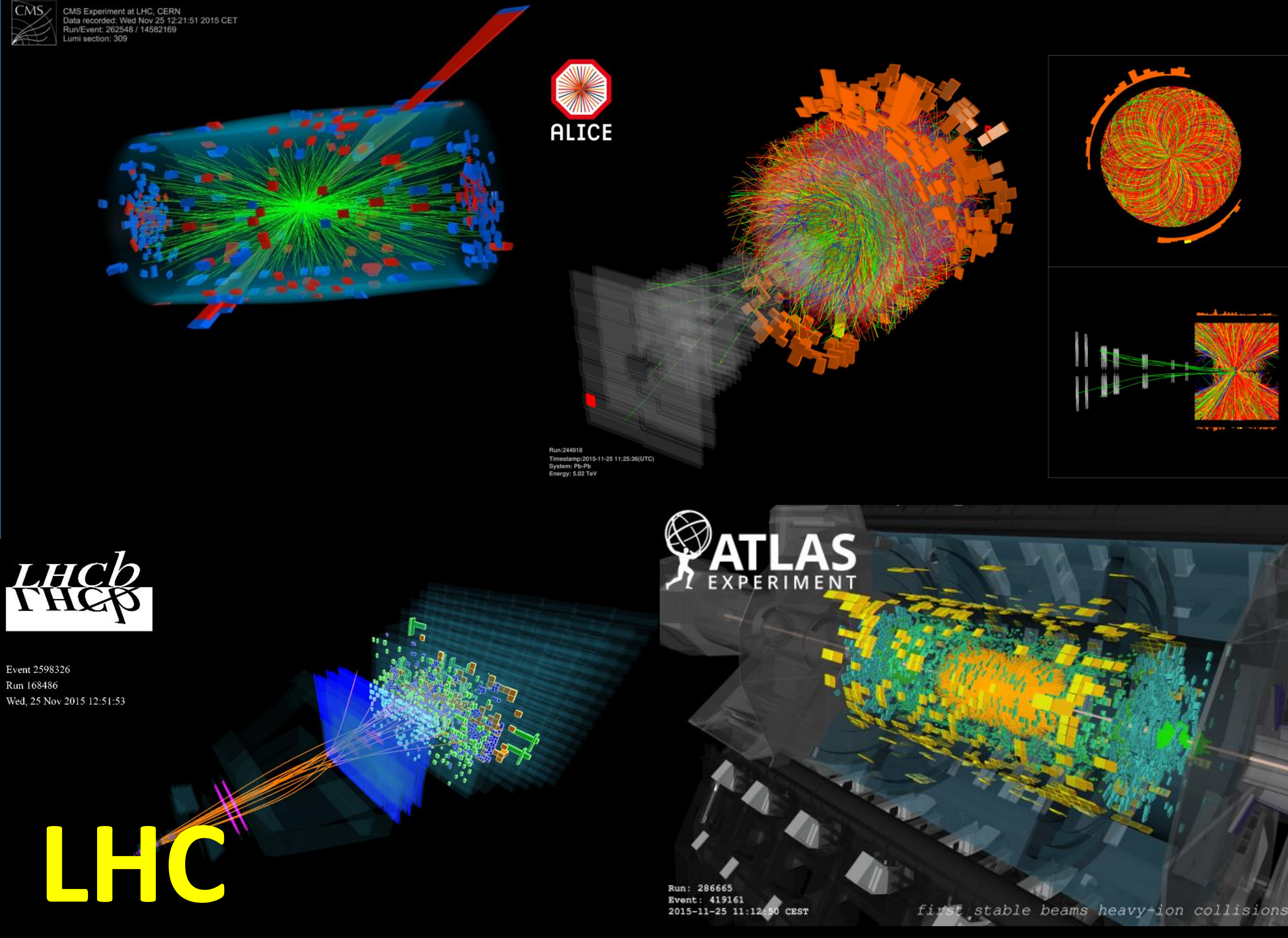
# Near and far future of Colliding Nuclear Beams at LHC and FCC

John Jowett, CERN

Thanks to Michaela Schaumann, Django Manglunki, Giovanni Rumolo, Tom Mertens, Reyes Alemany-Fernandez and many other colleagues at CERN.

# Plan of talk

- LHC (heavy-ion programme only)
  - Where we are: Run 1 and Run 2 so far
  - The path to High Luminosity heavy ions at LHC
  - Plan for p-Pb in 2016
  - The future beyond Long Shutdown 2
- The Future Circular (hadron) Collider FCC-hh
  - Potential as a heavy-ion collider (2016 update)


CMS
CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
Run/Event: 262548 / 14582169
Lumi section: 309
ALICE
Run:244918
Timestamp:2015-11-25 11:25:36(UTC)
System: Pb-Pb
Energy: 5.02 TeV
LHCb
Event 2598326
Run 168486
Wed, 25 Nov 2015 12:51:53
LHC
ATLAS
EXPERIMENT
Run: 286665
Event: 419161
2015-11-25 11:12:50 CEST
first stable beams heavy-ion collisions

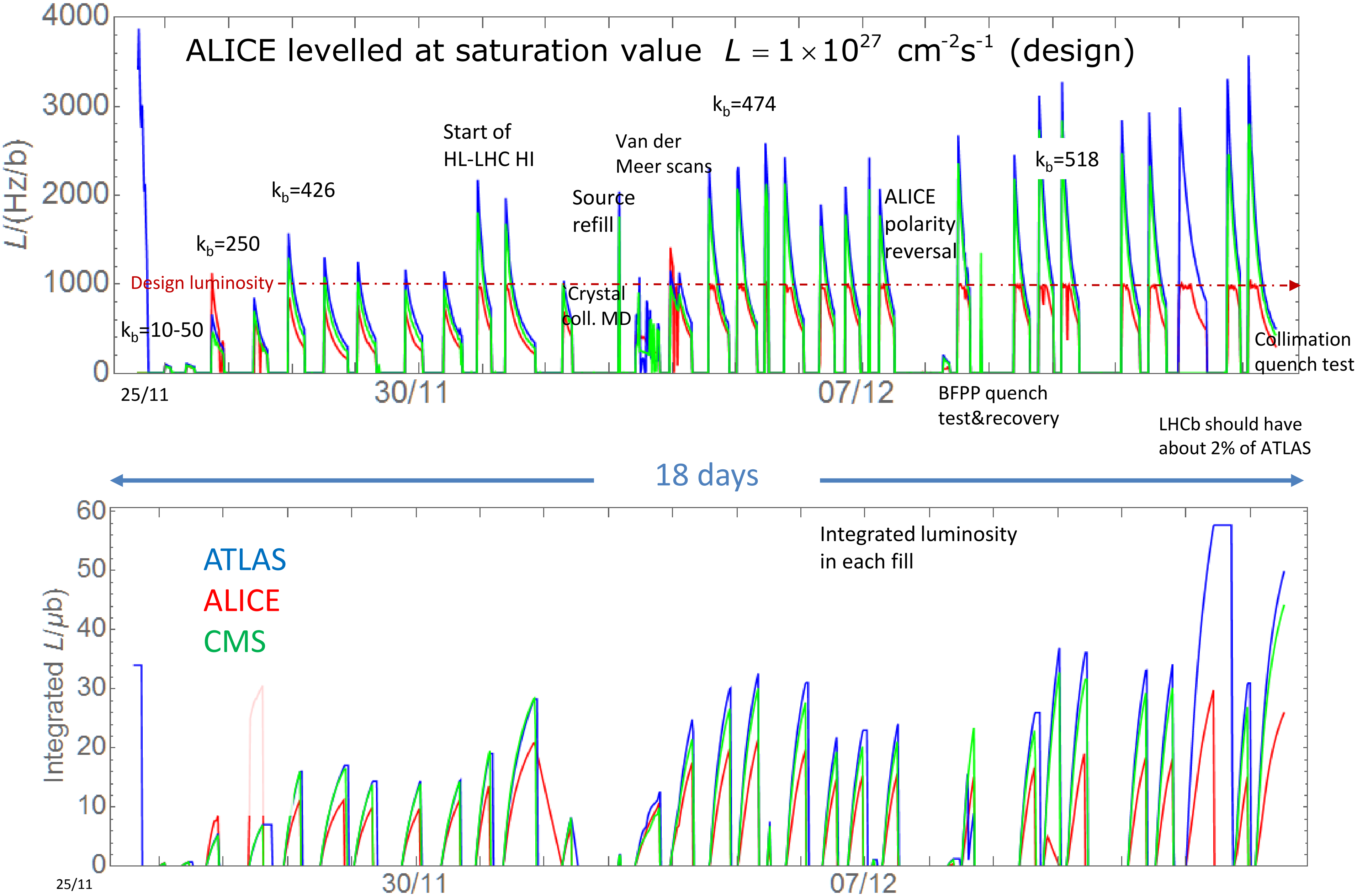
# Recently: 3 runs at equivalent energy

- Experiments wanted to compare 3 combinations of colliding species at same centre-of-mass energy per colliding nucleon pair:

$$\sqrt{s_{\mathrm{NN}}} = 5.02\ \text{TeV with} \begin{cases} \text{p-p} & E = 2.51 & \text{TeV} & \text{Nov 2015} \\ \text{p-Pb} & E = 4Z & \text{TeV} & \text{Jan-Feb 2013} \\ \text{Pb-Pb} & E = 6.37Z & \text{TeV} & \text{Nov-Dec 2015} \end{cases}$$

- Two new LHC configurations to be commissioned and put into production within one month run in Nov-Dec 2015
  - Very complicated first 10 days, switching back and forth between p-p and Pb-Pb optics and species
  - Further interruptions for special MDs, ion source refill, van der Meer scans, ALICE polarity reversal, …

# Luminosity since start of Stable Beams 10:59 25/11/2015



# Integrated nucleon-nucleon luminosity in Run 1 + 2015

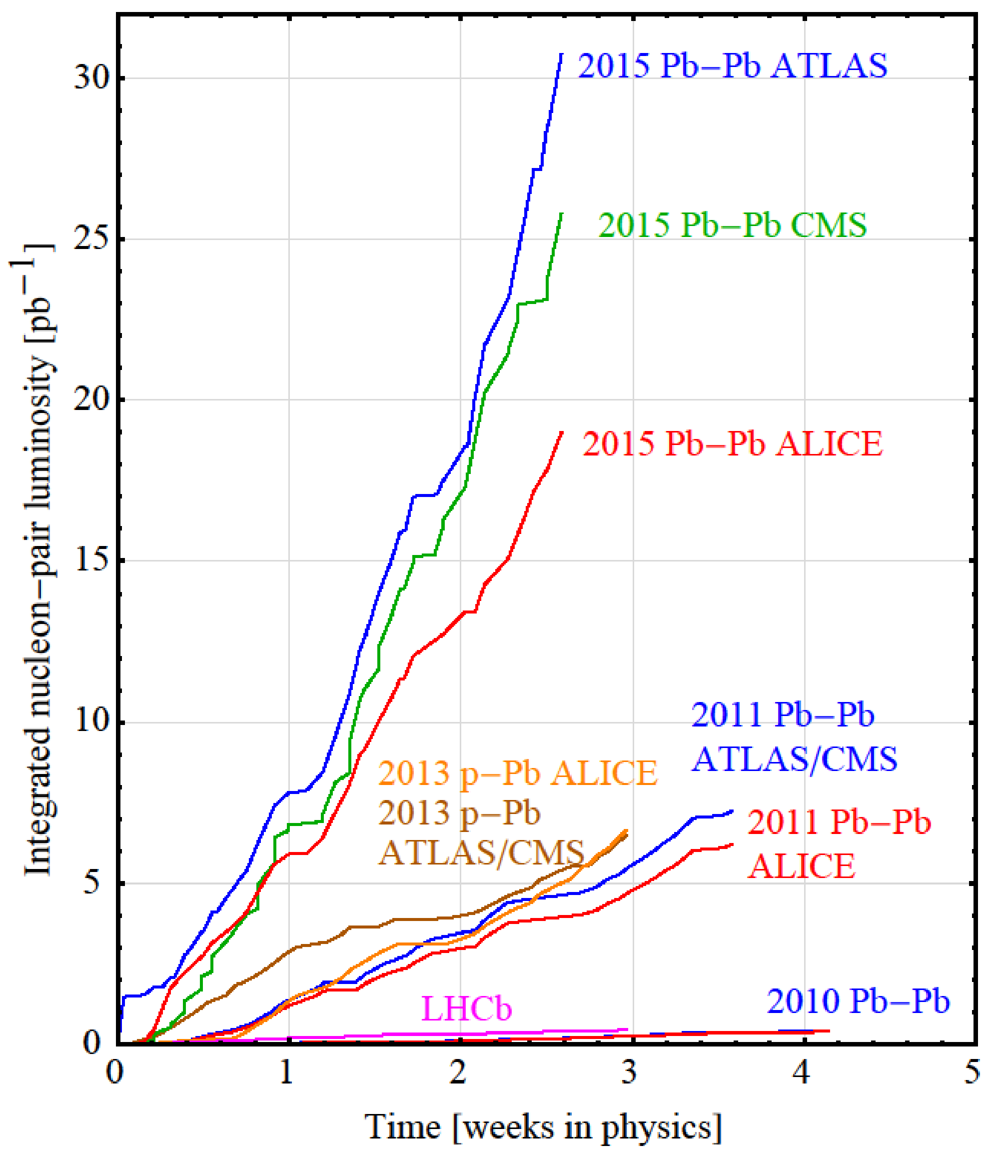
Expect to achieve LHC "first 10-year" baseline Pb-Pb luminosity goal of
1 AA $nb^{-1}$ = 43 NN $pb^{-1}$
in Run 2 (=2015+2018)

Goal of the first p-Pb run was to match the integrated nucleon-nucleon luminosity for the preceding Pb-Pb runs but it already provided reference data at 2015 energy.

$$\sqrt{s_{NN}} = 5.02 \text{ TeV}$$

$$\Rightarrow E_b = \begin{cases} 6.37Z \text{ TeV} & \text{in Pb-Pb} \\ 4\,Z \text{ TeV} & \text{in p-Pb} \end{cases}$$

But annual 1-month runs are getting shorter and more complicated … 2015 included p-p reference data and included LHCb.

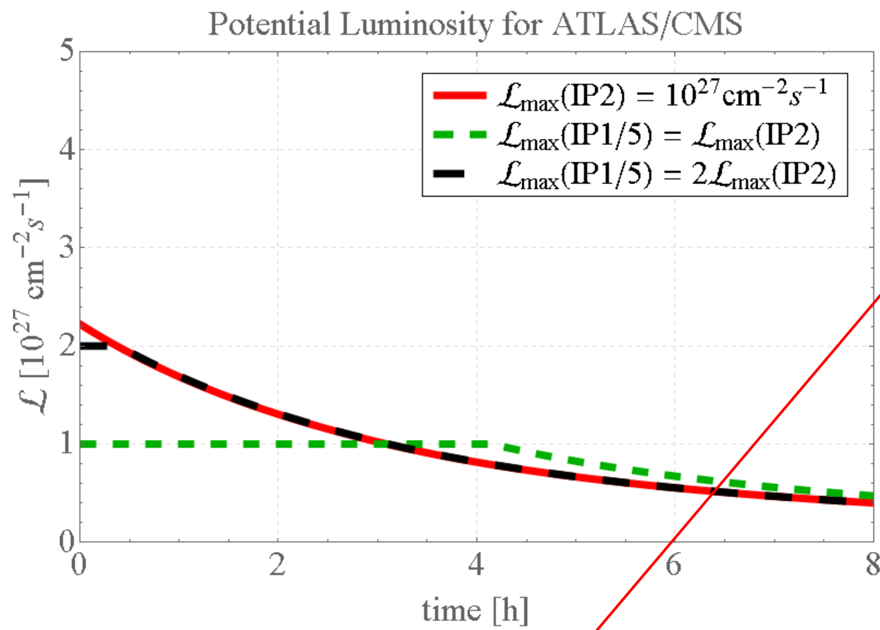


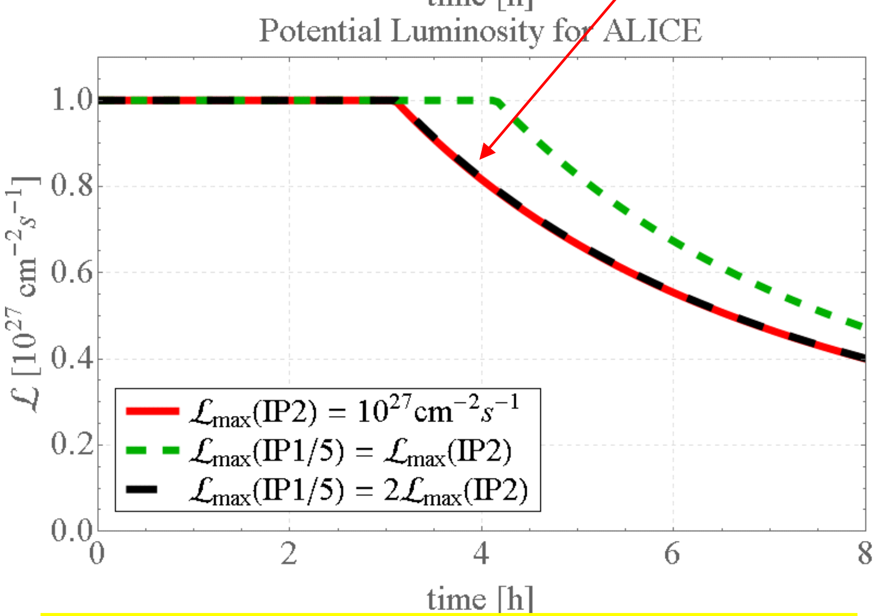

2012 pilot p-Pb run not shown (1 fill but major physics output)

# A word of caution

- Only 10 years ago, some experienced accelerator experts regarded the idea of commissioning a new configuration of a hadron collider *and* producing useful luminosity within a one-month run as implausible.
  - Traditional single-mode operational model, incremental improvement in steady operation
- Amazing build-quality, reproducibility and operation of LHC have decisively refuted this (see also RHIC).
  - 80% availability in 2015 Pb-Pb run.
- Nevertheless, risks to compromise short runs remain.

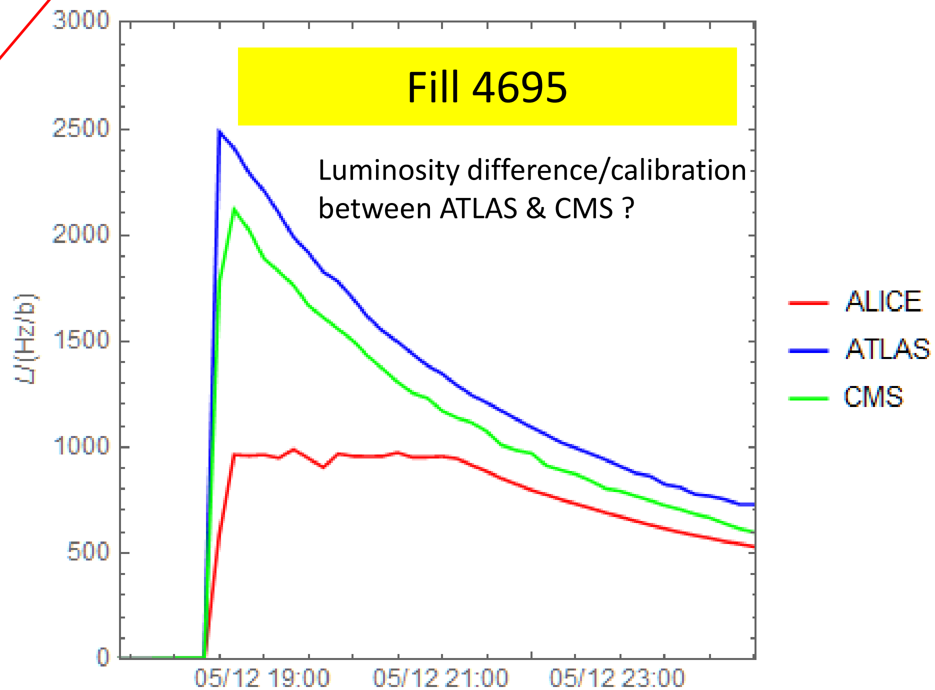
# Luminosity evolution: prediction vs reality



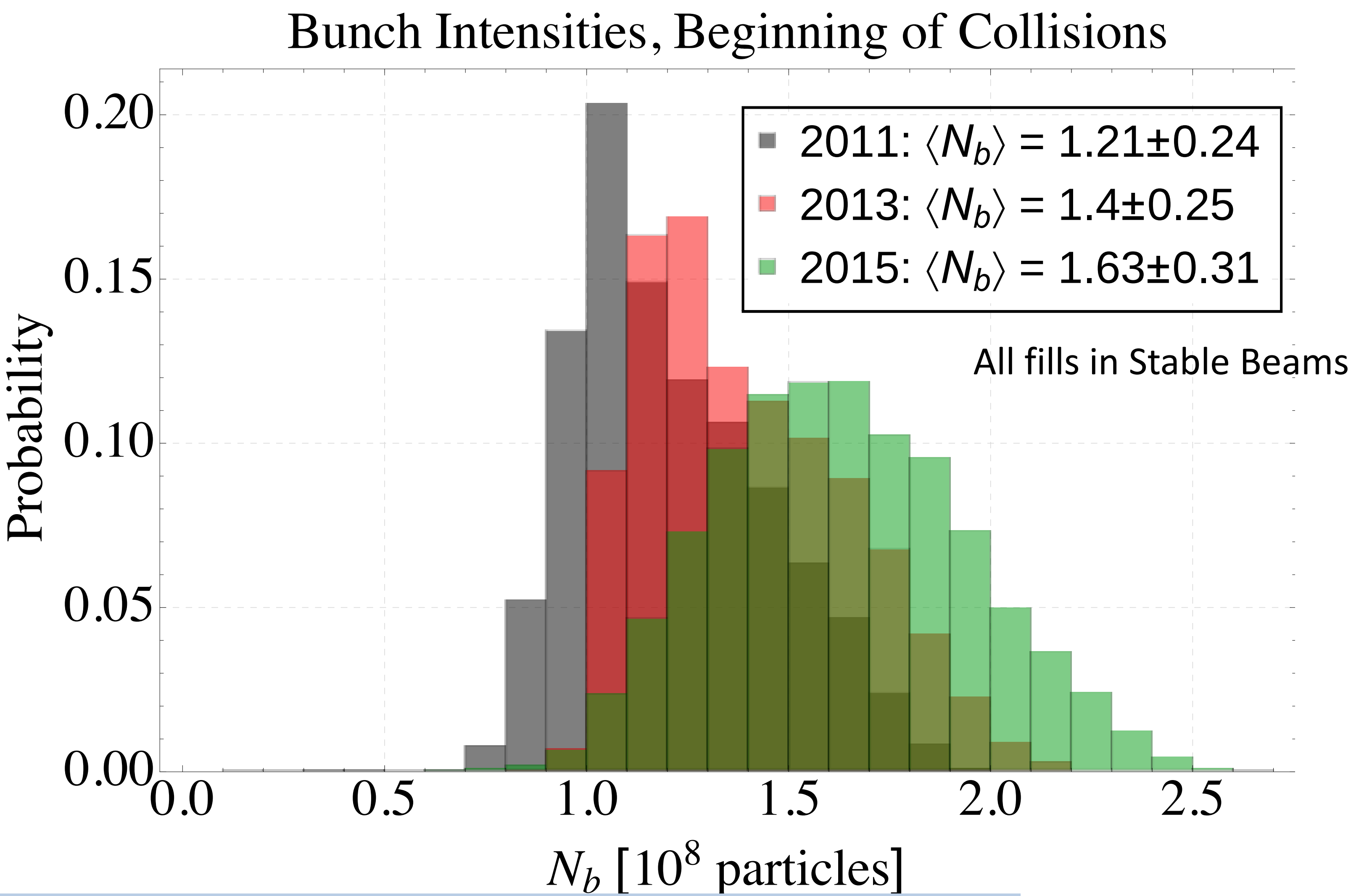

Simulation without LHCb (Michaela Schaumann)

Levelling scenario used is the red line (ALICE only)




CTE simulation (burn-off, radiation damping, IBS, debunching from RF bucket, crossing angles, etc) for individual bunches,
One ingredient of HL-LHC predictions.

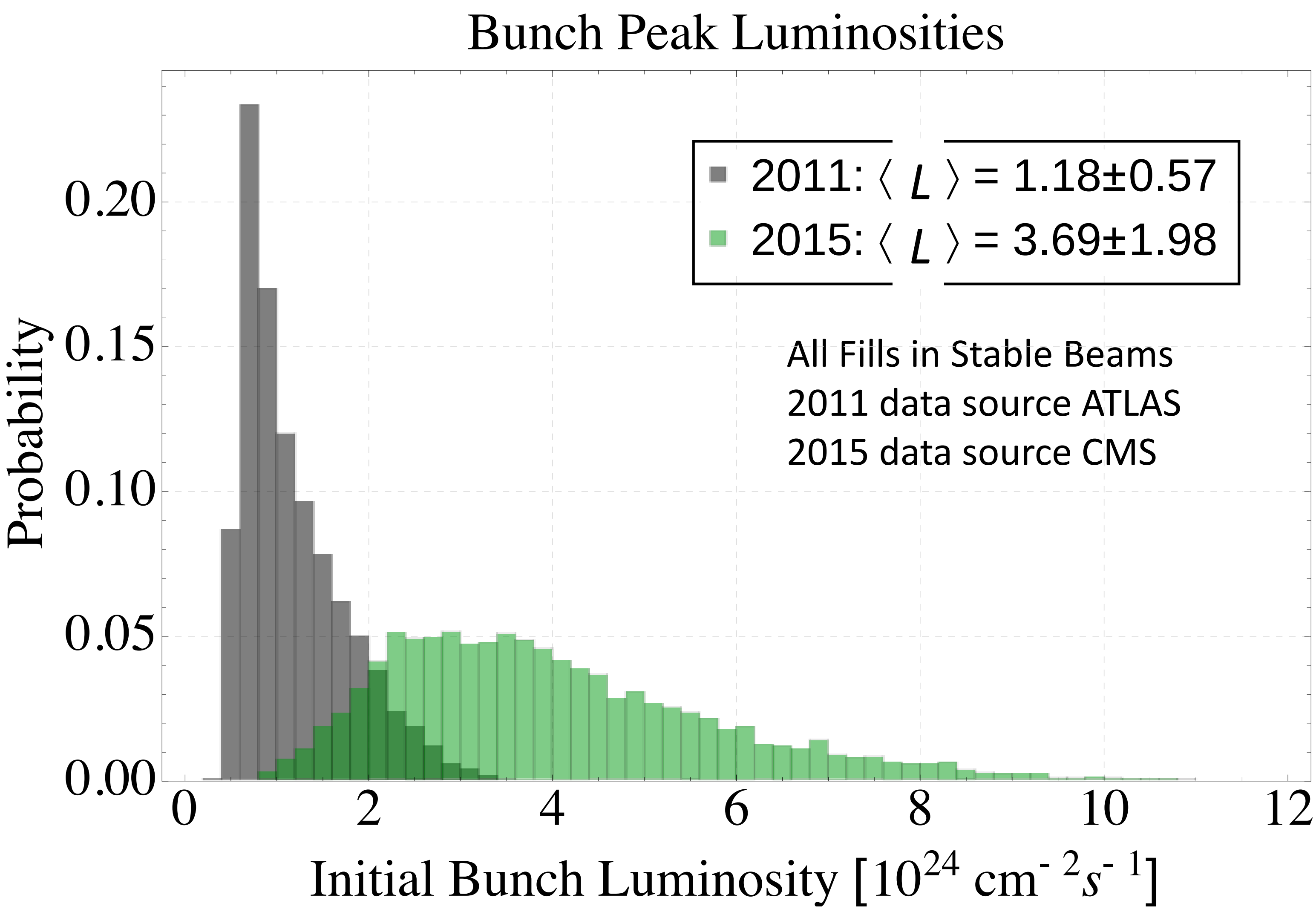
# Bunch intensities at the beginning of Stable Beams




Heavy-ion runs are complex – many bunch evolution histories in a single pair of beams. Pb-Pb and, even more so, p-Pb.

Michaela Schaumann

# Bunch pair luminosity distribution




Michaela Schaumann

# Ultraperipheral processes affecting collider performance

BFPP: $^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + e^{+},$

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

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

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

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

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

Strong luminosity burn-off of beam intensity.

Each of these makes a secondary beam emerging from the IP with rigidity change that may quench bending magnets.

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

Discussed for LHC since Chamonix 2003 … see several references.

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

# Electromagnetic Dissociation in Primary Collimator

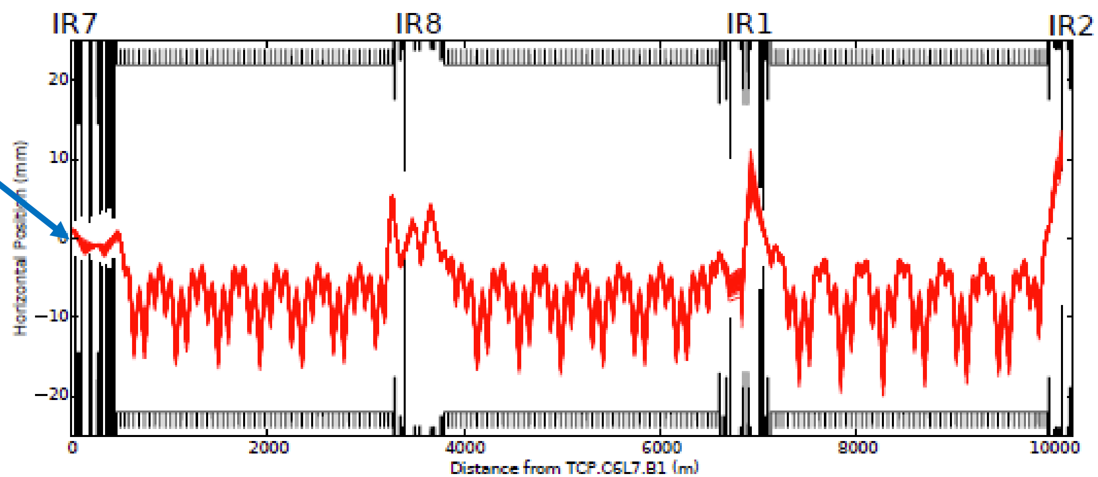
## IR2 losses : understanding and mitigations (2015)

- STIER : what ions are causing the TCT loss in IR2 ?

| Isotope (A,Z) | TCP jaw | Fraction (%) |
|---|---|---|
| **(207,82)** | **left** | **92.5** |
| (204,81) | right | 3.6 |
| (202,80) | left | 2.2 |
| (199,79) | right | 0.3 |

Primary collimator (TCP) in IR7, outer jaw

$$^{208}Pb^{82+} + {}^{12}C \xrightarrow[\gamma]{} {}^{207}Pb^{82+} + n + {}^{12}C$$



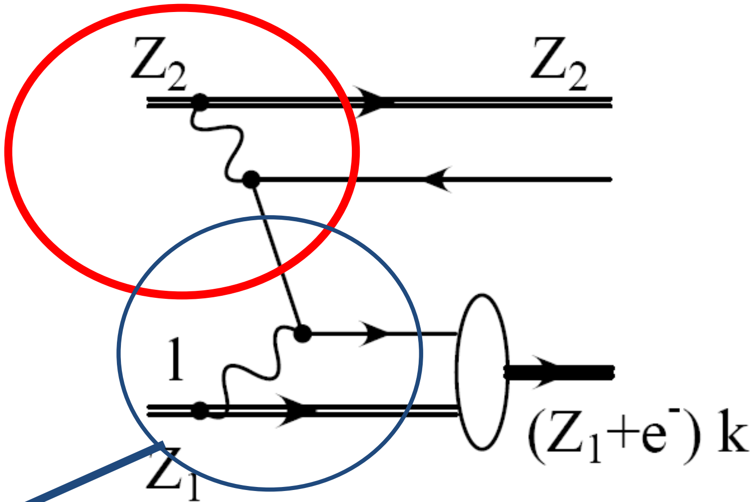

Pascal D. Hermes, CERN, University of Münster

Simulation Tools for Heavy-Ion Collimation

Pascal Hermes

# Pb-Pb BFPP cross-section

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

$$R_{10}(r) = \left(\frac{Z_1}{a_0}\right)^{3/2} 2\exp\left(-\frac{Z_1 r}{a_0}\right)$$

$$\Rightarrow \quad \Psi(0) \propto Z_1^{\,3/2} \quad \Rightarrow \quad \left|\Psi(0)\right|^2 \propto Z_1^{\,3}$$

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

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

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

has very strong dependence on ion charges (and energy)

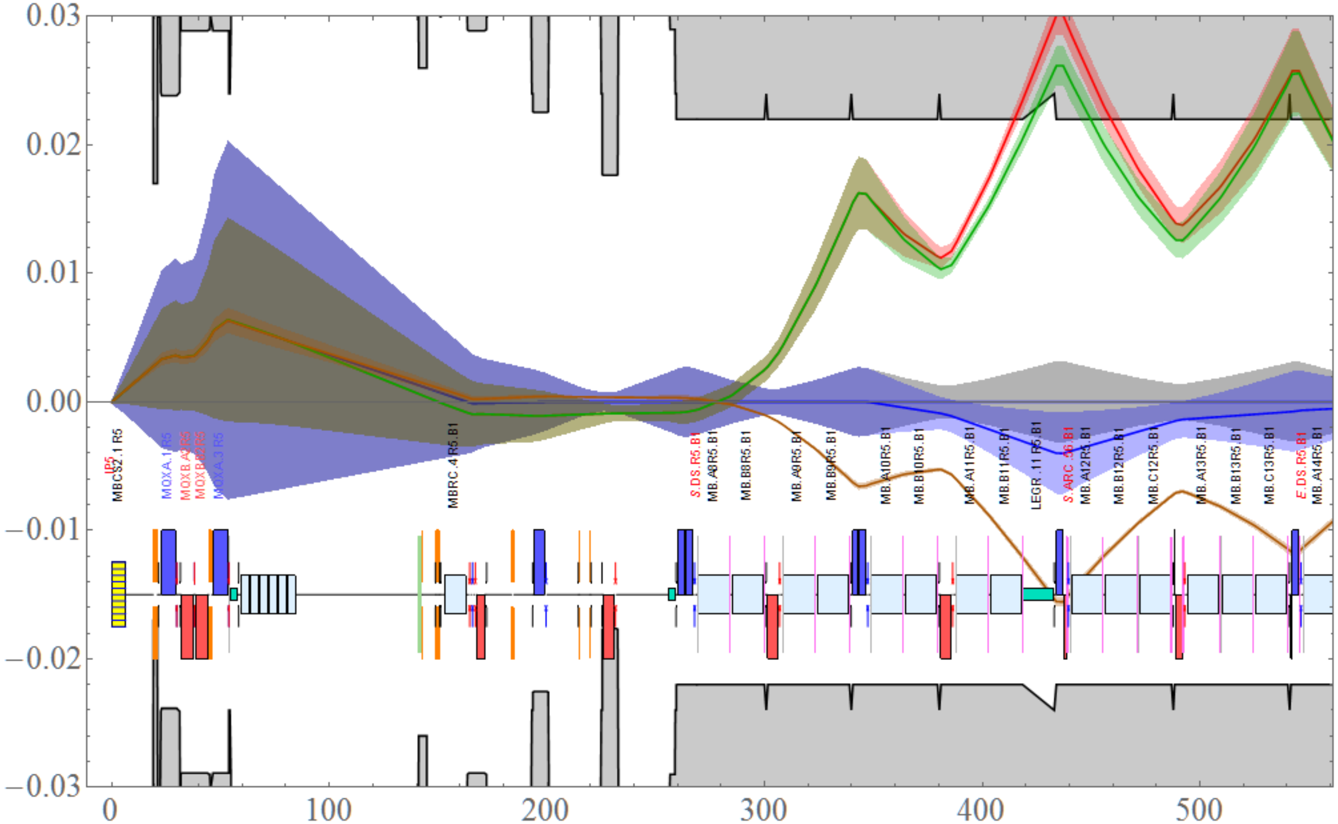
$$\sigma_{PP} \propto Z_1^{\,5} Z_2^{\,2} \left[A \log \gamma_{CM} + B\right]$$

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

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

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

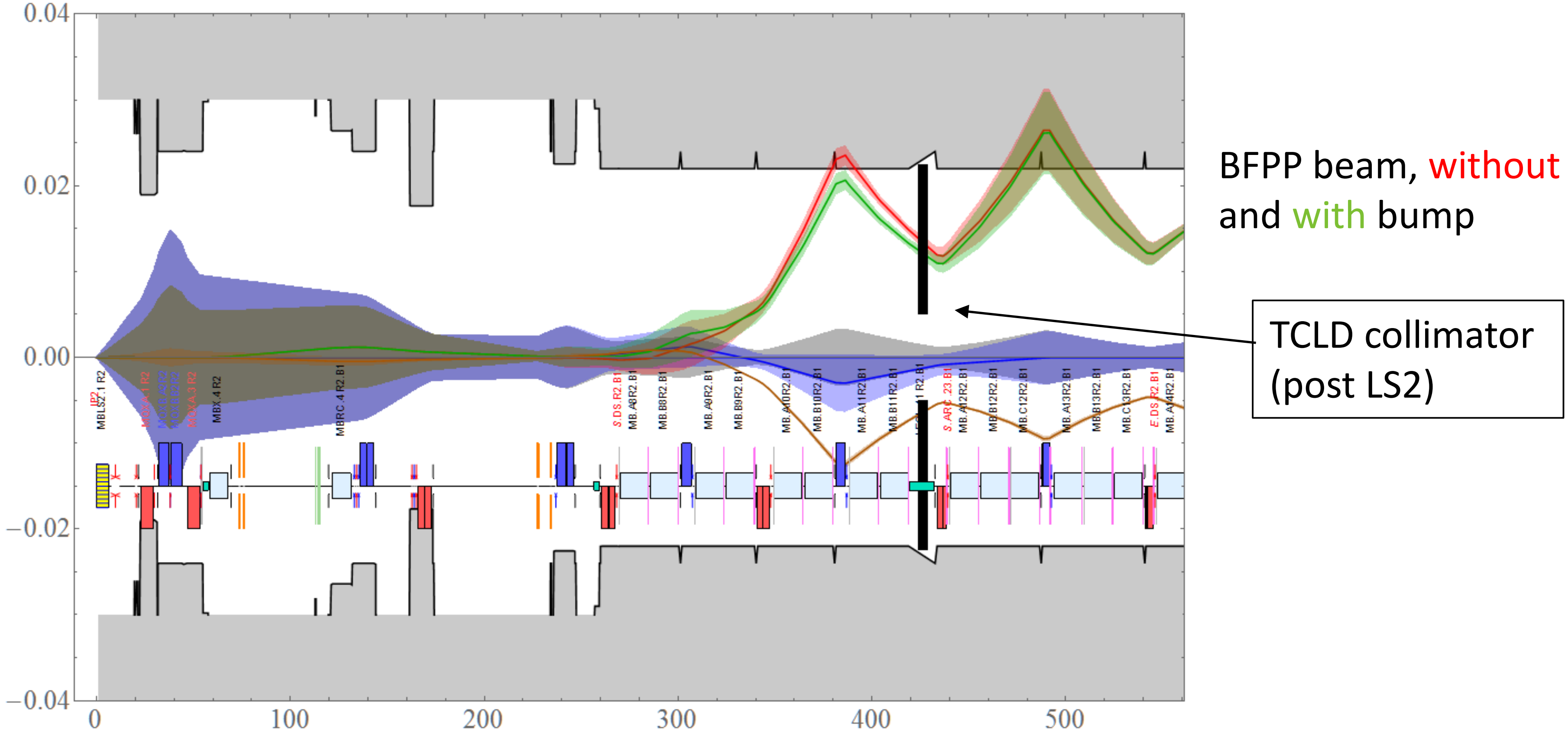
# Orbit bumps mitigate BFPP for CMS (or ATLAS)




BFPP beam, without and with bump

- Primary loss location close to the connection cryostat - details slightly optics-dependent (If necessary, bumps should avoid quenches at the start of physics
- Extra BLMs were specifically added for heavy-ion operation in loss region
- Variations of bump possible, uses moderate fraction of available corrector strengths
- We applied bumps like these with ~ 3 mm amplitude around CMS and ATLAS from the beginning of the run

# Orbit bumps alone are not effective for ALICE




- IR2 has different quadrupole polarity and dispersion from IR1/IR5
- Primary BFPP loss location is further upstream from connection cryostat
- Solution is to modify connection cryostat to include a collimator to absorb the BFPP beam –**design is being launched now to be ready for LS2 installation**
- With levelled luminosity in ALICE, quenches were not seen in Run 2

# Tests of strategy during 2015 Pb-Pb run

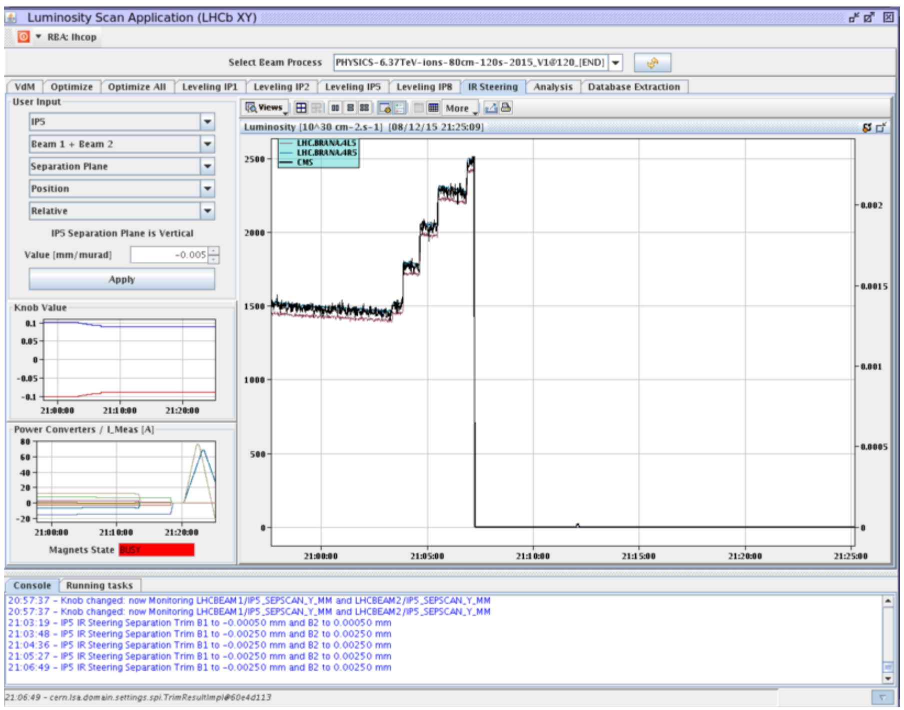
- For safety, mitigation bumps were implemented at 3 mm amplitude in validated physics setup
  - Expected to move losses around ATLAS/CMS into connection cryostat
    - Not quite true on left of IP5 – luminosity losses at start of later fills came close to (raised) BLM dump thresholds
  - Moved losses beyond connection cryostat in IR2
    - Levelled luminosity not expected to be a concern
- MD study around IP5 would attempt to quench by manipulating bump to move losses back into connection cryostat in controlled way
  - Based on latest estimates of steady state quench level, we did not expect a quench … but we tried anyway.
  - An extremely clean measurement of LHC dipole quench limit

# BFPP Quench MD – first luminosity quench in LHC

- BLM thresholds in BFPP loss region raised by factor 10 for one fill 8/12/2015 evening.
- Prepared as for physics fill, separated beams to achieve moderate luminosity in IP5 only.
- Changed amplitude of BFPP mitigation bump from -3 mm to +0.5 mm to bring loss point well within body of dipole magnet (it started just outside).
- Put IP5 back into collision in 5 μm steps.
- Unexpectedly quenched at luminosity value (CMS):

$$L \approx 2.3 \times 10^{27}\ \mathrm{cm^{-2}s^{-1}}$$

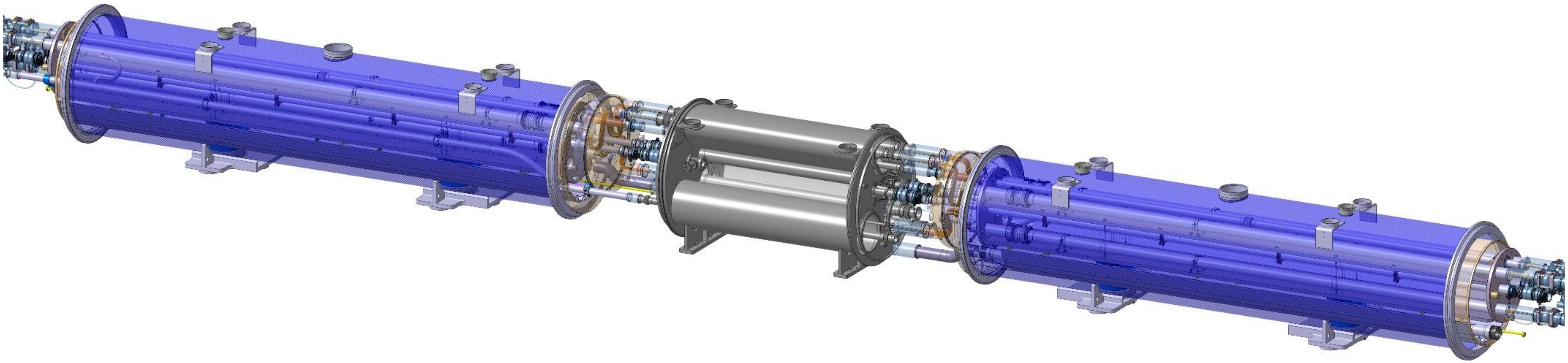
$\Rightarrow$ 0.64 MHz event rate, about 45 W of power in $Pb^{81+}$ beam into magnet

# Consequences of the BFPP quench result

- Strong-field QED (!) resolves long-standing (since mid-1990s) uncertainty on steady state quench limit of LHC superconducting magnets and BFPP luminosity limit
  - Factor 2-3 lower than recent expectations from magnet studies
  - Main errors BFPP cross section, luminosity
- Efficacy of BFPP bumps clear – we already needed them in 2015 to avoid luminosity quenches around ATLAS and CMS!
  - FLUKA analysis confirms this is still OK for further increase in luminosity.
  - Radiation effects and heat load may still be issues.
- Closes the case for collimators in the LHC dispersion suppressors around ALICE (where the bump mitigation alone does not work), discussed since Chamonix 2003 …
- Similar collimators with first 11 T dipoles needed for Pb collimation losses in IR7

# Cryo-bypass for DS collimator



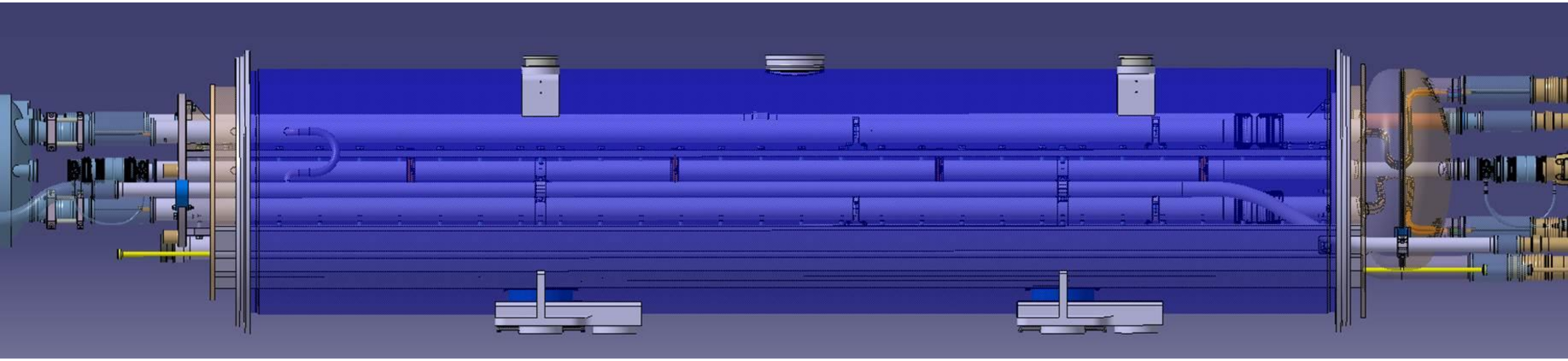
- During LS2, the current LHC connection cryostat has to be replaced to install the collimator in left and right sides of IR2
- The new CCC is designed to work in combination with the standard QEN bypass cryostat
- The continuity of the cryogenic and electric lines has to be guaranteed.
- In IR7 similar modules but containing Nb3Sn 11 T magnets will be used to replace standard LHC dipole magnets, collimators will intercept heavy-ion and proton collimation losses.

M. Moretti et al

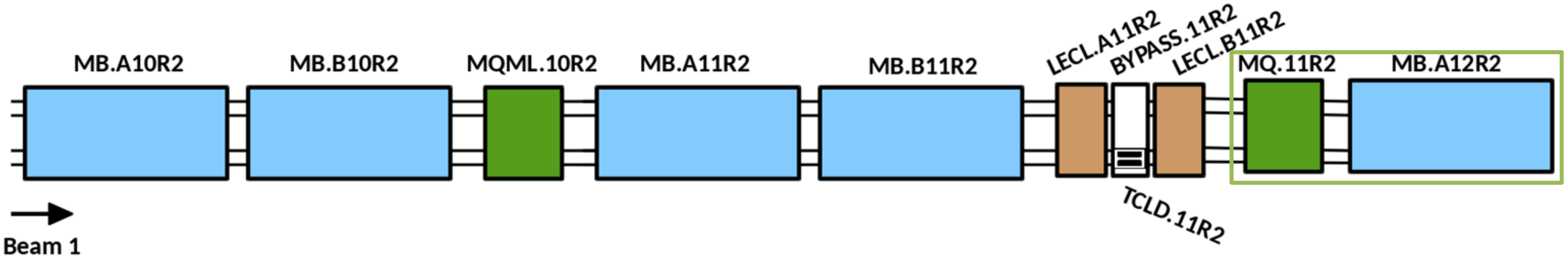
# Conceptual Design

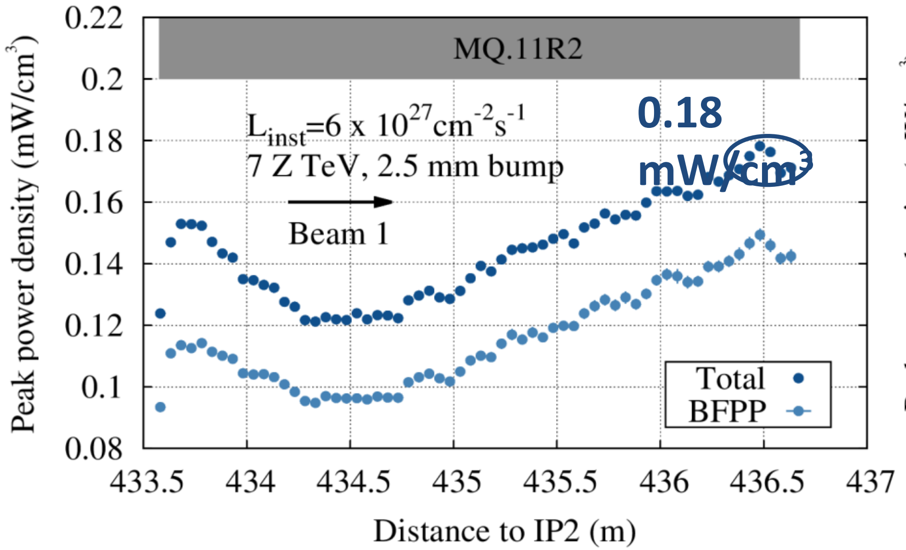
**The concept of the current LHC connection cryostat can be re-adapted**

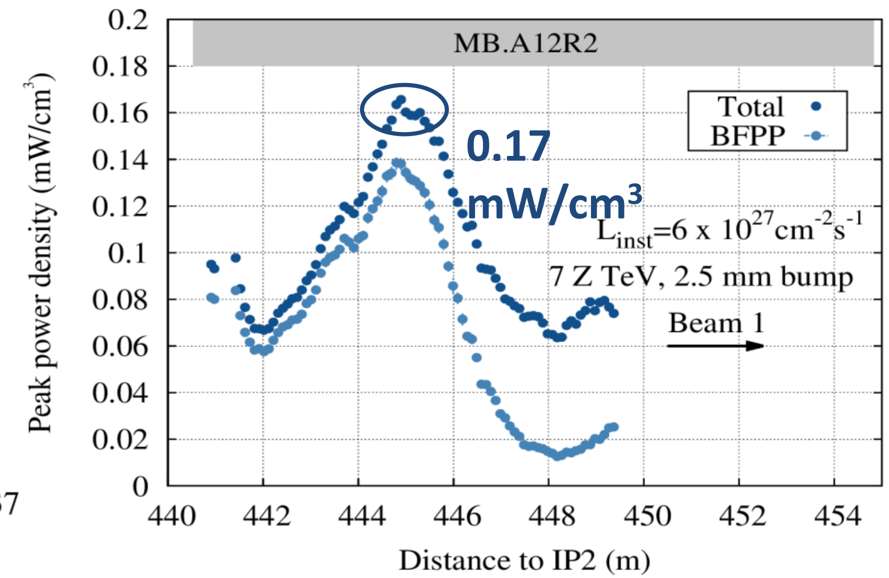
- Exploitation of vacuum vessel concept and cold supports
- Cold mass traversed by the cryogenic circuits, the bus-bars lines, the beam pipes and the related supporting and alignment systems
- Mechanical strength and assembly stability to be preserved
- Shuffling module for the bus-bars lyras and the feeding of LHe cooling
- Use of standard concept of bottom tray and thermal shield



# Quench risk: superconducting magnet coils

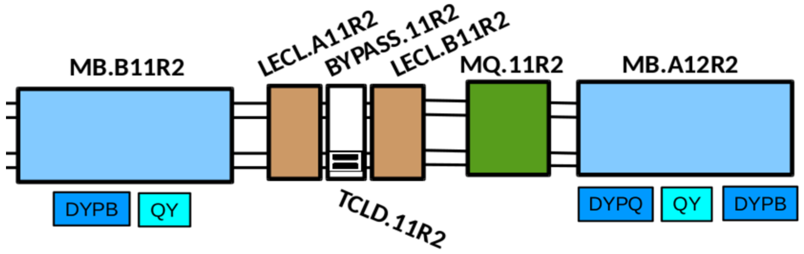


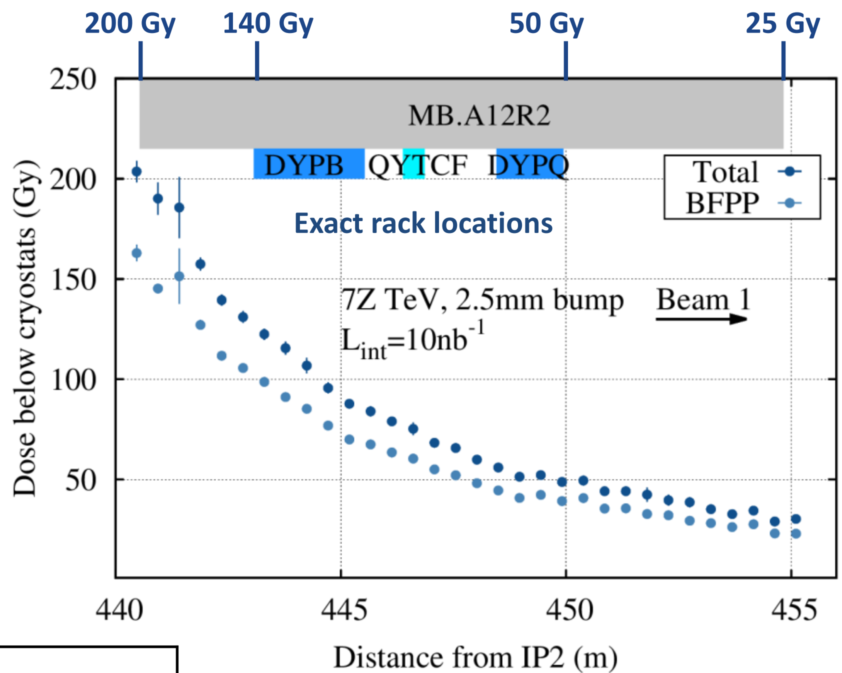




**Collimator maintains the peak power density in the magnet coils at least a factor 10 below their estimated quench limit**

# Radiation to Electronics: cumulative damage (dose)




**Results normalized to 10 $nb^{-1}$(target integrated luminosity for ALICE during the whole HL-LHC ion period)**

**Dose accumulated during ion runs over all years of HL-LHC operation**

**Moving the electronic racks towards the end of the MB would halve the dose they are exposed to**

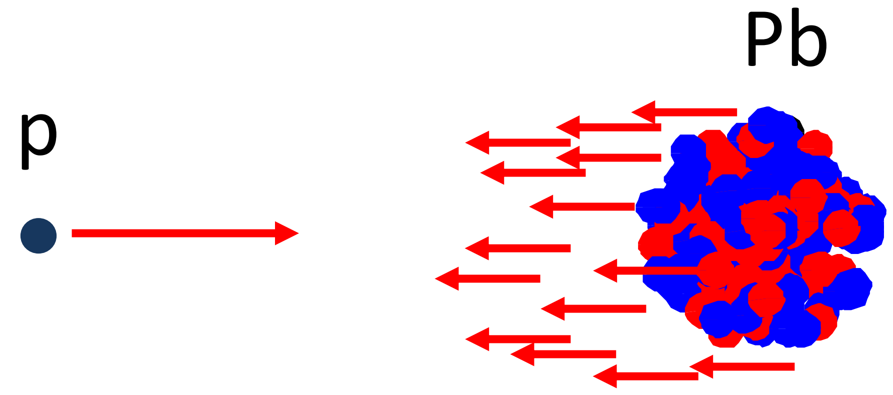
**For currently envisaged lifetimes <20 Gy/year or rack rotation** *(M. Brugger)*

**Rack rotation or non-electronic zone foreseen**

**R2E expectations based on data for proton runs on IR1/5**: target levels for electronics **per year**

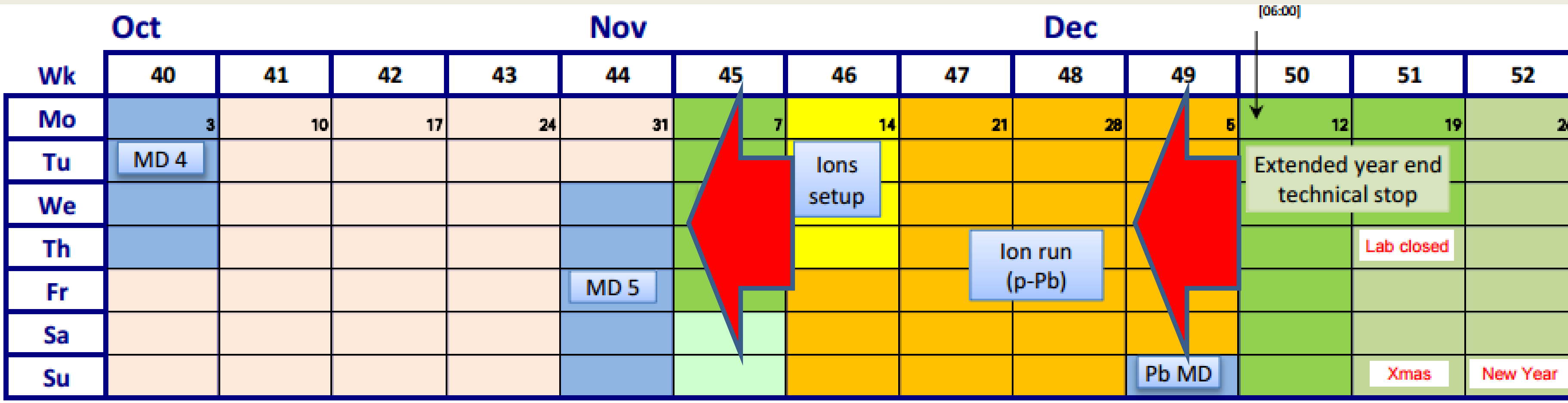
| Cumulative damage to electronics | Run 3 (100 $fb^{-1}$) | | Run 4 (200 $fb^{-1}$) | |
|---|---|---|---|---|
| | DS area (cell 7-11) Worst case | ARC area (cell 12-34) | DS area (cell 7-11) Worst case | ARC area (cell 12-34) |
| Dose | ~40 Gy | ~0.8 Gy | ~80 Gy | ~1.6Gy |

*M. Brugger*




# 2016 PROTON-LEAD PLANS

# The p-Pb run has just been rescheduled !!




- Advanced p-Pb run+TS3 by 1 week in order to leave 1 week before EYETS to train 2 sectors to 7 TeV field levels
  - One week less p-p, but integrated luminosity is ample
  - Technical stop and MD period also move.
- Decided on 31 August.

# Reminder of p-Pb run in 2013

- LHCC 13/3/2013 http://indico.cern.ch/event/239117/session/1/contribution/14
- Almost unprecedented mode of collider operation:
  - Injection and ramp with unequal revolution frequencies, resynch and cogging at flat-top ( ~impossible at RHIC 2003, re-confirmed 2015)
  - Complex filling scheme: p and Pb had to match up, led to 200/225 ns alternating bunch spacing, 338 bunches/beam
  - Off-momentum squeeze $\Rightarrow$ $\beta^*$=0.8 m from aperture limit around ALICE (took same for ATLAS/CMS)
  - ALICE levelling briefly at $L \approx 1 \times 10^{29}$ cm$^{-2}$s$^{-1}$
  - Proton bunch intensity equivalent to 1/$\beta^*$ (but limited by BPMs), integrated luminosity of a fill ~proportional to Pb intensity.
  - Lowest $\beta^*$=2 m ever for LHCb
  - Beam reversal *and* solenoid polarity reversal
  - Catch-up fills to equalise final integrated luminosity for ALICE
  - p-p reference done in extra time, after final whistle of Run 1

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

# Reminder of 2013 p-Pb run – in view of 2016

| | | |
|---|---|---|
| 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 complex after Christmas stop

>4 days lost to cryo, power failures

→ First injection in the LHC

→ Injection checks and Squeeze commissioning

5 TeV set-up simpler – 3 days

→ Collimation set up, IR2 ape … ions

8 TeV set-up, another 4 days

→ First Stable beams, first injection of trains of p and Pb

→ End of ALICE minimum bias data taking

→ ALICE polarity change

→ Van der Meer scans

→ Pb source refill

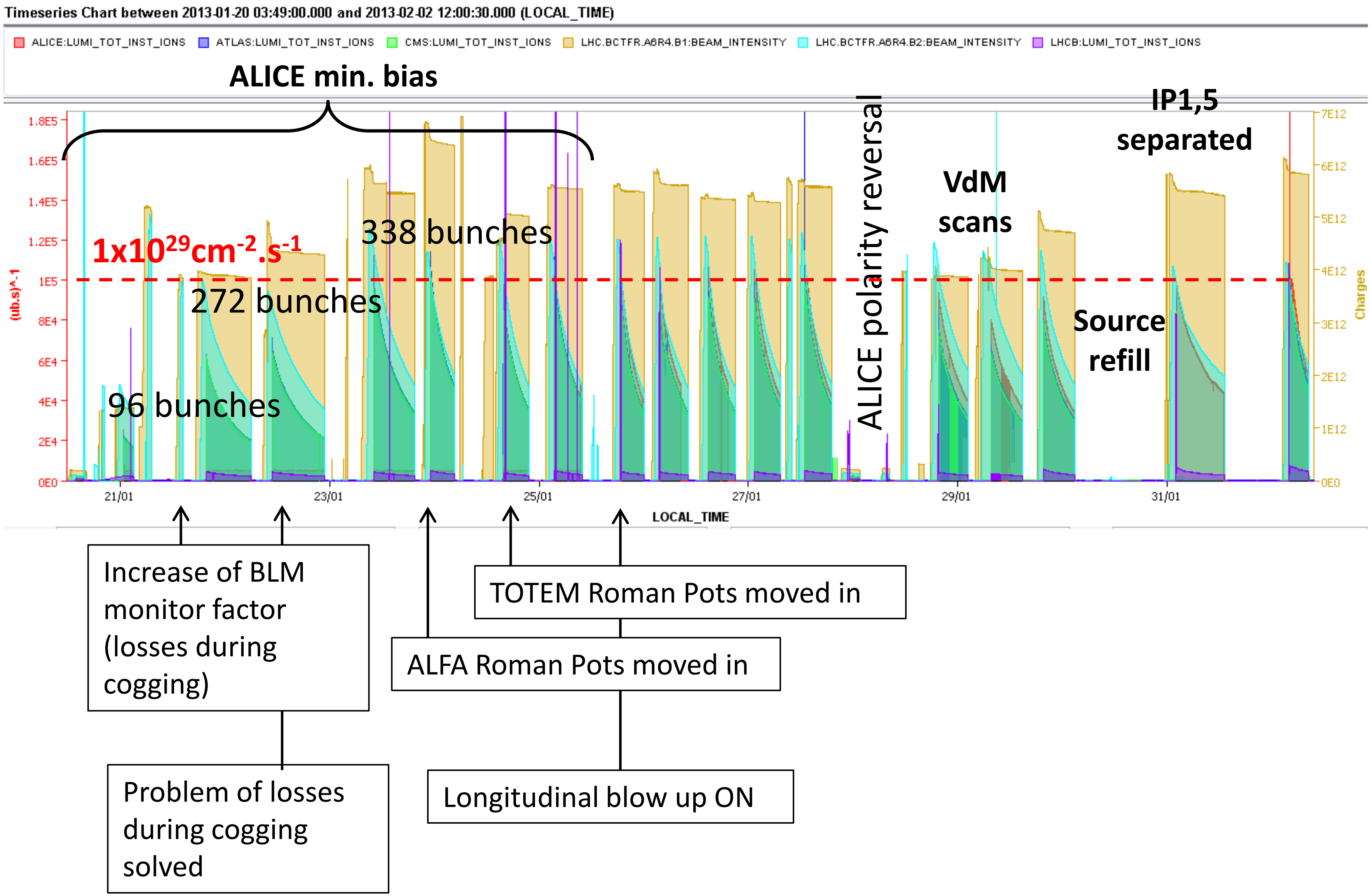
p-Pb

→ Beams reversal

→ Van der Meer scans

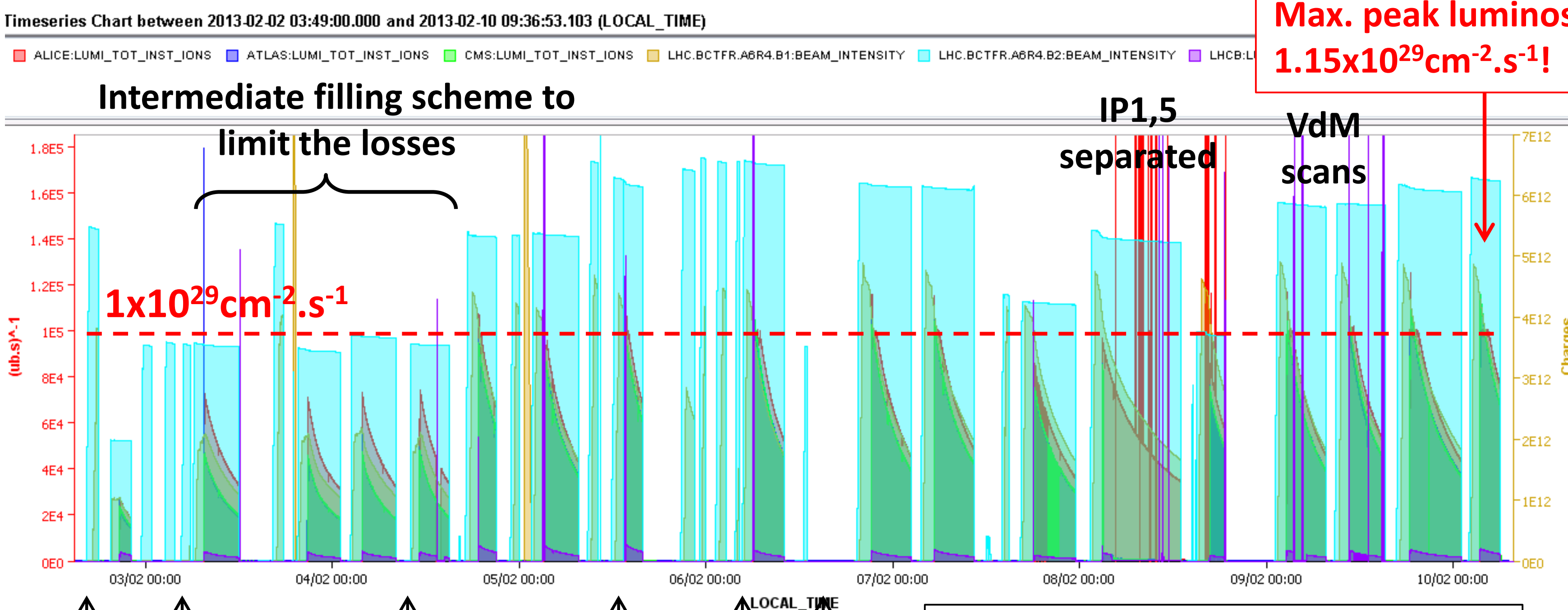
Pb-p

# 2013 Luminosity production in p-Pb mode



# 2013 Luminosity production in Pb-p mode

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




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

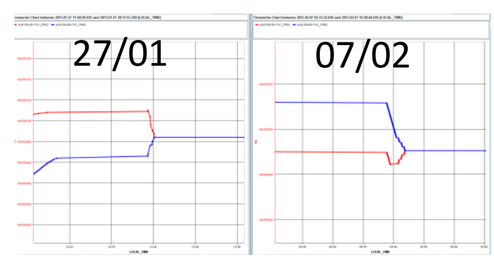
Increase bandwidth of orbit feedback

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

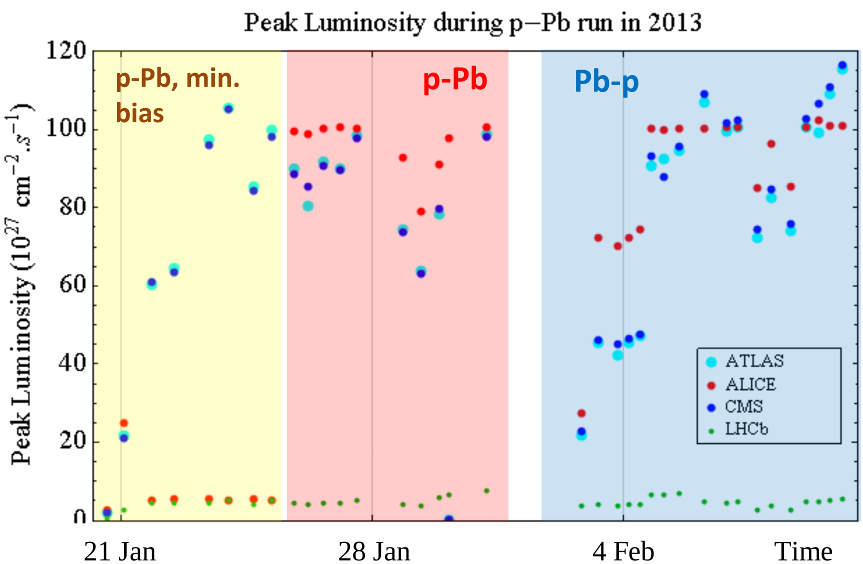
Increase of BLM monitor factor (losses at the start of the ramp), rematch injection energy to the SPS

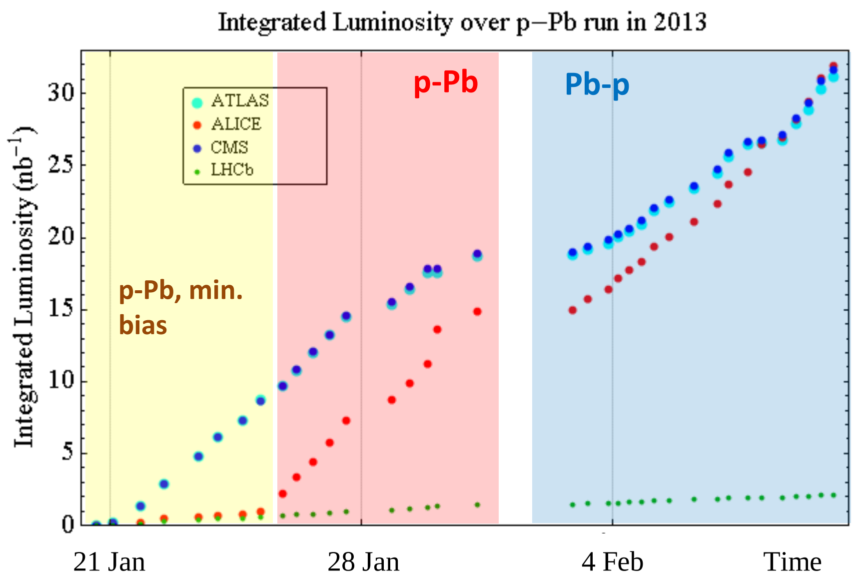
reduction of longitudinal blow-up at injection

Common frequency trimmed by -10Hz




RF frequencies




- Full instantaneous luminosity $1x10^{29}$ $cm^{-2}.s^{-1}$ already reached with the first fill with full filling scheme
- Levelling in ALICE at $1x10^{29}$ $cm^{-2}.s^{-1}$ 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 $1.15x10^{29}$ $cm^{-2}.s^{-1}$, record turn around of 2.37 h

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

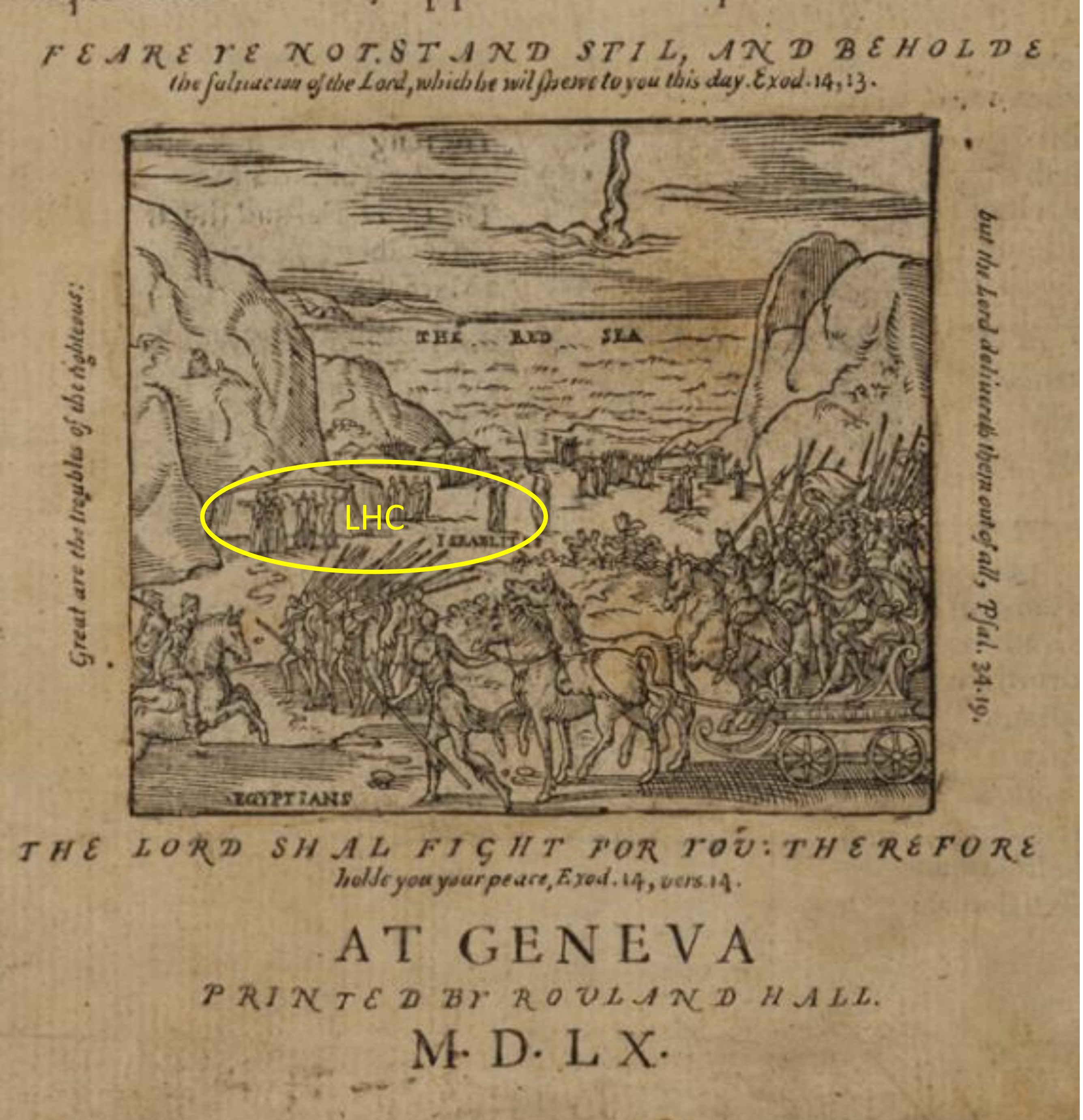
# Experiments' requests for 2016

- Experiments initially gave clear but incompatible requests for species (Pb-Pb, p-Pb, Ar-Ar, …) and energy for p-Pb case:

$E = 4\ Z$ TeV (where $Z = 1\ \&\ 82$) $\Rightarrow \sqrt{s_{\mathrm{NN}}} =$ 5.02 TeV (ALICE, low $L$)

$E = 6.5\ Z$ TeV $\Rightarrow \sqrt{s_{\mathrm{NN}}} =$ 8.16 TeV (ATLAS, CMS, LHCb, high $L$)

- Following LHC Chamonix workshop and LPC meetings: proposal for a p-Pb run at *both* energies, designed to:
  - Meet major/most physics goals of all experiments
  - Shortcut need for a full p-Pb setup at either energy as was done in 2013
  - Maintain overall set-up time and complexity at or below level of 2013



FEARE YE NOT. STAND STIL, AND BEHOLDE
the saluacion of the Lord, which he wil shewe to you this day. Exod. 14, 13.



THE LORD SHAL FIGHT FOR YOU: THEREFORE
holde you your peace, Exod. 14, vers. 14.

AT GENEVA

PRINTED BY ROULAND HALL.

M. D. LX.

Proposal inspired by
1 Kings 3:16-28

# Proposal for 2016 p-Pb run - Part 1

- Run Pb-p at 4 *Z* TeV beam energy mainly for ALICE
  - Full filling scheme > 400 bunches colliding for low μ in ALICE
  - Level ALICE at $10^{28}$ cm$^{-2}$ s$^{-1}$
    $\Rightarrow$ very long luminosity lifetime and very long fills
    $\Rightarrow$ Large fraction of time in Stable Beams (cf catch-up fills in 2013)
    $\Rightarrow$ Can fulfil ALICE requirement in a few days
  - Minimise set-up time by using moderately-squeezed optics β*~2 or 3 m in ALICE only
    - Relatively easy squeeze to set-up and correct
    - Fewer concerns about IR2 aperture (IP2 vertical shift, chromatic squeeze)
    - Will not need correction of off-momentum optics (known from 2013)
    - Just a few turn-arounds
    - Still have RF frequency locking/cogging
    - No spectrometer polarity reversals
    - No reversal of beams (p-Pb only, no Pb-p) required
    - Loss maps etc still required
    - Van der Meer fills similar to physics fills

$$\delta = \pm 1.45 \times 10^{-4}$$

- Possibly collide some bunches in the other experiments at much smaller luminosity ~$10^{27}$ cm$^{-2}$ s$^{-1}$ (unsqueezed) but drop in case of problems

# Proposal for 2016 p-Pb run – Part 2 at 6.5 *Z* TeV

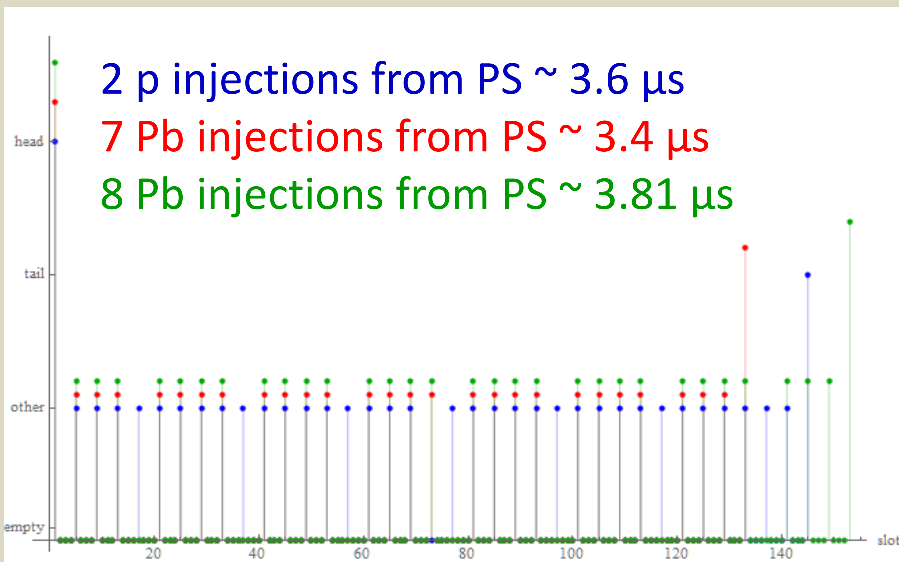
- Max luminosity for ATLAS/CMS but LHCb requests ~ 10-20 $nb^{-1}$ , ALICE also
  - Probably increase β*= 0.6 m for ATLAS/CMS $\delta = \pm 0.866 \times 10^{-4}$
    - Will not dramatically reduce integrated luminosity
  - Squeeze to
    β*~3 m for ALICE, β*~1.5-2 m for LHCb (new optics from Riccardo de Maria)
- Beam reversal p-Pb to Pb-p requested by LHCb and ALICE
  - quite expensive in time 1.5-2 days
- Van der Meer fills similar to physics fills
- No spectrometer polarity switches
- One day for short LHCf p-Pb run at low luminosity

- Return to optics details in another meeting

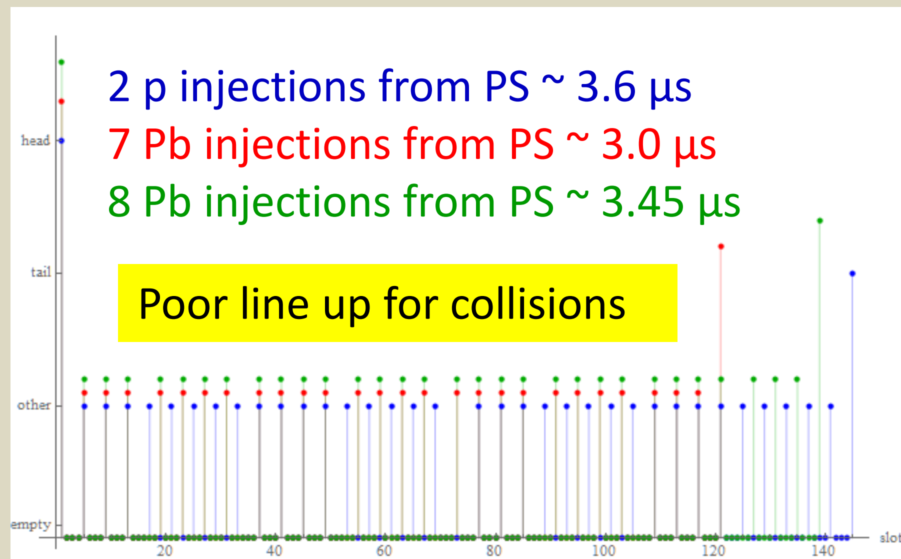
# Injection scheme

- Basic 100 ns spacing for both beams
  - 50 ns proton spacing may also be considered
- LHC injection kicker MKI limit – new development
  ~ 3.6 μs = 144 (25 “ns” slots)
  - 3.8 μs may be possible but uncertain and we want to specify length of SPS cycle to be prepared

SPS injection kickers (200,200) ns




SPS injection kickers (200,150) ns



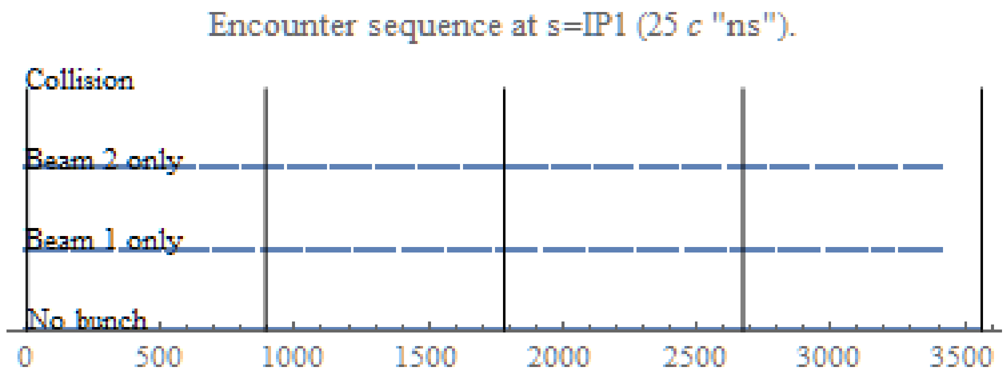

Choose 200 ns gap for both SPS injection kickers

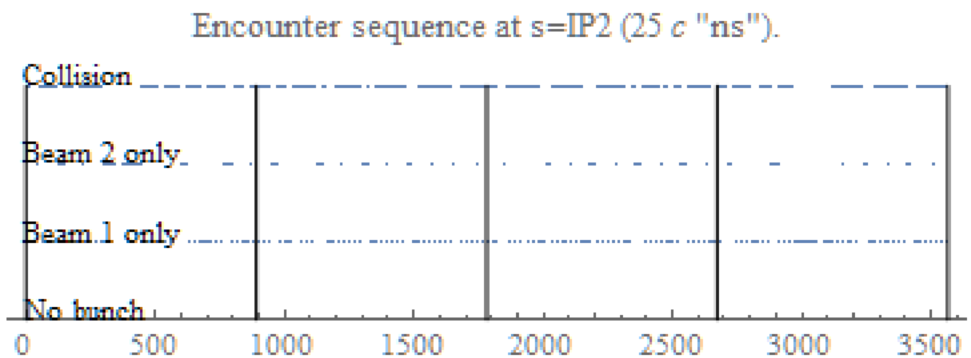
Choose 2 proton injections and 7 Pb injections from PS to SPS

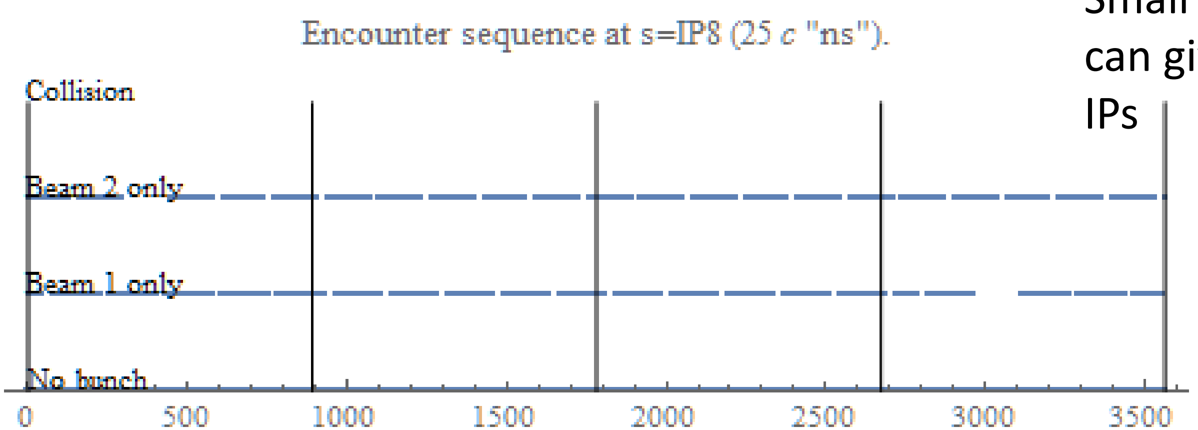
# Filling schemes for LHC at 4 *Z* TeV

- Now assuming 800 ns rise time for LHC injection kicker
  - Thanks to kicker team for demonstrating this recently!
- Assuming new abort gap keeper bucket  32851
- Maximise collisions in ALICE with options to provide a few to the other experiments
  - No need to fill by quadrant
  - Only need scheme for one beam direction: p-Pb
- Two strategies:
  - Maximise number of Pb bunches in LHC (~ integrated luminosity)
  - Pad out Pb trains to match p trains

# Collisions with schemes LHC5TeVPb3, LHC5TeVp7



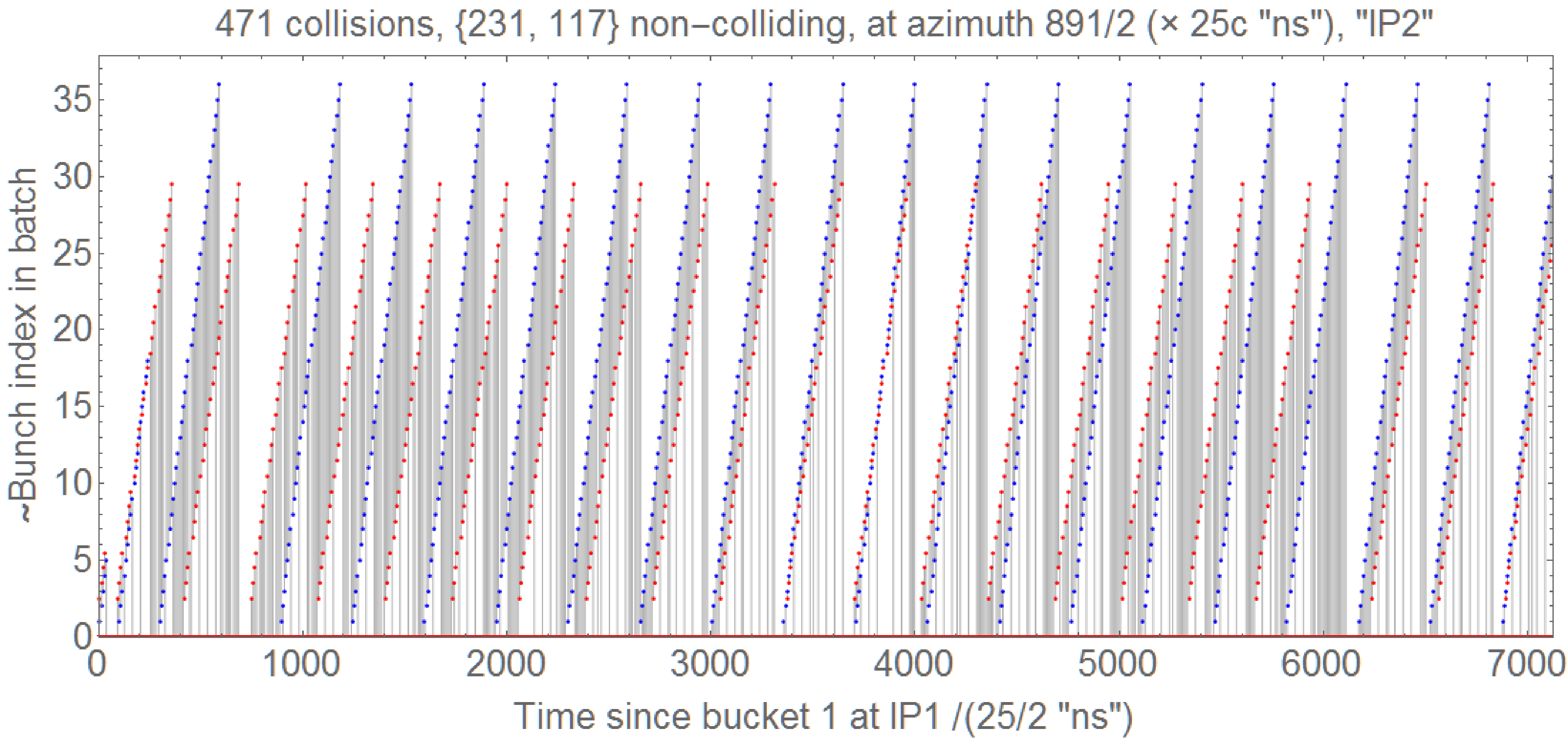

Collisions have to be optimised, and luminosity shared, using longer gaps and special selections of injection buckets in LHC.

Always some bunches that do not collide at all.

Beware of protection dumps when ANY ONE Pb bunch intensity drops below threshold. IP1->0,IP2->471,IP5->0,IP8->0,

Small variations of this scheme can give a few collisions in other IPs

# Collisions at IP2, LHC5TeVPb3ng[0], LHC5TeVp7



# Summary tables for padded Pb at 5 TeV

| | | kB1 | kB2 | IP1 | IP2 | IP5 | IP8 |
|---|---|---|---|---|---|---|---|
| LHC5TeVPb8 | LHC5TeVp10ng[0] | 702 | 548 | 0 | 480 | 0 | 0 |
| LHC5TeVPb9 | LHC5TeVp10ng[0] | 702 | 548 | 27 | 458 | 27 | 0 |
| LHC5TeVPb10 | LHC5TeVp10ng[0] | 702 | 548 | 0 | 458 | 0 | 22 |
| LHC5TeVPb11 | LHC5TeVp10ng[0] | 702 | 548 | 14 | 443 | 14 | 22 |

All options available with a single p filling scheme, small variations of the Pb scheme. Probably a better choice.

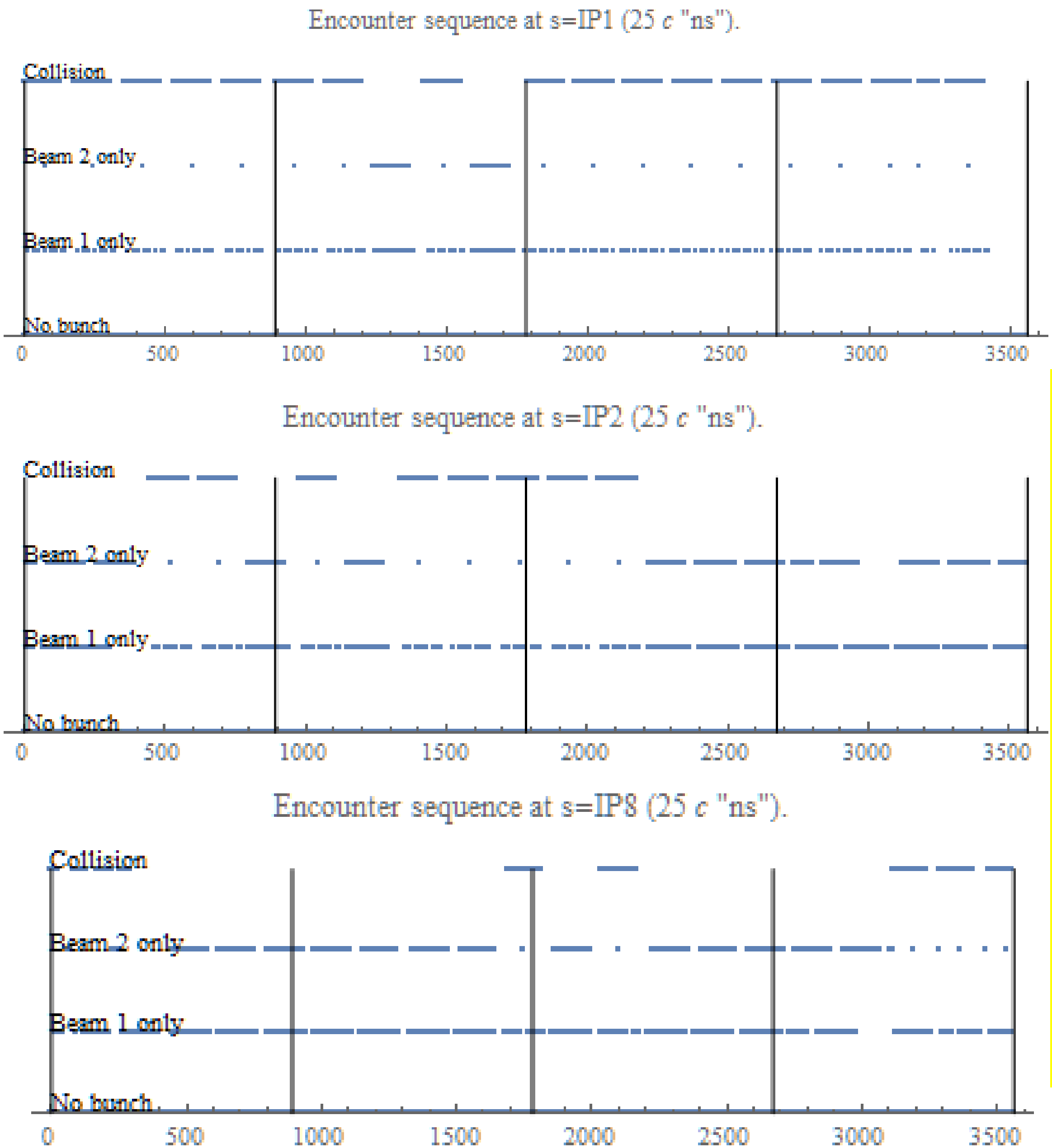
Padded better for all scenarios (except perhaps ALICE+LHCb) although luminosity lifetime might be better with maximal Pb.

Could take more from ALICE and give to the others …

# Filling schemes for LHC at 6.5 *Z* TeV

- Now assuming 800 ns rise time for LHC injection kicker
- Assuming new abort gap keeper bucket 32851
- Maximise collisions in ATLAS/CMS
- Try to get about 30% of number of collisions in the other experiments
  - Filling by quadrant more useful
  - Need versions for both p-Pb and Pb-p (not the same for LHCb)
- Two possibilities:
  - Maximise number of Pb bunches in LHC
  - Pad out Pb trains to match p trains
- So far, the second approach, has given better results

# Filling by almost 3 quadrants: **LHC8TeVp1, LHC8TeVPb1**




p-Pb

$$\text{IP1} \to 474, \text{IP2} \to 216, \text{"IP5"} \to 474, \text{"IP8"} \to 163$$

A reasonable scheme, which could be complemented by catch-up schemes giving more collisions to LHCb or ALICE.

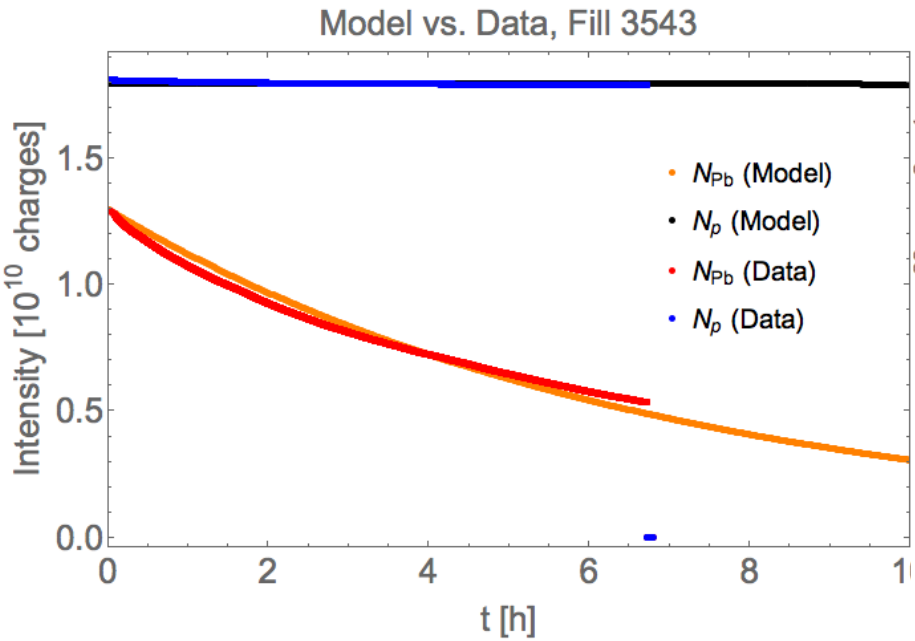
Simple switching for Pb-p gives:

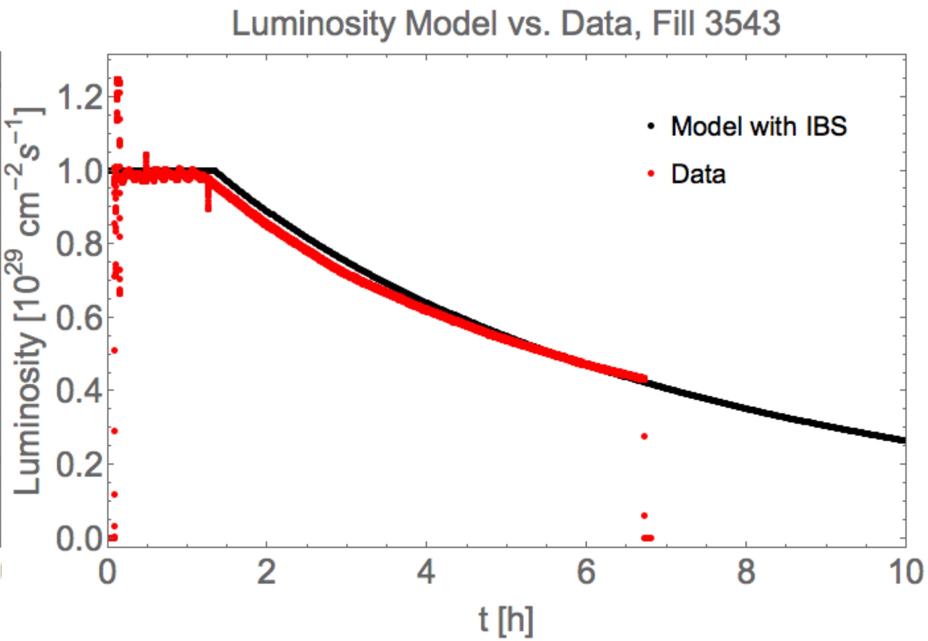
IP1->474,IP2->216,IP5->474,IP8->**116**

**Found variation with**
IP1->457,IP2->243,IP5->457,IP8->149
**But can probably do better.**

# Luminosity and beam lifetime

- Pb beam lifetime “should” be dominated by luminosity burn-off against protons but was higher in 2013 p-Pb run
  - Likely due to colliding unequal beam sizes, extra terms included in ODE model (M. Schaumann, R. Alemany)
  - Proton beam loss ~negligible

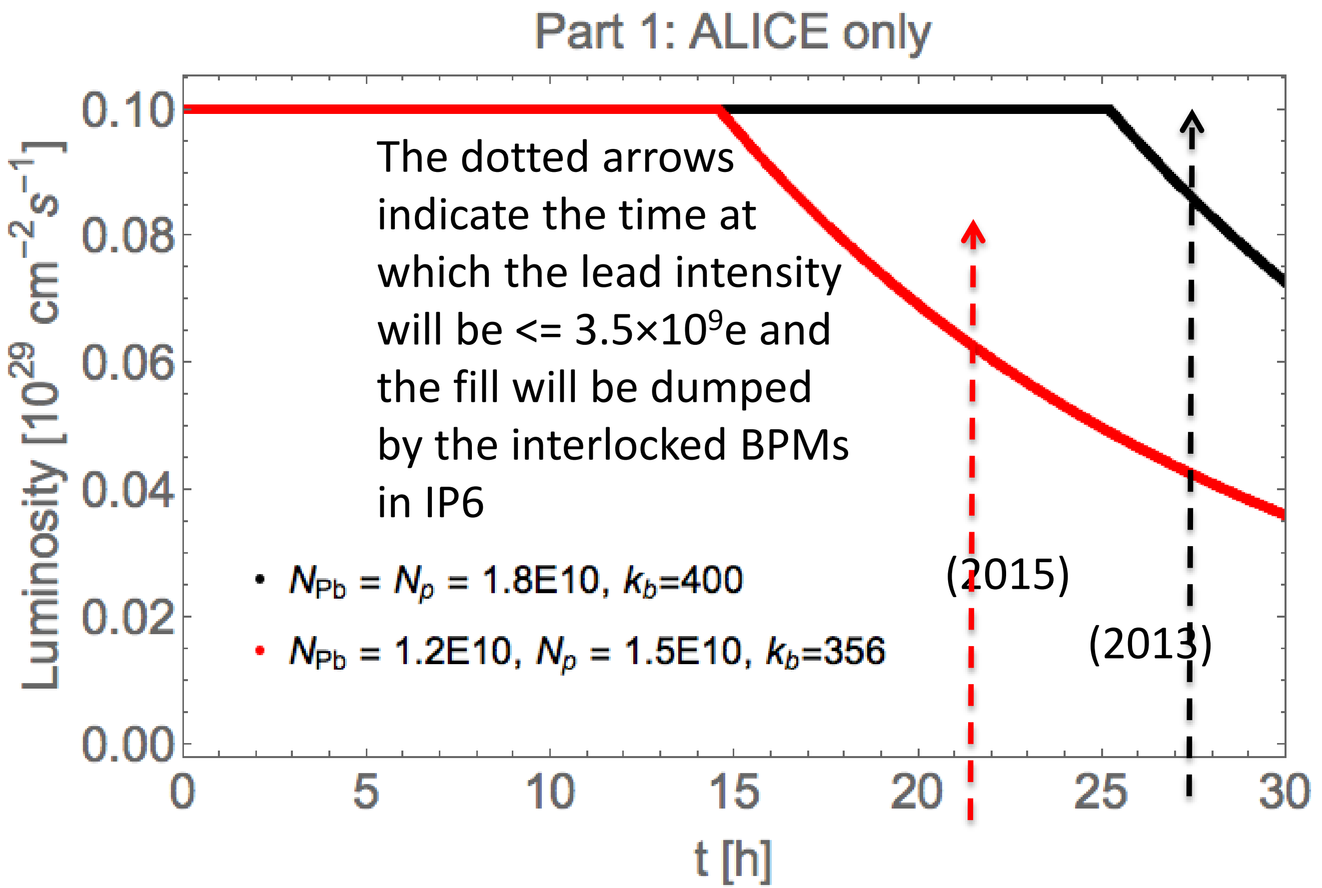



Simple model was basis for some preliminary predictions for 2016 … but needs update!

**PART 1 5 TeV:** ALICE levelled at 4Z TeV, β* = 3 m and at a constant luminosity of $1\times10^{28}$ $cm^{-2}s^{-1}$; ignoring possible small luminosity in other experiments.

Possible fill evolution using the model. Two different beam parameters are compared, the ones for one fill in 2013 and the ones corresponding to the 2015 performance. The plot shows a clear strong dependence on the beam parameters, as expected. However, even less favourable parameters as in 2013 give levelling times of 15 hours.




With cross-section of 2 b, one fill like this gives ~$2\times10^9$ events, of which $2\times10^8$ are taken by ALICE.

Need ~5 good fills like this.

**PART 2 8TeV:** IP1&5 head-on at 6.5Z TeV and beta* = 0.4 m; and then ALICE with the following three configurations:

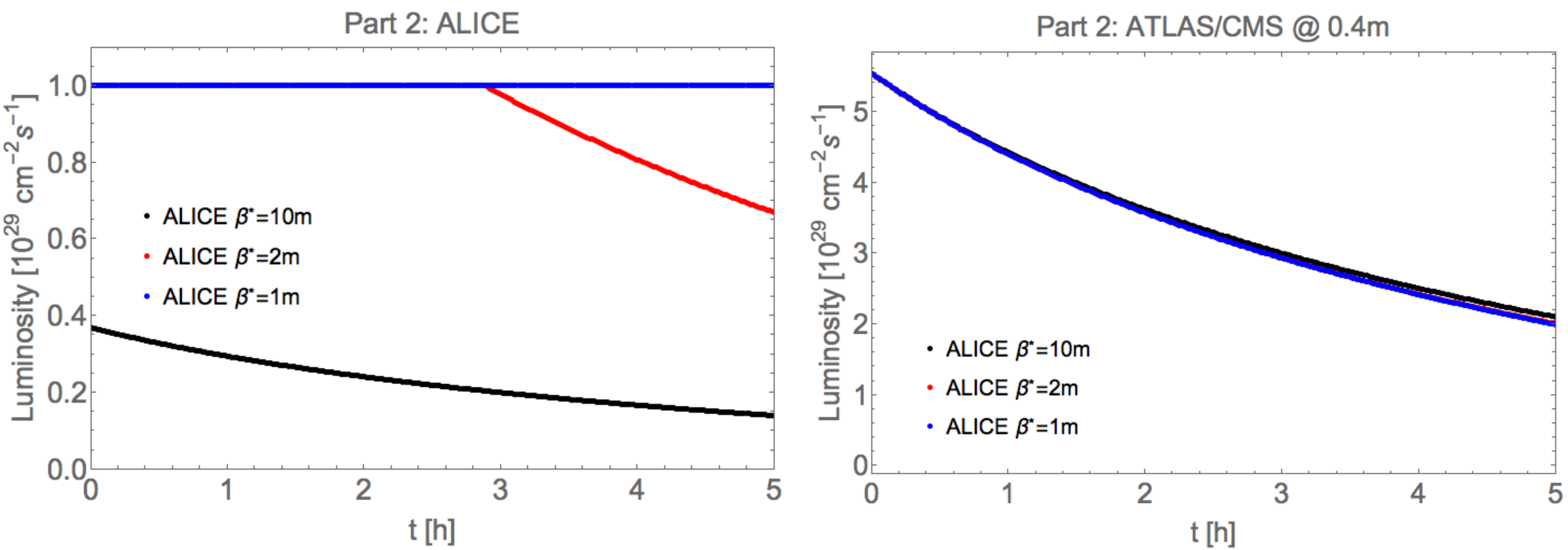
A. ALICE head-on with beta*= 10 m (peak luminosity is 3.7e28 cm-2s-1, no levelling needed);
B. ALICE levelled at constant luminosity of 1e29 cm-2s-1 with beta = 2 m (peak luminosity = 1.8e29 cm-2s-1); N.B. beta*=3 m not considered because it just gives a peak luminosity of 1e29 cm-2s-1.
C. ALICE levelled at constant luminosity of 1e29 cm-2s-1 with beta = 1 m (peak luminosity = 3.7e29 cm-2s-1);

| | Lint IP1/5 [$nb^{-1}$] | Lint IP2 [$nb^{-1}$] | tlevel [h] |
|---|---|---|---|
| Conf. A | 6.2 | 0.4 | 0 |
| Conf. B | 6.1 | 1.6 | 2.8 |
| Conf. C | 6.1 | 1.8 | 5 (6.4) |

Integrated luminosity values after 5h in stable beams and the duration of levelling in ALICE. Peak luminosity in ATLAS/CMS is 5.5e29 cm-2s-1.

Needs to be updated for new bunch numbers, they assumed 400 bunches colliding in ATLAS, CMS, ALICE and no LHCb, so factor 2 optimistic for ALICE.

# Luminosity Evolution for Part 2, 8 TeV

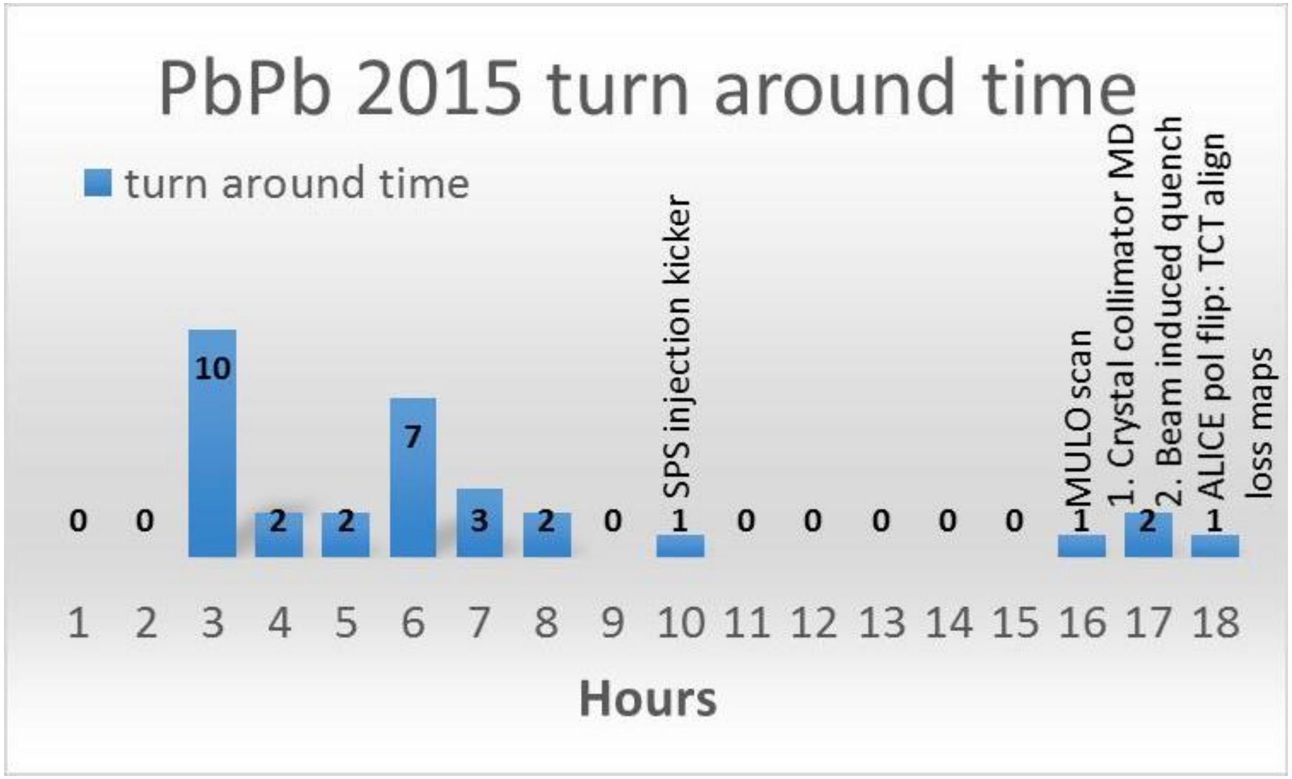



Needs to be updated for new bunch numbers, they assumed 400 bunches colliding in ATLAS, CMS, ALICE and no LHCb.

ALICE, LHCb should get 10-20

# Turn-around and integrated luminosity

From 2015 Pb-Pb run, the average turn around time we consider for 2016 is 5 hours, giving about 2 fills per day at 8 TeV. Expect 50-100 $nb^{-1}$ in 8 days for ATLAS/CMS, 10-20 $nb^{-1}$ for LHCb, 5-15 $nb^{-1}$ for ALICE.
Some scope for tuning the final outcome with catch-up fills, special filling schemes as we did in 2013.
An increase of β* in ATLAS/CMS could also help.



# Agreed outline - Coordinators' slides at LHCC

| | M | T | W | T | F | S | S |
|---|---|---|---|---|---|---|---|
| week1 | set up 5 | set up 5 | set up 5 | 5 TeV | 5 TeV | 5 TeV | 5 TeV |
| week2 | 5 TeV | 5 TeV* | set up 8 | set up 8 | set up 8 | set up 8 | 8 TeV |
| week3 | 8 TeV | 8 TeV | 8 TeV | 8 TeV | 8 TeV / LHCf run* | LHCf run* / reversal | reversal |
| week4 | reversal / 8 TeV | 8 TeV | 8 TeV | 8 TeV | 8 TeV | 8 TeV | MD |

| operation | days |
|---|---|
| 5 TeV setup | 3 |
| 8 TeV setup (both directions) | 4 |
| direction reversal | 2 |
| MD | 1 |
| LHCf run | 1 (hopefully less than 12hrs) |
| 5 TeV data taking | 6 |
| 8 TeV data taking | 11 days (5.5 for each direction) |
| **Total** | 28 days (= 4 weeks) |

*-source re-fill

Shorthand:
5 TeV = $\sqrt{s_{NN}}$ = 5.02 TeV
8 TeV = $\sqrt{s_{NN}}$ = 8.16 TeV

3

# Coordinators' slides at LHCC

## Proposed scheme – part-1

- Start with 5 TeV run
  - Less risk (low luminosity running, non-aggressive optics)
  - Hope to complete 5 TeV physics programme in short time
- Stop 5 TeV run when any of these criteria are met:
  - After 1B events delivered to ALICE
  - If by end of day-9 ≥700M events delivered
  - If the above criteria have not been met, continue the run till 700M events are delivered, unless this appears to significantly delay the start of the 8 TeV run
- During 5 TeV run
  - Protons in beam-1 / Moderate squeeze in ALICE (~3m)
  - Very long fills (~20hrs) luminosity leveled to $10^{28}$ $cm^{-2}$ $s^{-1}$ in ALICE
  - Can try to have very low luminosity collisions in other IPs (luminosity<$10^{27}$ $cm^{-2}$ $s^{-1}$) but stop this if any problems encountered

**Disclaimer**: We should leave some flexibility to change some of the cut-off numbers / dates, depending on the actual situation. With the goal of giving the best physics output of all parts of the programme.

LPC Heavy Ion proposal - LHCC May 2016 4

# Coordinators’ slides at LHCC

## Proposed scheme – part-2

- Default strategy for 8 TeV run
  - Moderate squeeze in ALICE (~3m) / LHCb (~2m)
  - ATLAS/CMS pp optics (40cm) or slight de-squeeze
    - To be determined by machine experts after more studies
  - Beam reversal
- If significantly behind expectation drop beam reversal (this would save ~2 days)
  - e.g. if <25/nb delivered to ATLAS/CMC by end of day-19
- Fills optimized to give luminosity to ATLAS/CMS
  - Short fills (~5hrs)
- Expectation (assuming no significant down time):
  - ~70/nb for ATLAS/CMS (~5.5/nb per ~5hr fill with 5hr turn-around time)
  - ~10/nb each for ALICE/LHCb* (less than requested)

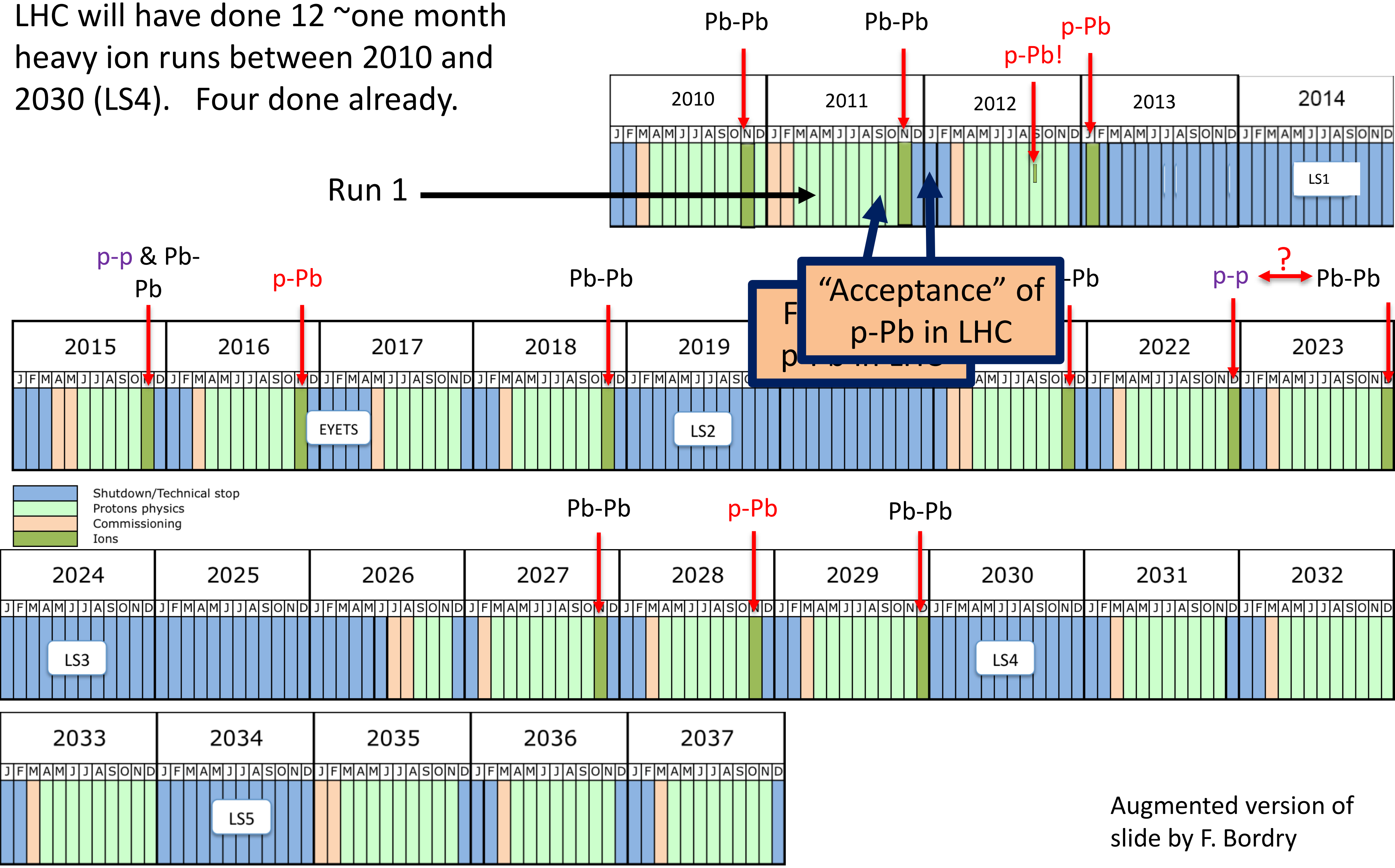
  (* - For LHCb this depends on exact filling schemes, which in turn depend on various kicker magnet rise-times which have not been measured yet).

**Disclaimer**: We should leave some flexibility to change some of the cut-off numbers / dates, depending on the actual situation. With the goal of giving the best physics output of all parts of the programme.

LPC Heavy Ion proposal - LHCC May 2016 5

# LHC heavy-ion runs, past & planned future
# + species choices according to ALICE 2012 LoI (could evolve if required)

LHC will have done 12 ~one month heavy ion runs between 2010 and 2030 (LS4). Four done already.




Augmented version of slide by F. Bordry

LHC Injectors Upgrade

# Target ion beam parameters and 25 ns bunch spacing option for Run3+Run4

G. Rumolo, H. Bartosik and M. Meddahi

With input from G. Arduini, H. Damerau, B. Goddard, A. Huschauer, J. Jowett, V. Kain, D. Manglunki, R. Scrivens, E. Shaposhnikova

CERN

# Goals and means of the LHC Injectors Upgrade (LIU) project (heavy ion part)

**Increase intensity/brightness in the injectors to match HL-LHC requirements for both protons and ions (luminosity goal)**

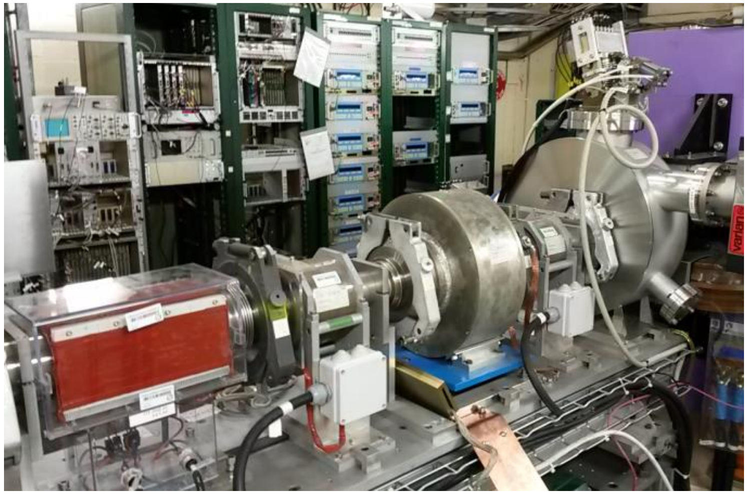
⇒ Boost the performance of the injectors of the ion chain (Linac3, LEIR, PS, SPS) and execute upgrades, where necessary, to produce the highly challenging ion beam parameters at the LHC injection

**Increase injectors' reliability and lifetime to cover HL-LHC run (until ~2035!) closely related to CONSolidation**

⇒ Upgrade/replace ageing equipment (power supplies, magnets, RF…)
⇒ Improve radioprotection measures (shielding, ventilation…)

# LIU upgrades for ions

- **YETS 2015-16 → Baseline implementations towards more intensity:**
  - Linac3/transfer line upgrades to allow 100 ms spaced injections into LEIR in 2016 (available for testing but not for production until LS2)
  - Modification to source + low energy transport region to remove aperture limitation and increase focusing



- **Until LS2 + LS2:**
  - Continue <u>beam studies</u> to further improve transmission through injector chain
    - Higher intensity in LEIR
    - Batch compression in PS
    - SPS losses: optics, working point, tests for slip stacking/RF noise at flat bottom
    - Loss reduction in transfers
  - LEIR dump (in YETS 2017-18)
  - LLRF deployment for slip stacking in SPS (in LS2)

→ **Machine studies in 2016-18 crucial for progress!**

# Ion parameter table
# (achieved, LIU achievable and HL-LHC requested)

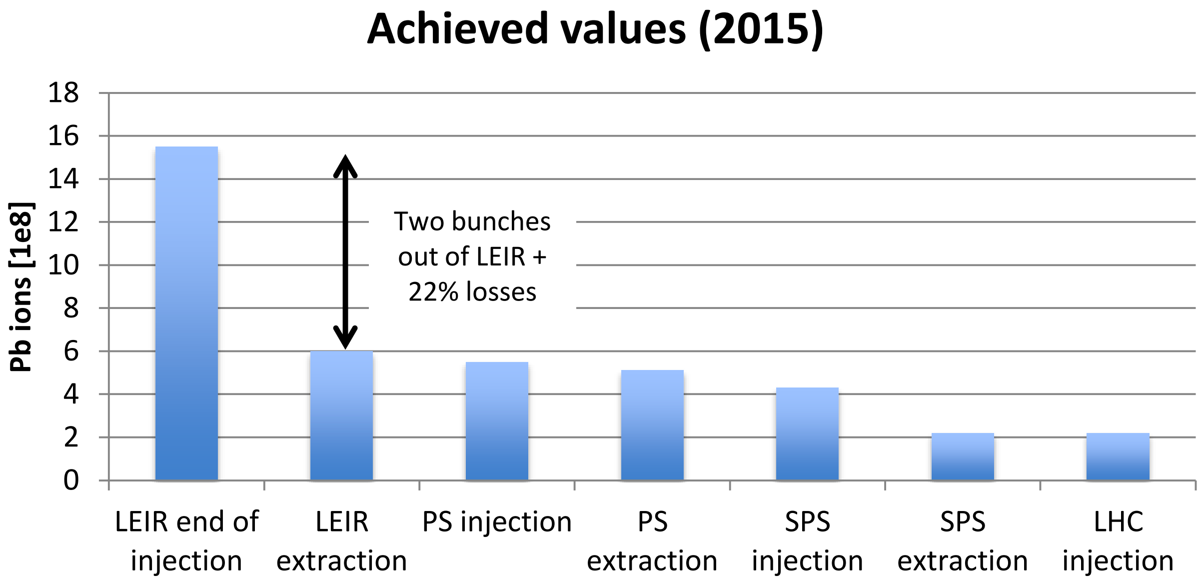
| | $N_{ions}$/bunch ($10^8$) | $\varepsilon_{x,y}$ (μm) | Bunches /injection | Bunch spacing (ns) | $N_{ions}$/bunch ($10^8$) | $\varepsilon_{x,y}$ (μm) | Bunches | Bunch spacing (ns) |
|---|---|---|---|---|---|---|---|---|
| **LEIR** | **Before RF capture ($54^+$, $E_{kin}$=0.0042 GeV/u)** | | | | **Extraction ($54^+$, $E_{kin}$=0.0722 GeV/u)** | | | |
| Achieved | 15.5 | 0.1, 0.4 | coasting beam | | 6.0 | | 2 | 354 |
| LIU-ions | 18.6 | | | | 7.4 | | 2 | 354 |
| HL-LHC | 29.5 | | | | 11.8 | | 2 | 354 |
| | | | | | | | | |
| **PS** | **Injection ($54^+$, $E_{kin}$=0.0722 GeV/u)** | | | | **Extraction ($54^+$, $E_{kin}$=5.9 GeV/u)** | | | |
| Achieved | 5.5 | | 2 | 354 | 5.1 | 0.9, 0.8 | 2 | 100 |
| LIU-ions | 6.8 | | 2 | 354 | 3.1 | 1.0 | 4 | 3x100 |
| HL-LHC | 10.9 | | 2 | 354 | 5.0 | 1.0 | 4 | 3x100 |
| | | | | | | | | |
| **SPS** | **Injection ($82^+$, $E_{kin}$=5.9 GeV/u)** | | | | **Extraction ($82^+$, $E_{kin}$=176.4 GeV/u)** | | | |
| Achieved | 4.3 | 1.0, 0.9 | 2 | 100 | 2.2 | | 24 | 11x(100+150)+100 |
| LIU-ions | 2.6 | 1.0 | 4 | 3x100 | 1.7 | 1.3 | 48 | 5x(7x50+100)+7x50 |
| HL-LHC | 4.2 | 1.0 | 4 | 3x100 | 2.1 | 1.3 | 48 | 47x50 |
| | | | | | | | | |
| **LHC** | **Injection ($82^+$, $E_{kin}$=176.4 GeV/u)** | | | | | | Total number of bunches | |
| Achieved | 2.2 | 1.5 | 24 | | | | 518 | |
| LIU-ions | 1.7 | 1.3 | 48 | | | | 1152 | |
| HL-LHC | 2.1 | 1.3 | 48 | | | | 1248 | |

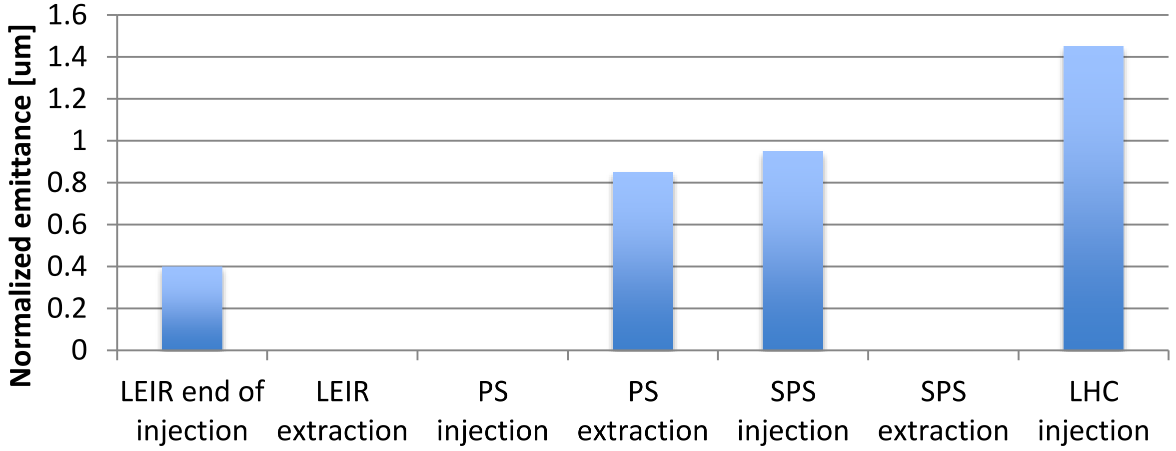
**HL-LHC**: J. Jowett et al., *HL-LHC heavy-ion beam parameters at LHC injection*, EDMS 1525065

**Achieved**: H. Bartosik et al., *Preliminary analysis of 2015 ion beams*, LIU Beam Parameter WG meeting #2

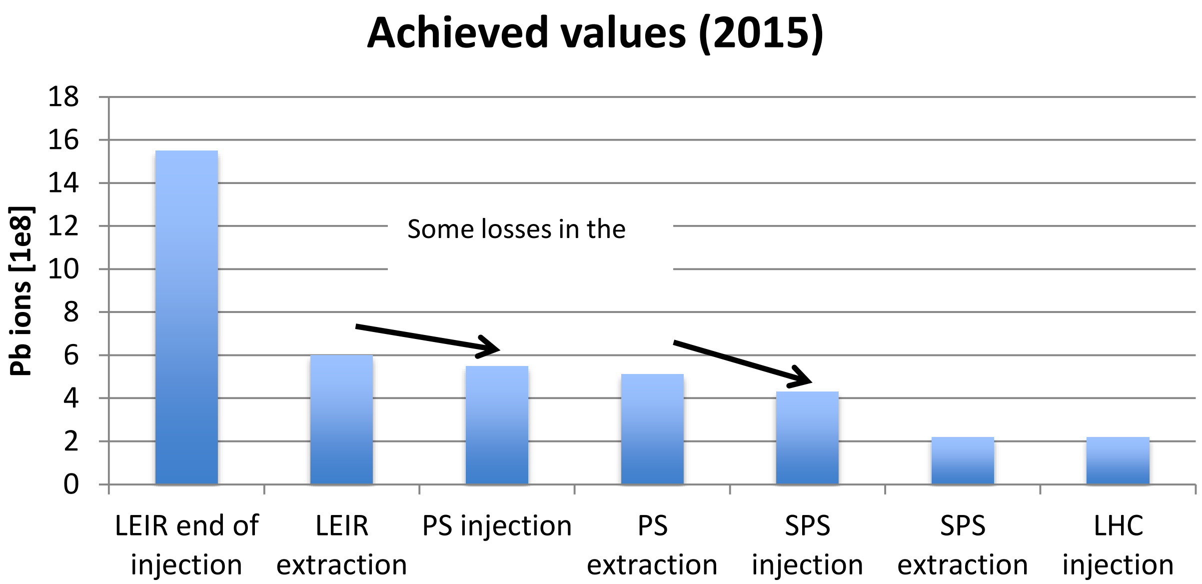
**LIU-ions**: H. Bartosik et al., *LIU beam parameters specification*, LIU Beam Parameter WG meeting #3

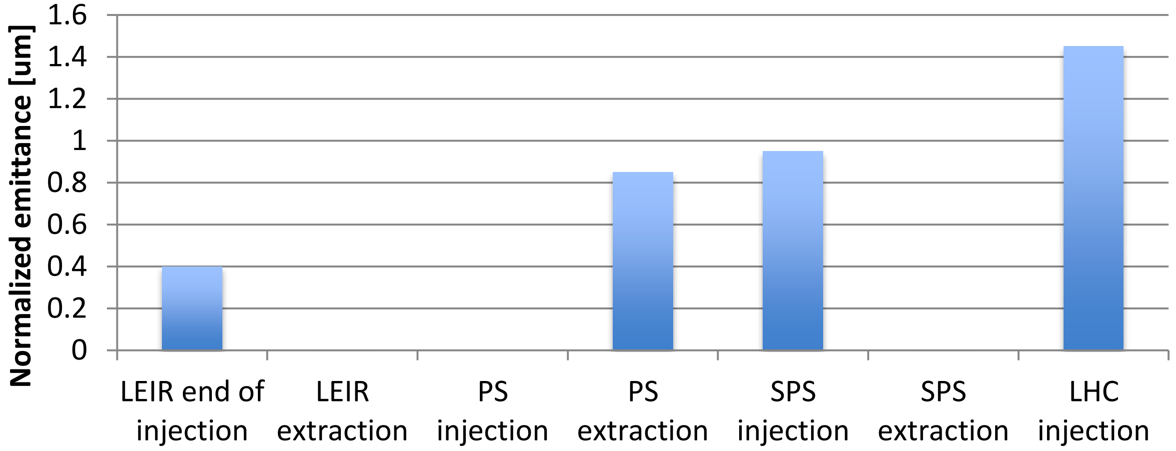
# Summary of achieved parameters (2015)



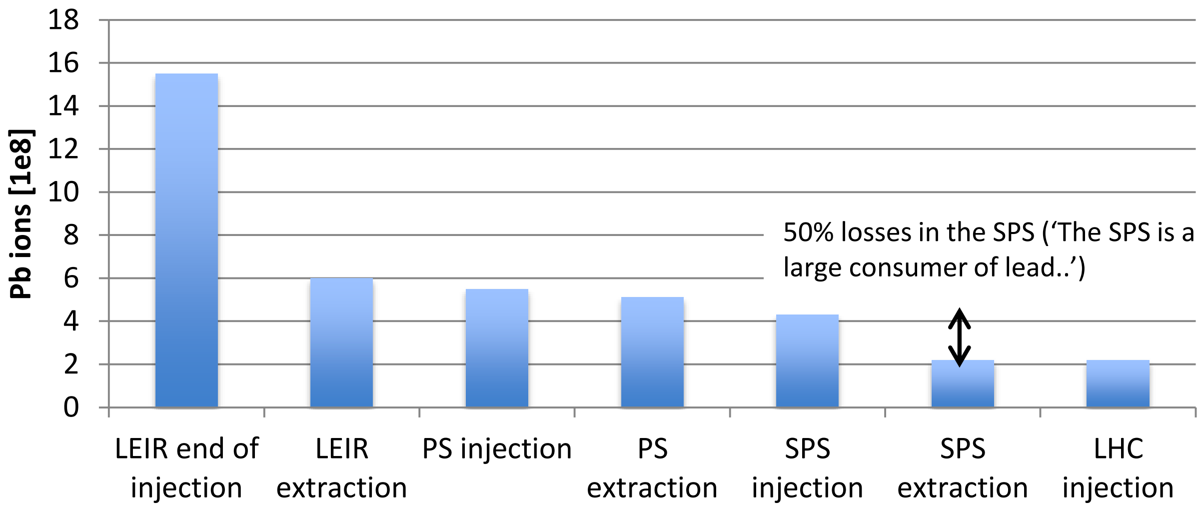
# Summary of achieved parameters (2015)

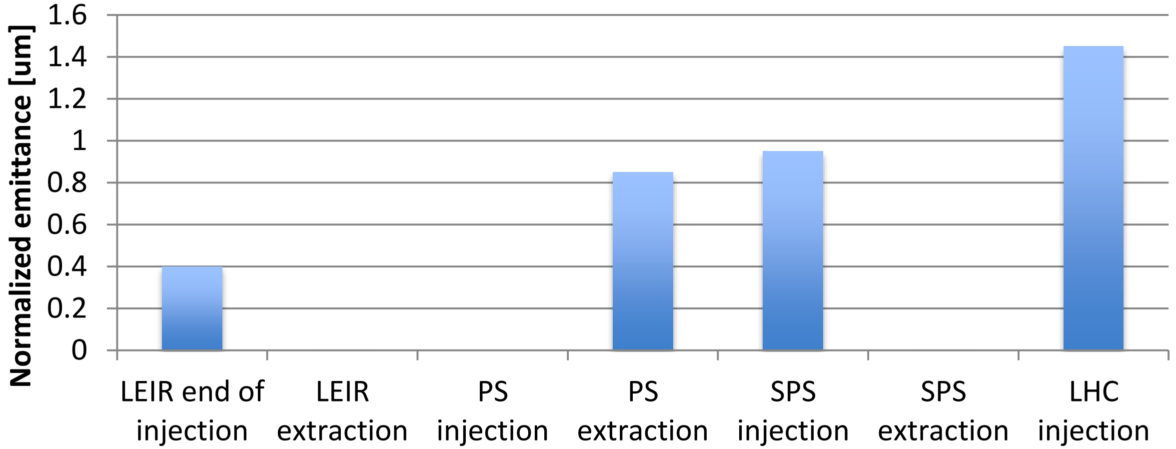


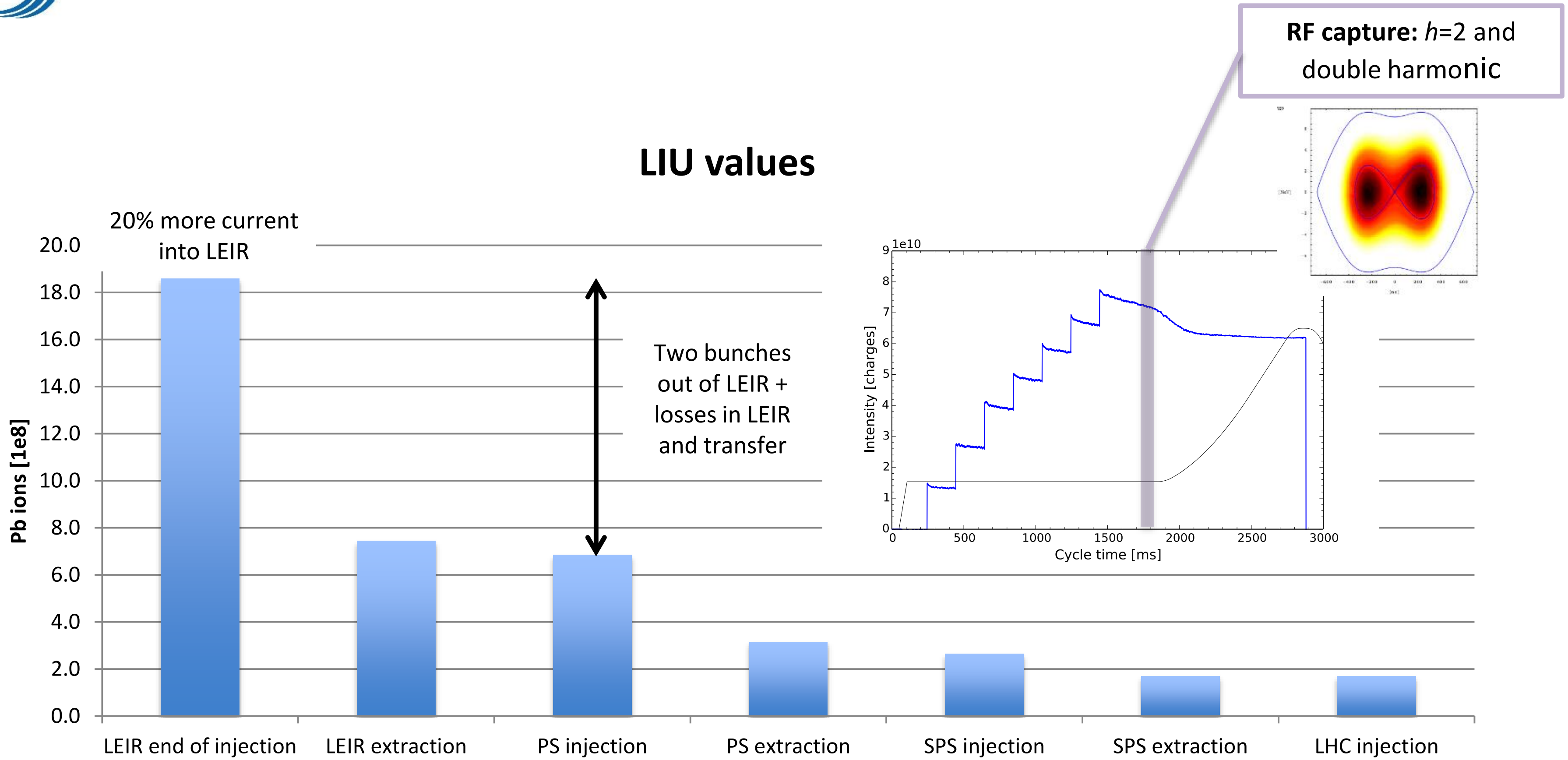
# Summary of achieved parameters (2015)

**Achieved values (2015)**



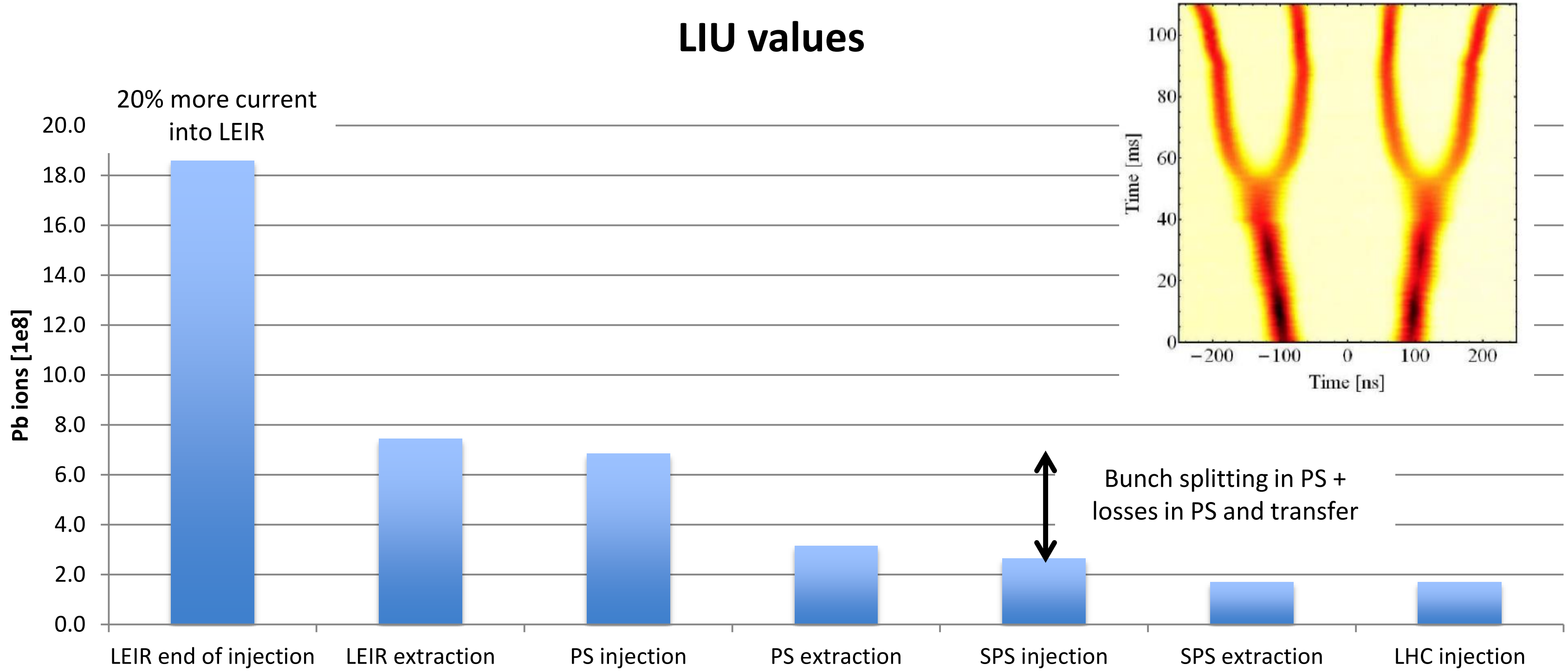
# LIU-ions beam parameter table




Assumptions for future operation (LIU)

- Improvements in source + Linac3 and 100 ms injection rate into LEIR will provide **20% more accumulated intensity into LEIR**
- Losses over LEIR cycle remain about **20%**
- Losses in LEIR-PS transfer remain ~**8%**

# LIU-ions beam parameter table

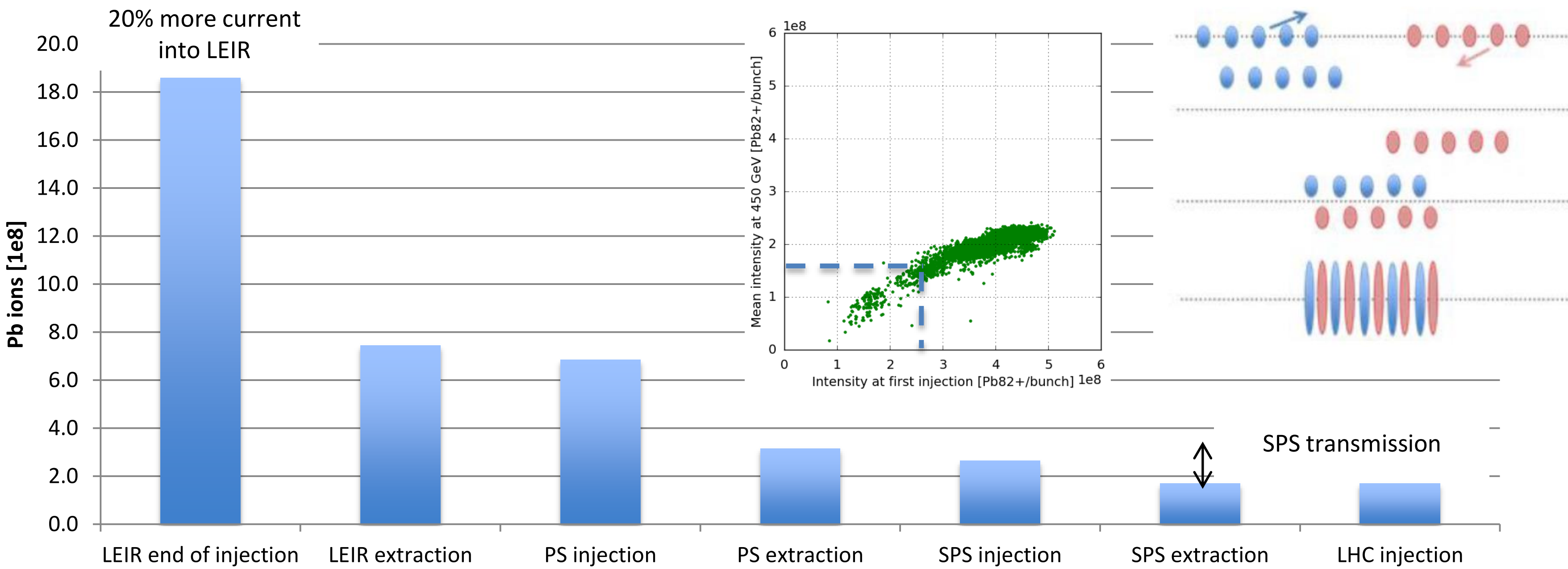



Assumptions for future operation (LIU)

- Bunch splitting in the PS provides 100 ns spacing and leads to lower intensity bunches at the SPS injection, which profit from better transmission
- Losses over PS cycle remain about **8%**
- Losses in PS-SPS transfer remain ~**16%**

# LIU-ions beam parameter table

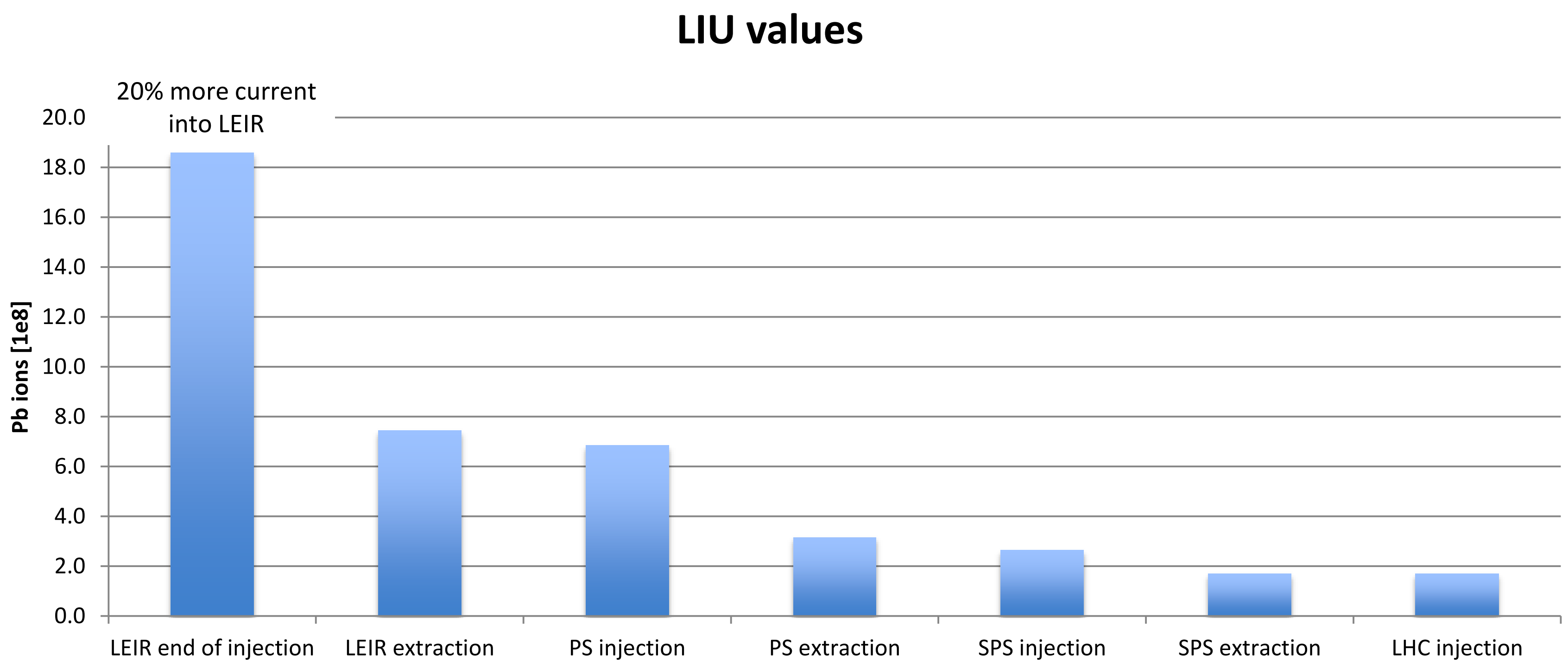
**LIU values**




Assumptions for future operation (LIU)

- SPS transmission as today (limited by IBS and space charge at injection)
- Slip stacking to provide the final 50 ns spacing [filling pattern 6x (50x8 + 100)]

# LIU-ions beam parameter table




| | | | |
|---|---|---|---|
| **SPS extraction/LHC injection** | **N = 1.7 x $10^8$ ions/b** | **$\varepsilon$ = 1.3 $\mu$m** | **1152 bunches** |

With 12 injections into the SPS
and slip stacking in the SPS

# LIU baseline reach and options

- **Present 'baseline' with Linac3 improvements, 10 Hz injection rate into LEIR, PS splitting, 150 ns MKP, SPS slip-stacking, mitigation of losses in LEIR and SPS**
  - Reach is 1152b filled in 42 minutes (12 injections from PS to SPS)
  - Integrated luminosity could become >80% of the target value if a higher performance efficiency is assumed for LHC (i.e. 62% instead of 50%)

**→ 100 ns upgrade of the SPS injection kicker system → Can provide 1248 instead of 1152 bunches in LHC (8% gain)**

- Significant new HW, cost is very high compared to potential gain (it was attractive before deployment of 150 ns MKP spacing in SPS)

**→ Filling schemes with 50 ns spacing in PS (25 ns in LHC)**

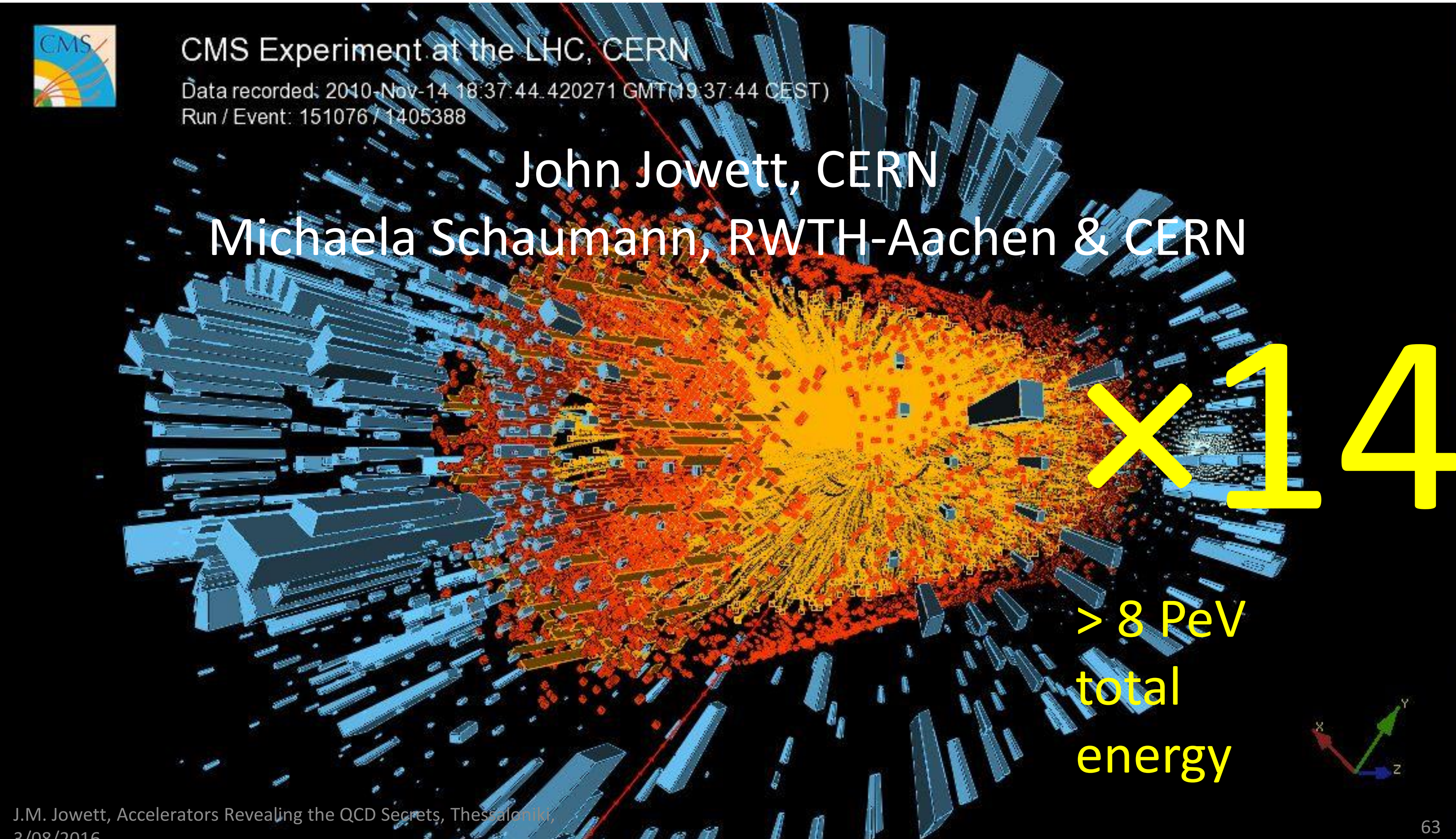
- Trains of two bunches with 50 ns spacing out of PS (through batch compression at flat top), resulting in 3x25+125 in SPS after slip stacking → ~1100b in LHC with ~100 minutes filling and high current per bunch (inefficient in the SPS and any improvement upstream of SPS would be useless)
- **Trains of four bunches with 50 ns spacing out of PS (through batch compression at flat top), resulting in 7x25+125 in SPS after slip stacking**

# Conclusions

- **LIU baseline established for Pb ions**
  - Based on 50 ns bunch spacing in LHC
  - Bunch currents ~20% lower than HL-LHC requirement, 8% fewer bunches in LHC
  - Achievable integrated luminosity 70-90% of the target value, depending on assumption on LHC performance efficiency

- **Alternative scenario with 25 ns under study**
  - Based on batch compression to 50 ns at top energy in PS
    - Requires proof of principle and new hardware in injectors
    - Cost and resources being evaluated
    - No objections from experiments
  - Could significantly boost the performance allowing for ~40% more bunches in LHC (possibly exceeding the luminosity goal → margin)
  - Could be an efficient mitigation measure in case of other unexpected underperformance

# FCC-hh as a Heavy-Ion Collider




John Jowett, CERN
Michaela Schaumann, RWTH-Aachen & CERN

×14

> 8 PeV total energy

# General FCC-hh Parameters

In relation to FCC-hh, assumed working as p-p collider, consider Pb-Pb and p-Pb collisions at maximum energy.

| | Units | Injection | Collision |
|---|---|---|---|
| Circumference | [km] | 100 | 100 |
| Main dipole strength | [T] | 1.0 | 16 |
| Bending radius | [m] | 10424 | 10424 |
| Proton equivalent energy | [TeV] | 3.3 | 50 |
| Pb energy | [TeV] | 270 | 4100 |
| Pb energy/nucleon | [TeV] | 1.3 | 19.7 |
| Pb-Pb CM energy $\sqrt{s}$ | [TeV] | | 8200 |
| Pb-Pb CM energy/nucleon pair $\sqrt{s_{NN}}$ | [TeV] | | 39.4 |
| p-Pb C.M. energy $\sqrt{s}$ | [TeV] | | 905 |
| p-Pb C.M. energy/nucleon pair $\sqrt{s_{NN}}$ | [TeV] | | 62.8 |

# Problems that are “in the shadow” of p-p

- Optics design
- Collective effects
  - lower charge per bunch, fewer bunches
  - Including impedance-driven, beam-beam, electron cloud
- Stored beam energy
  - Not as large as in p-p (but still large …)
  - Nevertheless collimation efficiency is likely to be much lower!

# What is new with heavy-ion beams w.r.t. protons?

- Synchrotron radiation damping is *twice as fast*

$$\alpha_\varepsilon \propto \frac{Z^5}{m^4} \text{ in the same magnetic field}$$

  - Free natural beam cooling, not limited by beam-beam tune-shift.
- Pb nuclei are accompanied by intense fluxes of high energy quasi-real photons:
  - (Physics interest …)
  - Leads to powerful secondary beams emerging from collision point
  - Extreme luminosity burn-off from electromagnetic cross-sections
  - More complicated interactions with collimators
- Stronger intra-beam scattering ultimately limits emittance

# Previous references on AA & pA in FCC-hh

- M. Schaumann, Ions at the Future Hadron Collider, 16-17 Dec. 2013, CERN https://indico.cern.ch/event/288576/
- M. Schaumann, FCC Study Kick-off Meeting, 12-15 Feb. 2014, Geneva https://indico.cern.ch/event/282344/
- M. Schaumann, Ions at the Future Hadron Collider https://indico.cern.ch/event/331669/ (update to 100 km)
- M. Schaumann, Chapter 9 of thesis, RWTH, Aachen
- M. Schaumann, "Potential performance for Pb-Pb, p-Pb and p-p collisions in a future circular collider", Phys. Rev. Accel. Beams 18, 091002 (2015)
- Major performance update for FCC week, 11-15 April 2016, Rome https://arxiv.org/abs/1605.01389 and forthcoming CERN report

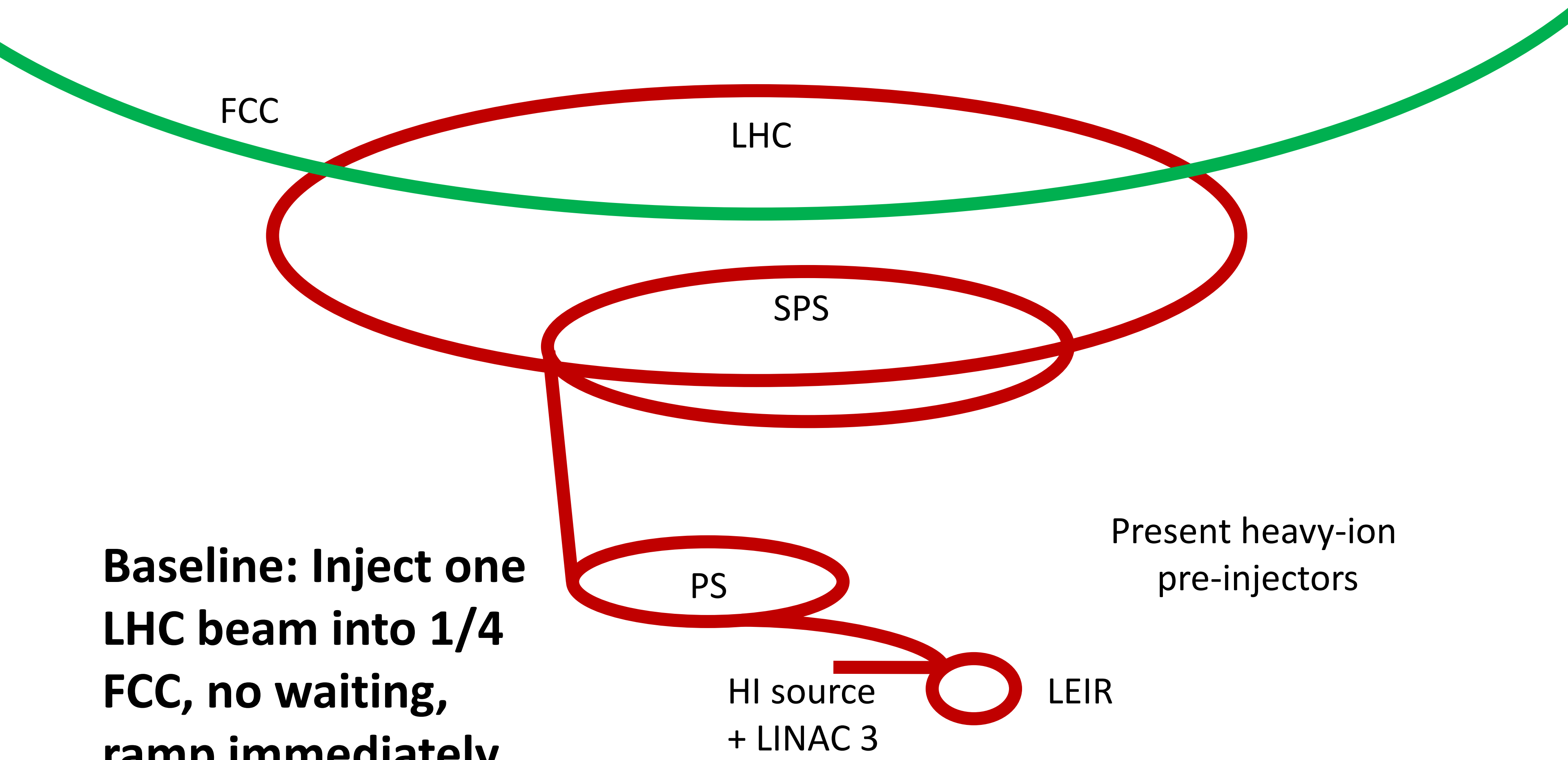
*Studies focussed on emittance and luminosity evolution with strong radiation damping, IBS and luminosity burn-off, etc.*

# CERN Heavy-Ion Injector Complex

- Present study *very conservatively* assumes the Pb injector performance achieved for LHC p-Pb run in 2013
- Potential upgrades needing study
  - Better ion source?
  - Upgrade/replacement of LEIR, faster cooling, higher injection into PS ?
  - Degradation of bunches along trains at SPS injection (alternatives to fixed harmonic acceleration with present 200 MHz RF system?)
- LHC as HEB injector into FCC-hh

# Heavy Ion Pre-Accelerator Chain

*Straw-man assumption to estimate (conservative) beam parameters and luminosity:*
**LHC, as it is today, but cycling to 3.3 Z TeV, is assumed to be the injector for FCC-hh.**




**Baseline: Inject one LHC beam into 1/4 FCC, no waiting, ramp immediately.**

# Pb Beam Parameters in LHC and FCC-hh

Best injector performance achieved in 2013 p-Pb run.

**Average beam parameters from 2013 are assumed as**
**VERY conservative baseline for FCC-hh!**
Improvements are already under study for HL-LHC!

| | LHC Design | LHC 2011 | LHC 2013 | FCC-hh |
|---|---|---|---|---|
| Beam Energy [Z TeV] | 7 | 3.5 | 4 | 50 |
| β-function at the IP [m] | 0.5 | 1.0 | 0.8 | 1.1 |
| No. Ions per bunch $[10^8]$ | 0.7 | $1.20 \pm 0.25$ | $1.40 \pm 0.27$ | 1.4 |
| Transv. normalised emittance $[\mu m.\mathrm{rad}]$ | 1.5 | $1.7 \pm 0.2$ | $\sim 1.5$ | 1.5 |
| RMS Beam Size at IP $[\mu m]$ | 15.9 | 33.9 | 26.6 | 8.8 |
| RMS bunch length $[\mathrm{cm}]$ | 7.94 | $9.8 \pm 0.7$ | $9.8 \pm 0.1$ | 8 |
| Number of bunches | 592 | 358 | 358 | 432 |
| Peak Luminosity $[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$ | 1 | 0.5 (Pb-Pb) | 110 (p-Pb) | ? |

Geometric emittance at injection > protons – possible issue for aperture choice?

# Beam and Luminosity Evolution

During the beams are in collision the instantaneous value of the luminosity will change:

$$\mathcal{L}(t) = A\frac{N_b^2(t)}{\sqrt{\epsilon_x(t)\epsilon_y(t)}}$$

The beam evolution with time is obtained by solving a system of four differential equations (dominant effects only  shown here, more included in simulations):

$$\frac{dN_b}{dt} = -\sigma_{c,\text{tot}} A\frac{N_b^2}{\sqrt{\epsilon_x\epsilon_y}}$$ Intensity

$$\frac{d\epsilon_x}{dt} = \epsilon_x(\alpha_{\text{IBS},x} - \alpha_{\text{rad},x})$$ Hor. Emittance

$$\frac{d\epsilon_y}{dt} = \epsilon_y(\alpha_{\text{IBS},y} - \alpha_{\text{rad},y})$$ Ver. Emittance

$$\frac{d\sigma_s}{dt} = \frac{1}{2}\sigma_s(\alpha_{\text{IBS},s} - \alpha_{\text{rad},s})$$ Bunch Length

with

$$A = f_{\text{rev}}k_b/(4\pi\beta^*)$$

- $f_{\text{rev}}$ : revolution freq.
- $k_b$ : no. bunches/beam
- $\beta^*$ : β-function at IP
- $N_b$ : no. particles/bunch
- $\epsilon$ : geom. emittances
- $\sigma_s$ : bunch length
- $\sigma_{c,\text{tot}}$ : total cross-section
- $\alpha_{\text{IBS}}$ : IBS growth rate
- $\alpha_{\text{rad}}$ : rad. damping rate

**Analytical solution difficult, due to dependence of $\alpha_{IBS}$ on $N_b, \epsilon_x, \epsilon_y, \sigma_s$.**

# Effects on the Emittance – a new regime

## Intra-Beam Scattering (IBS)

*Multiple small-angle Coulomb scattering within a charged particle beam.*

Emittance Growth

Growth rate dynamically changing with **beam properties**:

$$\alpha_{IBS} \propto \frac{r_0^2}{\gamma^4} \boxed{\frac{N_b}{\epsilon_x \epsilon_y \sigma_s \sigma_p}}$$

IBS is weak for initial beam parameters, but increases with decreasing emittance .

| Growth Times | Unit | FCC @ 50Z TeV |
|---|---|---|
| $1/\alpha_{\mathrm{IBS,s}}$ | [h] | 29.1 |
| $1/\alpha_{\mathrm{IBS,x}}$ | [h] | 30.0 |

## (Synchrotron) Radiation Damping

*A charged particle radiates energy, when it is accelerated, i.e. bend on its circular orbit.*

Emittance Shrinkage

Damping rate is **constant** for a given energy:

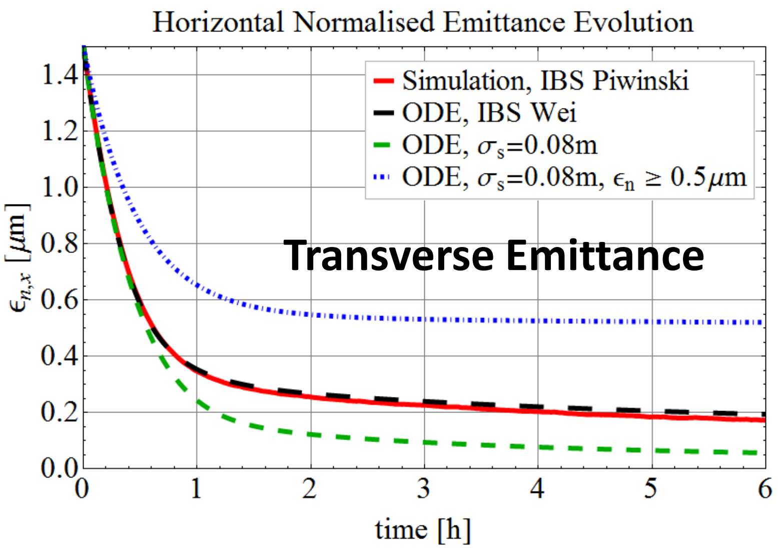
$$\alpha_{rad} \propto \frac{E^3 C_\alpha}{\rho_0 C_{ring}}$$

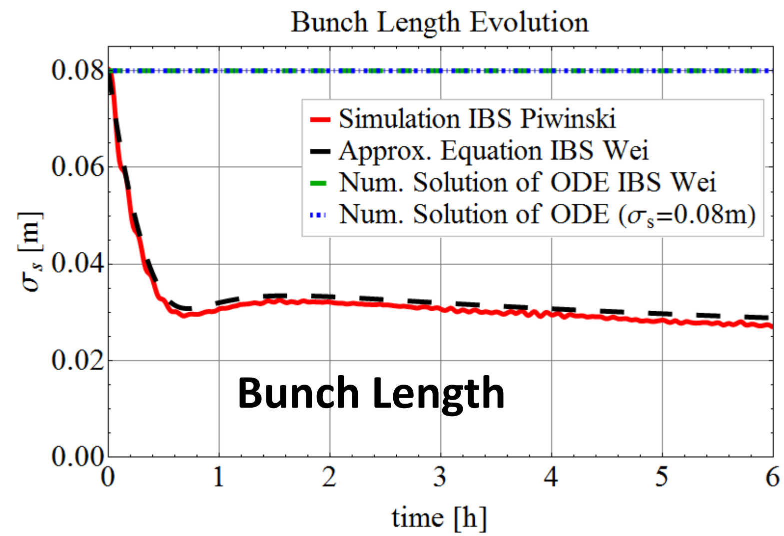
$$\frac{\alpha_{\mathrm{rad,FCC}}}{\alpha_{\mathrm{rad,LHC}}} \approx \frac{E^3_{\mathrm{FCC}}/C^2_{\mathrm{FCC}}}{E^3_{\mathrm{LHC}}/C^2_{\mathrm{LHC}}} \approx \frac{7^3}{4^2} \approx 22$$

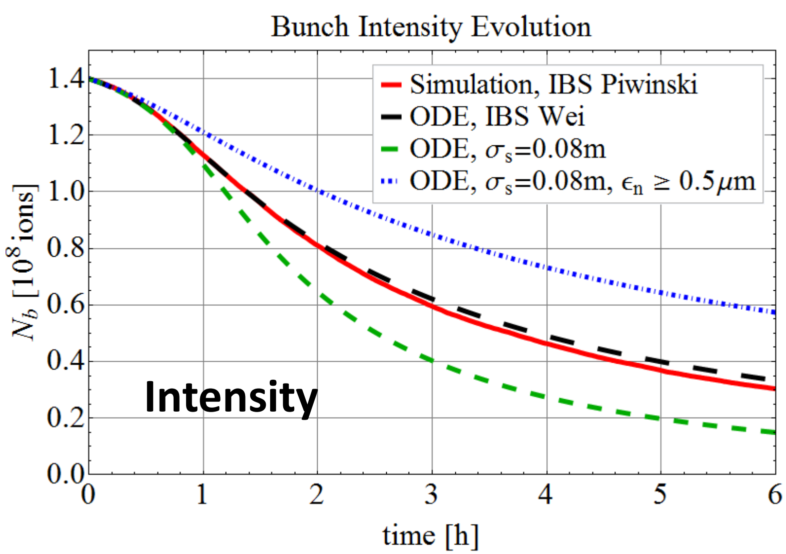
| Damping Times | Unit | FCC @ 50Z TeV |
|---|---|---|
| $1/\alpha_{\mathrm{rad,s}}$ | [h] | 0.24 |
| $1/\alpha_{\mathrm{rad,x}}$ | [h] | 0.49 |

**Fast emittance decrease at the beginning of the fill, until IBS becomes strong enough to counteract the radiation damping.**

# Pb-Pb Beam Evolution



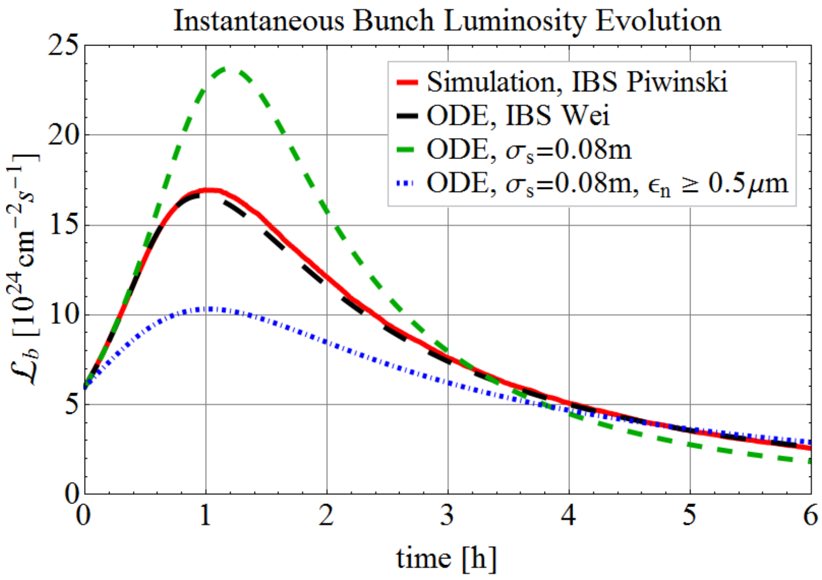




- **Red: tracking simulation** taking into account IBS, rad. damping, burn-off, …
- **Black:** numerical solution of the ODE system on slide 7, using J. Wei's analytical IBS formalism*.
  - → emittances and bunch length become very small!
- **Green:** $d\sigma_s/dt = 0$: artificial longitudinal blow-up to $\sigma_s$ = 8cm.
- **Blue:** artificial longitudinal and transverse blow-up to $\sigma_s$ = 8cm and $\epsilon_n \geq 0.5\mu m$.

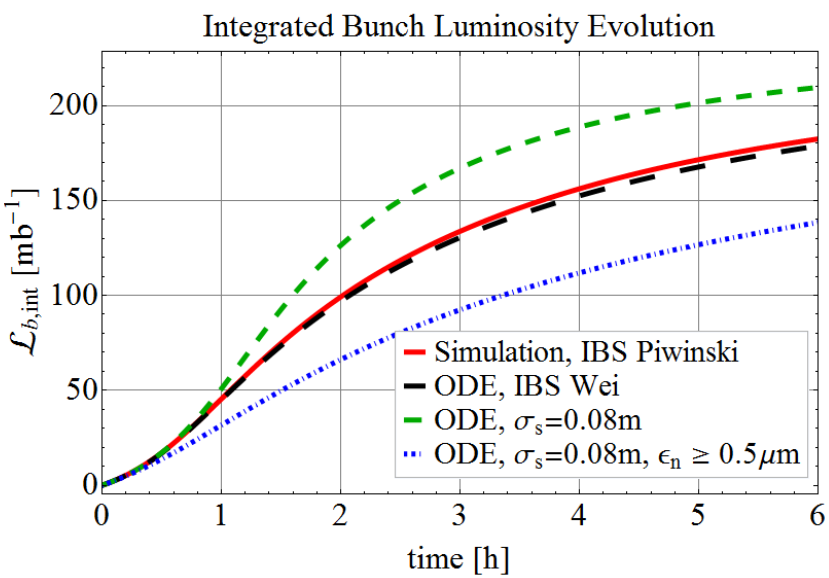
*J. Wei: *Evolution of Hadron Beams under Intrabeam Scattering*, Conf.Proc. C930517 (1993) 3651-3653, PAC 1993.

# Pb-Pb Luminosity Evolution




If the beam dimensions become too small and artificial blow-up has to be used, the luminosity will be affected:

- **Peak Enhancement for long. blow-up**, since long. and horizontal IBS are reduced, due to larger $\sigma_s \rightarrow$ smaller $\epsilon_n$.
- **Reduced luminosity**, due to blown-up $\epsilon_n$.

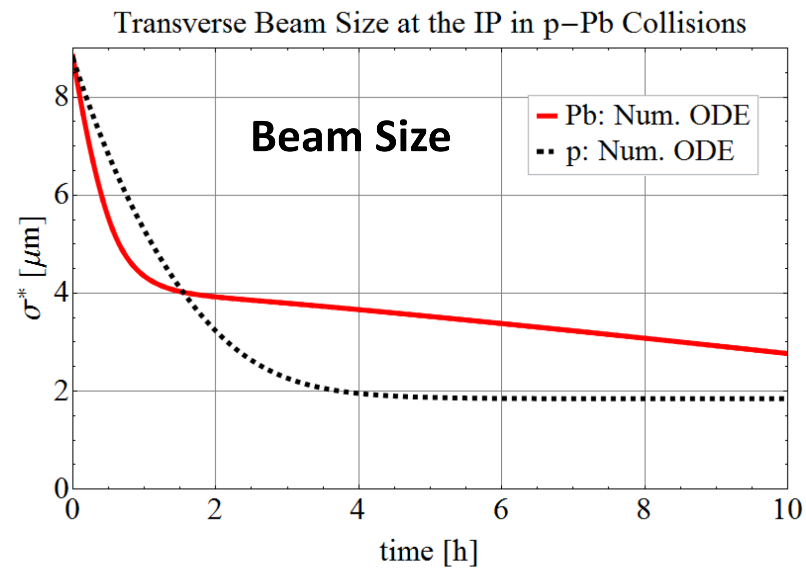


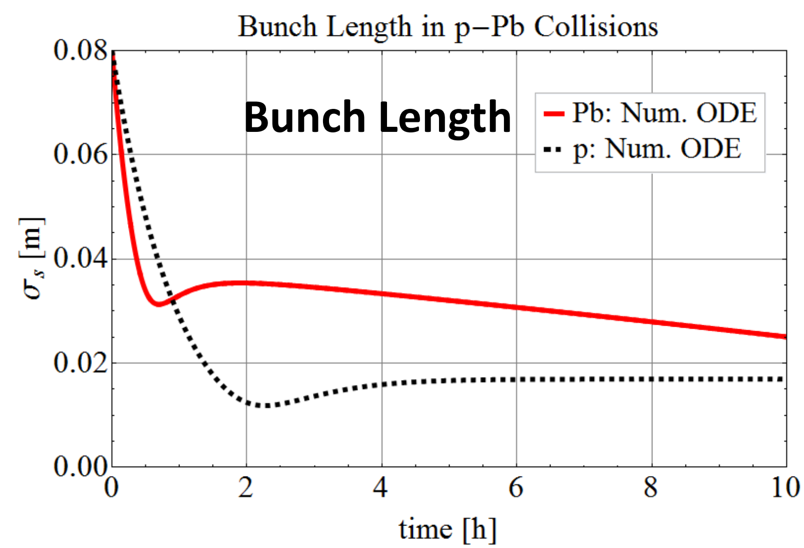

**Summary for free beam evolution**

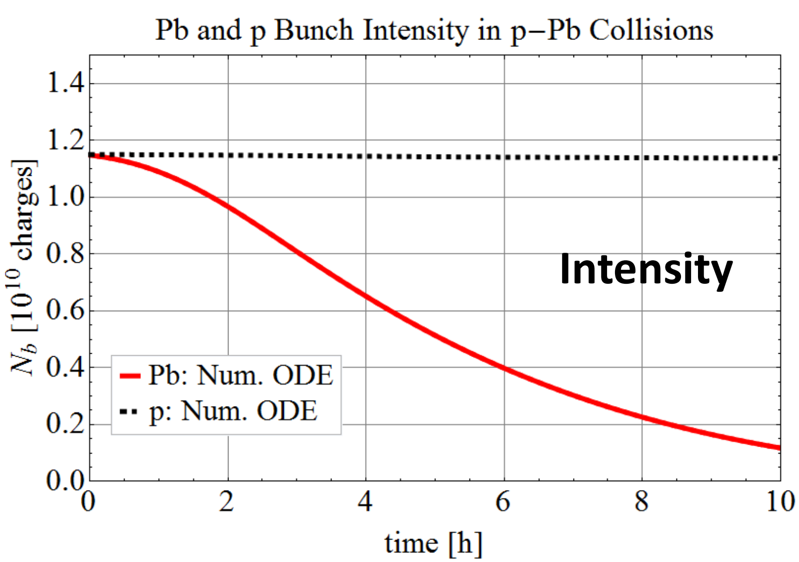
(no artificial blow-up)

| | Unit | per Bunch | whole Beam |
|---|---|---|---|
| $L_{\text{initial}}$ | [Hz/mb] | 0.006 | 2.6 |
| $L_{\text{peak}}$ | [Hz/mb] | 0.017 | 7.3 |
| $L_{\text{int,fill}}$ | [$\mu b^{-1}$] | 0.13 | 57.8 |

# p-Pb Beam Evolution (1 Experiment)



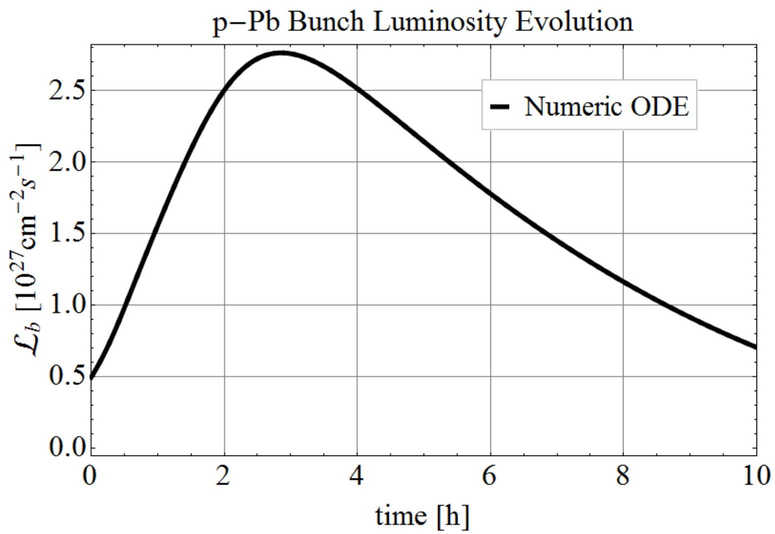



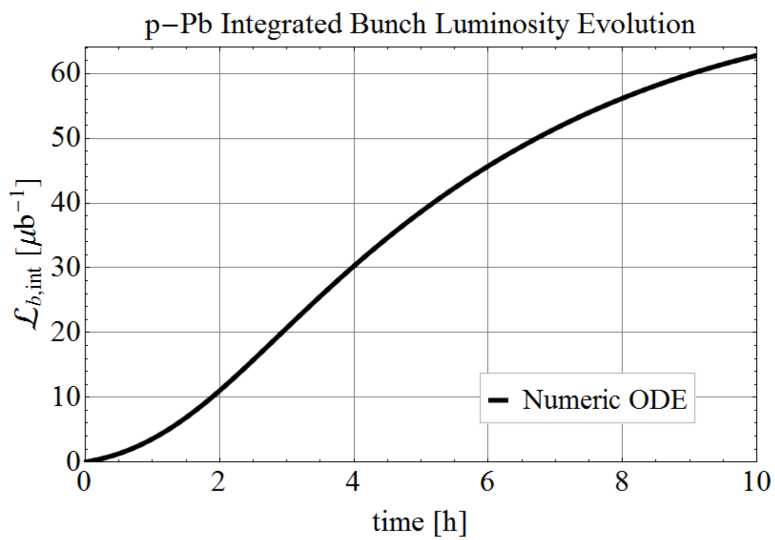




Initial conditions:

- Pb-beam as for Pb-Pb operation.
- Equal beam sizes, σ*, for p and Pb.
- Rad. damping $\propto Z^5/A^4 \approx 2$
  $\rightarrow 2\alpha_{rad}(p) \approx \alpha_{rad}(Pb)$
- IBS scales with $\propto (Z^2/A)^2 N_b$
- $N_b(\mathrm{p}) \approx 100\ N_b(Pb)$
  → Fast Pb burn-off, while
  $N_b(\mathrm{p}) \approx$ const.

# p-Pb Luminosity Evolution (1 Experiment)




Peak shifted to later times
→ p shrinks slower than Pb

$$2\alpha_{rad}(p) \approx \alpha_{rad}(Pb)$$

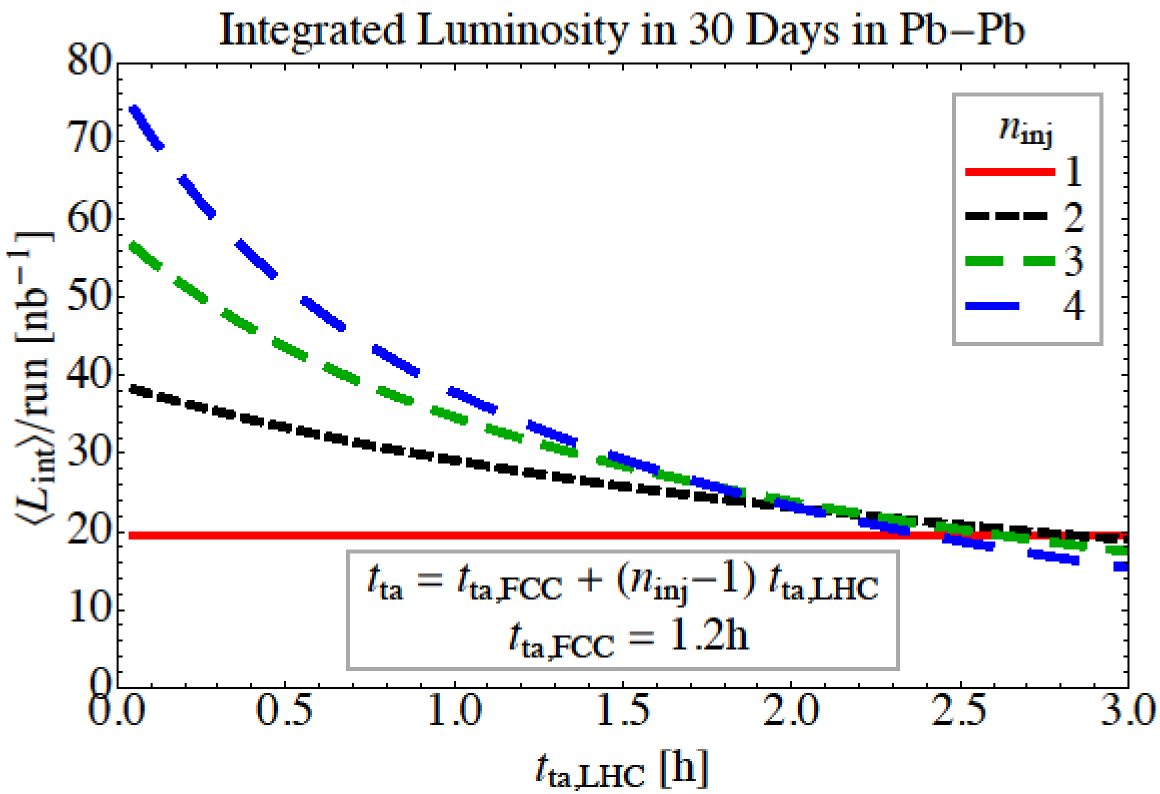
Luminosity decay slower
→ $N_b(\mathrm{p}) \approx$ const.
→ 1/e-Luminosity lifetime ≈ 14h.

| | Unit | per Bunch | whole Beam |
|---|---|---|---|
| $L_{\mathrm{initial}}$ | [Hz/mb] | 0.5 | 213 |
| $L_{\mathrm{peak}}$ | [Hz/mb] | 2.8 | 1192 |
| $L_{\mathrm{int,fill}}$ | [$\mu$b$^{-1}$] | 48.7 | 21068 |

# 2016 upgrade of FCC performance projections

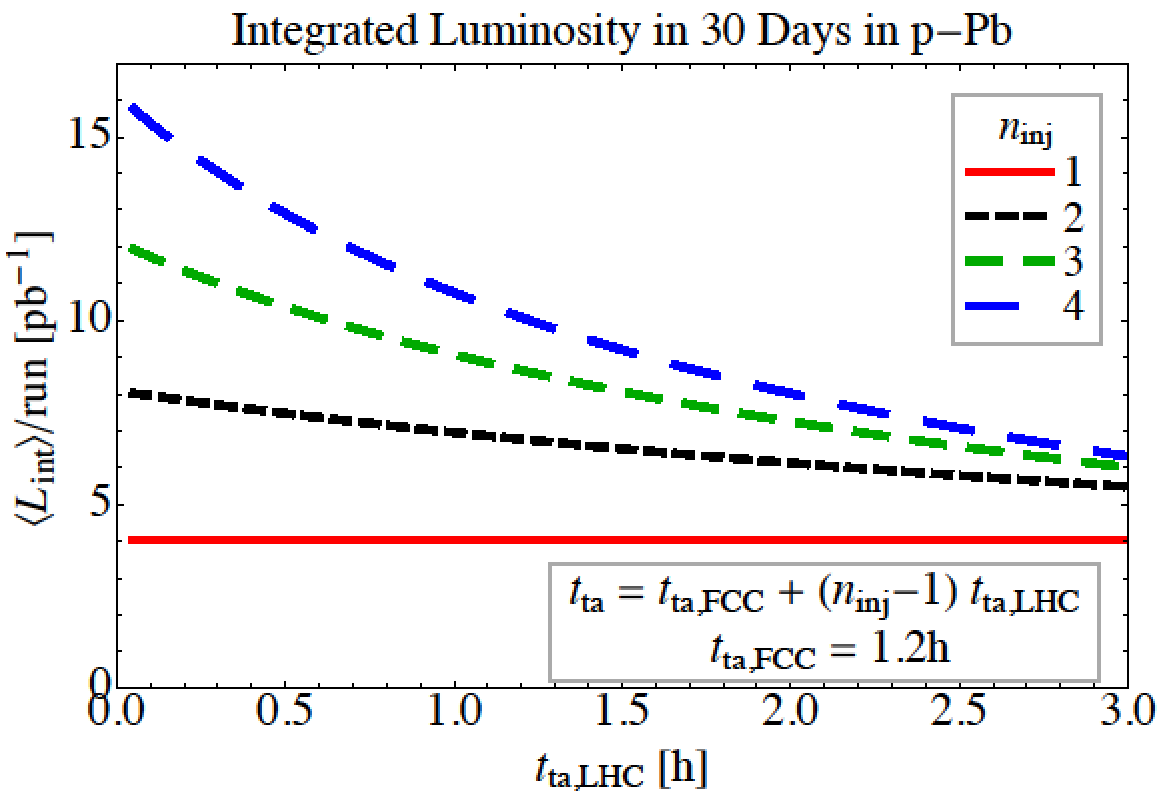
- Substantially higher performance of existing injectors seen in 2015 Pb-Pb run
  - Factor ~ 2.4 in peak and integrated luminosities.
- Measures envisaged to shorten the LHC magnetic cycle to ~ 9 min (see F. Zimmermann, G. de Rijk tomorrow …) mean that the optimum scheme is to fill the entire FCC ring using up to 4 LHC injection cycles:
  - further factor ~ 4× peak and integrated luminosities.
- Maintained the assumption of a single experiment taking data.
  - For n heavy-ion experiments the integrated luminosity per experiment will go down because of luminosity sharing but not as fast as 1/n.
  - Total luminosity, summed over experiments, will be somewhat increased.

# Integrated luminosity in 1 month Pb-Pb run




Full performance with perfect efficiency (no down time or other interruptions).
Assuming 1 heavy-ion experiment.

# Integrated luminosity in 1 month p-Pb run




Full performance with perfect efficiency (no down time or other interruptions).
Assuming 1 heavy-ion experiment.

# Updated parameter list 2016

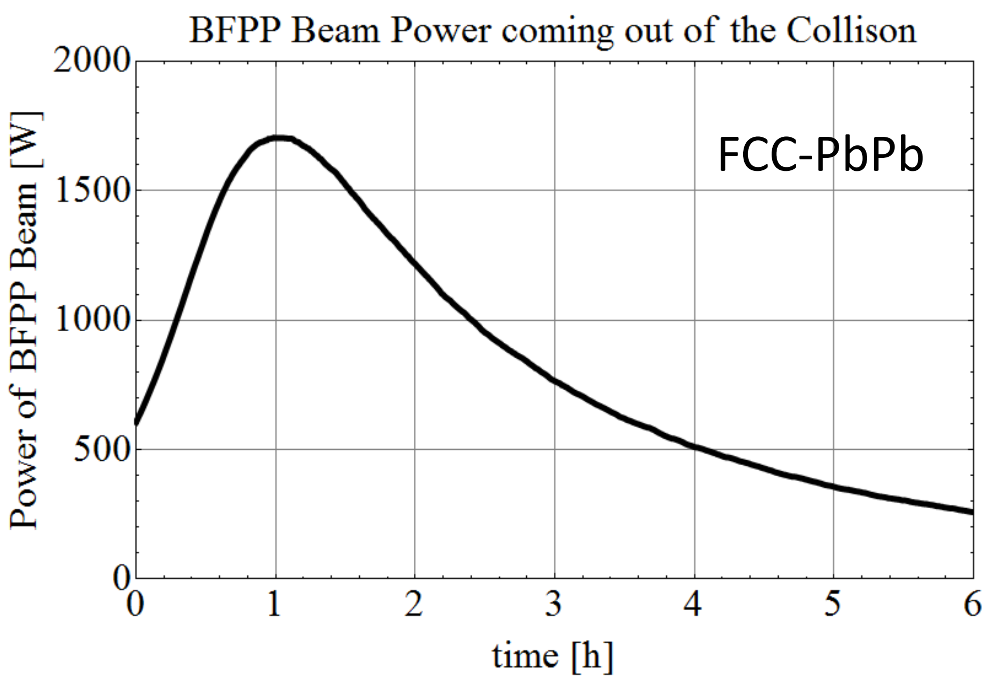
| | Unit | FCC Injection | FCC Collision | |
|---|---|---|---|---|
| Operation mode | - | Pb | Pb-Pb | p-Pb |
| Beam energy | [TeV] | 270 | 4100 | 50 |
| CM energy/nucleon pair $\sqrt{s_{NN}}$ | [TeV] | - | 39.4 | 62.8 |
| No. of bunches per LHC injection | - | 518 | 518 | 518 |
| No. of bunches in the FCC | - | 2072 | 2072 | 2072 |
| No. of particles per bunch | $[10^8]$ | 2.0 | 2.0 | 164 |
| Transv. norm. emittance | [$\mu$m] | 1.5 | 1.5 | 3.75 |
| Long. IBS emit. growth time | [h] | 4.5 | 20.9 | $3 \times 10^3$ |
| Hor. IBS emit. growth time | [h] | 7.9 | 23.4 | $4 \times 10^3$ |
| Hor. emit. rad. damping time | [h] | 1704 | 0.49 | 1.0 |
| $\beta$-function at the IP | [m] | - | 1.1 | |
| Number of IPs in collision | - | - | 1 | 1 |
| Crossing-angle | [$\mu$rad] | - | 0 | |
| Initial luminosity | $[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$ | - | 24.5 | 2052 |
| Peak luminosity | $[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$ | - | 57.8 | 9918 |
| Integrated luminosity per fill | [$\mu\mathrm{b}^{-1}$] | - | 553 | 158630 |
| Average luminosity | [$\mu\mathrm{b}^{-1}$] | - | 92 | 20736 |
| Time in collision | [h] | - | 3 | 6 |
| Assumed turnaround time | [h] | - | 1.65 | 1.65 |
| Integrated luminosity/run | [$\mathrm{nb}^{-1}$] | - | 33 | 8000 |

Integrated luminosity now includes operational efficiency factor of 50 % (as for HL-LHC).

# BFPP Beam Power in Pb-Pb for FCC-hh

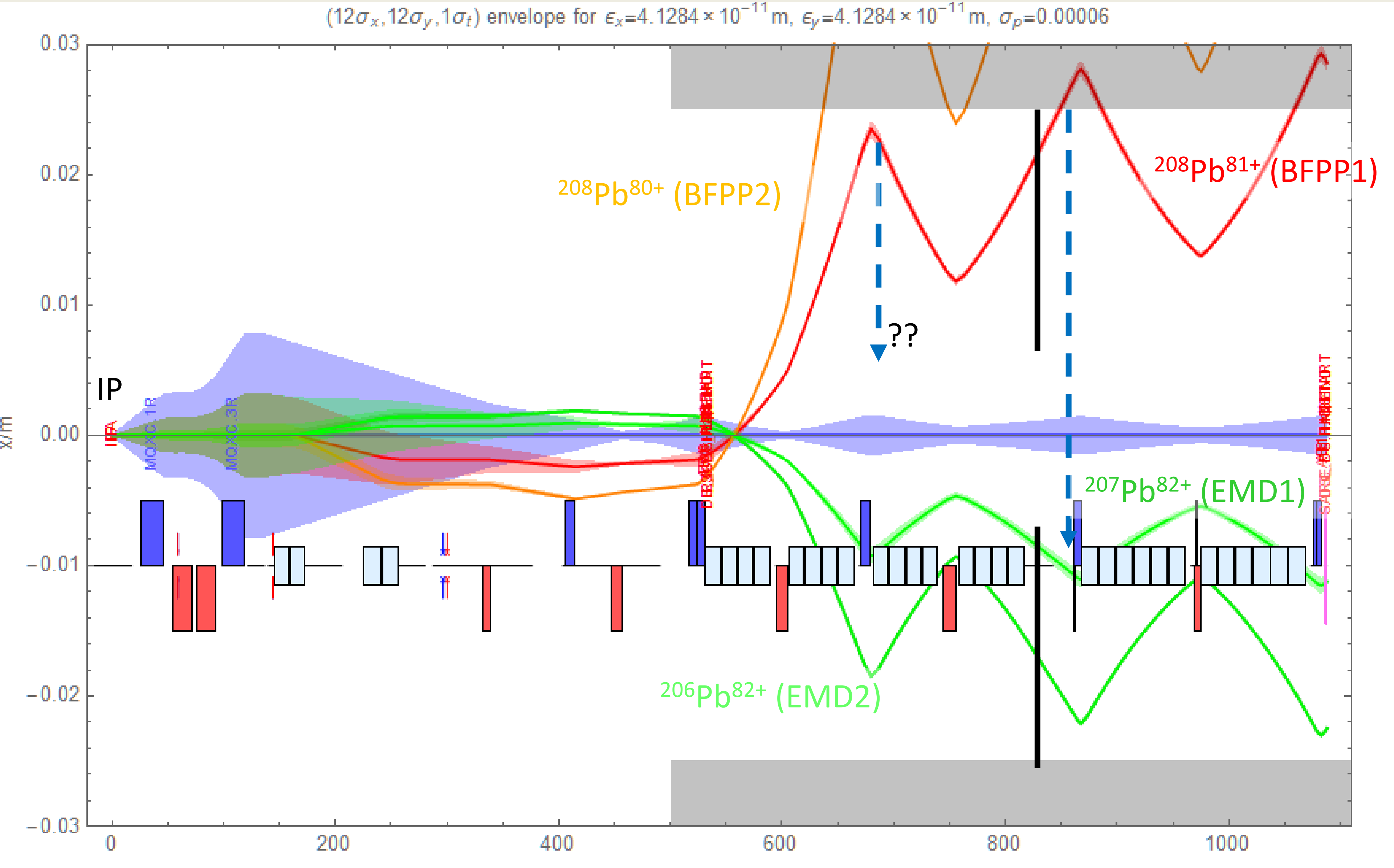
BFPP Beam power: $P = \sigma_c L \underbrace{E}_{4.1\ \mathrm{PeV}} \approx 6$ kW (peak)

c.f. HL-LHC: $P \approx 150$ W




**Countermeasures (e.g., DS collimators) have to be considered in initial lattice & hardware design.**

# Secondary beams from Pb-Pb collisions (Lattice V4 baseline)




ALICE-like solution with DS collimators (without change to optics) appears feasible.

# Conclusions (1)

- LHC has already demonstrated the path to "HL-LHC" Pb-Pb performance level
  - Mainly depends on injector upgrades now
- Diverse experimental requirements have led to a challenging plan for the LHC p-Pb run in 2016
  - Operation at both 5 TeV and 8 TeV
  - Achievable, assuming operational efficiency similar to 2013 and 2015 – overall complexity is similar
  - Otherwise re-prioritisation strategies are being put in place
- The FCC-hh has the potential to operate as a very efficient Pb-Pb and p-Pb collider, with another large step in energy beyond LHC.

# Conclusions (2)

- All hadron collisions (even p-p) can be heavy-ion collisions (?).
- All the world's hadron colliders (even LHC) are now heavy-ion colliders.
- All future hadron colliders (even FCC) can be heavy-ion colliders.
- All the world's hadron-collider experiments (even XXX(X)(X)) are now heavy-ion experiments.
- All the world's theorists …

# BACKUP SLIDES

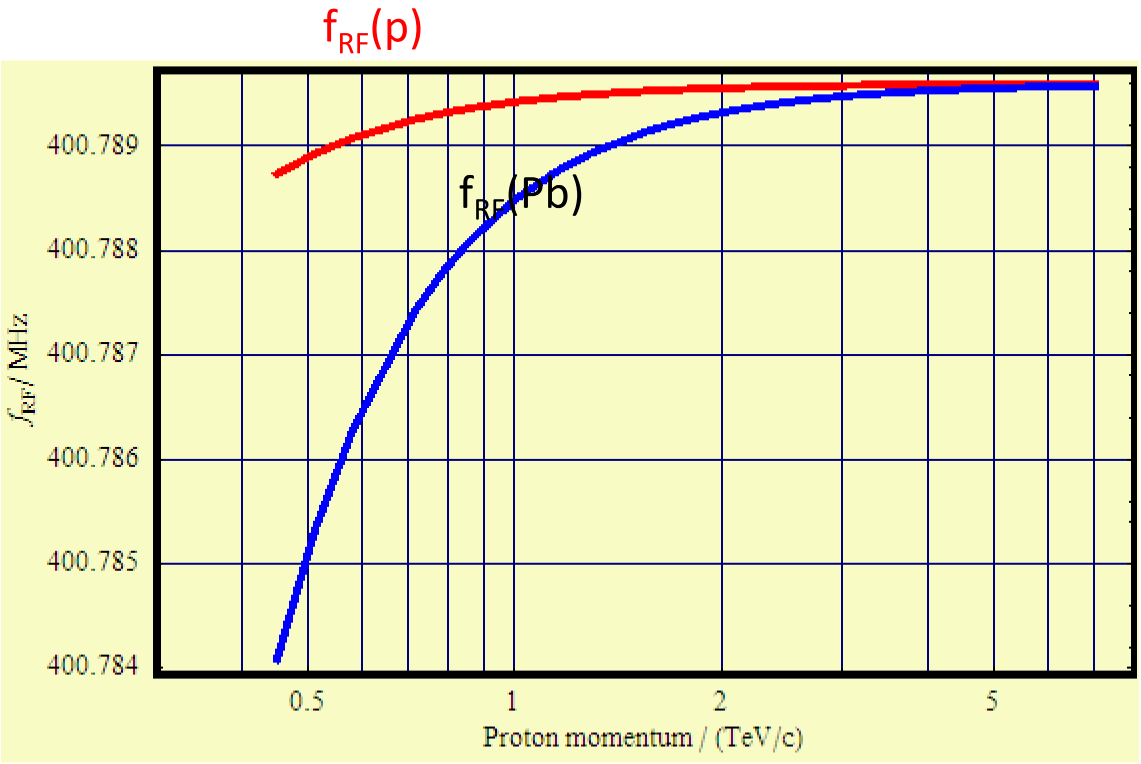
# RF Frequency for p and Pb in LHC

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

$$T(p_p, m, Q) = \frac{C}{c}\sqrt{1+\left(\frac{mc}{Qp_p}\right)^2} \quad \text{and RF frequency} \quad f_{RF} = \frac{h_{RF}}{T(p_p, m, Q)}$$

where the harmonic number $h_{RF} = 35640$ 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

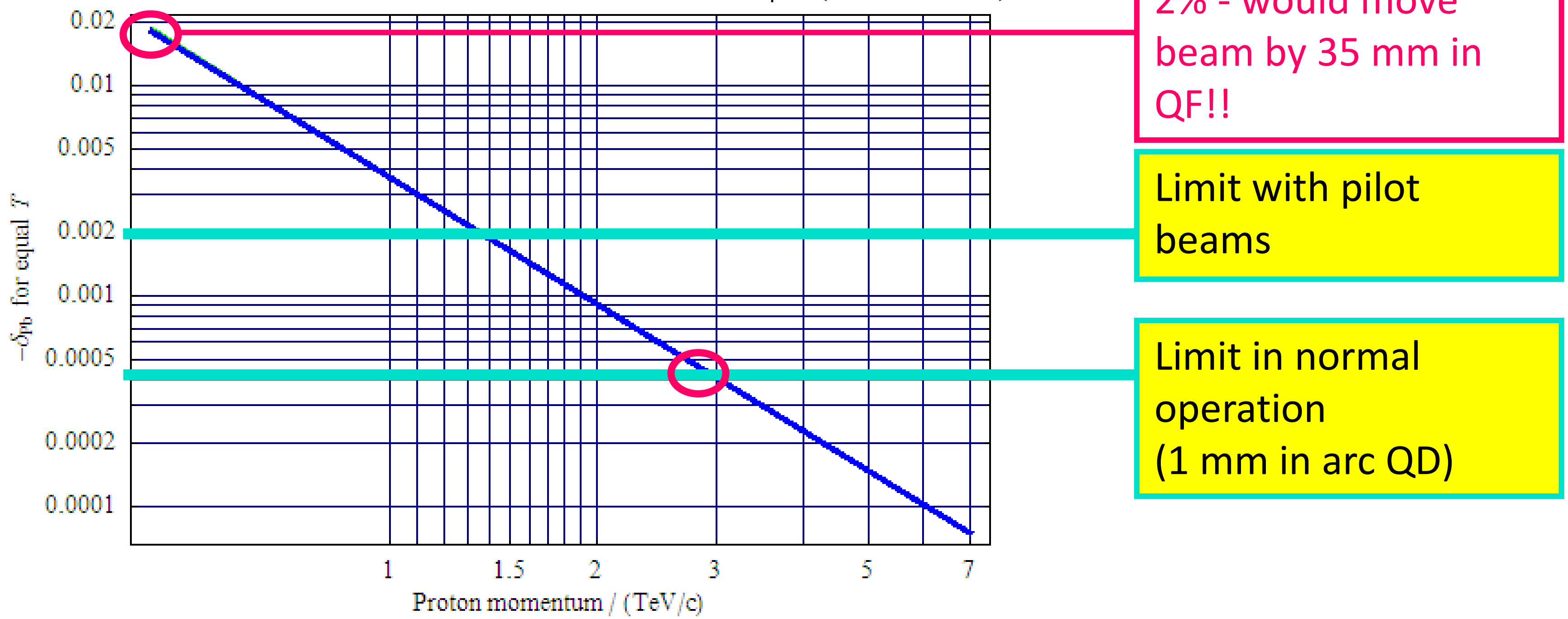
the phase-slip factor $\eta = \dfrac{1}{{\gamma_T}^2} - \dfrac{1}{\gamma^2}$, $\gamma = \sqrt{1 + \left(\dfrac{Qp_{\mathrm{p}}}{mc}\right)^2}$, $\gamma_T = 55.8$ for LHC optics.

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

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

# Momentum offset required through ramp

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

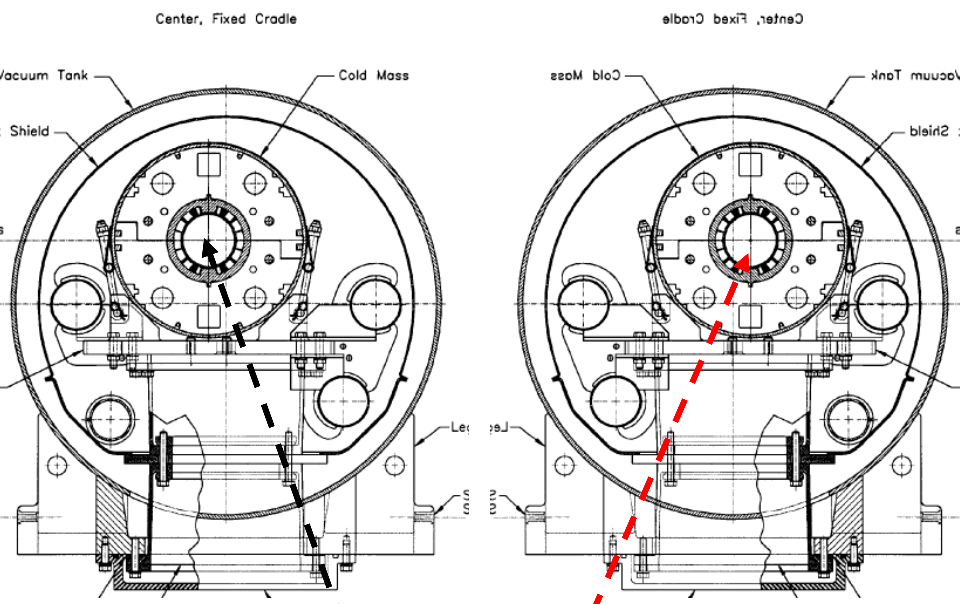


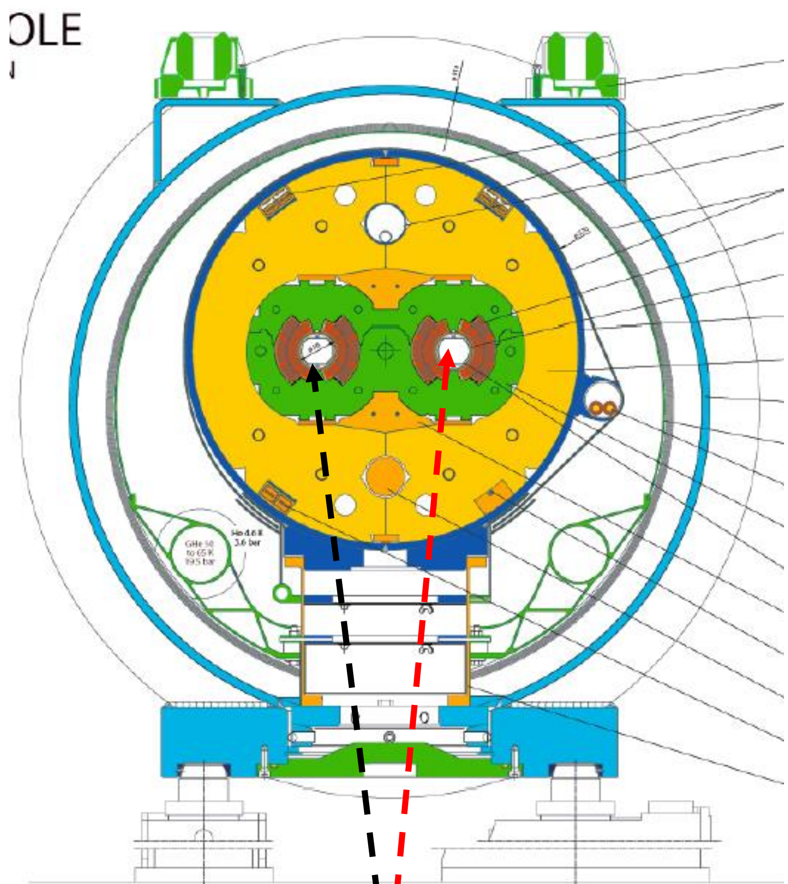

Revolution frequencies must be equal for collisions at top energy.

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

**RF frequencies must be unequal for injection, ramp!**

# 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

# 5 TeV or 8 TeV – which should come first ?

- Reasons for 8 TeV first:
  - 8 TeV configuration somewhat closer to p-p one
    - But LHC is very reproducible, not a great advantage
- Reasons for 5 TeV first:
  - Less risk in 5 TeV – get it in the bag
    - May also have time to learn/debug any p-Pb-specific problems that come up in the easier configuration
  - Ion source refill during Stable Beams
    - Advantage of very long 5 TeV fills, no time lost (unless bad luck!)
    - Refill timed during last physics fill should last for remainder of run

- Conclusion: prefer 5 TeV first

# Miscellaneous

- Plan to not lose set-up time in the case that we do not do the reversal (so setup the reversed beam only when necessary)
- Each new mode of running (5 TeV, 8 TeV direction1 and direction 2) will require a short intensity ramp-up for machine protection reasons (1 day for each part where we wont be running at full luminosity)
- Related to the LHCf run
  - Direction of first part should be as wanted by LHCf (e.g. protons in beam-1), as LHCf run foreseen in this part
  - LHCf/ATLAS common trigger rate of 400Hz try to minimize time of LHCf run
- VdM scans
  - No optics change for p-Pb VdM, so can be done in standard physics fills
  - Up to the experiments to decide if they want VdM for neither, one or both directions (but this will take away luminosity from them)

| | M | T | W | T | F | S | S |
|---|---|---|---|---|---|---|---|
| week1 | set up 5 | set up 5 | set up 5 | 5 TeV | 5 TeV | 5 TeV | 5 TeV |
| week2 | 5 TeV | 5 TeV* | set up 8 | set up 8 | set up 8 | set up 8 | 8 TeV |
| week3 | 8 TeV | 8 TeV | 8 TeV | 8 TeV | 8 TeV / LHCf run* | LHCf run*<br>reversal | reversal |
| week4 | reversal<br>8 TeV | 8 TeV | 8 TeV | 8 TeV | 8 TeV | 8 TeV | MD |

Switch to 8 TeV run if 700M events delivered to ALICE by this point (if not continue the run until 700M events are delivered, unless this appears to significantly delay the start of the 8 TeV run)

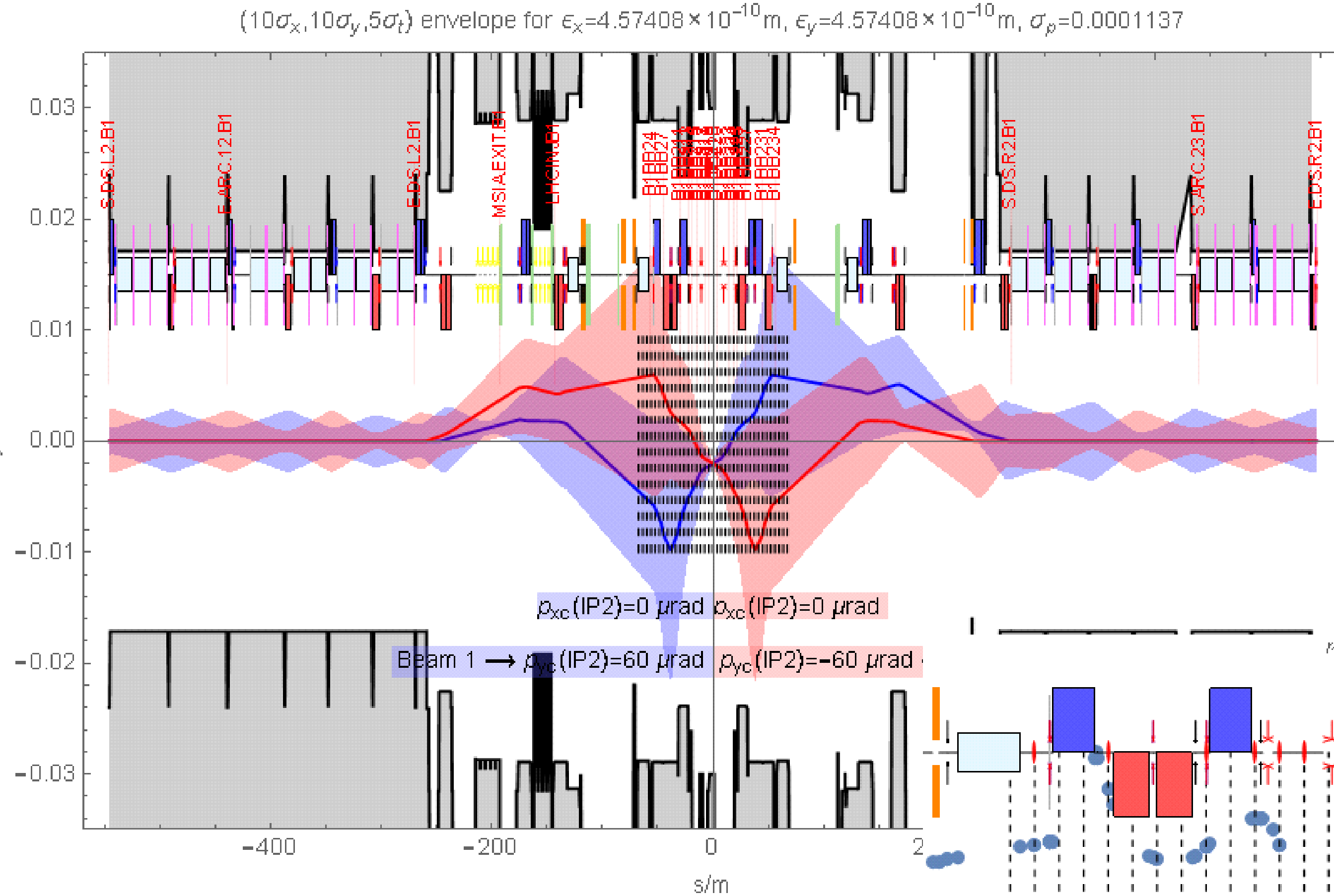
| | M | T | W | T | F | S | S |
|---|---|---|---|---|---|---|---|
| week1 | set up 5 | set up 5 | set up 5 | 5 TeV | 5 TeV | 5 TeV | 5 TeV |
| week2 | 5 TeV | 5 TeV* | set up 8 | set up 8 | set up 8 | set up 8 | 8 TeV |
| week3 | 8 TeV | 8 TeV | 8 TeV | 8 TeV | 8 TeV / LHCf run* | LHCf run*<br>reversal | reversal |
| week4 | reversal<br>8 TeV | 8 TeV | 8 TeV | 8 TeV | 8 TeV | 8 TeV | MD |

Drop beam-reversal if <25/nb delivered to ATLAS/CMS by this point

# Accelerator aspects of energy choice

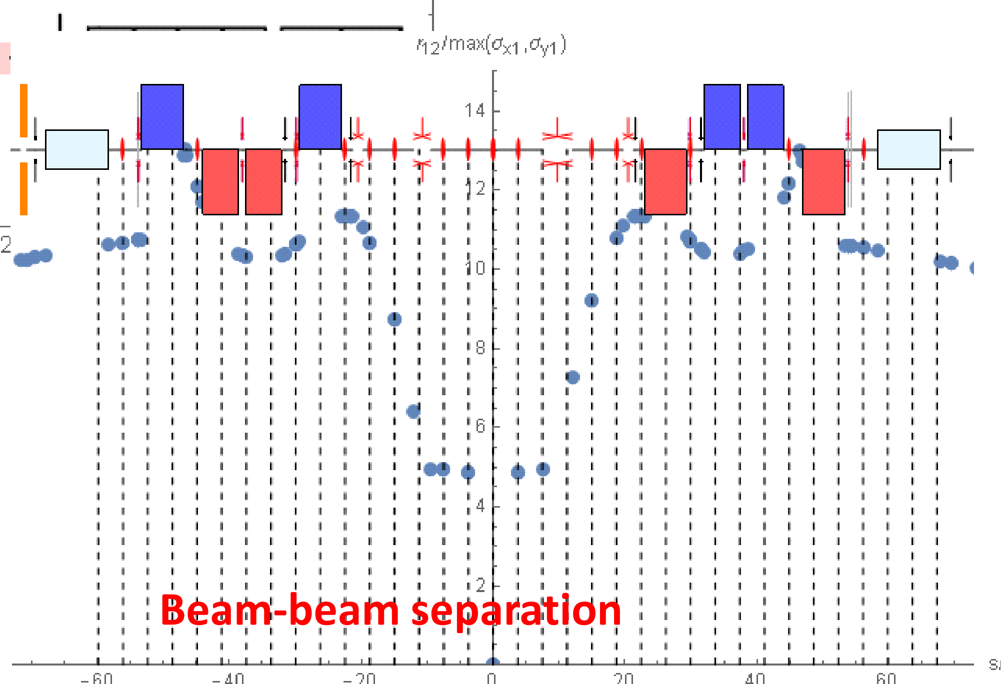
- 5 TeV
  - Full run would be re-run of 2013, more or less, some more bunches, higher luminosity (~77 $nb^{-1}$ RA in Chamonix)
    - May need to increase β*>0.8 m in ALICE (IP displacement + chromatic optics)
    - Levelling ALICE, need to explore potential for more *L* in LHCb
  - Fully squeezed p-Pb and Pb-p optics have different chromatic corrections (not needed above β* ~ 2 m)
- 8 TeV
  - Revolution frequency differences smaller so squeezed p-Pb and Pb-p optics might be identical (to study)
  - Expect less IBS, less effect of unequal beam sizes
  - Higher peak luminosity accessible, rapid burn-off (116 $nb^{-1}$ RA in Chamonix)
  - Levelling ALICE but lower β* potentially accessible
    - New squeeze setup, etc

# Spectrometer ON_ALICE=-7/6.37 (start of Pb-Pb run)

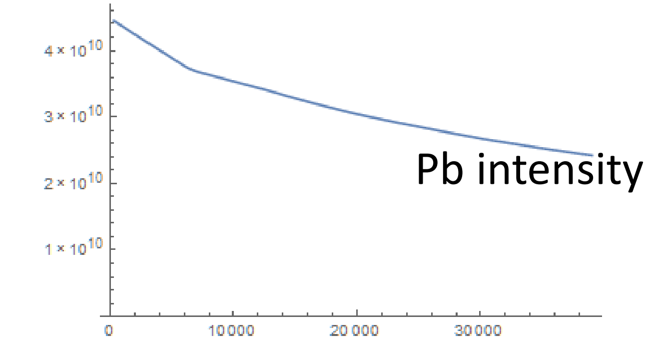


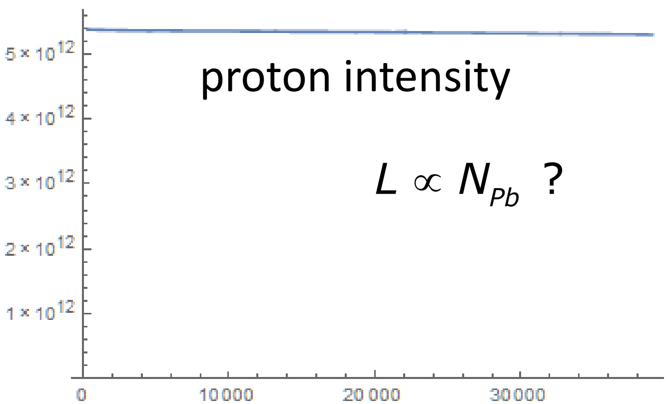

May constrain ALICE β*
for rest of Run 2
(important to fix in LS2).
To be studied

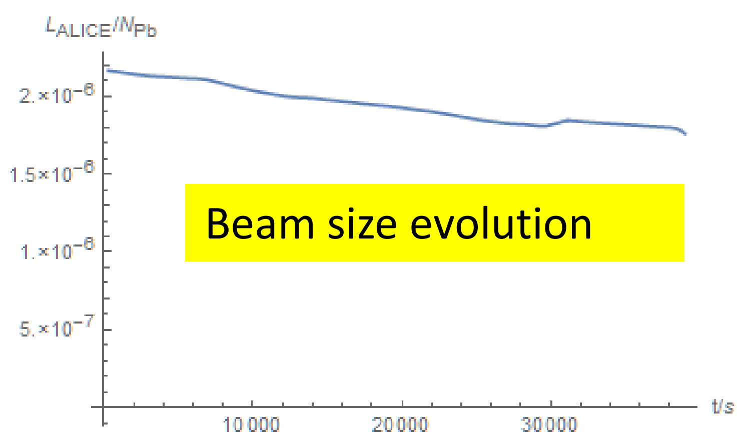
Spectrometer bump
angle -77 μrad,
external bump +137 μrad
for Beam 1.

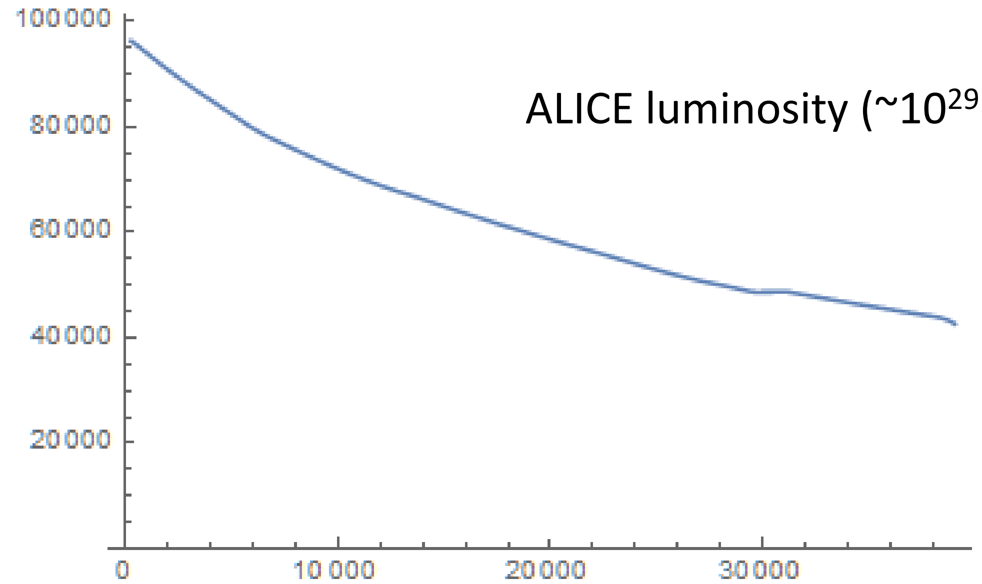


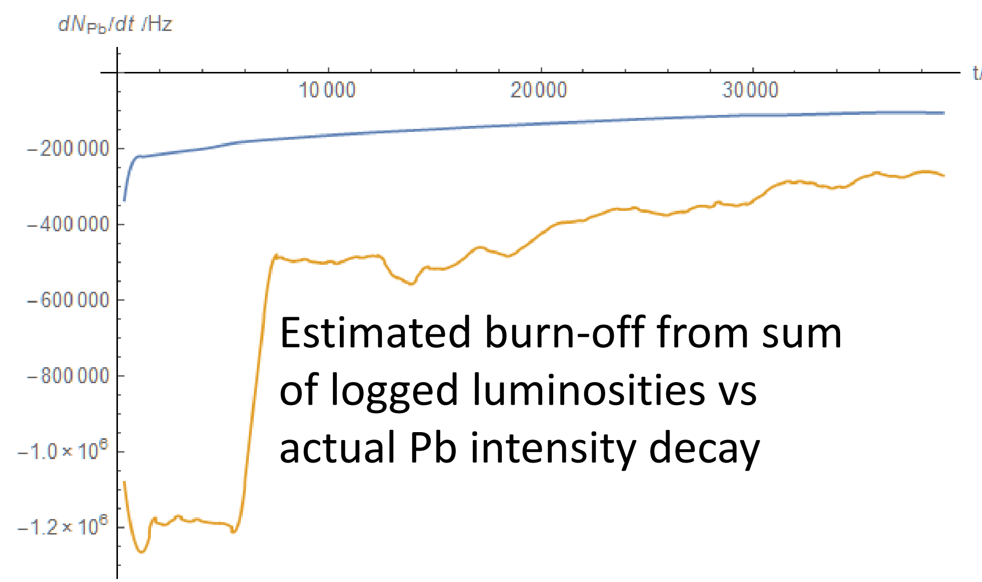
# Fill 3509 – only ALICE colliding, 31/1/2013 – 10 h



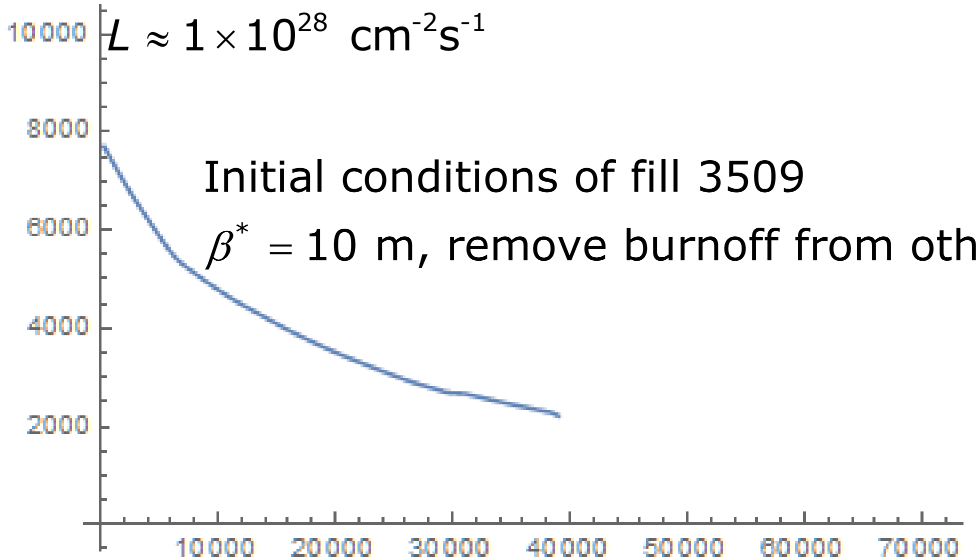




Need to understand 2013 losses better

# Rough estimate of levelled fill for ALICE alone

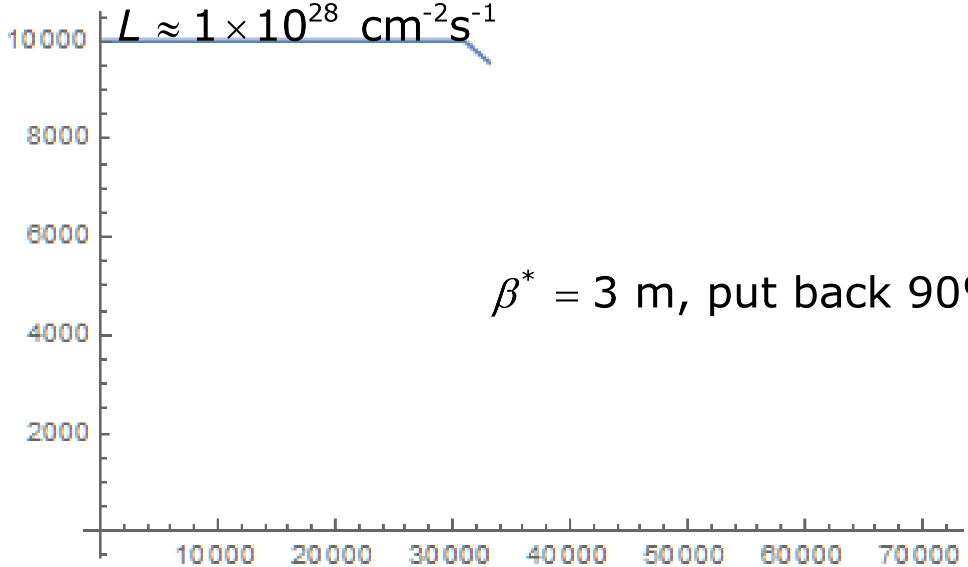



$L \approx 1 \times 10^{28}\ \mathrm{cm^{-2}s^{-1}}$

Initial conditions of fill 3509

$\beta^* = 10$ m, remove burnoff from other experiments, scale luminosity

24 h




$L \approx 1 \times 10^{28}\ \mathrm{cm^{-2}s^{-1}}$

$\beta^* = 3$ m, put back 90% of burnoff, scale luminosity, level

Could be better than this with higher initial Pb and p intensities (and less beam-beam from other experiments?)