LHC Injectors Upgrade
Proton throughput in the LHC Injectors Upgrade (LIU) era

Giovanni Rumolo

Special thanks to: H. Bartosik and R. Steerenberg

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http://indico.cern.ch/event/523655/
Outline of the talk

• CERN’s accelerator complex
  • Overview
  • Timeline out to 2035 and LHC Injectors Upgrade (LIU)

• Foreseen proton throughput including LIU upgrades
  • Outlook for non-LHC physics users (existing and future?)
  • General considerations
    – Optimisation of the delivery rates
    – Limitations and challenges

• Conclusions
**Timelines up to 2035**

- **LHC Injectors Upgrade (LIU) installations during Long Shutdown 2**
  - Preparation (studies, hardware design/production) until LS2
  - LIU beam commissioning during Run 3

- **High Luminosity LHC (HL-LHC) installations during Long Shutdown 3**

<table>
<thead>
<tr>
<th>Year</th>
<th>Q1</th>
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LHC Injectors Upgrade (LIU)

⇒ **AIM of the project**

- Increase intensity/brightness in the injectors for **LHC beams** to match High Luminosity LHC (HL-LHC) requirements
- Increase **injector reliability and lifetime** to cover HL-LHC run (until ~2035)

**Main baseline items**

- Replace Linac2 with **Linac4** → H⁻ charge exchange injection at 160 MeV into the PS-Booster
- **2 GeV** PS-Booster to PS transfer
- **Upgrade of main RF system** in SPS
**LHC Injectors Upgrade (LIU)**

- **LIU era**: beam commissioning towards the ultimate goal of matching the desired (HL-LHC) parameters at LHC injection.

- After LS3 proton delivery rate to LHC of about $3 \times 10^{17}$ p/year (and a similar, probably higher, number dumped in SPS for beam preparation).

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Present performance

Potential of improvement for non-LHC physics beams from LIU upgrades → next slides
ISOLDE

• **Perspectives for the Medium Term**
  - HIE being implemented (SC linac for post-accelerated beam to 10 MeV/u)
  - Higher intensity available from PSB after connection to Linac4 (LS2)
  - Option: Upgrade of extraction energy of beams to ISOLDE to 2 GeV (post-LS2)
• **Future beam to ISOLDE after LIU upgrades**
  - Higher intensity thanks to
    - $\text{H}^-$ charge exchange injection at 160 MeV
    - Increased RF power with new RF system
  - Limitations
    - Current at the end of Linac4
    - Injection and extraction losses

1.6 x $10^{13}$ p per pulse and per ring
with 40 mA (unchopped) from Linac4 and 100 turns injection

**Twice** as much as available today from PSB

_J. Abelleira et al, in LIU-PSB Injection meetings_
nTOF

• **Expected to run until 2030 and beyond**
  • Target exchange during LS2
    – To increase present limit of $1.66 \times 10^{12}$ pot/s to $3 \times 10^{12}$ pot/s
    – To accept up to $1.5 \times 2 \times 10^{13}$ pot/pulse
  • Expected lifetime of target ~10 years, many clients

• **Protons to nTOF: present and future**
  • $8 \times 10^{12}$ pot/pulse (17% of supercycle dedicated, 17% parasitic with half intensity)
    – RF power for acceleration and bunch rotation before extraction
    – Transverse instability
    – Losses at extraction septum

→ This results in the delivery of $1.9 \times 10^{19}$ pot/year

• Beam after LS2 and LIU upgrades (>10$^{13}$ pot/pulse?)
  – More intensity from the PS-Booster
  – Enhanced beam stability
  – Lower transverse emittance
• **Expected to run until 2030 and beyond**
  • Major renovation of AD target area during LS2. Main items
    − New air-cooled target and magnetic horn
    − Ventilation system and consolidation of buildings/tunnels
• **ELENA expected to start commissioning with beam (from external source) at the end of 2016**
  − After commissioning with beam from AD, most experiments will connect to ELENA
AD, ELENA

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- Protons to AD/ELENA: present and future
  - \( \sim 1.5 \times 10^{13} \text{ pot/pulse} \) – mainly limited by shielding in AD ring
  - Beam on AD target every \( \sim 100 \text{ s} \)
  - Similar AD beam request in the future (increase depends on improvement of AD shielding)
    - Higher proton rate for stacking (9.6 sec period after upgrade) and high energy antiprotons

\( 2 – 4 \times 10^{18} \text{ pot/year} \) limited mainly by the repetition rate
East Area

• **Expected to run until 2030 and beyond**
  • Test beams and irradiation facility
  • Major renovation plans during LS2
    – Redesign and renovation of transfer lines during LS2
    – Improvement of RP aspects, consolidation of infrastructure

• **Protons to East Area: present and future**
  • Low intensity: $1 - 5 \times 10^{11}$ p/spill
  • 17% of cycles in supercycle
  • No change expected in the East beam request in the future, maybe ion beams should be also included for irradiation tests

$\rightarrow \sim 10^{18}$ pot/year
SPS & users

CERN's Accelerator Complex
HiRadMat & AWAKE

**Plans for the Medium Term and beyond**

- Both experiments will be active until LS3 and beyond
  - Several clients for HiRadMat to test accelerator components
  - **AWAKE**: proof of concept for plasma wake acceleration (<LS2), demonstration of plasma wake acceleration with good beam quality, scalability and applications (>LS2)

**Protons to AWAKE and HiRadMat: present and future**

- HiRadMat: Single bunches \((10^{11} \text{ p/pulse})\) to full LHC beams (pulses of 288 bunches with \(1.2 \times 10^{11} \text{ p/b}\)) for ~10 experiments/year mainly limited by environmental impact
  - Double intensity expected after LIU upgrades
- AWAKE: Bright intense short single bunches \((\sim 3.5 \times 10^{11} \text{ p/pulse})\). With LIU:
  - RF power upgrade and longitudinal impedance reduction (stability, bunch shortening)
  - Lower transverse emittance

\[2 \times 10^{16} \text{ pot/year for HiRadMat and } 10^{17} \text{ pot/year for AWAKE}\]
North Area (and BDF scenario)

• Expected to run until 2030 and beyond
  • Several clients
    – T2, T4, T6 (TCC2) beam line users
    – Request for ions to TCC2 for about four weeks/year, expected to continue until 2030
    – Possible future scenario: Beam Dump Facility to share protons to North Area
  
• Some improvements planned if BDF
  – Replace existing splitter magnet with bipolar version and pulsed TT20 optics
  – Beam instrumentation (e.g. BLMs in area of splitter)
North Area (and BDF scenario)

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- **Protons to North Area: estimates from past experience**
  - $4 \times 10^{13}$ p/spill to TCC2
  - $4.2 \times 10^{13}$ p/spill to BDF
  - Both limited by losses and machine activation, margin to improve with smaller LIU beams and RF upgrade in SPS

→ Target for BDF is $4 \times 10^{19}$ pot/year – how much available to TCC2 targets?
**BDF scenario**

**Assumptions**
- Running scenario based on SPS operational experience in 2011-2012
- Spill of 9.7 s for beam to TCC2, 1 s for beam to BDF
- Several supercycle compositions considered (e.g. day and night, during LHC set up and filling)

Example of supercycle with CNGS, NA and LHC filling (2011)
BDF scenario: proton sharing

- 25% less protons to TCC2 to be (reasonably) expected due to:
  - HiRadMat (~10 days/year for set up and run)
  - Ions to NA (~4 weeks/year, assuming major set up is done during Machine Development time)
  - AWAKE to be included in the supercycle (for at least 2 months/year) if overlap

- BDF supercycles will limit proton delivery to physics users in PSB/PS

Optimisation of delivery rates

• **Increase limits of proton delivery rates on target**
  • Better compensation of the time distribution to users on timescale of weeks
  • Ex. nTOF/ISOLDE could increase the number of cycles in supercycle when other not online

• **Normal/spare mechanism in supercycle driven by direct request from users**
  • When one user’s request off, play spares to increase number of other physics users in supercycle compatibly with limitations
  • Concept already applied to AD due to its ‘sparse’ repetition rate
  • Avoid manual readjustments from the CCC and use all available time

• **Fully use the potential of the four PS-Booster rings**
  • Concept already applied when playing parasitic nTOF with EAST users
  • Whenever users needing one PS-Booster ring are served, other three rings could serve ISOLDE
    - Fast pulsing of the switching magnet
Outstanding intensity limitations for non-LHC beams

- **Beam losses in all accelerators → machine activation**
  - PSB: Losses at recombination septum limit vertical emittance of high intensity beams
  - PS: Losses at extraction → With currently operational Multi Turn Extraction (MTE) islands are extracted without need of intercepting device and losses are controlled
  - SPS:
    - Losses due to limited vertical acceptance
    - Losses on electrostatic septum (ES) during slow extraction – might pose in the future a serious limit on the maximum number of protons per year that can be extracted to the North Area
    - Capture losses

- **Other intensity limitations**
  - PS & SPS
    - RF power
    - Beam instabilities
    - Heating/outgassing/sparking of sensitive elements, stress on beam dump
Conclusions

• LIU upgrades implemented in LS2
  • Goal is to double intensity and brightness of LHC beams
  • Benefits for non-LHC physics beams
    − ISOLDE, HiRadMat, AWAKE
    − Potential for nTOF and SPS Fixed Target
    − Still limitations from beam loss and machine activation

• Future scenario with BDF at SPS
  • Will constrain proton delivery to TCC2 targets and physics users upstream
  • Options available to increase proton delivery in LIU era
THANK YOU FOR YOUR ATTENTION!
• Beam parameters
  • Based on operationally demonstrated fixed target beam intensity
    – Room for improvement thanks to LIU upgrades (smaller emittance, SPS RF upgrade)
TCC2 target experiments and SHiP (general-purpose fixed target facility to search for hidden particles)

Former CERN Neutrino to Gran Sasso (CNGS) 2006-2012. Now AWAKE: Proton-driven plasma wakefield acceleration experiment

HiRadMat: test area to evaluate the effect of high-intensity pulsed beams on materials or accelerator components
Typical PSB cycles (currently)

<table>
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<tr>
<th>User</th>
<th>Kinetic energy (GeV)</th>
<th>Intensity ($10^{10}$ p/ring)</th>
<th>Duration (s)</th>
<th>Notes</th>
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<td>ISOLDE</td>
<td></td>
<td>800</td>
<td>1.2</td>
<td>40% of cycles in supercycle</td>
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<tr>
<td>LHCPROBE/LH CINDIV</td>
<td>1.4</td>
<td>1 – 50</td>
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<td>Typically only Ring 3</td>
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<tr>
<td>LHC25</td>
<td></td>
<td>160</td>
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<td>4 + 2 rings</td>
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<td>TOF</td>
<td></td>
<td>800</td>
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<td>Only Ring 2</td>
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<td>AD</td>
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<td>EAST</td>
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<td>10 – 50</td>
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<td>Only Ring 3 (with possible parasitic TOF)</td>
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<tr>
<td>MD</td>
<td>0.05, 0.16, 1.4</td>
<td>1 – 900</td>
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ISOLDE

**Plans for the Medium Term**
- HIE being implemented (SC linac for post-accelerated beam to 10 MeV/u)
- Higher intensity available from PSB after connection to Linac4 (LS2)
- Upgrade of extraction energy of beams to ISOLDE to 2 GeV? (post-LS2)

**Beyond MT**
- Will be steered also by potential clients and new facilities coming online in the next years (SPES@LNL, Spiral2@GANIL), however it is reasonable to assume long term running
- A long term option is Eurisol with the construction of the “next-generation” European ISOL radioactive ion beam (RIB) facility (~100 kW, will require new injector)

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<th>Current</th>
<th>Power</th>
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<td>MT Target**</td>
<td>$6.4 \times 10^{13}$</td>
<td>6 μA</td>
<td>13 kW</td>
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** assumes 50% of the cycles to ISOLDE
BDF running scenario

- Example of impact of BDF supercycle on other physics users in PSB and PS
  - FT + BDF during day time (i.e. including an MD cycle in all machines)
  - TOF runs in dedicated and parasitic on East cycles (half intensity)
  - Intensity to ISOLDE assumed to be doubled (6.4e13 p/pulse)

3 µA to ISOLDE
(50% above present limitation, half of future limitation)

1.65 x 10^{12} p/s for TOF
(just compliant with present limitation and 55% of future limitation)
BDF running scenario – improved

- Example of impact of BDF supercycle on other physics users in PSB and PS
  - Implementing the optimisation on the PSB rings, i.e. combining three rings to ISOLDE with both TOF and East users
  - Immediate gain by >50% on ISOLDE, ~15% on TOF – could be redistributed

4.7 \( \mu \text{A} \) to ISOLDE
(80% of future limitation)

1.9 \( \times 10^{12} \) p/s for TOF
(65% of future limitation)
Challenges and areas of further exploration for non-LHC beams

**PSB**
- Full potential for high intensity beams will be determined by
  - Linac4 current depending on source performance – present assumption is 40 mA unchopped
  - Range of energy sweep of the debuncher for longitudinal painting

**PS**
- Explore intensity limitation after LIU upgrade and impedance reduction
- Extraction beam loss reduction
  - Test MTE with high intensity ($2.4 \times 10^{13}$ p/pulse and above)
  - Barrier bucket or bunched beam with MTE to avoid kicker rise time
  - Higher extraction energy, possible with MTE → new kickers required + impact on duty cycle
  - Three injections into SPS (two 3-turn and one 4-turn extractions from PS) → increase of cycle time

**SPS**
- Beam loss reduction and extension of intensity reach
  - Voltage modulation for individual capture of each batch with new LLRF
  - Use 800 MHz cavity during the cycle to improve beam stability
  - Higher injection energy (smaller beam size + avoid transition crossing)
  - Possibility of gamma jump quadrupoles for transition crossing with high intensity
  - Extraction beam loss on-line monitoring and control (ZS alignment, extraction orbit control)
  - Collimation system to control/localize losses
Conclusions

• **LIU upgrades implemented in LS2**
  • Goal is to double intensity and brightness of LHC beams, which will remain below 0.1% of the total proton delivery of the CERN complex even in the HL-LHC era

• **Perspectives for most of the present physics users up to 2030+**
  • Some of the beams will clearly benefit from LIU upgrades (e.g. ISOLDE)
  • Increase of target limitations is the key to improve throughput
    - Make a better use of potential higher intensity for non-LHC beams
    - Optimise time distribution between users on timescale of weeks and through normal/spare mechanism driven by user request

• **Beam Dump Facility scenario?**
  • Target is $4 \times 10^{19}$ pot/year
  • SPS: Proton delivery to TCC2 users likely to be limited below $10^{19}$ pot/year
  • PSB and PS: physics users also well below future target limits with BDF supercycles
    - Potential to improve by optimising the use of the four PSB rings

• **Main limitations and challenges**
  • Machine activation especially due to (extraction) losses in all machines
  • Several ideas to be tested to reduce losses