RF Power Limitations Studies and Start-of-ramp Losses

14th HL-LHC Collaboration Meeting, Genoa, Italy

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Acknowledgements: shift crews in the LHC and injectors

10th October 2024

Outline

- **Calibration campaign**
  - Loaded quality factor measurements
  - Implementations of RF voltage calibration
- **Operational experience with BCMS and standard beam**
  - Bunch length evolution
  - Start-of-ramp losses
- **High-intensity MDs in 2023 and 2024**
  - Measurements of the capture of 2.3×10^{11} p/b

Shown at the Last Year

Summary of expectations

Global analysis [6]

- Managed to capture 2.0×10^{11} p/b with up to 7 MV
- Several improvements have been implemented over 2022-2023
  - Pre-detuning removes the limitations from injection transients; focus now on peak power in steady state
  - Continuous operational optimisation of SPS-LHC energy matching lowers blow-up at injection
  - Operation with short bunches at 1.6×10^{11} p/b allows to capture with 5 MV
- Calibration measurements ongoing to verify margins in voltage and peak power
  - Voltage-based calibration shows a lack in voltage/power for 4/16 RF lines
- Projected HL-LHC peak power in the fully optimised (simulated) case is 330-340 kW
  - Even with high-efficiency klystrons, will need to find a way to lower the figures

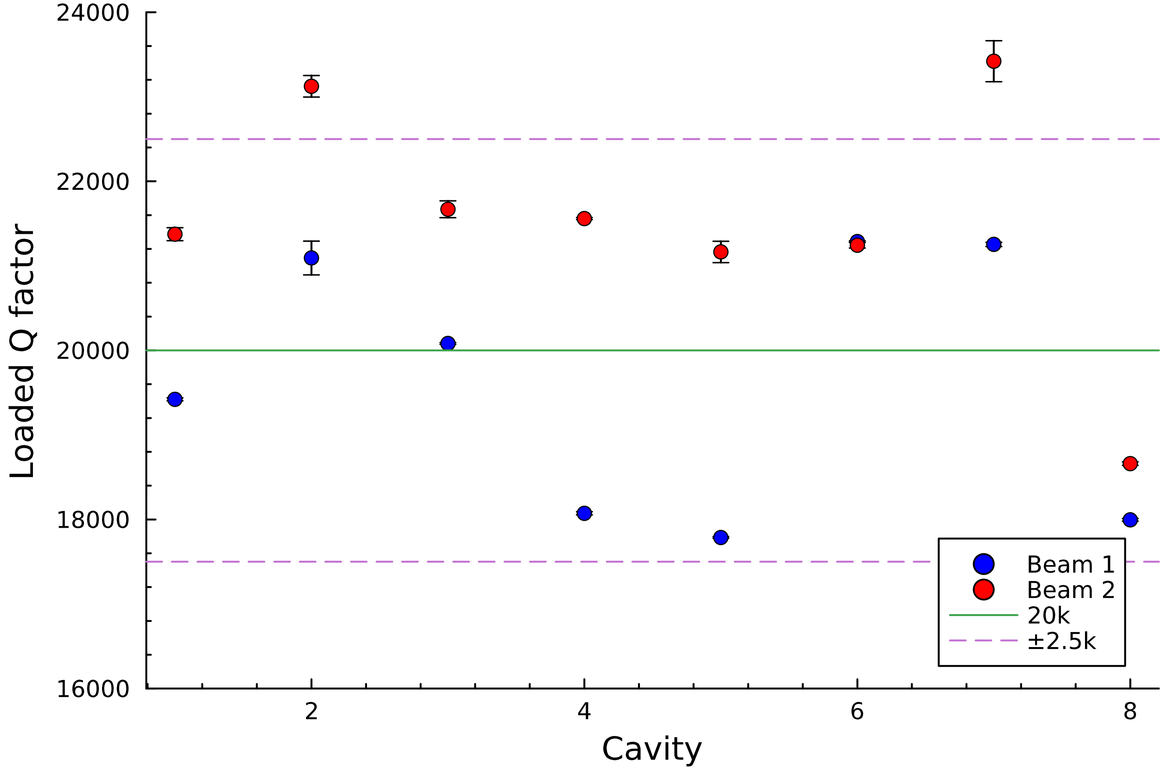
Next steps

- 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

[6] H. Timko *et al.*: 'Advances on LHC RF power limitation studies at injection', Proc. HB'23 workshop, CERN, Geneva, Switzerland, 2023.

Calibration Campaign for the LHC RF System

- **Loaded quality factor measurements**
  - Performed voltage decay measurements during hardware commissioning
  - Performed measurement with beam during beam commissioning
- **Confirmation of the voltage calibration**
  - Calibration measurement done in 2022 (3% precision)
  - Measurements were taken, but need to be analysed



Measured Q_L via voltage decay when setting the setpoint Q_L to 20k

Bunch Length and Start-of-ramp Losses in 2024

Off-momentum particles drifting around the ring

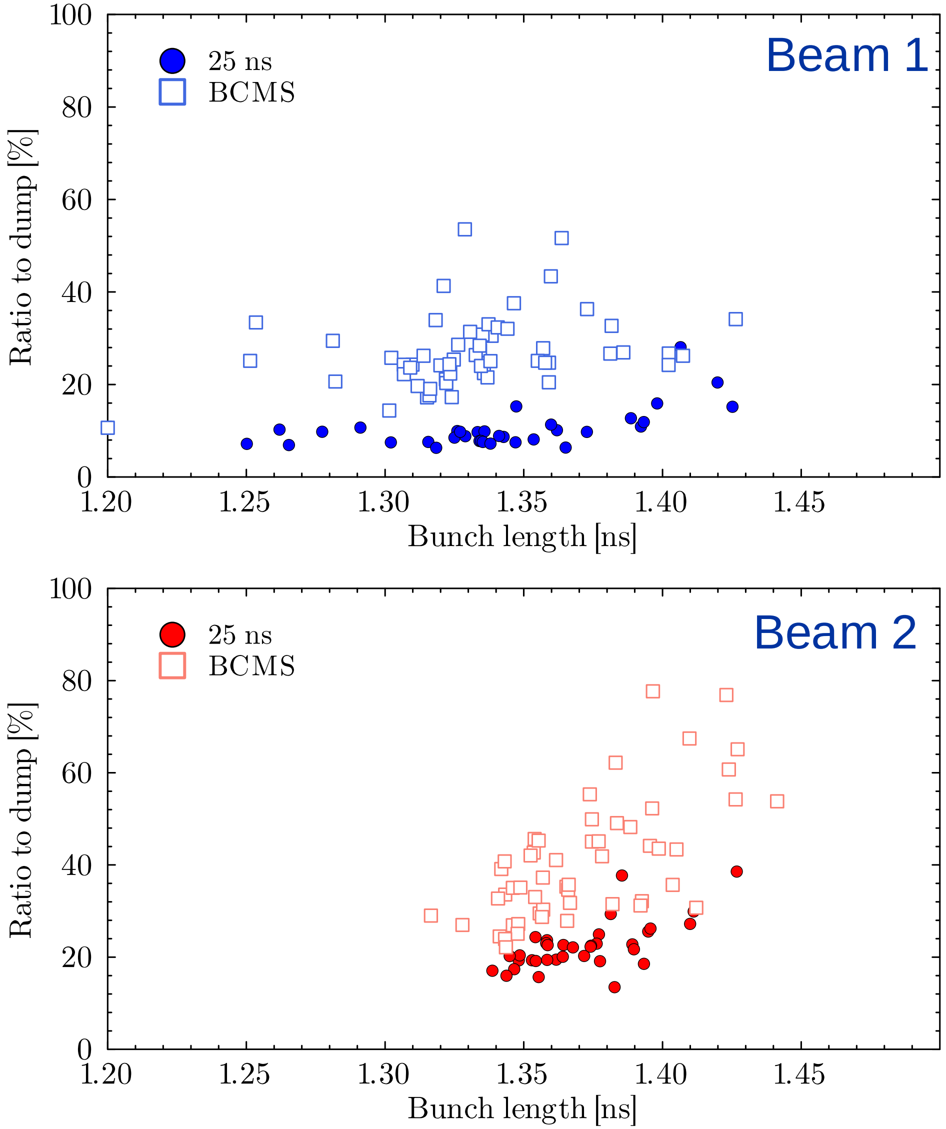
At capture

- Transient beam loading
- Injection errors in energy and phase

During flat bottom

- RF noise
- Intra-beam scattering
- Kicks from consecutive injections

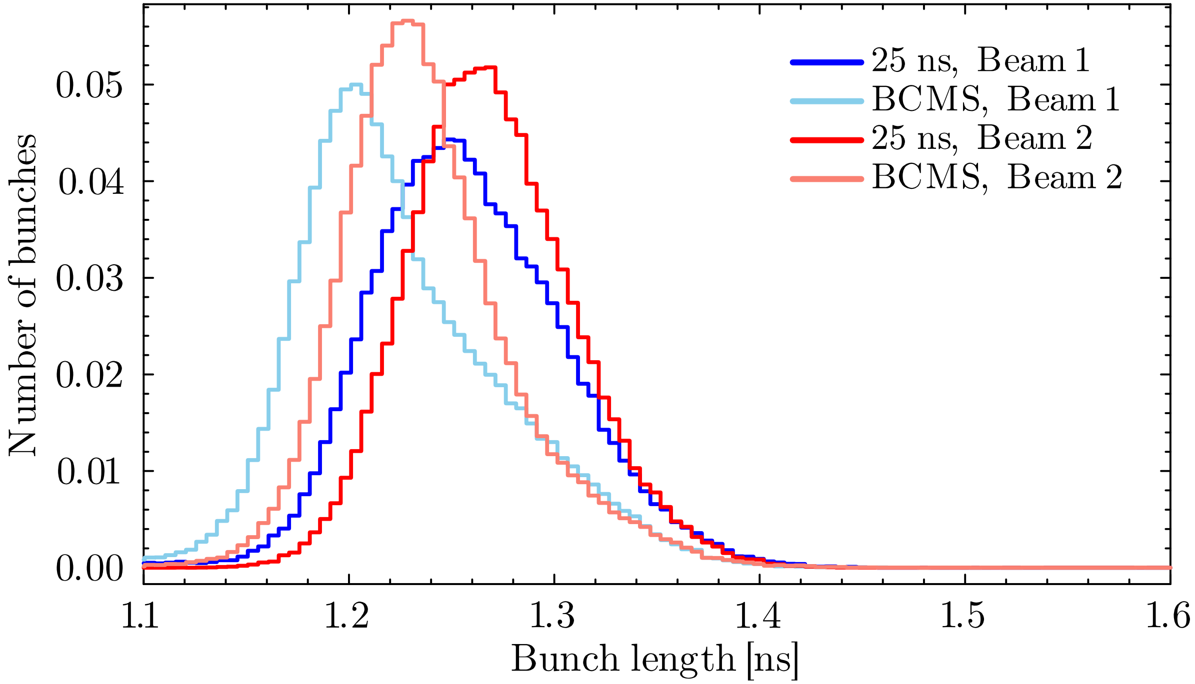
NB! Not a sum of the different contributions because of the ADT cleaning



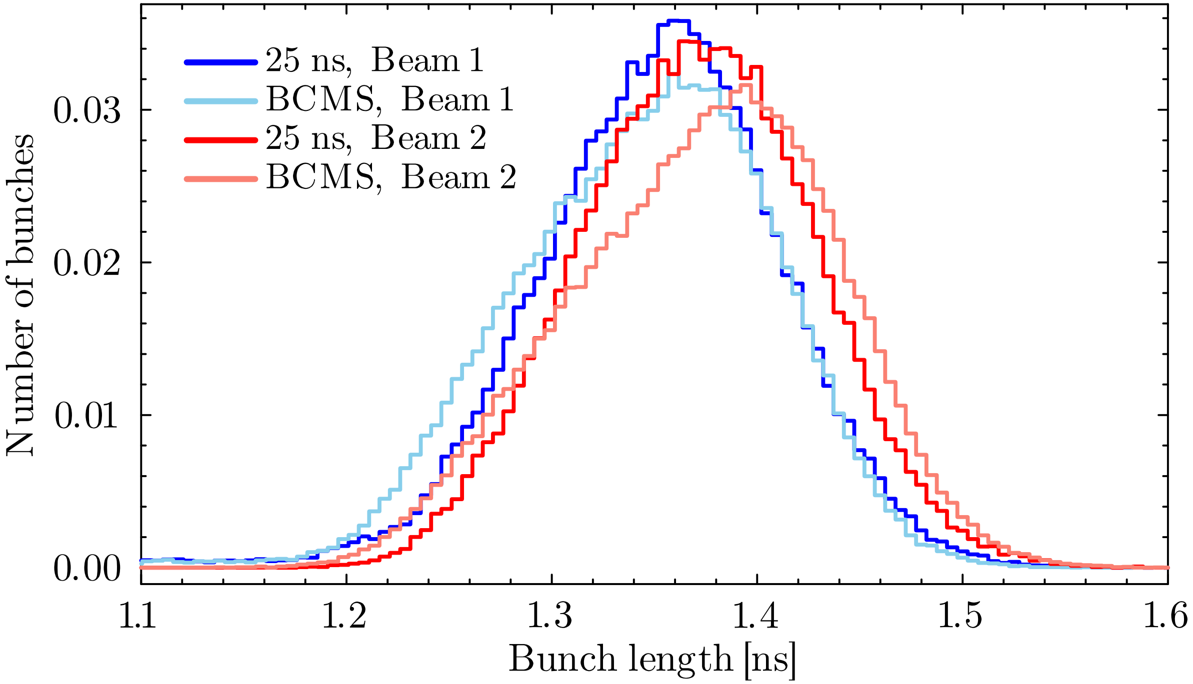
Standard Beam and the BCMS Beam in 2024

Increase in RF voltage from 5 MV to 5.5 MV
giving shorter bunches

At injection after filamentation



At the start of the ramp

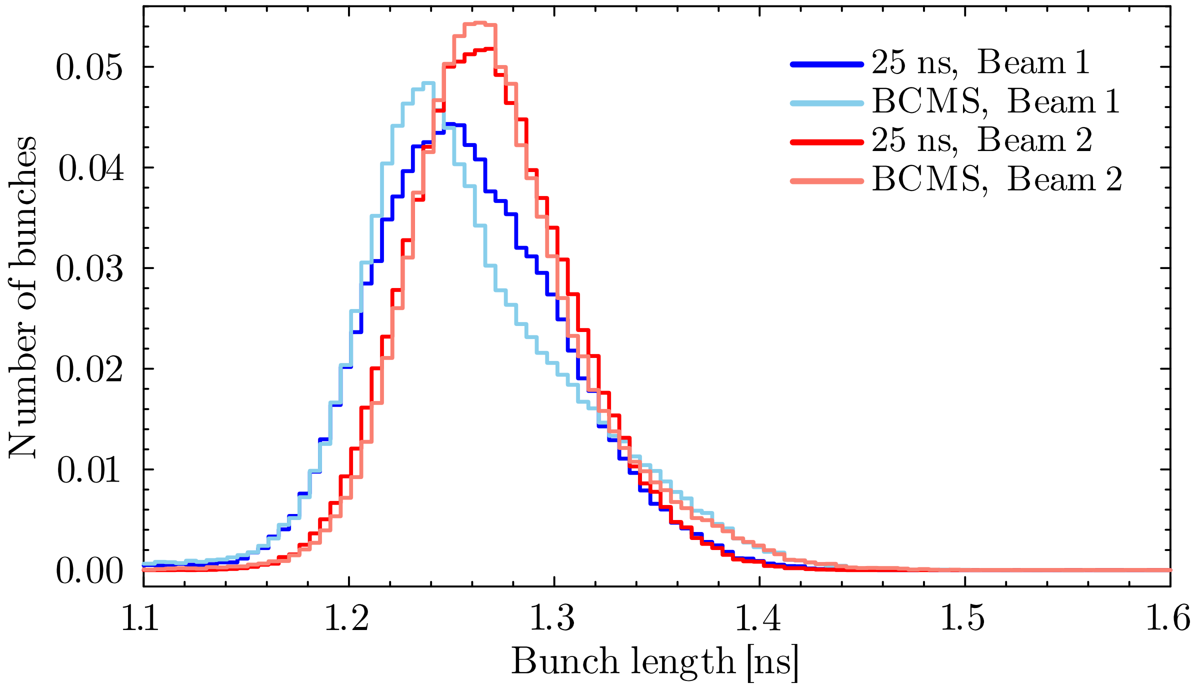


BCMS beam is in general shorter after filamentation (higher voltage). However, at the start-of-ramp they are approximately as long as the standard beam

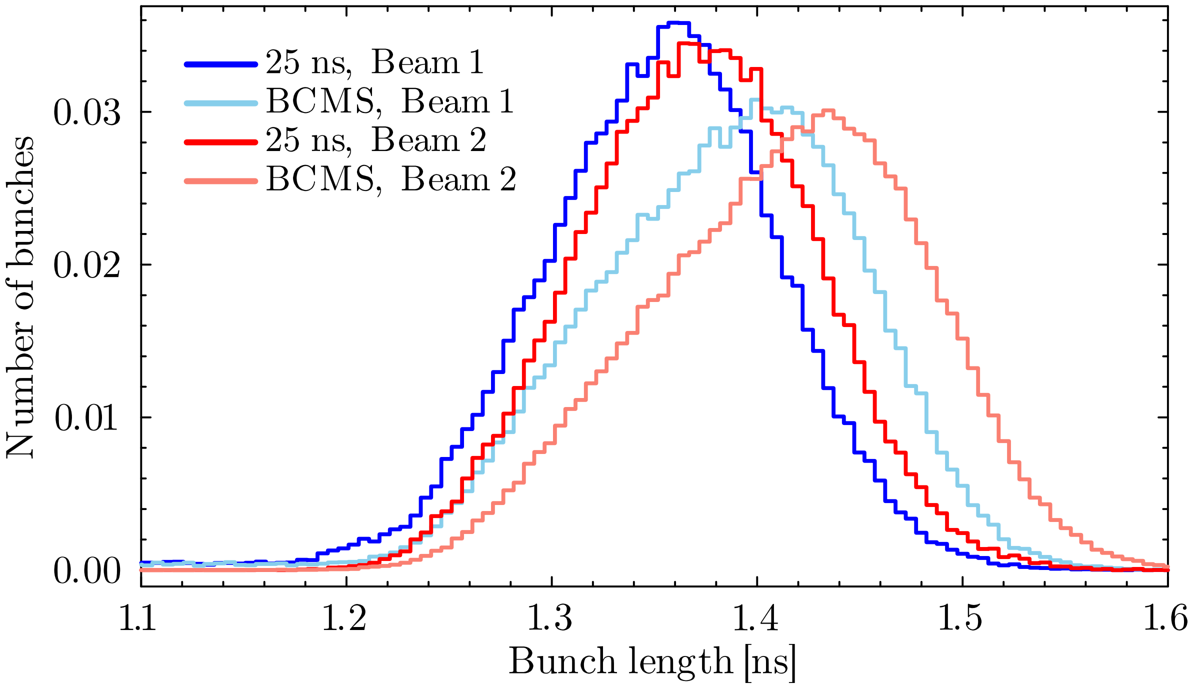
Standard Beam and the BCMS Beam in 2024

BCMS bunch length scaled from 5.5 MV to 5 MV (assuming constant emittance)

At injection after filamentation



At the start of the ramp



If the voltage increase is considered, the emittance from the SPS is approximately same at injection. However, BCMS emittance is consistently larger at the start of the ramp.

Accounting for the extra batches and longer flat bottom

- **Intra-beam scattering (assuming gaussian bunches)**

$$\tau = \tau_0 e^{\frac{t}{2T_z}}, \qquad T_z = T_z(\tau, \delta, \varepsilon_x, \varepsilon_y)$$

- **Diffusion due to RF noise (short bunch approximation)**

$$\tau_f = \tau_0 \sqrt{1 + \frac{t}{\tau_0} \Omega_{s0}^2 P(\Omega_{s0})}$$

- **Example:**
  - STD: 35 min. at flat bottom
  - BCMS: 45 min. at flat bottom

Relative increase in bunch length growth rate from STD to BCMS

	Beam 1	Beam 2
IBS	39%	35%
RF Noise	17%	16%

- **Note:**
  - We do not know the exact proportions of the two
  - Not exact numbers, e.g. the bunches are not gaussian and short bunch approximation

*Using the transverse parameters from: S. Kostoglou *et al*. “BCMS vs Standard”, LBOC presentation, June 4th 2024

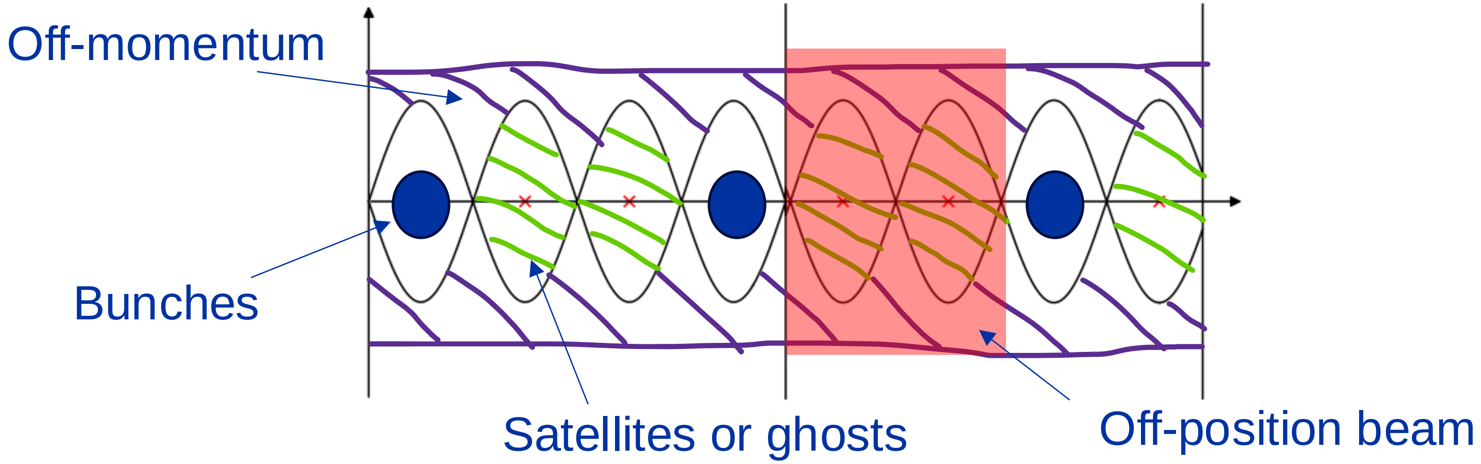
Analysis looking at off-position particles

Total amount of particles not in the correct RF buckets but still drifting around the ring

Fast BCT from injection to the ramp

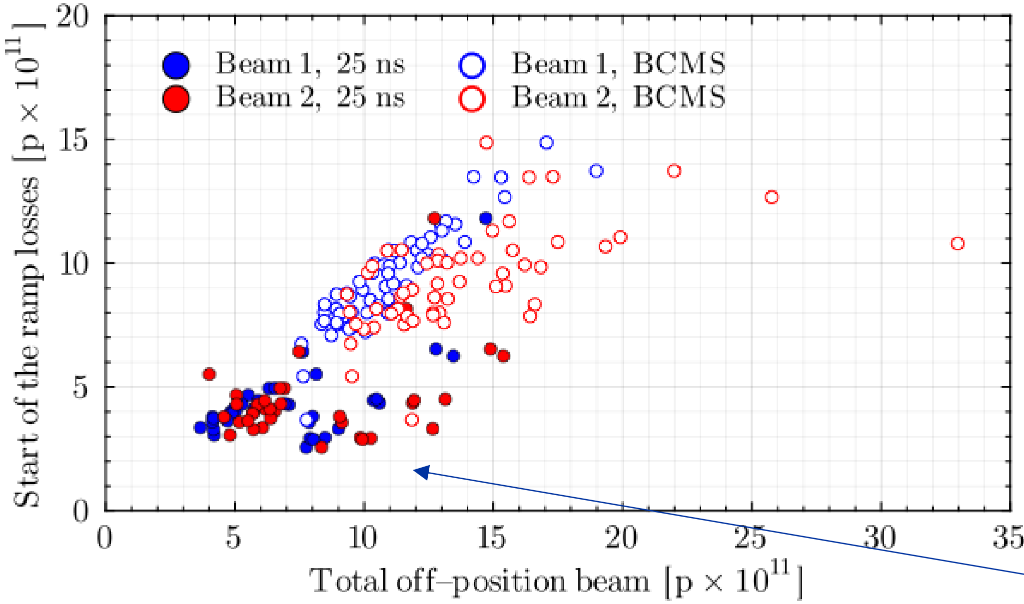
- Bunch intensity reduction
- Sum of intensity lost out of the ring and particles not in the correct bunch slot

- **DC BCT from batch injection to the ramp**
  - Gives total intensity injected into the LHC
  - The DC BCT measurement at the start of the ramp
- **Combining this one can estimate the number of particles off position**

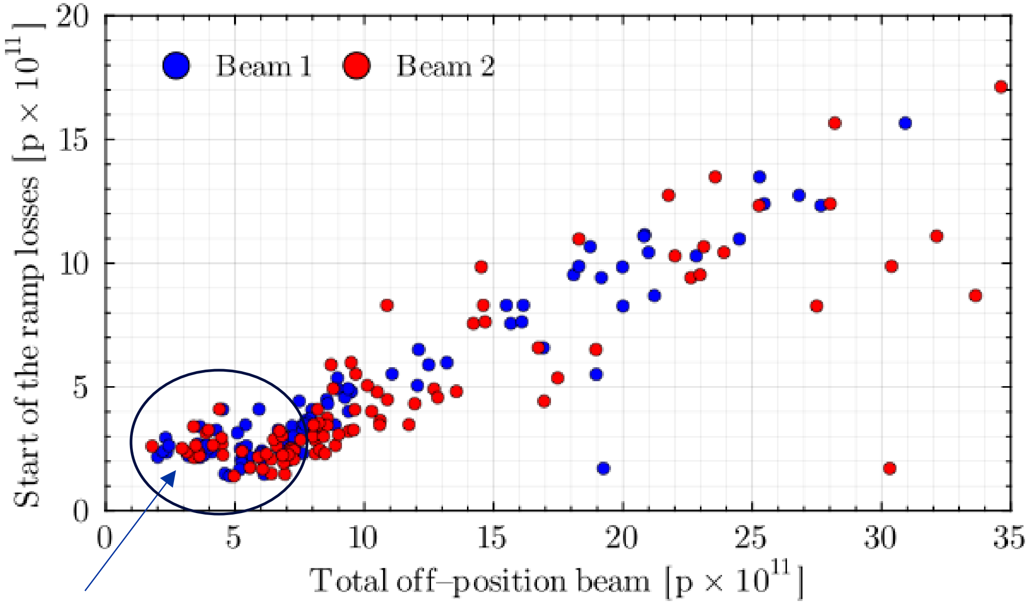


Correlation between off-position particles and losses at the start of the ramp

From fills in 2024



From fills in 2022 and 2023



Two populations of losses

BCMS has higher off-position beam as well as start-of-ramp losses

We get slightly higher start-of-ramp losses for the same amount of off-position beam with BCMS

The slope of the diagonal is higher in 2024 compared to 2023 and 2022 data

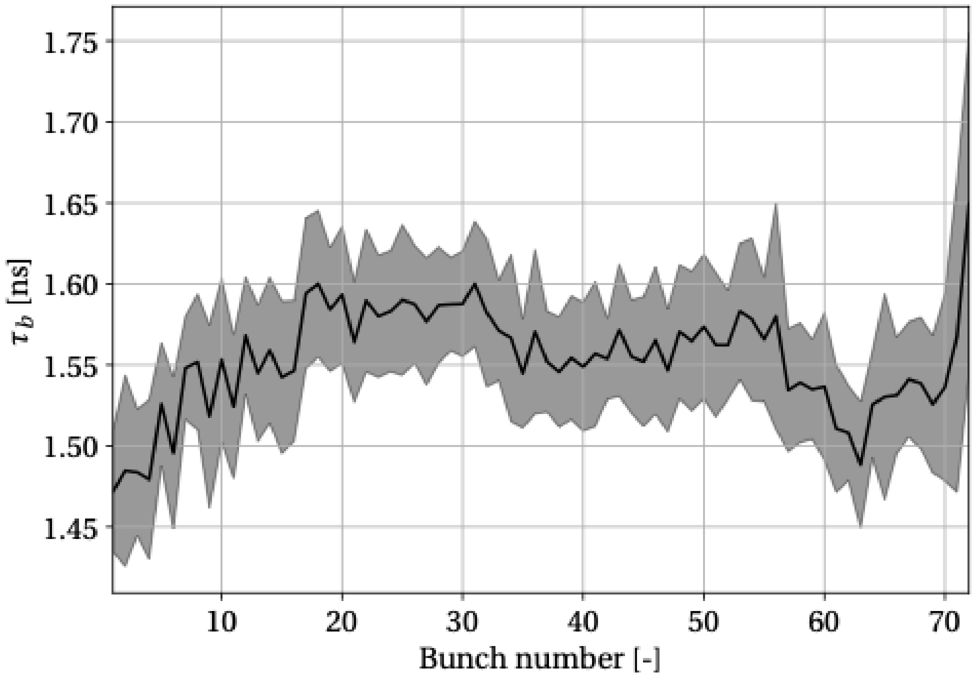
High-Intensity MDs in 2023 and 2024

- **In 2023 – 72-bunch trains, standard beam**
  - Captured 2.0 x 10^{11} p/b with 5 MV and 7 MV
- **In 2024 – 2x48-bunch trains, BCMS beam**
  - Captured 2.0 x 10^{11} p/b with 7 MV and accelerated it
  - Captured 2.3 x 10^{11} p/b with 6.5 MV without one-turn feedback

Year	Intensity	SPS bunch length	SPS Voltage 200 MHz	SPS Voltage 800 MHz	LHC Voltage	LHC bunch length	Simulated peak power at optimum Q_L
2023	2.0 x 10^{11} p/b	1.55 ns	9.4 MV	1.69 MV	5 MV	1.32 ns	178 kW
2023	2.0 x 10^{11} p/b	1.55 ns	9.4 MV	1.69 MV	7 MV	1.20 ns	263 kW
2024	2.0 x 10^{11} p/b	1.50 ns	8.5 MV	1.445 MV	7 MV	1.11 ns	269 kW
2024	2.3 x 10^{11} p/b	1.60 ns	8.5 MV	1.53 MV	6.5 MV	1.19 ns	283 kW (without OTFB: 238 kW)

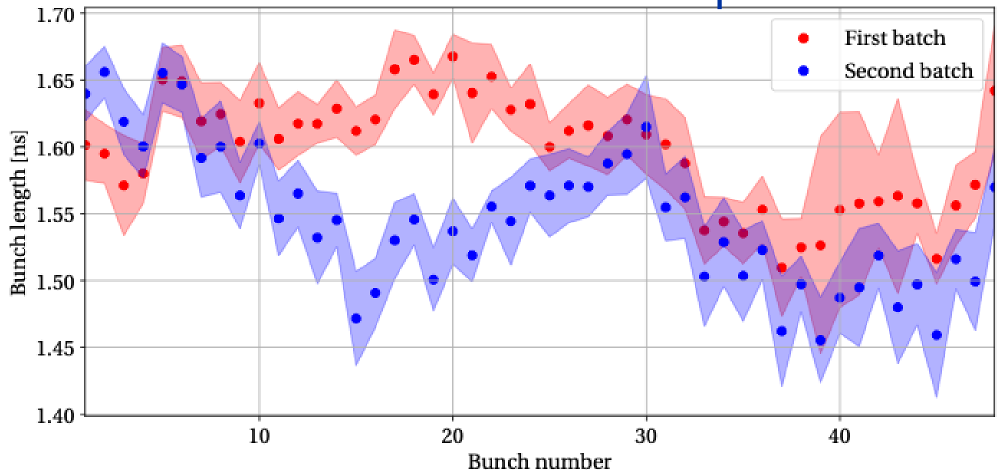
Bunch Length Delivered from the SPS at HL Intensity

72b with 2.0 x 10^{11} p/b



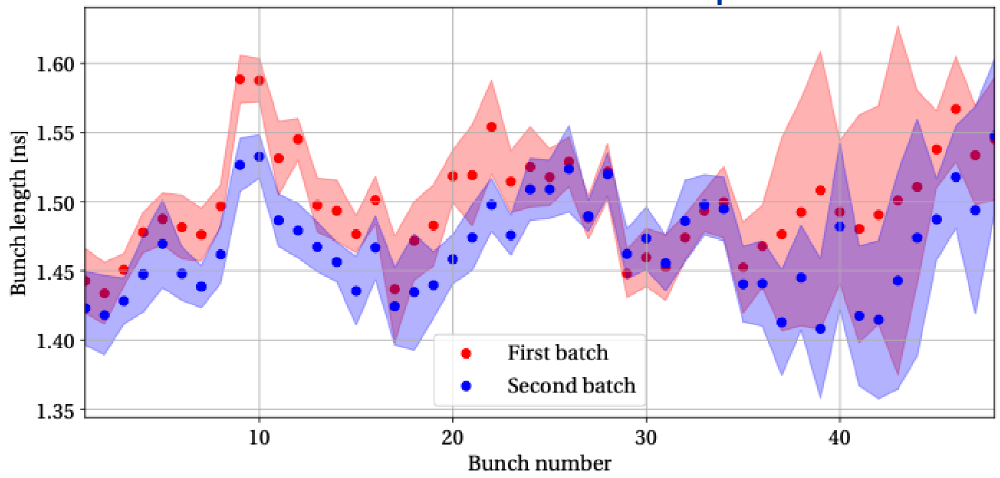
Average bunch length: (1.55 ± 0.06) ns, 10% peak-to-peak

2 x 48b with 2.3 x 10^{11} p/b



Average bunch length: (1.60 ± 0.05) ns, 16% peak-to-peak

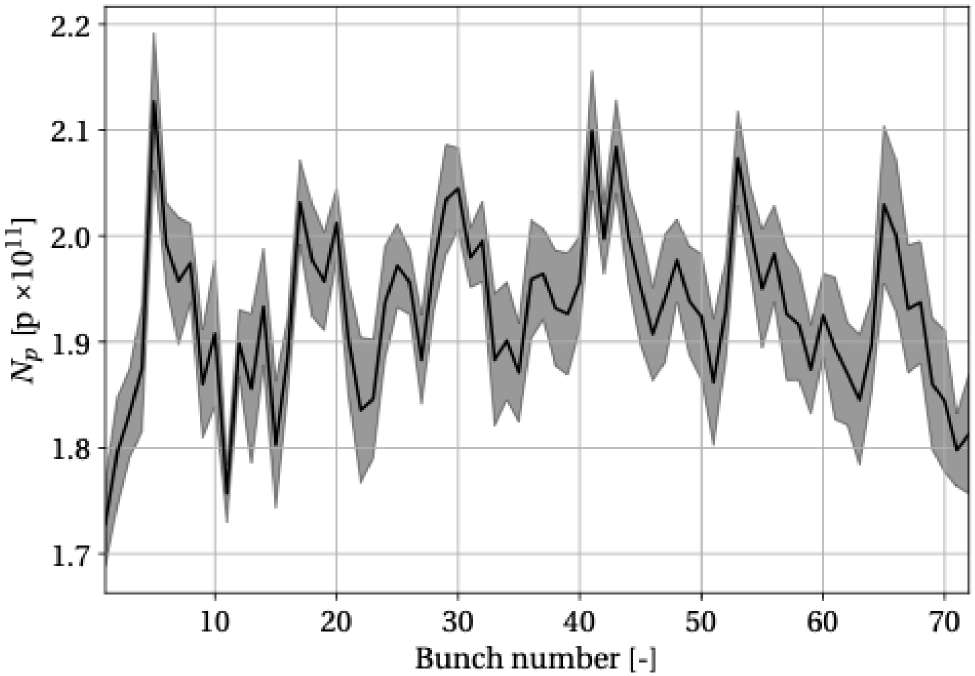
2 x 48b with 2.0 x 10^{11} p/b



Average bunch length: (1.50 ± 0.06) ns, 16% peak-to-peak

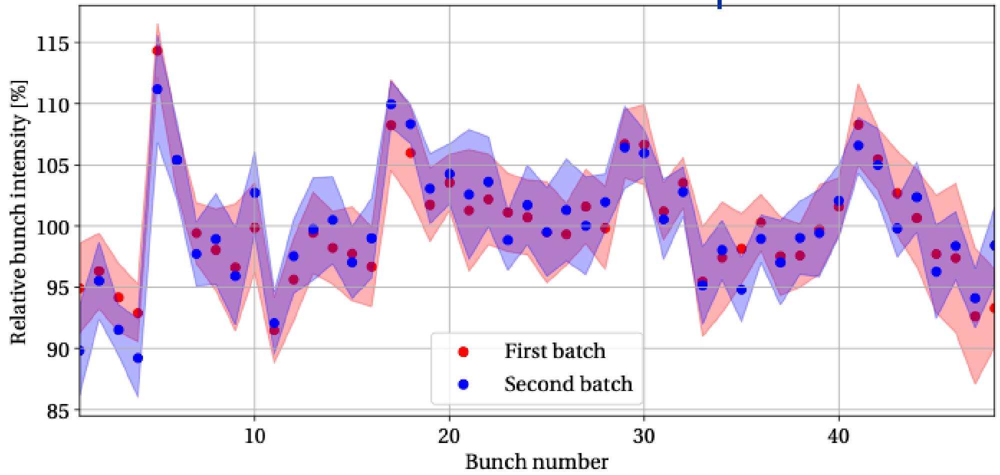
Bunch intensities Delivered from the SPS at HL Intensity

72b with 2.0 x 10^{11} p/b



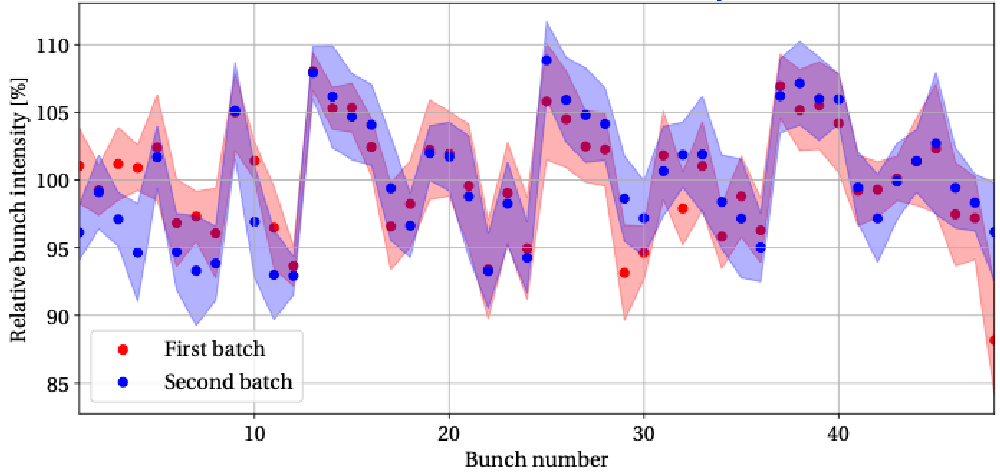
Average bunch intensity: 1.93 x 10^{11} p/b ± 4.8%, 9% pk-to-pk

2 x 48b with 2.3 x 10^{11} p/b



Average bunch intensity: 2.31 x 10^{11} p/b ± 5.7%, 27% pk-to-pk

2 x 48b with 2.0 x 10^{11} p/b



Average bunch intensity: 1.97 x 10^{11} p/b ± 5.4%, 23% pk-to-pk

Direct Measurements of Start-of-ramp Losses in MDs at 2.0 x 10^{11} p/b

- **Two ramps were performed 12b + 48b + 3 x 96b**
  - Waited 10 minutes between each 96-bunch injection
  - First with good phase and energy matching
  - Second with 0 deg., 0 deg., 40 deg., -40 deg., and 0 deg.
- **First ramp**
  - Beam 1: 0.47 x 10^{11} p → 0.016 % threshold to dump
  - Beam 2: 0.45 x 10^{11} p → 0.017 % threshold to dump
- **Second ramp**
  - Beam 1: 0.78 x 10^{11} p → 0.024 % threshold to dump
  - Beam 2: 0.65 x 10^{11} p → 0.032 % threshold to dump

Almost factor two between the two ramps

Cannot be directly compared to the result based on off-position beam due to:

1. The amount of bunches
2. Beam-phase loop is still efficient

Predicted Losses at the Start of the Ramp from Off-position Beam

- **From 2023 at 1.93 x 10^{11} p/b – 72-bunch trains (300 bunches)**
- **From 2024 at 1.97 x 10^{11} p/b – 48-bunch trains (348 bunches)**
- **From 2024 at 2.31 x 10^{11} p/b – 48-bunch trains (348 bunches)**

Based on BLM thresholds in 2023, but they are being revised

Beam 1

Year	Beam type	Bunch Intensity	RF Voltage	Off-position beam	Off-position beam Scaled to 2748 bunches*	Estimated Start-of-ramp Losses	Ratio to dump
2023	Standard	1.93 x 10^{11} p/b	5 MV	10.08 x 10^{11} p	19.28 x 10^{11} p	(8.2 ± 1.3) x 10^{11} p	(31.2 ± 4.9) %
2023	Standard	1.93 x 10^{11} p/b	7 MV	2.08 x 10^{11} p	8.93 x 10^{11} p	(4.03 ± 0.76) x 10^{11} p	(15.3 ± 2.9) %
2024	BCMS	1.97 x 10^{11} p/b	7 MV	0.59 x 10^{11} p	9.46 x 10^{11} p	(8.1 ± 1.5) x 10^{11} p	(30.8 ± 5.7) %
2024**	BCMS	1.97 x 10^{11} p/b	7 MV	1.07 x 10^{11} p	26.73 x 10^{11} p	(22 ± 2.9) x 10^{11} p	(84.0 ± 11.0) %
2024***	BCMS	2.31 x 10^{11} p/b	6.5 MV	5.88 x 10^{11} p	21.97 x 10^{11} p	(18.2 ± 2.4) x 10^{11} p	(69. ± 9.1) %

*Also scaled for an average time at flat bottom of 30 minutes
**With significant injection errors (40 degrees)
***With the OTFB open, note a few bunches saturated FBCT

Predicted Losses at the Start of the Ramp from Off-position Beam

- **From 2023 at 1.93 x 10^{11} p/b – 72-bunch trains (300 bunches)**
- **From 2024 at 1.97 x 10^{11} p/b – 48-bunch trains (348 bunches)**
- **From 2024 at 2.31 x 10^{11} p/b – 48-bunch trains (348 bunches)**

Based on BLM thresholds in 2023, but they are being revised

Beam 2

Year	Beam type	Bunch Intensity	RF Voltage	Off-position beam	Off-position beam Scaled to 2748 bunches*	Estimated Start-of-ramp Losses	Ratio to dump
2023	Standard	1.93 x 10^{11} p/b	5 MV	12.15 x 10^{11} p	29.99 x 10^{11} p	(11.4 ± 1.3) x 10^{11} p	(81.3 ± 9.3) %
2023	Standard	1.93 x 10^{11} p/b	7 MV	2.62 x 10^{11} p	10.54 x 10^{11} p	(4.12 ± 0.59) x 10^{11} p	(29.4 ± 4.2) %
2024	BCMS	1.97 x 10^{11} p/b	7 MV	0.26 x 10^{11} p	1.40 x 10^{11} p	(2.06 ± 0.93) x 10^{11} p	(14.7 ± 6.6) %
2024**	BCMS	1.97 x 10^{11} p/b	7 MV	1.02 x 10^{11} p	16.48 x 10^{11} p	(11.2 ± 1.4) x 10^{11} p	(79.9 ± 10.0) %
2024***	BCMS	2.31 x 10^{11} p/b	6.5 MV	13.57 x 10^{11} p	49.03 x 10^{11} p	(30.8 ± 3.4) x 10^{11} p	(220 ± 24) %

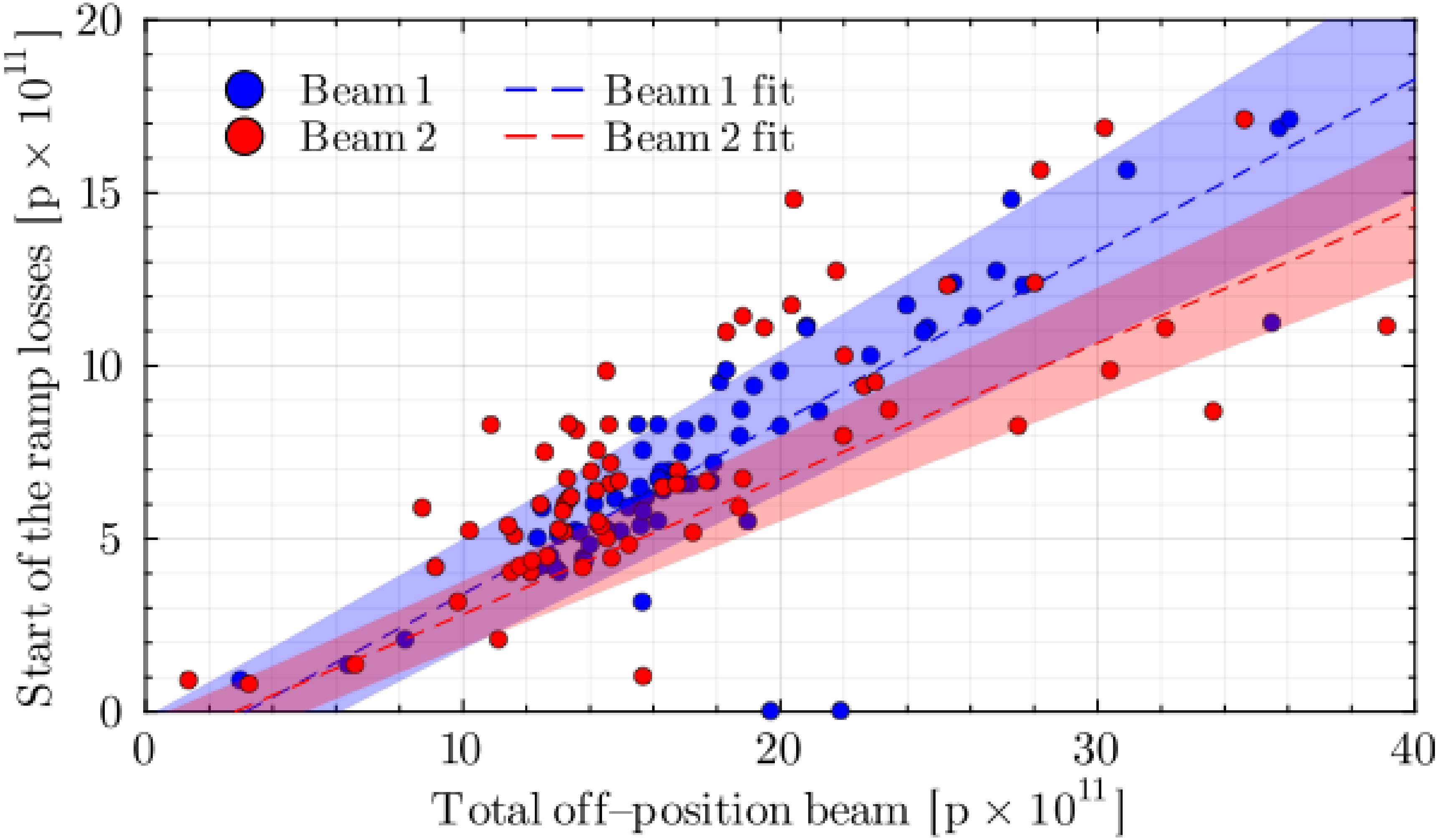
*Also scaled for an average time at flat bottom of 30 minutes
**With significant injection errors (40 degrees)
***With the OTFB open, note a few bunches saturated FBCT

Conclusions

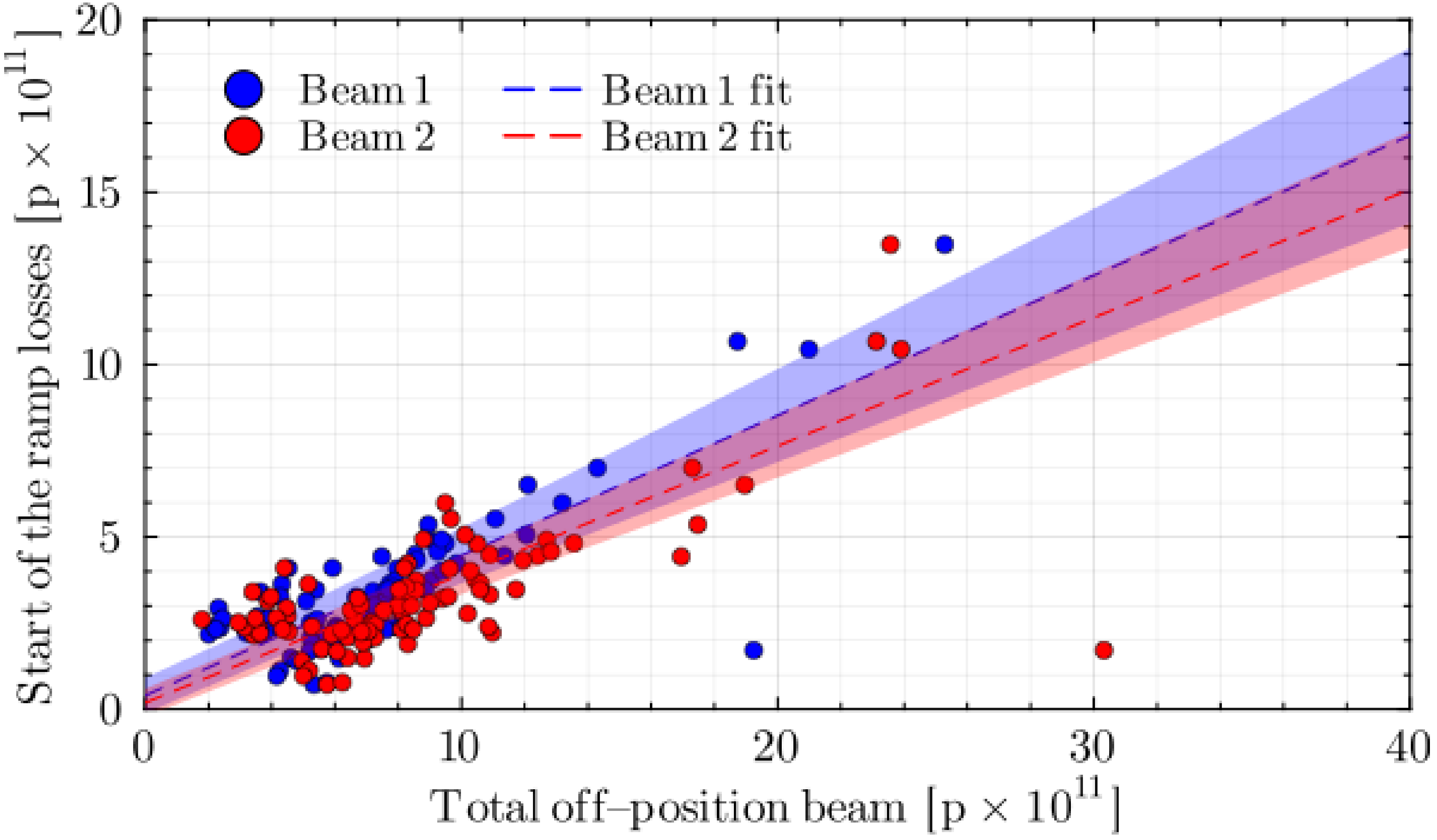
- **Calibration of RF power**
  - Three different measurements of Q_L have been performed
  - Voltage calibration implemented in the machine
  - Voltage calibration confirmation to be analysed
- **Operation in 2024 with BCMS**
  - Significantly more start-of-ramp losses
  - More blow-up due to smaller transverse emittances
  - More population off-momentum
- **High-intensity MDs in 2023 and 2024**
  - First capture of 2.3 x 10^{11} p/b
    - NB! Without the OTFB (perhaps not viable for production fills for HL-LHC)
  - Direct measurement of start-of-ramp losses with 2.0 x 10^{11} p/b
  - Off-position beam estimates suggest significant start-of-ramp losses for 2.3 x 10^{11} p/b

Backup

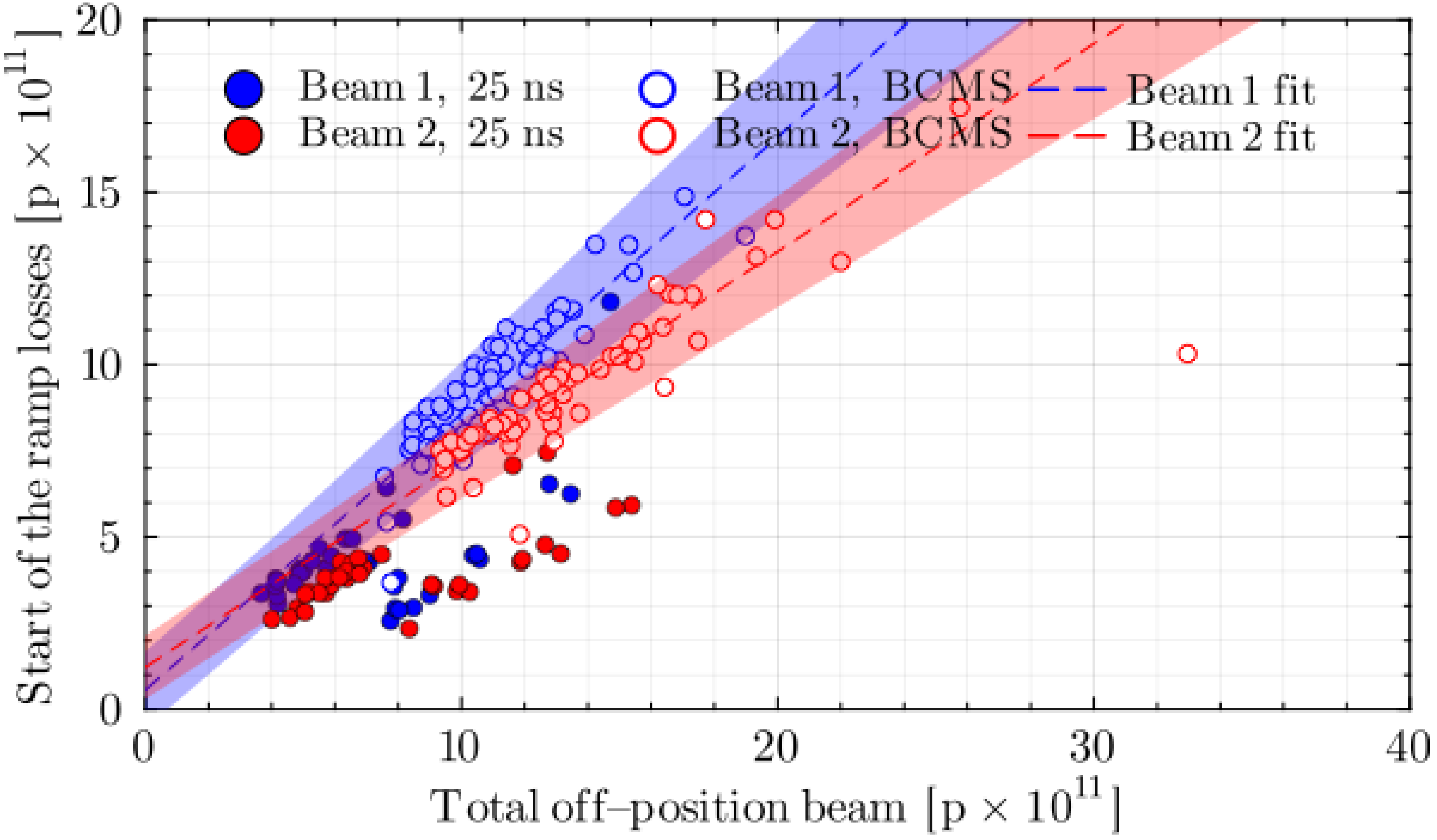
Fit Results of the Off-position Beam Versus Start-of-ramp Losses in 2022



Fit Results of the Off-position Beam Versus Start-of-ramp Losses in 2023

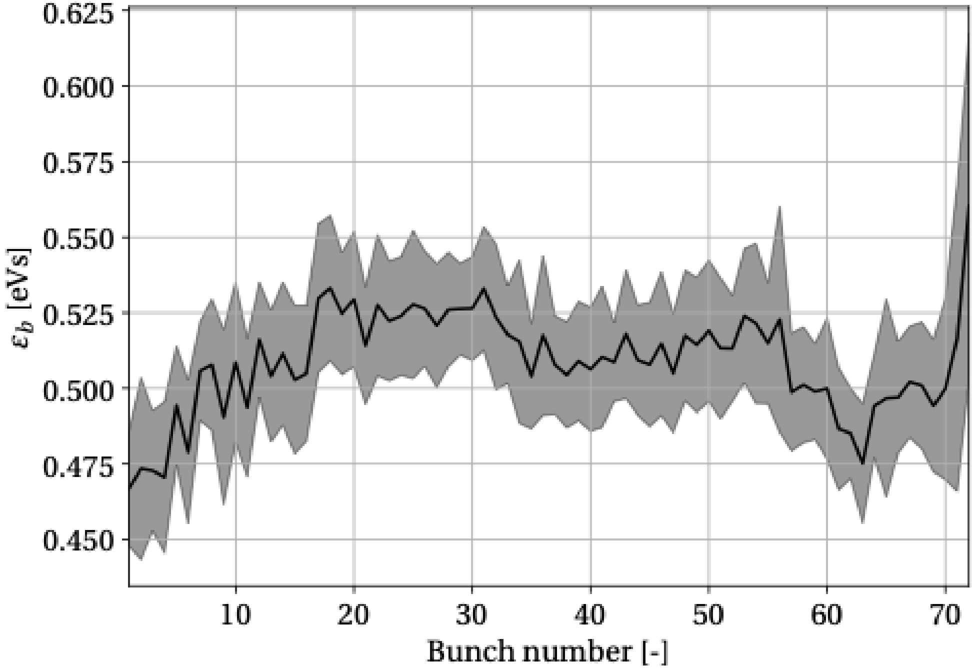


Fit Results of the Off-position Beam Versus Start-of-ramp Losses in 2024



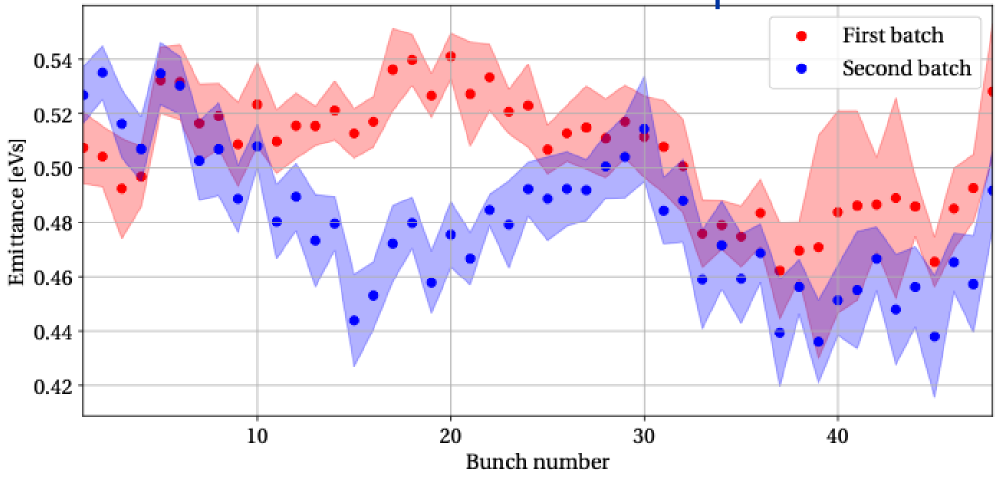
Longitudinal Emittances Delivered from the SPS at HL Intensity

72b with 2.0 x 10^{11} p/b



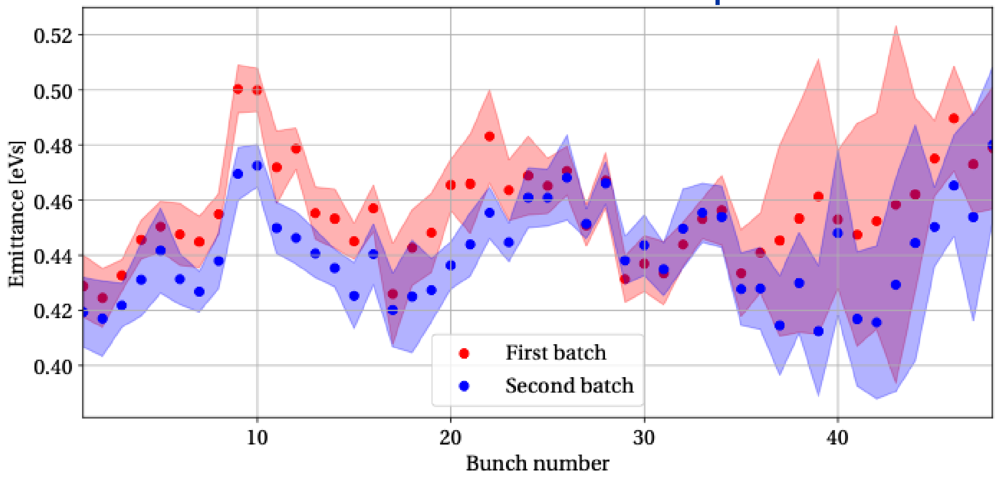
Average bunch length: (0.51 ± 0.03) eVs, peak-to-peak 16%

2 x 48b with 2.3 x 10^{11} p/b



Average emittance: (0.49 ± 0.03) eVs, peak-to-peak 25%

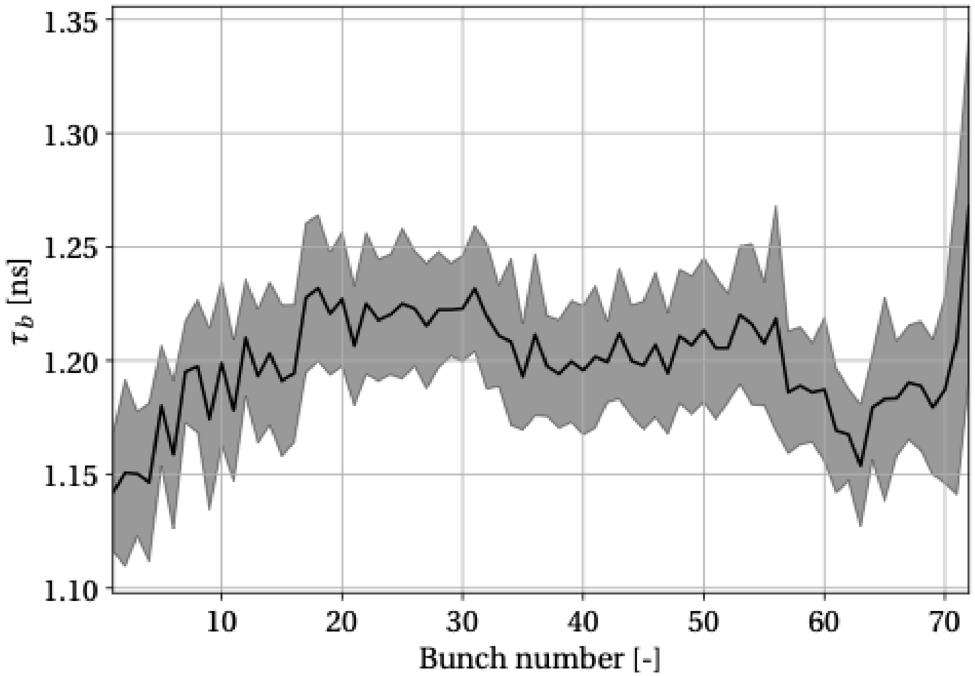
2 x 48b with 2.0 x 10^{11} p/b



Average emittance: (0.45 ± 0.03) eVs, peak-to-peak 22%

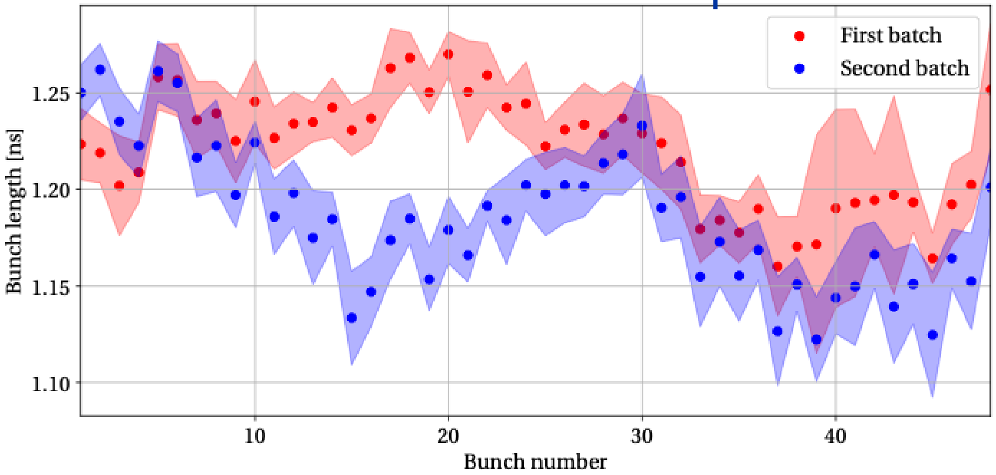
Bunch Length Delivered from the SPS at HL Intensity in the LHC

72b with 2.0 x 10^{11} p/b 7 MV



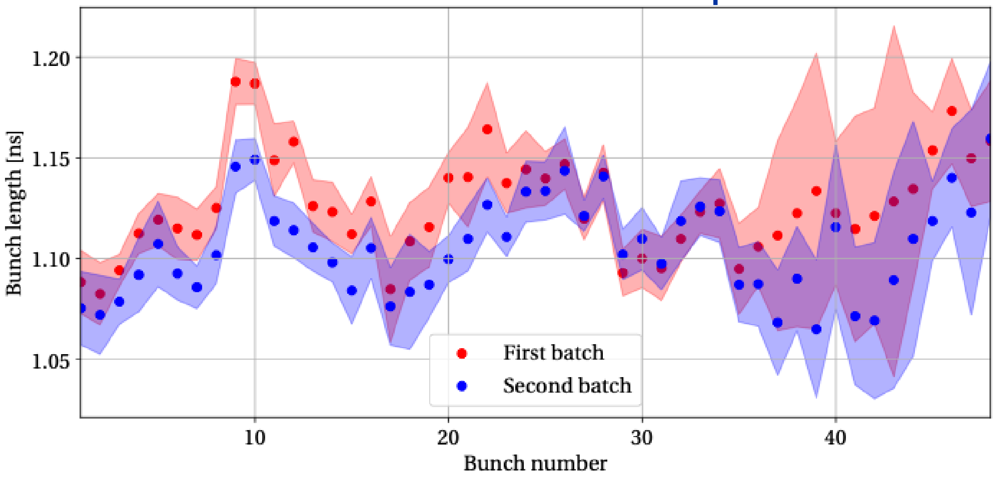
Average bunch length: (1.20 ± 0.04) ns, 9% peak-to-peak

2 x 48b with 2.3 x 10^{11} p/b



Average bunch length: (1.19 ± 0.04) ns, 15% peak-to-peak

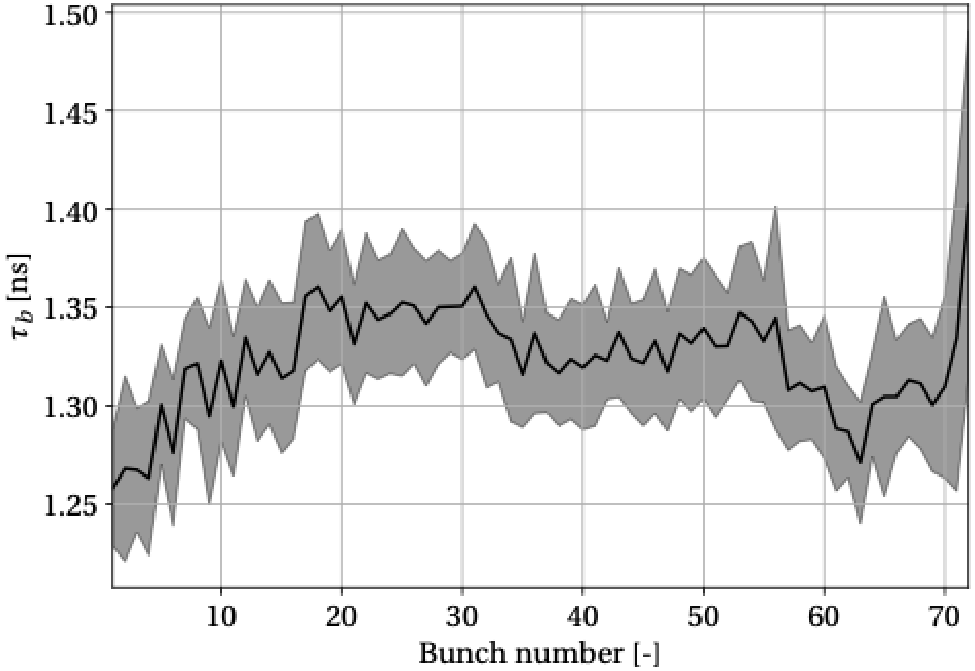
2 x 48b with 2.0 x 10^{11} p/b



Average bunch length: (1.11 ± 0.04) ns, 14% peak-to-peak

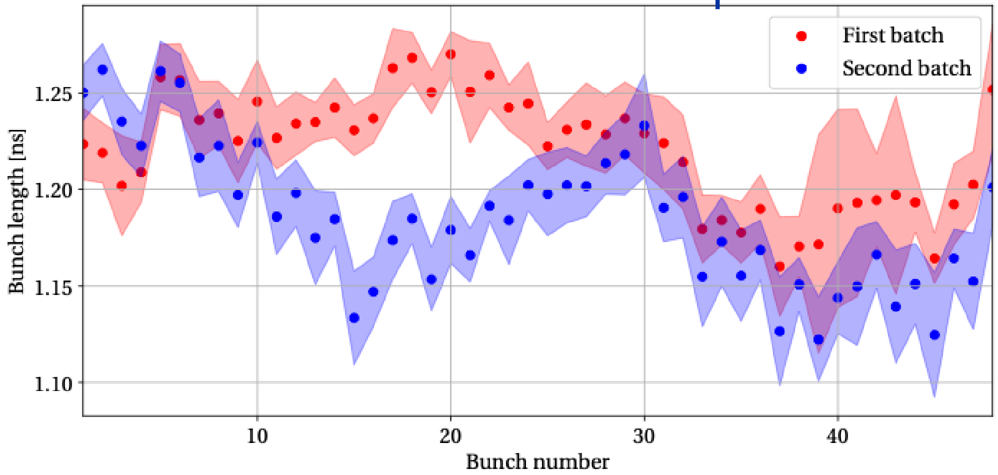
Bunch Length Delivered from the SPS at HL Intensity in the LHC

72b with 2.0 x 10^{11} p/b 5 MV



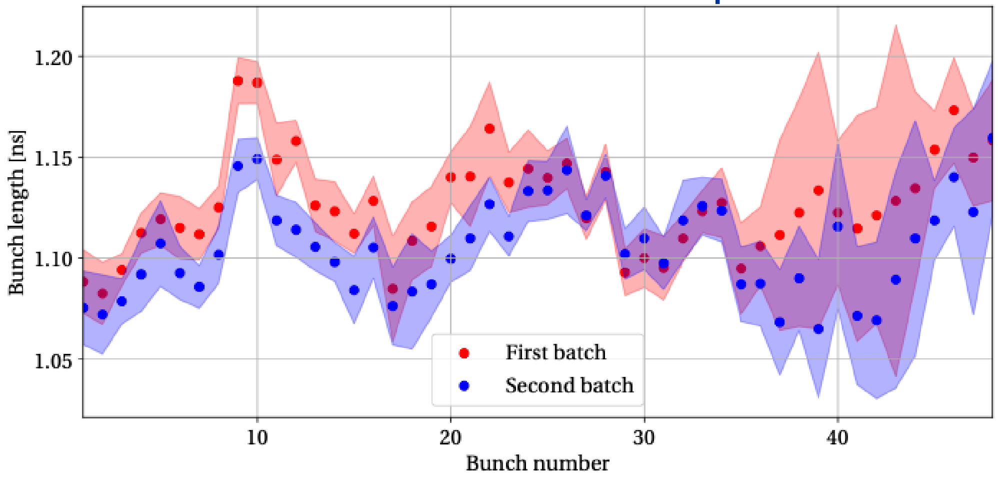
Average bunch length: (1.32 ± 0.05) ns, 10% peak-to-peak

2 x 48b with 2.3 x 10^{11} p/b



Average bunch length: (1.19 ± 0.04) ns, 15% peak-to-peak

2 x 48b with 2.0 x 10^{11} p/b



Average bunch length: (1.11 ± 0.04) ns, 14% peak-to-peak

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