LHC Accelerator: Future Perspectives for the Heavy Ion Programme

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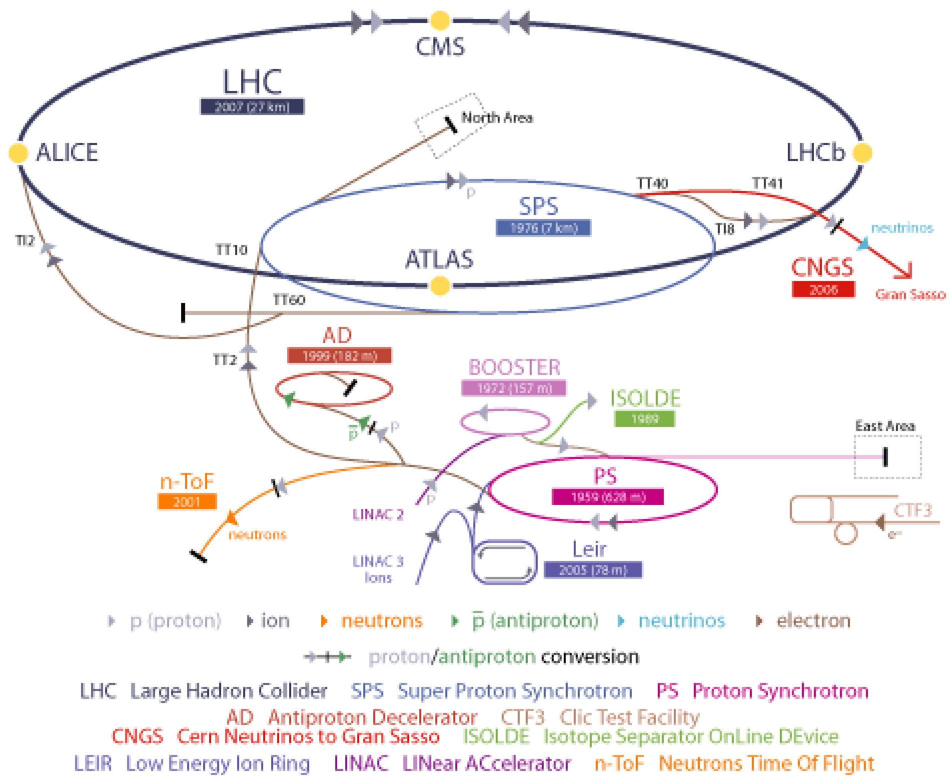
Thanks to John Jowett and Michaela Schaumann

EMMI Workshop – 15, 16th Feb. 2013



- The injector chain is responsible for the preparation and the pre-acceleration of the beams colliding in the LHC.
- Proton beam is first accelerated in LINAC2, then goes through the Booster, the PS, the SPS and is finally injected into the LHC,
- Pb beam is transferred from LINAC3 into LEIR, then goes in the PS, and the SPS,
- Beams are injected in the LHC at 450 Z GeV.

Future perspectives for the heavy ion programme in the LHC depends on the performances of the whole accelerator chain to provide the beams required to fulfill the experiments’ requests in terms of species and luminosity.

Outline

I. LHC luminosity

II. Performance and limitations during Pb-Pb runs in 2010 and 2011

III. The first p-Pb run in 2013

IV. The heavy ion programme from 2015

- Event rate R (in events per second) of a collider:

$$R = L\,\sigma_e$$

σ_e is the event cross section,
L is the instantaneous luminosity of the collider in $cm^{-2}.s^{-1}$.

- The luminosity of a collider describes the density of particles colliding per second.
  Luminosity for round beams of equal sizes:

$$L = F(\theta)\frac{N_1 N_2 n_b f}{4\pi\,\sigma^2}$$

N_1, N_2 are the number of particles in each colliding beams,
n_b is the number of colliding bunches,
f is the revolution frequency of the beams,
σ is the transverse beam size at the interaction point,
$F(\theta)$ is the reduction factor due to the crossing angle.

$$\frac{1}{\sigma^2} = \frac{\gamma}{\beta^*\varepsilon}$$

γ is the Lorentz factor,
β^* is the beta function at the interaction point,
ε is the normalized transverse emittance of the beams.

$$L = F(\theta)\frac{f}{4\pi}\frac{N_1 N_2 n_b \gamma}{\beta^*\varepsilon}$$

To increase the luminosity we need intense beams ($N_1 N_2 n_b$) of small emittances (ε) and strongly focused (β^*) at the interaction point.

$$\boldsymbol{L = F(\theta)\frac{f}{4\pi}\frac{N_1 N_2 n_b \gamma}{\beta^* \varepsilon}}$$

To increase the luminosity we need intense beams ($\boldsymbol{N_1 N_2 n_b}$) of small emittances ($\boldsymbol{\varepsilon}$) and strongly focused ($\boldsymbol{\beta^*}$) at the interaction point.

The luminosity decreases during data taking due to various effects affecting $\boldsymbol{N_1}, \boldsymbol{N_2}, \boldsymbol{\varepsilon}$, with the instantaneous time constant τ_L :

$$\frac{1}{\tau_L} = -\frac{\dot{L}(t)}{L(t)} = 2\frac{\sum_{IPs} L\sigma_{coll}}{n_b} + \frac{2}{\tau_s} + \frac{\dot{\varepsilon}(t)}{\varepsilon(t)}$$

Particle losses due to collisions at each Interaction Point (IP), total cross section for all processes is σ_{coll} = luminosity "burn-off"

Particle losses due to single beam processes leading to the beam lifetime τ_s

Transverse emittance growth contribution

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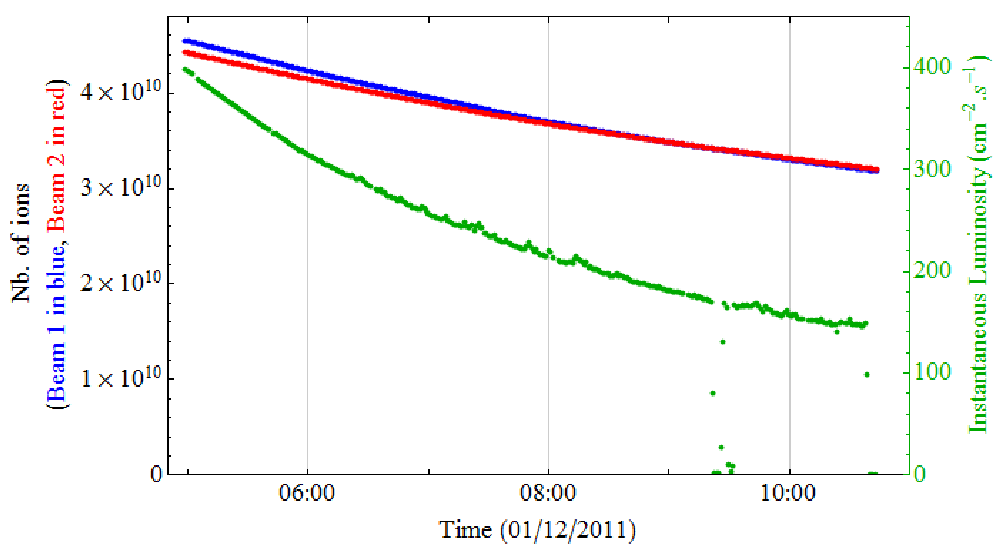
Parameter	Nominal	2010	2011
Beam energy per nucleon E (TeV)	2.76	1.38	1.38
Max. Pb ions per bunch at injection N	7 x 10^7	1.15 x 10^8	1.5 x 10^8
Bunch spacing (ns)	100	200	200
Number of bunches n_b	592	137	358
Beta function at ALICE interaction point β^* (m)	0.5	3.5	1.0
Transverse normalized emittances at injection $(\varepsilon_x, \varepsilon_y)$ (µm.rad)	(1.5, 1.5)	(0.5, 1.1)	(2.0, 0.8)
Peak luminosity L ($cm^{-2}.s^{-1}$)	1 x 10^{27}	3 x 10^{25}	5 x 10^{26}

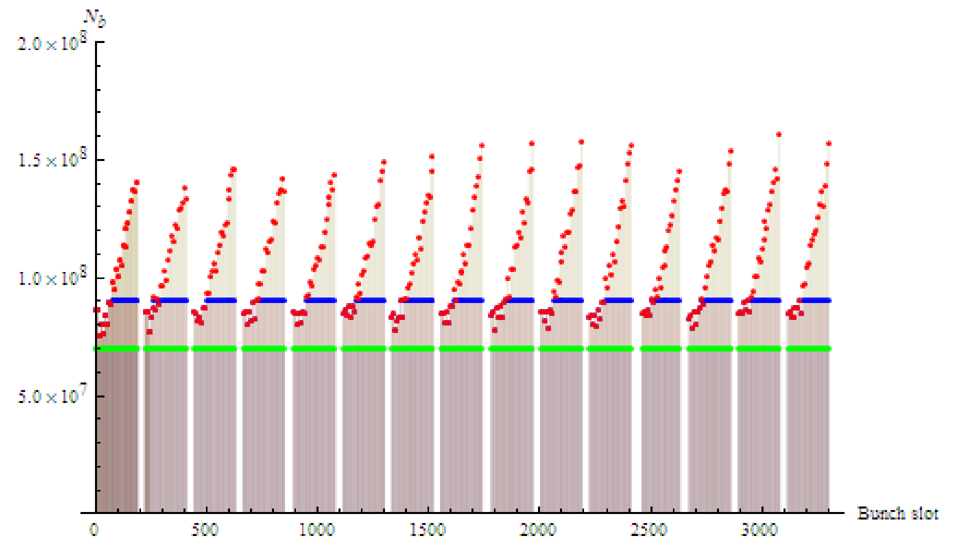
- Thanks to the very high performance of the injector chain, peak luminosity was twice the nominal value (scales with E^2),
- $\sim$ 15 % of the total integrated luminosity goal (1 nb^{-1}) was accumulated over the first two runs at half the design energy,
- Main limitations for high integrated luminosity are the intra-beam scattering in the SPS and in the LHC, particle losses on cold magnets from collisions and collimation inefficiency, and the luminosity burn-off (~proportional to the number of experiments).

- Luminosity decay is mainly driven by burn-off and IBS,
- IBS provokes particle losses and emittance blow up,
- Due to IBS and space charge in the SPS we observe a spread in the bunch intensities and emittances, leading to a spread of beam lifetimes,
- Average bunch intensity was still 1.6 times higher than nominal, which is good for peak luminosity but it increases IBS,
- A compromise between the luminosity decay and the refill time led to ~ 6 hour-long fills in 2011.

Total Intensities and Luminosity Evolution during a typical Pb–Pb fill in 2011



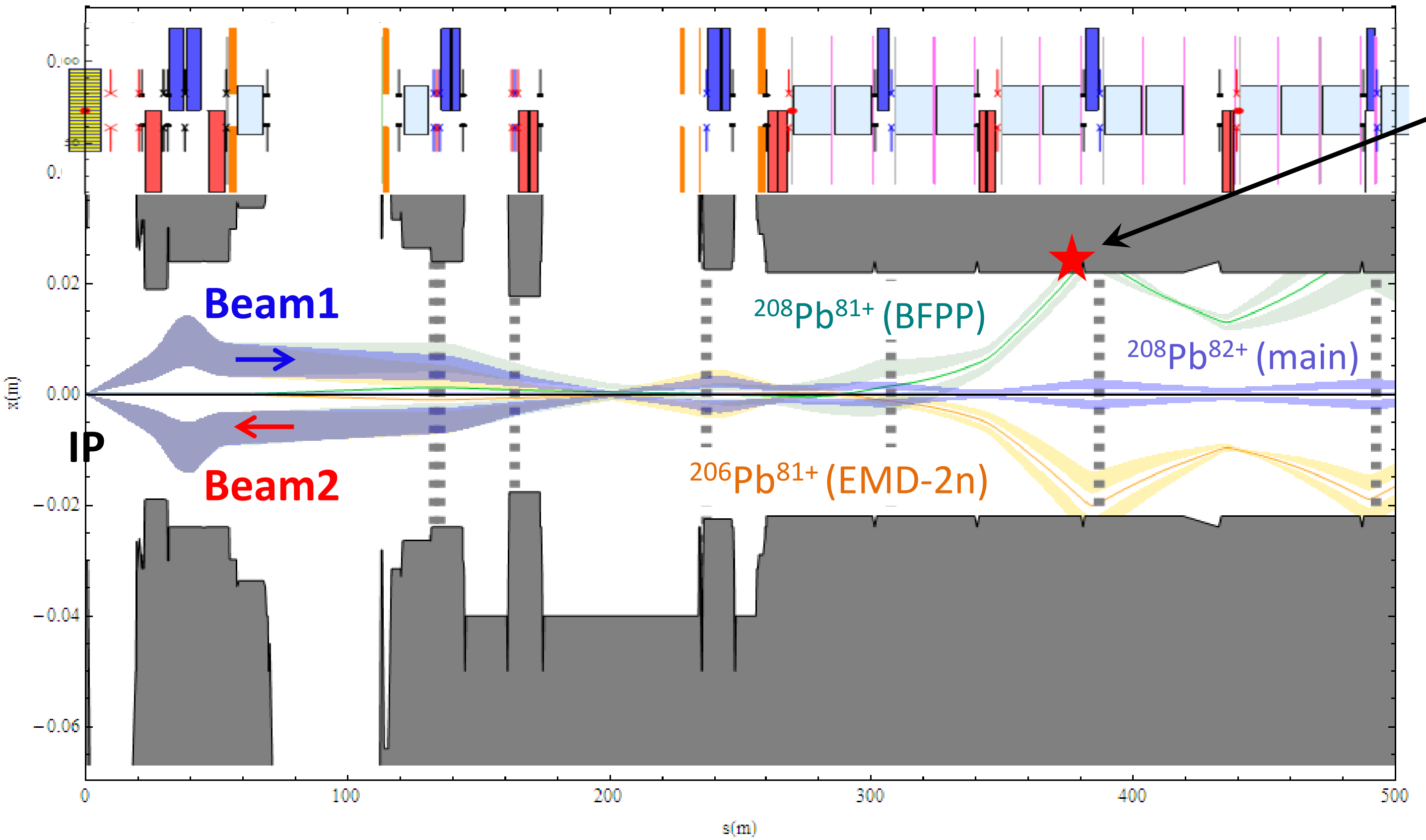
Bunch-by-bunch intensities (in nb of ions) at injection in the LHC



- Particle losses close to the Interaction Point resulting from Pb-Pb collisions:

Bound Free Pair Production $^{208}Pb^{82} + ^{208}Pb^{82+} \xrightarrow{\gamma} ^{208}Pb^{82+} + ^{208}Pb^{81+} + e^{+}$

ElectroMagnetic Dissociation $^{208}Pb^{82} + ^{208}Pb^{82+} \xrightarrow{\gamma} ^{208}Pb^{82+} + ^{207}Pb^{81+} + n$

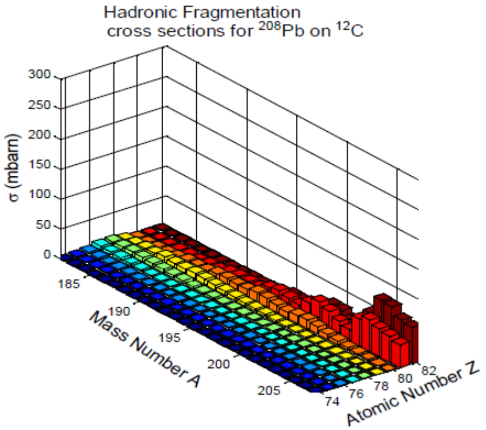


Loss spot on beam pipe, hadronic shower can provoke quenches of superconducting magnets.

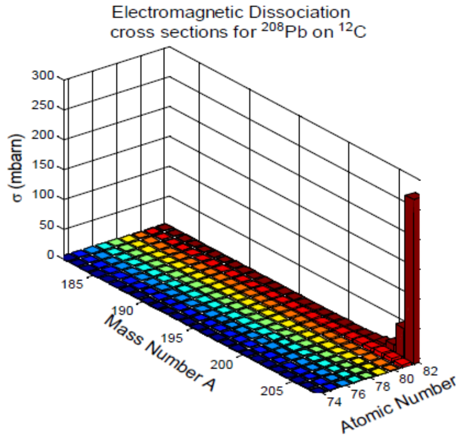
II. Performance and limitations during Pb-Pb runs in 2010 and 2011 (4/4)

- Particle losses due to nuclear reactions with collimator material (Carbon)

Physics interactions in the collimator

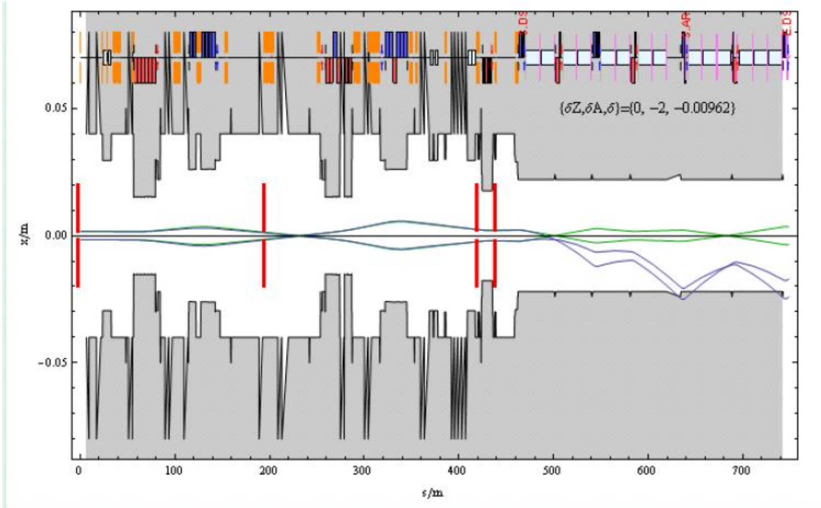


Large variety of daughter nuclei, Monte Carlo calculated specific x-sections



Mainly loss of 1 neutron (59%) or 2 (11%) → ^{207}Pb, ^{206}Pb

Example: losses in the aperture of Pb^{206} ions



G. Bellodi, *"Ion collimation outlook and Phase II improvements",* Conceptual Design Review LHC Phase II Collimation, 02/04/2009.

Baseline LHC collimation for protons is not efficient enough for ions, primary halo generate losses on superconducting magnets,

→ Maximum beam current is limited.

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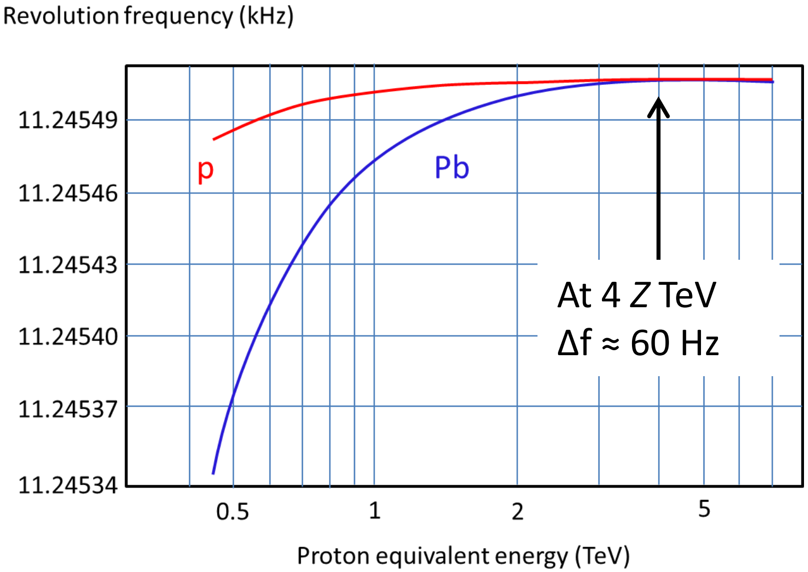
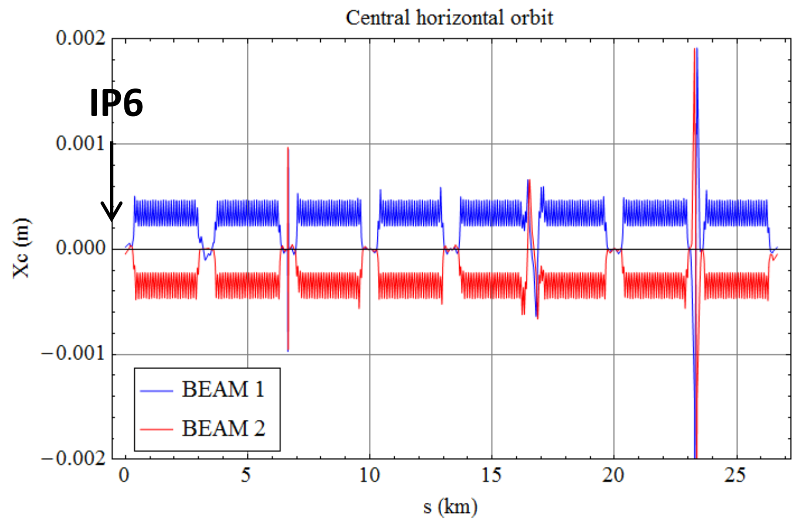
- Future perspectives for heavy ion physics in the LHC started this year when we collided protons and Pb ions for the first time,
- Asymmetric collisions were not part of the machine baseline, and many uncertainties remained before starting (commissioning time estimate, beam-beam effects…)
- But as for all ion runs, time is short so commissioning had still to be very fast.



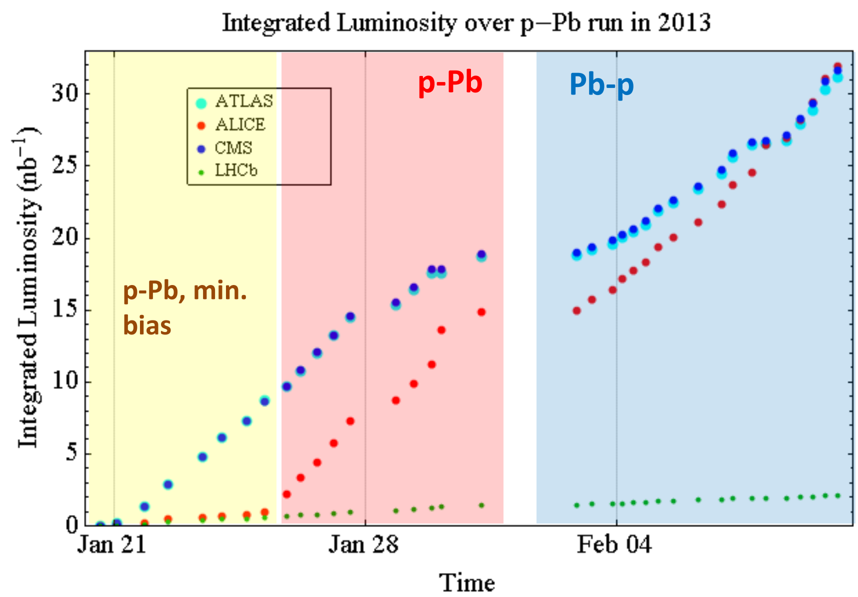


RF systems had to be decoupled as p and Pb have different Z/A ratios, which made beam-beam encounter points moving around the ring until RF frequencies were locked together.

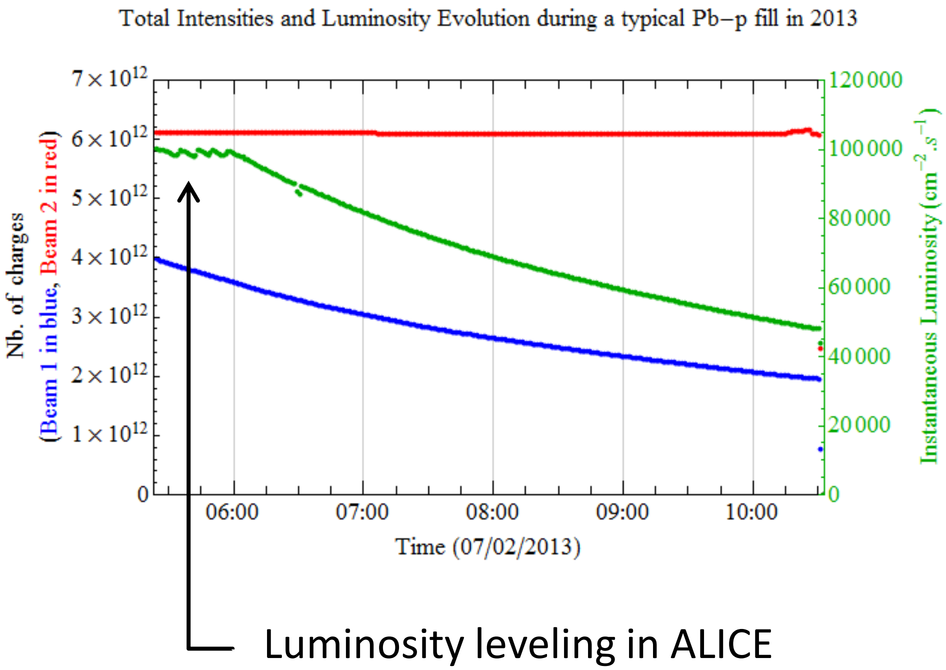
Beams were off-momentum at 4 *Z* TeV by $dp/p \approx \pm 2.3 \times 10^{-4}$, which generated orbit shifts in the arcs of about 0.5 mm max., leading to optics distortions.

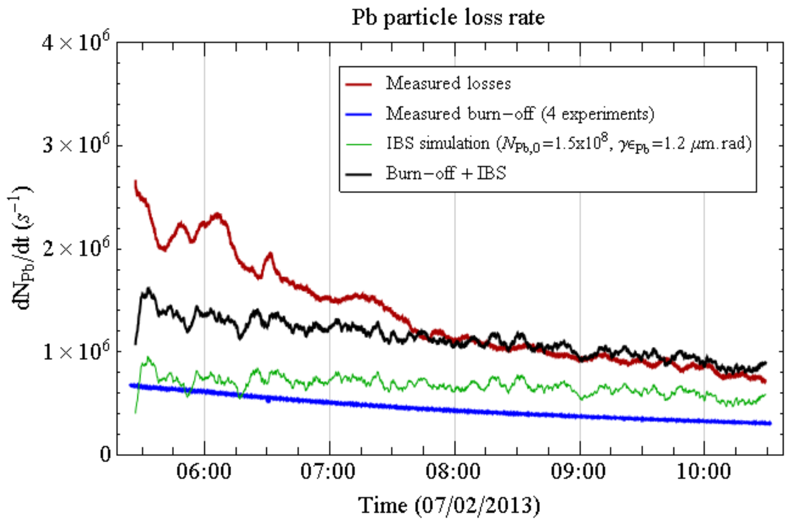
Parameter	Pb beam in 2011	Pb beam in 2012	p beam in 2012
Beam energy per nucleon E (Z TeV)	3.5	4	
Max. nb. of particles per bunch at injection N	1.5×10^8	2×10^8	1.8×10^{10}
Bunch spacing (ns)	200	200/225	
Number of bunches n_b	358	338	
Beta function at ALICE interaction point β^* (m)	1.0	0.8	
Transverse normalized emittances at injection $(\varepsilon_x, \varepsilon_y)$ (µm.rad)	(2.0, 0.8)	~(1.2, 0.8)	~ (1.0, 1.0)

- Injectors delivered very high quality Pb beam,
- Data taking was performed in both p-Pb and Pb-p configurations,
- Max. peak luminosity was 1.15×10^{29} cm^{-2}.s^{-1} . Leveling in ALICE was required,
- In the end many potential limiting effects were avoided thanks mainly to low proton intensity, and more than 30 nb^{-1} total integrated luminosity was reached!



- ALICE, ATLAS, CMS, LHCb, TOTEM, ALFA, LHCf took data,
- Luminosity evolution was driven by Pb beam lifetime, which was mainly affected by IBS and burn-off. Instabilities due to beam-beam effects were negligible. The proton beam was very stable.





- Additional source of Pb losses at the beginning of data taking were observed due to losses on collimators (tight settings were kept from p-p operation to limit the commissioning time).

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- Three shutdowns of the LHC are foreseen:

LS1, 2013-2014 Energy Increase

LS2, 2018-2019

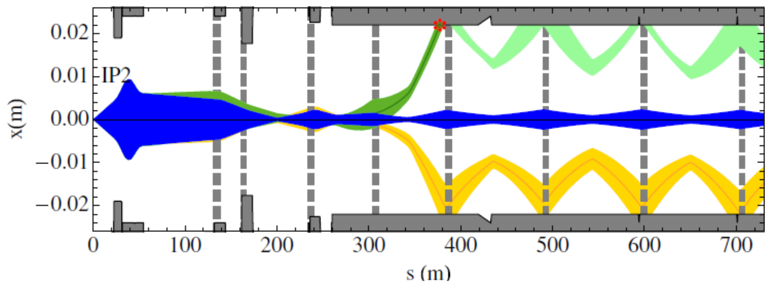
LS3, 2022-.. High Luminosity p-p upgrade

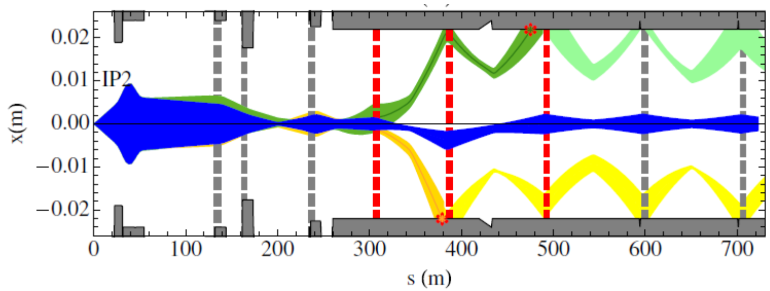
- Heavy ion physics target for the first phase of Pb-Pb: accumulate 1 nb^{-1}.
 This goal could be reached before LS2 thanks to:

→ high performance of the injectors proven in 2010-13,

→ and the bump method to mitigate losses from secondary beams emerging from IPs (tested in 2011) and losses from collimation (tested in 2013):

R. Bruce *et al.*, Phys. Rev. ST Accel. Beams 12, 071002 (2009)





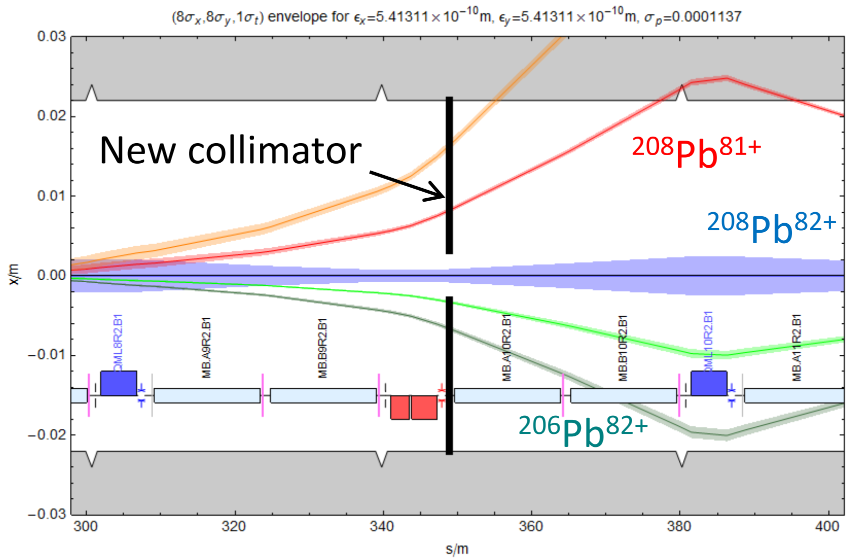
- But magnets quench limits are still uncertain.

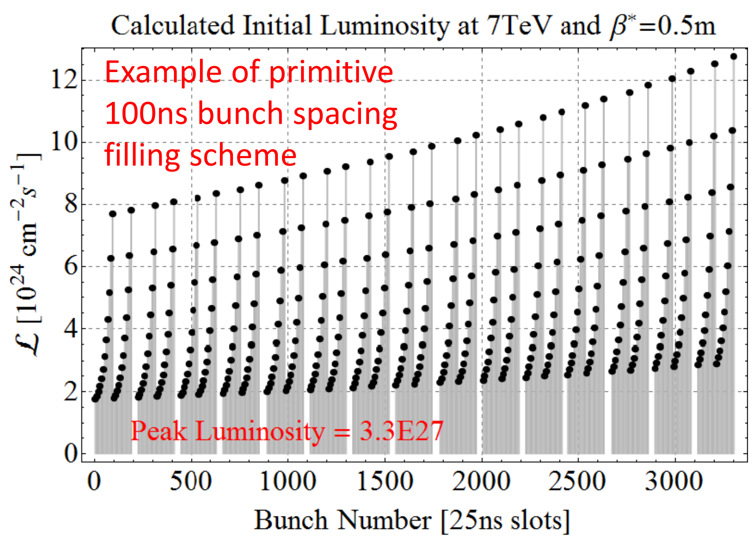
- Performance after LS2 : ALICE requested 5-6 times design luminosity to get 10 nb^{-1} by 2026 for the detector upgrade,
- Feasible but:

  → Injector upgrade is required to provide higher number of bunches,

  → Additional collimator are needed. They may be installed during LS2 to cope for secondary beams' losses around ALICE (≈ 350 m from IP2),

- Higher intensities implies longer injection times and stronger IBS which will still affect the instantaneous luminosity,
- To be studied: filling scheme optimisation, optics and beam-beam separation optimisation, implementation of stochastic cooling…





M. Schaumann (2012)

- Colliding other species than Pb ions could be considered with the present source, and the installation of a new source is being studied for the medical programme at CERN,
- Asymmetric collisions p-Pb or various nuclei A_1-A_2 may be envisaged after the very successful p-Pb run in 2013,
- Present heavy ion programme until LS3 in 2022 (most likely to evolve):

J. Jowett *et al.*, Chamonix Workshop (2012)

Year	Colliding Species	
2013-14		Long shutdown **LS1**, increase *E*
2015-16	Pb-Pb	Design luminosity, ~ 250 μb^{-1}/year, Luminosity levelling?
2017	p-Pb or Pb-Pb	P-Pb to enhance 2015-16 data. Energy? Pb-Pb if μb^{-1} still needed
2018		**LS2**: ? install DS collimators to protect magnets ? ALICE upgrade for 6 × design luminosity
2019	Pb-Pb	Beyond design luminosity … as far as we can. Reduce bunch spacing?
2020	p-Pb	
2021	Ar-Ar	Intensity to be seen from injector commissioning for SPS fixed target. Demanding collimation requirements?

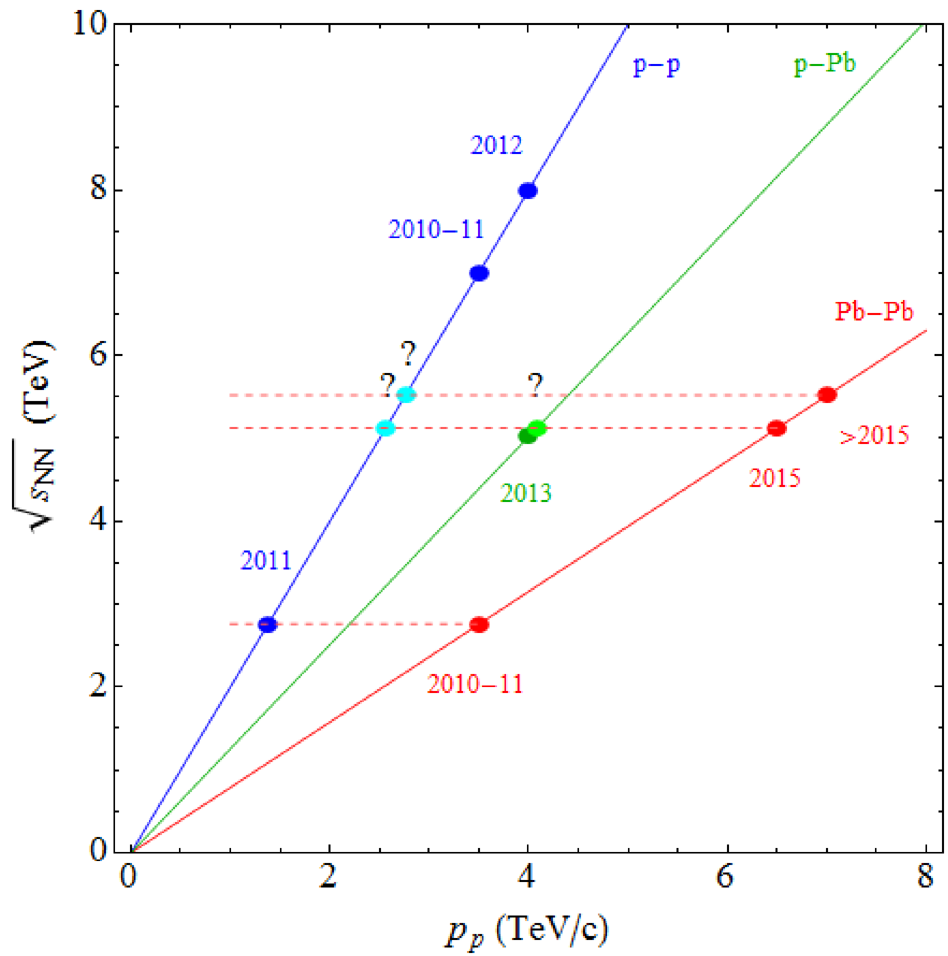
- Special calibration p-p runs at same center of mass energy per nucleon than in Pb-Pb runs may be requested by the experiments:

→ Energy per nucleon in the center of mass for two charges Z_1, Z_2 with equivalent proton momentum p_p is

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

→ Two special runs were done in March 2011 and February 2013 at $\sqrt{s_{NN}}$ = 2.76 TeV to calibrate Pb-Pb data from 2010 and 2011 heavy ion runs at 3.5 *Z* TeV,

→ 2013 p-Pb run at 4 *Z* TeV was very close to the energy per nucleon for Pb-Pb collisions at 6.5 *Z* TeV per beam, as foreseen in 2015.



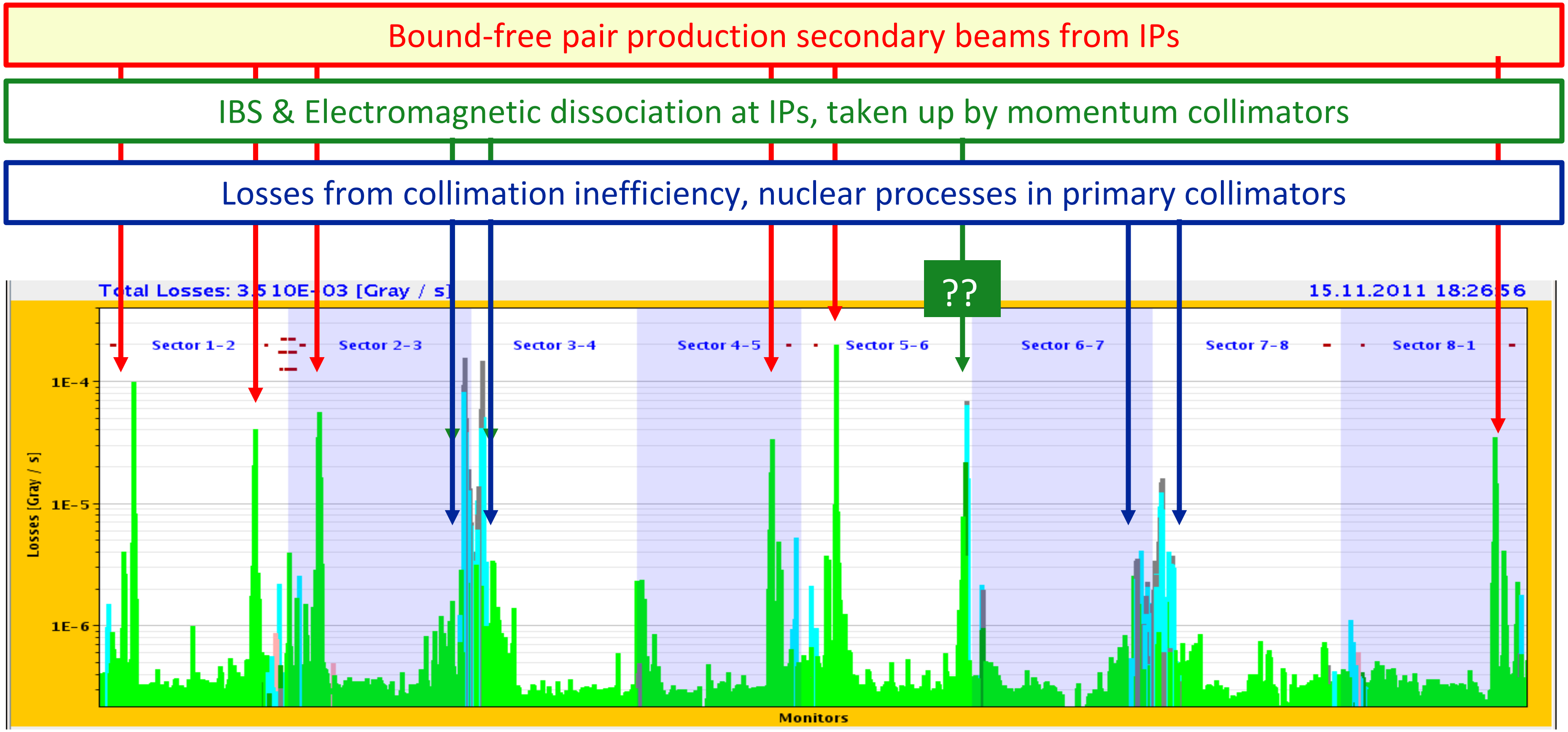
Conclusion

- The high performance of the whole accelerator complex allowed three very successful runs with Pb beams well beyond nominal characteristics,
- The Pb-Pb luminosity goal of 1 nb^{-1} for the first phase in the LHC may be reached by 2016,
- Main limitations for high luminosity during heavy ion runs are ions' burn-off, IBS and intensity limits due to losses on superconducting magnets,
- Ways to provide higher luminosity after LS2 are under study,
- Ar collisions could be considered in the near future as well as additional p-Pb runs given the first experience of colliding unequal beams this year,

- Perspectives beyond LS3 are very uncertain, LHC potential is very good, various species and asymmetric collisions at higher luminosity/energy could be considered,
- But LHC running time for heavy ions has to be planned in agreement with the possible upgrades, and resources for studies, R&D, injectors' development and preparation are not yet foreseen.

Thank you for your attention.

Spares



Bound-free pair production secondary beams from IPs
IBS & Electromagnetic dissociation at IPs, taken up by momentum collimators
Losses from collimation inefficiency, nuclear processes in primary collimators
??
Total Losses: 3.510E-03 [Gray / s]
15.11.2011 18:26:56
Sector 1-2
Sector 2-3
Sector 3-4
Sector 4-5
Sector 5-6
Sector 6-7
Sector 7-8
Sector 8-1
1E-4
1E-5
1E-6
Losses [Gray / s]
Monitors

Deuterons in LHC (D-A,p-D) collisions

- No deuteron beams in present CERN complex
- Linac4 cannot accelerate D, even with a D- source
- Linac2 should be shut down, eventually
- Only possibility with existing accelerators is to use present heavy ion Linac3
  - Requires new D source, RFQ, switchyard,
  - Several years' lead time to develop
  - Uncertain how LEIR would perform with D
  - Present studies of new light ion source (He to Ne) under way (medical use of LEIR), might be extended to D if officially requested (presently no formal request for LHC)
- Possible alternative (D. Kuchler): cyclotron injecting ~1 mA D directly to PS synchrotron
  - Could be cheaper, even table-top if injecting to LEIR

D-A performance

- Very rough for now … help from D. Kuchler

  Present source gives $^{208}\text{Pb}^{29+}$ with $Q/A = 1/7.2$.
  Space charge limit entrance of Linac3 $\approx 200\ \mu\text{A}$.
  For D with $Q/A = 1/2$, expect space charge limit $\approx 55\ \mu\text{A}$

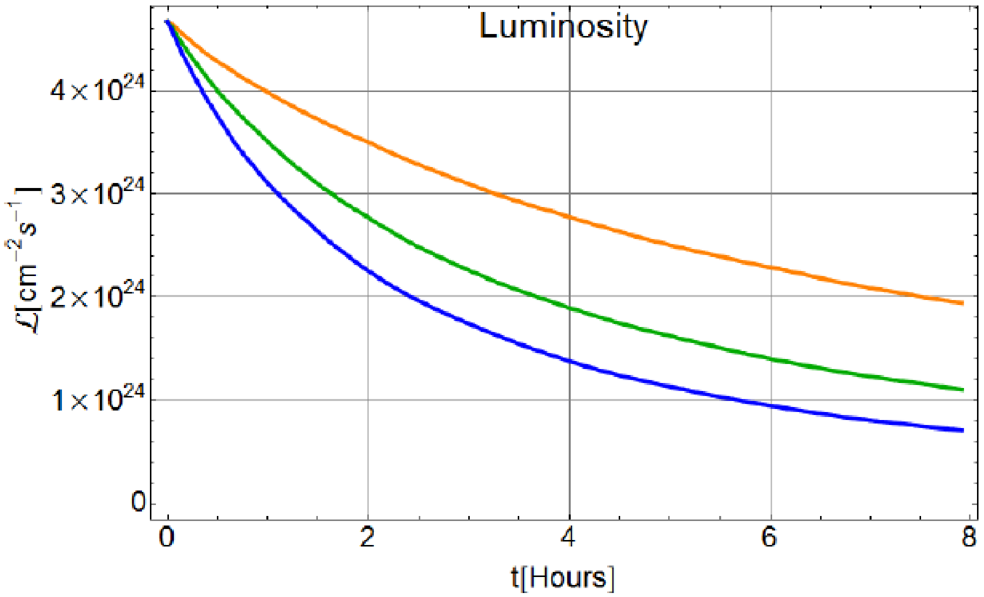
- However, this gives a big margin in fields and there are no losses from stripping.
- If source is intense enough and losses in Linac can be tolerated, can hope for 200-500 μA at end of linac (with somewhat degraded beam quality).

Scaling from Pb values to intensity in LHC

$$\frac{200-500\mu A}{50\mu A}\frac{82}{2}7\times 10^{7} = 1.5\times 10^{10}\ \text{D/bunch in LHC}$$

- Take safety reduction factor 5 for unknowns in PS, SPS, etc.
- D-A luminosities few times smaller than p-A

2011 beams at 7 Z TeV



Sample bunch behaviour

Luminosity decay for a *single pair* of Pb bunches colliding at nominal LHC energy (7 *Z* TeV per beam) with 1 (orange), 2 (green) or 3 (blue) experiments taking collisions with β*=0.5 m (regardless of possible luminosity limits in some IPs). The bunch intensity is a typical average value already achieved with 358 bunches per beam in 2011. (M. Schaumann.)

J.M. Jowett, LMC, 12/12/2012 J.M. Jowett 23

RHIC Run-12 U-U Run in CERN Courier

CERN COURIER

Sep 27, 2012

3D cooling for uranium collisions at RHIC

For the world's first uranium–uranium collisions, stochastic cooling in the longitudinal, vertical and horizontal planes was used to shrink the beam size and increase the collision rate.

Résumé

Refroidissement 3D pour les faisceaux d'uranium à RHIC

En mai, le collisionneur d'ions lourds relativistes RHIC du laboratoire national de Brookhaven a terminé sa première campagne avec faisceaux d'ions uranium, soit les ions les plus lourds jamais utilisés dans un collisionneur. C'était aussi la première fois que le système de refroidissement stochastique complet était utilisé au RHIC. Ce système permet le refroidissement sur le plan longitudinal, vertical et horizontal dans les deux anneaux d'aimants entrelacés de la machine. Le refroidissement a permis de réduire la taille du

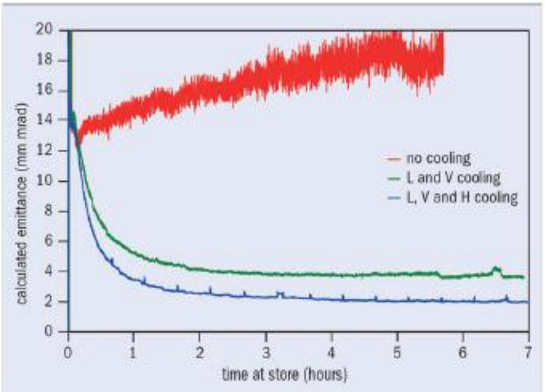


Fig. 1. Transverse emittances in stores without cooling; with longitudinal and vertical cooling; and with longitudinal, vertical and horizontal cooling. (Emittance is proportional to the square of the beam size.)

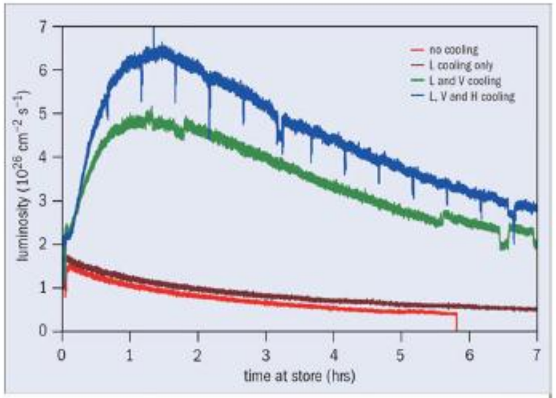


Fig. 2. Luminosity (collision rate) for stores without cooling; with longitudinal cooling only; with longitudinal and vertical cooling; and with cooling in all planes.

J.M. Jowett, LMC, 12/12/2012 J.M. Jowett 24