
CERN

3 years of LIU upgrade

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Outline

LHC Injectors Upgrade

- LIU protons
  - PS complex
  - SPS
- LIU ions
- Benefits for other beams
- Summary and outlook

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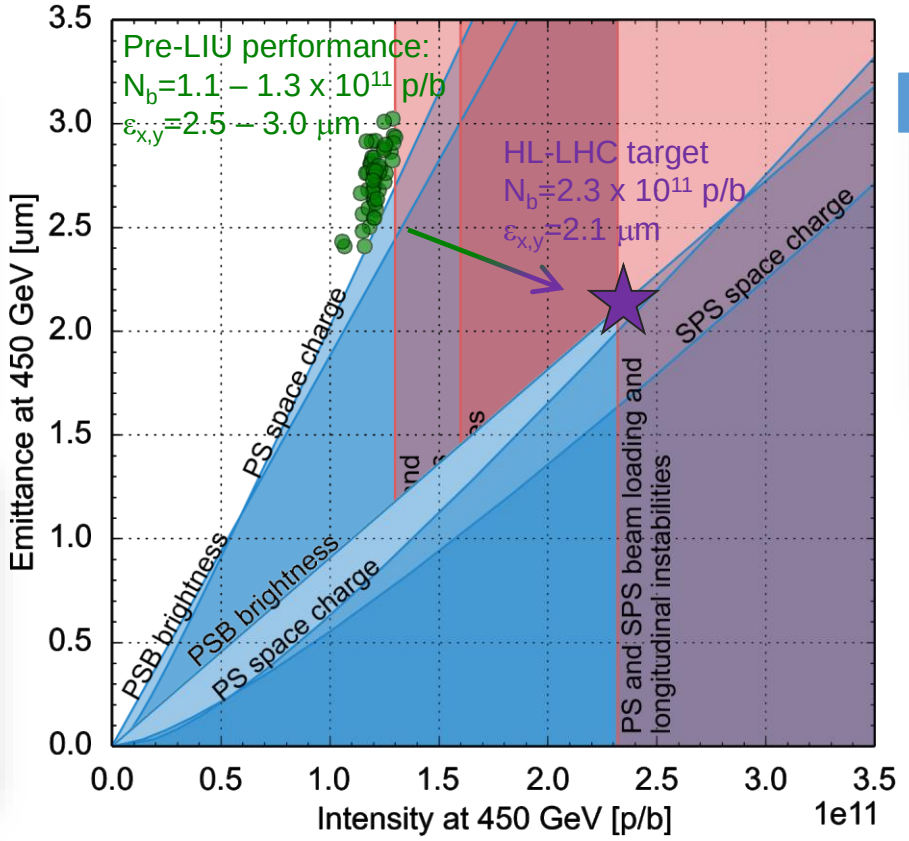
The LHC Injectors Upgrade (LIU) goal

LHC Injectors Upgrade

- LIU: Enable the injectors to produce LHC beams with HL-LHC parameters
  - Most of the LIU upgrades were implemented during LS2 (2019-20)

PSB new power supply building

PSB injection Line from Linac4



New SPS beam dump

PS Finemet cavity (damper)

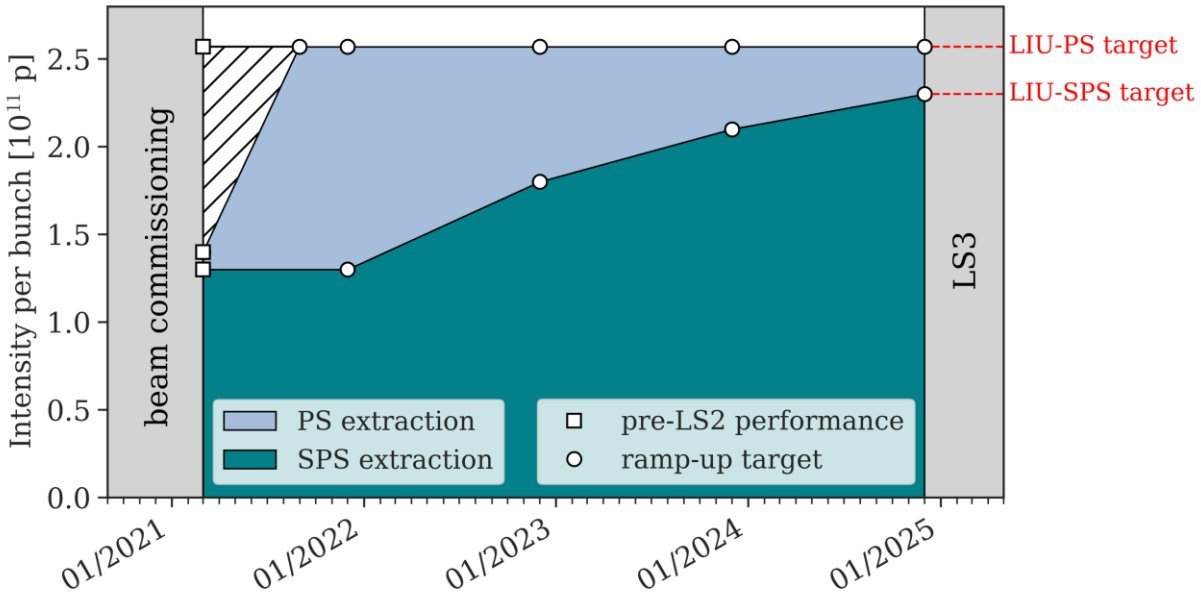
New SPS RF amplifier towers

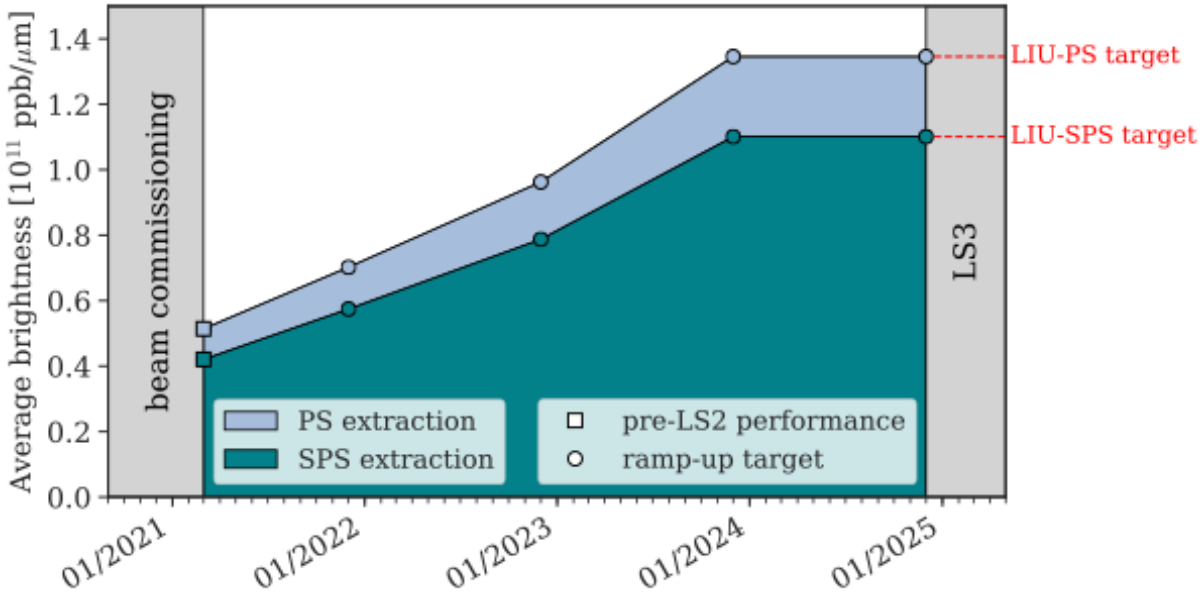
LIU beam commissioning in Run 3: ramp-up plan

LHC Injectors Upgrade

- Defined at the LIU Montreux workshop in 2020
  - Year-by-year intensity and brightness goals

A. Huschauer et al., LIU workshop 2020





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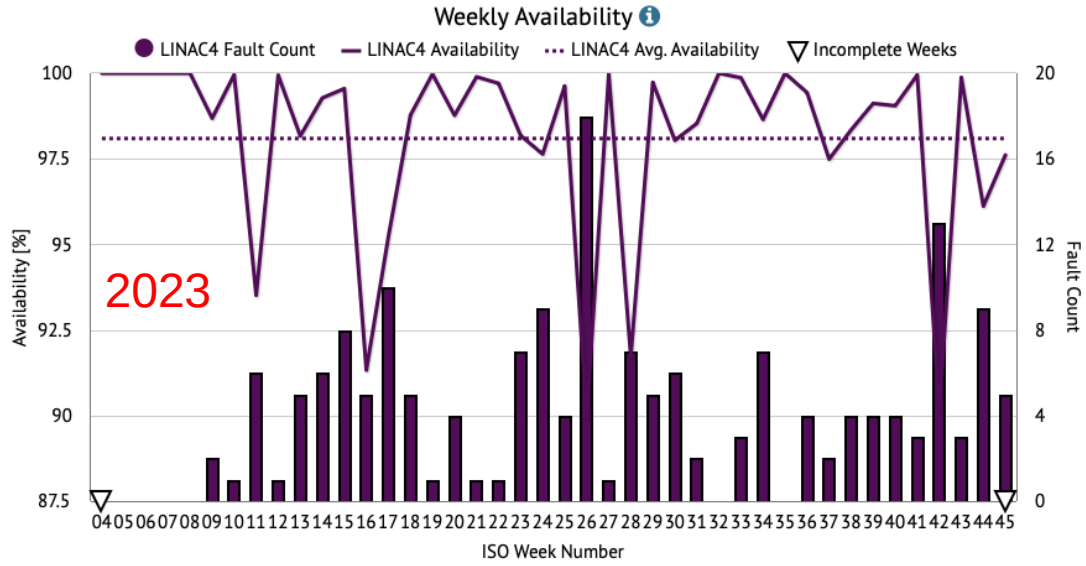
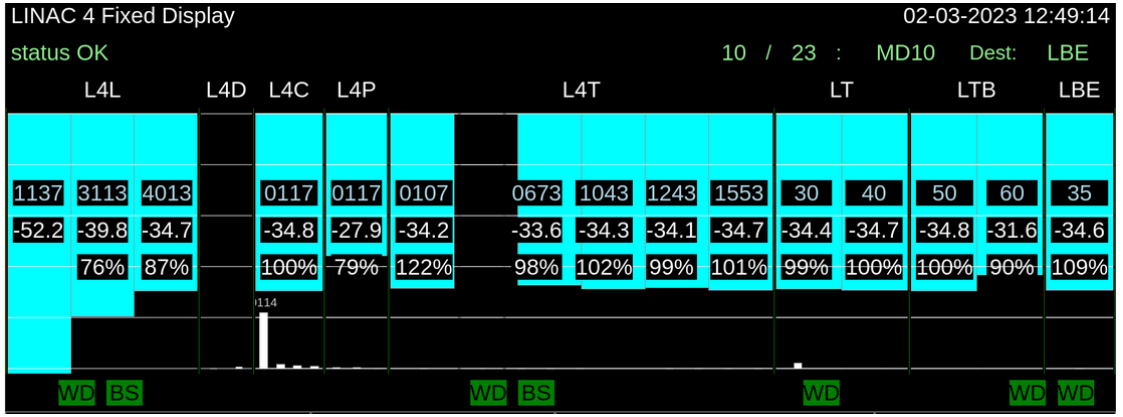
Linac4

LHC Injectors Upgrade

- The new Linac4 has been delivering beam as expected
  - **27 mA** before chopping within **0.3 um emittance** and pulse stability specifications
  - More than **98.5% availability** over the first three years operation
- Tests with new ISO4 source in 2023 demonstrated up to **35 mA** to the PSB



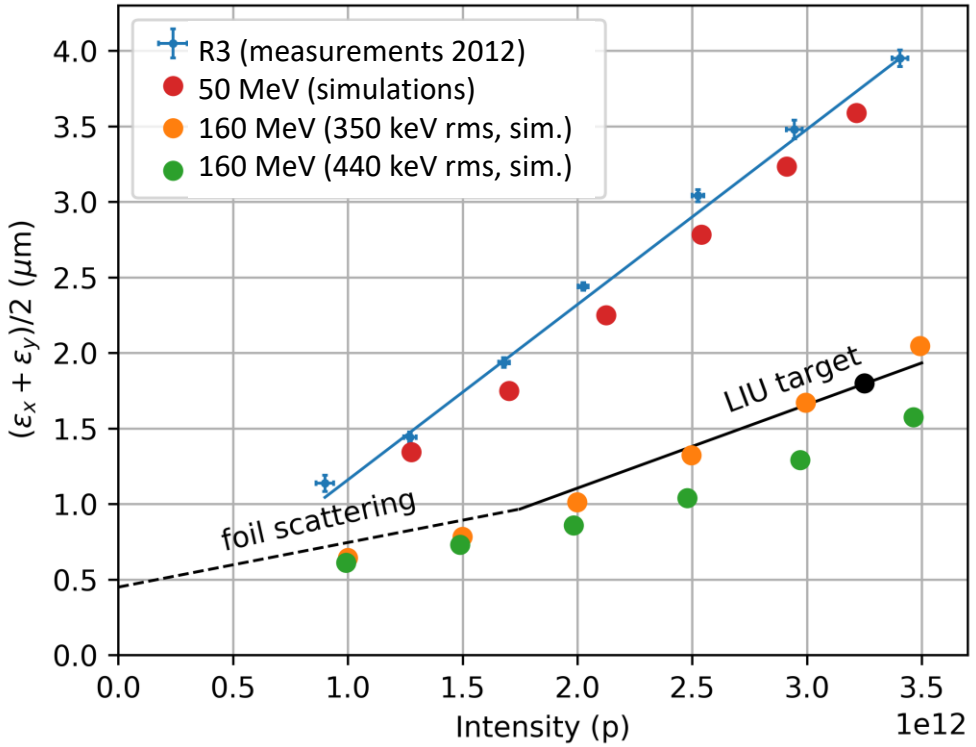


PSB

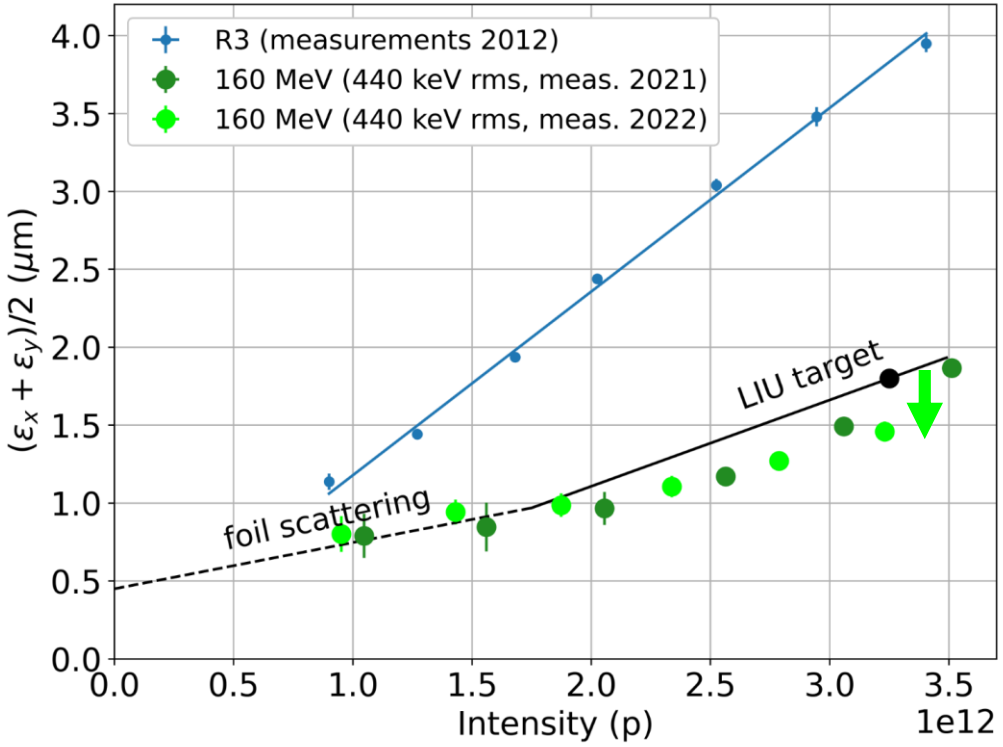
LHC Injectors Upgrade

- **PSB delivered LIU brightness (and beyond) quickly after LS2**

Pre-LS2 measurements and LIU predictions

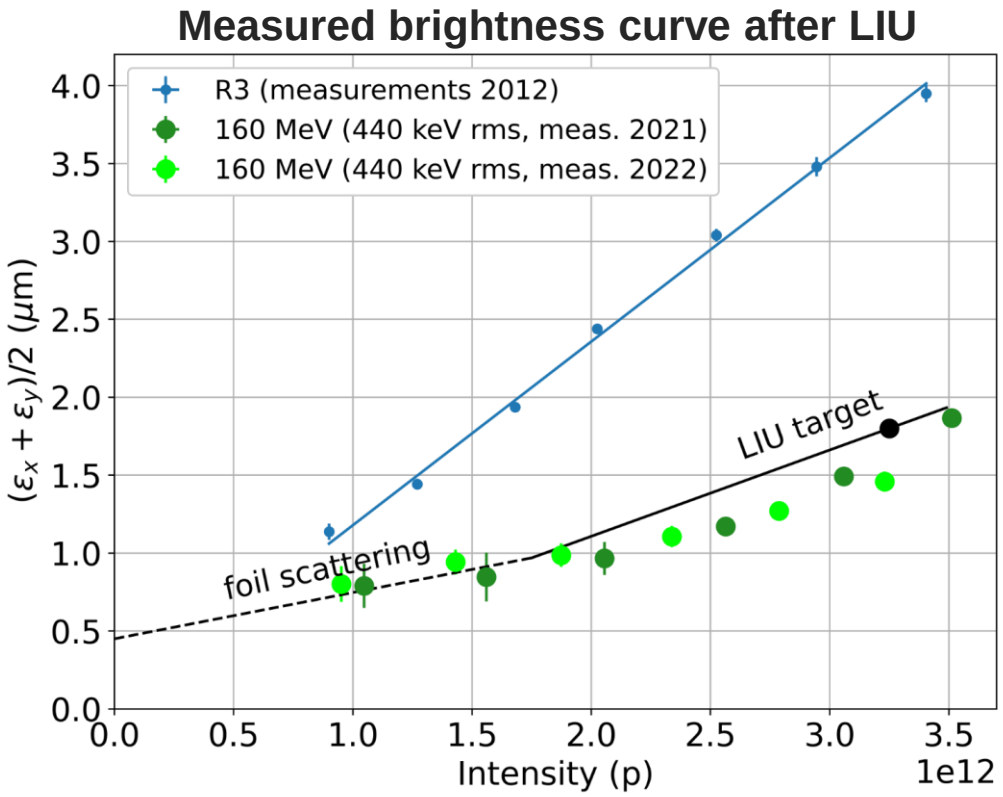


Measured brightness curve after LIU



PSB

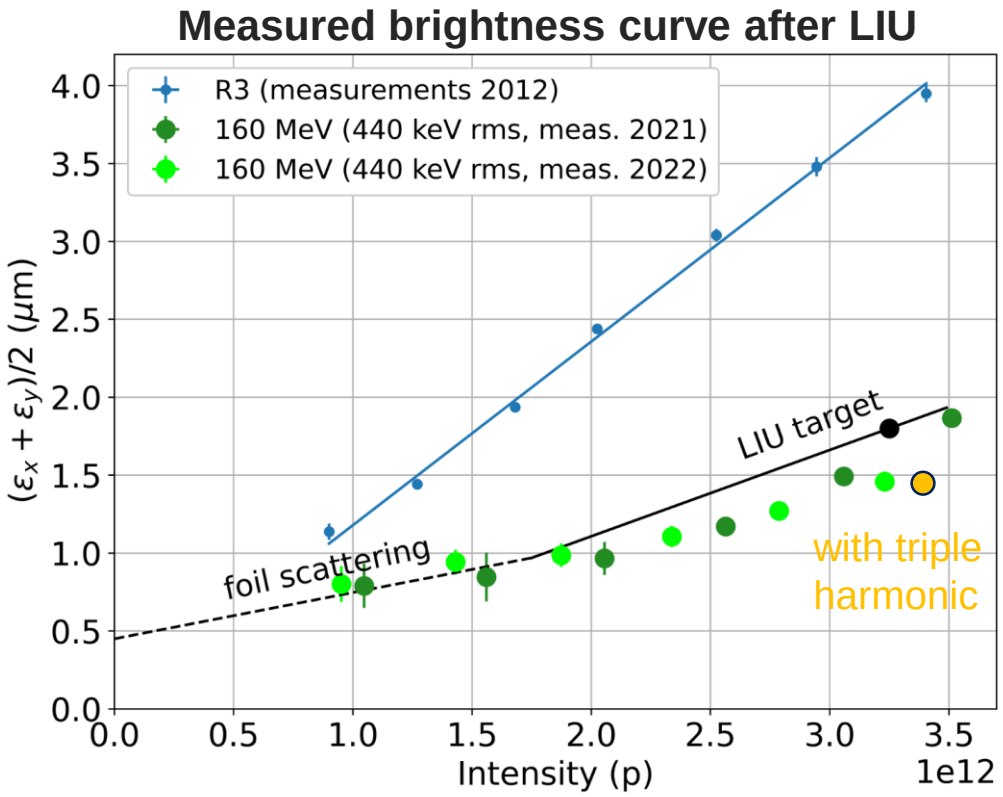
- **PSB delivered LIU brightness (and beyond) quickly after LS2**
- Ongoing work
  - **Minimization of transverse tails** through working point optimization and/or capture in triple harmonic to flatten bunch profile (Elleanor's talk)



PSB

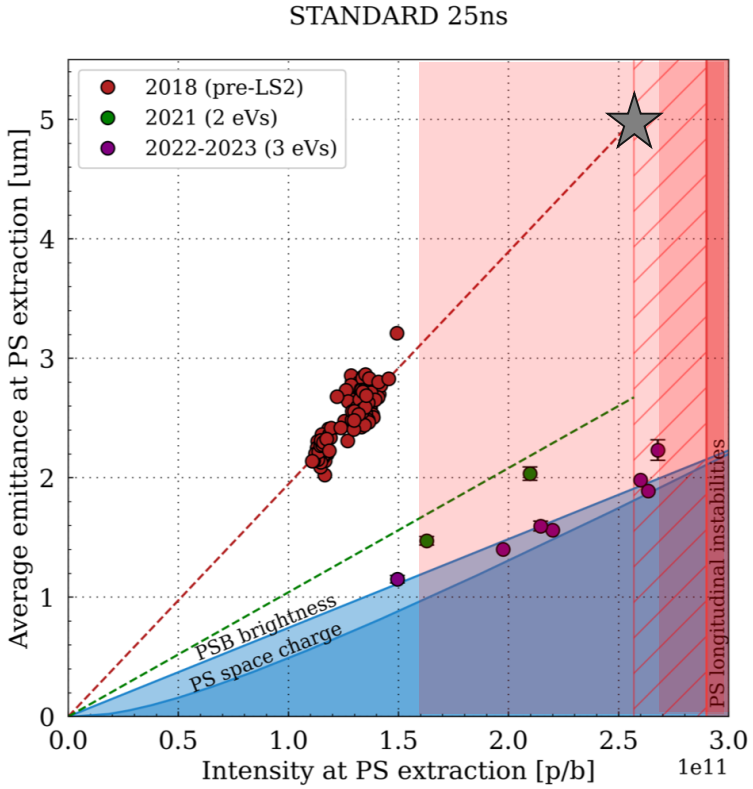
LHC Injectors Upgrade

- **PSB delivered LIU brightness (and beyond) quickly after LS2**
- Ongoing work
  - **Minimization of transverse tails** through working point optimization and/or capture in triple harmonic to flatten bunch profile (Elleanor's talk)
  - Possibly **gain further margin on brightness** through injection above half integer and/or capture in triple harmonic
  - Longitudinal painting for ISOLDE beams

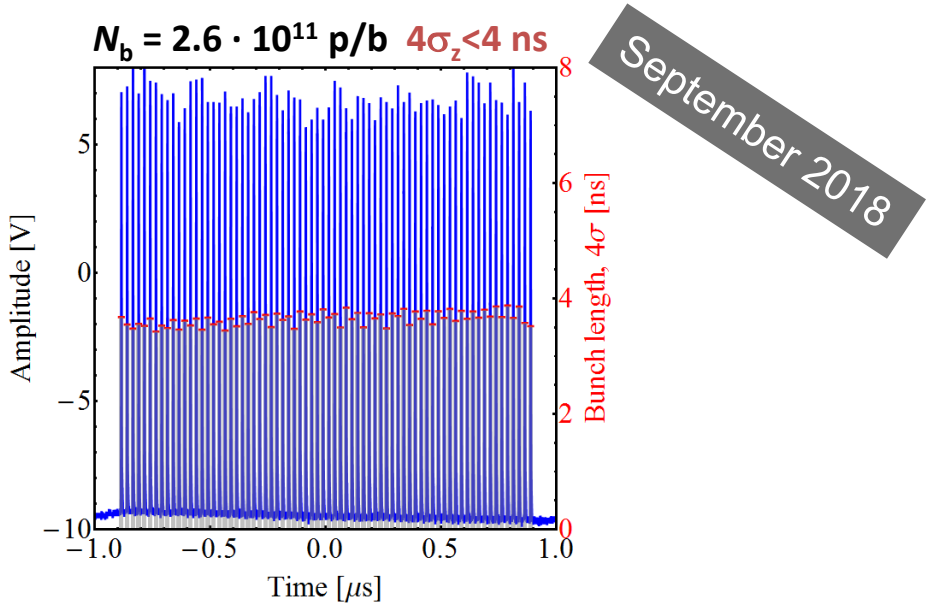


PS

- **LIU intensity**
  - Quickly recovered pre-LS2 performance in 2021 (i.e. LIU intensity)

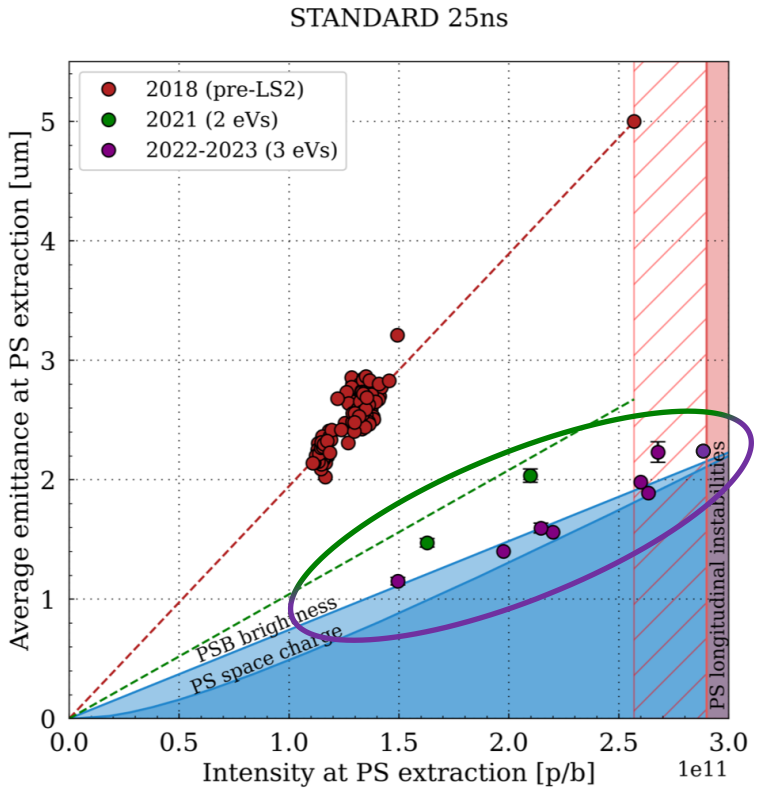


- LIU intensity demonstrated already in 2018 thanks to LIU longitudinal feedback prototype installed in 2014/15

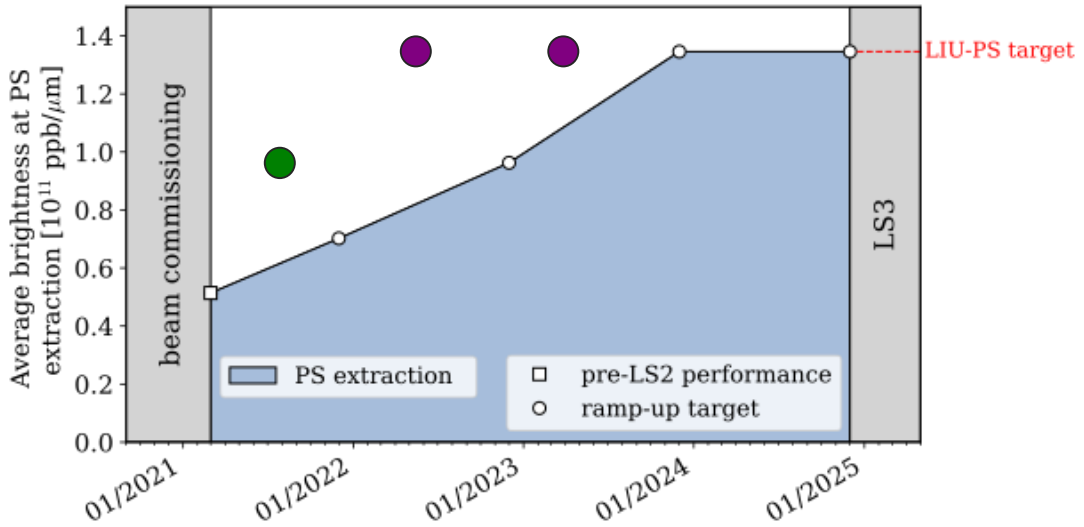


PS

- **LIU intensity**
  - Quickly recovered pre-LS2 performance in 2021 (i.e. LIU intensity) – and beyond



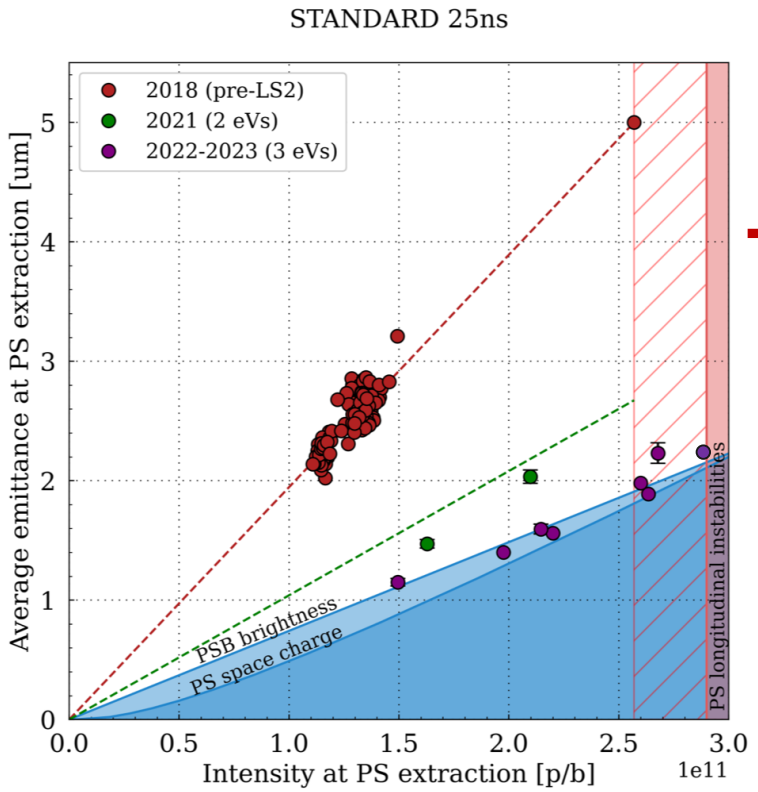
- LIU intensity demonstrated already in 2018 thanks to LIU longitudinal feedback prototype installed in 2014/15
- First step of brightness ramp-up (2021) with 2 eVs
- Full PS performance achieved in 2022 with 3 eVs (also thanks to new BTP transfer line layout/optics)

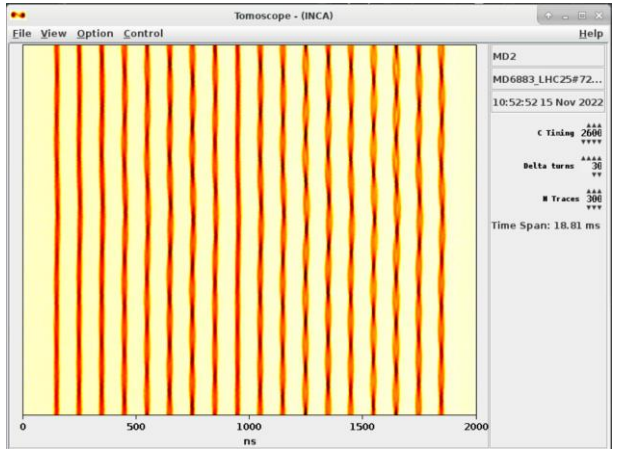


PS

LHC Injectors Upgrade

- **LIU intensity and brightness as of 2022**
  - Quickly recovered pre-LS2 performance in 2021 (i.e. LIU intensity) – and beyond





Higher intensities limited by quadrupolar instabilities

PS

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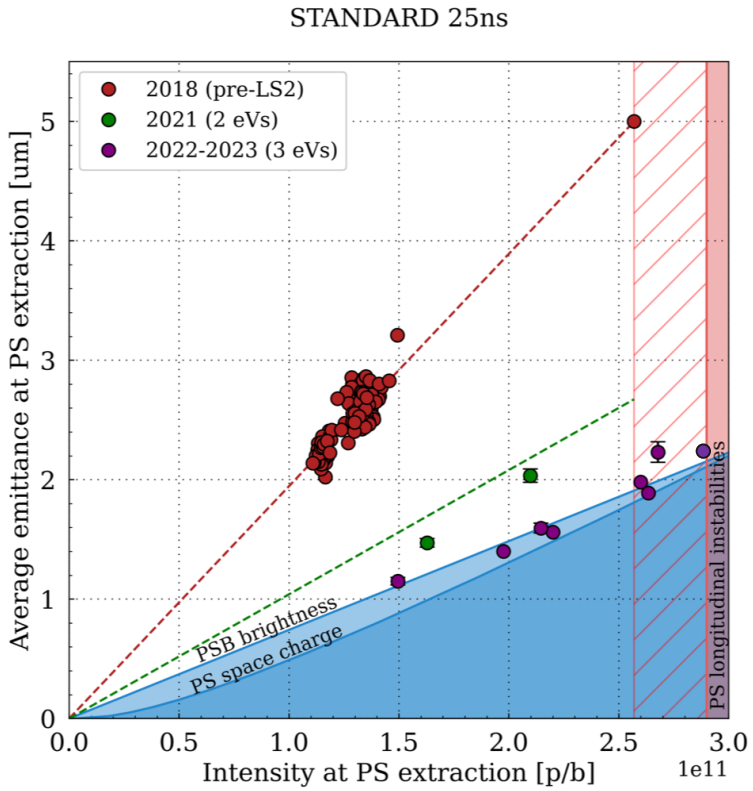
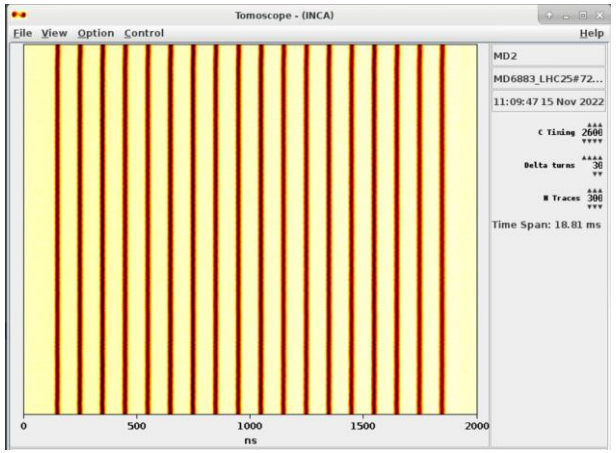
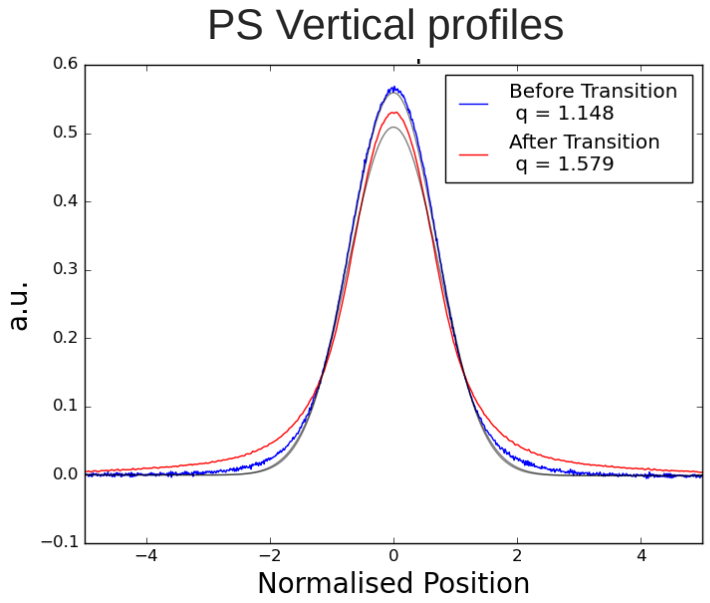


Stabilised by quadrupolar feedback (Finemet cavity) up to at least 3.15e11 p/b equiv. (2022)



PS

- **LIU intensity and brightness as of 2022**
  - Quickly recovered pre-LS2 performance in 2021 (i.e. LIU intensity) – and beyond
- Ongoing work / points to be addressed
  - **Transverse tail generation at transition crossing** – to be understood and mitigated (Elleanor's talk)



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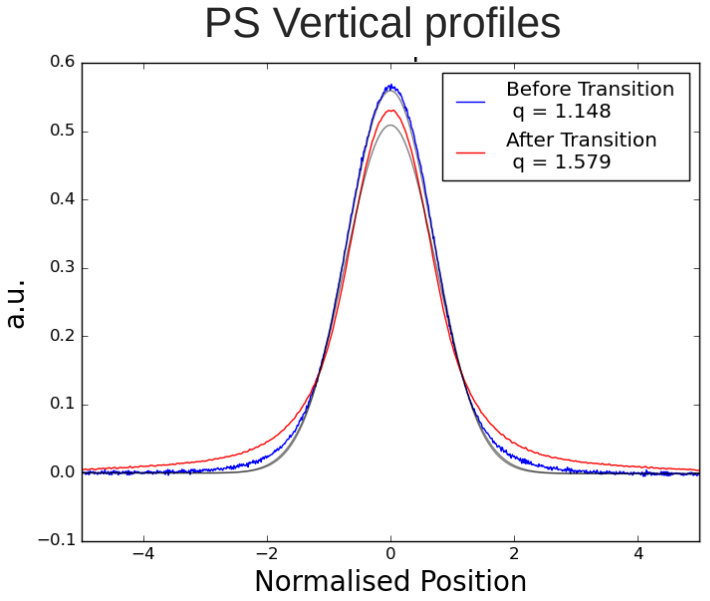
- Ongoing work / points to be addressed
  - **Transverse tail generation at transition crossing** – to be understood and mitigated (Elleanor's talk)
  - **High intensity still requires careful optimization of RF experts → establish margin** to operate comfortably at LIU parameters
  - Explore possible benefit from **smaller longitudinal emittance for SPS transmission** (but reduced intensity margin in PS)
  - Reliability of RF systems (Ivan's talk) including monitoring (Simon's talk)



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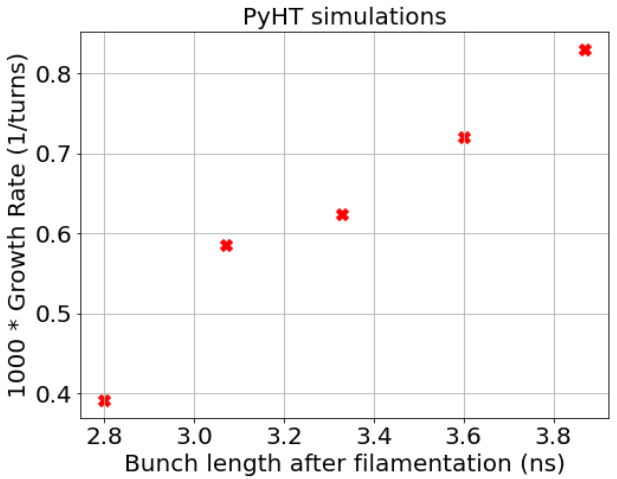
SPS transverse stability at injection energy

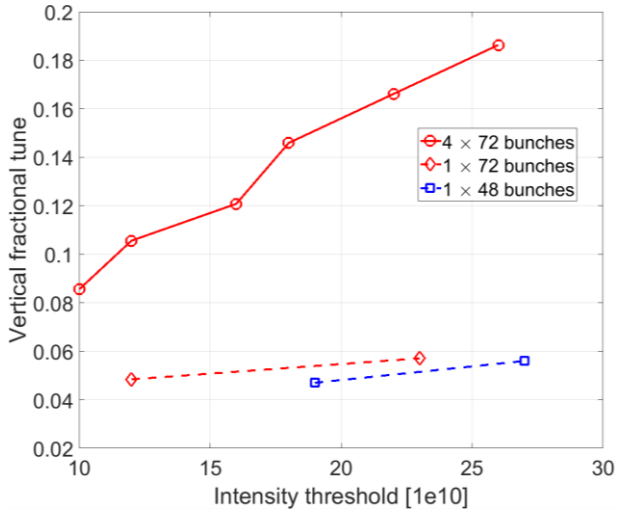
LHC Injectors Upgrade

- Horizontal headtail instability
  - Requires large horizontal chromaticity (Q'/Q ~ 0.7)
  - Discovered **criticality of short bunches at injection** (<3.9 ns) to ensure stability, also confirmed in simulations

(Ingrid's talk)

- Fast vertical coupled bunch instability
  - Strong dependence on vertical tune → need to operate with Q_y close to 20.25 resonance for LIU parameters
  - **Good control of tunes is critical** due to large bunch-by-bunch tune shift from impedance – excellent progress on operational correction

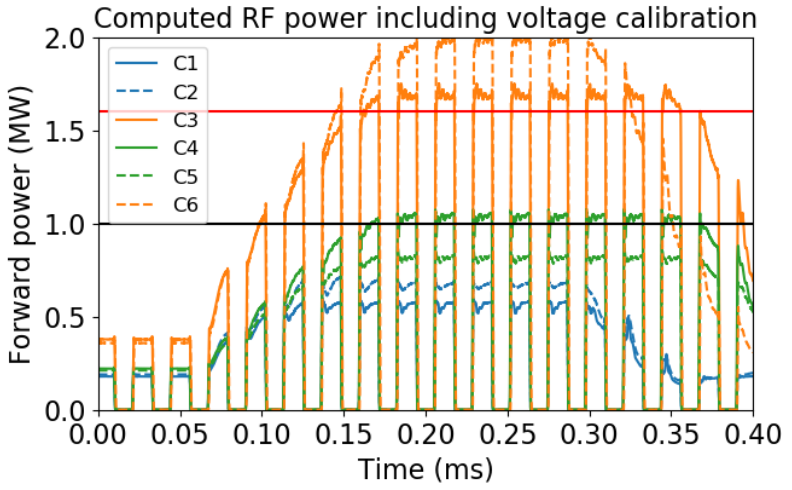




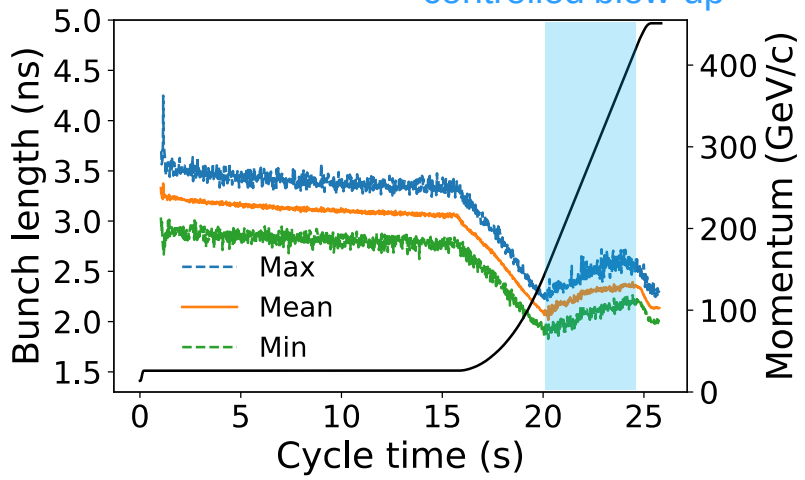
SPS RF & longitudinal aspects

LHC Injectors Upgrade

- **Successful commissioning of upgraded RF** system all through 2021-23
  - 1-turn delay feedback, feedforward, longitudinal damper, amplitude modulation
  - **Nominal RF voltage and power available on 4 out of 6 cavities** (SIEMENS plant currently at 80%), failure rate of solid-state amplifier modules to be understood
- **Longitudinal stability in check**
  - Improved understanding of longitudinal instabilities
  - Optimized voltage programs (exploiting higher voltage and power available) and controlled emittance blow-up (Ivan's talk)



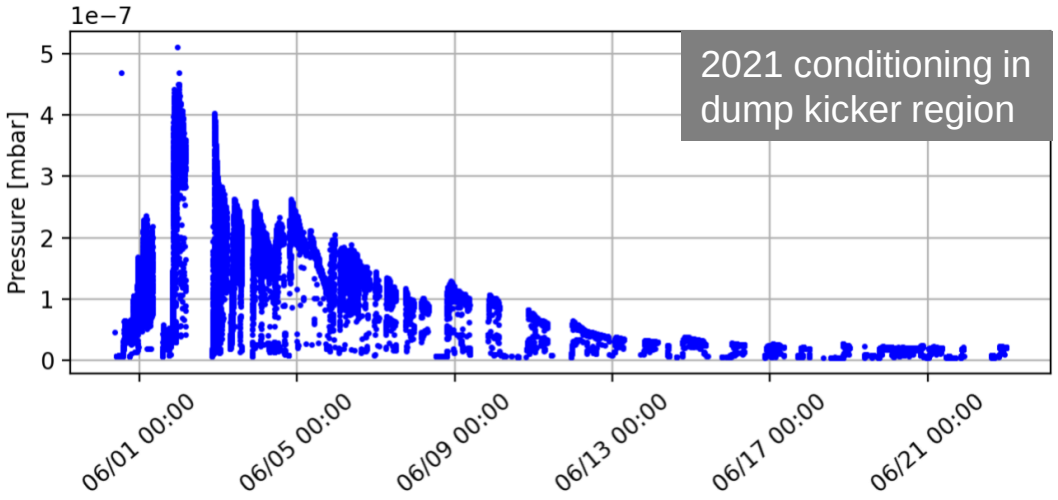
controlled blow-up

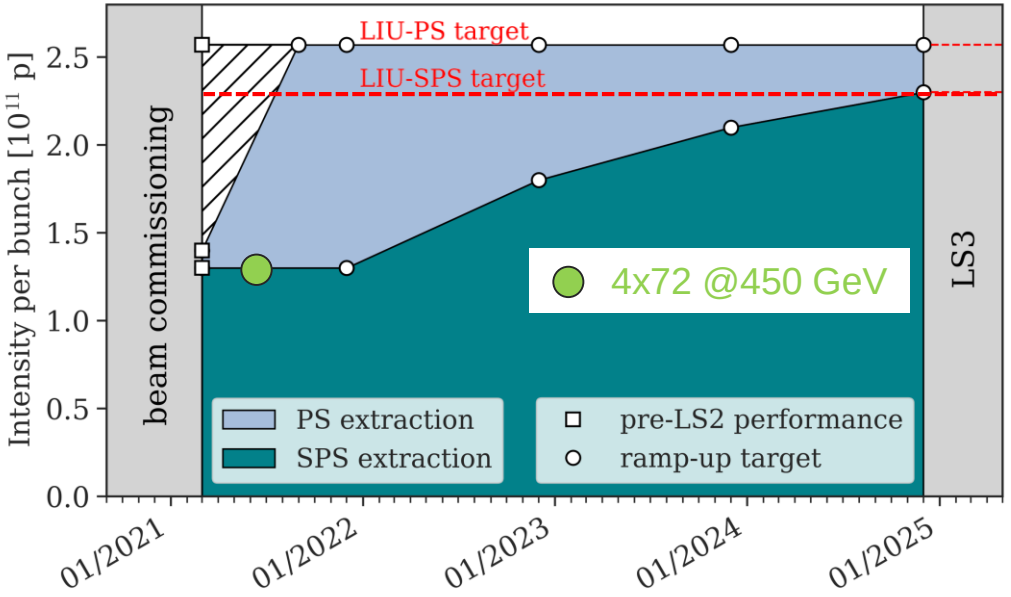


SPS Scrubbing and intensity ramp-up (Gianni's talk)

LHC Injectors Upgrade

- 2021
  - 3 weeks scrubbing, pre-LS2 intensity recovered
  - Limited by **non-conformity of MKDV** dump kicker





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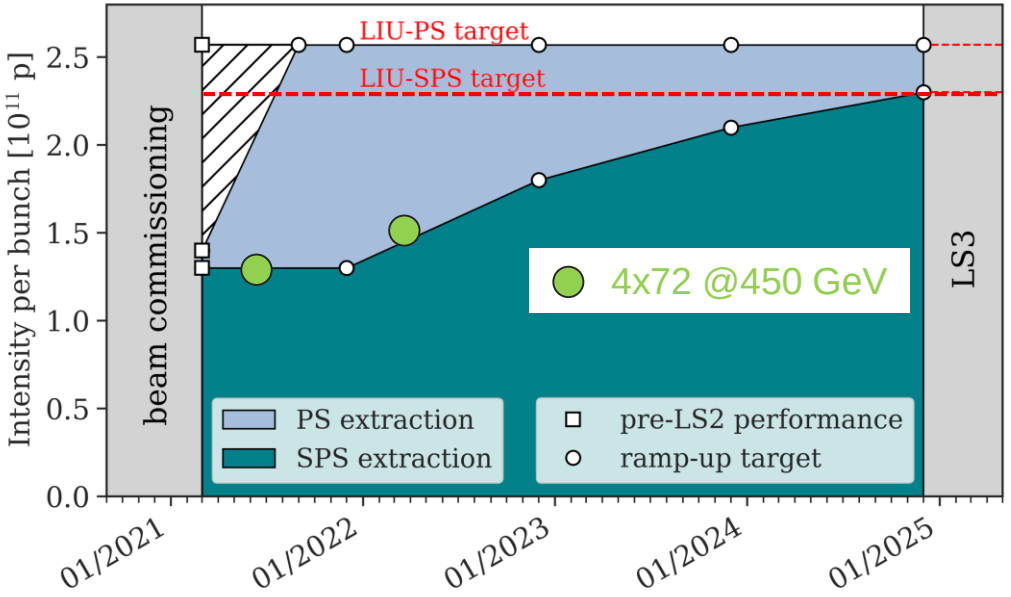
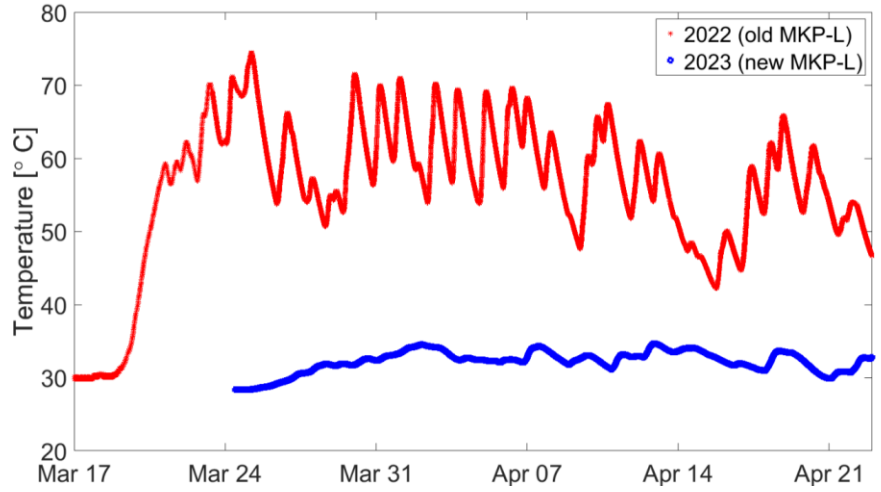
- 2022
  - 5 weeks scrubbing to condition new MKDV and for cooldown of **MKP-L (upgraded in YETS 22/23)**
  - **MKDH pressure spikes at flat top** limited intensity





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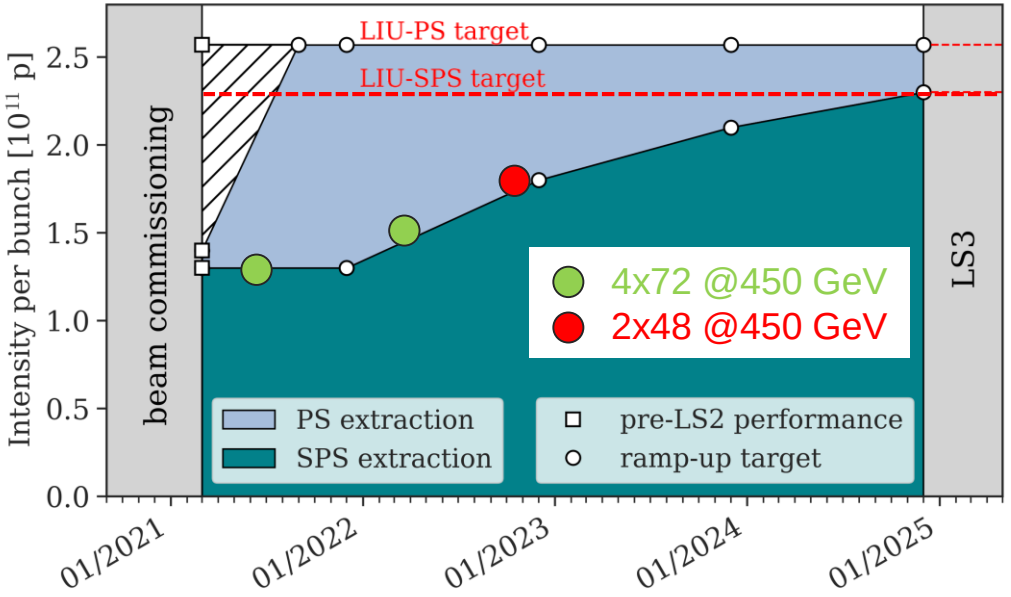

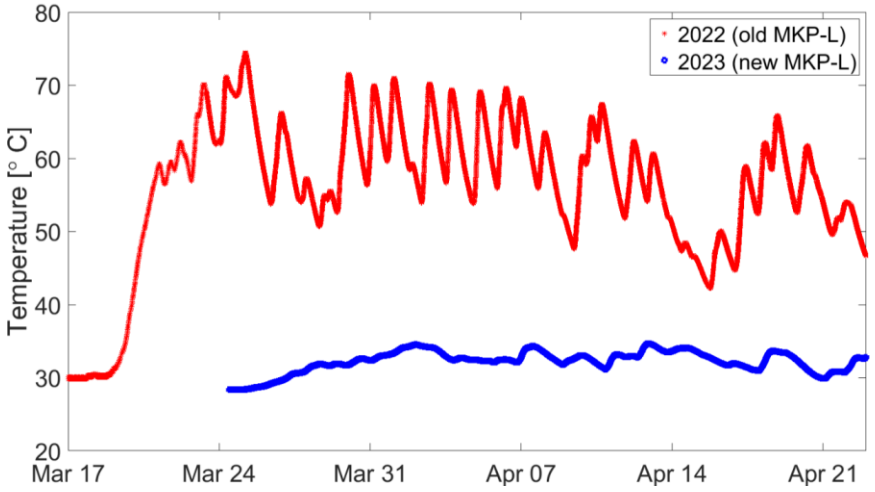

SPS Scrubbing and intensity ramp-up (Gianni's talk)

LHC Injectors Upgrade

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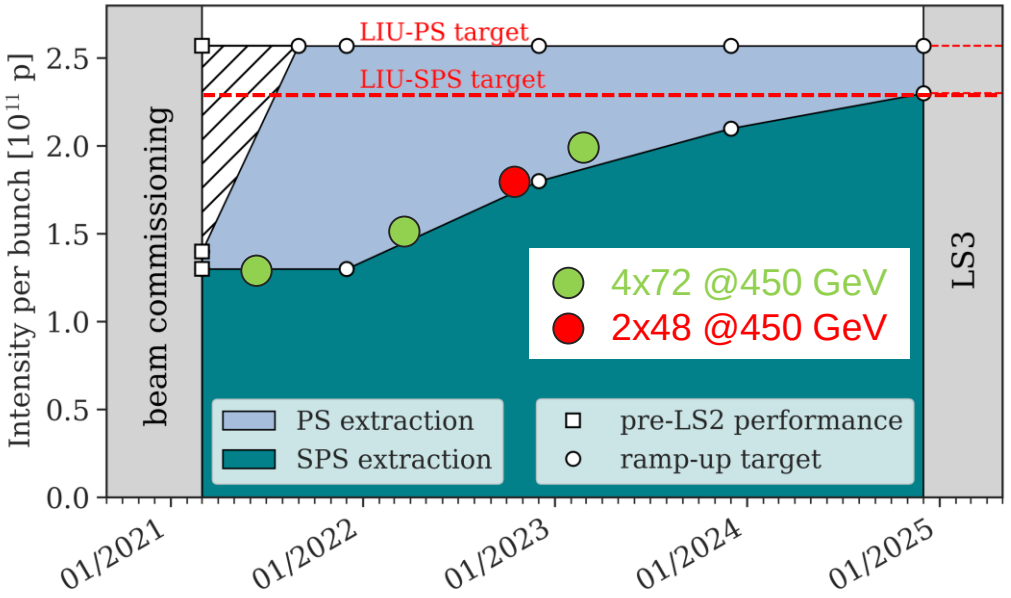
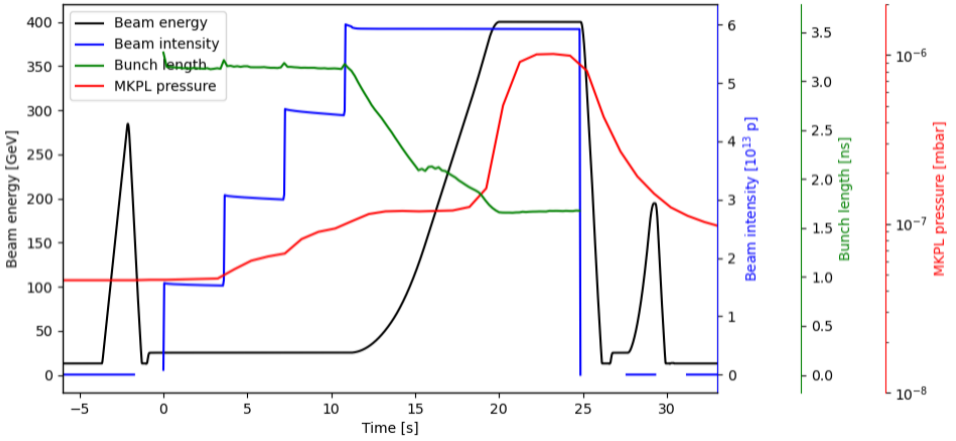
- 2022
  - 5 weeks scrubbing to condition new MKDV and for cooldown of **MKP-L (upgraded in YETS 22/23)**
  - **MKDH pressure spikes at flat top** limited intensity
- 2023 (Giorgia's talk)
  - 4 weeks scrubbing, **successful conditioning of MKDH and upgraded MKP-L** thanks to **long flat top cycle and modification of interlocks**

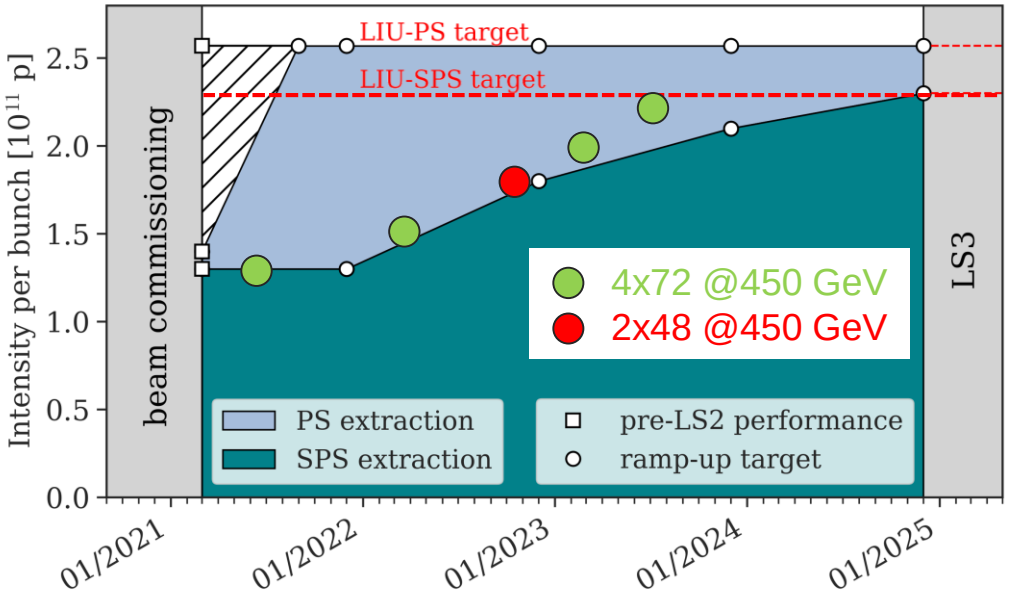




SPS Scrubbing and intensity ramp-up (Gianni's talk)

LHC Injectors Upgrade

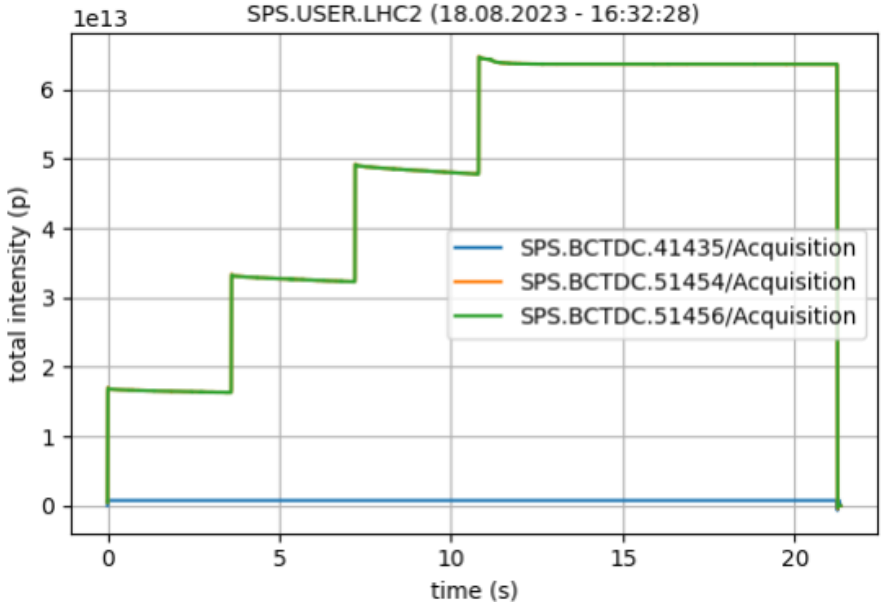
- 2021
  - 3 weeks scrubbing, pre-LS2 intensity recovered
  - Limited by **non-conformity of MKDV** dump kicker
- 2022
  - 5 weeks scrubbing to condition new MKDV and for cooldown of **MKP-L (upgraded in YETS 22/23)**
  - **MKDH pressure spikes at flat top** limited intensity
- 2023 (Giorgia's talk)
  - 4 weeks scrubbing, **successful conditioning of MKDH and upgraded MKP-L** thanks to **long flat top cycle and modification of interlocks**
  - Further scrubbing and intensity ramp-up in MDs

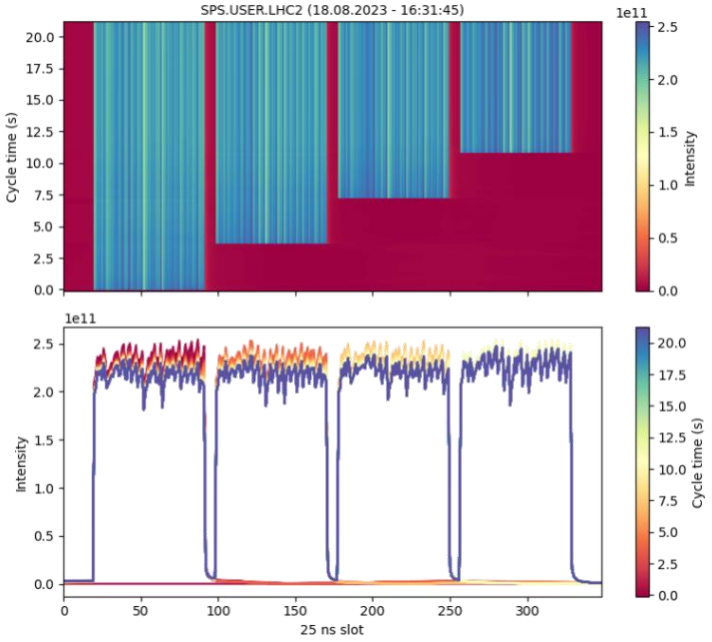


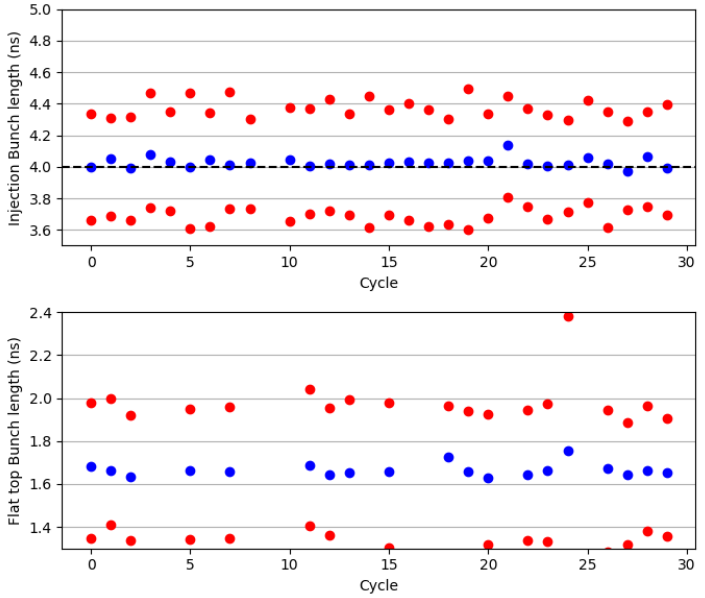
SPS achieved intensity – standard beam

LHC Injectors Upgrade

- **4x72 bunches with 2.2e11 p/b at flat top**
  - Excellent transmission (around 95% without scraping)
  - Bunch length at extraction reproducibly around 1.65 ns



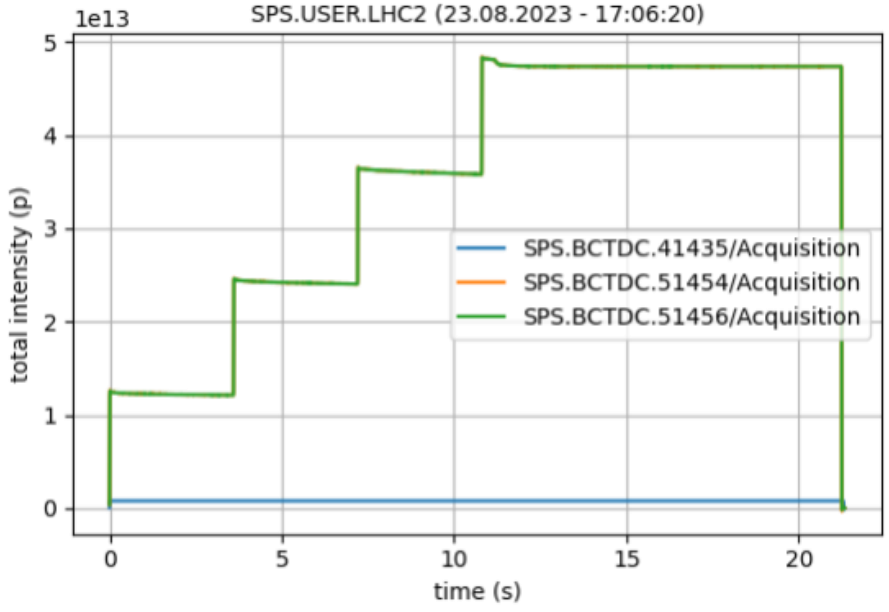


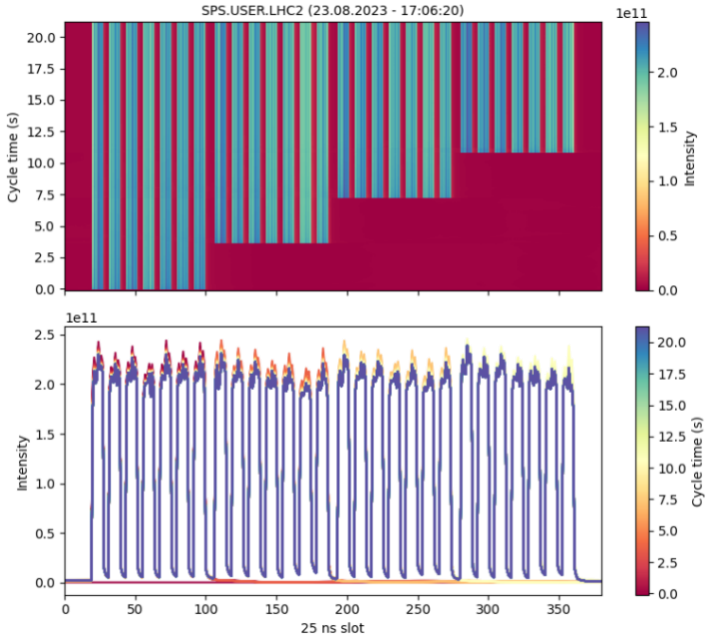


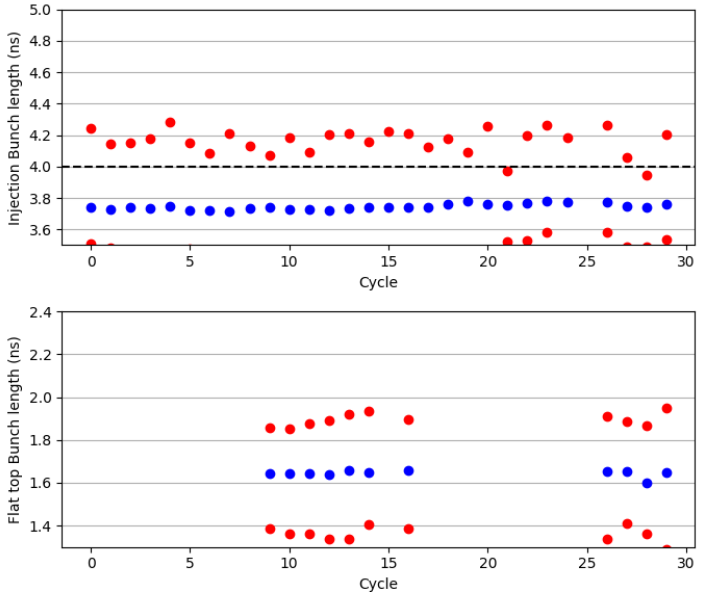
SPS achieved intensity - 8b4e beam

LHC Injectors Upgrade

- **4x56 with 2.15e11 p/b at flat top**
  - Excellent transmission (~95% without scraping)
  - Bunch length at flat top ~1.65 ns
  - Brightness not optimised

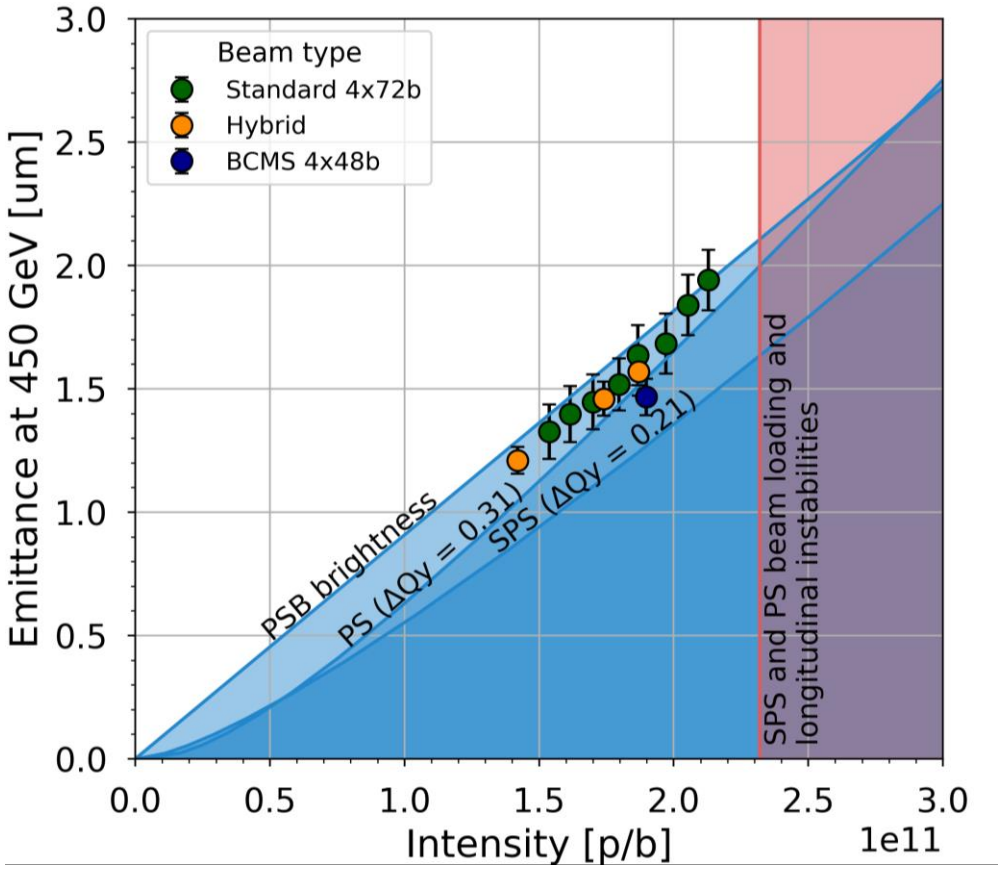






SPS achieved brightness

- Wire scanner measurements
  - At the end of the flat bottom
    (flat top not possible due to wire limitations)
    (Clara's talk)
- **LIU brightness target achieved for standard beam**
  - Slightly better than LIU target, consistent with target if including scraping
- **BCMS beam is slightly better**
  - Some margin for higher brightness through working point optimization at the expense of increased losses

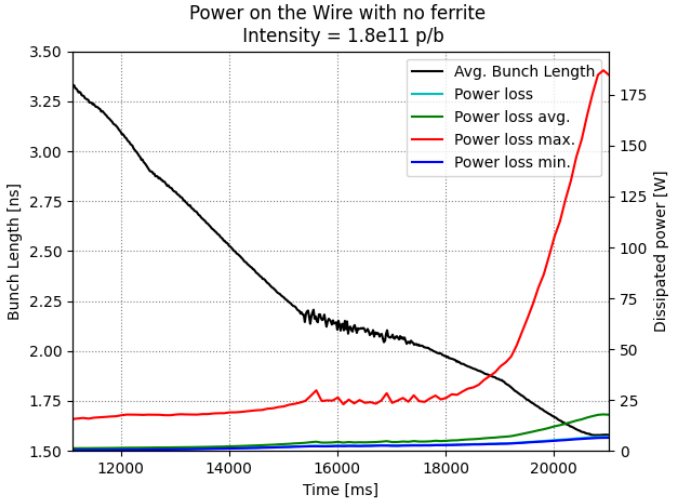


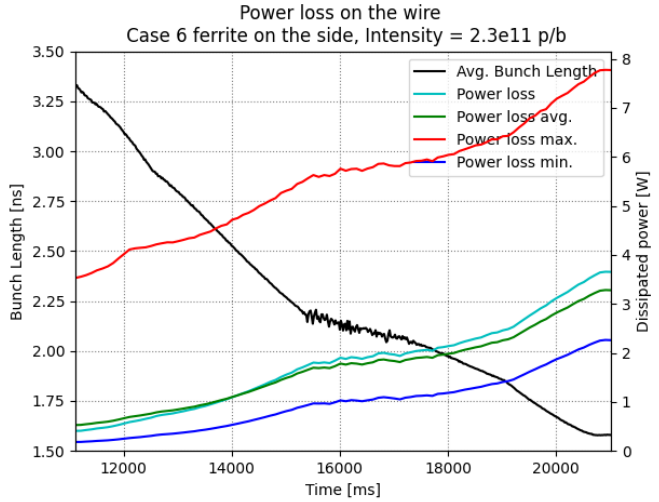
SPS unexpected issues

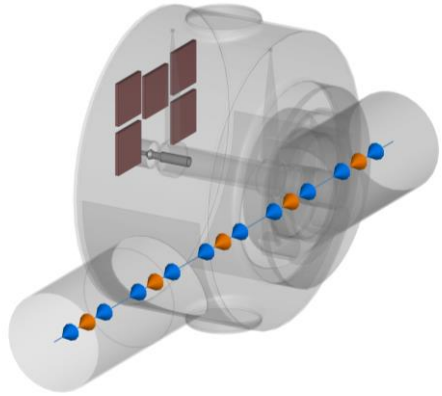
(Ingrid's talk)

LHC Injectors Upgrade

- **Wires of all LIU wire scanners broke in parking position** during scrubbing
  - 2 spares installed, but shortly broke again with 4x 72b with 1.8e11 p/b on LHC filling cycle
  - Identified impedance at 800 MHz causing intolerable wire heating when bunches are short
  - **Installation of ferrites and RF coupler during TS** significantly reduced wire heating
  - **These mitigations** (ferrites and coupler) **will be installed on all wire scanners (YETS)**





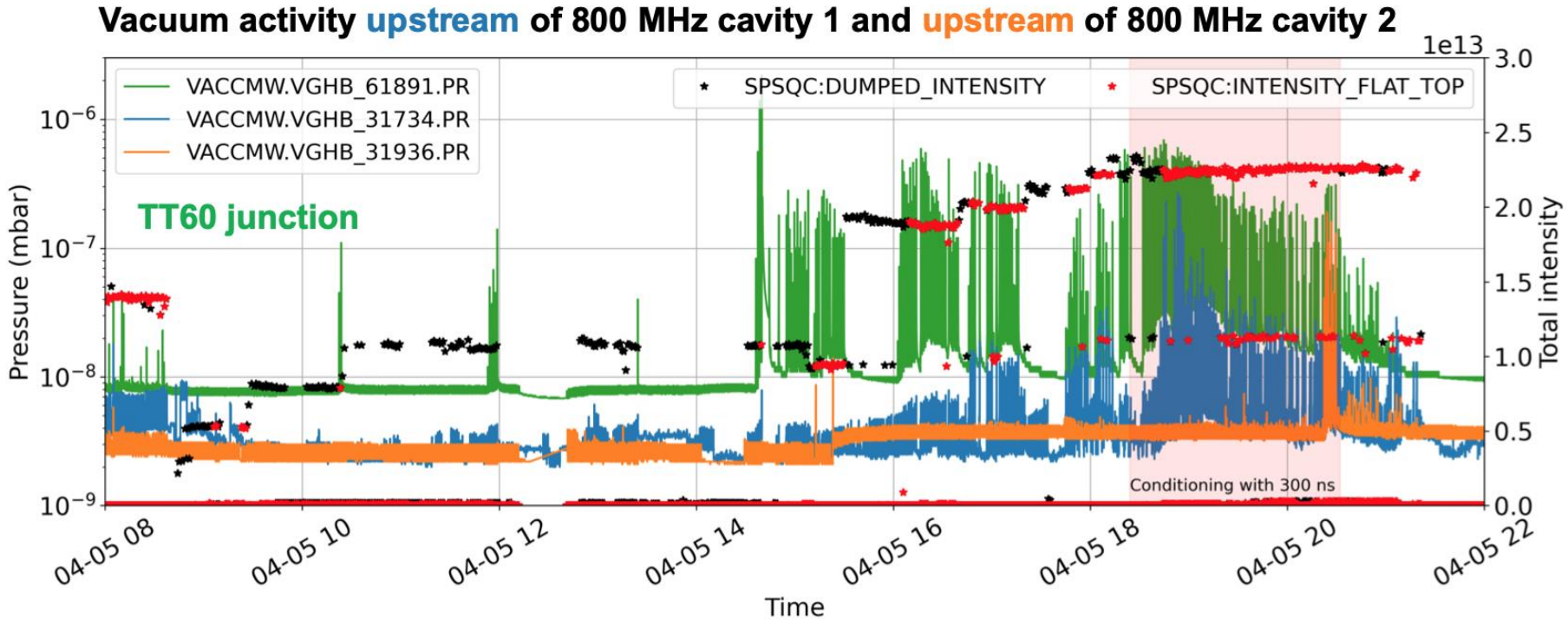


SPS unexpected issues

(Ingrid's talk)

LHC Injectors Upgrade

- **Pressure spikes with 8b4e** beam around 800 MHz cavity and TT60 junction
  - Strongly limiting intensity for 8b4e in 2022 – clear conditioning observed in 2023



SPS – ongoing work

LHC Injectors Upgrade

- Demonstrate LIU intensity
  - Continue intensity ramp-up
  - Explore intensity limits beyond LIU target (to gain operational margin) & improve reproducibility and robustness for operation (minimize need for expert tuning)
- Transmission and losses (Yann's talk)
  - PS-to-SPS transfer is still quite lossy (up to few % beam lost at transfer)
  - Slow losses on SPS flat bottom still not understood – need for collimation system?
  - Optimization of longitudinal parameters at PS-to-SPS transfer
  - Working point optimization (tradeoff between emittance blow-up and losses)
- Transverse tails
  - Minimize transverse tails (in SPS and pre-injectors) to reduce need for scraping in SPS and to optimize luminosity in LHC (Elleanor's talk)

Outline

LHC Injectors Upgrade

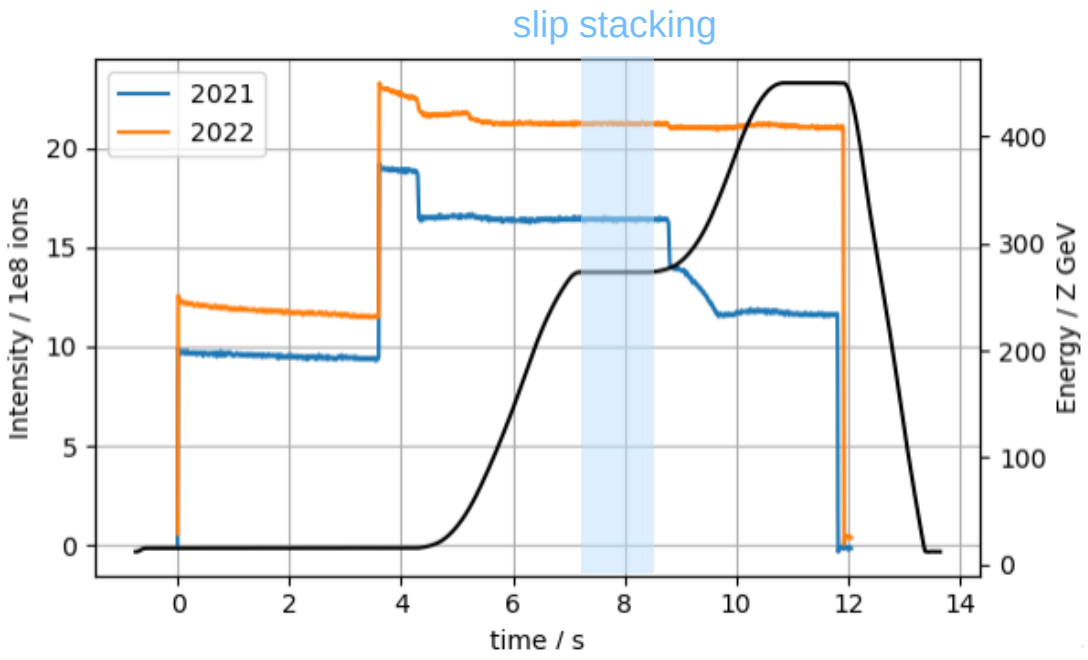
- LIU protons
  - PS complex
  - SPS
- LIU ions
- Benefits for other beams
- Summary and outlook

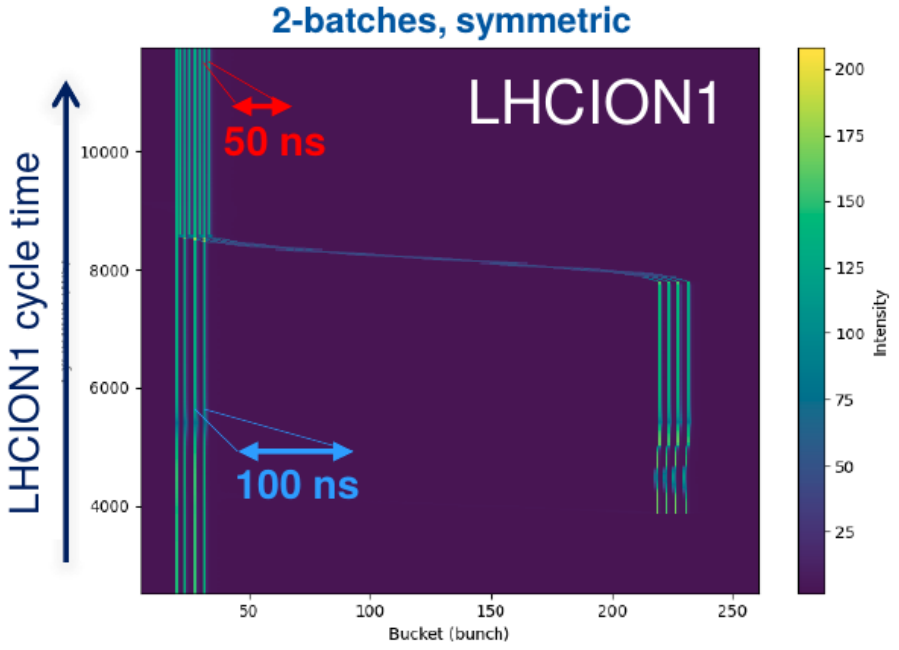
LIU ions

(Theo's talk)

LHC Injectors Upgrade

- The big challenge after LS2 was to commission the slip stacking in SPS
  - Started commissioning with 2 injections in 2021 and 2022, cycle with 14 injection in 2023



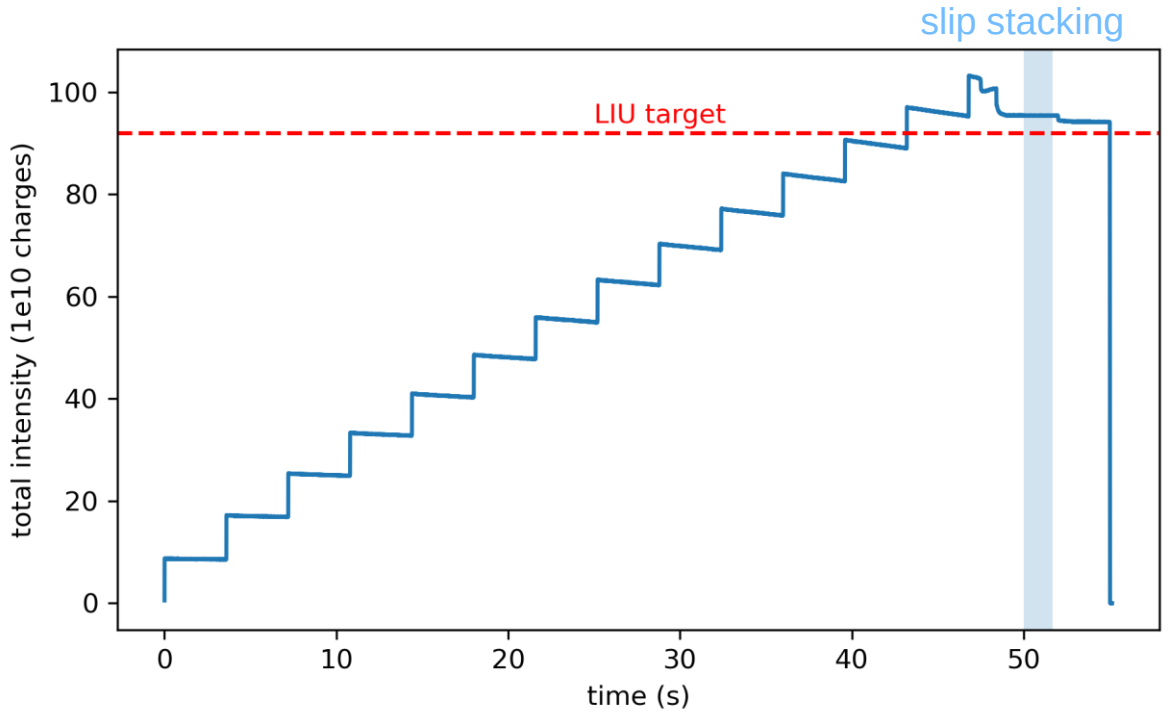


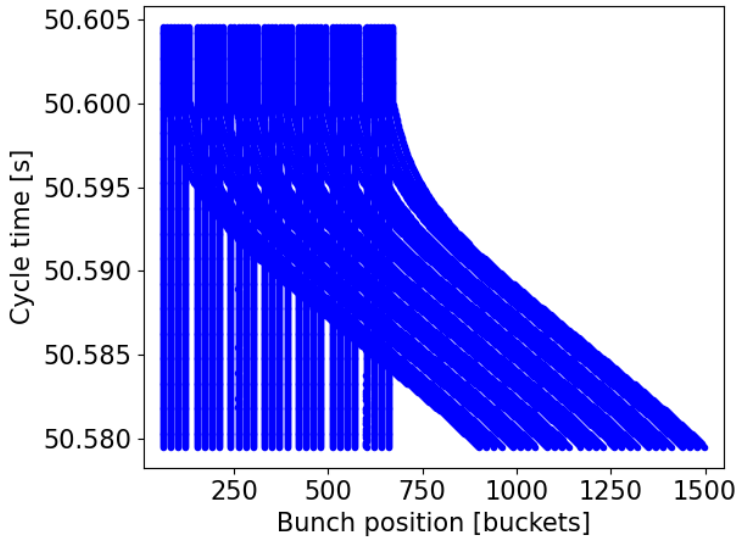
LIU ions

(Theo's talk)

LHC Injectors Upgrade

- The big challenge after LS2 was to commission the slip stacking in SPS
  - Started commissioning with 2 injections in 2021 and 2022, cycle with 14 injection in 2023
  - Ready for ion run in 2023 – with very good transmission after slip stacking



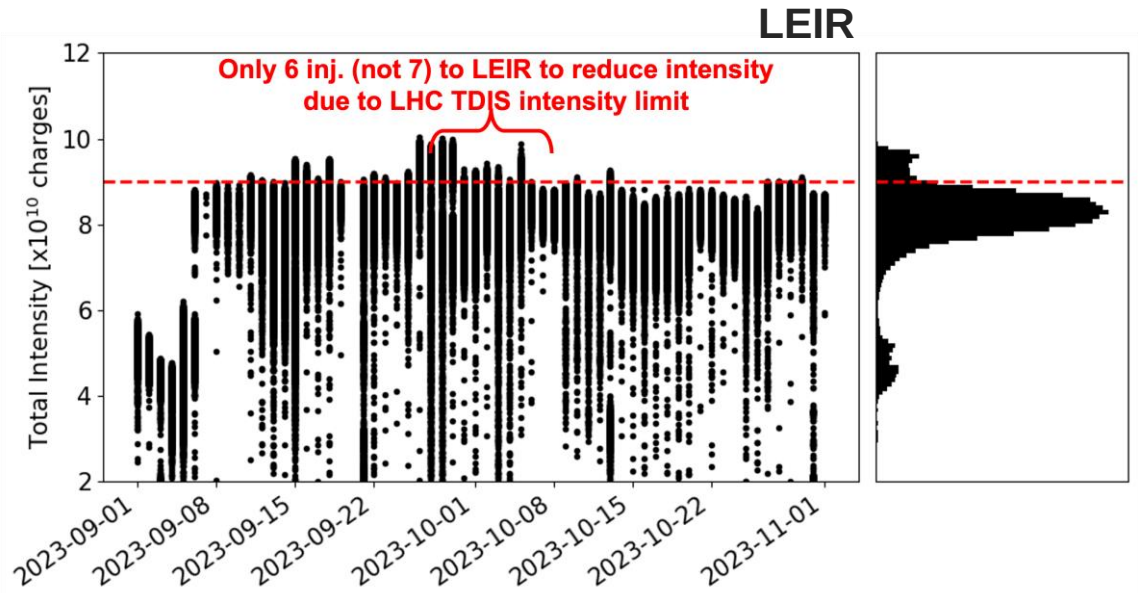


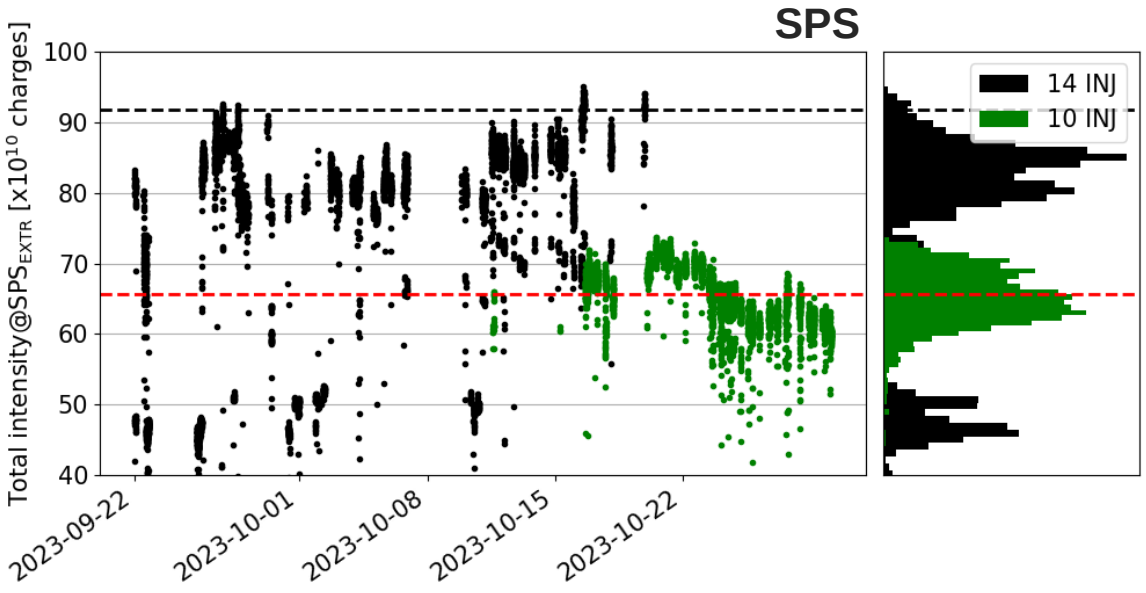
LIU ions

(Theo's talk)

LHC Injectors Upgrade

- The big challenge after LS2 was to commission the slip stacking in SPS
  - Started commissioning with 2 injections in 2021 and 2022, cycle with 14 injection in 2023
  - Ready for ion run in 2023 – with very good transmission after slip stacking
- LIU intensity demonstrated, reproducibility to be improved
  - Intensity not consistent along the run – needs tighter operational follow-up (LEIR and SPS)





Outline

LHC Injectors Upgrade

- LIU protons
  - PS complex
  - SPS
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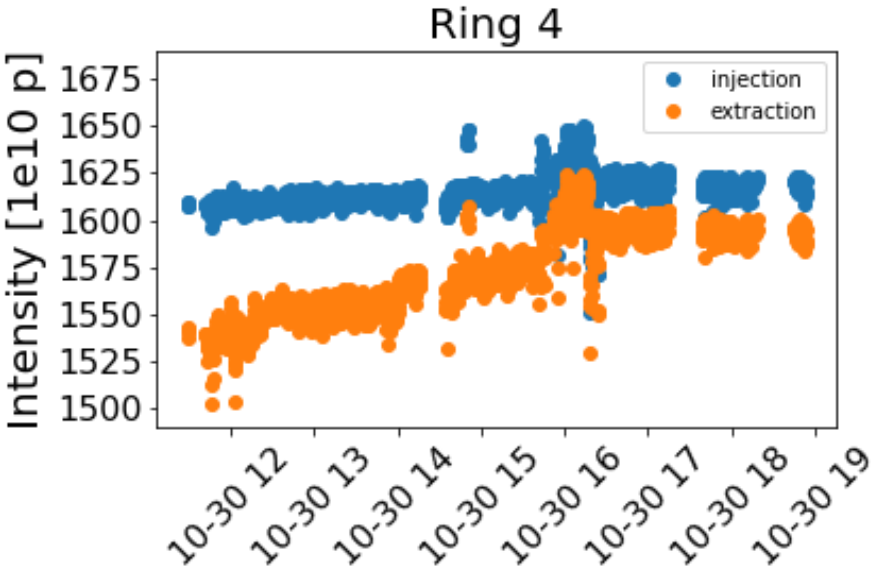
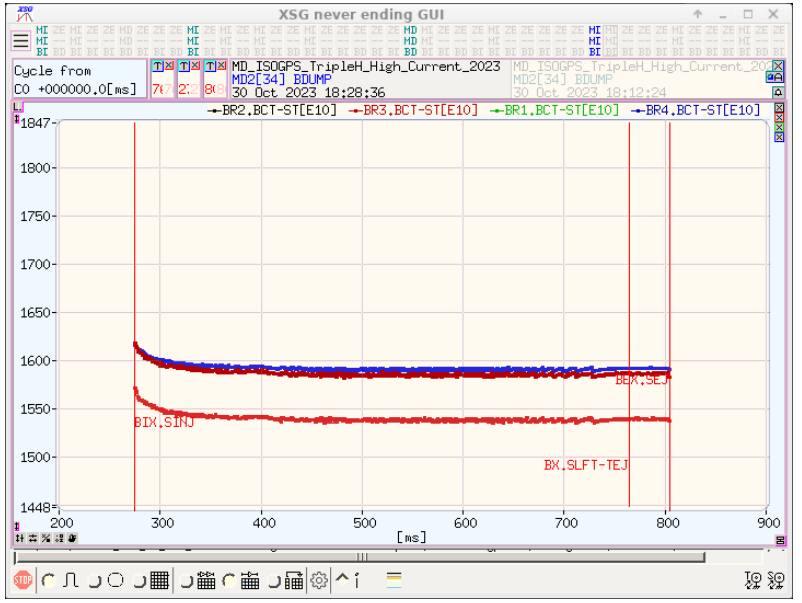
Other beams benefitting from LIU upgrades

LHC Injectors Upgrade

- Higher intensity and energy for ISOLDE (Tirsi's talk)
  - PSB reached up to 1.6e13 p per ring
  - Possibility to extract at 1.7 GeV (present transfer lines) and 2 GeV (transfer line upgrade)





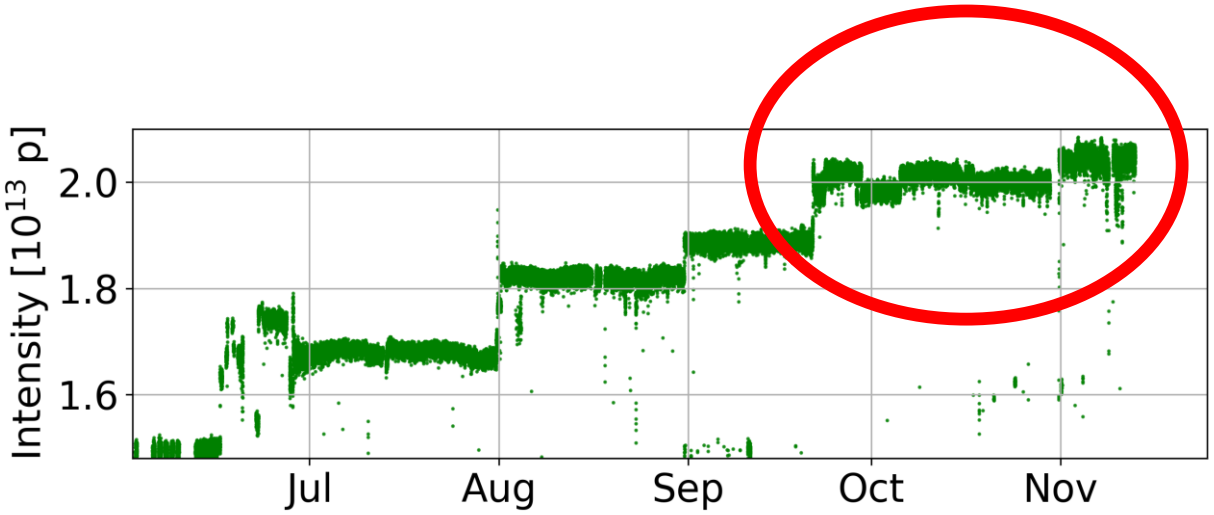
Other beams benefitting from LIU upgrades

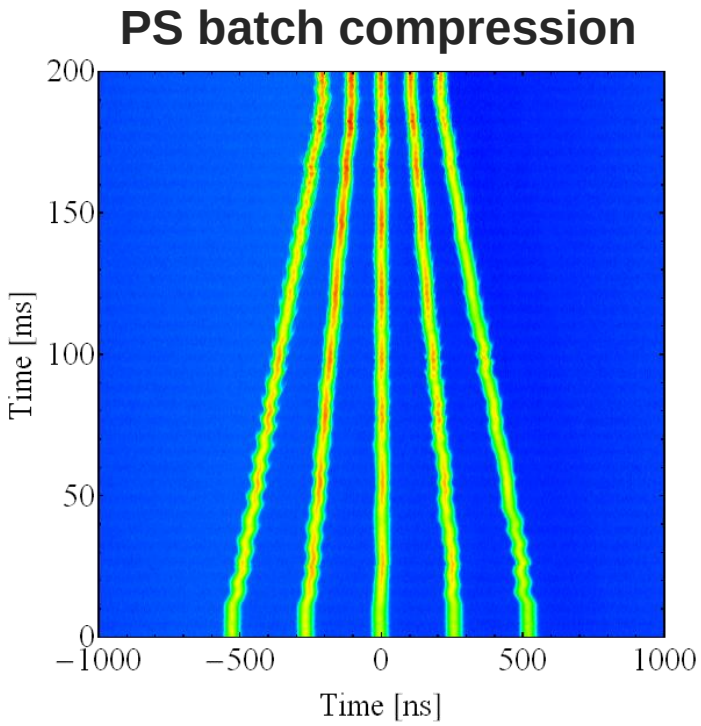
LHC Injectors Upgrade

- Higher intensity and energy for ISOLDE

(Tirsi's talk)

- Higher intensity for AD
  - Thanks to the LIU upgrades, one PSB ring can deliver two bunches with sufficient brightness

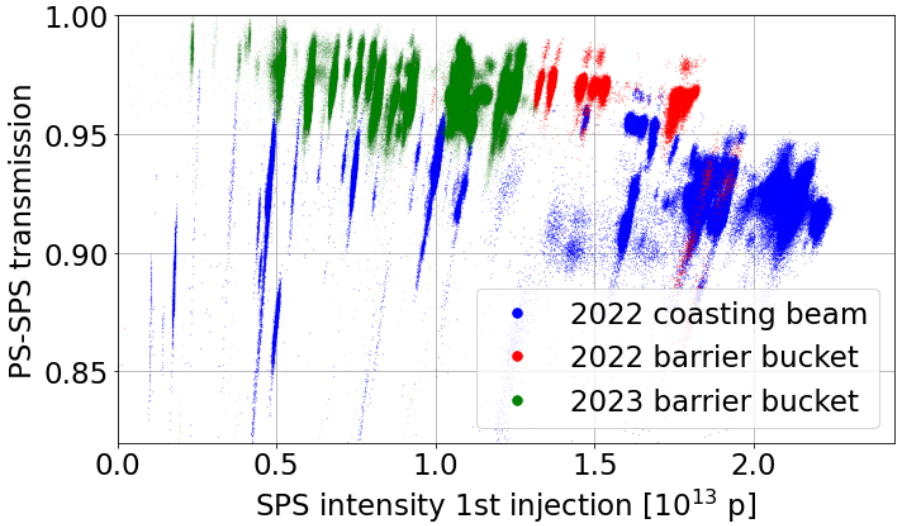




Other beams benefitting from LIU upgrades

LHC Injectors Upgrade

- Higher intensity and energy for ISOLDE (Tirsi's talk)
- Higher intensity for AD
- Reduced losses for SFTPRO
  - Smaller transverse emittance from the PSB
  - **Improved longitudinal stability** and higher intensity reach in PS (impedance reduction on 10 MHz cavities)
  - **Barrier bucket at PS extraction** (possible thanks to Finemet cavity in PS) for loss reduction with Multi-Turn-Extraction used operationally in 2023
  - **Dummy septum retracted** → reduced extraction losses for all high-intensity fast-extracted beams



Outline

LHC Injectors Upgrade

- LIU protons
  - PS complex
  - SPS
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Summary and outlook

LHC Injectors Upgrade

- LIU proton beams
  - LIU brightness reached (standard beam)
  - LIU intensity almost reached (2.2e11 vs 2.3e11 p/b) – ahead of LIU intensity ramp-up plan
  - Achieving operational margin and reproducibility expected to be a big challenge
  - Issues with pressure rise in kickers and wire scanner breakage – mitigations in place
  - Transverse tails and losses at PS-to-SPS and in SPS to be further improved
- LIU ions
  - Slip stacking successfully commissioned and LIU intensity reached
  - Achieving operational margin and reproducibility remains challenging
- Other beams profit from LIU upgrades
  - In particular ISOLDE and AD (higher intensity), and SFTPRO (reduced losses)

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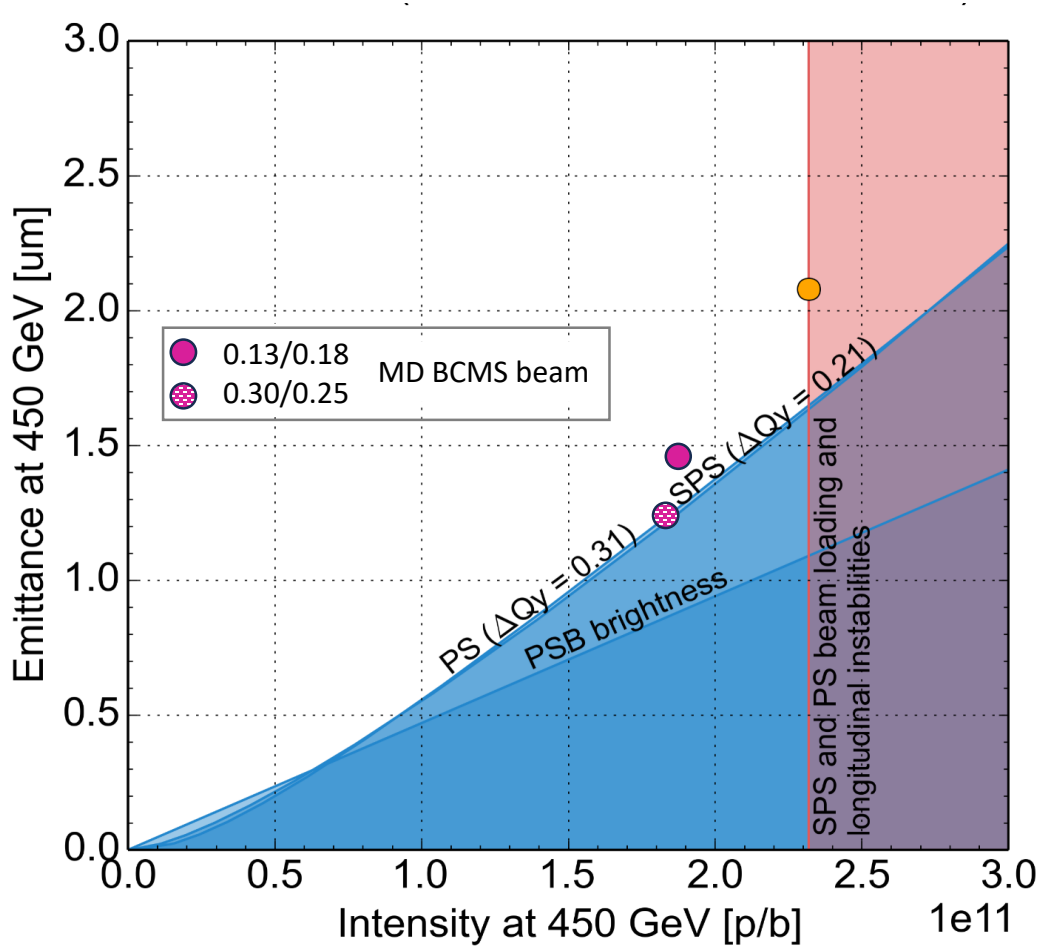
THANK YOU FOR YOUR ATTENTION

SPS achieved brightness – BCMS beam

LHC Injectors Upgrade

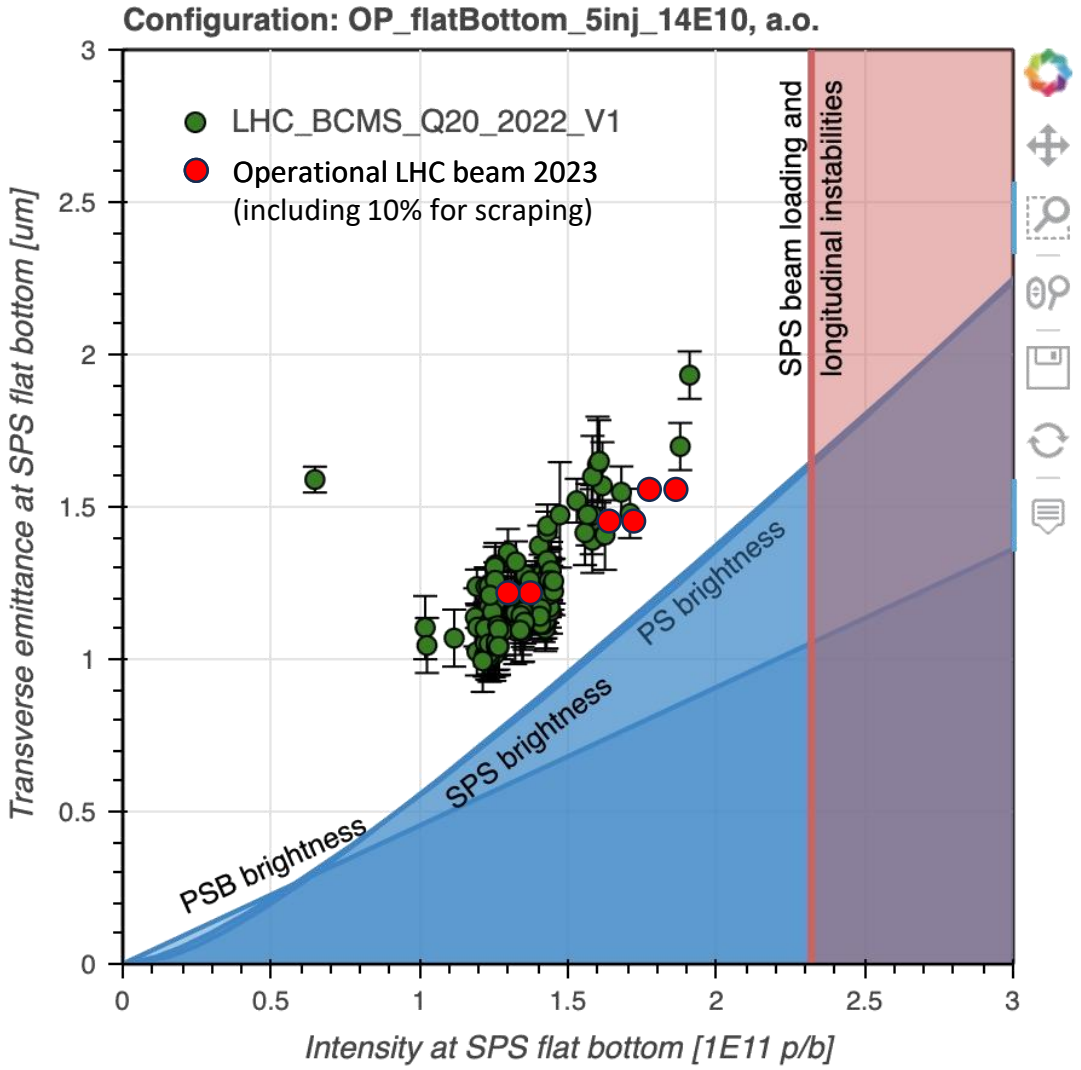
- **BCMS brightness** very close to target with high working point, however:
  - More losses in the SPS
  - Scraping not yet included
  - Obtained with 4x 48b, but expect degradation for longer flat bottom (i.e. >4 injections), which manifests in both more losses and more emittance growth



Beam to LHC – BCMS (2022) vs standard

LHC Injectors Upgrade

- Brightness of standard beam very close to BCMS beam from 2022
  - Still some margin for better brightness for BCMS (previous slide), but with higher losses in SPS
- Hybrid filling schemes with short trains (e.g. 56 + 5x36 bunches)
  - **No gain expected from BCMS scheme** (longer flat bottom → losses and blow-up in SPS + longer filling time in LHC)



The evolution of the LIU project

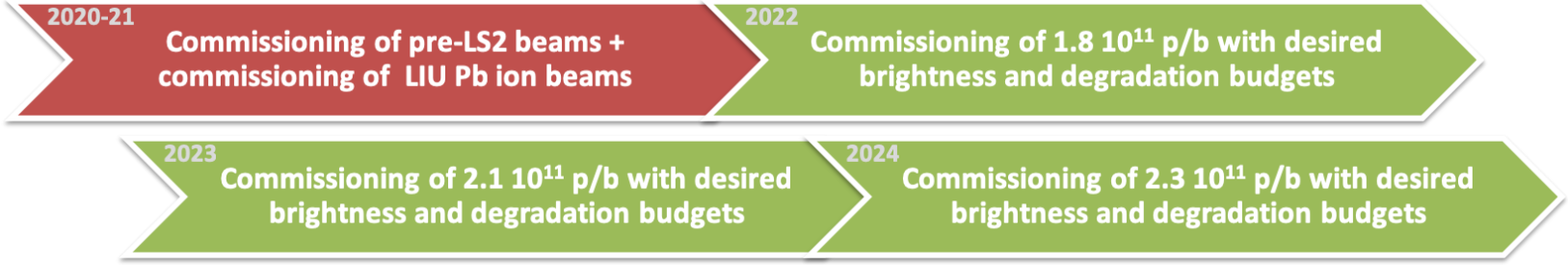
LHC Injectors Upgrade

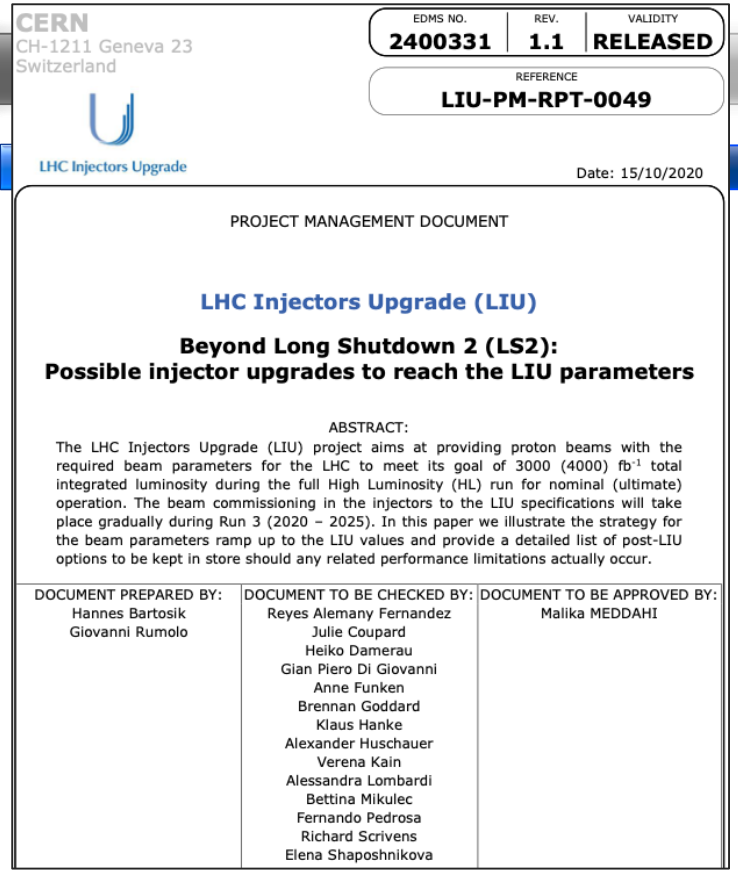
- A **10-years** long and **180 M€** worth project rich of progress and milestones

Only injectors

LIU legacy:

- A robust plan for LIU beam ramp-up over Run 3
- A risk register listing beyond-LIU items to be installed for possible shortcomings





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REFERENCE LIU-PM-RPT-0049

LHC Injectors Upgrade

Date: 15/10/2020

PROJECT MANAGEMENT DOCUMENT

LHC Injectors Upgrade (LIU)

Beyond Long Shutdown 2 (LS2):
Possible injector upgrades to reach the LIU parameters

ABSTRACT:

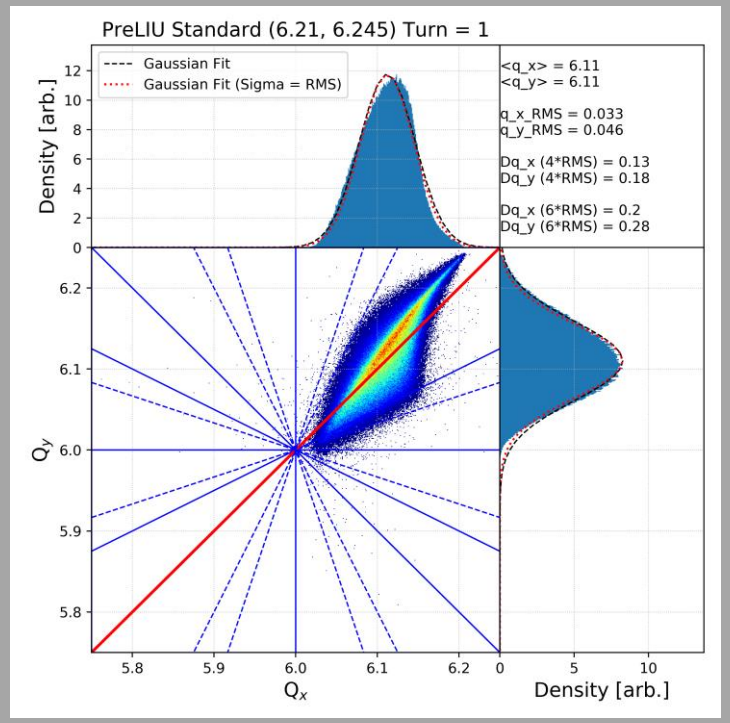
The LHC Injectors Upgrade (LIU) project aims at providing proton beams with the required beam parameters for the LHC to meet its goal of 3000 (4000) fb^{-1} total integrated luminosity during the full High Luminosity (HL) run for nominal (ultimate) operation. The beam commissioning in the injectors to the LIU specifications will take place gradually during Run 3 (2020 – 2025). In this paper we illustrate the strategy for the beam parameters ramp up to the LIU values and provide a detailed list of post-LIU options to be kept in store should any related performance limitations actually occur.

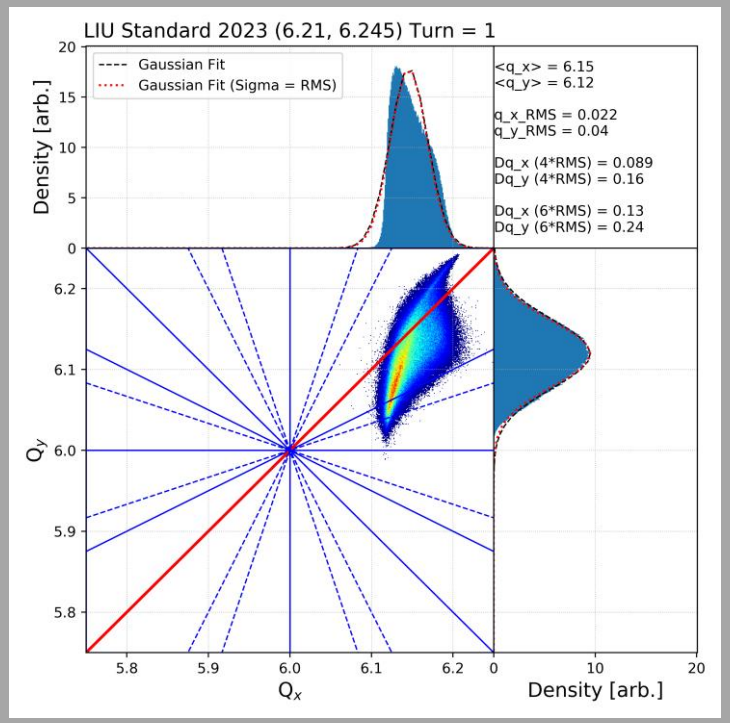
DOCUMENT PREPARED BY:	DOCUMENT TO BE CHECKED BY:	DOCUMENT TO BE APPROVED BY:
Hannes Bartosik Giovanni Rumolo	Reyes Alemany Fernandez Julie Coupard Heiko Damerau Gian Piero Di Giovanni Anne Funken Brennan Goddard Klaus Hanke Alexander Huschauer Verena Kain Alessandra Lombardi Bettina Mikulec Fernando Pedrosa Richard Scrivens Elena Shaposhnikova	Malika MEDDAHI

PS 2021-22

- LIU int[illegible]

Successfully constrained the tune footprint at injection between the integer and 6.25 structural resonance lines, as before LIU





in 2018

(2021) with

n 2022

LIU ions

(Theo's talk)

LHC Injectors Upgrade

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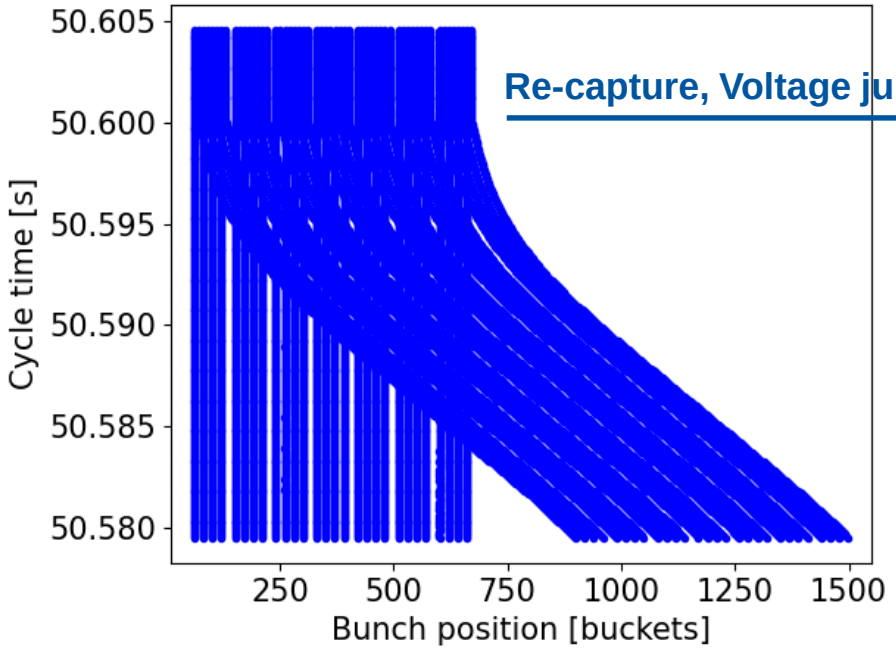
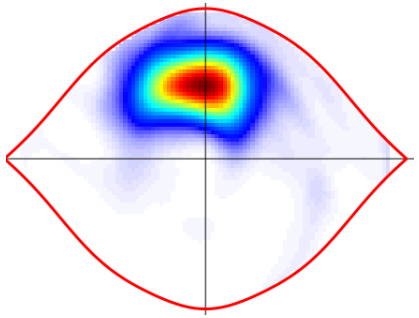
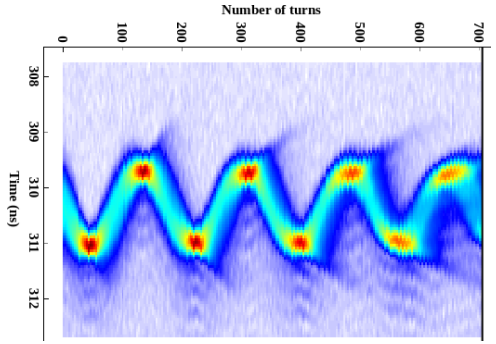
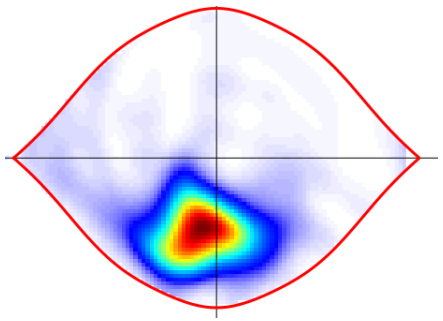


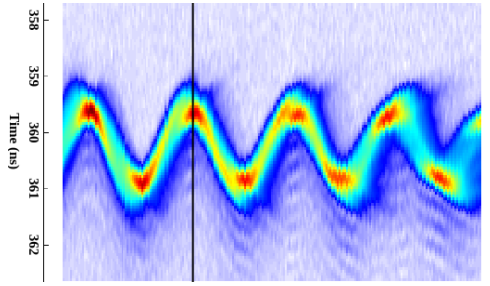
Beam1 – bunch1





Strong dipole oscillations at recapture





Hollow bunches generated after filamentation
→ bunch center is populated again after switching on Phase Loop

Beam2 – bunch1