MCBI for CERN LHC Injectors Upgrade (LIU) and High Luminosity LHC (HL-LHC)

Giovanni Rumolo, CERN, Genève, Switzerland

ICFA Mini-Workshop on Mitigation of Coherent Beam Instabilities in Particle Accelerators – MCBI 2019
23 – 27 September 2019, Zermatt (Switzerland)

• Why upgrades and what are the upgrades for LHC and its injector chain?

• Present intensity limitations and future performance of the LHC injectors
  • Where do we need mitigation of coherent beam instabilities?
  • How far we can go with the upgrades

• Mitigation of beam instabilities for HL-LHC
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Goals of upgrades in a nutshell (HL-LHC)

The **High Luminosity LHC (HL-LHC)** upgrade

- Aims at **3000 (4000) fb\(^{-1}\)** total integrated luminosity over HL-LHC run (2026 – 2037)
- Based on operation at levelled luminosity of **5 (7.5) \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)** by lowering \(\beta^*\)

### Beam properties @LHC injection

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<tr>
<th>N(_b) (x (10^{11}) p/b)</th>
<th>(\varepsilon_{x,y}) ((\mu)m)</th>
<th>Bunch spacing</th>
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The **LHC Injectors Upgrade (LIU)**

- Aims at **matching the beam parameters** at LHC injection with HL-LHC target
- Needs to deploy **means** to overcome **performance limitations** in all injectors!
A view on LHC Injectors and LIU

- Main RF system (200 MHz) upgrade
- Longitudinal impedance reduction & anti-e-cloud coating
- New beam dump and protection devices

- Acceleration of H⁻ to 160 MeV
- Nominal 40 mA within 0.4 μm

- 160 MeV H⁻ charge exchange injection
- Acceleration to 2 GeV with new main power
- 2 GeV injection
- New RF equipment including broadband feedback
A view on LHC and HL-LHC

**SUPERCONDUCTING LINKS**
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service galleries to the LHC tunnel.

**CRYOGENICS**
2 new large 1.9 K helium refrigerators for HL-LHC near ATLAS and CMS.

**CIVIL ENGINEERING**
2 new caverns and two new 300-metre service galleries, two new large shafts; new technical buildings on surface in P1 and P5 (ATLAS and CMS).

**FOCUSING MAGNETS**
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

**BENDING MAGNETS**
2 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

**COLLIMATORS**
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.
• Why upgrades and what are the upgrades for LHC and its injector chain?

• Present intensity limitations and future performance of the LHC injectors
  • Where do we need mitigation of coherent beam instabilities?
  • How far we can go with the upgrades

• Mitigation of beam instabilities for HL-LHC
Present performance limitations

- **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: HL-LHC target

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Lifting the brightness limitations

• Halve the slope of the **PSB brightness line**
  • 160 MeV H⁻ charge exchange injection from Linac4 replacing 50 MeV multiturn injection from Linac2 (demonstrated in simulations)

• Reduce **space charge at PS injection** to accommodate same tune spread as current LHC beam ($\Delta Q_y = -0.31$)
  • Increase of PS injection energy from **1.4 GeV to 2 GeV**
  • Increase of **longitudinal emittance** (compatibly with other constraints) at transfer in order to gain from decreasing $\lambda_{\text{max}}$ and increasing $\delta = (\delta p/p_0)$

• Concerning **beam stability**:
  • PSB H instability due to extraction kicker not expected to be an issue → Eirini’s talk
  • Larger longitudinal emittance beneficial to beam stability
Lifting the PS intensity limitation

• Bunch current limited around $1.6 \times 10^{11}$ p/b at extraction

• Above $1.6 \times 10^{11}$ p/b **longitudinal coupled bunch instabilities** appear on the ramp and at flat top for nominal longitudinal emittance
  - Dipolar oscillation, caused by 10 MHz RF system impedance (as found also in simulations)
Mitigation of the PS longitudinal instability

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over Run 2 (2015 – 2018) → Heiko’s talk

Commissioning of coupled bunch feedback with broadband cavity and operational optimization of feedbacks and 40 MHz as Landau system + transverse optimisation

New power converters for 40/80 MHz and

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Mitigation of the PS longitudinal instability

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over Run 2 (2015 – 2018) → Heiko’s talk

- Goal in terms of **intensity out of the PS** reached!
  - However, we may need to seek further stabilization in order to decrease the longitudinal emittance into the SPS (requirement to minimize capture losses)
  - In this case, the option of installing a Landau cavity in the PS with the right tuning range to cover ramp + flat top remains viable as a post-LIU action
Lifting the SPS intensity limitation

- **Beam loading** in the present 200 MHz TW RF system – intensity limited to about 1.3e11 p/b
- **Longitudinal instabilities** during ramp with very low threshold cured by
  - 800 MHz RF system in bunch shortening mode
  - Controlled emittance blow-up (with constraint of 1.7 ns bunch length at extraction) – not needed in Q20
Mitigation of the SPS longitudinal instability

- **Impedance reduction** needed in addition
  - Shielding of a subset of vacuum flanges
  - Enhanced damping of HOMs of 200 MHz (factor 3 desired) as baseline for LIU
  - Serigraphy on the injection kickers MKP

new HOM coupler

HL-LHC

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Mitigation of the SPS transverse instability

- **Transverse Mode Coupling Instability (TMCI)** threshold was raised from $1.6 \times 10^{11}$ p/b to $4 \times 10^{11}$ p/b when switching to a low gamma transition ($\gamma_t$) optics.

  See Yannis’ talk.

Measurements confirm 2.5 times higher threshold!
Mitigation of the SPS transverse instability

- **Electron cloud** responsible for instabilities, can be **mitigated by**
  - Beam induced scrubbing
  - Coating with a-C the chambers of the focusing quadrupoles and adjacent drift chambers
Mitigation of the SPS transverse instability

• **Horizontal coupled bunch instability**
  - Observed in 2017-18 for intensities above $1.8 \times 10^{11}$ p/b
  - Driven by resistive wall and narrow band horizontal impedances, but also destabilizing effect of impedance reduction $\rightarrow$ Carlo’s talk
  - Needs to be operationally stabilized for future operation – tradeoff with beam lifetime

\[ \xi_H \sim 0.1 - 0.2 \]
\[ \xi_H \sim 0.3 - 0.5 \]
A possible weapon for the unexpected …

- Prototype of **vertical (V) wideband feedback** system deployed at SPS
  - Using stripline pick-ups + two stripline kickers and a slotline kicker, bandwidth up to 1 GHz, power > 1 kW

- Damping of Transverse Mode Coupling Instability (TMCI) with single bunch demonstrated in machine experiments in 2017-18
Summary: Future LIU performance

- **PSB injection**: from Linac4
- **PS injection**: 2 GeV, larger longitudinal emittance
- **PS cycle**: Longitudinal coupled bunch feedback system, impedance reduction
- **SPS cycle**: RF power upgrade, longitudinal impedance reduction, beam scrubbing & partial a-C coating, low $\gamma_t$ optics

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HL-LHC target

Present

LIU matches HL-LHC

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• Why upgrades and what are the upgrades for LHC and its injector chain?

• Present intensity limitations and future performance of the LHC injectors
  • Where do we need mitigation of coherent beam instabilities?
  • How far we can go with the upgrades

• Mitigation of beam instabilities in the LHC
LHC beam stability

- LHC transverse beam instabilities observed with different types of beams and at different stages of the LHC cycle (see Xavier’s talk)

2010, single bunch during the ramp

2011-12, 50 ns beam during $\beta^*$ squeeze or while adjusting the beams to collide

2015-18, 25 ns beam at injection
LHC beam stability

- **LHC transverse beam instabilities** observed with different types of beams and at different stages of the LHC cycle (see Xavier’s talk)

- Sources are mainly
  - *Transverse impedance* (dominated by collimators, especially when closed at top energy) through loss of Landau damping due to beam-beam, electron cloud, linear coupling, cut tails, noise induced modifications of distribution
  - *Electron cloud*, at least with 25 ns beams

- Controlled through “**extreme**” *machine settings*, e.g. at 6.5 TeV $Q’=+15-20$, octupole strength close to maximum, maximum damper gain and bandwidth

- Need to gain some margin with stabilisation knobs for operation with HL-HLC beam parameters (double intensity, double brightness) → Impedance reduction, electron cloud understanding and partial mitigation
• Due to the small gaps, at 6.5 TeV the most critical impedance contributor (80%) is **collimators**

• Within HL-LHC primary and secondary collimators replaced by new ones **with Mo-Gr jaws** having same robustness and higher conductivity (with Mo coating on secondaries) → Alessio’s talk
LHC beam stability

- Example: Effect of impedance reduction on **TMCI threshold**

![Diagram showing comparison between Present LHC impedance model and HL-LHC impedance model after collimator impedance reduction.](image)

**Present LHC impedance model**

- Simulation
- Measurement

**Instability**

**HL-LHC impedance**

(after collimator impedance reduction)

- Simulation

**Instability**

**Graph Details**

- Mode frequency
- Bunch intensity / $10^{11}$ p. p. b.
- $Q_{x0} - Q_s$

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LHC beam stability

- Strong instabilities observed at 450 GeV with 25 ns beams, in both x and y
  - Stabilized with high chroma ($Q' = 20$), high octupole strength ($\Delta Q = 1.5e-3$)
  - Caused mainly by electron cloud in quadrupoles

- Simulations predict more stability for HL-LHC

Instability simulations (450 GeV)
(e-cloud in the arc quadrupoles - SEY 1.3)

E-cloud buildup simulations
arc quadrupoles
LHC beam stability

- Strong instabilities observed at 450 GeV with 25 ns beams, in both x and y
  - Stabilized with high chroma ($Q' = 20$), high octupole strength ($\Delta Q = 1.5 \times 10^{-3}$)
  - Caused mainly by electron cloud in quadrupoles

- Simulations predict more stability for HL-LHC (thanks to lower electron cloud)

- More electron cloud instabilities have been observed e.g. at flat top induced by decaying intensity and onset of central stripe in dipoles
Electron cloud mitigation

- In general, low SEY after scrubbing is crucial to cure e-cloud instabilities.
- Heat load measurements show that SEY may remain as high as 1.35 (in average) in some cells.
  - Reason for high remaining SEY under close scrutiny to improve opening procedures in the future.
- Critical sections like the new triplets will be a-C coated.
Electron cloud mitigation

• If electron cloud remains a problem with HL-LHC operation, a last resort safety net is the filling scheme …

→ Pure 25 ns and 8b+4e can be combined to reach the maximum heat load
LHC beam stability: longitudinal

- Instabilities at injection → Theodoros’ talk
  - Persistent oscillation, and even instability, from injection errors
  - Improved injection matching (voltage, energy)

- Controlled longitudinal emittance blow up during the ramp (target bunch length 1.1-1.2 ns) to avoid onset of instabilities → Helga’s talk

- Possible instabilities at flat top if bunch length decreases below 0.9 ns
To wrap up and conclude

- LHC and its injectors set to major upgrades: LIU, HL-LHC
  - Injectors upgraded in 2019-2020, LIU beam commissioning in 2021-2024
  - LHC upgraded in 2024-2025 and HL-LHC era >2026

- Mitigation of beam instabilities is **key to goal performance in the LHC injectors**
  - PSB, PS → Mainly rely on active feedback systems
  - SPS → Impedance reduction, electron cloud suppression, longitudinal emittance blow up, enhanced Landau damping, optics change

- Preservation of **beam stability in LHC** → Avoid loss of Landau damping, operational scenarios, impedance reduction, electron cloud build up & instability scaling, low electron cloud filling pattern
THANK YOU FOR YOUR ATTENTION
Mitigation of the PS longitudinal instability

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over Run 2 (2015 – 2018)

Feedback off \((N_b = 1.8 \cdot 10^{11} \text{ ppb})\)

Feedback on \((N_b = 1.8 \cdot 10^{11} \text{ ppb})\)
Mitigation of the PS longitudinal instability

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over the last three years
- With transverse optimisation, beam is now stable up to $2.6 \times 10^{11}$ p/b

$N_b = 2.6 \cdot 10^{11}$ ppb, $\Delta N/N < 5\%$
Timeline of the projects

### Proton Runs

- **Run 2**: Mainly LIU work
- **Run 3**: LIU beam commissioning through the injector chain
- **Run 4**: HL-LHC run with a period of ‘luminosity learning’

### Technical Stops

### Long Shutdowns

### Beam Commissioning

LHC Injectors

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Run 2

**Mainly LIU work**

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Run 3

**Mainly HL-LHC work**

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Run 4

We are here

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Lifting the PS intensity limitation

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over the last three years
- With transverse optimisation, beam is now stable up to $2.6 \times 10^{11}$ p/b
- Goal in terms of **intensity out of the PS** reached!
- Brightness still pending Linac4 and space charge mitigation in PS

![Graph showing emittance at PS extraction vs. intensity at PS extraction](image-url)
HL-LHC single particle dynamics

• Strong effect of **linear and nonlinear errors** in IRs due to large $\beta$
  $\rightarrow$ **Low Dynamic Aperture** in absence of correction

• **Pre-computed corrections** from magnetic measurements needed even for basic optics measurements

• $\beta^*$ levelling will require commissioning of a **large number of optical configurations** $\rightarrow$ Challenge for efficiency of the optics measurement and correction tools
Luminosity projection
LHC beam stability

- Strong instabilities observed at 450 GeV with 25 ns beams, in both x and y
  - Stabilized with high chroma ($Q' = 20$), high octupole strength ($\Delta Q = 1.5 \times 10^{-3}$)
  - Caused mainly by electron cloud in quadrupoles

- Simulations predict more stability for HL-LHC

Instability simulations (450 GeV)
(e-cloud in the arc quadrupoles - SEY 1.3)

E-cloud buildup simulations
arc quadrupoles
Beam induced heat load in LHC

- High heat load on beam screen in cold regions (cryo limit 160 W/hc in the arcs)
  - With 25 ns beams
  - Much higher than calculation from impedance + synchrotron radiation
  - Different among arcs
- Most observations compatible with electron cloud, probably localised in some magnets (or even some parts of magnets)
  - Coating with a-C for triplet quadrupoles to decrease SEY
E-cloud build up with intensity

Underlying mechanism:
When the SEY decreases the energy window for multipacting becomes narrower

For high bunch intensity the e- spectrum drifts to higher energies and can move outside the most efficient region
Inferring the average SEY

Simulations

6.5 TeV

Measurements

450 GeV

6.5 TeV

High-
load

Low-
load

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<td>Intensity (B1/B2) [p]</td>
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Inferring the average SEY

Simulations

450 GeV

Measurements

450 GeV
6.5 TeV

High-load
Low-load

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Beam induced heat load in LHC

- Two fold issue for HL-LHC
  - Less margin for cryostat with HL-LHC parameters (three-fold contribution from impedance and synchrotron radiation)
  - How does the additional load scale with bunch intensity? → We can make a prediction only if we assume it is caused by electron cloud

![Heat load per arc graph]

- Maximum allowed by cryogenics
- Margin ~7 kW
- Margin ~4 kW
- e-cloud S12 (2017) ~6 kW
- e-cloud S34 (2017) ~2 kW

2556b
- 1.15e11 p/bunch
- 6.5 TeV

2760b
- 2.2e11 p/bunch
- 7 TeV
Some other challenges in LHC

• Beam-beam interaction
  • Head-on beam-beam tune shift limit (based on past experience) currently surpassed
  • Effect of the long-range $\rightarrow 6\sigma$ DA comfortably achieved during the whole levelling process, even including the chromaticity and octupole settings necessary for beam stability

• Incoherent emittance growth along the cycle
  • Larger than expected from Intra Beam Scattering (with margin), but impact de-facto mitigated by $\beta^*$ levelling
  • Influence of noise $\rightarrow$ minimise sources by careful design of power converters, crab cavity controls, transverse damper upgrade (it might also benefit coherent instabilities)

• Beam halo active control for machine protection
  • Potentially large halo generation with HL-LHC beams, especially during commissioning
  • Cleaning techniques under study, option for Hollow Electron Lens
Some other challenges in LHC

- Beam-beam interaction
  - Head-on and long range (dynamic aperture during leveling), compensation techniques

- Incoherent emittance growth along the cycle
  - Sources to be understood, influence of noise

- Large beam halo generation with future beams
  - Halo active control for machine protection, cleaning techniques under consideration

- RF power and longitudinal stability
  - Power consumption for future injection voltage, transient beam loading, instabilities at flat bottom, longitudinal emittance blow up