Achievements and Performance Prospects of the upgraded LHC Injectors


IPAC’22, Bangkok, Thailand, June 12-17 2022
CERN Accelerator Complex – LHC Injector Complex

+ Non-LHC Physics

**ISOLDE**: the radioactive ion beam facility

**East Area**: secondary beam lines fed by PS protons on 2 targets

**nTOF**: pulsed neutron source

**AD/ELENA**: low energy antiprotons

**AWAKE**: proton driven plasma wake field acceleration

**HiRadMat**: high intensity /brightness to material test facility

**North Area**: secondary beam lines fed by SPS protons/ions on 3 targets. Multiturn extraction (MTE) beam.
CERN’s accelerator schedule for the years to come

- **Run 3: LHC started its final run**
  - 2022 - 2025

- **Next: installation of HL-LHC**
  - During Long Shutdown 3 (LS3)

- **One of main ingredients for HL-LHC: LHC Injector Upgrade (LIU)**

- **LIU installation 2019 – 2020 (LS2)**
  - 2021 first run of upgraded injector chain
LHC Injector Upgrade for HL-LHC

Increase intensity per $p^+$ bunch and brightness by factor 2

- remove limitations along the chain in 2 year shutdown (2019–20)

<table>
<thead>
<tr>
<th>HL-LHC parameters for protons and ions</th>
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<tbody>
<tr>
<td>$N (10^{11} \text{ p}/\text{b})$</td>
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<tr>
<td>HL-LHC</td>
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<tr>
<td>Achieved</td>
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| $N (10^8 \text{ ions}/\text{b})$ | $\epsilon_{x,y} (\mu\text{m})$ | Bunches |
| HL-LHC | 1.9 | 1.5 | 1248 |
| Achieved | 2.0 | 1.5 | 648 |
LIU in a nutshell

**Linac 4**
- Acceleration of 25 mA of H⁻ to 160 MeV

**PSB**
- 160 MeV H⁻ charge exchange injection
- Acceleration to 2 GeV with new main power supply and new RF systems

**SPS**
- Main RF system (200 MHz) upgrade
- Longitudinal **impedance** reduction & partial a-C coating
- New beam dump, collimators and protection devices

**PS**
- 2 GeV injection
- New RF equipment including broad-band feedback
Achievements and Performance Prospects of the upgraded LHC Injectors

• **Strategy to**
  ▪ Commission 6 accelerators post-LS2 and re-establish Fixed Target physics
  ▪ Achieve:
    - 2018 parameters for LHC and Fixed Target beams
    - Demonstration of feasibility of momentum slip stacking in the SPS for Pb ions

• **Progress towards HL-LHC parameters**

• **Remaining Challenges during LHC Run 3**
Commissioning strategy 2020 - 2021

• 3-months shift due to COVID-19. No other changes to schedule

- Prolonged commissioning period
  - Individual system tests (IST) end of shutdown
  - Hardware Commissioning from control room with operational tools
  - Standalone beam commissioning

First physics: ISOLDE 21 June

LHC: 2 weeks of pilot run in October
Commissioning coordination

• Common coordination meeting for overall approach
  ▪ General controls infrastructure
  ▪ Online check lists
  ▪ Synergies
  ▪ Common tools (reference measurement, performance tracking, ...)

• Dedicated commissioning teams per machine
  ▪ With dedicated coordination for beam dynamics, equipment, ...

• “Operational Readiness Analysis”
  ▪ Pre-beam reviews per machine to ensure consistency of approach
  ▪ Identify missing components for operation or commissioning
  ▪ Share expertise and experience and feed-forward to next machine
LIU commissioning strategy - Outcome

- **Overall result:** re-commissioned all 6 accelerators and fulfilled 2021 program

- **Lessons learned:**
  - **Software readiness** → global software coordinator and control room applications as part of system project definition
  - **Planning needs to include electronics, controls infrastructure,**... → in case of delays: clear priorities and potentially more frequent schedule updates
  - Build into design: capability for **easy aperture measurements** for every machine

Object in PS vacuum chamber

SPS: wrong transition piece in Long Straight Section 2

SPS: vertical aperture measurement
Availability – Hardware faults

• Large number of systems installed during LS2 → long list of faults post-LS2
  ▪ Expected ‘teething’ effect: most faults were fixed rapidly
  ▪ Some more serious persistent hardware problems (mainly in the SPS) limited the performance reach of injectors in 2021
  ▪ Examples:
    - Non-radiation hard electronics in the tunnel for new SPS access system → upgraded during winter stop 2021-2022
    - Slow conditioning and many faults of 200 MHz RF cavities in the SPS: reduced available voltage

2623 faults in 2021
885.3 h of downtime

2021 availability of injectors

<table>
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<tr>
<th>Accelerator</th>
<th>expected [%]</th>
<th>obtained 2021 [%]</th>
</tr>
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<tbody>
<tr>
<td>LINAC4</td>
<td>95</td>
<td>97.4</td>
</tr>
<tr>
<td>PSB</td>
<td>90</td>
<td>94.5</td>
</tr>
<tr>
<td>PS</td>
<td>87</td>
<td>88.1</td>
</tr>
<tr>
<td>SPS</td>
<td>84</td>
<td>73.4</td>
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  ▪ Examples:
    - Poor high voltage performance of 1 vertical dump kicker in the SPS → low vacuum thresholds; issue of vacuum deconditioning with time

Limited overall performance with 25 ns beams in 2021

288 bunches of $1.2 \times 10^{11}$ ppb for HiRadMat only possible with mini-scrubbing before each run
Progress towards HL-LHC parameters
Achieved 2021 performance in Linac4

- Remarkable performance of Linac4 during 2021
  - No particular difficulties, **excellent RF stability**
  - Around **97% availability**
  - Example: LHC single bunch beam **intensity stability** \(\sim 0.4\%\)
    - Very similar numbers for other LHC-type beams (~0.3 - 0.6%)

P. K. Skowronska *et al.*, “Summary of the First Fully Operational Run of LINAC4 at CERN”, MOPOST007
Achieved 2021 performance in the PSB

• LHC 25 ns beam
  • Already very close to the LIU target in the beginning of 2021 (Early 2021)
  
  • Further improvement in brightness by:
    - refining the resonance compensation schemes
    - optimization of the working point and
    - optimization of the injection chicane beta beating correction (Aug. 2021)

  • As expected, the emittance plateaus for lower intensities due to, e.g., scattering on the foil and injection errors
  • Now regularly exceeding LIU target

T. Prebibaj et al., MOPOST007
S. Albright et al., WEPOTK012
D. Quartullo et al., TUPOST006

S. Albright et al., WEPOTK013
Achieved 2021 performance in the PS – standard 25 ns beam

- LIU bunch intensity of $2.6 \times 10^{11}$ p/b recovered
  - Little margin even up to $2.8 - 2.9 \times 10^{11}$ p/b

- At even higher intensity:
  - Losses around transition crossing
  - Degradation of longitudinal parameters
  - Quadrupolar coupled-bunch instabilities during acceleration

H. Damerau et al., WEPOTK046
S. Albright et al., MOPOPT043
Achieved 2021 performance in the PS – standard 25 ns beam

- Quadrupolar coupled-bunch instabilities at equivalent to $\sim 3.1 \cdot 10^{11}$ p/b at extraction
  - Higher threshold during acceleration than before LS2, stronger instability at flat-top
  - 40 MHz RF system as Landau cavity in bunch shortening mode (in phase)
    - Provides sufficient damping even at highest intensities

![Graph 1: Single harmonic, 10 MHz](image1)

![Graph 2: Bunch shortening mode](image2)
Achieved 2021 performance in the PS

- Achievable brightness limited by space charge effects on the PS flat bottom
  - Planned to follow a gradual brightness ramp-up
  - PSB to provide 2.0 – 2.25 eVs instead of HL-LHC 3 eVs in 2021
  - Emittance measurements follow constant brightness even at 2.9x10^{11} ppb

A. Huschauer et al., “Beam Commissioning and Optimisation in the CERN Proton Synchrotron after the Upgrade of the LHC Injectors”, MOPOST006
Achieved 2021 performance in the SPS

- **Success of impedance reduction campaign is confirmed by**
  - Suppression of microwave instability for high intensity single bunches
  - Measurements with long bunches (peak at 1.4 GHz disappeared)

- **Stable beams with 4x72b at $1.2\times10^{11}$ ppb**
  - thanks to optimization of RF voltage programs (200 MHz + 800 MHz), blow-up settings, energy matching, and use of longitudinal damper
  - 2021: 1x48b at $1.8\times10^{11}$ unstable during the ramp due to lack of RF power

- **Accelerated for the first time $1.6\times10^{11}$ ppb in 72b to flat top**
 Achieved performance in the SPS since 2021

- Replacement of problematic vertical dump kicker during winter stop 2021-2022
  - 4 week scrubbing run for conditioning early 2021

- More RF voltage, better voltage calibration, optimized longitudinal blow-up
  - $1.8 \times 10^{11}$ p/b in 72 bunches @ 450 GeV with correct longitudinal parameters
  - Longitudinal emittance of 3 eVs between PSB and PS → brightness margin at injection in the SPS (purple dots in figure)

Remaining challenges:
- Vacuum spikes horizontal dump kicker
- Heating of injection kicker limits study time

LHC required injection bunch length (1.65 ns) @ exit of injectors achieved

- A. Spierer et al., TUPOST021
- G. Hagmann et al., TUPOST023
- I. Karpov et al., WEPOMS008
- D. Quartullo et al., TUPOST005
- N. Bruchon et al., TUPOST042
- D. Quartullo et al., WEPOMS009
Pb ion beams
Achieved 2021 performance in the SPS

- **HL-LHC bunch parameters already achieved in 2018**
  - But with 100 ns spacing. Outstanding: 50 ns bunch spacing with slip stacking

- **Major 2021 achievement in SPS → beam commissioning of slip stacking RF gymnastics**

2 x 4 bunches @ 100 ns → 8 bunches @ 50 ns

11/11/2021
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P. Baudrenghien et al.,
“The CERN SPS Low Level RF: Lead Ions Acceleration”, TUPOST022
Remaining challenges during Run 3
Parameter ramp-up during LHC Run 3

- Remaining challenges for HL-LHC parameters from the injectors are in the SPS
  - Working point @ injection, horizontal dump kicker vacuum behavior, transmission, reproducibility,…

- Defined goals for longitudinal and transverse emittance per year
  - E.g. 2 eVs for PSB-PS transfer in 2021

- Expect to provide trains with $1.8 \times 10^{11}$ p/b in 288 bunches at SPS extraction as of 2023

- Ions 2022: HL-LHC performance
Efficiency and Reproducibility Challenges

• Shorten LHC turn-around time, with least impact on other physics
  ▪ Dedicated “LHC filling”

• LHC beam to be re-tuned whenever taken

• → global effort to increase efficiency and stability of CERN accelerator complex

• Machine learning and numerical optimization as toolkit to
  ▪ Replace manual tuning
  ▪ Model eddy currents, hysteresis and other effects

F. Velotti et al., TUPOST045
N. Madysa et al., TUPOST040
Conclusion

• The equipment and software upgrade of the LHC injector chain to reach HL-LHC parameters was successfully completed in 2019-2020

• Goal of the 2021 run was to re-establish pre-shutdown LHC and fixed target physics parameters
  ▪ PSB and PS have already reached HL-LHC parameters

• Remaining challenges are now in the SPS
  ▪ Commissioning limited by slow conditioning of the 200 MHz cavities and various kicker systems

• Reproducibility and efficiency remain a concern with beams at edge of stability
  ▪ Automation and machine learning algorithms being developed to optimize performance
Performance ramp-up in 2022

- **Further increase of the brightness in the PSB**
  - **Triple harmonic operation** after capture to reduce longitudinal line density
    - very beneficial impact on transverse emittances observed during MDs at the end of the run this year
  - Setup of **phase noise longitudinal blow-up** to improve reproducibility and reach LIU target longitudinal emittance of 3 eVs

- **Brightness increase in the PS and improvements of longitudinal beam quality**
  - Benefit from **3 eVs at PS injection** and improve emittance preservation along the cycle
  - Address outstanding issues in the longitudinal plane
    - Satellite bunches (mainly at batch tail)
    - Losses due to longitudinal halo
    - Fine tuning of RF manipulations
Resonance compensation schemes

- Resonance compensation studies conducted at the early stages of the PSB recommissioning
  - Updated working point evolution
  - Reconnecting of several multipole correctors
  - POPS-B improvements
  
  \[\text{Need for refinement of the compensation scheme}\]

- Optimizer developed by OP "GeOFF" available for the new studies
  - Optimization algorithms allow for convergence to compensation values
    - Usually at least a couple of scans of 100-250 shots for each resonance!
  - Experimental investigation of global settings for the compensation of multiple correctors in the scan convergence is slower but still <100 shots.
    - Usually: impossible to test experimentally (would need multi-dimensional scans using the model)
  - Combination of multiple correctors for a single resonance refining the compensation
    - Usually: would need \(n(\text{#of correctors})\)-D scans

To be applied to the operational users soon
Beta-beating during the fall of the injection chicane

- After the POPSB regulation improvements successful deployment of beta-beat measurements and correction during the fall of the injection chicane
  - Beta-beating measured at the positions of two individually powered quadrupoles using the k-modulation method
    - In very good agreement with the model
  - Corrections calculated and implemented demonstrating a very good correction
  - Possibility to move injection $Q_Y$ closer to half integer without losses
Achieved 2021 performance in Linac3

• Excellent performance around an average intensity of 30 µA

• Stability significantly improved thanks to
  • New source crucible design (with beak)
    - 4 weeks of operation seems achievable with single oven refill
  • Improved stripping foils
Achieved 2021 performance in LEIR

• Extracted intensity of the NOMINAL beam reproducibly above the LIU target
  • Operating with a comfortable margin of ~10%

• Excellent Linac3 performance and stability is major ingredient to stable LEIR performance

• 2021 activities focused on improving additional reproducibility-related effects
  • Improved detection of stripping foil degradation
  • Detection of PS stray field effects thanks to injection transfer line BPMs
  • Power converter regulation issues in the injection line identified and being followed-up