The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.
Session Goal:

- Review the HL-LHC upgrade plans related to the ion physics program and summarize the required machine upgrades.
- Analyze the options for extended ion runs during the connection of LINAC4 to the PSB.
- Review the schedule and operation options for the ion beam operation during the HL-LHC period.

Session Content:

- Experiment perspective.
- Performance of the injectors with ions after LS1.
- [Options for running the LHC with ions during the LINAC4 connection].
- How to run ions in the future?
- Future heavy-ion performance of the LHC.
Experiments: [Emilio Meschi]

• Physics highlights:
  • Quark-Gluon plasma and phase transition and the search for the critical point.

• Physics requirements - wishes:
  • Need for control experiments (p-p data taking and p-Pb runs and runs at intermediate beam energies [e.g. Pb-Pb @ 5Tev, 5.5 TeV, p-Pb @ 5 TeV and 8.2 TeV]).
    ➔ all asymmetric collision configurations imply configuration change between Beam1 and Beam2!
  • Requires different machine configurations as compared to p-p operation!
  • p-p runs require 5 order of magnitude lower luminosity in ALICE as for the GP experiments ➔ Is it worth the effort?
  • Background considerations require a vacuum of 5 \times 10^{-9} or better.
### Physics:

![Phase diagram showing the transition from hadron gas to QGP](image.png)

**Run 2: ALICE**

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<thead>
<tr>
<th>Year</th>
<th>System</th>
<th>Luminosity</th>
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<tbody>
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<td>2015</td>
<td>pp – min bias (24 weeks)</td>
<td>$10^{29}$-$10^{30}$ cm$^{-2}$s$^{-1}$</td>
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<tr>
<td></td>
<td>p Pb – rare triggers (2 weeks)</td>
<td>$1 10^{29}$ cm$^{-2}$s$^{-1}$ - leveled</td>
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<tr>
<td>2018</td>
<td>LS 2</td>
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</tbody>
</table>
Experiments Perspective:

• Performance wishes:
  • 3nbarn$^{-1}$ by LS3 in ATLAS. All experiments like to collect at least 1nbarn$^{-1}$ during RunII.
  • 10nbarn$^{-1}$ for ALICE after upgrade during LS2.
  • LHCb: p-Pb NOT at the end of ion program of RunII ➔ compatibility with ALICE plan?
  • ALICE requires leveling during Pb-Pb and p-Pb (while ATLAS and CMS do not) ➔ coordination!!!
  • The Pb-Pb runs in 2015 and 2016 can NOT be grouped (trigger configurations) ➔ what is the minimum run separation times?
  • LHCb would like 10 times more integrated luminosity with p-Pb as compared to Run1.
  • All experiments prefer NOT to group the ion runs
  • ALICE polarity reversals on regular basis.

• Performance wishes after LS2:
  • Different beam species: Pb-Pb, p-Pb, Ar-Ar, p-Ar
  • 10 fold increase in beam performance expected from ALICE ➔ collimation upgrade and vacuum conditions?
  • LHCf interested in running with Nitrogen and Oxygen? ➔ Physics case @ LHCC required!
Performance of the injectors with ions after LS1: [Django]

- **Performance summary of RunI:**
  - 2 bunches with 200ns spacing in the PS ➔ 24 bunches in the SPS ➔ 360 bunches in the LHC @ collision

- **Upgrade Plans:**
  - Increasing the bunch intensity is not a viable option (IBS and luminosity burn off)
  - 100ns batch compression in the SPS (already envisaged for RunII in the PS but without the SPS injection upgrade ➔ 432 bunches for RunII).
  - Increasing the number of injections would increase the injection time and thus the emittance growth ➔ keep the number of PS injections into the SPS at 12 ➔ requires SPS injection system upgrade (recuperated equipment from PSB energy upgrade, not requiring new kicker magnets) ➔ 624 bunches in the LHC @ collision
  - Requires higher bunch intensities in LEIR (already above design and currently limited) ➔ further studies required
  - Slip stacking in the SPS to be re-evaluated ➔ smaller bunch spacing (e.g. 50ns?)
  - LINAC3 pulsing @ 10Hz (source already pulsing @ 10Hz)
How to run ions in the future? [Detlef Kuchler]

- **Performance summary of RunI:**
  - **Records:**
    - 215 eµA Pb\(^{27+}\) out of the spectrometer
    - 31 eµA Pb\(^{54+}\) at the end of the linac
  - **Operational:**
    - 100-120 eµA Pb\(^{29+}\) out of the RFQ
    - 20-25 eµA Pb\(^{54+}\) at the end of the linac (TRA25) (≈ 50% of the design value)
    - Changing ion species takes time (4 weeks Pb-> Ar & 10 weeks Ar -> Pb)

- **Upgrade Plans:**
  - 10Hz operation of the LINAC3 (source already running @10Hz)
  - Multi-charge acceleration.
  - **New Oven design and test-stand (ca. 5MCHF)!**

- **Wishes and requirements:**
  - Dedicated ion run in 2015 for Machine Development and tests
Future heavy-ion performance of the LHC: [John Jowett]

- **RunII performance projections:**
  - Bunch-by-bunch luminosity model (IBS and SPS injection)
  - $2.8 \times 10^{27}$ cm$^{-2}$ s$^{-1}$ for ATLAS and CMS for Pb-Pb @ 6.5 Z TeV with 2011 scheme
  - $3.7 \times 10^{27}$ cm$^{-2}$ s$^{-1}$ for ATLAS and CMS for Pb-Pb @ 6.5 Z TeV with 100ns BC.
  - Changing the magnetic configuration wrt the standard p-p run will take 1 to 2 days.
  - Before ALICE upgrade luminosity needs to be leveled at $1 \times 10^{27}$ cm$^{-2}$ s$^{-1}$ (ATLAS and CMS are not limited in peak luminosity).
  - Luminosity decay dominated by burn-off
  - p-Pb: $2.5 - 7 \times 10^{29}$ cm$^{-2}$ s$^{-1}$ @ 4 Z TeV/c and $4.3 - 12 \times 10^{29}$ cm$^{-2}$ s$^{-1}$ @ 7 Z TeV/c
    ➔ BPM resolution!

- **RunIII projections:**
  - $6 \times 10^{27}$ cm$^{-2}$ s$^{-1}$ for Pb-Pb @ 6.5 Z TeV with 100ns batch compression and SPS injection system upgrade (6 x design).

- **Peak luminosity limitations:**
  - Bound Free Pair Production and Electro Magnetic Disintegration and resulting secondary beams ➔ DS collimators
  - IBS!!! ➔ possibility of Stochastic Cooling a la RHIC, 200MHz and 800MHz RF in LHC?
Summary and Questions:

- LS1.5 (9-month shutdown between LS1 and LS2) is not desired by experiments.
- ALICE needs a clear commitment to a ‘standard running scenario’ but exceptional modifications for a given year are possible.
- Promising upgrade options for the machine should be further pursued (e.g. Stochastic cooling, 200MHz and 800MHz RF).
- Operation with different ion species needs to be requested well in advance! LHCC recommendation?
- Beam rigidity and machine configuration requests?
- DS collimators for IR1 and IR5 not yet foreseen!
- Injector: one could connect LINAC4 (50MeV protons) in 12 weeks but at reduced performance and without gain for LS2
  ➔ LINAC2 backup and BCMS still to be analyzed
- LS2 duration with LINAC4 connection (as H- injector) will take 20.5 month (LINAC4 proper will take 9 month)
Reserve Transparencies
Heavy Ion Physics

- **QGP: what is it**
  - A theoretical model of the phase of matter where partons are not (completely) confined
  - Produced in High-energy nucleus-nucleus interactions
  - Large energy density (~15 GeV/fm³ at LHC) over a large volume (~ 5000 fm³ at LHC)
  - Very high equivalent temperature (T~300 MeV)
  - Strongly interacting

- **How it is studied**
  - **Jets**: energy loss mechanism - collective effects in QCD, medium density
  - **Heavy flavour**: mass dependence of energy loss - probe the medium transport properties
  - **Quarkonium**: quarkonium dissociation and regeneration - probes deconfinement and medium temperature
  - **Low-mass di-leptons**: thermal radiation γ (→e+e-) - to map temperature and evolution
  - **Proton-Ion**: collective effects

- pp physics probes quarks and gluons as “free particles”
- Nuclear physics studies the bound states
- HI physics studies the intermediate phases of QCD matter which prevailed shortly after the big-bang
### Run 2: ALICE

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- For 2015 pp need 5 orders of magnitude luminosity reduction in IP2
- no filling scheme tricks available at 25ns ~all bunches collide in ALICE (except effect of abort gap)
- Larger $\beta^*$ not an option due to aperture issues in IP2
- A separation of order 5\sigma seems to be needed
- Would the level of background in IP2 be lower than signal? Will depend on quality of vacuum
- ALICE studied the beam-gas background conditions in LSS2-L assuming a 5 $10^{-9}$ vacuum.
  - the result is a rather strong MB trigger contamination (~50%) at L=1 $10^{29}$. on the other hand the contamination at L=1 $10^{30}$ is ~10%, but a pileup of 10 in the TPC is the price to pay.
- Further studies of optimization will be performed based on these results
Upgrades and studies

- Linac 3: increase intensity
  - 10Hz pulsing (included in consolidation - PIC)
  - multiple charge acceleration (unsure of benefit for LEIR)

- LEIR: Intensity limitation
  - ~+40% needed for additional splitting, but cause presently unknown

- PS: 50ns splitting or batch compression near transition
  - Tests of 2-bunch batch compression to 50ns with Ar
  - New cavity (Finemet)
    - Transition-distortion optics; imperfections?

- SPS
  - PFL on MKP + MSI-V septum for 100ns rise time injection / batch spacing
  - New beam control allowing RF gymnastics for slip-stacking
    - Are resulting imperfections after slip stacking acceptable by the LHC?
  - Improvement of beam behaviour on flat bottom (RF noise...)
Pb-Pb Summary: Peak luminosity & intensity (w.r.t. nominal) according to different schemes

- **Nominal**
- **Slip stacking**
- **50ns batch compression in the PS**
- **Proposed Baseline (100ns)**
- **2011/2013**
- **2015**

- **Peak luminosity**
- **Intensity/LHC ring**

- **Batch spacing in the SPS (ns)**
Schedule with LS1.5

Ar 2014-2015 ... first Pb-Pb run in November 2015 same as baseline

- Xe commissioning (Linac3/LEIR/PS/SPS) start early 2016 + FT Run in September 2016
- Switch to Pb November 2016, recommission Pb ion chain
- Stop protons 3 weeks before Xmas break
- Pb source standby during Xmas (cf Xmas 2012)
- Restart Pb ion chain in January

- 3.5 (max) months Pb run:
  - Ion MDs in chain
  - Primary Pb in NA
  - 8+ week LHC Pb-Pb run (grouping of 2016 & 2017 “November” runs)
  - Restart with protons, next Pb ion run as p-Pb just before LS2 (2019?)

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(B.Mikulec, J.B.Lallement)
## Design Baseline and Performance Achieved

“p-Pb not part of baseline”

<table>
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<tr>
<th></th>
<th>Pb-Pb Baseline</th>
<th>Injection 2011</th>
<th>Collision 2011</th>
<th>Injection 2013</th>
<th>Physics case paper</th>
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<td>450</td>
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<td>No. Ions per bunch []</td>
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<td>---</td>
<td>115</td>
<td>110</td>
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= 2 × design scaled with $E^2$
Reminder: Pb-p luminosity production in 2013

Intermediate filling scheme to limit the losses

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

The LHC experiments asked us to change operating conditions every few days.

Operating experience in all previous colliders has taught us that gradual optimisation of constant operating conditions is the path to high luminosity.

Nevertheless we fulfilled all requests, thanks to the quality of the LHC, meticulous planning and some judicious risk-taking (with performance).

So we do not need to fear “complicated” physics requests.
## Performance for p-Pb in Run 2

<table>
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<th>E (Z GeV/c)</th>
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<tr>
<td></td>
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<tr>
<td>($10^{10}$ protons/bunch)</td>
<td>1.8–5?</td>
<td>1.8–5?</td>
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<td>($10^8$ ions/bunch)</td>
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<td>(m)</td>
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<td>(μm.rad)</td>
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<td>(μm.rad)</td>
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<td>(kHz)</td>
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<td>($10^{29}$ cm$^{-2}.s^{-1}$)</td>
<td>2.5–7?</td>
<td>4.3–12</td>
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<td>(nb$^{-1}$)</td>
<td>60 (up to 180?)</td>
<td>110 (up to 300?)</td>
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- Increasing the proton intensity is constrained by Pb stability (moving long range encounters), and arc BPMs capabilities (still uncertain),
- $5 \times 10^{10}$ p/bunch is the maximum reachable in any case,
- Number of bunches per beam is taken from “baseline scenario” for Pb-Pb run in 2015-2016,
- Integrated luminosity assumes same integrated over peak luminosity ratio as in 2013.
- ALICE will level at $\sim 10^{28}$ and $10^{29}$ cm$^{-2}.s^{-1}$ in Run 2

J.M. Jowett, RLIUP Workshop, 31/11/2013