Capture losses: measurements and simulations

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Acknowledgements:

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SPS & PS operator team, BLonD dev team

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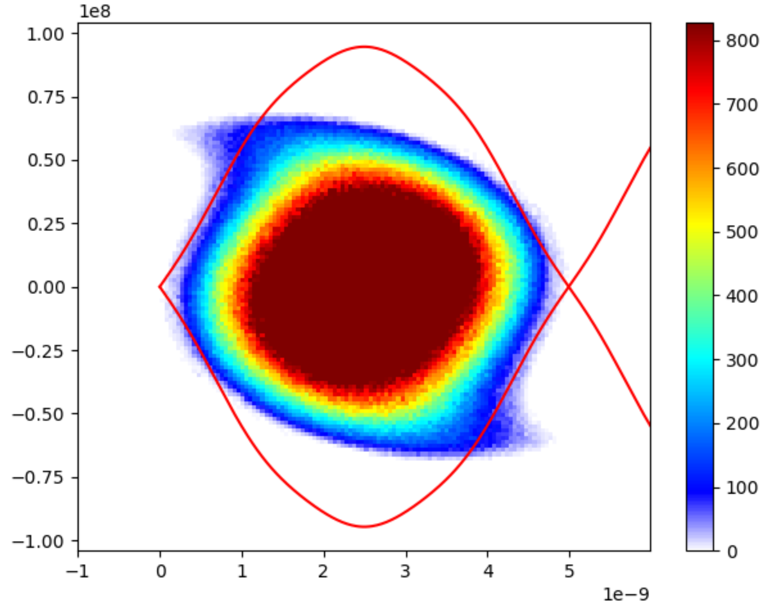
- Measurements
    - Flat-bottom losses
    - Capture losses
- Simulations
    - Model of SPS one-turn delay feedback
    - Capture losses
    - Improvements from future feedback system
- Summary

Sources of losses

1. Losses at injection, possible sources:
    1. Longitudinal effects (bunch shape from PS, uncaptured PS beam,…)
    2. SPS LLRF system
2. Losses at flat-bottom, possible sources:
    1. Momentum aperture and transverse emittance (details talk by V. Kain)
    2. Full bucket (intensity effects, noise from LLRF (details talk by G. Papotti), …)

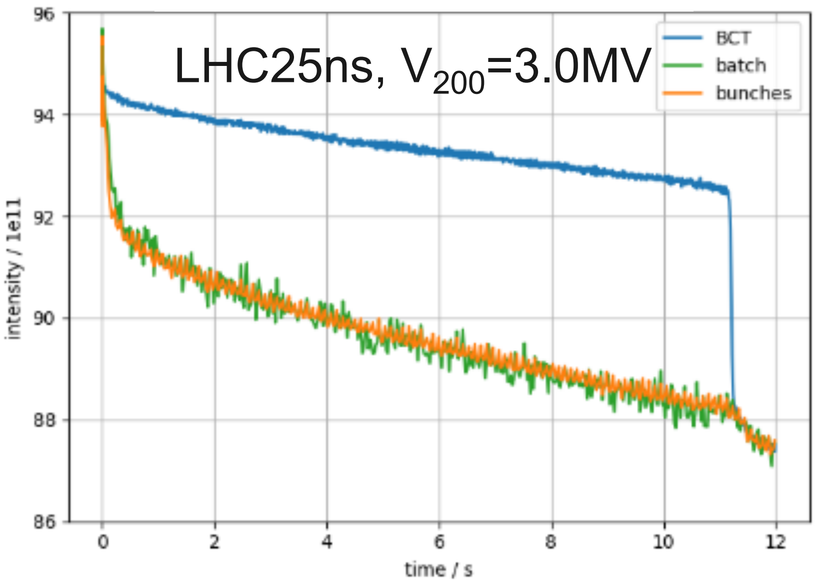


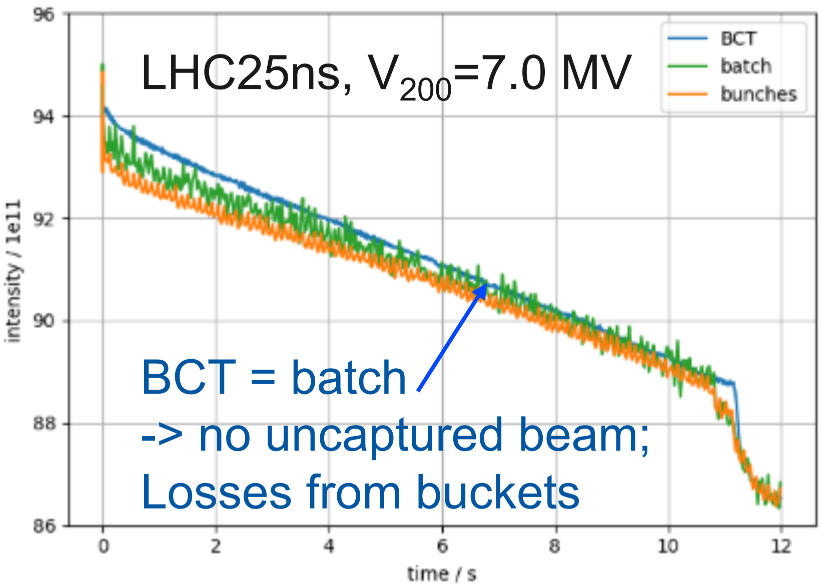
Simulated PS bunch in SPS RF-bucket (courtesy of A. Lasheen)

- Bunch fills entire RF-bucket
- Larger capture voltage leads to large emittance due to filamentation -> problem to accelerate
- Solution? Increase V_{200} on flat-bottom after capture to prevent particles escaping from bucket

Measurement with different V_{200}

- **72 bunches**, 25ns spacing, **1.3e11 particles per bunch**
- **LHC25 (Q20)**, $V_{800} = 0.1\ V_{200}$
- Flat-bottom 0-11.1s, data up to first part of ramp (11.830s ~ 29 GeV)
- Capture at V_{200}=4.5MV (nominal case), **change V_{200} at flat-bottom** (ramp 50ms to 100ms after injection and at 10.75s)

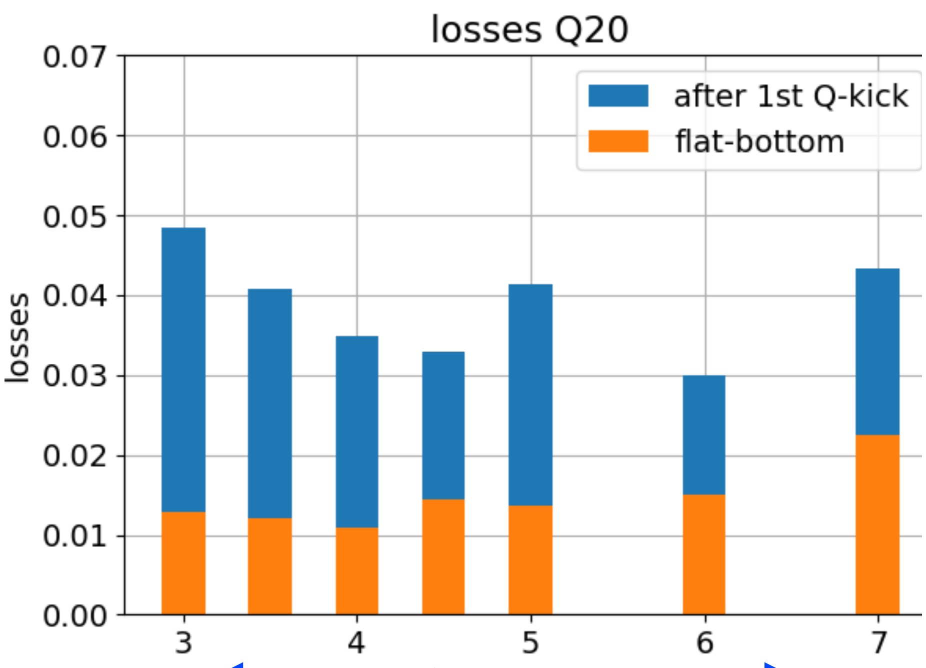


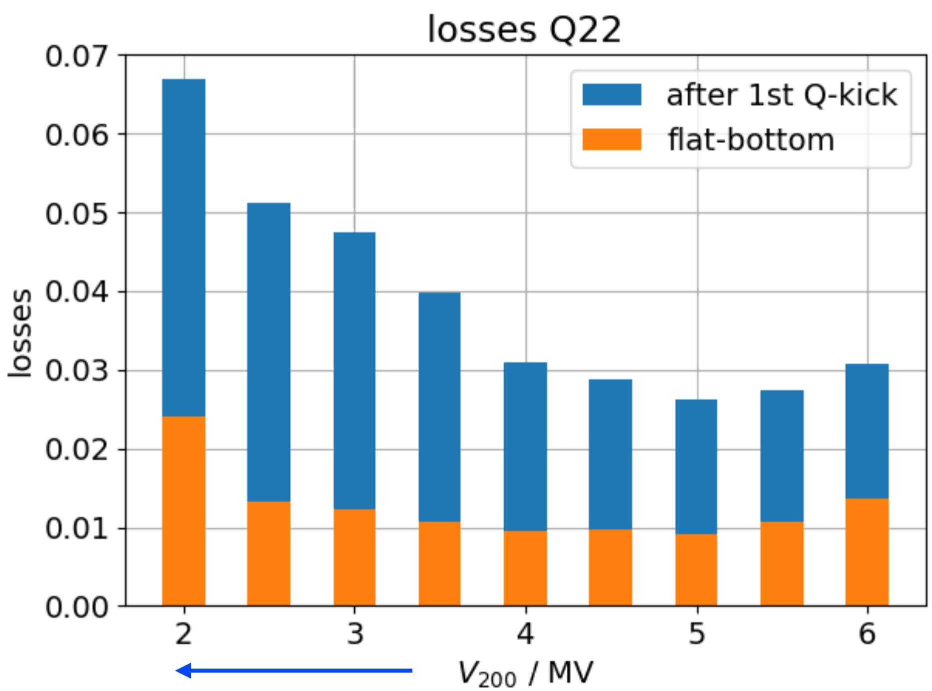


- Limited by momentum aperture (details talk by V. Kain) in Q20
- Less losses for smaller transverse emittance -> use BCMS (only 48 bunches)

Scan of RF-bucket area and optics

- **48 bunches**, 25ns spacing, **1.35e11 particles per bunch**
- V_{800} off; Feedback on; Feedforward off
- Flat-bottom 0-11.1s, ramp starts at 11.1s, tune-kick 2s after injection
- Compare **BCMS Q20** and **BCMS Q22**





Limited by intensity effects

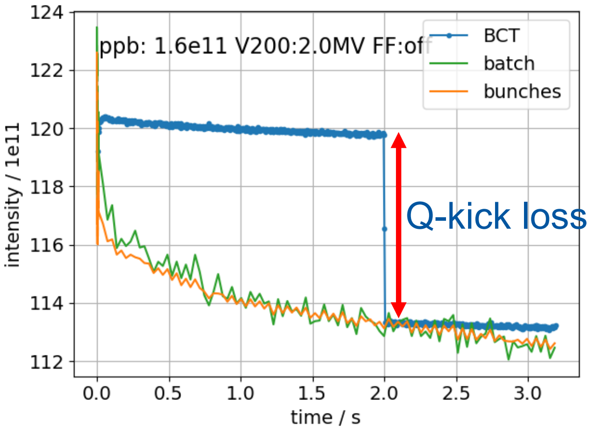
Limited by momentum aperture

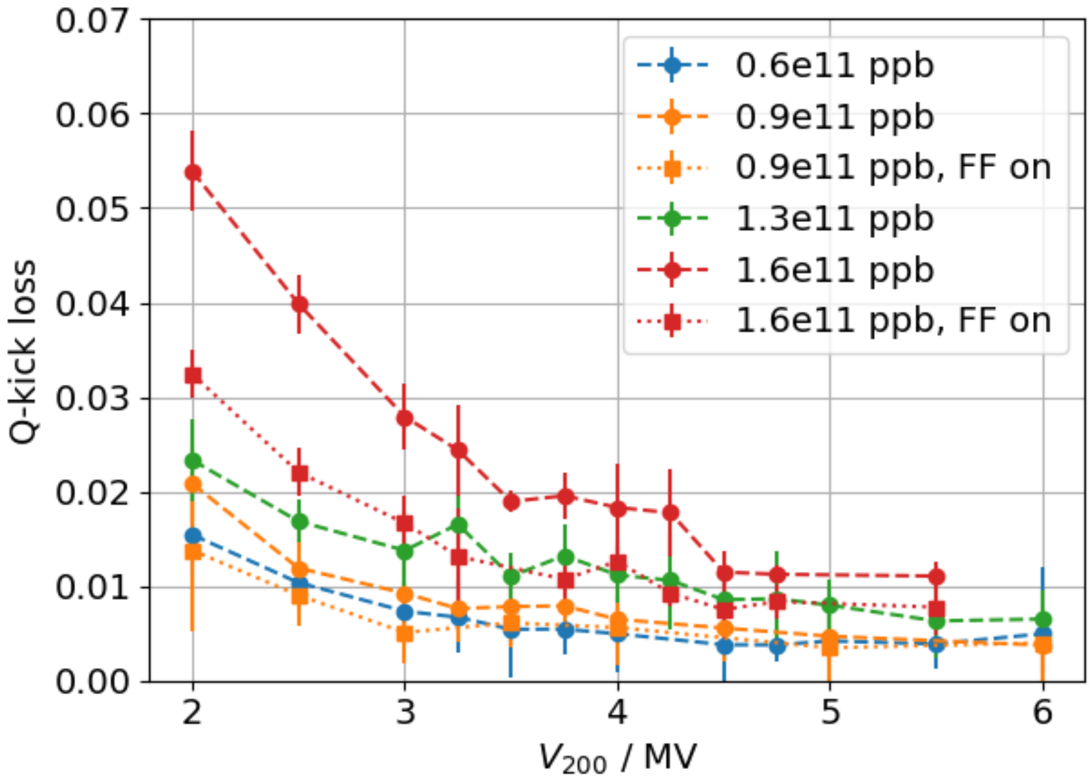
Limited by intensity effects

Optimum at V_{200} =4.5MV for Q20 (operational setting)

Different voltages and intensities

- 72 bunches, 25ns spacing, Q22
- V_{800} off; Feedback on; Feedforward **on/off**
- Remove uncaptured beam via tune kick at 2s

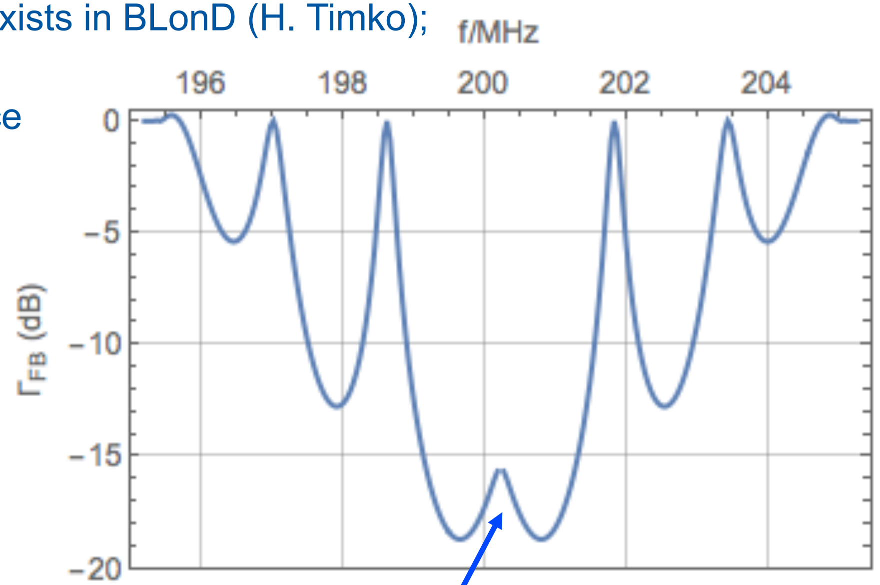




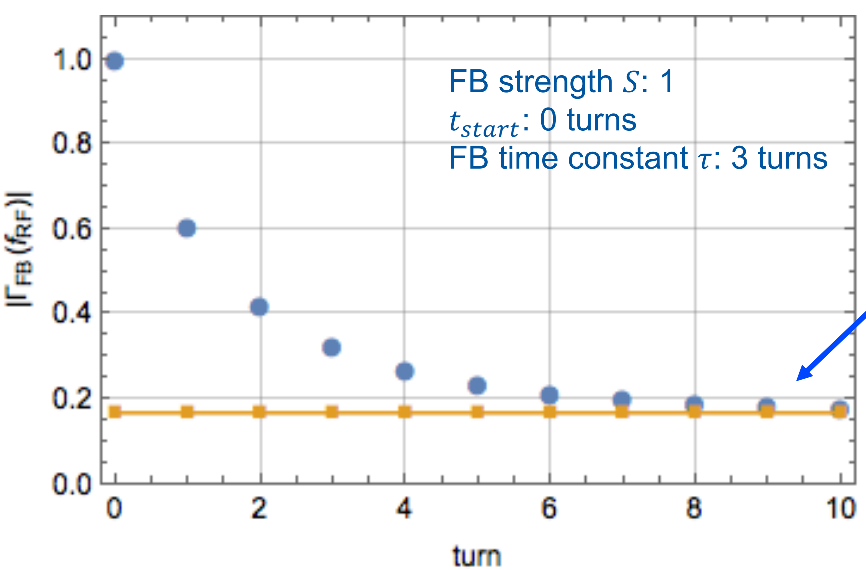
- Losses saturate at high V_{200}: uncaptured halo from PS
- Losses increase with intensity for low V_{200} : induced voltage in SPS

Longitudinal beam dynamics simulations

- Use simulated PS-bunch (courtesy A. Lasheen)
- Model injection by creating 72 bunches (25ns spacing) at the center of SPS RF-bucket
- impedance model:
  - present full SPS impedance model
  - impedances for long and short 200MHz TWC cavities
- Dynamic model of SPS 1-turn delay feedback system exists in BLonD (H. Timko); presently computationally too demanding
- Here: model effect of feedback by multiplying impedance with feedback-reduction factor:
  $Z_n = Z_{n-1}\,\Gamma_{FB}$ [P. Baudrenghien, Charmonix X, 2001]
- Continuously increase feedback strength:
  - $Z_n = Z_{n-1}\,(\Gamma_{FB})^{S\,att(t)}$ with $att(t) = 1 - e^{-(t-t_{start})/\tau}$
  - 'FB strength S', 'start time t_{start}', 'FB time constant τ'
  - individual parameters for 5- and 4- sections cavities



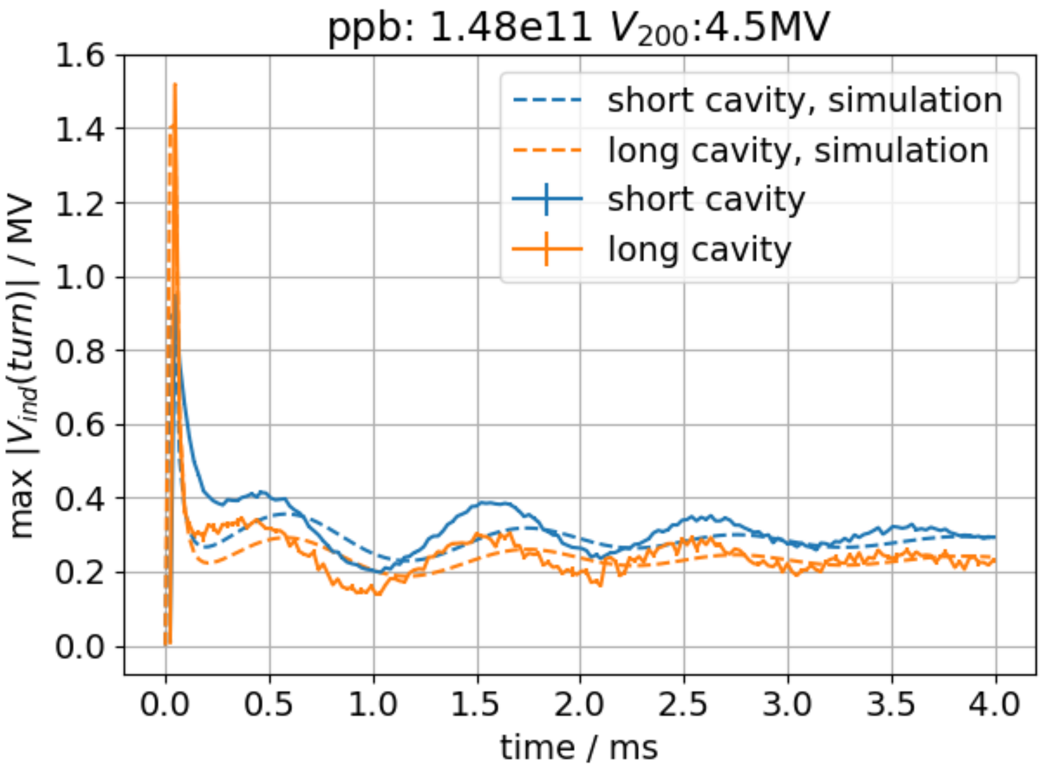
$\Gamma_{FB} = -15.5\ dB$ at f_{RF}
(i.e. $Z(f_{RF})$ multiplied by factor 0.17)



Calibration of feedback model parameters

- Measure beam loading in cavities at f_{RF}
- Simulate beam loading:
  - filter f_{RF} component of $V_{cav}(t)$
  - amplitude = $|V_{cav}(t)|$
- Use maximum amplitude at each turn
- Adjust 'FB strength S', 'start time t_{start}', and 'FB time constant τ' such that simulated amplitude agrees with measured one
- Fit function: $f(t) = A\sin(\omega t + \varphi)\exp(-{}^{t}/_{\tau}) + L$

	Short cavity measured	Short cavity simulation	Long cavity measured	Long cavity simulation
A / kV	2.01	1.29	1.15	1.07
T / ms	1.02	1.05	0.98	1.05
τ / ms	1.61	1.36	2.03	1.35
L / kV	302	283	235	233

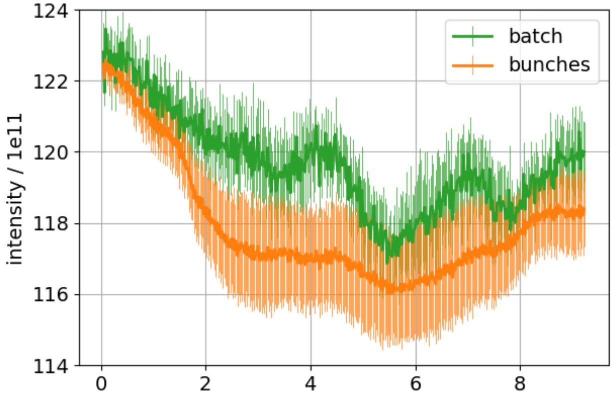


- Quadrupole oscillations ($0.5T_{s0}$ ~ 0.94ms) due to initial mismatch
- Good general agreement between simulations and measurement
  - Model has shorter transient than measurements
  - Model predicts smaller quadrupole oscillation amplitude
  - Asymptotic behavior agrees very well

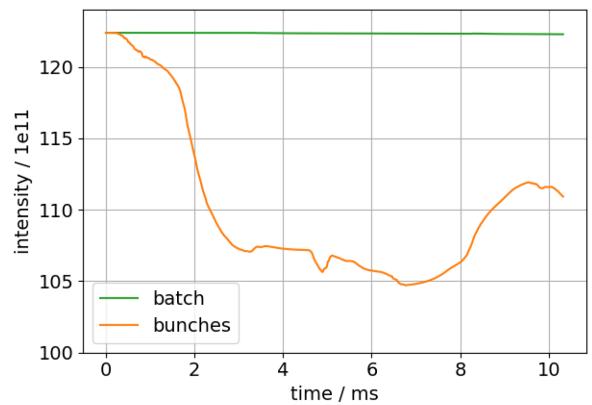
Comparison of measured and simulated losses

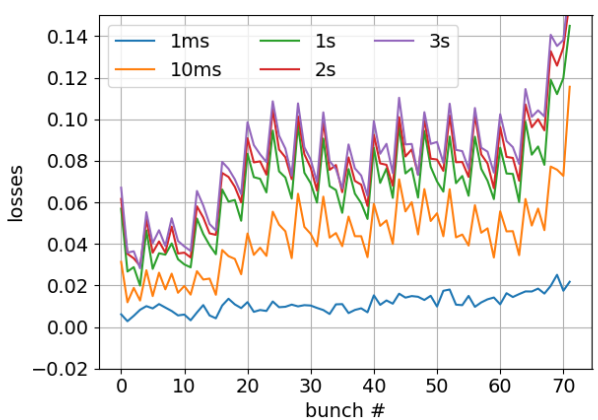
- 72 bunches (25ns spacing) and Q22 in both measurement and simulation
- Measured and simulated intensity obtained by integrating profile +/-0.575 RF-buckets around bunch peak
- Example with highest intensity (1.7e11ppb) in measurements and low V_{200} voltage (2.0MV)

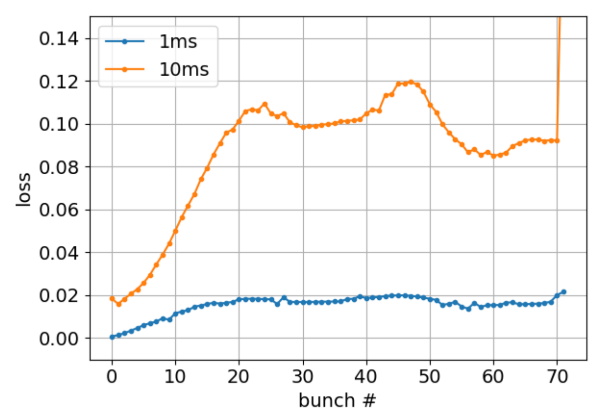
Measurement



Simulation





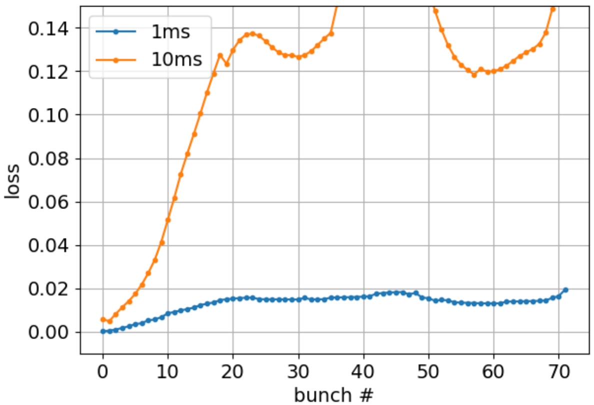


- Simulated losses larger than measured
  - All bunches matched to bare RF-bucket center; not taking injection phase due to beam loading into account
  - No phase loop in simulations
- Shape and time scale agree very well!

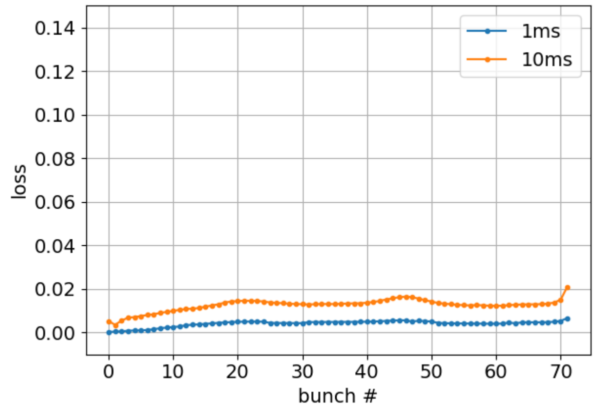
Simulated losses with improved feedback

- Simulating 72 bunches with **2.7e11 ppb** and V_{200} = 4MV
- same PS bunch (no intensity effects in PS)
- use present SPS impedance model
- only FB strength increased

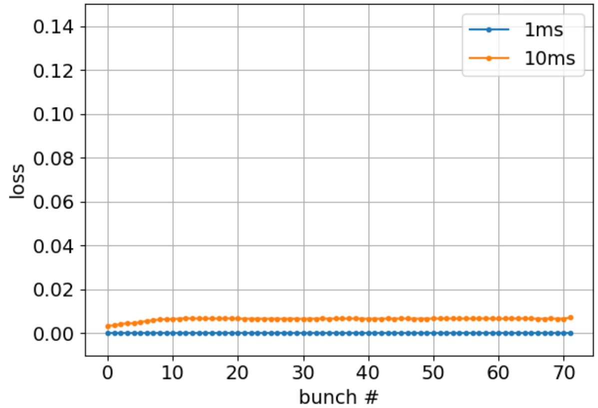
present feedback (-15dB)



future feedback(-26dB)



No 200 MHz TWC impedance



Without intensity effects losses well below 1% during first 10ms

With -26dB feedback, losses almost the same as if 200 MHz TWC had no impedance!

Summary

Two types of losses in the SPS:

- Capture loses
- Flat-bottom losses

Measured dependence of flat-bottom losses:

- Momentum aperture
- Transverse emittance

Capture losses depend on:

- Bunch shape coming from PS (details talk by A. Lasheen)
- Beam intensity and voltage at injection

Beam simulations:

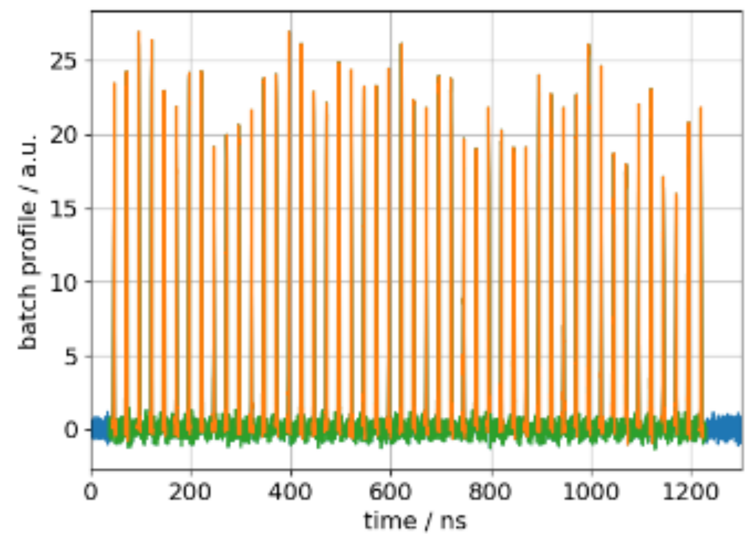
- Use 72 bunches and present SPS impedance model
- Model feedback system by impedance reduction
- With improved feedback system (-26dB impedance reduction) capture losses below 2% for 2.7e11 ppb

Thank you for your attention

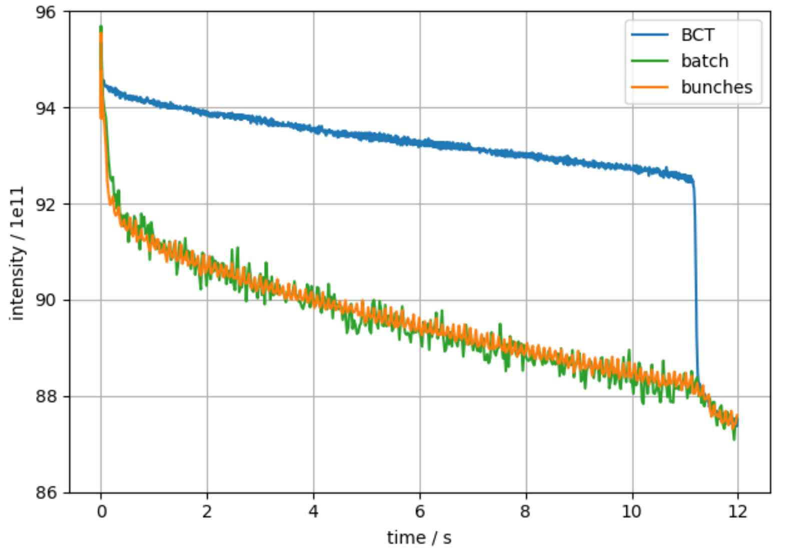
Appendix

Measurements of losses

- Measure longitudinal beam profiles
  - Obtain intensity of bunches by finding peaks (assumed to be center of bunch) and integrate profile in interval [-0.575, +0.575] RF-buckets
  - Obtain intensity of batch by integrating also parts between bunches
- Use same method also for simulated beam profiles to compare with measurements

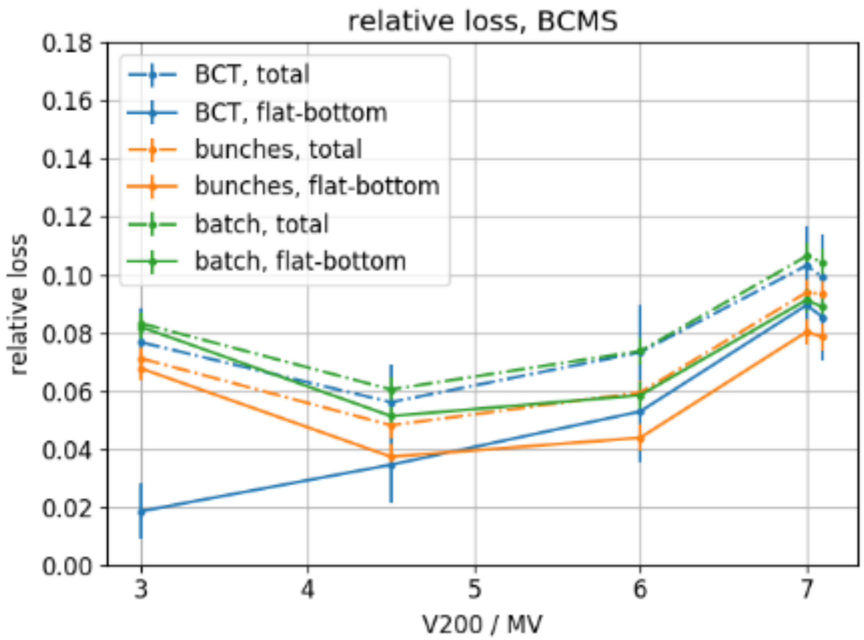


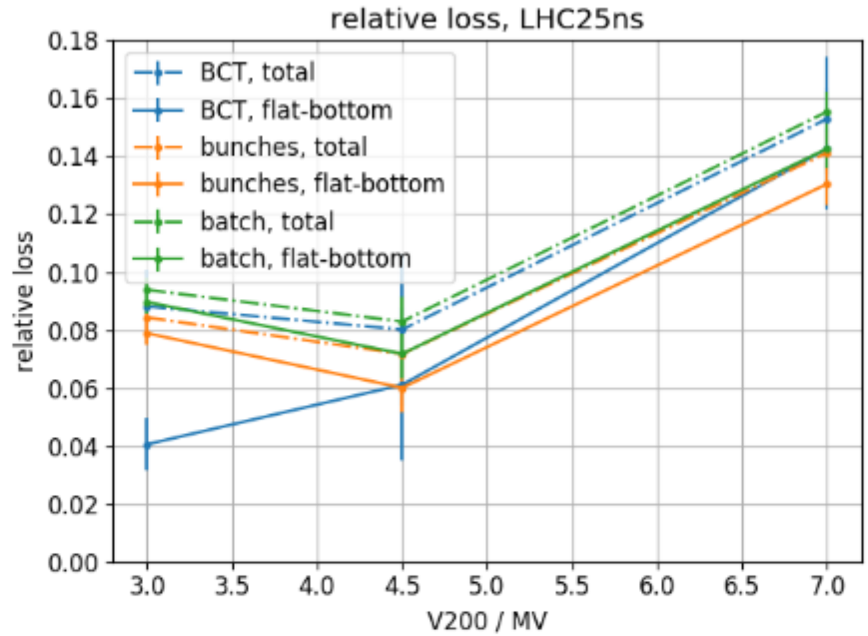
- Measure intensity in SPS with BCT
- Use BCT intensity to calibrate intensity from beam profiles
- Need to ensure that no uncaptured beam is in SPS -> use tune-kicker or ramp



Losses for different transverse emittances

- **48 bunches**, 25ns spacing, **1.52e11 particles per bunch**
- $V_{800} = 0.1\ V_{200}$
- Flat-bottom 0-11.1s, ramp to 450GeV 11.1-19.5s, flat-top 19.5-20s
- Here: data from injection to first part of ramp (11.830s ~ 29 GeV)
- Inject at V_{200}=4.5MV (nominal case), **change V_{200} at flat-bottom** (ramp 50ms to 100ms after injection and at 10.75s to 10.85s)
- Compare Q20 **LHC25ns** and **BCMS** (**transverse emittance reduced by factor 2**)





- Less losses for BCMS (smaller transverse emittance)
- Minimal losses at V_{200}=4.5MV

Measurement with different V_{200}

- **72 bunches**, 25ns spacing, **1.3e11 particles per bunch**
- **LHC25 (Q20)**, $V_{800} = 0.1 V_{200}$
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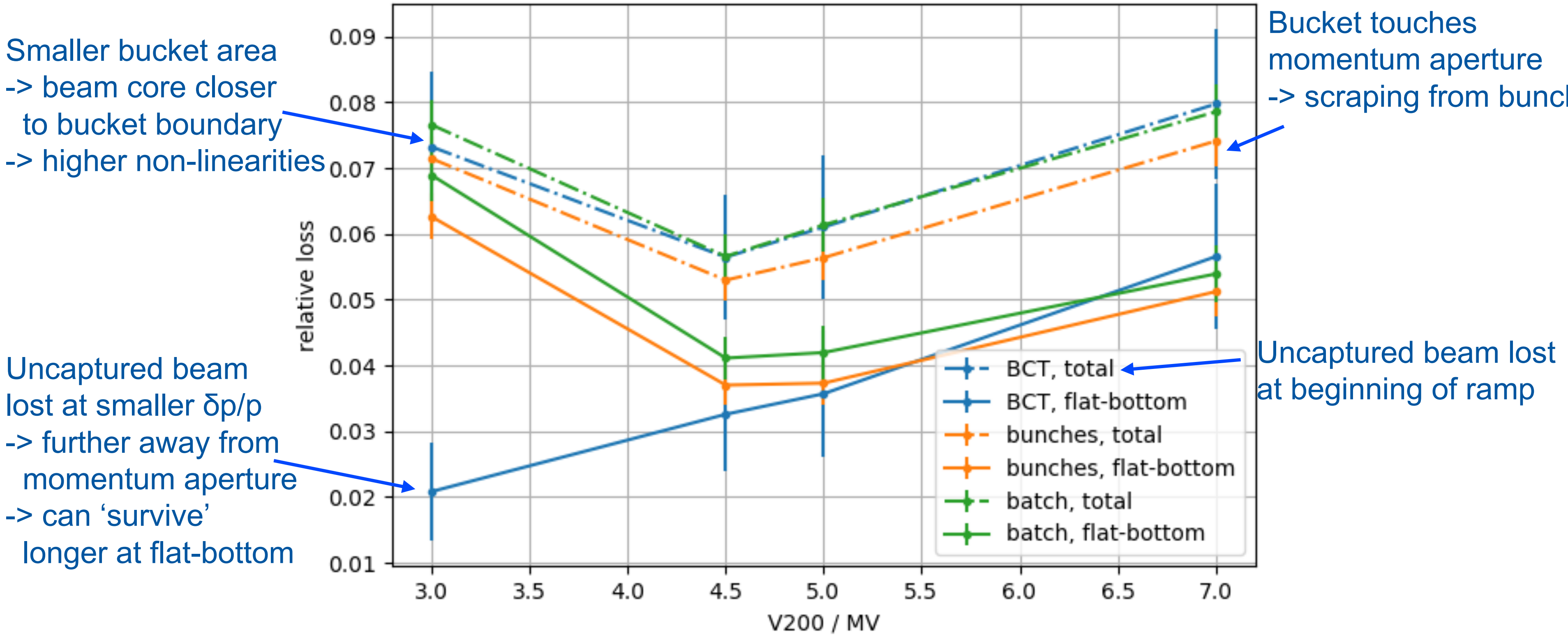

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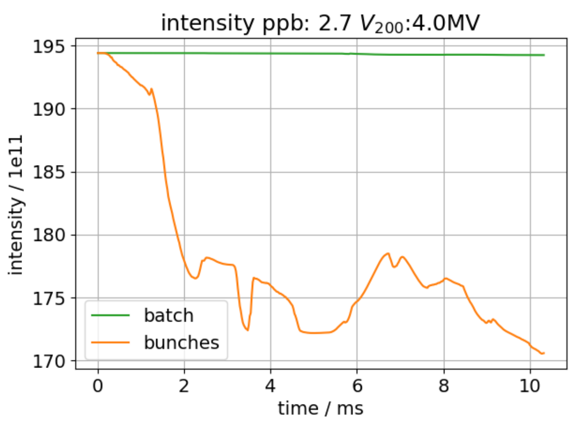
present feedback (-15dB)



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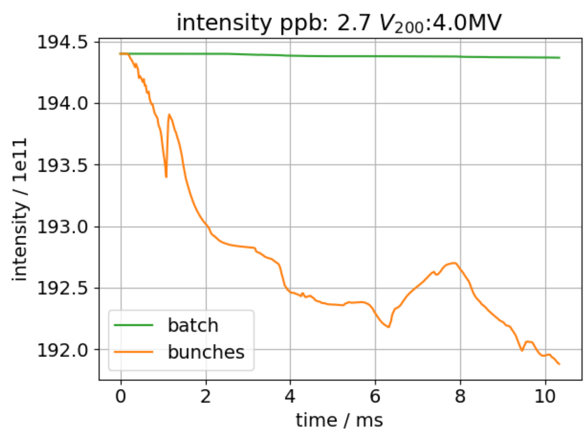
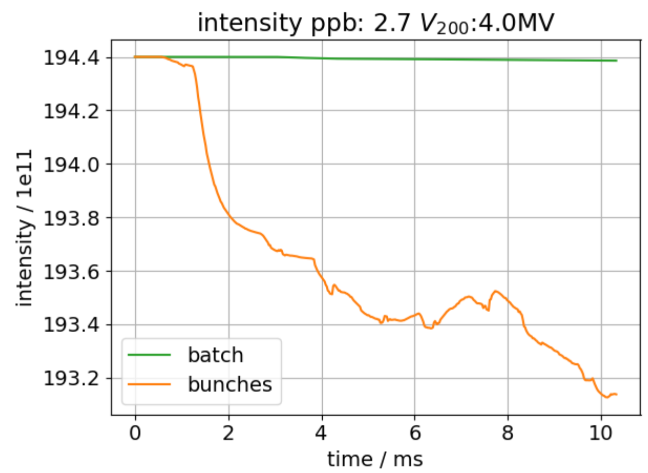


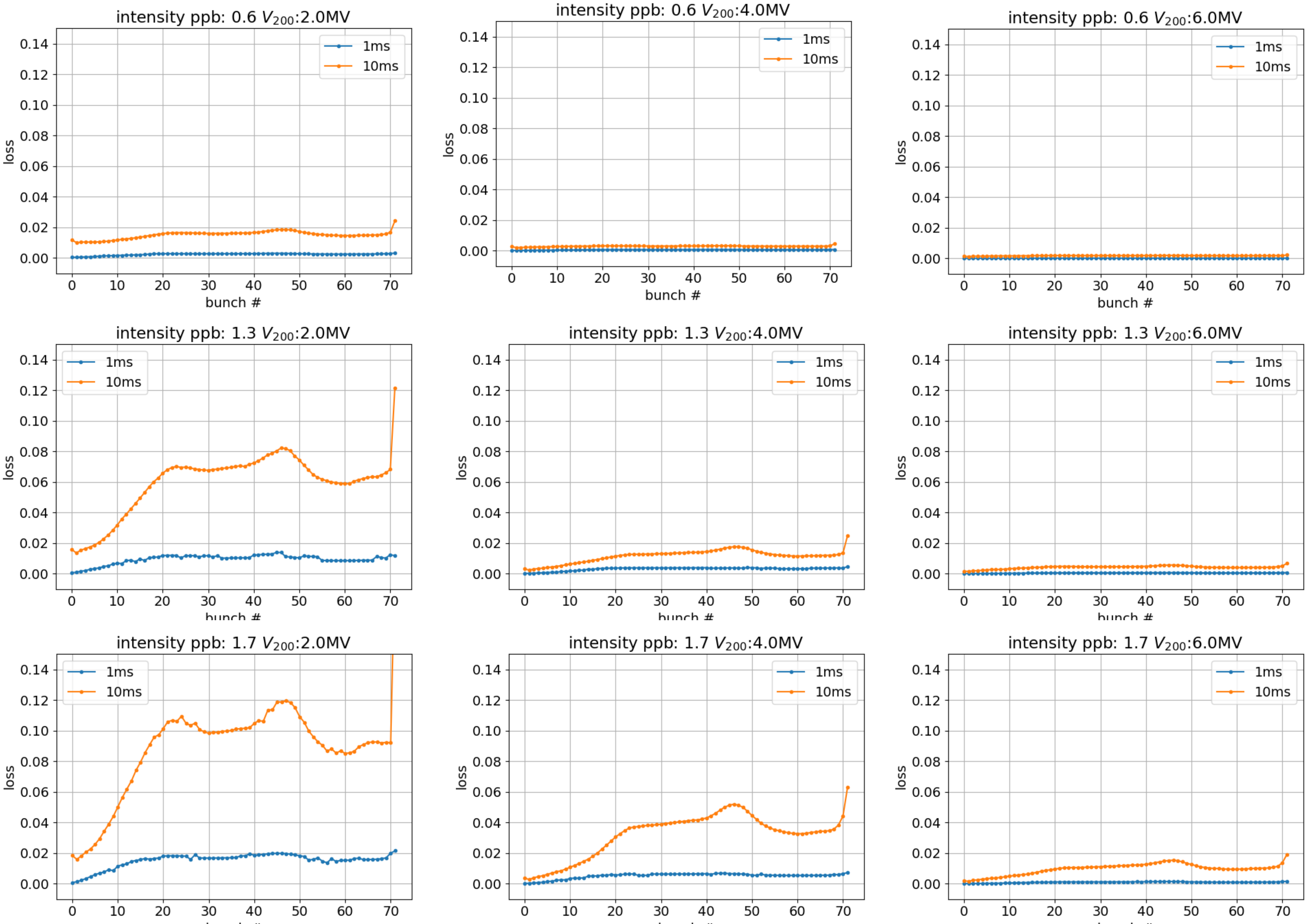
No 200 MHz TWC impedance



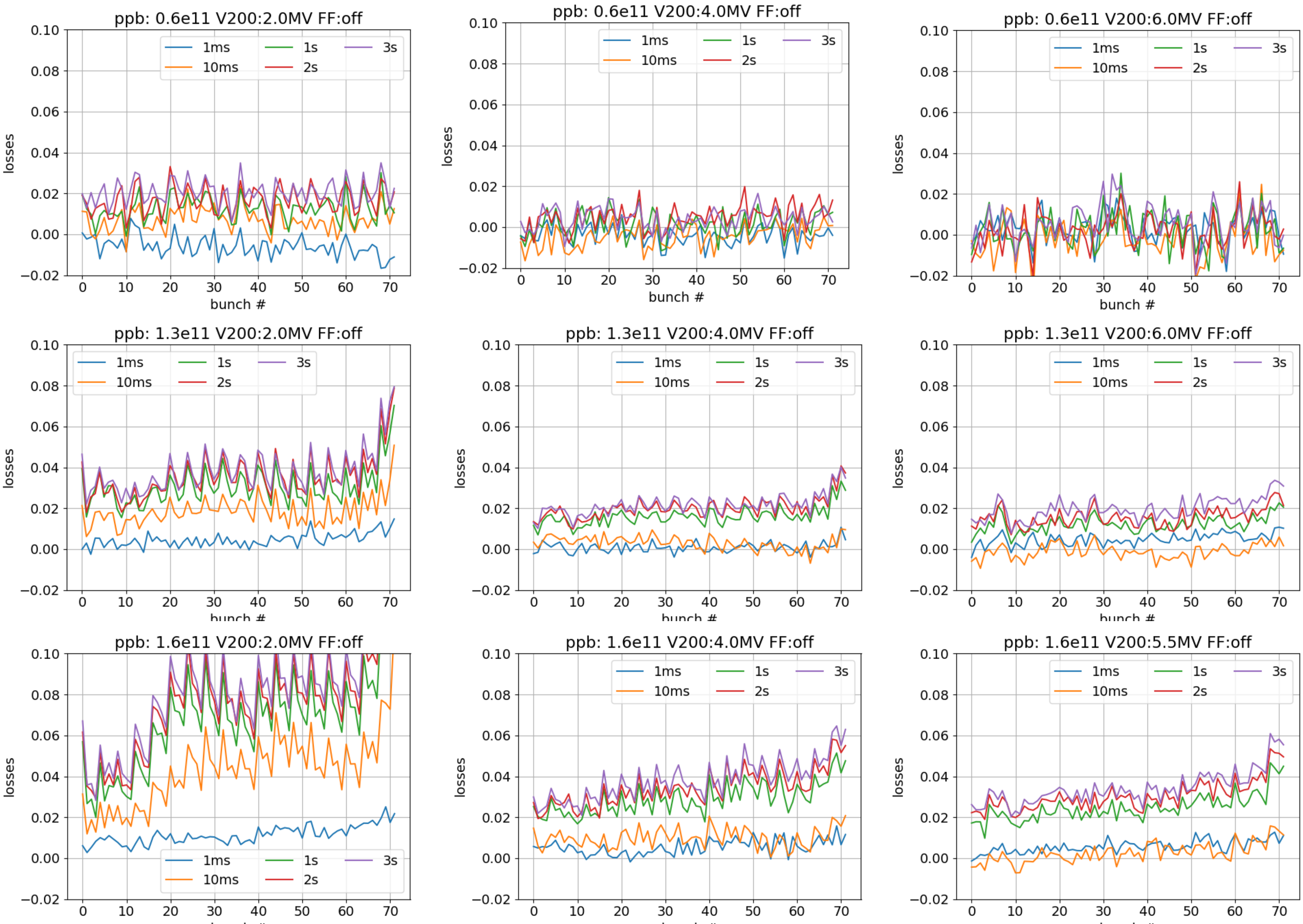
Without intensity effects losses well below 1% during first 10ms

With -26dB feedback, losses almost the same as if 200 MHz TWC had no impedance!

Simulated loss patterns, simulated for different V200 and intensity



Measured loss patterns, measured for different V200 and intensity



Simulation with dynamic OTFB model

- 72 bunches, 25ns spacing, 1.2e11 particles per bunch
- V_{200}=4.5MV (Q20) (no 800 MHz cavity)
- Initial condition (turn 0): 72 clones of simulated PS bunch (2x40MHz & 2x80MHz)
- Full SPS impedance model (without the fundamental mode of 200 MHz cavities, HOMs included)
- 100k macro particles per bunch
- **Only 32 bins per RF-bucket** (usually 256 bins)
- **Dynamic implementation of one-turn delay feedback (OTFB) (H. Timko)** (15 turns of pre-tracking)