LHC machine - Perspectives for nuclear beams

John Jowett (CERN)

On behalf of many colleagues past and present in CERN Accelerator and Technology Sector
Nucleus-nucleus programme status

- In ~8 weeks total Pb-Pb operation in 2010-11, the LHC has attained
  - Twice design Pb-Pb luminosity at half-design energy (scaling with $E^2$).
  - ~16% of the integrated luminosity goal (1 nb$^{-1}$) for the present phase of Pb-Pb.
- Pb-Pb in 2012 might give ~250 $\mu$b$^{-1}$
- Decision to go for p-Pb instead
  - Otherwise no p-Pb before 2016 or 2017
  - But this is a new, more complex and almost unprecedented mode of collider operation

Feasibility of p-Pb collisions?

- ALICE LoI emerged around time of this meeting

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

- Almost unprecedented mode of collider operation
  - See pA@LHC workshop
- 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 Heavy-Ion Programme to 2022

- 2013-14 Long shutdown LS1, increase $E$
- 2015-16 Pb-Pb Design luminosity $\times 1$, ~ 250 $\mu$b$^{-1}$/year
- 2017 p-Pb or Pb-Pb P-Pb to enhance 2015-16 data. Energy? Pb-Pb if $ub^{-1}$ still needed
- 2018 LS2: install DS collimators around ALICE to protect magnets (ALICE upgrade for 6 $\times$ 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.
- 2022 LS3, upgrades ?? Stochastic cooling ??

Part I - Conclusions

- 2011 results encouraging for future performance
  - Quench limits, strategies to help avoid them
  - Still many uncertainties
  - Still “only” design intensity in 100 ns Nominal injection scheme
- We do not yet have a clear path beyond about twice design luminosity
  - DS collimator installation for ALICE in LS2
  - Looking for solutions for more bunches in Injectors
11 weeks later: 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
Historical energy jumps

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

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

This was the largest factor of increase in the energy of a given type of collision ever achieved in the history of particle accelerators - and brought new, surprising physics results.

LHC Run 1 closed with a full p-Pb run, a further factor 1000 in luminosity, ... the first major upgrade of the LHC beyond its design (pp and PbPb only).
Second half of 2013 run - Luminosity production in Pb-p mode

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

Intermediate filling scheme to limit the losses

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

Increase bandwidth of orbit feedback

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

Common frequency trimmed by -10Hz

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

Set the style of future Pb-Pb and p-Pb runs.

~“Design” luminosity achieved at 4/7 design energy.
LHC Heavy 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
Improvements in upstream injectors allowed re-introduction of bunch-splitting in PS to stay below single-bunch limit in SPS (which remains the main intensity bottleneck).

NB we will take advantage of these gains in Pb-Pb for the first time in 2018.

Table 1: Representative simplified beam parameters at the start of the highest luminosity physics fills, in conditions that lasted for > 5 days, in each annual Pb-Pb and p-Pb run [12–16]. The original design values for Pb-Pb [4] and p-Pb [17] and future upgrade Pb-Pb goals are also shown (in these columns the integrated luminosity goal is to be attained over the 4 Pb-Pb runs in the 10-year periods before and after 2020). Peak and integrated luminosities are averages for ATLAS and CMS (ALICE being levelled). The smaller luminosities delivered to LHCb from 2013–2016 and in the minimum-bias part of the run in 2016 are not shown. Emittance and bunch length are RMS values. Single bunch parameters for p-Pb or Pb-p runs are generally for Pb. The series of runs with $\sqrt{s_{NN}} \approx 5.02$ TeV also included p-p reference runs, not shown here. Design and record achieved nucleon-pair luminosities are boxed for easy comparison. The upgrade value is reduced by a factor $\approx 3$ from its potential value by levelling.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>&quot;design&quot;</th>
<th>achieved</th>
<th>upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeks in physics</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fill no.</td>
<td>1541</td>
<td>2351</td>
<td>3544</td>
</tr>
<tr>
<td>Species</td>
<td>Pb-Pb</td>
<td>p-Pb</td>
<td>Pb-Pb</td>
</tr>
<tr>
<td>Beam energy $E[Z$ TeV]</td>
<td>7</td>
<td>3.5</td>
<td>4</td>
</tr>
<tr>
<td>Pb beam energy $E[ATeV]$</td>
<td>2.76</td>
<td>1.38</td>
<td>1.58</td>
</tr>
<tr>
<td>Pb beam energy $E[ATeV]$</td>
<td>2.76</td>
<td>1.38</td>
<td>1.58</td>
</tr>
<tr>
<td>Collision energy $\sqrt{s_{NN}}$ [TeV]</td>
<td>5.52</td>
<td>2.51</td>
<td>5.02</td>
</tr>
<tr>
<td>Bunch intensity $N_b[10^8]$</td>
<td>0.7</td>
<td>1.22</td>
<td>1.97</td>
</tr>
<tr>
<td>No. of bunches $k_b$</td>
<td>592</td>
<td>137</td>
<td>338</td>
</tr>
<tr>
<td>Pb norm. emittance $\epsilon_N$ [µm]</td>
<td>1.5</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Pb bunch length $\sigma_z$ m</td>
<td>0.08</td>
<td>0.07–0.1</td>
<td>0.08</td>
</tr>
<tr>
<td>$\beta*$ [m]</td>
<td>0.5</td>
<td>3.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Pb stored energy MJ/beam</td>
<td>3.8</td>
<td>2.3</td>
<td>0.65</td>
</tr>
<tr>
<td>Peak lumi. $L_{AA}[10^{27} cm^{-2}s^{-1}]$</td>
<td>1</td>
<td>150</td>
<td>0.03</td>
</tr>
<tr>
<td>NN lumi. $L_{NN}[10^{30} cm^{-2}s^{-1}]$</td>
<td>43</td>
<td>31</td>
<td>1.3</td>
</tr>
<tr>
<td>Integrated lumi./expt. [µb$^{-1}$]</td>
<td>1000</td>
<td>$10^5$</td>
<td>9</td>
</tr>
<tr>
<td>Int. NN lumi./expt. [nb$^{-1}$]</td>
<td>43000</td>
<td>21000</td>
<td>380</td>
</tr>
</tbody>
</table>

The 2018 Pb-Pb run (end of next week!) should implement and exploit most of the features of the configuration for “HL-LHC” luminosity.

Levelled, could be $\sim 15$. 

Paper at IPAC2018
https://doi.org/10.18429/JACoW-IPAC2018-TUXGBD2
TUXGBD2
+ its bibliography
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.

Equivalent energy runs

\[
\sqrt{s_{NN}} = 5.02 \text{ TeV} \quad (\sqrt{s} = 1.045 \text{ PeV})
\]

\[
\Rightarrow E_b = \begin{cases} 
6.37 \text{ TeV} & \text{in Pb-Pb} \\
4 \text{ Z TeV} & \text{in p-Pb} \\
2.51 \text{ TeV} & \text{in p-p}
\end{cases}
\]
Feasibility and first p-Pb run at 4 Z TeV in 2012/13.

Complex 2016 run plan determined after Chamonix 2016:

Minimum bias run at 4 Z TeV mainly for ALICE

High luminosity run for all experiments (+LHCf) at 6.5 Z TeV, with beam reversal p-Pb and Pb-p.

Ie, 2 new optics and 3 setups with full qualifications in 1 month.

Asymmetric beams, unequal frequency ramp, cogging for collisions off-momentum, etc.

Many filling schemes used for luminosity sharing.
Xe-Xe collisions in LHC, 13 October 2017 (16 h beam time total)

Future interest in lighter species

Papers at IPAC2018
http://accelconf.web.cern.ch/AccelConf/ipac2018/

MOPMF039 M. Schaumann et al, First Xenon-Xenon Collisions in the LHC

MOPMF038 N. Fuster-Martinez et al, Cleaning Performance of the Collimation System with Xe Beams at the Large Hadron Collider

TUPAF020 R. Alemany-Femandez et al, Performance of the CERN Low Energy Ion Ring (LEIR) with Xenon
Looking at loss maps along the ring: **no dangerous peaks with crystal**

First observation of channelling with nuclei – no fragmentation.

Very promising approach to what now appears to be the most severe intensity limit on future Pb beams.

Plan to test again with Pb beams during the 2018 run.
FUTURE PERFORMANCE (RUN 3+HL-LHC) FULFILLING THE ALICE 2012 LOI

For more details on the HL-LHC projections see HL-HE-LHC workshop 30/10/2017 https://indico.cern.ch/event/647676/contributions/2721132/ and other recent talks.
SPS momentum slip stacking for 50 ns bunch spacing

• Feasibility relies on
  – Large bandwidth of SPS 200 MHz travelling wave cavities
  – Low ion intensity (no need for feed-back, feed-forward, ...)
  – Independent cavity control (SPS LLRF upgrade in LS2)

• Macroparticle simulations show
  – Proof of principle (without intensity effects)
  – Longitudinal emittance blow-up (factor 2.5) at re-capture due to filamentation in large bucket
  – Bunch rotation at extraction becomes necessary for injection into LHC
  – Optimization of re-capture is crucial to keep losses <5%

H. Bartosik, Chamonix 2017
LIU baseline (Jan 2017) parameters at start of collisions

- **Simplified scenario** - see talk by H Bartosik, Chamonix 2017
  - All bunches are equal (consider single bunch pair simulation)
  - Initial bunch intensity (start of stable beams)
    \[ \langle N_b \rangle = 1.8 \times 10^8 = 95\% \times 1.9 \times 10^8 \text{ injected (c.f. design } 0.7 \times 10^8 \text{)} \]
  - Initial emittance (start of stable beams)
    \[ \varepsilon_{xn} = 1.65 \times 10^{-6} \text{m } (> \text{design, some blow up from injected } 1.5 \times 10^{-6} \text{m}) \]
  - Crossing angles 170, 100, 170 \( \mu \text{rad} \), operation at 7\( Z \)\( \text{TeV} \)
  - Other bunch parameters as Design Report nominal
  - Three **luminosity-sharing** scenarios, just for illustration of the possibilities (equal \( \beta^* \) scenario is nominal!):

\[
\beta^* = \begin{cases} 
(\infty, 0.5, \infty) & \text{m (only ALICE colliding)} \\
(1.0, 0.5, 1.0) & \text{m (ATLAS/CMS at half ALICE)} \\
(0.5, 0.5, 0.5) & \text{m (equal)}
\end{cases}
\]

- Some collisions in LHCb (not shown in detail)
23 injections of 56-bunch trains give total of 1232 in each beam.
1136 bunch pairs collide in ATLAS CMS, 1120 in ALICE, 81 in LHCb (longer lifetime).
Optics compatibility with p-p operation

- ATS optics will be used for p-p operation
- The $\beta^* = 0.5$ m values assumed for heavy-ion operation do not require ATS
  - Rather little gain from low $\beta^*$ in high burn-off regime
- However to minimise set-up we can use essentially the same squeeze as ATS (telescopic part of squeeze has not started yet)
  - Interaction region squeeze sequences
  - Must add a squeeze of ALICE as usual
- Necessary functionality is included in ATS optics design
  - ( Might consider further squeezing later.)

We will use this optics in 2018!
Completely new optics cycle compared with p-p optics has (almost) been commissioned.
Interplay of radiation damping, IBS, luminosity burn-off couples all 4 quantities. Different evolution according to luminosity-sharing scenario. (Does not include additional emittance growth usually seen in operation.)
Luminosities in an ideal (prolonged) fill

ALICE, levelling at maximum acceptable (rates around 50 kHz), assuming 1100 bunches colliding

Baseline is the orange scenario with similar luminosities in 3 experiments.

ATLAS or CMS, assumed levelling at similar levels to ALICE (not strictly necessary, just an assumption to simplify presentation).
Integrated luminosity in prolonged fills

Ultimate luminosity to share

\[ L_{\text{int, max}} = \frac{k_c N_b}{\sigma_c} \]

Fraction obtained is the luminous efficiency.
Effect of turn-around time on average luminosity

\[ \langle L \rangle = \frac{1}{T_f + T_p} \int_0^{T_p} L(t) \, dt \]

\[ \beta^* = (0.5, 0.5, 0.5) \text{ (equal)} \]

Turn around time =\( (3, 5, 7, 9) \text{ h} \)

Turn around time =\( 3 \text{ h} \)

Shown for each luminosity sharing scenario
Assumes the operators know that the next turn-around time will be the same value.

Break-down of the minimum turn-around time as for p-p

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp down/pre-cycle</td>
<td>60</td>
</tr>
<tr>
<td>Pre-Injection checks and preparation</td>
<td>15</td>
</tr>
<tr>
<td>Checks with set-up beam</td>
<td>15</td>
</tr>
<tr>
<td>Nominal injection sequence</td>
<td>45</td>
</tr>
<tr>
<td>Ramp preparation</td>
<td>5</td>
</tr>
<tr>
<td>Ramp</td>
<td>25</td>
</tr>
<tr>
<td>Squeeze/Adjust</td>
<td>40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>200</strong></td>
</tr>
</tbody>
</table>
Integrated luminosity in annual Pb-Pb run

\[ \beta^* = (0.5, 0.5, 0.5) \text{ m} \text{ scenario} \]

\[ L_{\text{int,annual}} = \eta \langle L \rangle T_{\text{run}} \]

\[ = (50\%) (3.0 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1})(24 \text{ day}) \]

\[ \approx 3.1 \text{ nb}^{-1} \text{ (c.f. target of 2.85 nb}^{-1}) \]

where we (pessimistically!) assume an operational efficiency \( \eta = 50\% \)
and \( T_{\text{run}} = 24 \text{ day} \) (i.e., no p-p reference run or similar).

Implies about 35 ideal fills (start-up absorbed in efficiency).

\[ \approx 12 \text{ nb}^{-1} \text{ in the 4 Pb-Pb runs}\]

foreseen after LS2.

Similar analysis for p-Pb suggests \( \sim 1 \text{ pb}^{-1} \) is possible in a full one-month run.

Operation efficiency in last Pb-Pb run in 2015 was 62\%. Even higher in 2016 p-Pb.
LHC will have done 12 ~one month heavy ion runs between 2010 and 2030 (LS4). 6/12 done very soon.

J.M. Jowett, Town Meeting: Relativistic Heavy Ion Physics 24/10/2018
UPC processes at the collision point

\[ \text{BFPP: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \rightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{81+} + e^+, \]
\[ \sigma = 281 \text{ b}, \quad \delta = 0.01235 \]

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

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

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

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

Strong luminosity burn-off of beam intensity.

Discussed for LHC since Chamonix 2003 ... see several references.

Hadronic cross section is 7.7 b (so luminosity debris contains much less power).
Steady-state losses during Pb-Pb Collisions in 2011

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

Beam loss monitors in the full LHC Ring

No time to fully discuss major topic of heavy-ion collimation in this talk.
Orbit bumps mitigate BFPP for CMS (or ATLAS)

- 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 2015 run

Plan to test this strategy further to fully validate the nominal HL-LHC levelled luminosity at ATLAS/CMS during the 2018 run (no further mitigation upgrades are planned for these experiments).
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 – to be ready for LS2 installation
- With levelled luminosity in ALICE, quenches were not seen in 2015
- TCLDs should allow luminosity increase for upgraded ALICE to run at 50 kHz

Also during LS2, further TCLD collimators will be installed between 11 T magnets in IR7 to improve Pb collimation (first application of Nb$_3$Sn superconductors in an operating accelerator).
BEYOND HL-LHC BASELINE: LIGHTER NUCLEI
Bunch intensity at SPS extraction for various species

- Experience with other species in LHC injectors for fixed target
  - Less stringent requirements on beam quality (emittance)

Postulate simple form for bunch intensity dependence on species charge only

\[ N_b(Z, A) = N_b(82, 208) \left( \frac{Z}{82} \right)^p \]

where \( p = \begin{cases} 1.9 & \text{fixed target experience} \\ 0.75 & \text{Xe run vs best Pb} \end{cases} \)

Use this highly simplified scaling to project future luminosity performance as a function of \( p \).
Assume that other quantities (like geometric beam size), filling scheme, other loss rates, etc, are equal.

Treat results only as tentative and indicative only!

Don’t go too low in \( Z \) with this!
Not everything in the periodic table will work well in the ion source.
\[ \frac{dN}{dt} = -\left( \sigma_{\text{had}} + \sigma_{\text{EMD}} + \sigma_{\text{BFPP}} \right) L - \frac{N}{\tau_{\text{other}}} , \]  
\[ L = \frac{N^2 f_0}{4\pi\beta^2 \varepsilon_{xn} k_c} \]

\[ \sigma_{\text{EMD}} \approx (3.42 \, \mu b) \frac{(A-Z) Z^3}{A^{2/3}} \log(2\gamma^2 - 1) , \]

\[ \sigma_{\text{EMD}} \approx 1.95 \, \sigma_{\text{EMD}}^{1} \text{ (total for all EMD channels)} \]

\[ \sigma_{\text{BFPP}} \approx Z^7 (A \log(2\gamma^2 - 1) + B) \]

List of species are examples that are of interest.

Some species (e.g., Cu) are difficult to produce in the ECR heavy ion source.

Noble gases are particularly favourable.

**Cross section scalings from papers by G. Baur et al, S. Klein, I. Pshenichnov, ....**

<table>
<thead>
<tr>
<th>Species</th>
<th>( \gamma )</th>
<th>( \sigma_{\text{E0}} / b )</th>
<th>( \sigma_{\text{BFPP}} / b )</th>
<th>( \sigma_{\text{had}} / b )</th>
<th>( \sigma_{\text{tot}} / b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{16}\text{O}^{8-})</td>
<td>3000.</td>
<td>0.074</td>
<td>0.000024</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>(^{40}\text{Ar}^{18+})</td>
<td>3400.</td>
<td>1.2</td>
<td>0.0069</td>
<td>2.6</td>
<td>3.8</td>
</tr>
<tr>
<td>(^{48}\text{Cu}^{23+})</td>
<td>3800.</td>
<td>1.6</td>
<td>0.014</td>
<td>2.6</td>
<td>4.2</td>
</tr>
<tr>
<td>(^{78}\text{Kr}^{35+})</td>
<td>3500.</td>
<td>12.</td>
<td>0.88</td>
<td>4.1</td>
<td>17.</td>
</tr>
<tr>
<td>(^{84}\text{Kr}^{35+})</td>
<td>3200.</td>
<td>13.</td>
<td>0.88</td>
<td>4.3</td>
<td>18.</td>
</tr>
<tr>
<td>(^{129}\text{Xe}^{54+})</td>
<td>3100.</td>
<td>52.</td>
<td>15.</td>
<td>5.7</td>
<td>73.</td>
</tr>
<tr>
<td>(^{208}\text{Pb}^{32+})</td>
<td>3000.</td>
<td>220.</td>
<td>280.</td>
<td>7.8</td>
<td>510.</td>
</tr>
</tbody>
</table>

Pb is worse in this respect because of high BFPP and EMD cross-sections.
Makes short fills, more time spend refilling, ramping, etc.
Higher nucleon-nucleon luminosity with lighter ions

• Extrapolations of present experience to possible future fully-prepared “one-month run” conditions with lighter species.

• Preliminary estimates for a range of the scaling factor $p$. $p = 1.5$ seems reasonable.

• Detailed operational cycles to be worked out.

• Longer fills from smaller UPC cross-sections. Plus: more luminosity events are hadronic.

• Possible limits from collimation losses, radio-protection in Linac3/LEIR (lightest species), etc, are still to be properly analysed on species-by-species basis.
Higher nucleon-nucleon luminosity with lighter ions

• Extrapolations of present experience to possible future fully-prepared “one-month run” conditions with lighter species.
  – No discussion of calendar here.

• Simplified comparatives estimates for a range of the scaling factor $p$. $p = 1.5$ seems reasonable.

• Detailed operational cycles to be worked out.

• Longer fills from smaller UPC cross-sections. Plus: more luminosity events are hadronic.

• Possible limits from collimation losses, radio-protection in Linac3/LEIR (lightest species), etc, are still to be properly analysed on species-by-species basis.
Simplified scenario:

Fill lengths optimized for 2.5 h turn-around (dump to next Stable Beams).

Analytical estimates assuming beam losses dominated by luminosity burn-off (no simulations of other physics as for canonical Pb-Pb projections).

Assume 3 experiments taking full luminosity - no levelling of any experiment!

Overall operational efficiency factor 50% (standard HL-LHC assumption).

Gives reasonable indication of potential increase in integrated NN-luminosity from lighter species.
Pessimistic “no-gain” scaling (p=1)

<table>
<thead>
<tr>
<th></th>
<th>$^{16}$O$^{8+}$</th>
<th>$^{40}$Ar$^{18+}$</th>
<th>$^{48}$Ca$^{20+}$</th>
<th>$^{78}$Kr$^{36+}$</th>
<th>$^{86}$Kr$^{38+}$</th>
<th>$^{129}$Xe$^{54+}$</th>
<th>$^{208}$Pb$^{84+}$</th>
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<tr>
<td>$\gamma$</td>
<td>3760.</td>
<td>3390.</td>
<td>3760.</td>
<td>3470.</td>
<td>3220.</td>
<td>3150.</td>
<td>2960.</td>
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<tr>
<td>$\sqrt{s_{NN}}$ / TeV</td>
<td>7.</td>
<td>6.3</td>
<td>7.</td>
<td>6.46</td>
<td>6.</td>
<td>5.86</td>
<td>5.52</td>
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<tr>
<td>$c_{\text{ran}}$ / b</td>
<td>1.41</td>
<td>2.6</td>
<td>2.6</td>
<td>4.06</td>
<td>4.26</td>
<td>5.67</td>
<td>7.8</td>
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<tr>
<td>$c_{\text{tot}}$ / b</td>
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<td>18.3</td>
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<td>1.71</td>
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<td>1.58</td>
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<td>0.0841</td>
<td>0.0857</td>
<td>0.088</td>
<td>0.0798</td>
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<td>$W_b$ / MJ</td>
<td>21.5</td>
<td>21.5</td>
<td>21.5</td>
<td>21.5</td>
<td>21.5</td>
<td>21.5</td>
<td>21.5</td>
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<tr>
<td>$L_{\text{Mn}}$ / cm$^2$-s$^{-1}$</td>
<td>$1.43 \times 10^{33}$</td>
<td>$2.82 \times 10^{33}$</td>
<td>$2.29 \times 10^{28}$</td>
<td>$7.66 \times 10^{28}$</td>
<td>$7.66 \times 10^{28}$</td>
<td>$3.14 \times 10^{28}$</td>
<td>$1.36 \times 10^{28}$</td>
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<td>$L_{\text{NN}}$ / cm$^2$-s$^{-1}$</td>
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<td>$4.52 \times 10^{32}$</td>
<td>$3.66 \times 10^{32}$</td>
<td>$4.3 \times 10^{32}$</td>
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<td>$P_{\text{BFPP}}$ / W</td>
<td>0.000302</td>
<td>0.0392</td>
<td>0.0738</td>
<td>2.51</td>
<td>2.51</td>
<td>28.6</td>
<td>350.</td>
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<tr>
<td>$P_{\text{BFPP}}$ / W</td>
<td>0.485</td>
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<td>$\tau_{\text{LB}}$ / h</td>
<td>52.4</td>
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<td>19.1</td>
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<td>1.57</td>
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<tr>
<td>$T_{\text{cpl}}$ / h</td>
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<td>15.1</td>
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<td>$3.8 \times 10^{27}$</td>
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<tr>
<td>$\langle L_{\text{NN}} \rangle$ / cm$^2$-s$^{-1}$</td>
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<td>$3.33 \times 10^{32}$</td>
<td>$2.7 \times 10^{32}$</td>
<td>$2.76 \times 10^{32}$</td>
<td>$3.16 \times 10^{32}$</td>
<td>$2.6 \times 10^{32}$</td>
<td>$1.64 \times 10^{32}$</td>
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<tr>
<td>$\int_{\text{month}} L_{\text{Mn}} dt / nb^{-1}$</td>
<td>1390.</td>
<td>269.</td>
<td>219.</td>
<td>58.8</td>
<td>58.1</td>
<td>20.3</td>
<td>4.92</td>
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<tr>
<td>$\int_{\text{month}} L_{\text{NN}} dt / pb^{-1}$</td>
<td>356.</td>
<td>431.</td>
<td>350.</td>
<td>358.</td>
<td>410.</td>
<td>338.</td>
<td>213.</td>
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<tr>
<td>$R_{\text{had}}$ / kHz</td>
<td>2020.</td>
<td>734.</td>
<td>595.</td>
<td>286.</td>
<td>301.</td>
<td>178.</td>
<td>106.</td>
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<td>$\mu$</td>
<td>0.16</td>
<td>0.0583</td>
<td>0.0472</td>
<td>0.0227</td>
<td>0.0239</td>
<td>0.0141</td>
<td>0.00842</td>
</tr>
</tbody>
</table>

Stored energy in beam $W_b$ is identical in this case $\Rightarrow$ Collimation risks $\sim$ comparable.  
$f_{\text{IBS}}$ indicates strength of IBS emittance growth – all cases better than Pb.  
Overestimates integrated luminosity for Pb-Pb wrt official values (since no levelling, etc).  
Initial event rates are high! Much longer fills.
Plausible scaling (p=1.5)

<table>
<thead>
<tr>
<th></th>
<th>$^{16}$O$^{8+}$</th>
<th>$^{40}$Ar$^{18+}$</th>
<th>$^{40}$Ca$^{28+}$</th>
<th>$^{78}$Kr$^{35+}$</th>
<th>$^{81}$Kr$^{35+}$</th>
<th>$^{129}$Xe$^{44+}$</th>
<th>$^{208}$Pb$^{82+}$</th>
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<tr>
<td>$\gamma$</td>
<td>3750.</td>
<td>3390.</td>
<td>3750.</td>
<td>3470.</td>
<td>3220.</td>
<td>3150.</td>
<td>2960.</td>
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<td>$\sqrt{s_{NN}}/\text{TeV}$</td>
<td>7.</td>
<td>6.3</td>
<td>7.</td>
<td>6.45</td>
<td>6.</td>
<td>5.86</td>
<td>5.52</td>
</tr>
<tr>
<td>$c_{\text{had}}/b$</td>
<td>1.41</td>
<td>1.65</td>
<td>1.48</td>
<td>3.85</td>
<td>5.42</td>
<td>6.24</td>
<td>7.8</td>
</tr>
<tr>
<td>$c_{\text{tot}}/b$</td>
<td>2.6</td>
<td>2.5</td>
<td>4.05</td>
<td>4.18</td>
<td>6.53</td>
<td>6.53</td>
<td>568.</td>
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<tr>
<td>$N_b$</td>
<td>$6.24 \times 10^9$</td>
<td>$1.85 \times 10^9$</td>
<td>$1.58 \times 10^9$</td>
<td>$6.53 \times 10^8$</td>
<td>$6.53 \times 10^8$</td>
<td>$3.56 \times 10^8$</td>
<td>$1.9 \times 10^8$</td>
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<tr>
<td>$e_{\text{em}}/\mu$m</td>
<td>1.8</td>
<td>2</td>
<td>2</td>
<td>1.85</td>
<td>1.71</td>
<td>1.67</td>
<td>1.58</td>
</tr>
<tr>
<td>$f_{\text{IBS}}/\langle m/\text{Hz} \rangle$</td>
<td>0.0862</td>
<td>0.0894</td>
<td>0.105</td>
<td>0.13</td>
<td>0.12</td>
<td>0.114</td>
<td>0.167</td>
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<tr>
<td>$W_b/MJ$</td>
<td>58.9</td>
<td>45.9</td>
<td>43.6</td>
<td>32.5</td>
<td>32.5</td>
<td>26.5</td>
<td>21.5</td>
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<tr>
<td>$L_{\text{A}}/\text{cm}^2\text{s}^{-1}$</td>
<td>$1.46 \times 10^{31}$</td>
<td>$1.29 \times 10^{30}$</td>
<td>$9.38 \times 10^{29}$</td>
<td>$6.61 \times 10^{20}$</td>
<td>$6.61 \times 10^{20}$</td>
<td>$4.76 \times 10^{20}$</td>
<td>$3.6 \times 10^{20}$</td>
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<td>$L_{\text{NN}}/\text{cm}^2\text{s}^{-1}$</td>
<td>$3.75 \times 10^{33}$</td>
<td>$2.86 \times 10^{33}$</td>
<td>$1.5 \times 10^{33}$</td>
<td>$9.79 \times 10^{32}$</td>
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<td>$7.93 \times 10^{32}$</td>
<td>$5.88 \times 10^{32}$</td>
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<td>$P_{\text{IBS}}/W$</td>
<td>0.0031</td>
<td>0.179</td>
<td>0.303</td>
<td>5.72</td>
<td>5.72</td>
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<td>$P_{\text{Em}}/W$</td>
<td>4.98</td>
<td>15.5</td>
<td>16.9</td>
<td>40.5</td>
<td>43.7</td>
<td>67.6</td>
<td>141.</td>
</tr>
<tr>
<td>$\tau_{\text{L}}/\text{h}$</td>
<td>15.4</td>
<td>21.3</td>
<td>23</td>
<td>13.5</td>
<td>12.7</td>
<td>5.87</td>
<td>1.57</td>
</tr>
<tr>
<td>$T_{\text{Co}}/\text{h}$</td>
<td>9.04</td>
<td>10.3</td>
<td>10.7</td>
<td>8.23</td>
<td>7.96</td>
<td>5.42</td>
<td>2.8</td>
</tr>
<tr>
<td>$\langle L_{\text{A}}\rangle/\text{cm}^2\text{s}^{-1}$</td>
<td>$8.99 \times 10^{28}$</td>
<td>$8.34 \times 10^{28}$</td>
<td>$6.17 \times 10^{28}$</td>
<td>$9.46 \times 10^{28}$</td>
<td>$9.32 \times 10^{28}$</td>
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<td>$3.8 \times 10^{27}$</td>
</tr>
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<td>$\langle L_{\text{NN}}\rangle/\text{cm}^2\text{s}^{-1}$</td>
<td>$2.3 \times 10^{32}$</td>
<td>$1.33 \times 10^{32}$</td>
<td>$9.87 \times 10^{32}$</td>
<td>$5.76 \times 10^{32}$</td>
<td>$6.57 \times 10^{32}$</td>
<td>$3.71 \times 10^{32}$</td>
<td>$1.64 \times 10^{32}$</td>
</tr>
<tr>
<td>$\int_{\text{month}} L_{\text{A}} , dt/\text{nb}^{-1}$</td>
<td>11700.</td>
<td>1380.</td>
<td>799.</td>
<td>123.</td>
<td>121.</td>
<td>28.9</td>
<td>4.92</td>
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<tr>
<td>$\int_{\text{month}} L_{\text{NN}} , dt/\text{nb}^{-1}$</td>
<td>2980.</td>
<td>1730.</td>
<td>1280.</td>
<td>746.</td>
<td>852.</td>
<td>481.</td>
<td>213.</td>
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<tr>
<td>$R_{\text{had}}/\text{kHz}$</td>
<td>20700.</td>
<td>3340.</td>
<td>2440.</td>
<td>653.</td>
<td>686.</td>
<td>270.</td>
<td>166.</td>
</tr>
<tr>
<td>$\mu$</td>
<td>1.64</td>
<td>0.266</td>
<td>0.194</td>
<td>0.0518</td>
<td>0.0544</td>
<td>0.0215</td>
<td>0.00842</td>
</tr>
</tbody>
</table>

Stored energy in beam $W_b$ increased in this case $\Rightarrow$ Collimation risks higher

$f_{\text{IBS}}$ indicates strength of IBS emittance growth – still better than Pb.

NB still no luminosity levelling, etc. High event rates! Some pileup $\mu \sim 1$. Fills still longer.
Optimistic scaling (p=1.9)

Stored energy in beam $W_b$ several times Pb $\Rightarrow$ Collimation risks higher, may need new solutions

$f_{\text{IBS}}$ indicates strength of IBS emittance growth – comparable to Pb.

NB still no luminosity levelling, etc. High event rates! Some pileup $\mu \sim 1$. Fills still longer.
Caveats about lighter species

• Collimation is more complicated, needs careful study
  – See first measurements with Xe vs. Pb in MOPMF038 paper in IPAC2018
  – Simulations done for Ar, Xe (by Pascal Hermes) have not yet included effects of DS collimators in IR7.
    • Planned for study (N. Fuster-Martinez)
  – Crystal collimation (tested with Xe) may be a solution for the future (Pb also)
  – It takes time to change species in the injector chain, therefore it is hard to gain experience.
  – The dramatic improvements in transmitted Pb intensity in 2015-16 were the result of many detailed studies and improvements.
Special runs with other species

• The 2012 p-Pb run and the 2017 Xe-Xe run used a special rapid-commissioning strategy to go from scratch to physics delivery in a 16 h shift.
  – Limits on total stored energy in beam to avoid lengthy validation.
  – May have to use the operational p-p optics (not so good for ALICE)

• Other short runs can be envisaged within these constraints

• Example of current interest
  – O-O run: needs to be separated in time from Pb-Pb to allow lengthy switchover of ion source and injector chain. Springtime of a typical year?
  – Could be followed by short p-O run of interest for cosmic ray physics
Conclusions

• It has been possible to rapidly recommission the LHC in multiple new heavy-ion configurations very efficiently and substantially exceed design performance.

• The baseline performance goals for Pb-Pb integrated luminosity from the ALICE LoI of 2012 appear to be within reach by end of Run 4
  – Most features already available for 2018 Pb-Pb run
  – Greatest remaining uncertainties: collimation in LHC, slip-stacking in SPS.

• We can go further with p-Pb luminosity than we did in 2016.

• The feasibility of runs with lighter species has been demonstrated with Xe-Xe in 2017.
  – There is very good hope for substantially higher integrated nucleon-nucleon luminosity than with Pb-Pb but further studies (and resources) are certainly required.

• Scope for special short runs (O-O,p-O, ...) at small cost in LHC time and within certain limits of intensity and scheduling.
BACKUP SLIDES
References in these slides

• References to International Particle Accelerator Conferences (IPAC) up to 2017 can be found at

• References to IPAC2018 (two weeks ago) can be found in the pre-press proceedings
  – http://accelconf.web.cern.ch/AccelConf/ipac2018/

• Fairly comprehensive list of references on LHC heavy ion programme to date in IPAC2018 survey talk TUXGBD2
Summary (from QM2018)

• Since its startup in 2009, the Large Hadron Collider at CERN has spent about 3 months of its operating time providing nucleus-nucleus (Pb-Pb) collisions.

• Peak Pb-Pb luminosity is now over 3 times design and integrated luminosity is expected to attain the initial design goal of 1 nb-1 in the 4th Pb-Pb run in late 2018.

• Following the demonstration of their feasibility in 2012, two one-month runs have been devoted to proton-nucleus (p-Pb) collisions in multiple conditions, with luminosity far beyond expectations.

• Recently, Xe-Xe collisions have also been demonstrated in a short run.

• All the LHC experiments now participate fully in the heavy-ion programme.

• With this experience in hand, strategies to overcome physical performance limits established, and upgrades to the LHC and its injector chain in the pipeline, it is timely to take stock of the prospects and challenges for future performance of the LHC with nuclear beams.
Heavy-ion runs of LHC are very short but very complex. Experiments have many requests for changes of conditions.

This run was preceded by a week of equivalent energy p-p collisions to provide reference data.

Completely different from classical operation of Tevatron or LHC p-p.
Pb bunch intensity in LHC during 2016 p-Pb run

R. Alemany, M. Schaumann
Common BPMs and moving encounters had constrained charge of p and Pb bunches to be similar.

Increase in p intensity to \(~3 \times 10^{10}/\text{bunch}\) enabled by new synchronous orbit mode of beam position monitors (R. Alemany, J. Wenninger, beam instrumentation group ...)

Pb intensity to \(~2.1 \times 10^8/\text{bunch}\)

25% increase in ATLAS/CMS from filling scheme

Peak luminosity a factor ~6 beyond original “design” value


Could have gone higher still by further increase of p intensity but limited at present by Pb beam luminosity debris in magnets of Sector 12.
### Goals of 2016 p-Pb run surpassed

<table>
<thead>
<tr>
<th>$\sqrt{s_{\text{NN}}}$</th>
<th>Experiments</th>
<th>Primary goal</th>
<th>Achieved</th>
<th>Additional achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 TeV p-Pb</td>
<td>ALICE (priority)</td>
<td>700 M min bias events</td>
<td>780 M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ATLAS, CMS</td>
<td></td>
<td></td>
<td>&gt;0.4 /nb min bias</td>
</tr>
<tr>
<td></td>
<td>LHCb</td>
<td></td>
<td></td>
<td>SMOG p-He etc</td>
</tr>
<tr>
<td>8 TeV p-Pb or Pb-p</td>
<td>ATLAS, CMS</td>
<td>100 /nb</td>
<td>194,183 /nb</td>
<td></td>
</tr>
<tr>
<td>or Pb-p</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Beam energy 6.5 Z TeV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 TeV p-Pb</td>
<td>ALICE, LHCb</td>
<td>10 /nb</td>
<td>14,13 /nb</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LHCf</td>
<td>9-12 h @ $10^{28}$ cm$^{-2}$ s$^{-1}$</td>
<td>9.5 h @ $10^{28}$ cm$^{-2}$ s$^{-1}$</td>
<td>Min bias ATLAS, CMS, ALICE</td>
</tr>
<tr>
<td>8 TeV Pb-p</td>
<td>ALICE, LHCb</td>
<td>10 /nb</td>
<td>25,19 /nb</td>
<td></td>
</tr>
</tbody>
</table>

Note: ALICE and LHCb are asymmetric experiments, with different coverage according to beam direction.

Reminder: first 1 month p-Pb/Pb-p run at 5 TeV in 2013 gave 31/nb to ALICE, ATLAS, CMS and 2/nb to LHCb.
Beam intensity roughly as expected.

See discussion of cross-sections later.
Xe lifetime analysis

Table 2: Beam-beam equivalence classes with their respective colour code used throughout the paper. In addition, the sum of inverse-$\beta^*$ and the intensity lifetimes during Stable Beams of fill 6295 are displayed. The intensity lifetime of the non-colliding class (class 0) is obtained via linear fit of the loss rates (see Fig. 4).

<table>
<thead>
<tr>
<th>Class</th>
<th>IPs</th>
<th>$\sum_i \frac{1}{\beta_i^*}$ [m$^{-1}$]</th>
<th>$\tau$ [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>0</td>
<td>87.8 ± 5.9</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>0.10</td>
<td>79.2 ± 4.6</td>
</tr>
<tr>
<td>2</td>
<td>2/8</td>
<td>0.43</td>
<td>72.1 ± 3.8</td>
</tr>
<tr>
<td>3</td>
<td>1/2/5</td>
<td>6.77</td>
<td>17.5 ± 0.8</td>
</tr>
<tr>
<td>4</td>
<td>1/2/5/8</td>
<td>7.10</td>
<td>16.3 ± 1.1</td>
</tr>
</tbody>
</table>

Figure 4: Relative loss rates versus $\sum_{IP} 1/\beta_{IP}^*$ during Stable Beams of fill 6295. Triangles indicate Beam 1 and circles Beam 2. The dashed lines are linear fits to obtain the non-colliding intensity lifetime.

Figure 3: Bunch-intensity evolution of Beam 1 during fill 6295 after declaration of Stable Beams. The colour of each class is listed in Table 2.

Shows that beam intensity decay was dominated by luminosity burn-off (other effects on 100 h time scale).
Luminosity lifetime ~agrees with $p=0.75$ value (later in this talk).

Analysis by Marc Jebramcik, Michaela Schaumann. See IPAC2018 paper.
Conclusions

• It has been possible to rapidly recommission the LHC in multiple new configurations very efficiently.
• The baseline performance goals for Pb-Pb integrated luminosity from the ALICE LoI of 2012 appear to be within reach
  – Most of them already available for 2018 Pb-Pb run
  – Greatest remaining uncertainties: collimation in LHC, slip-stacking in SPS.
• We can go further with p-Pb luminosity than we did in 2016.
• The feasibility of runs with lighter species has been demonstrated with Xe-Xe in 2017.
  – There is very good hope for substantially higher integrated nucleon-nucleon luminosity than with Pb-Pb but further studies (and resources) are certainly required.
• Not discussed: it is easy to switch from Pb to O so short p-O runs (for cosmic ray physics, etc) should be feasible (using the model of p-Pb in 2012, Xe-Xe in 2017).
• Prepares beams for LHC using electron cooling
• circumference 25 pm (1/8 PS)
• 70 turn injection into horizontal+vertical+longitudinal phase planes
• Fast Electron Cooling: Electron current from 0.5 to 0.6 A with variable density
• RF capture
• Dynamic vacuum (NEG, Au-coated collimators, scrubbing)
Intensity transmission: injection to collision, Pb in 2016

Data from 2016 p-Pb run, for Pb beam only. Expect Pb-Pb to be generally better.

Previous estimates of future Pb-Pb performance assumed 90% transmission from injection to collision.

Data justify using 95% now (previously 90%).

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>100% due to FBCT re-calibration
• 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):
\[ L \approx 2.3 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1} \]
\[ \Rightarrow 0.64 \text{ MHz event rate, about 45 W of power in Pb}^{81+} \text{ beam into magnet} \]
Resolved decades of uncertainty about steady-state quench level of LHC dipole magnets. Later a second collimation quench test with Pb was also successful.
DS collimators

• **IP7**, for both proton and heavy-ion collimation losses
  - Design, fabricate, test, and install during **LS2**, around **IP7**, two 11 T Dipole Full Assemblies (replace the MBs MBA-B8L7 and MBB-B8R7)
  - Fabricate and test one spare 11 T Dipole Full Assembly
  - Plan includes 14 magnet models, and 21 full-length prototype

• **IP2**, for heavy-ion secondary beams
  - Design, fabricate, and install during **LS2**, around **IP2**, two Connection Cryostat Full Assemblies, i.e. no 11 T Dipole magnet needed for this
  - Fabricate one spare Connection Cryostat Full Assembly
  - A Connection Cryostat Full Assembly contains two new connection cryostats, **LEP**, and one by-pass cryostat, **LEN**
Spectrometer ON_ALICE=-7/6.37 (start of 2015 Pb-Pb run)

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

Include downward shift of IP by -2 mm (detector sank).

Constraints on crossing angle to allow spectator neutron cone to reach Zero Degree Calorimeters.