Heavy Ions at FCC-hh

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Introduction

- **LHC works extremely well as nucleus-nucleus and proton-nucleus collider**
  - Largest steps in collision energy in history of accelerators
  - Already far into “HL-LHC” performance regime
  - $3 \times (\text{Pb-Pb})$ and $8 \times (\text{p-Pb})$ design luminosity after 12 and 8 weeks total operation time (2010-2016)
  - High precision heavy-ion physics and unexpected discoveries
  - New beam physics limitations seen, solutions established

- **FCC-hh can perform even better than LHC**
  - Strong radiation damping can be fully exploited
  - LHC solutions can be extended to FCC-hh
  - Physics case being elaborated, includes QGP physics but also ultra-peripheral photon-photon collisions (Higgs, top, ...)

*More details about physics cases: David d’Enterria, today 16:10*
Outline

• General Assumptions
  • Beam parameters
  • Filling Pattern
  • Filling Time
  • Run Schedule

• Update on Performance Estimates: Pb-Pb & p-Pb
  • Luminosity and Beam Evolution
  • Secondary Beams

• Other Ion Species

• Further Studies
• Conclusions
## General Parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC achieved</th>
<th>HL-LHC baseline</th>
<th>FCC-HH baseline</th>
<th>FCC-HH ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>26.66 km</td>
<td></td>
<td>97.75 km</td>
<td></td>
</tr>
<tr>
<td>Beam Energy [Z TeV]</td>
<td>6.5</td>
<td>7</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>β-function at the IP [m]</td>
<td>0.6</td>
<td>0.5</td>
<td>1.1</td>
<td>0.3</td>
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<tr>
<td>No. Ions per bunch [1e8]</td>
<td>2.2</td>
<td>1.8</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Transv. normalised emittance [μm.rad]</td>
<td>~1.5</td>
<td>1.65</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>100</td>
<td>50</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>518</td>
<td>1256</td>
<td>2760</td>
<td>5400</td>
</tr>
<tr>
<td>Stored energy/beam [MJ]</td>
<td>10</td>
<td>21</td>
<td>362</td>
<td>709</td>
</tr>
<tr>
<td>Stored energy/beam at Injection [MJ]</td>
<td>0.7</td>
<td>1.5</td>
<td>24</td>
<td>47</td>
</tr>
</tbody>
</table>

- New layout
- LHC experience
- 30% larger beam size as protons
- More than 10x smaller as for protons
Filling Pattern (Baseline)

Trains of 5x4 Bunches = 20 Bunches/Train, spaced by 100ns
(limited by LHC extr. kicker flat top length)

1\textsuperscript{st} LHC transfer: 1 Pilot + 36 Trains

2\textsuperscript{nd}, 3\textsuperscript{rd}, 4\textsuperscript{th} LHC transfer: 34 Trains

\sim 690 bunches per LHC cycle \rightarrow 2760 colliding bunches
**Filling Time (Current LHC Injectors)**

*with small upgrades*

**SPS cycle time per train = 32.4 s**

Assuming:
- LEIR/PS cycle time = 2.4 s
- PS injections/train = 2x5
- Preparation time = 8.4 s

**LHC preparation time = 7 min (+ 2 min 1\textsuperscript{st} Filling)**

→ FCC filling time (2 beams) = 105 min
→ (8x more SPS-LHC transfers than in p-p)

*Current estimate for p-p: 44 min*

W. Bartmann, Today at 15:30
**Tentative Run Schedule**

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Run 5</th>
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<tbody>
<tr>
<td>1</td>
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</tr>
</tbody>
</table>

**Month**

Similar strategy as for LHC:

- 1-month-long Heavy-Ion runs before each Technical Stop or Shutdown
- 3 such ion runs per FCC-Run of 5 years

15 x 1 month Ion-Physics time

See Talk by A. Niemi, Thu 1 Jun, 15:30
Beam Evolution Studies

- Time evolution of beam parameters obtained from numerical solution of a **system of four coupled differential equations**
  - \( \frac{dN}{dt}, \frac{d\varepsilon_{xy}}{dt}, \frac{d\sigma_s}{dt} \).
  - Includes luminosity burn-off, intra-beam scattering (IBS) and synchrotron radiation damping.

- Pb damps \(~2x\) faster than protons.
  - Radiation damping times for Pb \(~0.5h\).

- Initial IBS is weak, but damping is very fast.
  - Fast emittance decrease at the beginning of the fill until IBS starts to counteract the damping.

*Plots of beam evolution can be found in the Extra Slides.*
Pb-Pb Luminosity Evolution

Scenarios:
- Baseline and Ultimate
- 1 (solid) and 2 (dashed) experiments in collisions in **main IPs**

The available total integrated luminosity is shared.

Case of a special heavy-ion experiment installed in secondary IP:
- *larger* $\beta^*$, *less colliding bunches*
- Luminosity would be reduced
- *We do NOT consider this scenario at present.*
Pb-Pb Integrated Luminosity per Run

Considers:
- Particle losses on FCC injection plateau of already circulating trains.
- Optimum turn around
- Optimum time in collision for each scenario

Neglects:
- Down time due to failures

Including a performance efficiency factor of 50%

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1 exp. $L_{\text{int}}$/run</th>
<th>2 exp. $L_{\text{int}}$/run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>35nb$^{-1}$</td>
<td>23nb$^{-1}$</td>
</tr>
<tr>
<td>Ultimate</td>
<td>110nb$^{-1}$</td>
<td>65nb$^{-1}$</td>
</tr>
</tbody>
</table>

Current LHC injectors estimate 2x faster injectors min. in 2016
p-Pb Luminosity Evolution

Same color code as for Pb-Pb

Assumed:
• same Pb-beam as in Pb-Pb
• p-beam with the same number of charges and geometrical emittance as Pb-beam.

Longer luminosity lifetime, because for 82-Pb charges only 1-p is burned-off.

*Potential to increase p intensity as already done at LHC in 2016.*
p-Pb Integrated Luminosity per Run

Current LHC injectors estimate

2x faster injectors

min. in 2016

Including a **performance efficiency factor** of 50%

Baseline:
1 exp. L_{int}/run: 8pb⁻¹
2 exp. L_{int}/run: 6pb⁻¹

Ultimate:
29pb⁻¹
18pb⁻¹
\( \gamma - \gamma \) and \( \gamma - A \) processes in Pb-Pb collisions

Ultra-peripheral electromagnetic interactions dominate the total cross-section during Pb-Pb collisions.

**Bound-Free Pair Production**

- **BFPP1:** \( ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \rightarrow ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{81+} + e^+ , \)
  
  \( = 354 \) b, \( = 0.01235 \)

- **BFPP2:** \( ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \rightarrow ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{80+} + 2e^+ , \)
  
  \( \approx 10 \) mb, \( = 0.02500 \)

**Electro-magnetic Dissociation**

- **EMD1:** \( ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \rightarrow ^{208}\text{Pb}^{82+} + ^{207}\text{Pb}^{82+} + n , \)
  
  \( = 200 \) b, \( = 0.00485 \)

- **EMD2:** \( ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \rightarrow ^{208}\text{Pb}^{82+} + ^{206}\text{Pb}^{82+} + 2n , \)
  
  \( = 35 \) b, \( = 0.00970 \)

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

*Each of these makes a secondary beam emerging from the IP.*
Secondary Beam Power

\[ P = \sigma_c L E \approx 19kW \] (Baseline, 1 exp.)

75kW (Ultimate, 1 exp.)

Continuous and very localised losses

nominal LHC: \( P \approx 26W \)

→ mitigation methods are already required, long-term damage expected

Special collimators are required to absorb those beams and enable the FCC to run with heavy ions.
Secondary Beam Trajectories

Main IPs have different crossing.

Dispersion Suppressor Collimator positions for p-p can also absorb secondary beams from Pb-Pb collisions.

Very localized loss: $1\sigma$ beam size on collimator front plane $\geq 85/33\mu$m (beam size at IP = 4µm)

To be studied, if these collimators can absorb the deposited power
Other Ion Species

• Intensities form Injectors: possibly similar number of charges per bunch = more ions per bunch for lower Z

• Contribution of ultra-peripheral electromagnetic processes to the total cross-section would be reduced:
  • $\sigma_{BFPP} \sim Z^7$
  • $\sigma_{EMD} \sim Z^4$
Other Ion Species (Baseline)

- **Increased luminosity lifetime**, more particles available for hadronic interactions.

\[ N_{\text{hadronic}} = \sigma_h \int L \, dt \propto \frac{\sigma_h}{\sigma_h + \sigma_{\text{BFPP}} + \sigma_{\text{EMD}}} N_{\text{tot}} \propto Z^{-(6--8)} \]
Other Ion Species (Baseline)

- Reduced secondary beam power emerging from collision point.

\[ \sigma_{\text{BFPP}} \sim Z^7 \]

Worth considering small Z reduction from Pb!
Outlook & Further Studies

• Heavy-ion beams to be included in the future evolution of the injector chain.
  • Define beam parameters and requirements.

• Heavy-ion collimation studies are crucial.
  • DS collimators (few 10\textsuperscript{th} kW secondary beams)
  • Beam Cleaning System
  • Collimator design, material, shower calculations, quench risk, cleaning efficiency, etc.

• Decisions/Input from Experiments:
  • Dedicated time for Heavy-ion operation
  • Number and requirements of active experiments
  • Preferred ion species
Conclusions

• **FCC-hh** could be a very high performance heavy-ion collider.

• **Complete review of all parameters** and estimates has been performed since FCC week 2015
  • *Baseline and ultimate scenarios have been studied*
  • *1 or 2 experiments in main IPs have been taken into account*

• Keep as close as possible **to p-p operation and design**.

• The most **important studies to be done before the CDR concerns** **collimation**.
Extra Slides
References

Presentations:
- M. Schaumann et al., *A first look at heavy ion operation of the FHC*, Ions at the Future Hadron Collider, 16-17 Dec. 2013, CERN.
  ➔ [https://indico.cern.ch/event/288576/timetable/#20131216](https://indico.cern.ch/event/288576/timetable/#20131216)
  ➔ [https://indico.cern.ch/event/282344/timetable/#20140212](https://indico.cern.ch/event/282344/timetable/#20140212)
- M. Schaumann et al., *Potential Performance for nucleus-nucleus and proton-nucleus collisions in the FCC-hh*, Ions at the Future Hadron Collider, 22-23 Sep. 2014. (update to 100km)
  ➔ [https://indico.cern.ch/event/331669/timetable/#20140922](https://indico.cern.ch/event/331669/timetable/#20140922)
  ➔ [http://indico.cern.ch/event/340703/contributions/802113/](http://indico.cern.ch/event/340703/contributions/802113/)
  ➔ [https://indico.cern.ch/event/438866/contributions/1084977/](https://indico.cern.ch/event/438866/contributions/1084977/)
- M. Schaumann et al., Current Status of the studies on Heavy Ions in the FCC-hh, FCC-hh General Design Meeting, 2 Mar. 2017, CERN.
  ➔ [https://indico.cern.ch/event/617603/](https://indico.cern.ch/event/617603/)

Documents:
Filling Time (2x Faster Injectors)

SPS cycle time per train = 16.2 s
Assuming:
• LEIR/PS cycle time = 1.2 s
• PS injections/train = 2x5
• Preparation time = 4.2 s

LHC preparation time = 7 min (+ 2 min 1st Filling)

→ FCC filling time (2 beams) = 67 min
(8x more SPS-LHC transfers than in p-p)
Injection at 1.2 Z TeV

- **Ramping** of the superconducting magnets becomes a significant fraction of the SPS cycle length
  - ~2x 12sec ramp vs. 12-24sec filling

- **Filling FCC** with 2x138 trains into FCC takes ~1.5h-2h
  - For heavy-ions one SPS cycle produces 2 train with 20 bunches

- Debunching losses from **IBS are enhanced** at lower energy.

→ **Reduction of total intensity**
  → Generally **more losses** and a **longer dwell time**
  → Detailed studies needed.
Pb-Pb Free Beam Evolution, Diff. Cases

Single bunch evolution is shown, therefore the blue cases with \( \beta^* = 0.3 \text{m} \) and 2760 bunches is hidden behind the green.
Available luminosity is shared between (equal) experiments
BFPP1 Power, Diff. Cases

Secondary Beam Power coming out of the Collison

- **Baseline**: $\beta^* = 1.1 \text{m}, \#b = 2760$
- **$\beta^* = 0.3 \text{m}, \#b = 2760$**
- **Ultimate**: $\beta^* = 0.3 \text{m}, \#b = 5400$

- Solid: 1 exp. colliding
- Dashed: 2 exp. colliding

Power of BFPP1 Beams [kW] vs Time [h]
Pb-Pb Beam and Luminosity Evolution, Baseline Scenario with Artificial Blow-up

**Bunch Intensity**
- Baseline, free evolution
- Baseline, $\sigma_x=0.08\text{m}$
- Baseline, $\sigma_x=0.08\text{m}, \epsilon_x \geq 0.5\mu\text{m}$

**Horizontal Normalised Emittance**
- Baseline, free evolution
- Baseline, $\sigma_x=0.08\text{m}$
- Baseline, $\sigma_x=0.08\text{m}, \epsilon_x \geq 0.5\mu\text{m}$

**Bunch Length**
- Baseline, free evolution
- Baseline, $\sigma_x=0.08\text{m}$
- Baseline, $\sigma_x=0.08\text{m}, \epsilon_x \geq 0.5\mu\text{m}$

**Instantaneous Bunch Luminosity**
- Baseline, free evolution
- Baseline, $\sigma_x=0.08\text{m}$
- Baseline, $\sigma_x=0.08\text{m}, \epsilon_x \geq 0.5\mu\text{m}$

**Integrated Bunch Luminosity**
- Baseline, free evolution
- Baseline, $\sigma_x=0.08\text{m}$
- Baseline, $\sigma_x=0.08\text{m}, \epsilon_x \geq 0.5\mu\text{m}$
Particle losses on FCC injection plateau

Consider 4 LHC injections:
→ Dwell time at FCC injection plateau

\[ t_{ta} = t_{ta, FCC} + (n_{inj} - 1)t_{ta, LHC} \]

→ Particle losses (& emittance growth)
   → Loss rate of Pb at 3.3TeV in FCC (from tracking simulations):

\[ R_{loss} = 5\% \]

→ Total beam intensity:

\[ N_{beam} = k_bN_b \sum_{i=1}^{n_{inj}} (1 - R_{loss}t_{ta}(i - 1)) \]
p-Pb Beam Evolution

1 proton is lost for 82-Pb charges
→ Proton beam loses ~1% of its initial intensity, while the Pb intensity is completely burned-off

Radiation damping time for p = ½ Pb
p-Pb Integrated Luminosity per Fill

Integrated Luminosity

Solid: 1 exp. colliding
Dashed: 2 exp. colliding

Baseline: $\beta^* = 1.1\text{m}$, $\#b = 2760$

$\beta^* = 0.3\text{m}$, $\#b = 2760$

Ultimate: $\beta^* = 0.3\text{m}$, $\#b = 5400$

$\mathcal{L}_{\text{int}}$ [nb$^{-1}$]

0 1 2 3 4 5 6

time [h]
Main IPs have different crossing, which influences trajectory of secondary beams and their capture in collimators.
Other Ion Species

![Hadronic Event Rate per Bunch](image)

- **Ar40**
- **Cu63**
- **Xe129**
- **Au197**
- **Pb208**
- **U238**

**Event Rate [kHz]**

**time [h]**

0 5 10 15 20

0 1 2 3 4 5