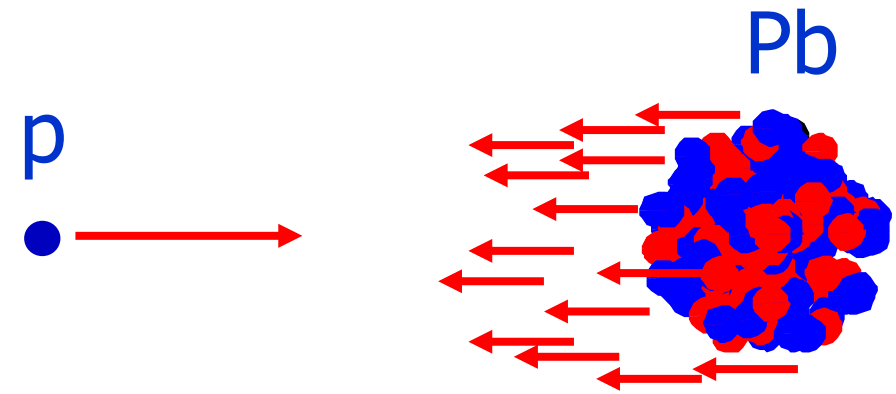


Proton-Nucleus Collisions in the LHC

J. M. Jowett, R. Alemany-Fernandez, P. Baudrenghien, D. Jacquet, M. Lamont, D. Manglunki, S. Redaelli, M. Sapinski, M. Schaumann, M. Solfaroli Camillocci, R. Tomás, J. Uythoven, D. Valuch, R. Versteegen, J. Wenninger

CERN, Geneva, Switzerland

With thanks for their contributions to many other colleagues in the CERN Accelerator and Technology Sector

Abstract

Following the high integrated luminosity accumulated in the first two Pb-Pb collision runs in 2010 and 2011, the LHC heavy-ion physics community requested a first run with p-Pb collisions.

This almost unprecedented mode of collider operation was not foreseen in the baseline design of the LHC whose two-in-one magnet design imposed equal rigidity and, hence, unequal revolution frequencies, during injection and ramp. Nevertheless, after a successful pilot physics fill in 2012, the LHC provided 31 nb^{-1} of p-Pb luminosity per experiment, at an energy of 5.02 TeV per colliding nucleon pair, with several variations of the operating conditions, in early 2013. Together with a companion p-p run at 2.76 TeV, this was the last physics before the present long shutdown.

We summarise the beam physics, operational adaptations and strategy that resulted in extremely rapid commissioning.

Finally, we give an account of the progress of the run and provide an analysis of the performance.

RF Frequency for p and Pb in LHC

$$f_{\mathrm{RF}} = \frac{h_{\mathrm{RF}}}{T(p_{\mathrm{p}}, m, Q)} \quad , \quad T(p_{\mathrm{p}}, m, Q) = \frac{C}{c}\sqrt{1 + \left(\frac{mc}{Qp_{\mathrm{p}}}\right)^2}\,(1 + \eta\delta), \quad h_{\mathrm{RF}} = 35640 \text{ in LHC}$$

LHC has independent RF systems in each ring.

Equal f_{RF} at injection

$\Rightarrow$ ±35 mm orbit displacement in arcs

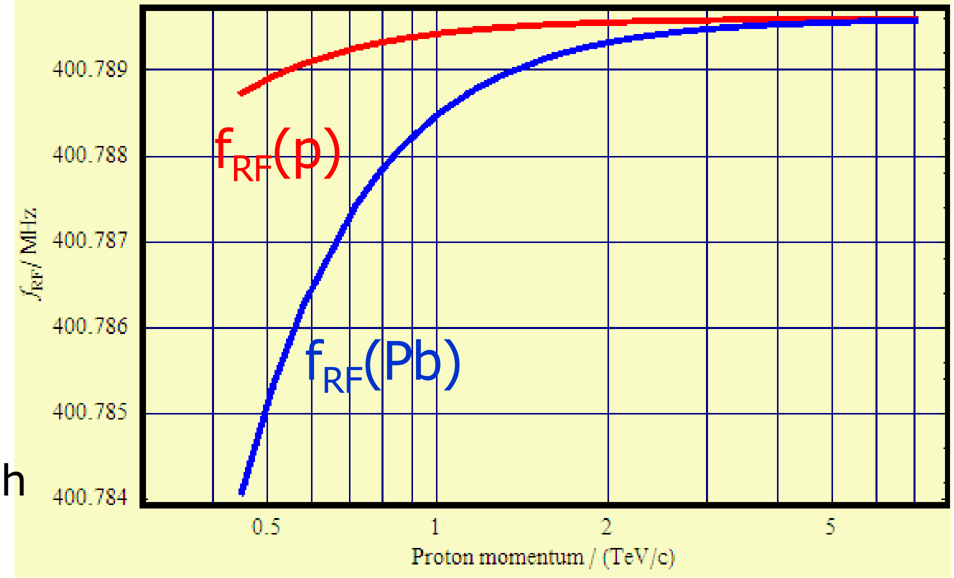
Must ramp with unequal f_{RF}

$\Rightarrow$ long-range beam-beam encounters are moving

$\Rightarrow$ kicks vary from turn-to-turn

$\Rightarrow$ modulated beam-beam kicks

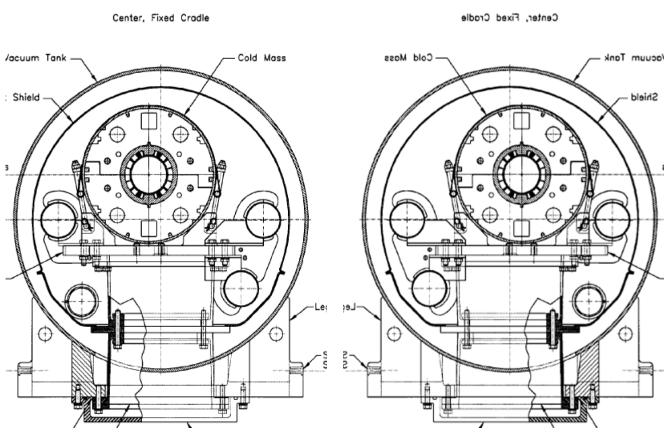
$\Rightarrow$ possible instability, emittance growth



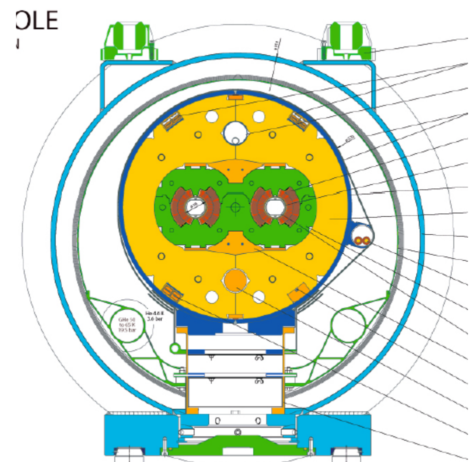
At top energy, 4*Z* TeV in 2012-13, it is possible to equalise revolution frequencies with equal and opposite ±0.3 mm displacements of the proton and lead beams. Can only do this after ramp.

RHIC D-Au in 2003 (PAC'2003, TPPB043)

- Initial attempts with equal rigidity, unequal frequencies as in LHC
  - *"modulated long-range beam-beam forces created untunable beam loss"*
  - Doubts of feasibility for LHC; not part of LHC TDR



RHIC: Independent bending field for the two beams – switched to equal-frequency injection and ramp for successful D-Au operation.



LHC: Identical bend field in both apertures of two-in-one dipole – no choice!

History and preparations for p-Pb physics

- 2005 CERN workshop on pA in LHC
  - Predicted that p-Pb in LHC could work
  - Detailed physics case written up
- 2010-11 first two Pb-Pb runs of LHC make 10 μb^{-1} + >150 μb^{-1}
  - Urgent need for p-Pb comparison data (30 nb^{-1})
  - Request from ALICE considered, early 2011
- Detailed review and adaptation of all LHC systems, machine protection, operational procedures
- Feasibility test 31 October 2011
- Go-ahead for further tests and pilot run in 2012
  - But all machine study time in 2012 lost for various reasons …

First asymmetric collisions at LHC

2012 PROTON-LEAD PILOT RUN

Concept

- Take LHC through the new operational sequence for physics for the first time
- Provide experiments with first useful physics data to set up their triggers in advance of production run a few months later
- Beam parameters (no squeeze, few bunches) chosen to allow shortest possible set-up and yet satisfy machine protection requirements in the course of a typical LHC machine study period (16 h allocated)

Pilot p-Pb run, night of 13-14 September 2012

- **16:00** Starting injection, problems with ions, timing events not sent out correctly.
- 18:30 Filling Pb ions, first time in 2012
- 19:00 Start of ramp. Lost the beam on TCT position interlocks, revert collimator settings and try again ….
- QPS problems. RF problems.
- **22:52 15 p and 15 Pb bunches at 4 *Z* TeV, 8 colliding per experiment, 3 sacrificial for collimation setup**
- 23:35 Beams in collision, unsqueezed, optimising …
- 00:50 Start of loss maps to set up collimation
- **01:26 Stable beams for p-Pb Physics**
- 06:04 Adjust mode to move IP for ALICE
- 06:25 Stable beams again, IP moved by -0.5 m
- 07:55 Stable beams again, IP moved by +0.5 m
- 09:35 Beams dumped by operators

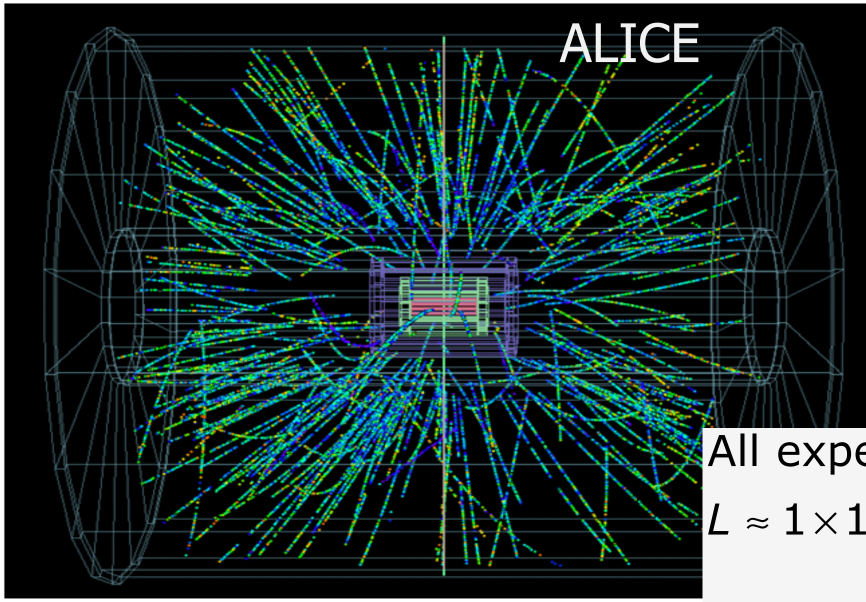
Predictions for p-Pb performance in pilot fill

Main choice:	**Units**	Single_13b_8_8_8.txt	
Beam energy/(Z TeV)	*Z* TeV		4
Colliding bunches			8
β^*	m		10/11
Emittance protons	μm		1.5
Emittance Pb	μm		1.5
Pb/bunch	10^8		1.2
p/bunch	10^{10}		1.15
RMS Beam size (Pb)	**μ m**		**~94**
Bunch length	cm		~7
Initial Luminosity L_0	10^{25} cm^{-2} s^{-1}		**1-10 (max)**

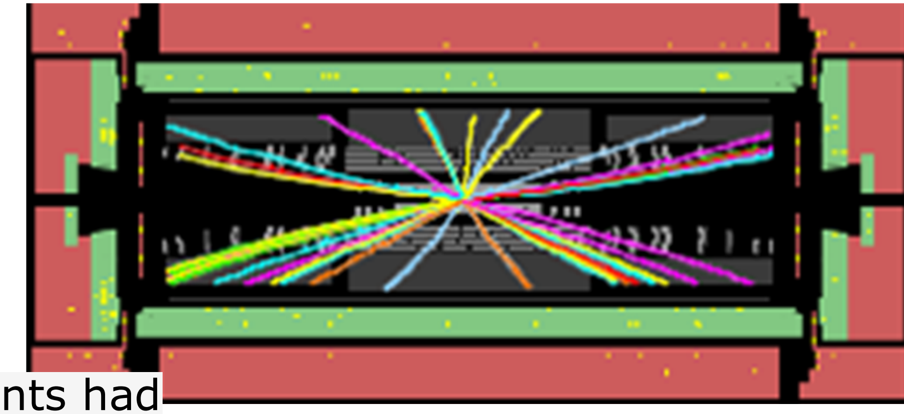
The maximum luminosity was achieved.

Integrated luminosity of 1 μb^{-1} from one fill.

Collisions in all experiments

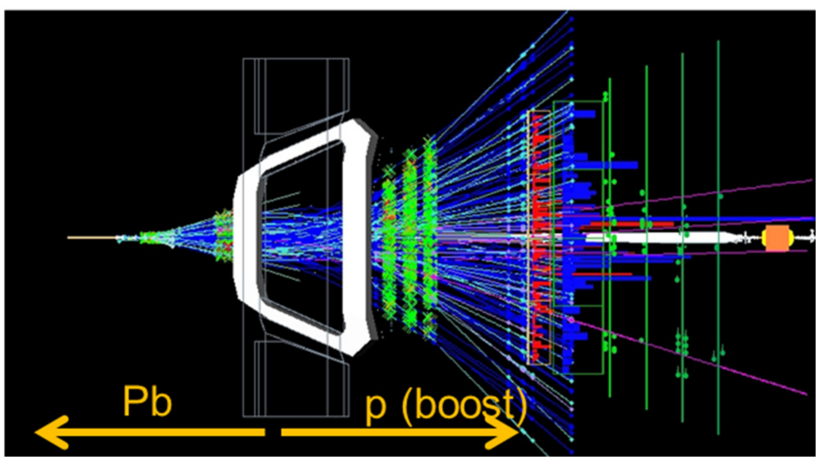


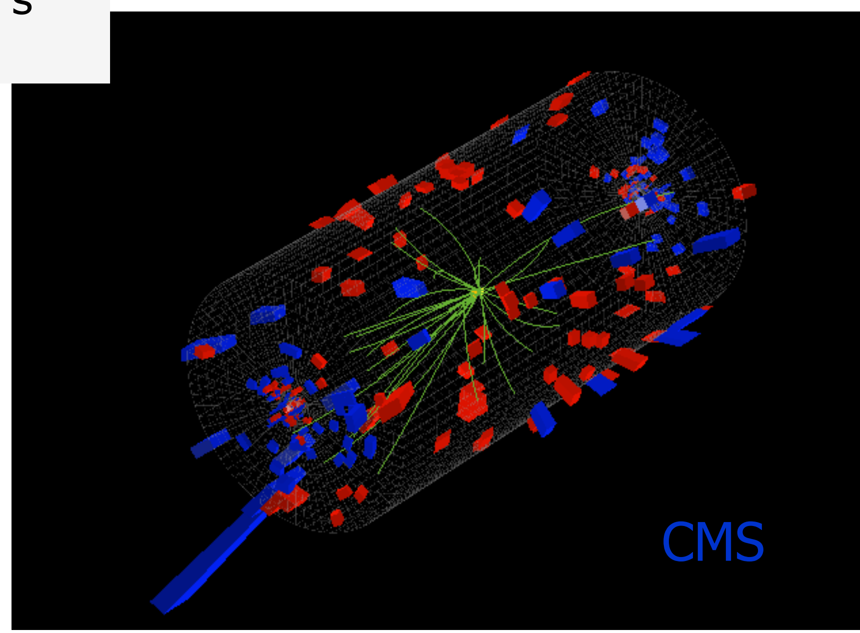
ATLAS



All experiments had
$L \approx 1 \times 10^{26}\ \mathrm{cm^{-2}s^{-1}}$

LHCb I

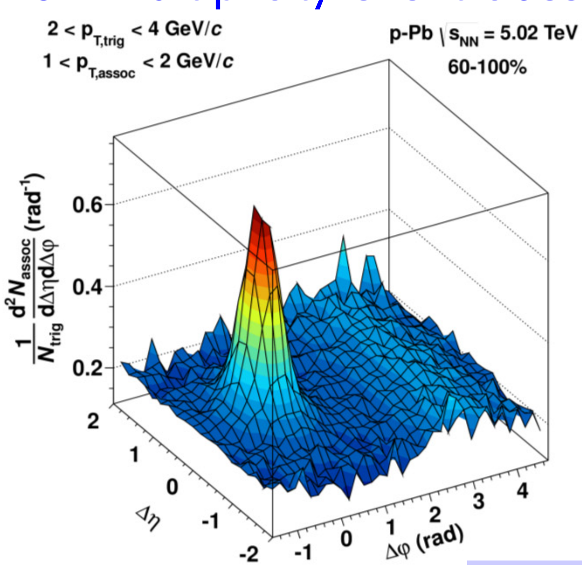




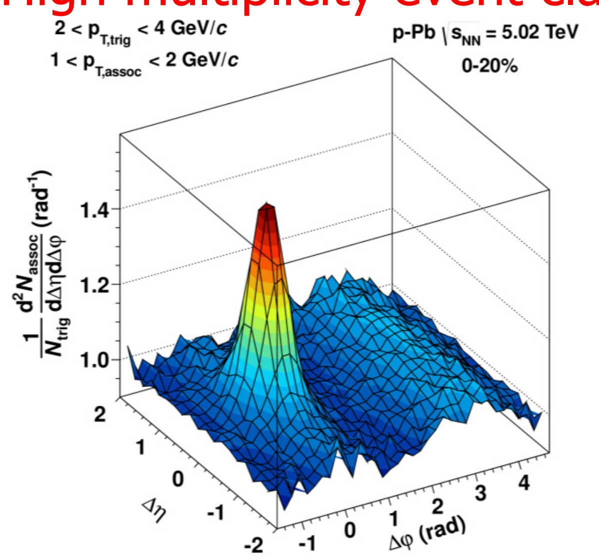
Correlations in p-Pb: the unexpected "ridge"

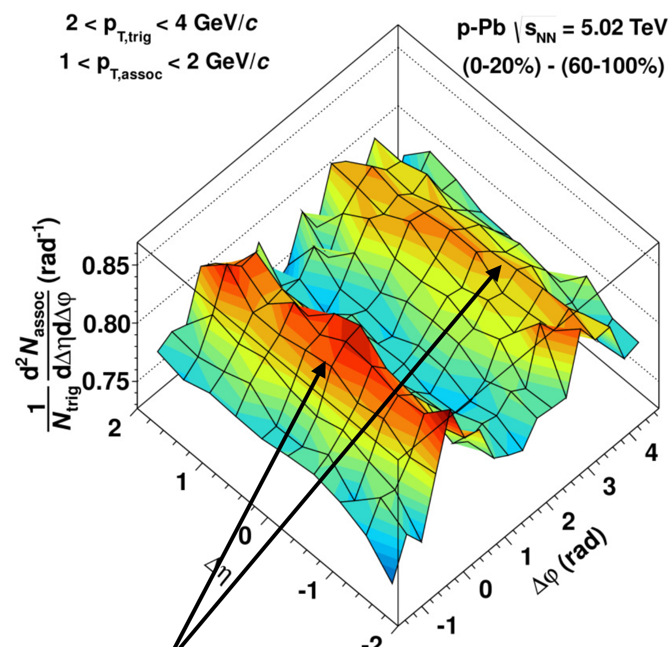
- A double-ridge structure appears, with remarkable properties:
  - Can be expressed in terms of $v_{2,3}$, Fourier coefficients of single particle azimuthal distribution, with $\mathbf{V}_{2,3}$ increasing with p_T and v_2 also with multiplicity
  - **Same yield near and away side for all classes of 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 sign of saturation effects)
  - In agreement with viscous hydro calculations ?!

Low multiplicity event class



High multiplicity event cla





P. Giubellino,
Evian Dec 2012

Double-ridge structure

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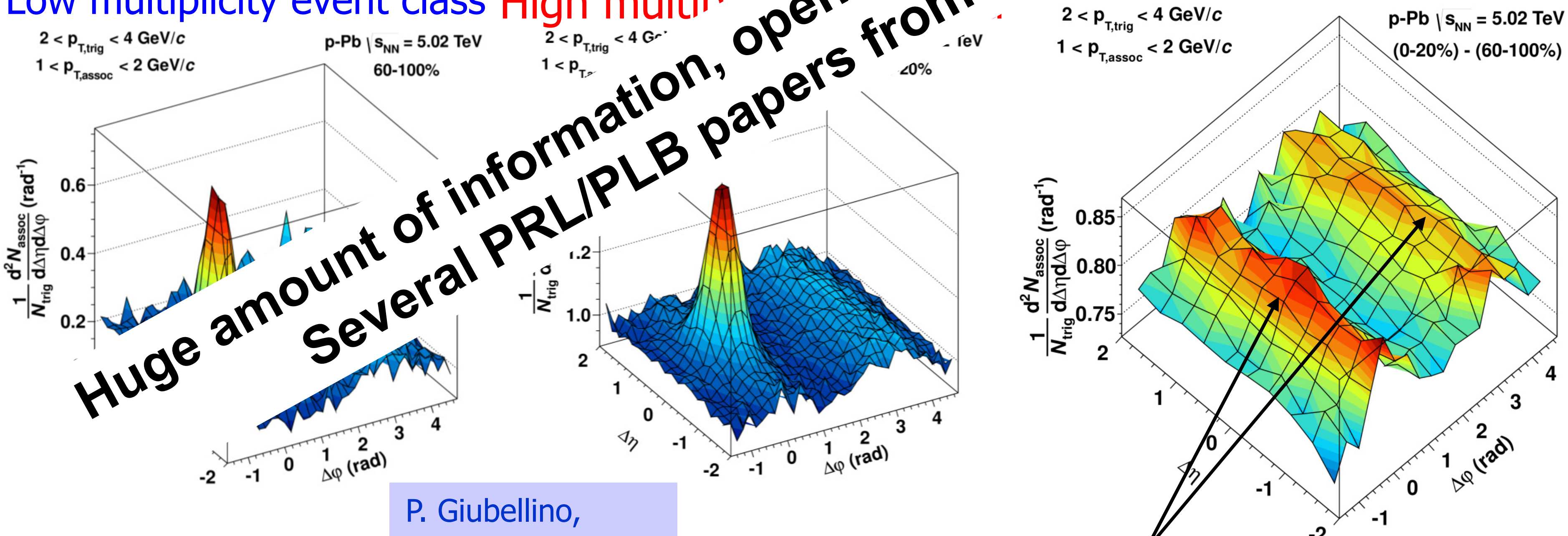
  - In agreement with viscous hydro calculations ?!

Huge amount of information, opening a new window in the field

Several PRL/PLB papers from 4 h of collisions

Low multiplicity event class High multip[…]



P. Giubellino, Evian Dec 2012

Double-ridge structure

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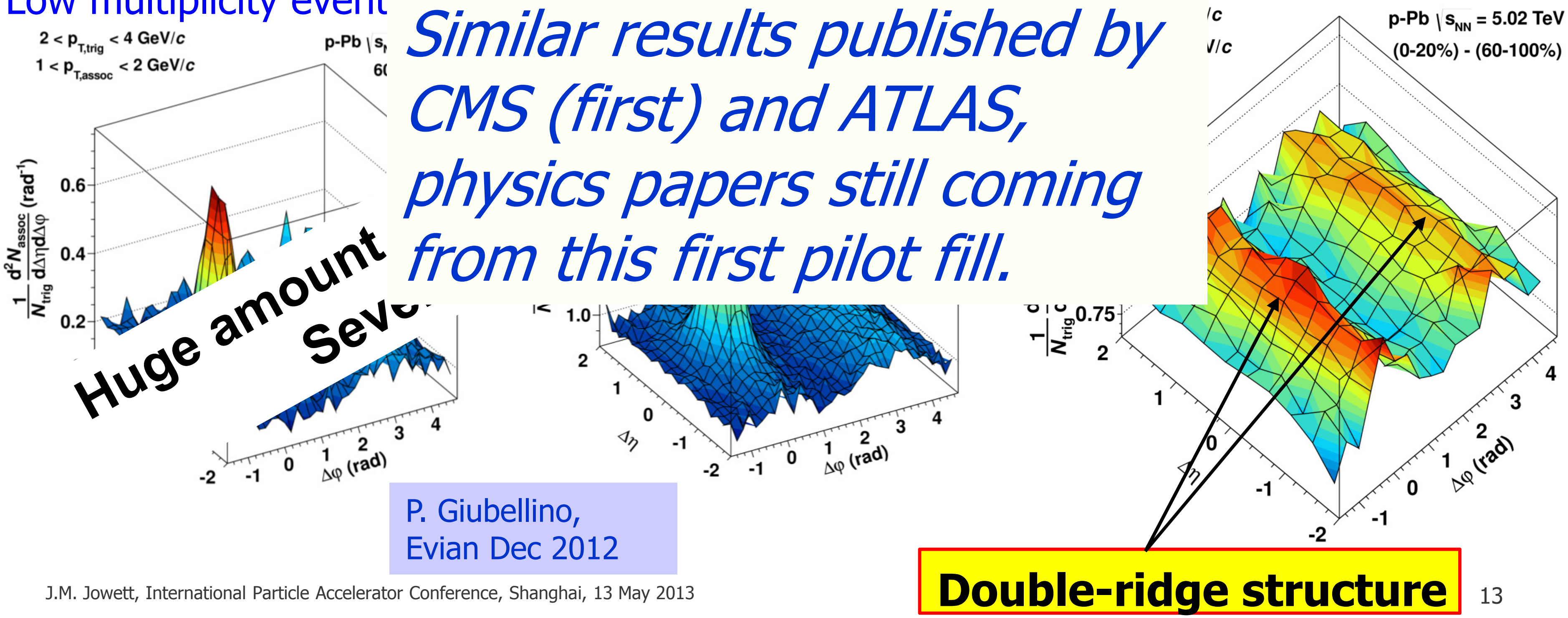
…ing a new window in the field

… 4 h of collisions

Low multiplicity event…



Huge amount …

Seve…

Similar results published by CMS (first) and ATLAS, physics papers still coming from this first pilot fill.

P. Giubellino,
Evian Dec 2012

First asymmetric collisions at LHC

2013 PROTON-LEAD RUN

Physics requests for the 2013 p-Pb run

- Initial minimum bias p-Pb for ALICE

$$\left.\begin{array}{l} L_{\text{ALICE}} < 0.05\times 10^{29}\ \text{cm}^{-2}\text{s}^{-1} \\ \mu_{\text{ALICE}} < 0.003 \end{array}\right\} \text{at } \sqrt{s_{\text{NN}}} = 5.02\ \text{TeV}\ (4Z\ \text{TeV/beam})$$

- Integrate 30 nb^{-1} in ALICE respecting the constraints:

$$L_{\text{ALICE}} < 1.\times 10^{29}\ \text{cm}^{-2}\text{s}^{-1}$$

$$\mu_{\text{ALICE}} < 0.05$$

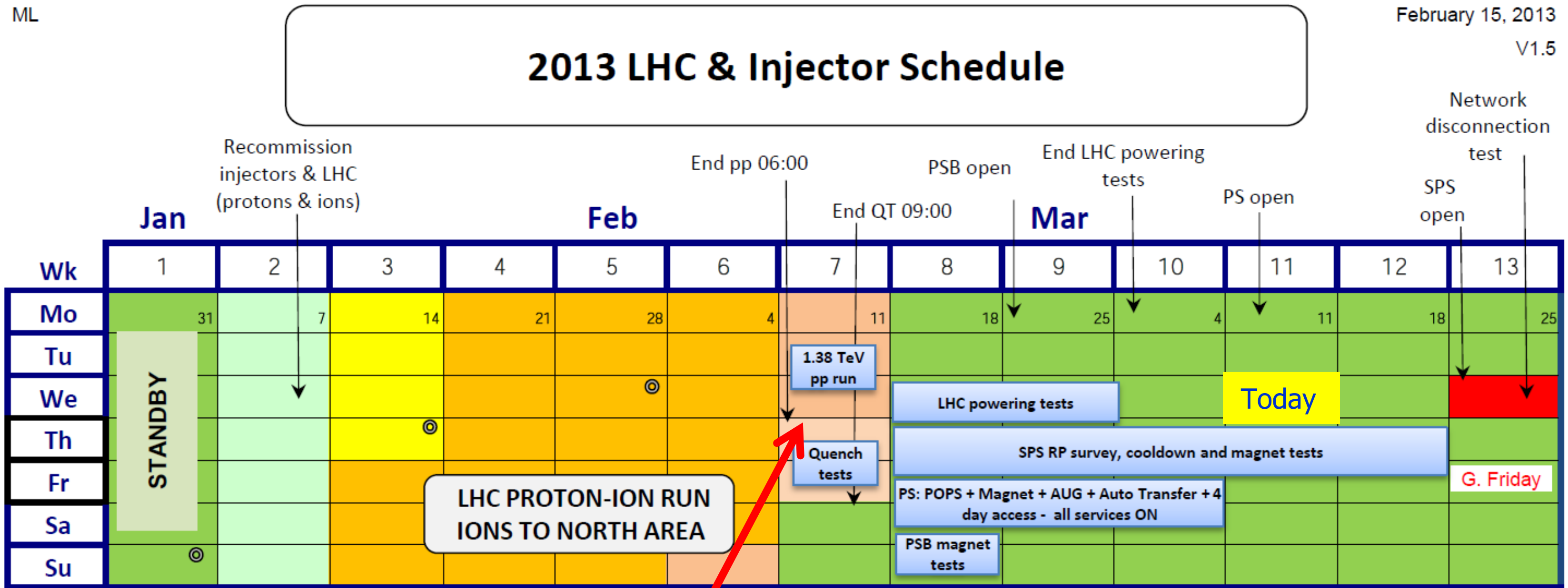
~ 30000 pilot runs

- Similar (or more) luminosity in ATLAS and CMS
- Beam reversal p-Pb to Pb-p for ALICE, LHCb
- 2 ALICE polarity reversals (also LHCb)
- Few nb^{-1} in LHCb (new to heavy-ion operation)
- Van der Meer (luminosity) scans

- 2$^{\text{nd}}$ priority: intermediate energy p-p operation

$$\sqrt{s_{\text{NN}}} = 2.76\ \text{TeV}\ (1.38\ \text{TeV/beam})$$

  - Integrate 5 nb^{-1} in ATLAS, CMS
- 3$^{\text{rd}}$ priority: p-Pb with injection optics for LHCf
  - About 1 day required to commission and run



2013 run was finally extended by 2 days to allow time to reach integrated luminosity goals for both p-Pb and intermediate energy p-p.

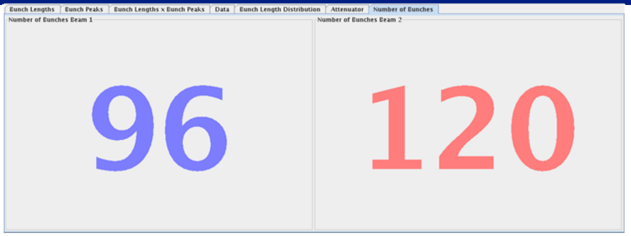
Commissioning p-Pb operation, January 2013

- Still no test of unequal frequency injection ramp with required intensity … factor 1000 in luminosity to gain over pilot run
- From ~cold start after end-of-year stop
  - Pb pre-injectors kept running
  - → **D. Manglunki et al, WEPEA061, Wed** (remarkable performance of Pb injectors later!)
- Detailed plan of essential stages, adapted in real time
  - Decided to re-make optics squeeze from scratch (new low values in ALICE, LHCb)
  - Off-momentum collisions, many new features
  - New collimation set-up
  - → **R. Versteegen et al, TUPFI041, Tue**
- Unprecedented new operation mode of LHC commissioned in < 10 days (including ~4 days down-time for power, cryo)
  - Quality of LHC hardware, systems, operation

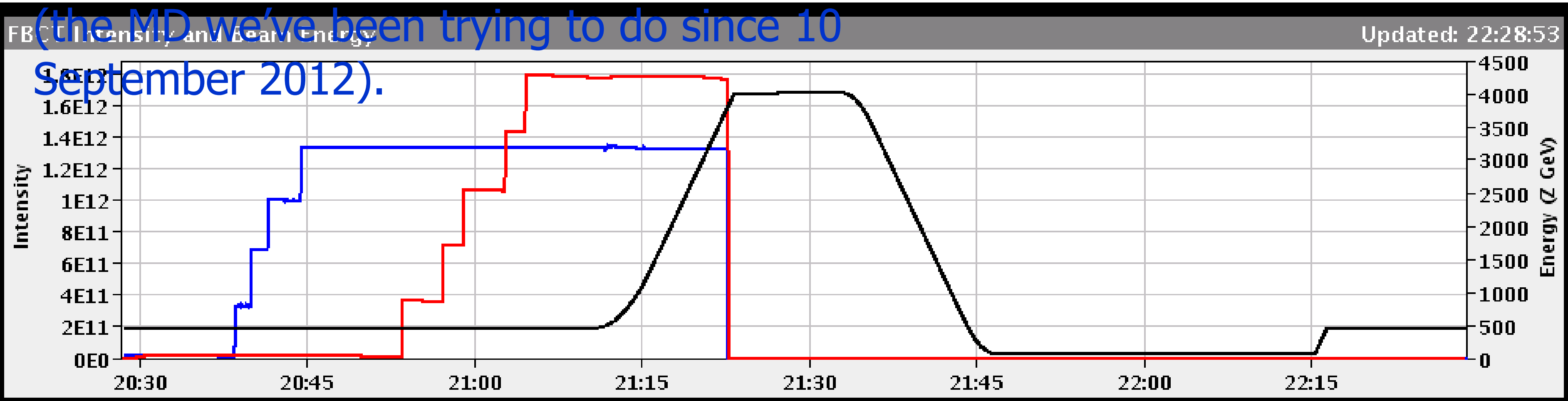
The Moment of Truth, finally, 20/1/2013

Fill 3474

First injection and ramp of Pb trains against proton trains

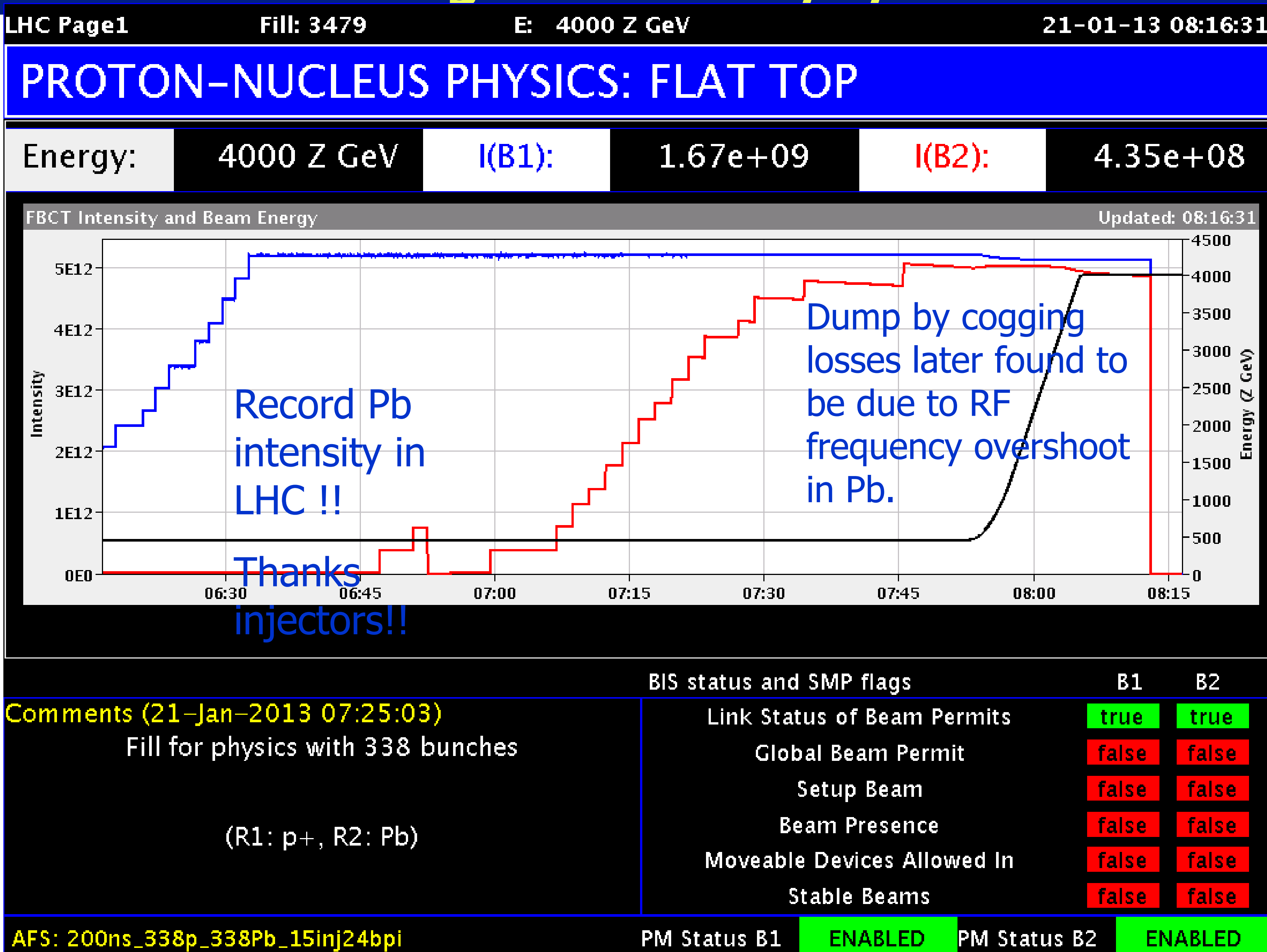


(the MD we've been trying to do since 10 September 2012).



Moving long-range beam-beam encounters do not cause significant beam losses or emittance blow-up with LHC parameters

Full filling scheme 21/1/2013



Record Pb intensity in LHC !!

Thanks injectors!!

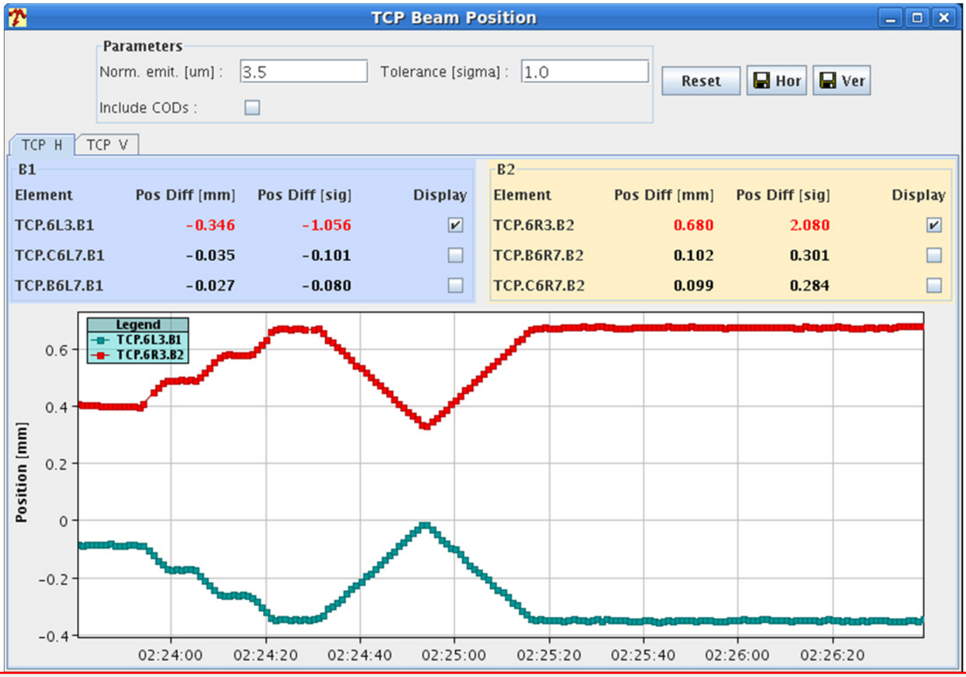
Dump by cogging losses later found to be due to RF frequency overshoot in Pb.

During commissioning

Pb-p Intensity ramping was delayed by several dumps caused by losses at the start of cogging, when the two beams are brought to the same frequency

Losses were reduced by making a slower frequency trim (3 steps of 10 Hz max, and 10 s waiting time in between)

- The BLM beam dump threshold was increased in selected BLMs. This was also needed to cope with losses in squeeze and start of ramp
- All problems were in the Pb ring, probably linked to the lower collimation efficiency
- Ring 2 was somewhat less “touchy”.
  p-Pb caused fewer problems than Pb-p



Horizontal position B1 and B2. Visible are the three steps (~ 10 Hz each) with the 10 s waiting. The following triangle brings the intersection point (IP) in the exact center of the detectors. To achieve this, the beams are briefly brought back to the center orbit.

RF "cogging" during and after energy ramp

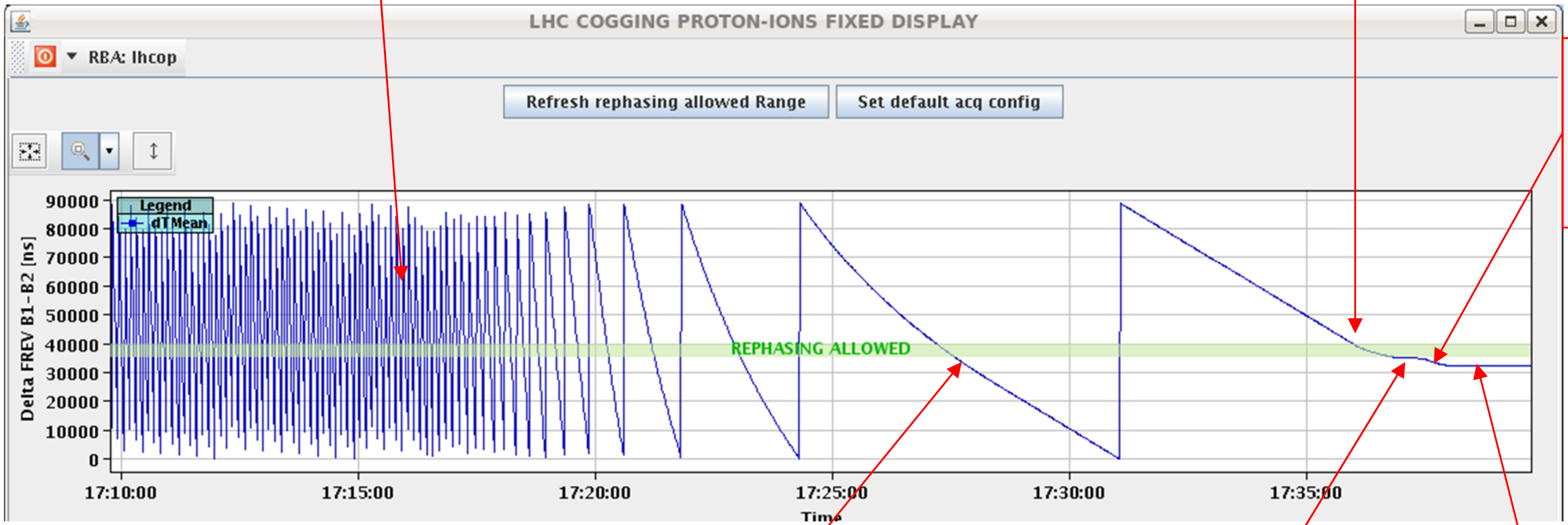
We monitor the time interval between the revolution frequency markers (bucket 1 of both rings)

Cogging takes 15 minutes maximum

Fully automatic. The references were calibrated at the beginning of the run and not touched during the four weeks

IP close to desired position, we move the beams to the common frequency

Ramping



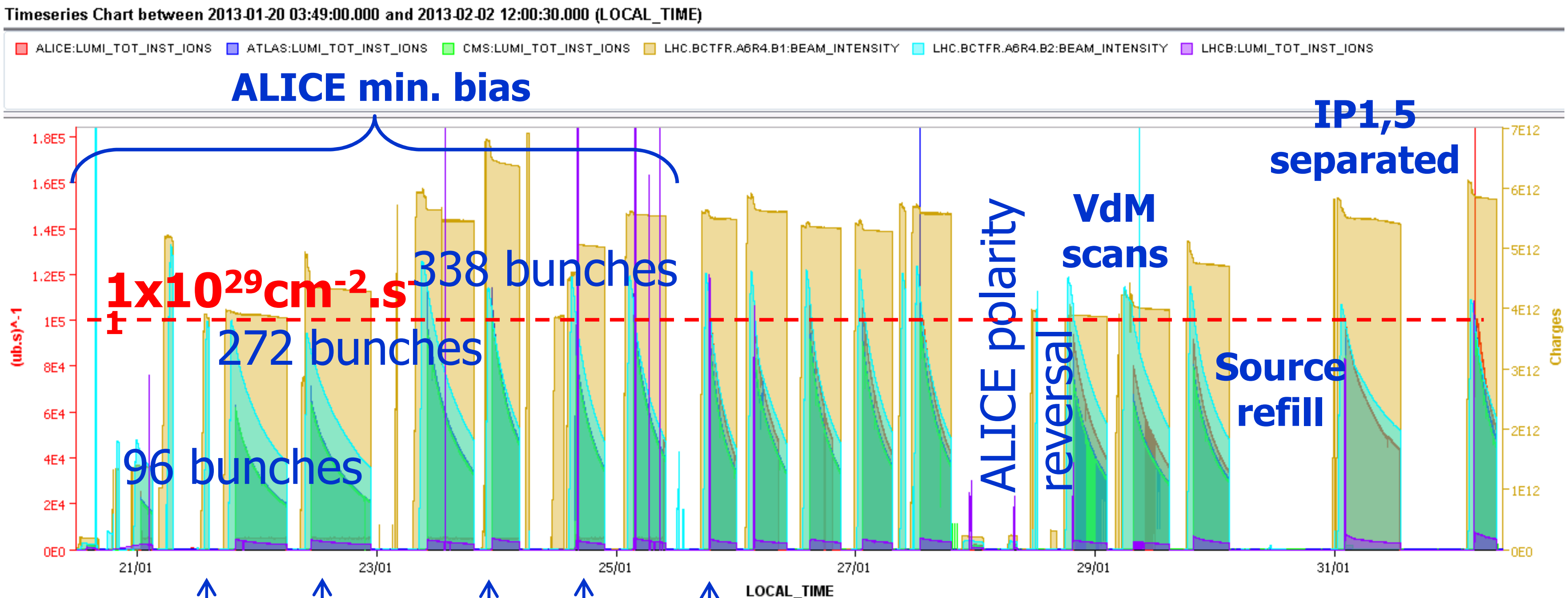
One last orbit bump to get IP exact

Start flat top but the IP is very far from the desired collision point. We move the beams onto the central orbits. With 60 Hz difference, IP makes one turn in 11 minutes

Same frequency but IP not exact

Done!

Run overview: p-Pb luminosity production



Increase of BLM monitor factor (losses during cogging)

Problem of losses during cogging solved

TOTEM Roman Pots moved in

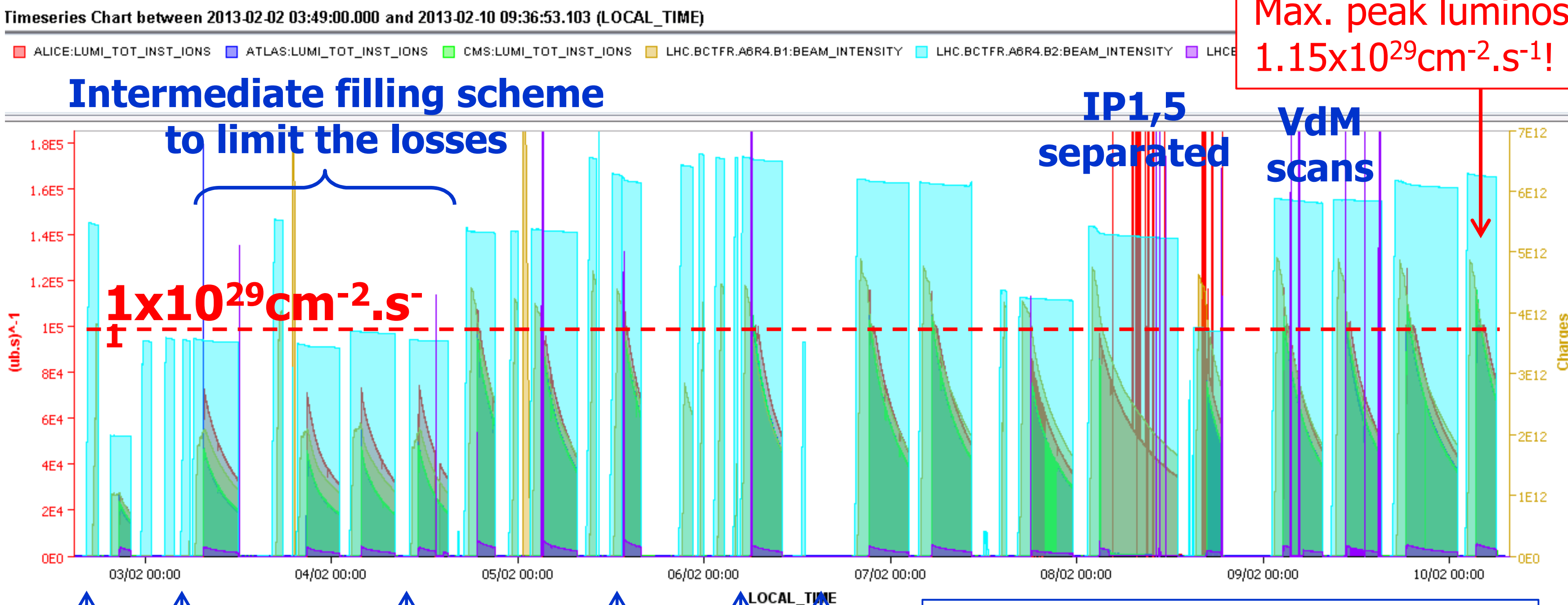
ALFA Roman Pots moved in

Longitudinal blow up ON

R. Versteegen

Run overview: Pb-p luminosity production

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



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

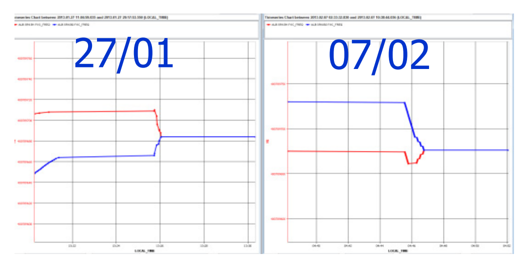
Increase bandwidth of orbit feedback

Increase of BLM monitor factor (losses during the squeeze),

Increase of BLM monitor factor (losses at the start of the ramp), rematch injection energy to the SPS

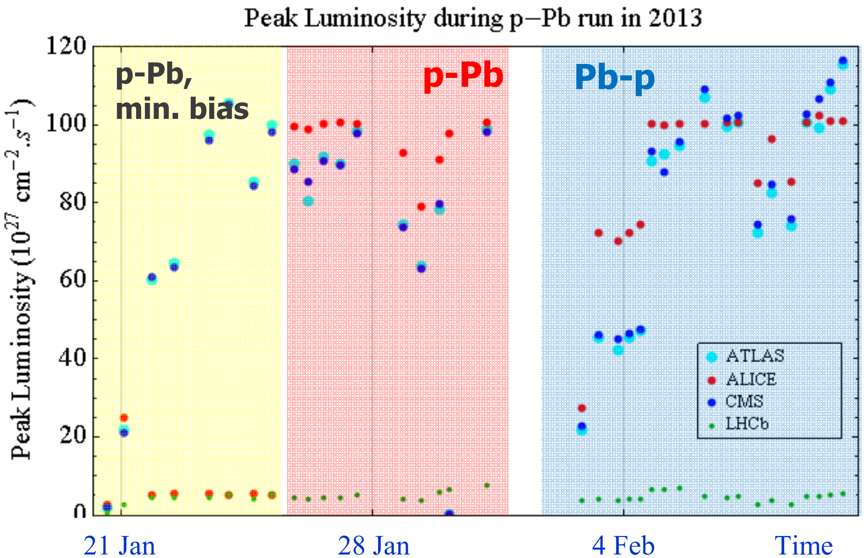
reduction of longitudinal blow-up at injection

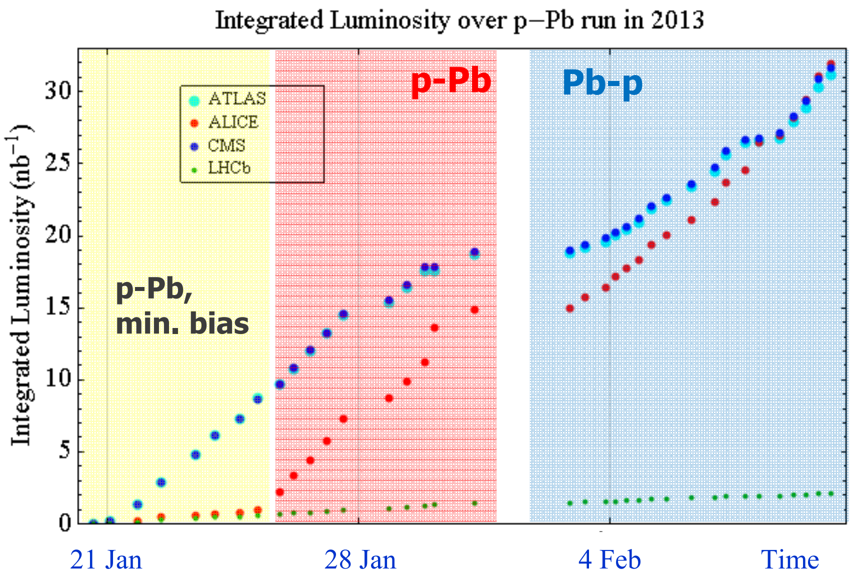
Common frequency trimmed by -10Hz



RF frequencies

Peak and integrated luminosity evolution

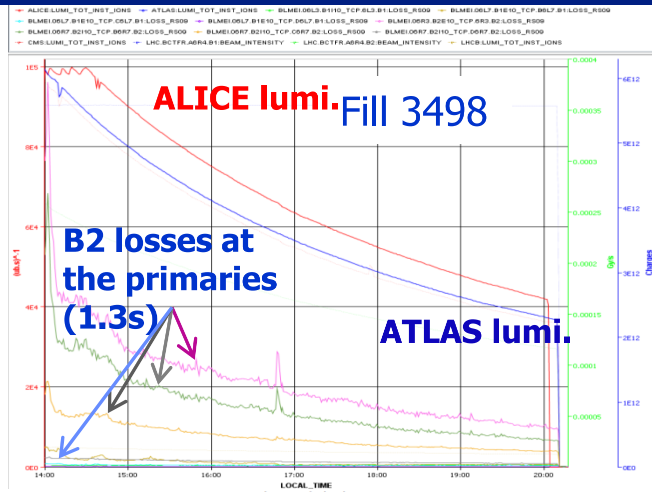


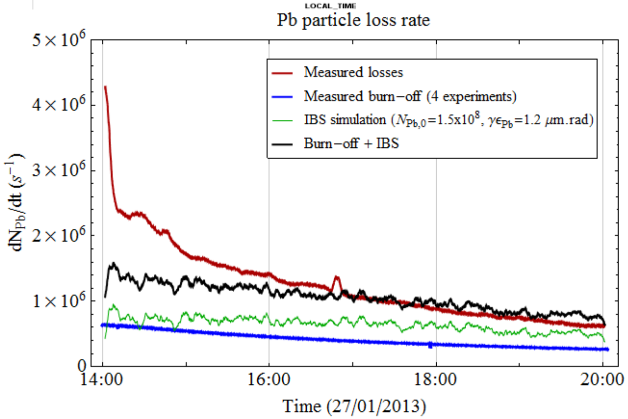


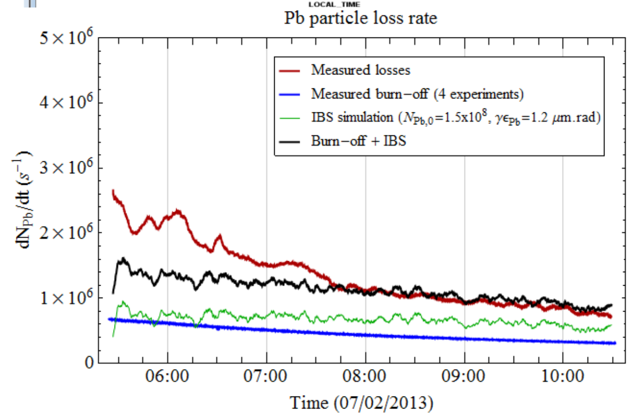
- Full instantaneous luminosity 1×10^{29} cm^{-2}.s^{-1} already reached with the first fill with full filling scheme
- Levelling in ALICE at 1×10^{29} cm^{-2}.s^{-1} in almost all standard fills
- Two catch-up fills done with IP1 and 5 separated, allowing ALICE to catch up after initial minimum-bias
- Van der Meer scans done in both configurations
- Final integrated luminosity above experiments' request of 30 nb^{-1}
- The run ended with record peak luminosity of 1.15×10^{29} cm^{-2}.s^{-1}, record turn around of 2.37 h

ALICE: 31.94 nb^{-1} ATLAS: 31.2 nb^{-1} CMS: 31.69 nb^{-1} LHCb: 2.12 nb^{-1}

Luminosity evolution during a fill

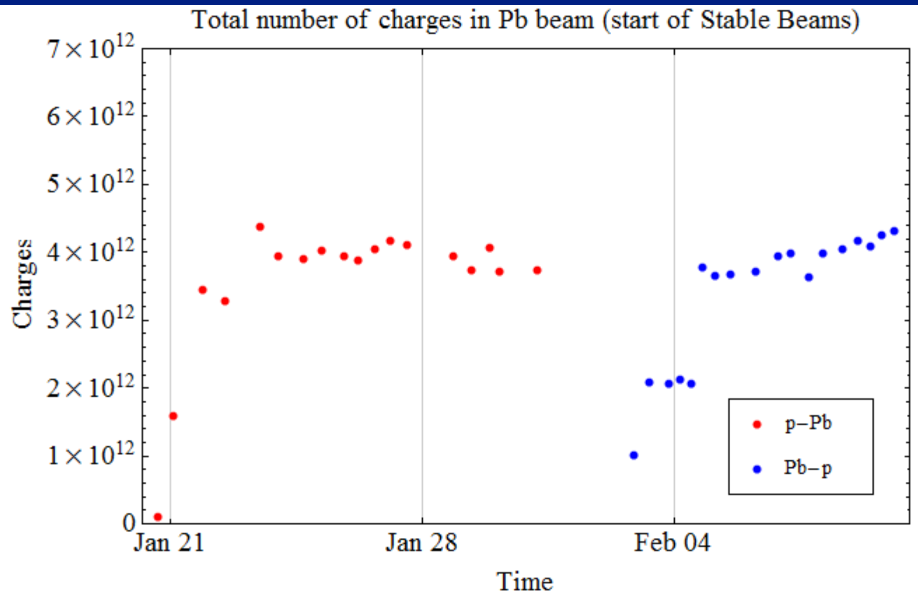


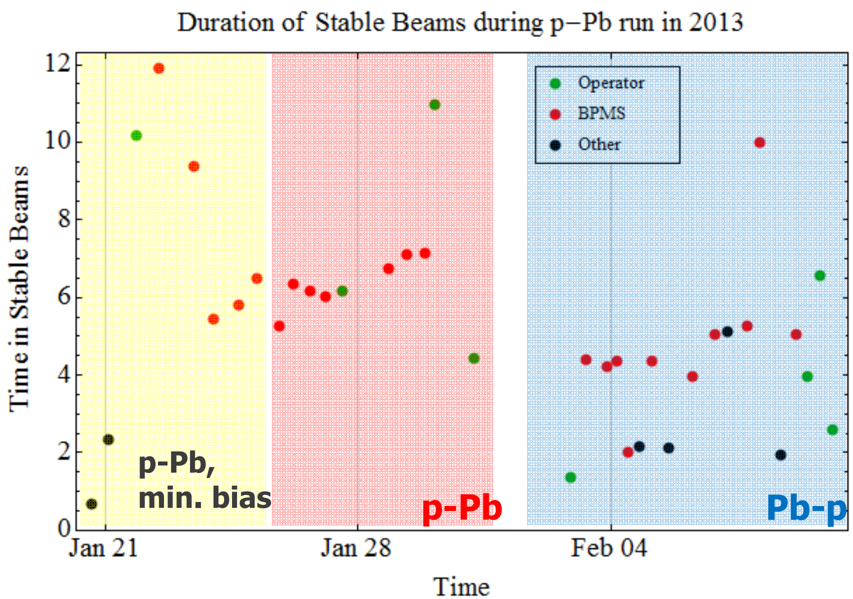




- Luminosity evolution was driven by Pb intensity decay.
- Sources of losses were mainly luminosity burn-off and intra-beam scattering (IBS), possibly also beam-beam (unequal beam sizes in collision)
- Additional losses at start of stable beams are comparable to Pb beam BLM signals, likely due to tight collimator settings.

Pb intensity evolution, fill duration





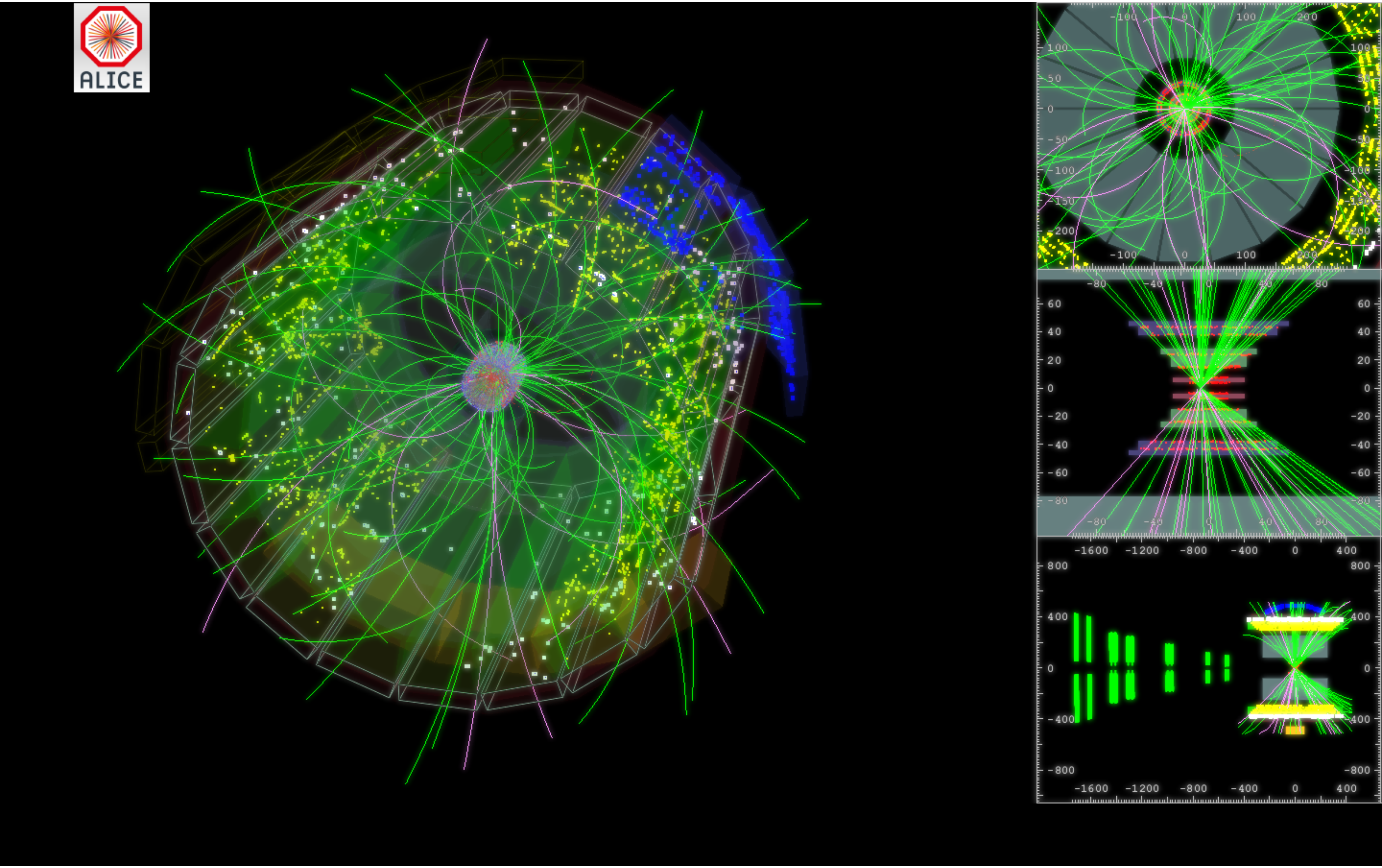
- Injectors provided very good quality Pb beams: average number of ions per bunch was 1.44×10^8 at start of stable beams (mean over the run), i.e. almost twice the nominal intensity,
- Most fills were dumped by the BPMSs thresholds in IR6 due to misreading for lowest intensity Pb bunches
- BPMSs' limit was reached faster with B1 (Pb-p) than with B2 (p-Pb),
- Maximum fill durations of more than 10h were reached with intermediate filling schemes and special fills colliding only in ALICE (and LHCb).

Peak performance in p-Pb runs

	2012 pilot	2013 production
$E\,/\,(Z\ \text{TeV})$	4	4
k_c	(8,8,8,8)	(296,288,296,39)
β^*/m	(11,10,11,10)	(0.8,0.8,0.8,2.0)
$\gamma\varepsilon$(p)/ μm	1.7	2
$\gamma\varepsilon$(Pb)/ μm	1.2	1.5
N_{bp}	1.2×10^{10}	1.6×10^{10}
$N_{b\mathrm{Pb}}$	7×10^{7}	12×10^{7}
$L\,/\,(10^{29}\ \mathrm{cm}^{-2}\mathrm{s}^{-1})$	0.001	(1.12,1.01,1.16,0.05)

- Some numbers are averages because of the wide distribution of individual bunch parameters.
- Sets of four values correspond to the interaction points IP1(ATLAS), IP2(ALICE), IP5(CMS), IP8 (LHCb).

http://alice-logbook.cern.ch/aliceOnline/alice_online.html



symmetry of particle physics

A joint Fermilab/SLAC publication

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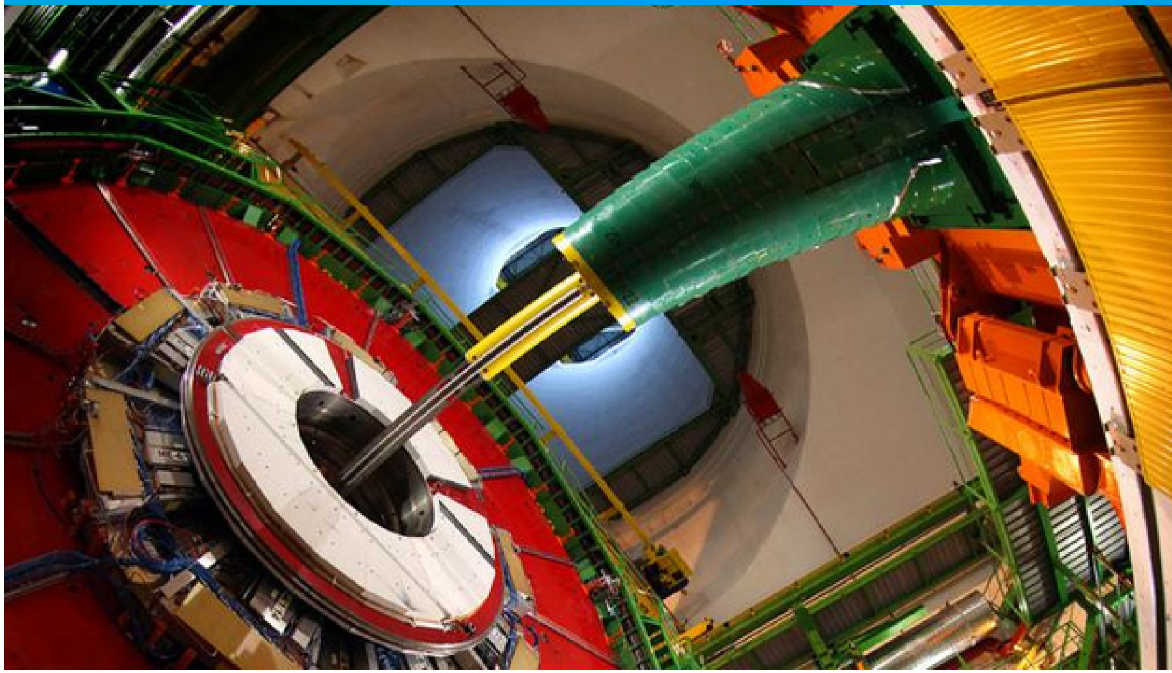


Photo: Michael Hoch / CERN

breaking

May 07, 2013

Smallest lab-made drop of liquid might cause strange particle behavior

A new result from the CMS collaboration takes a step toward revealing the origin of the mysterious 'ridge effect.'

By Kelly Izlar

PDF Download

Related *symmetry* content

The Large Hadron Collider is known for a list of impressive facts—it's the world's largest and most powerful particle collider; it accelerates particles to nearly the speed of light; its cryogenic system keeps it colder than outer space.

Now it's under consideration for a new superlative: Scientists there might have created the most minuscule drop of liquid ever formed in a

most popular

April 30, 2013

Matter, antimatter, we all fall down—right?

Scientists perform the first direct investigation into how antimatter interacts with gravity.

May 7, 2013

Smallest lab-made drop

May 11, 2013

This week's top tweet: Smallest lab-made drop of liquid might be

First results from 2013 run now emerging:

Collective effects on a scale where they were not expected: viscous hydrodynamics of Quark-Gluon Plasma, gluon saturation (colour-glass condensate), ...?

Summary of first LHC p-Pb run

- A new mode of operation, unforeseen in the baseline design of the LHC, was commissioned in 10 days (including >4 days' down time).
- The physics requirements were fulfilled in both configurations p-Pb and Pb-p
- ALICE, ATLAS, CMS, LHCb, ALFA, TOTEM, LHCf all took data.
- Pb beam from injectors: very high quality, new intensity records.
- No serious beam-beam effects thanks to low proton beam intensity, allowing us to break a few rules (only way to give LHCb collisions).
- Proton beam intensity could not be increased because of bad readings on beam-dump interlock BPMs at their sensitivity limit.
- No clear effects of moving long-range beam-beam encounters at injection and ramp.
- Duration of fills given by strong luminosity burn-off and IBS.
- Beam loss monitor dump thresholds were pushed to theoretical quench limits, losses might have been reduced with more relaxed (=more open) collimator settings.
- Lack of emittance measurement capability during run
- Many other features not described here …
- Prospect of about another order of magnitude in luminosity in future LHC runs at higher energy

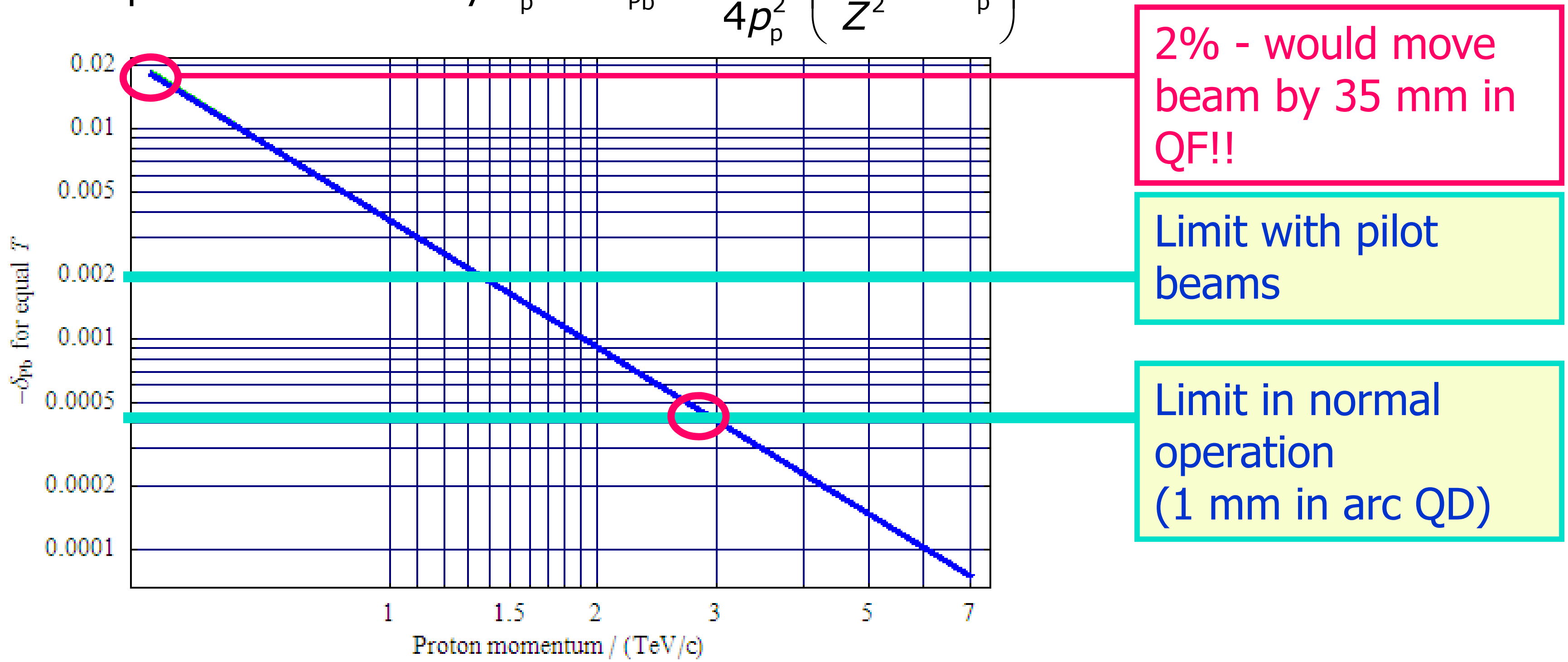
More about LHC p-Pb run

- R. Versteegen et al,
  - Operating the LHC Off-momentum for p-Pb Collisions
  - TUPFI041, Fire Poster Area, Tuesday
- D. Manglunki et al,
  - The First LHC p-Pb run: Performance of the Heavy Ion Production Complex
  - WEPEA061, Earth Poster Area, Wednesday
- Links to these, posters, other papers, talks, news items, videos, etc. **http://cern.ch/ipac2013-LHC-heavyion**

BACKUP SLIDES

Momentum offset required through ramp

Minimise aperture needed by $\delta_p = -\delta_{Pb} = \frac{c^2 \gamma_T^{\,2}}{4 p_p^2}\left(\frac{m_{Pb}^2}{Z^2} - m_p^2\right)$.

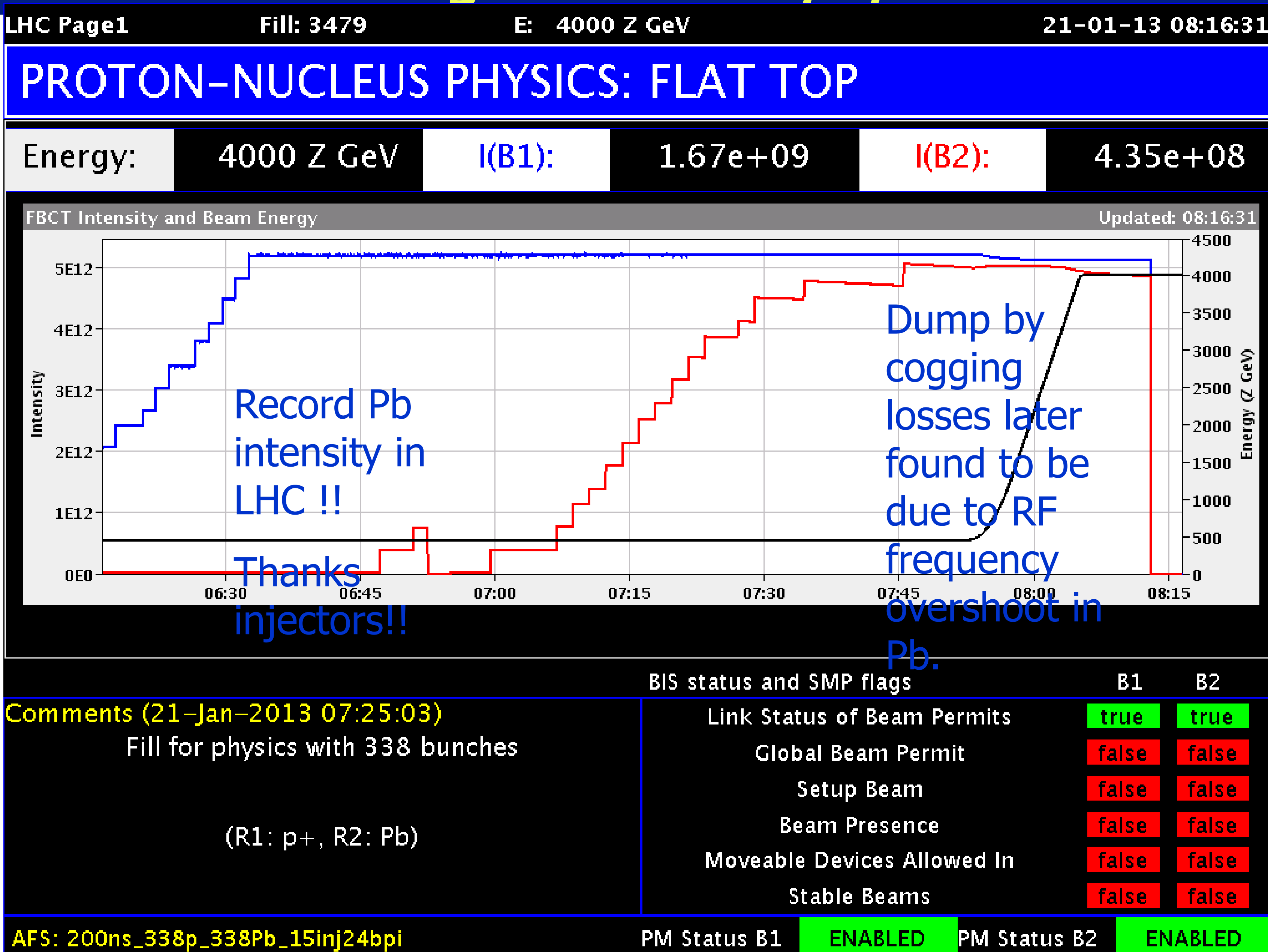


Revolution frequencies must be equal for collisions at top energy.

Lower limit on beam energy for p-Pb collisions, E=2.7 Z TeV.

RF frequencies must be unequal for injection, ramp!

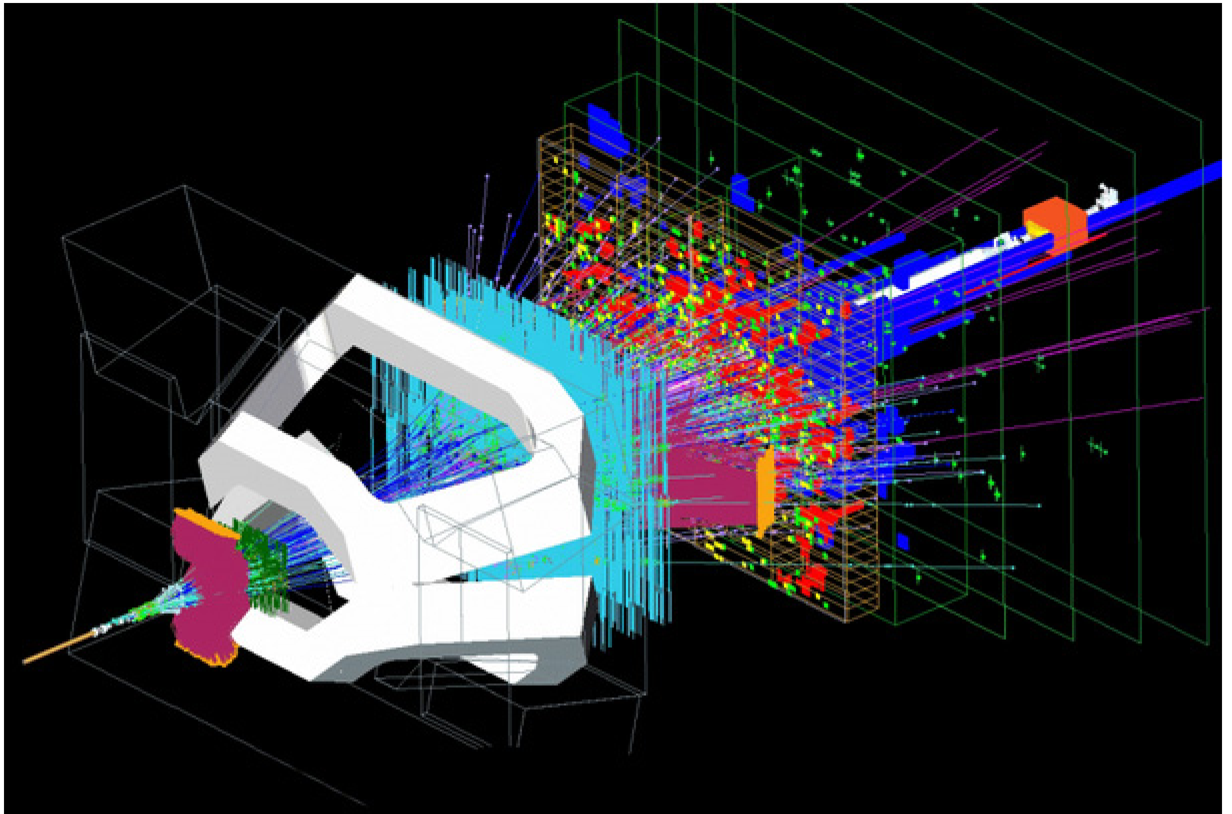
Full filling scheme 21/1/2013



CERN Accelerating science

Proton-lead run brings new physics reach to LHCb

Antonella del Rosso

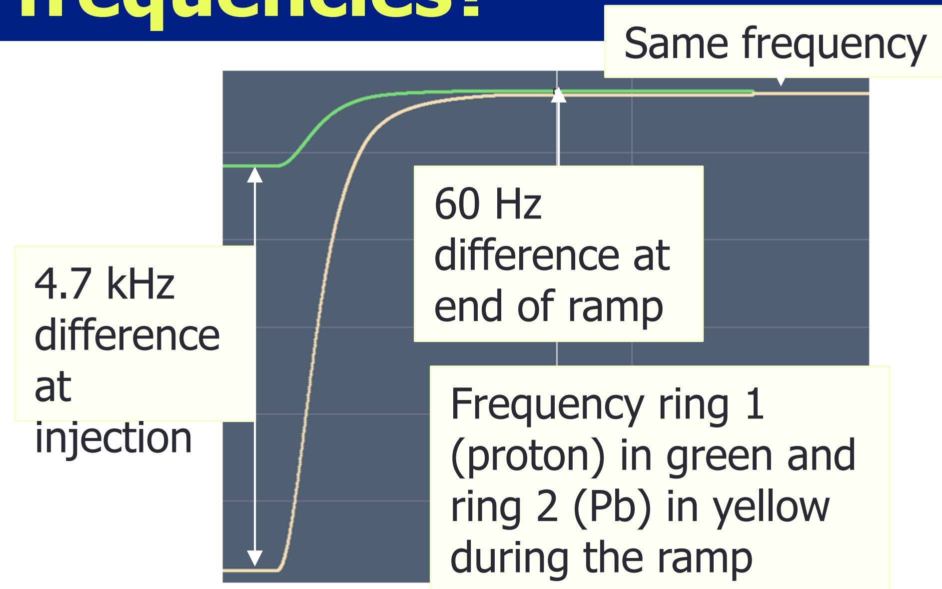


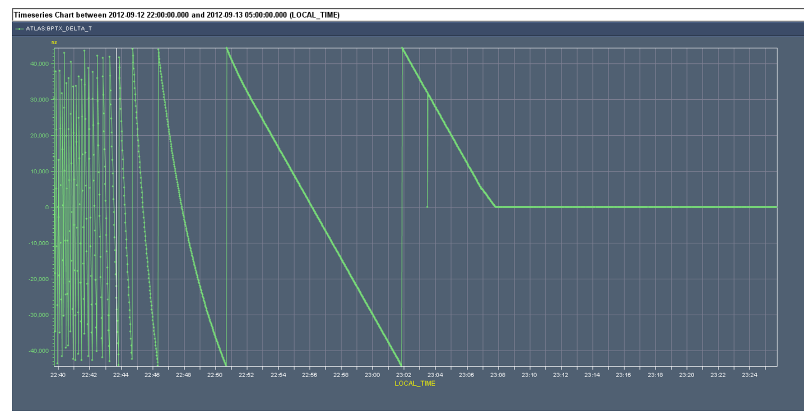
A proton-lead ion collision, as observed by the LHCb detector during the 2013 data-taking period (Image: LHCb/CERN)

During the recent lead-proton run at the Large Hadron Collider (LHC), the Large Hadron Collider beauty (LHCb) experiment took data from collisions between protons and ions for the first time.

Why unequal frequencies?

- The two LHC rings see identical strength but opposite sign magnetic field
- The two RF systems are independent
  - At injection we have 4.7 kHz difference between the two rings (at 400 MHz)
  - At the end of the 4 TeV ramp the difference is 60 Hz only
- On flat top we lock the two rings on the same frequency, resulting in a +0.3 mm offset of the p ring and -0.3 mm offset of Pb ring
- We then gently cog the two rings to achieve crossing in the detector. It takes 11 minutes maximum for the 27km long ring. The intersection point moves around *Pays de Gex* at ~150 km/h!

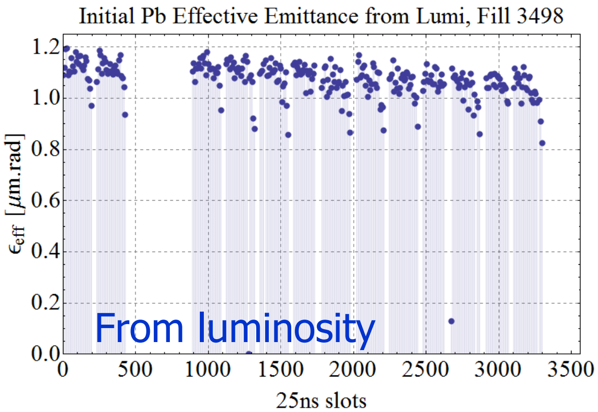


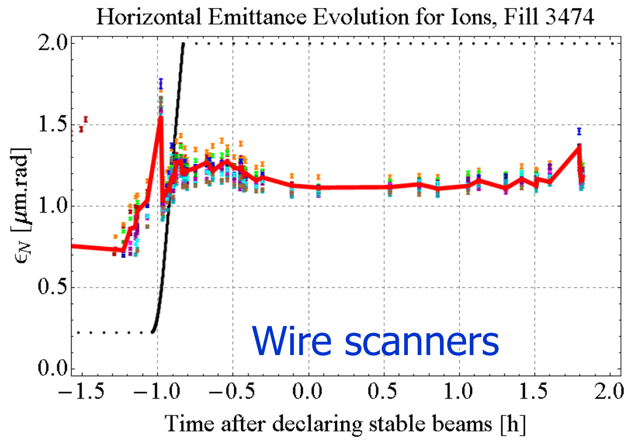


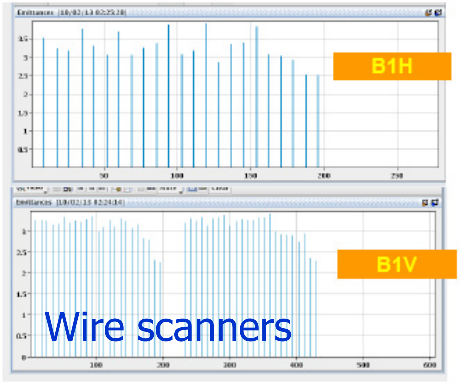
ATLAS BPTX from end-ramp to end-rephasing. Measures the time interval between passage of bucket 1 of both rings in the detector

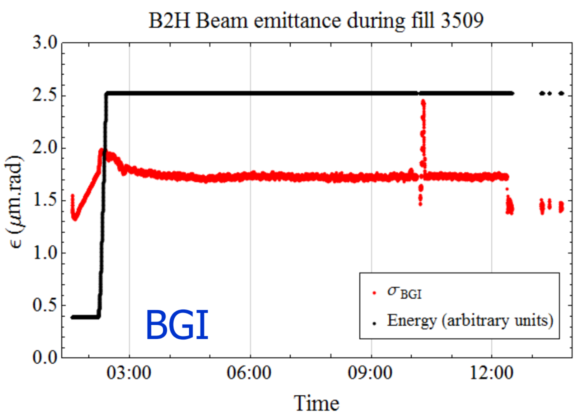
Beam performances over the run – emittances 2/2

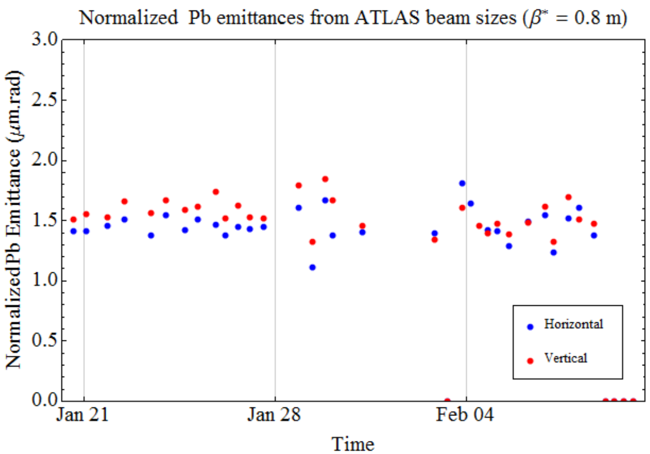
M. Sapinski, M. Schaumann, G. Trad











From ATLAS lumi data: stable emittance over the run, close to 1.5 μm.rad (=nominal)

- Wire scanners available during commissioning and Pb-p modes,
- BGI available for B2,
- BSRTs signal at injection very low → set to mean over the bunches,
- Absolute calibration very difficult for all measurements,
- Emittance from luminosity assumes equal beams which was not the

R. Versteegen

Beam-beam effects 1/2

Baseline performance extrapolated from Pilot Fill

$f0 \to 11245.5$ Hertz
$\sigma pPb \to 2.$ Barn
$\gamma p \to 4263.16$
$\gamma Pb \to 1693.45$
$\beta alice \to 0.8$ Meter
$\beta atlas \to 0.8$ Meter
$\beta lhcb \to 2.$ Meter
$NPb \to 1.2 \times 10^{8}$
$Np \to 1.5 \times 10^{10}$
$kb \to 318$
$kc15 \to 276$
$kc2 \to 276$
$kc8 \to 42$
$Nexp \to 3$
$EmittPbx \to 1.4 \times 10^{-6}$ Meter
$EmittPby \to 1. \times 10^{-6}$ Meter
$Emittpx \to 1.7 \times 10^{-6}$ Meter
$Emittpy \to 1.7 \times 10^{-6}$ Meter

	ATLAS	ALICE	CMS	LHCb
N_{Pb}	1.2×10^{8}			
N_p	1.5×10^{10}			
β^*	0.8	0.8	0.8	2.
$L/cm^{-2}s^{-1}$	1.01×10^{29}	1.01×10^{29}	1.01×10^{29}	6.14×10^{27}
μ	0.065	0.065	0.065	0.026

Already close to ALICE maximum luminosity with emittances of pilot fill, good Pb intensity, fairly conservative proton intensity – leaves room to try to increase it up to a factor ~3 (level ALICE if necessary).

Can easily be worse if we have blow-up or losses at injection or ramp (from moving encounters, IBS, …).

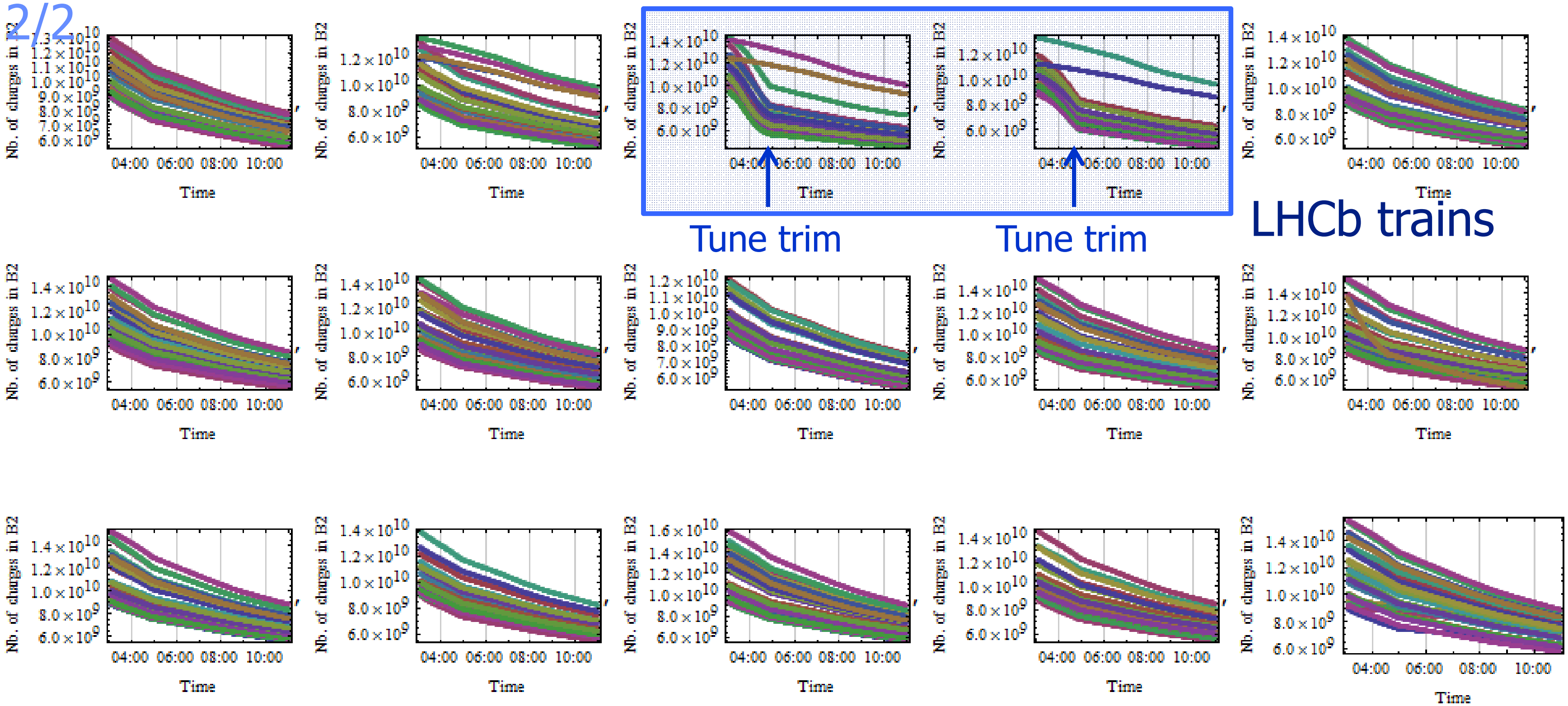
Unequal beam sizes were OK in pilot fill with higher β*. Emittance increase will probably reduce luminosity for all experiments and pile-up for ALICE.

This is our preferred first goal for the run. But, on the basis of present knowledge, it is by no means a "safe set of parameters" (except for optics).

- Proton intensity could not be increased further than 1.8×10^{10} charges because of BPMs bad readings (injection of 3×10^{10} p/bunch was tested on 17/01/2013),
- No obvious effects observed due to moving encounters at injection and during the ramp,
- Low intensity beams allowed us to get around beam-beam effects related to unequal beam sizes, or small separation for 'bad' polarity of ALICE…

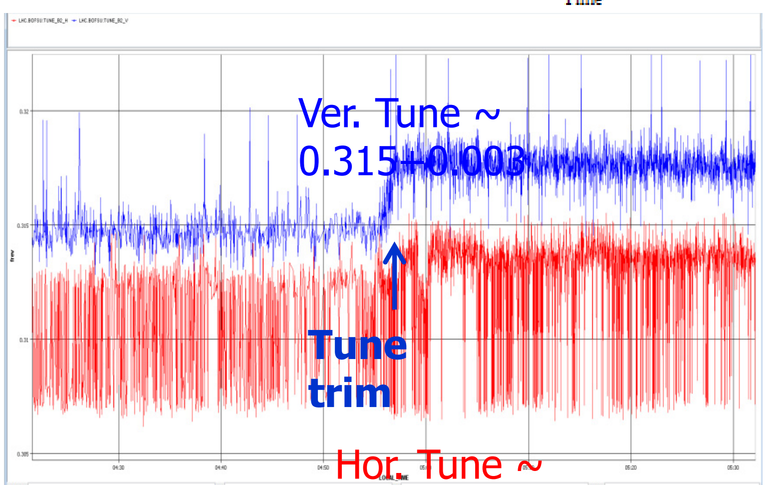
R. Versteegen

Beam-beam effects 2/2



… but still beam-beam effects were there.

LHCb bunches in p-Pb configuration had parasitic encounters at small separation in IR2 (≈ 1σ) and suffered more than the others from a small tune error (fill 3509).



Openings for future ion runs – batch by batch blow up at injection 2/2

- Batch by batch blow up to 1.4 – 1.6 ns at injection was tested to reduce IBS effect on transverse emittances,
- No clear effect on p-Pb luminosity,
- No clear conclusion from beam size measurements yet, analysis on going. IBS simulations results for 1.4 – 1.5 ns bunch length (M. Schaumann):

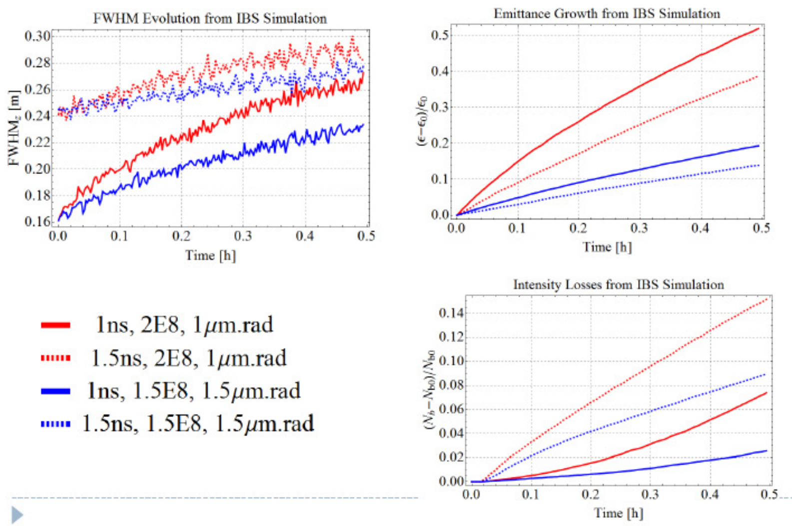
- Horizontal emittance growth is slowed down by >10% after 30min

- Vertical emittance is not affected (as expected)

- Losses are enhanced for blown up bunches by about ~5% after 30min

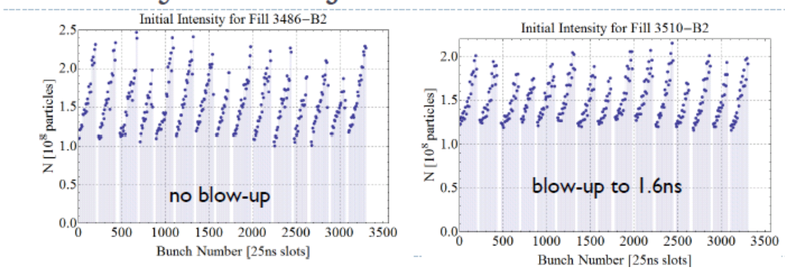
P. Baudrenghien, J. Jowett, T. Mastoridis, M. Sapinski, M. Schaumann

Compare Best with Average Bunch

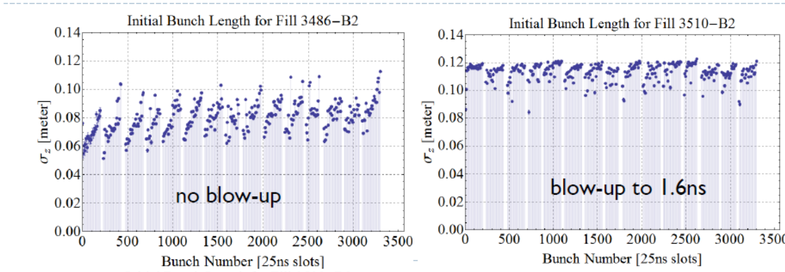


Intensity after injection

M. Schaumann



Bunch length after injection



Choice of operating energy for p-Pb in 2012

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

$$\sqrt{s_{NN}} \approx 2c\, p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}},$$

$$y_{NN} = \frac{1}{2} \log \frac{Z_1 A_2}{A_1 Z_2}$$

2.2 *Z* TeV "ideal" but would cost factor ~6-7 in integrated luminosity and exceeds 1 mm orbit limit in LHC arcs.

4 *Z* TeV, the final choice for 2012, will be "easiest" from accelerator point of view.