LIU intensity ramp-up: longitudinal beam dynamics and RF aspects

Ivan Karpov on behalf of the RF group with input from
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and many other OP and RF team members

Joint Accelerator Performance Workshop, 5-8 December 2022

LIU performance ramp-up plan* - reminder

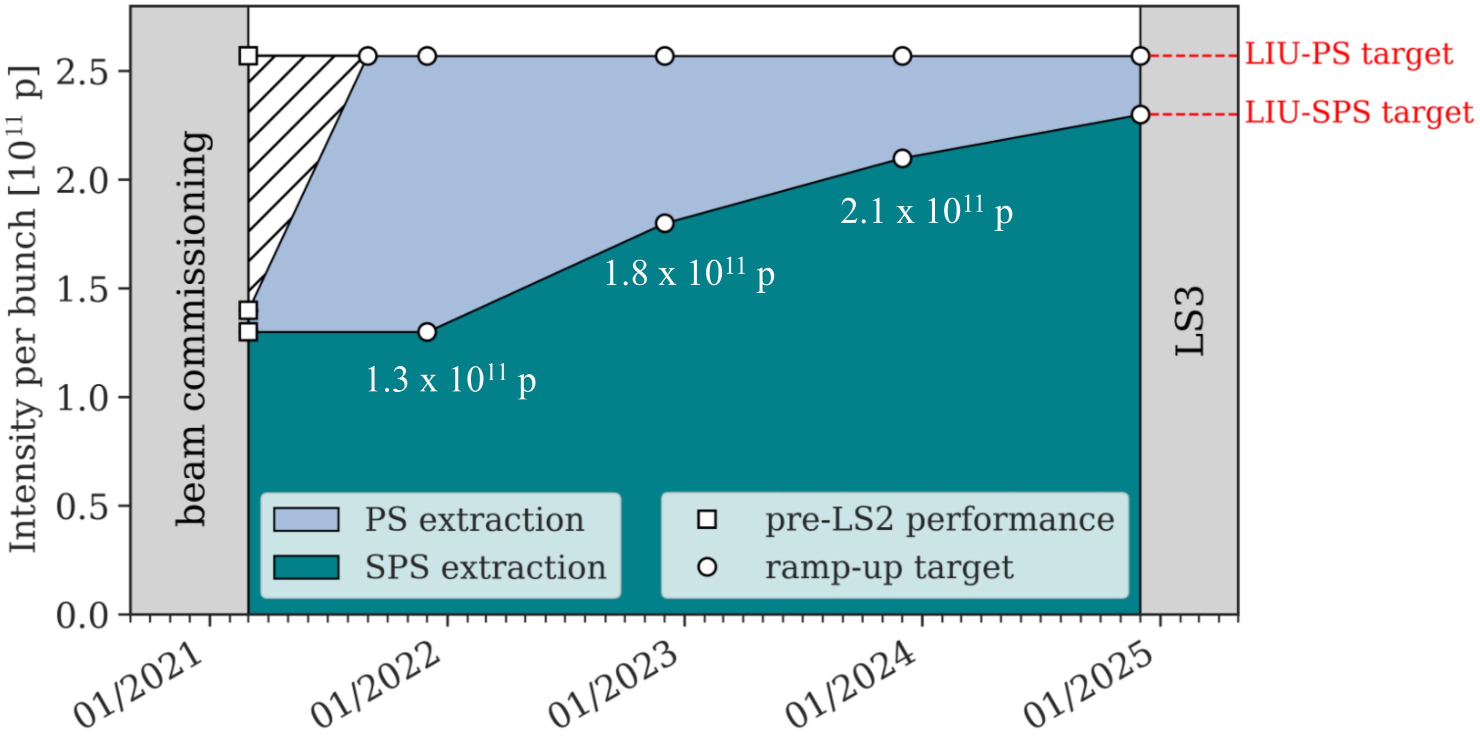
LIU target beam parameters at LHC injection (from EDMS1296306)

	intensity per bunch	transverse emittance [μm]	bunch length [ns]	longitudinal emittance [eVs]	number of bunches
Standard beam	$\mathbf{2.32 \times 10^{11}}$	**2.1**	1.65	0.57	4 x 72

Brightness ramp-up
→ Determined by the PSB and PS performance (details in C. Zannini's talk)

Intensity ramp-up for the standard beam
→ LIU-PS intensity target successfully recovered in 2021
→ Plan for the gradual ramp-up of SPS intensity until the end of 2024 **remains unchanged**

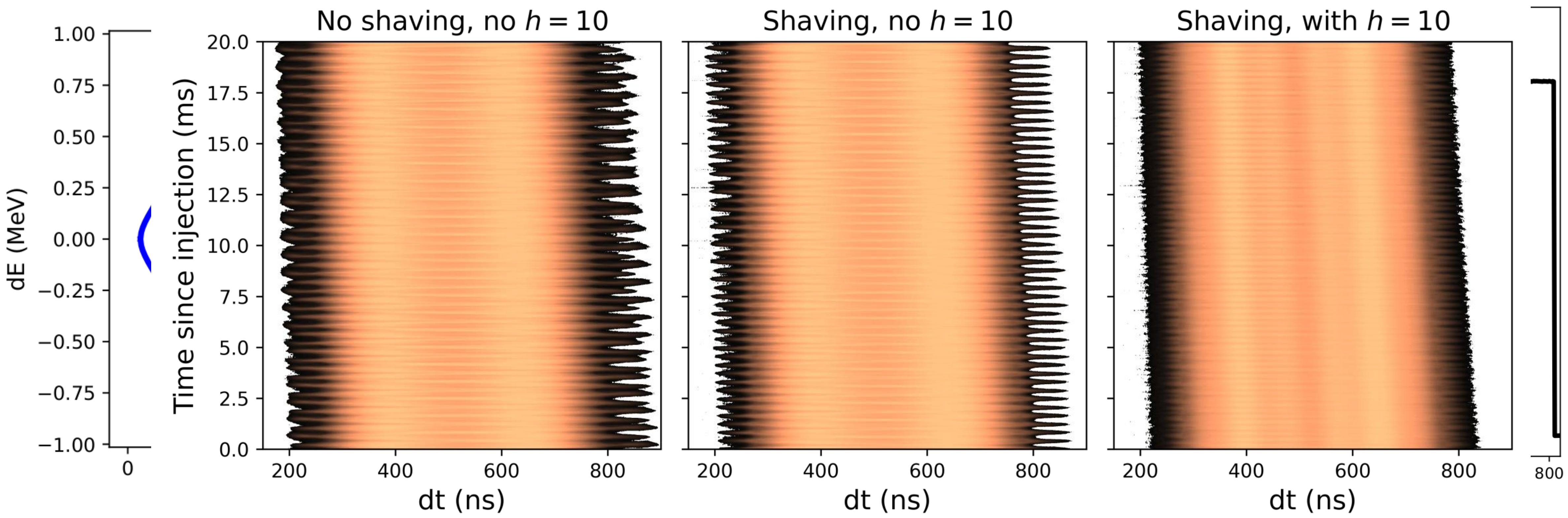
RF issues in dedicated talk of A. Lasheen



*A. Huschauer, LIU Workshop, Montreux 2020

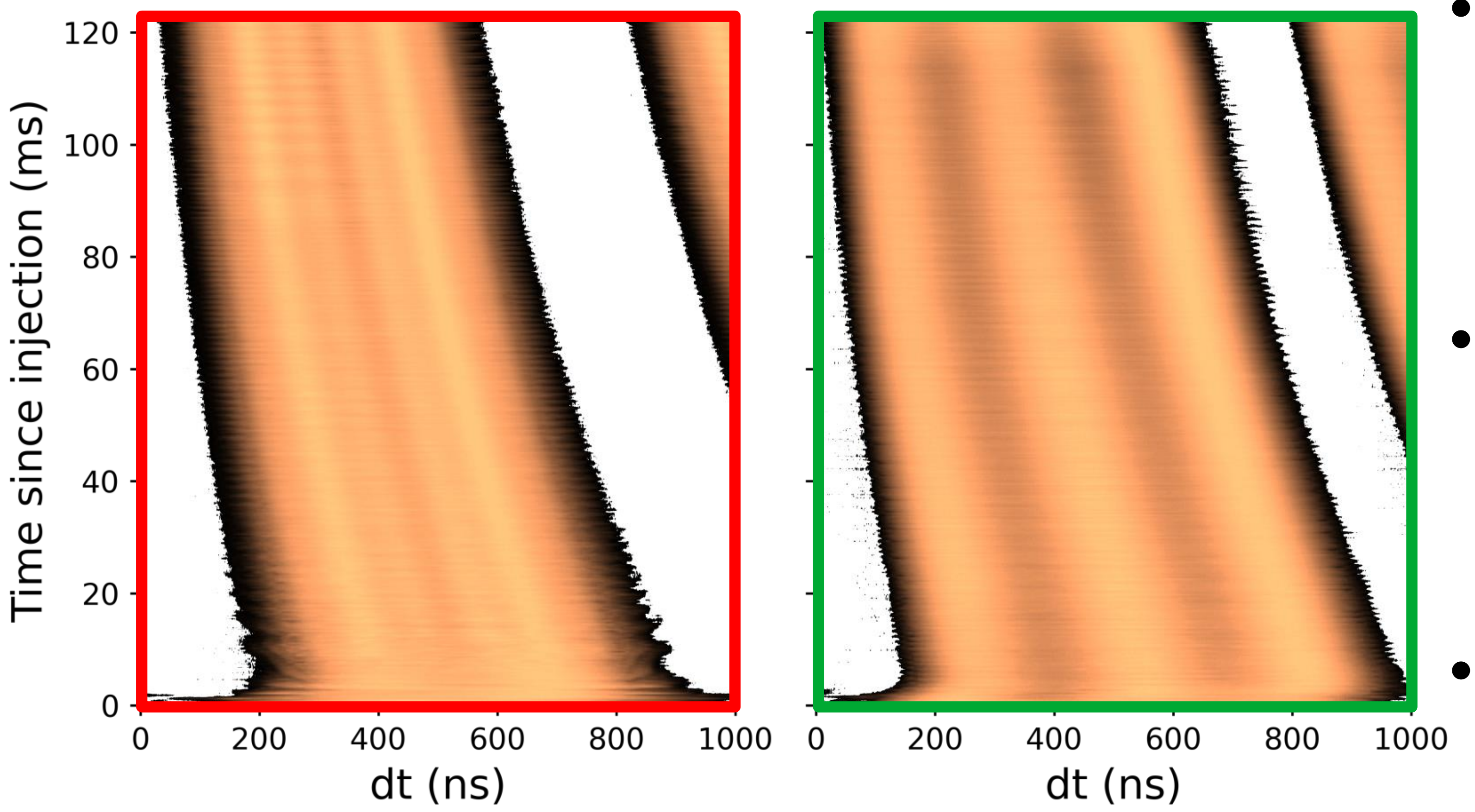
PSB

Longitudinal Tails and Losses



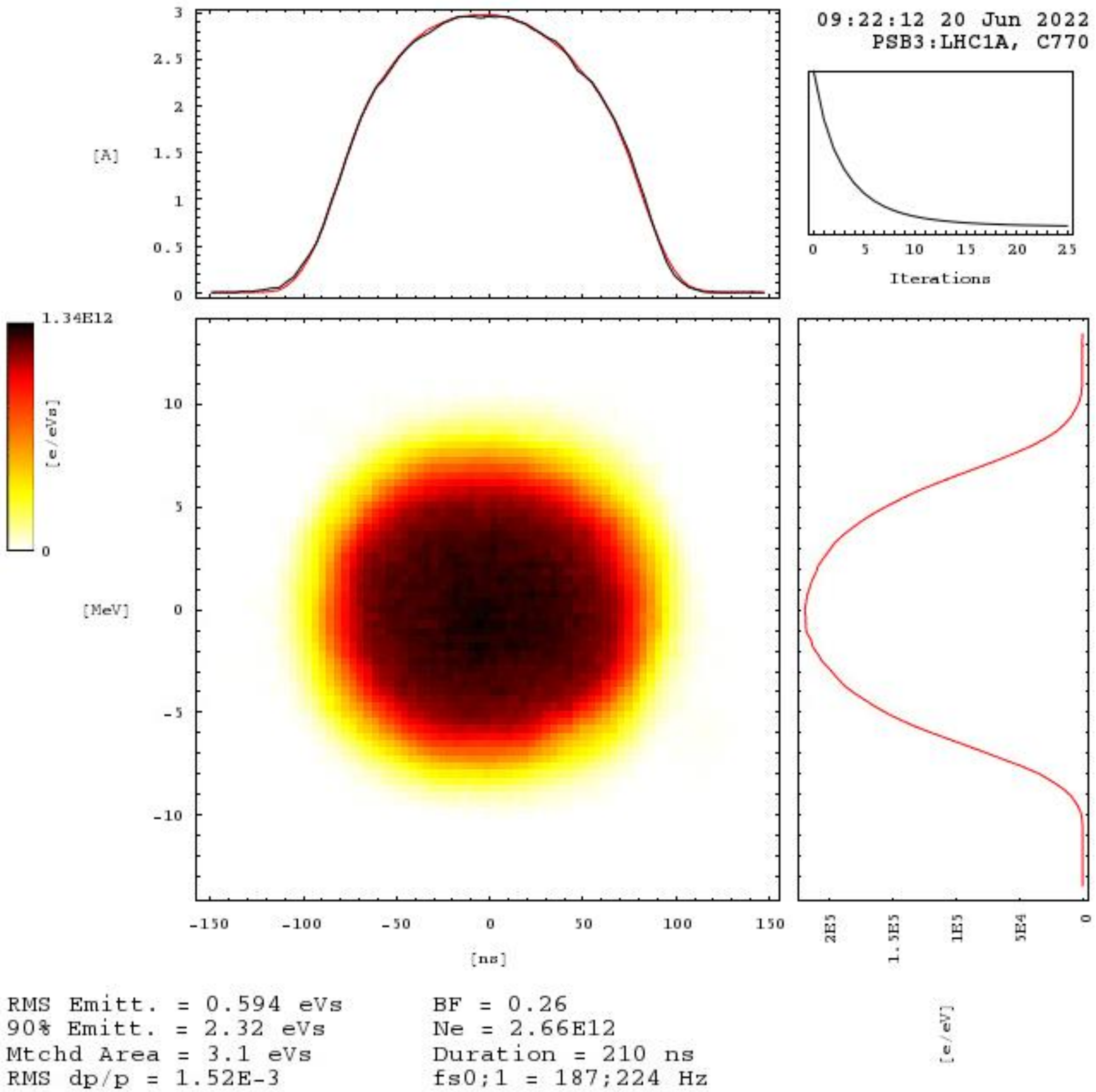
- The beam is intentionally injected larger than the bucket
- This is followed by longitudinal shaving
- With the addition of RF voltage at h=10, longitudinal tails are removed

Triple Harmonic



- Double harmonic in bunch lengthening mode is the standard for PSB beam production
- Triple harmonic operation was (first tested pre-LS2) allows further bunch lengthening
- MDs in 2022 showed higher brightness was possible (see C. Zannini's talk)

3 eVs Beam Production



- 3 eVs used operationally in 2022
- Controlled longitudinal emittance blow-up currently uses phase modulation of *h=10*
- Band limited phase noise is the preferred operational method, but development is ongoing
- Blow-up to 3.6 eVs has been achieved for MD purposes

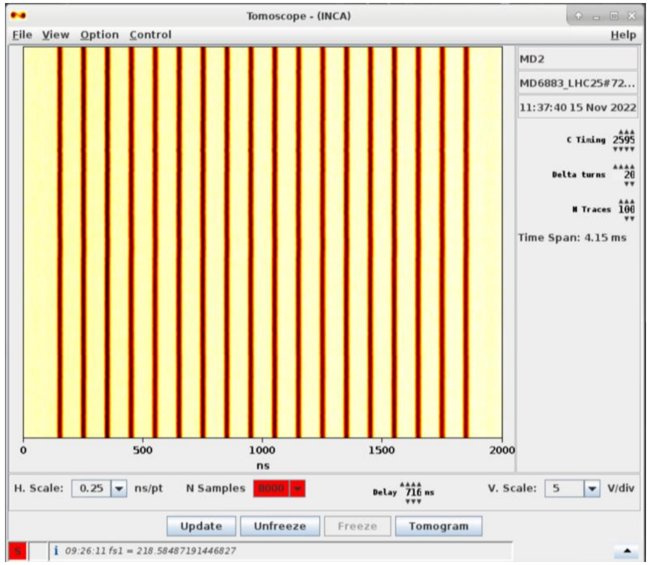
PS

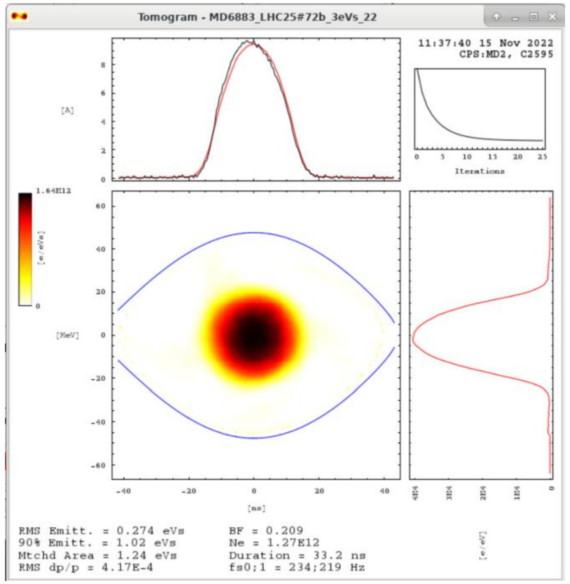
Coupled-bunch instabilities and Feedback

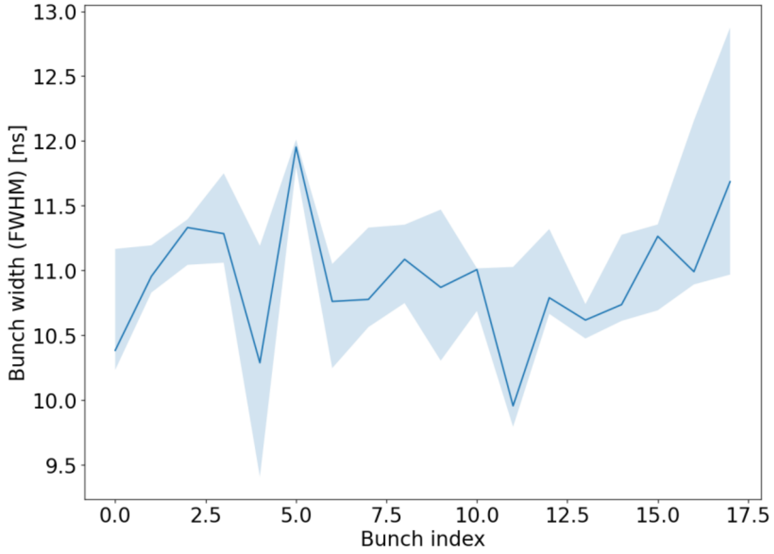
LIU bunch intensity of 2.6×10^{11} p/b recovered in 2021

At intensity > 3×10^{11} p/b:

- Quadrupolar longitudinal coupled-bunch instabilities during acceleration are observed
- 40 MHz RF system as Landau cavity in bunch shortening mode provides sufficient stability
- Now, a newly developed **Quadrupole-mode feedback** system can suppress it as an alternative cure

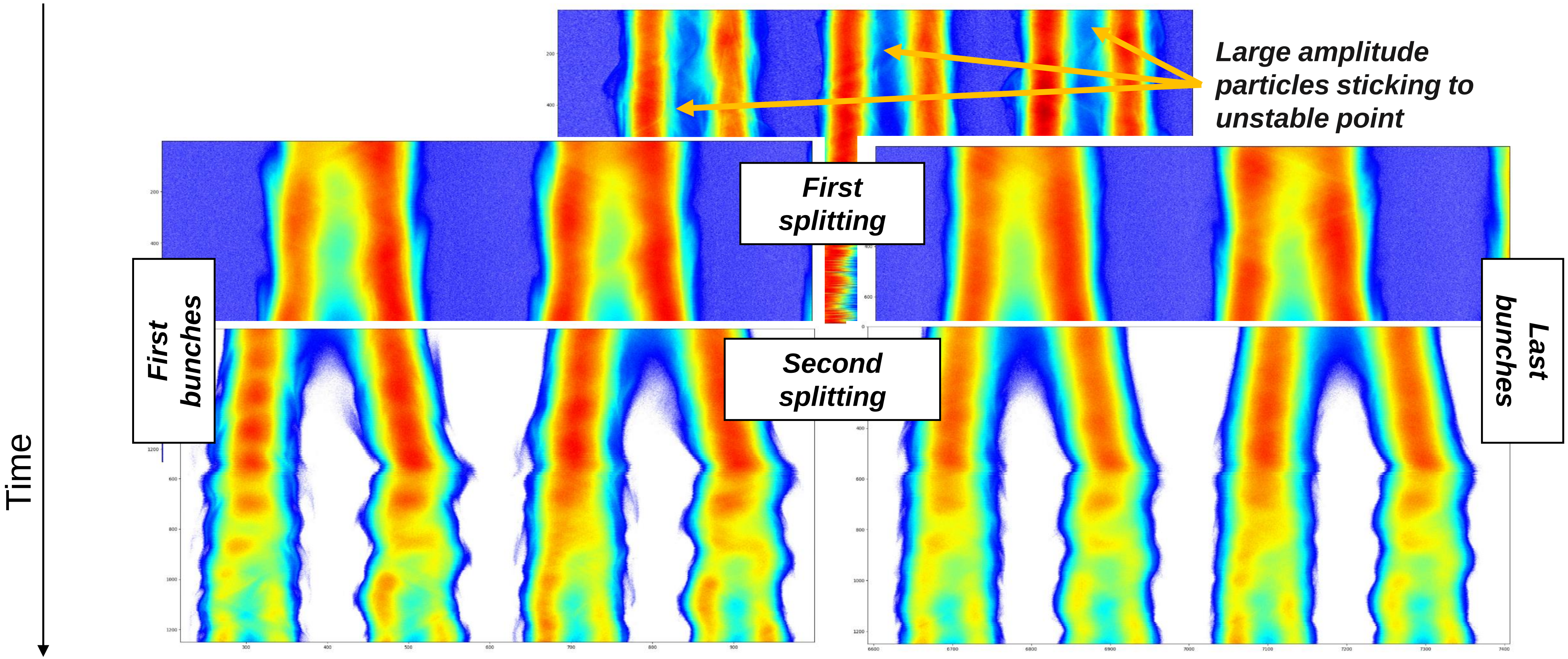






→ Since the target intensity is exceeded with a good margin, the focus is now on beam quality and reproducibility: emittance/tails/bunch-by-bunch spread

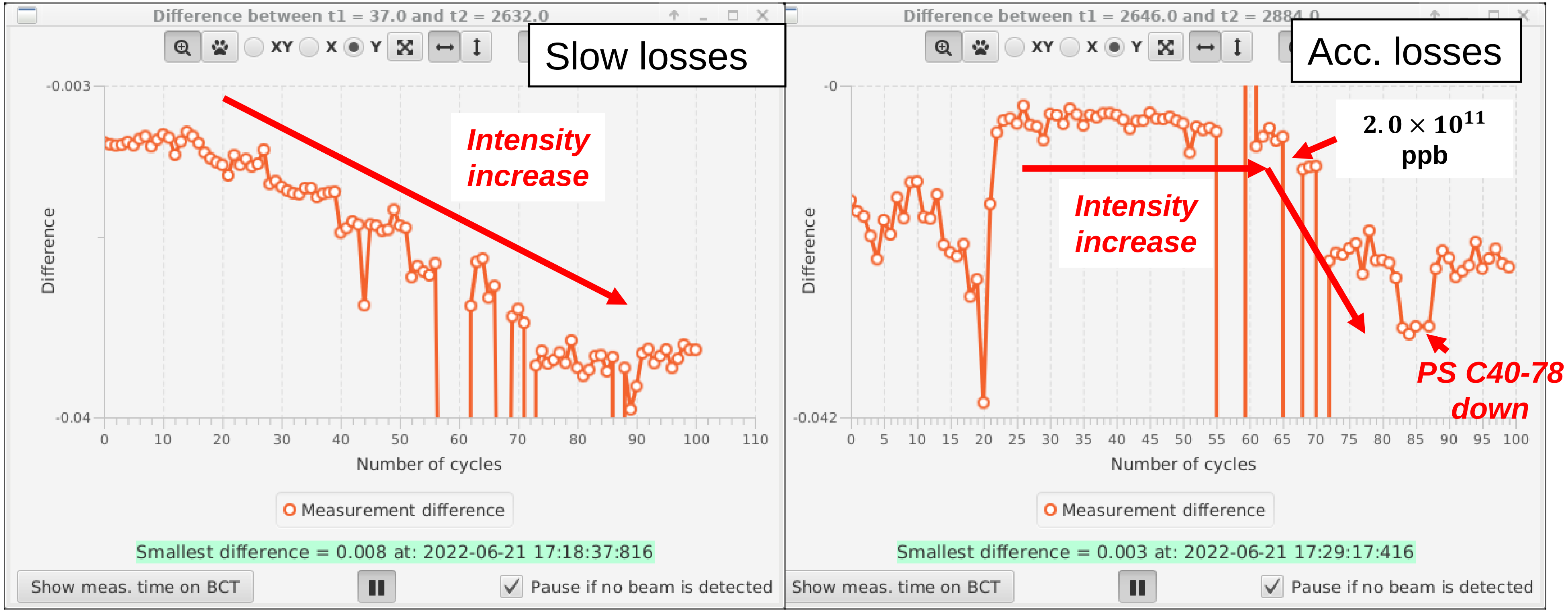
Oscillations During Splittings in PS



At LIU intensity, these oscillations can cause longitudinal halo

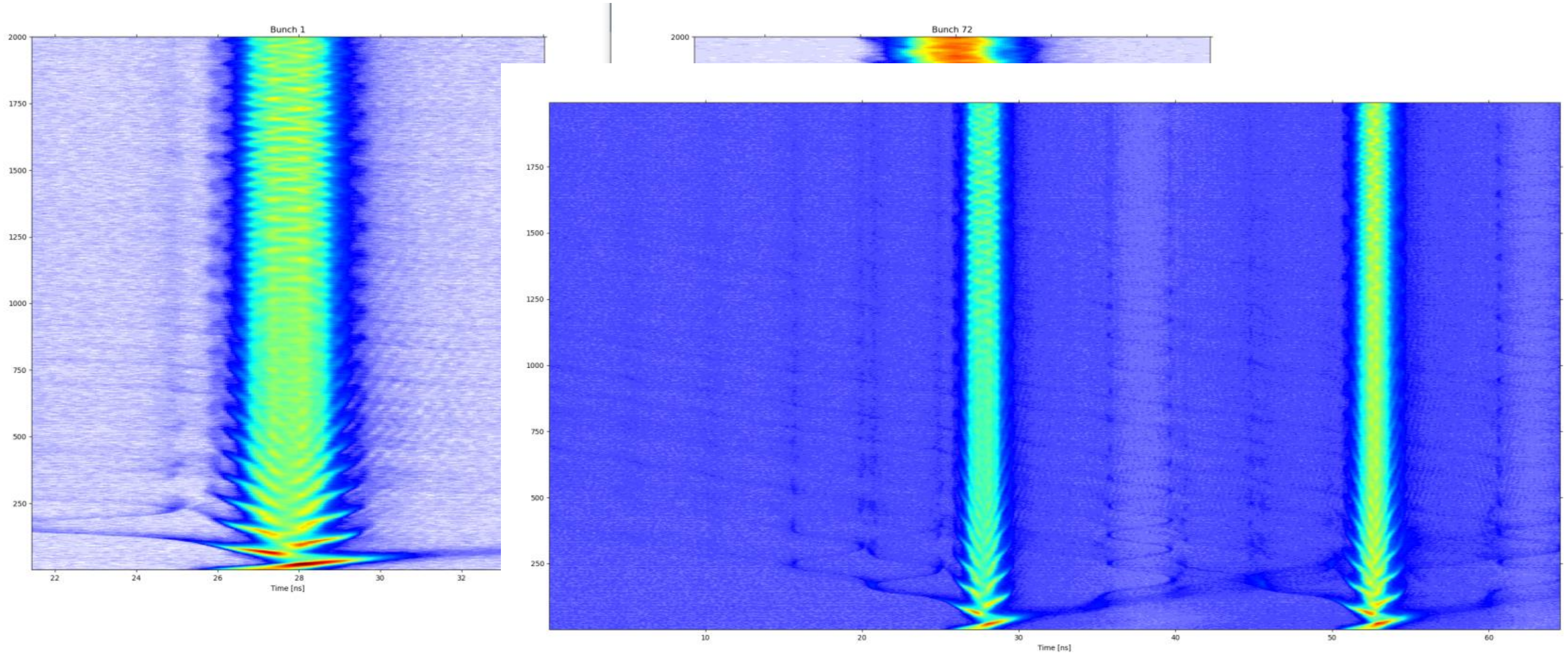
PS-SPS

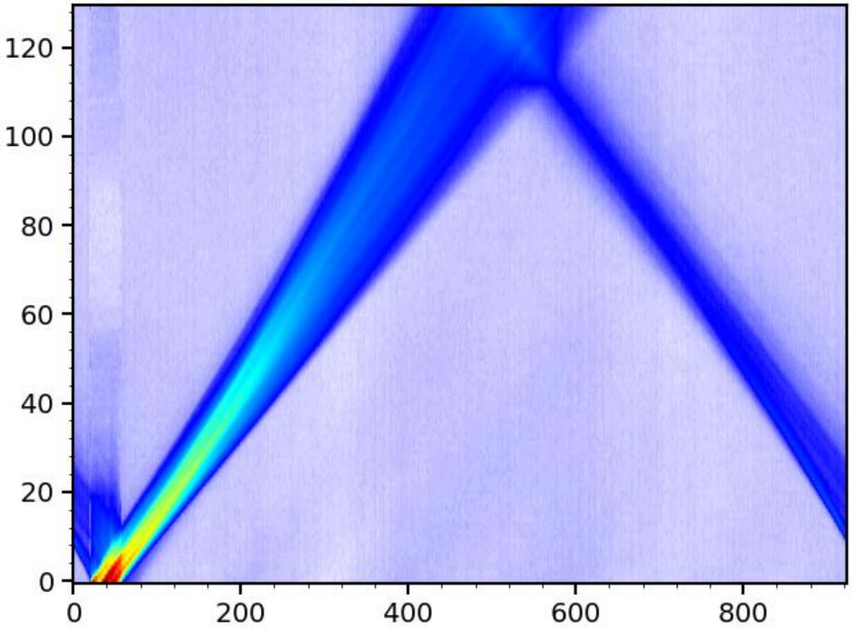
Distribution of losses on the SPS flat bottom



- Investigating on the sources of losses (slow vs. acceleration), to disentangle between longitudinal and transverse contributions
- Scanning intensity from 1.3×10^{11} ppb to 2.6×10^{11} ppb.
- The slow losses scale linearly with the intensity, the acceleration losses (capture) increase starting from 2.0×10^{11} ppb. Losses also increase with the number of bunches.

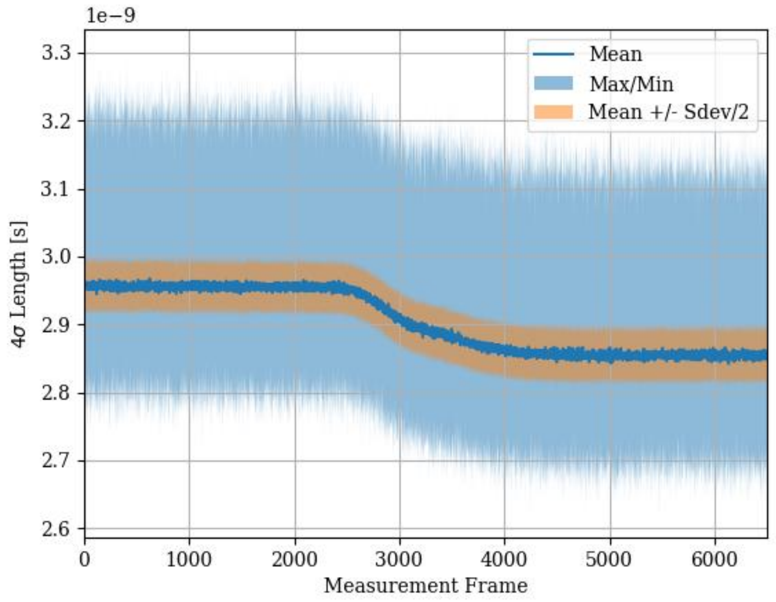
Longitudinal uncaptured beam

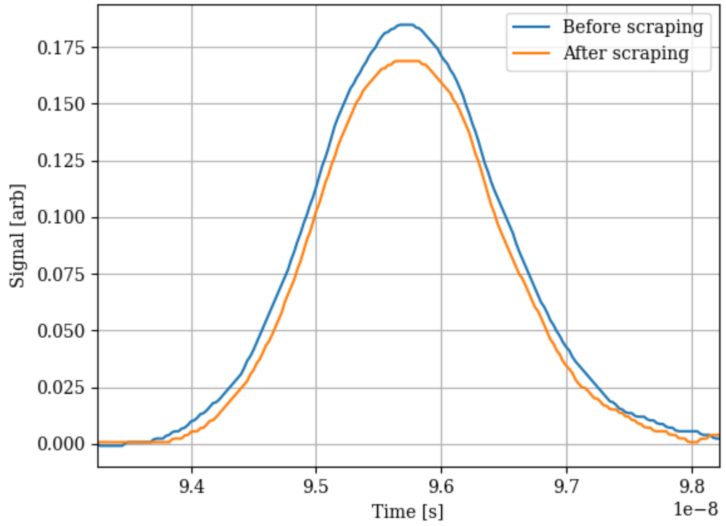


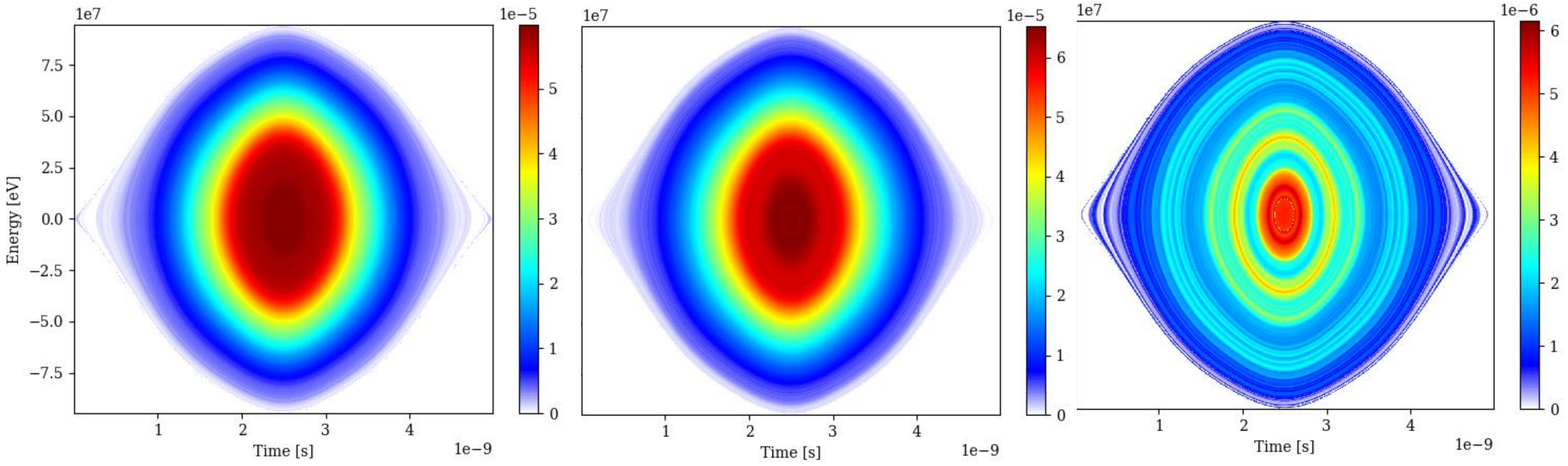


- Uncaptured beam at injection is measurable on the MD beam observation system (PS-SPS dedicated system in the future).
- A new approach was to apply controlled emittance blow-up on the flat bottom to push particles out of the SPS RF buckets on purpose and see how losses were distributed.
- Losses are measured at the start of acceleration. This source of losses can be mostly attributed to longitudinal dynamics (calibration with tomography in PS and simulation ongoing to disentangle between PS tails and SPS transient beam loading).

Longitudinal reconstruction of vertically scraped bunches







- Observation of reduced slow losses and bunch length during vertical scraping.
- Reconstruction of longitudinal density indicates that lost particles are distributed all over the SPS RF bucket (higher losses in the core in absolute, larger losses on tails in relative).
- New observation that will require thorough investigation in 2023.

SPS

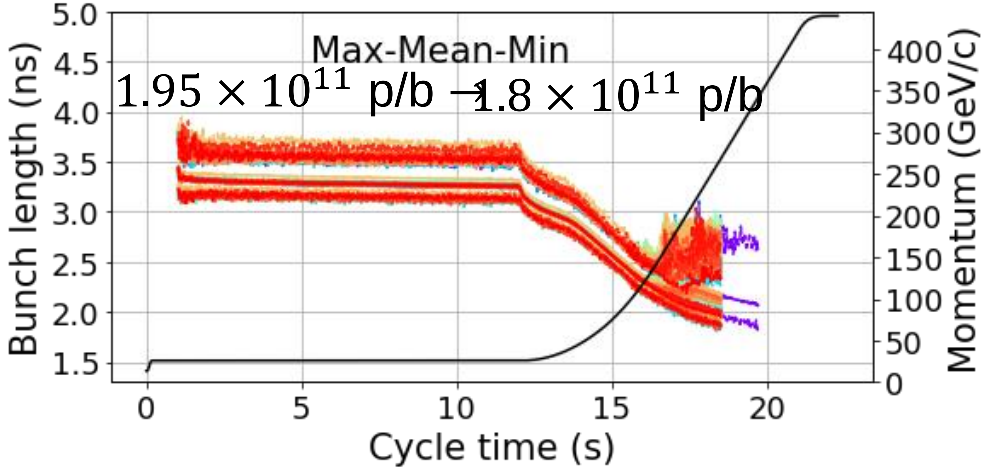
Pushing RF power limits

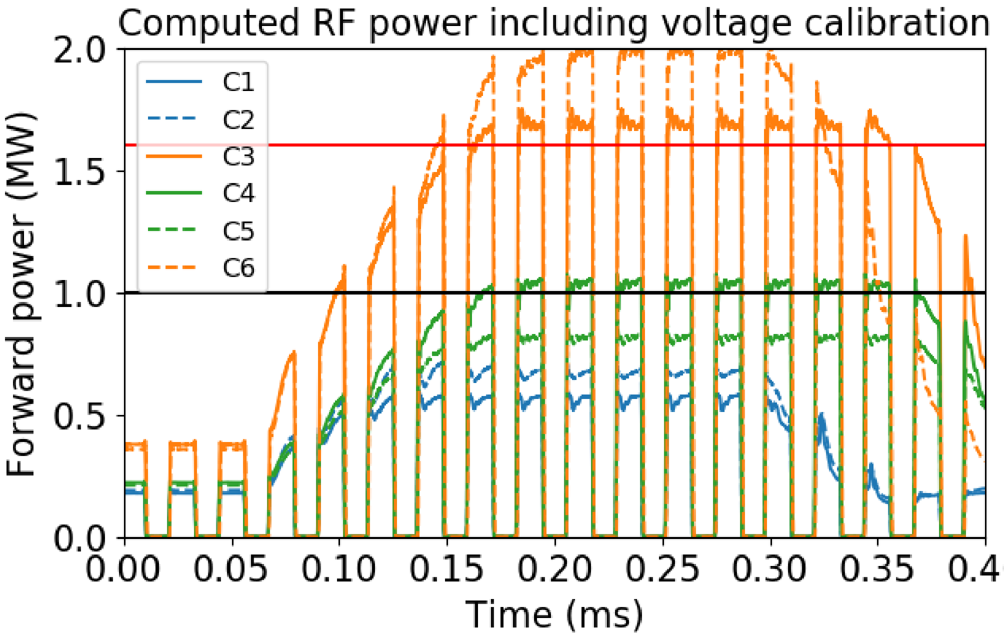
In 2021, a single batch of 48 bunches was unstable above 1.7×10^{11} p/b in the first part of the ramp due to a lack of RF power

→ What are the limits in 2022?

Power can be computed based on measured RF voltage
RF voltage was re-calibrated during YETS after an extensive campaign of beam-based measurements (*D. Quartullo, SPS MPC #21*)
→ Knowledge of RF power without RF measurement
→ Peak power of cavities 3, 4, and 6 fulfill the LIU target, but for short pulses
→ Other 3-section cavities require gradual replacement of the amplifier tubes
→ LIU target is still to be reached for longer pulses

Bunch length evolution during cycle





Intensity reach at the SPS flattop*

Standard

4×72 with 1.63×10^{11}– 26.03.2022 (first days of scrubbing in the ramp)

- Very long bunches (> 2 ns) to avoid spikes of MKDH and MKP-L
- To get 1.65 ns intensity must be reduced to $\sim 1.4 \times 10^{11}$

4×72 with 1.73×10^{11} – 27.09.2022 (HiRadMat run)

- Same story…

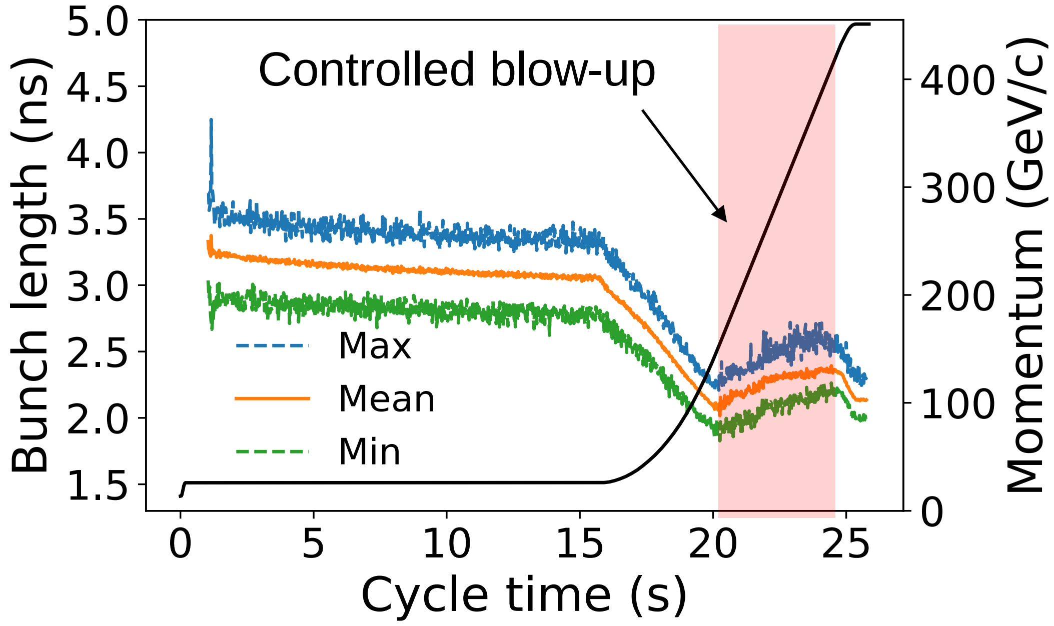
BCMS*

4×48 with 2.32×10^{11} – 23.11.2022 (last MD)

- 2.4 ns long bunches & 700 ns batch spacings (strange losses, no time for optimization)
- Could be reduced to 2.1 ns for a single batch

What are the key points besides the increased RF power limits?

Bunch length evolution during cycle



*Detailed table on the slides of C. Zannini

Optimizations at flat bottom

Amplitude modulation of RF voltage

- Allows using maximum peak RF power for LHC-type cycles

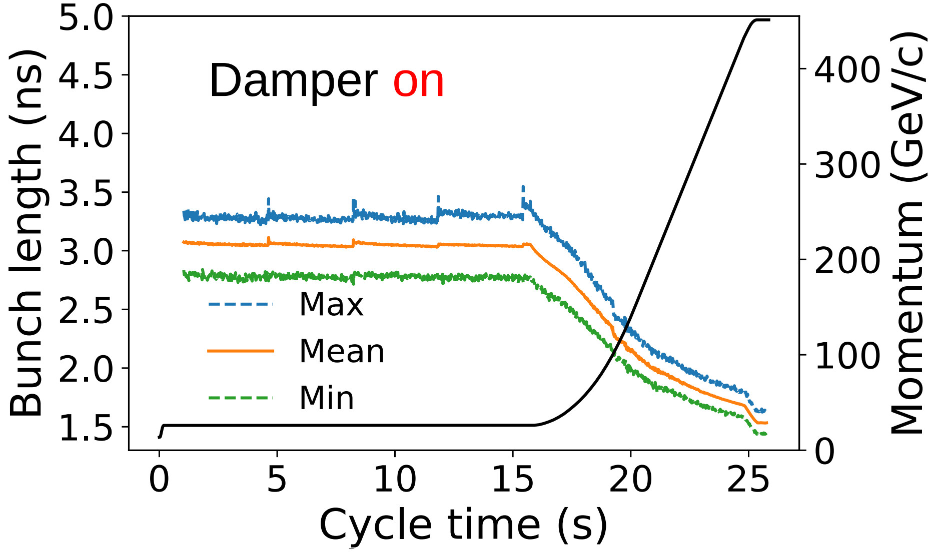
Longitudinal damper

- Mainly prevents emittance blow-ups for multiple injections
- Smaller longitudinal emittance from PS is preferable for the efficient use of the 800 MHz RF system *(M. Schwarz, LIU SPS BD WG, 21.02.2019)*

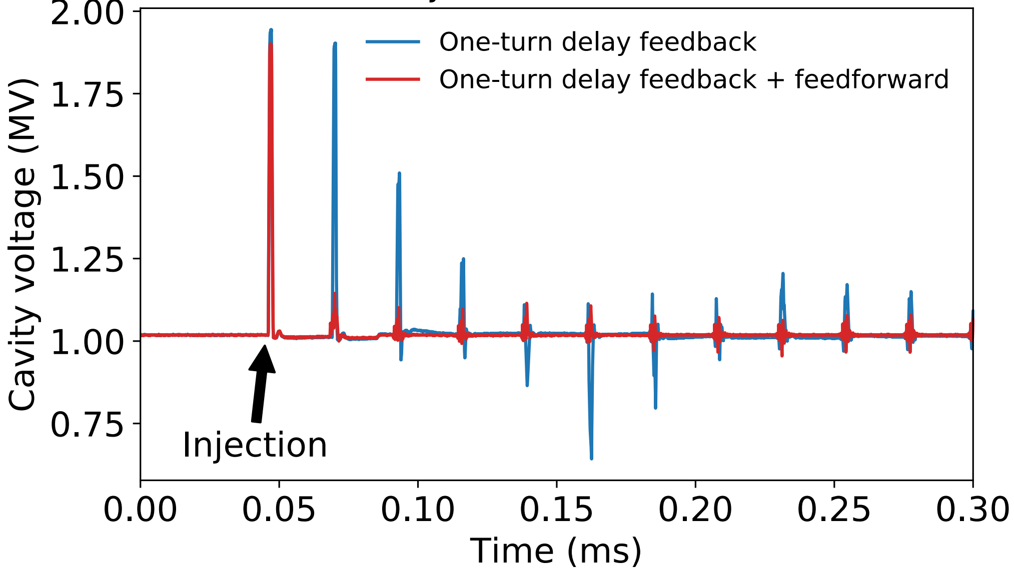
Feedforward

- Reduce transient beam loading already the **2nd turn**
- Improvement of capture losses to be further studied in MDs
- Still, a firmware update during YETS is required for compatibility of **feedforward** with **amplitude modulation**

Bunch length evolution during cycle



C6, injection of 48x2.2e11



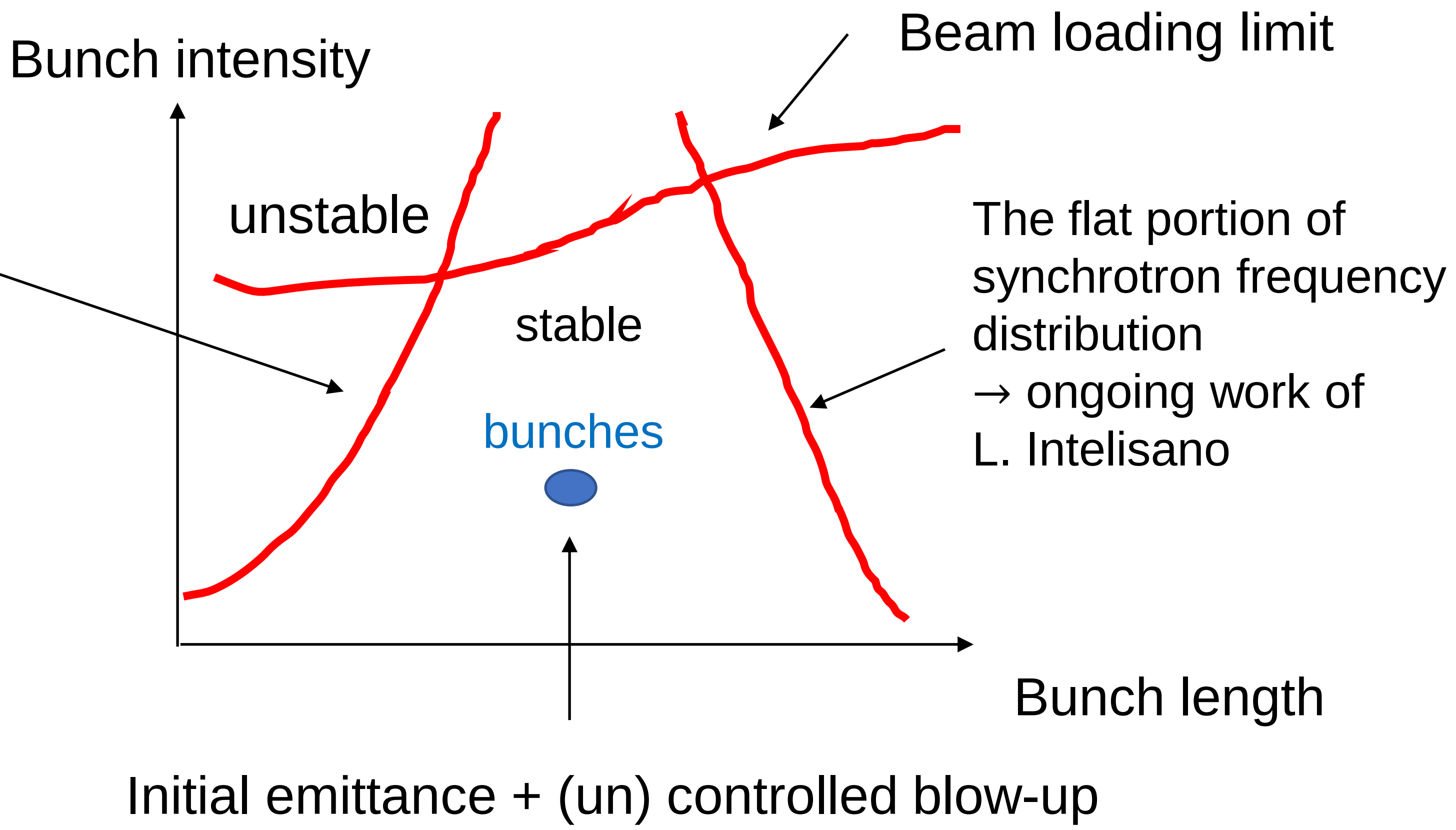
Longitudinal multi-bunch stability during acceleration

Coupled-bunch instability threshold is linked to the single-bunch loss of Landau damping threshold (*IK and E. Shaposhnikova, IPAC 2022*)

LLD threshold in double RF (*L. Intelisano, et al, HB 2021*)

$$N_{\mathrm{LLD}} \propto \frac{\left(1 + 64\frac{V_{800}}{V_{200}}\right) V_{200}\cos\phi_s}{\sqrt{1 + 4\frac{V_{800}}{V_{200}}}}\tau^{\alpha}$$

$\alpha \approx 3 - 4$



→ Higher V_{200} is better, but limited due to beam loading

→ Optimum V_{800} depends on emittance

→ Voltage programs must be designed considering the controlled emittance blow-up

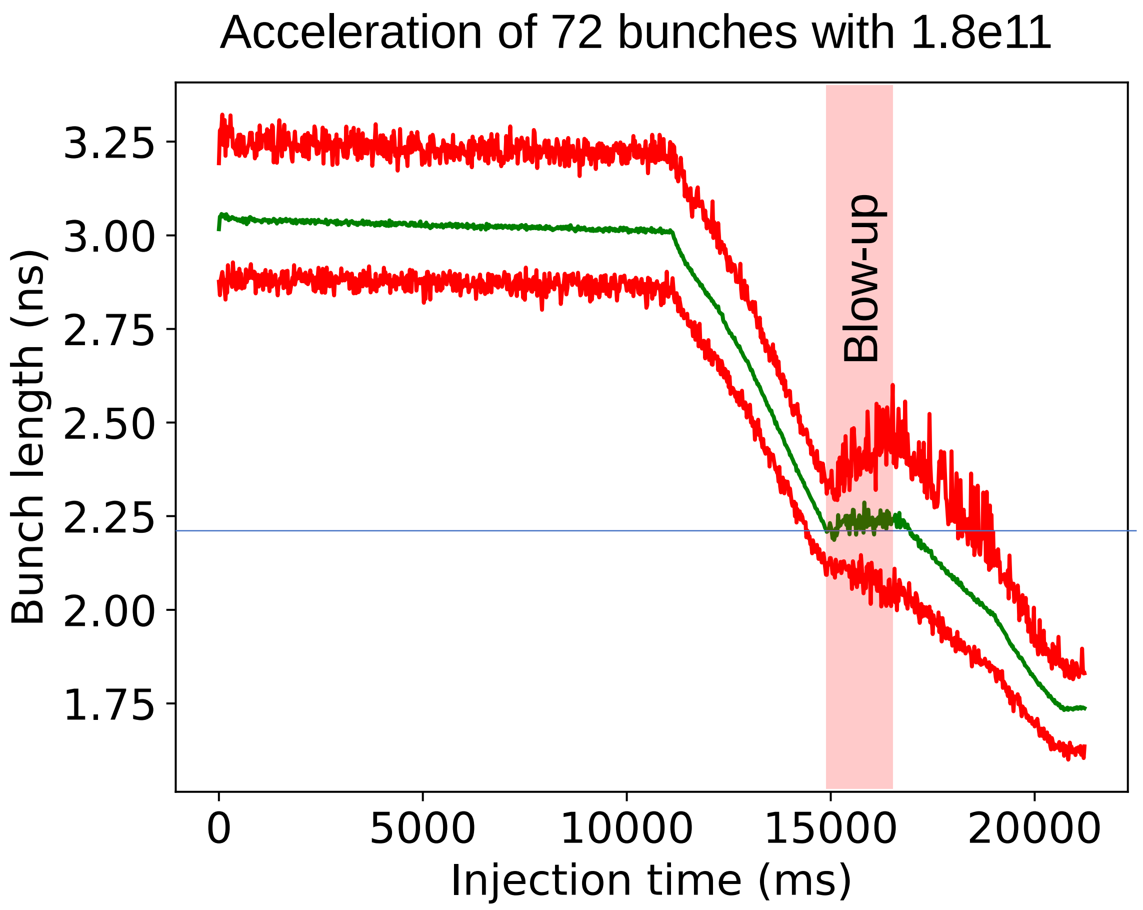
Approach to simplify setting-up

If V_{200}, V_{800}, ϕ_s, are "almost" constant and we force the bunch length to be constant during the blow-up
→ instability threshold, margin high, and margin low are fixed

$V_{800}/V_{200} = 0.1$ during blow-up to avoid flattening of fs, then increases to 0.16 towards flattop to maintain stability

→ Only amplitude and blow-up duration need to be adjusted to follow the desired bunch length

→ Used during scrubbing run and MDs



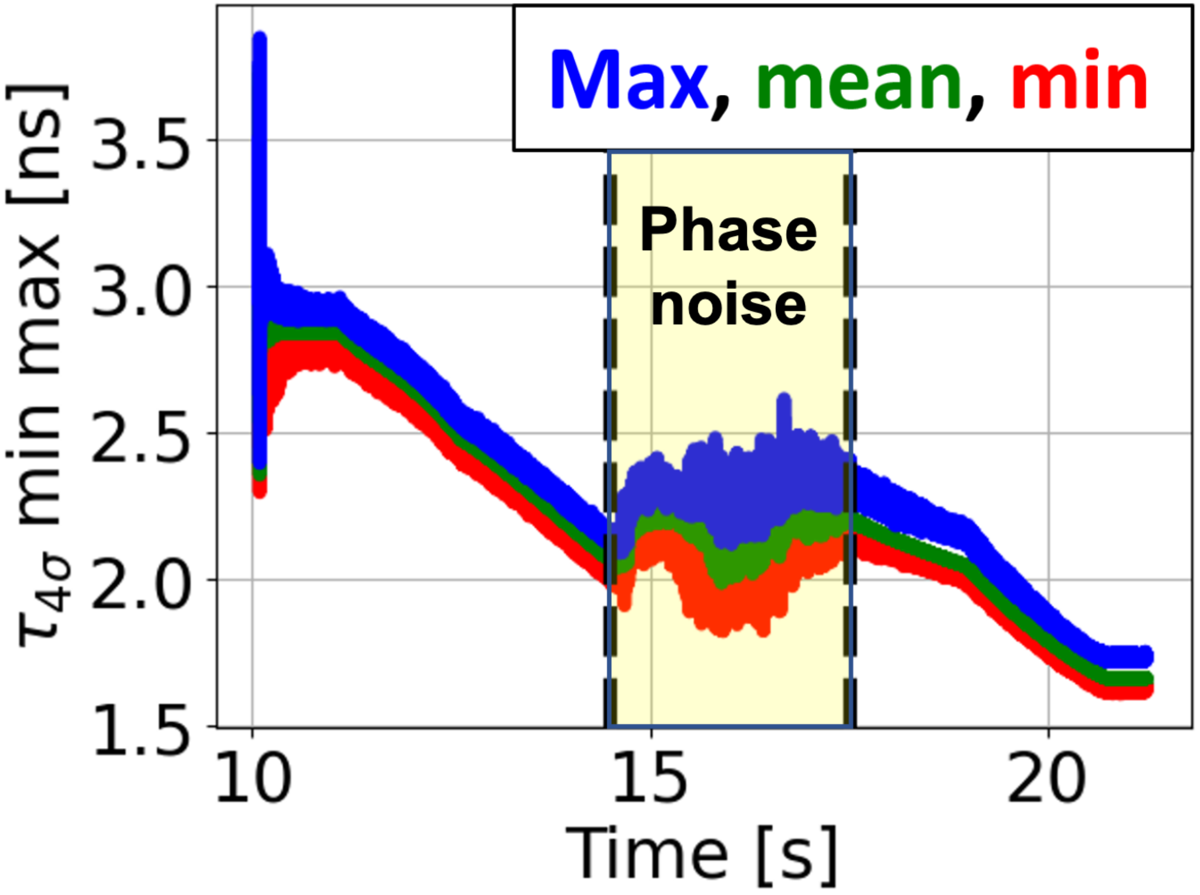
Simulations for HL-LHC parameters

Detailed models for beam-based loops and transfer function model of one-turn delay feedback are implemented in BLonD (*D. Quartullo, IPAC 2022)*

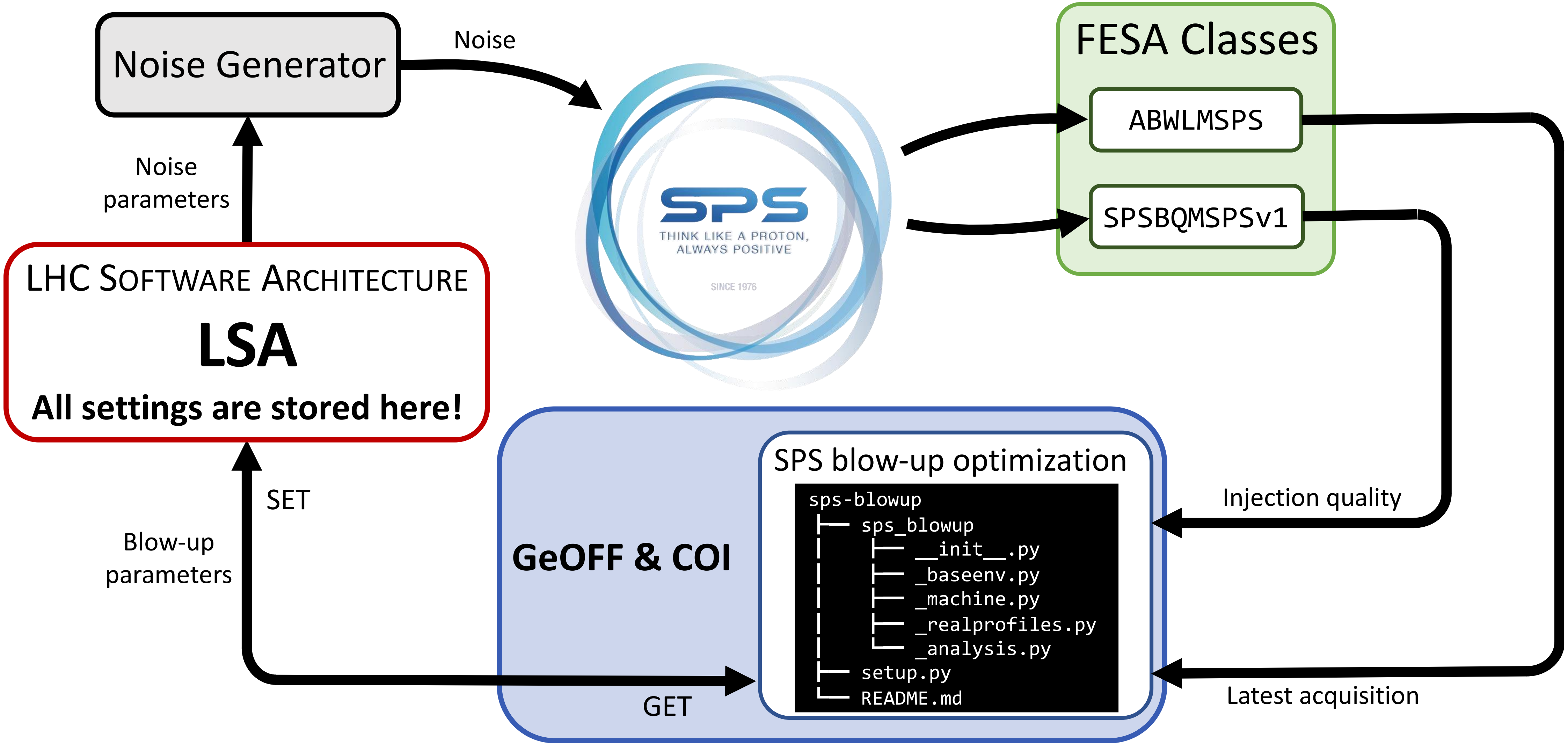
→ LIU target for 72 bunches is reached in simulations

→ The dynamic LLRF model with RF power limitations is still to be included *(contribution from B. Karlsen-Baeck and H. Timko)*

Bunch length evolution for 72 bunches

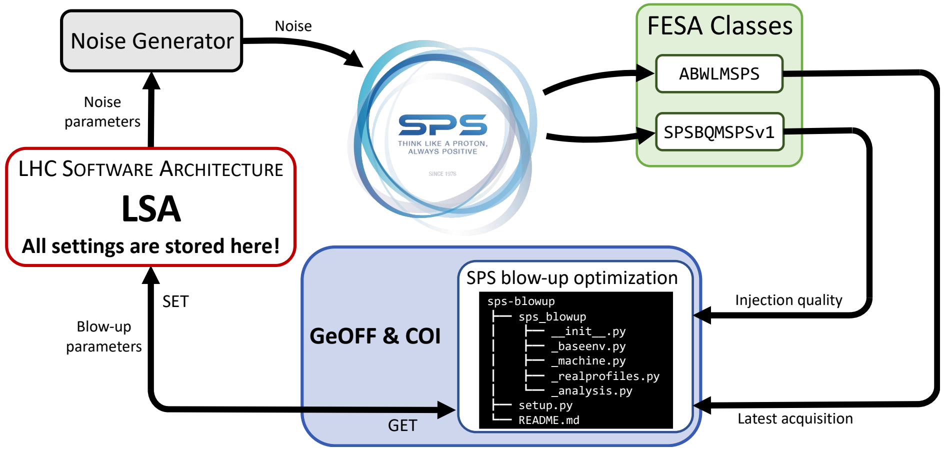


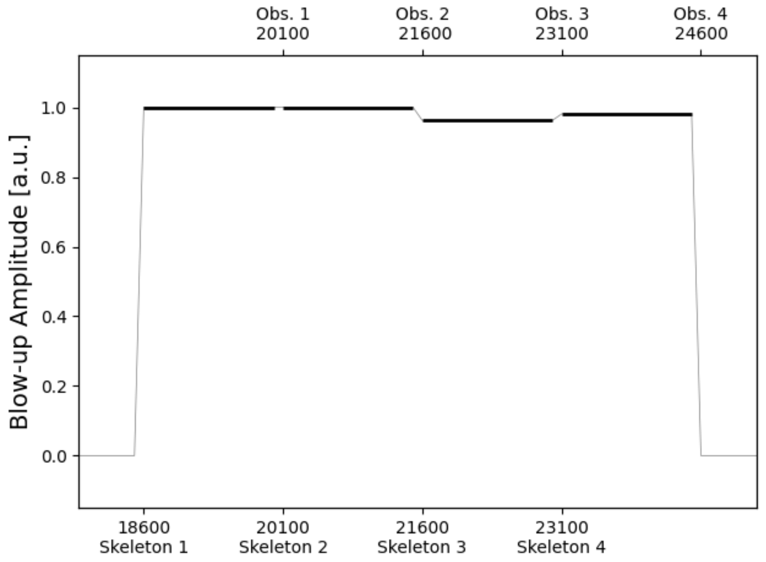
Automatic setting up of controlled blow-up



Details are in (N. Bruchon, ML and data analytics community forum, 30.11.2022)

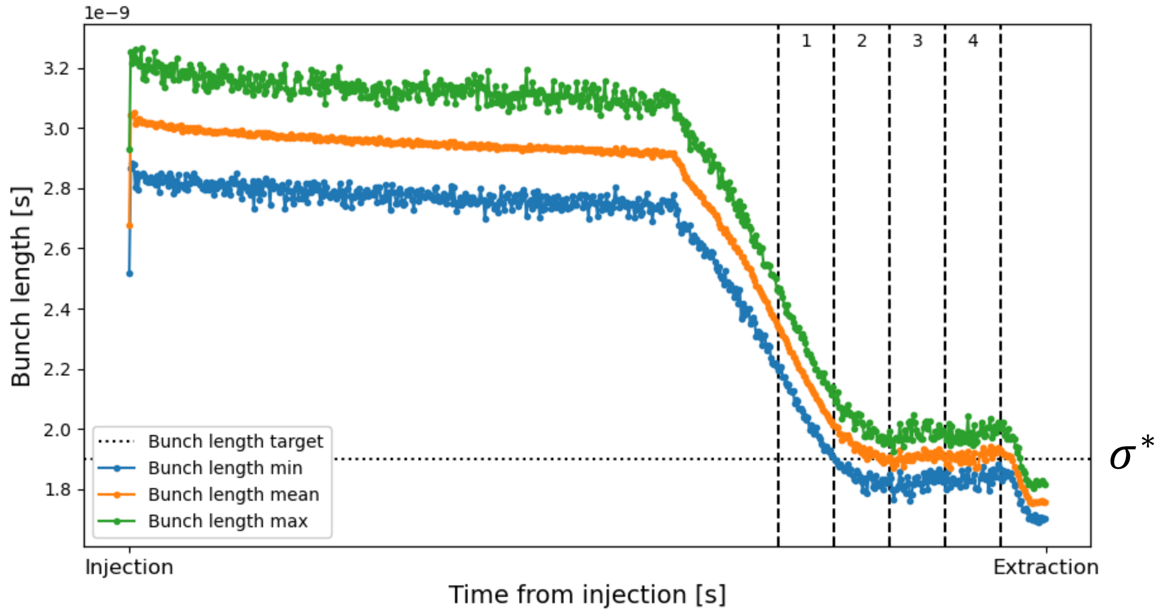
Automatic setting up of controlled blow-up





Blow-up optimized for single batch, 06-10-2022.

- Intensity per bunch: 1.2×10^{11} p/b
- Average bunch length per extraction: 1.76 ns
- Average bunch length at injection: 2.68 ns



→ Successful tests during MDs

Details are in [(N. Bruchon, ML and data analytics community forum, 30.11.2022)]

8b4e mystery

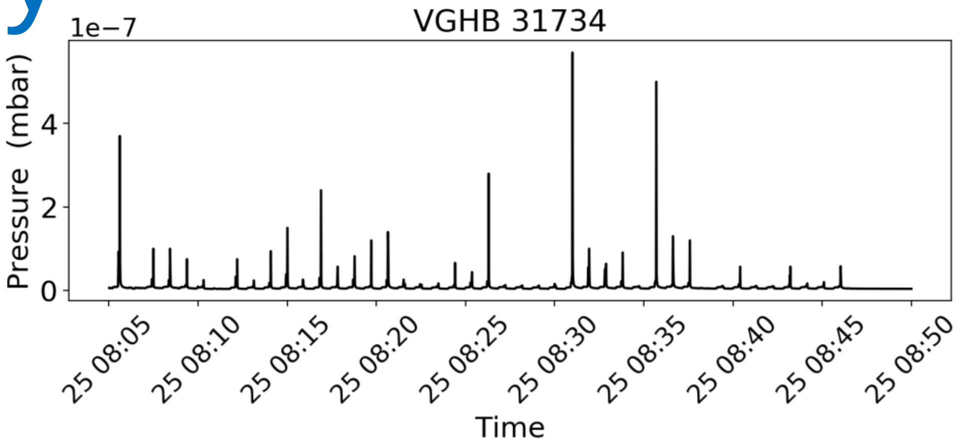
QD.31710 – AETA – AEW – APWL – AEWA – AEG – ACL31735

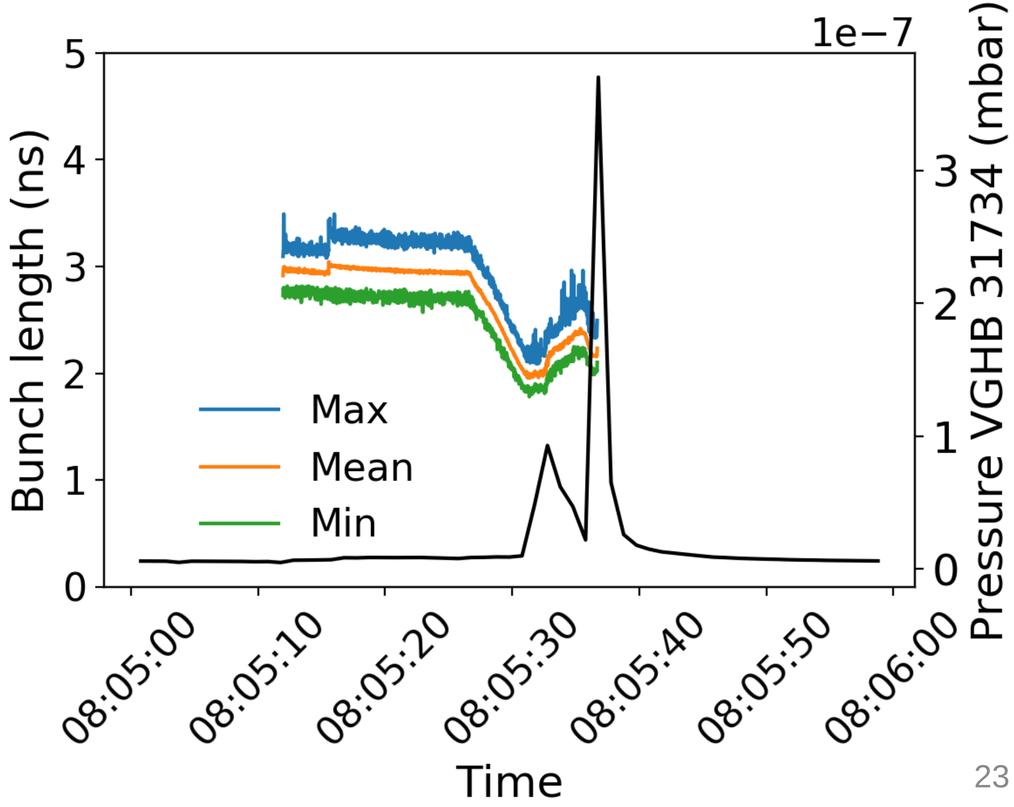
[SPS MPC #31, 29.11.2022]

Vacuum spikes trigger interlocks around cavity 1 800 MHz as soon as more than 2 batches of 8b4e with more than 1.8×10^{11} p/b are accelerated

Pressure strongly depends on bunch length and bunch spacing *(C. Zannini's presentation)*

Investigations are ongoing…





Summary

PSB

LIU target is reached

PS

The intensity target is reached and surpassed, and work on beam quality and reproducibility is ongoing.

SPS

Peak power limits are demonstrated for short pulses.

LIU LLRF upgrade is completed (feedforward is commissioned).

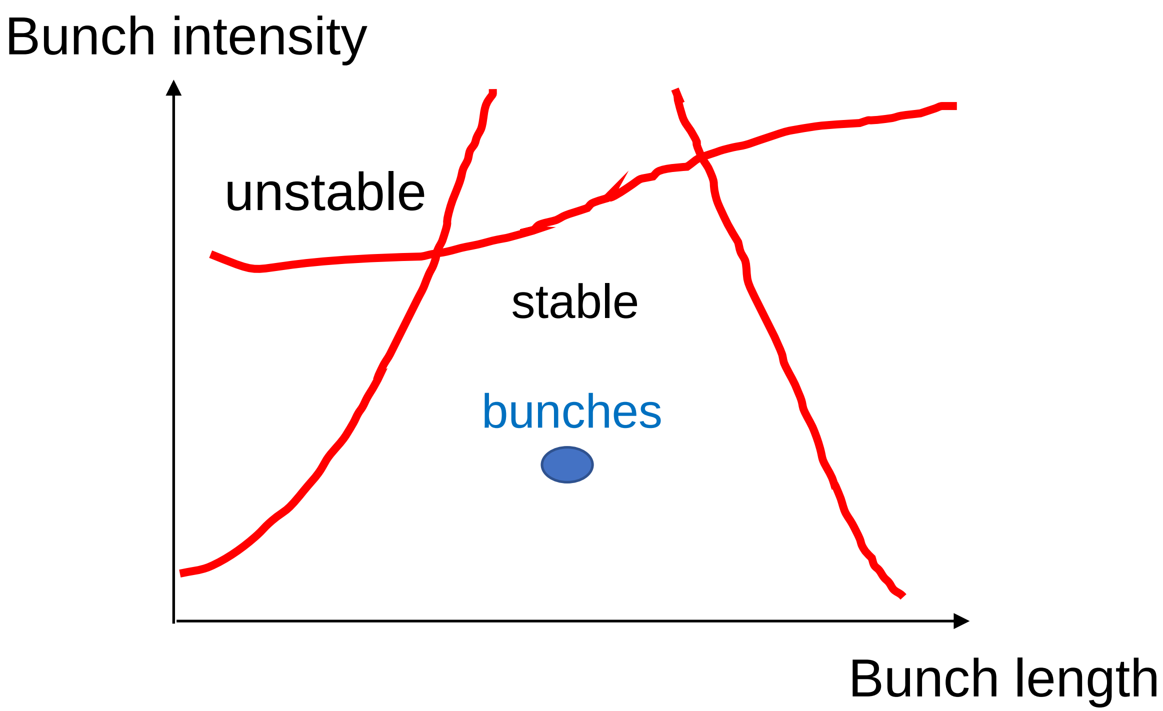
Understanding of stability is improved, simulations are further developed, and an automated tool for controlled emittance blow-up is tested.

Stability at 450 GeV for LIU parameters is still to be demonstrated.

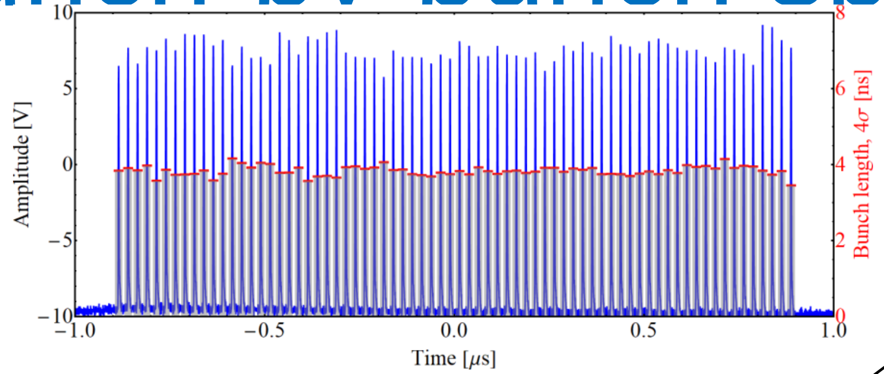
Progress is presently limited by vacuum spikes of MKDH and MKP-L for Standard and BCMS beams, while by vacuum spikes around cavity 1 800 MHz for 8b4e beam.

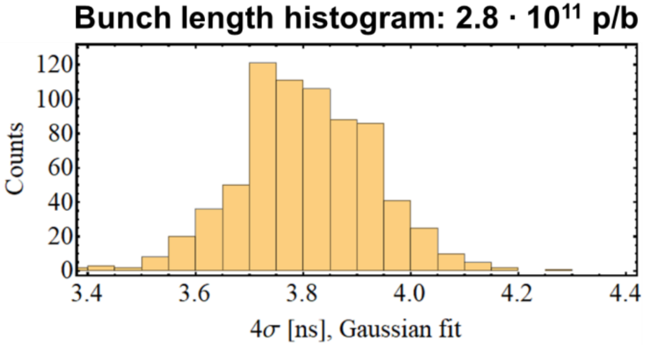
Thank you for your attention!

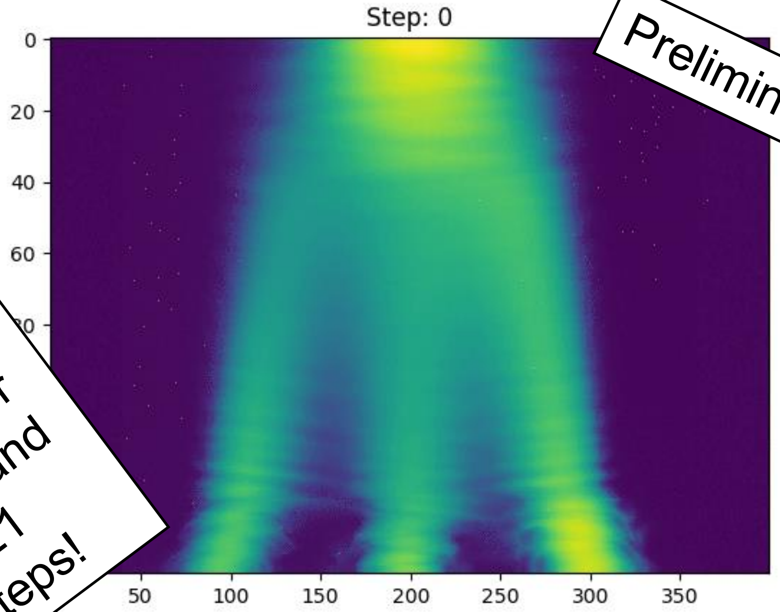
Spare slides


Bunch intensity
unstable
stable
bunches
Bunch length

Bunch-by-bunch spread and optimization

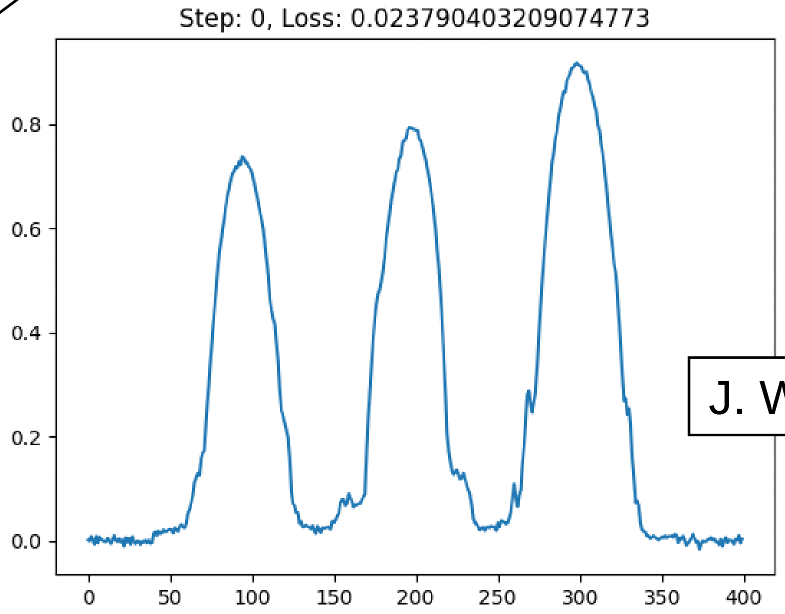






Preliminary!

From +10° phase error in h=14 and h=21 3 steps!



J. Wulff

- Bunch-by-bunch spread already within specifications (+- (5)**10**% intensity and length).

- Development of reinforcement learning to automatize and systematize beam performance.

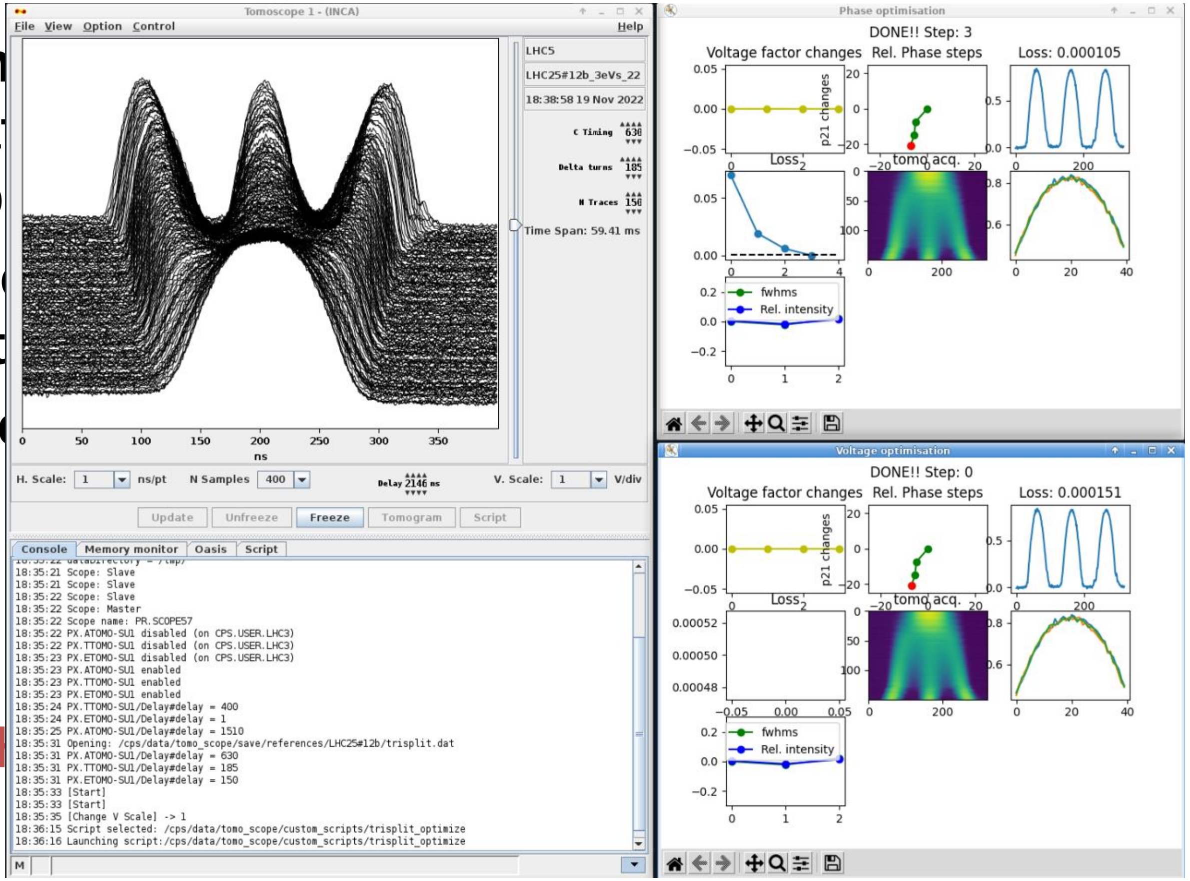
Automatic bunch splitting adjustments

- Reinforcement learnin
application to automat
optimize PS bunch sp

→ Now faster than a spe
or experienced operat

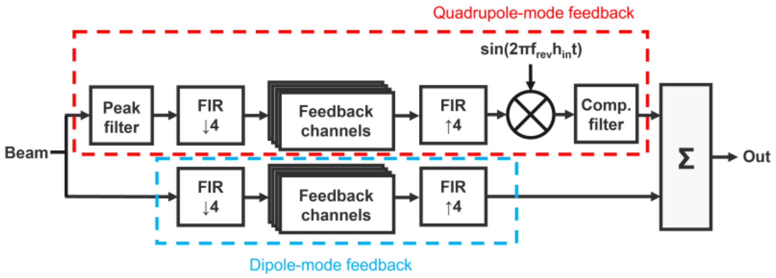
→ Reproducible outcom

→ Well advanced on pat
MDs to operation

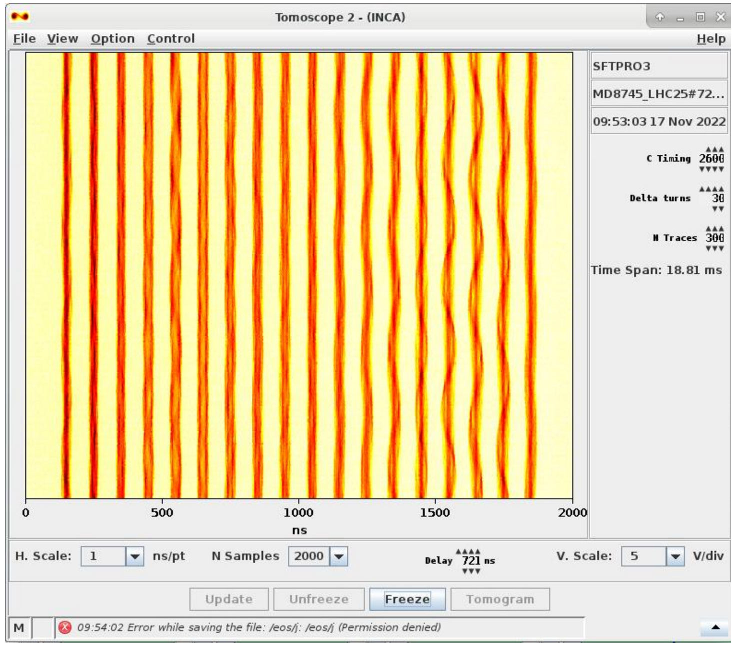


CB Instability and Feedback

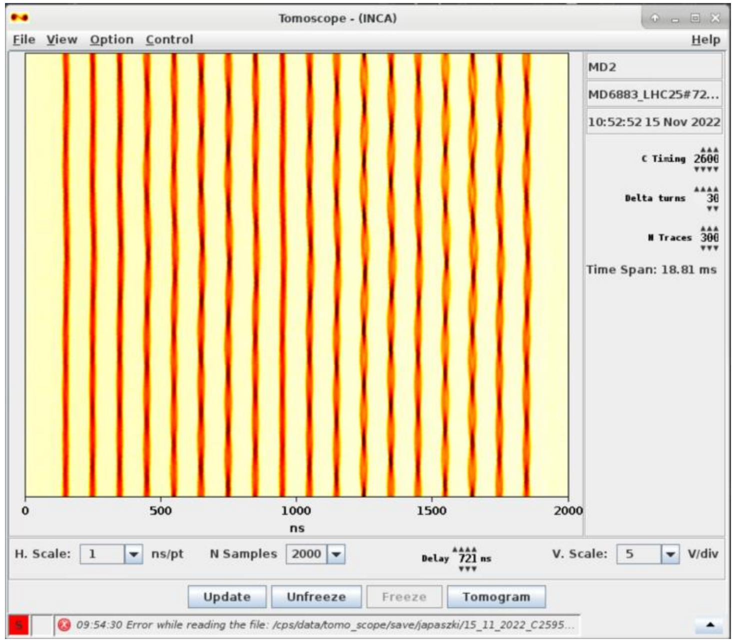
- Frequency-domain approach: one channel per f_{rev} harmonic
- 10 (+6 spare) signal processing channels over 4 PS One-Turn Feedback boards
- Dipole-mode feedback necessary for multi-bunch LHC beam
- Quadrupole-mode feedback relevant for high intensities.



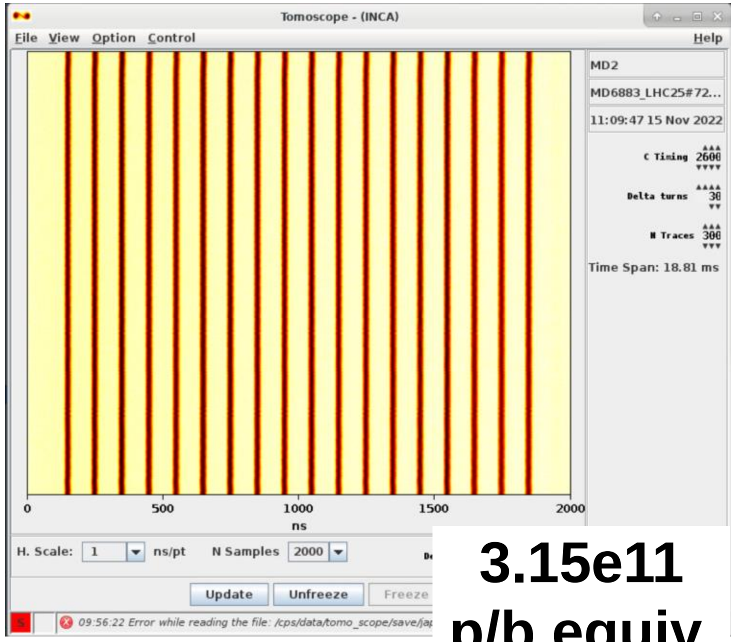
No CBFB



Dipole FB only (no Landau)

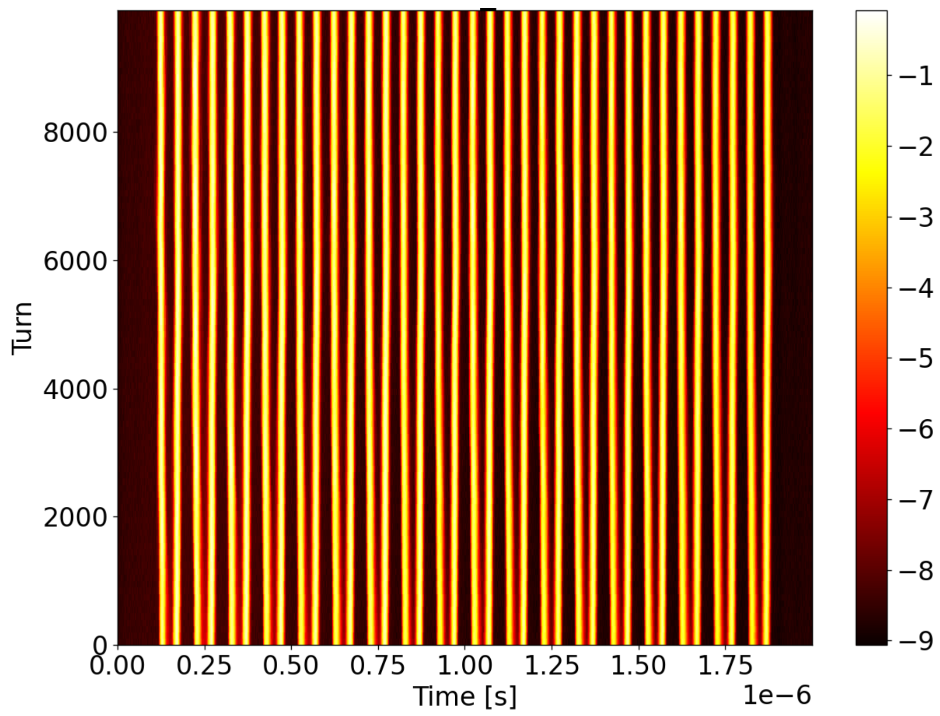


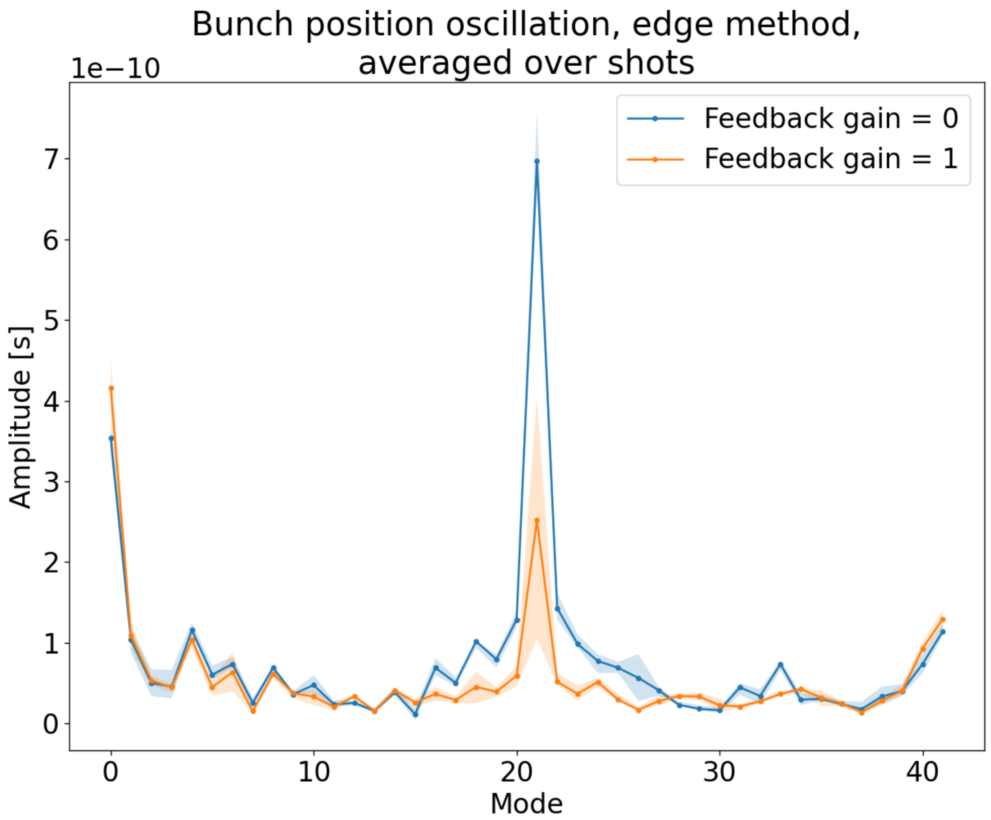
Dipole and quad FBs (no Landau)



3.15e11 p/b equiv.

Oscillations During Splittings in PS



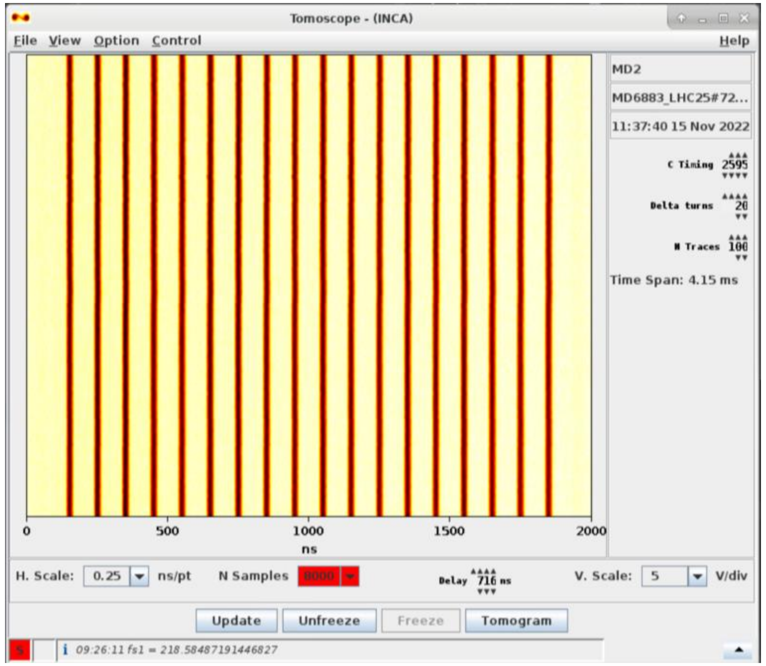


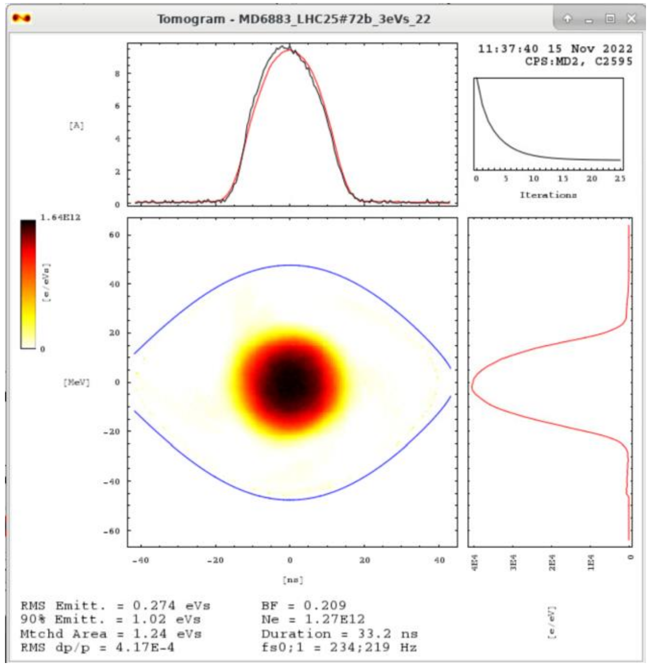
Investigations are ongoing to see if the spare CBFB channels can help

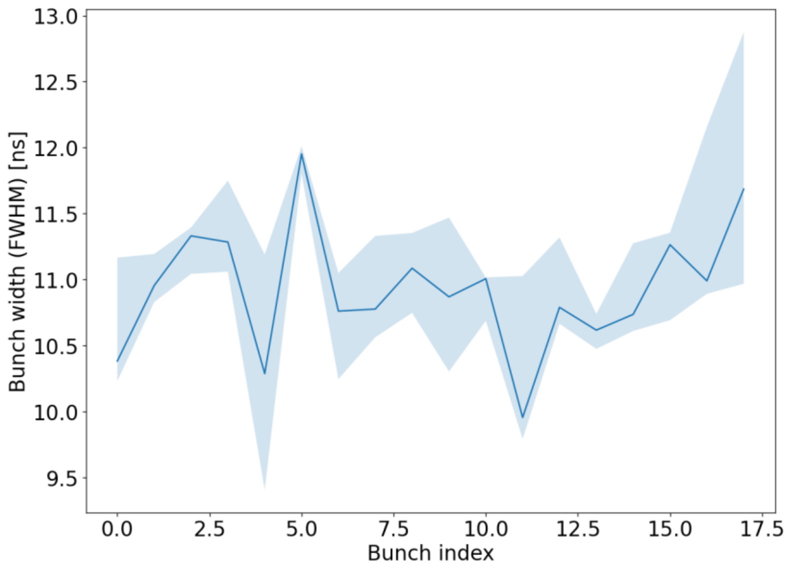
E.g., Feedback on h21 after the first double splitting suppresses oscillations

Quadrupole Feedback at High Intensity

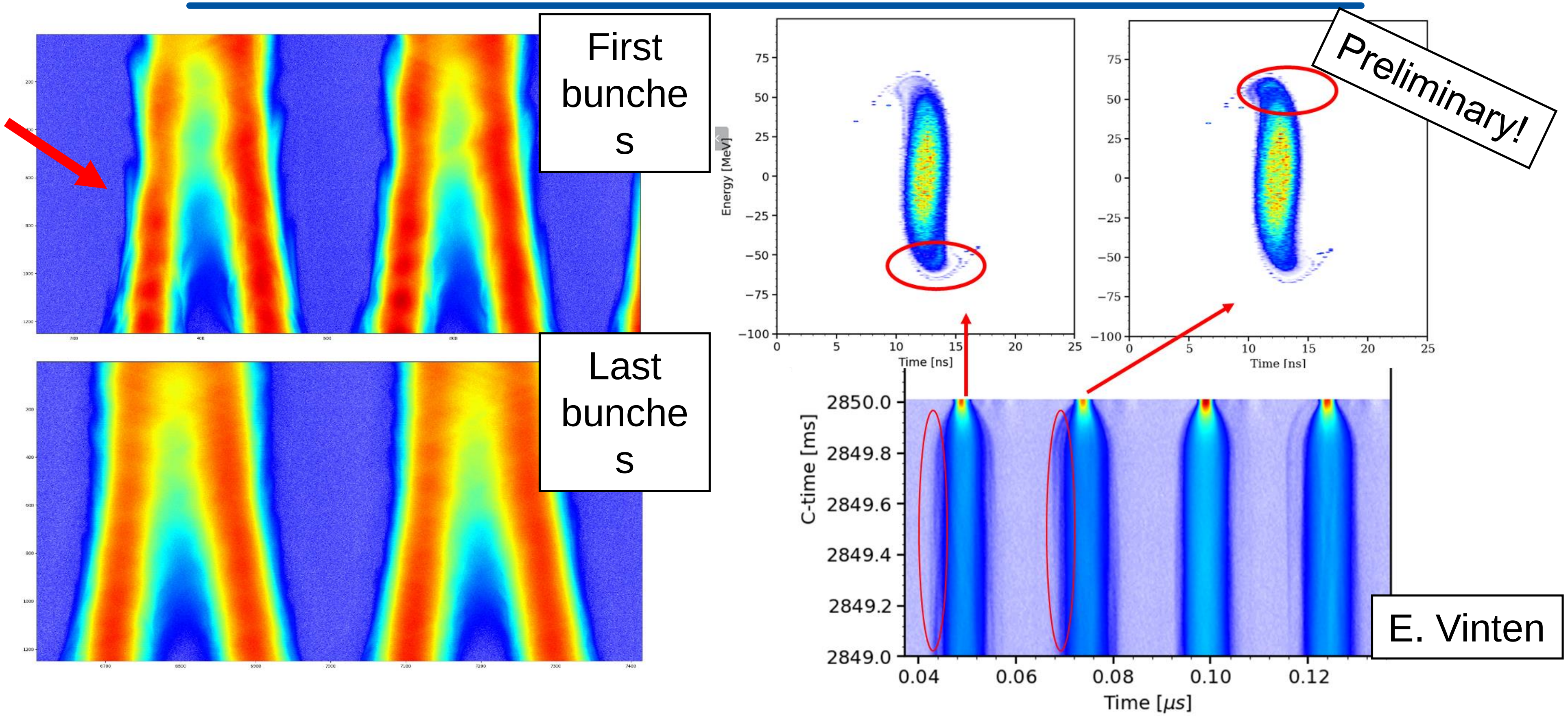
- **1.02 eVs 90% emittance on arrival at flat-top at 3.15e11 p/b equiv.**
  - Quadrupole feedback on
  - 40 and 80 MHz cavities cause issues above 3.0e11 p/b (still plenty of margin above LIU baseline): off for these tests
- **Emittance limited by instabilities at transition crossing.**







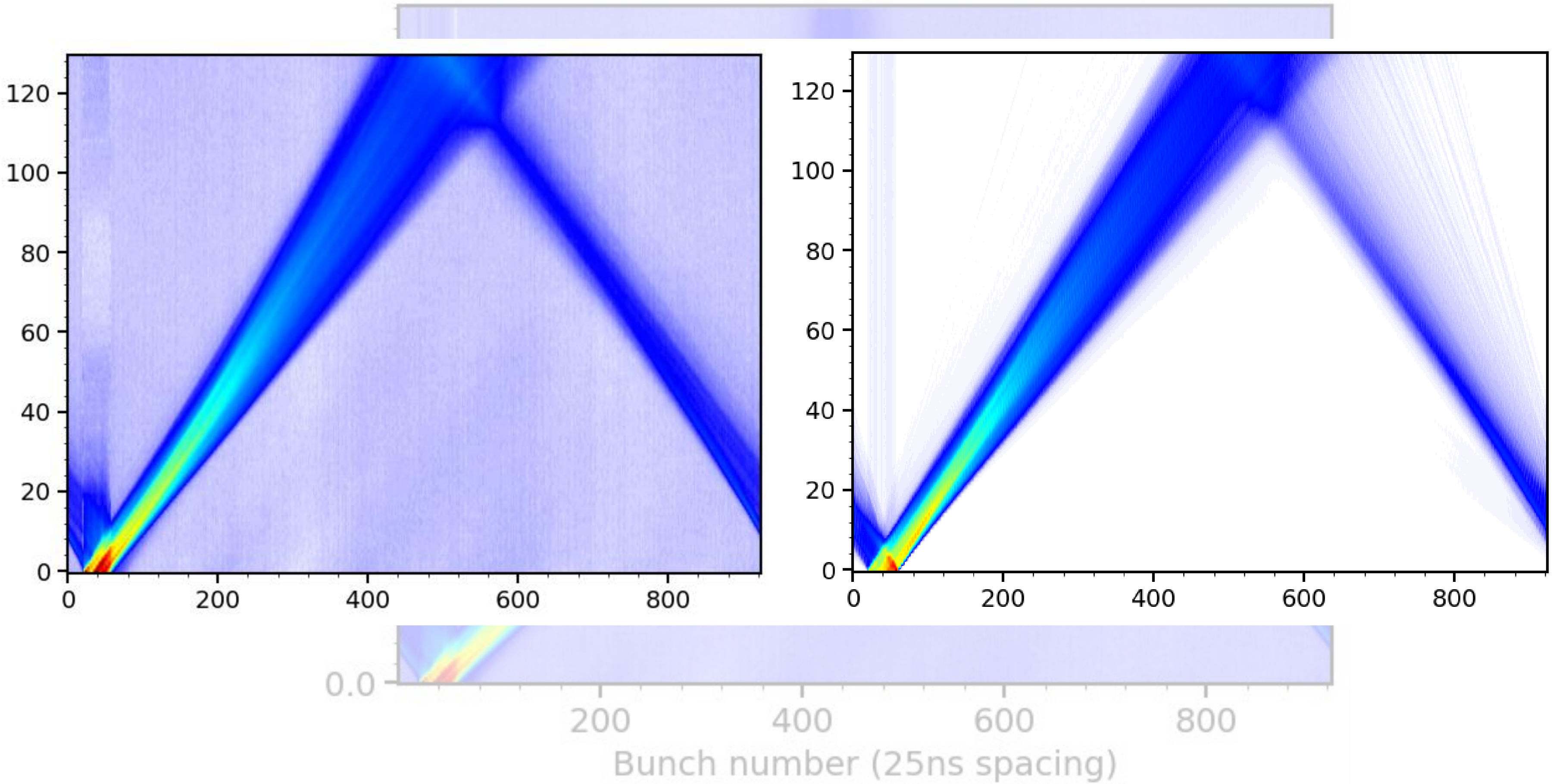
Longitudinal halo at PS-SPS transfer



- Sources of longitudinal halo are being investigated (oscillations during splittings, uncontrolled emittance blow-up).

- Necessary hardware and settings were re-setup to do MDs with longitudinal shaving and linearization of the bunch rotation, guided by improved observables (tomography during bunch rotation).

Tomography of uncaptured beam



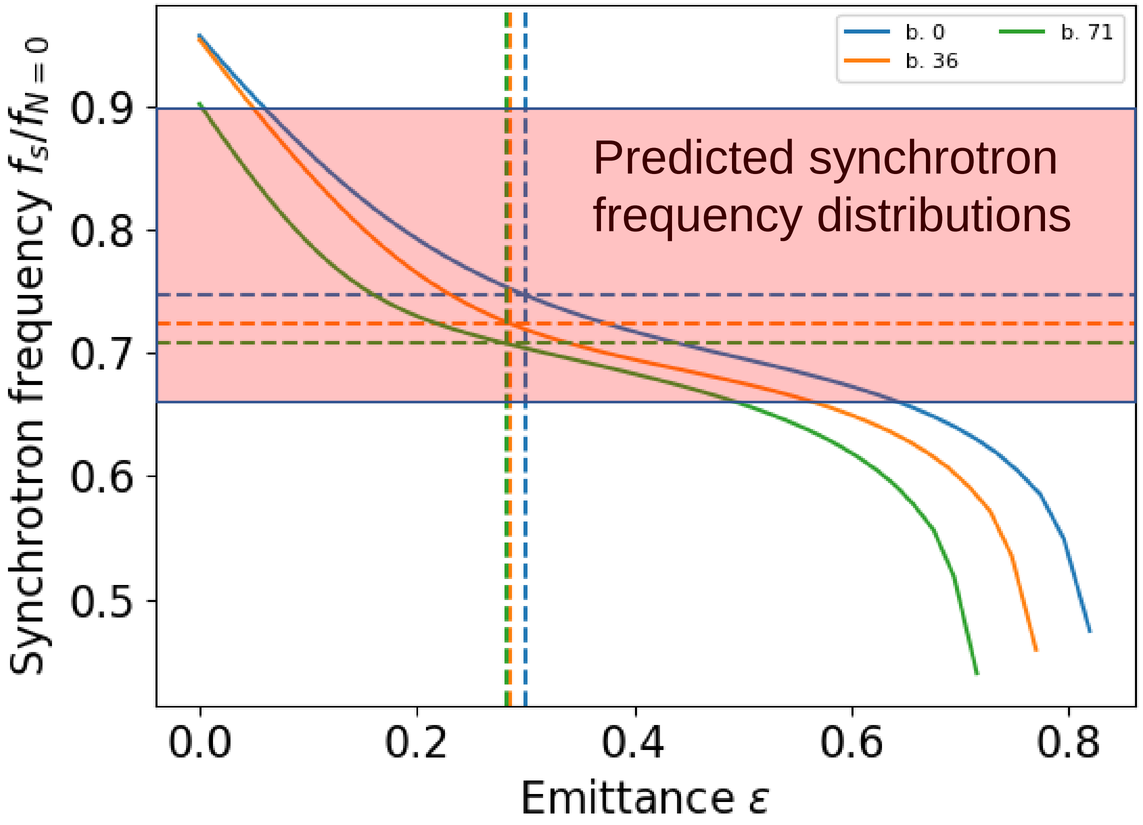
- Custom tomography applied only on particles outside of the SPS buckets (and important data treatment).
- No synchrotron period, but backprojection over ~ revolution period is enough for the back projection.

Hardware Reliability Aspects

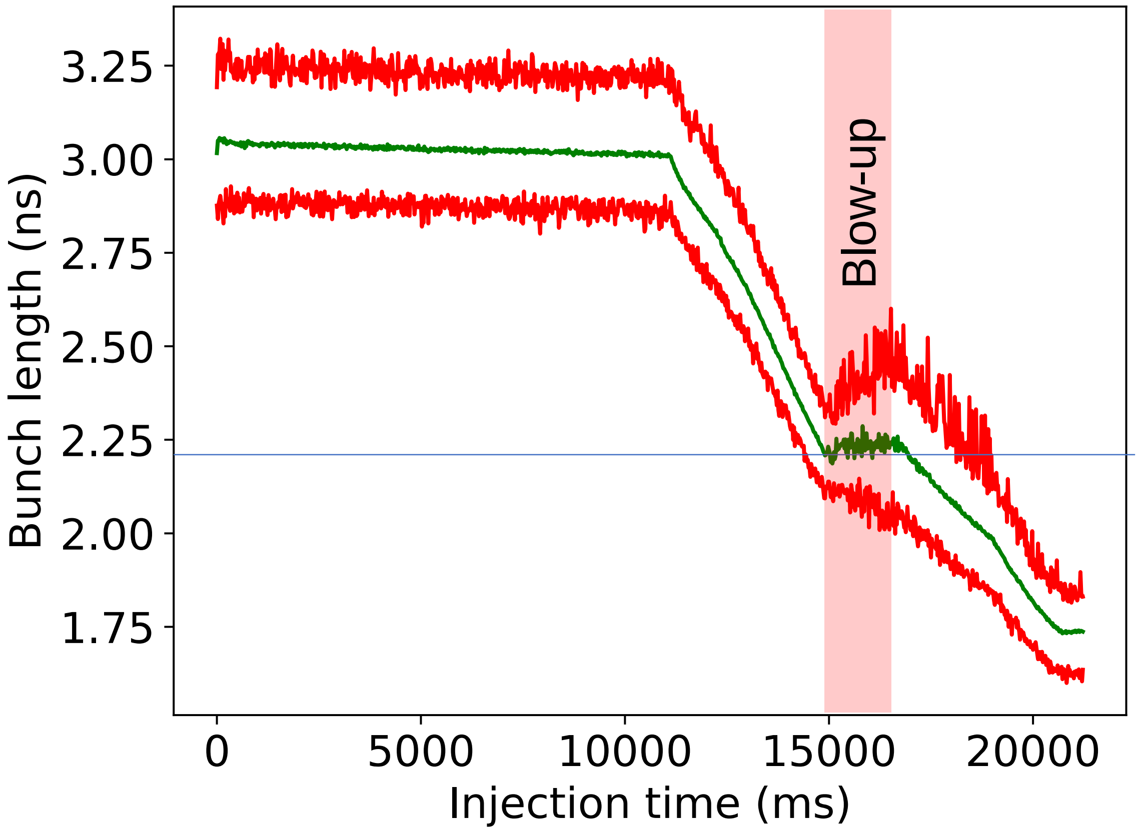
- The presently reached performance in intensity for LHC-type beams is 3.2e11 protons per bunch (p/b), beyond the LIU requirements of 2.6e11 p/b
- At that intensity, high frequency cavities (40/80MHz) trip more frequently
  - not critical as plenty of margin above LIU baseline available.
- Careful analysis of cavity faults and statistics
  - Teething issues of new interlocks (originally set without beam)
  - Adjustments of the cavity tuning and feedbacks
  - Work is ongoing - some faults have already been resolved and.
- Remaining faults identified and being addressed: coarse tuning and crowbar on final amplifier
  - These do not appear to be related to the present LHC-type beam performance.

Example of well-adjusted settings

Bunch length 2 ns, 72 bunches, 1.8e11 ppb



Acceleration of 72 bunches with 1.8e11



→ Bunch length stays constant during blow-up + beam stable at the SPS flat top

→ Frequency margins do not fully agree with predictions (different 800 MHz RF voltage?)

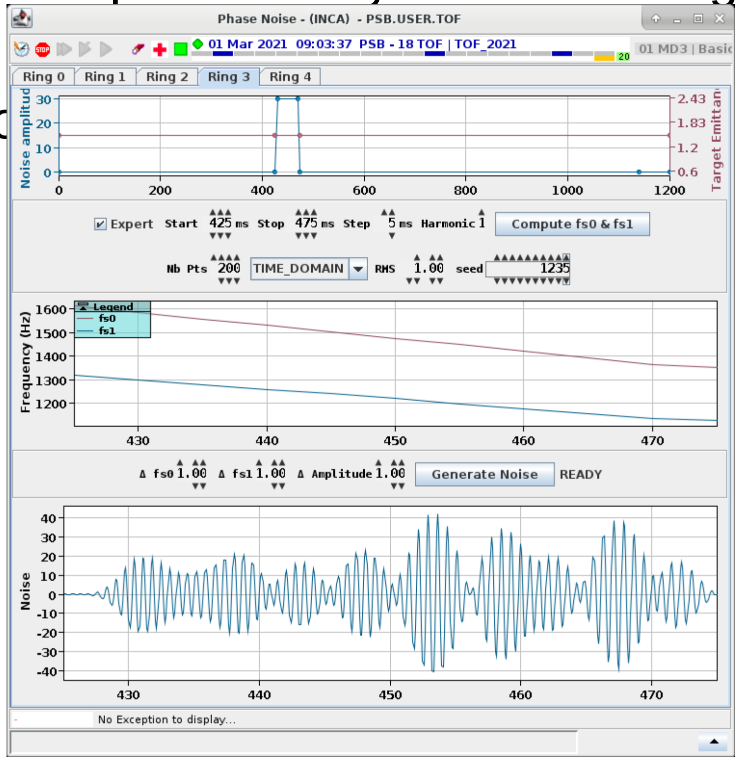
Production of 3 eVs variant

LIU target longitudinal emittance of 3 eVs is required to mitigate space charge effects on PS flat bottom

Fully operational in 2022

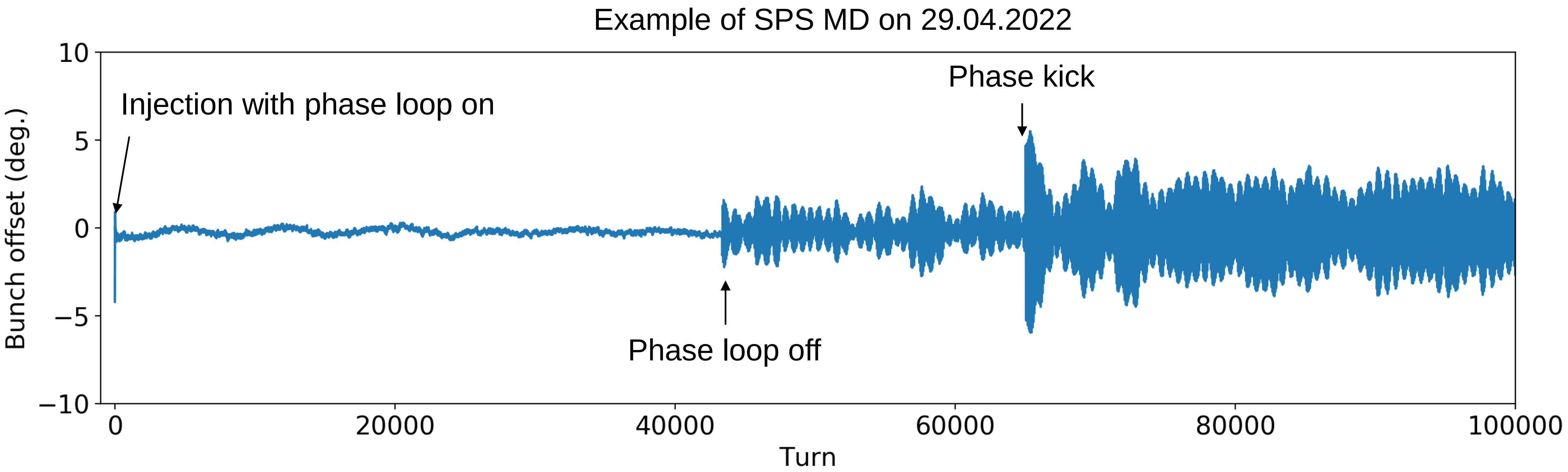
-> two

- Requires setup of **phase noise blow-up** to improve reproducibility and achieve goal
- Commissioning started in early 2021, **to be made**
- **Performance tracking** of longitudinal emittance to be put in place to **identify deviations** at an early stage



Beam-based measurements of LLD threshold

Different measurements were performed before LS2 (*J. E. Muller, PhD thesis, 2016)*



→ This technique is already used in the SPS and PS *(PhD project of L. Intelisano)*

→ Precise knowledge of RF voltage is important *(see details in talk by B. Karlsen-Baeck)*

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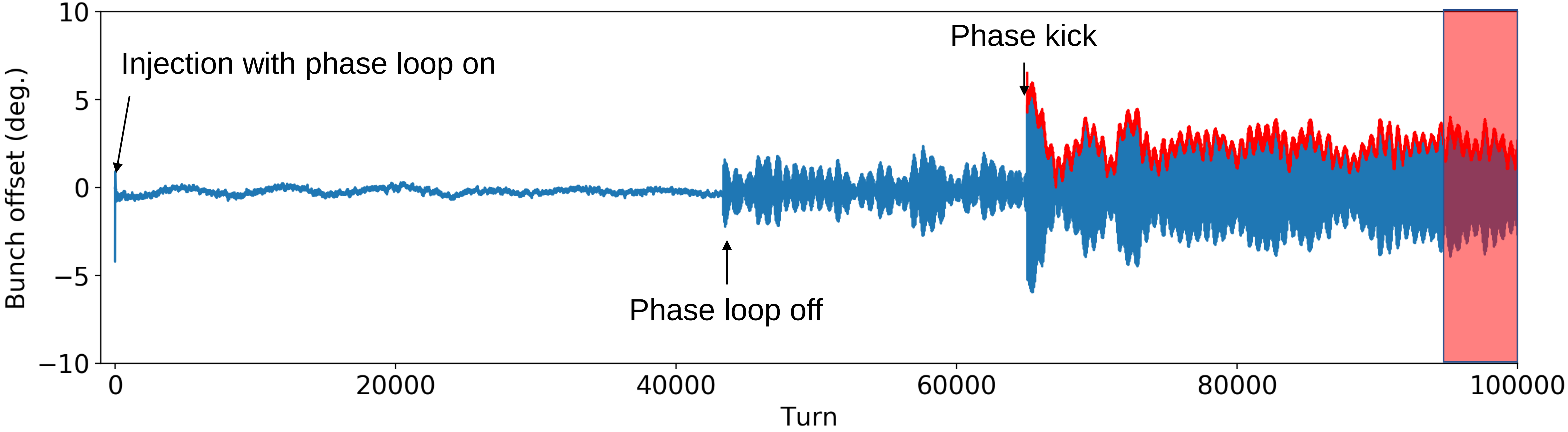
Example of SPS MD on 29.04.2022



→ This technique is already used in the SPS and PS *(PhD project of L. Intelisano)*
→ Precise knowledge of RF voltage is important *(see details in talk by B. Karlsen-Baeck)*
→ Residual oscillation amplitude contains information about impedance
(IK, T. Argyropoulos, and E. Shaposhnikova, PRAB, 2021)

Intensity reach in 2022

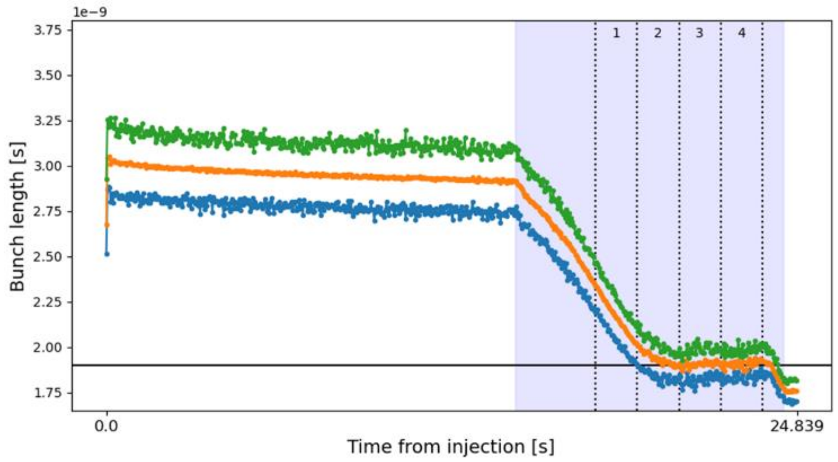
Standard
4x72x1.63e11 - reached after a few days of scrubbing but for very long bunches (> 2 ns); Used during HiRadMat

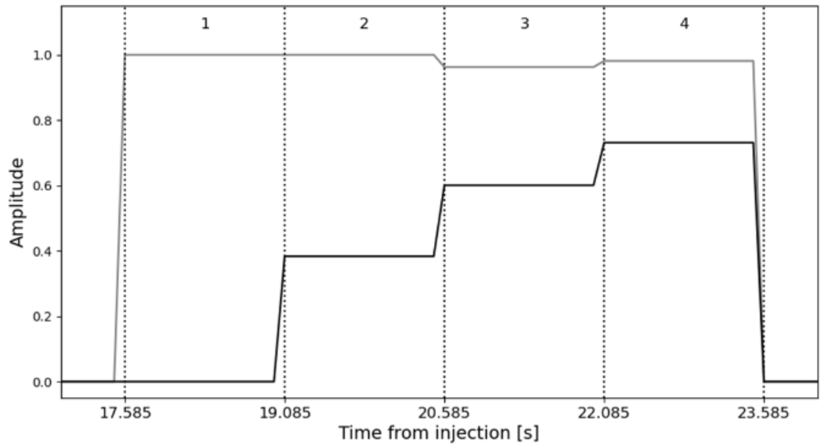
BCMS
5x48x1.8e11 - accelerated during MD after summer, however, the 36-bunch variant had to be used during LHC MDs in November

8b4e
5x56x1.6e11 – maximum intensity is limited by interlock on the vacuum of C1 800 MHz cavity

Longitudinal stability is maintained thanks to optimized RF voltage programs and controlled emittance blow-up

Results of automated blow-up amplitude adjustment

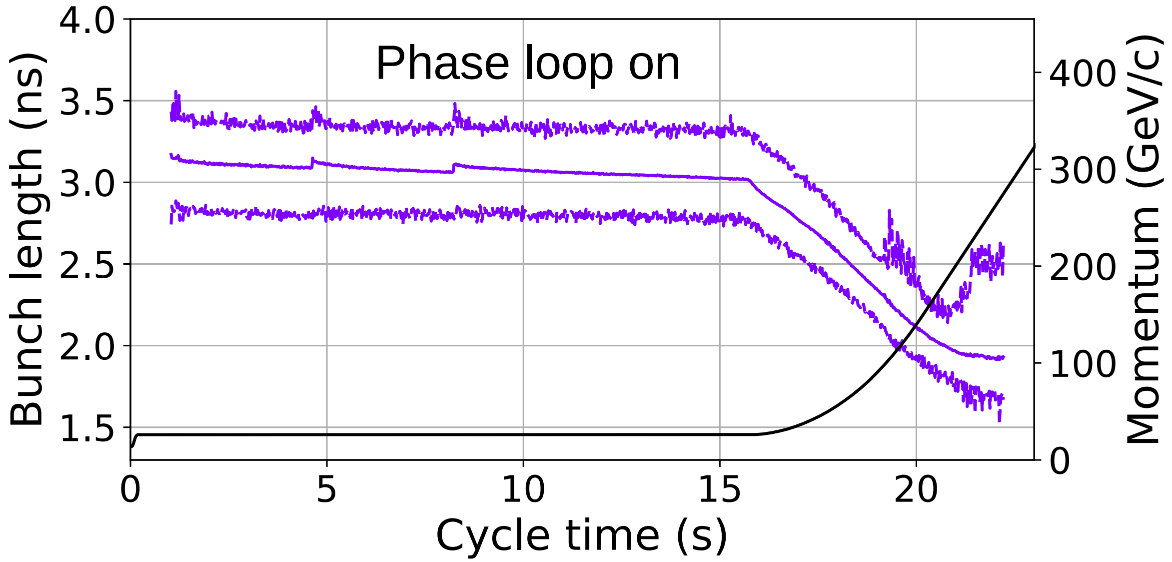


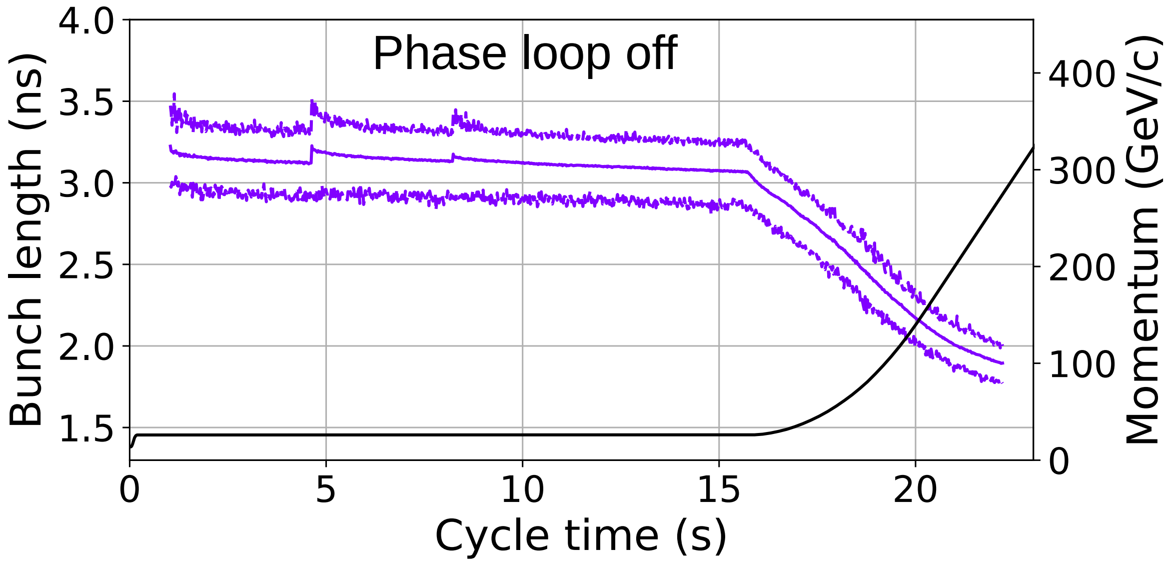


Latest observations and open questions

4x48 and 5x48 bunches with 2.3e11 p/b become "unstable" early in the ramp

Similar behavior is already present for 1.9e11 p/b for more than one batch, but unclear if impedance driven





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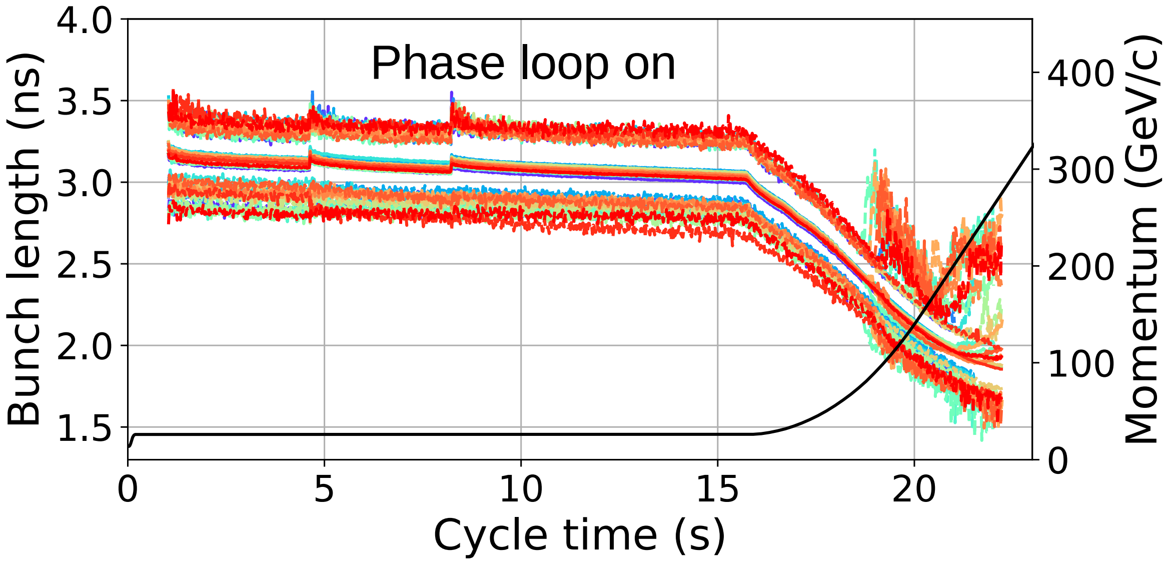
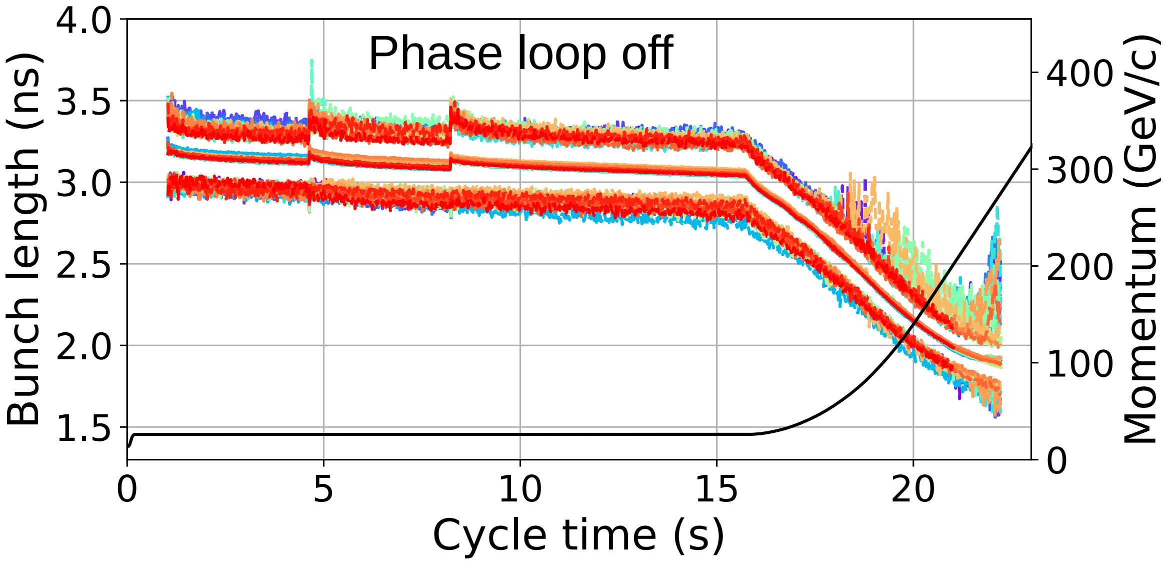




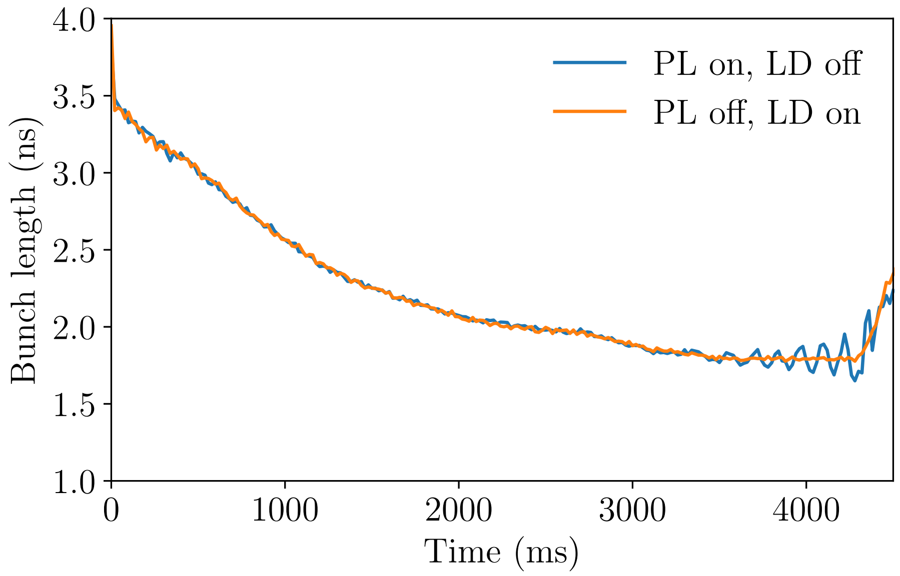
Some hints

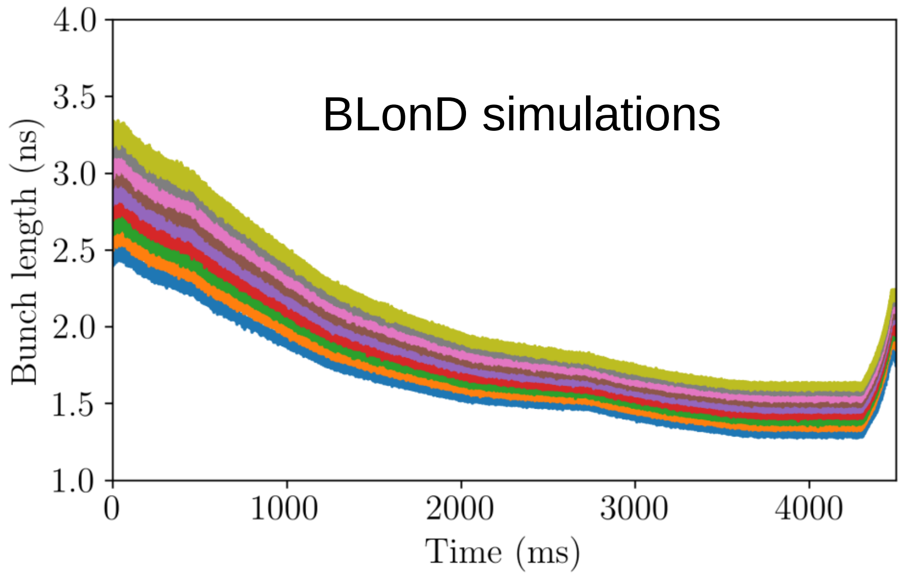
High-intensity single bunches (AWAKE cycle with 3e11) become unstable during acceleration

→ Temporarily solved by opening phase loop at the beginning of the ramp

→ Simulations without loops and noise indicate that bunches remain stable

Does bunch length oscillate due to some external excitation?





Status of SPS LLRF

All feedback loops are operational (polar loop, one-turn delay feedback including low pass branch)
100 % amplitude modulation
Longitudinal damper

LIU Commissioning of Feed forward

- Reduce transient beam loading already the **2nd turn**
- Improve transient beam loading compensation at **head & tail** of the batch

Firmware update during YETS for compatibility with Feedforward and AM

Key ingredients

- Increased RF power (peak power limits reached for AWAKE cycle)
- Longitudinal damper and amplitude modulation (presentation of G. Hagmann)
- Adjustments on PS side (e.g., bunch rotation, controlled emittance blow-up, presentation of A. Lasheen)
- Voltage programs and controlled emittance blow-up optimization, this talk

RF power requirements

Cavity voltage

RF component of beam current

RF power $$P = A\,V_{cav}^2 + BI_{beam}^2 + CV_{cav}I_{beam}$$

Two regimes

- High beam loading – LHC 25ns & SFTPRO
- No beam loading – AWAKE & LHCION

Expected performance: peak 1/1.6 MW and average 600/800 kW for 3/4 section cavities

Thanks to amplitude modulation, mostly the peak power limits are relevant for LIU beams, but average power limits must be also respected

Optimizations at flat bottom

Amplitude modulation

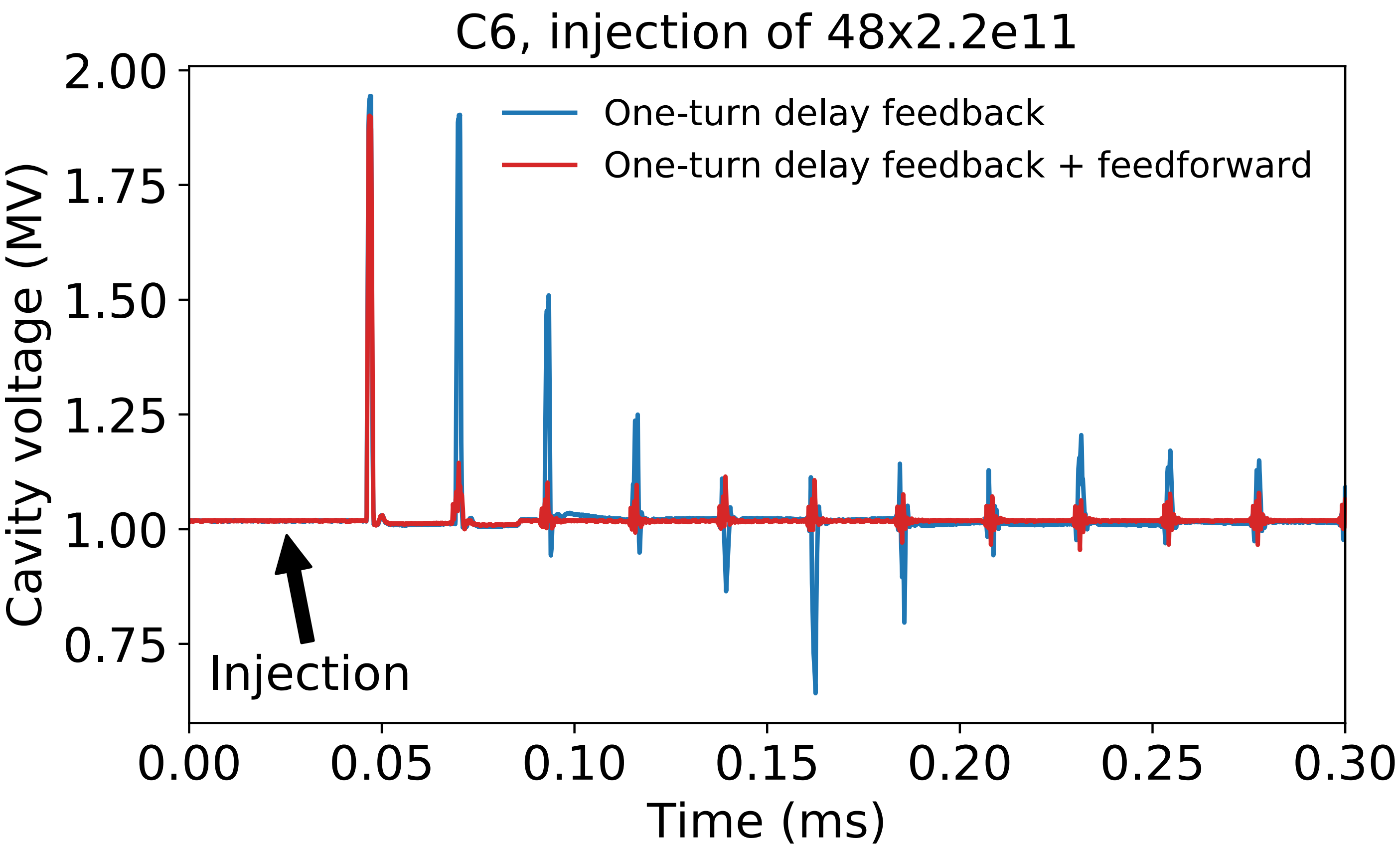
- Allows using maximum peak RF power for LHC-type cycles

Longitudinal damper

- Prevent emittance blow-ups for multiple injections
- Smaller longitudinal emittance from PS is preferable for the efficient use of 800 MHz RF system *(M. Schwarz, LIU SPS BD WG, 21.02.2019)*

Feedforward

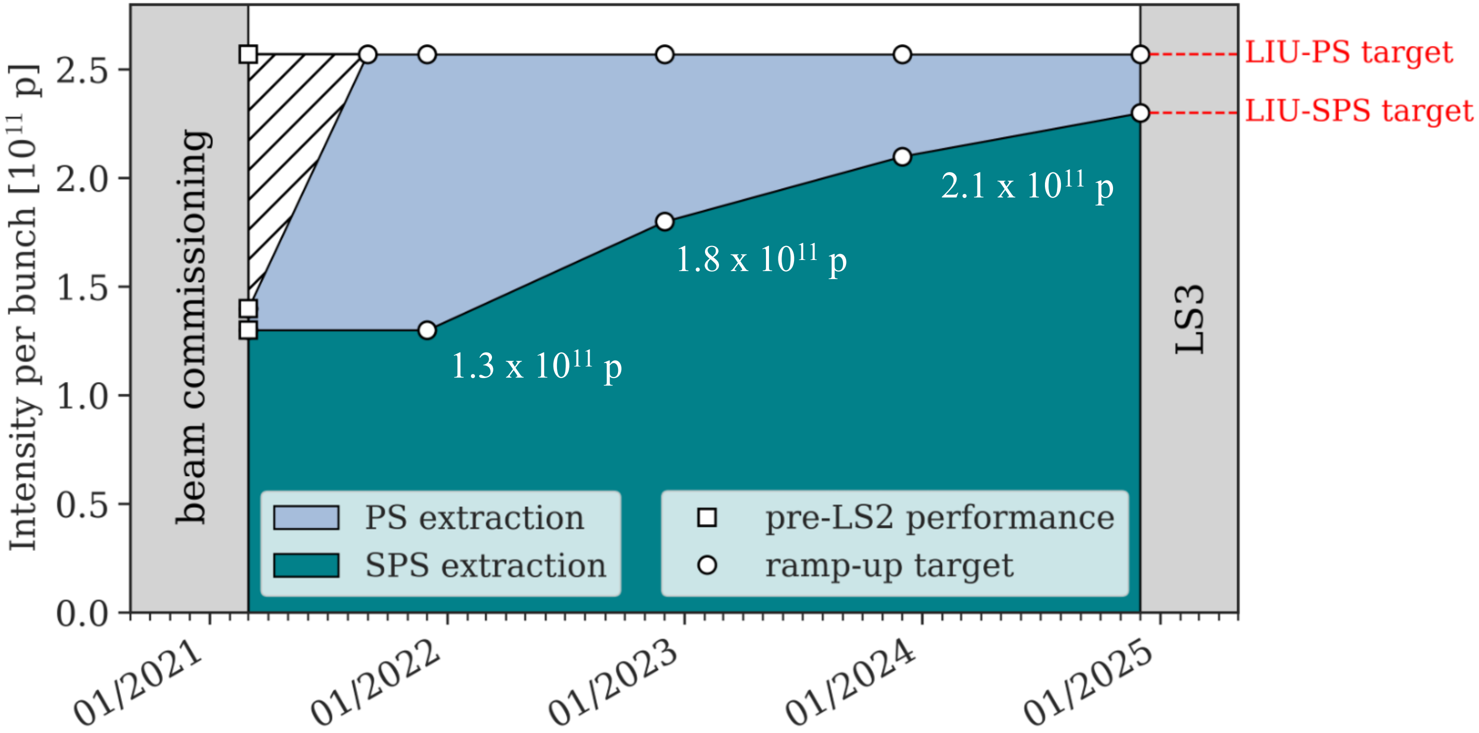
- Reduce transient beam loading already the **2nd turn**
- Improvement of capture losses to be further studied in MDs. Firmware update during YETS is required for



LIU performance ramp-up plan - a reminder from Montreux 2020

Intensity ramp-up for the LIU beams (normally standard)

- LIU-PS intensity target successfully recovered in 2021
- The plan for the gradual ramp-up of SPS intensity until the end of 2024 **remains unchanged**



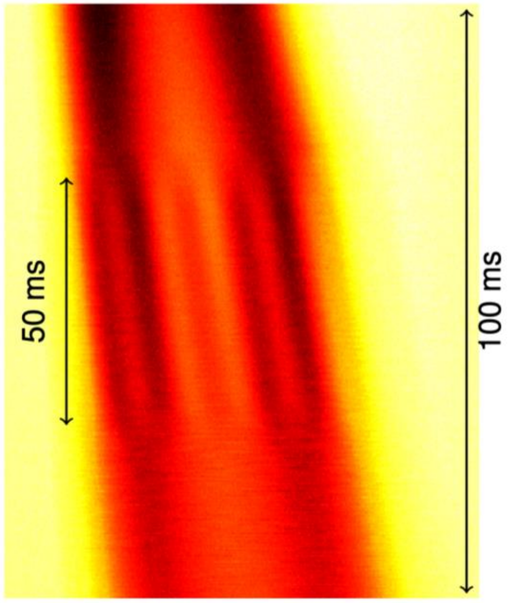
Other types of beams are tested and prepared during the year (BCMS, 8b4e, hybrid 8b4e + BCMS)

Production of 3 eVs

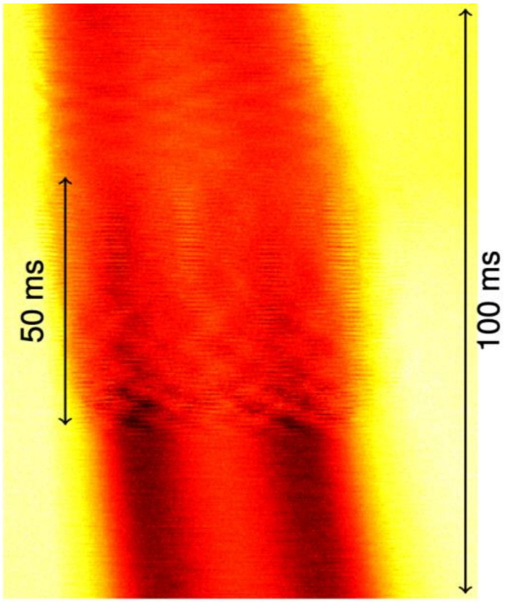
LIU target longitudinal emittance of 3 eVs is required to mitigate space charge effects on PS flat bottom.

It became fully operational in 2022 and requires a controlled longitudinal blow-up.
Two methods are available:

Phase modulation of the 10th harmonic (operational)

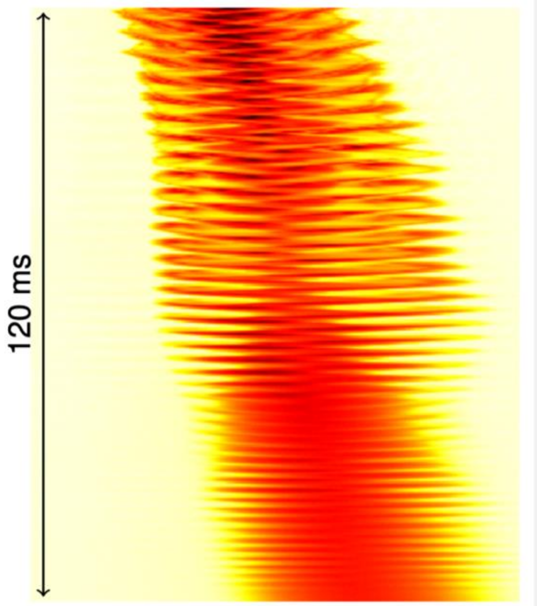


Example not from an LHC cycle



Example not from an LHC cycle

Band limited phase noise



Example not from an LHC cycle

→ Both have their pros and cons, but phase noise is a preferred option for the future.

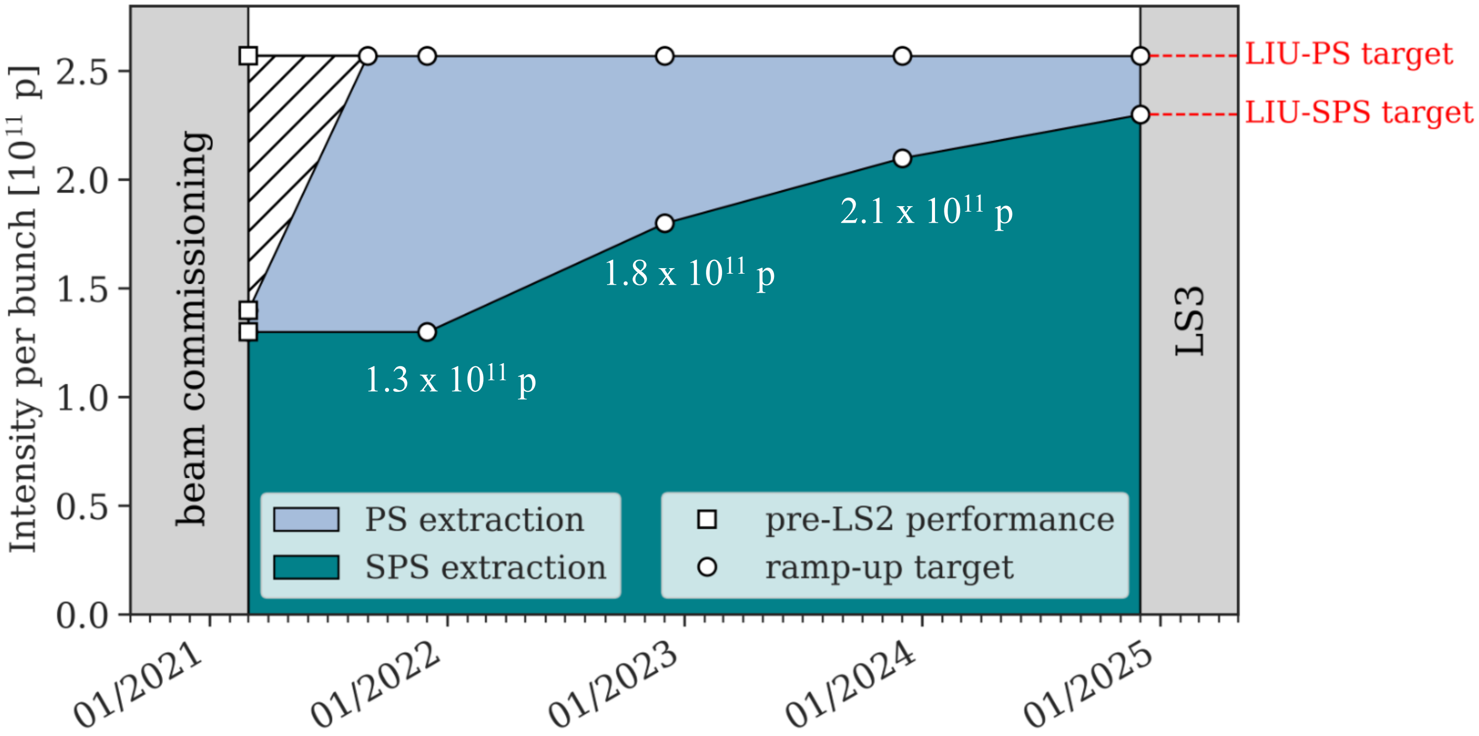
LIU performance ramp-up plan* - reminder

LIU target beam parameters at LHC injection (from EDMS1296306)

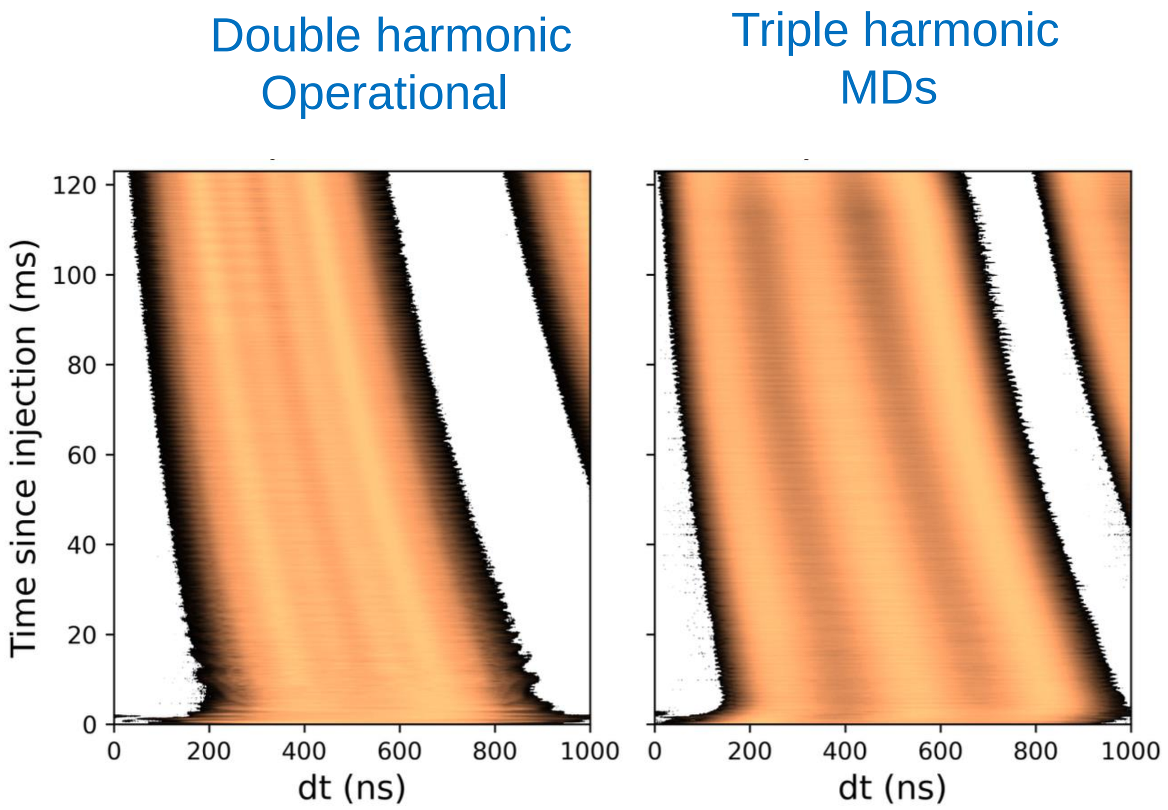
	intensity per bunch	transverse emittance [μm]	bunch length [ns]	longitudinal emittance [eVs]	number of bunches
Standard beam	$\mathbf{2.32 \times 10^{11}}$	**2.1**	1.65	0.57	4 x 72

Brightness ramp-up
→ determined by the PSB and PS performance (details in C. Zannini's talk); Longitudinal aspects are discussed here

Intensity ramp-up for the standard beam
-> LIU-PS intensity target successfully recovered in 2021; PS2SPS transfer studies ongoing
-> Plan for the gradual ramp-up of SPS intensity until the end of 2024 **remains unchanged**
RF issues in talk of A. Lasheen



Triple harmonic



Double harmonic (bunch lengthening) has been a routine part of PSB operation for a long time, both for space charge reduction and beam stability

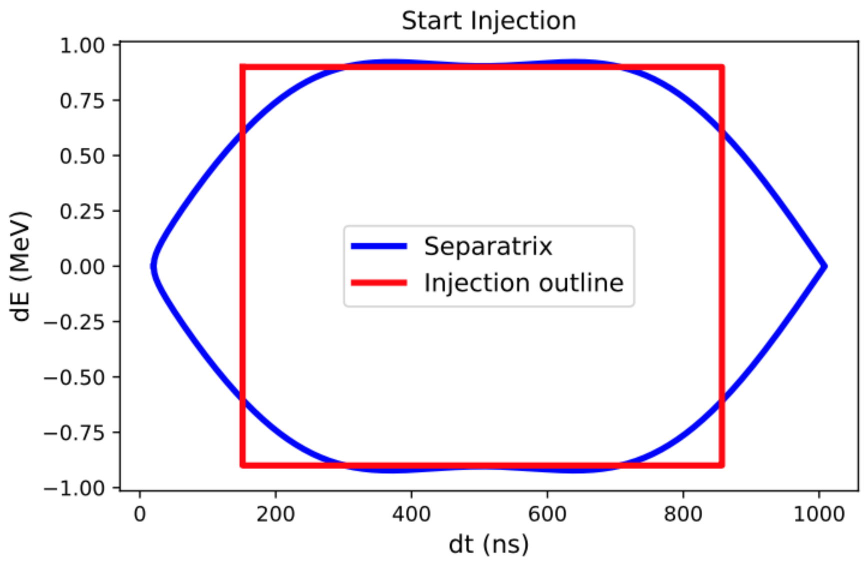
With the new Finemet RF systems, it becomes possible to add the third harmonic, further lengthening the bunch and reducing the line density

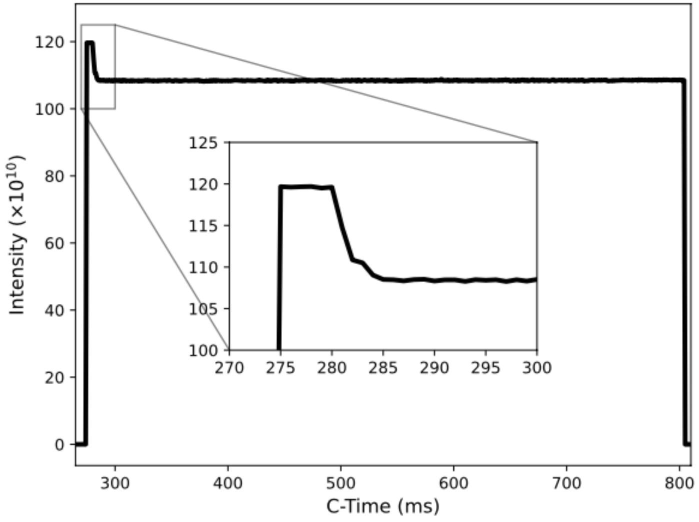
→ The improvement in brightness has been demonstrated
(see C. Zannini’s talk)

Longitudinal tails and losses

Capture Losses

- By design, there is a fast beam loss at the start of acceleration for all LHC multi-bunch physics beams
- Large energy spread beams are injected to reduce the transverse density and therefore tune spread
- A small dip in the bucket area at the start of the ramp is used to shave off the longitudinal tails





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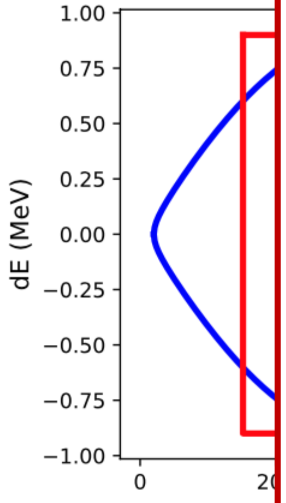

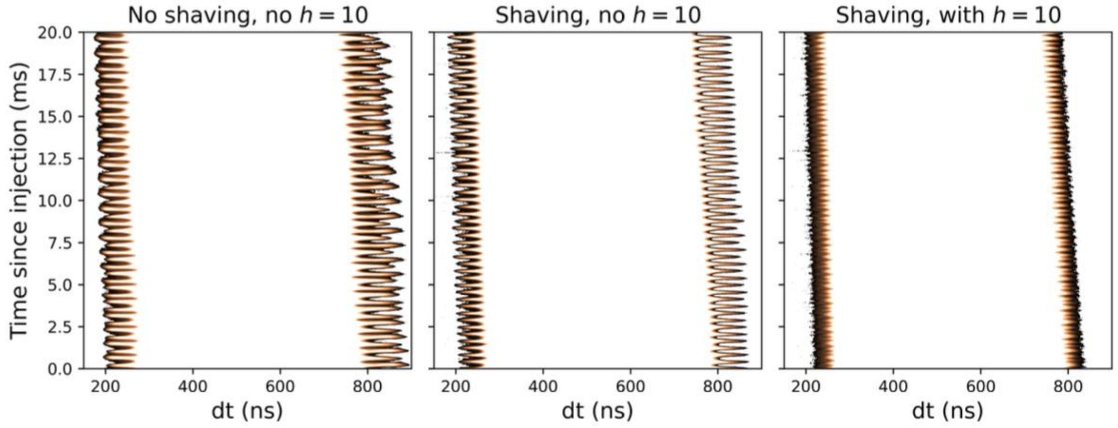

- With no shaving and no $h = 10$ component, strong longitudinal tails are present
- With shaving, the tails are reduced but not eliminated
- With shaving and $h = 10$, the tails are almost entirely removed