CERN

Beam performance with the LHC Injectors Upgrade (LIU)

Giovanni Rumolo

S. Albright, R. Alemany, M.E. Angoletta, C. Antuono, T. Argyropoulos, F. Asvesta, M. Barnes, H. Bartosik, P. Baudrenghien, G. Bellodi, N. Biancacci, C. Bracco, N. Bruchon, E. Carlier, J. Coupard, H. Damerau, G.P. Di Giovanni, E. de la Fuente Garcia, A. Findlay, M. Fraser, A. Funken, R. Garoby, S. Gilardoni, B. Goddard, G. Hagmann, K. Hanke, A. Huschauer, G. Iadarola, V. Kain, I. Karpov, J.B. Lallement, A. Lasheen, T. Levens, K. Li, A. Lombardi, E. Maclean, D. Manglunki, I. Mases Sole, M. Meddahi, L. Mether, B. Mikulec, E. Montesinos, Y. Papaphilippou, G. Papotti, K. Paraschou, C. Pasquino, F. Pedrosa, T. Prebibaj, S. Prodon, D. Quartullo, F. Roncarolo, B. Salvant, M. Schenk, R. Scrivens, E. Shaposhnikova, L.Sito, P. Skowronski, A. Spierer, R. Steerenberg, M. Sullivan, F. Velotti, R. Veness, C. Vollinger, R. Wegner, C. Zannini, LIU teams, OP crews & all equipment experts

Outline

LHC Injectors Upgrade

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

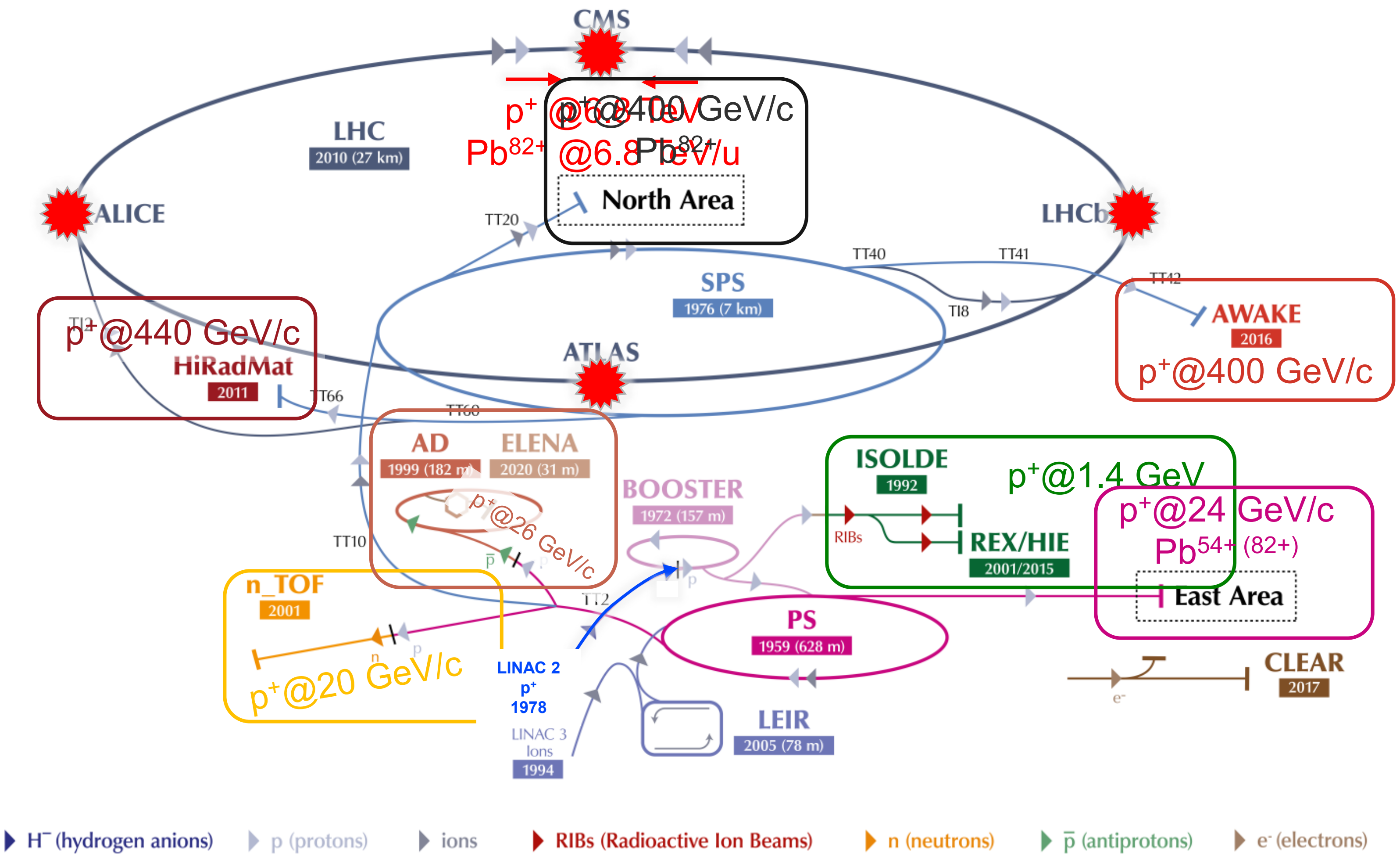
Outline

LHC Injectors Upgrade

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

The CERN accelerator complex

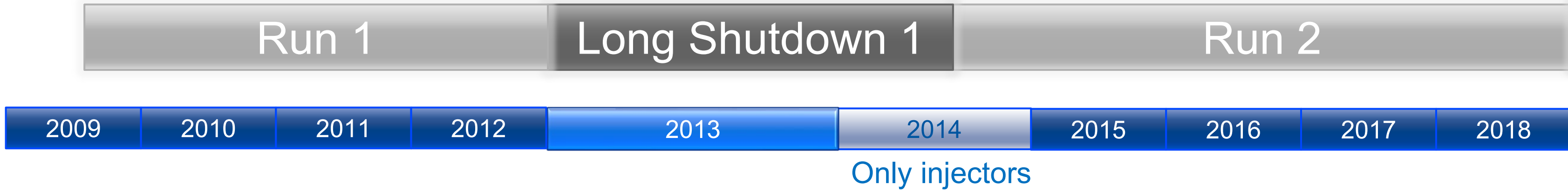
LHC Injectors Upgrade

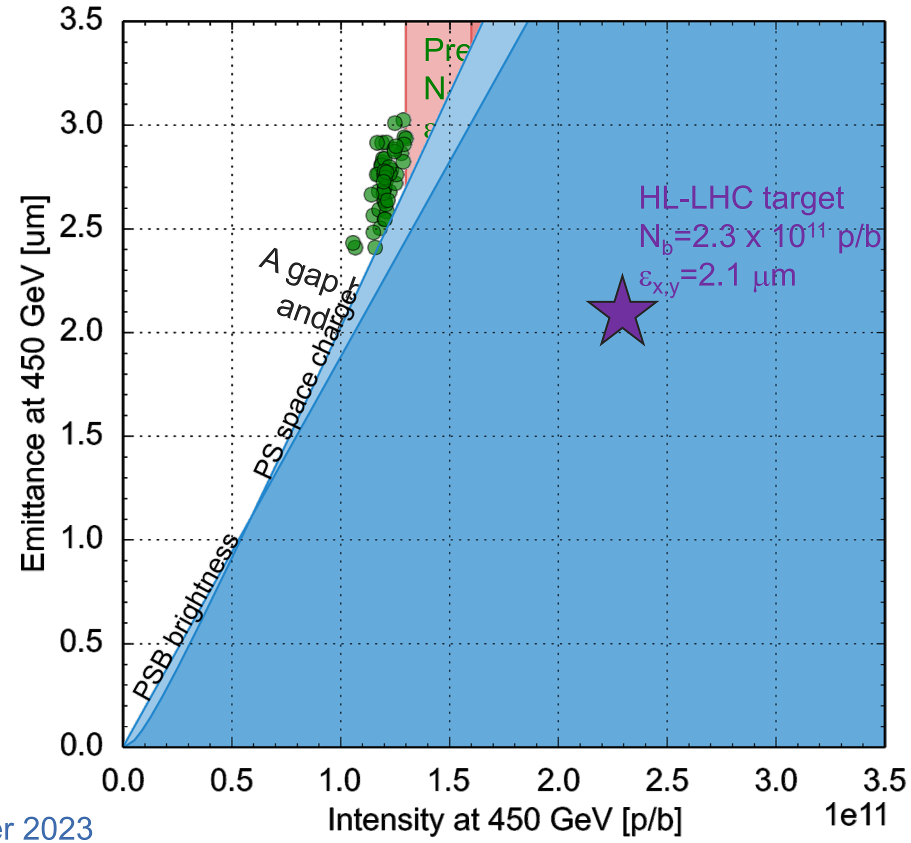


- Chain of linear and circular accelerators to serve:
  - The four LHC experiments
  - A variety of Fixed Target experiments/facilities at the different energy stages reached along the chain
- Before 2020 **LINAC 2** was injecting protons into PSB
- Under the **LHC injectors Upgrade (LIU) project**,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

The LIU goal

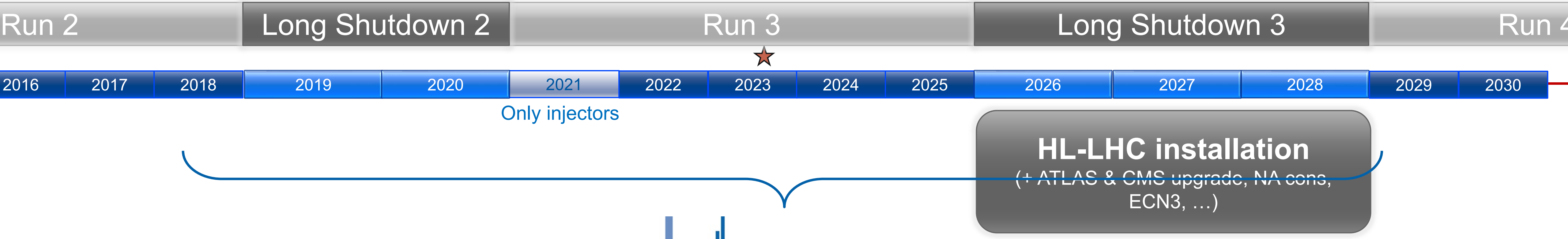
LHC Injectors Upgrade





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

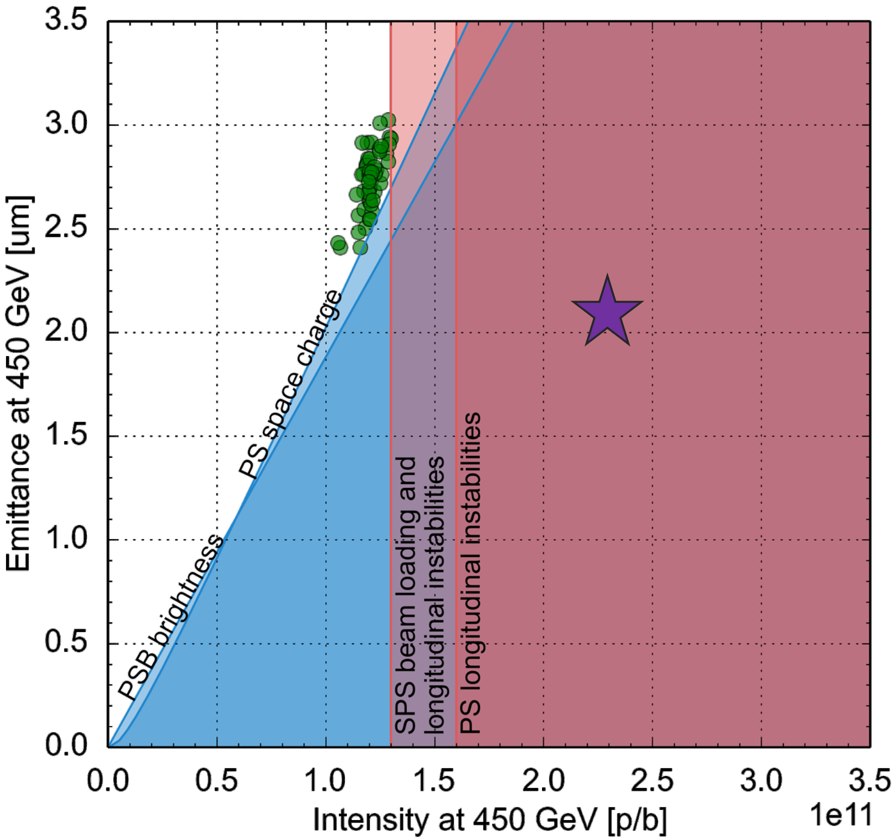
The LIU installation

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



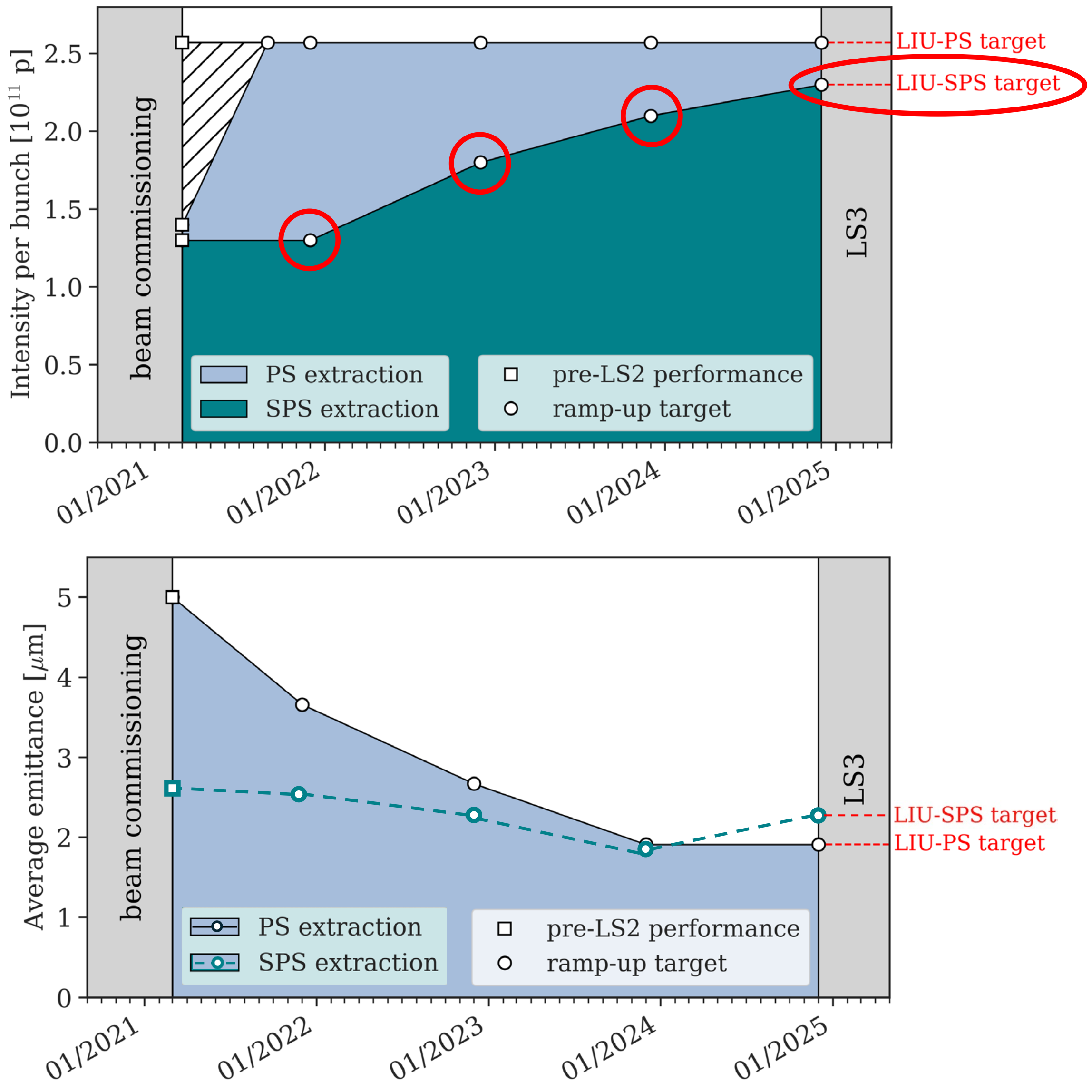
New SPS beam dump

PS longitudinal damper

New SPS RF amplifier towers

LIU beam commissioning in Run 3: ramp-up plan

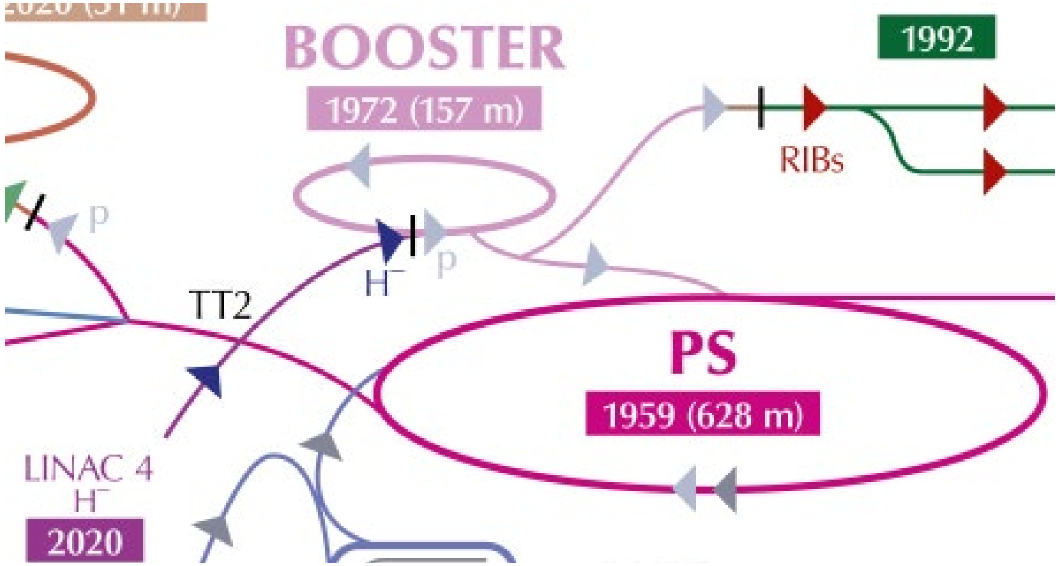
- Year-by-year intensity goals of the ramp-up at SPS extraction
  - Pre-LS2 beam parameters recovered by the end of 2021 – **1.3e11 p/b**
  - **1.8e11 p/b** in MD by the end of 2022 – to be ready for LHC in 2023 (operation)
  - **2.1e11 p/b** in MD by the end of 2023 – to be ready for LHC in 2024 (MD)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

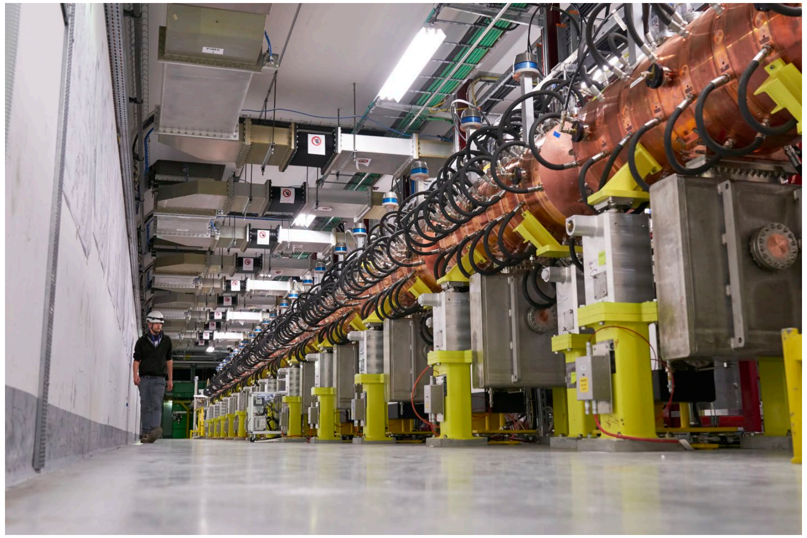
Outline

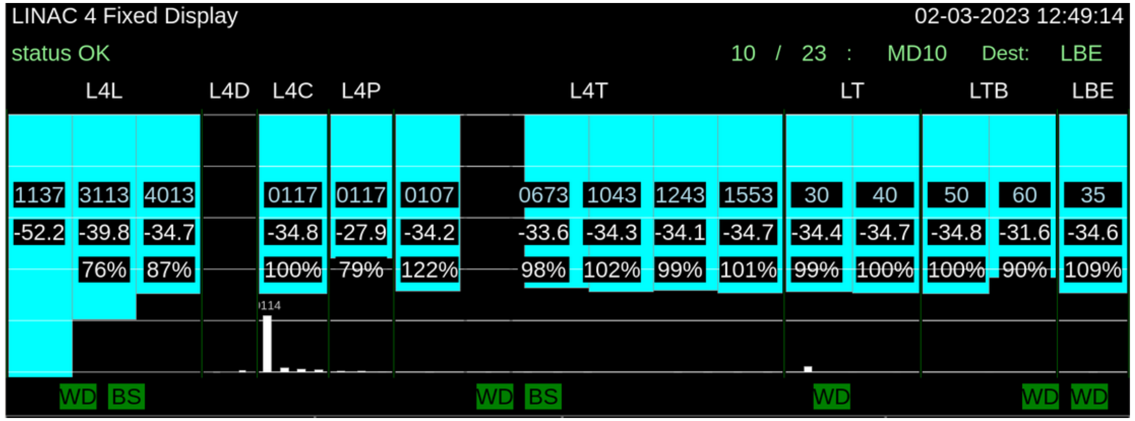
- LHC Injectors Upgrade (LIU) project goal and ramp-up plan
- Performance achieved to date
  - PS complex
  - SPS
- Summary & outlook



Linac4

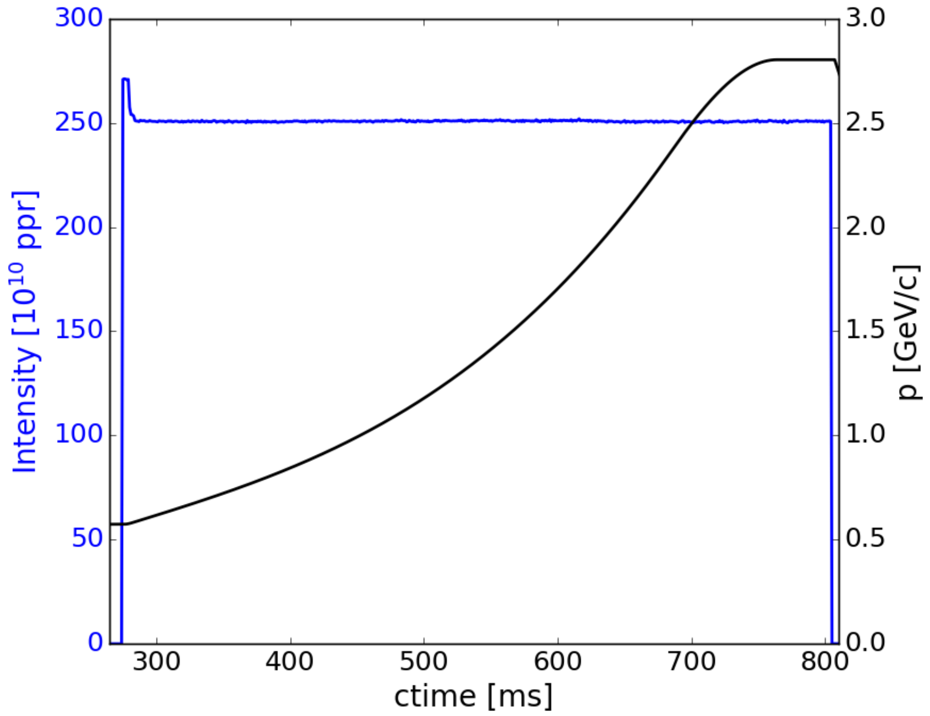
- The new Linac4 has been delivering beam as expected
  - **27 mA** before chopping within **0.3 um emittance** and pulse stability specifications
  - More than **98.5% availability** over the first three years operation
- 2023 dedicated tests with new source have demonstrated up to **35 mA** deliverable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





PSB

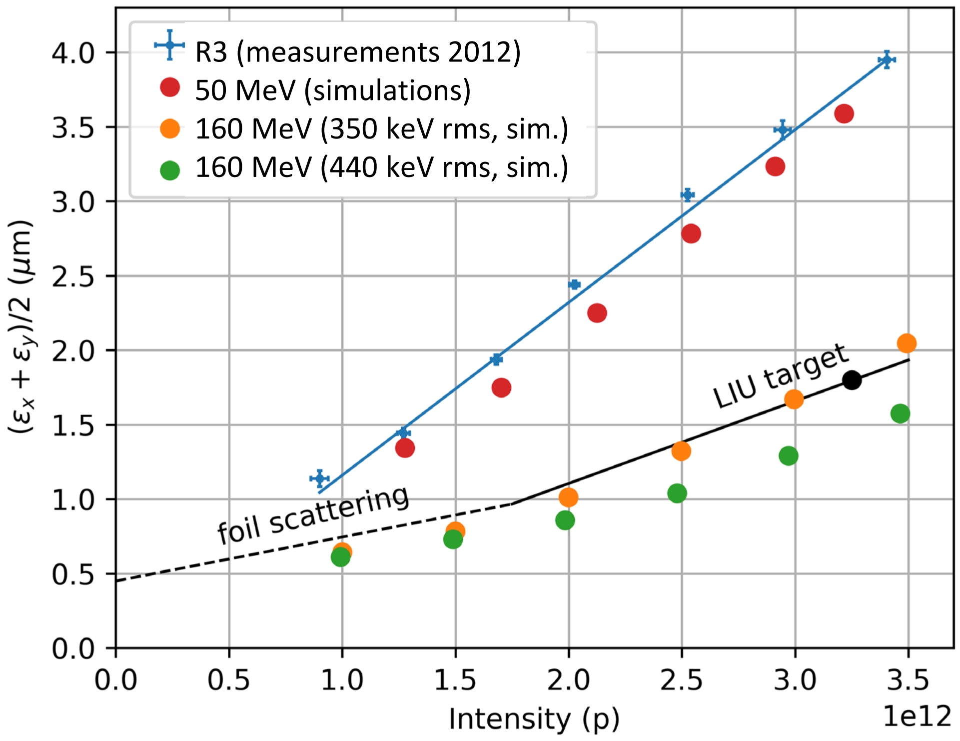
- The PSB accelerates 1 bunch/ring (four rings) from 160 MeV to 2 GeV
  - Brightness is defined by space charge and H- charge exchange injection from Linac4
  - Cleaning of longitudinal tails at beginning of ramp, otherwise lossless acceleration

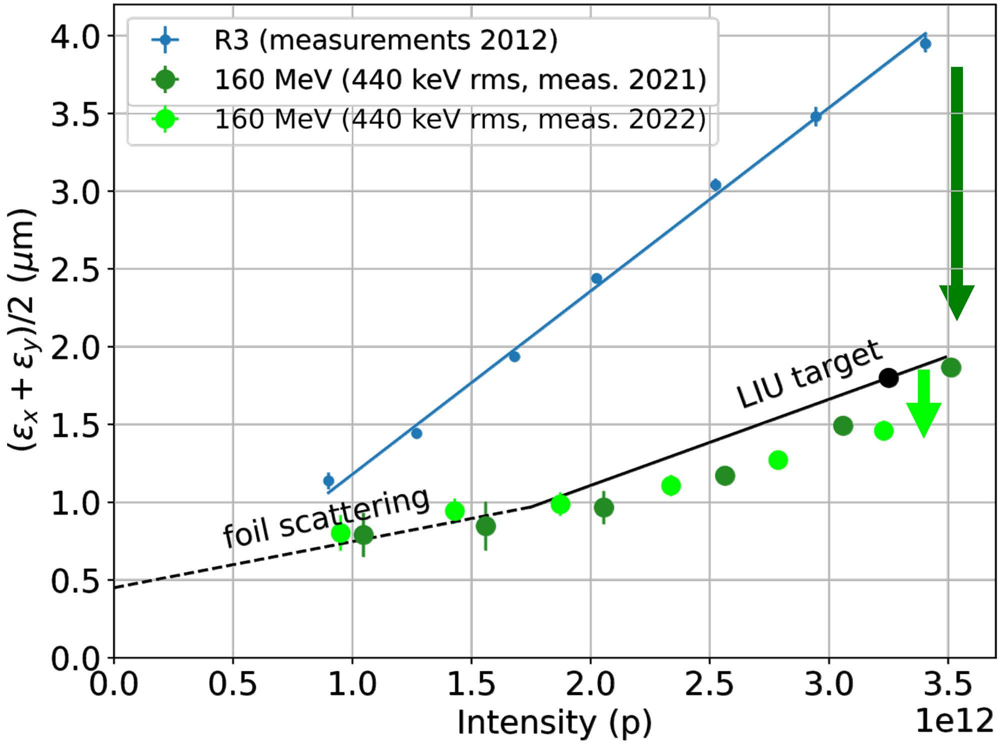


PSB

LHC Injectors Upgrade

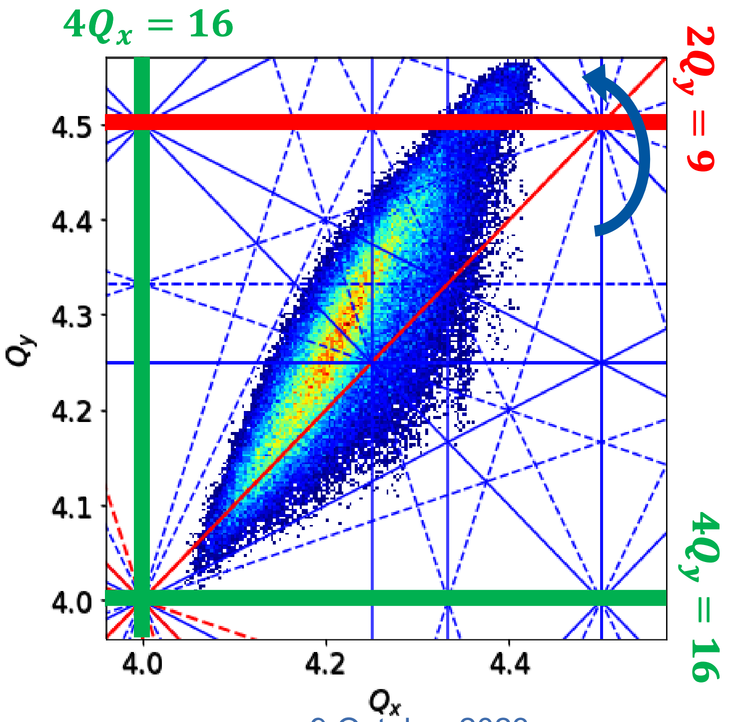
- **PSB brightness line after connection with Linac4**

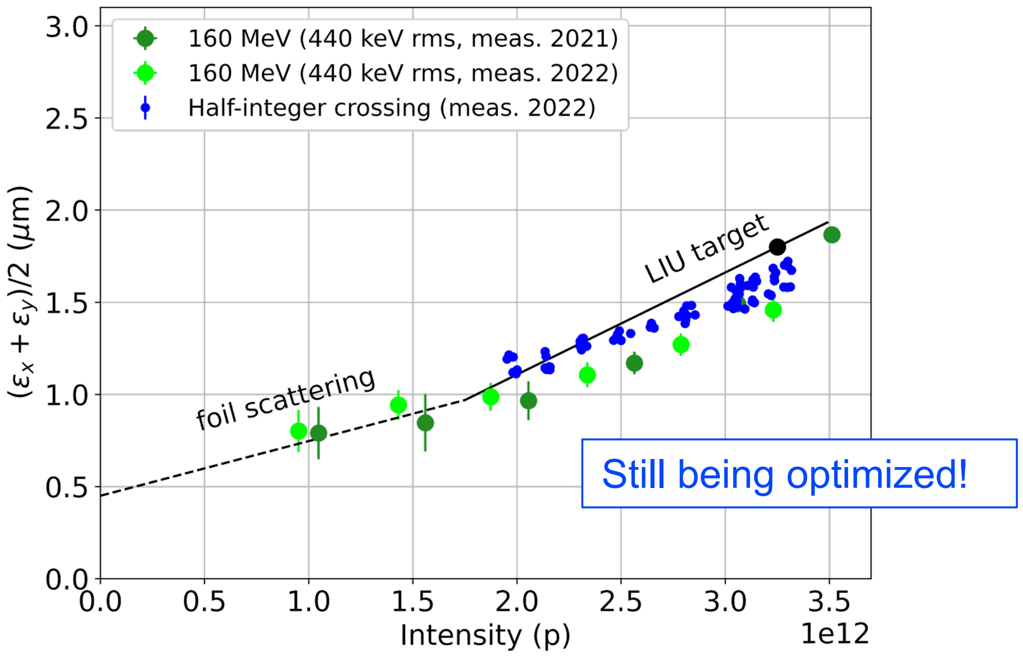




PSB

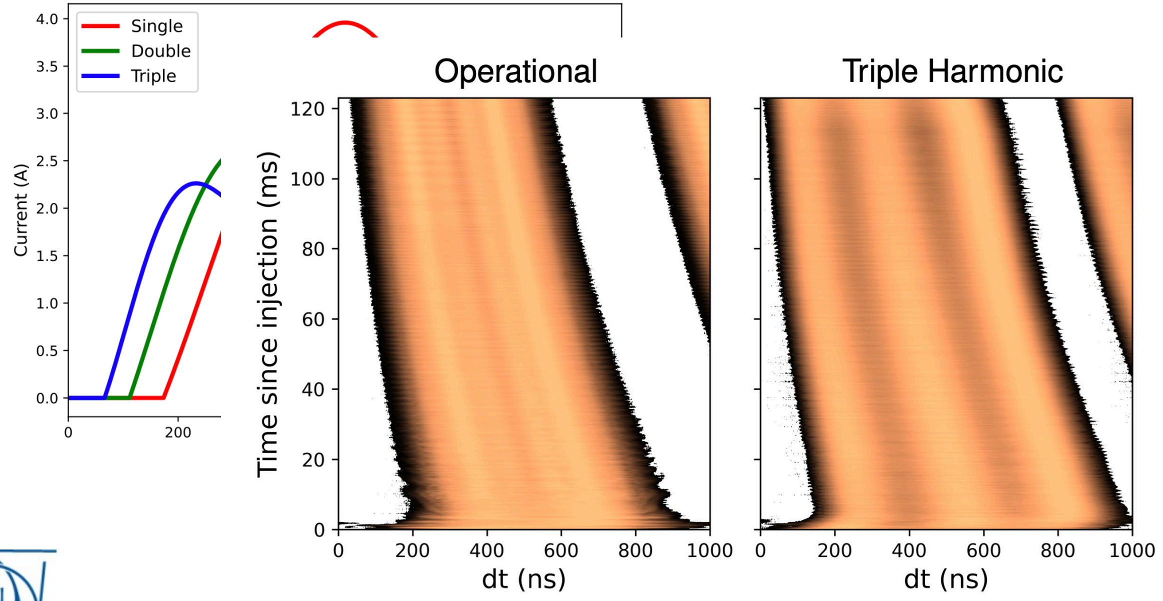
- **PSB brightness line after connection with Linac4**
- Can we gain even more margin?
  - Injection above the half-integer to limit blow-up driven by integer resonance crossing

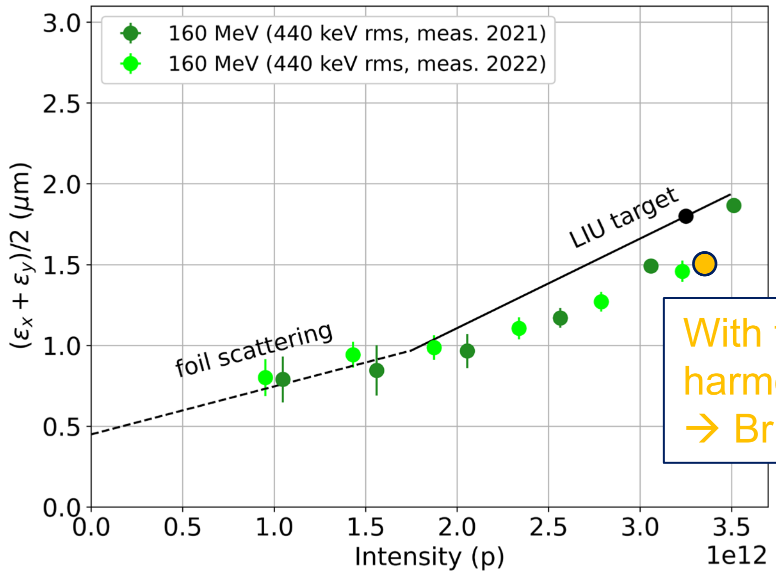




PSB

- **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

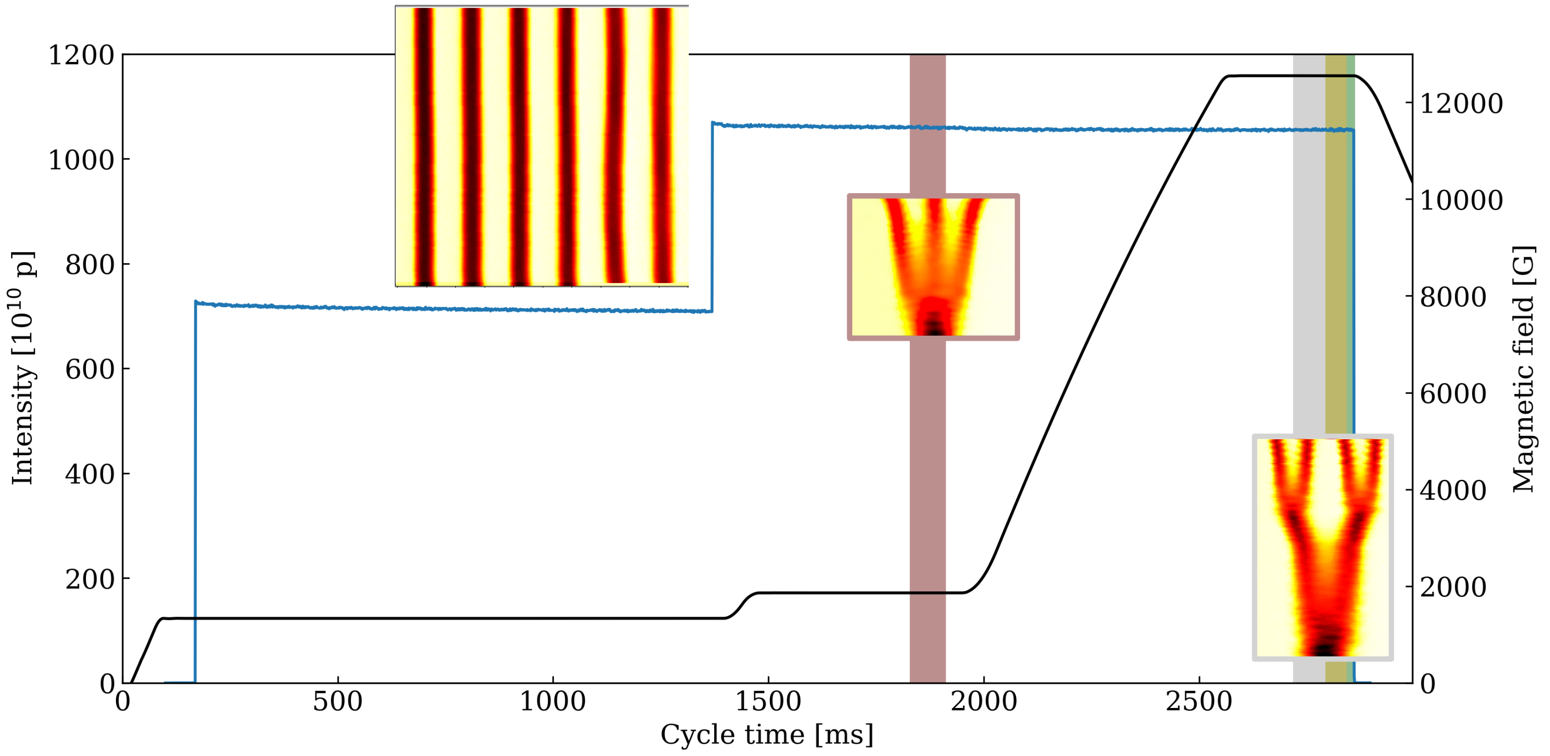




With triple harmonic → Brighter!!

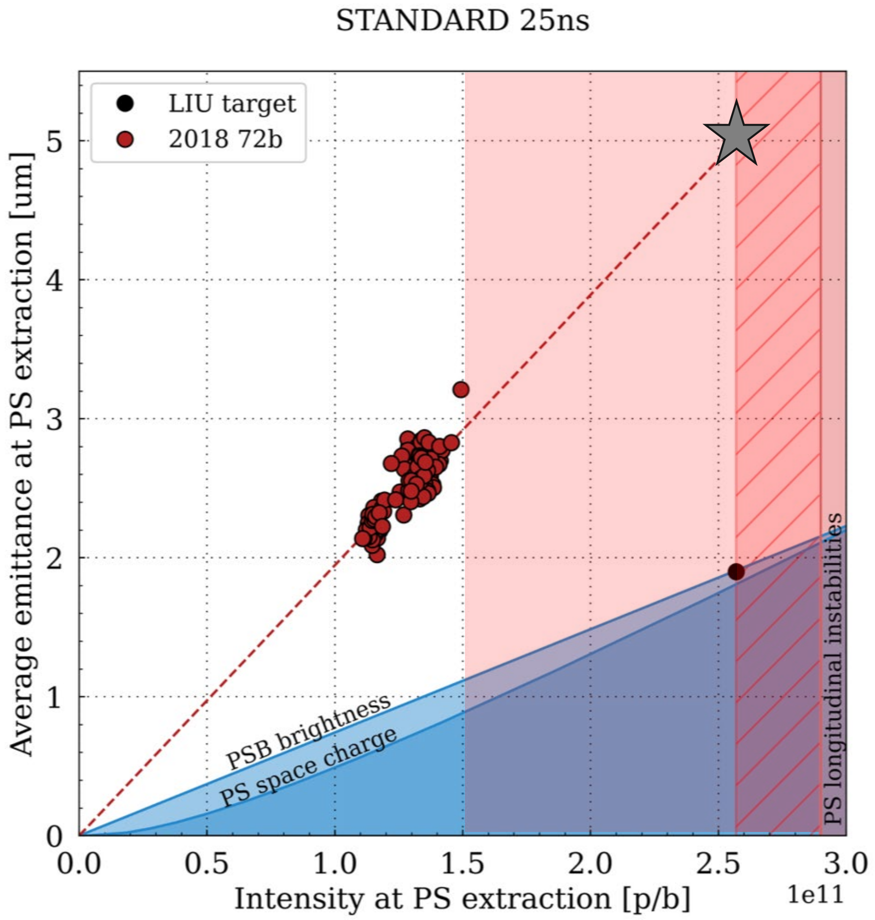
PS

- 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

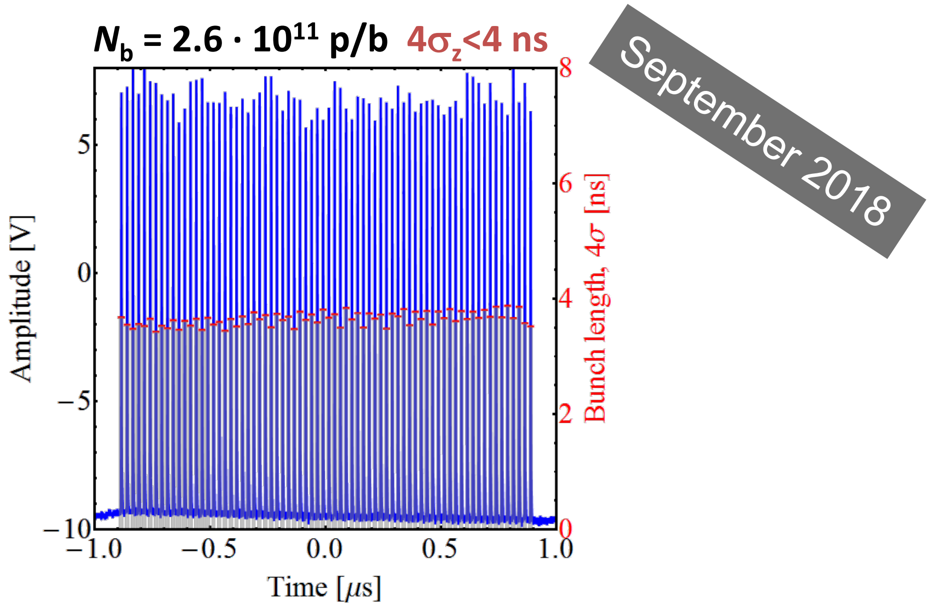


PS

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

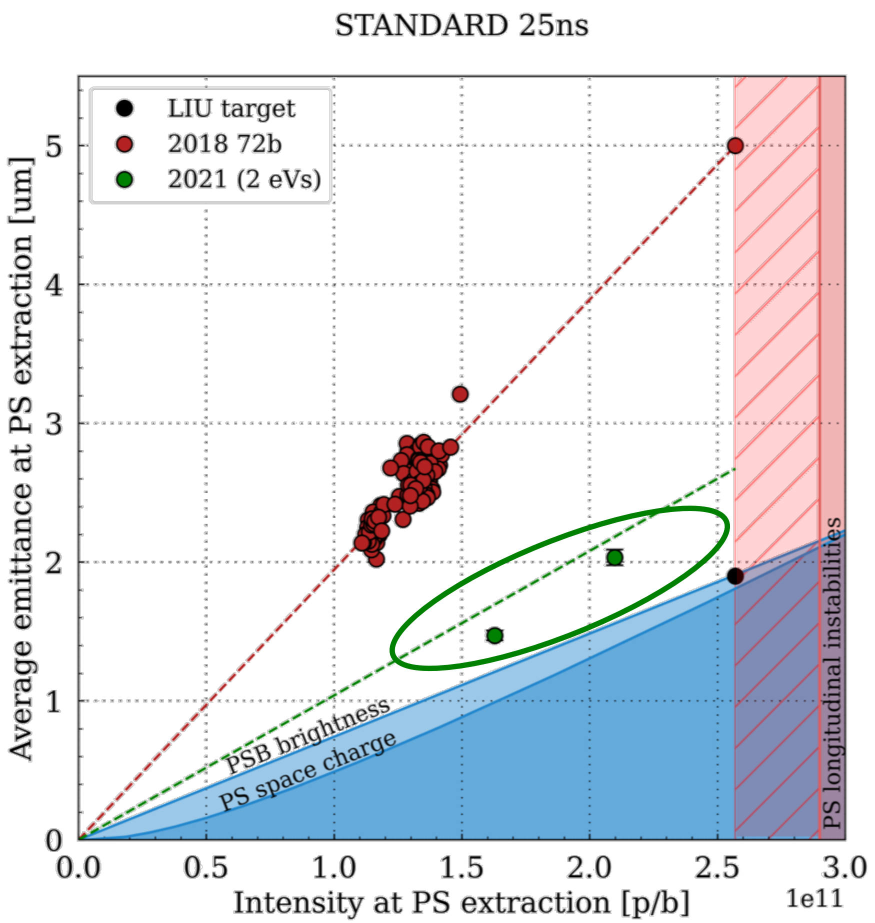


- Intensity demonstrated already in 2018 thanks to LIU coupled-bunch feedback prototype installed in 2014



PS

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



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

PS

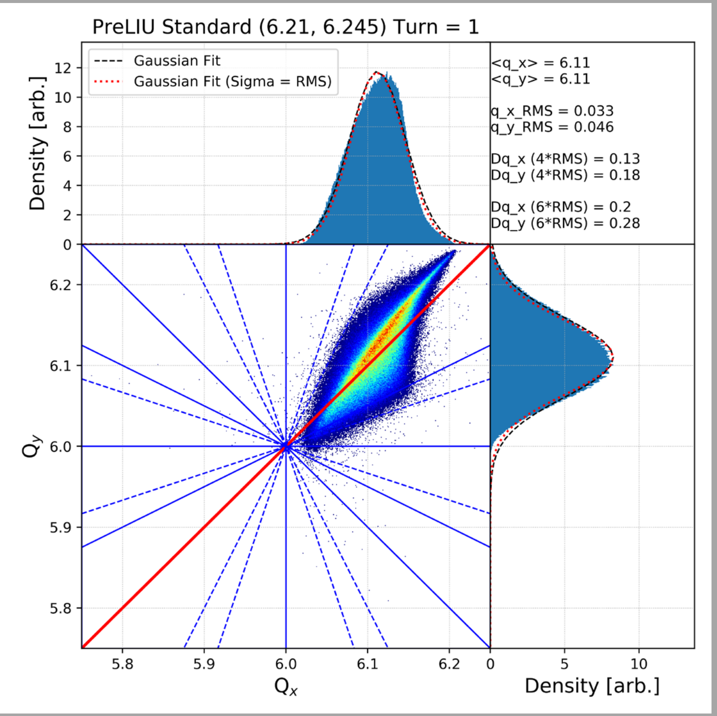
- LIU i…

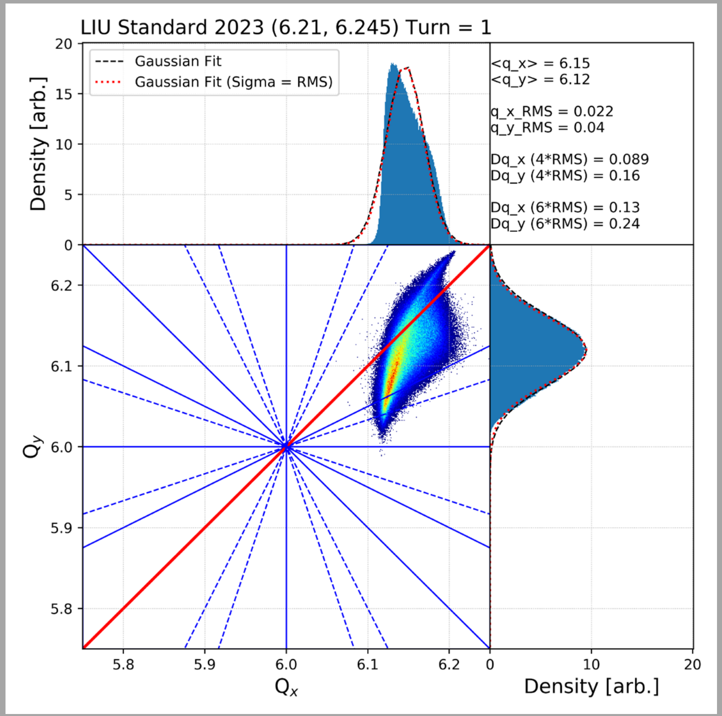
…in 2018

…(2021) with

…n 2022

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

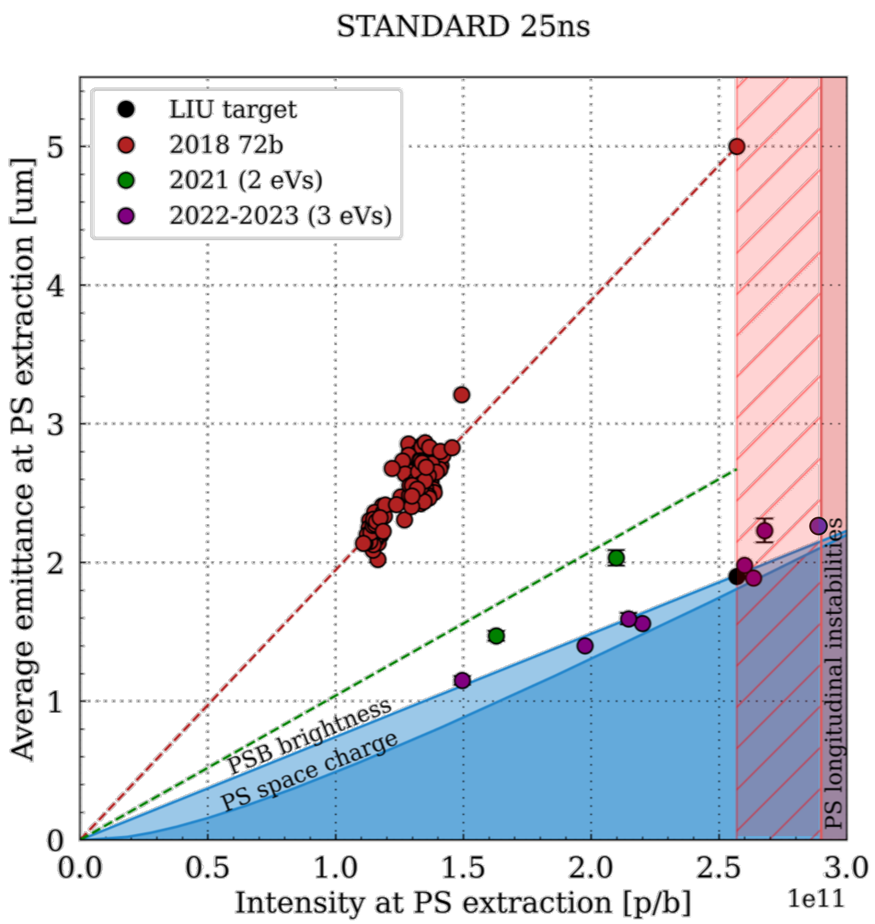




PS

LHC Injectors Upgrade

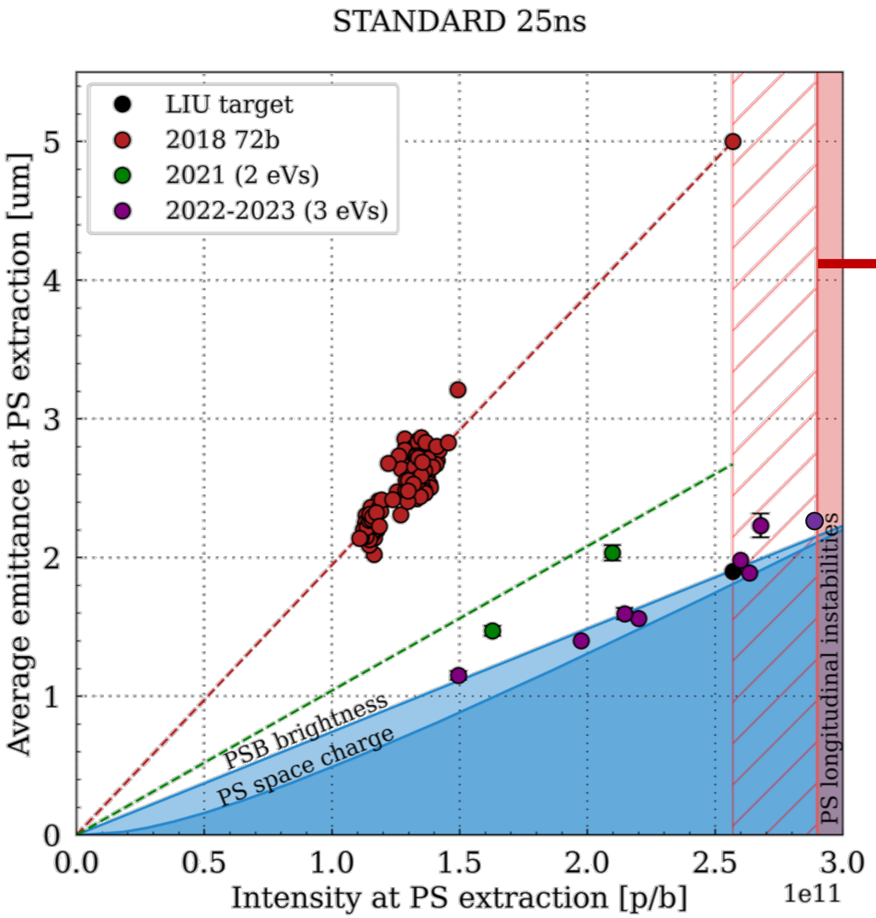
- LIU intensity and brightness in the PS from 2018 to 2023

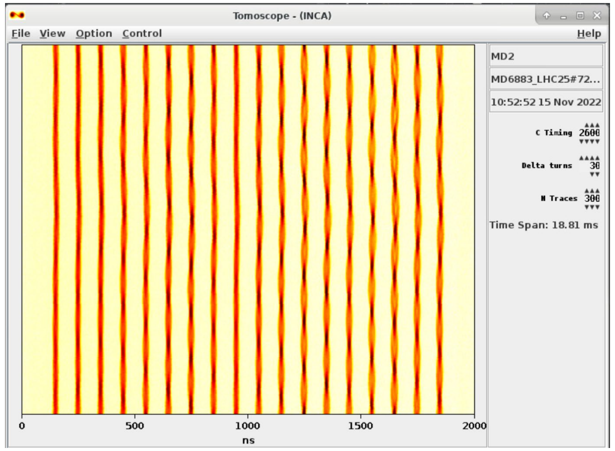


- Intensity demonstrated already in 2018
- First step of brightness ramp-up (2021) with 2 GeV and 2 eVs injection
- Full PS performance achieved in 2022 thanks to 3 eVs injection
- Actually 2.9 • 10^{11} p/b successfully achieved out of the PS

PS

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



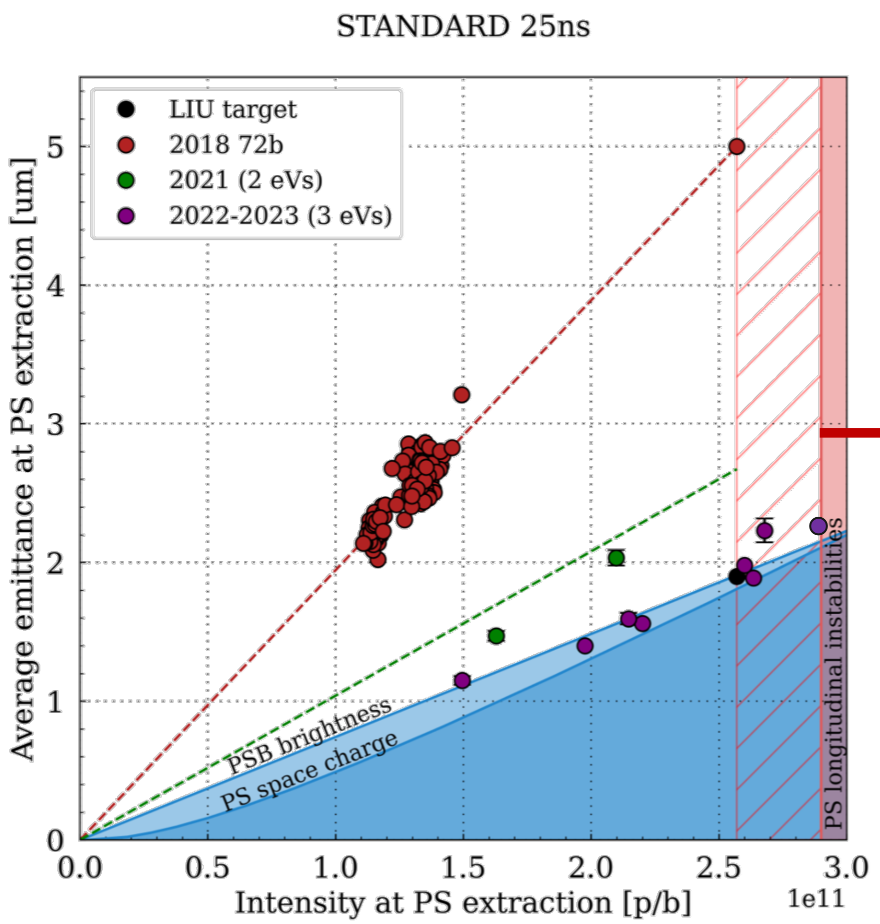


Higher intensities limited by quadrupolar instabilities

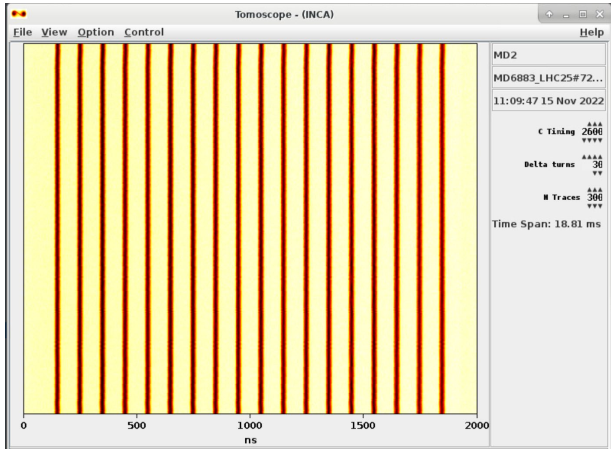
PS

LHC Injectors Upgrade

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



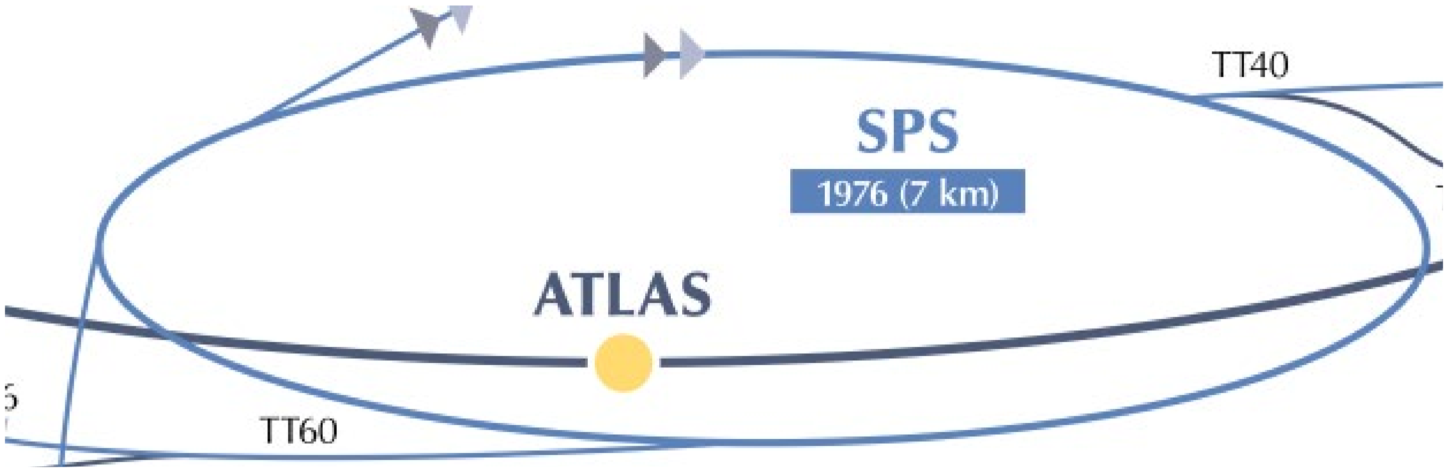
Stabilised by quadrupolar feedback up to at least $3.15 \cdot 10^{11}$ p/b equiv. (2022)



Outline

LHC Injectors Upgrade

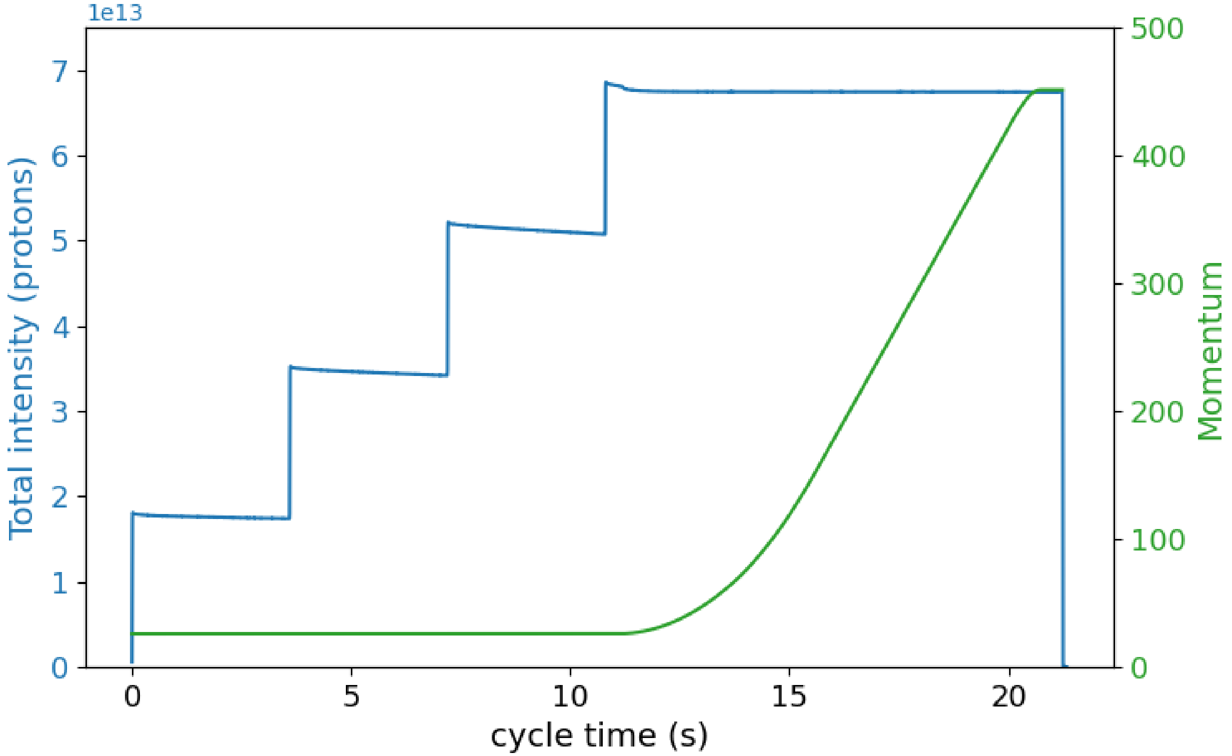
- LHC Injectors Upgrade (LIU) project goal and ramp-up plan
- Performance achieved to date
  - PS complex
  - SPS
- Summary & outlook



SPS

LHC Injectors Upgrade

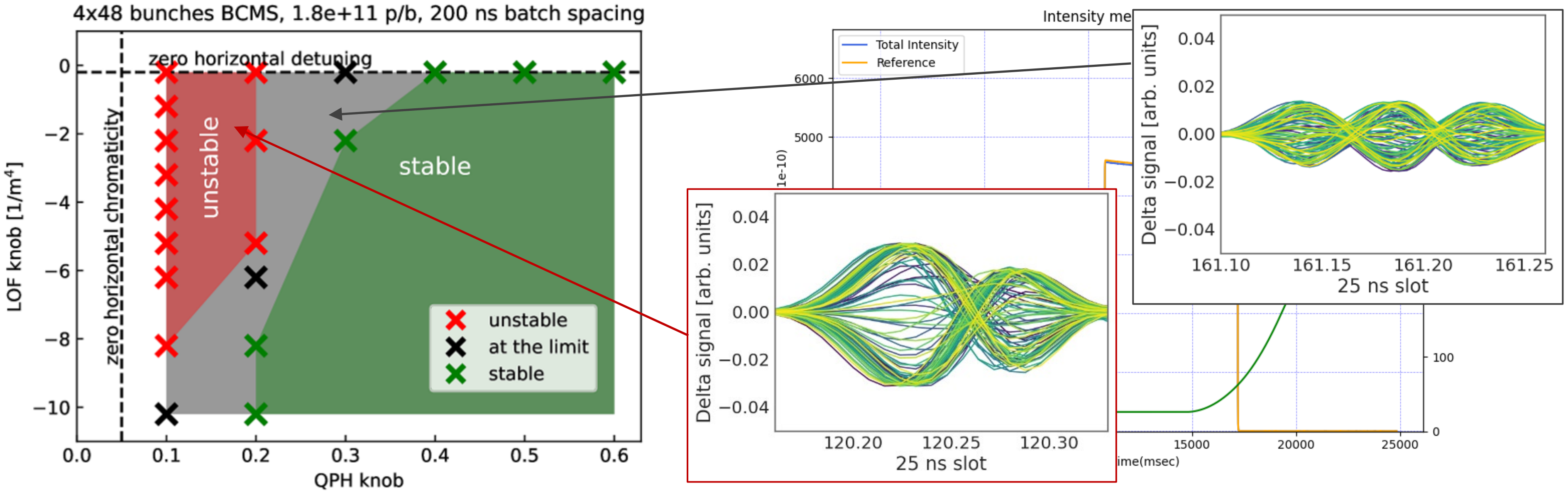
- The SPS receives 4 trains of 72 bunches from PS
  - Long injection plateau @26 GeV
  - Acceleration to 450 GeV



SPS: Horizontal stability at injection

LHC Injectors Upgrade

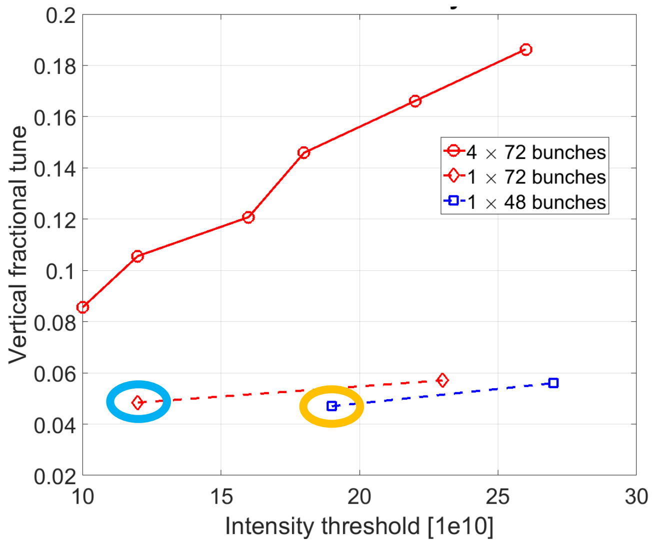
- Horizontal instabilities @26 GeV studied in detail in 2018 for 1.8e11 p/b
  - Mitigation strategy developed in simulations: high chromaticity + octupoles
- Successfully tested in 2022 and 2023 with up to 2.5e11 p/b injected
  - 5x 48 and 4x 72 bunches
  - Discovered criticality of short bunches (<3.5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

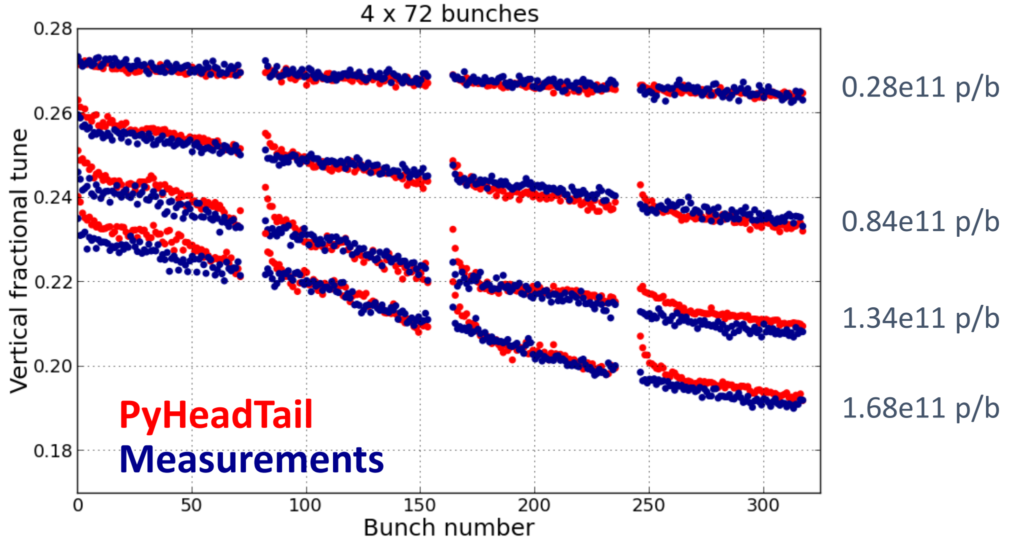


SPS: Vertical stability and working point

LHC Injectors Upgrade

- 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)

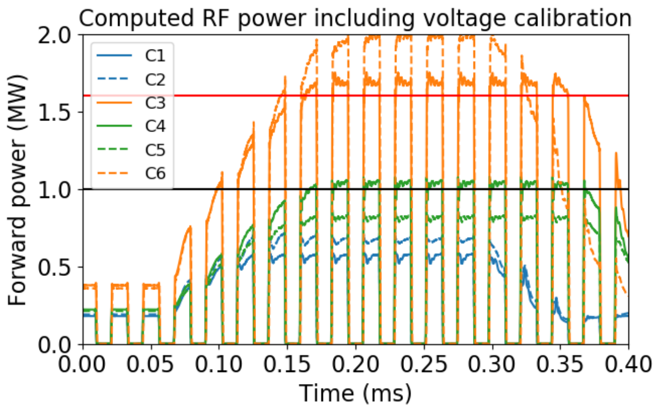


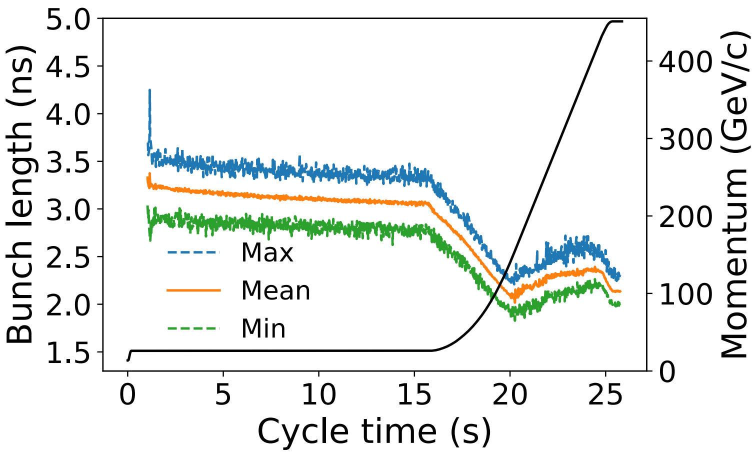


SPS: Longitudinal beam stability and control

LHC Injectors Upgrade

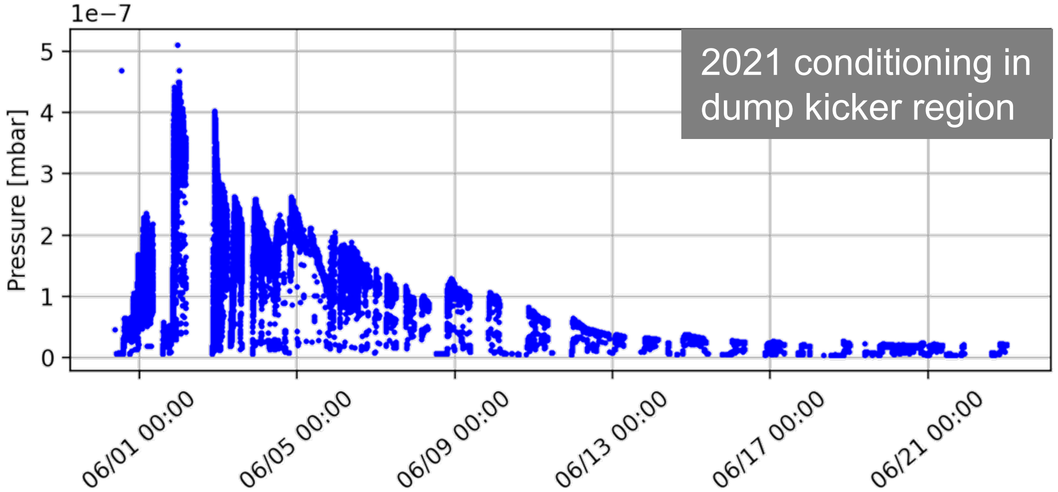
- Successful commissioning of upgraded RF system all through 2021-23
  - 1-turn delay feedback, feedforward, longitudinal damper, amplitude modulation
  - **Nominal RF voltage and power available on 4 out of 6 cavities** (SIEMENS plant currently at 80%), failure rate of solid-state amplifier modules 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)

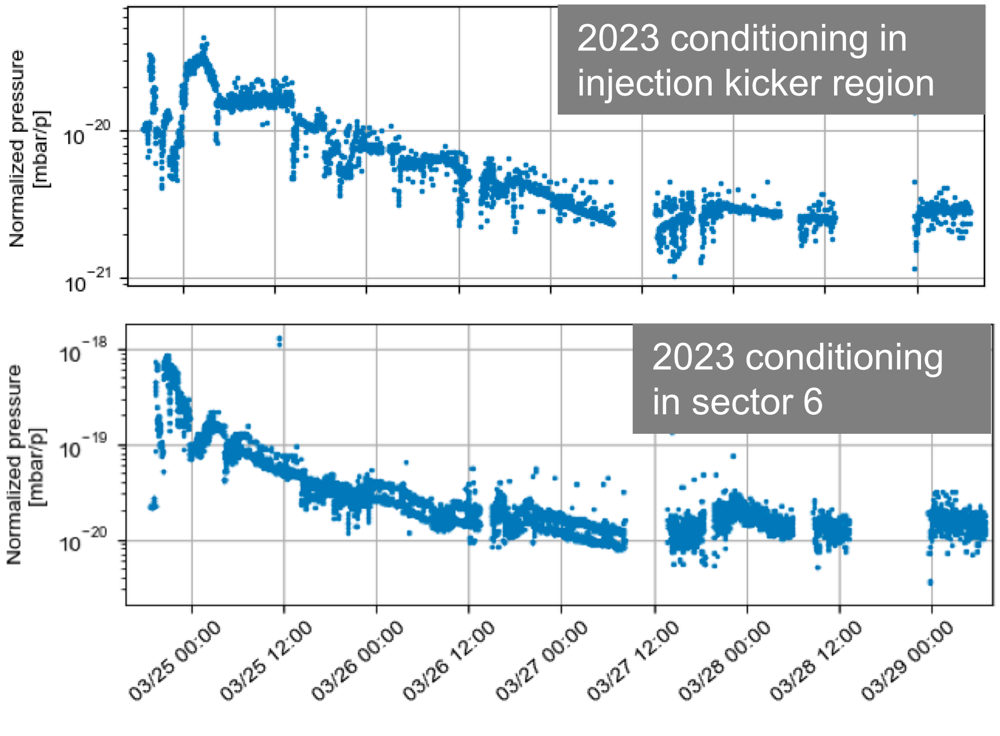




SPS scrubbing

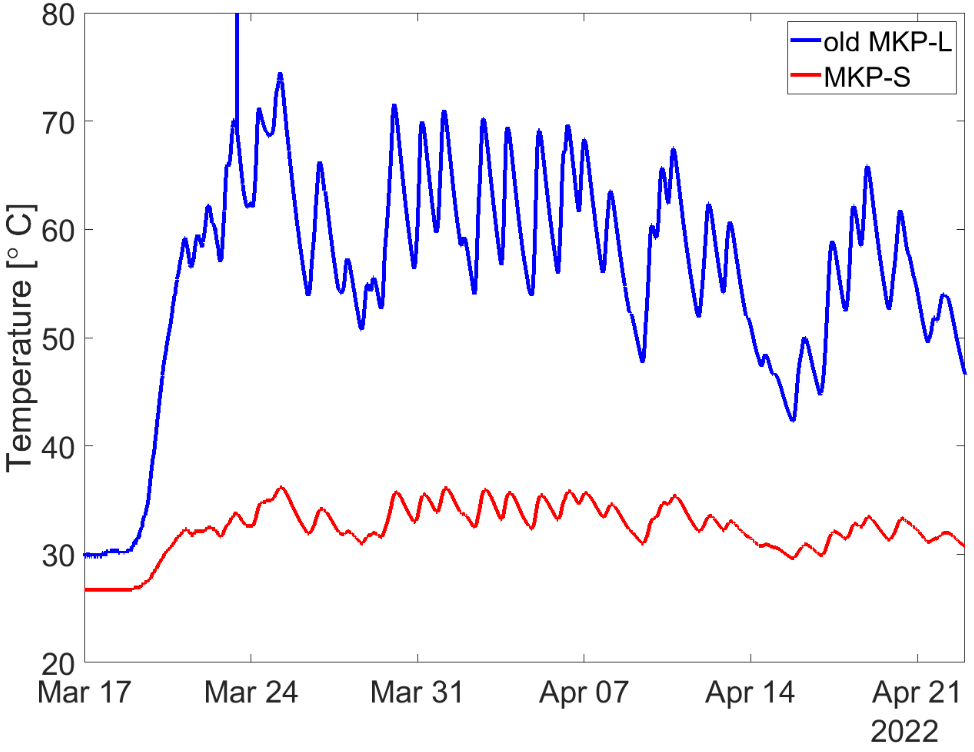
- Extended scrubbing needed in 2021 to recover global SPS conditioning state
- Scrubbing runs still necessary in 2022 and 2023
  - Regions open for intervention during YETS's
  - New kicker magnets in the machine with low pressure interlock thresholds
  - Progressive intensity ramp-up leading to larger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





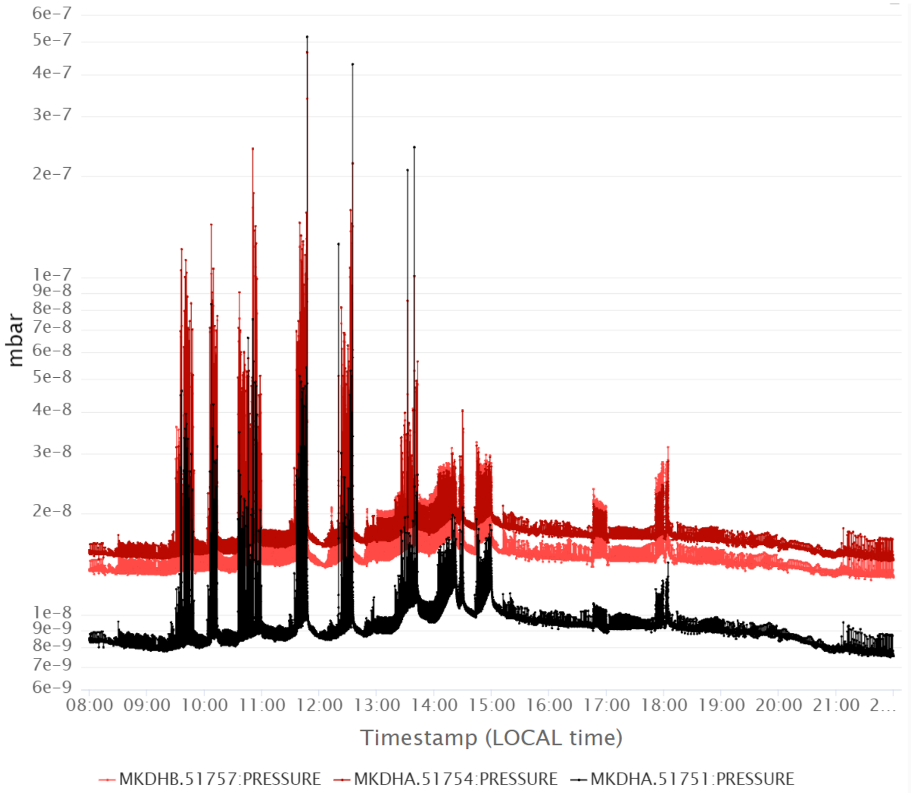
Encountered limitations

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



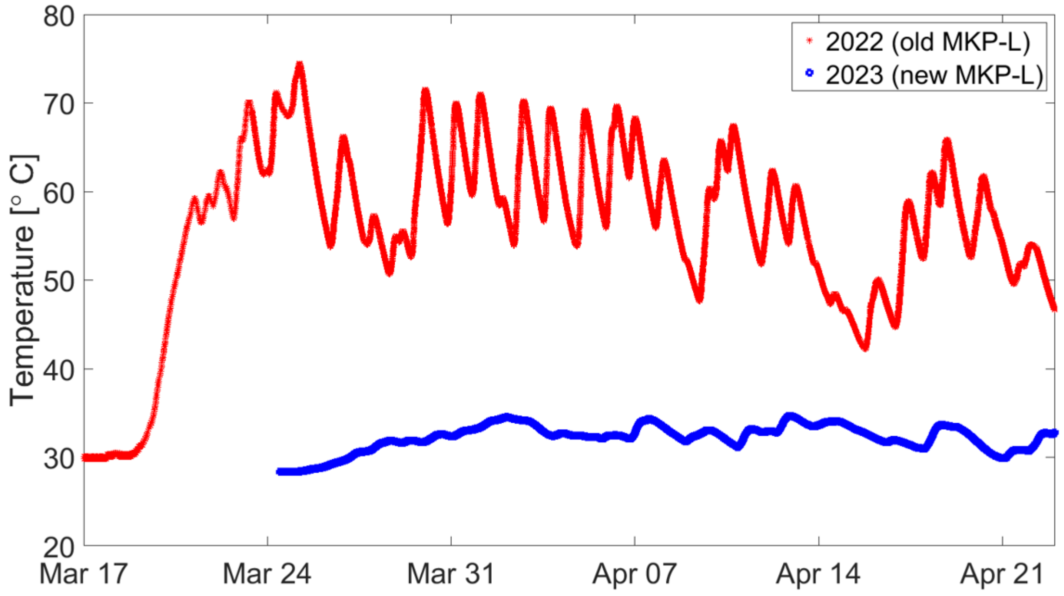
Encountered limitations

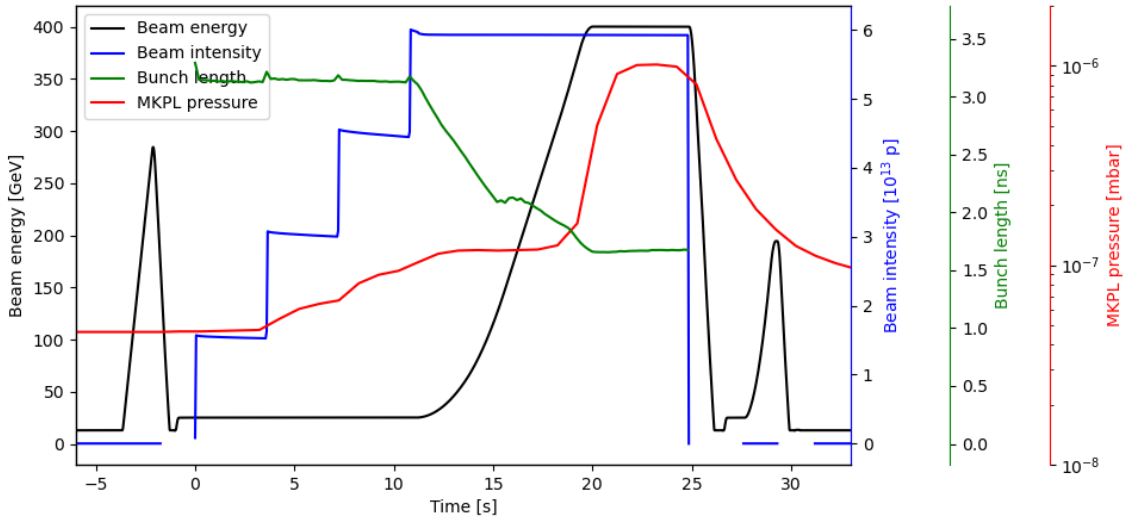
- Heating of a module of the injection kicker system (MKP-L)
  - Low scrubbing efficiency to allow for cooling
  - Hard limit for high intensity studies
- Pressure spikes at large peak currents occurring on injection and dump kickers (MKP-L and MKDH) for high intensity, long trains and short bunches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



Solutions

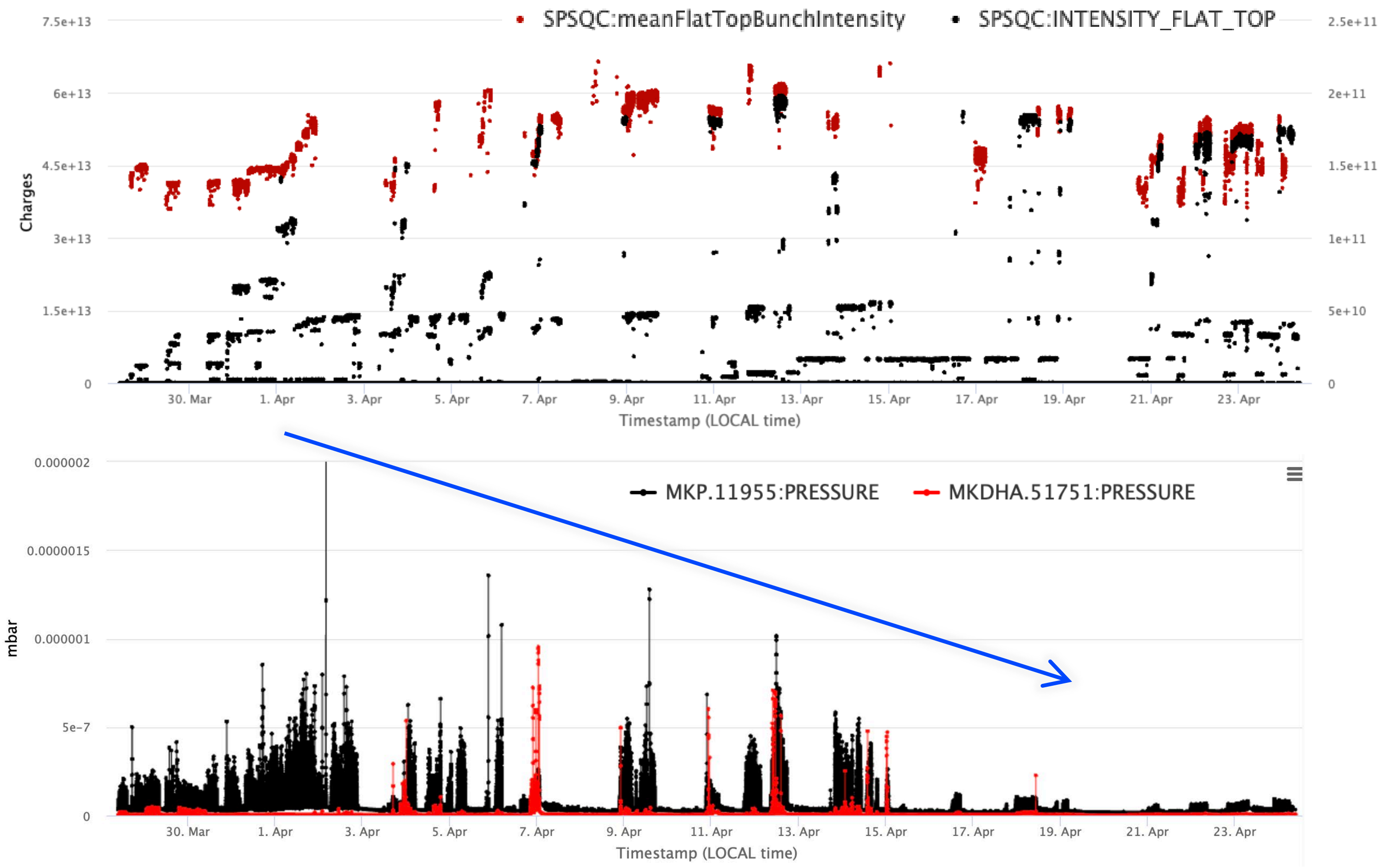
- New low-impedance MKP-L installed
  - Heating largely mitigated and increased scrubbing efficiency
- Long flat top cycle
  - Increased effective scrubbing time for injection and dump kickers





Conditioning of kickers

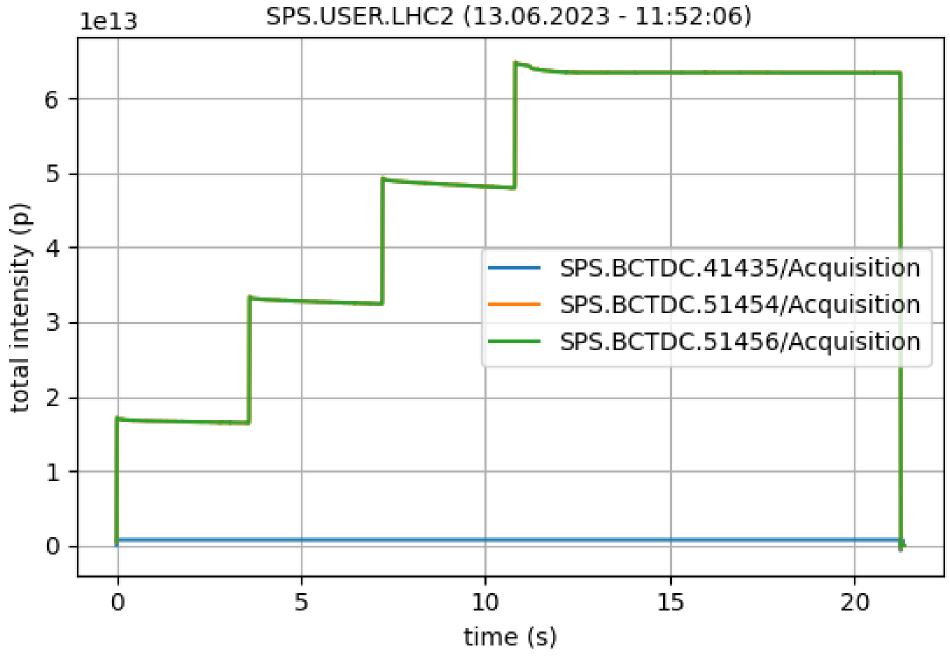
- In these conditions the newly installed MKP-L and old MKDH could be successfully conditioned in 2023 allowing for continuation of ramp-up

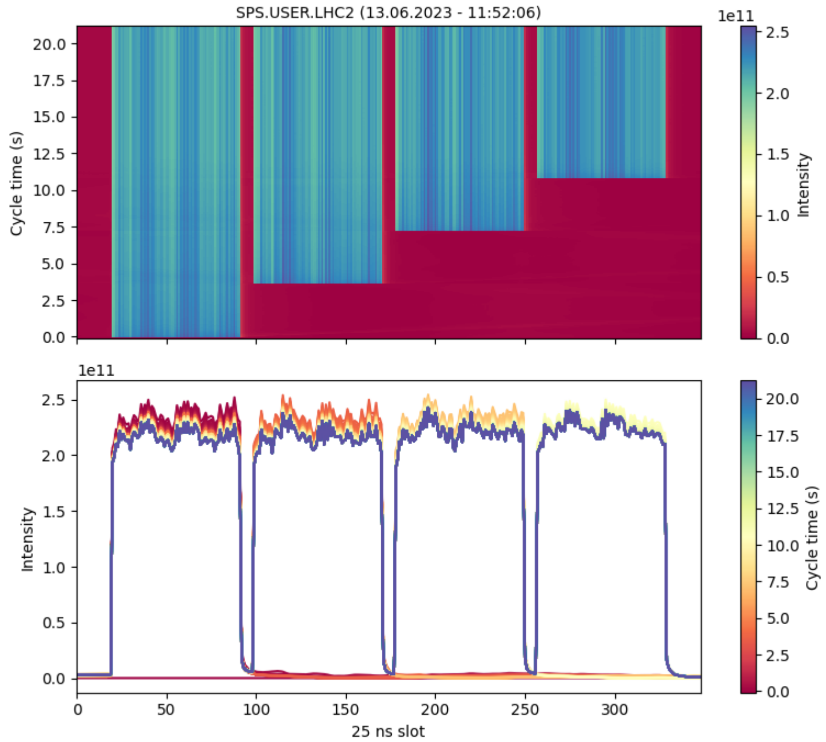


Achieved SPS performance – intensity

LHC Injectors Upgrade

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

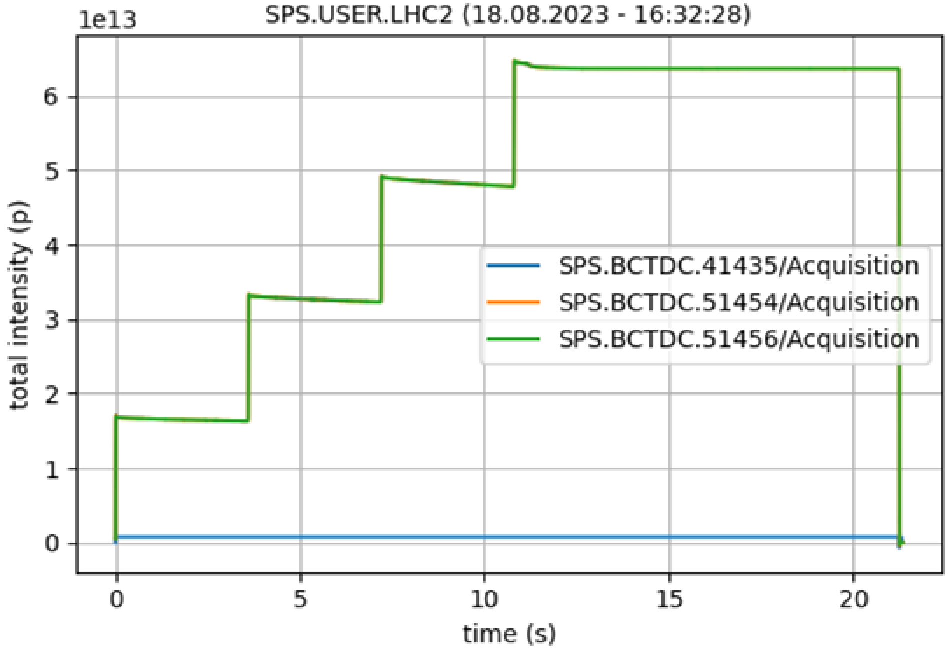


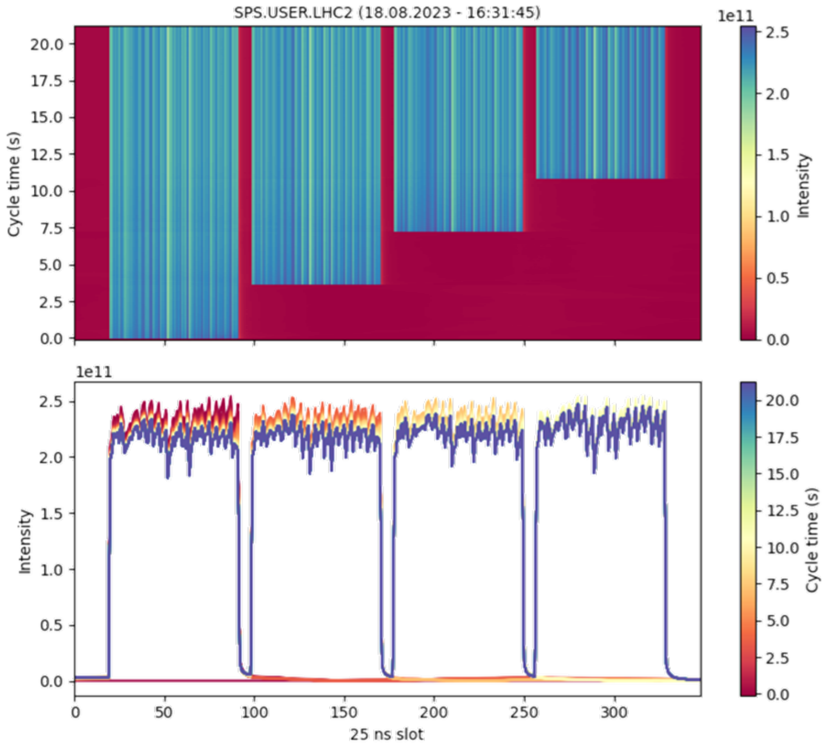


Achieved SPS performance – intensity

LHC Injectors Upgrade

- **Intensity reach demonstrated on 13.06.23, 18.08.23 and 15.09.23:**
  4x72 with 2.2e11 p/b at flat top
  - Excellent transmission (~95% without scraping)

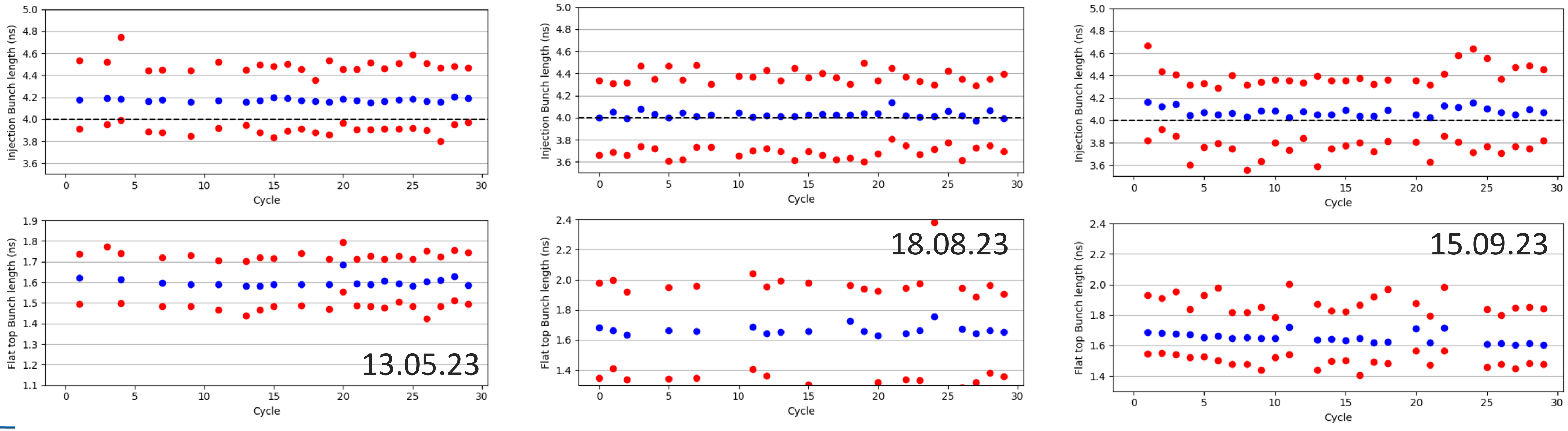




Achieved SPS performance – intensity

LHC Injectors Upgrade

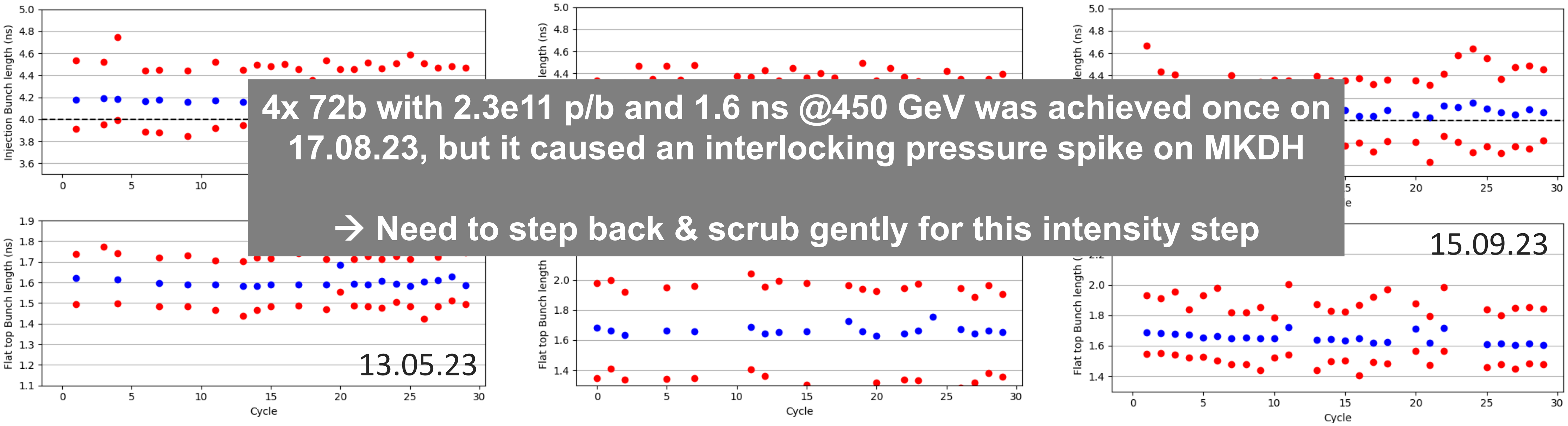
- **Intensity reach demonstrated on 13.06.23, 18.08.23 and 15.09.23:** **4x72 with 2.2e11 p/b at flat top**
  - Excellent transmission (~95% without scraping)
  - Bunch length at flat top around 1.65 ns – reproducibly!



Achieved SPS performance – intensity

LHC Injectors Upgrade

- **Intensity reach demonstrated on 13.06.23, 18.08.23 and 15.09.23:**
  4x72 with 2.2e11 p/b at flat top
  - Excellent transmission (~95% without scraping)
  - Bunch length at flat top around 1.65 ns – reproducibly!



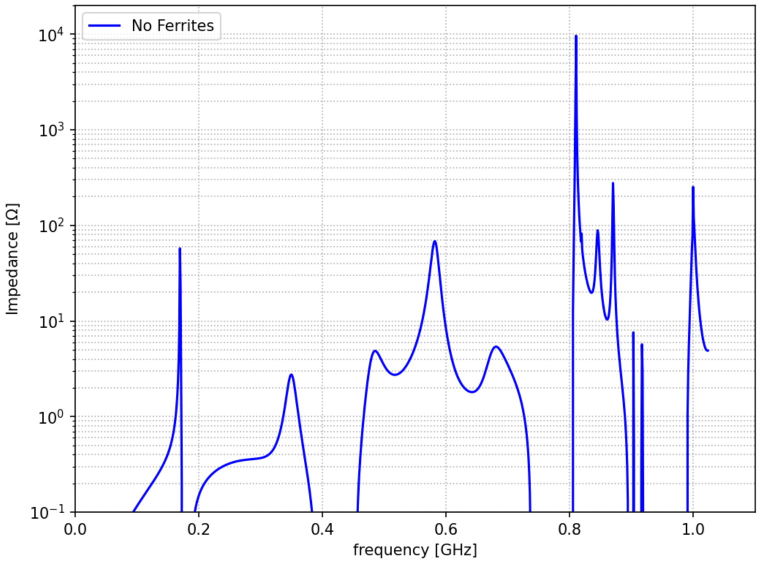
4x 72b with 2.3e11 p/b and 1.6 ns @450 GeV was achieved once on 17.08.23, but it caused an interlocking pressure spike on MKDH

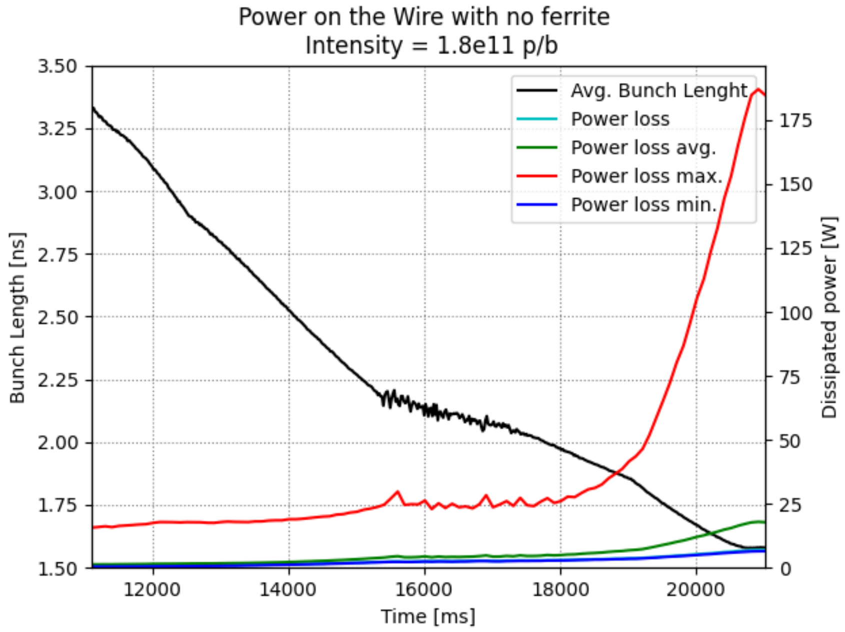
→ Need to step back & scrub gently for this intensity step

Problem with the wire scanners (I)

LHC Injectors Upgrade

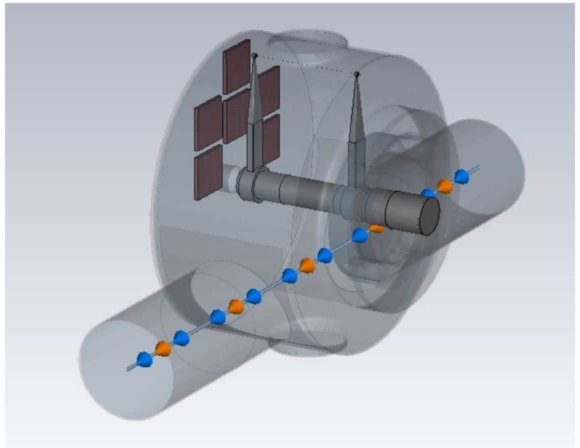
- During scrubbing **wires of all new 4 LIU wire scanners broke**
  - Spares were installed in sextant 4 (V), but shortly broke again when accelerating 4x 72b with 1.8e11 p/b on nominal LHC filling cycle
  - Main suspect impedance peak at around 800 MHz causing intolerable wire heating when bunch shortening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

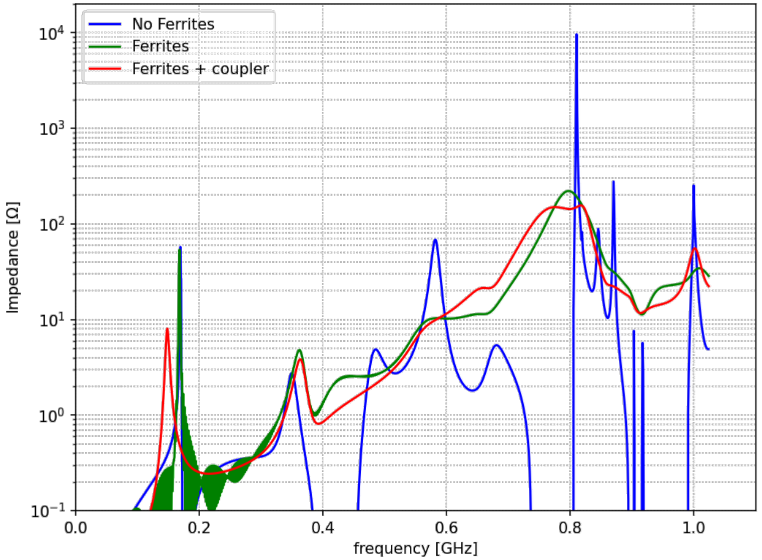


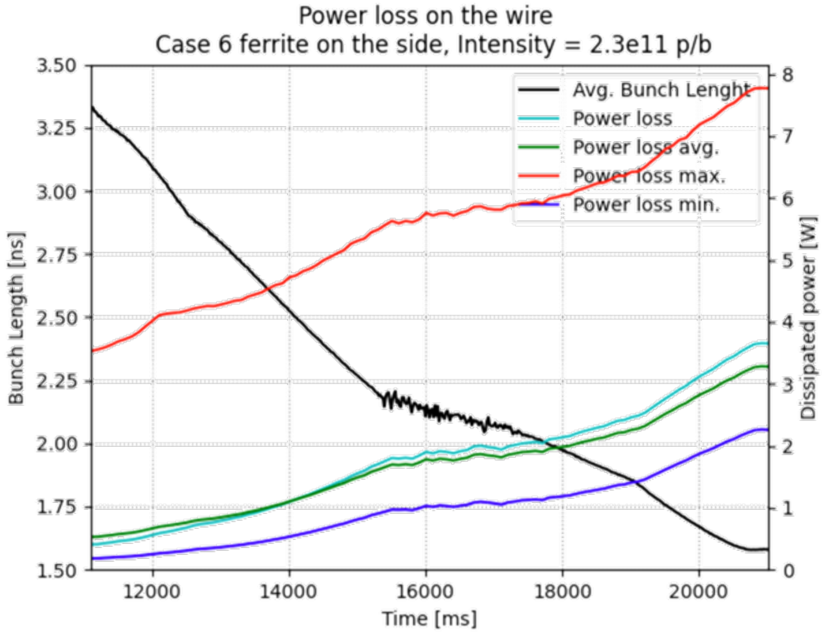


Problem with the wire scanners (II)

- **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



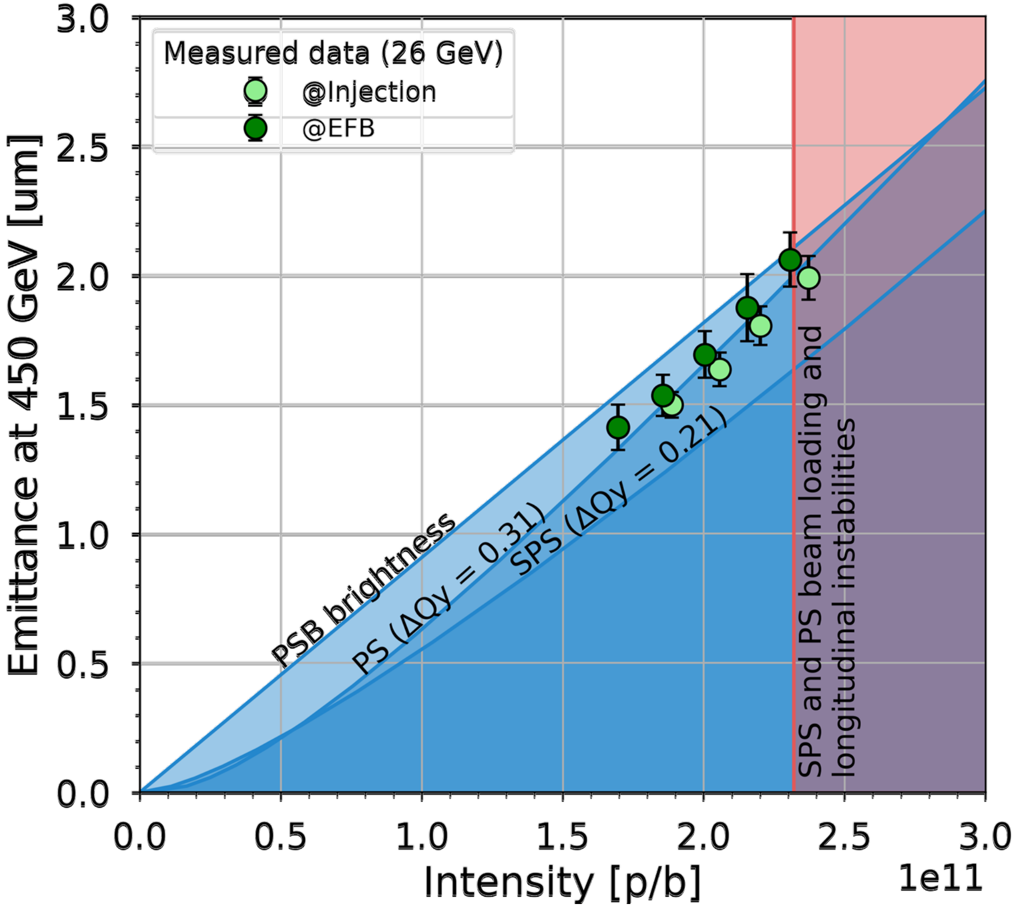




Achieved SPS performance – brightness

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 and PSB performing beyond 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

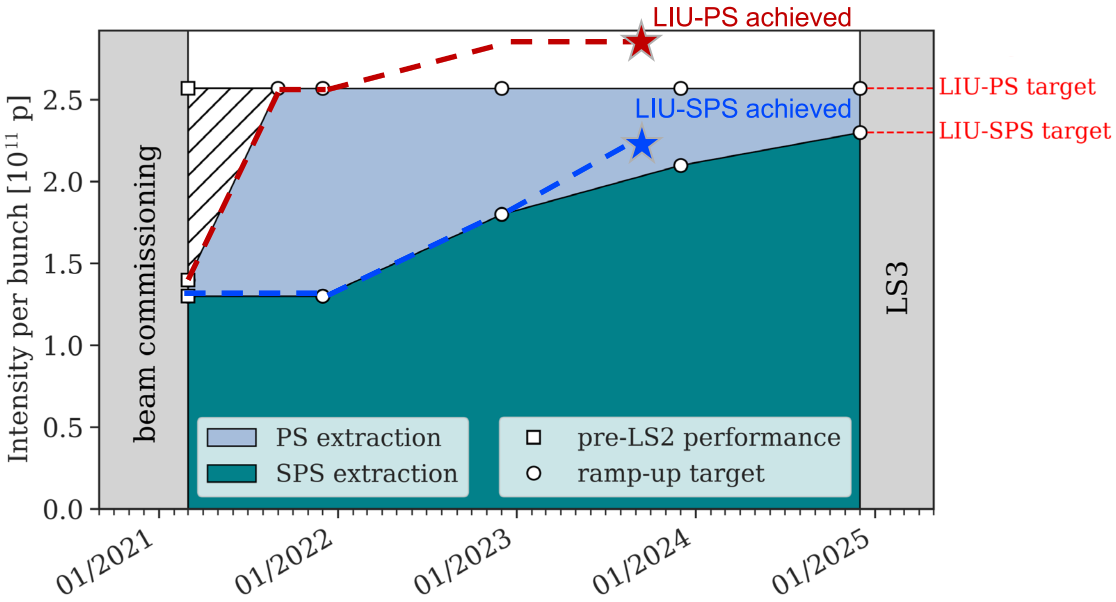


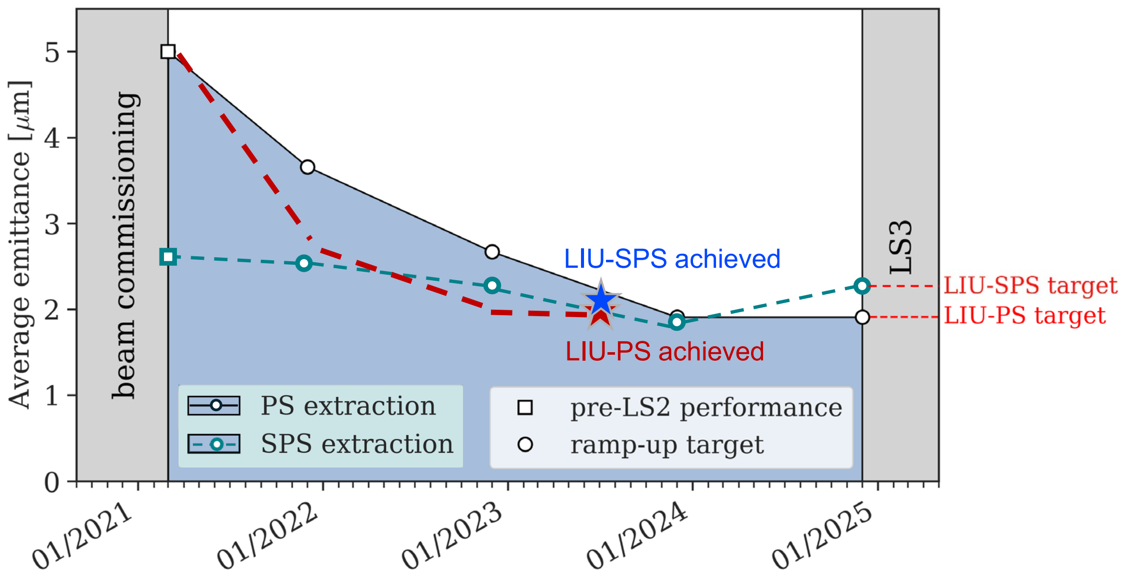
Outline

LHC Injectors Upgrade

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

Summary & outlook





- 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)

S. Albright, R. Alemany, M.E. Angoletta, C. Antuono, T. Argyropoulos, F. Asvesta, M. Barnes, H. Bartosik,
P. Baudrenghien, G. Bellodi, N. Biancacci, C. Bracco, N. Bruchon, E. Carlier, J. Coupard, H. Damerau,
G.P. Di Giovanni, F. de la Fuente Garcia, A. Findlay, M. Fraser, A. Funken, R. Garoby, S. Gilardoni, B. Goddard,
G. Hagmann, K. [...] heen, T. Levens, K. Li,
A. Lombardi, E. M[...] E. Montesinos,
Y. Papaphilippou, [...] D. Quartullo,
F. Roncarolo, B. S[...] A. Spierer, R. Steerenberg,
M. Sullivan, F. Ve[...] & all equipment experts

www.cern.ch