Longitudinal aspects of the intensity limitations in the injectors

Simon Albright, Philippe Baudrenghien, Niky Bruchon, Rama Calaga, Gino Cipolla, Heiko Damerau, Frank Gerigk,
Gregoire Hagmann, Leandro Intelisano, Ivan Karpov, Alexandre Lasheen, Eric Montesinos, Giulia Papotti,
Danilo Quartullo, Suitbert Ramberger, Christophe Renaud, Carlo Rossi, Arthur Spierer, Evin Vinten, Ben Wooley

Acknowledgments: Foteini Asvesta, Hannes Bartosik, Alexander Huschauer, Giovanni Iadarola,
Elena de la Fuente, Verena Kain, Kevin Li, Ingrid Mases, Lotta Mether, Bettina Mikulec, Konstantinos Paraschou,
Giovanni Rumolo, Benoit Salvant, Michael Schenk, Francesco Maria Velotti, Carlo Zannini,
and many other OP, ABP, and RF team members

Joint Accelerator Performance Workshop, 5-7 December 2023

Reminder of LIU target

Key longitudinal parameters at injection for Standard beam

	Emittance (eVs)	Length (ns)	# particles
PS	3	205	3.25×10^{12}
SPS	0.35	4	2.57×10^{11}
LHC	0.56	1.65	2.32×10^{11}

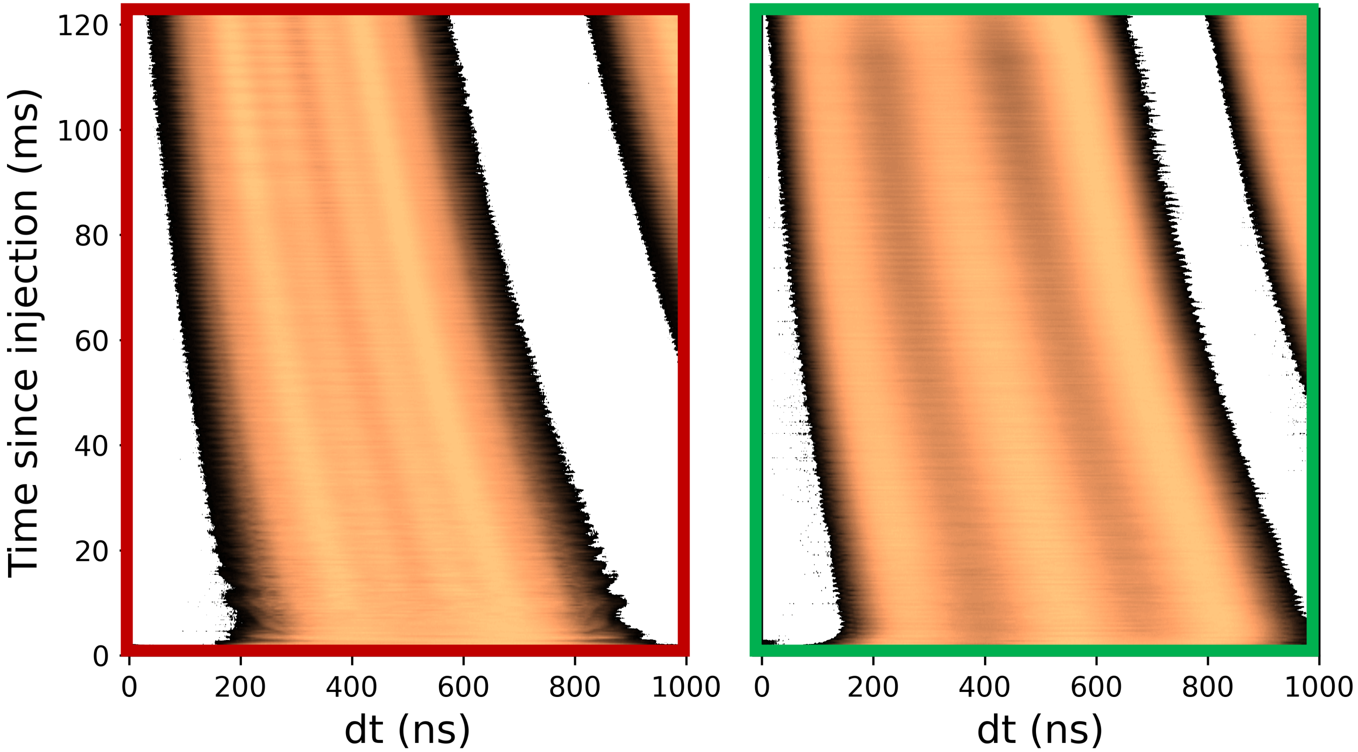
EDMS1296306

What are the remaining limitations in reaching LIU performance?

PSB

PSB: multi-harmonic configurations

Limitations only for beam parameters far beyond the LIU target
→ Room for improvement in brightness and tail population



Double harmonic is still used for production in 2023

Triple harmonic enables either:
- reduced tails (at target brightness)
- increased brightness (with no change in tails)

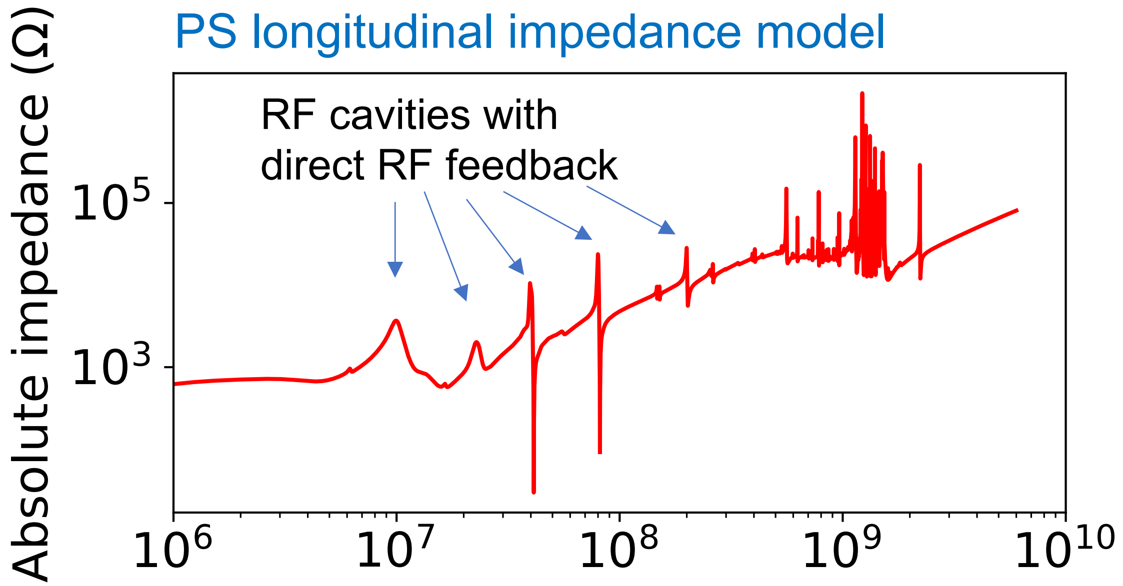
→ Try to make triple harmonic operational in 2024

PS

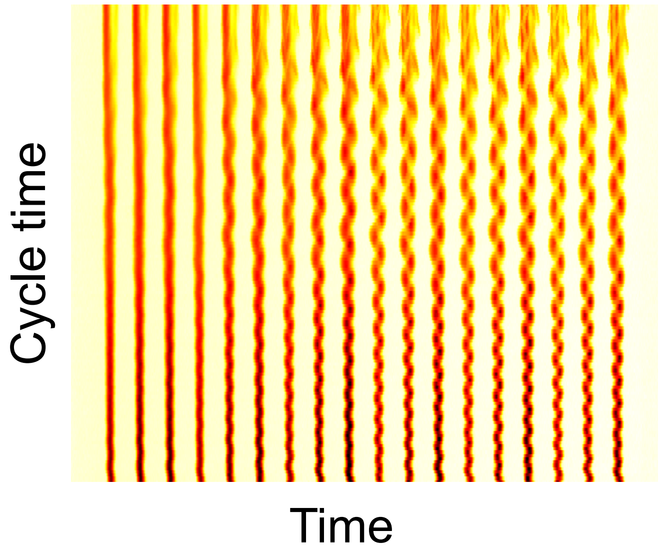
Coupled-bunch instabilities

Necessary complexity and flexibility of RF systems comes with significant contribution to impedance

PS longitudinal impedance model



Example of instability during the setting-up period



Beam stability is guaranteed by:

- the combination of feedback (FB) systems (one-turn delay, multi-harmonic, coupled-bunch)
- 40 MHz RF system as 4th-harmonic Landau system
- controlled emittance blow-up with a 200 MHz RF system

Peak performance

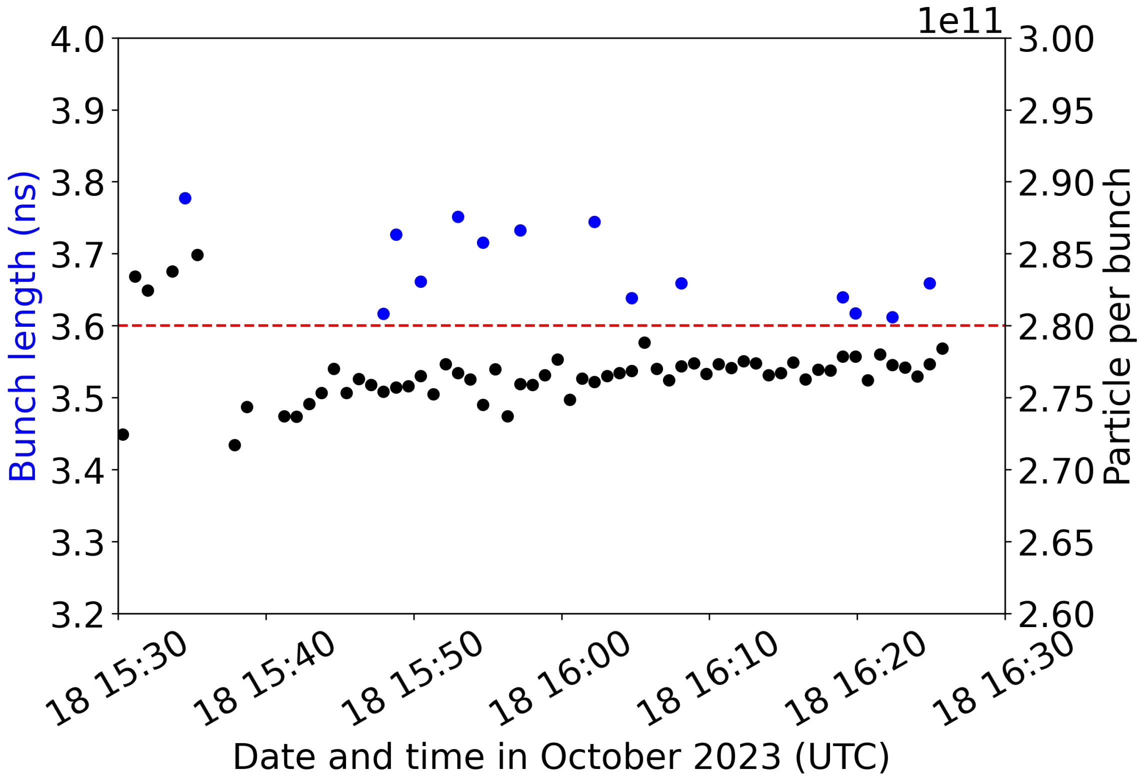
Beam stability for the LIU target and beyond has been demonstrated since 2018

Bunch length of 4 ns might not be sufficient for SPS transverse stability *(see talk of I. Mases)*

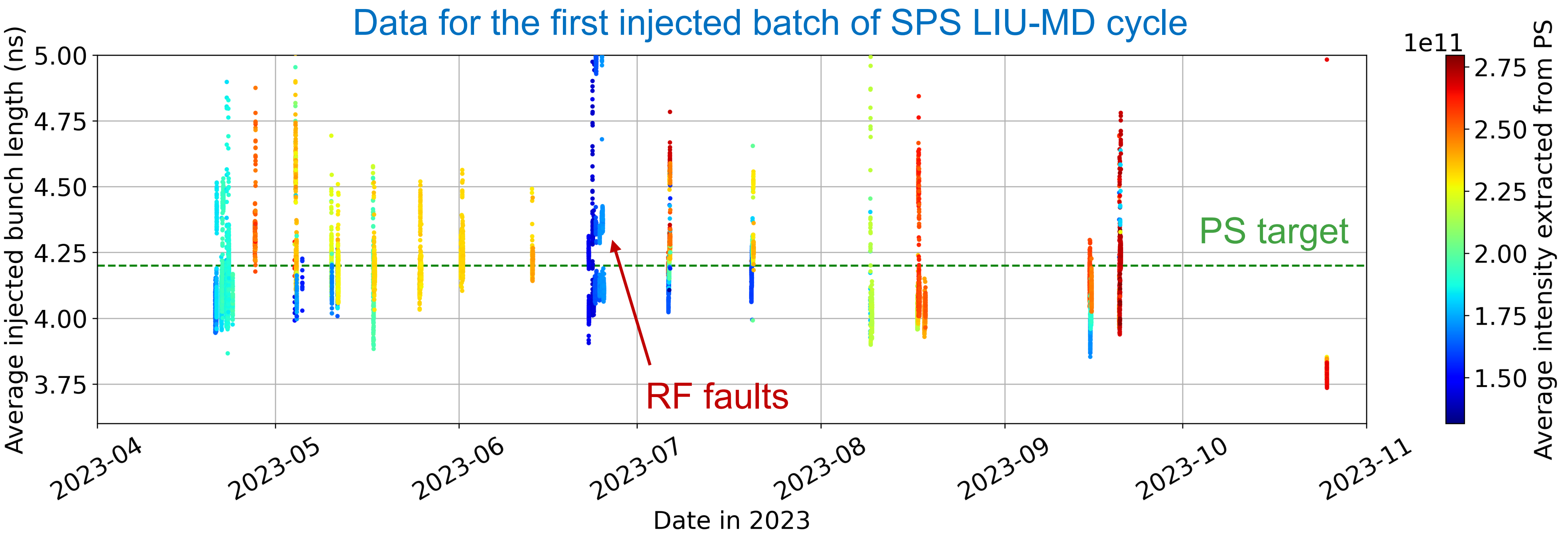
→ MDs in PS demonstrated a possible reduction to 3.6 ns up to beam intensity of 2.8×10^{11} (small margin due to space charge limit at 2 GeV)

→ Future MDs should address the smallest longitudinal emittance for LIU intensity for all variants (especially a 36-bunch variant requires additional development)

Beam parameters during MD



Availability vs intensity

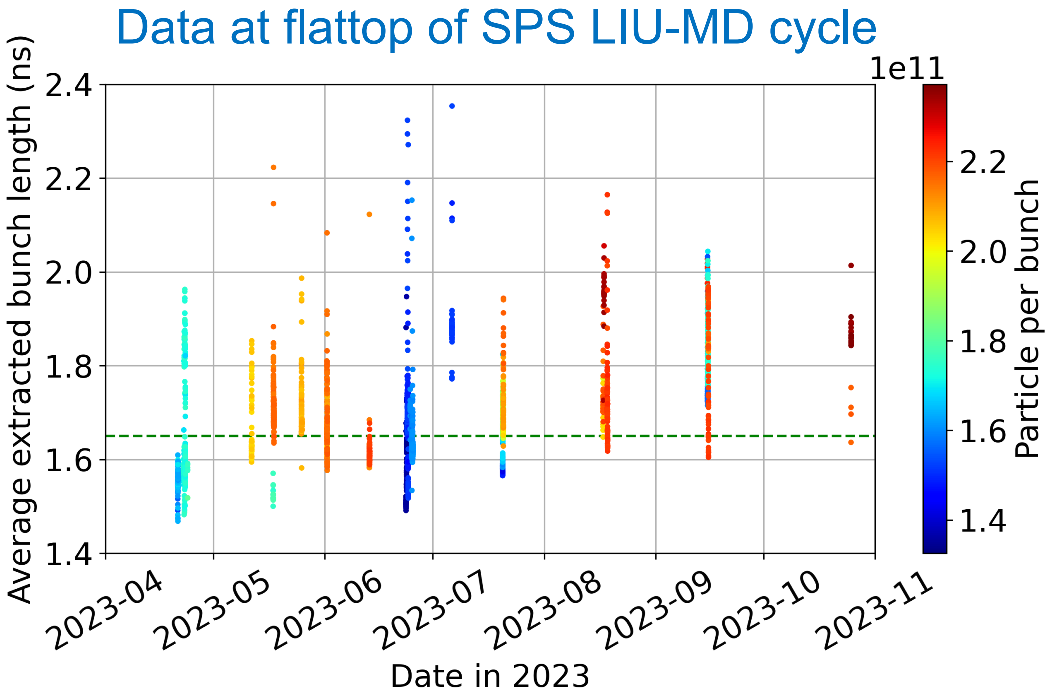


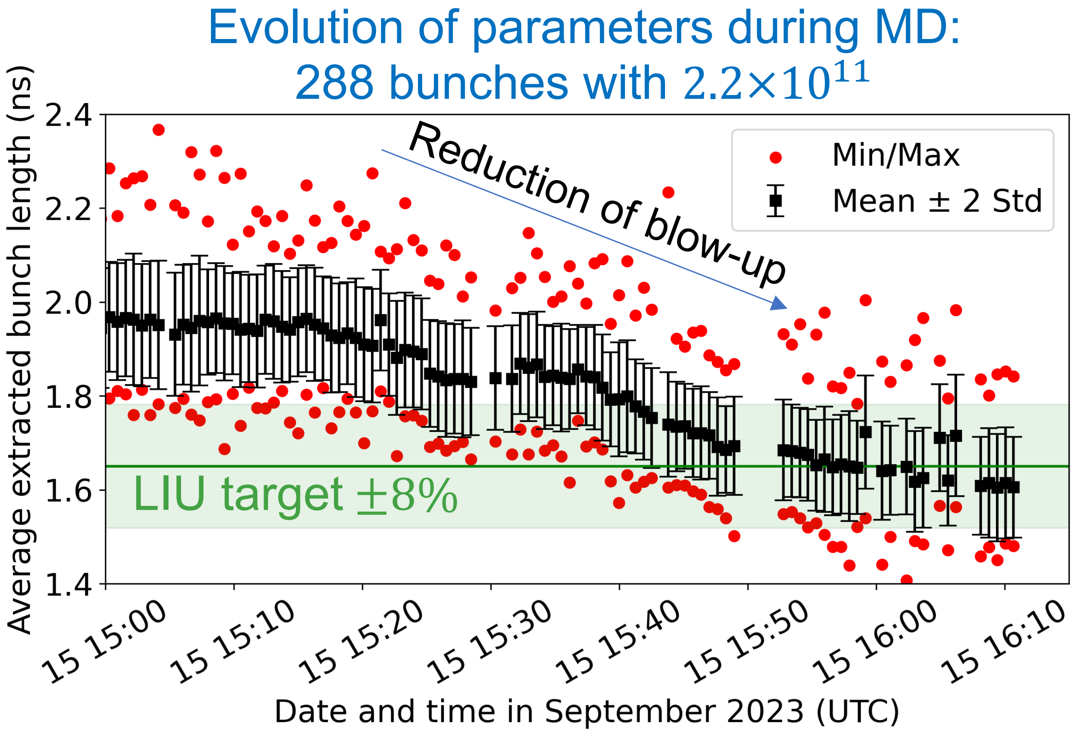
Reliable operation of all systems is critical
Possible causes of RF system trips under investigation (e.g., coarse synchronization and/or tuning)
Recorded diagnostic messages allow detailed studies, also to assess potential dependence with beam intensity (work in progress)

→ Best achievable performance should be repeated yearly and be maintained through the run

SPS

Beam parameters at 450 GeV


Data at flattop of SPS LIU-MD cycle


Evolution of parameters during MD: 288 bunches with $2.2{\times}10^{11}$

Improvements since 2022:

- increased RF power for beam loading compensation
- availability of all LLRF systems
- full integration of automated emittance blow-up *(N. Bruchon, SPS MPC, 06.06.2023)*

→ Ahead of LIU ramp-up plan for 2023

RF power limits in 2023

Measurements in 2022:

LIU peak power values were reached for cavities 3, 4, and 6

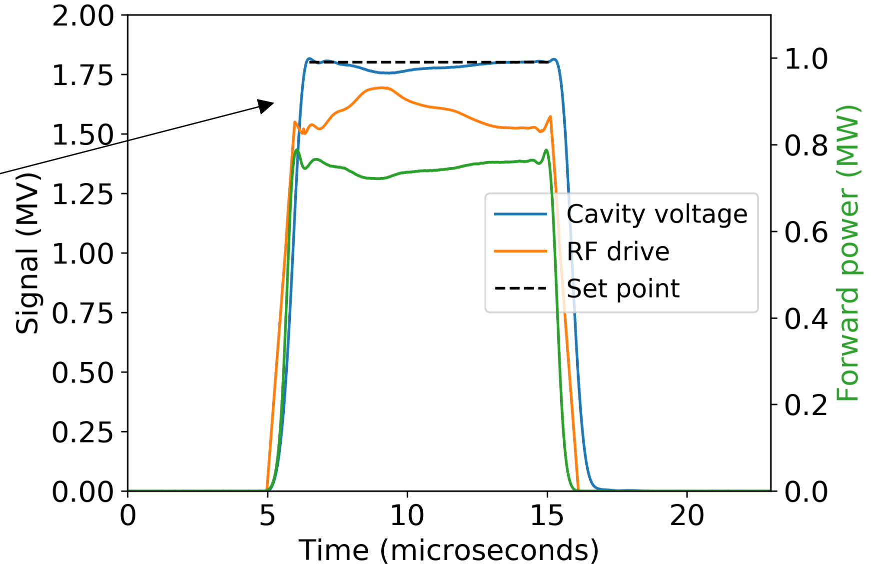
→ Lower power of other 3-section cavities was addressed during YETS 2022/23 *(E. Montesinos, 321st IEFC)*

→ Performance of remaining cavities has been improved

→ The reduction of the “gain” within a pulse for C1 and C2 needs to be addressed*

	Siemens		**Philips**		**Thales**	
Power (MW)	**C1**	**C2**	**C4**	**C5**	**C3**	**C6**
Peak value						
LIU target	1.1				1.6	
2022	0.6	0.7	1.1	0.8	1.6	2
2023	0.8*	1*	1.1	1.1	>1.6	>1.6

Measurement of peak power for C1



LLRF readiness

Commissioned systems:

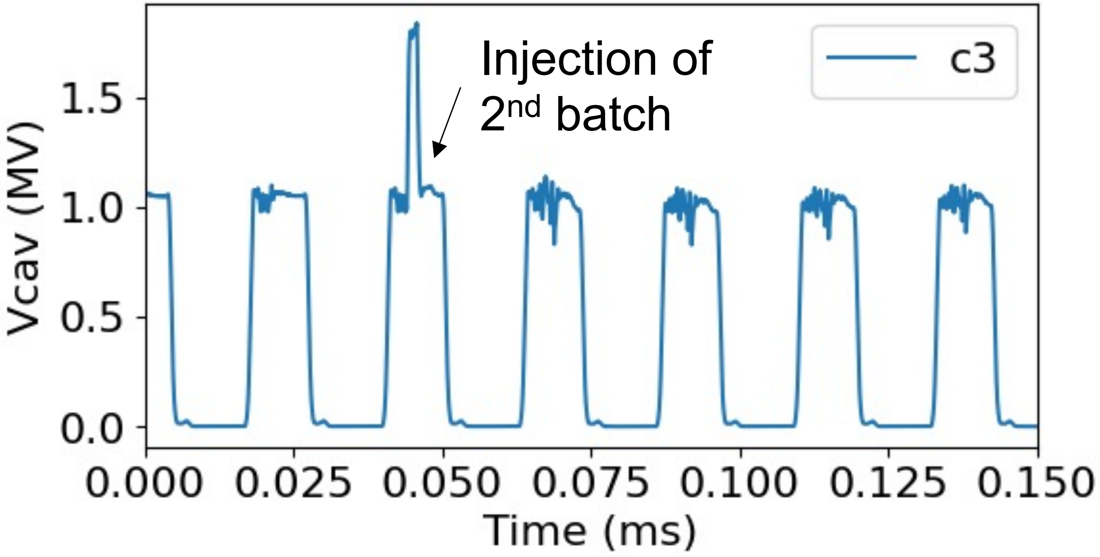
- one-turn delay feedback (incl. low-pass branch)
- longitudinal damper
- one-turn feedforward (compatibility with amplitude modulation was addressed during YETS 2022/23)

→ Improved beam loading compensation

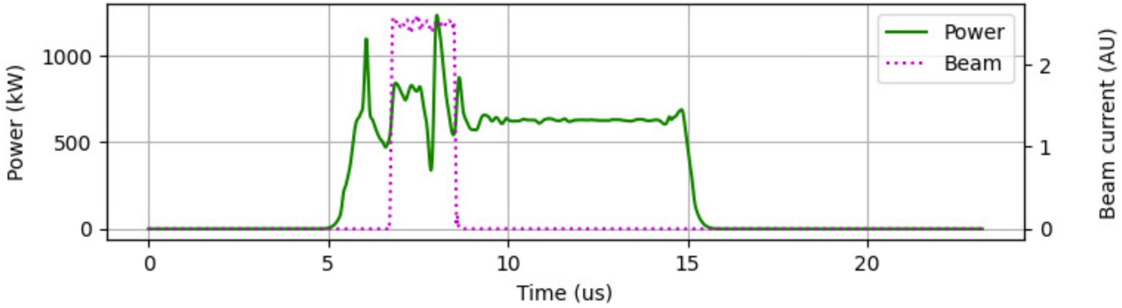
Items to address:

- Instability in the presence of feedforward only and possible reduction of power transients (cavities 3 and 6)
- Correlation of random beam dumps during acceleration with the reboot of cavity controller module

RF voltage transients with feedforward



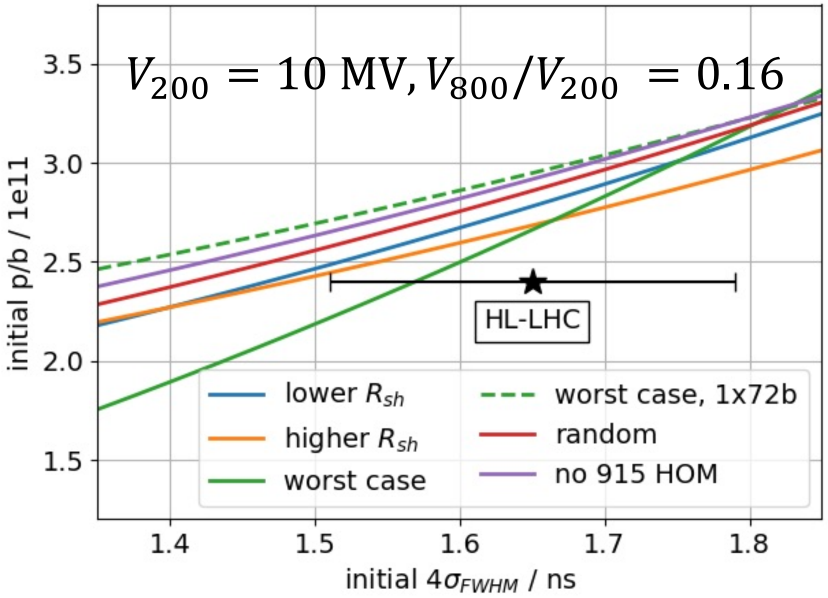
Single-turn RF power transients



P. Baudrenghien, et al, IPAC 2023

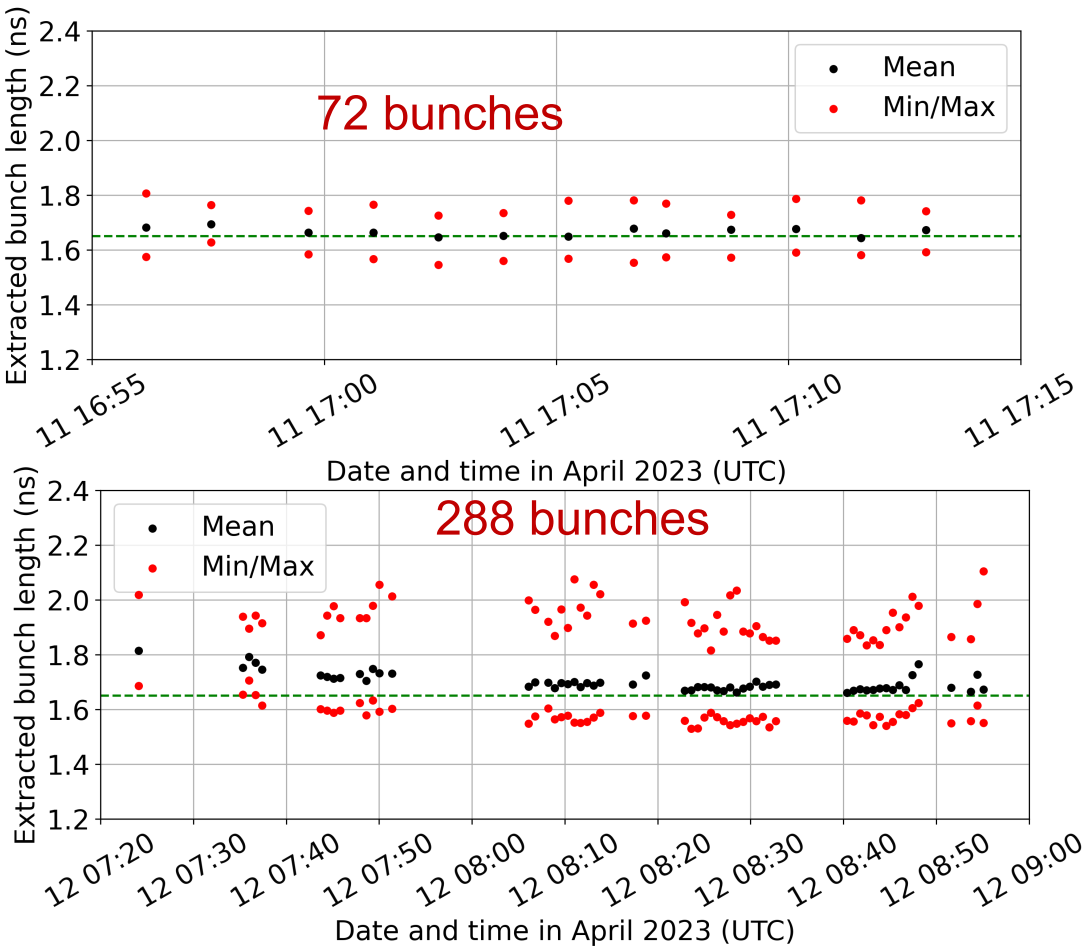
Steps from 2.2×10^{11} to LIU target and beyond

Instability threshold at 450 GeV (BLonD) for different models of higher-order modes (HOMs) around 915 MHz of 200 MHz RF cavities



M. Schwarz, LIU-SPS BD WG meeting, 19.12.19

Beam parameters during scrubbing run with 2×10^{11} and same RF parameters



- Model is not well-defined due to unknown boundary conditions
- Reduction of instability threshold is consistent with measurements for multi-batch beams

Probing 915 MHz impedance

Instability of fixed-target beams (5-ns bunch spacing) is driven by HOM around 915 MHz even for 1/10th of operational intensity*

Generalized instability threshold**

$$\frac{1}{N_{\text{th}}} \approx \frac{1}{N_{\text{LLD}}} + \frac{1}{N_{\text{CBI}}}$$

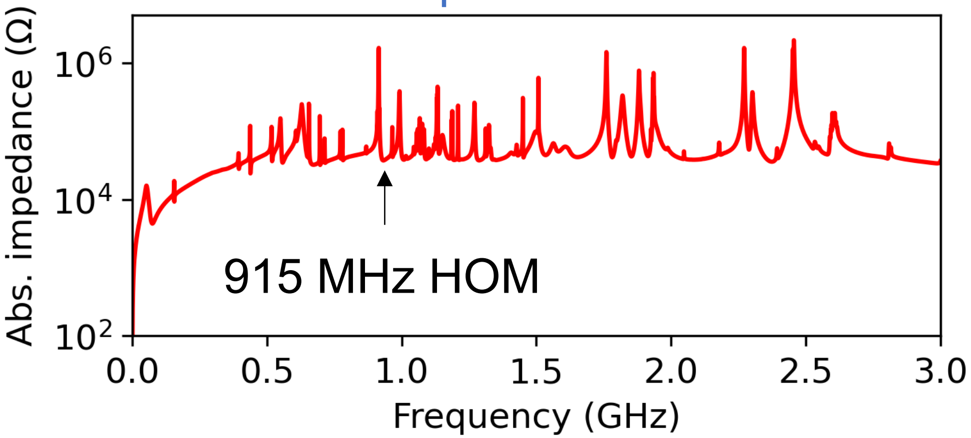
Defined by broadband impedance

Defined by HOM

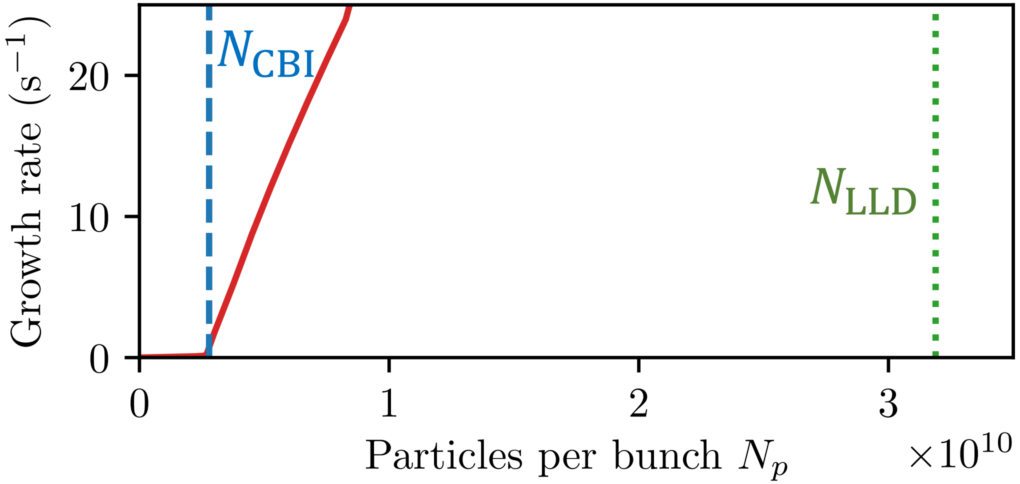
→ LLD has no impact on the stability of fixed-target beams

→ Low-intensity FT MDs are planned for 2024 to evaluate 915 MHz HOM parameters

SPS impedance model



Growth rates of most unstable modes for a fixed-target beam in single RF (MELODY)



*E. Shaposhnikova, Analysis of coupled bunch instability spectra, 1999

**IK and E. Shaposhnikova, IPAC 2022

Summary

PSB

LIU target is reached; ongoing optimization of brightness and tail population

PS

The intensity target is reached and surpassed

Small (10%) margin to reduce longitudinal emittance

Analysis of RF system faults is ongoing

SPS

Peak power limits are demonstrated for short pulses except for Siemens power plant

LIU LLRF upgrade is completed (follow-up of some open items and fine-tuning are required)

LIU ramp-up target for 2023 is exceeded

Pushing to $2.32{\times}10^{11}$ + a margin to move from MD style (all experts around) to operational performance

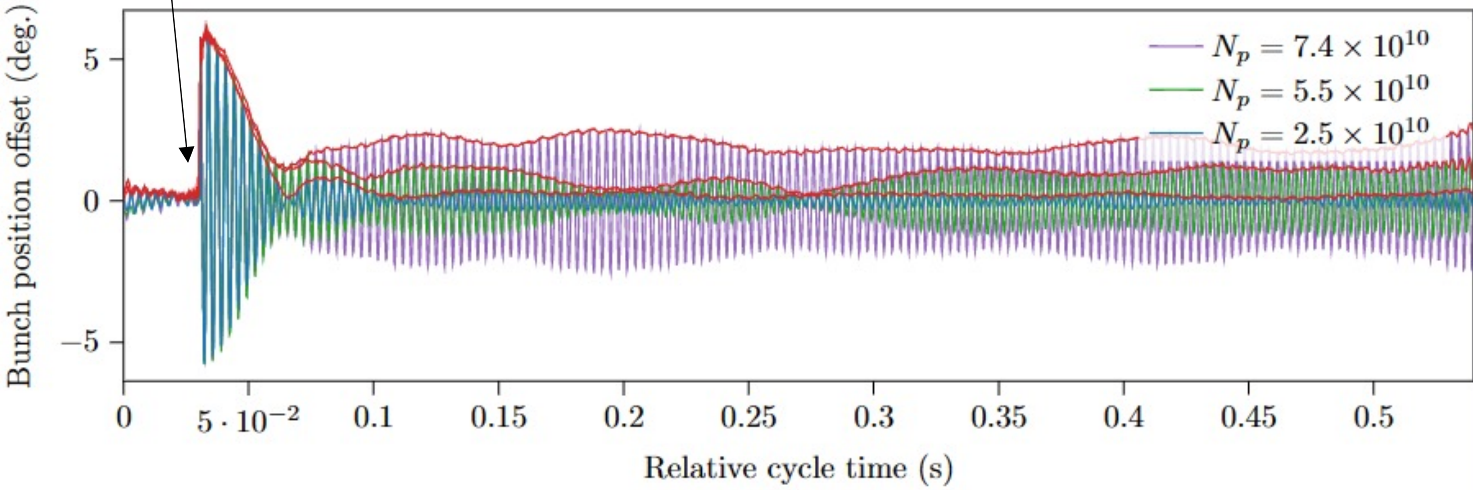
Thank you for your attention!

Backup slides

LLD threshold in single RF configuration

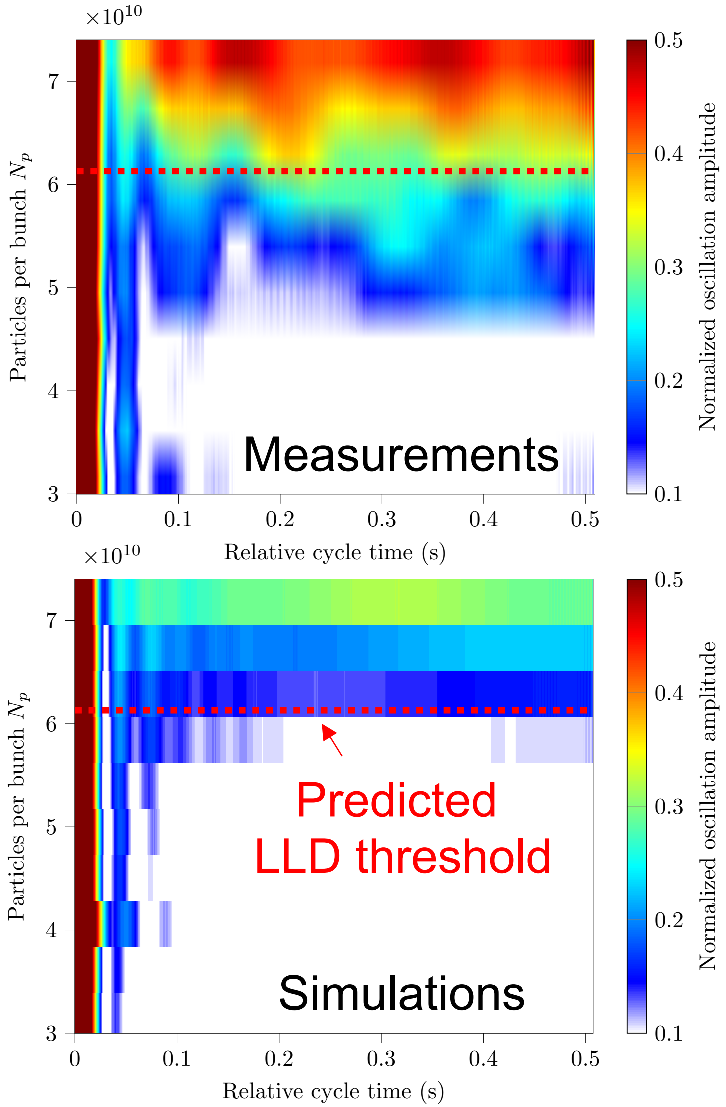
Phase kick

Measurement technique



L. Intelisano et al, IPAC 2023

Amplitude evolution after a kick



Measurements were performed in the SPS at 200 GeV
→ About 20-30% lower threshold is observed in measurements in comparison to predictions

→ Additional probing of broadband impedance via single-bunch instability measurements is necessary

Feedforward improvements

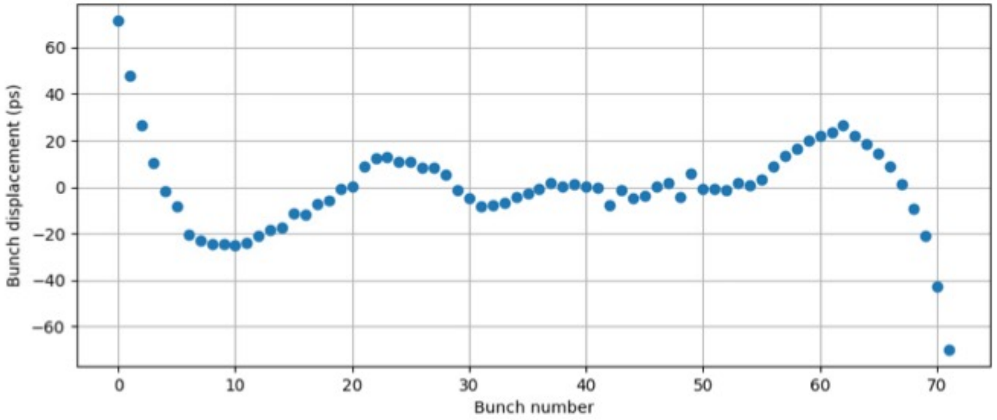
Feedforward commissioning was done in 2022
(G. Hagmann, IPP 2022)

Compatibility with amplitude modulation was addressed during YETS 2022/23

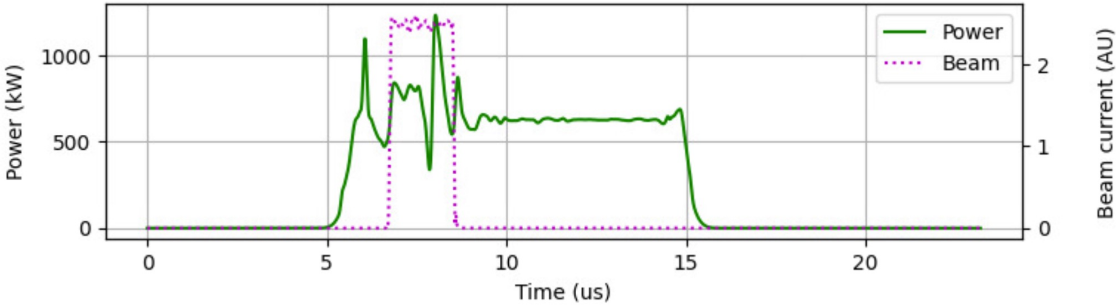
→ Improved beam loading compensation (less bunch-by-bunch phase deviations)

Items to address:
- Beam instability in the presence of FF only (4-section structures)
- Further tuning might be required to reduce RF power modulation for 4-section cavities
- Correlation of random beam dumps during acceleration with the reboot of beam control module

Bunch-by-bunch position at 450 GeV, 04.04.2023



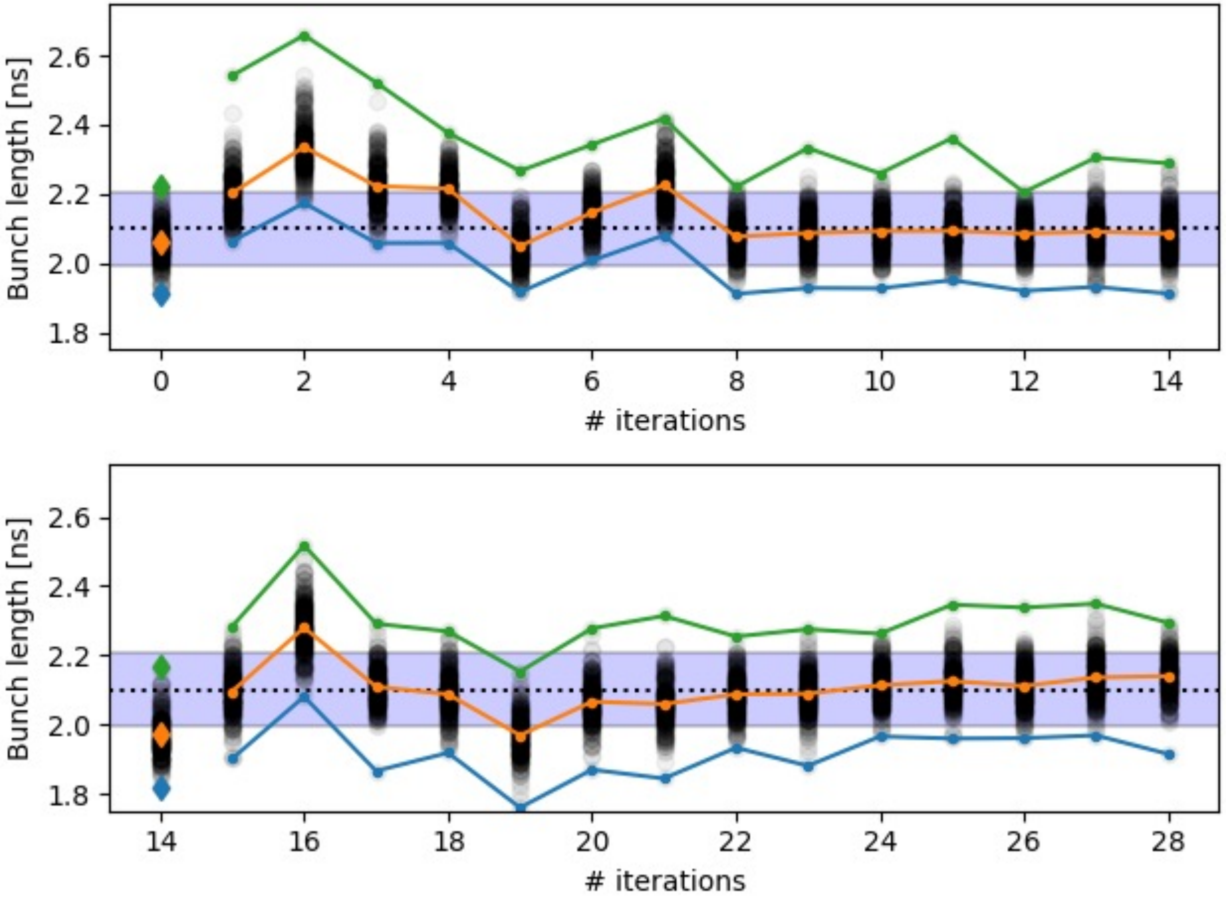
Single-turn RF power transients



(P. Baudrenghien, et al, IPAC 2023)

Operational tool for automatic setup of emittance blow-up*

- ✓ **Integration** in LSA and the CERN optimization framework
- ✓ Simple objective function is based on **RMSE**
- ✓ **Sequential** setup by splitting blow-up duration in sub-intervals
- ✓ Noise amplitude, margin low, and margin high optimizable at once
- ✓ Beams in MD sessions kept stable and at desired bunch length
- ✓ Settings found for single batch also valid for multi batch



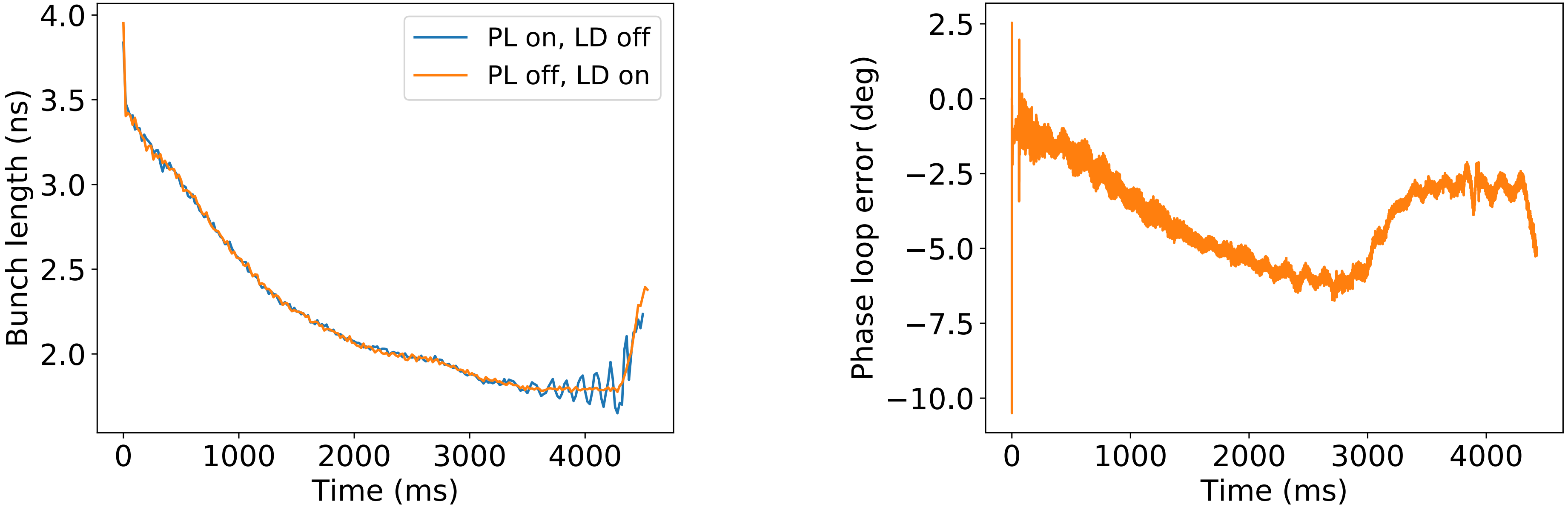
USER: LHC2

 # bunches: 288

Intensity: 2.15×10^{11}ppb

**N. Bruchon, SPS MPC, 06.06.2023*

AWAKE instability for 3×10^{11}



Bunch length oscillations appear when the phase loop is active
- The temporal solution is to open the phase loop at the beginning of the ramp and active the longitudinal damper

Studies of different combinations of loops (Phase Loop ON/OFF, Long. Damper ON/OFF) are important for LHC–type beams

Intensity limitations and their cures

Sources

Broadband impedance
Fundamental mode impedance
Higher-order-mode impedance
Noise

Cures

Impedance management

Landau damping enhanced by
- higher harmonic-RF systems
- controlled emittance blow-up

Active damping by feedback and feedforward systems

Effects

Loss of Landau damping
(Transient) beam loading
Mode-coupling instabilities
μ-wave instability after transition
Coupled-bunch instabilities
…

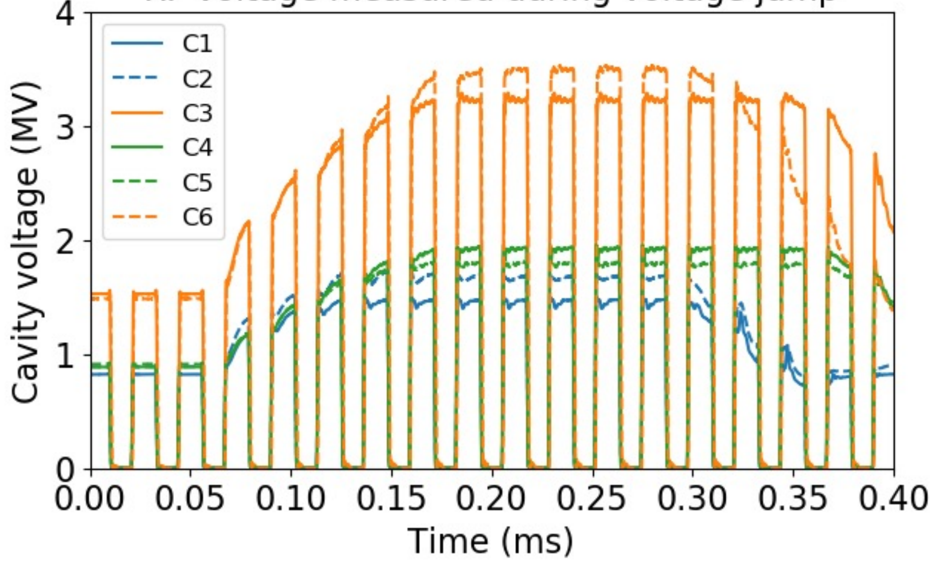
→ Main limitations for LHC-type beams in PSB, PS, and SPS will be discussed

RF power reach in 2022

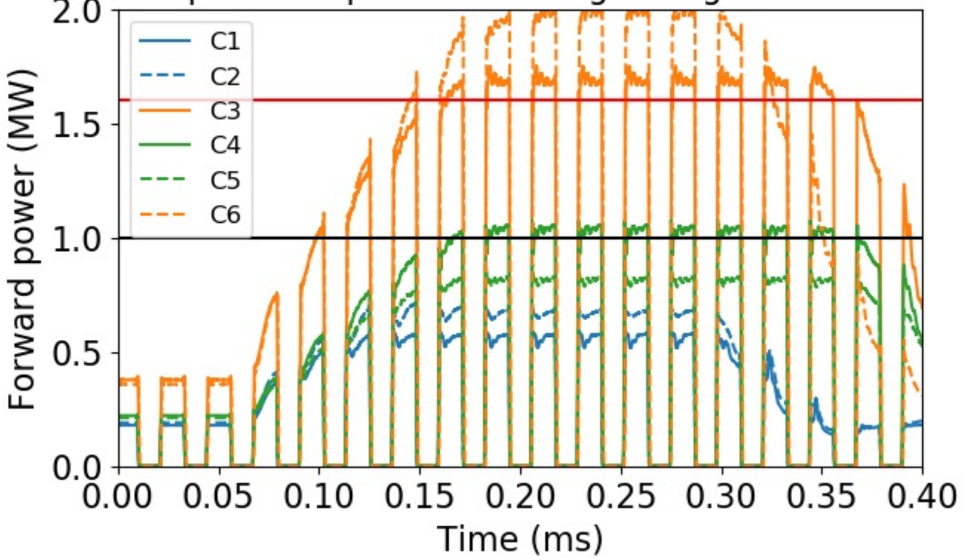
At the end of 2022, the RF power evaluated based on measured RF voltage

Acquisitions during RF voltage jump
→ Peak power of cavities 3, 4, and 6 fulfil the LIU target, but for short pulses
→ Lower power of other 3-section cavities was addressed during YETS 2022/23 *(E. Montesinos, 321st IEFC)*

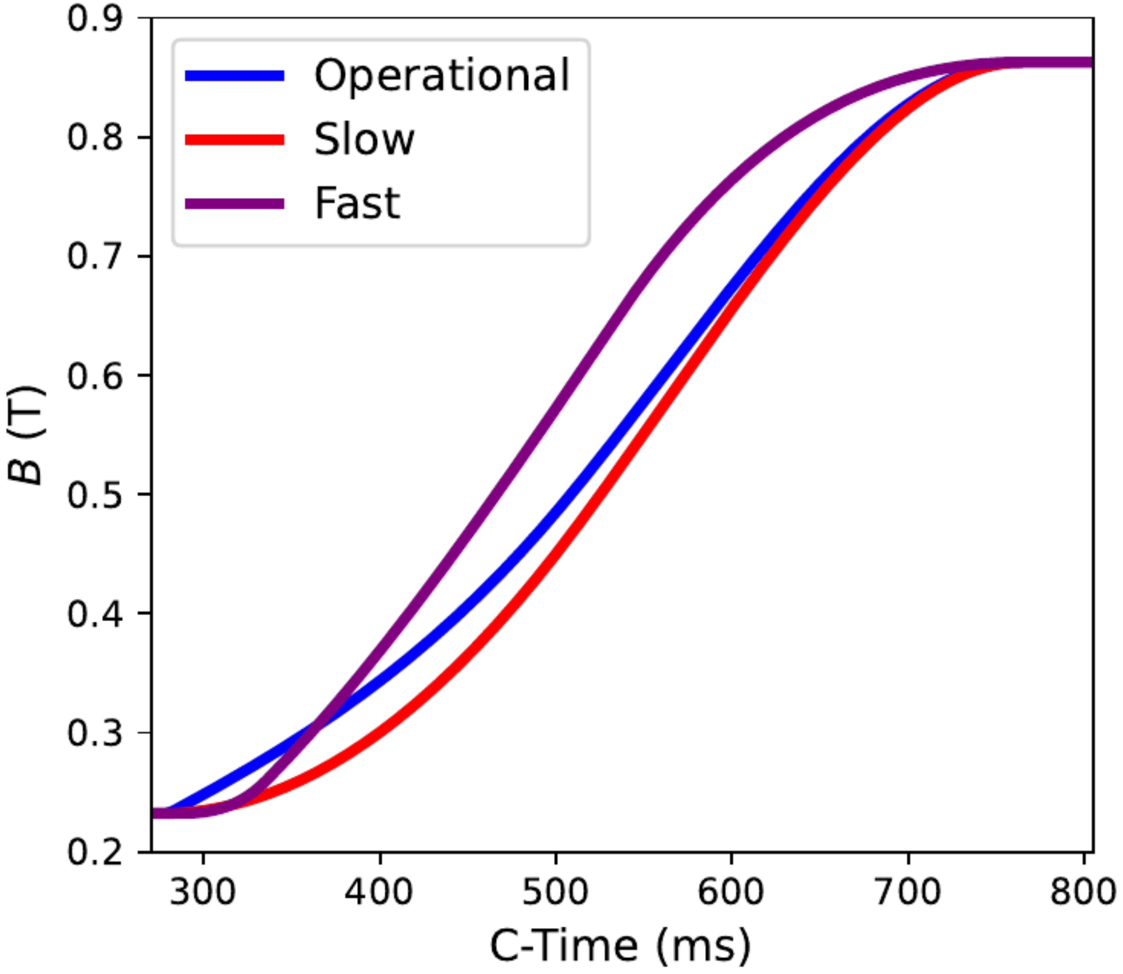
RF voltage measured during voltage jump



Computed RF power including voltage calibration



PSB: alternative cycle designs



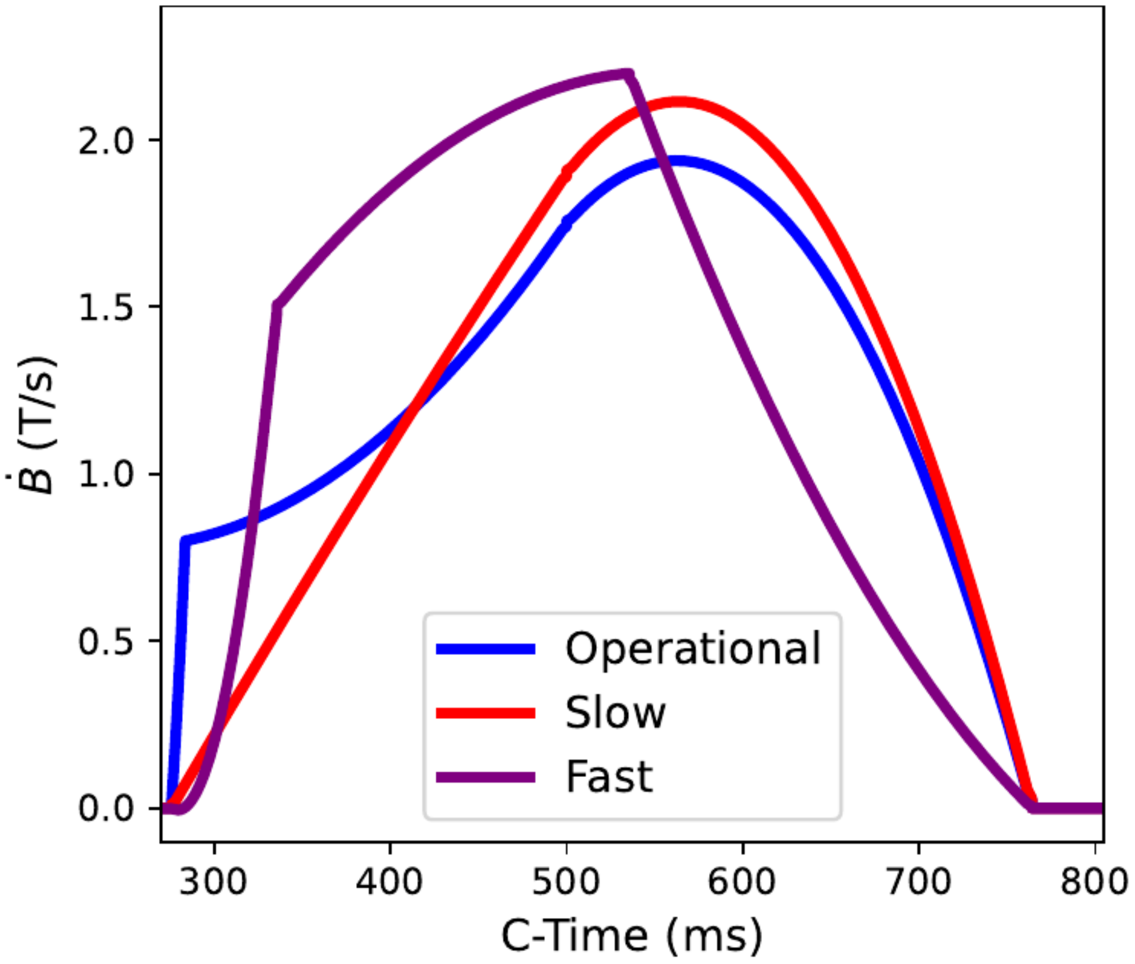
The current cycle meets the operational requirements but could be further optimized by lowering initial $\ddot{B}$ (less demanding for power converters)

Two new cycles were designed
"Slow" cycle:
Larger possible longitudinal emittance but slower increase in $\beta\gamma^2$

"Fast" cycle:
Smaller possible longitudinal emittance but faster increase in $\beta\gamma^2$

→ Possible improvements in brightness due to impact on transverse blow-up

PSB: alternative cycle designs



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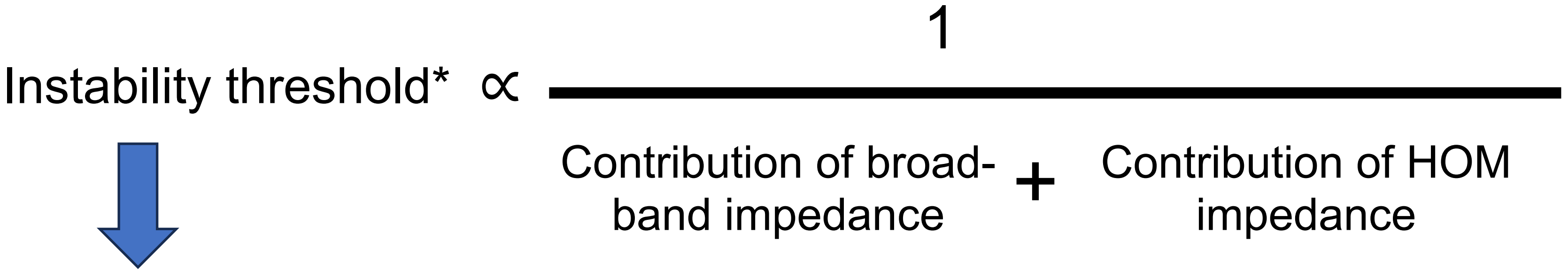
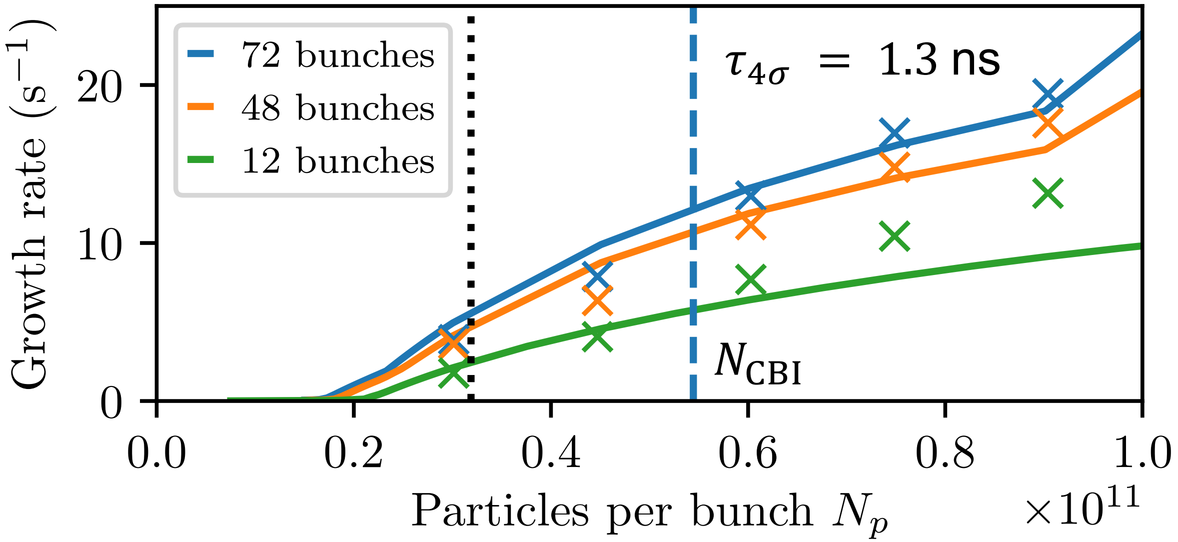
Generalized instability threshold



Instability threshold* $\propto \dfrac{1}{\text{Contribution of broad-band impedance} + \text{Contribution of HOM impedance}}$

$$\frac{1}{N_{\rm th}} \approx \frac{1}{N_{\rm LLD}} + \frac{1}{N_{\rm CBI}}$$

Bunch trains $V_{\rm rf} = 7.2$ MV, $E = 450$ GeV
Lines – MELODY, crosses - BLonD



Loss of Landau damping (LLD) threshold can strongly impact multi-bunch stability

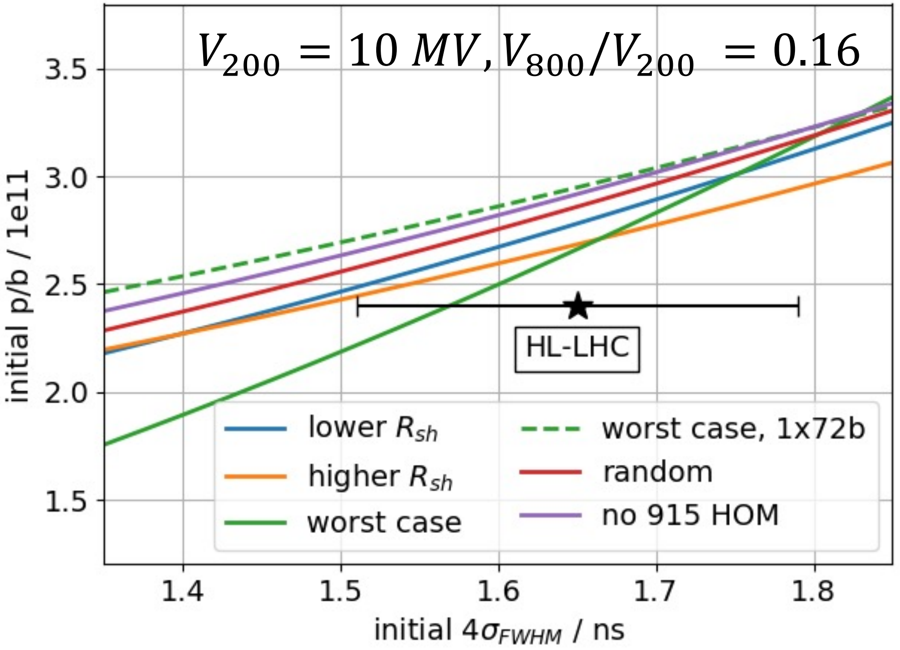
In SPS, the 800 MHz RF system and controlled emittance blowup boost the LLD threshold

**IK and E. Shaposhnikova, IPAC 2022*

Steps from 2.2×10^{11} to LIU target and beyond

Need to move from MD style (all experts around) to operational performance
→ 2.32×10^{11} + proposed margin to be demonstrated

Instability threshold at 450 GeV (BLonD)



M. Schwarz, LIU-SPS BD WG meeting, 19.12.19

Predictions for LIU target are impacted by precise parameters of higher-order mode (HOM) around 915 MHz

Generalized instability threshold

$$\text{Instability threshold*} \propto \frac{1}{\text{Contribution of broad-band impedance} + \text{Contribution of HOM impedance}}$$

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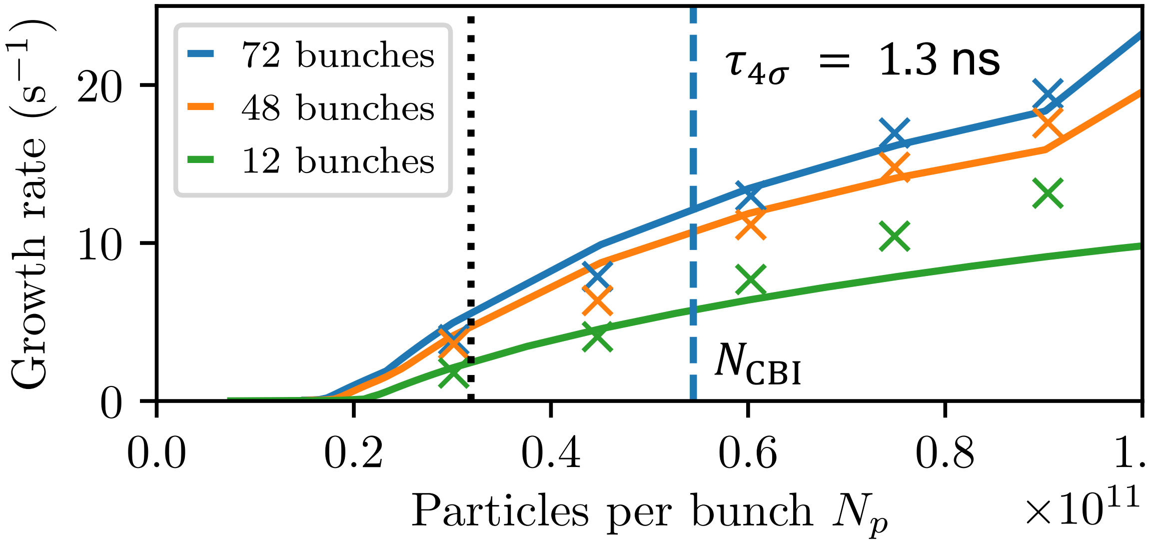

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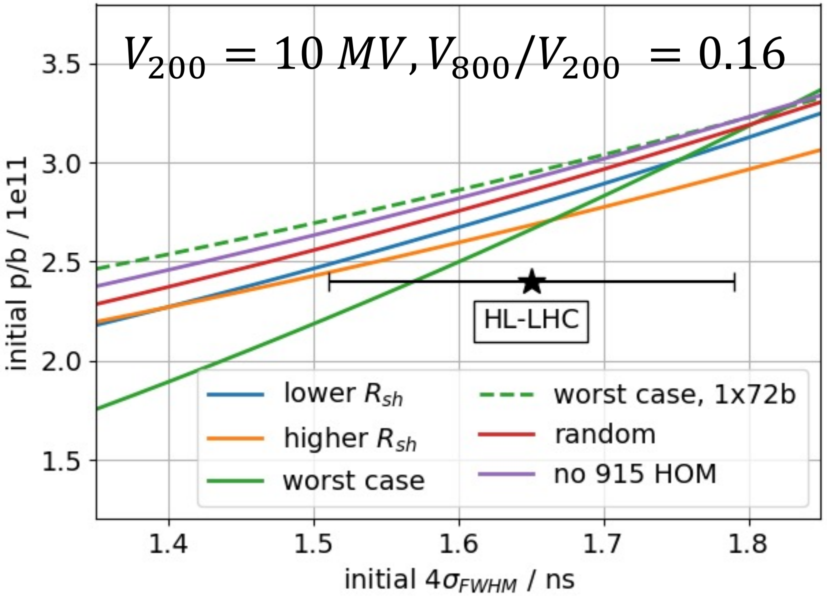

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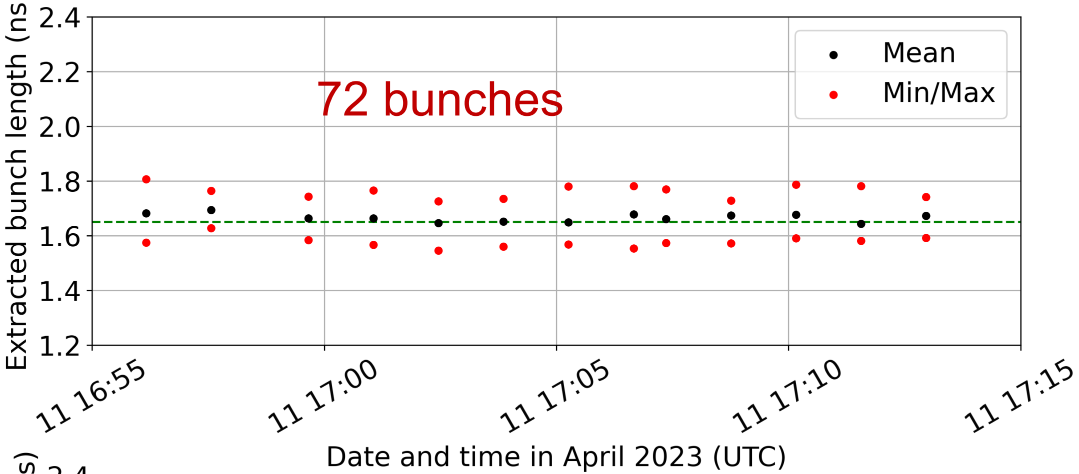
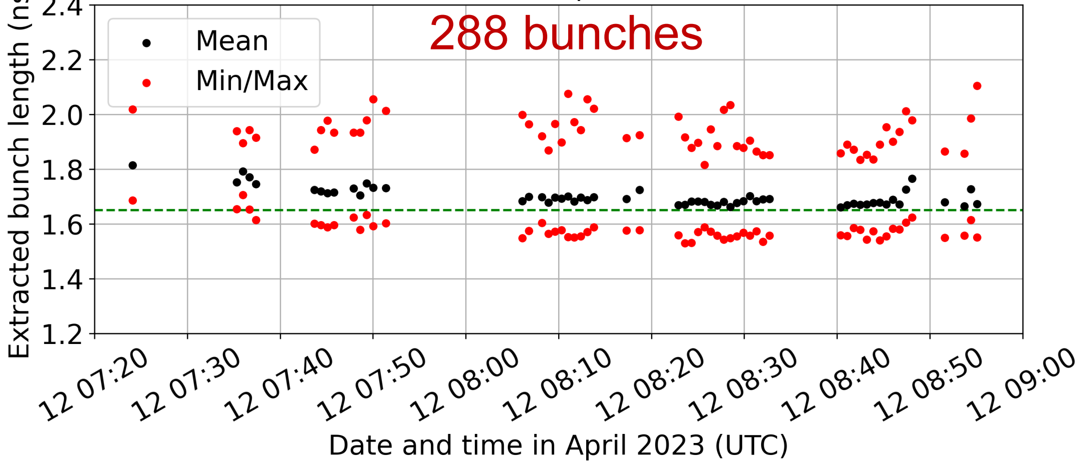
Beam parameters during scrubbing run with 2×10^{11} and same RF parameters





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Need to move from MD style (all experts around) to operational performance

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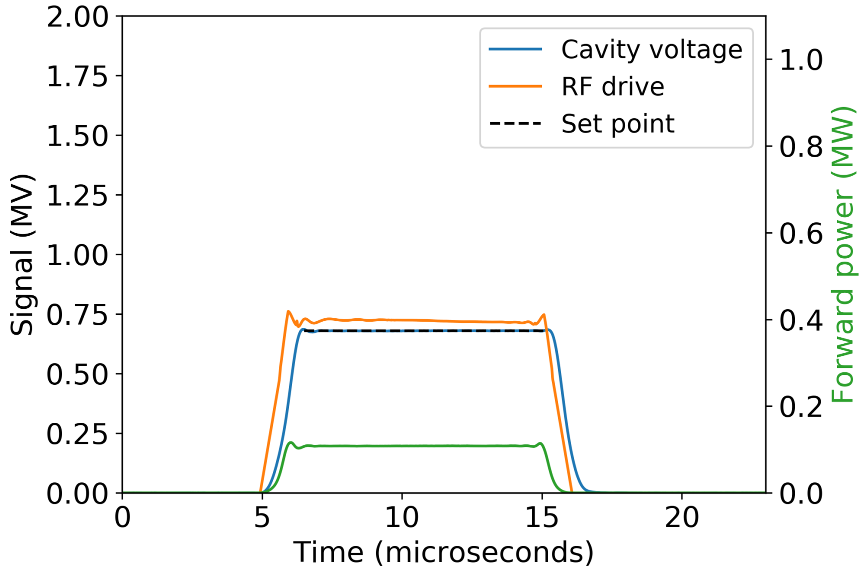
Reduction of instability threshold for multi-batch beam

More details on RF power limits in 2023

Amplitude modulation and voltage jump were set up on the MD1 cycle
→ Flexibility for data taking throughout this year
Following electrical recalibration during YETS 2022/23 done by G. Hagmann, RF voltage errors < 1% were observed with a beam-based technique *(D. Quartullo & G. Papotti)*
→ RF power can be precisely computed based on the measured RF voltage and cavity impedance model



Siemens (C1, C2)

C1 trips at the 800-kW power level (~600 kW in 2022)
The reduction of the “gain” within a pulse for C1 and C2 is under investigation