Repurposing the Large Hadron Collider

John Jowett, CERN

With thanks to many colleagues at CERN.

Aim of this talk

- Quick introduction to main features of the LHC
  - Basic physics should be familiar …
- Emphasis on the nuclear collision ("heavy-ion") operation, designed to study nuclear matter at extreme temperature and density, collective effects in QCD, quarks and gluons are deconfined, the Quark-Gluon Plasma, first few μs of cosmic history
- Describe the implementation of a new and unexpected mode of hybrid collisions in record time
- [This is *not* a talk about the particle or nuclear physics results from the LHC experiments.]

Hot and dense matter

ALICE has measured the thermal photon spectrum from the QGP, the highest temperature ever seen in the lab:

$T_{\text{ALICE}} = 304\ \text{MeV} / k_B = 3.51 \times 10^{12}\ \text{K}$

Compare temperature from nuclear fusion at core of sun

$T_{\text{sun}} = 1.6 \times 10^{7}\ \text{K} = \dfrac{T_{\text{ALICE}}}{200000}$

Energy density in LHC Pb-Pb collisions is

$u_{\text{QGP}}\ ;\ 15\ \text{GeV/fm}^3$

Consider all the electrical energy generated in Europe in one year

$U_{\text{Ey}} = 3.6 \times 10^{12}\ \text{kWh}$

and squeeze it, all at once, into a sphere of radius r chosen to get the same energy density as the QGP:

$\dfrac{U_{\text{Ey}}}{(4/3)\pi r^3} = u_{\text{QGP}} \Rightarrow r = 1.1 \times 10^{-6}\ \text{m}$

Mass of this speck of dust ≈ 143 kg

One LHC Pb-Pb collision $\approx 10^{-23} U_{\text{Ey}}$

The LHC Programme

- LHC spends most of its time colliding protons
  - World's dominant particle physics programme with 4 large experiments ATLAS, CMS, ALICE, LHCb plus other smaller ones
- About one month per year colliding nuclei ("heavy ions") in ALICE (specialised experiment) and ATLAS, CMS (general purpose experiments) and now LHCb
  - This is nevertheless one of the world's largest physics communities and programmes
  - Continues beyond RHIC at Brookhaven and previous fixed target facilities (SPS, AGS, …).

Protons in LHC:

0.45 TeV (injection from SPS) $\leq p_p \leq$ 7 TeV (collision)

(so far only 3.5 and 4 TeV)

$^{208}\mathrm{Pb}^{82+}$ nuclei in LHC ($Z = 82, A = 208$):

$0.45Z$ TeV $= 0.177A$ TeV $=$ 36.9 TeV

$\leq p_{\mathrm{Pb}}$

$\leq 7Z$ TeV $= 2.76A$ TeV $=$ 574 TeV

So far $3.5Z$ (2010-11) and $4Z$ TeV (2012-13),

$6.37Z$ TeV (yesterday)

Reminder: Luminosity of a hadron collider (1)

Event rate for process with given cross section $= \sigma L$

Particles removed from beam by collisions

$$\frac{dN_b}{dt} = -\sigma_{\text{tot}} L + (\text{other single beam physics})$$

$$\sigma_{\text{tot}} = \begin{cases} 0.09 \text{ b (proton-proton)} \\ 520 \text{ b (Pb-Pb)} \end{cases}$$

al amplitude functions:

$= \beta_y^* = \beta^*$,

metric and normalised emittance:

$$\varepsilon_x^* = \varepsilon_y^* = \varepsilon^* = \frac{\varepsilon_n}{\sqrt{\gamma^2 - 1}}$$

$\Rightarrow$ Round beams at IP:

$$\sigma_x^* = \sigma_y^* = \sigma^* \approx \sqrt{\frac{\beta^* \varepsilon_n}{\gamma}}$$

(N.B. LHC uses RMS emittances.)

- Parameters in luminosity
  - No. of particles per bunch N
  - No. of bunches per beam k_b
  - No. of bunches colliding at IP k_c
    - $(k_c < k_b)$
  - Relativistic factor γ
  - Normalised emittance ε_n
  - Beta function at the IP β^*
  - Crossing angle factor F
    - Full crossing angle θ_c
    - Bunch length σ_z
    - Transverse beam size at the IP σ^*

Reminder: Luminosity of a hadron collider (2)

$$L = \frac{N_b{}^2 k_c f}{4\pi\sigma_x\sigma_y} F = \frac{N_b{}^2 k_c f_0 \gamma}{4\pi\,\varepsilon_n \beta^*} F(\theta_c)$$

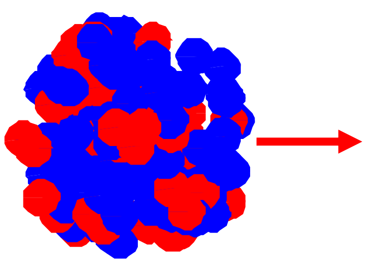
Hour glass factor: $F = 1 / \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$

We want to collide many high intensity, low-emittance bunches, at an interaction point where the beam is focused down to a small point (at least as long as the number of events per bunch collision, the "pile-up" can be handled by the experiment).

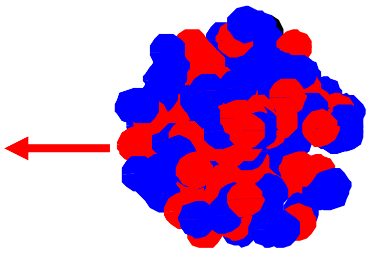
- Luminosities quoted for lead ions may seem low compared to pp or e^+e^-
- But comparisons should be made on the basis of nucleon pair luminosities

For collisions of (Z_1, A_1) with (Z_2, A_2)

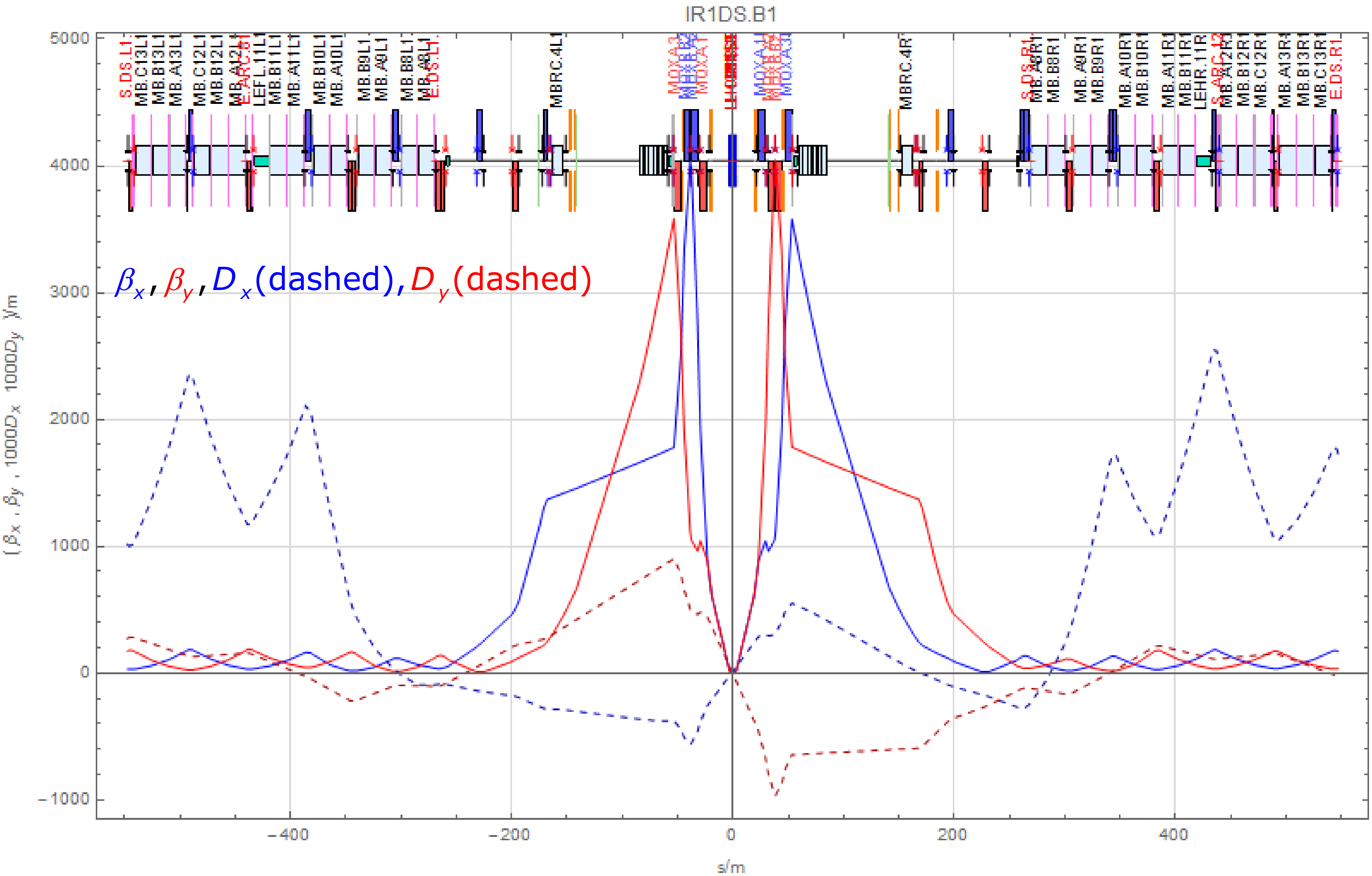
$$L_{\mathrm{NN}} = A_1 A_2 L_{AA}$$



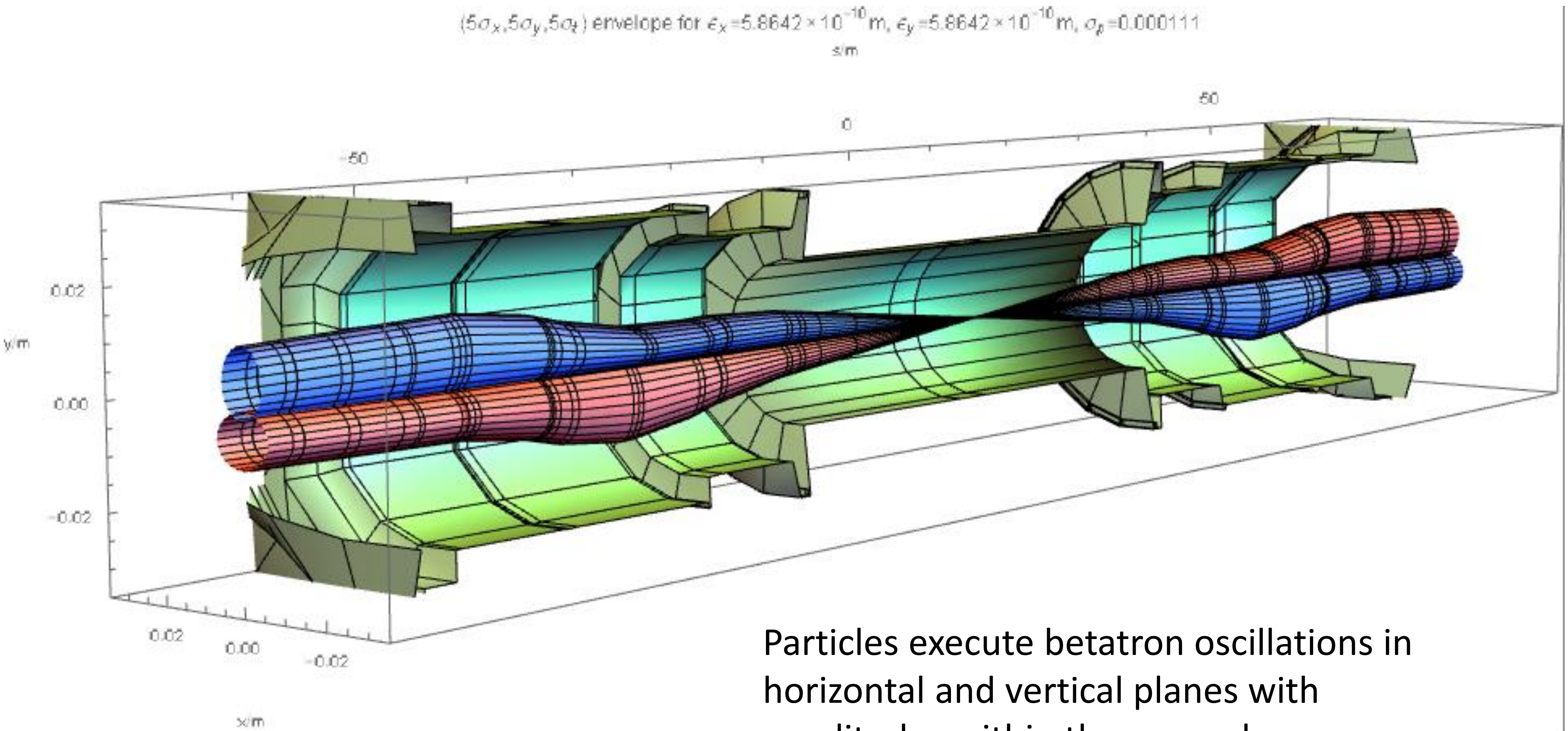
$$L = 1.0 \times 10^{27}\ \text{(Pb)(Pb) cm}^{-2}\text{s}^{-1}$$
$$= 4.3 \times 10^{31}\ \text{(nucleon)(nucleon) cm}^{-2}\text{s}^{-1}$$



Collision beam optics around ATLAS

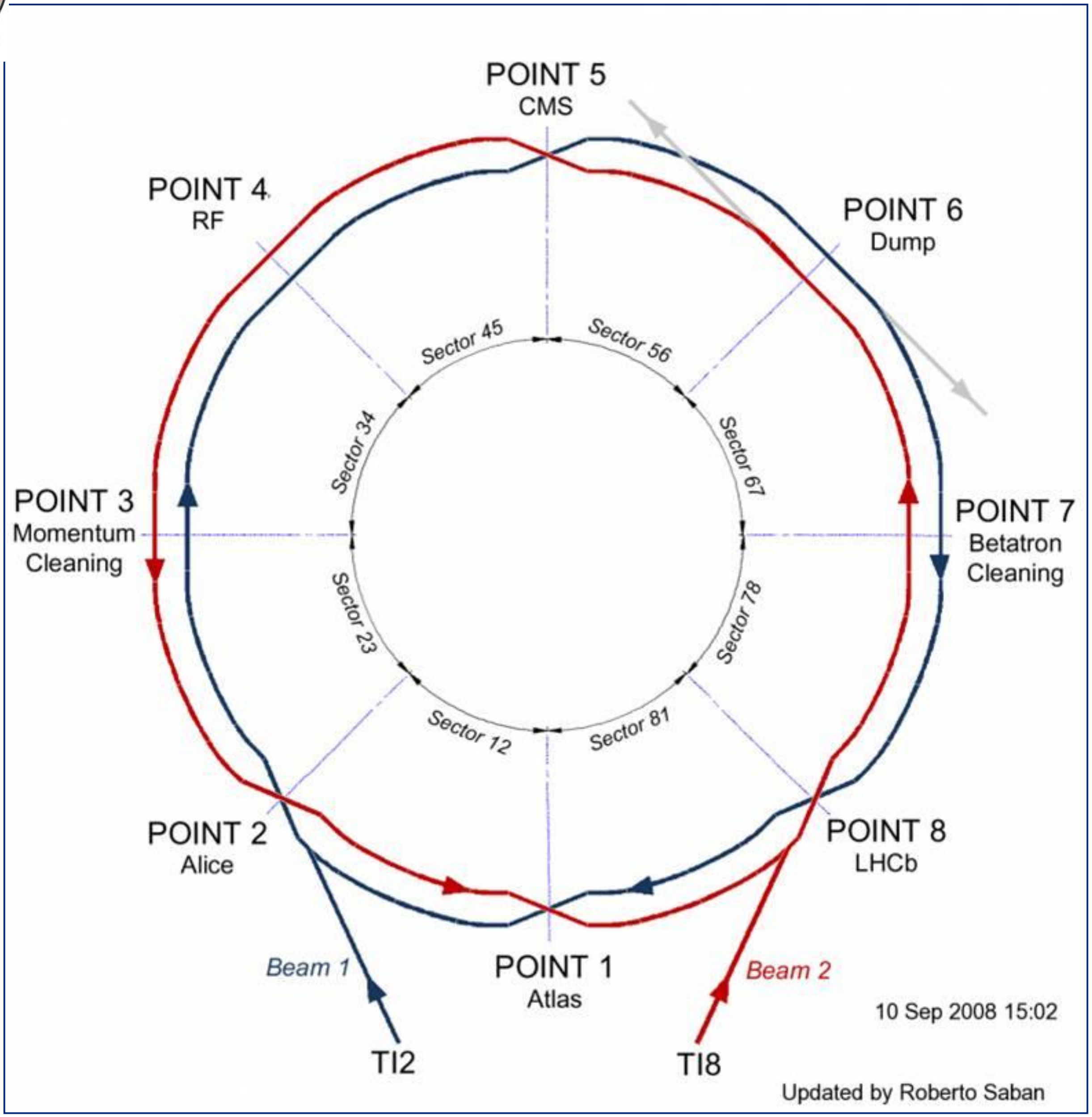


Collision beam envelopes (5σ) around ATLAS (Run 1)



Particles execute betatron oscillations in horizontal and vertical planes with amplitudes within these envelopes.
π/2 phase advance across interaction region.

LHC orientation



Three large and highly capable heavy-ion physics experiments:

ALICE

ATLAS

CMS

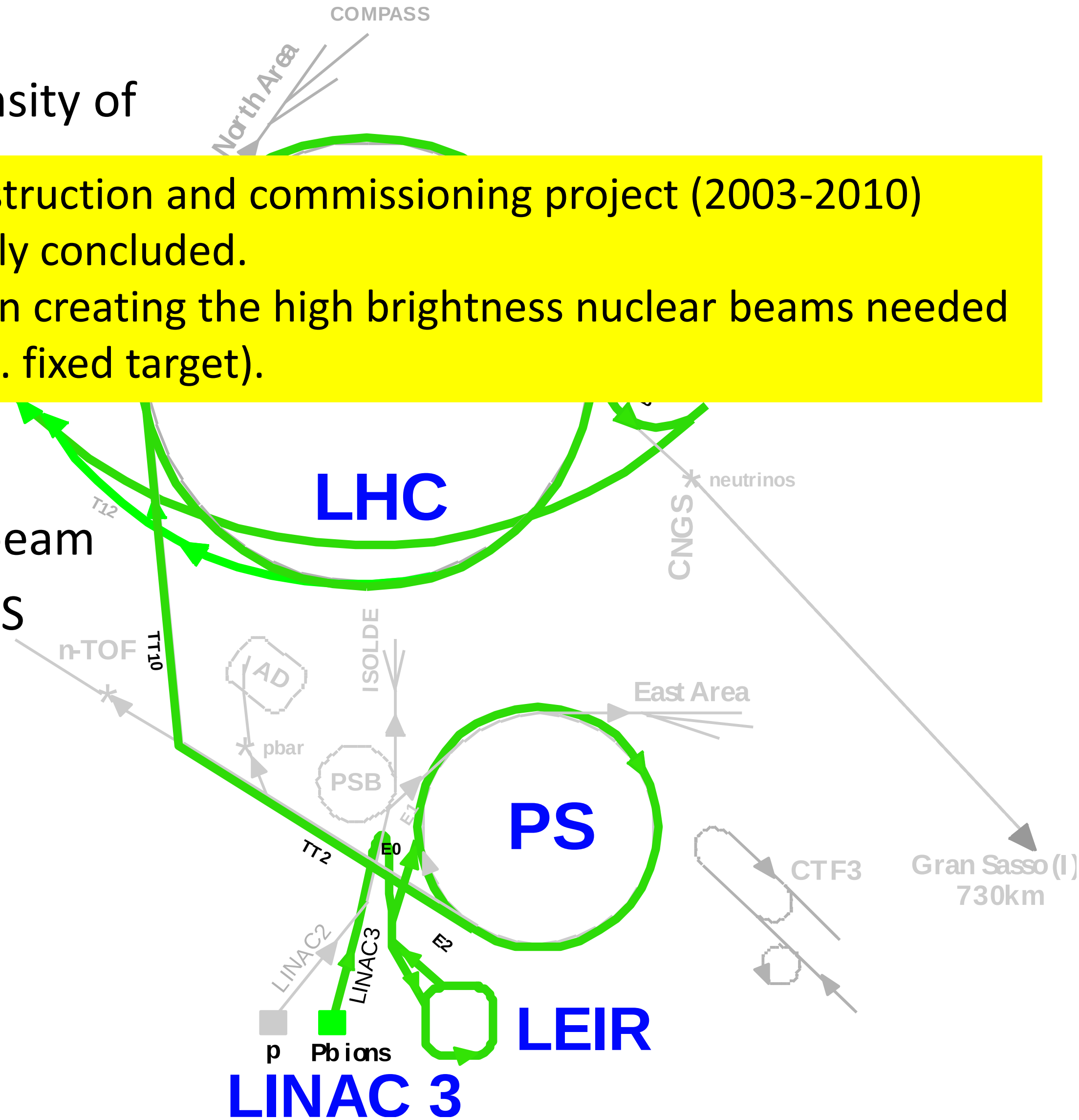
LHCb takes p-Pb collisions, just starting to take Pb-Pb

THE LHC AS A NUCLEUS-NUCLEUS COLLIDER

LHC Ion Injector Chain

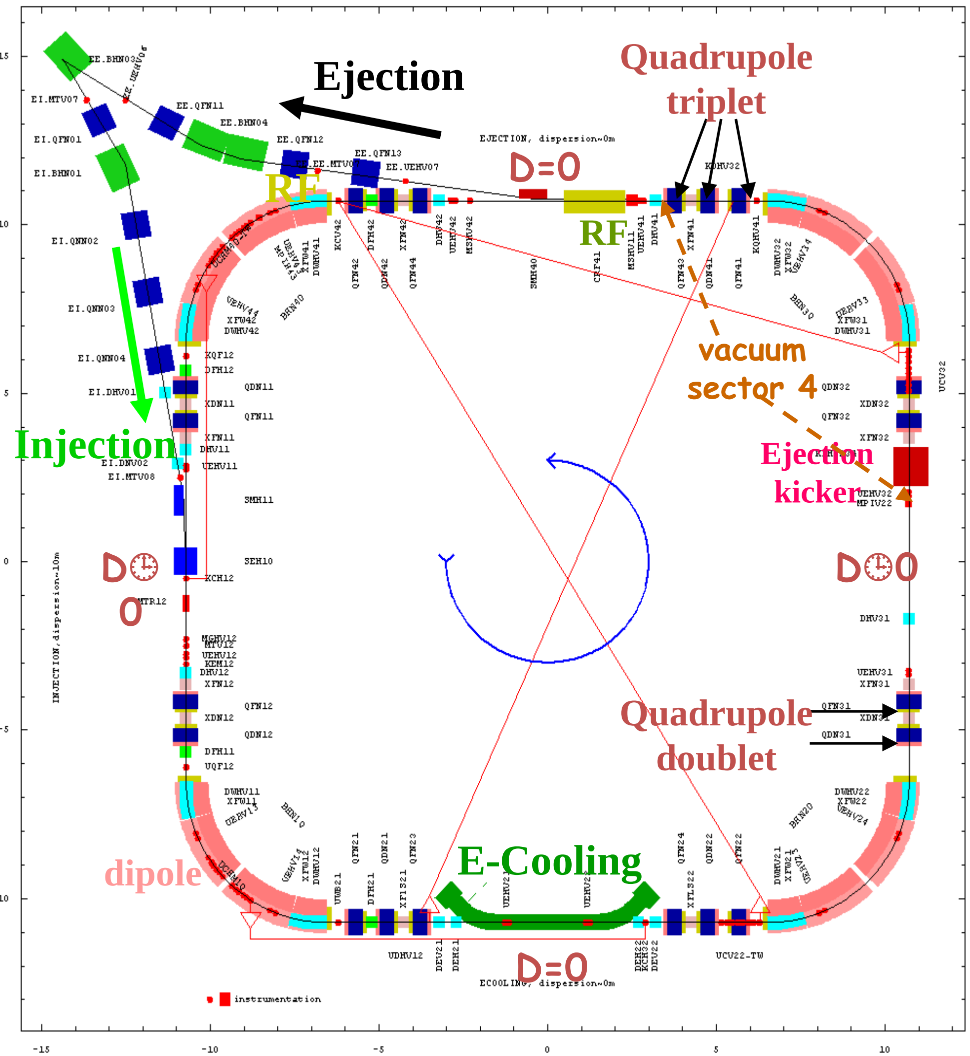
- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and cool Linac3 beam
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme of LHC

I-LHC construction and commissioning project (2003-2010) successfully concluded.
Vital role in creating the high brightness nuclear beams needed by LHC (vs. fixed target).



LEIR (Low-Energy Ion Ring)

- Prepares beams for LHC using electron cooling
- circumference 25p m (1/8 PS)
- Multiturn injection into horizontal+vertical+longitudinal phase planes
- Fast Electron Cooling : Electron current from 0.5 to 0.6 A with variable density
- Dynamic vacuum (NEG, Au-coated collimators, scrubbing)



LHC Pb Injector Chain:
Design Parameters for luminosity 10^{27} cm^{-2} s^{-1}

	ECR Source →	Linac 3 → (4)	LEIR →	PS → (13,12,8)	SPS → (12)	LHC
Output energy	**2.5 KeV/n**	**4.2 MeV/n**	**72.2 MeV/n**	**5.9 GeV/n**	**177 GeV/n**	**2.76 TeV/n**
^{208}Pb charge state	**27+**	**27+ → 54+**	**54+**	**54+ → 82+**	**82+**	**82+**
Output Bρ [Tm]		2.28 → 1.14	4.80	86.7 → 57.1	1500	23350
bunches/ring			2 (1/8 of PS)	4 (or 4x2)[4]	52,48,32	592
ions/pulse	$9\ 10^9$	$1.15\ 10^9$ [1])	$9\ 10^8$	$4.8\ 10^8$	$\leq 4.7\ 10^9$	$4.1\ 10^{10}$
ions/LHC bunch	**$9\ 10^9$**	**$1.15\ 10^9$**	**$2.25\ 10^8$**	**$1.2\ 10^8$**	**$9\ 10^7$**	**$7\ 10^7$**
bunch spacing [ns]				100 (or 95/5)[4]	100	100
ε*(nor. rms) [μm][2]	**~0.10**	**0.25**	**0.7**	**1.0**	**1.2**	**1.5**
Repetition time [s]	0.2-0.4	0.2-0.4	3.6	3.6	~50	**~10'fill/ring**
ε_{long} per LHC bunch[3]			0.025 eVs/n	0.05	0.4	1 eVs/n
total bunch length [ns]			200	3.9	1.65	1

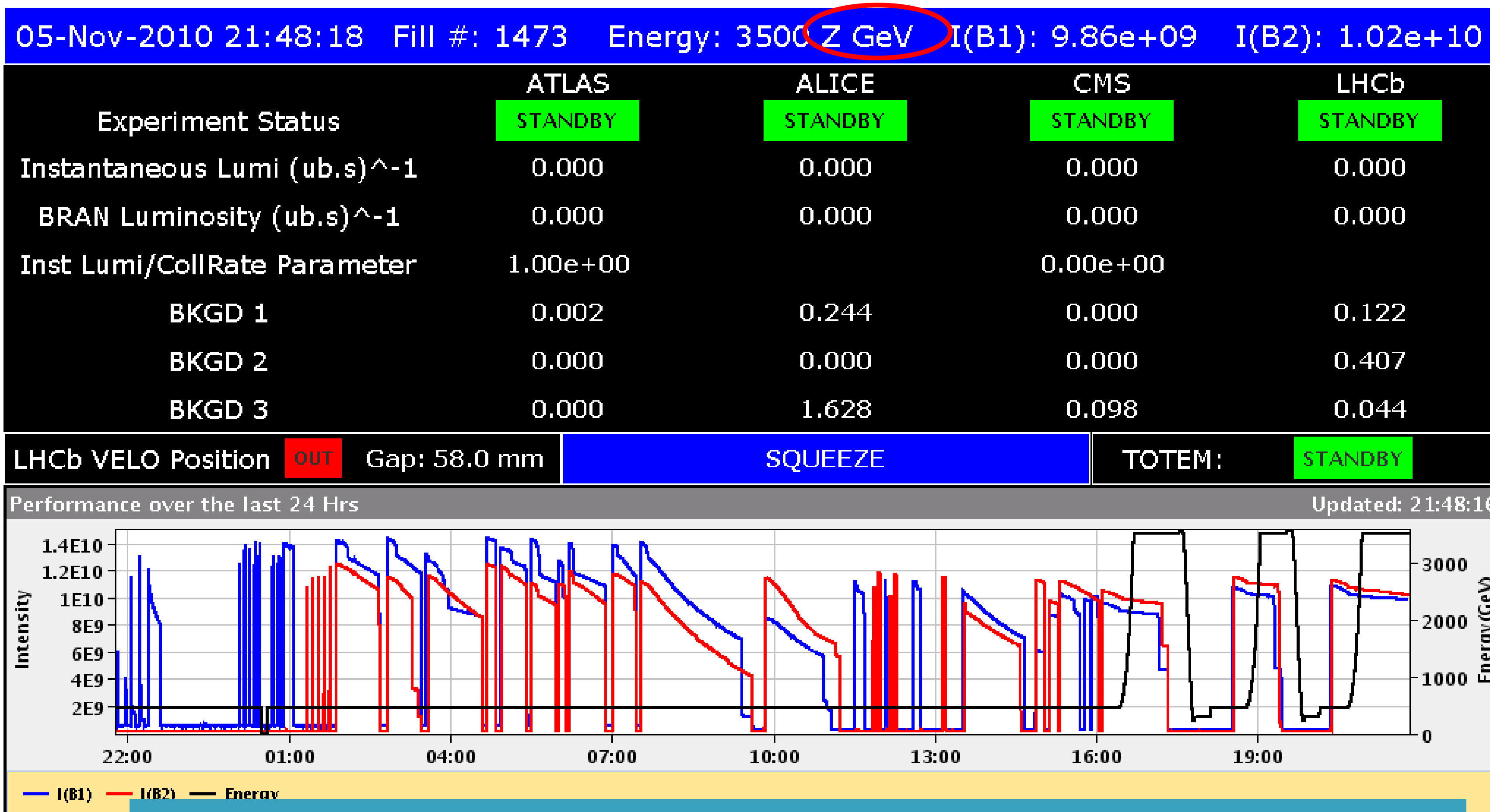
Stripping foil

[1] 50 eμA$_e$ x 200 μs Linac3 output after stripping

[2] Same physical emittance as protons,

$$\varepsilon^* \equiv \varepsilon_n = \sqrt{\gamma^2 - 1}\,\varepsilon_{x,y}$$ is invariant in ramp.

2010 Heavy Ion Run: first 24 h, Thu-Fri 4-5 Nov



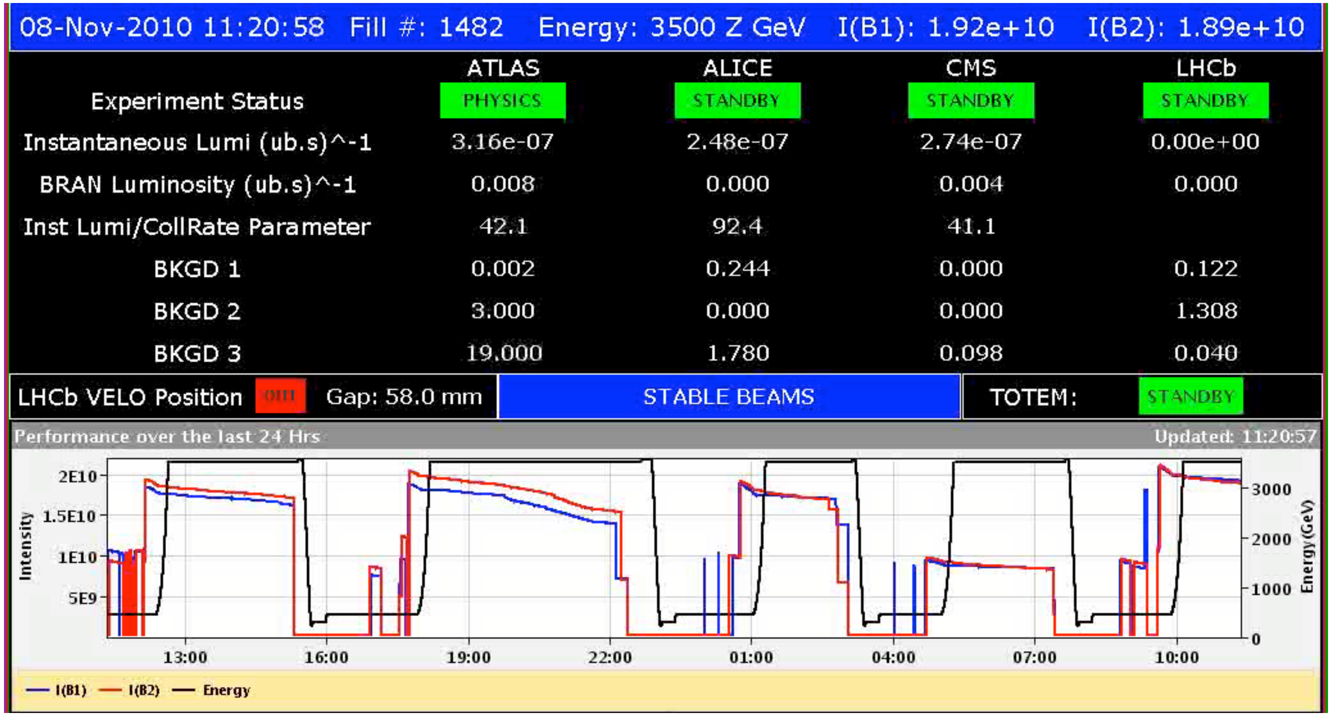
Rapid commissioning plan exploited established proton cycle to speed through initial phase of magnetic setup (injection, ramp, squeeze) . Collision crossing angles and collimation conditions different.

Beam 1

Circ.

& Captu

Monday morning: First Stable Beams for Pb-Pb



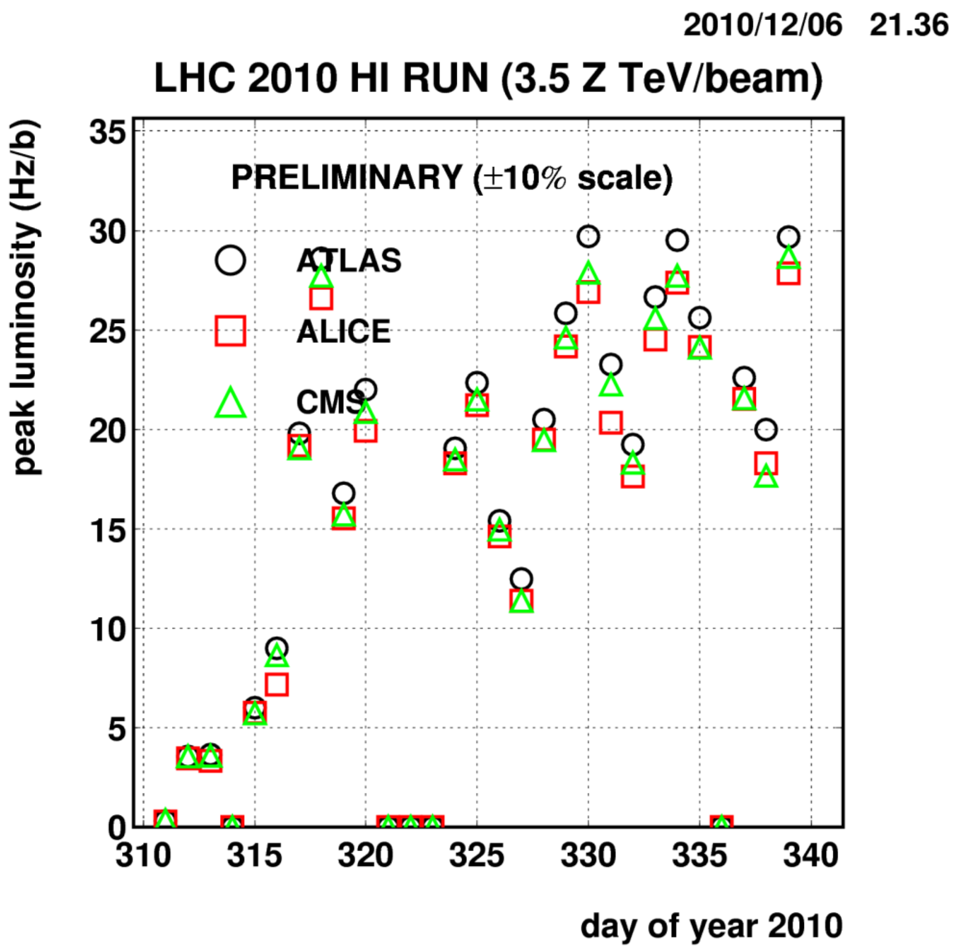
First stable beam with 2 bunches/beam (1 colliding)

Later same day, 5 bunches/beam, then increased on each fill: 17, 69, 121
Factor 100 in peak luminosity within 6 days.
Many interesting new RF manipulations in LHC in first 2 weeks.
Ion injectors exceeded design intensity/bunch by 70%.

Peak luminosity in fills

Interrupted twice by source refills (+ few days “parasitic” proton MD), some time to recover source performance (improvements for 2011).

Last few days: bunch number increased again to 137 with 8-bunches/batch from SPS.



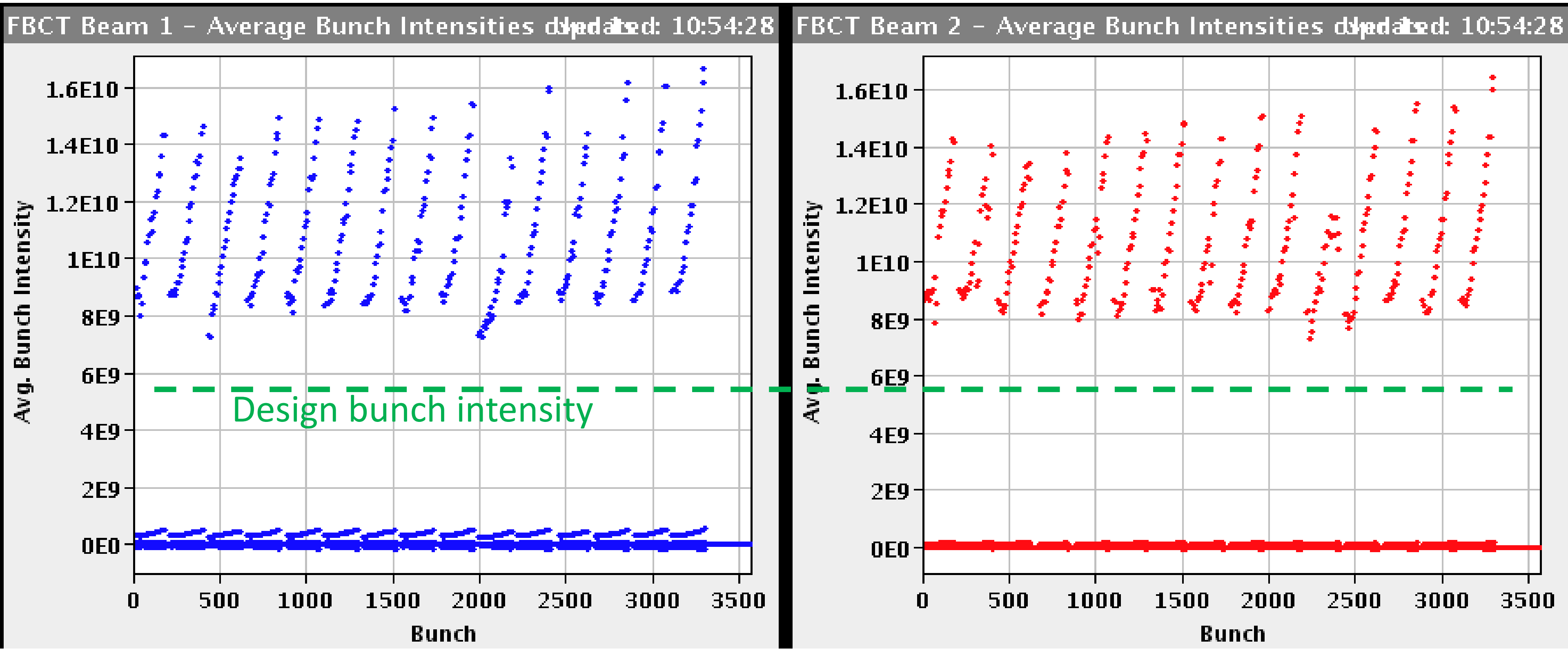
Beam instrumentation

- Major concern in preceding years
  - BPMs intensity threshold – no problem
  - Emittance: harder than protons
    - WS: Wire scanner at low energy and intensity – best absolute calibration
    - BSRT: synchrotron light from nuclei appeared in ramp (world first!), only bunch-by-bunch – typical large spread in emittance set in at injection
    - Beam-gas ionisation (BGI) monitor provides continuous measurement of average emittance, som being resolved

2011 Pb-Pb run

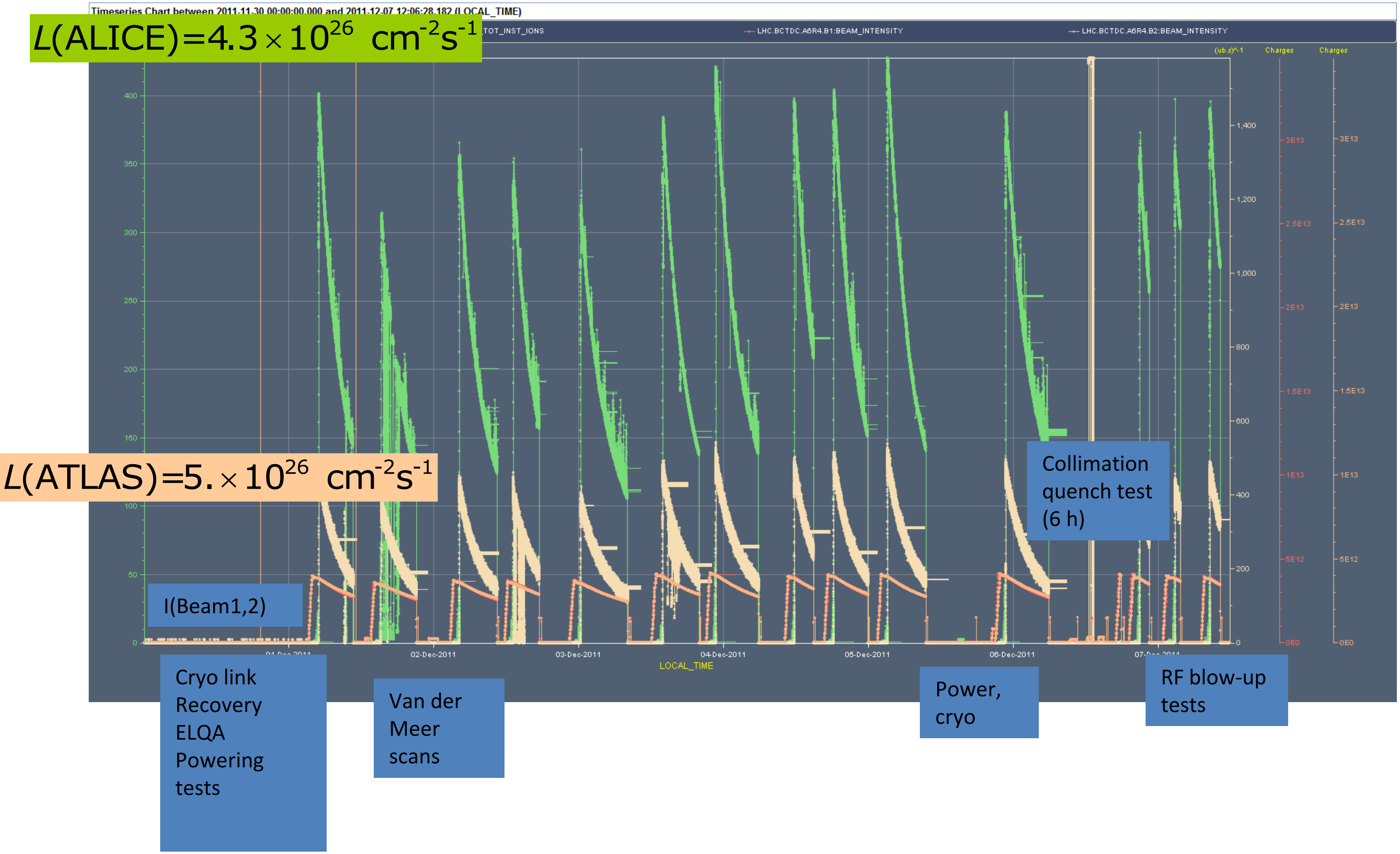
- Aimed to increase integrated luminosity from ~10 μb^{-1} of 2010 to around 70 μb^{-1} by injecting trains of bunches from the SPS
- Final result was ~150 μb^{-1} in each of the 3 experiments
- But life became much more complicated because of intensity decay along trains due to combination of intra-beam scattering, space-charge and RF noise effects at injection in the SPS

Typical bunch intensity distribution



Outstanding injector chain performance!

Intensity and luminosity ~final week

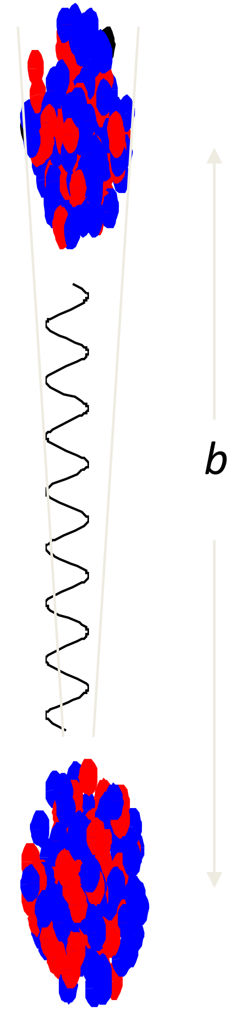


What limits the luminosity we can achieve?

- Limits for Pb-Pb include new effects that do not affect p-p
  - (Some p-p effects are no problem for Pb-Pb/)
- Intra-beam scattering (multiple small-angle Coulomb scattering within bunch) blows up beam emittance, especially at low energy (and in SPS) and may cause intensity losses, stronger for high charge
- Losses in collimation process (more complicated nuclear physics …)
- Ultraperipheral electromagnetic interactions of colliding nuclei (completely new in LHC, describe in following)

- Electromagnetic interactions in encounters which are not close enough to overlap nuclear densities
  - –Extremely Lorentz-contracted Coulomb fields (equivalent quasi-real photons in Fermi-Weizsacker-Williams method)
  - –In this sense, LHC is a $\gamma\gamma$ collider.
  - –Frequency spectrum of FWW photons depends on impact parameter, *b.*

$$\gamma_{\text{target}} = 2\gamma^2 - 1 \approx 1.7 \times 10^7$$



$$\text{Coupling } Z\alpha = \frac{82}{137} \approx 1$$

Pair Production in Heavy Ion Collisions

Racah formula (1937) for free pair production in heavy-ion collisions

$$Z_1 + Z_2 \to Z_1 + e^- + e^+ + Z_2$$

$$\sigma_{PP} = \frac{Z_1^2 Z_2^2 \alpha^4 \lambda_e^2}{\pi} \frac{28}{27}\left[L^3 - 2.198L^2 + 3.821L - 1.632\right] \text{ with } L = \log(\gamma_1 \gamma_2)$$

$\approx$ 225 kb for Pb-Pb at LHC

Cross section for Bound-Free Pair Production (BFPP) (various authors)

$$Z_1 + Z_2 \to (Z_1 + e^-)_{1s_{1/2},\dots} + e^+ + Z_2$$

has very different dependence on ion charges (and energy)

$$\sigma_{PP} \propto Z_1^5 Z_2^2 \left[A \log \gamma_{CM} + B\right]$$

$$\propto Z^7 \left[A \log \gamma_{CM} + B\right] \text{ for } Z_1 = Z_2$$

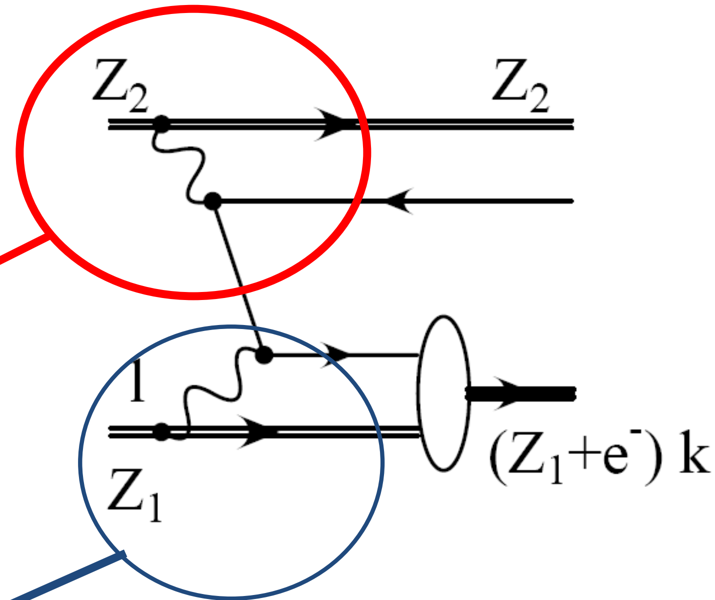
$$\approx \begin{cases} 0.2 \text{ b for Cu-Cu RHIC} \\ 114 \text{ b for Au-Au RHIC} \\ 281 \text{ b for Pb-Pb LHC} \end{cases}$$

We use BFPP cross section values from Meier et al, Phys. Rev. A, **63**, 032713 (2001), includes detailed calculations for Pb-Pb at LHC energy.
Also papers by Serbo and others for higher order processes.

Dependence of BFPP cross-section on Z

Typical diagram contributing to

$$Z_1 + Z_2 \to \left(Z_1 + \mathrm{e}^-\right)_{1s_{1/2},\ldots} + \mathrm{e}^+ + Z_2$$



Pair production $\propto Z_1^{\,2} Z_2^{\,2}$

Radial wave function of $1s_{1/2}$ state of hydrogen-like atom in its rest frame

$$R_{10}(r) = \left(\frac{Z_1}{a_0}\right)^{3/2} 2\exp\left(-\frac{Z_1 r}{a_0}\right) \Rightarrow \Psi(0) \sim Z_1^{\,3/2} \Rightarrow \left|\Psi(0)\right|^2 \sim Z_1^{\,3}$$

Total cross-section $\sim Z_2^{\,2} Z_1^{\,5}$

Hand-waving, over-simplified argument!

G. Baur et al, Phys. Rept. 364 (2002) 359

Electromagnetic processes in Pb-Pb collisions

$$\text{BFPP1: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{81+} + e^{+},$$
$$\sigma = 281\text{ b}, \quad \delta = 0.01235$$

$$\text{BFPP2: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{80+} + 2e^{+},$$
$$\sigma \approx 6\text{ mb}, \quad \delta = 0.02500$$

$$\text{EMD1: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{207}\text{Pb}^{82+} + n,$$
$$\sigma = 96\text{ b}, \quad \delta = -0.00485$$

$$\text{EMD2: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{206}\text{Pb}^{82+} + 2n,$$
$$\sigma = 29\text{ b}, \quad \delta = -0.00970$$

Discussed since Chamonix 2003 …

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).

Luminosity Limit from bound-free pair production

LIMITS TO THE PERFORMANCE OF THE LHC WITH ION BEAMS*

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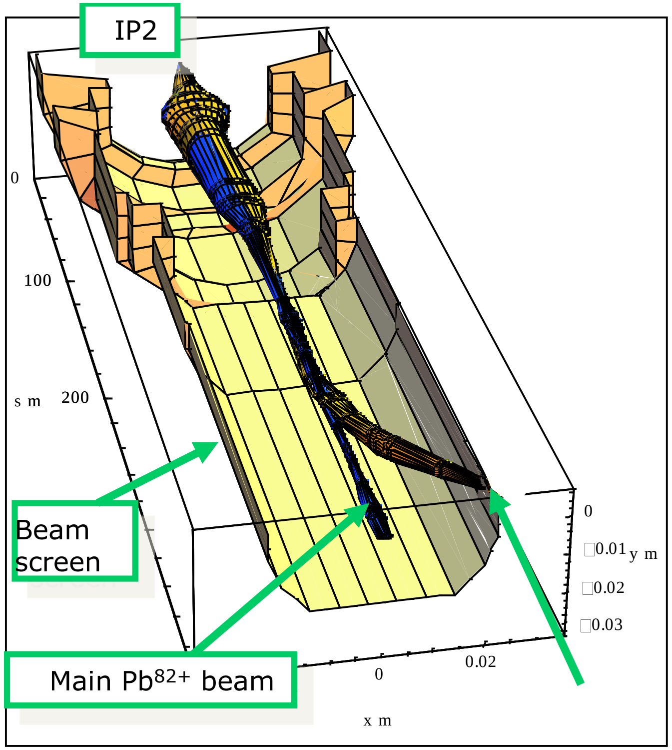
EPAC 2004, Chamonix 2004, LHC Design Report



Secondary Pb^{81+} beam (25 W at design luminosity) emerging from IP and impinging on beam screen. Hadronic shower into superconducting coils can quench magnet.

Also new model of luminosity evolution with IBS, radiation damping and luminosity burn-off from these processes.

Companion paper (principal author Hans Braun) introduced simulations of heavy ion interactions with collimators.

Distinct EMD process (similar rates) does not form spot on beam pipe

$$^{208}Pb^{82+} + ^{208}Pb^{82+} \xrightarrow{GDR} ^{208}Pb^{82+} + ^{207}Pb^{82+} + n$$

BFPP beam detected at RHIC

RHIC collides Cu-Cu in early 2005 and we realise that BFPP should be detectable (but only just!).

Rush to RHIC to set up experiment with help of Angelika Drees.

PRL **99,** 144801 (2007) PHYSICAL REVIEW LETTERS week ending 5 OCTOBER 2007

Observations of Beam Losses Due to Bound-Free Pair Production in a Heavy-Ion Collider

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(Received 13 June 2007; published 3 October 2007)

We report the first observations of beam losses due to bound-free pair production at the interaction point of a heavy-ion collider. This process is expected to be a major luminosity limit for the CERN Large Hadron Collider when it operates with $^{208}Pb^{82+}$ ions because the localized energy deposition by the lost ions may quench superconducting magnet coils. Measurements were performed at the BNL Relativistic Heavy Ion Collider (RHIC) during operation with 100 GeV/nucleon $^{63}Cu^{29+}$ ions. At RHIC, the rate, energy and magnetic field are low enough so that magnet quenching is not an issue. The hadronic showers produced when the single-electron ions struck the RHIC beam pipe were observed using an array of photodiodes. The measurement confirms the order of magnitude of the theoretical cross section previously calculated by others.

View towards PHENIX

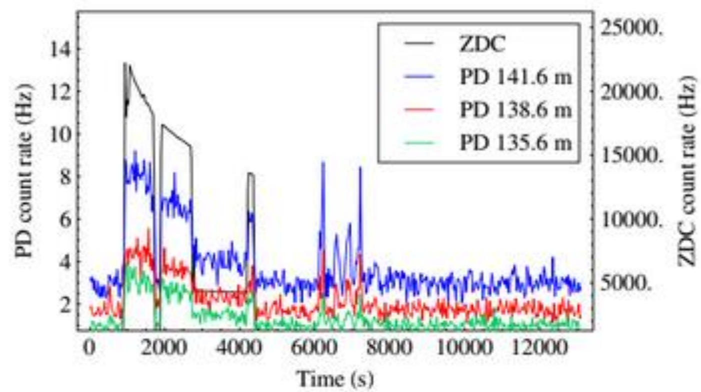
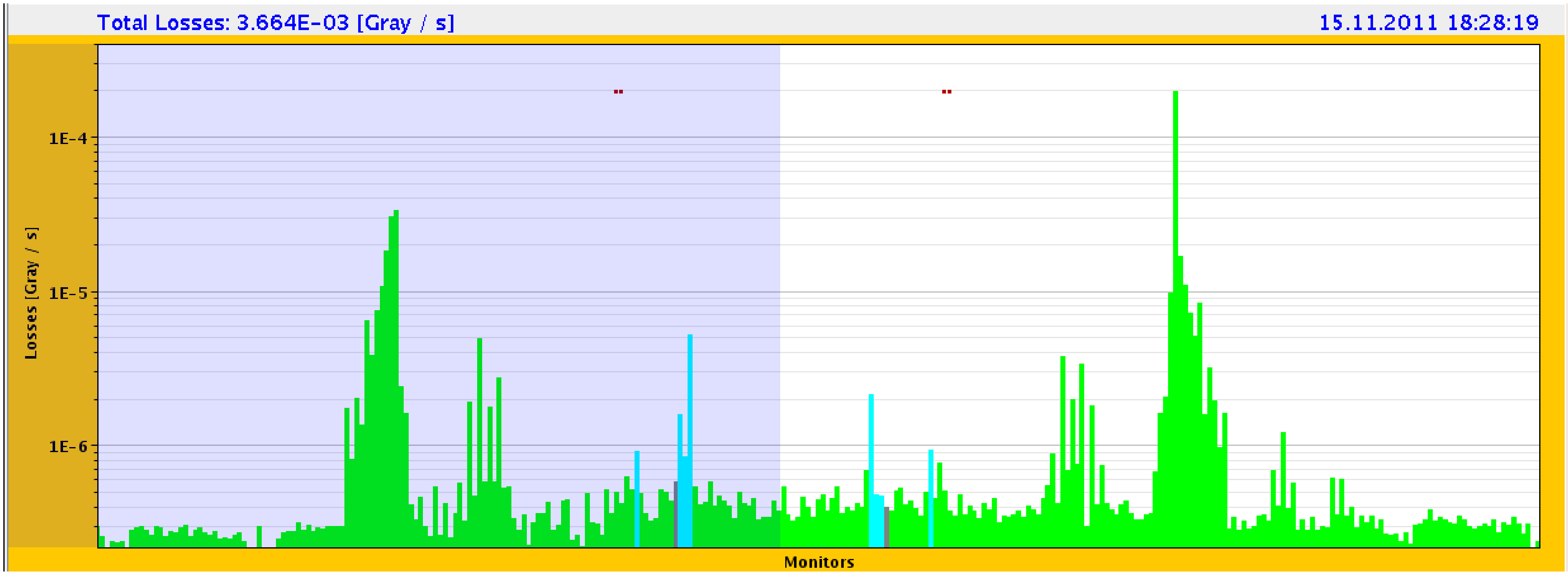


FIG. 4 (color online). Count rates measured on the ZDC luminosity monitors (black, right scale) and the three PDs with the highest signal [shades of gray, left scale (colors online)] during a store with the WPD. The data was binned in 30 sec intervals. A clear correlation between the luminosity and the PD count rates can be seen.


2202
Beam loss monitor
(ionisation chamber),
many around the ring

Bound-free Pair Production losses around CMS in 2011

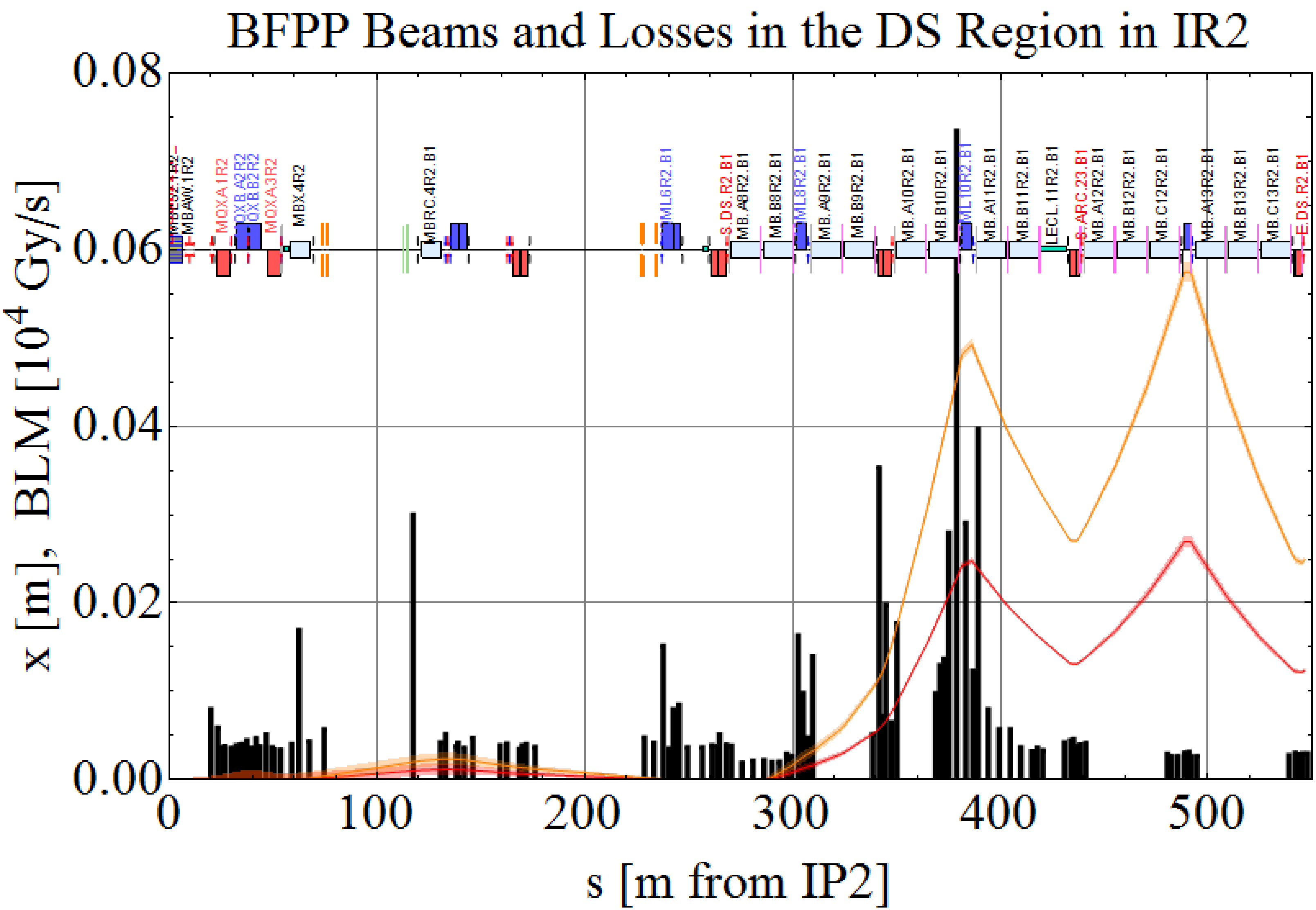


Standard display in the LHC Control Room – BFPP stares you in the face during Pb-Pb collisions !

Special BLMs were installed in predicted locations, up to 36% of threshold on 170 bunch fill, we went up later to 356 bunches.

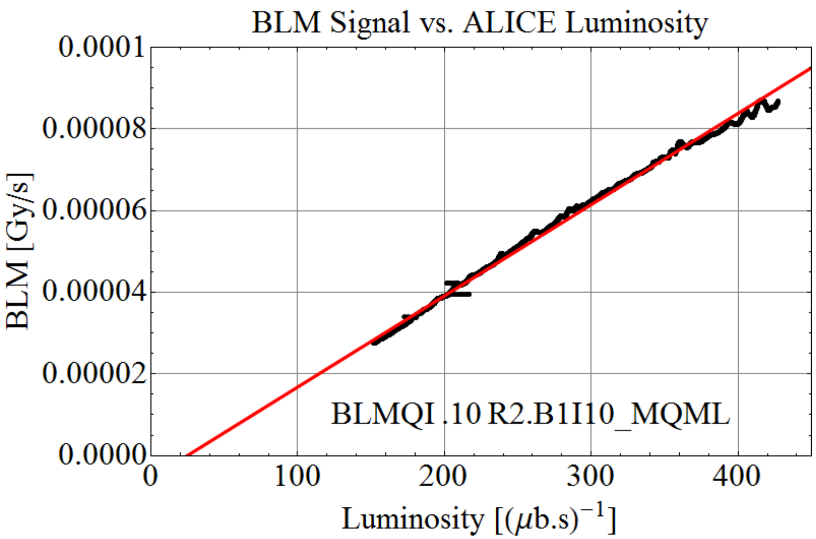
BLM dump thresholds (which were cautious …) had to be doubled.
LHC had never had a beam-induced magnet quench.

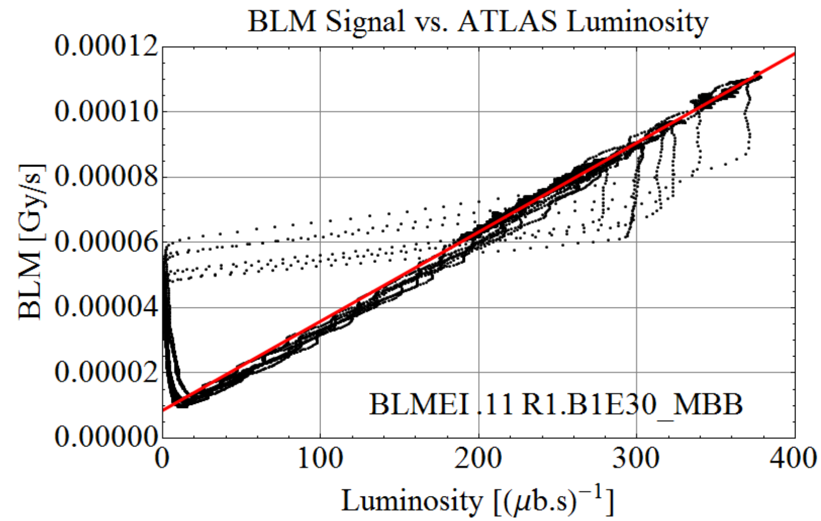
2011 Pb-Pb operation



M. Schaumann

Main losses in DS are correlated with luminosity

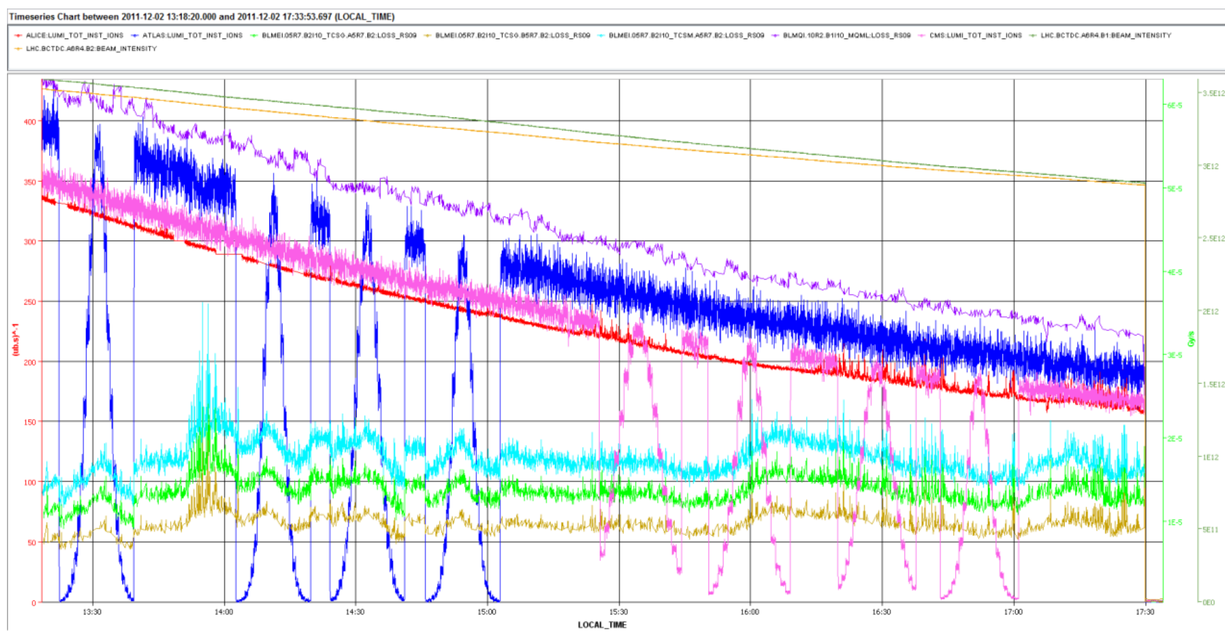




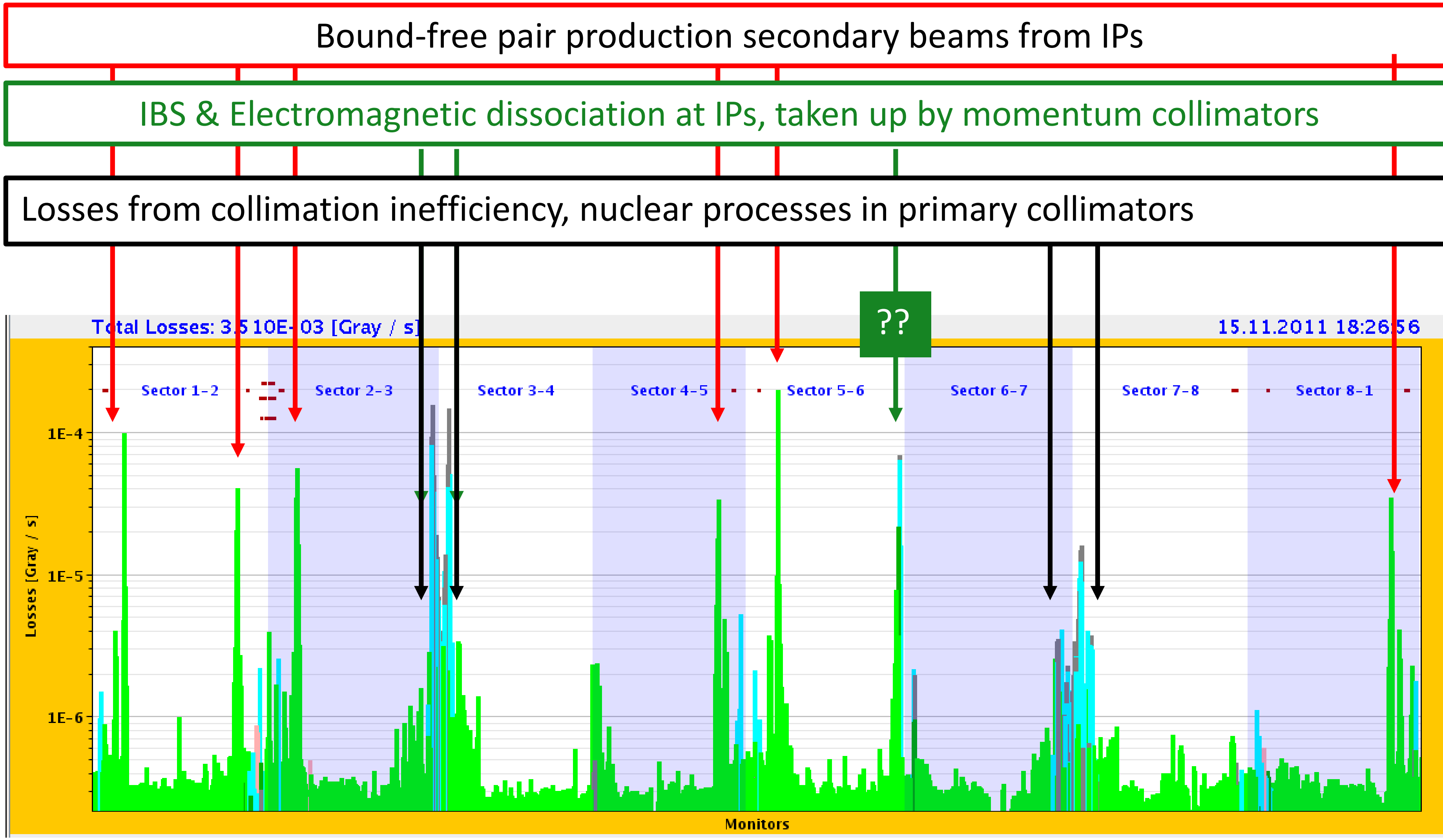
Regular physics fill

From van der Meer scans

M. Schaumann

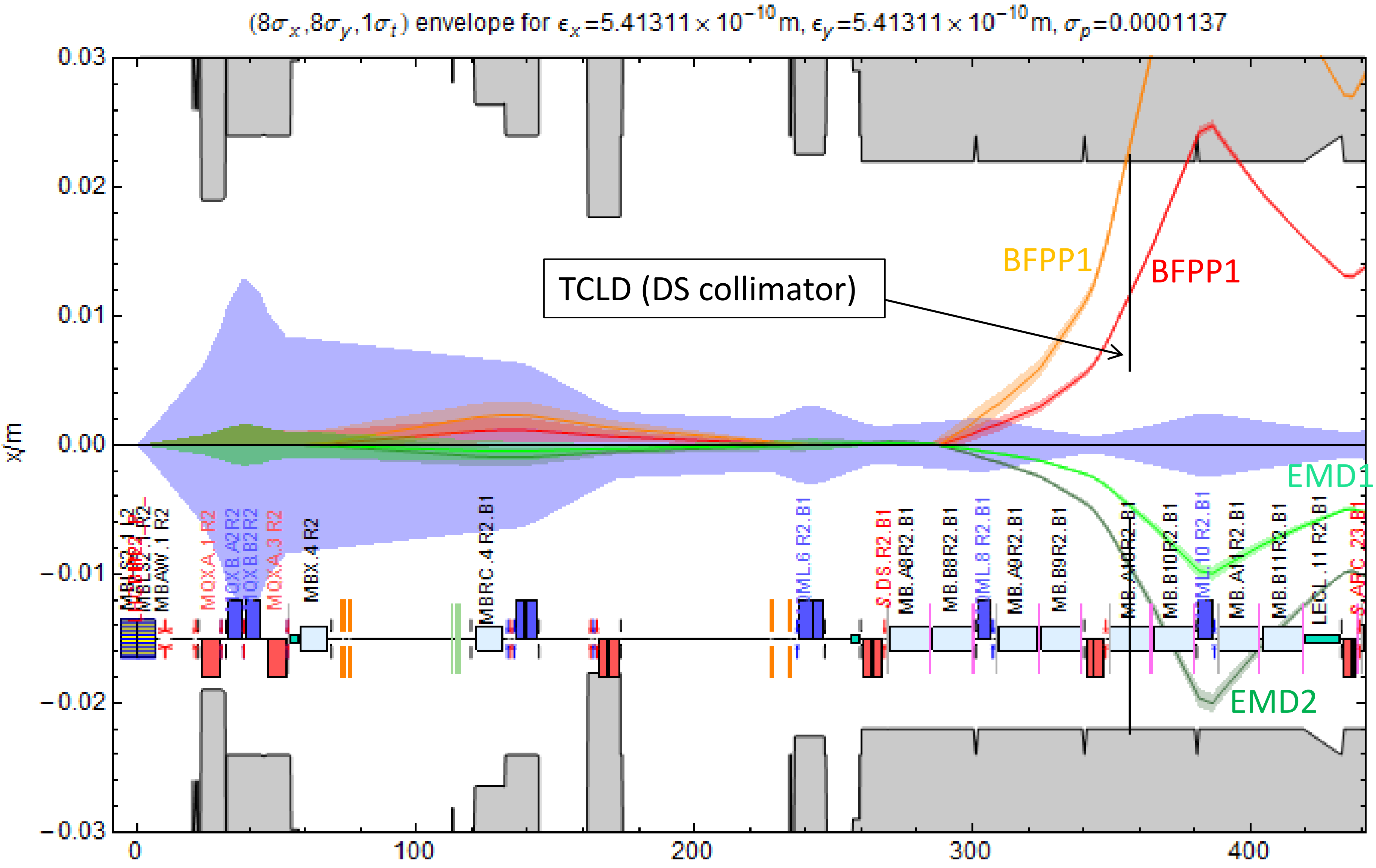


Steady-state losses during Pb-Pb Collisions in 2011



Beam loss monitors in the full LHC Ring

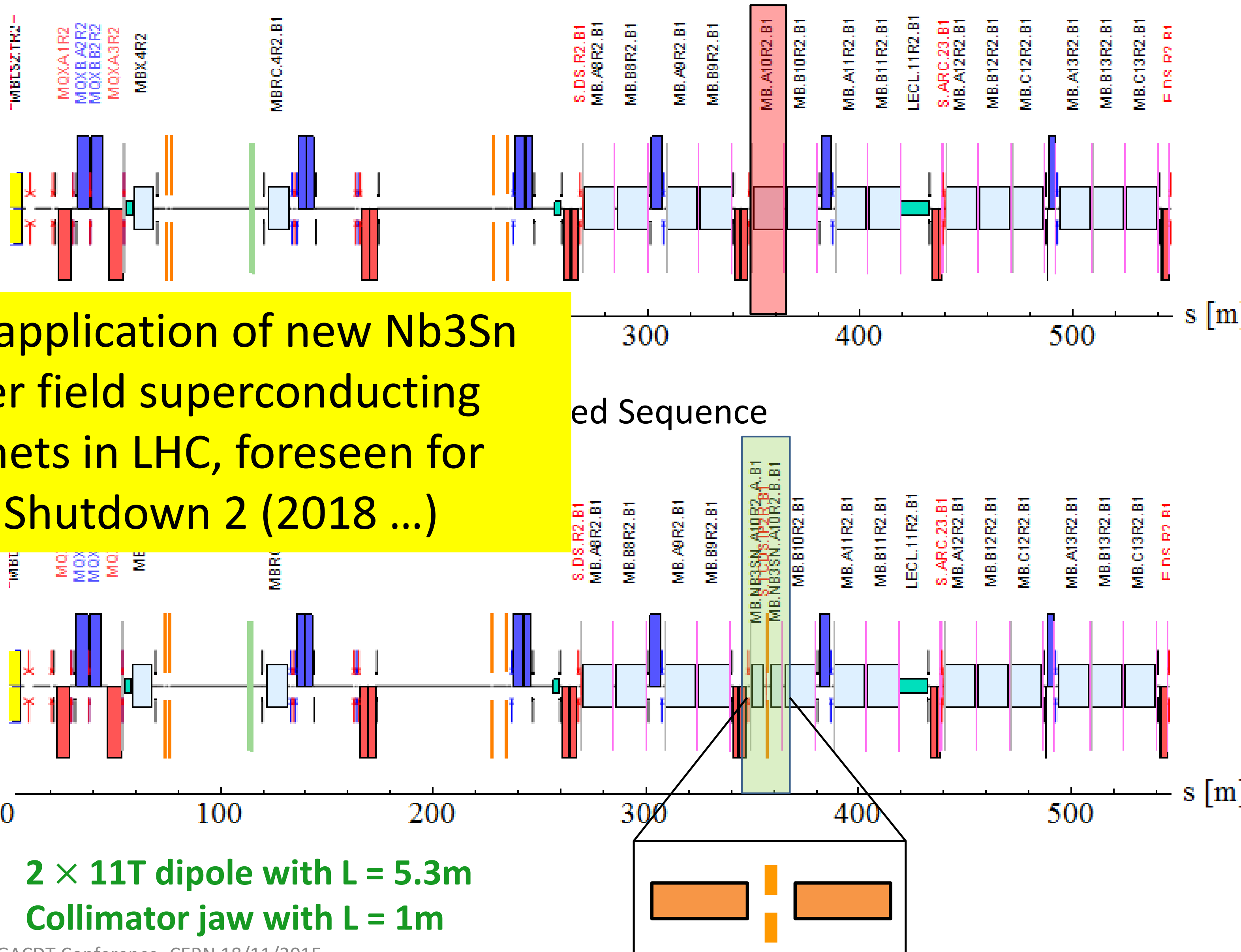
Secondary beams from Beam 1 in IR2 (horizontal plane)



Cannot separate BFPP and main beam in warm area (TCLs not useful)
BFPP beam is smaller than main beam (source is luminous region).

DS collimator installation in IR2

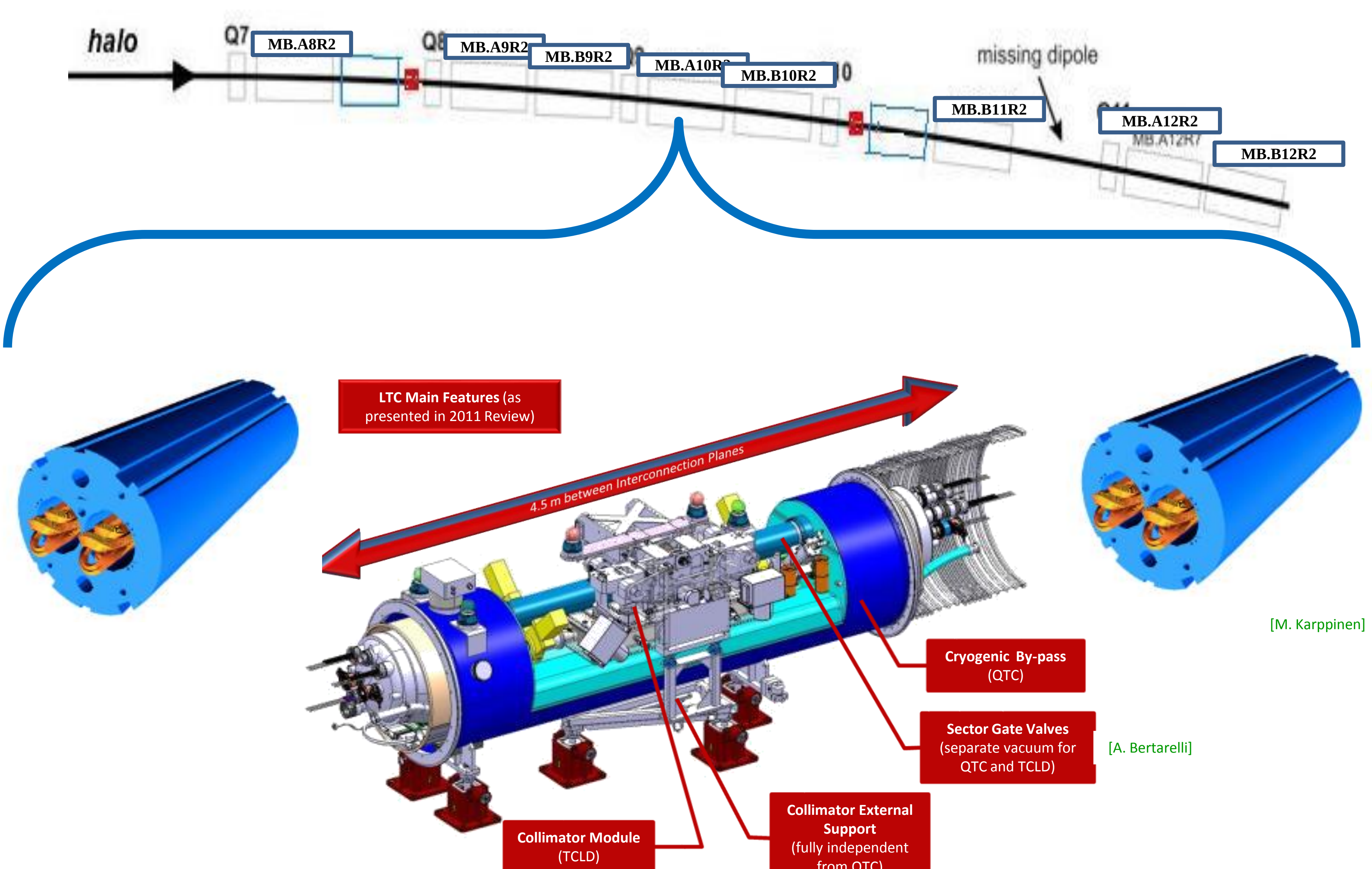
Magnet to be replaced **MB.A10R2**



First application of new Nb3Sn higher field superconducting magnets in LHC, foreseen for Long Shutdown 2 (2018 …)

2 × 11T dipole with L = 5.3m
Collimator jaw with L = 1m

Integrated technological solution for point 2
(same solution deployable in IP 7 in case of need)



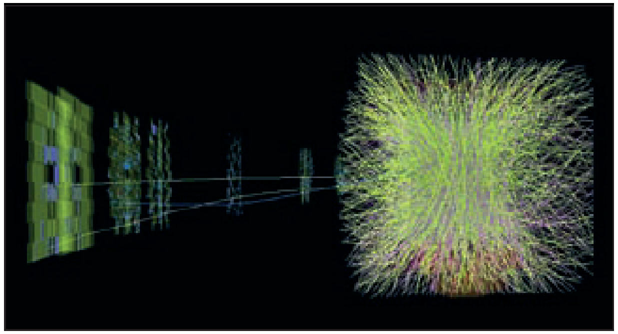
Pb-Pb collisions produce both the messiest (high-multiplicity) and the cleanest events at the LHC.

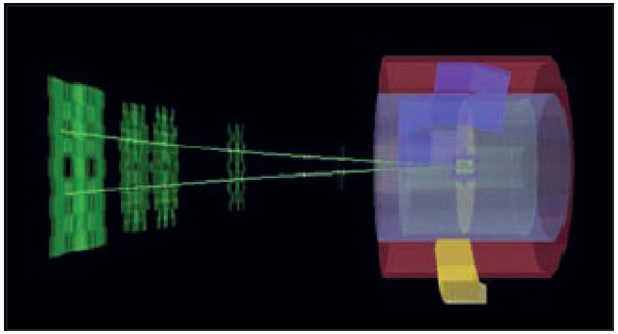
Using the LHC as a photon collider

ALICE

The protons and nuclei accelerated by the LHC are surrounded by strong electric and magnetic fields. These fields can be treated as an equivalent flux of photons, making the LHC the world's most powerful collider not only for protons and lead ions but also for photon–photon and photon–hadron collisions (*CERN Courier* October 2007). This is particularly so for beams of multiply charged heavy-ions, where the number of photons is enhanced by almost four orders of magnitude compared with the singly charged protons (the photon flux is proportional to the square of the ion charge).

The ALICE collaboration has recently taken advantage of this effect in a study of coherent photoproduction of J/ψ mesons in lead–lead (PbPb) collisions. The J/ψ is detected through its dimuon decay in the muon arm of the ALICE detector, which also provides the trigger for these events. The relevant collisions typically occur at impact





J/ψ candidates in a central PbPb collision (left) and in an ultra-peripheral collision (right).

events (see figure) stands in sharp contrast to central heavy-ion collisions, where thousands of particles are produced.

These interactions carry an interesting message about the partonic substructure of heavy nuclei. Exclusive photoproduction of heavy vector mesons is believed to be a good probe of the nuclear gluon distribution. The cross-section measured in a heavy-ion collision Pb+Pb → Pb+Pb+J/ψ is a convolution of the equivalent photon spectrum with the photonuclear cross-section for γ+Pb → J/ψ+Pb. The latter exchange of two gluons.

At the rapidities (y around 3) studied in ALICE, J/ψ photoproduction is sensitive mainly to the gluon distribution at values of Bjorken-x of about 10^{-2}. Although the experimental error is rather large, the conclusion from ALICE is that the data favour models that include strong modifications to the nuclear gluon distribution, known as nuclear shadowing.

• Further reading

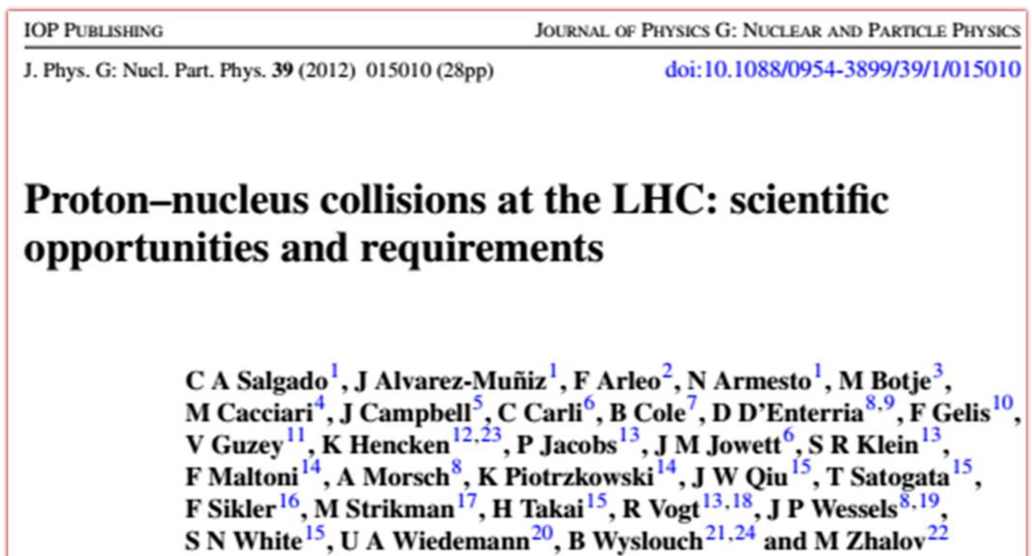
B Abelev *et al.* (ALICE collaboration) 2012

PROTON-LEAD COLLISIONS

First asymmetric collisions at LHC

History of proton-nucleus collisions at LHC (1)

- Long considered desirable by experiments but never included in baseline design of LHC
- 2003: RHIC finds a way to collide deuterons and gold nuclei but this way is not open to LHC …
- 2005 CERN workshop on pA in LHC
  - Predicted that p-Pb in LHC could work (despite RHIC …)
  - Physics case written up much later


IOP PUBLISHING — JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **39** (2012) 015010 (28pp) doi:10.1088/0954-3899/39/1/015010

Proton–nucleus collisions at the LHC: scientific opportunities and requirements

C A Salgado[1], J Alvarez-Muñiz[1], F Arleo[2], N Armesto[1], M Botje[3], M Cacciari[4], J Campbell[5], C Carli[6], B Cole[7], D D'Enterria[8,9], F Gelis[10], V Guzey[11], K Hencken[12,23], P Jacobs[13], J M Jowett[6], S R Klein[13], F Maltoni[14], A Morsch[8], K Piotrzkowski[14], J W Qiu[15], T Satogata[15], F Sikler[16], M Strikman[17], H Takai[15], R Vogt[13,18], J P Wessels[8,19], S N White[15], U A Wiedemann[20], B Wyslouch[21,24] and M Zhalov[22]

History of proton-nucleus collisions at LHC (2)

- 2006 First paper at European Particle Accelerator Conference, in Edinburgh
- Early 2011, LHC Chamonix workshop – go-ahead given for feasibility tests on LHC
- Preparation of LHC systems during 2011
- 31/10/2011 successful feasibility test
- Early 2012, after high Pb-Pb luminosity in Nov 2011, experiments *really* want p-Pb comparison data
- 13/9/2012 Successful pilot collision run (one night) yields new physics
- Full 1 month run postponed to early 2013 to allow more p-p data taking before long shutdown
- Jan-Feb 2013 first full physics run

- LHC accelerates protons through the momentum range

$$0.45 \text{ TeV (injection from SPS)} \le p_p \le 7 \text{ TeV (collision)}$$

  - p_p is measure of magnetic field in main bending magnets
- The two-in-one magnet design of the LHC fixes the relation between momenta of beams in the two rings (equal "*magnetic rigidity*")

$$p_{\text{Pb}} = Z p_{\text{p}}$$

where $Z = 82, A = 208$ for fully stripped Pb in LHC

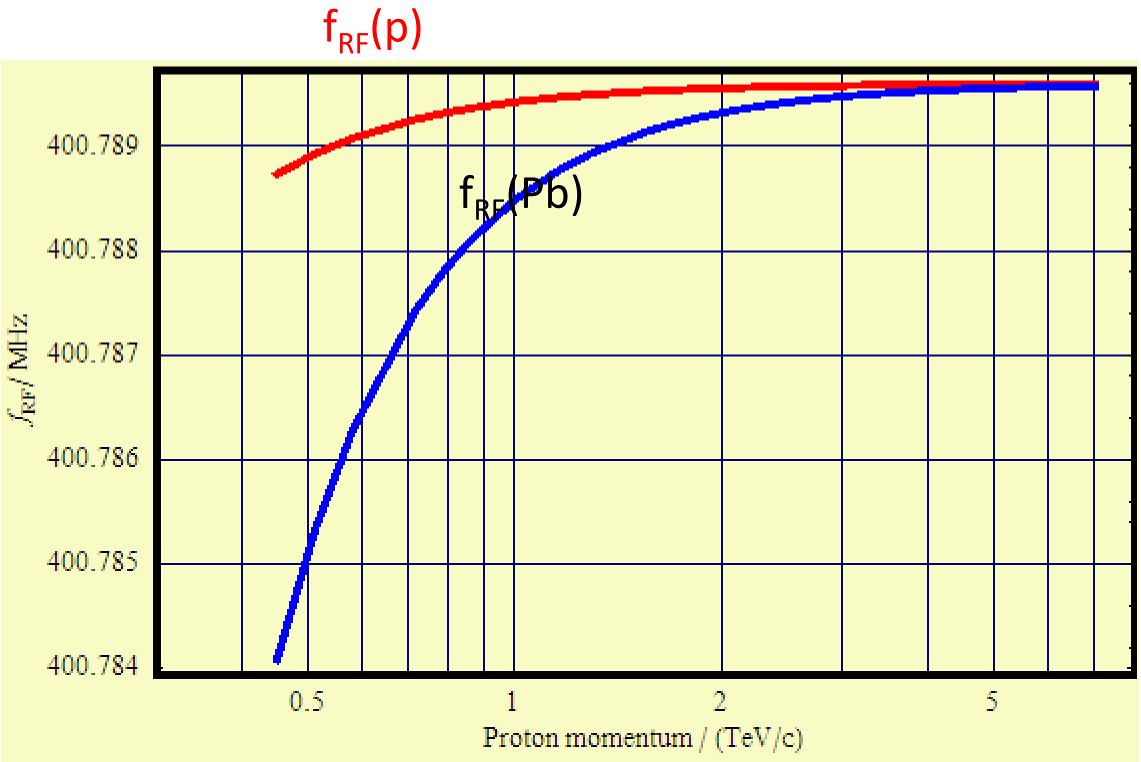
RF Frequency for p and Pb in LHC

Revolution time of a general particle, mass *m*, charge *Q*, is

$$T\left(p_{\mathrm{p}},m,Q\right)=\frac{C}{c}\sqrt{1+\left(\frac{mc}{Qp_{\mathrm{p}}}\right)^{2}}$$ and RF frequency $$f_{\mathrm{RF}}=\frac{h_{\mathrm{RF}}}{T\left(p_{\mathrm{p}},m,Q\right)}$$

where the harmonic number $h_{\mathrm{RF}}=35640$ in LHC

RF frequencies needed to keep p or Pb on stable *central* orbit of constant length *C* are different at low energy.



No problem in terms of hardware as LHC has independent RF systems in each ring.

Distorting the Closed Orbit

- Additional degree of freedom: adjust length of closed orbits to compensate different speeds of species.
  - Done by adjusting RF frequency

$$T\left(p_{\mathrm{p}},m,Q\right)=\frac{C}{c}\sqrt{1+\left(\frac{mc}{Qp_{\mathrm{p}}}\right)^2}\,(1+\eta\delta)$$

where $\delta=\dfrac{(p-Qp_{\mathrm{p}})}{Qp_{\mathrm{p}}}$ is a fractional momentum deviation and

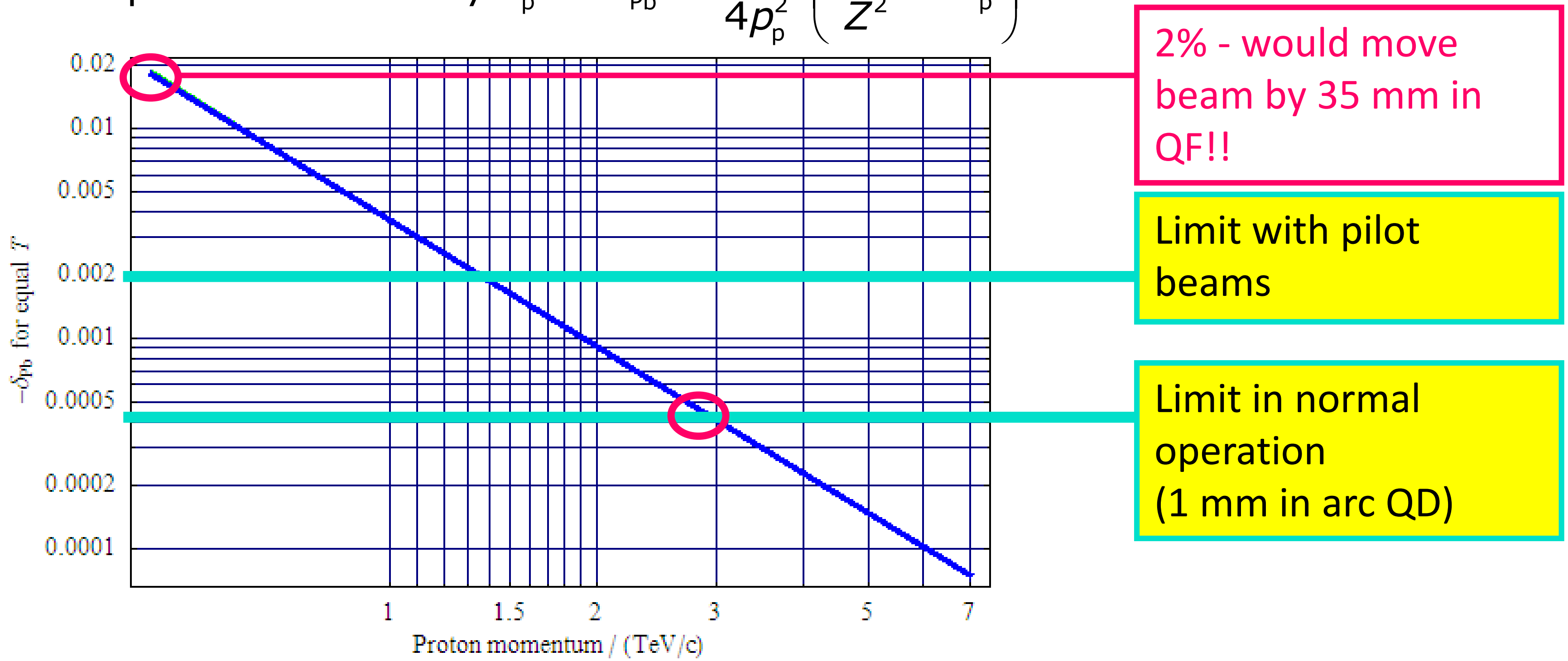
the phase-slip factor $\eta=\dfrac{1}{{\gamma_T}^2}-\dfrac{1}{\gamma^2}$, $\quad\gamma=\sqrt{1+\left(\dfrac{Qp_{\mathrm{p}}}{mc}\right)^2}$, $\quad\gamma_T=55.8$ for LHC optics.

Moves beam on to off-momentum orbit, longer for $\delta>0$.

Horizontal offset given by dispersion: $\Delta x=D_x\left(s\right)\delta$.

Momentum offset required through ramp

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



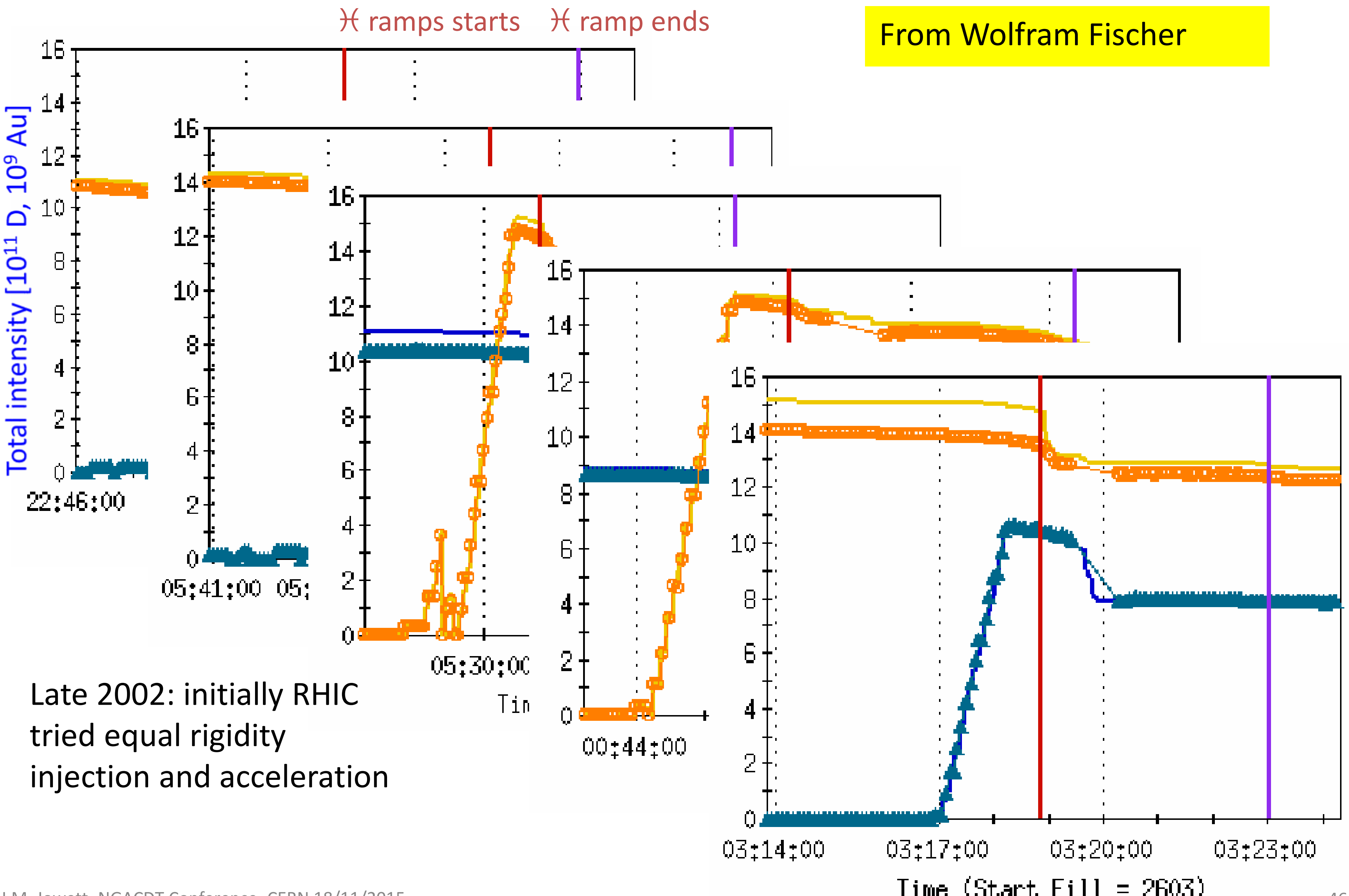
Revolution frequencies must be equal for collisions at top energy.

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

RF frequencies must be unequal for injection, ramp!

RHIC D-Au injection and ramp $(B\rho)_d = (B\rho)_{Au}$

From Wolfram Fischer



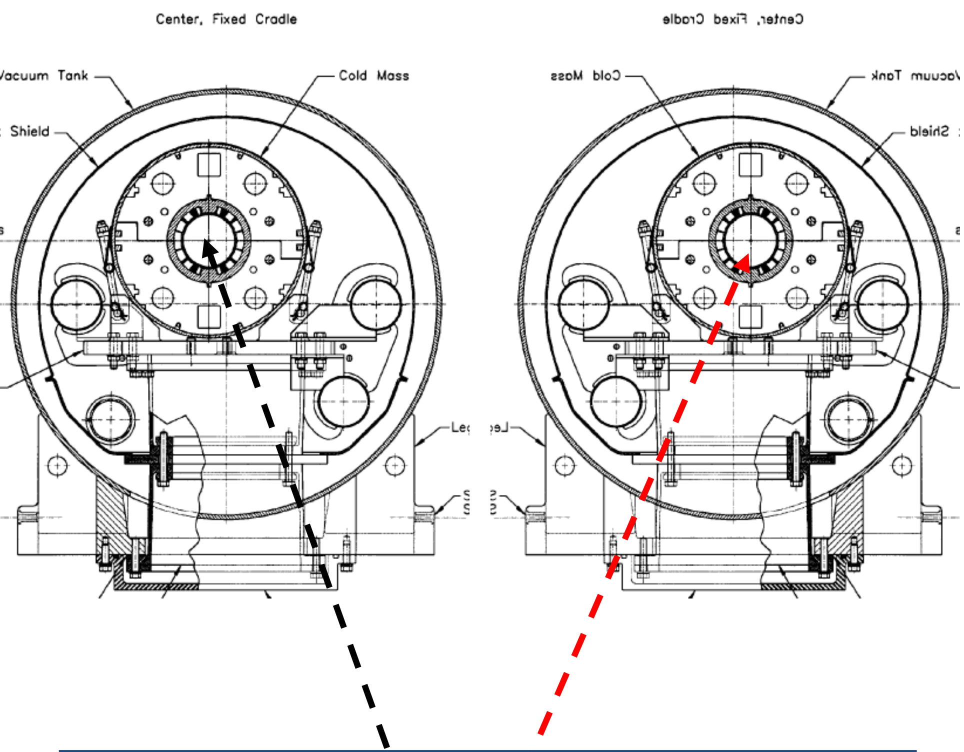
Late 2002: initially RHIC tried equal rigidity injection and acceleration

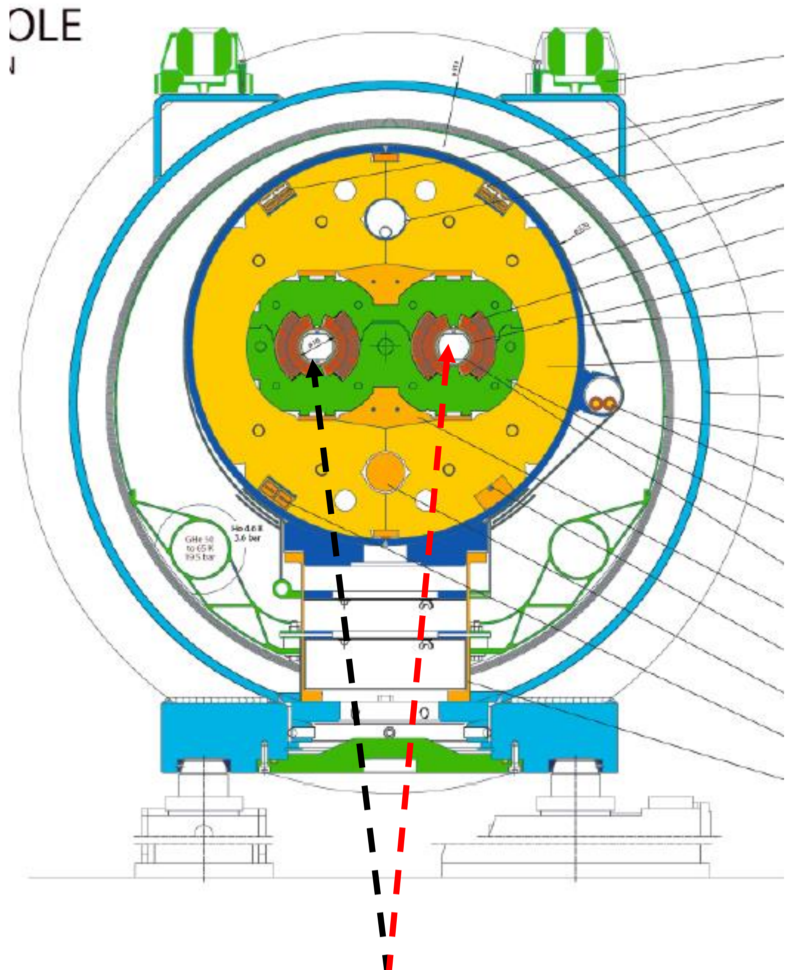
Unequal-frequency beam dynamics

- Broken symmetry $\Rightarrow$ new modes
  - Symmetry restored at high energy

- Present understanding:
  - "Overlap knock-out" resonances shown not to be a problem for LHC
  - Diffusion mechanisms were likely source of problems for RHIC but have been shown to be weaker in LHC

Critical difference between RHIC and LHC





RHIC: Independent bending field for the two beams – they abandoned equal-rigidity and switched to equal-frequency D-Au.

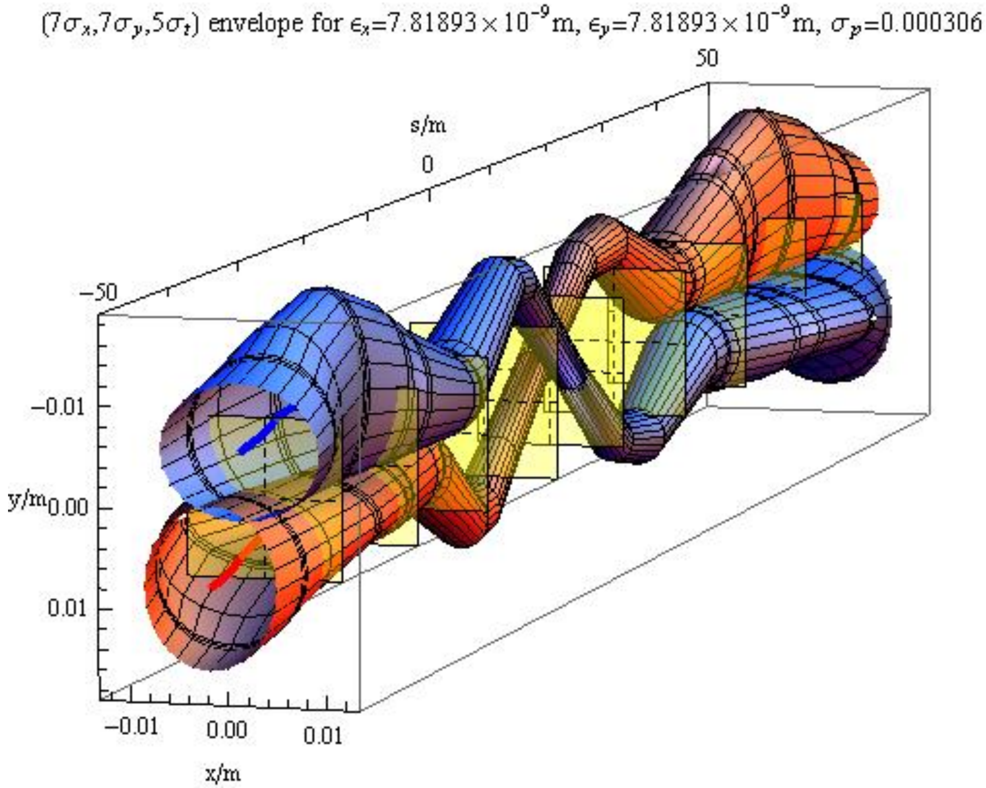
LHC: Identical bending field in both apertures of
two-in-one dipole – no choice

Outline of p-Pb physics cycle (Pb-p similar)

- Inject p beam in Ring 1, f_{RF1} for p
- Inject Pb beam in Ring 2, f_{RF2} for Pb
- Ramp both beams on central orbits
  - Orbit feedback decouples RF frequencies
- Bring f_{RF} together to lock, beams are slightly off central orbits
- RF re-phasing to position collision point
- Squeeze
- Change ALICE crossing angle to collision configuration
- Collide

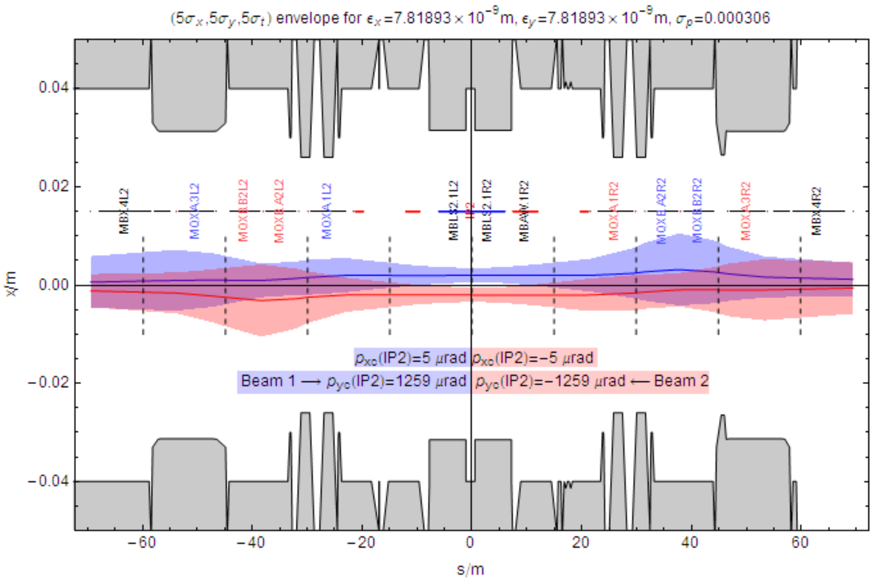
At injection the proton beam makes 8 more revolutions per minute than the Pb beam

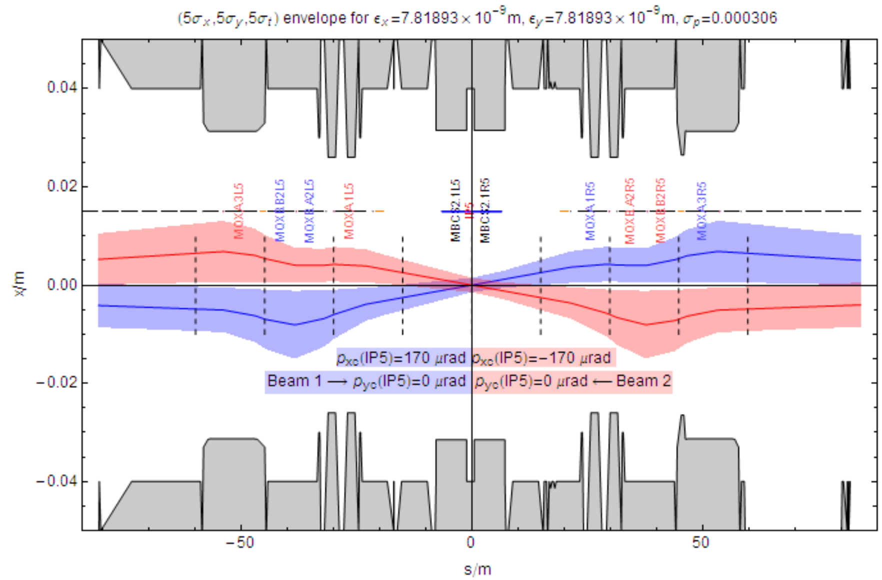
Beam envelopes around ALICE at injection

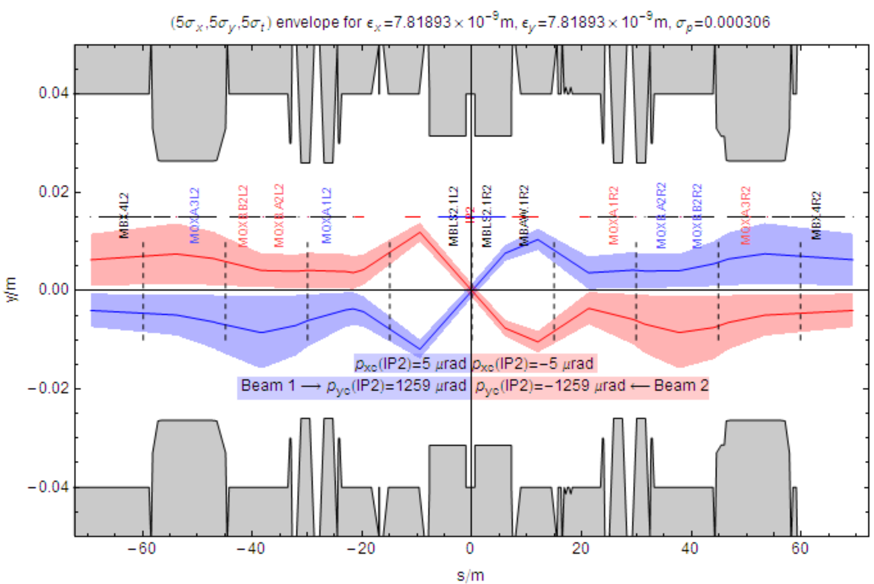


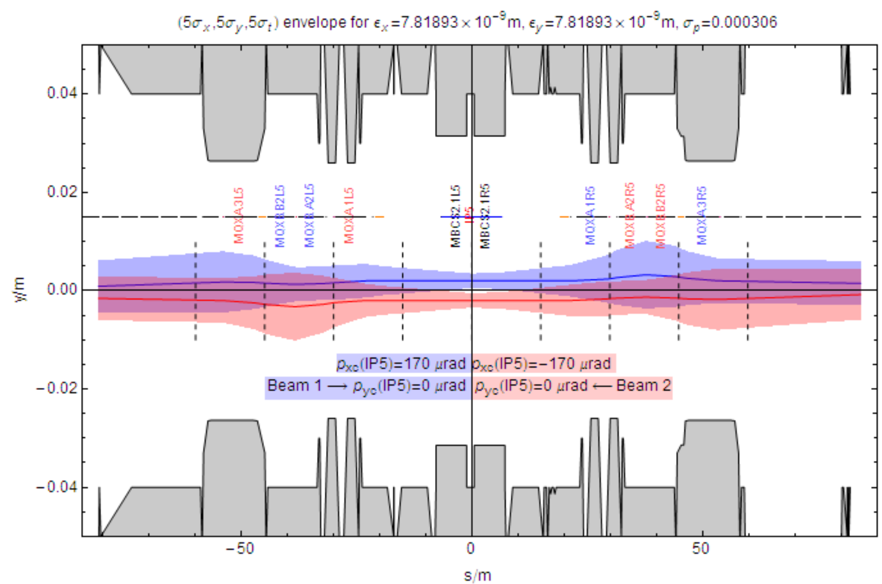
Crossing angle from spectrometer and external bump separates beams vertically everywhere except at IP (also in physics).
Parallel separation also separates beams horizontally at the IP during injection, ramp, squeeze.
Other experiments have different separation schemes …

ALICE – Separation at injection - CMS

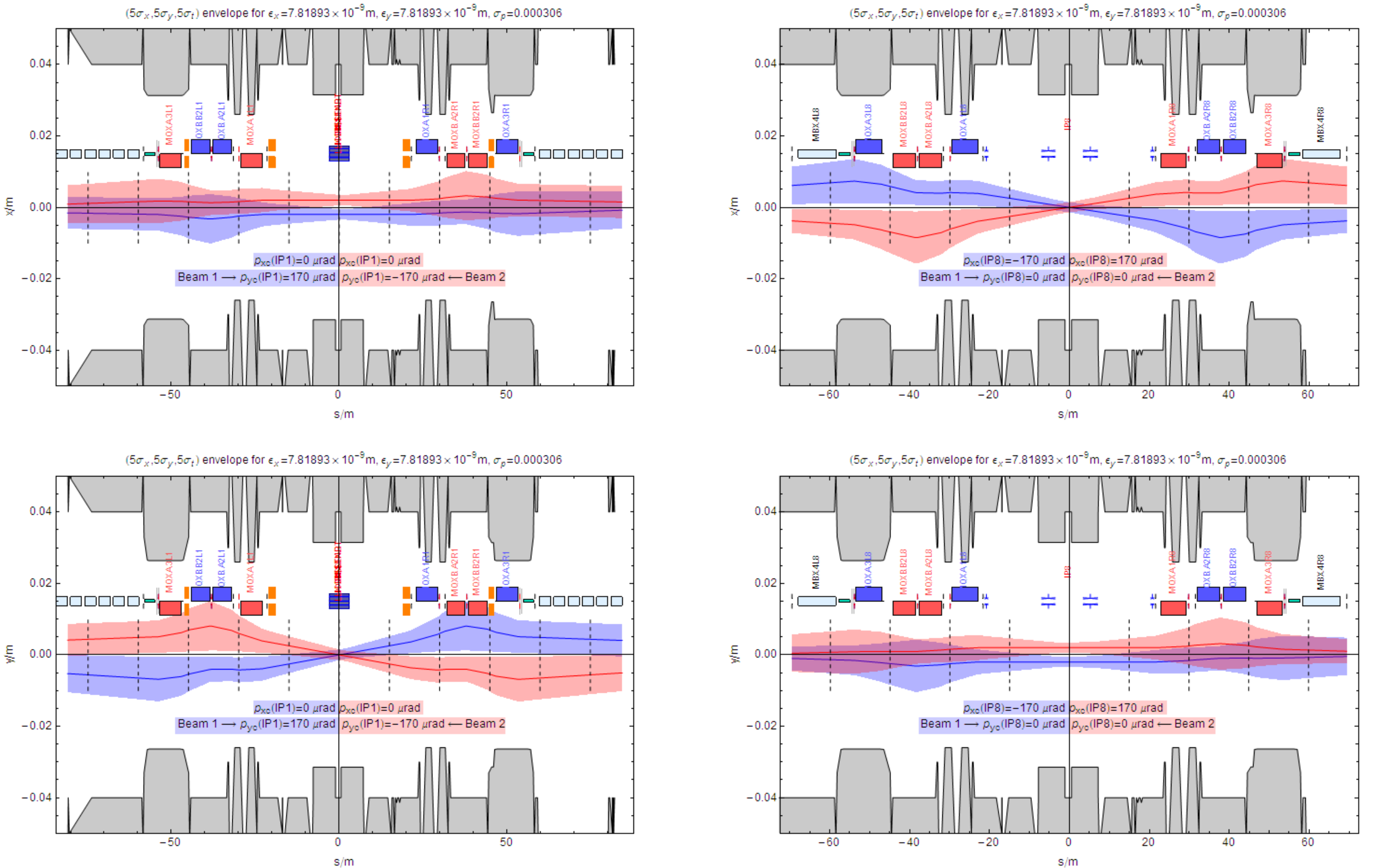








ATLAS - Separation at injection - LHCb



Long-range beam-beam effects

For separations $x, y \gg \sigma_{x,y}$, the (angular) beam-beam kick on a particle of charge Ze, due to an opposing beam of total charge Ne is

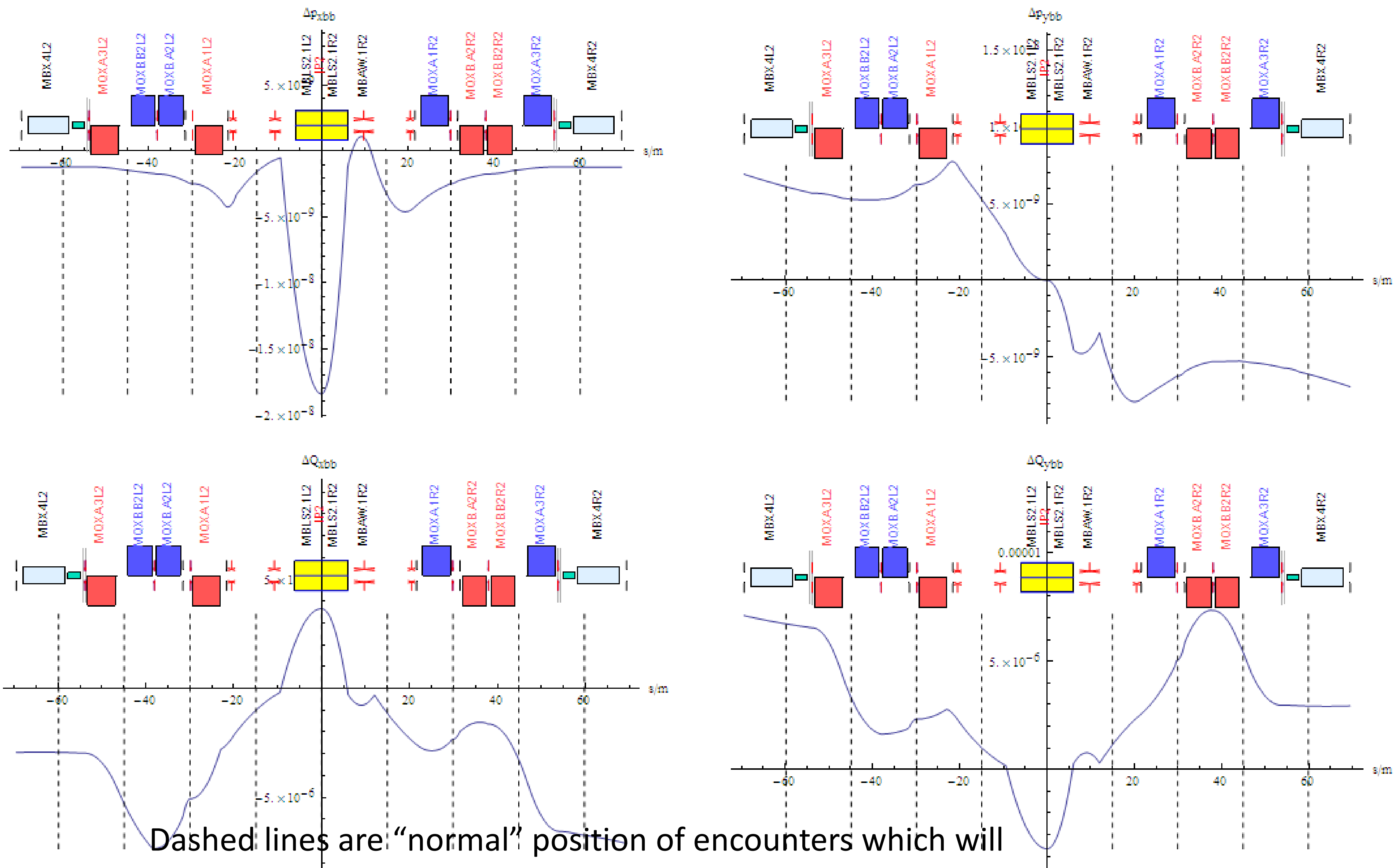
$$(\Delta p_x, \Delta p_y) = \frac{2ZNr_0}{\gamma} \frac{(x, y)}{x^2 + y^2}, \qquad \text{where} \quad r_0 = e^2 / (4\pi\epsilon_0 m c^2)$$

and gives rise to perturbative betatron tune-shifts

$$\Delta Q_{x,y} = -\frac{\beta_{x,y}}{4\pi} \partial_{x,y} \Delta p_{x,y} = \frac{ZNr_0}{2\pi\gamma} \frac{(\beta_x, -\beta_y)(x^2 - y^2)}{(x^2 + y^2)^2}$$

LHC separation configurations were chosen to minimise the tune effects in physics ("footprint").

Example: beam-beam for Pb around ALICE



Dashed lines are "normal" position of encounters which will move 15 cm along IR on next turn …

Overlap knock-out resonances ?

Encounter points move at speed $V = \frac{v_{\rm p} - v_{\rm Pb}}{2} = 1734\ \text{m/s} = 0.15\ \text{m/turn}$

Hamiltonian is no longer periodic in s.

Excites modulational resonances

$$\underbrace{m_x Q_x + m_y Q_y}_{\substack{m_{x,y}=1,2,\ldots \\ \text{transverse modes}}} = p + \underbrace{k}_{\substack{\text{Bunch harmonic,} \\ 891 \\ \text{or at most } 3564}} \underbrace{\left(\frac{v_{\rm p} - v_{\rm Pb}}{2c}\right)}_{\substack{3.\times 10^{-6} \text{ at injection,} \\ \text{decreases in ramp}}} \ ; \quad m_x, m_y, p, k \in \mathbb{Z}$$

Known as "overlap knock-out resonances" at the ISR.

However with LHC tunes, $Q_x \approx 64.3, Q_x \approx 59.3$, only extremely high-order resonance conditions can be satisfied.

Very unlikely to be a problem (similar in RHIC, W. Fischer).

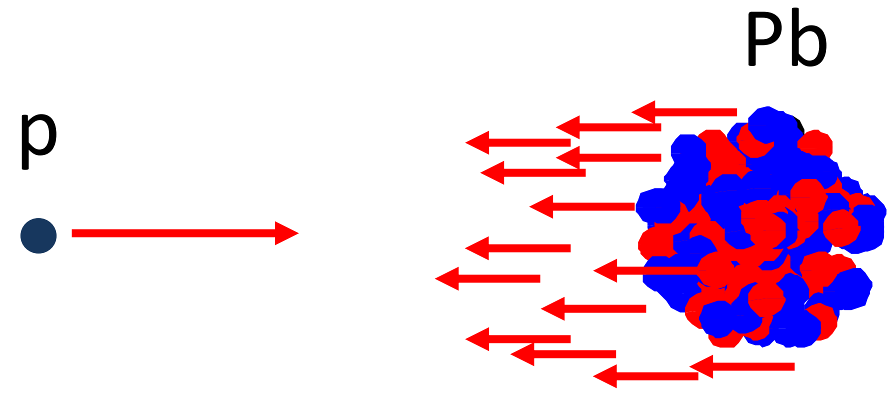
Diffusion models

- Naively regarding the kicks as purely random
  - Works fairly well for RHIC data (W. Fischer)

$$\frac{d\varepsilon_{x,yn}}{dt} = \frac{1}{2} f_0 \sqrt{\gamma^2 - 1} \left[\beta_{x,y}(s) \left(\Delta p_{x,y}(s) \right)^2 \right]$$

where [..] denotes mean-square deviation
gives an emittance doubling time around 40 min

- Better calculate combination of beam-beam kicks on a particle on a given turn as the encounters move
  - Add them up with proper betatron phases
    - Partial compensations
  - Take out static component (closed-orbit) from long-term averaging and look at fluctuations around it
  - RMS fluctuation gives emittance growth rate



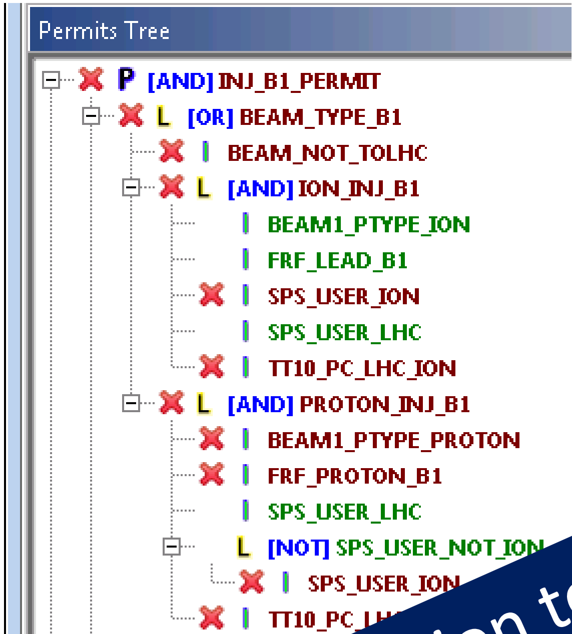
PROTON-LEAD FEASIBILITY TEST IN 2011

Repurposing LHC as proton-nucleus collider

- Systems/procedures developed during 2011 to enable this new mode of operation:
  - Machine Protection ➔ new Software Interlock permit tree to avoid the injection of protons into a ring configured for ions and vice versa
  - RF ➔ New rephasing and cogging procedure, plus FESA properties and sequencer tasks to configure each ring for the right particle type
  - BI ➔ New BPM calibration task to calibrate independently each beam according to the bunch spacing
  - Sequences ➔ New LHC PROTON-NUCLEUS NOMINAL Sequence
  - Timing ➔ New Accelerator Mode = PROTON-NUCLEUS PHYSICS & new telegram line with PARTICLE TYPE "PER" RING
  - Injection schemes ➔ New injection schemes mixing protons and ions
  - Transverse feedbacks already independent

R. Alemany-Fernandez,
P. Baudrenghien, …

Machine Protection: new SIS permit tree



Proton/Pb conditions – applied for each ring

LHC: **RF frequency** within 1kHz of proton referenc…

Monitoring at 0.2 Hz, accuracy ~ 20 Hz…

LHC : **particle type** in CPTY telegram …

SPS: **user name** LHCx or LHCFA… …,4…)

SPS: **injection line TT10** … 26 GeV/17 GeV:

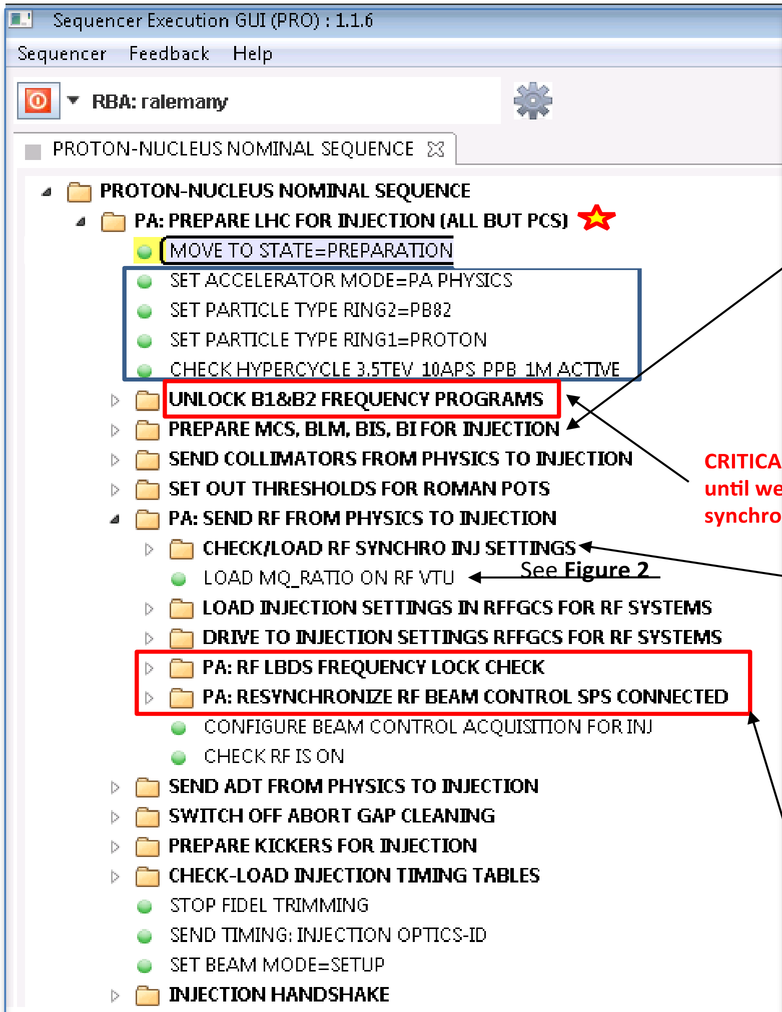
Curre… …and 2 main quadrupole

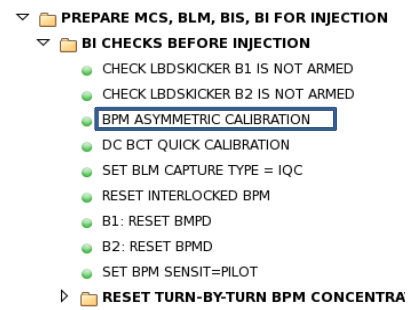
Extension to more general cases often introduces useful clarifications in system design.

The S… …w injection into a given ring if the settings are consistent with ions or wit… …rotons. On top of being an efficient machine protection mechanism, it is flexible – no a priori knowledge on which ring is used for which species. It will also work to avoid injecting ions during p-p runs (and vice-versa).

R. Alemany-Fernandez, J. Wenninger

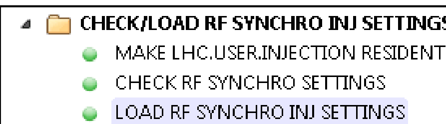
New LHC PROTON-NUCLEUS NOMINAL Sequence





BPM ASYMMETRIC CALIBRATION: Allows to use a different bunch spacing for each ring. For the **100 ns proton** beam **select 125 ns bunch spacing**, for the **single bunches** or the **200 ns Pb** trains select **single bunch calibration**.

CRITICAL: The RF FREQ are unlocked all the time until we lock them after the ramp and the RF synchronization of both beams.



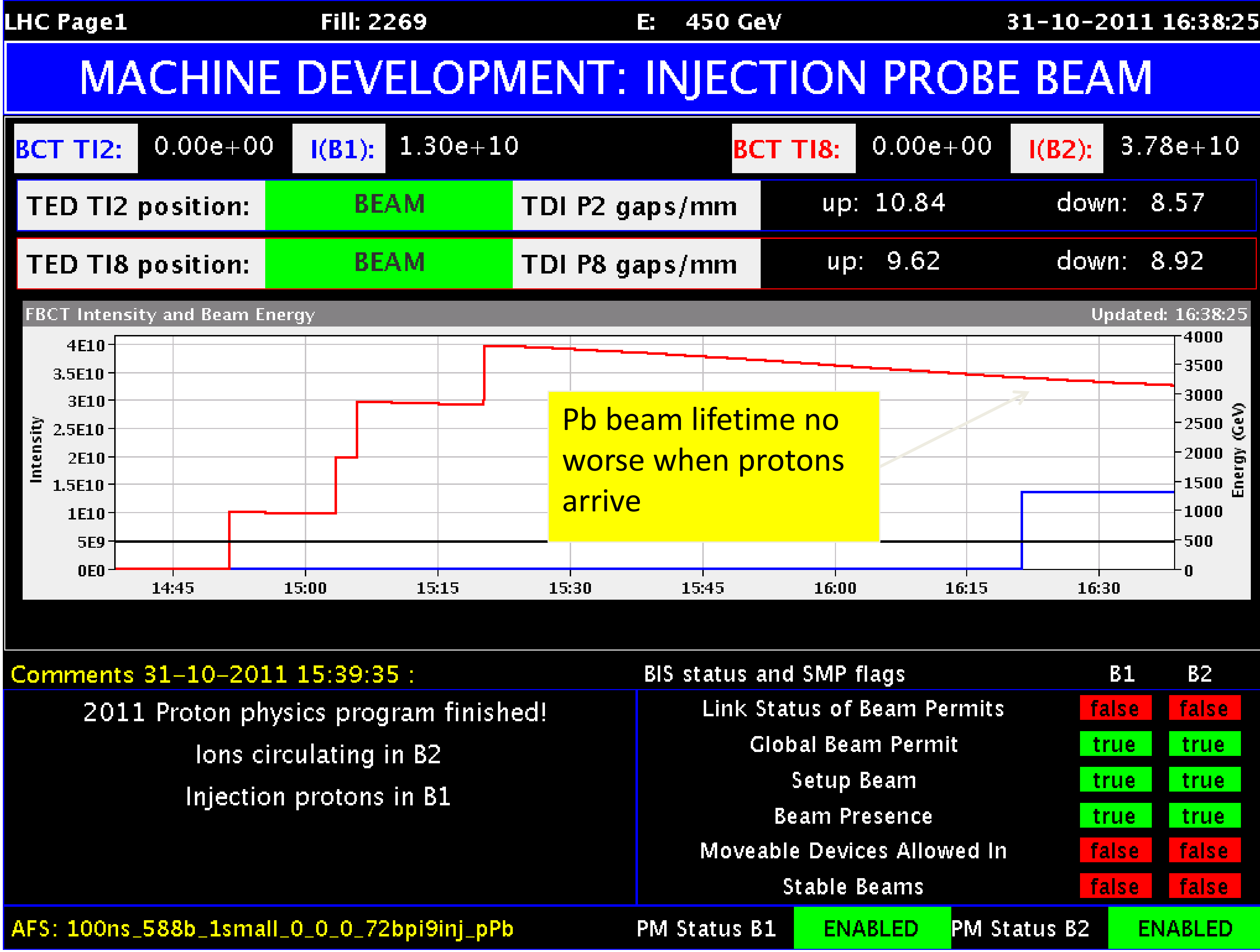
This action has to be done before the SPS-LHC synchronization sub-sequence, since each time we change the **InjPulseDelay#Ring1/2Bt one has to reset the RF synchro crate.** See **Figure 1** for details

As the pp or PbPb nominal sequences except the RF FREQ is never locked at the end of the sub-sequence

R. Alemany-Fernandez

p-Pb feasibility test, Part 1, 16h on 31/10/2011

- Several hours setup of first Pb beam of the year (timing, many details…)
- Stored 4 Pb bunches in presence of 304 p bunches (~10% nominal intensity) at injection
  - Lifetime no worse for presence of p bunches
  - Emittance blow-up, does not appear to be worse than for Pb alone
- Dumped and re-injected 4 fresh Pb
  - Still OK
- Ramped 2 Pb and 2 p bunches, good lifetime
- Re-phased RF (cogging) to move bunches 1 encounter point 9 km back to ATLAS, *no losses*

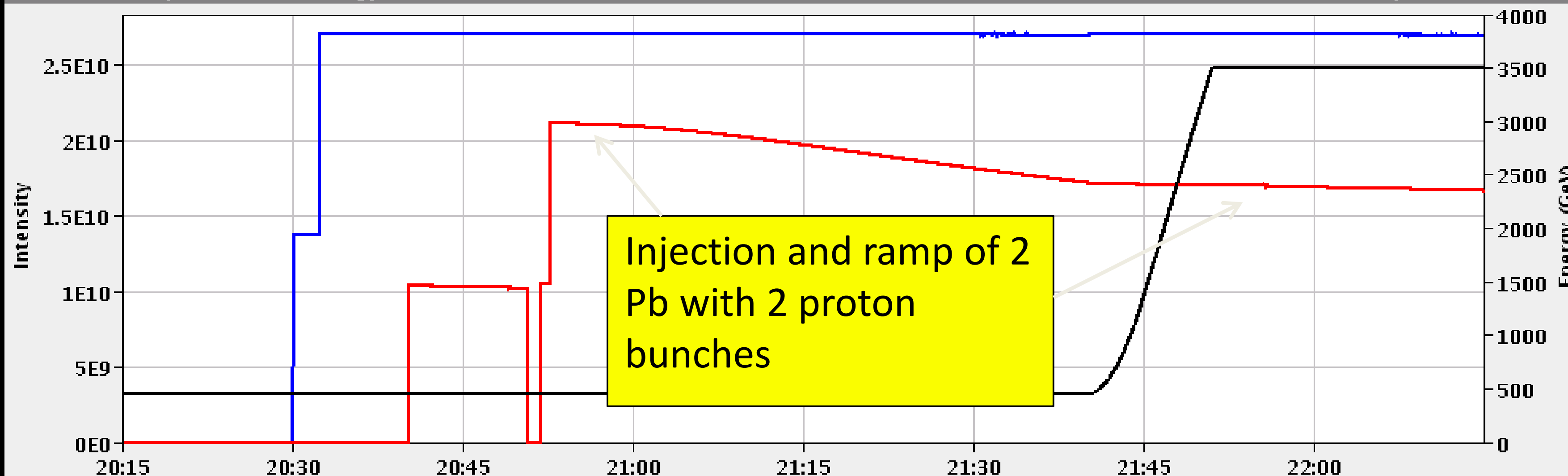

LHC Page1
Fill: 2269
E: 450 GeV
31-10-2011 16:38:25
MACHINE DEVELOPMENT: INJECTION PROBE BEAM
BCT TI2: 0.00e+00
I(B1): 1.30e+10
BCT TI8: 0.00e+00
I(B2): 3.78e+10
TED TI2 position: BEAM
TDI P2 gaps/mm
up: 10.84
down: 8.57
TED TI8 position: BEAM
TDI P8 gaps/mm
up: 9.62
down: 8.92
FBCT Intensity and Beam Energy
Updated: 16:38:25
Intensity
4E10
3.5E10
3E10
2.5E10
2E10
1.5E10
1E10
5E9
0E0
14:45
15:00
15:15
15:30
15:45
16:00
16:15
16:30
Energy (GeV)
4000
3500
3000
2500
2000
1500
1000
500
0
Pb beam lifetime no worse when protons arrive
Comments 31-10-2011 15:39:35 :
2011 Proton physics program finished!
Ions circulating in B2
Injection protons in B1
BIS status and SMP flags
B1
B2
Link Status of Beam Permits false false
Global Beam Permit true true
Setup Beam true true
Beam Presence true true
Moveable Devices Allowed In false false
Stable Beams false false
AFS: 100ns_588b_1small_0_0_0_72bpi9inj_pPb
PM Status B1 ENABLED
PM Status B2 ENABLED

LHC Page1 | Fill: 2269 | E: 3500 GeV | 31-10-2011 22:14:56

MACHINE DEVELOPMENT: FLAT TOP

Energy:	3500 GeV	I(B1):	2.54e+10	I(B2):	1.87e+10

FBCT Intensity and Beam Energy | Updated: 22:14:56



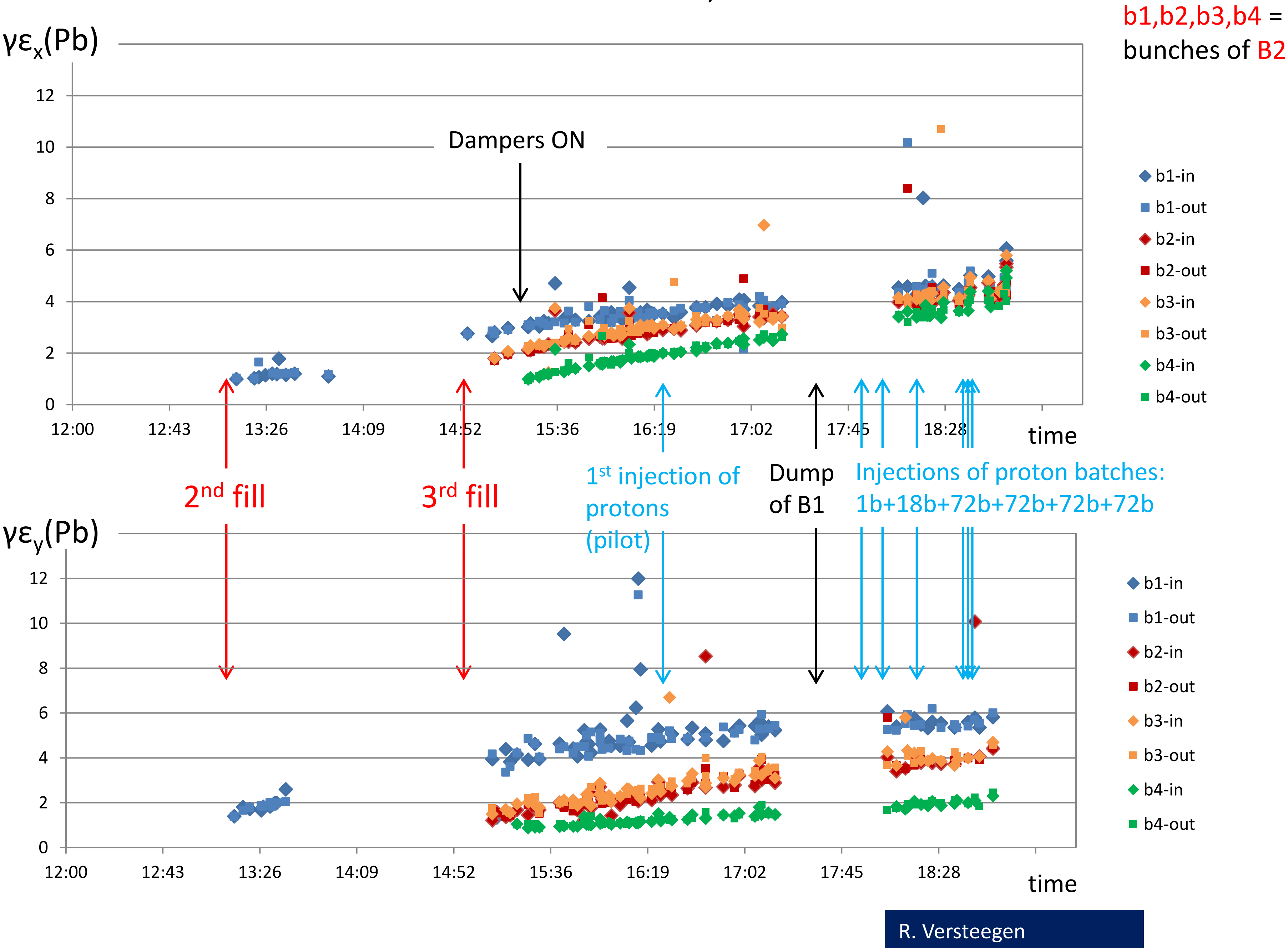
Comments 31-10-2011 21:55:27 :

2011 Proton physics program finished!
Proton and lead ion beams together for the first time at 3.5 Z TeV.
2 bunches each, will try rephasing RF.

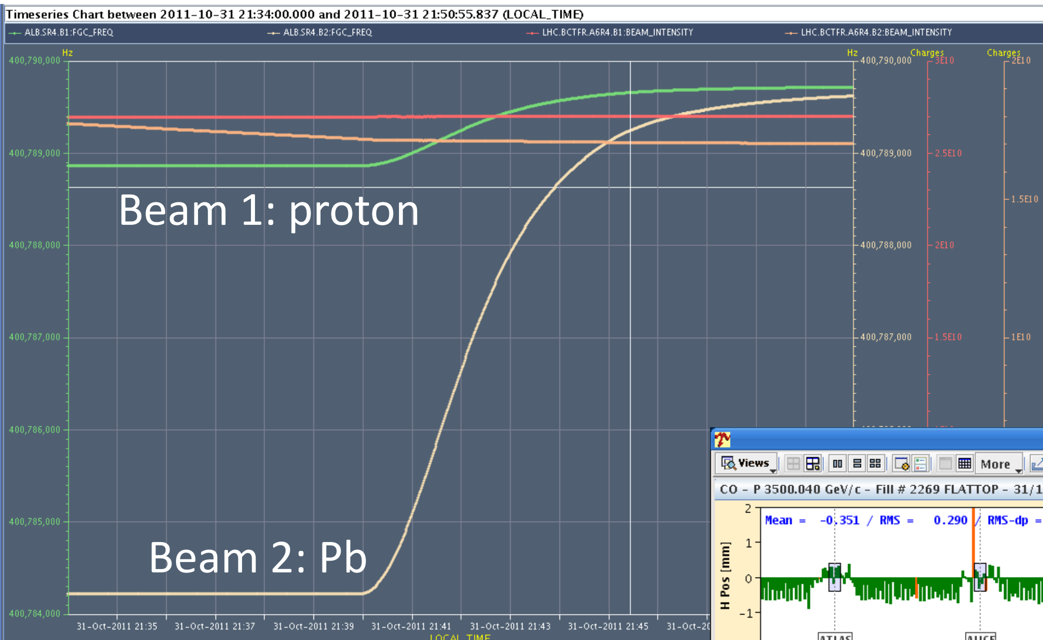
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: pPb_2b_1_1_1_1bpi2inj | PM Status B1 ENABLED | PM Status B2 ENABLED

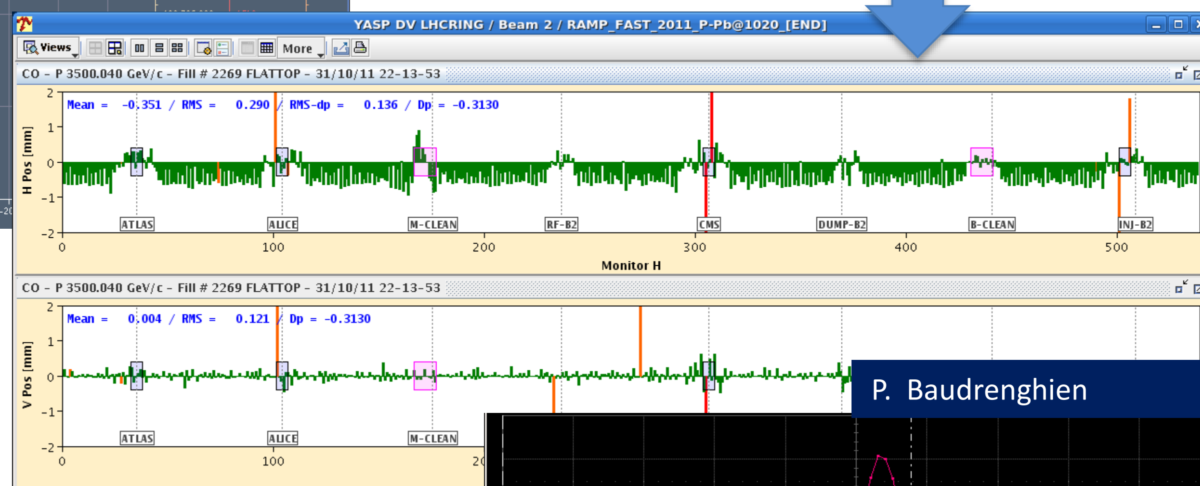
Wire scans of Pb beam B2, 2nd and 3rd fills



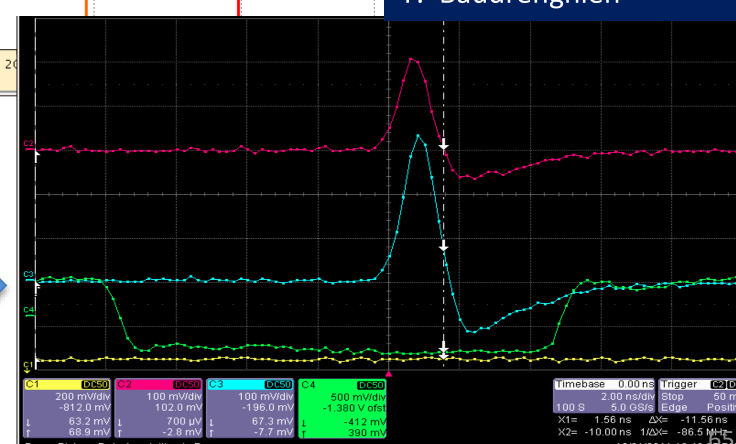
RF: New rephasing and cogging procedure



At top energy, f_{RF}(B1) = 400.789715 MHz and f_{RF}(B2) = 400.789639 MHz. Locking RF frequencies together imposes offsets of the central trajectories. We chose to get approximately the mean RF frequency, implying that the momentum offset would be ~ $\pm 3\times 10^{-4}$

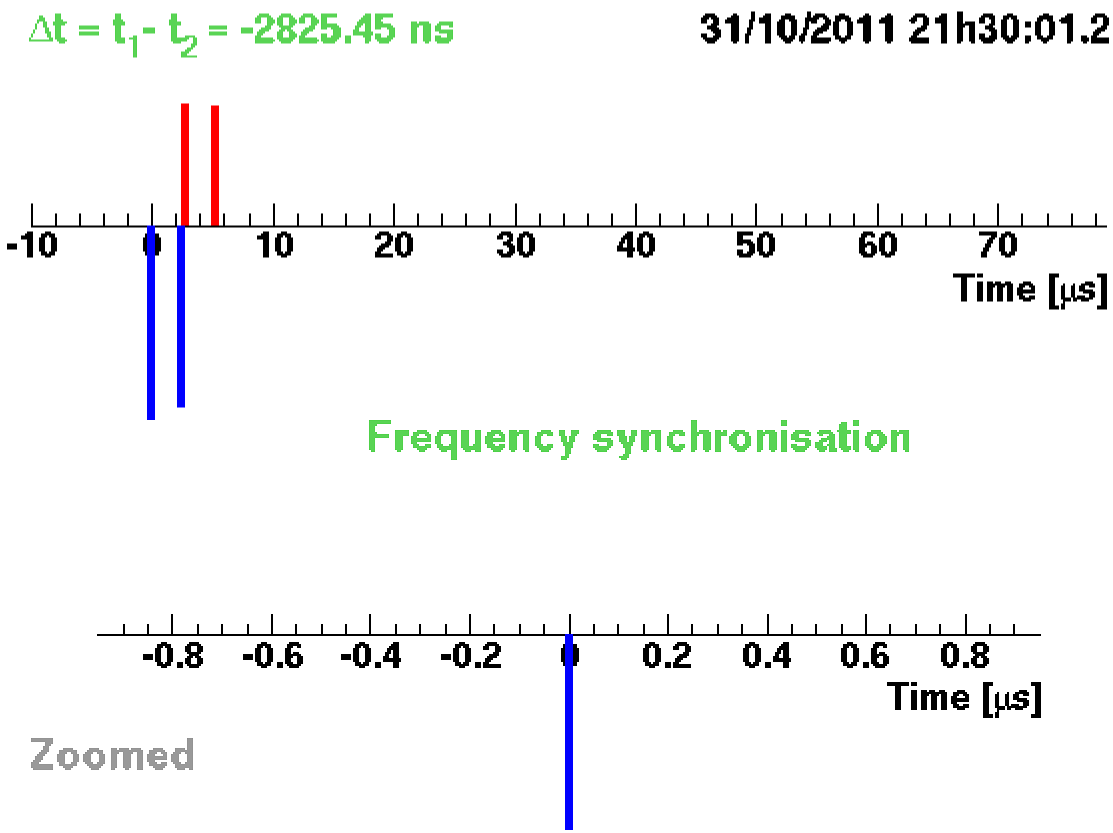


P. Baudrenghien



The final frequency was f_{RF} = 400.789685 MHz.

Moving the collision point by 9 km

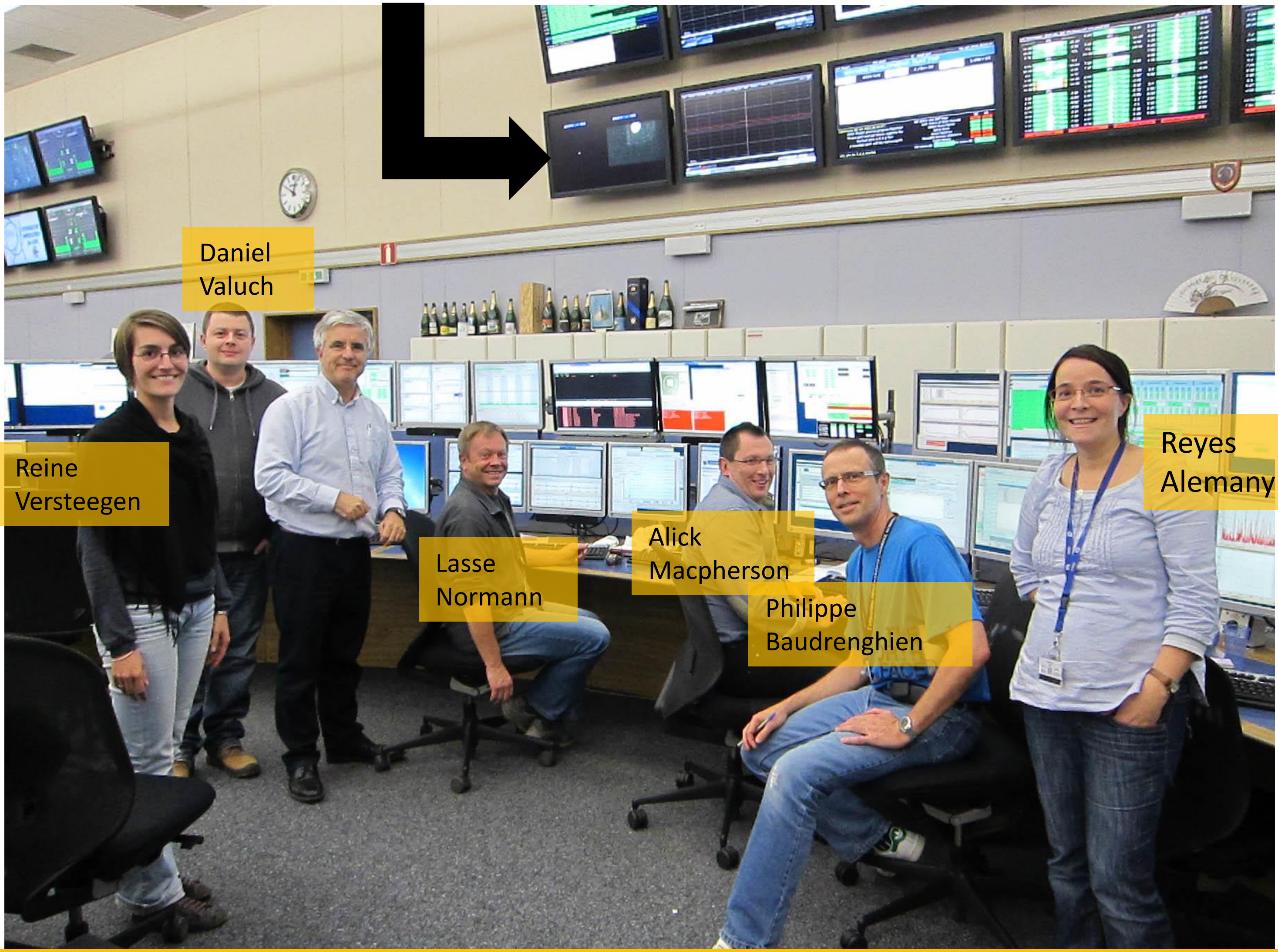


Real-time clock

RF cogging by Philippe Baudrenghien

Video from BPTX data by Thilo Pauly (ATLAS)

Hallowe'en 2011: first p and Pb at 3.5 Z TeV



Vital contributors to this 16-hour experiment not in photo:
J. Wenninger, S. Redaelli, M. Schaumann, M. Lamont, D. Jacquet, …

P-Pb feasibility test, Part 2

- Scheduled for 16-17 Nov 2011, plan was:
  - Ramp many p and some Pb bunches
    - We have NOT demonstrated this
  - Pilot physics fill with moderate no. of bunches
    - Would have clarified potential of detectors
- Cancelled because of leak in PS proton injection septum
  - Continuing with protons = risk of major leak and ~ 1 week of LHC down time (could have happened in p-p!), jeopardizing 2011 Pb-Pb run.
- So … we had to base the 2012 physics programme with a complex new operating mode on a single partial test
- Strong motivation to do Part 2 in Aug-Sep 2012!

Our work inspired an unknown artist working for the CERN Bulletin to create this moving depiction of the angst of an LHC proton

2012 PROTON-LEAD PILOT RUN

First asymmetric collisions at LHC

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} in each experiment from one fill.

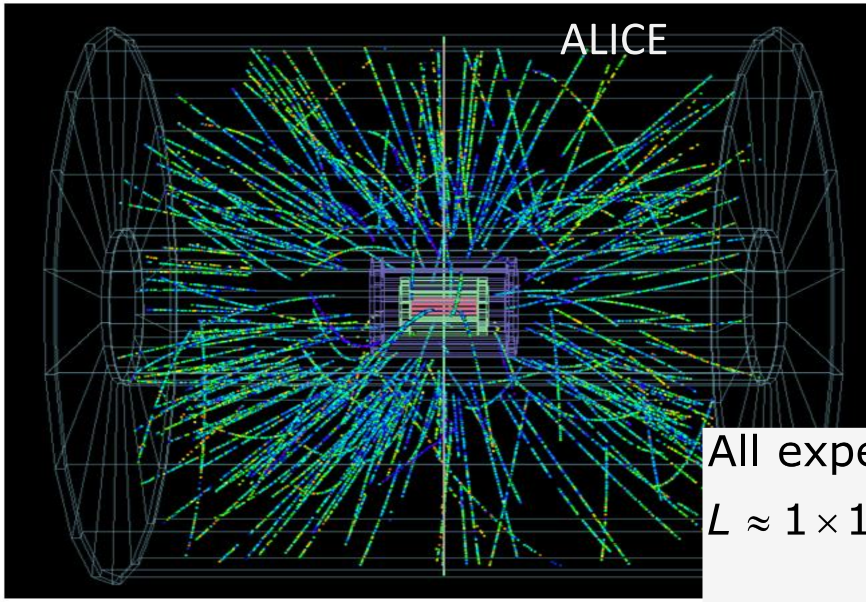
Historical energy jumps

$\sqrt{s_{NN}}$ is the centre-of-mass energy per colliding nucleon pair

Collision type	Before	$\sqrt{s_{NN}}$ / GeV	After	$\sqrt{s_{NN}}$ / GeV	Jump
e^+e^-	any		any		2-3
pp,$\bar{p}$p	PS, AGS	7.1	ISR	52	7.3
pp,$\bar{p}$p	ISR	59	S$\bar{p}$pS	540	9.0
pp,$\bar{p}$p	S$\bar{p}$pS	540	Tevatron	1960	3.6
pp,$\bar{p}$p	Tevatron	1960	LHC (pp)	7000	3.6
DIS (e/μ)*p*	E665 (μp)	29.7	HERA (ep)	314	10.6
AA	RHIC (Au-Au)	200	LHC(Pb-Pb)	2760	13.8
(p/d)*A*	RHIC (d-Au)	200	LHC(p-Pb)	5023	25.1

This was the largest factor of increase in the energy of a given type of collision ever achieved in the history of particle accelerators.

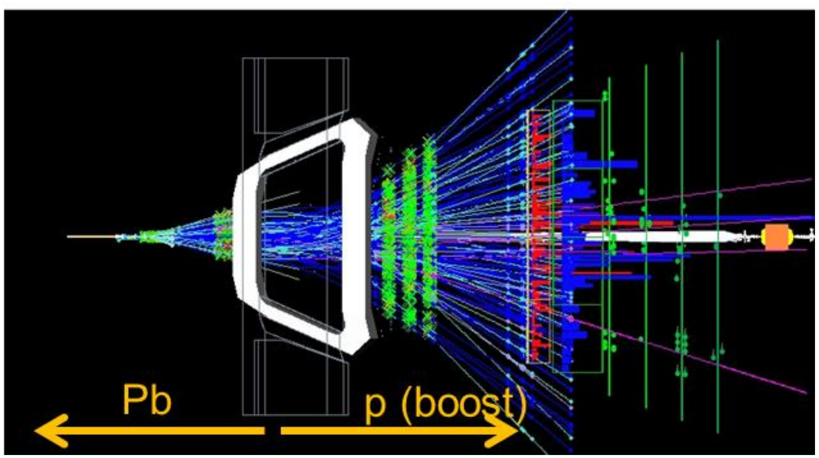
Collisions in all experiments

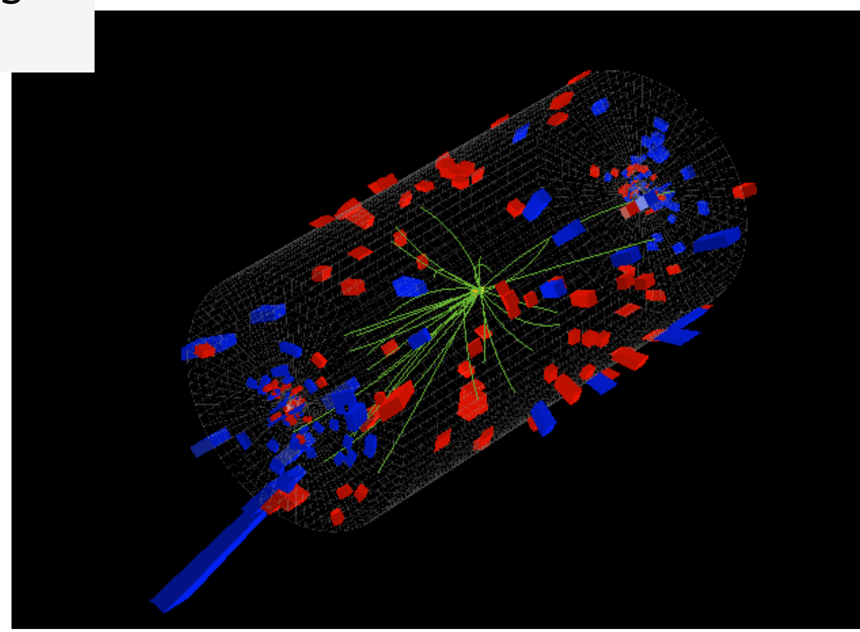


ATLAS

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

LHCb





CMS

Some of the members of the ion team celebrate proton–ion collisions in the CERN control centre, but the road to success is not always easy.

Reine Versteegen

Michaela Schaumann

Reyes Alemany-Fernandez

Carlos Salgado (guest theorist)

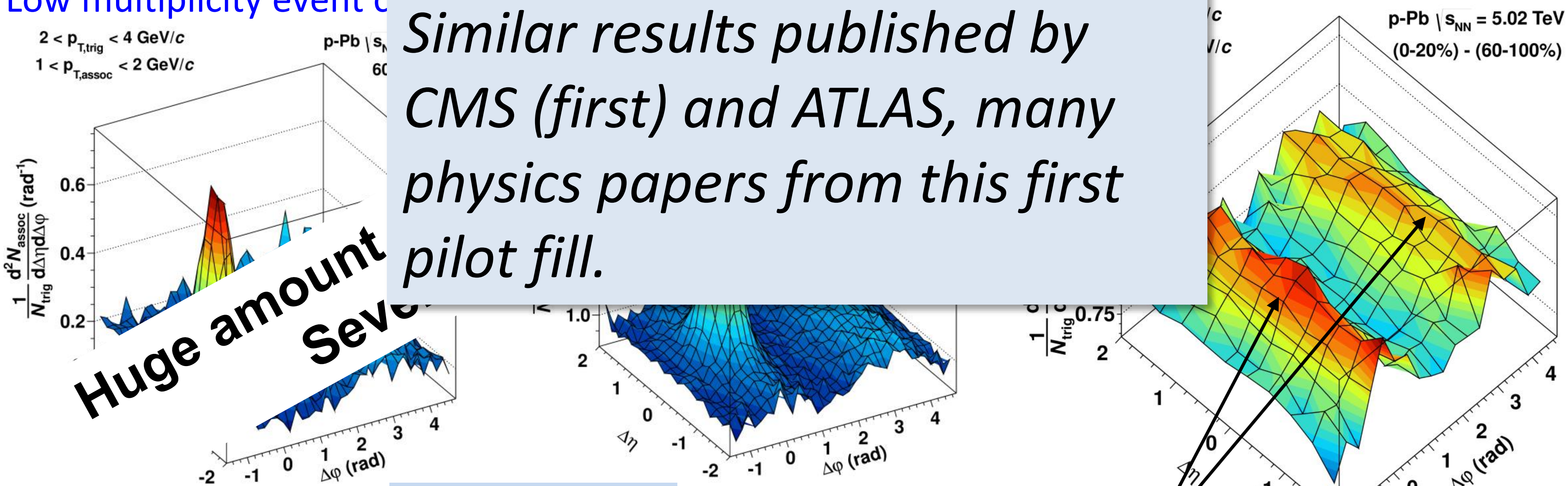
Correlations in p-Pb: the unexpected "ridge"

- A double-ridge structure appears, with remarkable properties:
  - Can be expressed in terms of $v_{2,3}$, Fourier coefficients of single particle distribution, with $V_{2,3}$ increasing with p_T and v_2 also with multiplicity
  - **Same yield near and away side for all classes of p_T and multiplicity: common underlying process**
  - Width independent of yield
  - No suppression of away side observed (its observation a... RHIC is considered a sign of saturation effects)
  - In agreement with viscous hydro calculations ?'

...ing a new window in the field

...4 h of collisions

Low multiplicity event c...



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

Huge amount

Seve...

P. Giubellino, Evian Dec 2012

Double-ridge structure

Status of p-Pb operation at start of 2013

- Successful Hallowe'en MD back in 2011
  - Few bunches of Pb with ~300 p bunches at injection
  - Few bunches of p and Pb ramped, RF locked and first demonstration of cogging process to restore IP
- Very successful p-Pb pilot run in September 2012
  - Setup, collimation, new cogging process and physics in a single fill
  - 12 Pb and 12 p in collision, unsqueezed, 4 h physics, ~1 μb^{-1}
- MD studies on intensity limits, carefully planned and scheduled in 2012, *were all lost*
  - Vacuum leaks, IR6 interlock BPM problems, …
  - **No test of our prediction that p-Pb with unequal frequency injection and ramp was feasible** (unlike analogous situation with D-Au in RHIC exactly 10 years ago, OKO resonances at ISR, …)
  - An almost unprecedented mode of collider operation, physics community "expecting" factor 1000 in luminosity

Physics requests for the p-Pb run

- Initial minimum bias p-Pb for ALICE

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

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

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

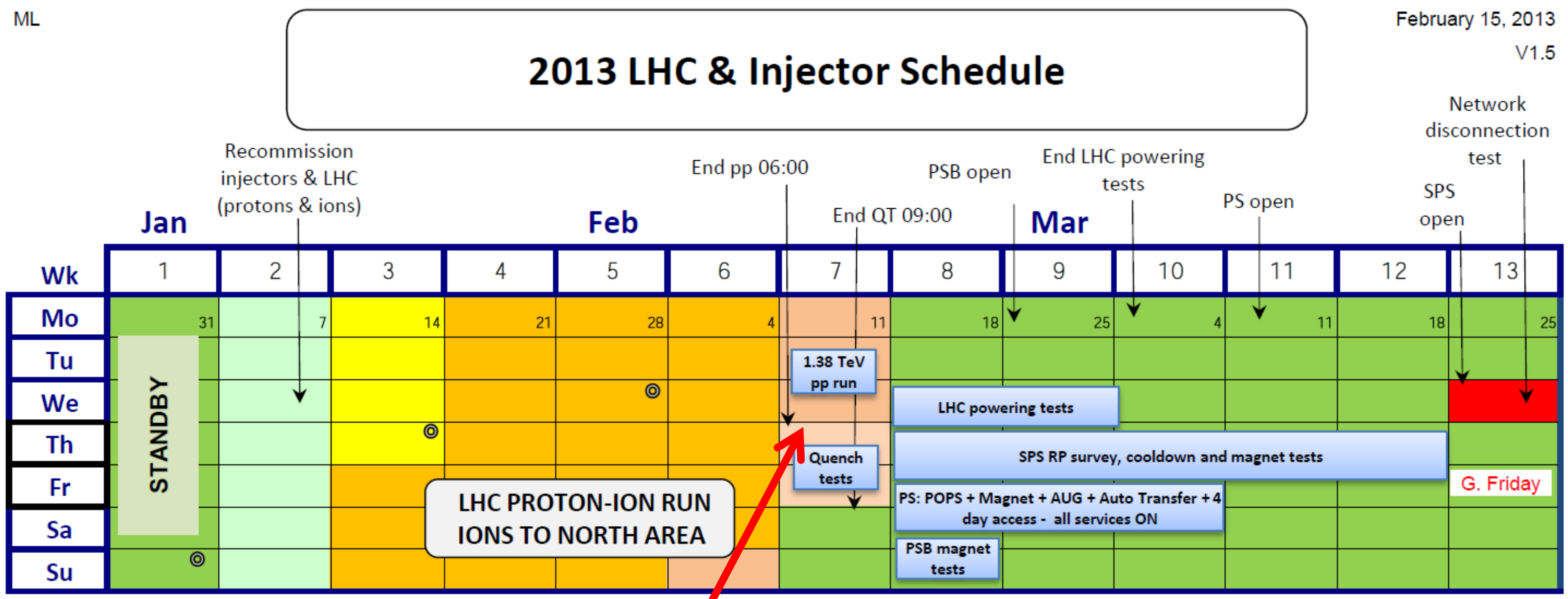
$$\mu_{\text{ALICE}} < 0.05$$

~ 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)
- 2nd 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
- 3rd priority: p-Pb with injection optics for LHCf
  – About 1 day required to commission and run



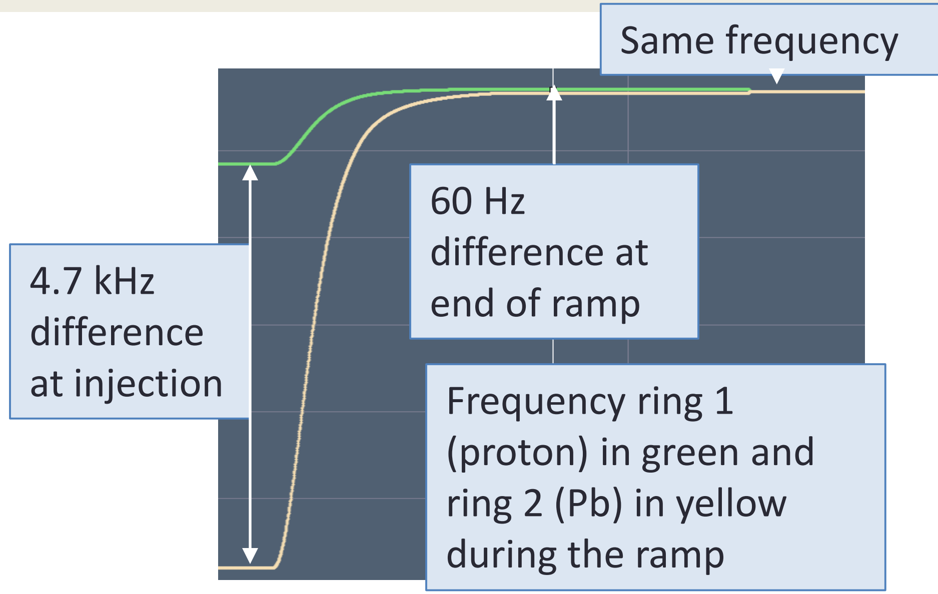
2013 run was finally extended by 2 days to allow time to reach integrated luminosity goals for both p-Pb and intermediate energy p-p.

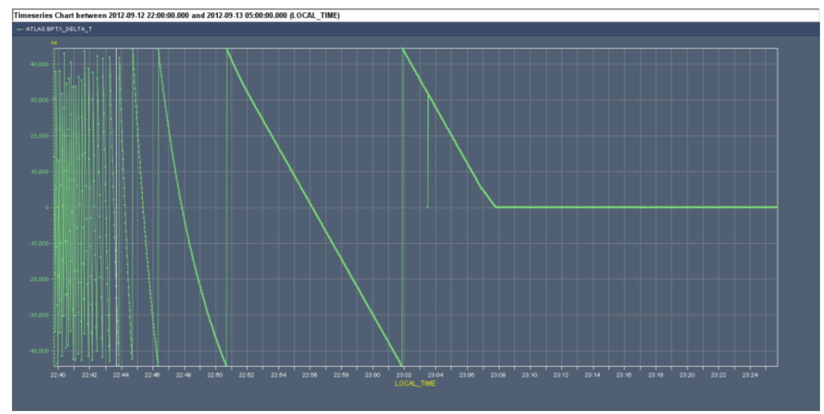
LHC new features (see earlier talks for more details)

- Unequal revolution frequency injection and ramp
  - Potential problems of moving long-range beam-beam kicks (killed this mode of operation of RHIC)
- Frequency-locking, off-momentum operation at top energy, cogging of IPs back to proper positions
- New squeeze from scratch including ALICE to 0.8 m and LHCb to 2 m
- Off-momentum correction of squeeze
- Many collimation setups, loss maps in various conditions
- Small crossing angle in ALICE (for ZDC)
- New filling scheme with collisions of 2 trains in LHCb
  - Very close encounters near ALICE

Final operational beam frequency locking and coggin

- 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!

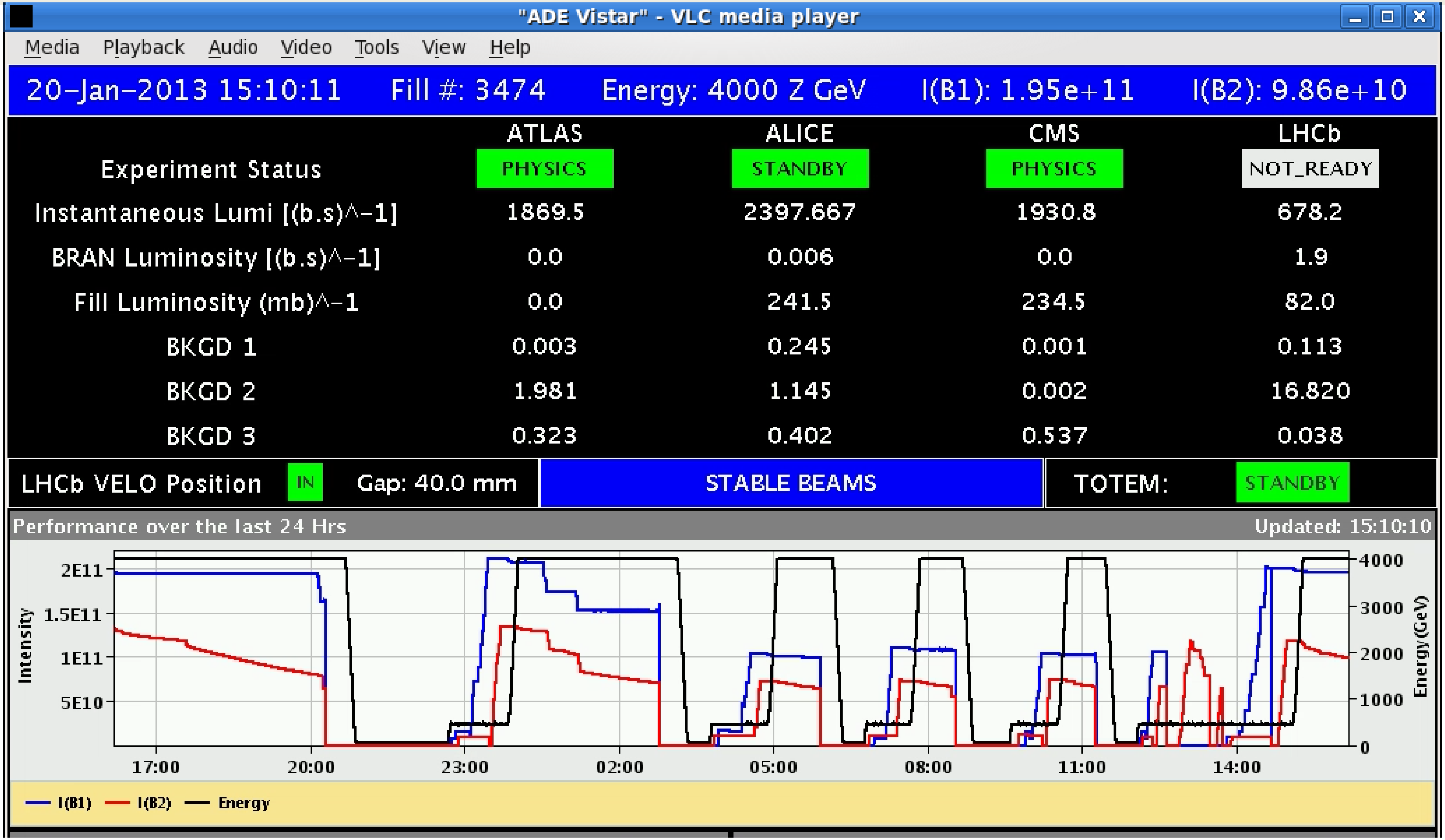




ATLAS BPTX from end-ramp to end-rephasing. Measures the time interval between passage of bucket 1 of both rings in the detector

P. Baudrenghien

Fills for loss maps during commissioning

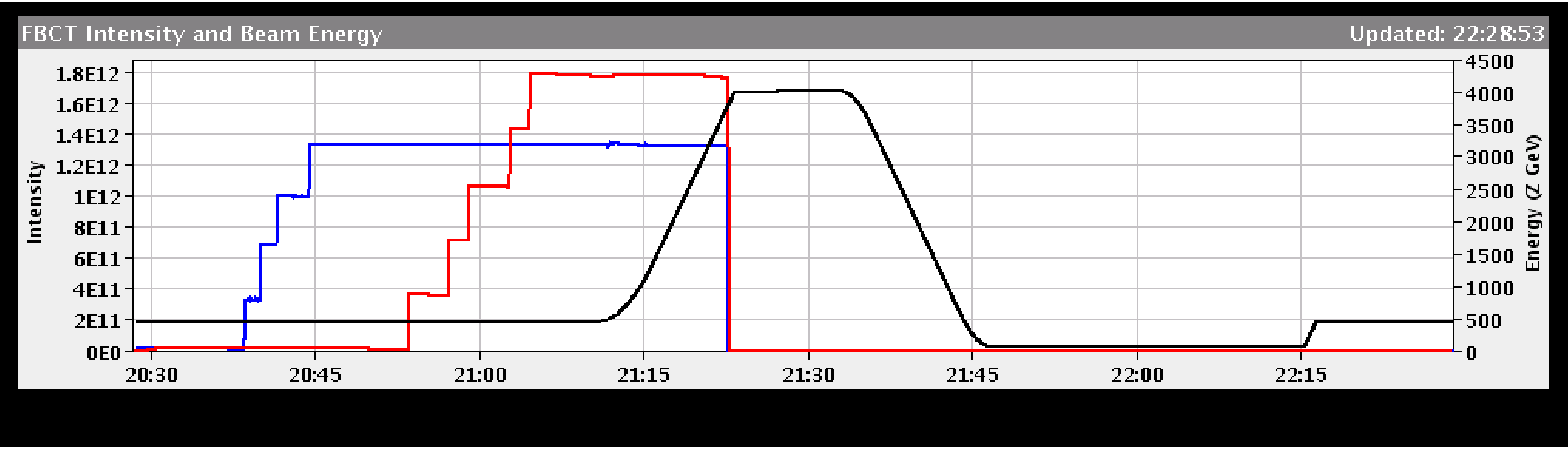


Intense work and analysis by collimation and operations teams, also alignment of TOTEM and ALFA Roman pots

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

Fill 3474

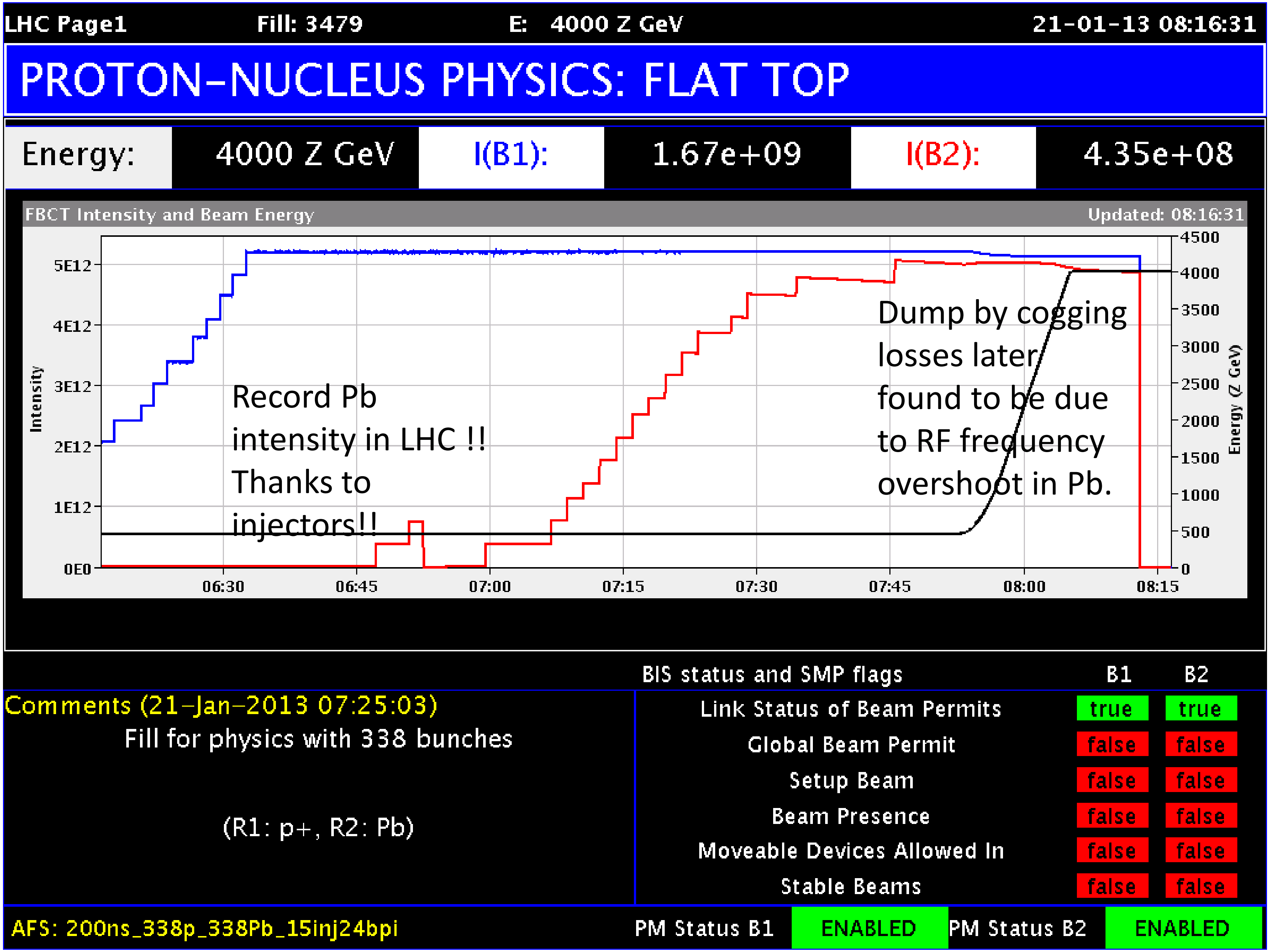
First injection and ramp of Pb trains against proton trains (trying to do this since 10 September 2012 …).



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

c.f. RHIC, D-Au equal rigidity injection and ramp, exactly 10 years ago

Full filling scheme 21/1/2013



Run overview 1/3

Monday	7	January
Tuesday	8	January
Wednesday	9	January
Thursday	10	January
Friday	11	January
Saturday	12	January
Sunday	13	January
Monday	14	January
Tuesday	15	January
Wednesday	16	January
Thursday	17	January
Friday	18	January
Saturday	19	January
Sunday	20	January
Monday	21	January
Tuesday	22	January
Wednesday	23	January
Thursday	24	January
Friday	25	January
Saturday	26	January
Sunday	27	January
Monday	28	January
Tuesday	29	January
Wednesday	30	January
Thursday	31	January
Friday	1	February
Saturday	2	February
Sunday	3	February
Monday	4	February
Tuesday	5	February
Wednesday	6	February
Thursday	7	February
Friday	8	February
Saturday	9	February
Sunday	10	February

Restart (7–10 January)

First injection in the LHC (11 January)

Injection checks and Squeeze commissioning (12–15 January)

Collimation set up, IR2 aperture measurements, first collisions (17–19 January)

First Stable beams, first injection of trains of p and Pb (20 January)

End of ALICE minimum bias data taking (25 January)

ALICE polarity change (27 January)

Van der Meer scans (28–29 January)

Pb source refill (30 January)

Beams reversal (1–2 February)

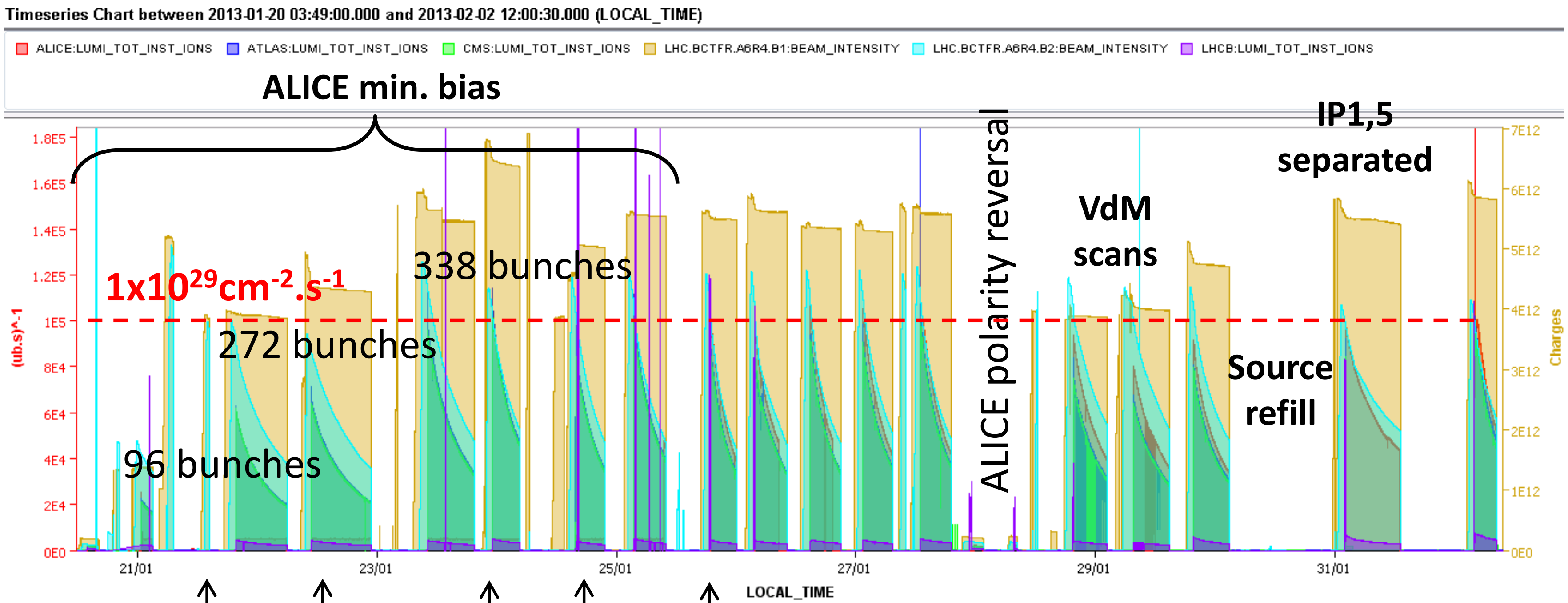
Van der Meer scans (8–9 February)

p-Pb (21–31 January)

Pb-p (3–10 February)

>4 days lost to cryo, power failures

R. Versteegen



Increase of BLM monitor factor (losses during cogging)

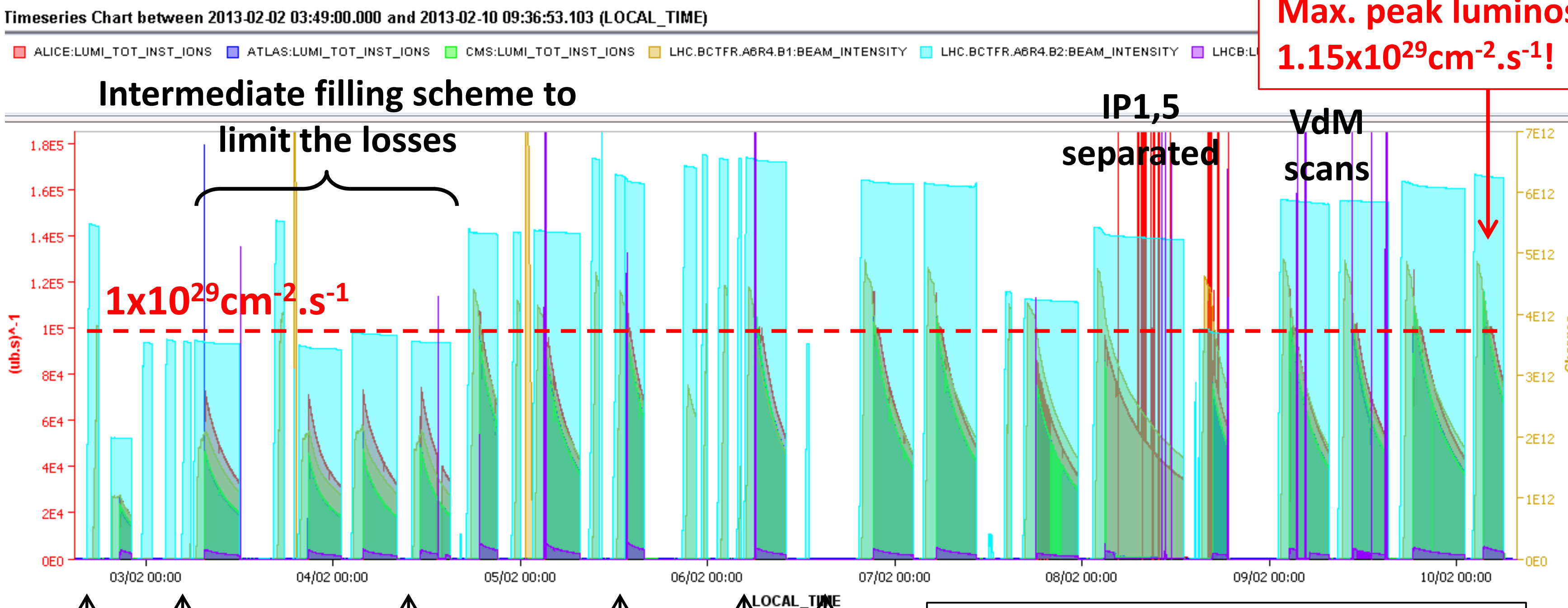
Problem of losses during cogging solved

TOTEM Roman Pots moved in

ALFA Roman Pots moved in

Longitudinal blow up ON

R. Versteegen



Max. peak luminosity $1.15\times10^{29}cm^{-2}.s^{-1}$!

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

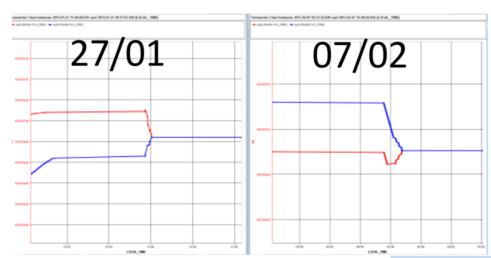
Common frequency trimmed by -10Hz

Increase bandwidth of orbit feedback

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

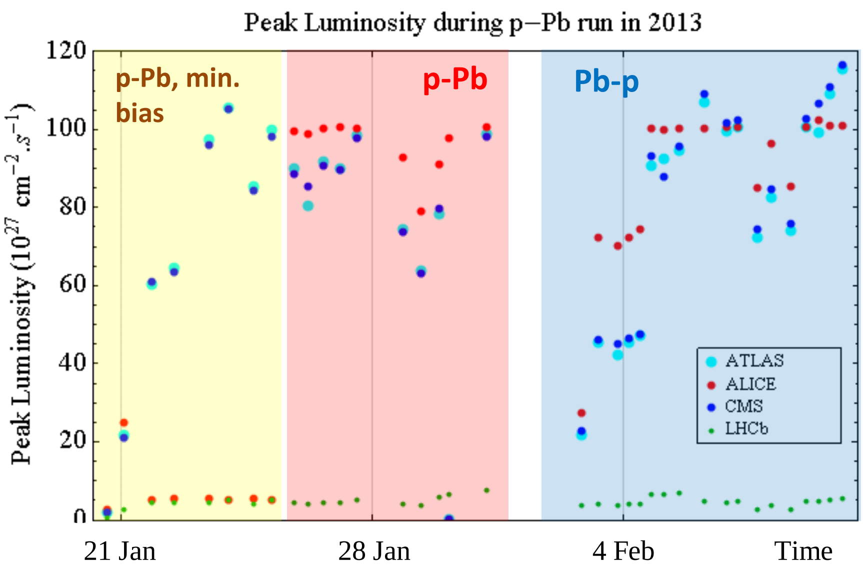
Increase of BLM monitor factor (losses at the start of the ramp), rematch injection energy to the SPS

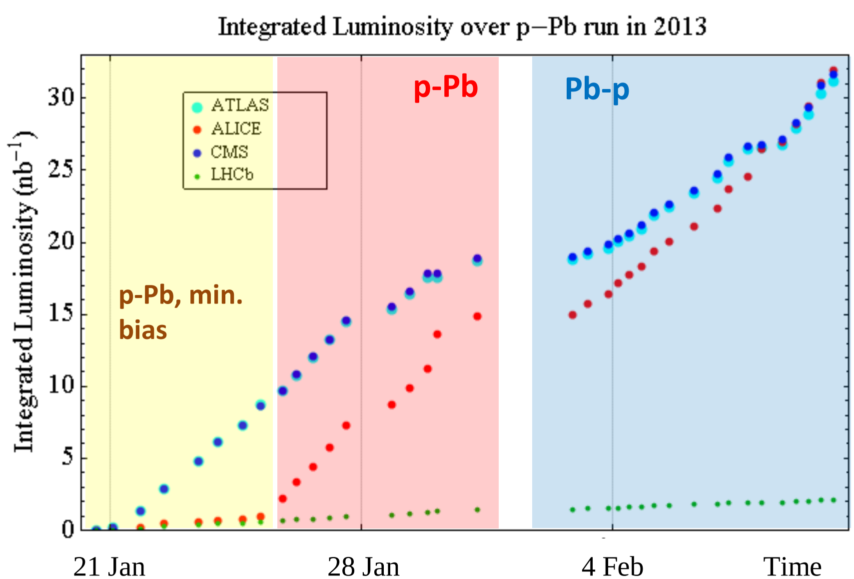
reduction of longitudinal blow-up at injection



RF frequencies

R. Versteegen

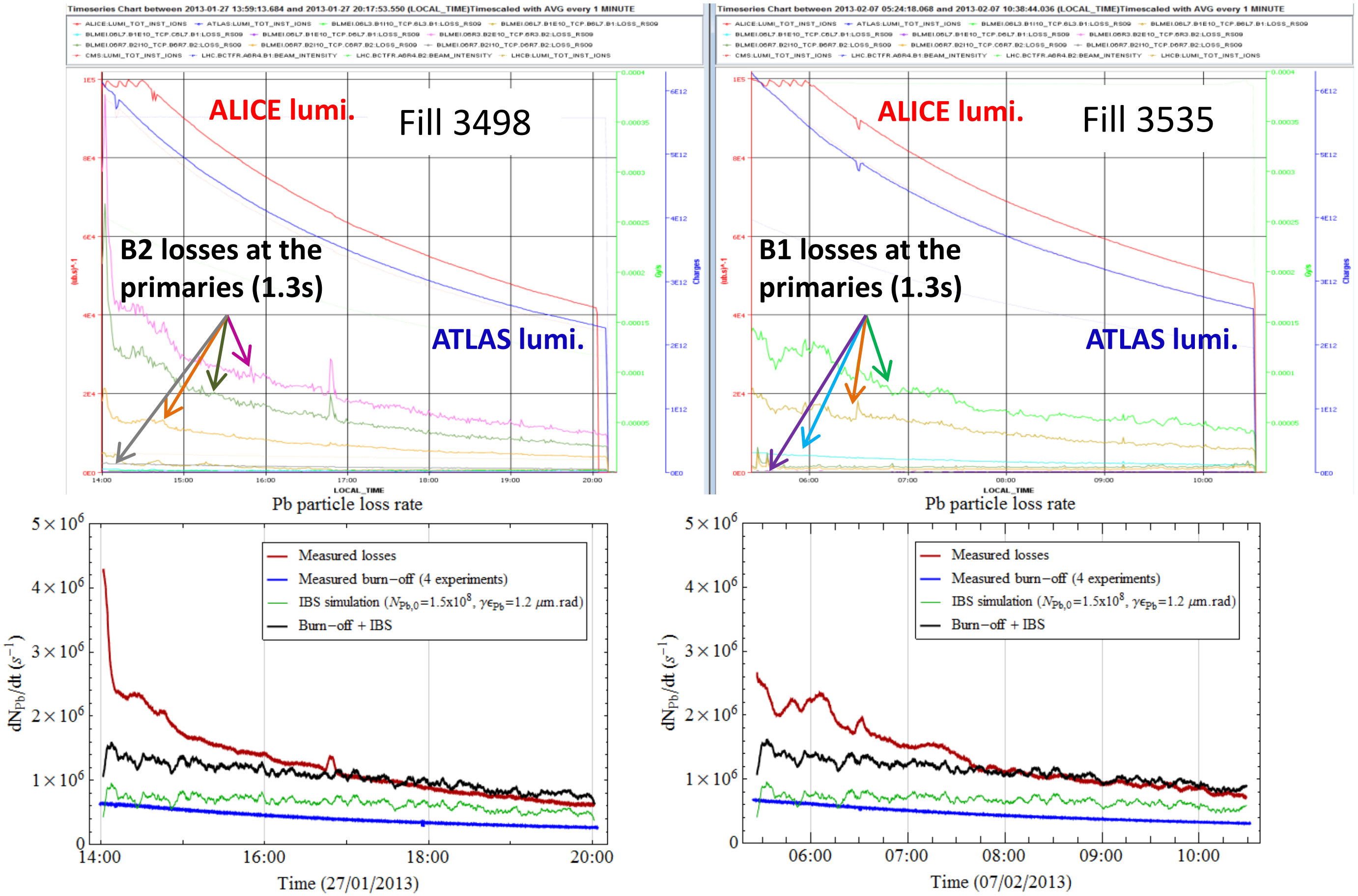




- Full instantaneous luminosity 1×10^{29} cm^{-2}.s^{-1} already reached with the first fill with full filling scheme
- Levelling in ALICE at 1×10^{29} cm^{-2}.s^{-1} in almost all standard fills
- Two fills were done with IP1 and 5 separated, allowing ALICE to catch up after initial minimum-bias
- Van 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

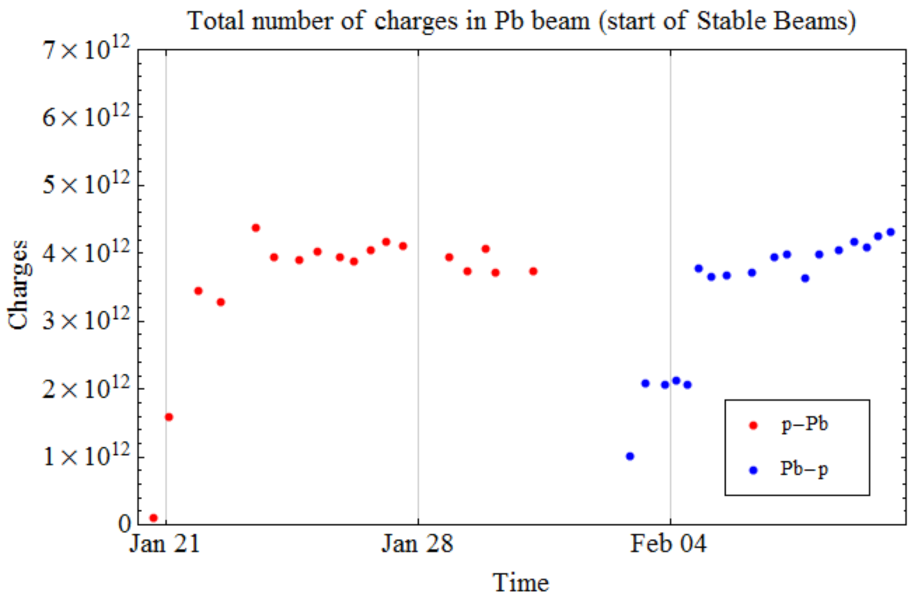
R. Versteegen

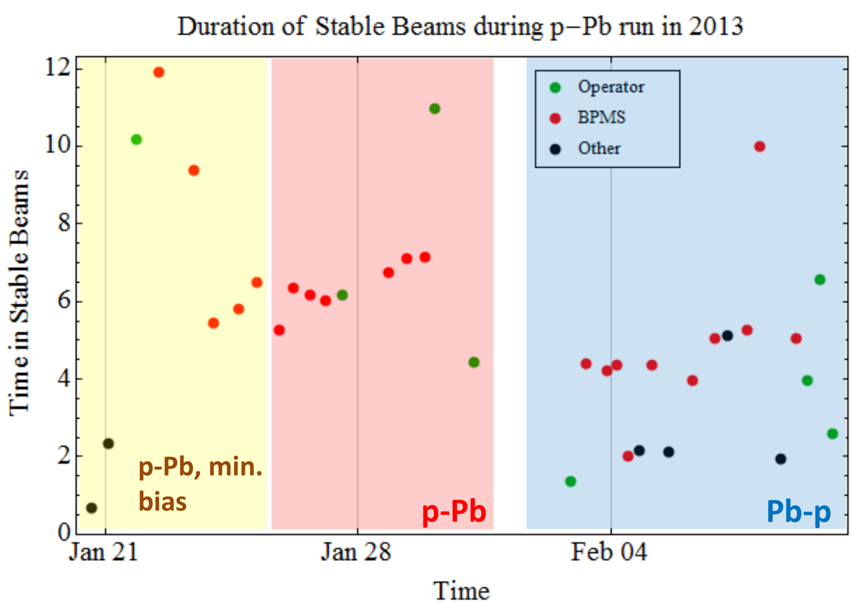
ALICE: 31.94 nb^{-1} ATLAS: 31.2 nb^{-1} CMS: 31.69 nb^{-1} LHCb: 2.12 nb^{-1}



- The luminosity evolution was driven by the number of Pb ions,
- Sources of losses were mainly luminosity burn-off and IBS (simulations by M. Schaumann),
- Additional losses at start of stable beams are comparable to Pb beam BLMs' signals, and were probably resulting from tight collimators' settings.

R. Versteegen

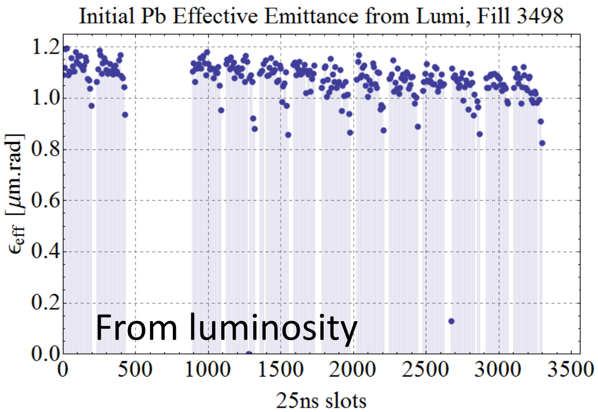


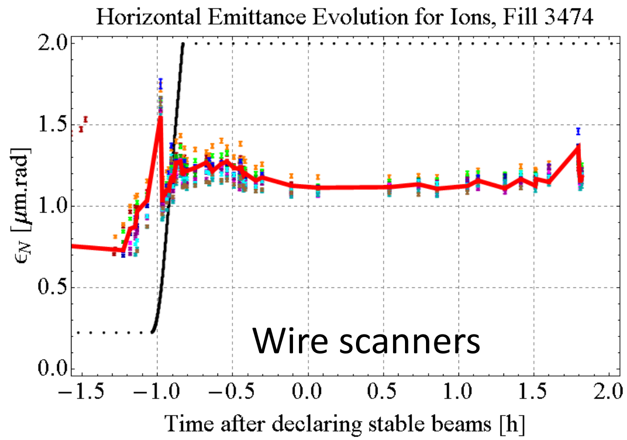


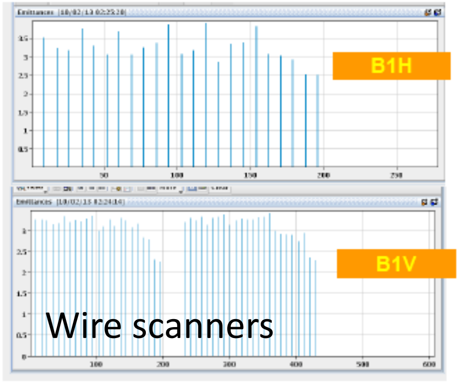
- Injectors provided very good quality Pb beams: average number of ions per bunch was 1.44×10^8 at start of stable beams (mean over the run), i.e. almost twice the nominal intensity,
- Most fills were dumped by the BPMSs thresholds in IR6 due to misreading for low intensity Pb bunches
- BPMSs' limit 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).

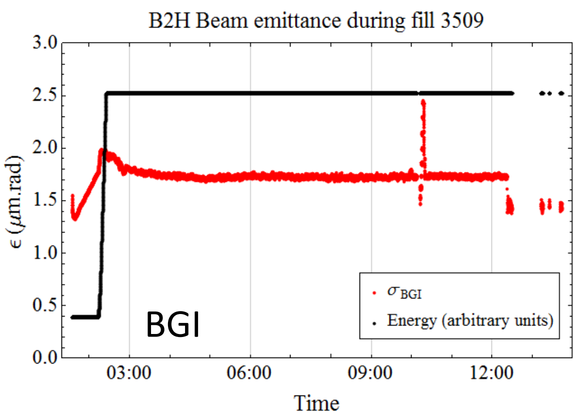
R. Versteegen

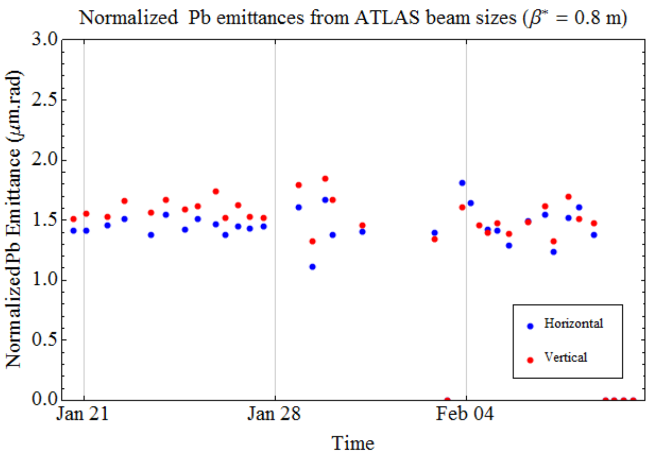
M. Sapinski, M. Schaumann, G. Trad









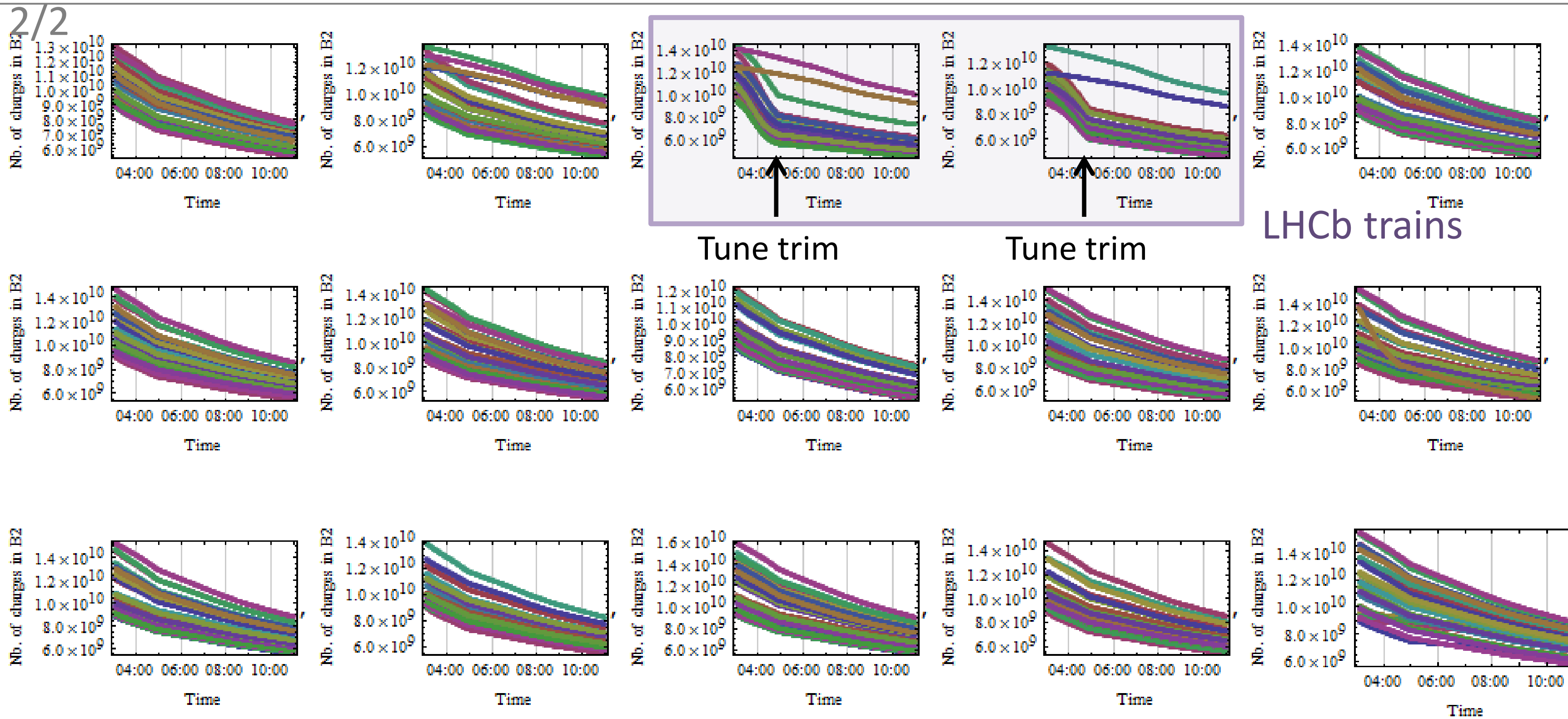


From ATLAS lumi data: stable emittance over the run, close to 1.5 µm.rad (=nominal)

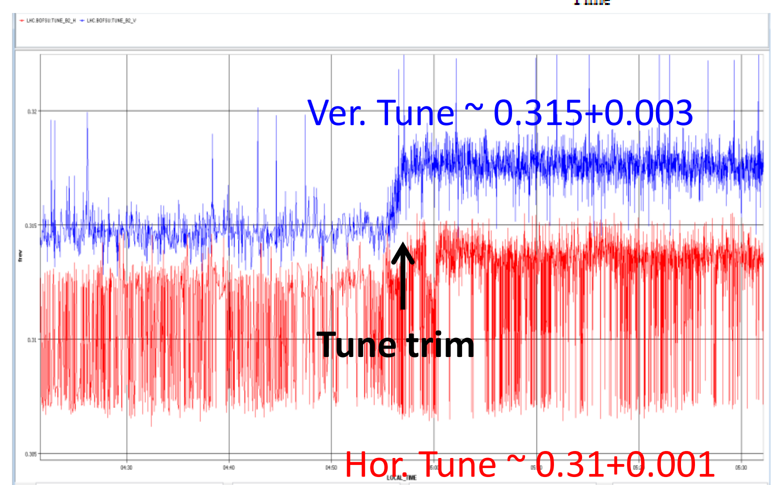
- Wire scanners available during commissioning and Pb-p modes,
- BGI available for B2,
- BSRTs signal at injection very low → set to mean over the bunches,
- Absolute calibration very difficult for all measurements,
- Emittance from luminosity assumes equal beams which was not the case.

R. Versteegen

Beam-beam effects in collision 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).



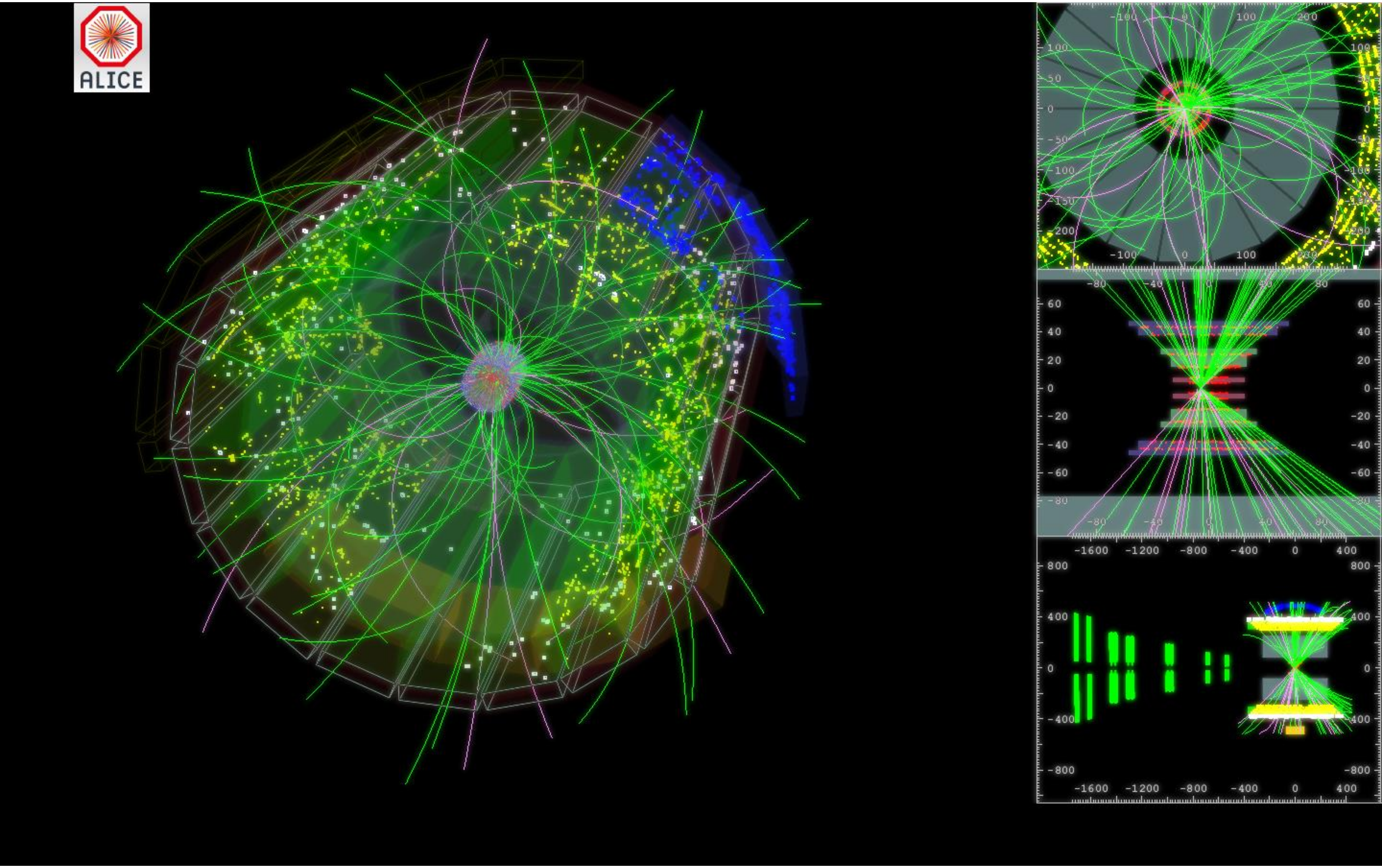
R. Versteegen

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)
γε(p)/ μm	1.7	2
γε(Pb)/ μm	1.2	1.5
N_{bp}	1.2×10^{10}	1.6×10^{10}
$N_{b\text{Pb}}$	7×10^{7}	12×10^{7}
$L\,/\,(10^{29}\ \text{cm}^{-2}\text{s}^{-1})$	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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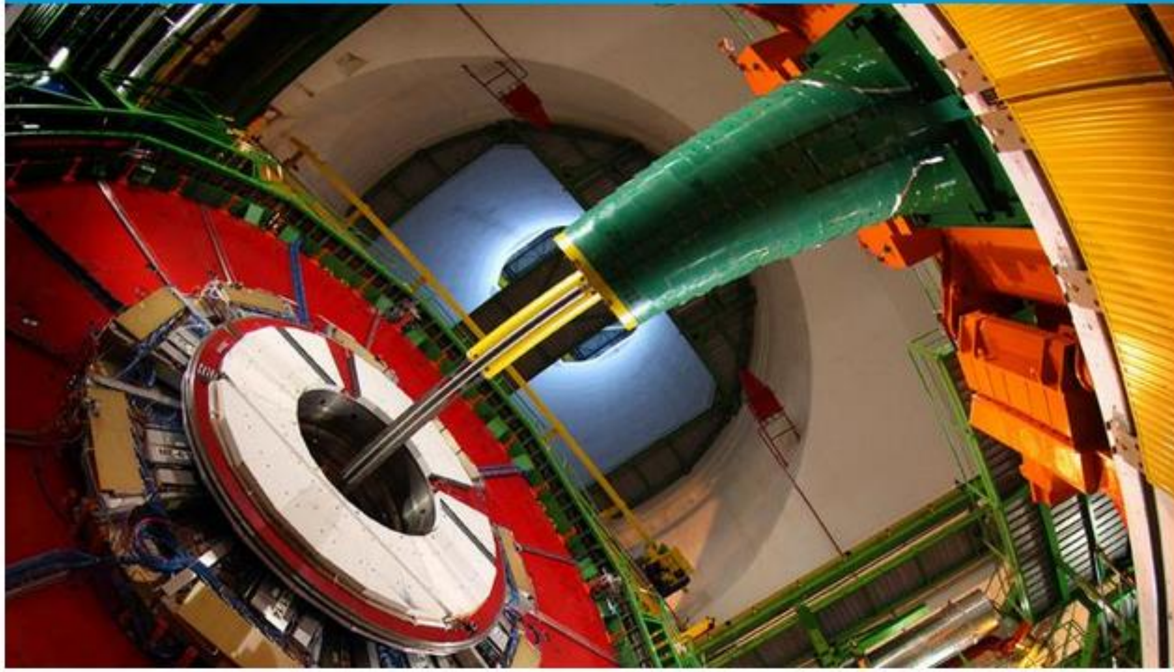


Photo: Michael Hoch / CERN

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 …

2013 INTERMEDIATE ENERGY PROTON-PROTON RUN

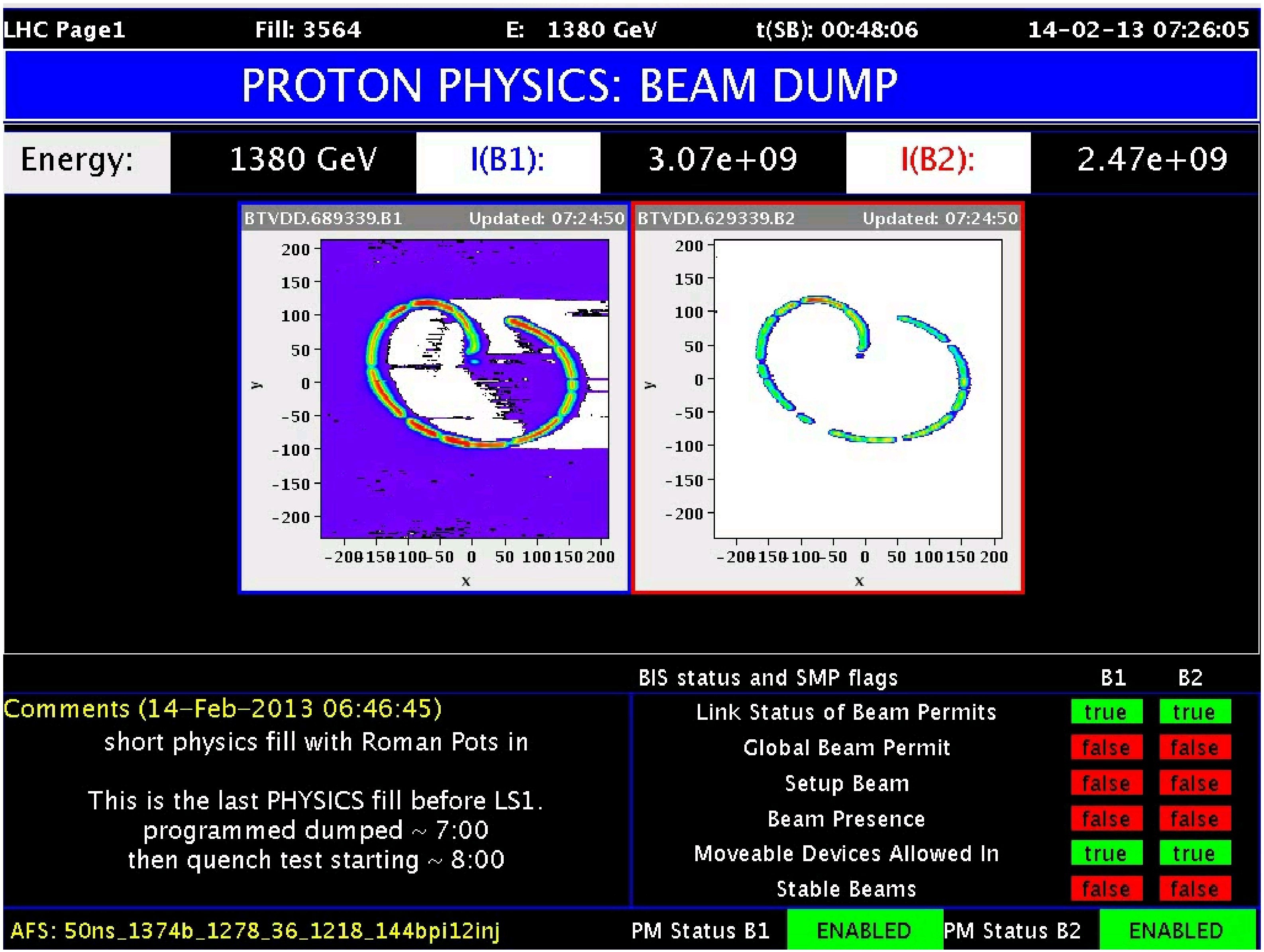
Short run to provide reference data for 2011 Pb-Pb run.

Proton-proton fills at 1.38 TeV/beam

Fill	Nb	Nc	Stable	Peak L	Int L [pb^{-1}]	Dump
3555	100 mix	46	1h47m	2.7e30	.001	Loss map
3556	510	504	5h28m	5.6e31	0.59	OP
3557	1374	1278	1h28m	1.28e32	0.39	missing frame packet on the BLM optical link
3558	1374	1278	1h9m	1.48e32	0.50	RF crow bar
3559	1374	1278	8h18m	1.48e32	2.06	OP
3560	1374	1278	5h12m	1.14e32	1.6	SIS interlock on orbit tolerances when starting length scale calib
3562	39	29	2h12m	2.7e30	0.008	missing frame packet on the BLM optical link
3563	39	29	4h31m	2.4e30	0.002	Loss maps
3564	1374	1278	48m	1.24e32	0.27	OP

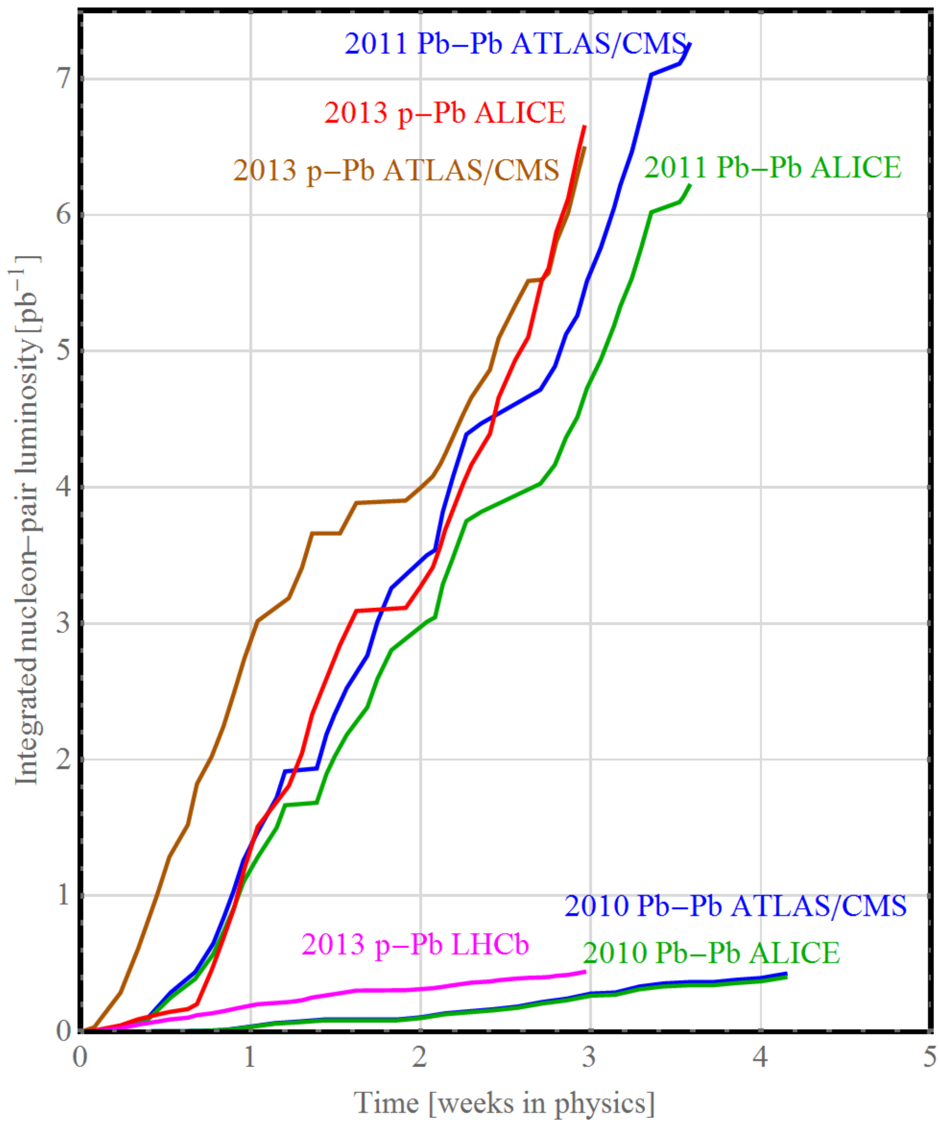
ALICE: 129.12 nb^{-1} ATLAS: 5.03 pb^{-1} CMS: 5.41 pb^{-1} LHCb: 4.19 pb^{-1}

THE LAST PHYSICS BEAM OF LHC RUN 1 (2009 - 2013)



Integrated nucleon-nucleon luminosity in Run 1

Goal of the first even p-Pb run was to match the integrated nucleon-nucleon luminosity for the preceding Pb-Pb runs.



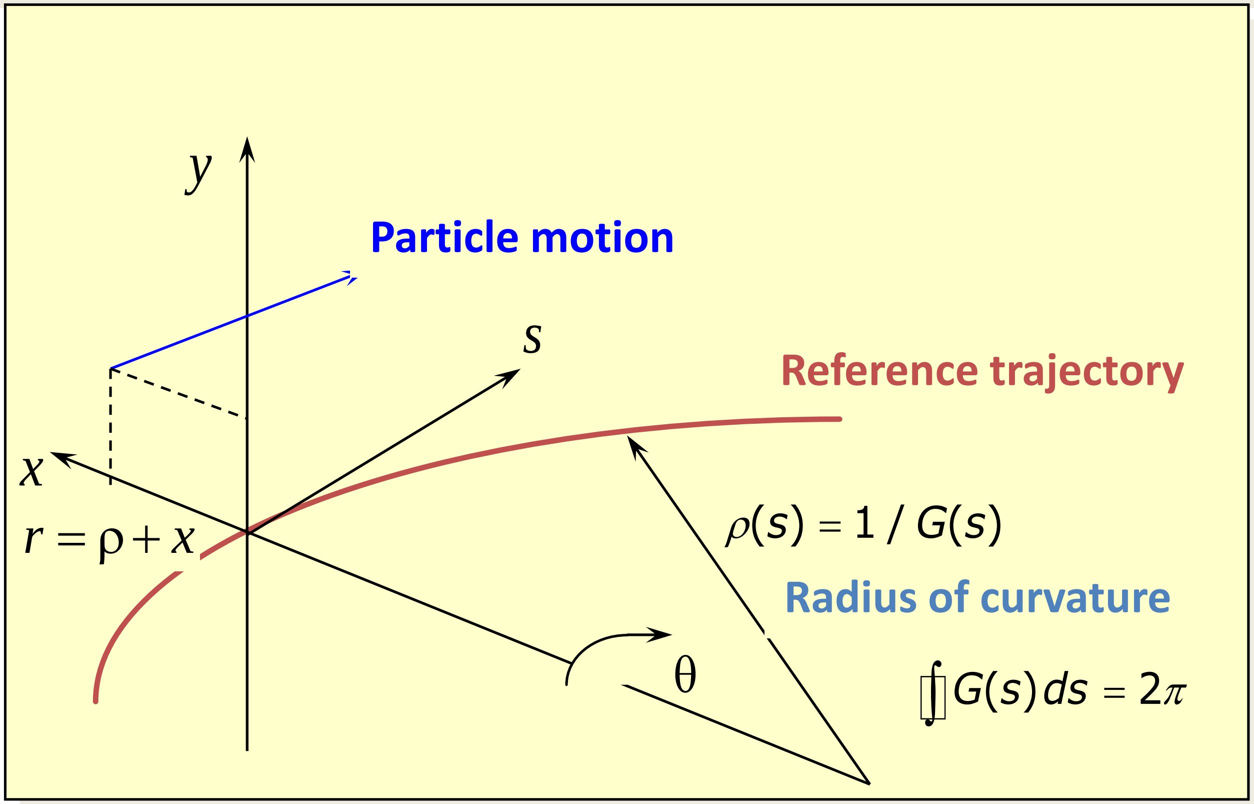
BACKUP SLIDES

Hamiltonian for charged particle in EM field

$$H = e\phi + e\sqrt{m^2c^2 + \left(\mathbf{p} - e\mathbf{A}\right)^2}$$

where $\mathbf{p} = \mathbf{P} + e\mathbf{A}(\mathbf{x},t)$ is the canonical momentum,
$\mathbf{P}$ is the kinematic momentum,
$\phi(\mathbf{x},t), \mathbf{A}(\mathbf{x},t)$ are the applied electromagnetic potentials,
e is the charge of the particle (replace by Ze for nuclear beams),
m is the mass of the particle
and time t is the independent variable.

Coordinate system for cyclic accelerator



- Particles move in a neighbourhood of a reference trajectory (ideally a curve passing through centres of all magnets) defined by "bends", etc

In these coordinates

$$H = e\phi + e\sqrt{m^2c^2 + \frac{(p_s - eA_s)^2}{(1+Gx)^2} + (p_x - eA_x)^2 + (p_y - eA_y)^2}$$

where

$$p_x = \mathbf{p.e}_x,\ p_y = \mathbf{p.e}_y,\ p_s = \mathbf{p.e}_s(1+Gx)$$

$$A_x = \mathbf{A.e}_x,\ A_y = A.\mathbf{e}_y,\ A_s = \mathbf{A.e}_s(1+Gx)$$

Change of independent variable

Azimuthal coordinate *s* can play role of time (independent variable) provided the particle never moves backwards (*s* is monotonic in *t*).

Time t becomes the coordinate for the third degree of freedom (different particles pass s at different times).

Solve previous Hamiltonian, value E, for p_s to use new Hamiltonian

$$\tilde{H} = -p_s\left(x, y, t, p_x, p_x, -E\right)$$

$$x' = \frac{\partial \tilde{H}}{\partial p_x} \qquad p_x{}' = -\frac{\partial \tilde{H}}{\partial x}$$

$$x' = \frac{\partial \tilde{H}}{\partial p_x} \qquad p_y{}' = -\frac{\partial \tilde{H}}{\partial y}$$

$$t' = \frac{\partial \tilde{H}}{\partial(-E)} \qquad (-E)' = -\frac{\partial \tilde{H}}{\partial t}$$

In a *circular* accelerator, the Hamiltonian is a periodic function of *s.*
Floquet theory applies for the normal modes of particle oscillations.
Crucially important for stability, the strong-focussing principle, and why circular accelerators work so well.

Applied electromagnetic fields

Simplify, just for presentation, vector potential described by longitudinal component (flat ring, dipoles, upright quadrupoles, sextupoles, thin-lens RF cavities, neglect solenoids, etc).

Define scaled gradients in terms of reference momentum p_0 and all these fields can be derived from a single component of the vector potential:

$$
\begin{aligned}
A_s(x,y,t,s) &= \mathbf{A}.\mathbf{e}_s\left(1+G(s)x\right) \\
&= -\frac{p_0 c}{e}\left[xG(s)\left(1+G(s)\frac{x}{2}\right)+\tfrac{1}{2}K_1(s)\left(x^2-y^2\right)+\tfrac{1}{6}K_2(s)\left(x^3-3xy^2\right)+\ldots\right] \\
&\quad +\sum_k \frac{e\hat{V}_k}{\omega_{\mathrm{RF}}}\delta_C(s-s_k)\cos\left(\omega_{\mathrm{RF}}t+\phi_k\right)
\end{aligned}
$$

where $G(s)=eB_0(s)/p_0$ is curvature of reference orbit.

Hamiltonian is manifestly periodic only if RF cavities are off.

Canonical transformations

Canonical transformation to new longitudinal variables

$$(t, -E) \mapsto (z_t, p)$$

effected by means of the mixed-variable generating function

$$F_2(p,t) = -ct\sqrt{p^2 + m^2c^2}$$

What are these new variables? According to the rules:

$$(-E) = \frac{\partial F_2}{\partial t} = -c\sqrt{p^2 + m^2c^2}$$

$$\Rightarrow p = \sqrt{E^2 / c^2 + m^2c^2} = \text{(magnitude of kinematic momentum)}$$

$$z_t = \frac{\partial F_2}{\partial p} = -ct\frac{p}{\sqrt{p^2 + m^2c^2}} = -ct\sqrt{1 - m^2c^4 / E^2}$$

$$= -t \times \text{(instantaneous speed)}$$

The kinematic term in the new Hamiltonian no longer contains the mass

$$H(x, y, z_t, p_x, p_x, p; s) = -eA_s(x, y, t(z_t, p), s) - (1 + G(s)x)\sqrt{p^2 - p_x^2 - p_y^2}$$

but what is the catch?

Equations of motion

$$x' = (1+Gx)\frac{p_x}{\sqrt{p^2 - p_x^2 - p_y^2}} \approx (1+Gx)\frac{p_x}{p}$$

$$y' = (1+Gx)\frac{p_y}{\sqrt{p^2 - p_x^2 - p_y^2}} \approx (1+Gx)\frac{p_y}{p}$$

$$z_t{}' = -(1+Gx)\frac{p}{\sqrt{p^2 - p_x^2 - p_y^2}} \approx (1+Gx) \approx ct'$$

$$p_x' = -G(p-p_0) - p_0\left(G^2 + K_1\right)x - \tfrac{1}{2}p_0K_2\left(x^2 - y^2\right) + \dots$$

$$p_y' = p_0K_1y + \tfrac{1}{2}p_0K_2xy + \dots$$

$$p' \approx -\sum_k \frac{e\hat{V}_k}{c}\delta_C(s-s_k)\cos\left(\omega_{\mathrm{RF}}\frac{\sqrt{p^2 + m^2c^2}\,z_t}{pc} + \phi_k\right)$$

No mass terms in transverse motion!

Slightly more complicated to compute the kicks imparted by cavities and these do involve the particle mass. Still no problem to implement, eg, in tracking.

Betatron motion

Betatron part of the Hamiltonian (horizontal plane)

$$H = \frac{p_{x\beta}^{\ 2}}{2} + K_x(s)\, x_\beta^{\ 2}, \quad \text{where } K(s+C) = K(s)$$

Action-angle variables for the Hamiltonian are obtained through a canonical transformation which introduces the β- and α-functions of Courant and Snyder[56,59] :

$$(x_\beta, y, p_\beta, p_y) \mapsto (\psi_x, \psi_y, I_x, I_y). \tag{5.48}$$

The generating function for this transformation is

$$\begin{aligned} S(\psi_x, x_\beta) = &-\frac{x_\beta^2}{2\beta_x(s)}\{\alpha_x(s) + \tan\phi_x(\psi_x, s)\} \\ &-\frac{y^2}{2\beta_y(s)}\{\alpha_y(s) + \tan\phi_y(\psi_y, s)\}, \end{aligned} \tag{5.49}$$

where we have defined two phase functions depending on the phases $\psi_{x,y}$ and s:

$$\phi_{x,y}(\psi_{x,y}, s) = \psi_{x,y} + \int_0^s \left\{\frac{1}{\beta_{x,y}(\sigma)} - \frac{\nu_{x,y}}{R}\right\} d\sigma. \tag{5.50}$$

Note that the actual dynamical variables are $\psi_{x,y}$ and that $\phi_{x,y}$ are just convenient auxiliary functions.

Solving the transformation equations, we can express the old coordinates in terms of the new; the results are the familiar expressions

$$\begin{aligned} x_\beta &= \sqrt{2\beta_x(s) I_x}\cos\phi_x(\psi_x, s), \\ p_\beta &= -\sqrt{\frac{2I_x}{\beta_x(s)}}\{\alpha_x(s)\cos\phi_x(\psi_x, s) + \sin\phi_x(\psi_x, s)\}, \\ y &= \sqrt{2\beta_y(s) I_y}\cos\phi_y(\psi_y, s), \\ p_y &= -\sqrt{\frac{2I_y}{\beta_y(s)}}\{\alpha_y(s)\cos\phi_y(\psi_y, s) + \sin\phi_y(\psi_y, s)\}, \end{aligned} \tag{5.51}$$

Provided we choose the arbitrary functions $\alpha_{x,y}(s)$, $\beta_{x,y}(s)$ to be the periodic solutions of the differential equations

$$\alpha_{x,y} = -\beta'_{x,y}/2, \qquad \alpha'_{x,y} = K_{x,y}\beta_{x,y} - (\alpha_{x,y}^2 + 1)/\beta_{x,y}, \tag{5.52}$$

the coefficients of the terms in $\cos(2\phi_{x,y})$ and $\sin(2\phi_{x,y})$ in the new Hamiltonian will vanish. Provided also that we choose the constants $\nu_{x,y}$ to be the *betatron tunes*,

$$\nu_{x,y} = \frac{1}{2\pi}\int_0^{2\pi R} \frac{ds}{\beta_{x,y}(s)}, \tag{5.53}$$

the s-dependence of the of the Hamiltonian for linear betatron motion is eliminated and we have, simply,

$$H_5(\psi_x, \psi_y, I_x, I_y) = \nu_x I_x/R + \nu_y I_y/R. \tag{5.54}$$

The average of the betatron action over a bunch of particles is the emittance $\varepsilon_x = \langle I_x \rangle$

Squeeze commissioning – 1/3

Andy Langer, Yngve Levinsen, Meghan McAteer, Ewen McLean, Tobias Persson, Piotr Skowronski, Rogelio Tomas, Reine Versteegen, Jorg Wenninger, …

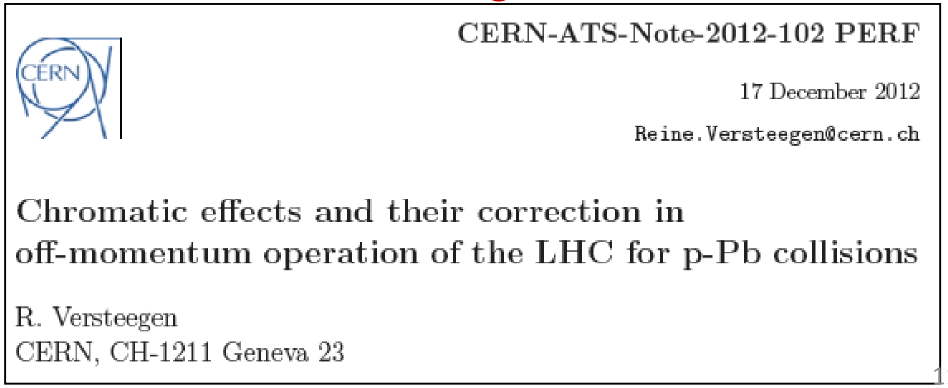
- New squeeze goes down to β*(IP1, IP2, IP5, IP8) = (0.8, 0.8, 0.8, 2.0) and will be done off-momentum (new for LHC)

- Optics measurements and correction were done in three steps with proton beams:

- **on momentum** squeeze in steps with flat machine, measurements at flat top, 7 m, 3 m, 1 m, and 0.8 m,

- **on momentum** squeeze in steps applying local IR corrections, same 5 stops to measure beta-beating, additional measurement at 0.8 m with global correction applied,

- **on momentum** squeeze in steps with experiments bumps ON and beat-beating correction (measurements at 0.8 m), followed by 2 **off momentum** measurements at 0.8 m with intrinsic beta-beating knob ON, with ± 0.00023 dp/p.


CERN-ATS-Note-2012-102 PERF

17 December 2012

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Chromatic effects and their correction in off-momentum operation of the LHC for p-Pb collisions

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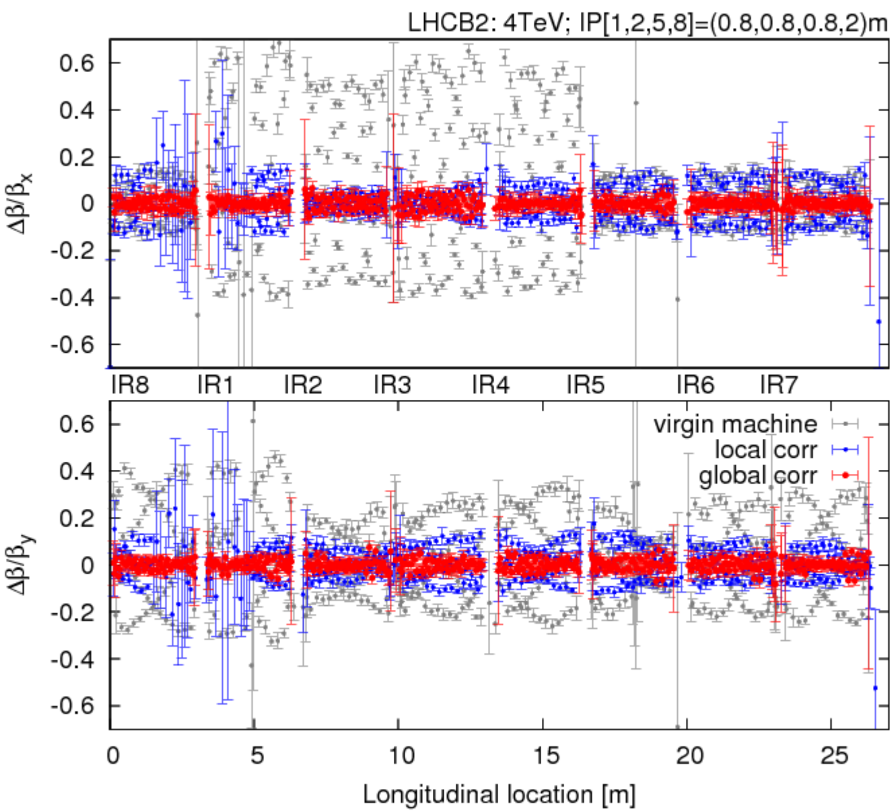
Squeeze commissioning – 2/3

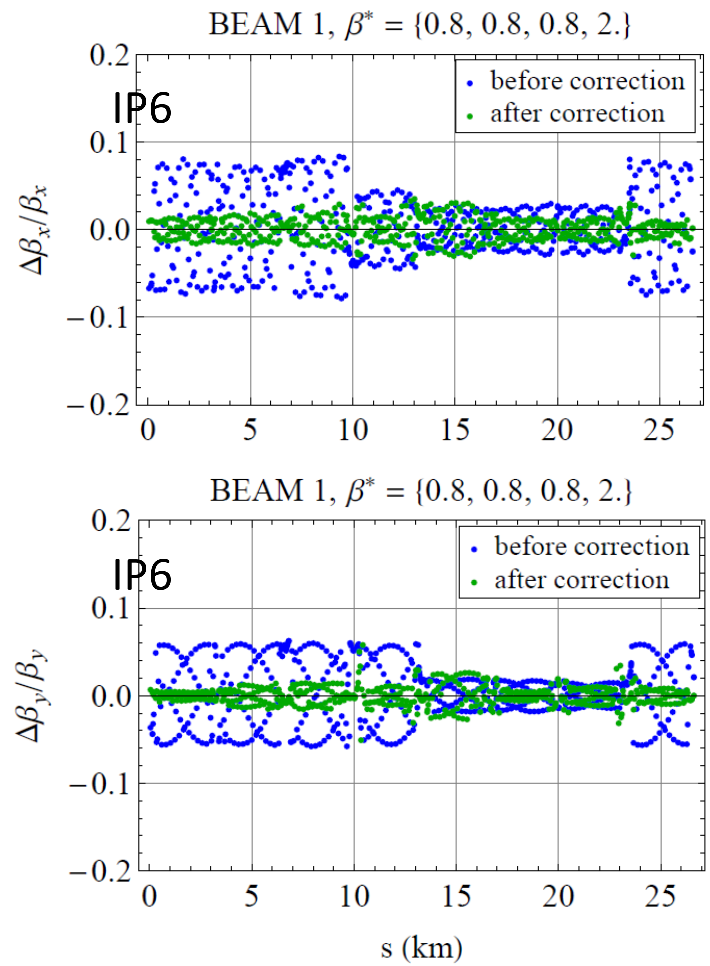
Andy Langer, Yngve Levinsen, Meghan McAteer, Ewen McLean, Tobias Persson, Piotr Skowronski, Mattteo Solfaroli, Rogelio Tomas, Reine Versteegen, Jorg Wenninger, …

On momentum correction:

- More than 60% beta-beating without correction (in gray),
- Down to 20% with local correction (in blue),
- Down to 5% with global correction (in red).



Off momentum intrinsic beta-beating correction knob (as calculated for B1):

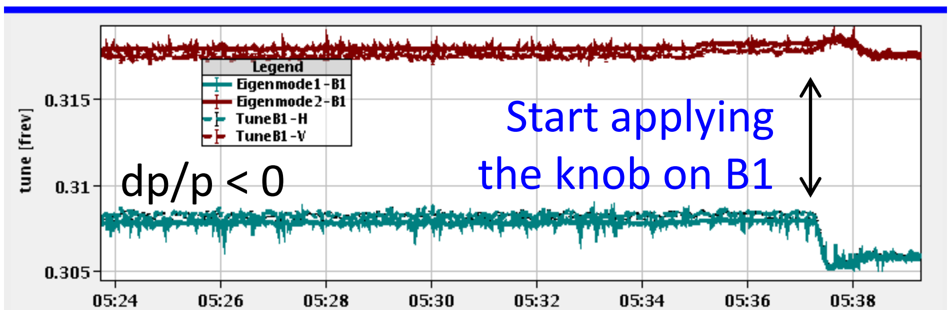


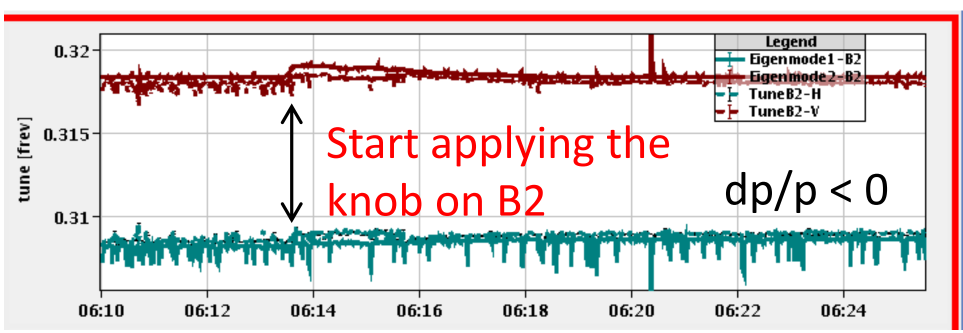
Squeeze commissioning – 3/3

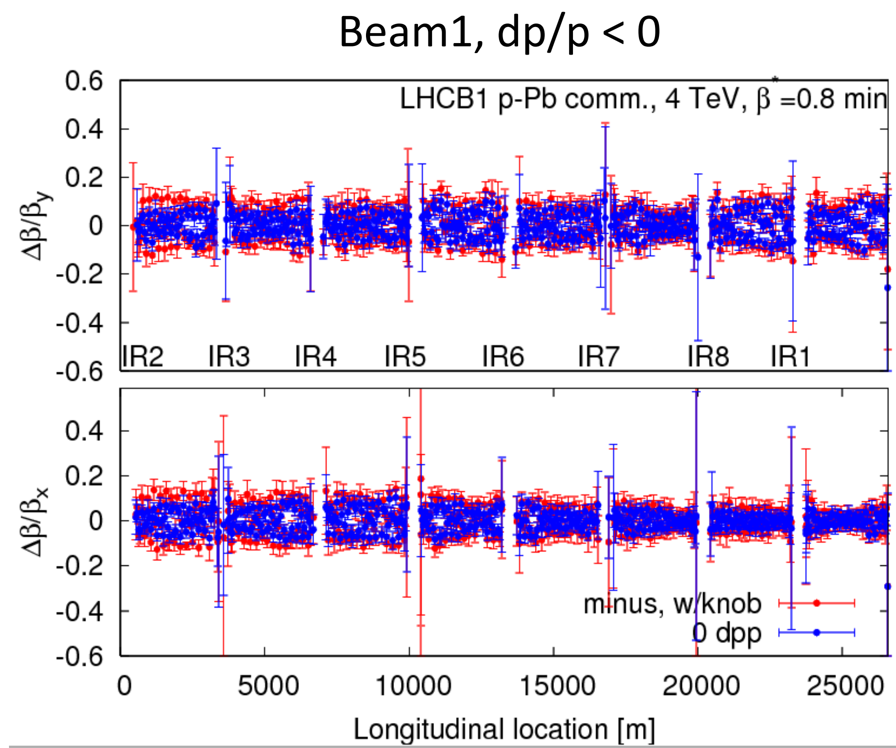
Andy Langer, Yngve Levinsen, Meghan McAteer, Ewen McLean, Tobias Persson, Piotr Skowronski, Mattteo Solfaroli, Rogelio Tomas, Reine Versteegen, Jorg Wenninger, …

Off momentum measurements (with bumps), including intrinsic beta-beating correction knob:

- Chromaticity was set two ~2 units,
- Off-momentum knob acts on MQTs magnets,
- Tune changed suddenly when 20% of the knob was applied for B1, negative dp/p, but did not come back applying -30% -> Hysteresis? Did not happen for pos. dp/p nor for B2.







-> Beta-beating stays below 10% off-momentum (so correction works).

Off-momentum optics, beta-beating, etc

We are very well prepared to handle the new squeeze in ALICE, correct for off-momentum beta-beating and set up the collimation system.

ATS-Note-2012-051 PERF

2012-06-07

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Optics, crossing angle and aperture in p-Pb physics conditions in the LHC

R. Versteegen, J. M. Jowett / BE-ABP

Keywords: p-Pb operation, aperture, beam-beam, separation, crossing angle

ATS/Note/2012/(

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ALICE spectrometer polarity reversal

R. Alemany-Fernandez, G.H. Hemelsoet, J.M. Jowett, M. Lamont, D. Manglunki, S.
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CERN-ATS-Note-2012-XXX

Waiting for approval

6 November 2012

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Chromatic effects and their correction in off-momentum operation of the LHC for p-Pb collisions

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CERN-ATS-Note-2012-094 MD

27 November 2012

Re

First proton-nucleus collisions in the LI
pilot physics fill

R. Alemany, M. Angoletta, P. Baudrenghien, R. Bruce
D. Jacquet, J.M. Jowett, V. Kain, M. Kuhn, M. Lamo
S. Redaelli, B. Salvachua, M. Sapinski, M. Schaumann
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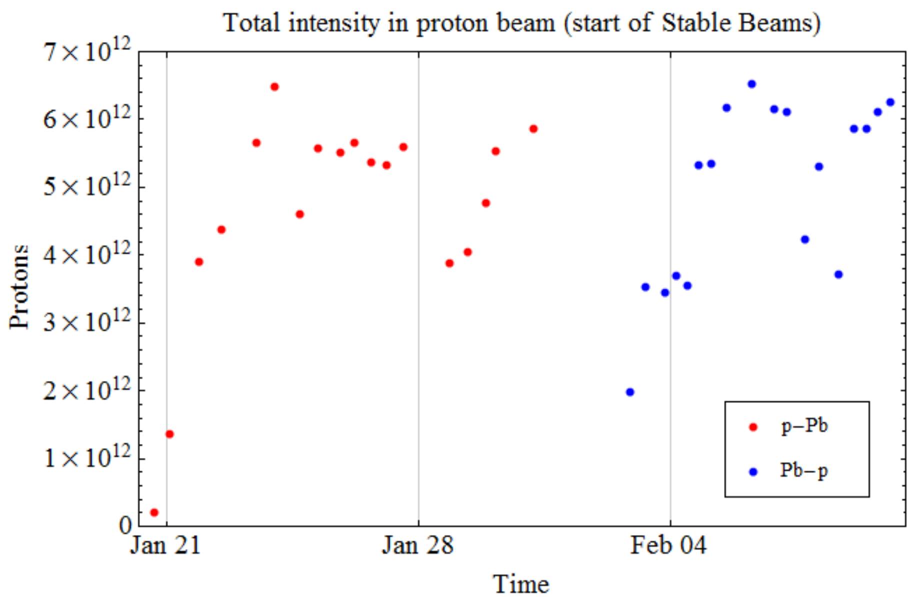
Monday, December 3, 2012 *Collimation working group*

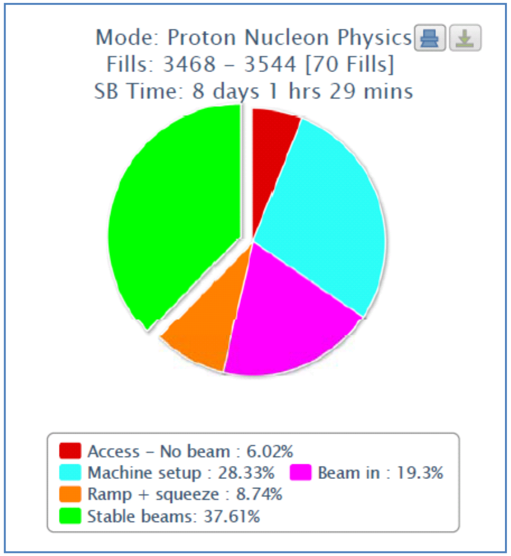
16:00 - 16:20 p-Pb run: general commissioning plans, machine parameters and r
Speaker: Dr. John Jowett (CERN)
Material: Slides

16:20 - 16:40 Expected orbit shifts and beta-beat at the collimators during p-Pb
Speaker: Reine Versteegen (CERN)
Material: Slides

16:40 - 17:00 Beam loss maps during the last p-Pb MD *20'*
Speaker: Belen Maria Salvachua Ferrando (CERN)
Material: Slides



Total intensity in proton beam (start of Stable Beams)
Protons
7×10^{12}
6×10^{12}
5×10^{12}
4×10^{12}
3×10^{12}
2×10^{12}
1×10^{12}
0
Jan 21
Jan 28
Feb 04
Time
p−Pb
Pb−p



Ending the pPb Run with Records

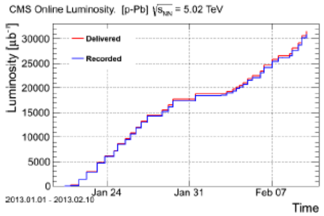
- Sun 10/2 6:04 OP dump of the last Pb-p fill – **lumi requests from experiments surpassed**

ALICE: 31.14 nb^{-1}

ATLAS: 30.25 nb^{-1}

CMS: 30.79 nb^{-1}

LHCb: 2.08 nb^{-1}

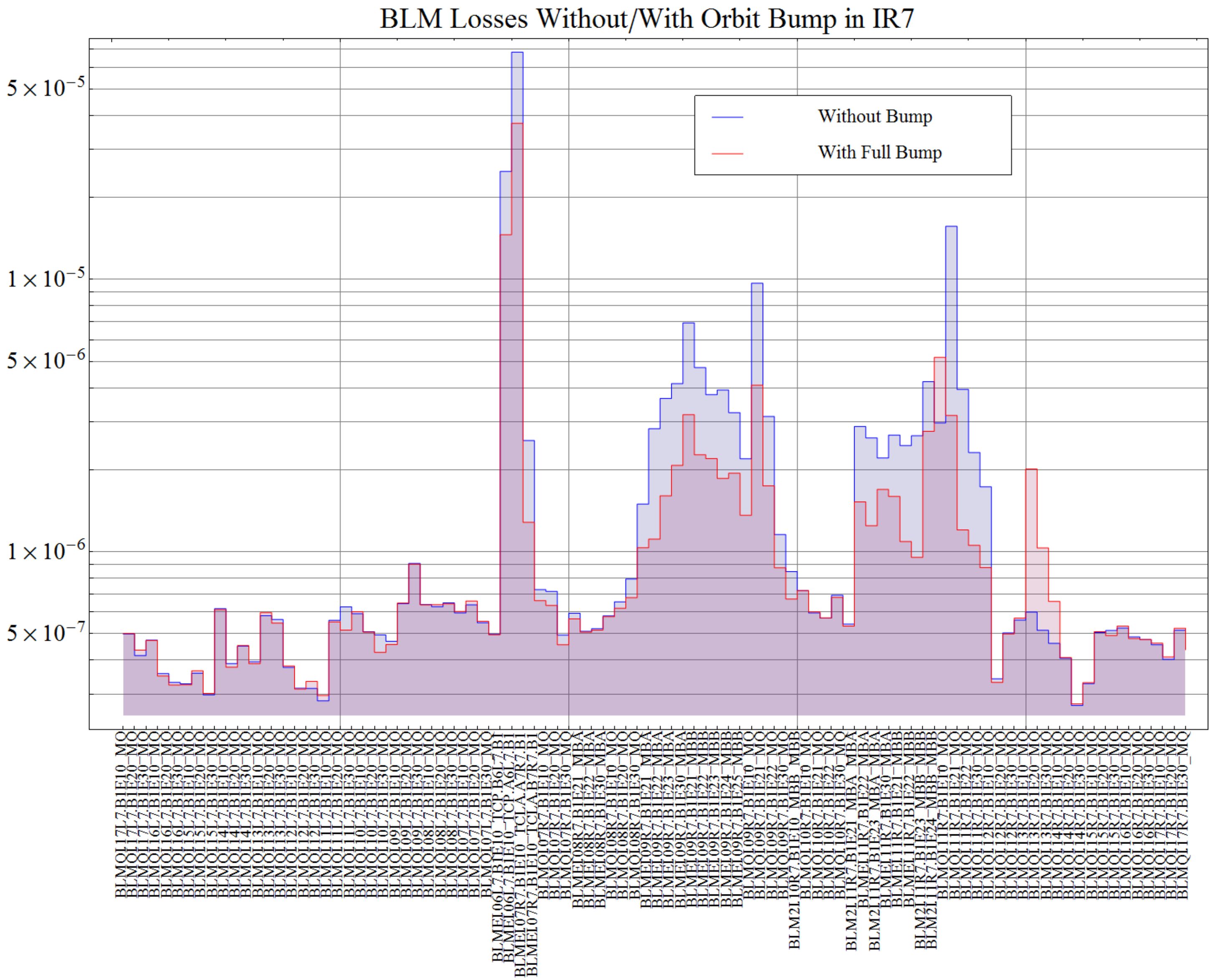


- ATLAS records

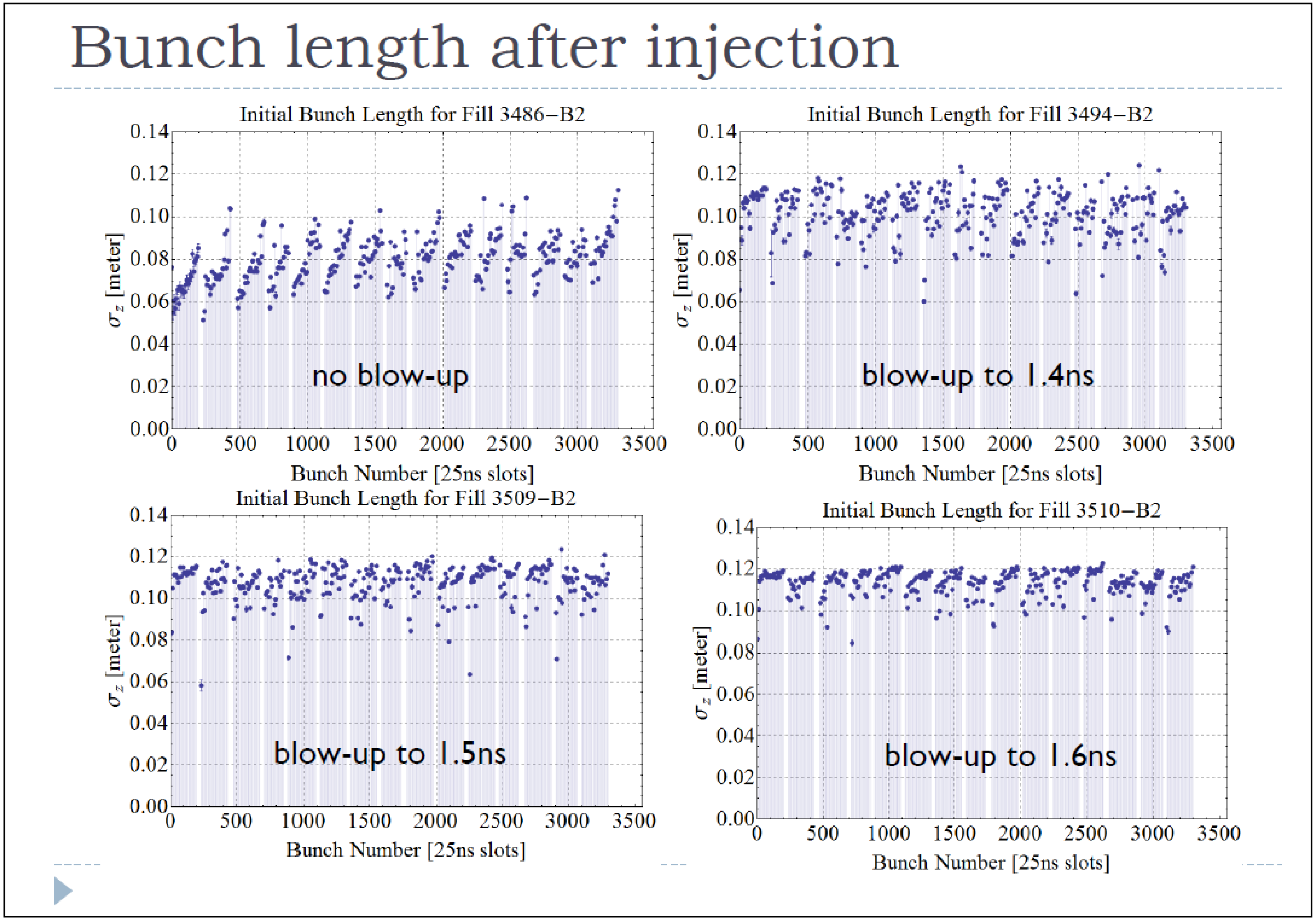
Peak Stable Luminosity Delivered	1.12×10^{29} $cm^{-2}s^{-1}$	Fill 3544	13/02/10, 00:11
Maximum Luminosity Delivered in one fill	1905.6 ub^{-1}	Fill 3485	13/01/23, 03:30
Maximum Luminosity Delivered in one day	3591.75 ub^{-1}	Saturday 09 February, 2013	
Maximum Luminosity Delivered in 7 days	14679.82 ub^{-1}	Monday 21 January, 2013 - Sunday 27 January, 2013	
Maximum Colliding Bunches	296	Fill 3485	13/01/23, 03:30
Maximum Peak Events per Bunch Crossing	3.95	Fill 3482	13/01/22, 06:07
Maximum Average Events per Bunch Crossing	0.07	Fill 3544	13/02/10, 00:11
Longest Time in Stable Beams for one fill	12.0 hours	Fill 3482	13/01/22, 10:53
Longest Time in Stable Beams for one day	18.0 hours (74.9%)	Tuesday 22 January, 2013	
Longest Time in Stable Beams for 7 days	82.1 hours (48.9%)	Monday 21 January, 2013 - Sunday 27 January, 2013	
Fastest Turnaround to Stable Beams	2.37 hours	Fill 3544	13/02/10, 00:06

8:30 meeting 2013-02-11 EBH 2

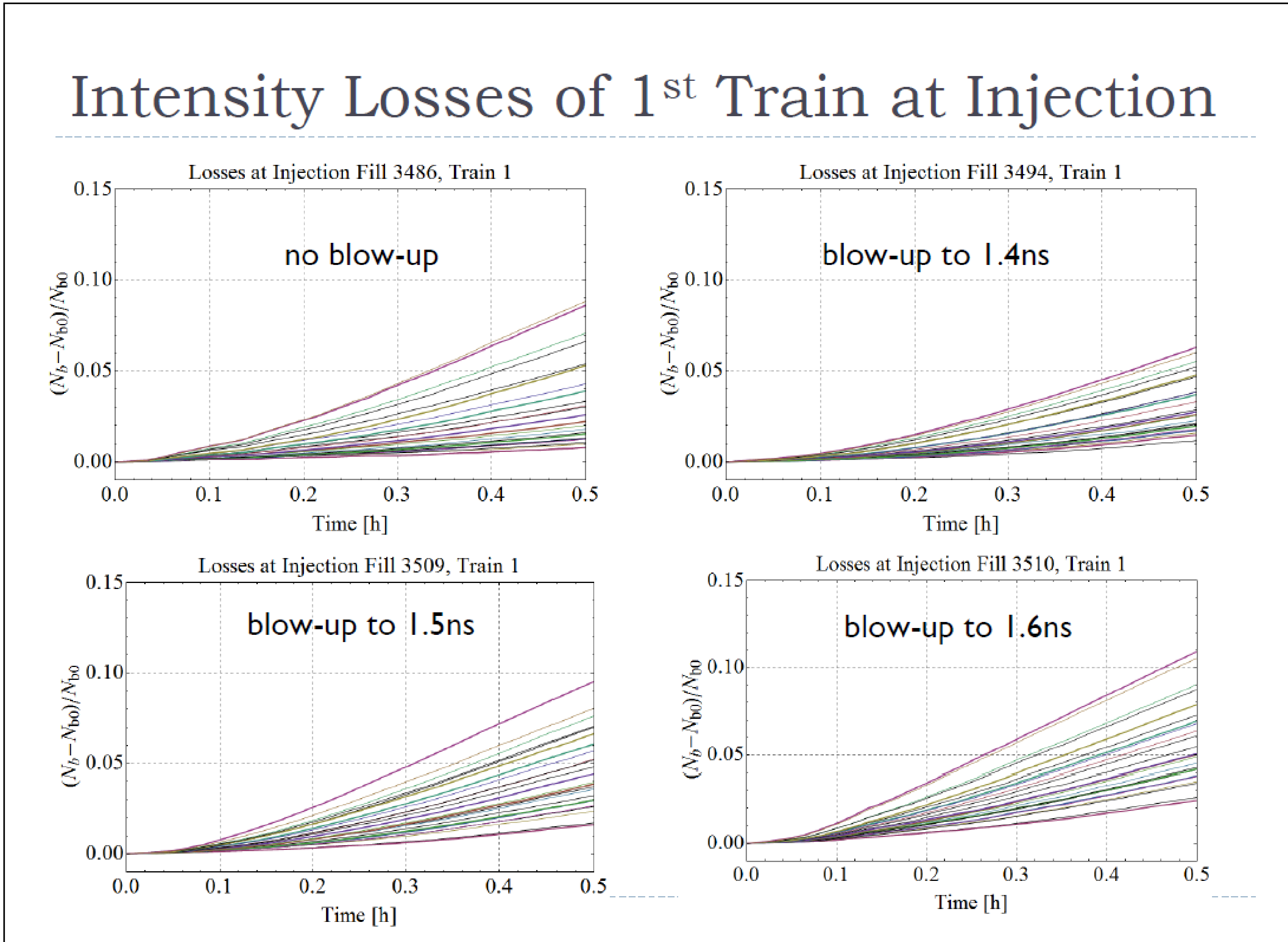
Unnormalized BLM losses during bump method test in IR7



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

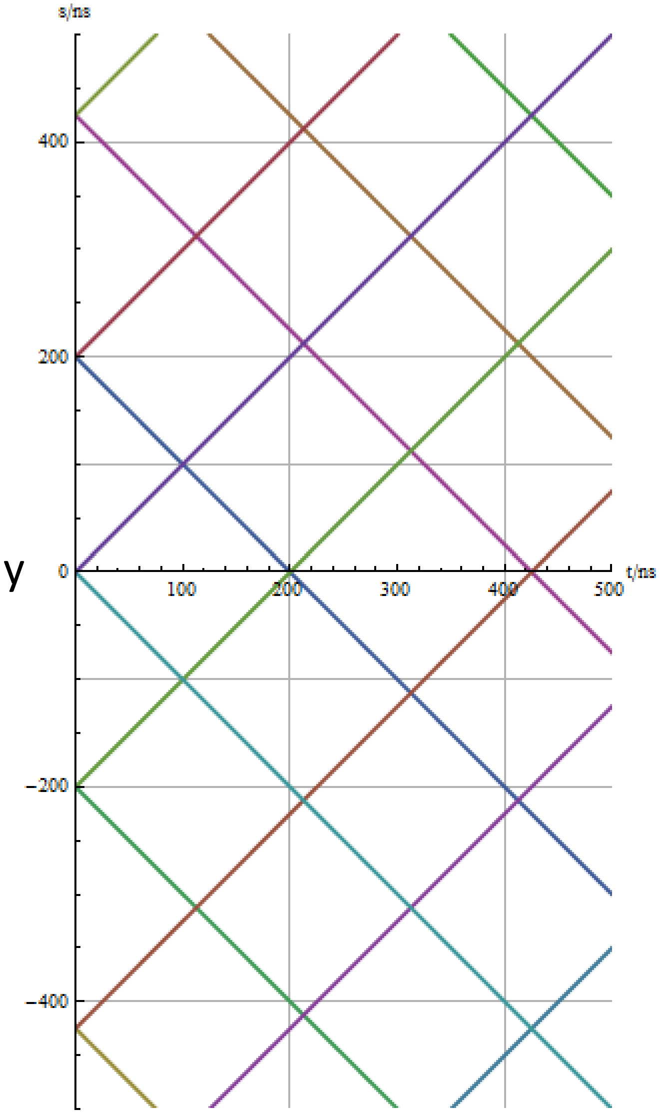


Batch by batch blow up measurements analysis (M. Schaumann)



Encounters around an IP with 200/225 ns spacing

Collisions at IP only



Encounter points at 0., 100., 112.5, 200., 212.5, 312.5, 325., 412.5, … ns from IP.