Projections for 2025 and HL-LHC in the longitudinal plane

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Outline

Recap from 2023

- Estimates
- Follow-up of plans

Experience with beam 2024

- MD results with 2.0×10^{11} p/b and 2.3×10^{11} p/b
- Operation with BCMS vs standard
- IBS and debunching

Updated estimates

- Progress with high-efficiency klystrons
- Plans for 2025-2026

Where were we in 2023?

Estimates on power/voltage reach for the main RF system

- Based on 2023 operation with **hybrid** beam of **1.6×10^{11} p/b**
  - Captured with 5 MV, bunch length increased on flat bottom from 1.08 ns (injection) to 1.23 ns (start of ramp)
- Maximum voltage was 7 MV in MD with **standard** beam of 72b and **2.0×10^{11} p/b**

Scenario	Bunch parameters		SPS parameters			LHC parameters					
	Bunch intensity	Bunch emittance	Main RF voltage	4th harm. voltage	Momentum spread	Main RF voltage	Bunch length	Optimum detuning	Optimum Q_L	Average power	Peak power
2023 (hyb)	1.6×10^{11} p/b	0.36..0.45 eVs	9.4 MV	1.7 MV	$(4.24..4.68) \times 10^{-4}$	5 MV	1.08..1.23 ns	-11.8..-11.0 kHz	17.0..18.3 k	119..127 kW	**160-230 kW**
2023 (max)	2.0×10^{11} p/b	0.55 eVs	9.4 MV	1.7 MV	5.09×10^{-4}	7 MV	1.25 ns	-9.7 kHz	20.6k	**206 kW**	**230-310 kW**
HL-LHC	2.3×10^{11} p/b	0.58 eVs	10 MV	2 MV	5.32×10^{-4}	6.5..7.9 MV	1.25..1.32 ns	-11.6..-9.9 kHz	17.3..20.3 k	**212..267 kW**	**320±15 kW**

Next steps we had outlined in 2023

- Year-end shutdown: implement the corrections from the beam-based voltage calibration
- 2024: repeat calibration measurements w/ and w/o beam
- Try reducing operational capture voltage to probe margins
- Prepare continuous adjustment of Q_L at injection

Improvements in 2024

Voltage calibration

- New calibration factors implemented in EYETS 23/24
- Performed some beam-based checks, final measurements during 2025 commissioning

Loaded Q calibration

- Compared three methods: based on beam measurements, open loop response, voltage decay
    - The voltage decay measurement will be used next year — easiest and with least sources of error
- An automatic adjustment algorithm will still need to be devised

Half-detuning adjustment

- Automatic measurements of power transients implemented for faster cavity-by-cavity detuning adjustment
    - Based on BLonD control loop models
    - To be further automatised and incorporated in OP controls

Minimum voltage

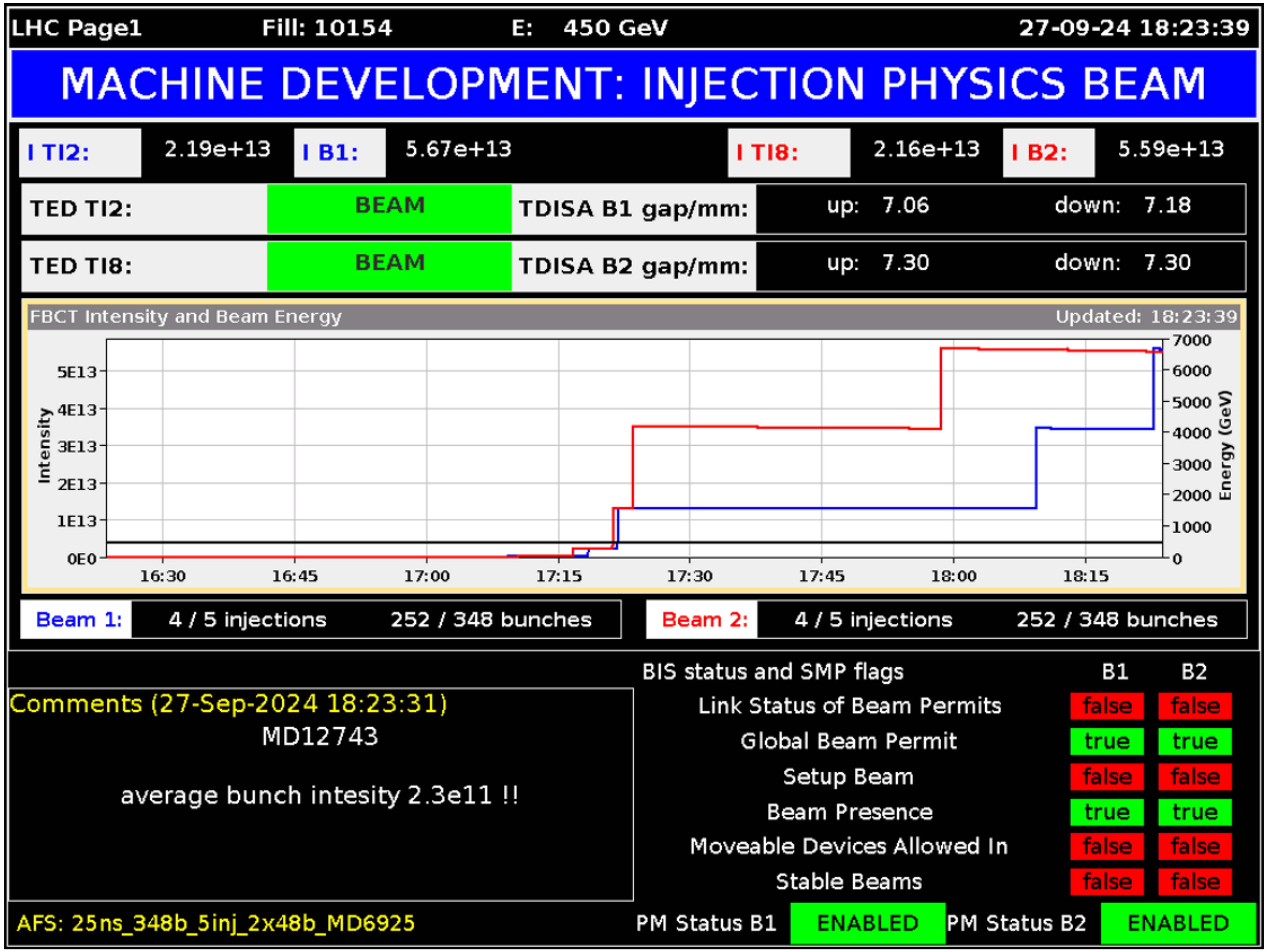
- Continuously operating with each beam type and for each intensity at the minimum voltage possible

Captured HL-LHC beams for the first time!

A milestone towards HL-LHC

Still a long way to operational capture

- Significant debunching on flat bottom
  - Data to be analysed
- With LIU-SPS parameters, both momentum spread and bunch length would increase at capture
  - Decreases debunching
  - Makes capture losses worse
- Almost all RF lines saturating
  - Frequent trips dumping the beam
  - For good availability, we will need operational margin!



MD results on power limitations

One MD with 2.0x10^{11} p/b BCMS with 2x48b batches

- With OTFB closed, maximum voltage: 7 MV
  - Results in line with 2023 MD using 72b standard beam at 1.95x10^{11} p/b

One MD with 2.3x10^{11} p/b BCMS with 2x48b batches

- OTFB was unstable at the optimum Q_L and had to be disabled
- With OTFB open, maximum voltage: 6.5 MV
  - OTFB estimated to require 50 kW extra margin in peak power, data to be analysed
  - To be evaluated: do we need it at injection for HL-LHC?
- Most lines saturating — **not** an **operational** configuration
  - MD after us tried to operate in these conditions and got two beam dumps by RF line trips
- No signs of longitudinal instabilities
- Significant beam losses observed, data to be analysed

SPS 200 MHz RF limited to ~7.5-8.5 MV this year cf. LIU baseline of 10 MV

- Smaller dp/p at extraction → helps with capture losses, but increases flat bottom losses

Bunch-by-bunch spread

Why is it important, how does it affect us?

- Short and/or high-intensity bunches can become unstable earlier
  - Differences in synchrotron frequency shift could affect controlled emittance blow-up in the ramp
- Longer bunches cause more beam losses

What is the LIU baseline for standard beam?

- Based on 2018 operational data
  - Bunch length at SPS extraction: (1.65 ± 0.15) ns, peak to peak
  - Bunch intensity spread at SPS extraction: $(2.3 \pm 0.2)\times10^{11}$ p/b

More recent data

- Currently updating our expectations based on more recent operational and MD data

When	Bunch length			Bunch intensity		
	Average	Minimum	Maximum	Average	Minimum	Maximum
2024 BCMS	1.23 ns	1.11 ns	1.33 ns	1.63×10^{11} p/b	1.45×10^{11} p/b	1.79×10^{11} p/b
2024 standard	1.26 ns	1.18 ns	1.36 ns	1.55×10^{11} p/b	1.35×10^{11} p/b	1.70×10^{11} p/b
2023 hybrid	1.18 ns	1.08 ns	1.32 ns	1.62×10^{11} p/b	1.40×10^{11} p/b	1.85×10^{11} p/b

Bunch length and intensity spread from representative operational fills (108b for 2024, 128b for 2023)

BCMS & standard are in line with ±10 % estimates

Experience with different beam types

2024 experience with BCMS vs standard

- Two beam types used in operation this year
- Longitudinally the same beam quality arriving from the SPS
- Same filling scheme, on average same time spent on flat bottom
- Still, BCMS requires operation with 5.5 MV cf. 5 MV with standard
  - Due to increased start-of-ramp losses
  - Intra-beam scattering (IBS) dominated ⇒ transverse emittance counts, we need to think 6D!

Projections for capture voltage

- Always assumed scaling for standard beam
- Lesson learned: we need to increase our projections by **+10 %** for BCMS

Debunching on flat bottom

Intra-beam scattering (IBS) dominated

- As of ~1.55 ns bunch length, losses are significant
- At SPS extraction, having the maximum voltage and bunch length helps
  - Both for beam stability and for debunching on flat bottom
- Despite the same time spent at flat bottom, and same longitudinal parameters, the smaller transverse emittance reduces the lifetime significantly
  - Stronger longitudinal blow-up

When	Beam parameters		Bunch length		
	Intensity	H, V emitt.	At injection	After 30 min	After 60 min
2024 BCMS	1.63x10[11] p/b	1.15 um	1.23 ns	~1.5 ns	~1.65-1.7 ns
2024 std	1.55x10[11] p/b	1.55 um	1.26 ns	~1.45-1.5 ns	~1.6-1.65 ns

Analytical estimate for bunch length growth due to IBS

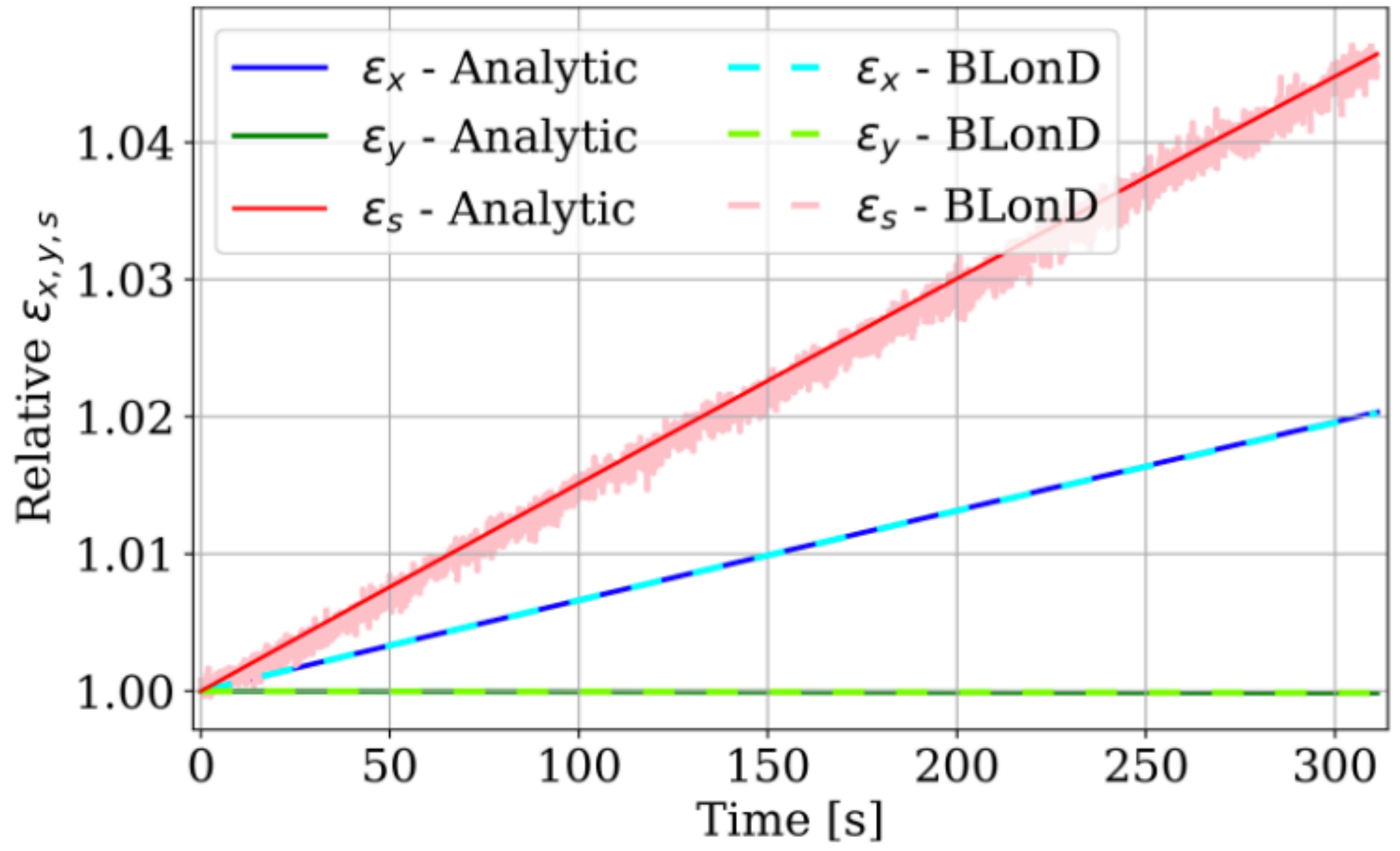
Milestone: IBS model implemented in BLonD

- Will use this model to fold in debunching losses

Emittance (µm)	B1H	B1V	B2H	B2V	
Fills 9575-9663	1.57	1.59	1.5	1.5	std
Fills 9664-9694	1.19	1.27	1.13	1.16	BCMS
%	-24.2	-20.1	-24.7	-22.7	

Standard vs BCMS transverse emittances at injection

Courtesy H. Bartosik et al., presentation at LBOC #167



Benchmarking the BLonD IBS model

Courtesy of B. Karlsen-Baeck and M. Zampetakis, see IPAC'24 paper

What to optimise beyond the RF?

BLM thresholds for start-of-ramp losses being reviewed (2024-2026)

- **Potentially** a x2-4 that could be gained
  - For BCMS, a x2 represents a decrease in bunch length from 1.42 ns to 1.35 ns
  - Maintaining the same working point in terms of losses and bunch length, this corresponds to a decrease from 5.5 MV to 4.5 MV, i.e. **-18 %** in voltage

Improve the cleaning of debunched beam

- Optimise the present cleaning to have less losses at the start of the ramp?

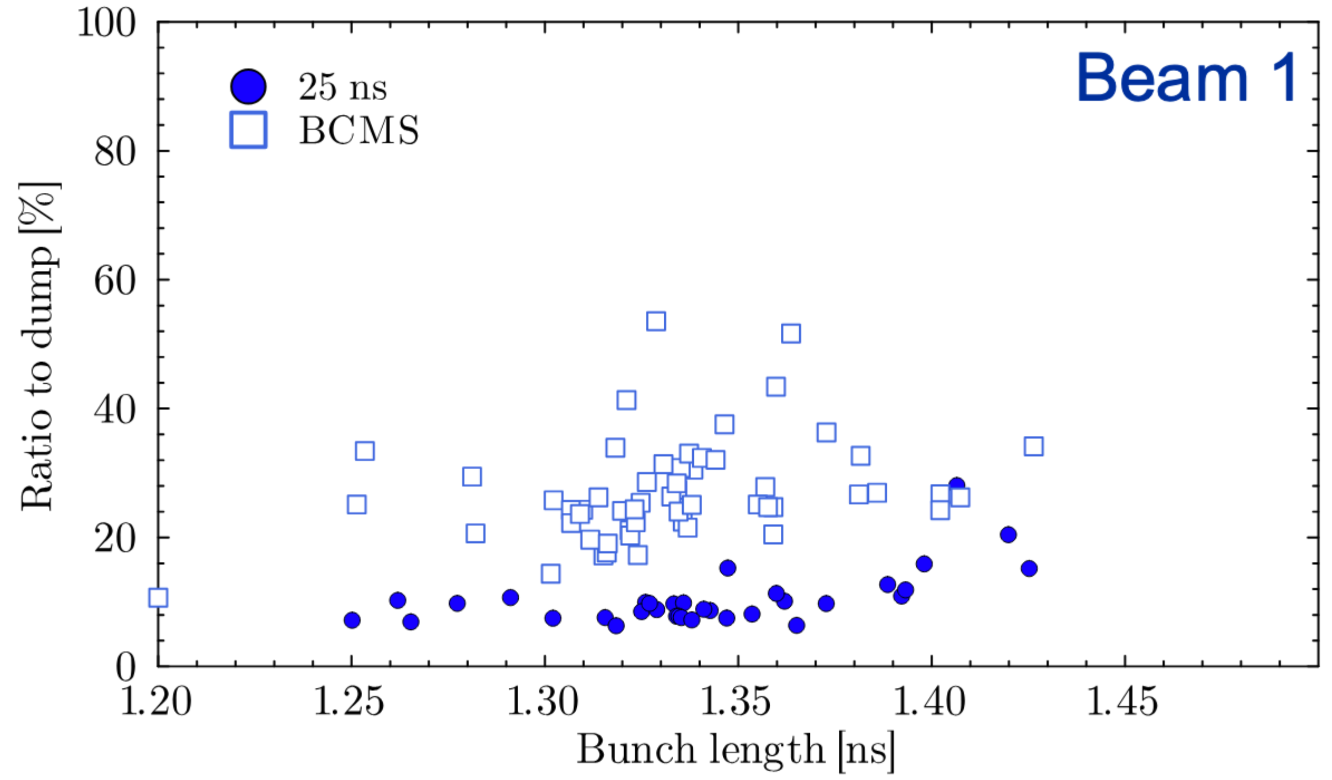
Minimise the time spent at flat bottom

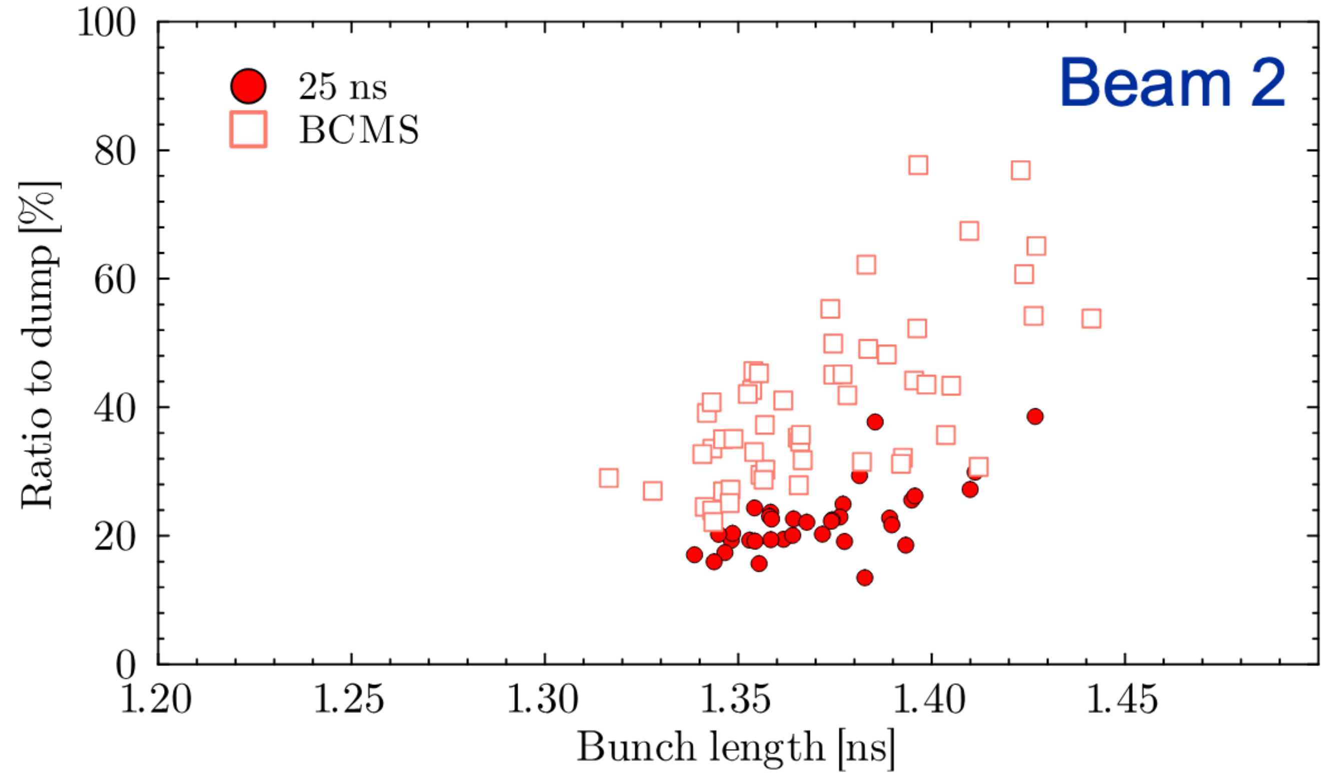
- Favour filling schemes with less injections
- Dedicated LHC filling using improved magnetic hysteresis in the injectors

	N_b	Collisions IP1/5	IP2	IP8	Heat load [W/hc] 1.6e11	1.8e11	N_{bpi}	N_{inj}	SPS flat bottom [s]
5x36b	**2496**	2484	2121	2260	170	184	180	16	14.4
4x36b	**2460**	2448	2005	2146	167	180	144	20	10.8
3x36b	**2352**	2340	2004	2133	158	171	108	24	7.2
Hybrid-48b	**2452**	2440	1952	2240	153	166	248	12	14.4
Hybrid-36b	**2464**	2452	1842	1821	142	154	236	12	18

Filling scheme options for 2025

L. Mether and K. Paraschou at LBOC #171 meeting





Losses vs bunch length for BCMS and standard beam

See talk by B. Karlsen-Baeck

Updated projections for HL-LHC

From capture to flat bottom losses

- Estimates based on dp/p are simple, but describe mainly capture losses
- Reality is a mix of capture losses and debunching along the flat bottom
  - What is the ratio of the two? We don't have exact numbers so far…
  - Attempt to disentangle the two with IR3 collimator scraping was not conclusive
- BCMS calls for increased capture voltage, but reviewed BLM thresholds could help to be more comfortable

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2024 (BCMS)	2.0x10^{11} p/b	0.46 eVs	8.5 MV	1.53 MV	4.58x10^{-4}	7 MV	1.12 ns	-10.3 kHz	19.5k	**218 kW**	**230-310 kW**
HL-LHC (std)	2.3x10^{11} p/b	0.58 eVs	10 MV	2 MV	5.32x10^{-4}	7.9 MV	1.25 ns	-9.9 kHz	17.3 k	**267 kW**	**320±15 kW**
HL-LHC (BCMS)*	2.3x10^{11} p/b	0.58 eVs	10 MV	2 MV	5.32x10^{-4}	7.1 MV	1.29 ns	-10.8 kHz	18.6k	**236 kW**	**280±15 kW**

HL-LHC projections based on MD experience in the LHC

** hypothetical: assuming BCMS beam and a x2 increase in IR3 start-of-ramp BLM thresholds*

Progress with HE klystrons

Retrofit the present LHC klystrons to increase efficiency from 60-62% to ≥67%

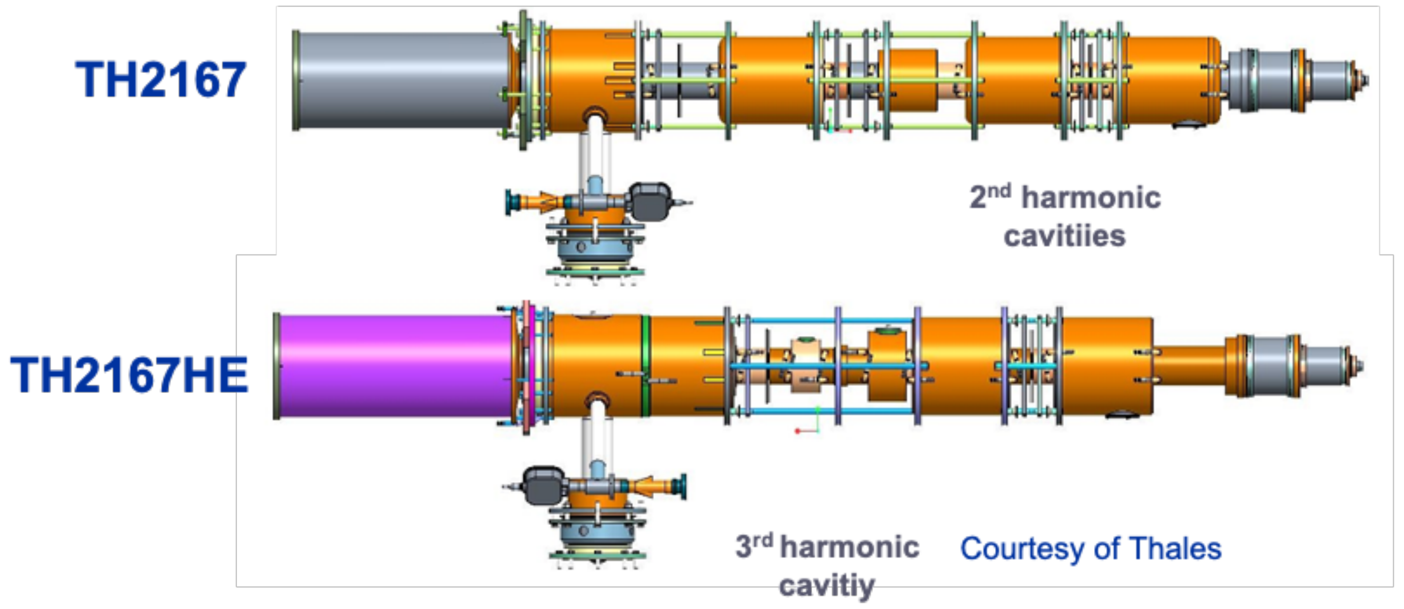
- Provide 350 kW output power
- Operating point compatible with present HV system

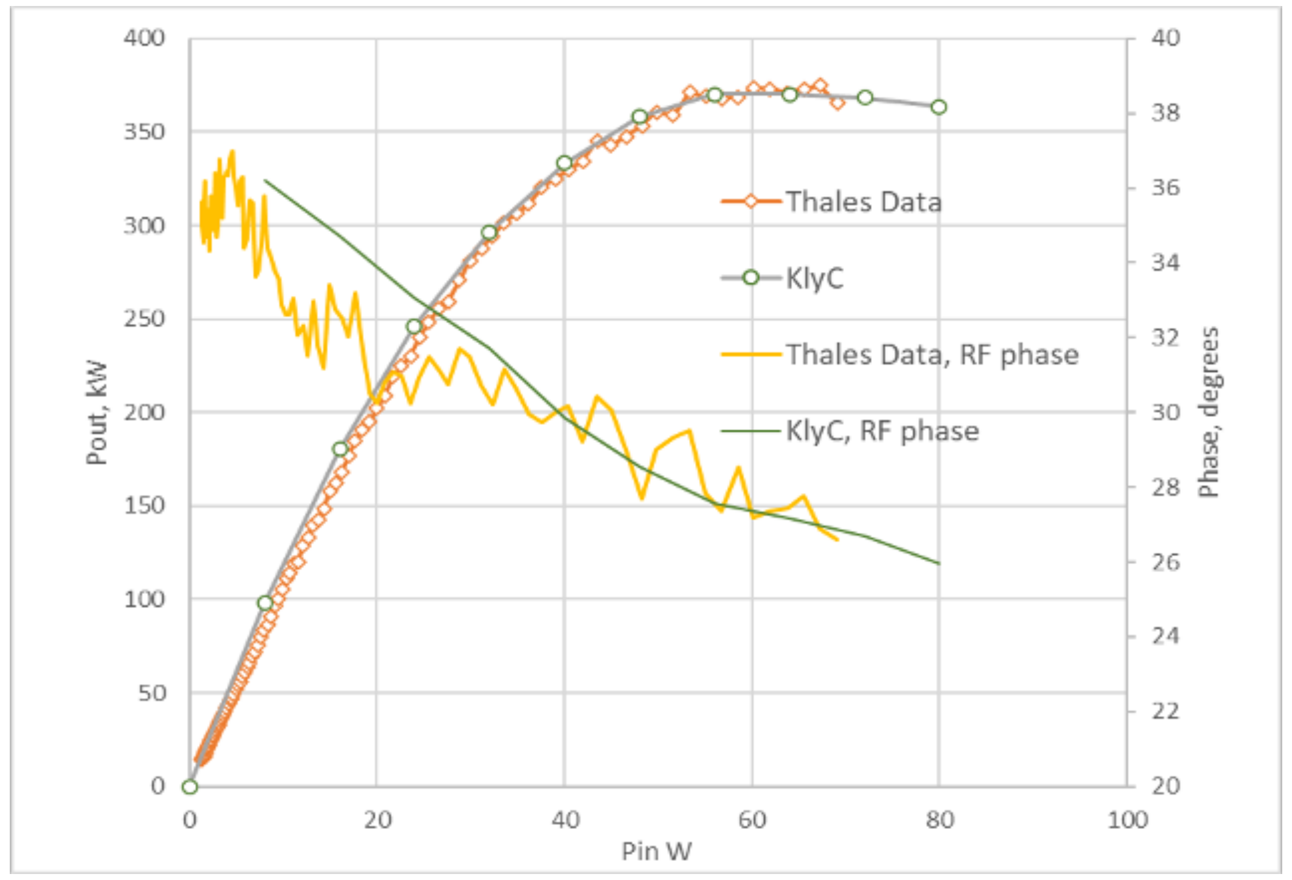
	TH2167	TH2167HE
Power [kW]	**300**	**350**
Frequency [MHz]	400.8	400.8
Gun microPerveance	1.65	1.65
Beam microPerveance	0.7	0.7
Cathode voltage [kV]	58	58
Anode Voltage [kV]	≤ 35	≤ 35
Beam current [A]	**8.5**	**9**
Efficiency [%]	**60**	**≥ 67**
Gain [dB]	≥ 37	≥ 37
Bandwidth [MHz]	+/- 1	+/- 0.7
Group delay [ns]	130	≤ 250

First prototype being tested

- Design done at CERN
- Manufacturing started in 2022 after validation of CERN design at Thales
  - TH2167 S/N 01 "St. Paul" was sent back to Thales after being removed from LHC due to poor vacuum; parts have been re-used for the HE prototype
  - Tube currently under test at Thales
  - Main performances and efficiency already confirmed by tests
- Tube back to CERN by November 2024

Courtesy of C. Marrelli, N. Catalan et al.





Blow-up optimisations

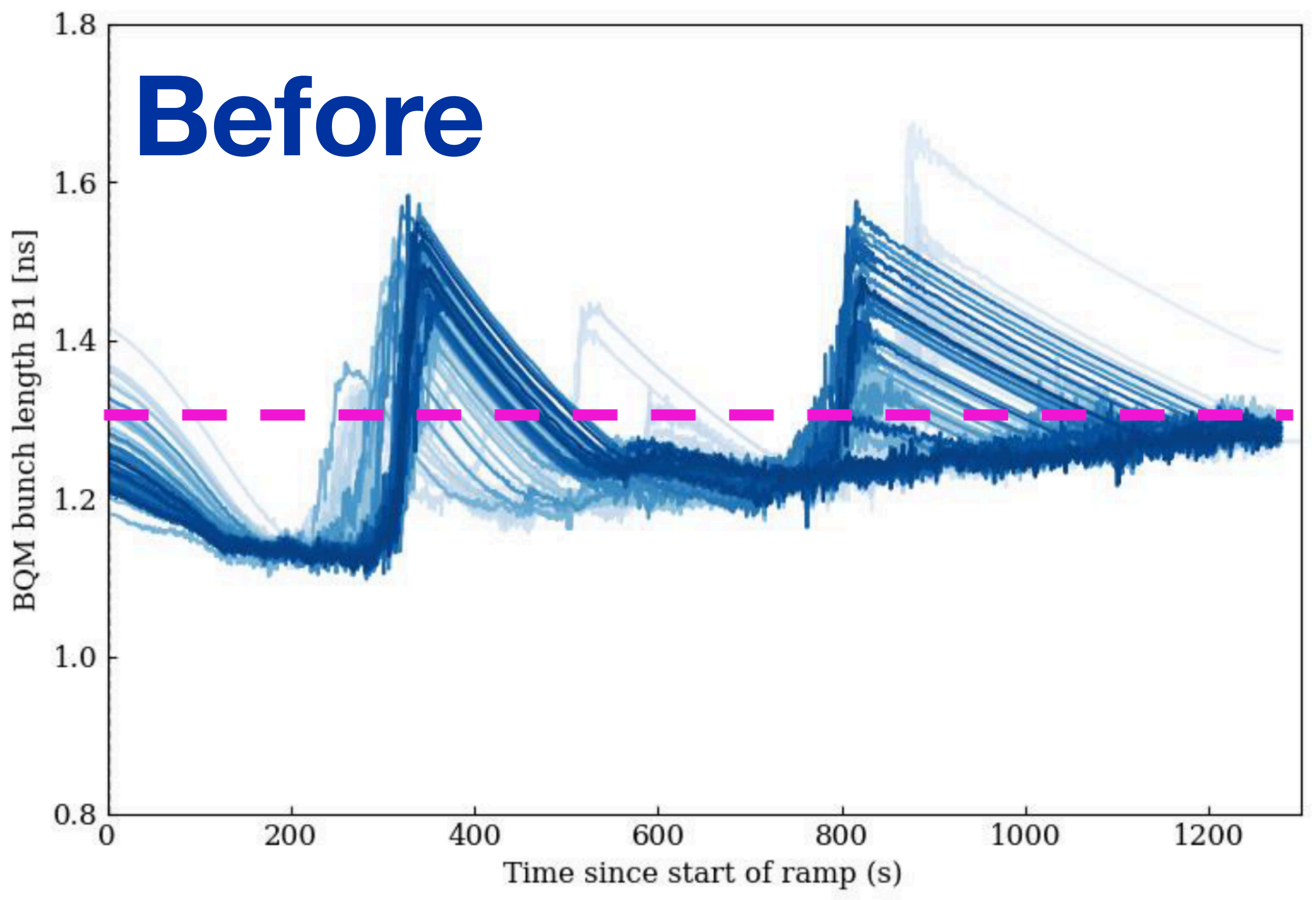
Beam-induced heating in critical LHC components calls for increased bunch length throughout the cycle

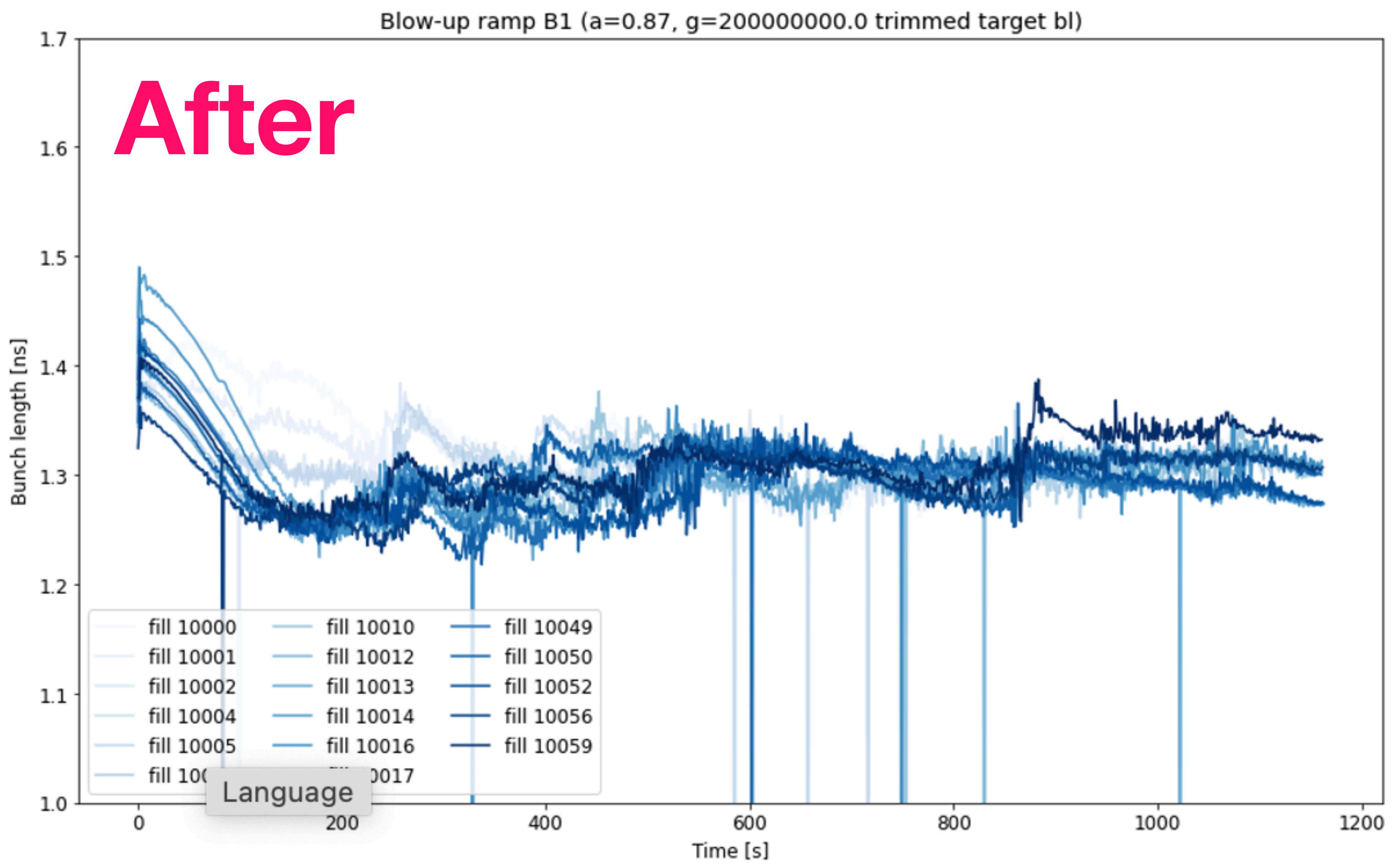
- Bottleneck in Run 3 was the controlled emittance blow-up during the acceleration ramp
  - RF noise injection in a narrow band around the central synchrotron frequency
  - Bunch length feedback regulates the noise amplitude

Improvements in 2024 operation

- Excellent control of bunch length with very little peak-to-peak excursions
  - New implementation with shorter delays between measurement and feedback action
  - Optimised feedback parameters with beam dynamics simulations

Courtesy of N. Gallou





Bunch length throughout the ramp before and after the changes

Plans for 2025-2026

Commissioning activities

- Voltage calibration with beam
- Loaded Q calibration with voltage drop

Beam measurements

- Minimum voltage with 1.8×10^{11} p/b and updated BLM thresholds in operation
- Ramp batches of 2.3×10^{11} p/b to quantify start-of-ramp losses, compare different beam types
- Analyse bunch-by-bunch spreads in SPS and LHC

Operational optimisation

- Automatising the half-detuning adjustment
- Defining the strategy for loaded Q adjustment

Final estimates for HL-LHC

- Answer the fundamental question about the ratio of capture to flat bottom losses
- Simulation scans with control loops, IBS, and losses, folding in also beam stability
- Merging simulation results with measurements to give our final estimates for HL-LHC

Summary

Operation is limited by start-of-ramp losses

- IR3 BLM thresholds are being reviewed
- Capture losses call for increased capture voltage and smaller momentum spread at injection
  - Optimised already: energy matching has been improved operationally
- IBS-induced losses call for increased capture voltage and larger momentum spread at injection
  - Transverse emittance (beam type) strongly affects, too
- Instability-induced losses call for decreased capture voltage and longer bunches

Operation of the ACS system in HL-LHC era

- Requirements on capture voltage constrain the working point to a small range
- Will require operational margin for availability
- Will require dynamic optimisation of detuning and Q_L
- High-efficiency klystron prototype tests are promising

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Thank you for your attention!