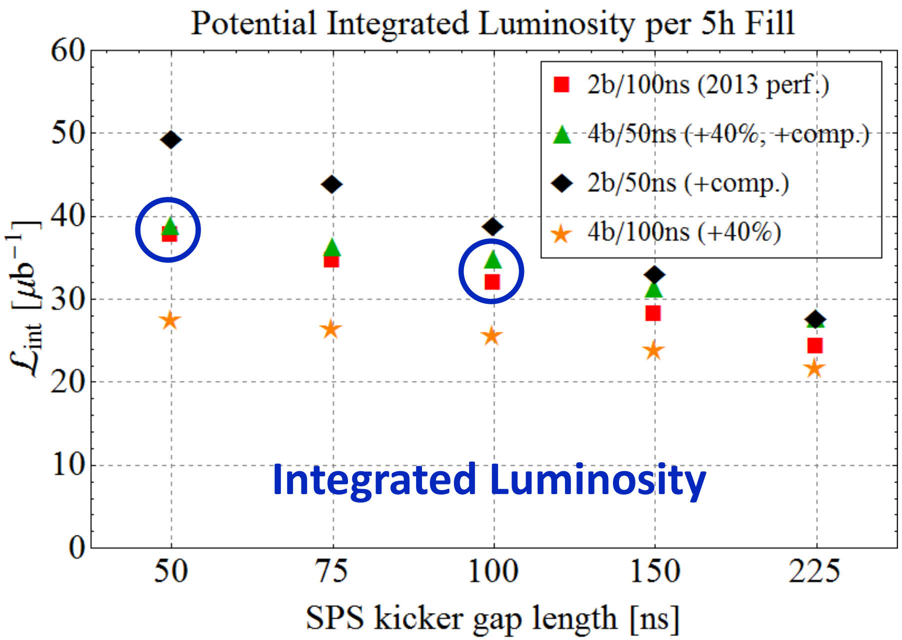
$$L_{peak} = 5 \times 10^{27}\,\mathrm{cm^{-2}s^{-2}}$$





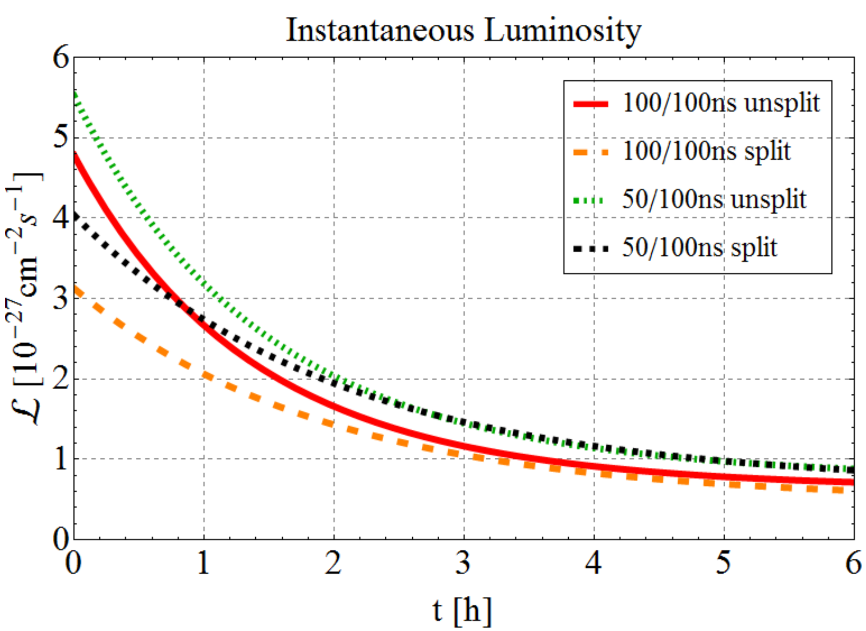
Estimates for after LS2





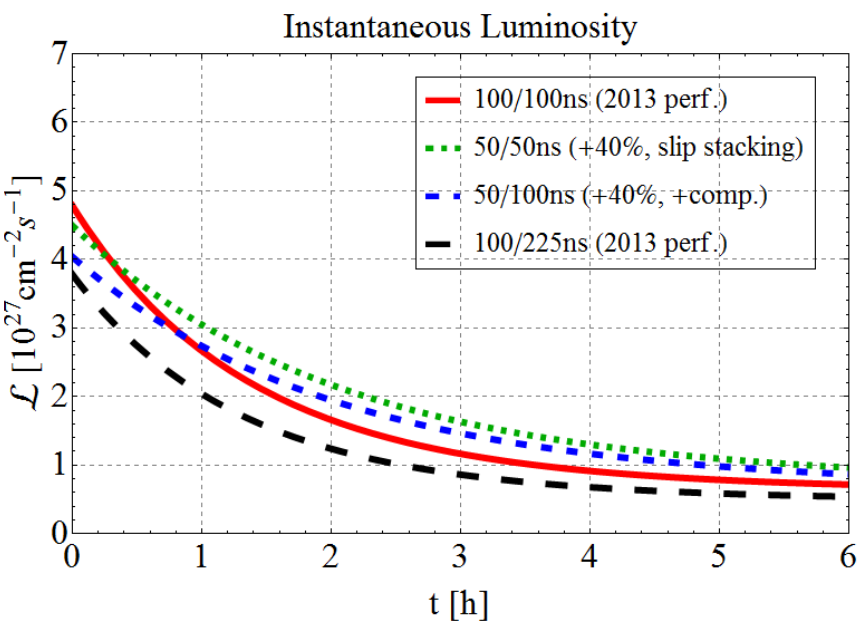
Peak luminosity higher for 100ns PS spacing with unsplit bunches.
→ Higher brightness bunches decay faster.
→ Higher integrated luminosity for 50ns PS spacing with split bunches.

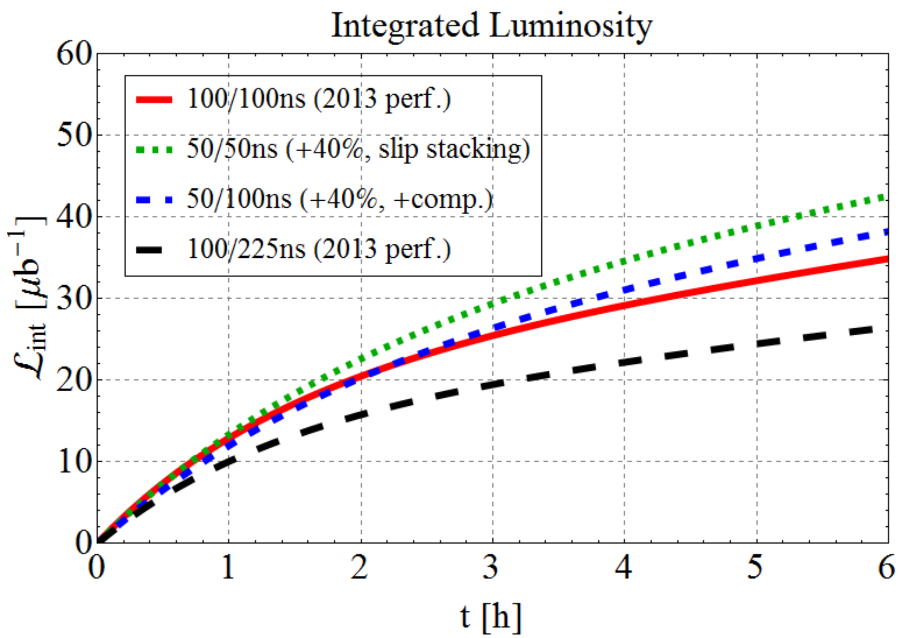
50/100ns split → ~1000 bunches/beam
100/100ns unsplit → ~600 bunches/beam



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

Luminosity projection summary

- Does not include any improvements beyond injection schemes and natural change of β*=0.5 m and beam size at 7 Z TeV. Some will be mentioned on next slide.
- Model will be re-fitted to real injector chain performance in the run-up to a given Pb-Pb run to re-optimise the length of the SPS trains. Improvements on SPS flat bottom can have a big impact.

Scenario	L_{peak} [Hz/mb]	L_{int} after 3h $[\mu b^{-1}]$	L_{int} after 5h $[\mu b^{-1}]$	L_{int} in run with 30×5h	$L_{int,run}$ naïve "Hubner Factor"	
200/200ns	2	15	21	$0.64\ nb^{-1}$	$0.64 nb^{-1}$	2011 @ 7Z TeV
100/225ns	3.7	19	25	$0.8\ nb^{-1}$	$1.2\ nb^{-1}$	Run 2
100/100ns	5.0	25	32	$1.0\ nb^{-1}$	$1.6\ nb^{-1}$	**Baseline**
50/50ns	4.6	29	39	$1.2\ nb^{-1}$	$1.5\ nb^{-1}$	Slip Stacking
50/100ns	4.1	26	35	$1.1\ nb^{-1}$	$1.3\ nb^{-1}$	Batch Compression

Caveats and anti-caveats on luminosity projections

- Assumed no peak luminosity limit
  - May have to level ATLAS, CMS with no DS collimators (but see later)
  - Integrated luminosity estimates are always very sensitive to a few days down-time in a 24 day run (so far we have been fairly lucky …)
  - No time deducted for possible p-p reference data runs
- Assumed no improvements beyond injection schemes
  - 200 MHz RF system in LHC potentially very beneficial for heavy ions (reduce IBS, better injection capture, …)
  - Greater operational efficiency than 2011 would help, obviously
  - Some possibilities later in this talk

RUN 2 PROTON-NUCLEUS PERFORMANCE PROJECTIONS

CERN

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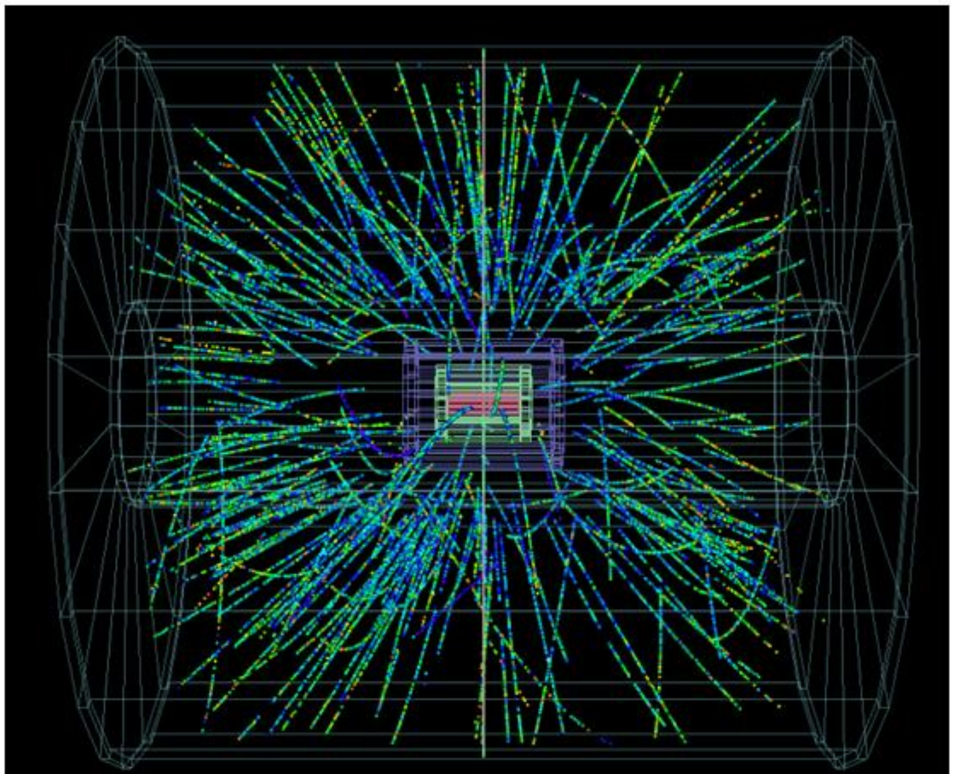
LHC collides protons with lead ions for the first time

Cian O'Luanaigh



A proton collides with a lead nucleus, sending a shower of particles through the ALICE detector. The ATLAS, CMS and LHCb experiments also recorded collisions (Image: ALICE/CERN)

feedback

Single pilot fill, night of 13-14 September 2012

Injection and ramp of p and Pb beams with unequal revolution frequencies.
RF frequencies locked, collision points moved to experiments.

Setup of collimation, declaration of Stable Beams with unsqueezed optics.

4 hours physics, 2 more hours with IPs displaced by +- 0.5 m.

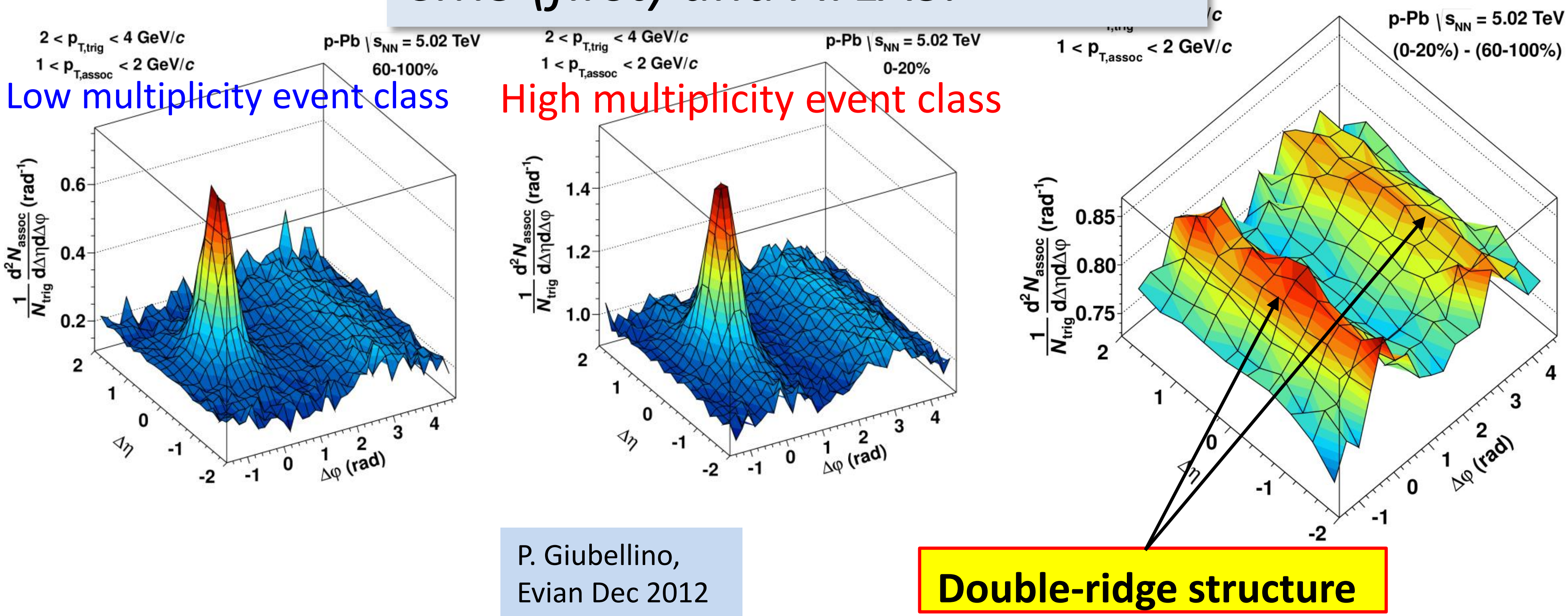
Largest increase of centre-of-mass energy in history of accelerators.

+ *unexpected physics discoveries*

Correlations in pA: subtracting low-mult from the high-mult…

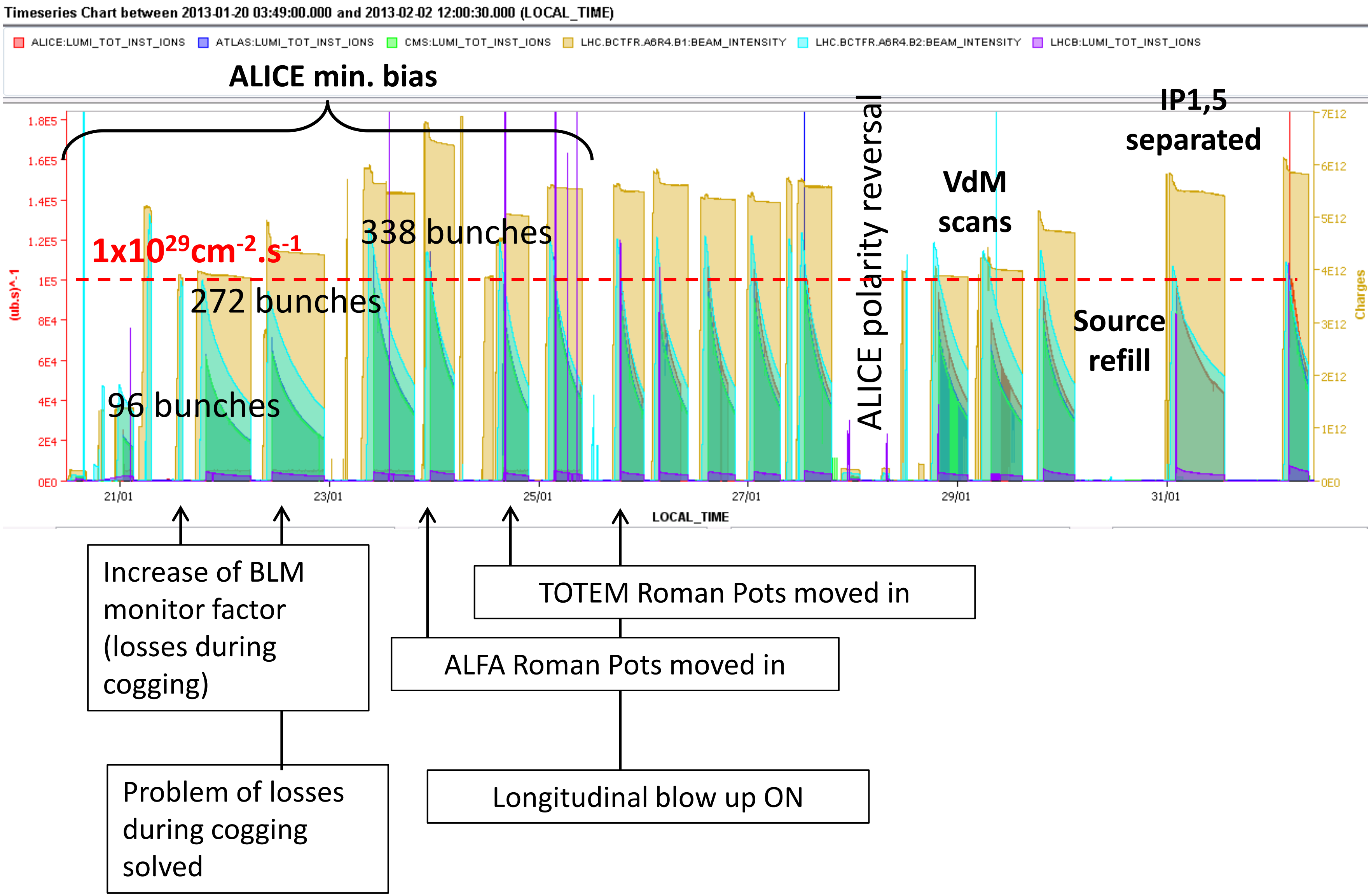
- A double-ridge structure appears, with remarkable properties:
  - Can be expressed in terms of $v_{2,3}$, Fourier coefficients of single particle azimuthal distribution, with $\mathbf{V}_{2,3}$ increasing with p_T and v_2 also with multiplicity
  - **Same yield near and away side for all classes of p_T and multiplicity: suggest common underlying process**
  - Width independent of yield
  - No suppression of away side observed (its observation at similar x-values at RHIC is considered a sig
  - In agreement wi

Similar results published by CMS (first) and ATLAS.



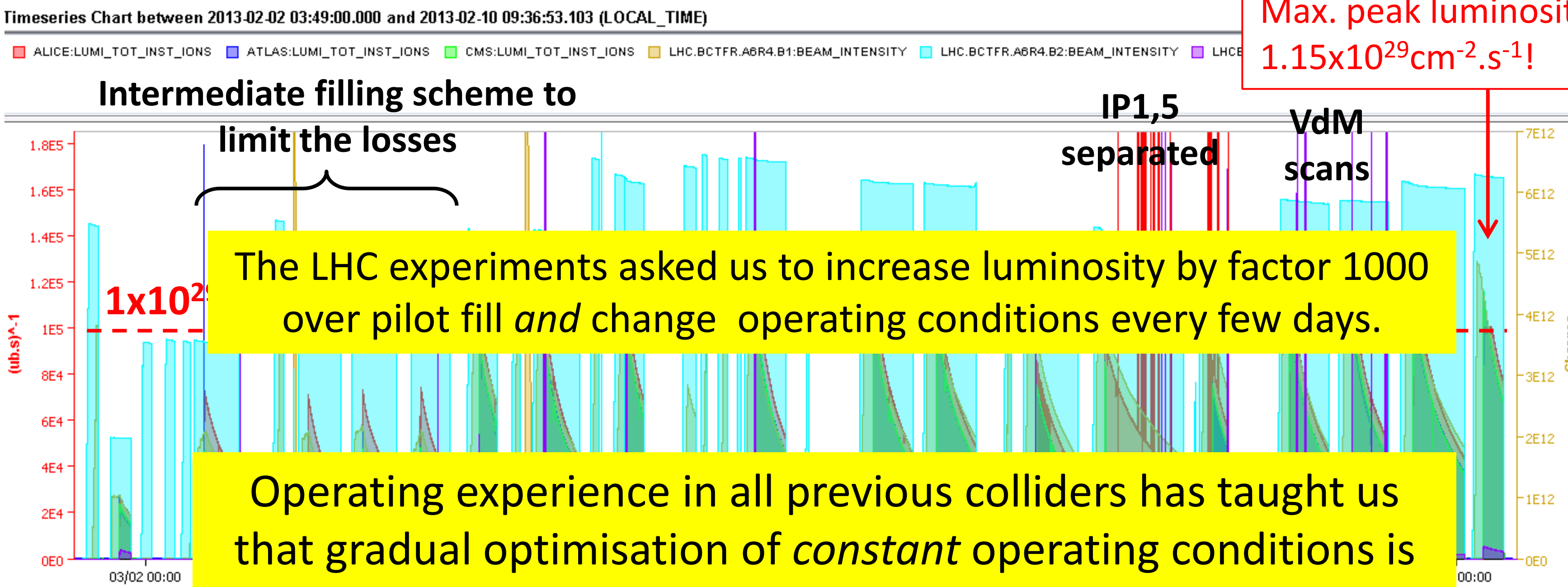
P. Giubellino, Evian Dec 2012

Reminder: p-Pb luminosity production in 2013



R. Versteegen

Reminder: Pb-p luminosity production in 2013



Max. peak luminosity 1.15×10^{29} cm^{-2}.s^{-1}!

The LHC experiments asked us to increase luminosity by factor 1000 over pilot fill *and* change operating conditions every few days.

Operating experience in all previous colliders has taught us that gradual optimisation of *constant* operating conditions is the path to high luminosity.

Increase of BLM monitor factor (losses end of ramp + squeeze)

Increase bandwidth of orbit feedback

…sses at the start of the ramp), rematch injection energy to the SPS

Co… tri…

Nevertheless we fulfilled all requests, thanks to the quality of the LHC, meticulous planning and some judicious risk-taking (with performance, I hasten to add).

So we do not need to fear "complicated" physics requests.

…es

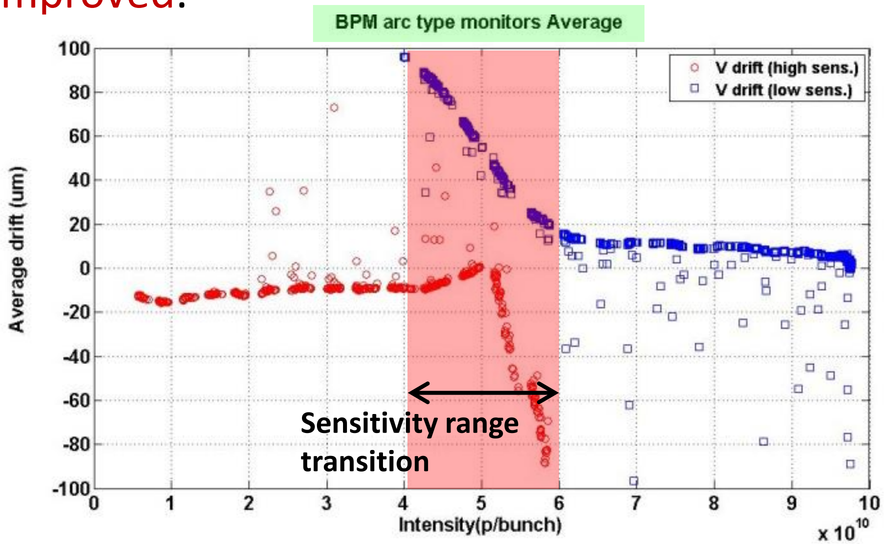
Bunch by bunch intensity ranges for p-Pb operation

- **Low intensity Pb-bunches:**

The monitors of IR6 interlock BPMSs are being replaced by matched terminated striplines so that high attenuation (used to reduce reflections in p beams in 2013 run) will not be needed. It will require tests with beams but low intensity Pb-bunches should not trigger the beam dump anymore.

- **Increasing p-bunch intensity:**

Max. in 2013 was 1.8 10^{10} p/bunch. A test with 3 10^{10} p/bunch showed misreading of a few BPMs, which source is still under investigation. If manageable (change of a few cards, or recalibration?), we could go up to ~5 10^{10} p/bunch (high sensitivity limit).
But tests with beam most probably required to clarify the observation. It is not obvious that the situation can be improved.



E. Calvo Giraldo, *et al.*, DIPAC2011, TUPD12

Performance for p-Pb in Run 2

E (Z GeV/c)	4	7
γ_p	4264	7463
N_p (10^{10} protons/bunch)	1.8–5?	1.8–5?
N_{Pb} (10^8 ions/bunch)	1.6	1.6
n_b	430	430
β^* (m)	0.5	0.5
$\varepsilon_{n,p}$ (µm.rad)	3.5	3.5
$\varepsilon_{n,Pb}$ (µm.rad)	1.5	1.5
f (kHz)	11.245	11.245
L_{peak} (10^{29} $cm^{-2}.s^{-1}$)	**2.5–7?**	**4.3–12**
L_{int} (nb^{-1})	**60 (up to 180?)**	**110 (up to 300?)**

- Increasing the proton intensity is constrained by Pb stability (moving long range encounters), and arc BPMs capabilities (still uncertain),
- 5 10^{10} p/bunch is the maximum reachable in any case,
- Number of bunches per beam is taken from “baseline scenario” for Pb-Pb run in 2015-2016,
- Integrated luminosity assumes same integrated over peak luminosity ratio as in 2013.
- ALICE will level at ~10^{28} and 10^{29} $cm^{-2}s^{-1}$ in Run 2

Performance for p-Pb in Run 2 and beyond

- A run at the same energy as preceding p-p will be more efficient in several ways (less setup time, smaller momentum shifts, …) than a run at reduced energy
- p-Pb runs are complicated, many changes of configuration, higher risk …
- Hope to increase LHCb luminosity in Run 2 and possible adjustments of filling scheme
  - Possibility of $\beta^* = 0.5\text{-}1\ \mathrm{m}$ to be confirmed.
- Further increases of p-Pb luminosity in Run 3 and beyond depend mainly on more bunches but other limits (eg BFPP) will come into play

PEAK LUMINOSITY LIMITS

Electromagnetic processes in Pb-Pb collisions

$$\text{BFPP1: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{81+} + e^{+},$$

$$\sigma = 281\ \text{b}, \quad \delta = 0.01235$$

$$\text{BFPP2: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{80+} + 2e^{+},$$

$$\sigma \approx 6\ \text{mb}, \quad \delta = 0.02500$$

$$\text{EMD1: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{207}\text{Pb}^{82+} + n\ ,$$

$$\sigma = 96\ \text{b}, \quad \delta = -0.00485$$

$$\text{EMD2: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{206}\text{Pb}^{82+} + 2n\ ,$$

$$\sigma = 29\ \text{b}, \quad \delta = -0.00970$$

Each of these makes a secondary beam emerging from the IP with rigidity change

$$\delta = \frac{1 + \Delta m / m_{\text{Pb}}}{1 + \Delta Q / Q} - 1$$

Hadronic cross section is 8 b (so much less power in debris).

Discussed since Chamonix 2003 …

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS
12, 071002 (2009)

Beam losses from ultraperipheral nuclear collisions between $^{208}Pb^{82+}$ ions in the Large Hadron Collider and their alleviation

R. Bruce,[1,*] D. Bocian,[2,1,†] S. Gilardoni,[1] and J. M. Jowett[1]
[1]*CERN, Geneva, Switzerland*
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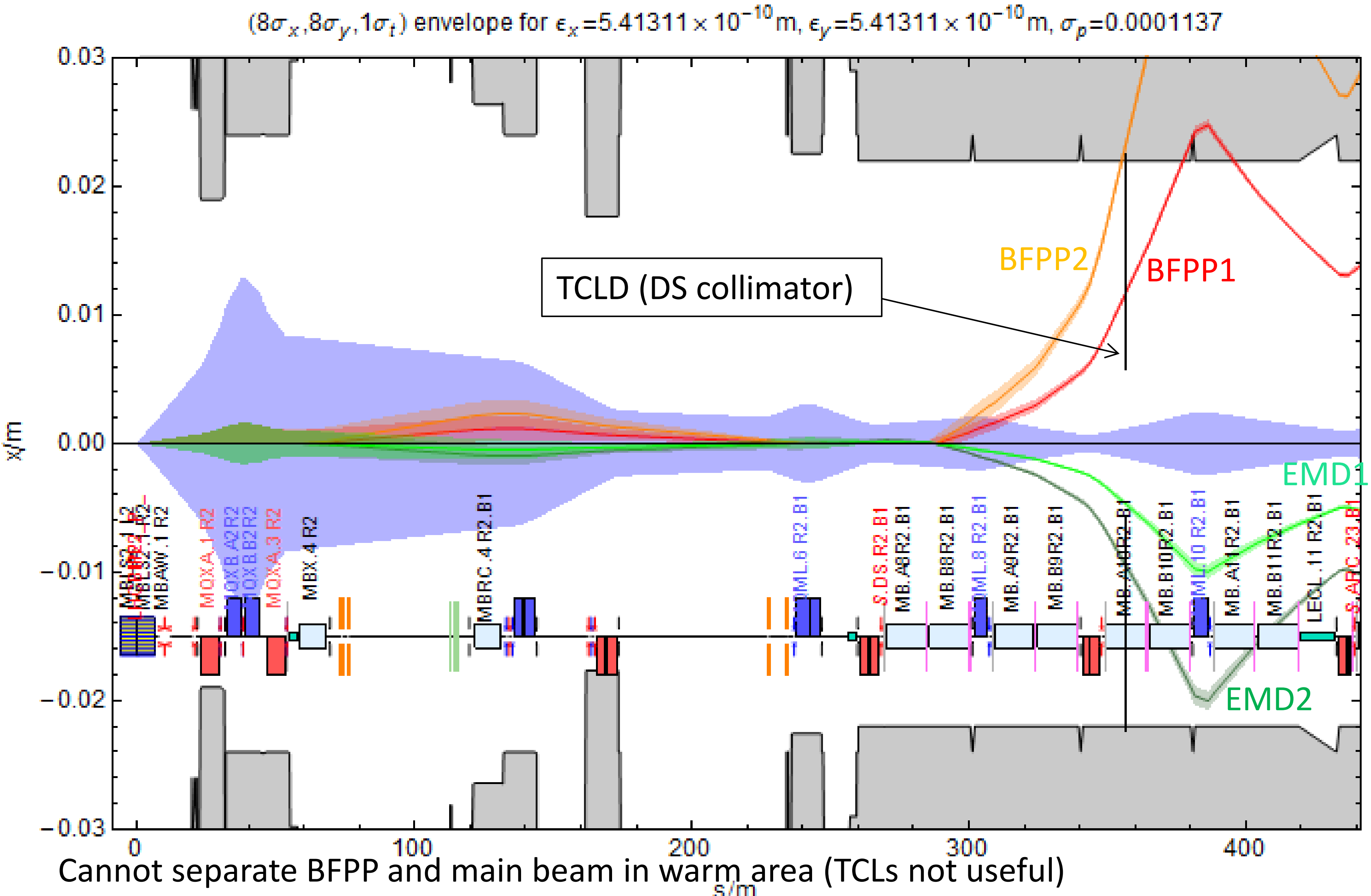
(Received 13 May 2009; published 29 July 2009)

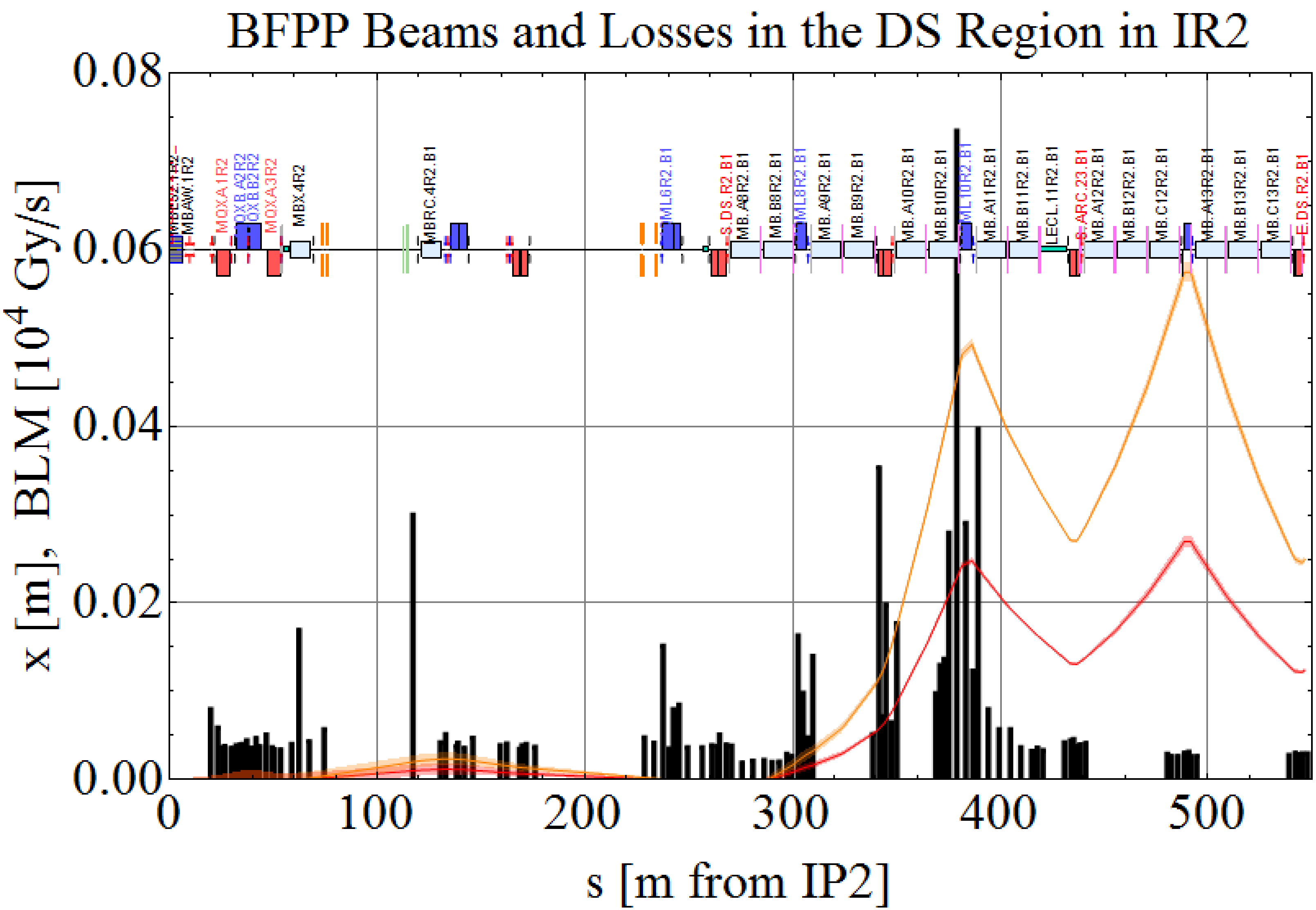
Secondary beams from Beam 1 in IR2



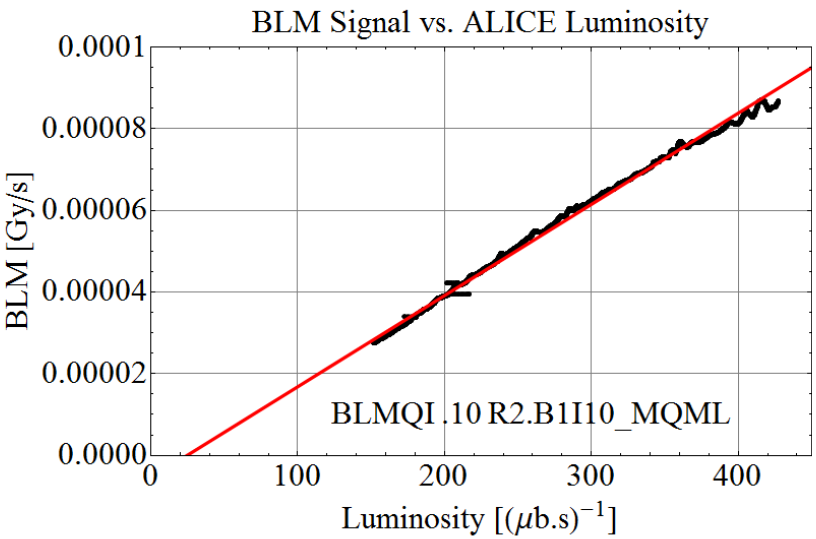
Cannot separate BFPP and main beam in warm area (TCLs not useful)

BFPP beam is smaller than main beam (source is luminous region).

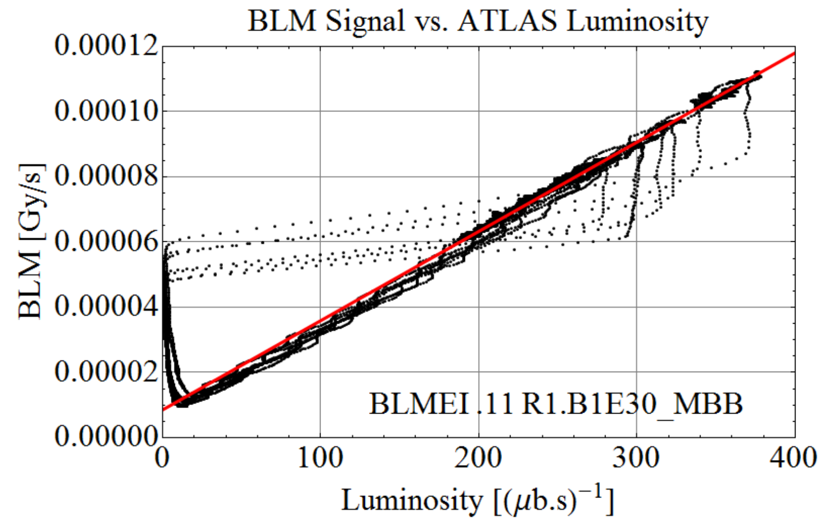
2011 Pb-Pb operation



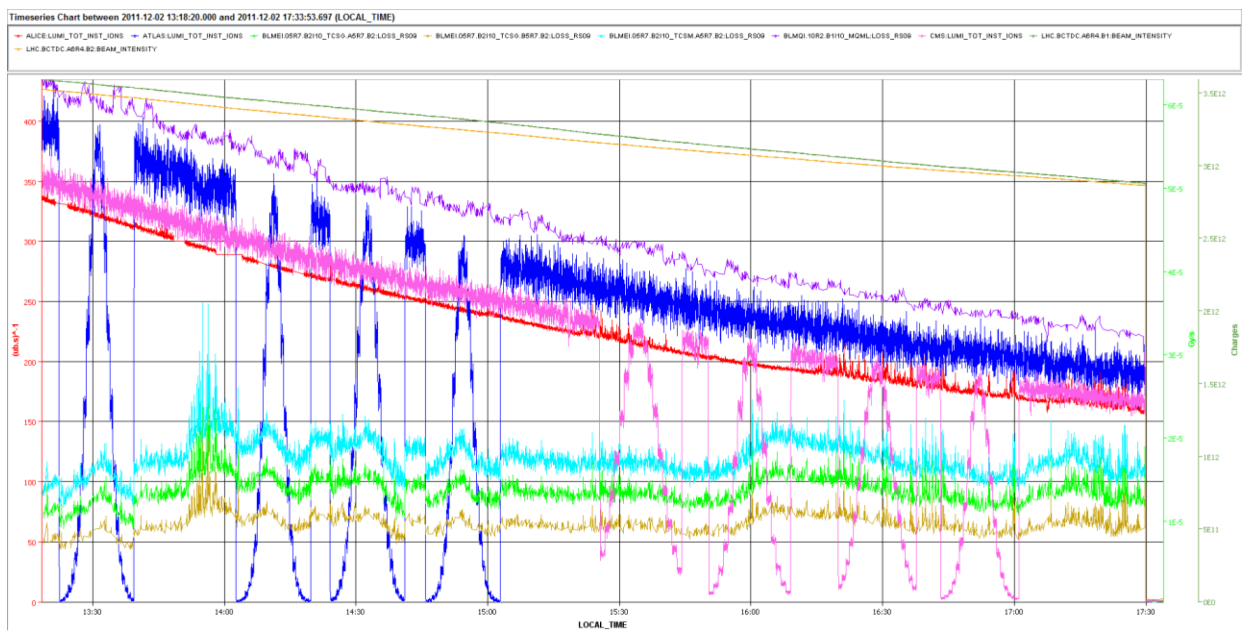
Main losses in DS are due to luminosity



Regular physics fill



From van der Meer scans



HL-LHC Performance Goals for Pb-Pb collisions

With upgrade of Pb injectors, etc, indicative parameter goals:

ALICE upgrade integrated luminosity goal for post-2018 period

$\int L\,dt = 10\ \mathrm{nb}^{-1}$ $=10\times$(first phase)

equivalent to $\int L_{NN}\,dt = 0.43\ \mathrm{fb}^{-1}$ nucleon-nucleon luminosity.

Annual integrated luminosity (1 month run) $\approx 1.5\ \mathrm{nb}^{-1}$

Peak luminosity $L \approx 6\times 10^{27}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} = 6\times$design

Up to $k_b = 912$ bunches with mean intensity $N_b = 2.2\times 10^{8}$ Pb.

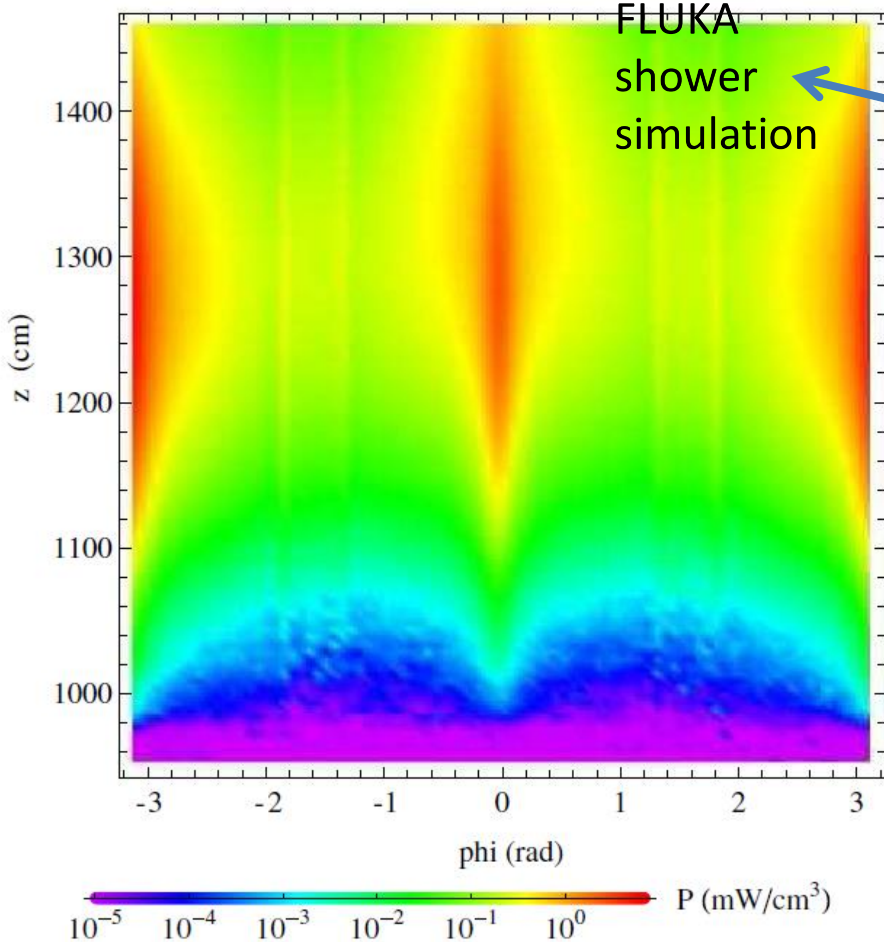
Stored energy in beam: W $\approx$ 18 MJ = 4.8 $\times$design

Power in BFPP1 beam: $P_{\mathrm{BFPP1}} = 155$ W

Power in EMD1 beam: $P_{\mathrm{EMD1}} = 53$ W

ATLAS and CMS also taking luminosity (high burn-off).
Levelling strategies may reduce peak luminosity but we must aim for high intensity.
Comparison data: p-Pb runs at high luminosity may become comparable to Pb-Pb (on one side of IP).

Power density in superconducting cable



FLUKA shower simulation

FIG. 7. (Color) The heating power from beam losses caused by BFPP in the inner layer of the coil of an LHC main dipole as simulated with FLUKA. The power density was averaged over the width of the cable and is shown as a function of azimuthal angle ϕ and longitudinal coordinate z, with $z = 0$ in the beginning of the magnet. The beam loss is centered around $z = 1206$ cm and $\phi \approx -3.11$ rad.

Newer FLUKA studies – see talk by A. Lechner

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R. Bruce,[1,*] D. Bocian,[2,1,†] S. Gilardoni,[1] and J. M. Jowett[1]

Maximum power density in coil at 7 Z Te

$P = 15.5$ mW/cm^3 at design luminosity.

For upgrade luminosity, expect

$P \approx 93$ mW/cm^3

See other talks!

c.f. quench limit (latest from A. Verweij)

200 mW/cm^3 at 4 Z TeV

40-50 mW/cm^3 at 7 Z TeV

(higher than used previously)

Nevertheless, expect to quench MB and possibly MQ!

Radiation damage

Knowing the power density, *P*, for a given luminosity, *L*, and the coil material density, $\rho = 7\ \mathrm{g\ cm^{-3}}$ (combined superconductor and polyimide insulation), we can estimate the radiation dose per unit of integrated luminosity (in the Pb-Pb runs only!)

$$\frac{P}{\rho L} = 2.2\ \mathrm{MGy/(nb^{-1})}.$$

Thus, in attaining the HL-LHC luminosity goal, the coil may be exposed to a dose of some 22 MGy.

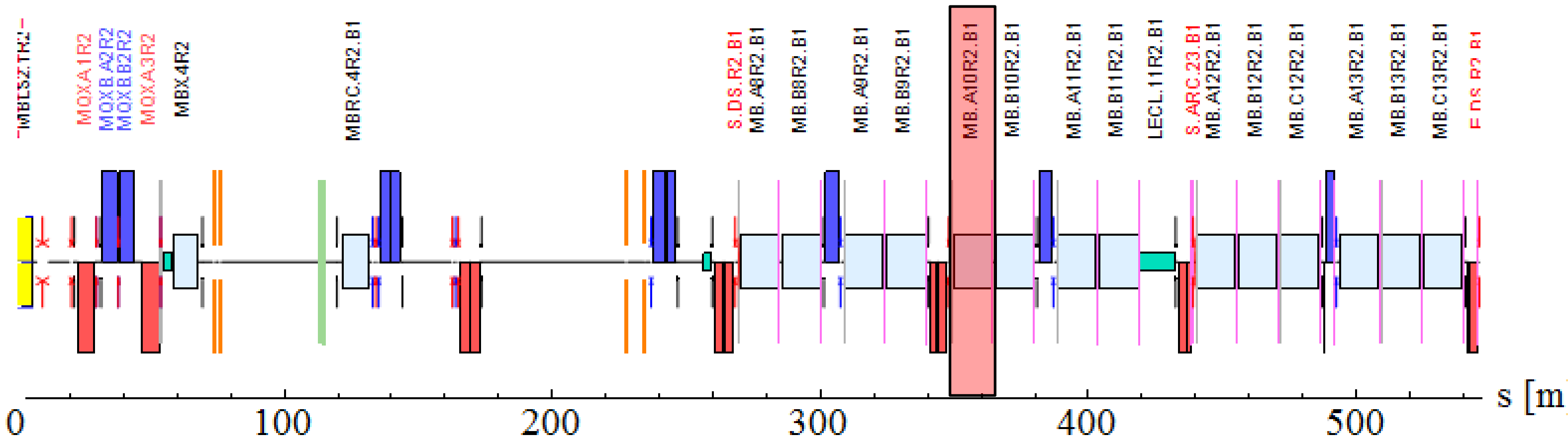
Comparable to damage limit of polyimide insulator.

Discussion on nuclide fluences in coils following talk by Paolo Fessia – to be confirmed.

DS collimator installation in IR2

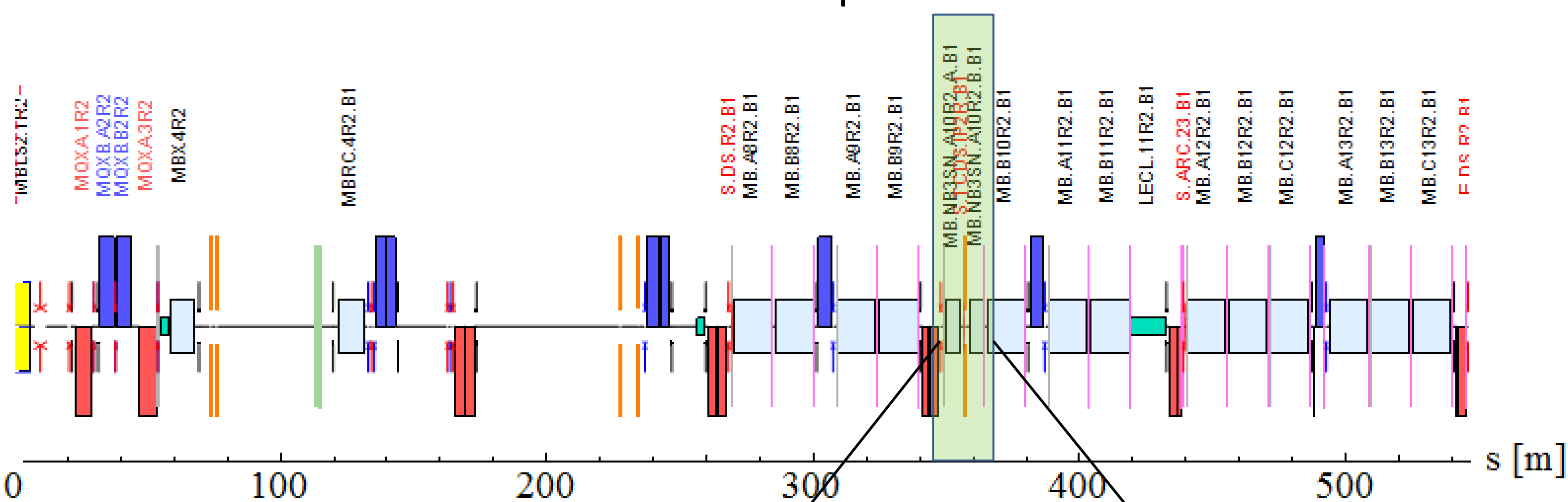
Magnet to be replaced **MB.A10R2**

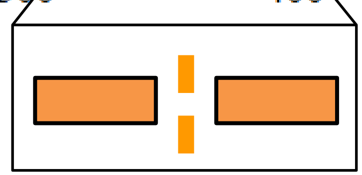
Nominal Beam Line



IP2

Modified Sequence





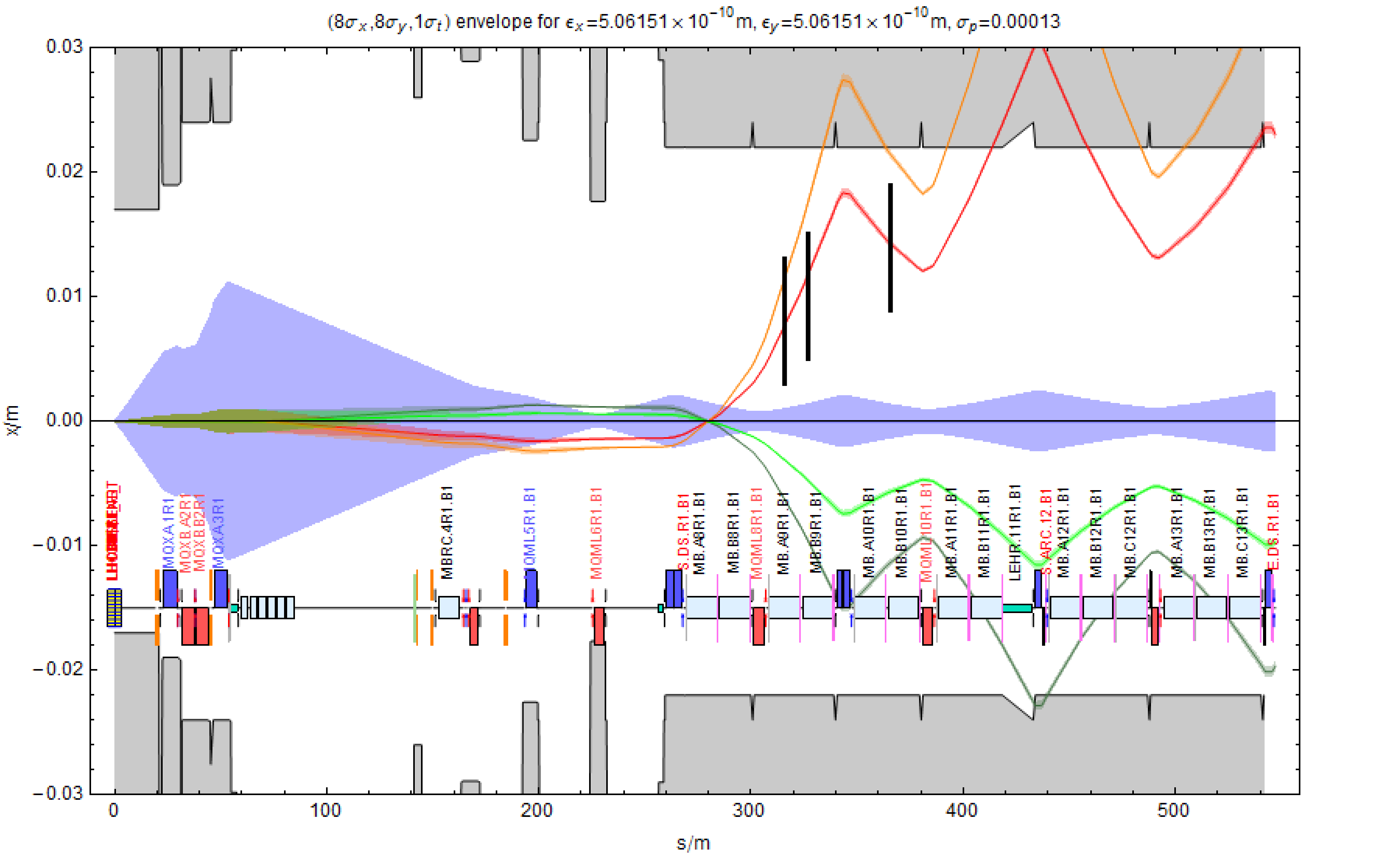
2 × 11T dipole with L = 5.3m

Collimator jaw with L = 1m

ATLAS and CMS ?

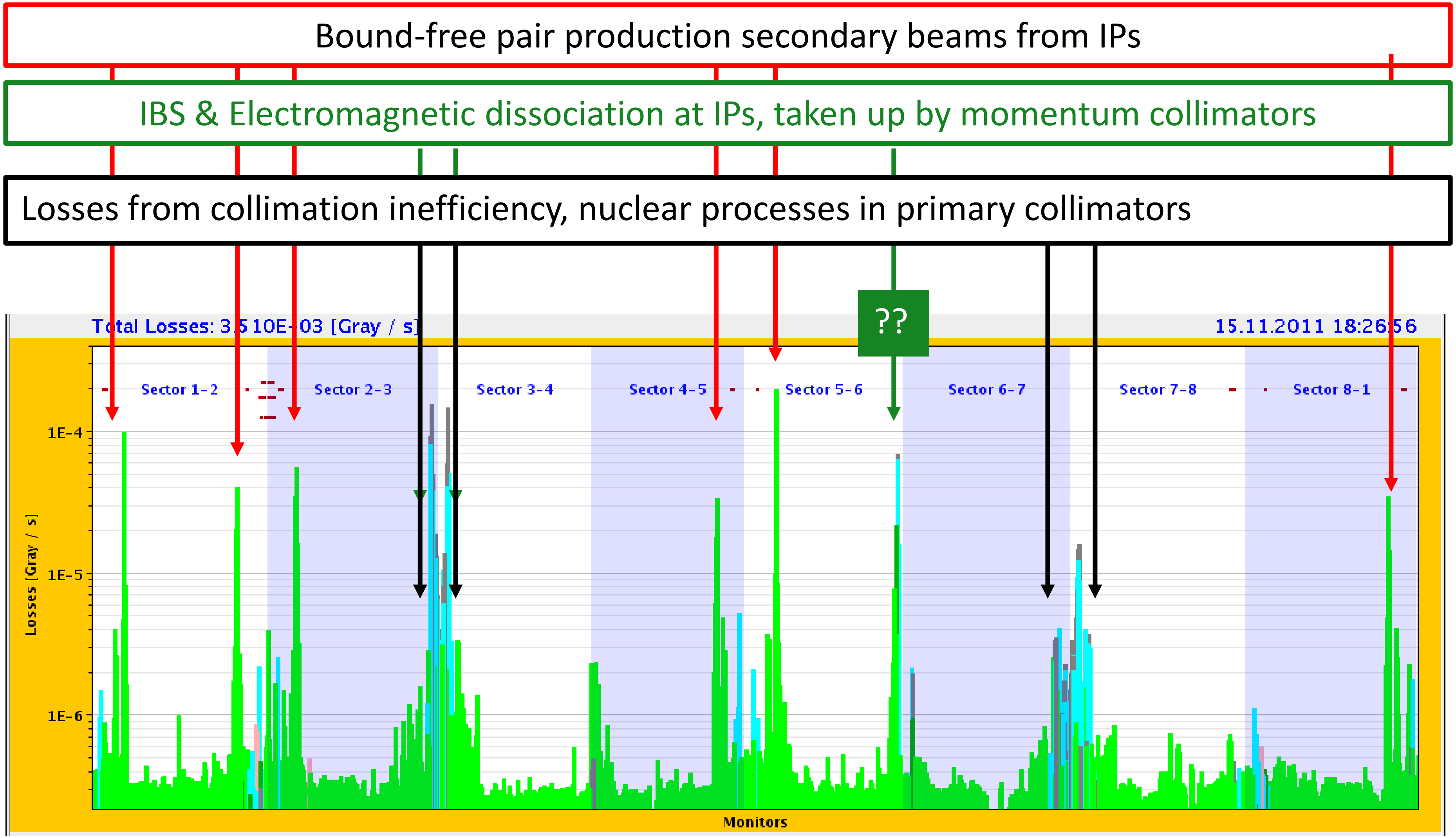
- ATLAS and CMS also take high-luminosity Pb-Pb
- The same problem of BFPP losses exists in the DSs around IP1 and IP5
  - Details of loss locations somewhat different
  - Highest BLM signals from BFPP in 2011 were right of IP5
  - We have some scope for mitigation using the orbit bump method tested in 2011 (will be made operational for Run 2 anyway) - **backup slides**

DS Collimator locations around ATLAS or CMS



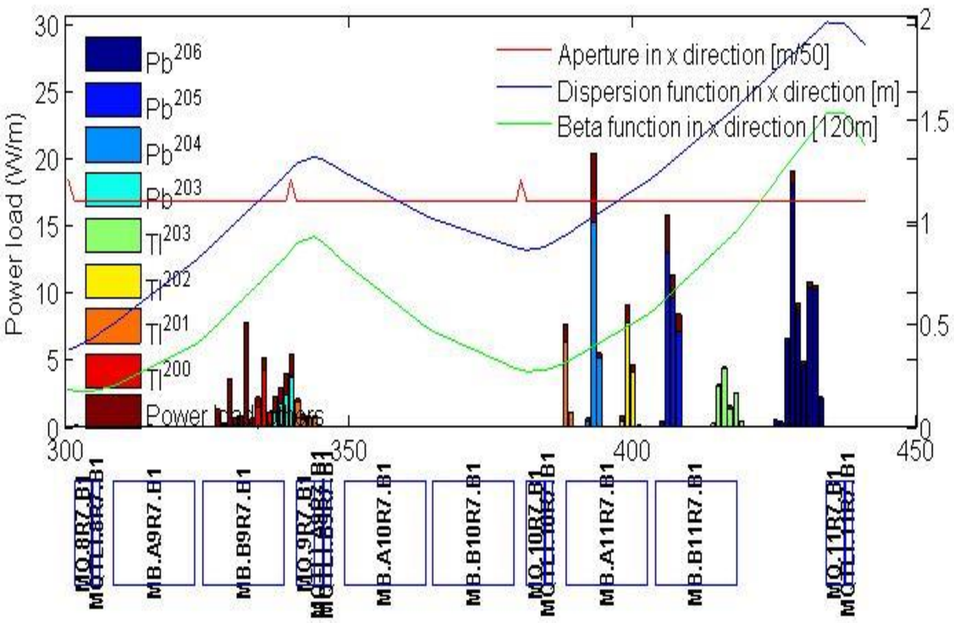
Different from IR2 but various locations would be effective

Steady-state losses during Pb-Pb Collisions in 2011

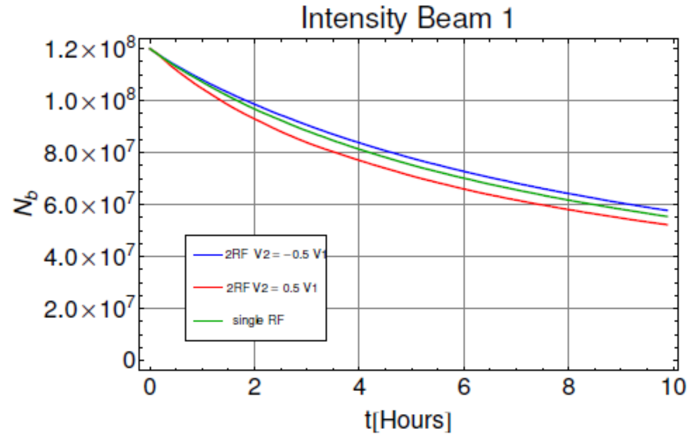


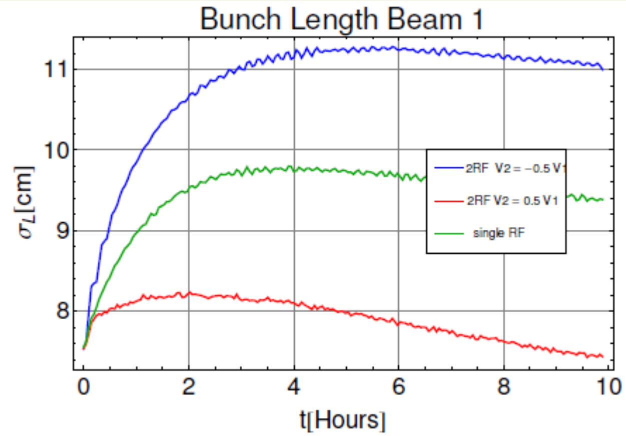
Collimation Inefficiency

- Discussed extensively in the past
- Mainly a limit on total intensity
  - Some situations (Pb beam sizes larger than p, putting beams into collision, off-momentum p-Pb orbits more critical)
  - Mitigation – some success with bump strategy – *backup slides*
  - New simulation activity starting

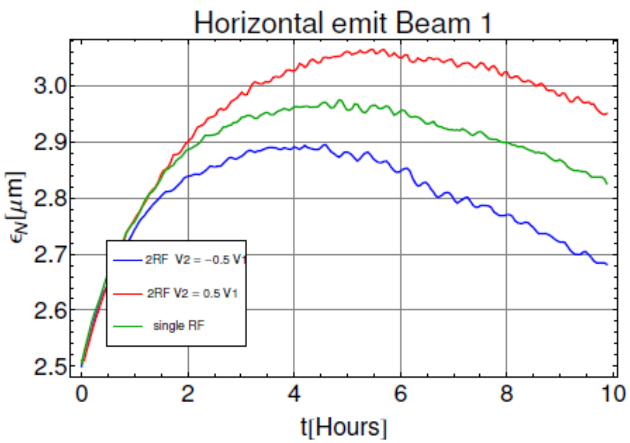


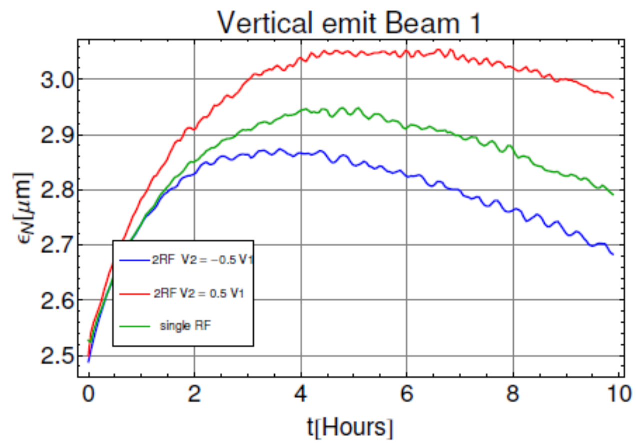
Higher harmonic (800 MHz) RF system, Pb-Pb 7 *Z* TeV





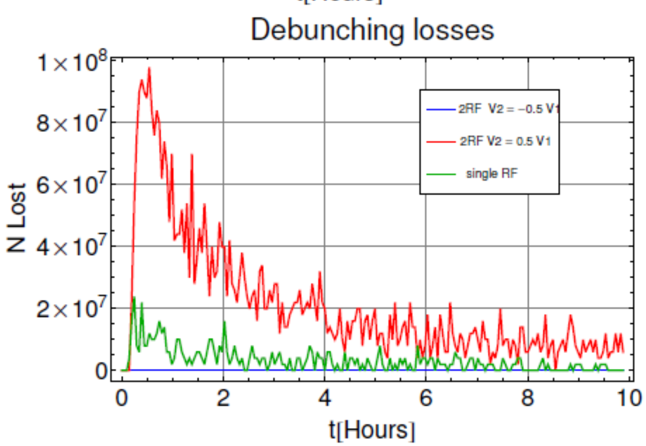
800 MHz RF system provides useful gain in luminosity.

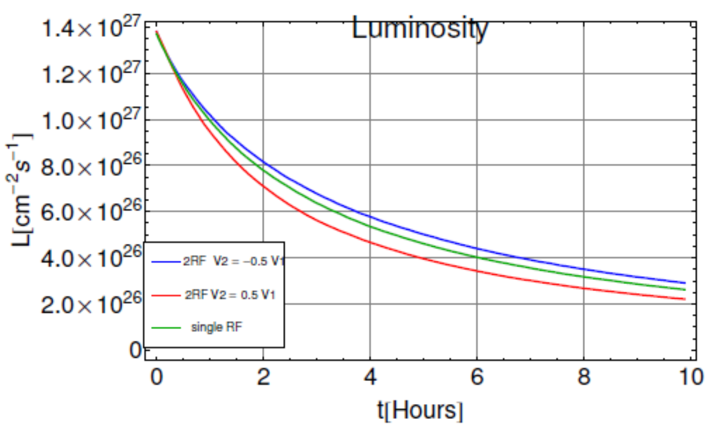




Tom Mertens

http://cds.cern.ch/record/1377067





Lower Harmonic (200 MHz) RF system

- Will be studied in Collider Time Evolution (CTE) program
  - Expect reduction of IBS growth and debunching losses in LHC at both injection and collision
- Longer bunches will reduce bandwidth and kicker voltage requirements for stochastic cooling system (see later)
- Injection requirements
- Likely more useful than 800 MHz (to be confirmed)

STOCHASTIC COOLING

Stochastic cooling of Pb beams

- Inspired by spectacular luminosity enhancement by 3D stochastic cooling of bunched Au and U beams at RHIC
- First study with Mike Blaskiewicz during visit in June
- Simulations and paper at COOL'13 workshop

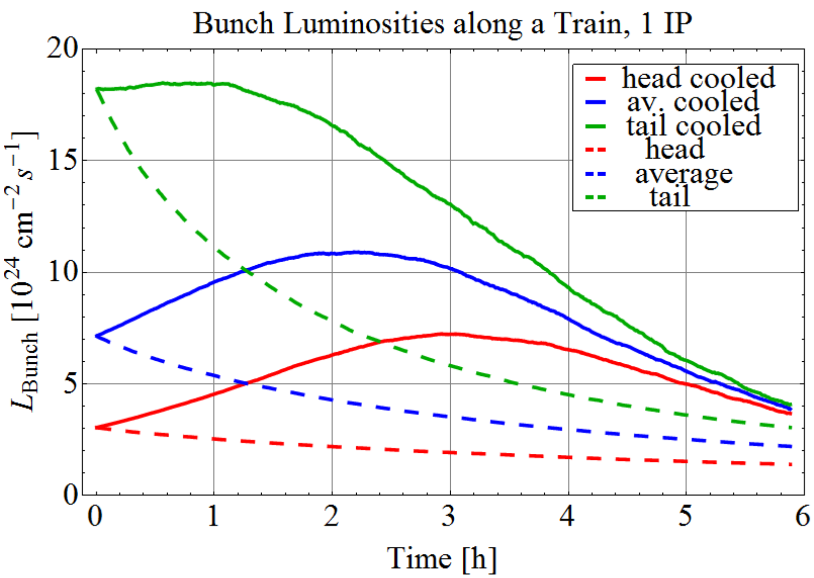
CERN-ATS-2013-043

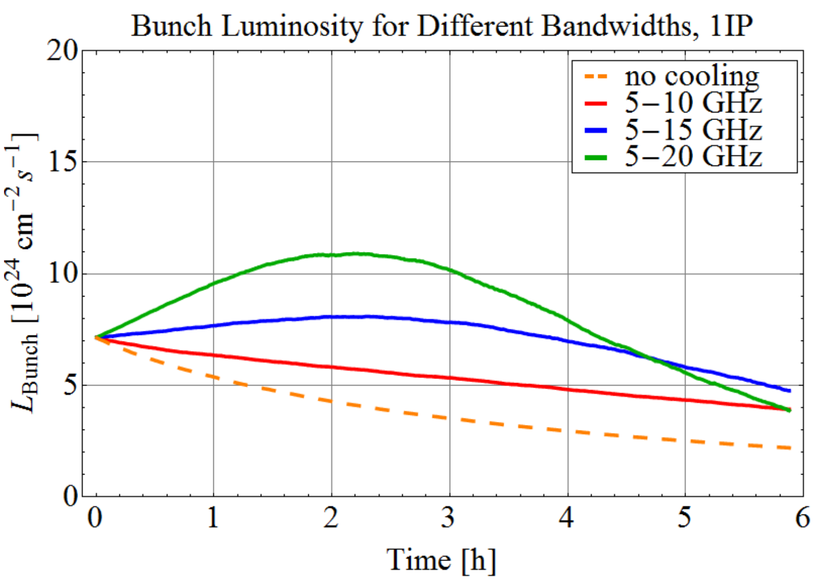
POTENTIAL OF STOCHASTIC COOLING OF HEAVY IONS IN THE LHC

M. Schaumann*, J.M. Jowett, CERN, Geneva, Switzerland
M. Blaskiewicz, BNL, Upton, NY, USA

The dynamics of the high intensity lead beams in the LHC are strongly influenced by intra-beam scattering (IBS), leading to significant emittance growth and particle losses at all energies. Particle losses during collisions are dominated by nuclear electromagnetic processes and the debunching effect arising from the influence of IBS, resulting in a non-exponential intensity decay during the fill and short luminosity lifetimes. In the LHC heavy ion runs, 3 experiments will be taking data and the average fill duration will be rather short as a consequence of the high burn-off rate. The achievements with stochastic cooling at RHIC suggest that such a system at LHC could substantially reduce the emittance growth and the debunching component during injection and collisions. The luminosity lifetime and fill length could be improved to optimize the use of the limited run time of 4 weeks per year. This paper discusses the first results of a feasibility study to use stochastic cooling on the lead ion beams in the LHC. The present and expected future performance without cooling is presented and compared to preliminary simulations estimating the improvements if stochastic cooling is applied.

Stochastic Cooling Simulations, Pb beam at 7 *Z* TeV





- IBS horizontal growth time ≈ 8h.
- Radiation damping time ≈ 13h
  → radiation damping not included in the simulations on this slide.
- Assuming a stochastic cooling system with a 5-20GHz bandwidth and average 2013 Pb bunches [4]:

$$T_{\mathrm{cool}} = \frac{N_b C_{\mathrm{LHC}}}{4\sigma_z W}\left[\frac{M+U}{(1-\tilde{M}^{-2})^2}\right] \approx 1.8\,\mathrm{h}$$

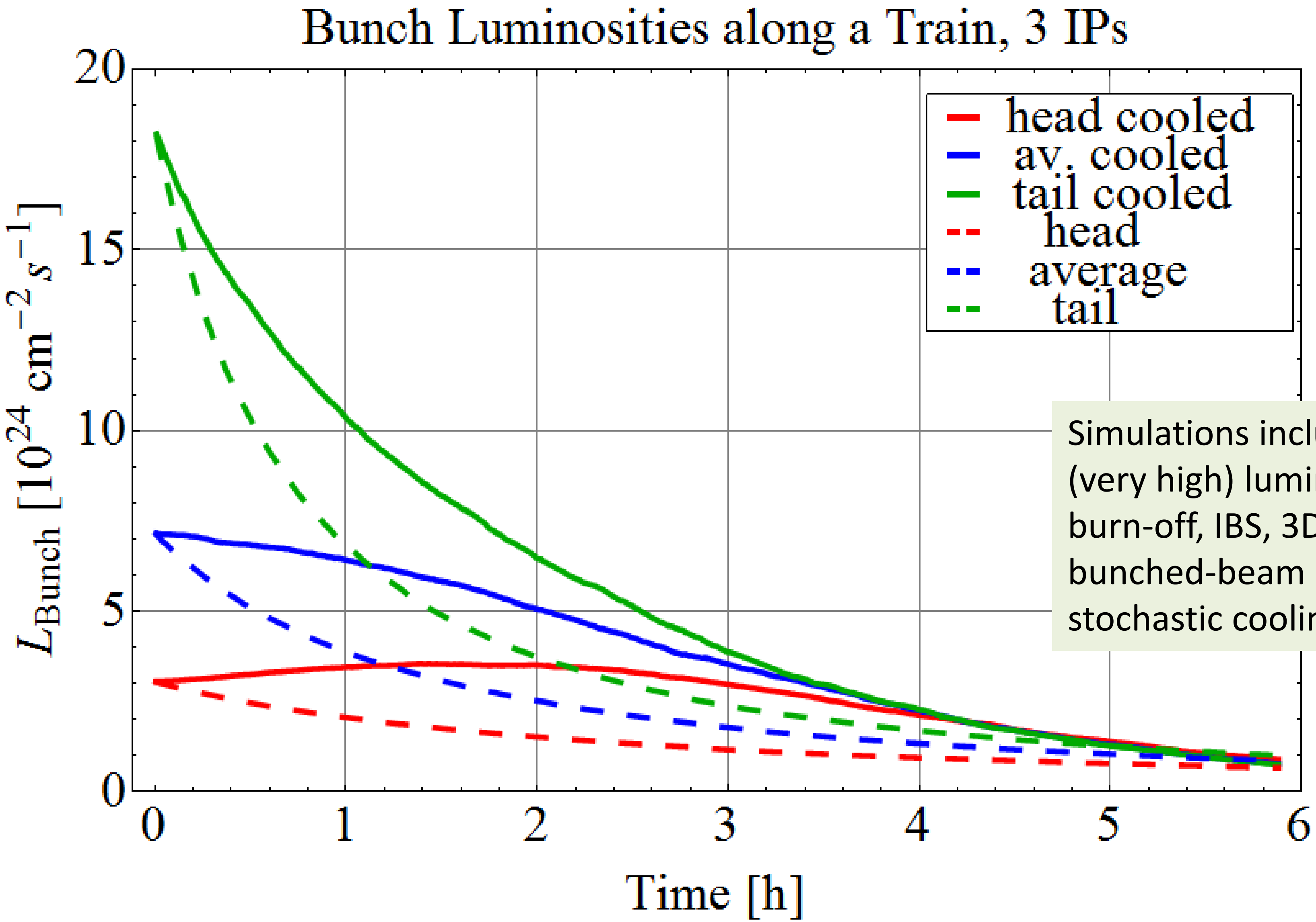
- First estimate for RMS voltage per cavity (assuming a system with 16 cavities as in RHIC):

$$V_{cavity} = 2\,\mathrm{kV}$$

- Integrated luminosity could be increased by a factor 2.
- Larger bandwidth and higher upper frequency, lead to higher integrated luminosity.

M. Schaumann

ALICE, ATLAS, CMS illuminated

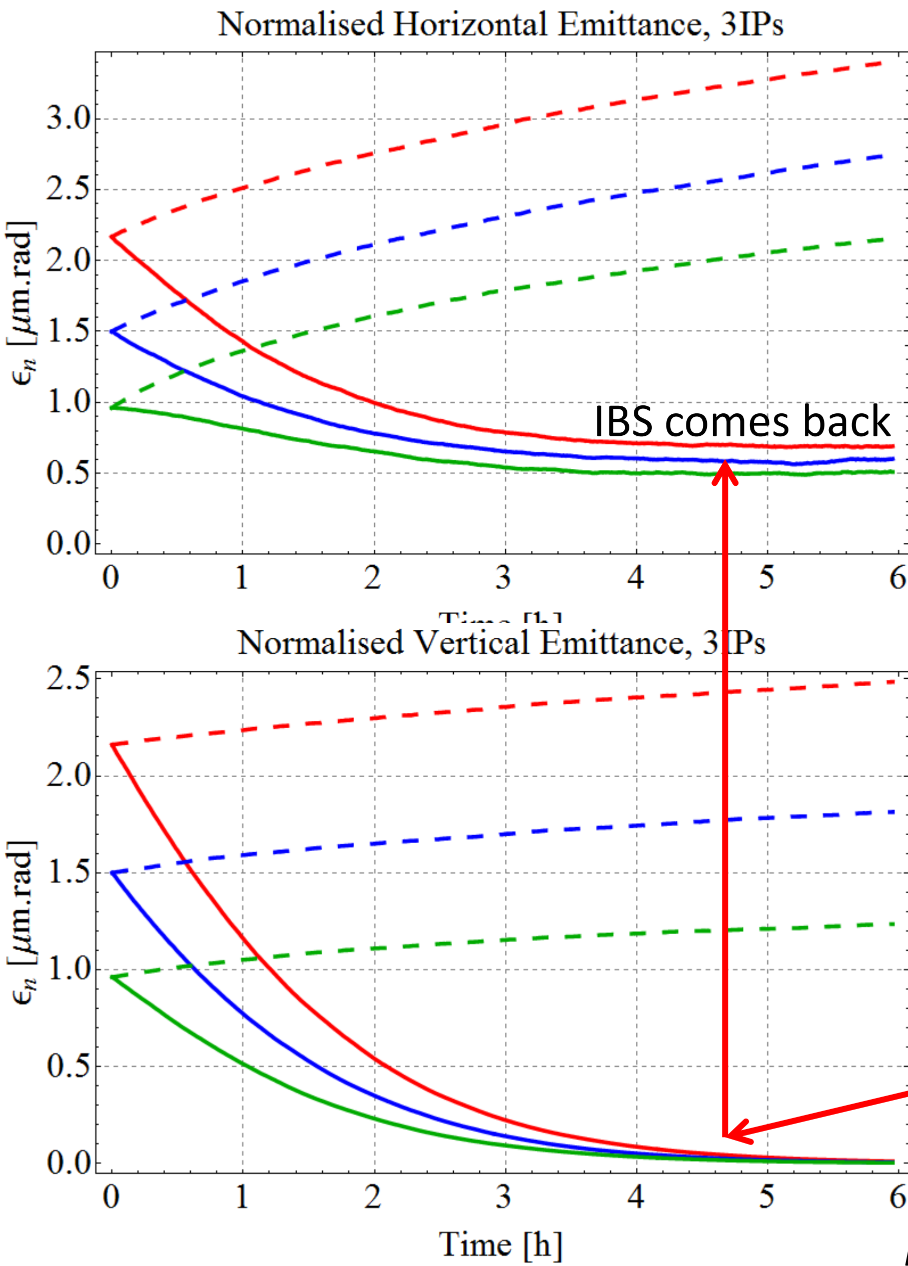


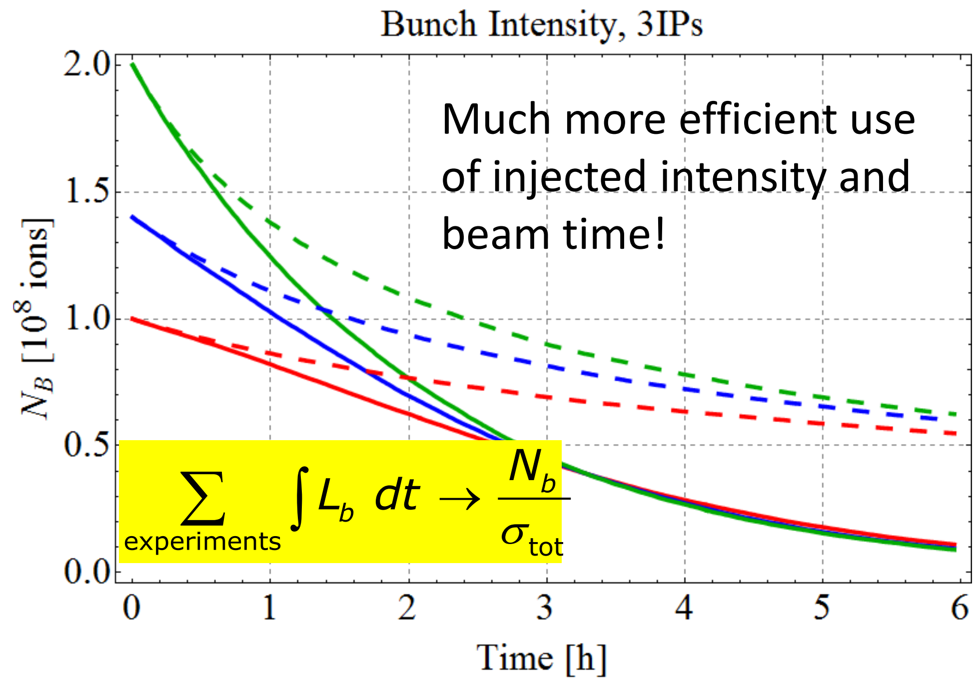
Simulations include (very high) luminosity burn-off, IBS, 3D bunched-beam stochastic cooling, etc.

What is happening here? See next slide …

M. Schaumann

Bunch parameters with cooling (3 experiments)





Extremely small vertical beam sizes, vertical orbit stability may become the limit (we can always reduce vertical cooling).
Parametric study of betatron coupling: although it is usually small in LHC, may be desirable to introduce some.

Need new definition of "operational efficiency."

How to proceed - tentative

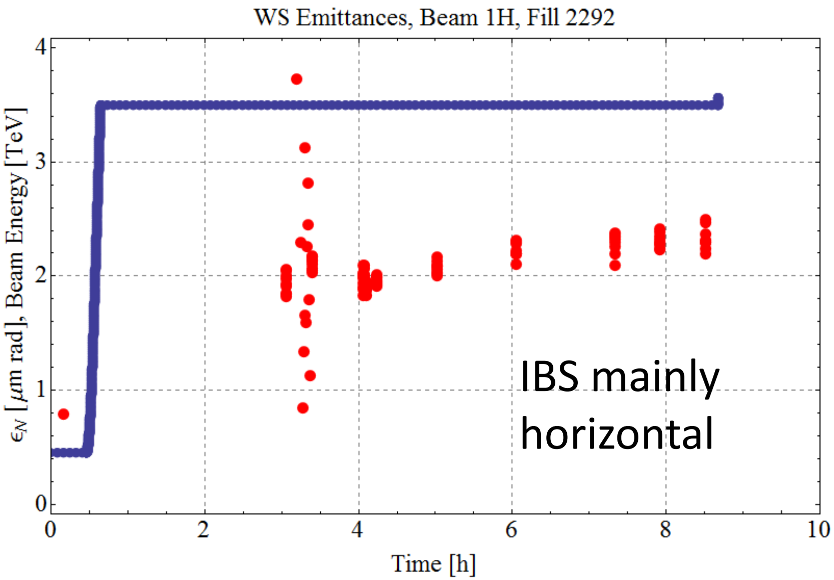
- Further studies on feasibility and to define necessary hardware systems
  - Space reservation in IR4 (kicker systems) and elsewhere (IR4, IR2, IR6 …?) for pickups
  - Challenge: kicker cavities that open and close (only at Pb physics energy) and can co-exist with LHC proton beam
- Demonstration of longitudinal cooling in ~2015-16
  - Existing Schottky as pickup
  - "Off-the-shelf" 5 GHz amplifier (to be checked)
  - Replace existing unused shaker chamber in IR4 with kicker (when ready) in technical stop/end-of-year shutdown
- Collaboration with BNL, benefit from their experience to define fast-track implementation
- 200 MHz RF system proposed for p-p should improve cooling

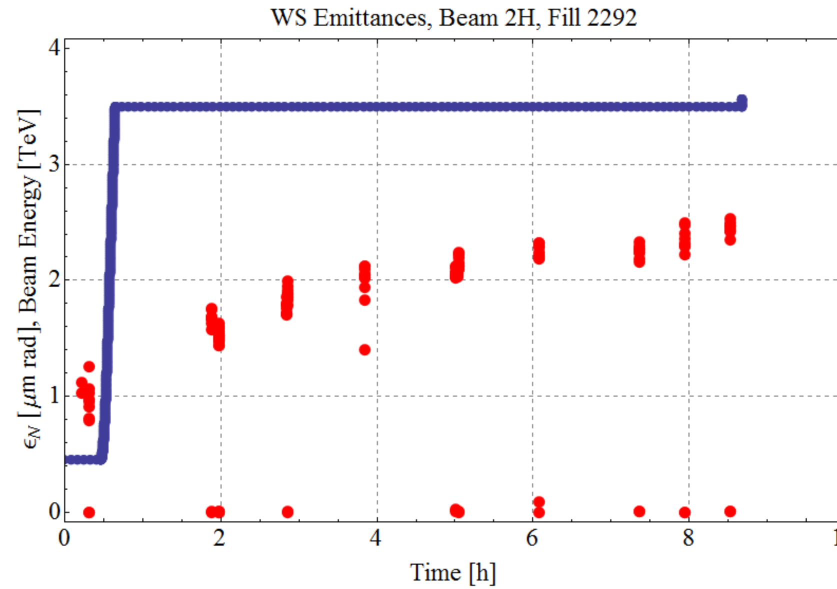
Conclusions

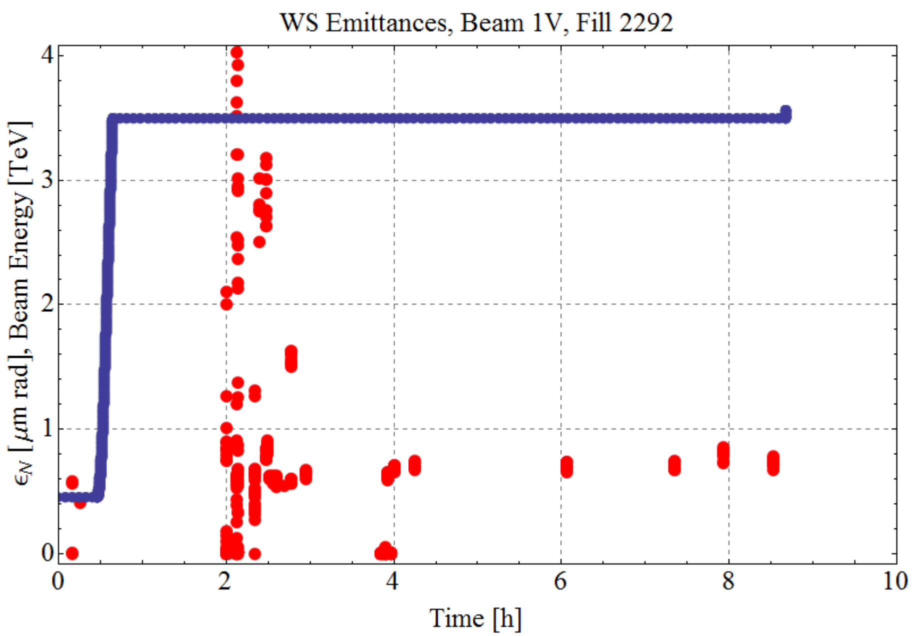
- Run2
  - Pb-Pb and p-Pb luminosities already beyond design, should exceed LHC Phase 1 goal of 1 nb^{-1} in Pb-Pb
- Run3 and beyond
  - Further gains from injectors, stochastic cooling (?)
- High priority developments to achieve 10 nb^{-1}
  - SPS injection kicker upgrade
  - Other LIU … source intensity, LEIR intensity limits
  - Injection schemes for more, and brighter, bunches (50 ns)
  - **Reduce intensity decay in SPS !?!**
  - Dispersion suppressor collimators (ALICE, …)
  - Initiate fast track to stochastic cooling implementation
  - 200 MHz RF system proposed for p-p should also help Pb beams in several ways (to be quantified)
  - Potential p-Pb performance depends critically on resolution of BPM problems

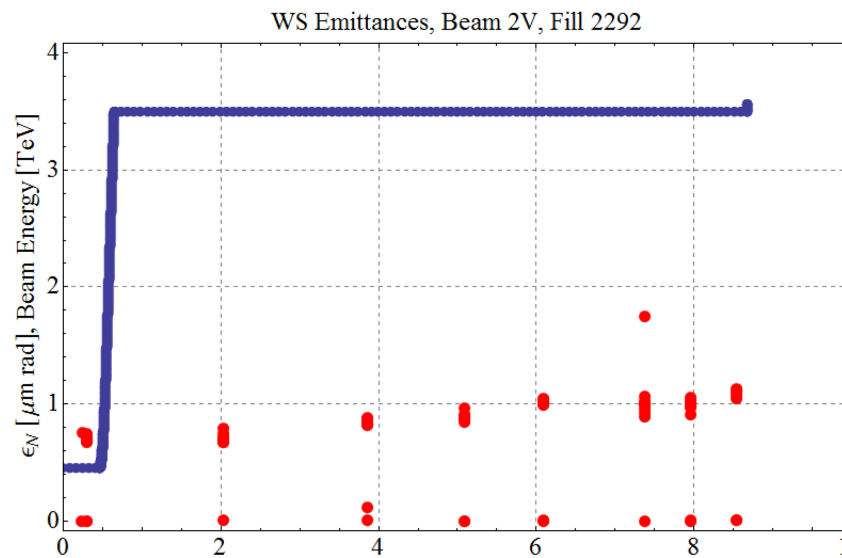
BACKUP SLIDES

More detail on emittances from wire scans









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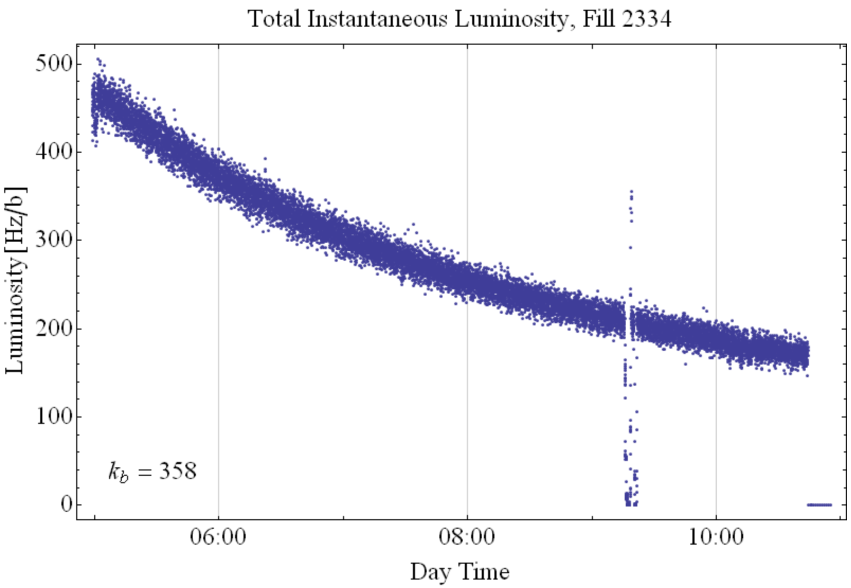
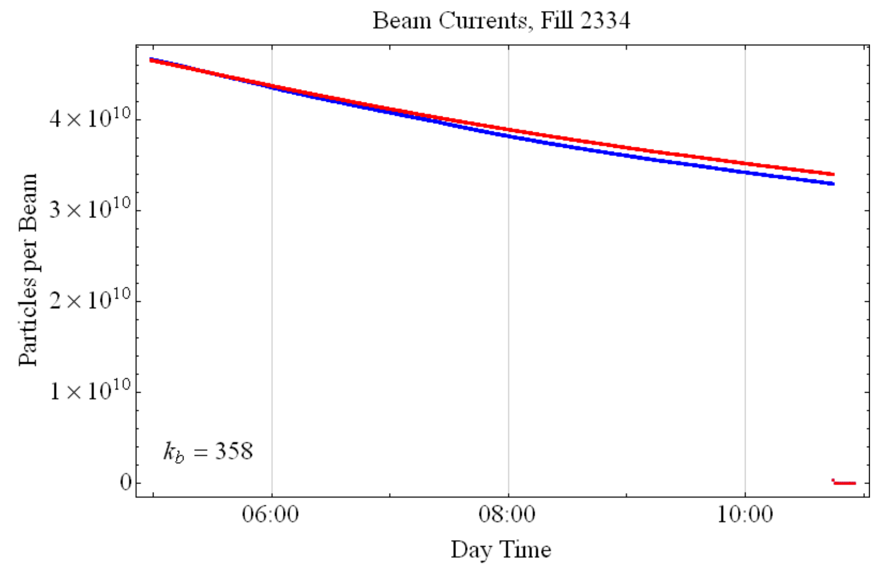
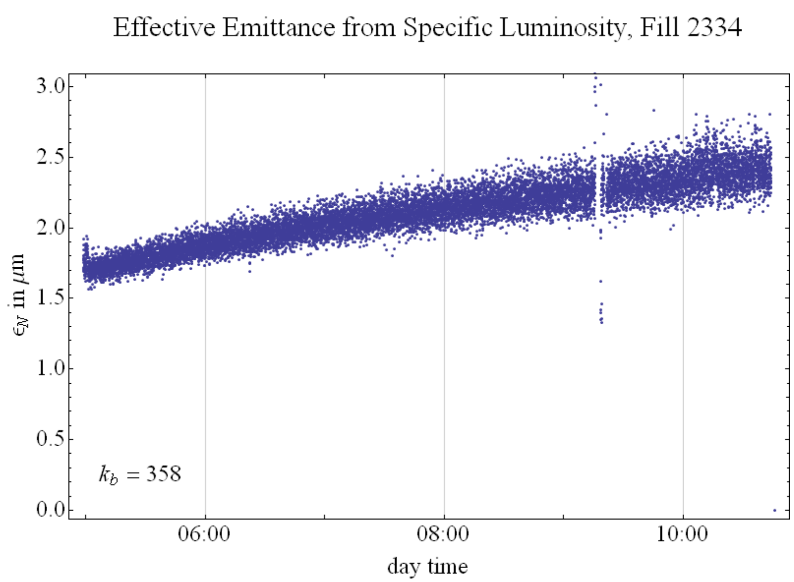
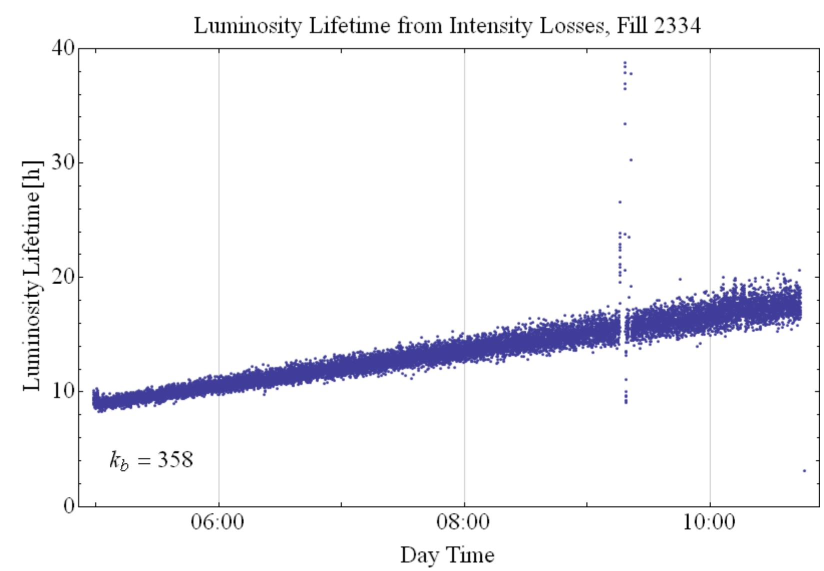
Beam parameter evolution, not the best fill





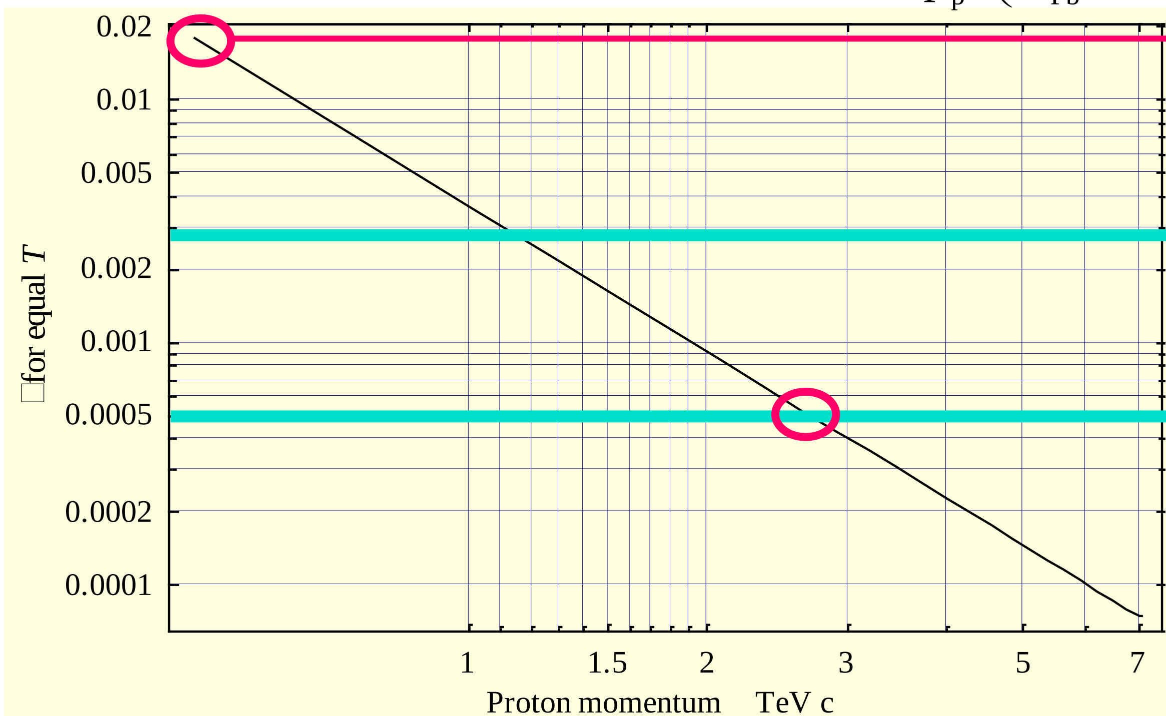




M. Schaumann

Momentum offset required to equalise frequencies (2-in-1 magnets!)

Minimise aperture needed by $\delta_{\mathrm{p}} = -\delta_{\mathrm{Pb}} = \dfrac{c^2 \gamma_T{}^2}{4 p_{\mathrm{p}}^2} \left(\dfrac{m_{\mathrm{Pb}}^2}{Z_{\mathrm{Pb}}^2} - m_{\mathrm{p}}^2 \right).$



Would move beam by 35 mm in QF!!

Limit with pilot beams

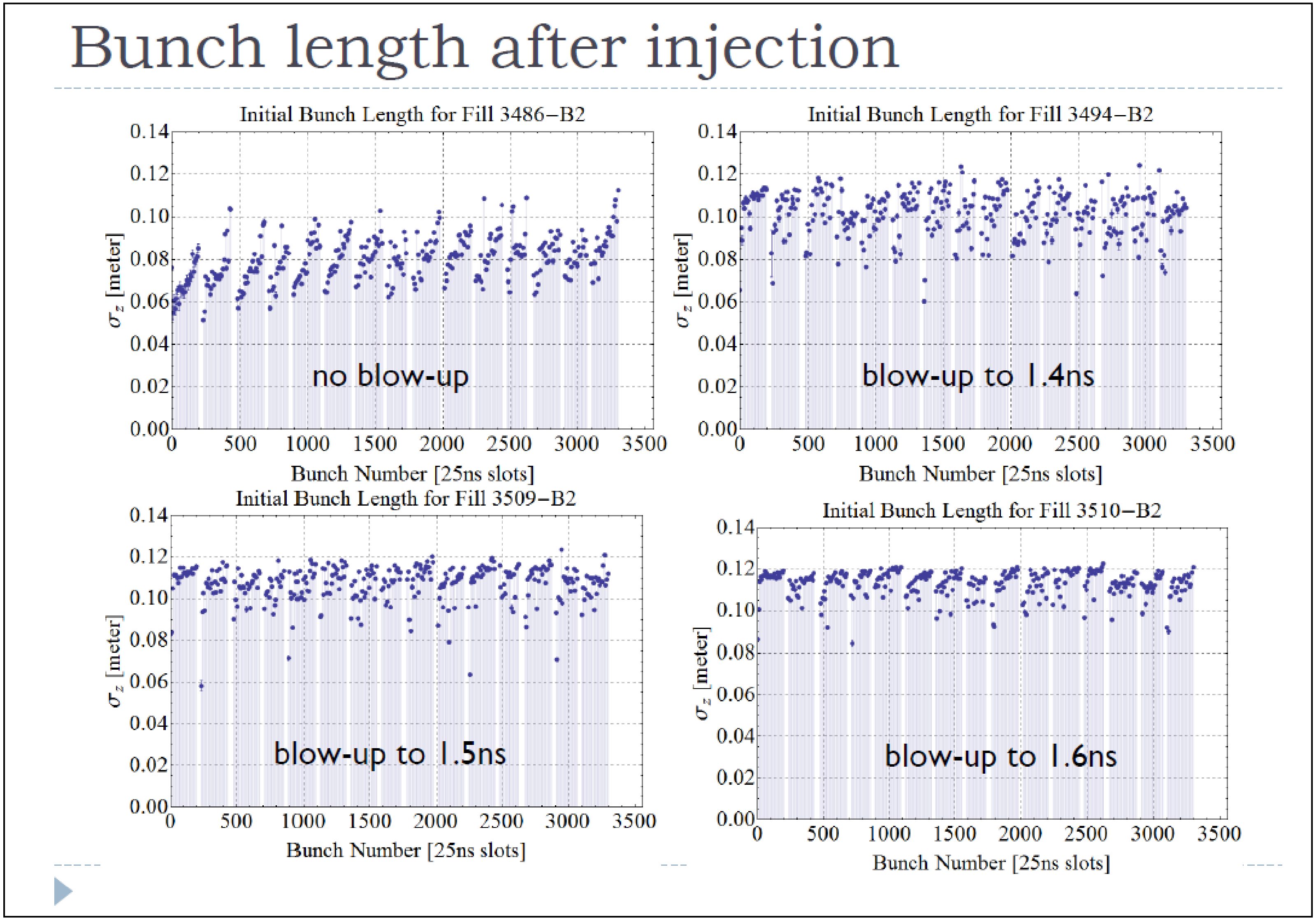
Limit in normal operation

Injection and acceleration with unequal revolution frequencies

Revolution frequencies must be equal for collisions.

⇒Lower limit on energy of p-Pb collisions, E_p ~ 2.7 TeV .

Batch by batch blow up measurements analysis (M. Schaumann)



ALICE Crossing Angle

- Possible upgrade of TCLIA collimator for ZDC
  - Up to now always had crossing angle constraint
  - Aperture clearance for spectator neutrons from IP to ZDC
  - Possibly inadequate beam-beam separation for 50 ns (also parasitic luminosity)
  - Under study …