Many thanks to all the speakers and contributors!

Wrap-up of LHC Performance Workshop (Chamonix 2016)

Summary of Session 6

LHC Injectors Upgrade (LIU)

M. Meddahi and G. Rumolo

Many thanks to all the speakers and contributors!

Outline:
• LIU baseline and timelines
• Pb ion injector chain: progress and beam parameters
• Proton injector chain: progress and beam parameters
• Concluding remarks
LIU baseline as of 1/1/16 (main items)

- **PSB**
  - New H\(^-\) charge exchange injection at 160 MeV from Linac4 to double brightness
  - Acceleration to 2 GeV with new RF system and new main power supply

- **Linac3 + LEIR**
  - 100 ms injection rate into LEIR to increase accumulated ion current

- **PS**
  - New injection at 2 GeV for protons to mitigate space charge
  - Newly installed and upgraded longitudinal feedbacks (impedance reduction and against CBI)

- **SPS**
  - Upgrade of the main 200 MHz RF system (power, LLRF)
  - Electron cloud mitigation through beam induced scrubbing + a-C coating of QFs and one arc (MBBs)
  - New beam dump system in LSS5 and new design of protection devices to comply with the target HL-LHC beam parameter values
  - Impedance reduction (QF-SSS flange shielding and improvement of HOM damping in 200 MHz cavities)
LIU baseline as of 1/1/16 (main items)

• PSB ➔ Talk by K. Hanke
  • New H+ charge exchange injection at 160 MeV from Linac4 to double brightness
  • Acceleration to 2 GeV with new RF system and new main power supply

• Linac3 + LEIR ➔ Talk by R. Scrivens
  • 100 ms injection rate into LEIR to increase accumulated ion current

• PS ➔ Talk by K. Hanke
  • New injection at 2 GeV for protons to mitigate space charge
  • Newly installed and upgraded longitudinal feedbacks (impedance reduction and against CBI)

• SPS ➔ Talk by B. Goddard
  • Upgrade of the main 200 MHz RF system (power, LLRF)
  • Electron cloud mitigation through beam induced scrubbing + a-C coating of QFs and one arc (MBBs)
  • New beam dump system in LSS5 and new design of protection devices to comply with the target HL-LHC beam parameter values
  • Impedance reduction (QF-SSS flange shielding and improvement of HOM damping in 200 MHz cavities)

Other LIU talks ➔ Linac4 status (A. Lombardi)
  ➔ RF upgrades for LIU (H. Damerau)
  ➔ Transverse feedback (W. Höfle)
  ➔ LS2 planning for LIU (J. Coupard)
Timelines of LIU

- **Activities until LS2**
  - Beam and simulation studies (e.g. space charge, electron cloud, impedance) to validate beam performance
  - Design, procurement and test of hardware (e.g. protection devices, cables, power converters, amplifiers)
  - Installation/cabling work during (E)YETS’s when possible
  - Work on surface (e.g. civil engineering, racks), Linac4 commissioning & Half Sector Test

- **Main LIU installations and hardware work during LS2**

- **Beam commissioning of LIU beams after LS2**
  - Ion beams to be ready for [2021 LHC ion run](#)
  - Proton beams during Run 3 to be ready for LHC physics after LS3

---

**Run 2**

**Run 3**

**LS 2**

**LS 3**

**Run 4**

**PHASE 1** with LIU studies, equipment design & test, installation

**PHASE 2**

**HL-LHC installation**
Pb ions
Ion beam performance

- Intensive study program at the end of 2015 to push injector performance and systematically identify bottlenecks and loss/emittance growth distribution

Achieved values (2015)

<table>
<thead>
<tr>
<th></th>
<th>$N$ ($x\ 10^8$ ions/b)</th>
<th>$\varepsilon$ ($\mu$m)</th>
<th># of bunches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieved</td>
<td>2.2</td>
<td>1.5</td>
<td>518</td>
</tr>
</tbody>
</table>

- Pb ions\ extr. bunch [1e8]

- LEIR end of injection
- LEIR extraction
- PS injection
- PS extraction
- SPS injection
- SPS extraction
- LHC injection

- Normalized emittance [$\mu$m]

- LEIR end of injection
- LEIR extraction
- PS injection
- PS extraction
- SPS injection
- SPS extraction
- LHC injection
Ion beam performance

- Intensive study program at the end of 2015 to push injector performance and systematically identify bottlenecks and loss/emittance growth distribution

Achieved values (2015)

<table>
<thead>
<tr>
<th></th>
<th>N (x 10^8 ions/b)</th>
<th>ε (μm)</th>
<th># of bunches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieved</td>
<td>2.2</td>
<td>1.5</td>
<td>518</td>
</tr>
</tbody>
</table>

- LEIR operational transmission increased to ~80%
- Space charge identified as responsible for the losses with bunched beam
Ion beam performance

- Intensive study program at the end of 2015 to push injector performance and systematically identify bottlenecks and loss/emittance growth distribution

**Achieved values (2015)**

<table>
<thead>
<tr>
<th></th>
<th>( N ) (x 10^8 ions/b)</th>
<th>( \varepsilon ) (( \mu )m)</th>
<th># of bunches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieved</td>
<td>2.2</td>
<td>1.5</td>
<td>518</td>
</tr>
</tbody>
</table>

- LEIR operational transmission increased to ~80%
- Space charge identified as responsible for the losses with bunched beam
- Losses at SPS flat bottom and transition decreased
- MKP rise time significantly improved to enable 150 ns batch spacing in SPS
LIU upgrades for ions

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

- **Until LS2 + LS2:**
  - Continue beam studies to further improve transmission through injector chain
    - Higher intensity in LEIR
    - SPS losses: optics, working point, tests for slip stacking/RF noise at flat bottom
    - Reduce losses in transfers
  - LEIR dump
  - LLRF deployment for slip stacking in SPS (in LS2)

→ **Machine studies in 2016-18 crucial for progress!**
LIU performance reach with ion beams

- LIU achievable parameter table obtained by combining
  - Extrapolation from information collected in 2015 (transmission, emittance growth)
  - Predicted performance after baseline upgrades

- The gap with the parameters needed to fulfill the experiment luminosity goal is already being addressed by the LIU and HL-LHC projects together
  - LIU beam parameters specifications for ions at the exit of the SPS, EDMS 1581381

<table>
<thead>
<tr>
<th></th>
<th>N (x 10^8 ions/b)</th>
<th>ε (μm)</th>
<th># of bunches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieved</td>
<td>2.2</td>
<td>1.5</td>
<td>518</td>
</tr>
<tr>
<td>LIU</td>
<td>1.7</td>
<td>1.3</td>
<td>1152</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>2.1</td>
<td>1.3</td>
<td>1248</td>
</tr>
</tbody>
</table>
Protons
Linac4 progress

- **Commissioning of 50 MeV**
  - H⁺ source can reliably produce **50 mA**, but only 2/3 of the current can be transmitted through the RFQ (emittance larger than nominal)
  - **20 mA** with **0.45 μm** at 50 MeV
  - Transversally and longitudinally the beam is as predicted → Both **tracking codes and beam diagnostics** work as expected.

- **Staged plan to increase current up to 40 mA by**
  - improving the current/reducing the emittance from the source
  - improving the matching through the LEBT
  → Results expected by summer
Linac4 progress

- **Commissioning of 50 MeV**
  - H\(^+\) source can reliably produce 50 mA, but only 2/3 of the current can be transmitted through the RFQ (emittance larger than nominal)
  - 20 mA with 0.45 \(\mu\)m at 50 MeV
  - Transversally and longitudinally the beam is as predicted \(\rightarrow\) Both tracking codes and beam diagnostics work as expected.

- **Staged plan to increase current up to 40 mA by**
  - improving the current/reducing the emittance from the source
  - improving the matching through the LEBT
  \(\rightarrow\) Results expected by summer

- **Next steps:** commission 100 MeV, then 160MeV (from September 2016), and deliver first beam to the Half Sector Test (HST) by October 2016.
New H⁻ injection at 160 MeV from Linac4

- All new equipment on track to be ready by end 2016 (in the unlikely event of an early Linac4 connection)

- Half Sector Test has to start in October 2016, no further delay can be tolerated as it is supposed to feed back into the hardware design

- Detailed simulations of PSB with Linac4 confirm the expectation of double brightness
• **New H⁻ injection at 160 MeV from Linac4**
  - All new equipment **on track to be ready by end 2016** (in the unlikely event of an early Linac4 connection)
  - **Half Sector Test** has to start in October 2016, no further delay can be tolerated as it is supposed to feed back into the hardware design
  - Detailed simulations of PSB with Linac4 confirm the expectation of **double brightness**

• **New RF system**
  - 10 prototype Finemet modules installed in Ring 4 widely tested throughout 2015
  - Review in September led to the decision to **replace all PSB RF systems (C02, C04 and C16) with a Finemet based RF system (LS2)**

• **MPS building (including infrastructure) in progress, to be ready by end Q1 2016**

• **Magnets and extraction elements on track to be ready for LS2**

• **Decabling campaign successfully proceeding**
  - ~2700 cables (previously identified and tagged) disconnected
  - PSB start up going well so far, only 2-3 cables found with wrong connections!
  - Cables will be removed in EYETS
• **New injection at 2 GeV from PSB**
  - All design choices for *injection region* frozen (new bumpers, new septum, upgraded kicker)
  - Partly in EYETS, mainly for LS2
  - **Space charge limit** due to structural resonance identified at injection energy, more studies ongoing (different optics, longitudinal beam parameters at PSB-PS transfer)

• **Feedbacks**
  - **Longitudinal feedback** with Finemet cavity as kicker, endorsed at the September review
  - New power amplifiers for the *transverse feedback* under design
• **New injection at 2 GeV from PSB**
  • All design choices for *injection region* frozen (new bumpers, new septum, upgraded kicker)
  • Partly in EYETS, mainly for LS2
  • **Space charge limit** due to structural resonance identified at injection energy, more studies ongoing (different optics, longitudinal beam parameters at PSB-PS transfer)

• **Feedbacks**
  • *Longitudinal feedback* with Finemet cavity as kicker, endorsed at the September review
  • New power amplifiers for the *transverse feedback* under design

• **RF systems**
  • Improved wide-band feedback for **10 MHz** (EYETS + LS2)
  • New 1-turn delay feedbacks for **20, 40 and 80 MHz** for beam stability and bunch-to-bunch equalisation during splittings (EYETS)
  • New anode power supplies for **40 MHz and 80 MHz** and upgrade to a *digital beam control* for reliability and long term maintainability (LS2)
  • New ferrite tuners for **80 MHz** to use cavities simultaneously for protons and ions (LS2)

• **Internal dumps under design (with shielding and support structure)** – LS2

• **TT2 recently introduced in LIU-PS scope**
• Impedance reduction
  • Identified **QF-SSS vacuum flanges** and **200 MHz HOMs** as main remaining impedance sources driving longitudinal coupled bunch instability
  • Shielding of flanges (EYETS and LS2) and enhancement the HOM damping (under study)
- **Impedance reduction**
  - Identified **QF-SSS vacuum flanges** and **200 MHz HOMs** as main remaining impedance sources driving longitudinal coupled bunch instability
  - Shielding of flanges (EYETS and LS2) and enhancement the HOM damping (under study)

Can we gain even more margin by allowing long bunches to be injected into LHC (where is the experimental limit now, 200 MHz system in LHC)?
**SPS**

- **Impedance reduction**
  - Identified **QF-SSS vacuum flanges** and **200 MHz HOMs** as main remaining impedance sources driving longitudinal coupled bunch instability
  - Shielding of flanges (EYETS and LS2) and enhancement the HOM damping (under study)

- **Upgrade of the 200 MHz RF system**
  - **Rearrangement** of main 200 MHz cavities
  - Two **additional RF power plants** (new amplifiers with solid state technology, new building)
  - **LLRF upgrade** for beam stability and slip stacking for the ions

- **Electron cloud mitigation**
  - Decision to rely on **scrubbing**, while a-C coating of all QFs + one arc including MBBs during LS2 → Validation in Run 3, when intensity could be limited by enhanced beam losses
  - **Transverse feedback systems** to stabilise beam (current and wide-band prototype)

- **Dumps and protection devices**
  - **LSS5 dump system**: layout and specs finalised, relocation of other systems defined, preparatory civil engineering and cabling begun
  - Upgrade defined for **extraction protection, transfer line stoppers and collimators**, few technical details to be finalised (HiRadMat tests), new interlocking systems needed
LIU performance reach for protons before SPS impedance reduction

<table>
<thead>
<tr>
<th></th>
<th>$N$ ($x 10^{11}$ p/b)</th>
<th>$\varepsilon$ ((\mu m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIU Baseline</td>
<td>2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>2.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>
LIU performance reach for protons with SPS impedance reduction

<table>
<thead>
<tr>
<th></th>
<th>( \mathcal{N} ) (x 10^{11} p/b)</th>
<th>( \varepsilon ) (( \mu )m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIU Baseline</td>
<td>2.3</td>
<td>2.2</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>2.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Present performance

- PSB brightness
- PS (\( \Delta Qy = 0.31 \))
- SPS (\( \Delta Qy = 0.21 \))
- SPS beam loading and longitudinal instabilities

HL-LHC request
LIU performance reach for protons with SPS impedance reduction

- The increased intensity reach is in the process of being verified by the LIU beam parameter WG (check that no other limitations appear).
- When this is approved, LIU and HL-LHC beam parameters at LHC injection will match within the error bars of our estimations!
In summary

• **LIU project on track to be ready for hardware installations during LS2**
  • Meanwhile, significant amount of work advanced in YETS’s and EYETS, equipment design/procurement/test, work on surface, beam (machine and simulation) studies in progress
  • **End-2016 deadline** for Linac4 connection still valid and **Half Sector Test** to be completed by beginning 2017
  • **Resources need to be secured** for upgrade of critical systems, whose functionality and reliability are crucial for LIU, like **RF systems and transverse dampers**

• **Important progress on beam parameter match between LIU and HL-LHC**
  • **Ions:**
    − Both HL-LHC request and LIU performance reach defined
    − Gap with HL-LHC only ~20% in luminosity at this stage, LIU and HL-LHC closely collaborating to identify best options to bridge it
  • **Protons:**
    − LIU beam parameter WG actively working to follow baseline evolution
    − SPS impedance reduction expected to enable SPS to deliver beams that meet the HL-LHC requirements
    − LIU and HL-LHC investigating together on means to gain additional margin
  • The commissioning of **LIU beams during Run 3** will validate LIU anti-ecloud strategy in SPS (scrubbing, losses) and allow testing important design options for HL-LHC
THANK YOU FOR YOUR ATTENTION!

LHC Injectors Upgrade