Beam losses at SPS flat-bottom

M. Schwarz

Acknowledgements:

A. Lasheen, J. Repond, E. Shaposhnikova, H. Bartosik, V. Kain, H. Timko, T. Bohl,

G. Papotti, P. Baudrenghien, P. Kramer, I. Karpov

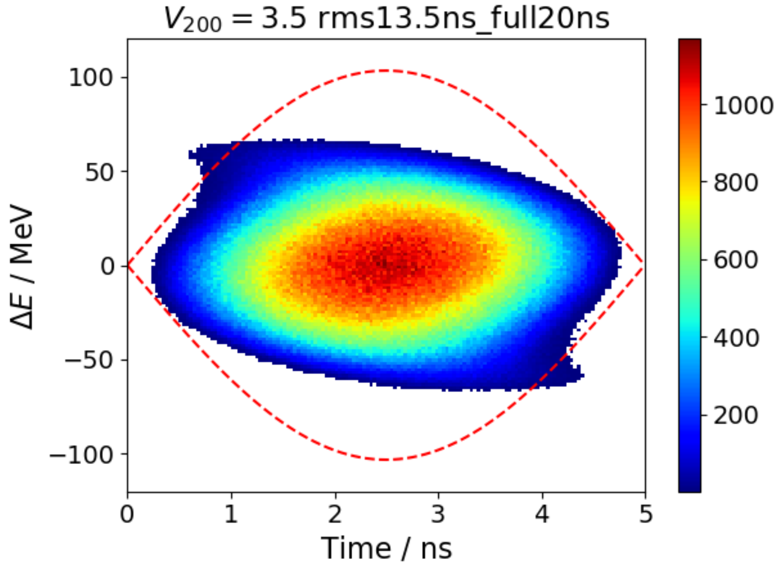
SPS & PS operator team, BLonD dev team

Content

- Introduction
- 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
   2. Full bucket (intensity effects, noise from LLRF)

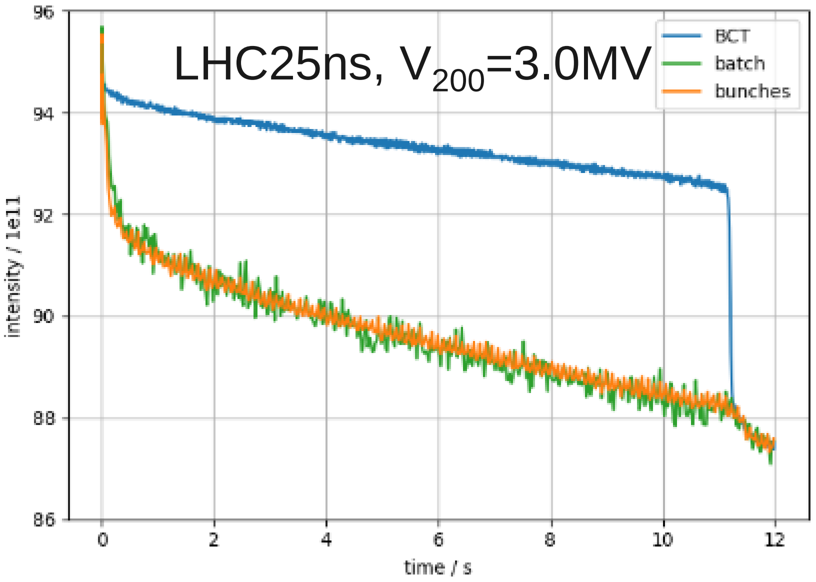


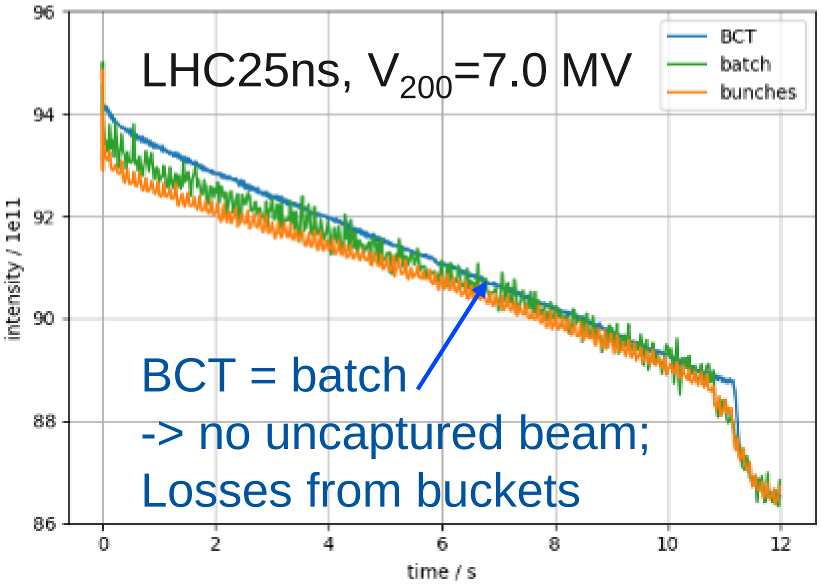
Simulated PS bunch in SPS RF-bucket (courtesy of A. Lasheen)

- 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)

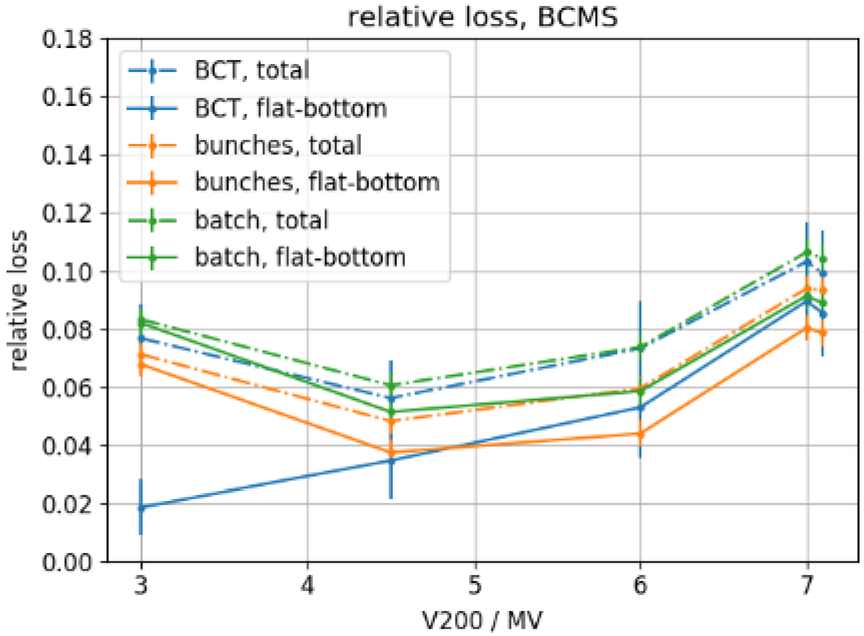


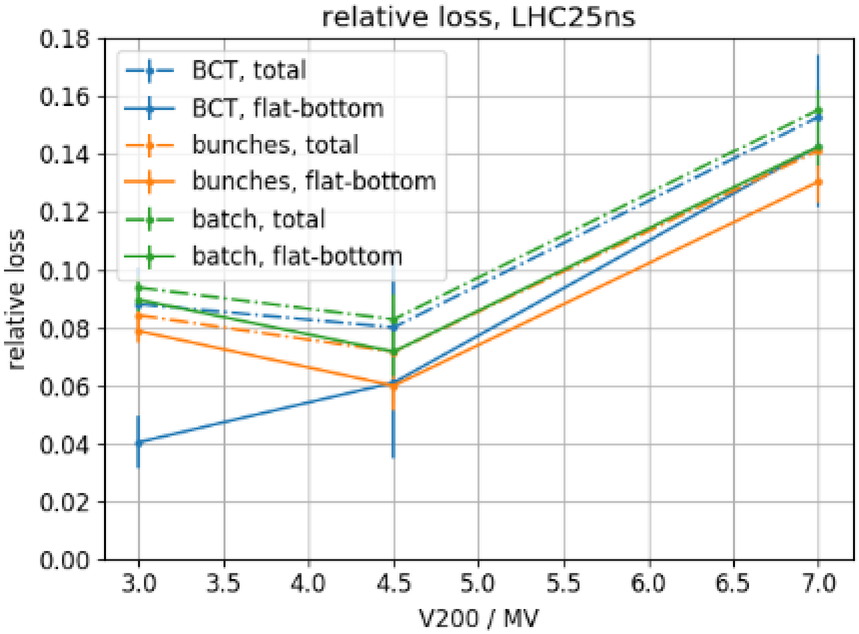


- Limited by momentum aperture in Q20
- Less losses for smaller transverse emittance -> use BCMS (only 48 bunches)

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**)

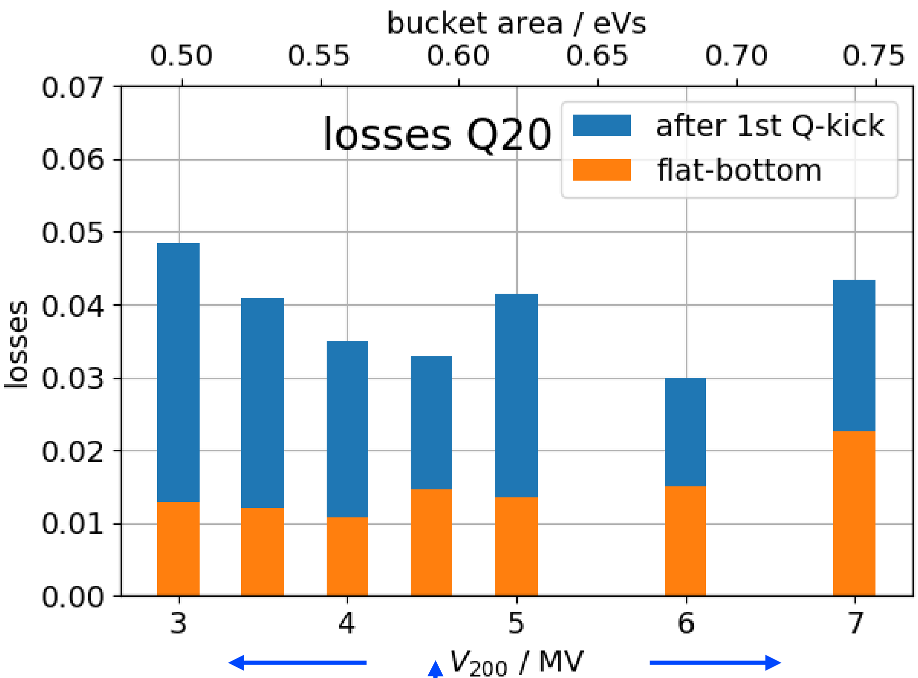


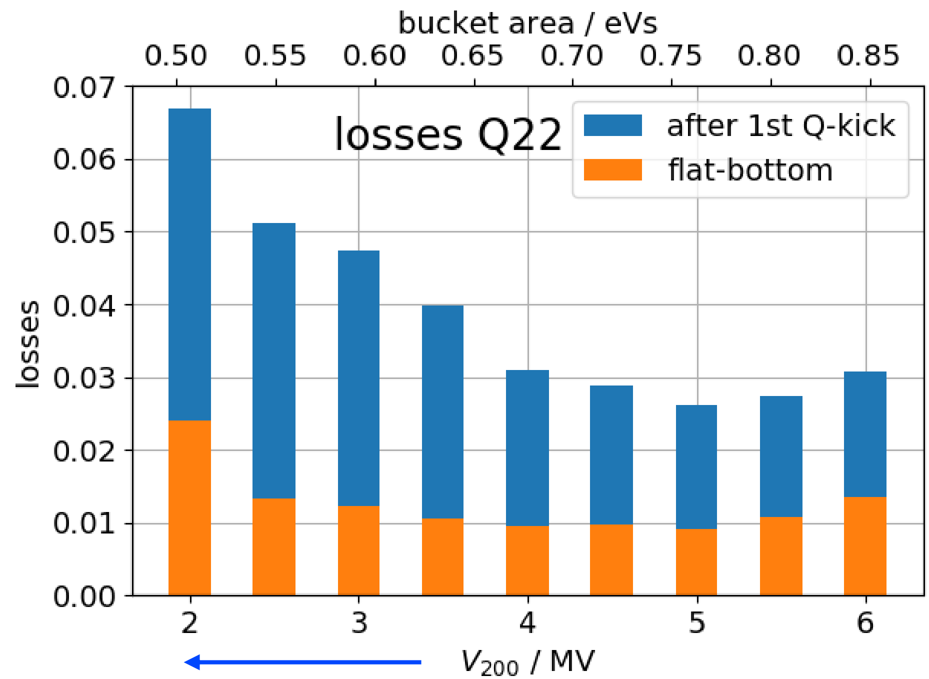


- Less losses for BCMS (smaller transverse emittance)
- Minimal losses at V_{200}=4.5MV

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

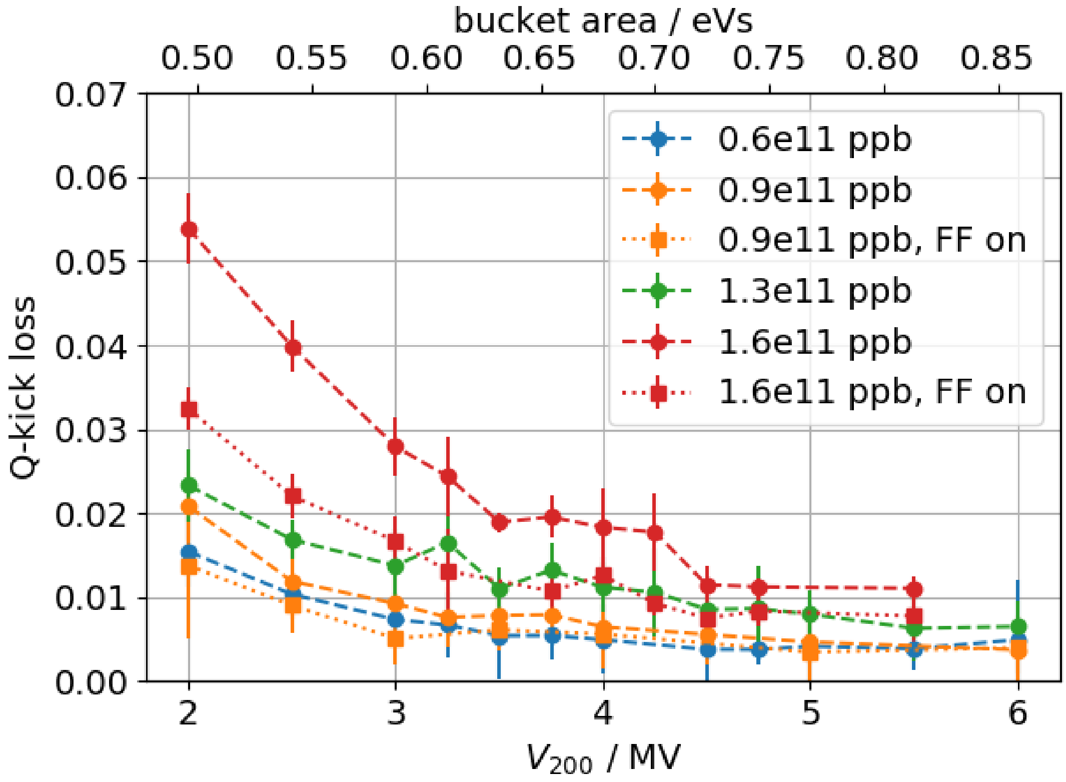
Limited by momentum aperture

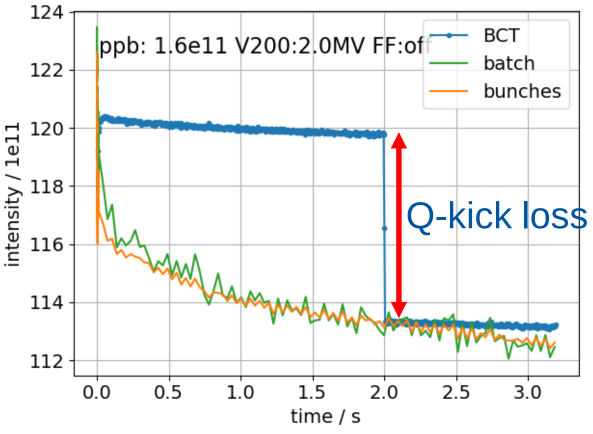
Limited by intensity effects

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

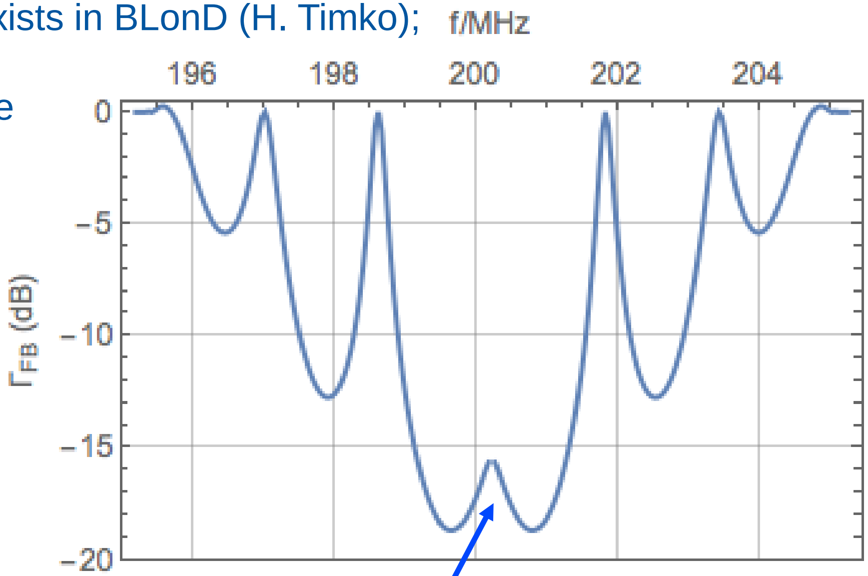


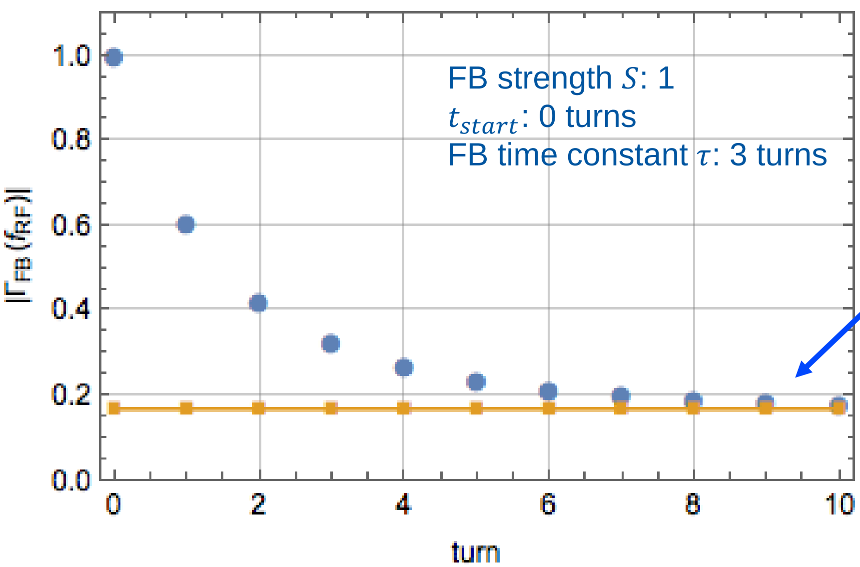


- Losses saturate at high V_{200}: uncaptured halo from PS
- Losses increase with intensity for low V_{200} : induced voltage in SPS

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); need to adjust gain margin
  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



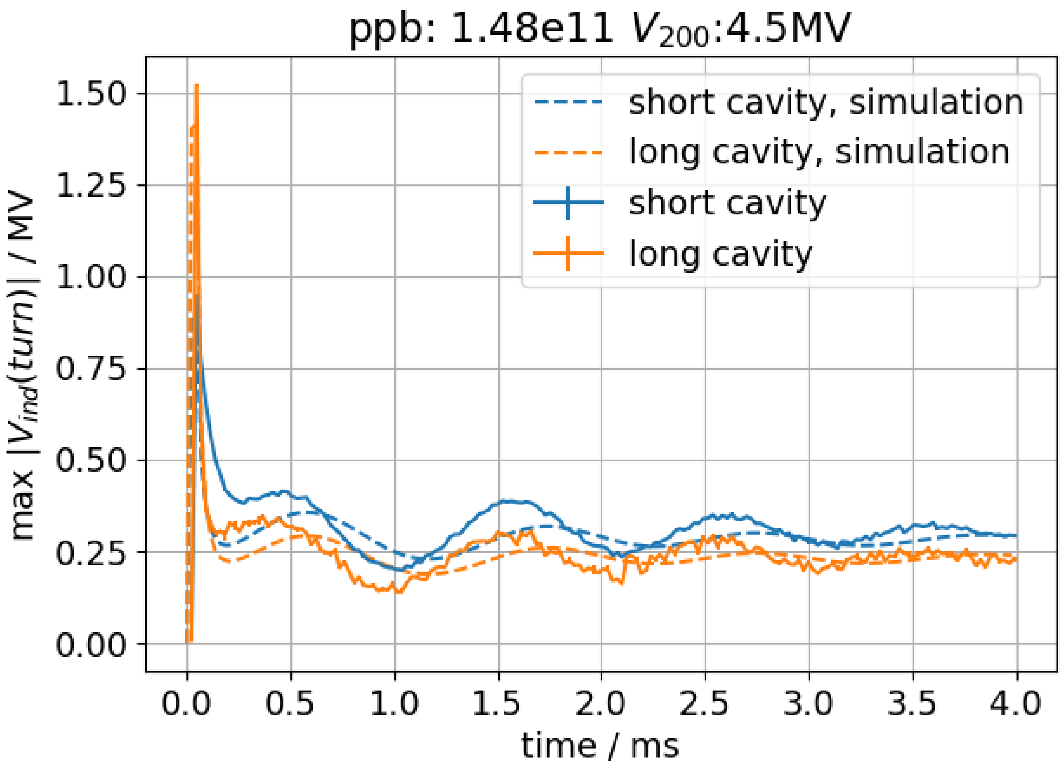


$\Gamma_{FB} = -15.5\ dB$ at f_{RF}
(i.e. $Z(f_{RF})$ multiplied by factor 0.17)

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

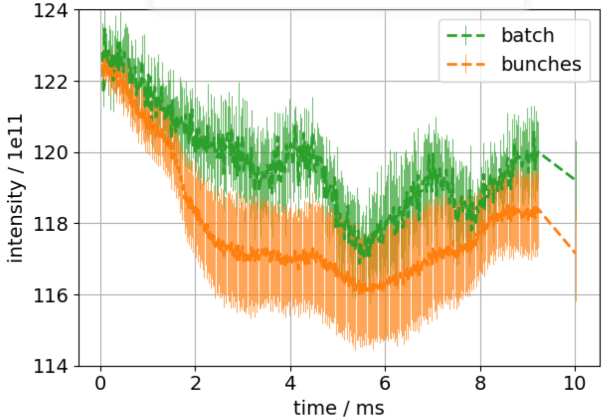


- Quadrupole oscillations ($0.5T_{s0}$ ~ 0.94ms) due to initial mismatch
- Good general agreement between simulations and measurement
  - Model has shorter transient than measurements
  - Model predicts smaller quadrupole oscillation amplitude
  - Asymptotic behavior agrees very well

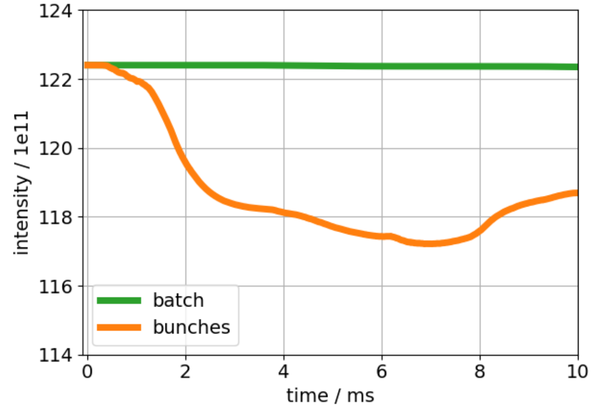
Comparison of measured and simulated losses

- 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
- Measurements and simulations with feedback and phase loop
- Example with highest intensity (1.7e11ppb) in measurements and low V_{200} voltage (2.0MV)

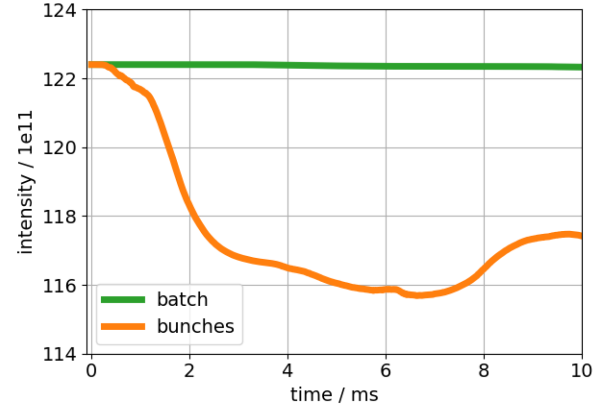
Measurement

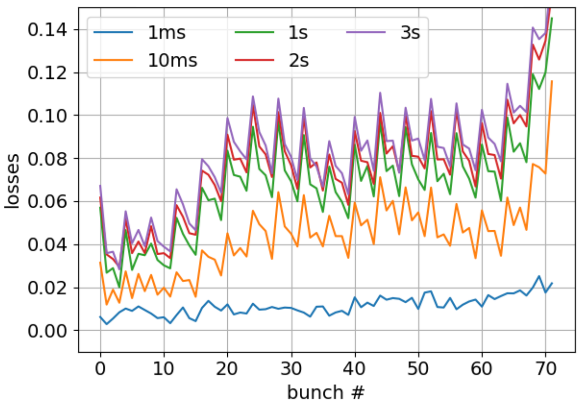


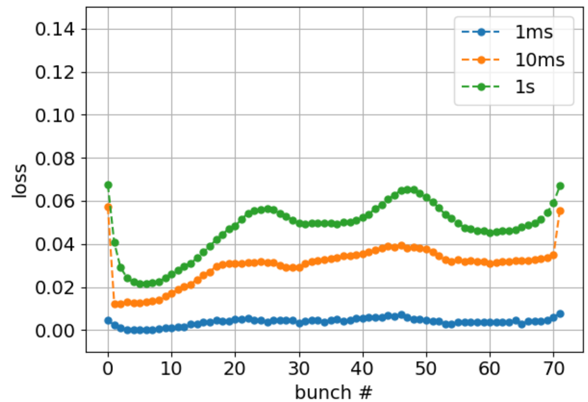
Simulation (distribution 2)

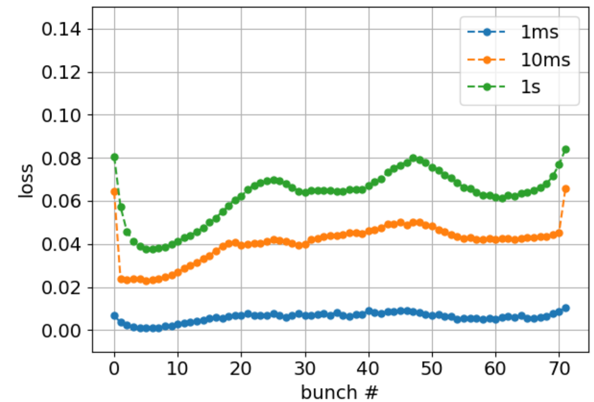


Simulation (distribution 3)





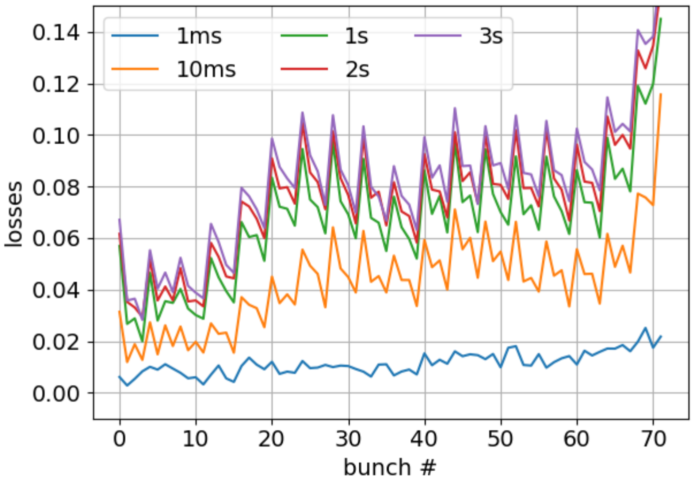


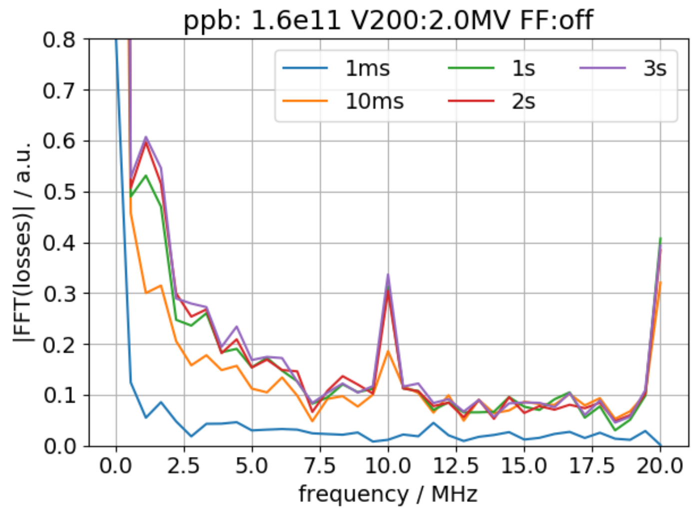


- Qualitative and quantitative agreement
  - … but no strong rise of simulated losses at end of batch
  - … simulated bunch-by-bunch losses don't display 'oscillation'

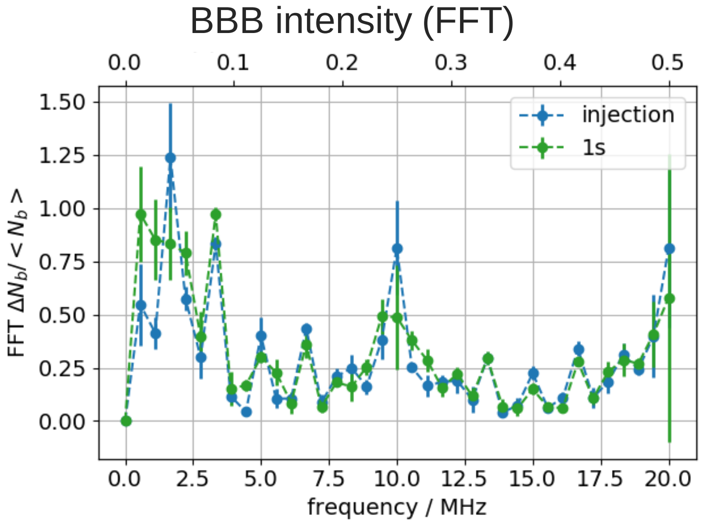
Measured oscillation in bunch-by-bunch loss pattern

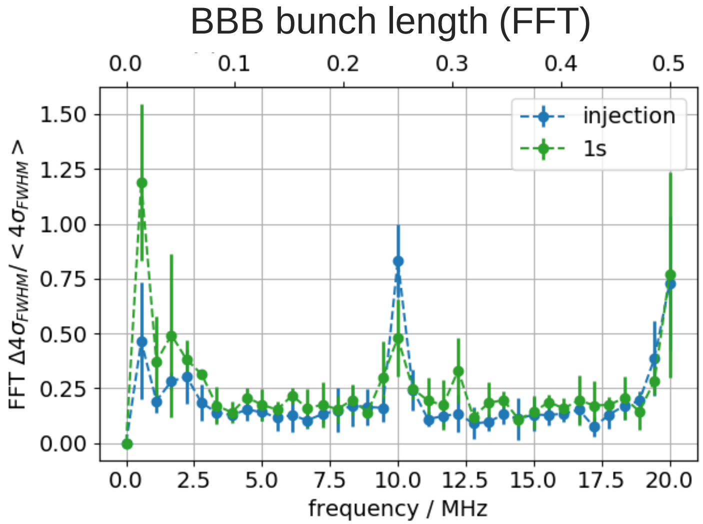
- Notice 10 & 20 MHz oscillation in measured bunch-by-bunch loss pattern (every 4th & 2nd bunch) present after 10 ms





- Same oscillations also present in bunch-by-bunch intensity and bunch length from injection

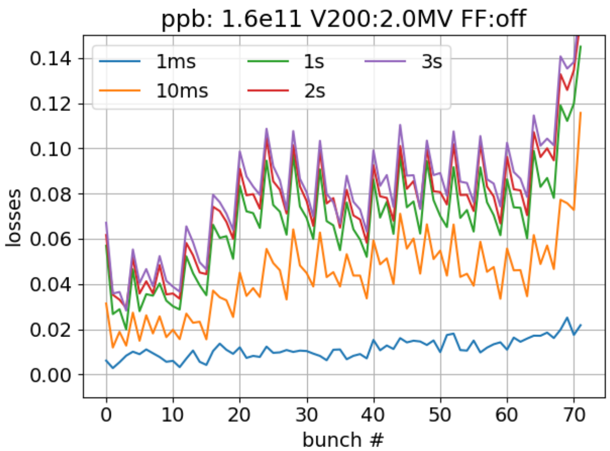




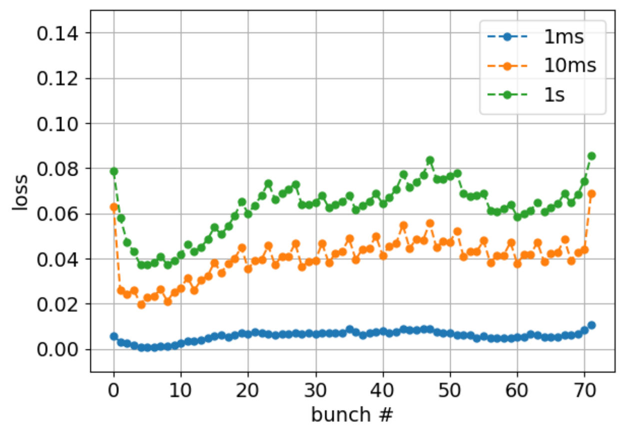
Comparison of measured and simulated losses

- In simulation use
  - a) same distribution with different intensities (# macro-particles)
  - b) distributions with different bunch lengths

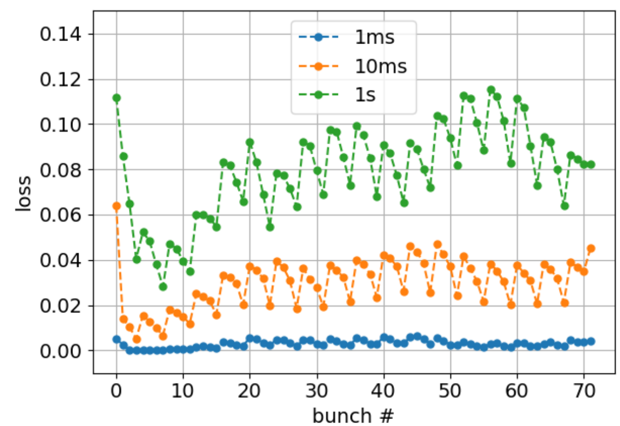
Measurement



Simulation a)
intensity modulation



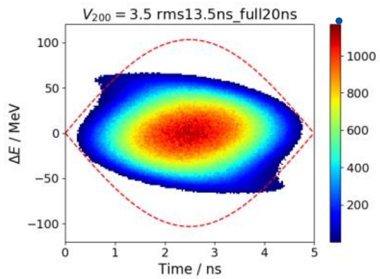
Simulation b)
bunch length modulation



- Simulated bunch-by-bunch losses display oscillation
  - Varying bunch shape has stronger influence than varying intensities
- Presently, injected bunches from PS are adjusted to have equal intensities

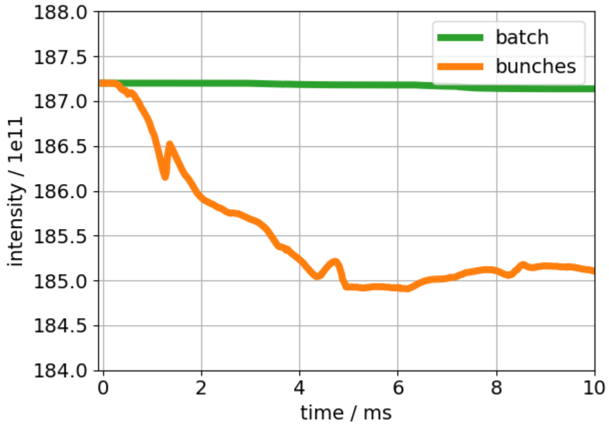
Simulated losses for high intensity, 2.6e11 ppb

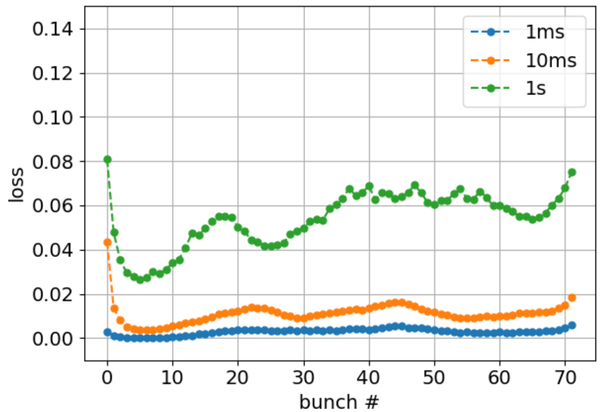
- Simulation parameters **present**:
  - 72 bunches, 2.6e11 ppb
  - V_{200} = 3.5 MV
  - Feedback strength at **-15 dB reduction**
  - Phase loop **averages over 12 bunches**
  - Two 5-section and two 4-section cavities
  - **Present** SPS impedance model



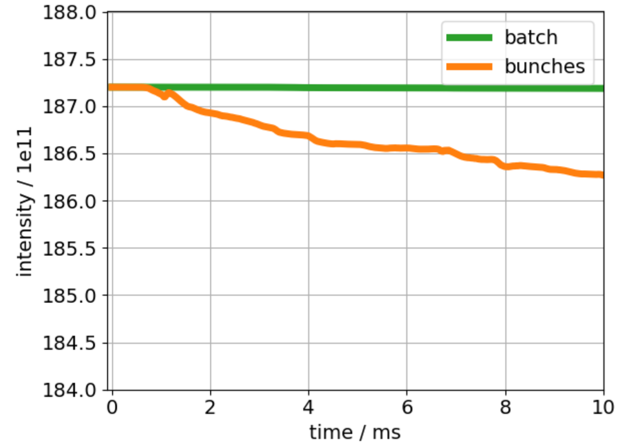
- Simulation parameters **future**:
  - 72 bunches, 2.6e11 ppb
  - V_{200} = 3.5 MV
  - Feedback strength at **-26 dB reduction**
  - Phase loop **averages over all bunches**
  - Two 4-section and four 3-section cavities
  - **Future** SPS impedance model

present

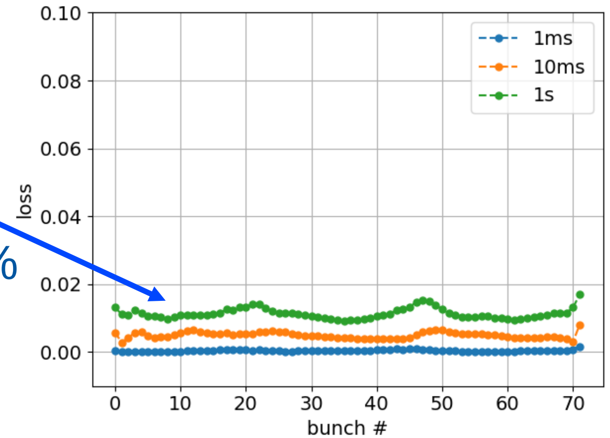




future



Losses below 2%



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
- Beam intensity and voltage at injection

Beam simulations:

- Use 72 bunches and present SPS impedance model
- Model feedback system by impedance reduction
- Good agreement between simulation and measurements
- With future setup (FB, cavities, SPS impedance) simulated capture losses below 2% for 2.6e11 ppb
- Need to investigate stability of simulation for long (1s) simulation times

Planned MDs:

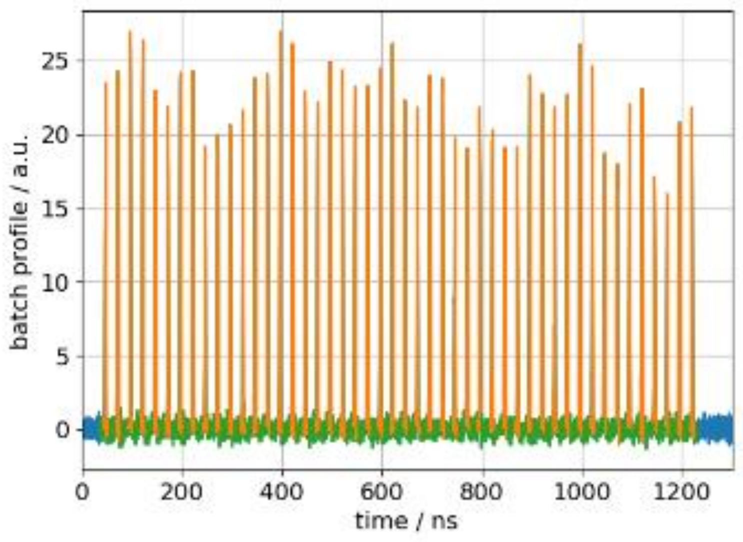
- Study impact of FF on flat-bottom losses
- Losses at higher intensities

Thank you for your attention

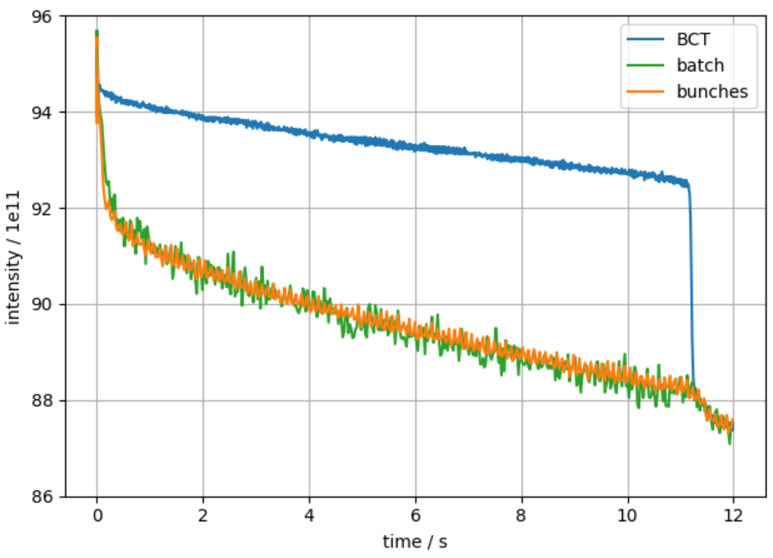
Appendix

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

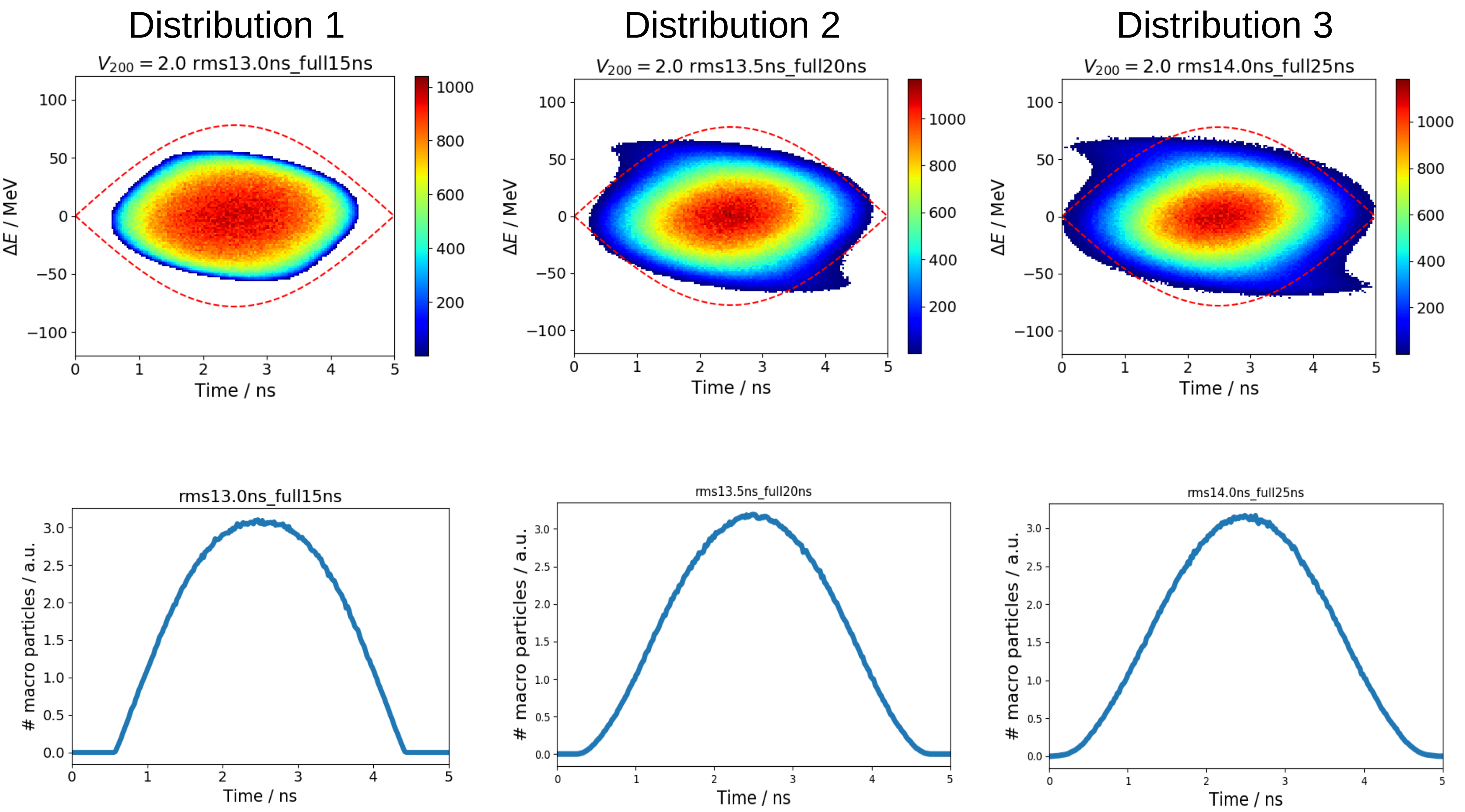


- Measure intensity in SPS with BCT
- Use BCT intensity to calibrate intensity from beam profiles
- Need to ensure that no uncaptured beam is in SPS -> use tune-kicker or ramp

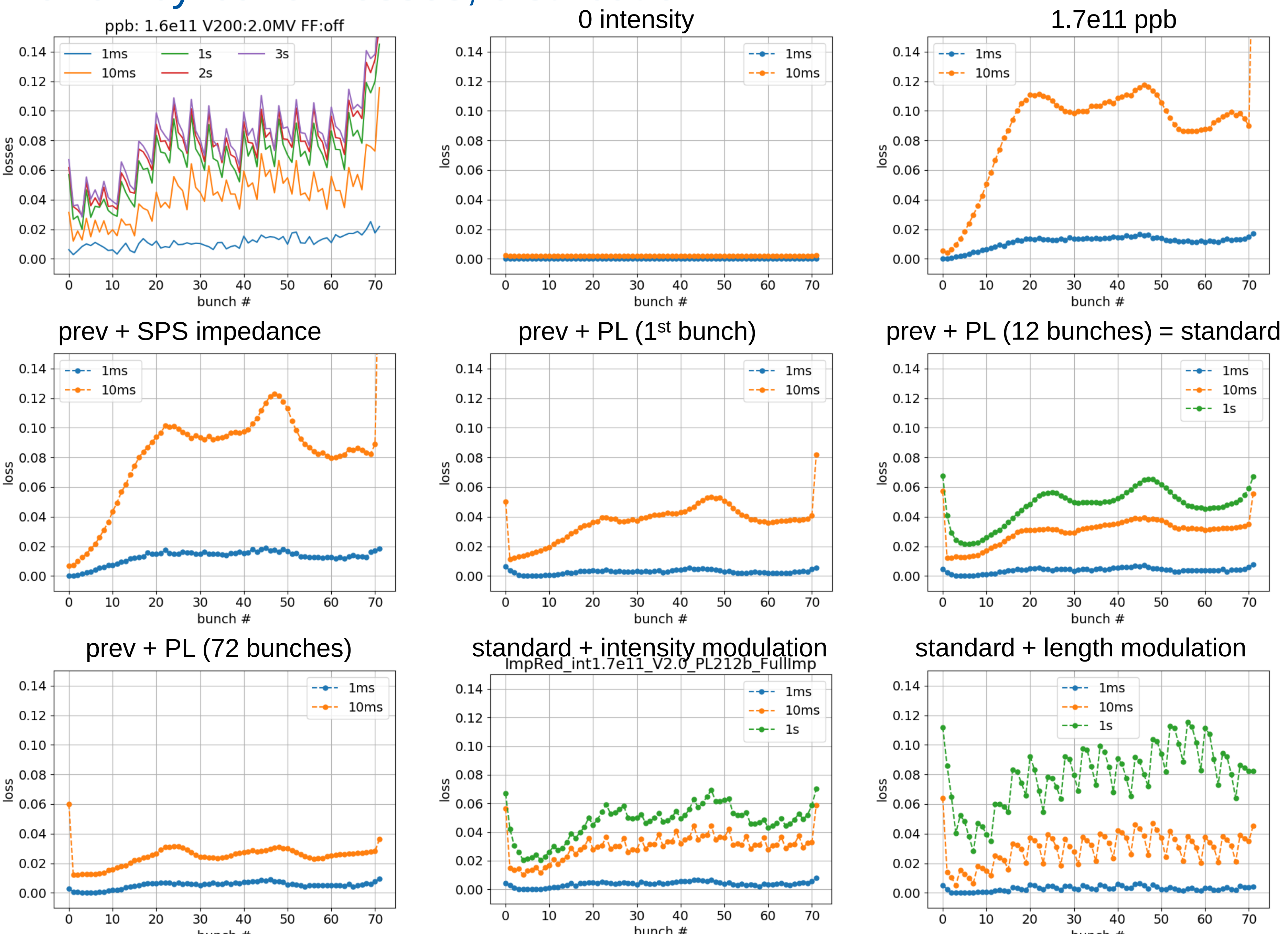


Simulated particle distributions used

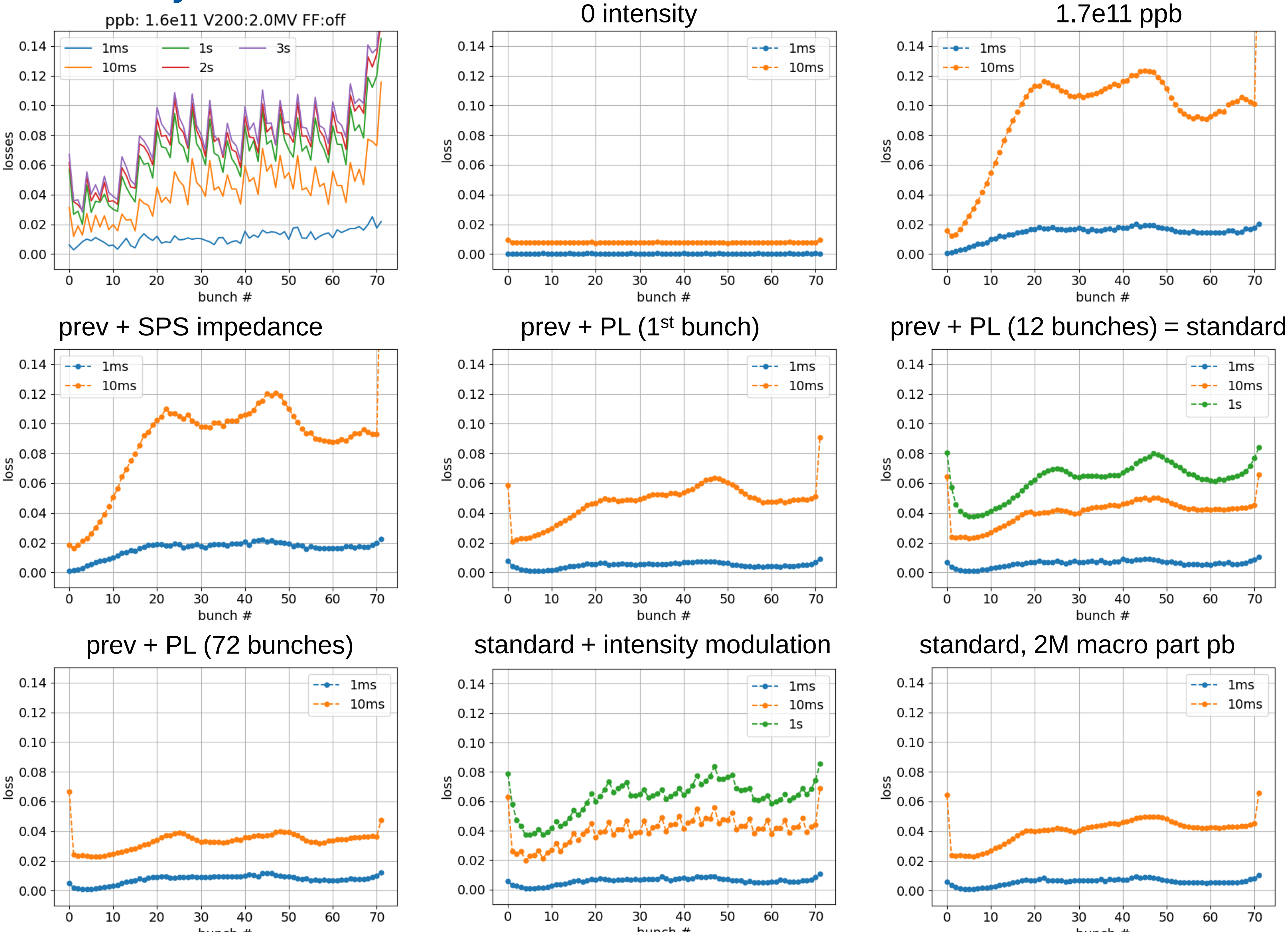
- Use different bunch distributions simulated in the PS (courtesy of A. Lasheen)
  - Out of the 4M macro-particles, randomly select 1M macro-particles for tracking in the SPS for each of the 72 bunches
  - Place bunches at center of bare RF-bucket
  - Use ‘impedance reduction’ method to simulate SPS one-turn delay feedback
- Full SPS impedance model



Bunch-by-bunch losses; distribution 2

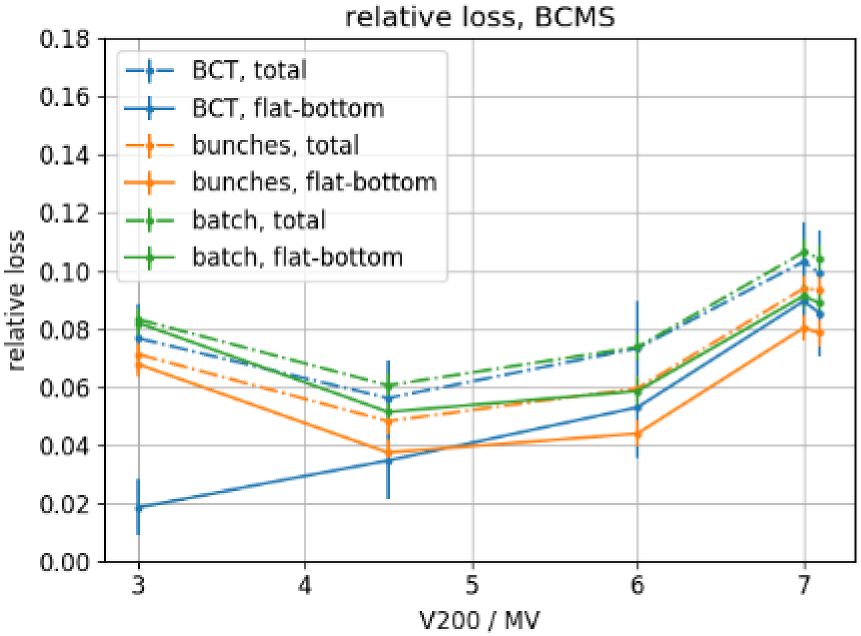


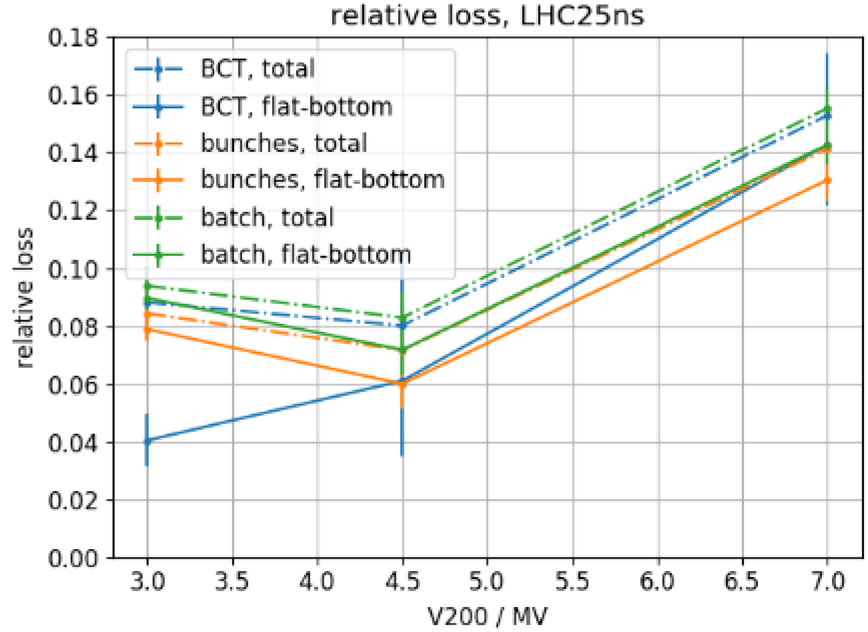
Bunch-by-bunch losses; distribution 3



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**)





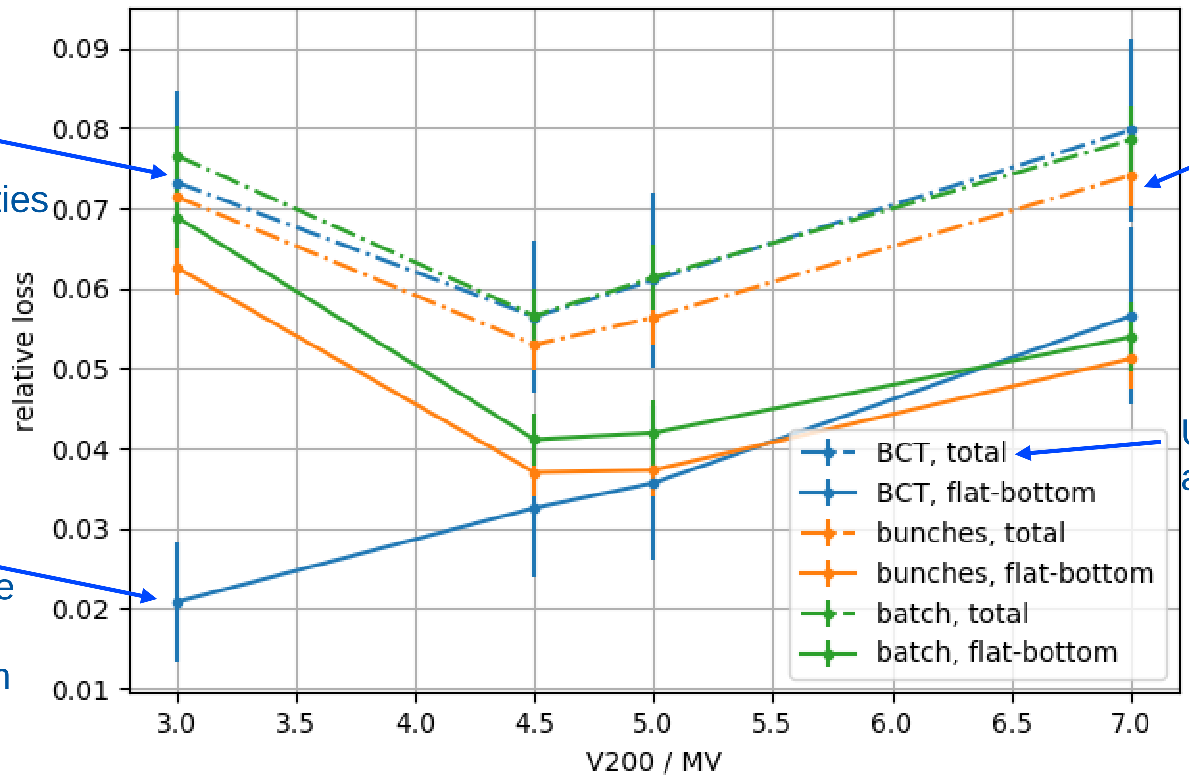
- Less losses for BCMS (smaller transverse emittance)
- Minimal losses at V_{200}=4.5MV

Measurement with different V_{200}

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

Smaller bucket area
-> beam core closer to bucket boundary
-> higher non-linearities

Uncaptured beam lost at smaller δp/p
-> further away from momentum aperture
-> can 'survive' longer at flat-bottom

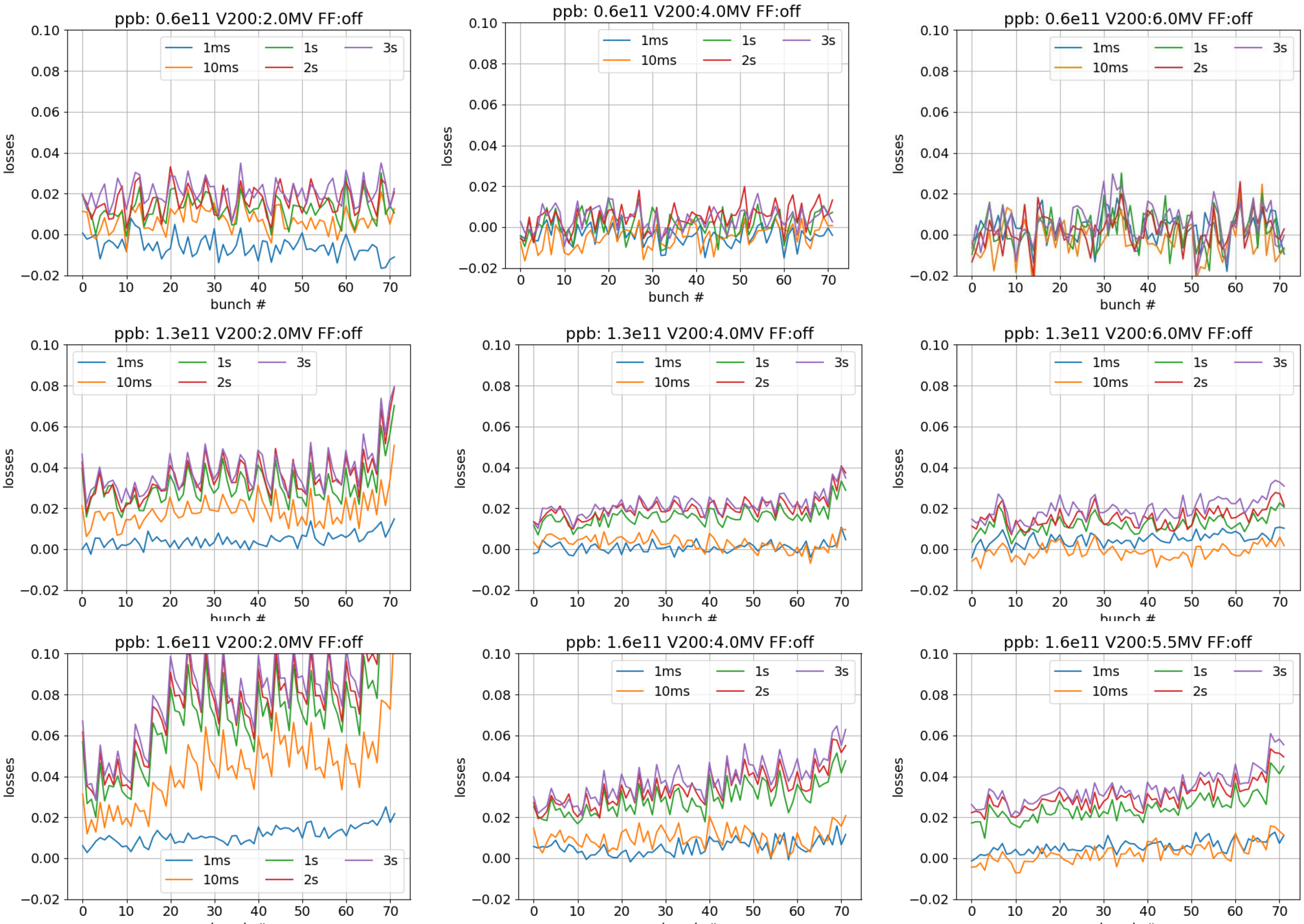


Bucket touches momentum aperture
-> scraping from bunc

Uncaptured beam lost at beginning of ramp

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

Measured loss patterns, measured for different V200 and intensity



Status of OTFB

Measurements:

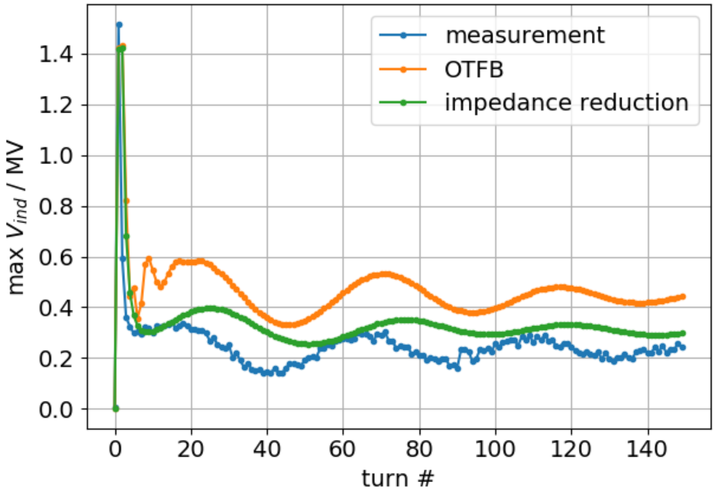
- 48 bunches, 1.48e11 ppb
- V_{200} = 4.5 MV, Q22 optic

Simulation parameters:

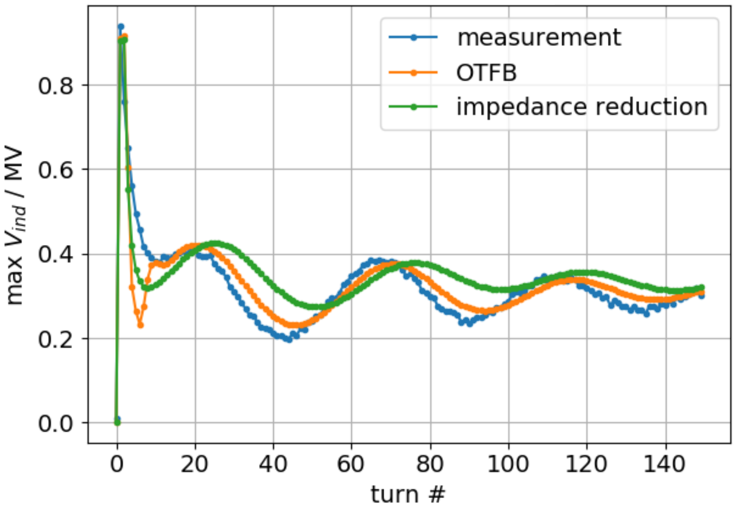
- 48 bunches, 1e6 macro-particles per bunch
- V_{200} = 4.5 MV, Q22 optic
- Present full SPS impedance model

Present 'best settings' (G_LLRF_4 = 8.0, G_LLRF_5 = 10.0)

long cavity



short cavity



Results:

- Induced voltage in short TWC 'undershoots' around turn 10; asymptotic behavior represented well
- For long TWC, OTFB does not reduce induced voltage enough -> gain margin missing