CERN

Beam performance with the LHC Injectors Upgrade (LIU)

Giovanni Rumolo

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Outline

LHC Injectors Upgrade

- LHC Injectors Upgrade (LIU) project goal and ramp-up plan
- Performance achieved to date
  - PS complex
  - SPS
- Summary & outlook

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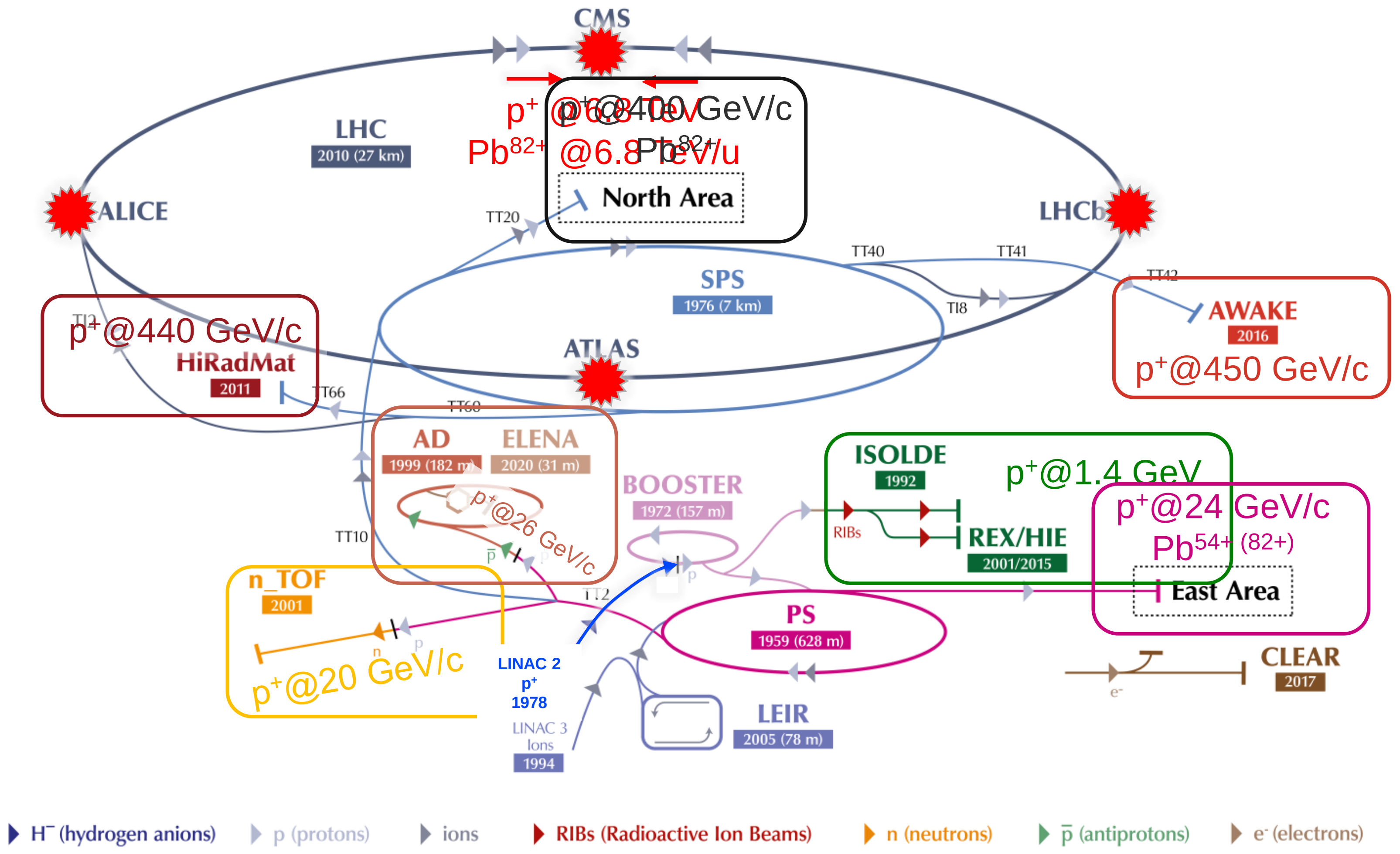
The CERN accelerator complex

LHC Injectors Upgrade



- Chain of linear and circular accelerators to serve:
  - The four LHC experiments
  - A variety of Fixed Target experiments/facilities at the different energy stages reached along the chain
- Before 2020 **LINAC 2** was injecting protons into PSB
- Under the **LHC injectors Upgrade (LIU) project**, a big revamp of the whole injector chain took place!

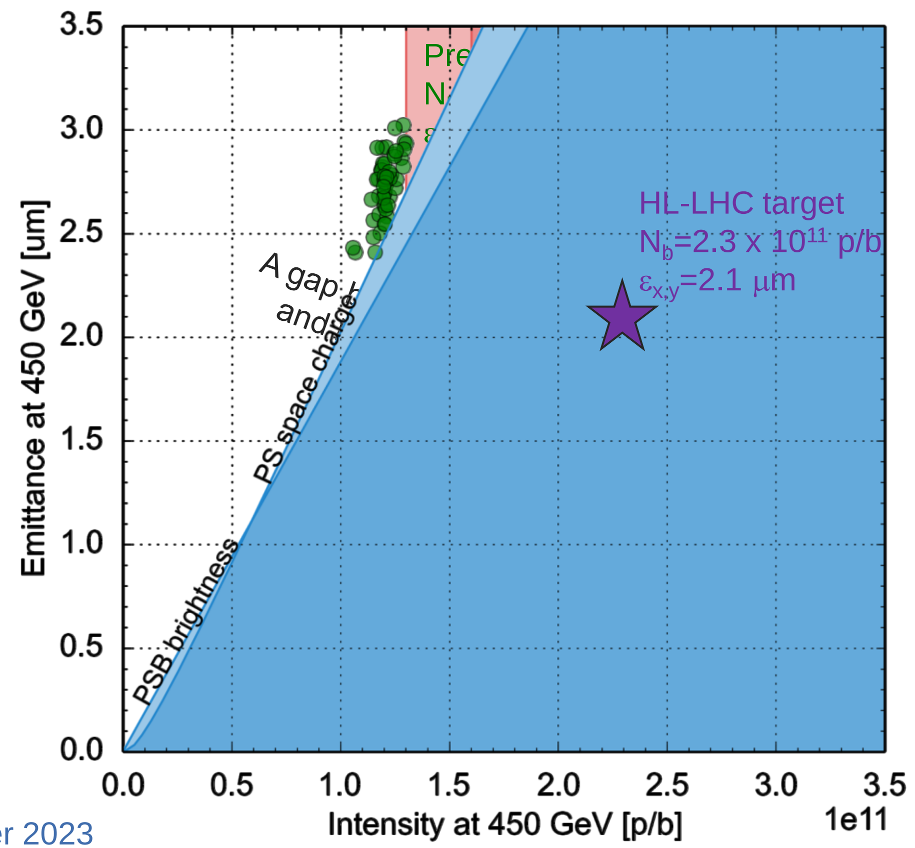
The LIU goal

LHC Injectors Upgrade

Run 1	Long Shutdown 1	Run 2

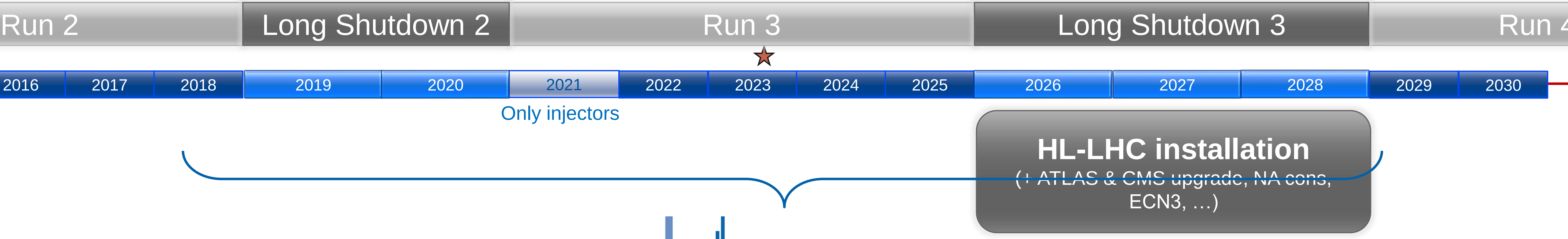
2009	2010	2011	2012	2013	2014	2015	2016	2017	2018

Only injectors



The LIU goal

LHC Injectors Upgrade



LHC Injectors Upgrade (2010 – 2021)

- ✓ Definition of initial solid set of baseline items based on existing knowledge of the accelerators and then further adjustment based on studies
- ✓ Hardware design, prototyping, installation, test with beam → Model improvement
- ✓ Peak installation phase in **Long Shutdown 2 (LS2)**
- ✓ Project closure with **performance ramp-up plan** and back-up items

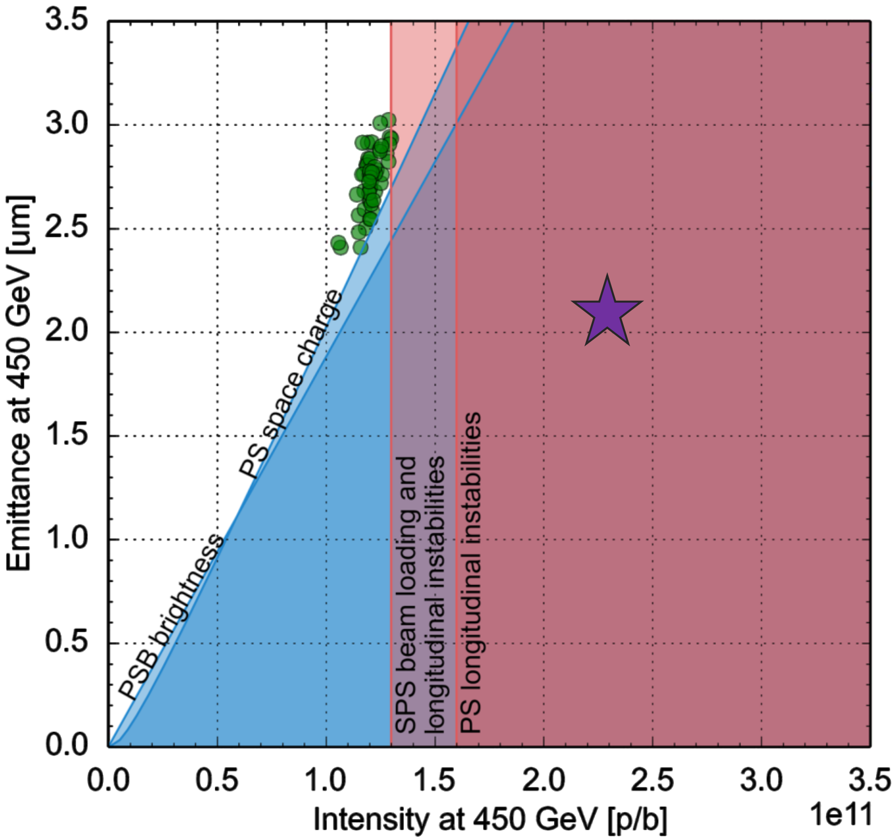
The LIU installation

LHC Injectors Upgrade

- Connection of PSB to Linac4 and acceleration to 2 GeV in PSB
- PS & SPS RF upgrades + e-cloud & impedance reduction, new SPS optics, new dumps & stoppers, etc.

PSB new power supply building

PSB injection Line from Linac4



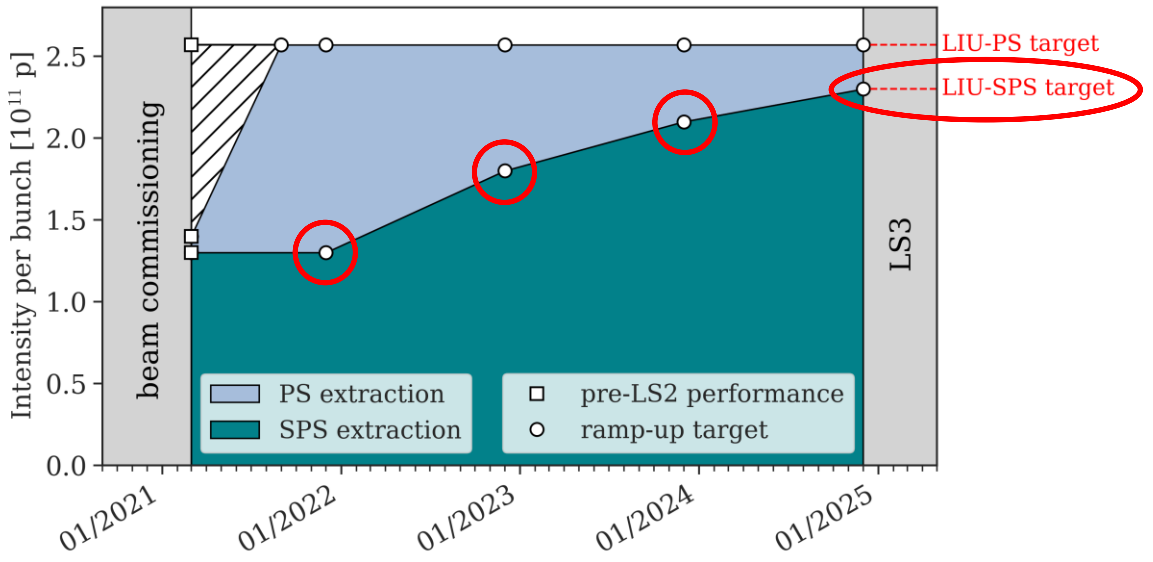
New SPS beam dump

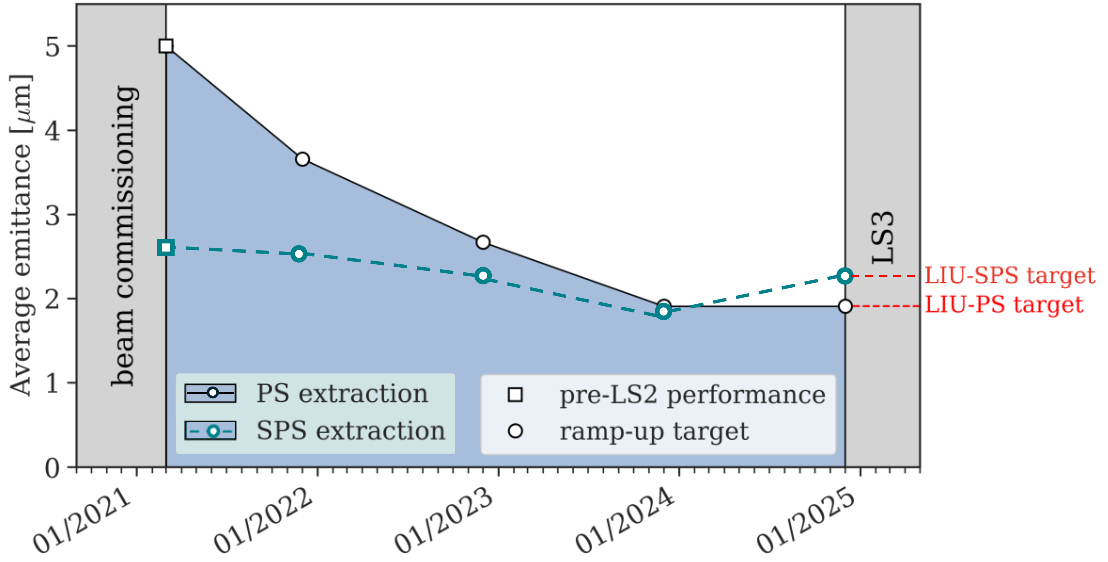
PS longitudinal damper

New SPS RF amplifier towers

LIU beam commissioning in Run 3: ramp-up plan

- Year-by-year intensity goals of the ramp-up at SPS extraction
  - Pre-LS2 beam parameters recovered by the end of 2021 – **1.3e11 p/b**
  - **1.8e11 p/b** in MD by the end of 2022 – to be ready for LHC in 2023 (operation)
  - **2.1e11 p/b** in MD by the end of 2023 – to be ready for LHC in 2024 (MD)
  - **2.3e11 p/b** in MD by the end of 2024 – to be ready for HL post-LS3





[A. Huschauer et al., LIU workshop 2020](#)

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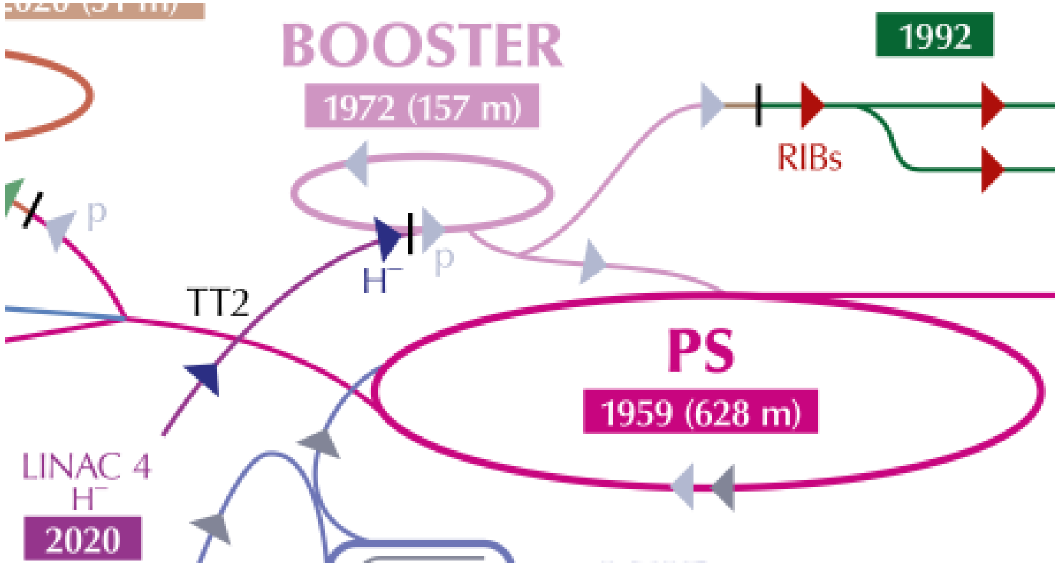
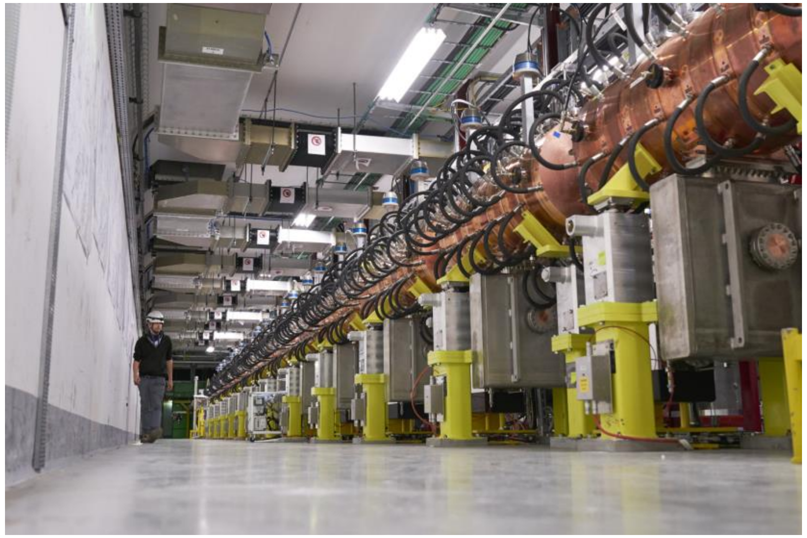
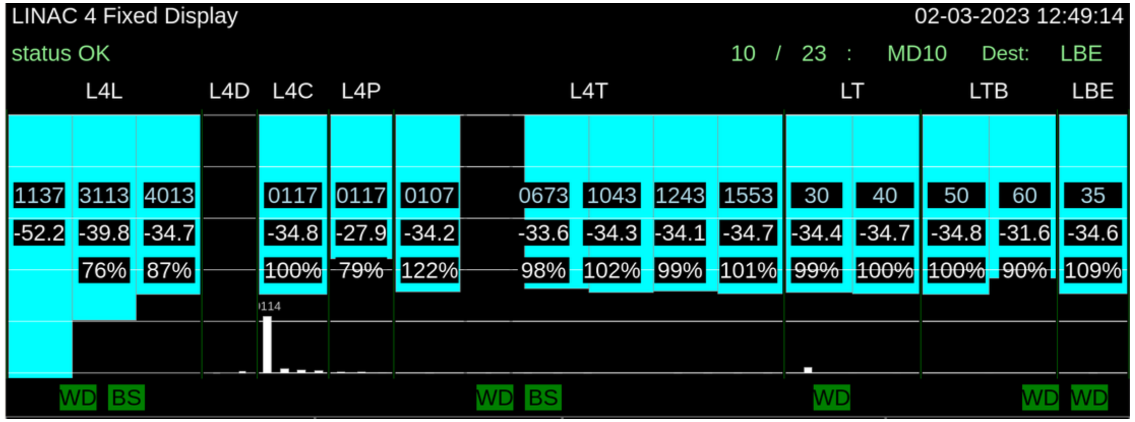


Linac4

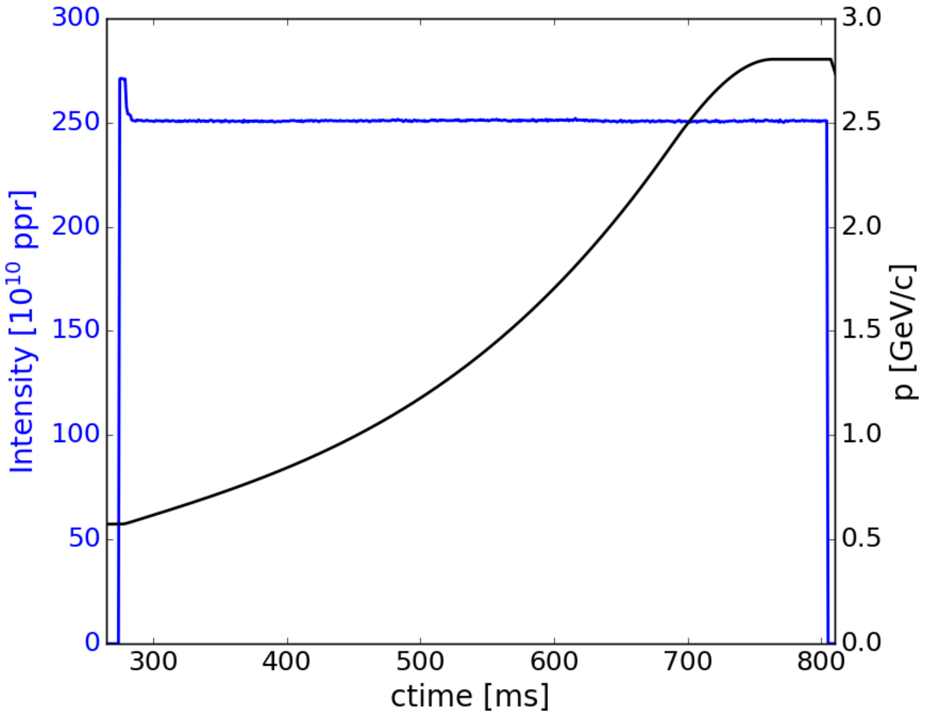
- The new Linac4 has been delivering beam as expected
  - **27 mA** before chopping within **0.3 um emittance** and pulse stability specifications
  - More than **98.5% availability** over the first three years operation
- 2023 dedicated tests with new source have demonstrated up to **35 mA** deliverable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





PSB

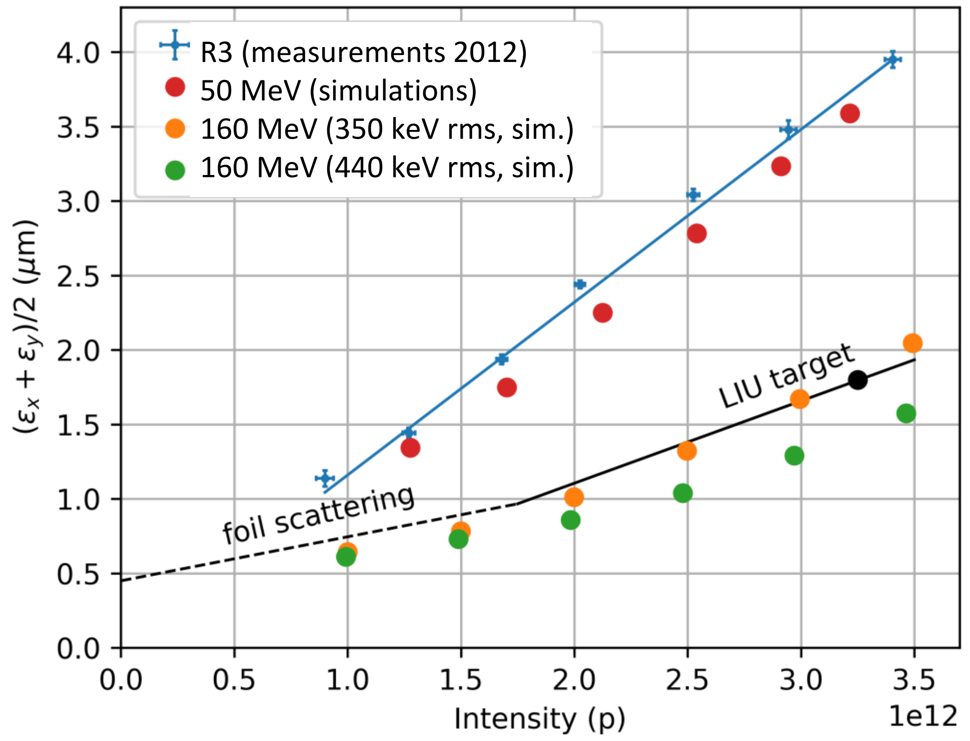
- The PSB accelerates 1 bunch/ring (four rings) from 160 MeV to 2 GeV
  - Brightness is defined by space charge and H- charge exchange injection from Linac4
  - Cleaning of longitudinal tails at beginning of ramp, otherwise lossless acceleration

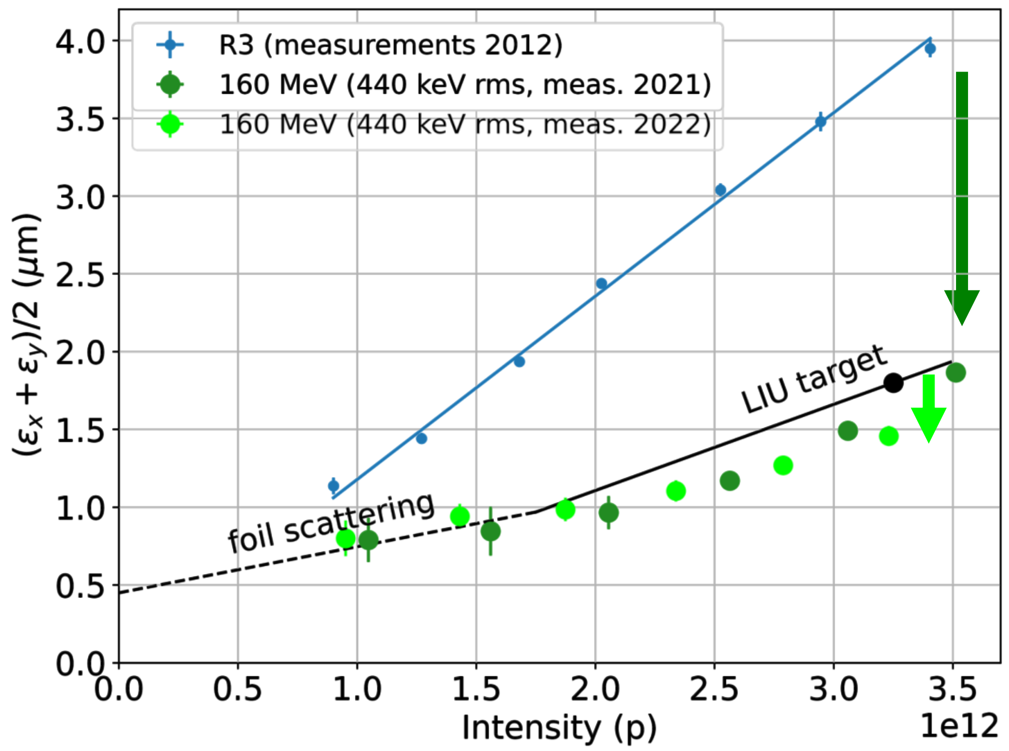


PSB

LHC Injectors Upgrade

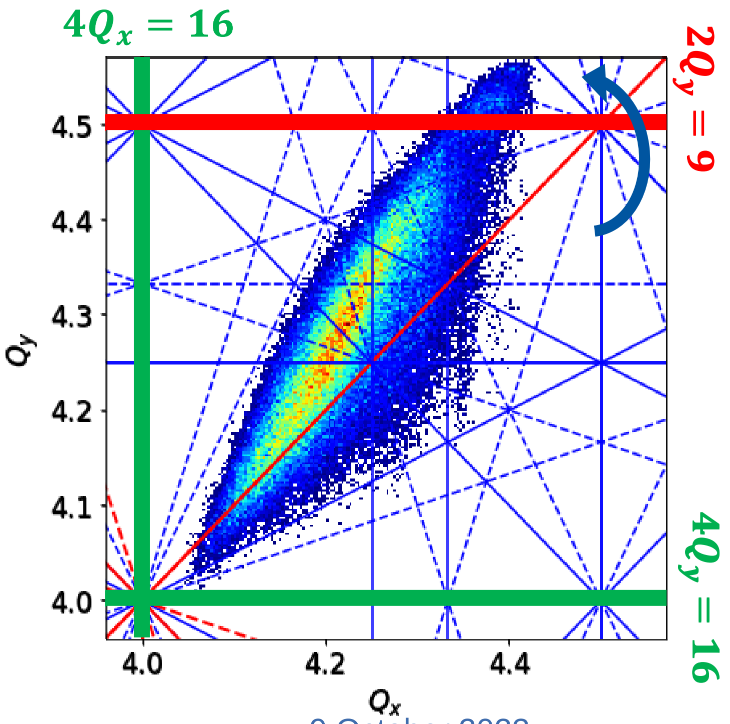
- **PSB brightness line after connection with Linac4**

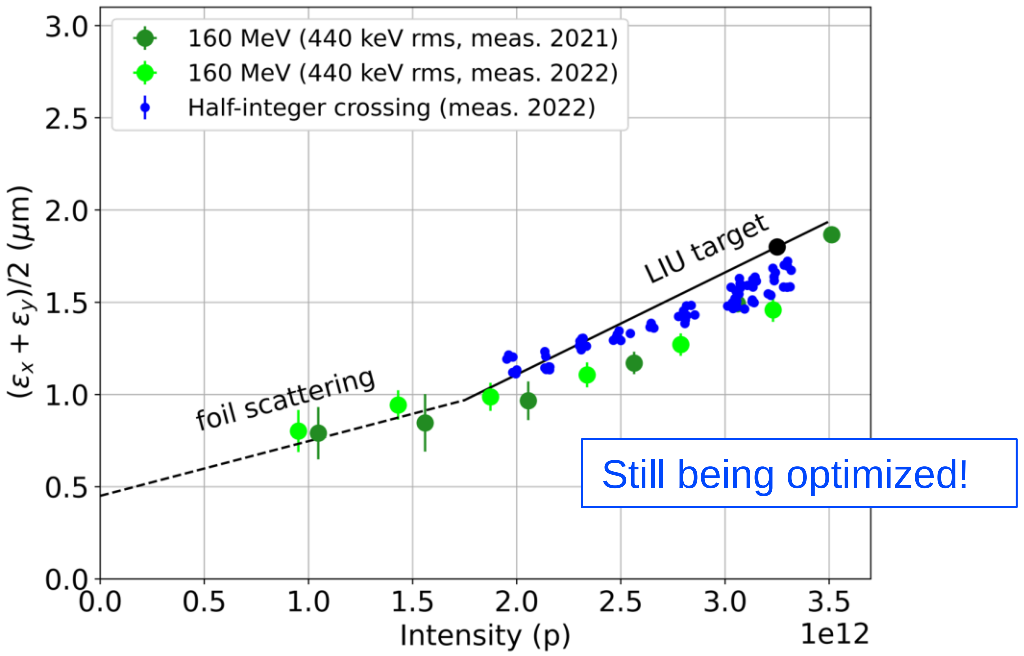




PSB

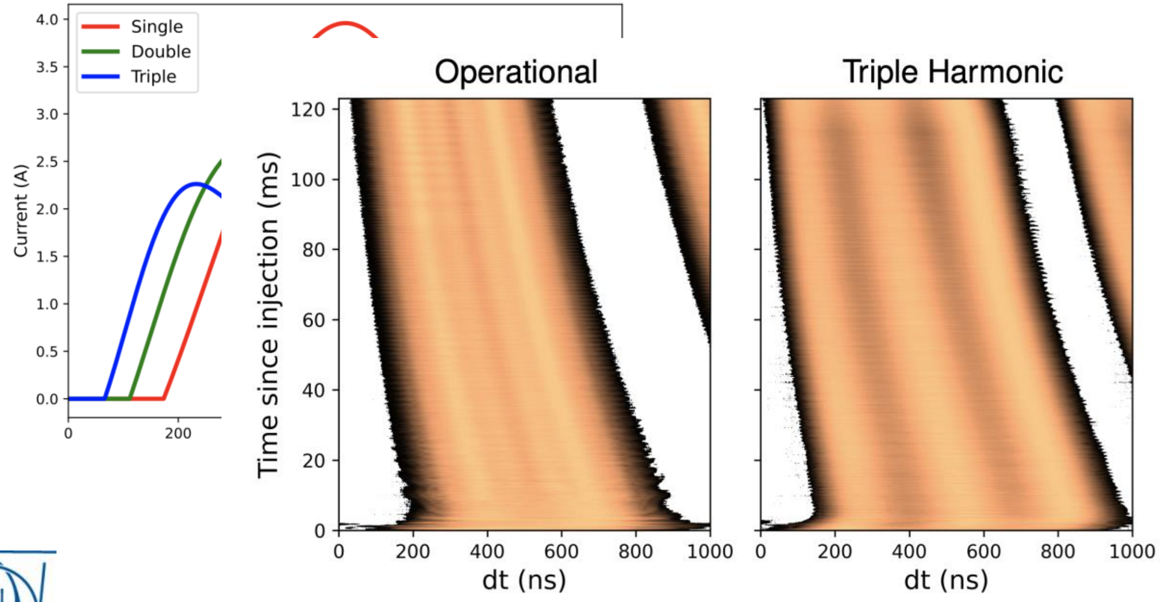
- **PSB brightness line after connection with Linac4**
- Can we gain even more margin?
  - Injection above the half-integer to limit blow-up driven by integer resonance crossing

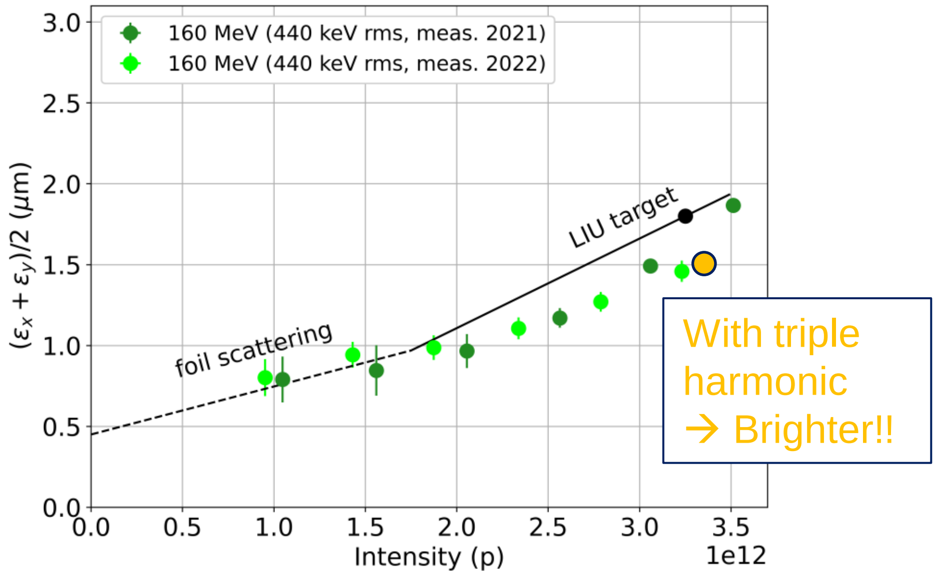




PSB

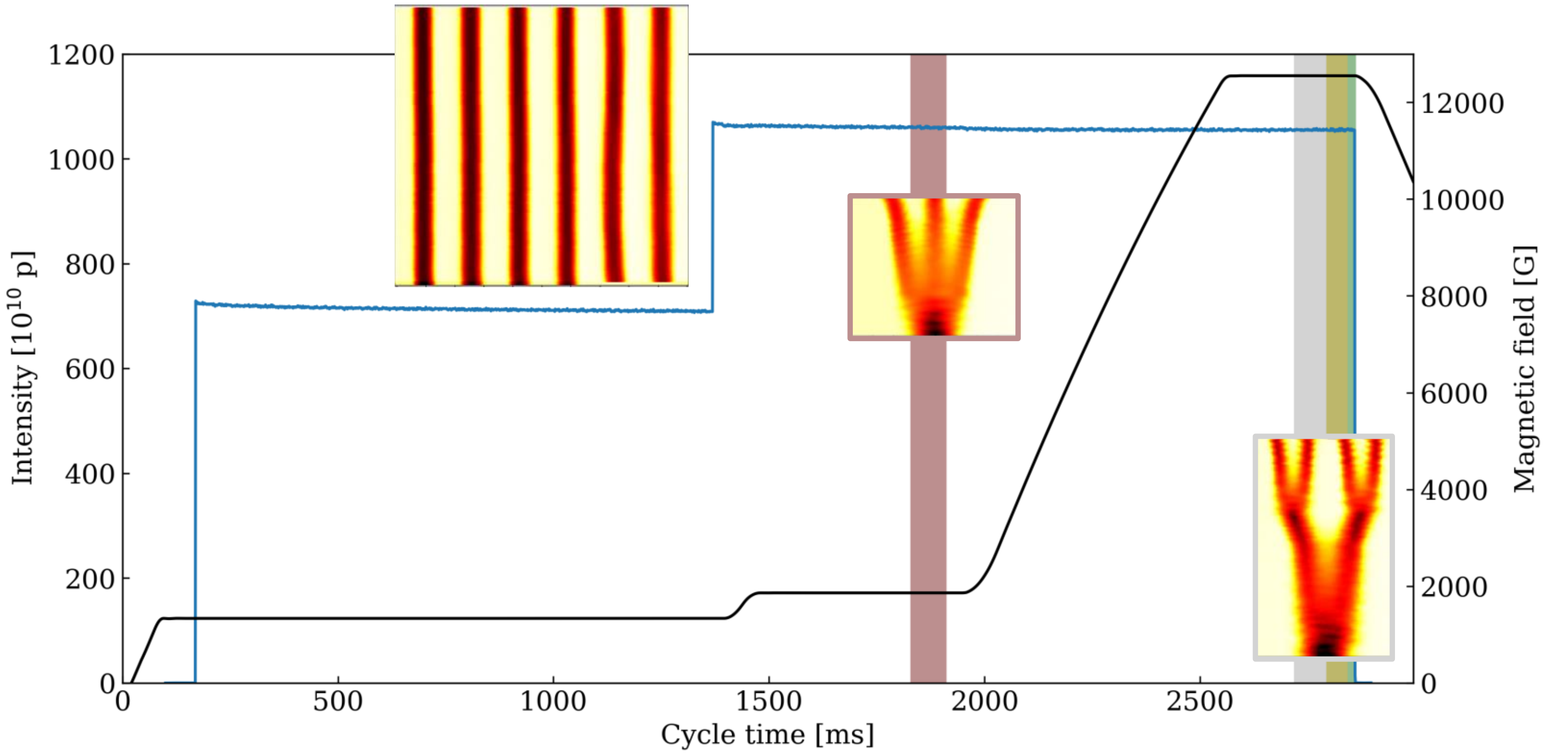
- **PSB brightness line after connection with Linac4**
- Can we gain even more margin?
  - Injection above the half-integer to limit blow-up driven by integer resonance crossing
  - Injection into triple harmonic bucket to flatten bunch and mitigate space charge





PS

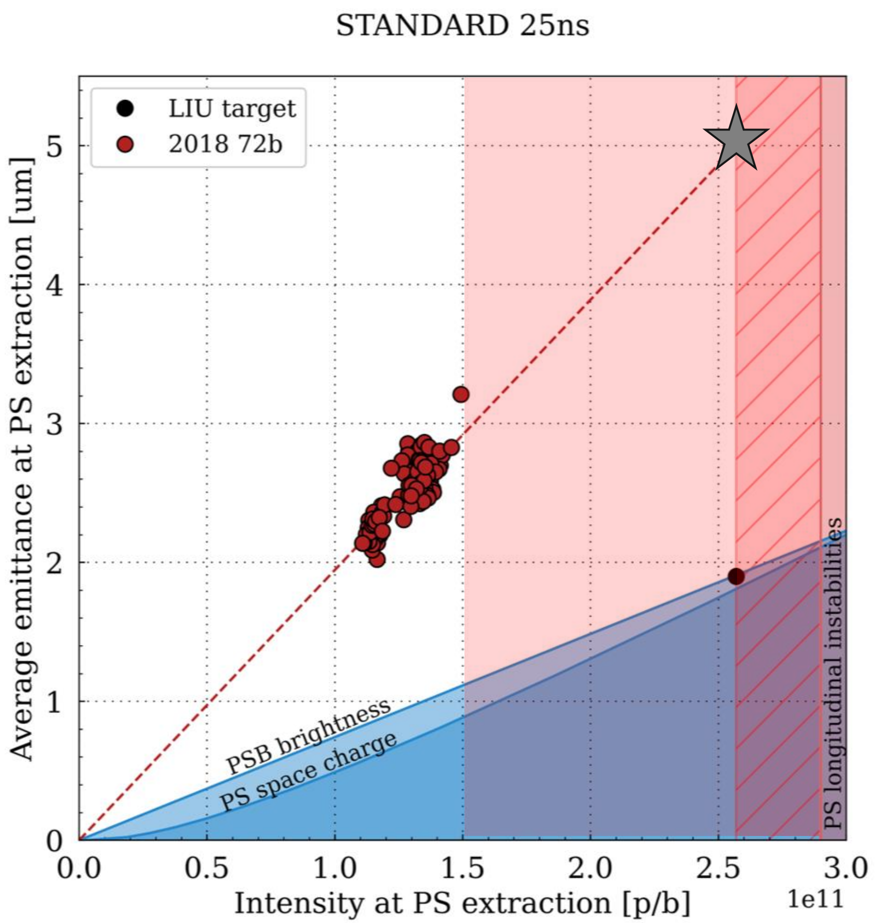
- The PS receives 6 (4+2) bunches over two subsequent injections from PSB
  - Triple splitting at 3 GeV
  - Double double splitting at top energy 26 GeV with fast bunch rotation before extraction



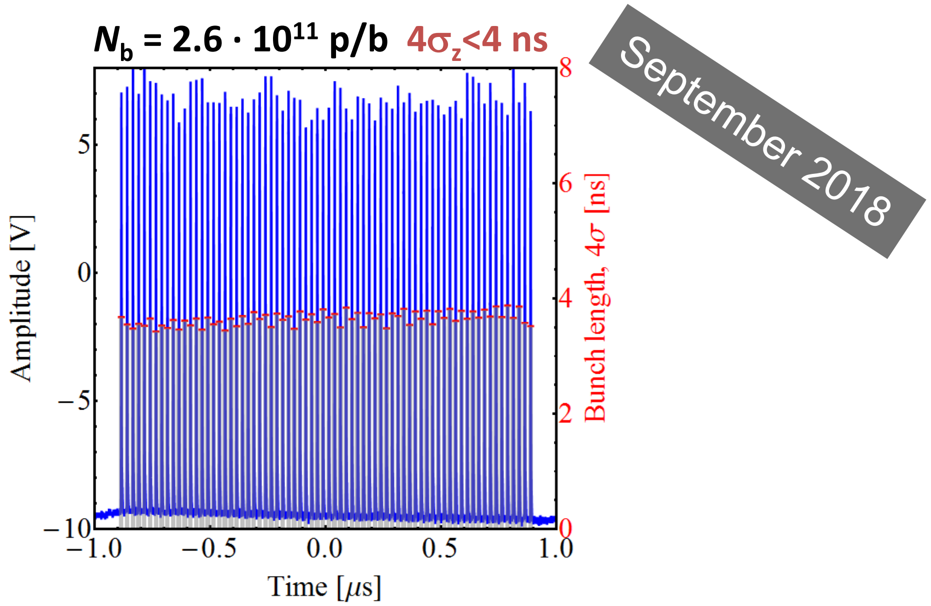
PS

LHC Injectors Upgrade

- LIU intensity and brightness in the PS from 2018 to 2023



- Intensity demonstrated already in 2018 thanks to LIU coupled-bunch feedback prototype installed in 2014



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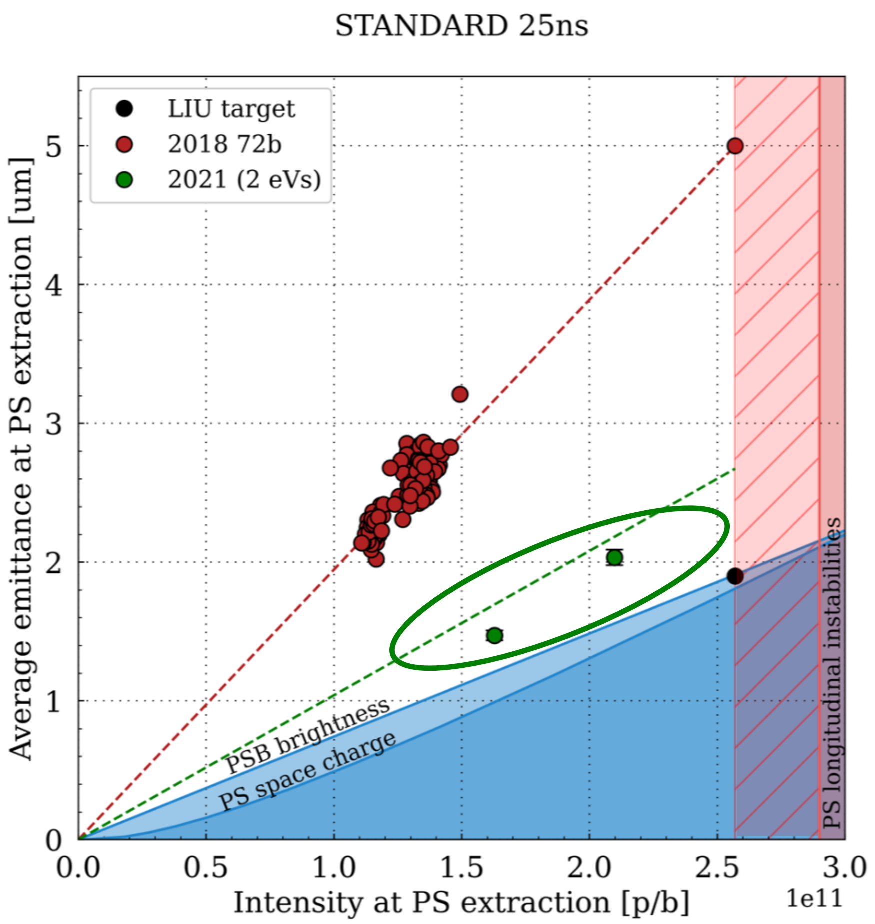
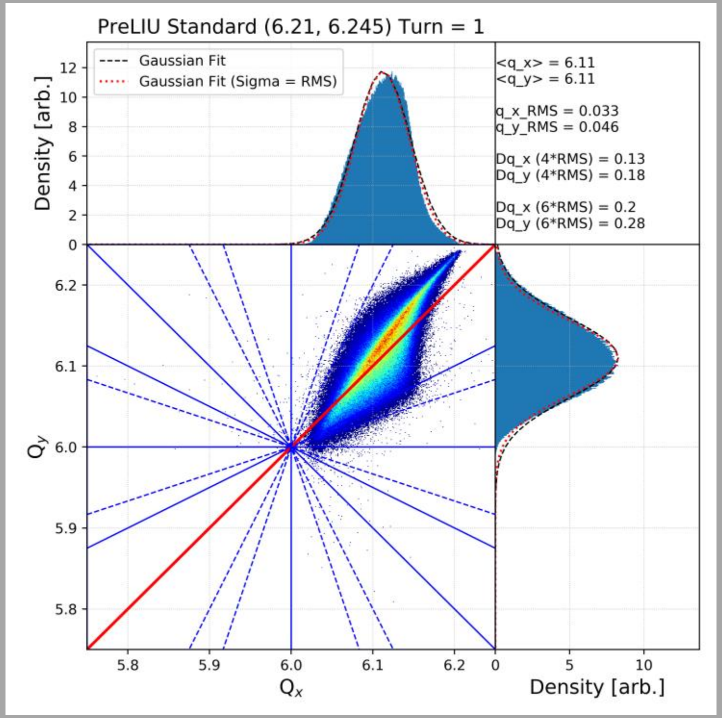


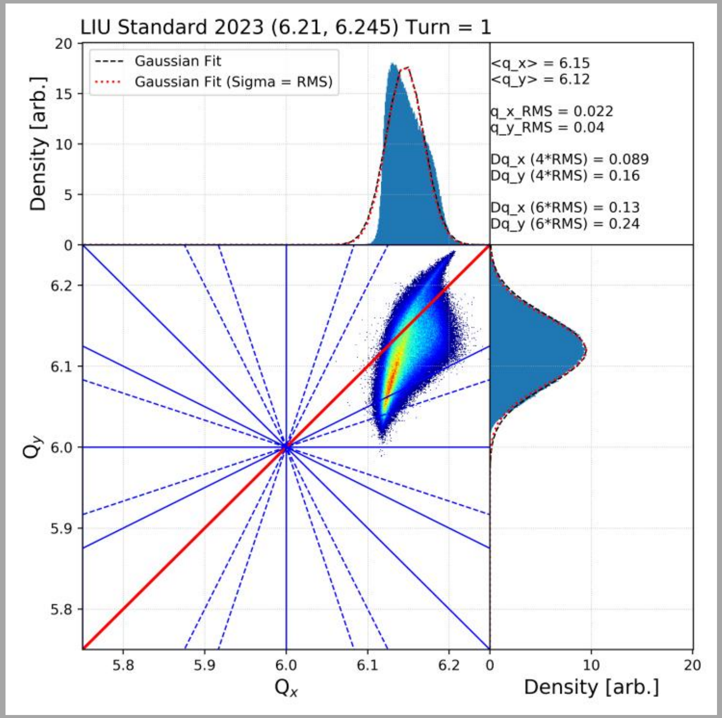
- Intensity demonstrated already in 2018
- First step of brightness ramp-up (2021) with 2 GeV and 2 eVs injection

PS

- LIU i

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

PS

LHC Injectors Upgrade

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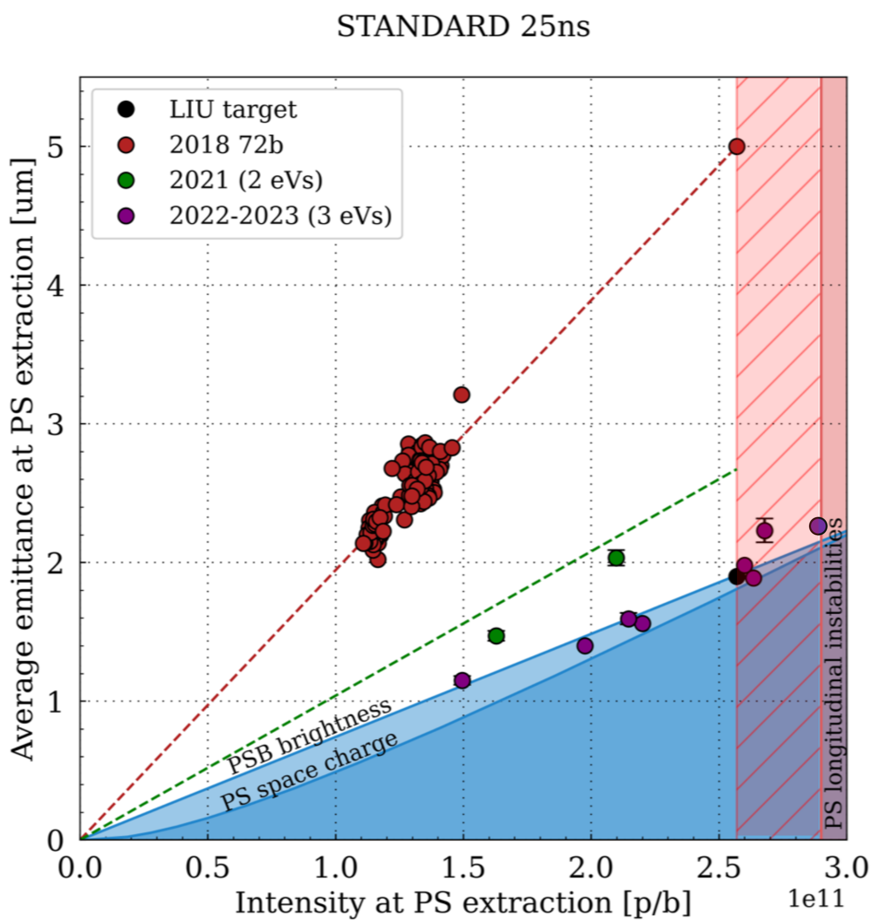
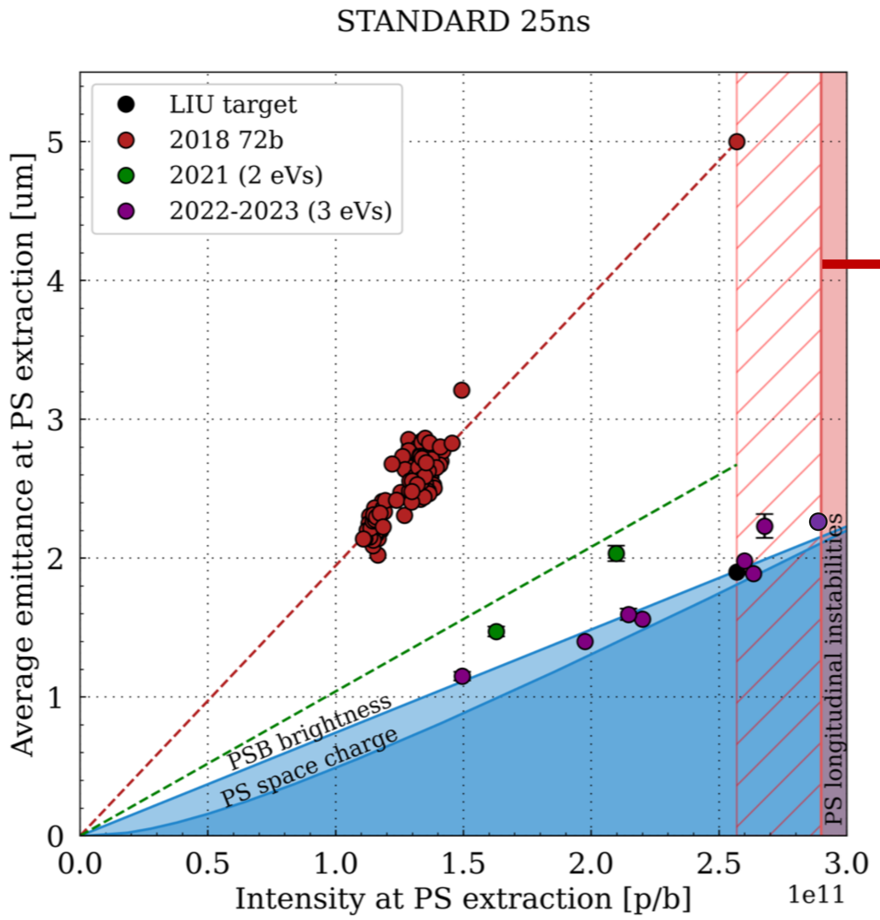
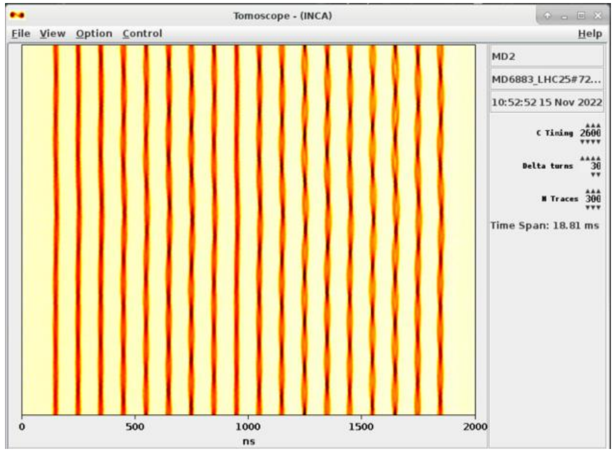


- Intensity demonstrated already in 2018
- First step of brightness ramp-up (2021) with 2 GeV and 2 eVs injection
- Full PS performance achieved in 2022 thanks to 3 eVs injection
- Actually 2.9 • 10^{11} p/b successfully achieved out of the PS

PS

- LIU intensity and brightness in the PS from 2018 to 2023





Higher intensities limited by quadrupolar instabilities

PS

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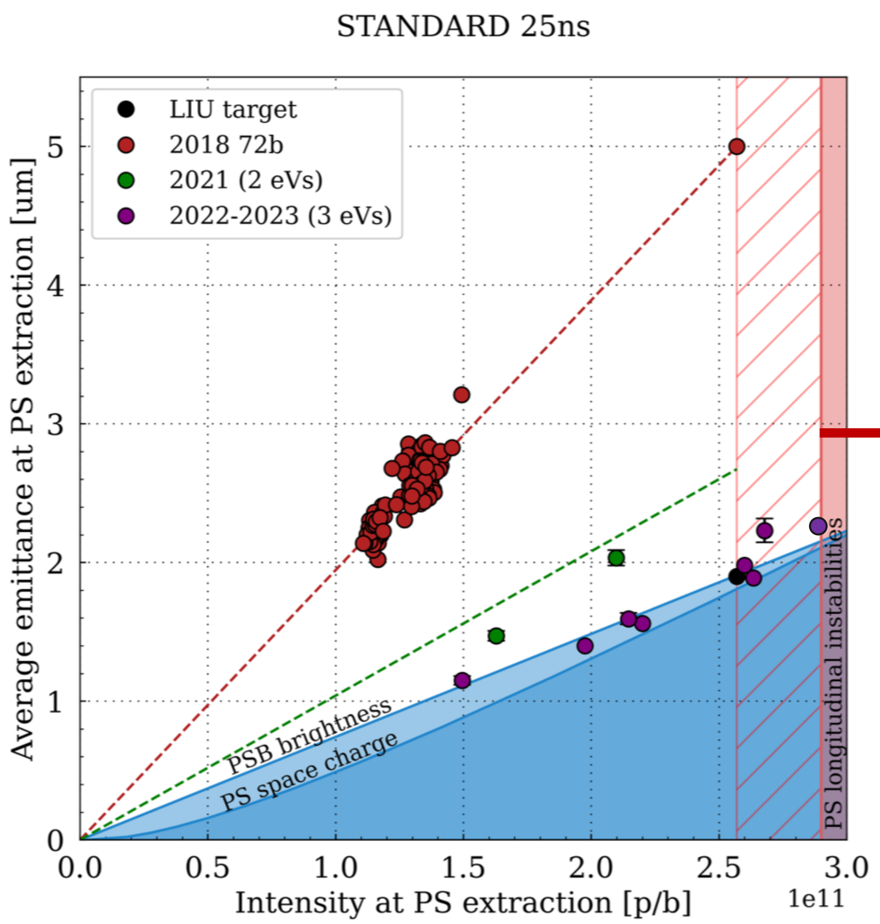
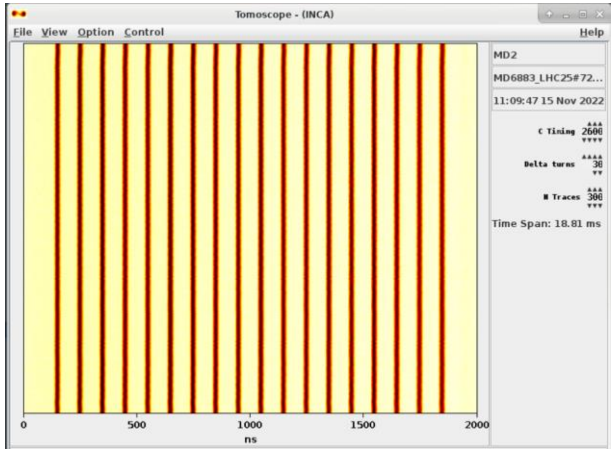


Stabilised by quadrupolar feedback up to at least $3.15 \cdot 10^{11}$ p/b equiv. (2022)



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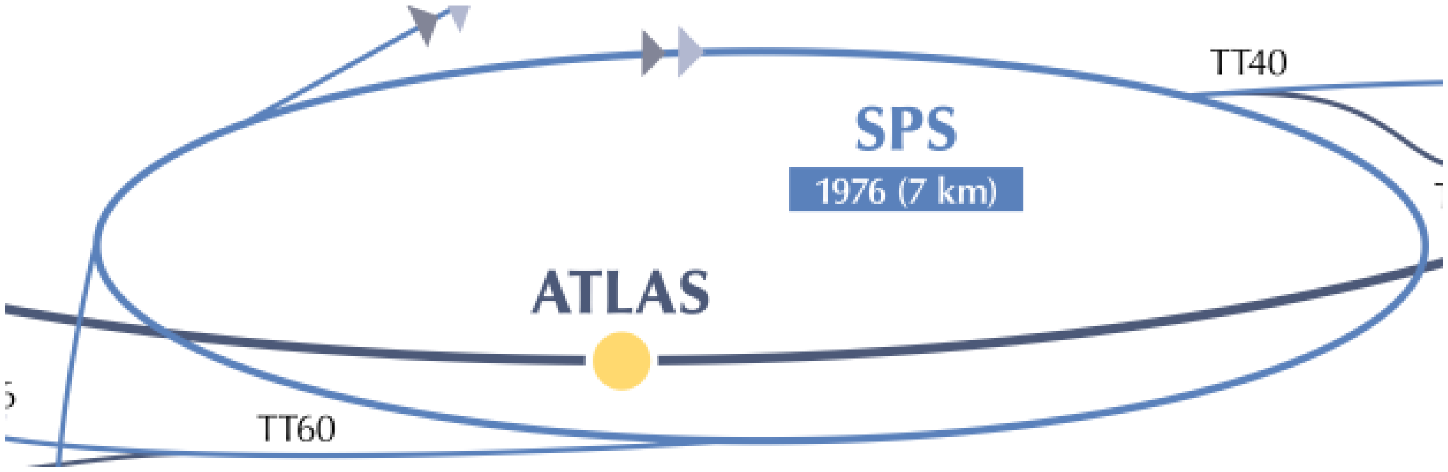
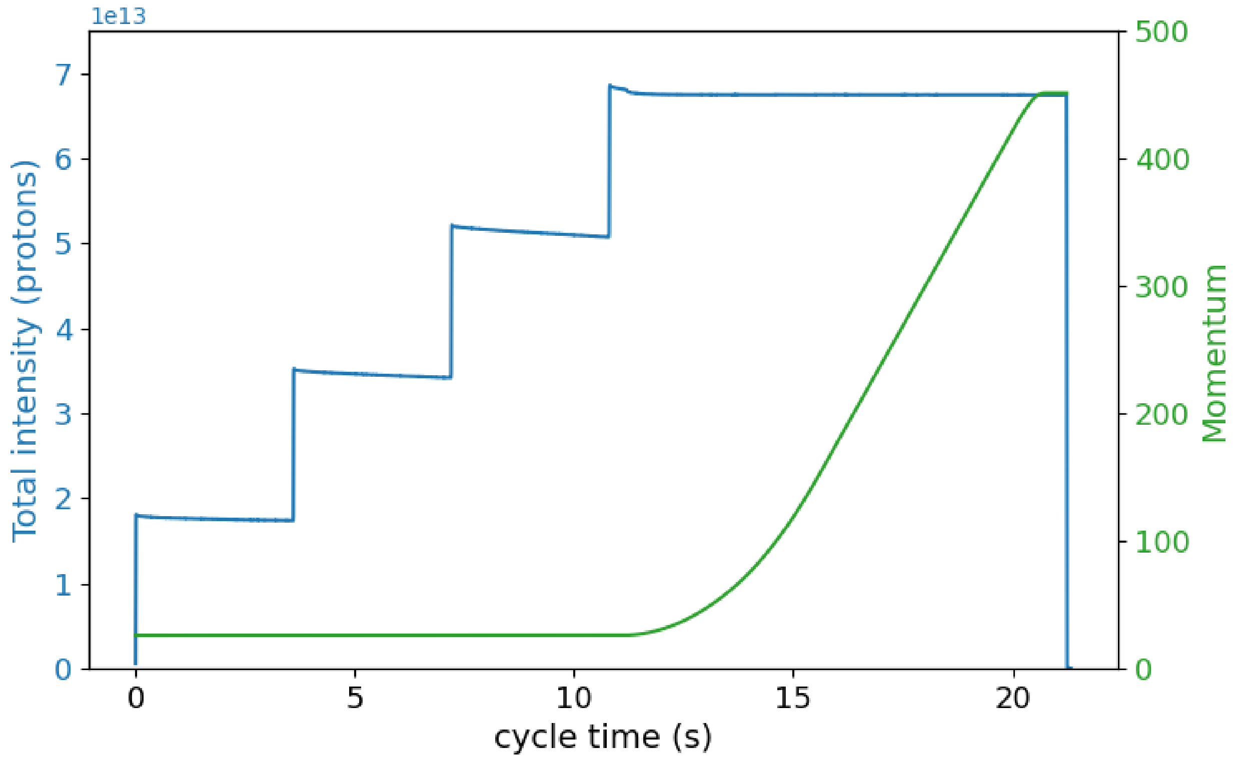


SPS

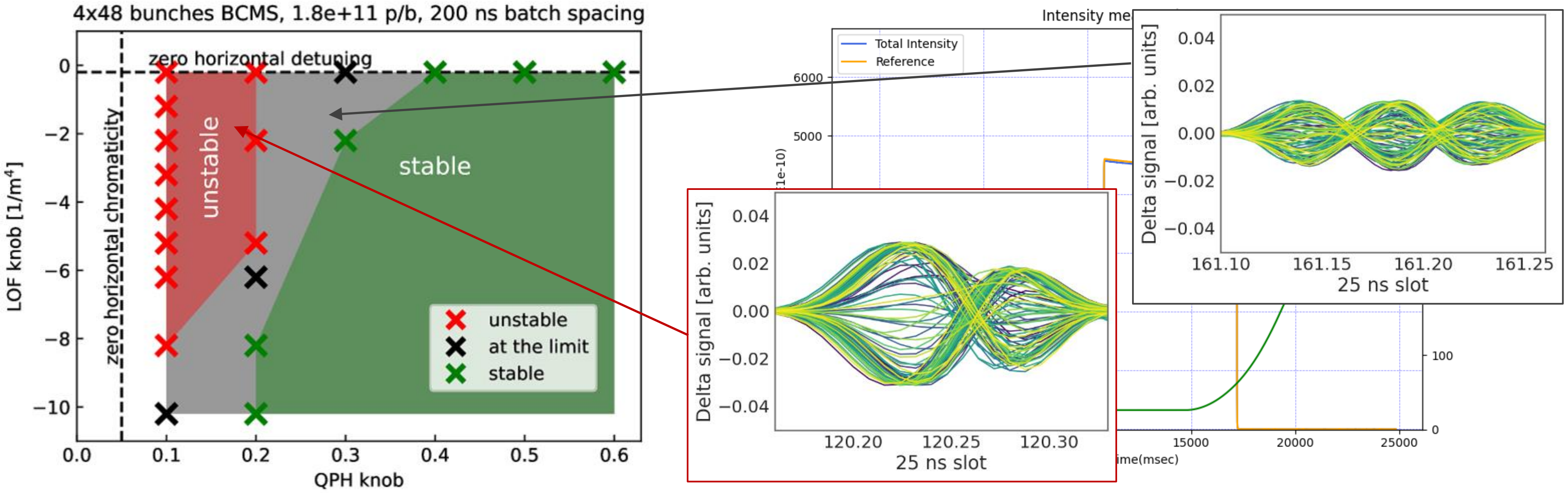
- The SPS receives 4 trains of 72 bunches from PS
  - Long injection plateau @26 GeV
  - Acceleration to 450 GeV



SPS: Horizontal stability at injection

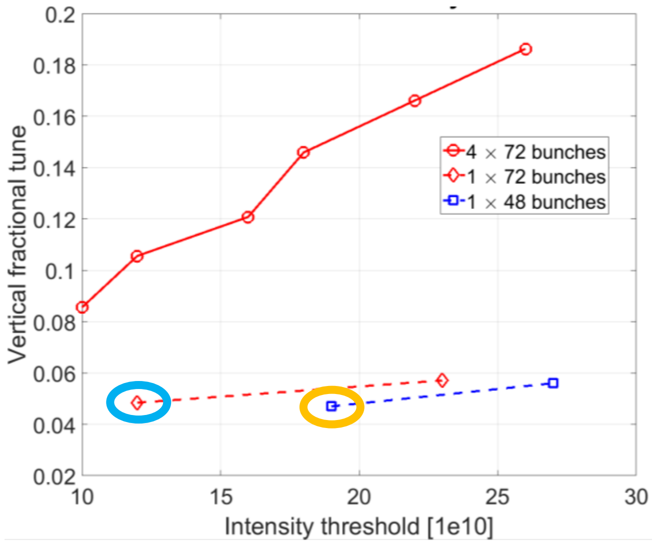
LHC Injectors Upgrade

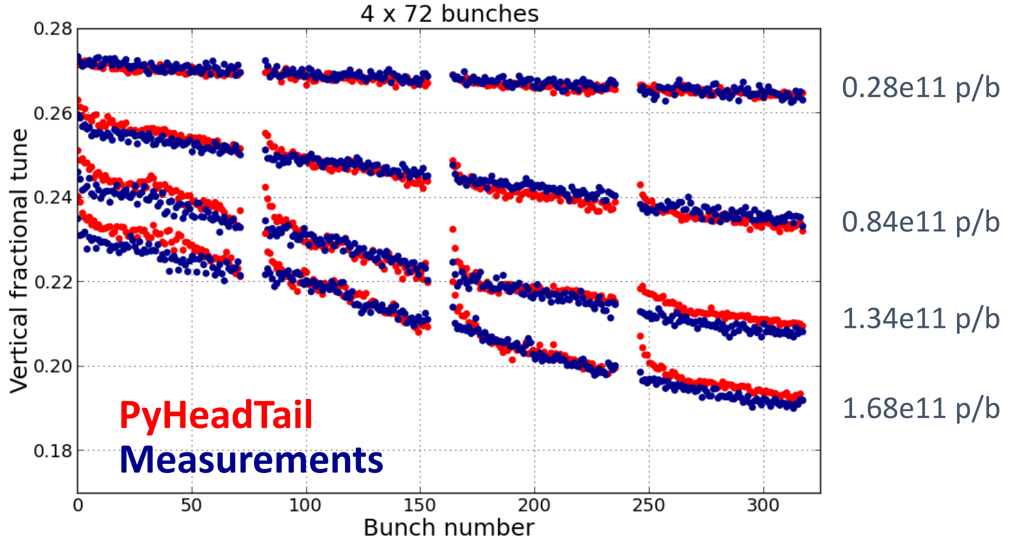
- Horizontal instabilities @26 GeV studied in detail in 2018 for 1.8e11 p/b
  - Mitigation strategy developed in simulations: high chromaticity + octupoles
- Successfully tested in 2022 and 2023 with up to 2.5e11 p/b injected
  - 5x 48 and 4x 72 bunches
  - Discovered criticality of short bunches (<3.5 ns) at injection to ensure stability



SPS: Vertical stability and working point

- Extremely fast vertical instability (few turns risetime) predicted in simulations
  - Threshold depends on vertical tune setting (mainly driven by resistive wall)
  - Experimentally confirmed with 1 batch and low intensity
- Vertical tunes close to 20.25 resonance required for LIU parameters
  - Control of tunes is critical due to large bunch-by-bunch tune shift from impedance – excellent progress on operational correction (model-based application)

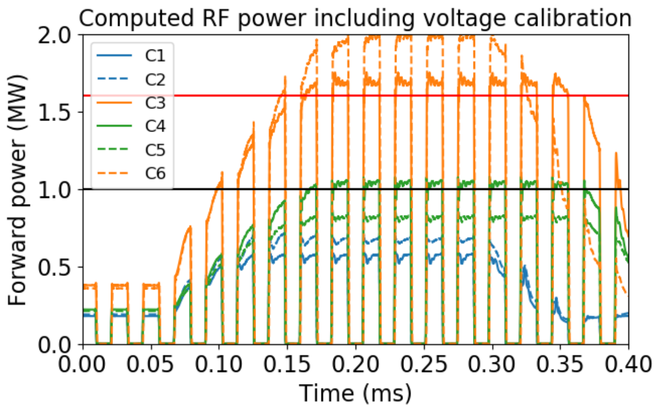


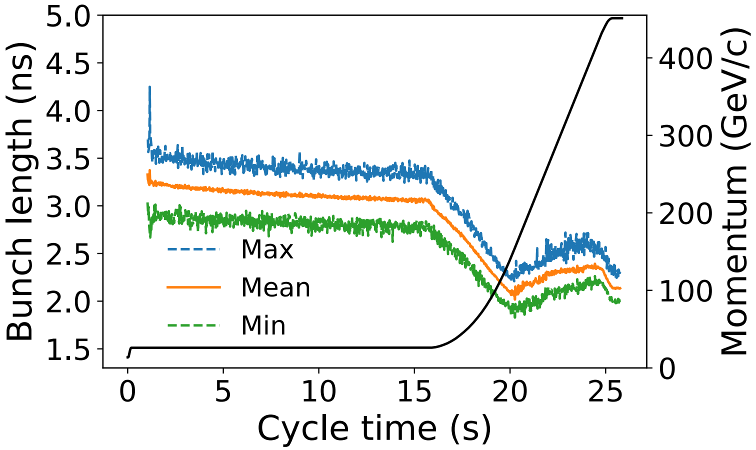


SPS: Longitudinal beam stability and control

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
  - Thanks to optimized 200 MHz voltage program with higher voltage available, 800 MHz voltage program and controlled emittance blow-up (with automatized setup)

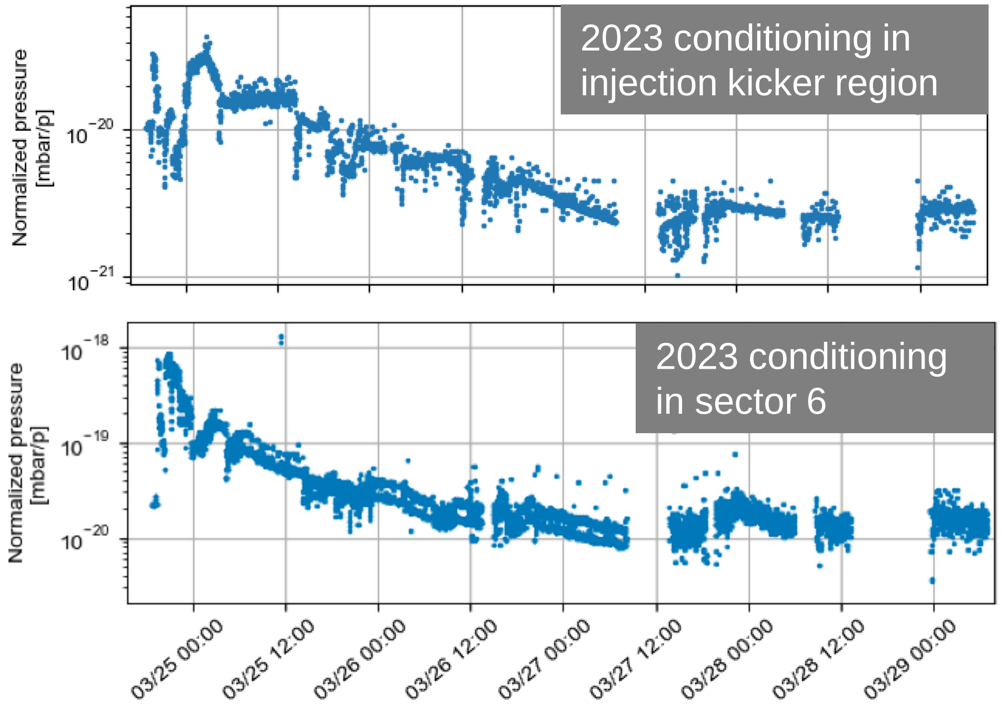


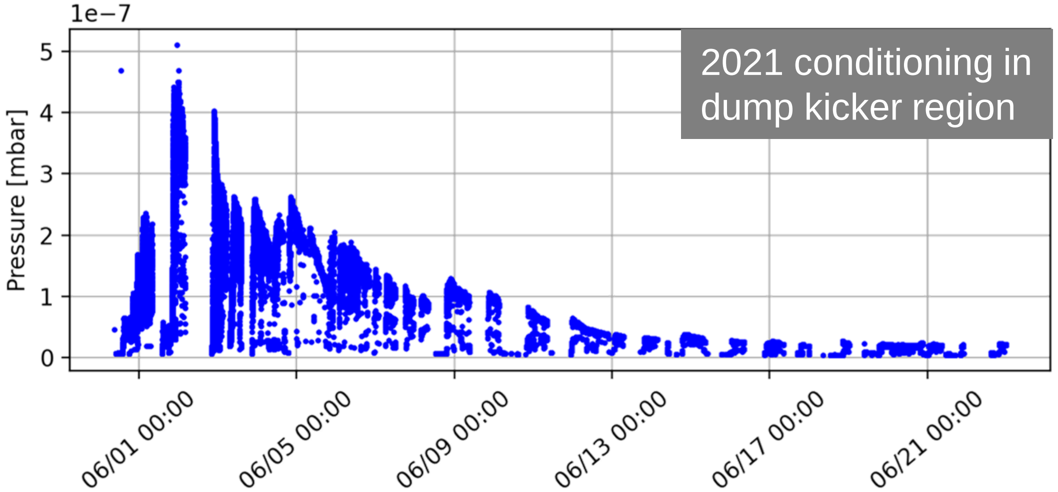


SPS scrubbing

LHC Injectors Upgrade

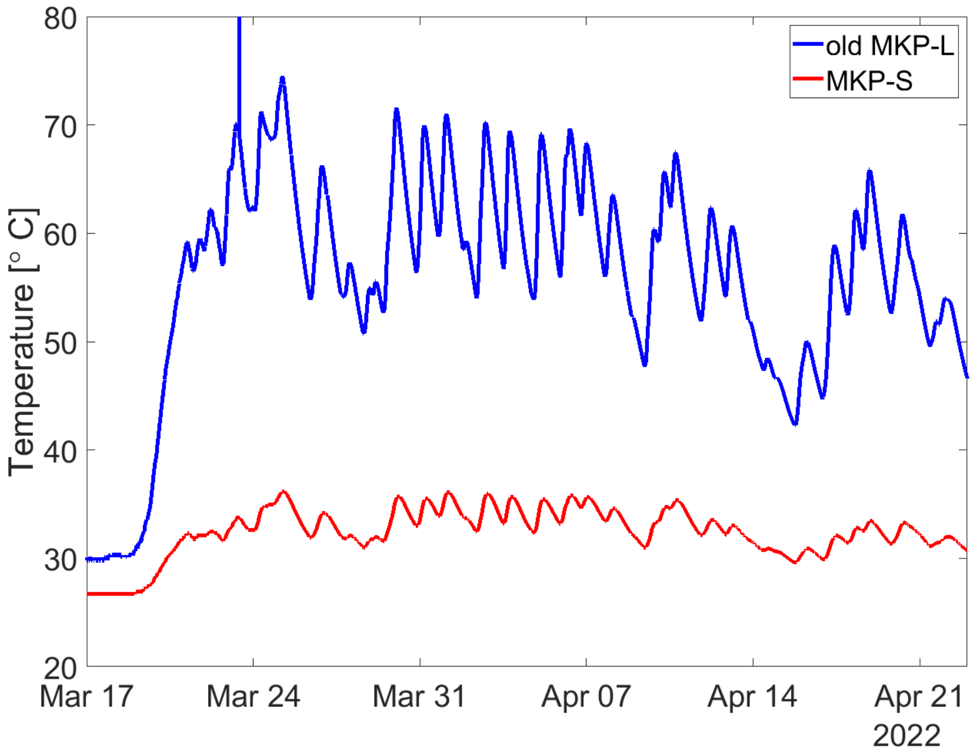
- Extended scrubbing needed in 2021 to recover global SPS conditioning state
- Scrubbing runs still necessary in 2022 and 2023
  - Regions open for intervention during YETS’s
  - New kicker magnets in the machine with low pressure interlock thresholds
  - Progressive intensity ramp-up leading to larger peak densities and pressure spikes





Encountered limitations

- Heating of a module of the injection kicker system (MKP-L)
  - Low scrubbing efficiency to allow for cooling
  - Hard limit for high intensity studies



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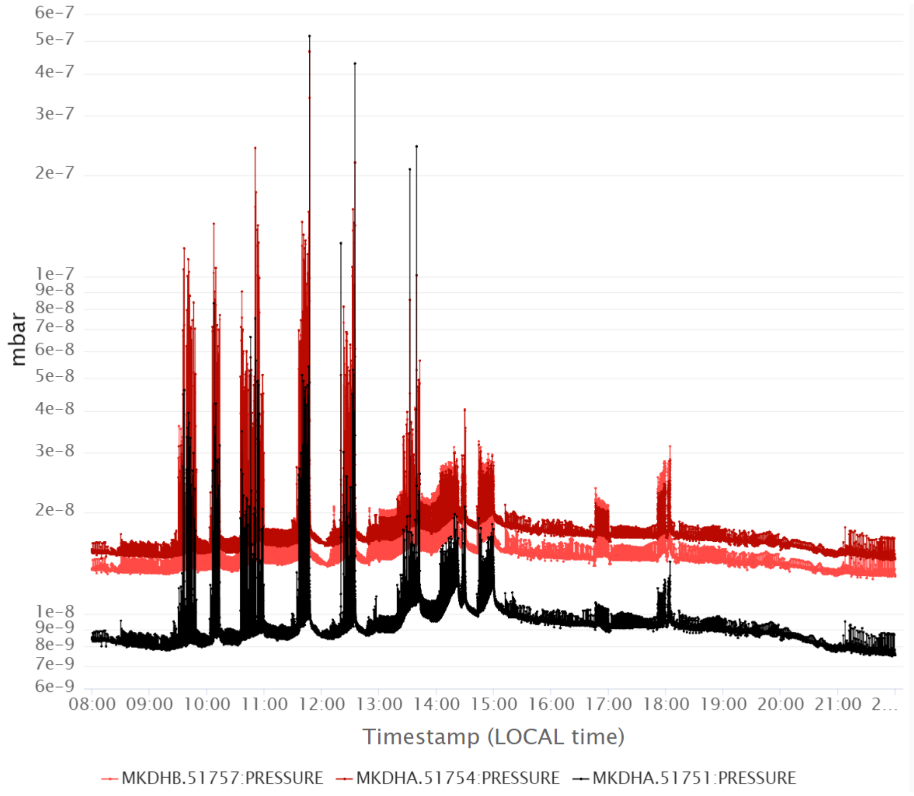
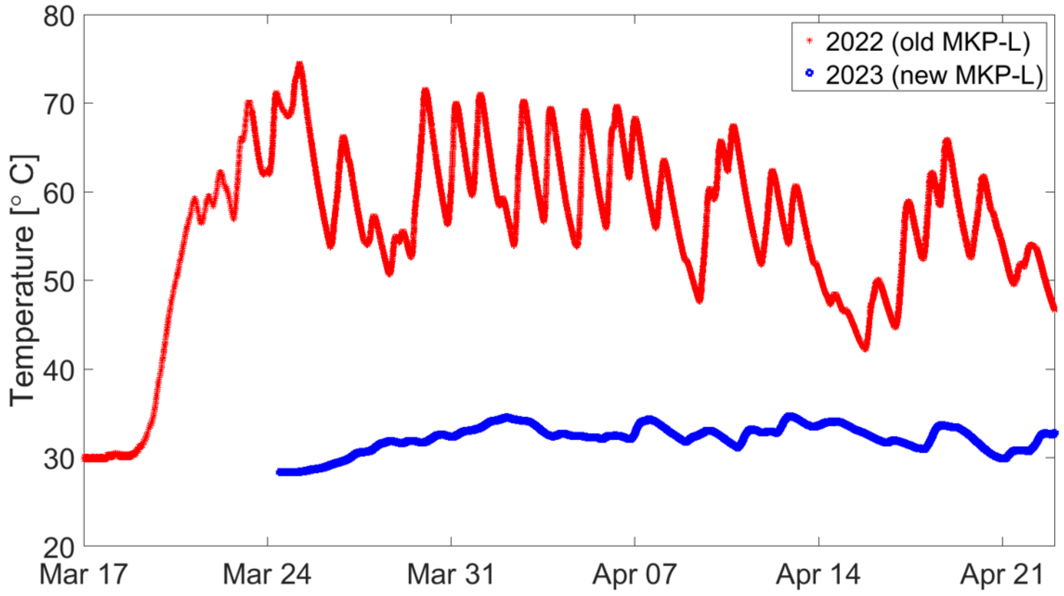
LHC Injectors Upgrade

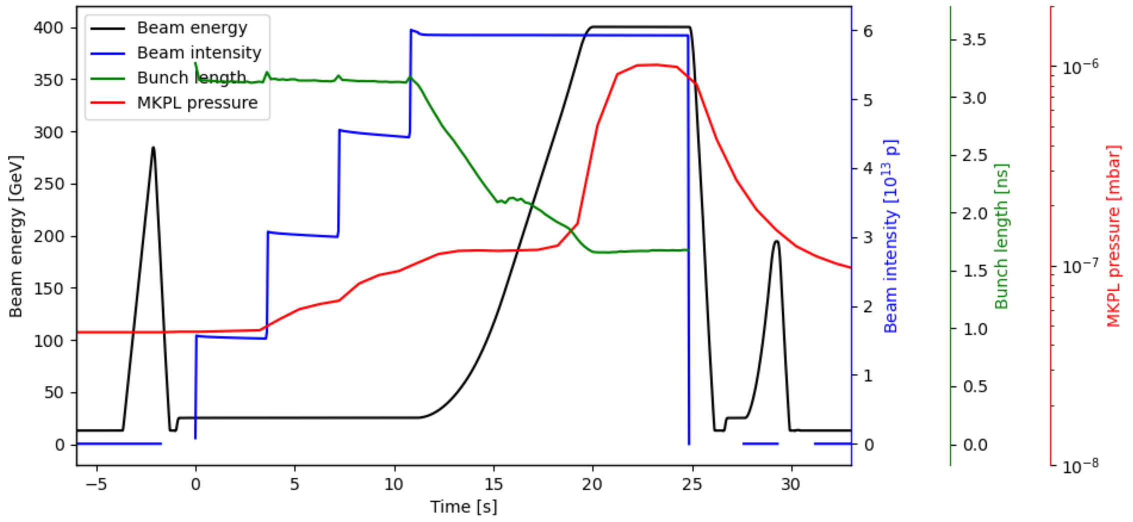
- Heating of a module of the injection kicker system (MKP-L)
  - Low scrubbing efficiency to allow for cooling
  - Hard limit for high intensity studies
- Pressure spikes at large peak currents occurring on injection and dump kickers (MKP-L and MKDH) for high intensity, long trains and short bunches
  - Limited the number of bunches that could be accelerated to 450 GeV in 2022
  - Not easily conditionable because of short-lived pressure rises



Solutions

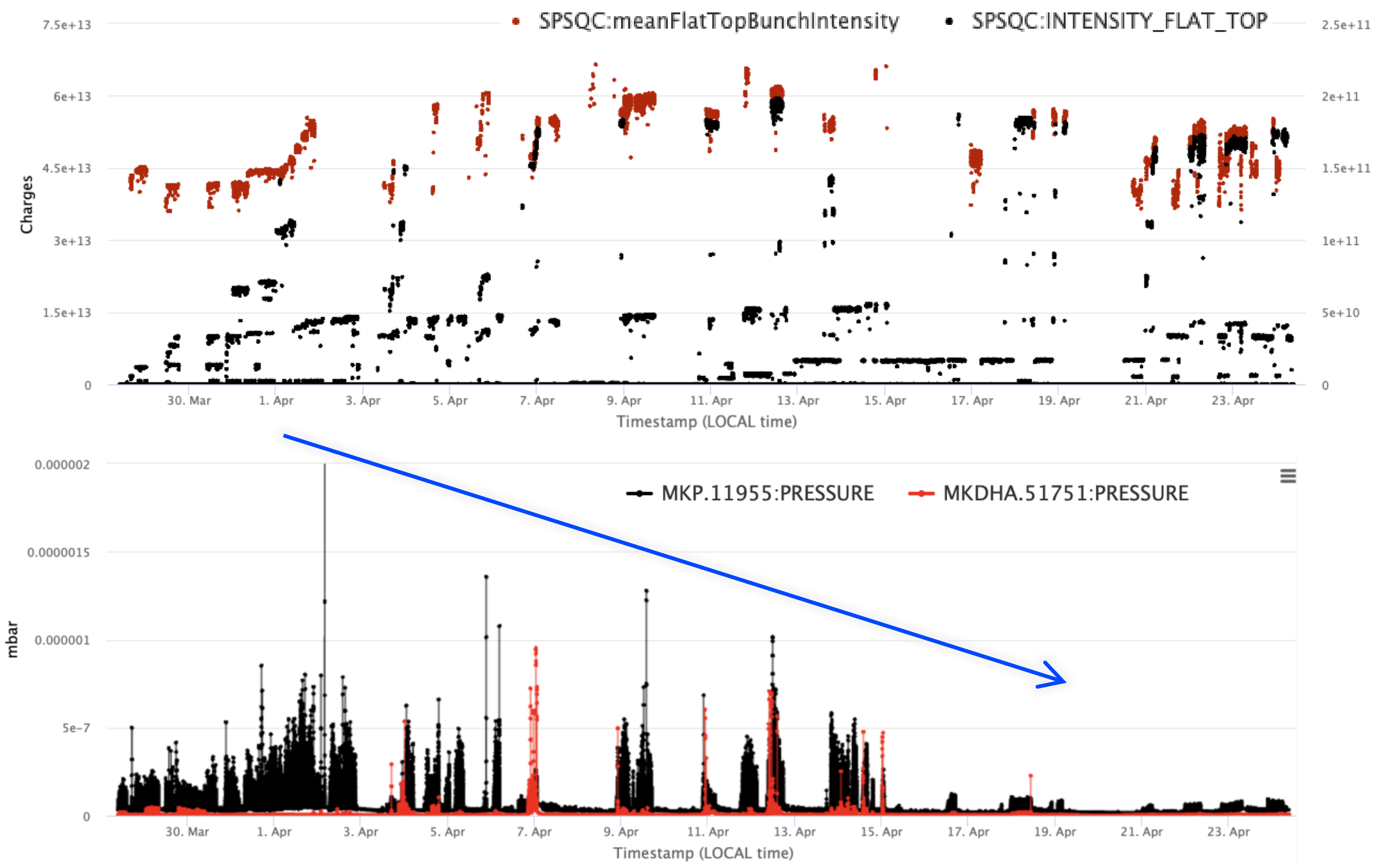
- New low-impedance MKP-L installed
  - Heating largely mitigated and increased scrubbing efficiency
- Long flat top cycle
  - Increased effective scrubbing time for injection and dump kickers





Conditioning of kickers

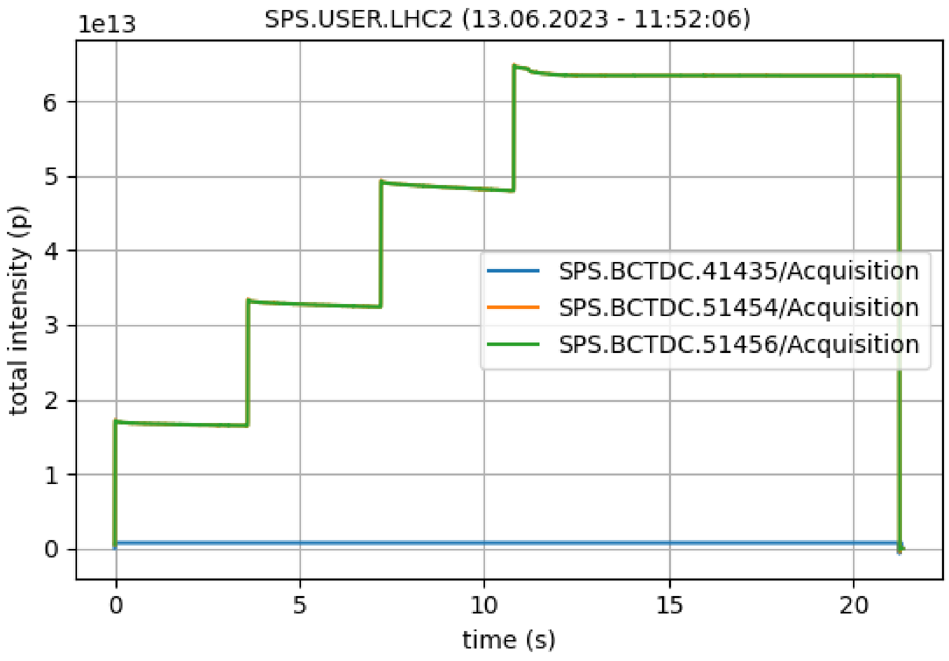
- In these conditions the newly installed MKP-L and old MKDH could be successfully conditioned in 2023 allowing for continuation of ramp-up

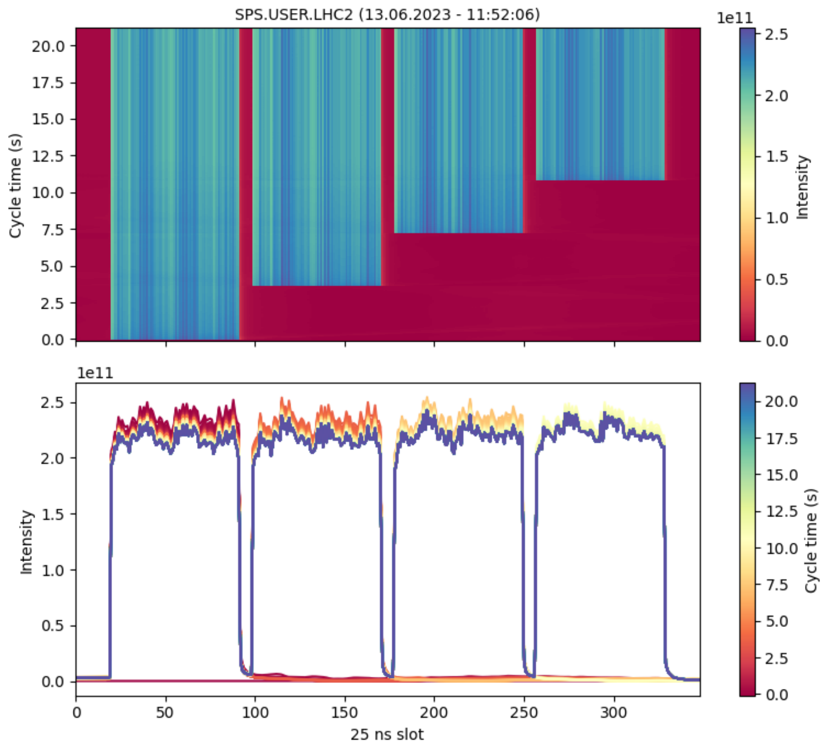


Achieved SPS performance – intensity

LHC Injectors Upgrade

- **Intensity reach demonstrated on 13.06.23:**
  <u>4x72 with 2.2e11 p/b at flat top</u>
  - Excellent transmission (~95% without scraping)





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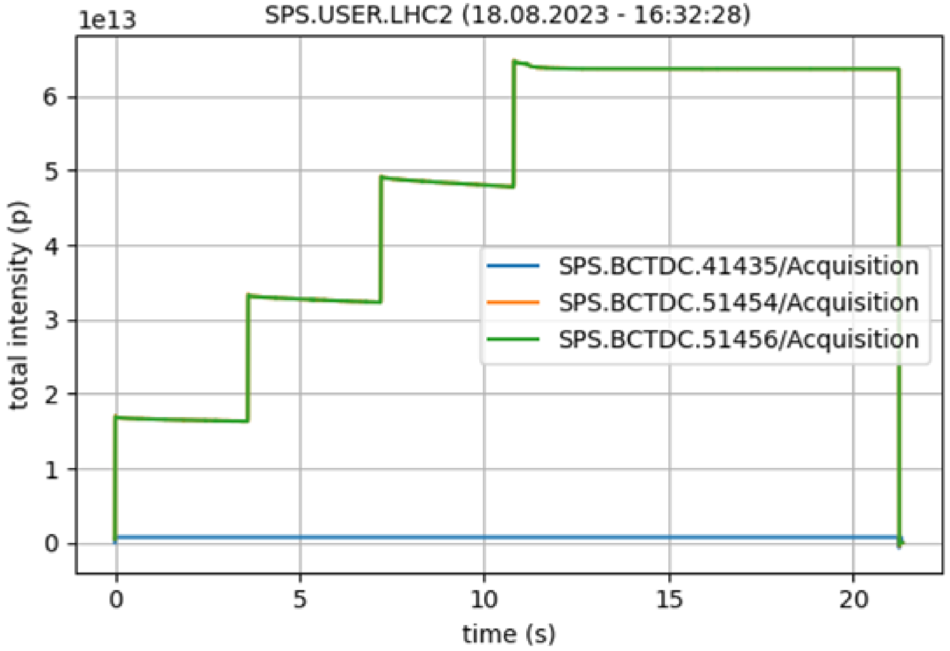

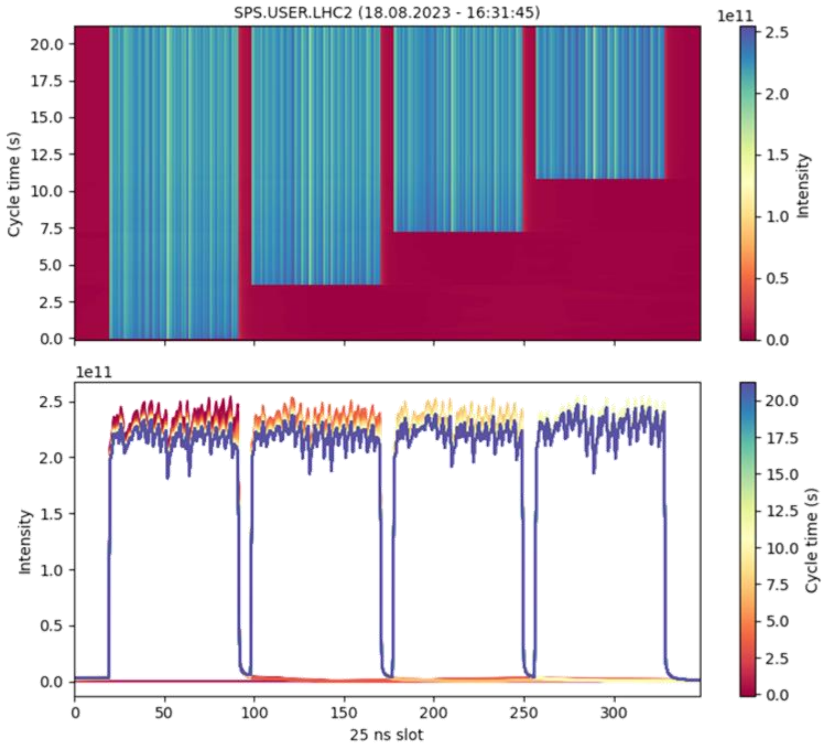

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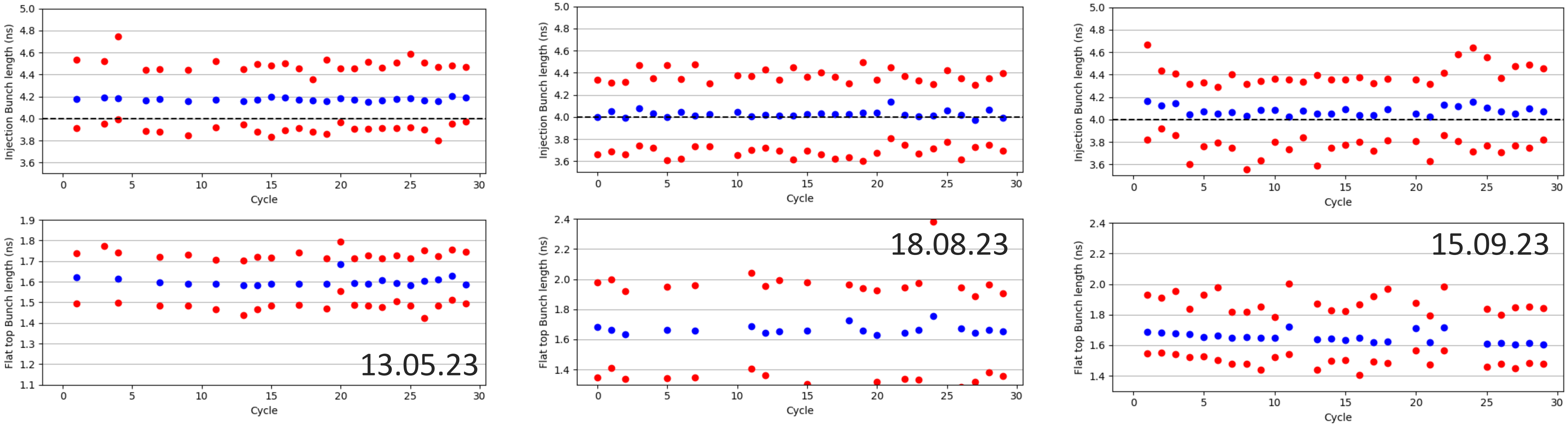

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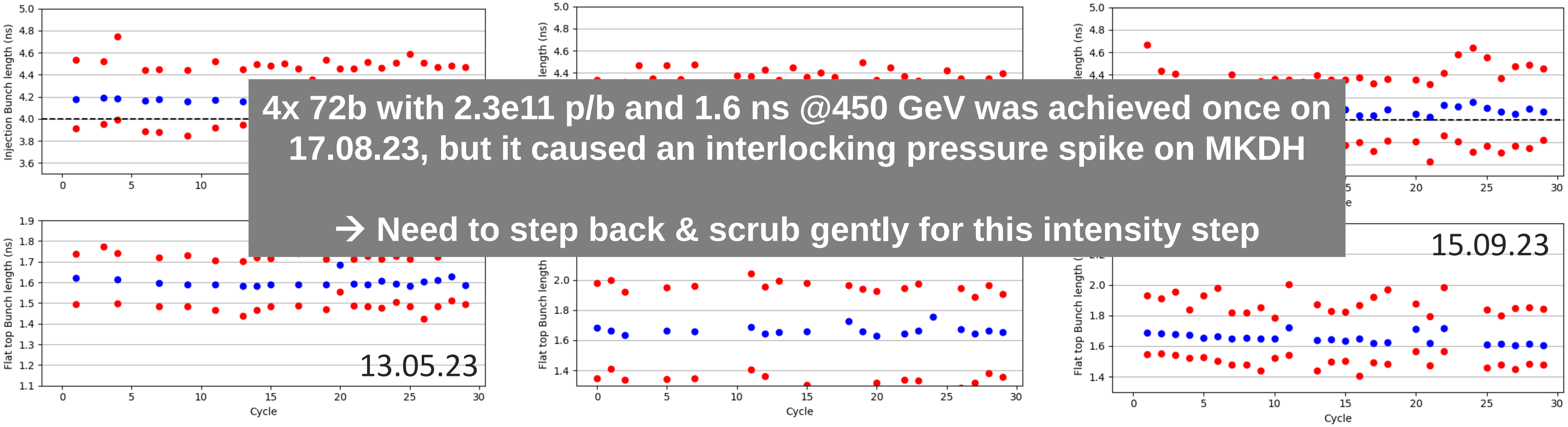


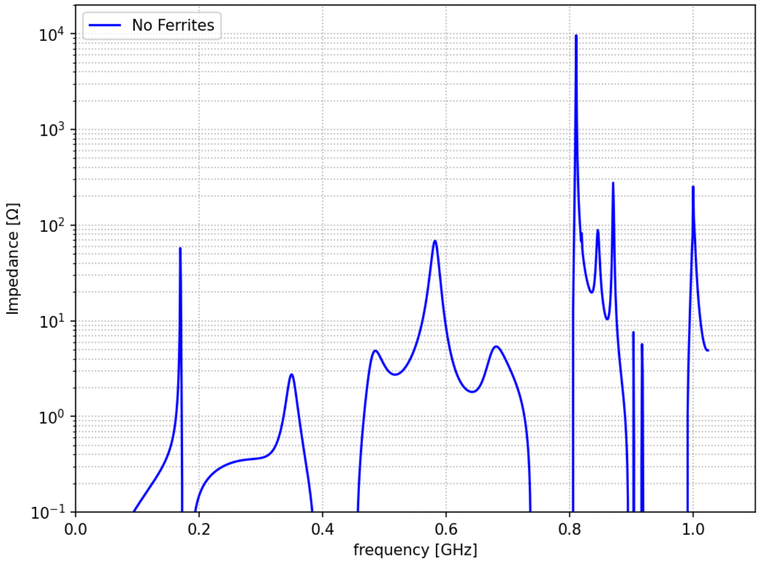
4x 72b with 2.3e11 p/b and 1.6 ns @450 GeV was achieved once on 17.08.23, but it caused an interlocking pressure spike on MKDH

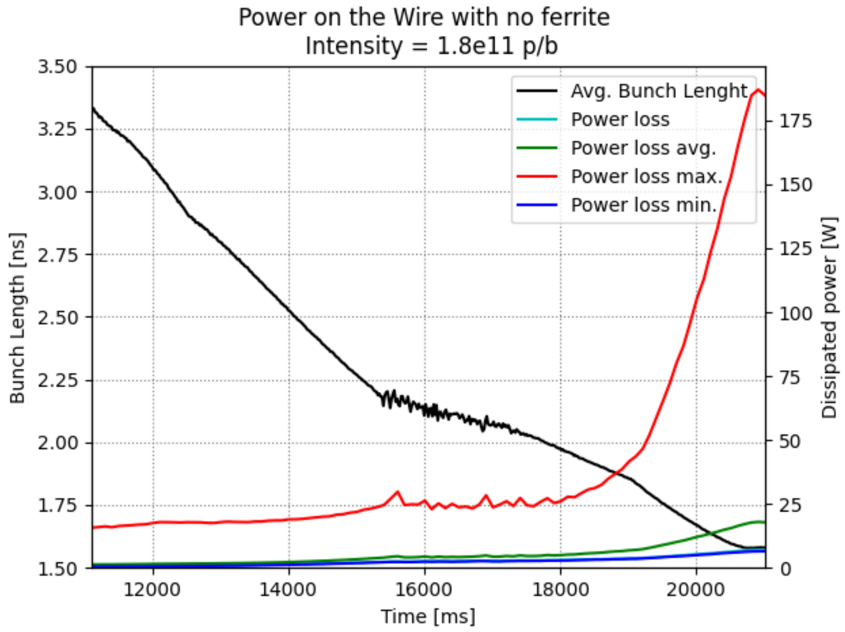
→ Need to step back & scrub gently for this intensity step

Problem with the wire scanners (I)

LHC Injectors Upgrade

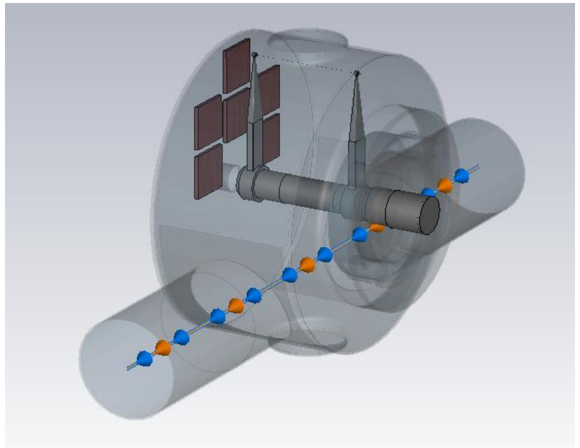
- During scrubbing **wires of all new 4 LIU wire scanners broke**
  - Spares were installed in sextant 4 (V), but shortly broke again when accelerating 4x 72b with 1.8e11 p/b on nominal LHC filling cycle
  - Main suspect impedance peak at around 800 MHz causing intolerable wire heating when bunch shortening at the end of the cycle

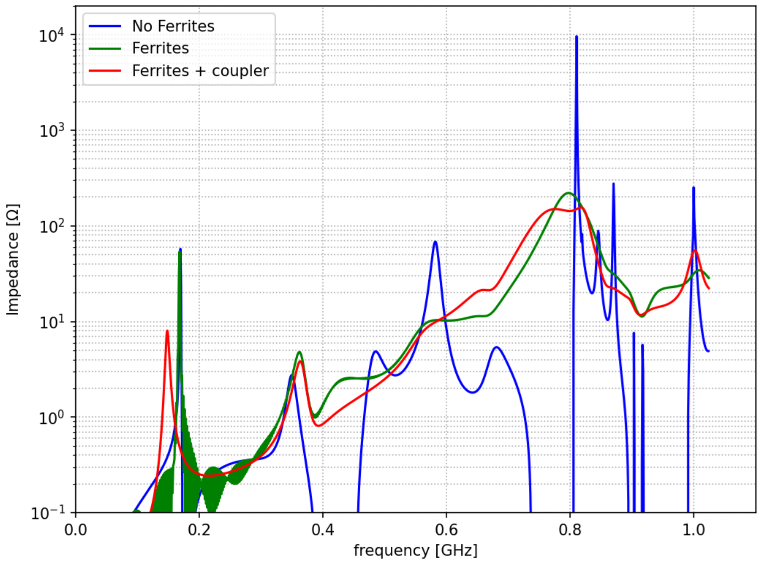


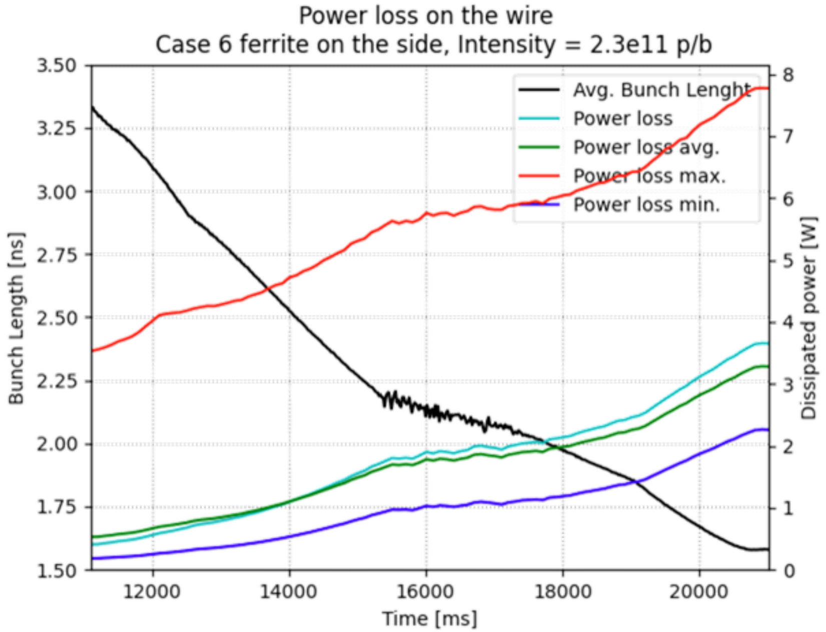


Problem with the wire scanners (II)

- **Mitigation strategy** developed within dedicated task force
  - Installation of ferrites and coupler, expected to significantly reduce wire heating
  - Improvement seen on online “wire temperature” measurement and **no more breakage** even in conditions of large peak densities



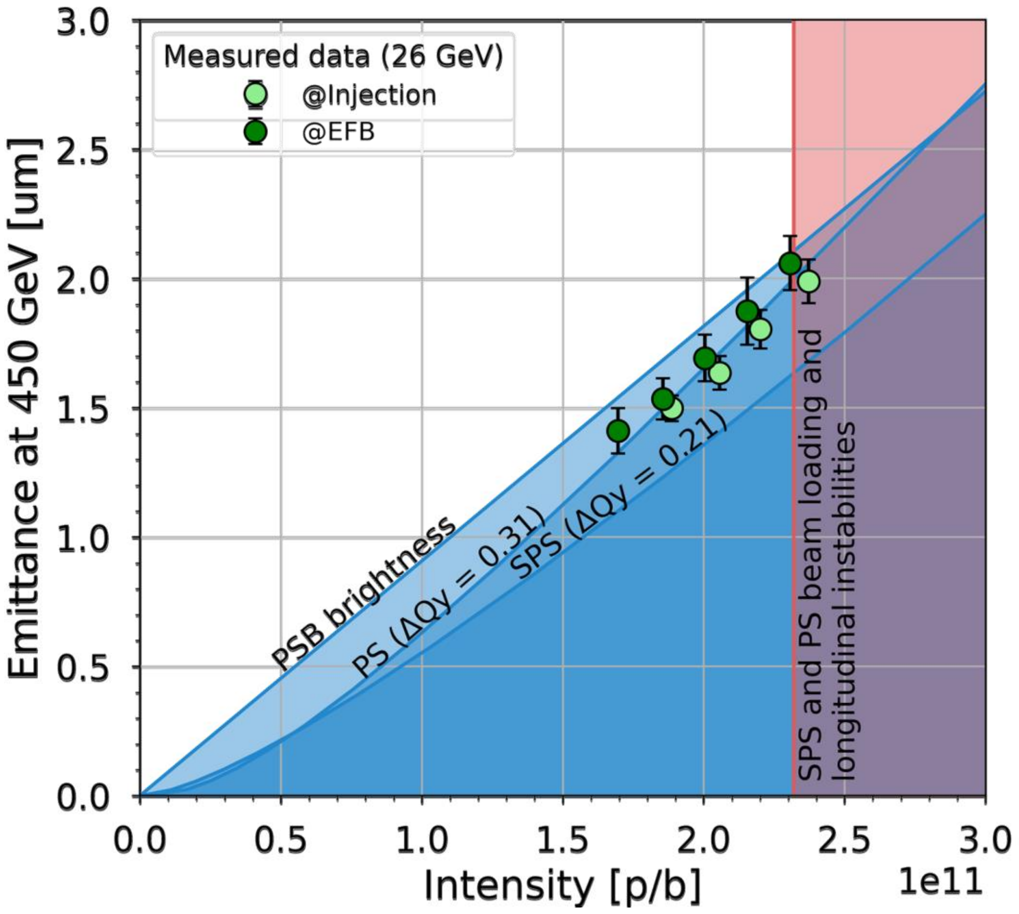




Achieved SPS performance – brightness

LHC Injectors Upgrade

- **LIU target brightness for standard beam** reached (end of SPS flat bottom)
  - Points measured right at injection fully consistent with **PS extraction target**
  - Points measured at the end of the long injection plateau still better than expected brightness at SPS exit
    → Margin needed for halo scraping before extraction to LHC & further emittance blow-up on the ramp



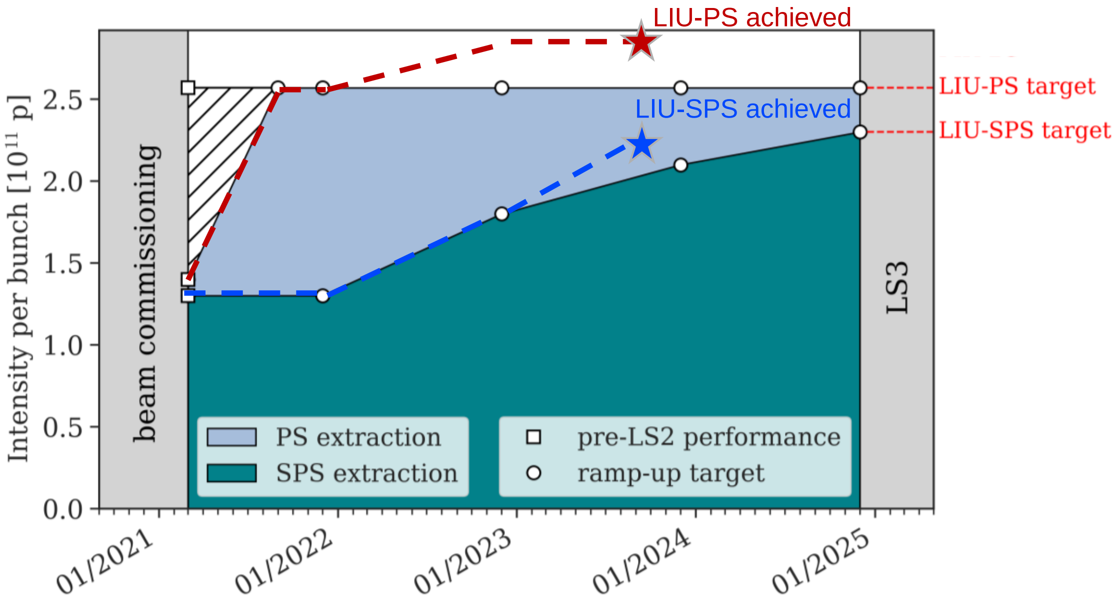
Outline

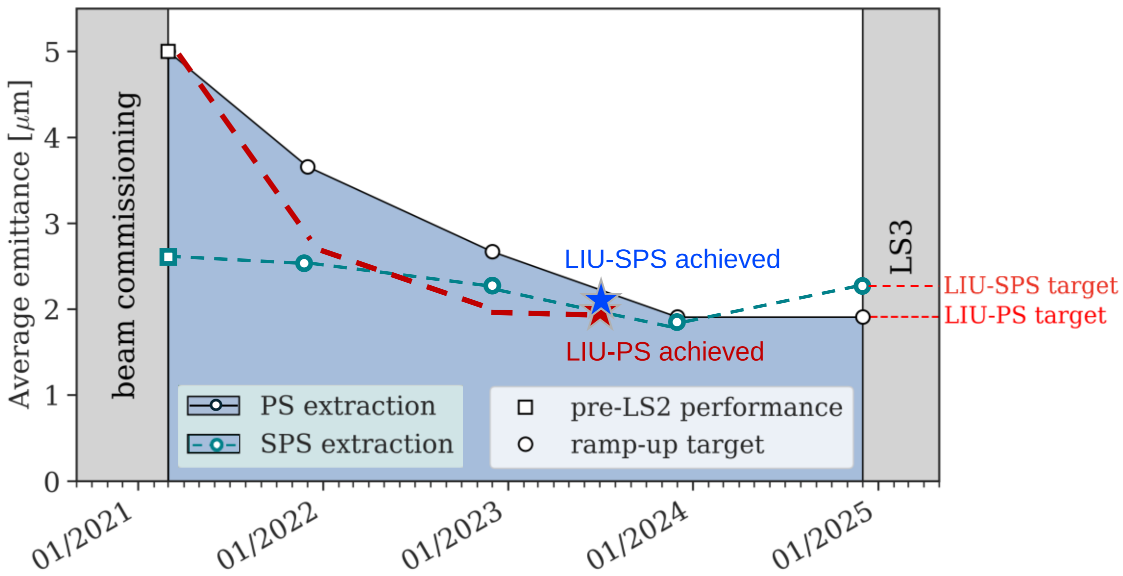
LHC Injectors Upgrade

- LHC Injectors Upgrade (LIU) project goal and ramp-up plan
- Performance achieved to date
  - PS complex
  - SPS
- Summary & outlook

Summary & outlook

LHC Injectors Upgrade





- LIU project ended on time & budget
- LIU beam commissioning is advancing well and is currently ahead of schedule both in terms of achieved beam intensity and brightness
- Some surprises encountered on the way but no major showstoppers!

Thanks a lot …

LHC Injectors Upgrade

- To the audience for the attention
- To all the contributors (non-exhaustive list)

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LIU project team *@End-of-LIU event, 28.06.2021*

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