LIU beam performance reach

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Overview

• Beams for HL-LHC
• LIU baseline for protons
  o Removing the present limitations
  o Sensitivity of HL-LHC luminosity to beam parameters
• Performance with protons
  o Linac4, PSB, PS and SPS
• Performance with lead ions
  o Linac3, LEIR, PS and SPS
• Conclusions
  o Main challenges
  o Progress summary
Menu of beams for HL-LHC

<table>
<thead>
<tr>
<th>Beam type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 72b standard</td>
<td>Nominal beam with up to $4 \times 72b$ from SPS</td>
</tr>
<tr>
<td>2. 72b + 24b mixed</td>
<td>Optimized version with more bunches in LHC</td>
</tr>
<tr>
<td></td>
<td>Mixed $24b + 72b + 72b$ from SPS ( )</td>
</tr>
<tr>
<td>3. 48b BCMS</td>
<td>Up to $5 \times 48b$, no advantage for $6 \times 48b$</td>
</tr>
<tr>
<td>4. 8b+4e mixed with BCMS</td>
<td>Mixed $2 \times 56b + 3 \times 48b$ and $1 \times 56b + 1 \times 48b$</td>
</tr>
<tr>
<td></td>
<td>Reduce electron cloud heat load</td>
</tr>
<tr>
<td>5. 80b + 32b</td>
<td>$4 \times 80b$ and $1 \times 32b + 1 \times 80b$ ( )</td>
</tr>
</tbody>
</table>

→ Mixed schemes might require improving operational flexibility of injectors
→ Shorter fills have impact on injector operation
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  o Main challenges
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LIU performance reach for protons

- **Linac4-PSB connection**
  → Reduced space charge, double PSB brightness

- **PS upgrade**
  → 2 GeV injection + large longitudinal emittance transfer from PSB
  → RF feedbacks to suppress longitudinal instabilities and reduce transient beam loading
LIU performance reach for protons

- **Linac4-PSB connection**
  → Reduced space charge, double PSB brightness

- **PS upgrade**
  → 2 GeV injection + large longitudinal emittance transfer from PSB
  → RF feedbacks to suppress longitudinal instabilities and reduce transient beam loading

- **SPS upgrade**
  → 200 MHz RF power upgrade and new LLRF
  → Q20, scrubbing + partial (staged) SPS aC coating
  → New beam dump & transfer line collimators
  → Longitudinal impedance reduction (flange shielding and HOM reduction)
Parameter sensitivity of HL-LHC

• 2% luminosity loss of nominal can be caused by Injectors

  → $0.13 \cdot 10^{11}$ p/b less at constant brightness
  → 0.4 μm larger emittance at constant intensity
  → 14 minutes turn around time
  → $\beta^*$ increase by 8 cm
  → 1% efficiency reduction
Parameter sensitivity of HL-LHC

- 2% luminosity loss of nominal can be caused by Injectors
  - $0.13 \cdot 10^{11}$ p/b less at constant brightness
  - 0.4 $\mu$m larger emittance at constant intensity
  - 14 minutes turn around time
  - $\beta^*$ increase by 8 cm
  - 1% efficiency reduction

Trade off performance with speed to serve LHC?
Parameter sensitivity of HL-LHC

- 2% luminosity loss of ultimate can be caused by Injectors
  - $0.09 \cdot 10^{11}$ p/b less at constant brightness
  - 0.2 μm larger emittance at constant intensity
  - 10 minutes turn around time
  - $\beta^*$ increase by 4 cm
  - 1% efficiency reduction

Trade off performance with speed to serve LHC?
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Reliable operation with 25 mA current after RFQ ensures $1.25 \cdot 10^{13}$ p/ring

- All pre-LS2 beams can be reproduced
- Reproducible transmission between 3 MeV and 160 MeV
- Continuous source cesiation demonstrated to improve source stability

Challenges

- Position and energy variations along the pulse
- Current flatness and shot-to-shot reproducibility
- Make 45 mA from available by 2023

→ LLRF regulation
→ Further tests during LBE run
PSB longitudinal

- Finemet technology fully demonstrated before LS2
  → Reliability runs since 2015
- Blow-up technique based on phase noise validated and well understood
  → Improved control of final distribution
  → Reliability run in 2018
- Impedance of new Finemet RF no issue for LHC-type beams
- Potential concerns with
  → Very high-intensity beams
  → Operational complexity of multi-harmonic feedback
PSB transverse

- **Brightness curves** with Linac2 well reproducible during run 2
  - Doubled brightness with Linac4 + 2 GeV confirmed with simulations

- Progress with understanding of emittance
  - Measured $\beta$ and $D$, beta beating
  - Deconvolution for large $\varepsilon_1$ beams

- Prototype wire scanner validated
- Detailed studies of $^3$H injection
# Key studies in PSB

<table>
<thead>
<tr>
<th>Activity</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conclude on transverse emittance measurements as input for brightness curve</td>
<td>Q2/2019</td>
</tr>
<tr>
<td>Establish common model for space charge simulations, including imperfections, to define optics choices at injection</td>
<td>Q3/2019</td>
</tr>
<tr>
<td>Study impact of unmatched termination of extraction kicker (horizontal instability)</td>
<td>Q3/2019</td>
</tr>
<tr>
<td>Prepare tool to optimize alignment of all rings after LS2</td>
<td>Q1/2019</td>
</tr>
<tr>
<td>Controlled longitudinal blow for longitudinal shaving</td>
<td>Q3/2019</td>
</tr>
<tr>
<td>Definition of longitudinal parameter sets for all beams</td>
<td>Q3/2019</td>
</tr>
<tr>
<td>Renovation and possible upgrade of longitudinal Tomography</td>
<td>Q1/2020</td>
</tr>
<tr>
<td>Longitudinal emittance model after LS2</td>
<td>2020</td>
</tr>
</tbody>
</table>
PS injection

- Mismatch in PSB-PS transfer line
  → Important dispersion mismatch
  → Almost no betatronic mismatch
- Studies of systematic errors
  → Measured optics functions ($\beta$ and $D$)
- Deployment of turn-by-turn SEM grids
  → Turn-by-turn beam size essential
  → Electronics and software ready in 2018
- Extensive kicker pulse measurements
  → Ripple in expected range

### Table

<table>
<thead>
<tr>
<th>Beam type</th>
<th>OP optics $\Delta \varepsilon$ abs. [mm mrad]</th>
<th>Rematched optics $\Delta \varepsilon$ abs. [mm mrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
<td>Measured</td>
</tr>
<tr>
<td>BCMS OP</td>
<td>0.15</td>
<td>0.33 ± 0.06</td>
</tr>
<tr>
<td>BCMS 1.5 eVs</td>
<td>0.36</td>
<td>0.43 ± 0.06</td>
</tr>
</tbody>
</table>
PS Intensity reach

- LIU target intensity reached at nominal $\varepsilon_l = 0.35$ eVs
- Large transverse emittance: $\sim 5 \, \mu\text{m}$
- Excellent transmission of $\sim 98\%$ even at highest intensities
- Transverse stability
  - Careful tune and chromaticity adjustment
  - Transverse damper

- Multi-harmonic feedbacks
- 40 MHz RF as Landau system
- Suspected feedback saturation
- Optimization 2017
- Finemet dipole-mode coupled-bunch feedback
- Reach with C10-86/96 coupled-bunch feedback (2005)*

*Intensities $> 1.3 \cdot 10^{11}$ p/b were delivered <2016, but not with sufficient quality for LHC
# Key studies in PS

<table>
<thead>
<tr>
<th>Activity</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Analysis of KFA45 field measurements</td>
<td>Q2/2019</td>
</tr>
<tr>
<td>Conclude on <em>emittance blow-up measurement</em> (systematic errors)</td>
<td>Q2/2019</td>
</tr>
<tr>
<td>PSB-PS transfer line matching using turn-by-turn acquisitions</td>
<td>Q4/2019</td>
</tr>
<tr>
<td>Simulations to understand relevance of space charge after injection</td>
<td>Q4/2019</td>
</tr>
<tr>
<td><strong>Longitudinal</strong></td>
<td></td>
</tr>
<tr>
<td>Identify <em>impedance source exciting longitudinal instabilities</em></td>
<td>Q2/2019</td>
</tr>
<tr>
<td>Performance <em>predictions for RF upgrades during LS2</em></td>
<td>Q2/2019</td>
</tr>
<tr>
<td>Review longitudinal <em>parameters at PS-SPS transfer</em></td>
<td>Q4/2019</td>
</tr>
<tr>
<td>Longitudinal impedance model after LS2</td>
<td>Q4/2019</td>
</tr>
</tbody>
</table>
SPS transverse

- Horizontal instability $N_b > 1.8 \cdot 10^{11}$ p/b
  - Cured by either chromaticity, octupoles or combination at present intensities
- Coherent tune shift at 26 GeV will be on the order of $\Delta Q_y \sim 0.04$ with LIU intensities
  - Wide tune acceptance of damper shown with beam in 2018
  - Implications on working point choice to be studied in simulations
- Electron cloud
  - Mini scrubbing run in 2018 demonstrated emittance growth reduction to 10-15% at around $2 \cdot 10^{11}$ p/b
SPS intensity reach

- Insufficient RF power with pre-LS2 SPS
  - Losses increasing with total beam intensity
  - Limited to $1.4 \cdot 10^{11}$ p/b in long batches
  - Advance beam studies using 12 bunches

$4 \cdot 12$ bunches, $2 \cdot 10^{11}$ p/b

- Measurements and simulation agree well for 12 bunches and single harmonic case
- Stability improvement with 800 MHz
  - Measured with high-intensity in 2018
  - BLonD simulations for post-LS2
SPS longitudinal, what to expect after LS2

- Simulations of stability at flat-bottom in SPS (48b, 25ns, Q20)

2.6 \cdot 10^{11} \text{ p/b}
800 MHz off

800 MHz on
10% ratio

Nominal emittance 15% less 30% less

\rightarrow \text{unstable} \quad \rightarrow \text{unstable} \quad \rightarrow \text{unstable}

\rightarrow \text{Stabilisation by 800 MHz RF system with 0.1 voltage ratio}
\rightarrow \text{15% smaller longitudinal might be possible from PS}

- Little interest in Q22 optics (beam loading, long. stability)
### Key studies in SPS

<table>
<thead>
<tr>
<th>Activity</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Transverse</strong></td>
<td></td>
</tr>
<tr>
<td>Removal of momentum aperture restrictions (MBB-SSS), decision on installation</td>
<td>Q1/2019</td>
</tr>
<tr>
<td>Benchmarking of bunch-by-bunch tune shift measurement with impedance model</td>
<td>Q2/2019</td>
</tr>
<tr>
<td>Horizontal instability at SPS injection, identification of source</td>
<td>Q4/2019</td>
</tr>
<tr>
<td>Impact of bunch-by-bunch tune shift on incoherent tune footprint of different bunches for working point optimization</td>
<td>2020</td>
</tr>
<tr>
<td><strong>Longitudinal</strong></td>
<td></td>
</tr>
<tr>
<td>630 MHz HOM damper (shift of fundamental mode), decision on installation</td>
<td>Q2/2019</td>
</tr>
<tr>
<td>Beam loss at flat-bottom and beginning of ramp, smaller longitudinal emittance</td>
<td>Q3/2019</td>
</tr>
<tr>
<td>Impact of smaller longitudinal emittance during acceleration</td>
<td>Q4/2019</td>
</tr>
<tr>
<td>Impact of installing 200 MHz cavities for eSPS (for PBC and CLIC)</td>
<td>Q4/2019</td>
</tr>
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Linac3 and LEIR

Pb source and Linac3
- Source autopilot
- Continuous support during LHC run
- 30 uA golden value for LIU reached

LEIR
- **Improved accumulation and reduced losses in LEIR**
  - Careful tuning and understanding
  - RF capture with frequency modulation
  - Elimination of tune ripple
- **Improved reliability**
  - Automatic tools and optimizers
  - Improved beam instrumentation

→ Linac3/LEIR ready to operationally deliver LIU target parameters
PS

- LIU baseline
  → Split 2 bunches from LEIR at intermediate plateau into 4 bunches spaced 100 ns

- Alternative
  → 3 bunches, 75 ns

- Potential issues
  → Instability after transition crossing for $N_b > \sim 5 \cdot 10^8$ ions/b
  → Cured by controlled blow-up, but satellite bunches at ±12.5 ns

→ Little margin, but PS reaches LIU target
SPS

- Longitudinal instability after transition crossing
  → Instability often starts at energy of plateau for future slip stacking
SPS

- Longitudinal instability after transition crossing
  → Instability often starts at energy of plateau for future slip stacking

- Simulation of slip-stacking with intensity effects
  → Instability often starts at energy of plateau for future slip stacking
  
  → Slip-stacking challenging
Ions

- **Achievements**
  - ✔️ 2 bunches at LEIR-PS transfer
  - ✔️ RF manipulations in PS
  - ✔️ 4 bunches spaced by 100 ns at PS-SPS
  - ✔️ Multiple injections (~14) into the SPS
- **Alternative**
  - ✔️ 3 bunches with 75 ns spacing
- **Challenges**
  - → Longitudinal instabilities SPS
  - → Slip stacking: 100 ns → 50 ns spacing in SPS
  - → Beam studies in 2018
  - → LLRF upgrade
## Key studies with ions

<table>
<thead>
<tr>
<th>Activity</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space charge and IBS studies of capture beam losses</td>
<td>Q2/2019</td>
</tr>
<tr>
<td>Maximum accumulated intensity in LEIR (injection process, cooling)</td>
<td>Q4/2019</td>
</tr>
<tr>
<td>Analyse beam stability versus intensity in LEIR (impedance and cooling)</td>
<td>2020</td>
</tr>
<tr>
<td>Injection optics to reduce losses from Linac3 to LEIR</td>
<td>2020</td>
</tr>
<tr>
<td>Optimum longitudinal emittance from LEIR</td>
<td>Q4/2019</td>
</tr>
<tr>
<td>Microwave instability at PS transition crossing, impedance source identification</td>
<td>Q4/2019</td>
</tr>
<tr>
<td>Simulate longitudinal ion instability in SPS and propose mitigation</td>
<td>Q3/2019</td>
</tr>
<tr>
<td>Definition of scenario for slip-stacking in SPS</td>
<td>2020</td>
</tr>
</tbody>
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## Challenges on the path to LIU performance

<table>
<thead>
<tr>
<th>Protons</th>
<th>Mitigation</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large momentum spread transfer PSB-PS</td>
<td>Matched transfer line optics</td>
<td>In depth analysis of 2018 data and simulations</td>
</tr>
<tr>
<td>PS-SPS transfer</td>
<td>Smaller longitudinal emittance from PS</td>
<td>Simulation studies of transfer and long. stability in SPS</td>
</tr>
<tr>
<td>Transverse stability and e-cloud in SPS</td>
<td>Landau damping, wideband feedback system, scrubbing</td>
<td>Identification of instability source</td>
</tr>
<tr>
<td>Beam losses at SPS injection</td>
<td>Lower longitudinal emittance from PS, enlarge momentum aperture</td>
<td>Analysis of efficiency and margins, lift momentum aperture restrictions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ions</th>
<th>Mitigation</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal stability in SPS (for slip-stacking)</td>
<td>Controlled emittance blow-up before transition</td>
<td>Simulation studies</td>
</tr>
</tbody>
</table>
Progress summary

→ HL-LHC parameters reached with lead ion at PS extraction
Smaller longitudinal emittance from PS for transfer?

\( \varepsilon_l (90\%) \) at start of flat-top, per bunch at ejection versus controller blow-up after transition, \( 2.6 \cdot 10^{11} \) p/b

- Blow-up 4 with \( 4 \times 4.5 \text{kV} \)
- \( 3 \times 4.5 \text{kV} \)
- \( 2 \times 4.5 \text{kV} \)
- \( 1 \times 4.5 \text{kV} \)

No blow-up after transition

Corresponds to nominal \( \varepsilon_l \) at extraction

→ Margin to deliver longitudinal emittance of 15% below nominal

→ How low can we go in longitudinal emittance?
PS-SPS smaller emittance at transfer

- 2.0 GeV, post-LS2, LIU baseline, $0.35 \text{ eVs}$

- Large momentum spread required for $\Delta Q_y = 0.31$
- Corresponds to $\varepsilon_i = 3 \text{ eVs/12}$ (standard)
- $\varepsilon_i = 1.5 \text{ eVs/6}$ (BCMS)
  at PS flat-bottom
- Little margin for RF manipulations in PS

- Gain margin by reducing longitudinal emittance already from PSB?

LIU Workshop, 13-15 February 2019

H. Damerau, G. Rumolo
PS-SPS smaller emittance at transfer

- 2.0 GeV, post-LS2, **0.25 eVs** at PS ejection (if stable)

  ![Splitting factor: 12](image1.png)
  ![Splitting factor: 6](image2.png)

- **Large momentum spread required** for $\Delta Q_y = 0.31$
- Corresponds to
  - $\varepsilon_i = 3 \text{ eVs/12 (standard)}$
  - $\varepsilon_i = 1.5 \text{ eVs/6 (BCMS)}$
- at PS flat-bottom
- Little margin for RF manipulations in PS

  ![Interesting for standard (72b) beam, but not BCMS](image3.png)
• For the BCMS beam
  • Same bunch intensity reach as standard 25 ns
    • Due to SPS intensity limitation
    • Extraction/transfer/injection protection devices validated for this brightness
  • 25% higher brightness in trains of 48 bunches
    • Almost same number of bunches in LHC
    • Shorter trains are usually easier in injectors and lead to lower e-cloud effects
    • Brightness gain limited by hitting space charge limit in both PS and SPS
Intensity reach of PS, 25 ns standard

- LIU target intensity reached at $\varepsilon_l = 0.35$ eVs

![Intensity per bunch at extraction graph]

- Multi-harmonic feedbacks
  - C40-78 as Landau RF system
- Suspected feedback saturation
- Optimization 2017
- Finemet dipole-mode coupled-bunch feedback
- Reach with C10-86/96 coupled-bunch feedback (2005)*

*Intensities >1.3 \(10^{11}\) p/b were delivered <2016, but not with sufficient quality for LHC
LIU target intensity reached at $\varepsilon_l = 0.35$ eVs

- Longitudinally more stable than in 2017
  - Suspected feedback saturation
  - Not systematically checked

- Finemet dipole-mode coupled-bunch feedback

- No systematic beam tests to push intensity before 2017
Bunch-by-bunch variations (protons)

- Transverse variations
  - Differences between PSB rings (emittance and intensity)
  - First and second transfer PSB-PS (blow-up in PS)
  - Multiple transfers PS-SPS (blow-up in SPS)

- Longitudinal variations
  - Differences between PSB rings (emittance and intensity)
  - Longitudinal emittance from PS due to splitting
Protons

- **Baseline**
  - Linac4 injection and H- injection at 160 MeV
  - 2 GeV PSB-PS transfer (large $\varepsilon_l = 3.0/1.5$ eVs)
  - Triple splitting (standard) or BCMS and controlled long. blow-up
  - Up to 288 bunches accelerated in SPS, controlled long. blow-up

- **Alternatives**
  - 8b4e, 80b
  - None of them validated up to $2.6 \cdot 10^{11}$ p/b
Linac4

- **Short term goal (2018)**
  - 25mA peak current after the RFQ (acceptance 2.6 mm mrad total normalised)
  - Pulse length of 600µs
  - Stability shot-to-shot of 2%
  - Pulse flatness over
    - 600µsec : 5%
    - 120µsec : 2%

- **Long term goal (2023)**
  - 45mA peak current after the RFQ (acceptance 2.6 mm mrad total normalised)
  - Pulse length of 600µs
  - Stability shot-to-shot of 2%
  - Pulse flatness over
    - 600µsec : 5%
    - 120µsec : 2%

Intensity can be compensated (to a certain limit) with injection turns
In-Stability cannot be compensated
Reliability is key
Charge questions

Wrap up of Session 1: LIU beam performance reach, Giovanni + Heiko (20’+10’)

- Keywords: LIU target performance, risks, mitigations, challenges for post-LS2 and LIU beam commissioning, protons and ions
- Questions to be answered:
  - What are the baseline beam parameters for LIU and the alternative production schemes (protons and ions)?
  - What are the assumptions, do we need to review any of the assumptions based on 2018 experience or gained knowledge on some other items?
  - What we can definitely tick out from Run 2 experience and what we still need to study in LS2 and prove in Run 3 (simulation and post-LS2 MDs)?
  - How to balance pushing performance for protons and ions after LS2?
  - Bunch-by-bunch variations within trains?
LIU performance reach for protons

- **PSB injection**: Brightness limited by efficiency of multi-turn injection process and space charge effects.
- **PS and SPS injection**: Brightness limited by space charge – $\Delta Q < 0.31$ (PS) and 0.21 (SPS), to limit beam degradation.
- **PS cycle**: Bunch intensity limited by longitudinal coupled bunch dipolar instability.
- **SPS cycle**: Bunch intensity limited by RF power, longitudinal coupled bunch instability.

<table>
<thead>
<tr>
<th>HL-LHC target</th>
<th>$N_b \times 10^{11}$ p/b</th>
<th>$\varepsilon_{x,y}$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td>1.3</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

$N_b (x 10^{11} \text{ p/b})$ and $\varepsilon_{x,y}$ (μm) values for HL-LHC target and present conditions.