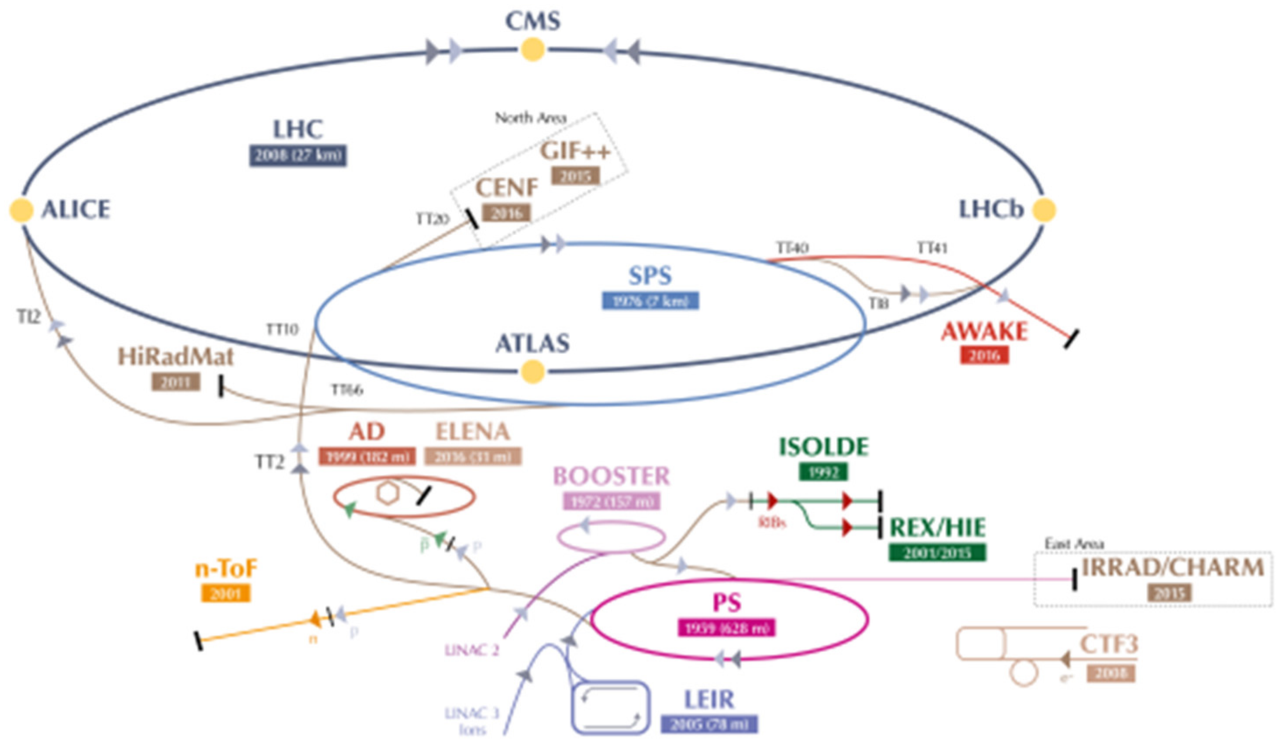
Studies of Capture and Flat-Bottom Losses in the SPS

M. Schwarz, H. Bartosik, A. Lasheen, J. Repond, E. Shaposhnikova, H. Timko

Acknowledgements:
P. Baudrenghien, B. Goddard, T. Bohl, V. Kain, I. Karpov, P. Kramer, G. Papotti
SPS & PS operator team, SPS injection losses working group, BLonD dev team

Introduction: CERN accelerator complex



Goal for High-Luminosity LHC: 2.2e11 protons per bunch (ppb) at LHC flat top

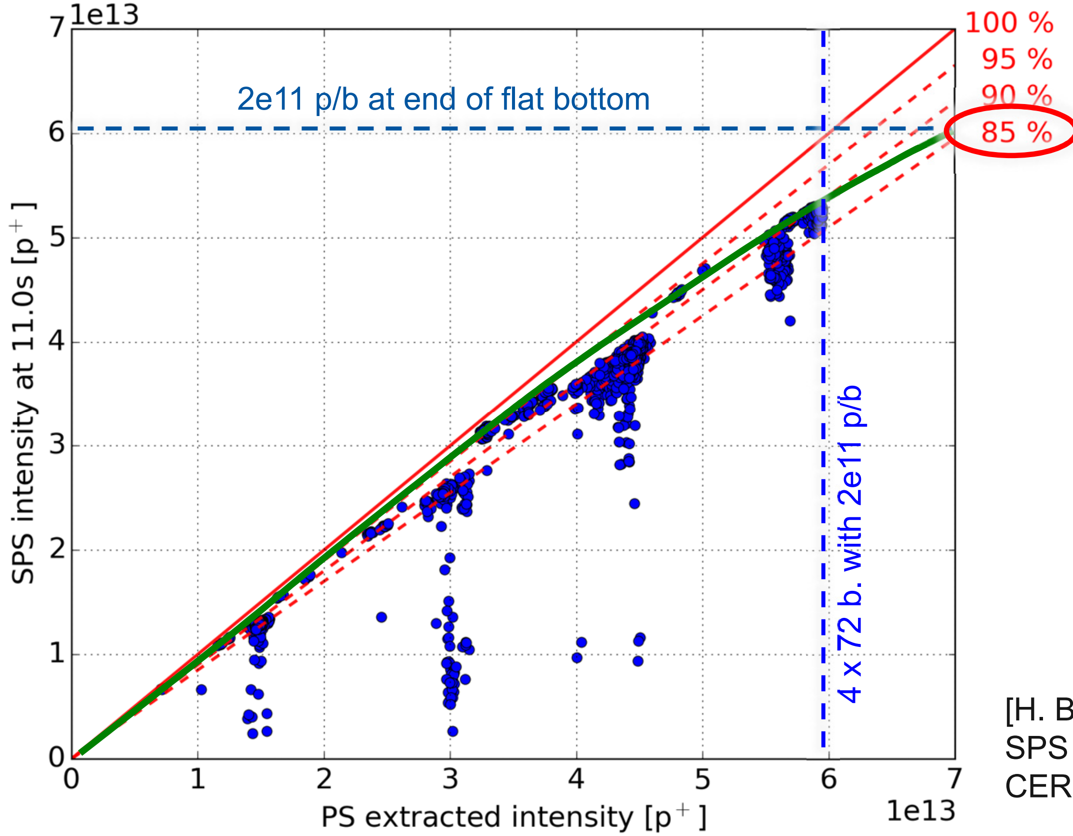
Challenge: losses in the LHC injector chain: PS booster -> PS -> SPS -> LHC

One bottleneck are losses at SPS flat bottom

1. Capture losses at PS-to-SPS RF bucket transfer:
    - Longitudinal effects (bunch shape from PS, uncaptured PS beam, …)
    - SPS LLRF system (feedback, beam phase loop, …)
2. Losses during remaining flat bottom:
    - Momentum aperture and transverse emittance
    - Full RF bucket (intensity effects, noise from LLRF, …)

Losses in the SPS

- Need to 2.6e11 ppb injected into the SPS to take account for the loss budget of 10% from injection to extraction
- Measurements in 2015 with injected 2.0e11 ppb already gives 15% losses at flat bottom!



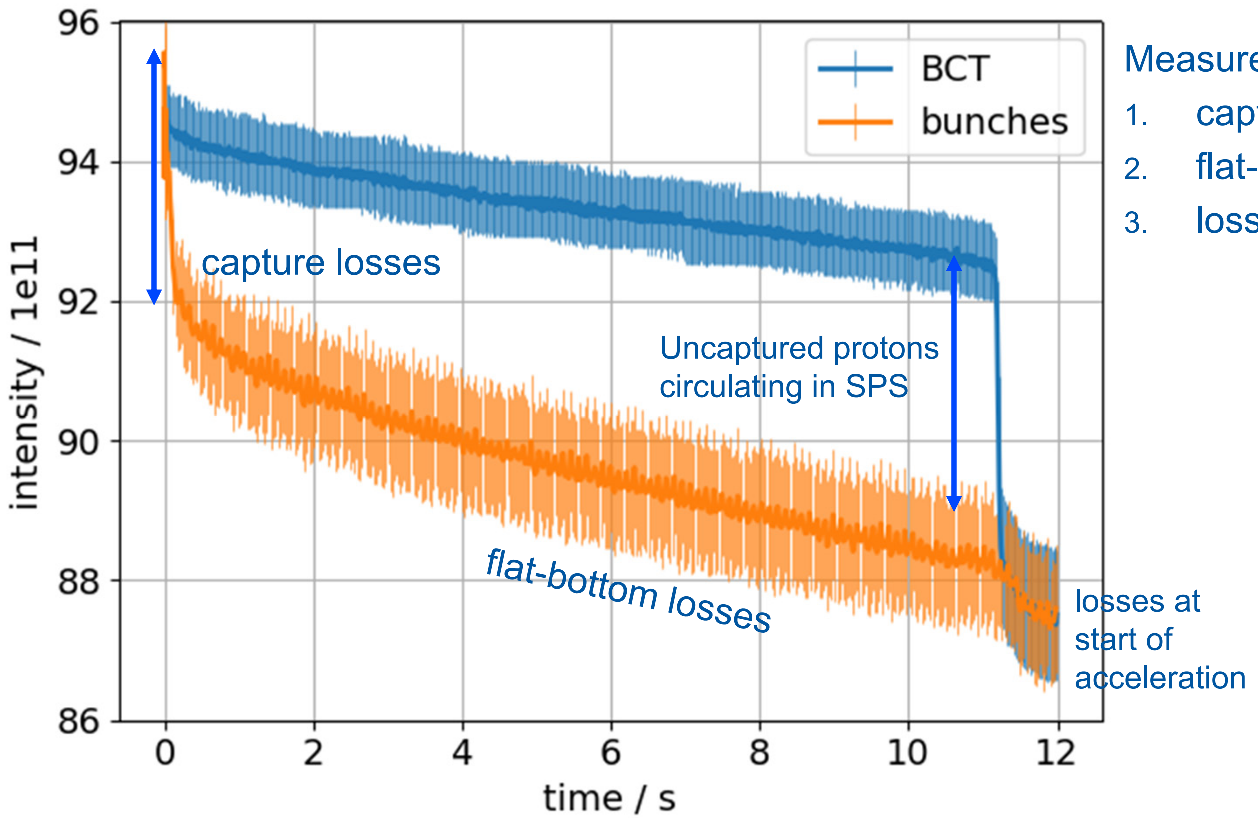
[H. Bartosik et al., SPS injection loss review, CERN,2017]

- Extrapolation to 2.6e11 ppb gives 20% losses from injection to extraction
[H. Bartosik et al., IPAC16, MOPOR022]
- Need better understanding to control flat bottom losses!

Losses in the SPS

Measure beam intensity in SPS with

- Bunch Current Transformer (BCT)
  - gives absolute numbers of particles in the machine
  - not fast enough to measure beam intensity during first few milliseconds after injection
  - measures all particles circulating in the machine
- integrated bunch profiles observed with wall current monitor
  - Bunch-by-bunch intensity on a turn-by-turn basis starting from injection
  - Needs to be calibrated with BCT intensity
  - Uncaptured particles above/below RF bucket are counted as well



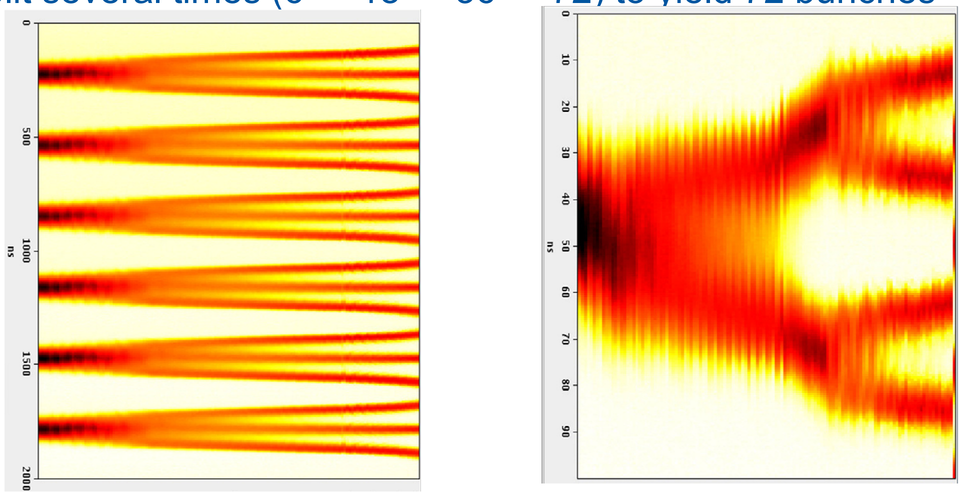
Measured intensity along SPS flat bottom:

1. capture losses
2. flat-bottom losses
3. losses during acceleration and flat top

Bunches from the PS

RF manipulations in PS:

1. Initial 6 bunches split several times (6 -> 18 -> 36 -> 72) to yield 72 bunches

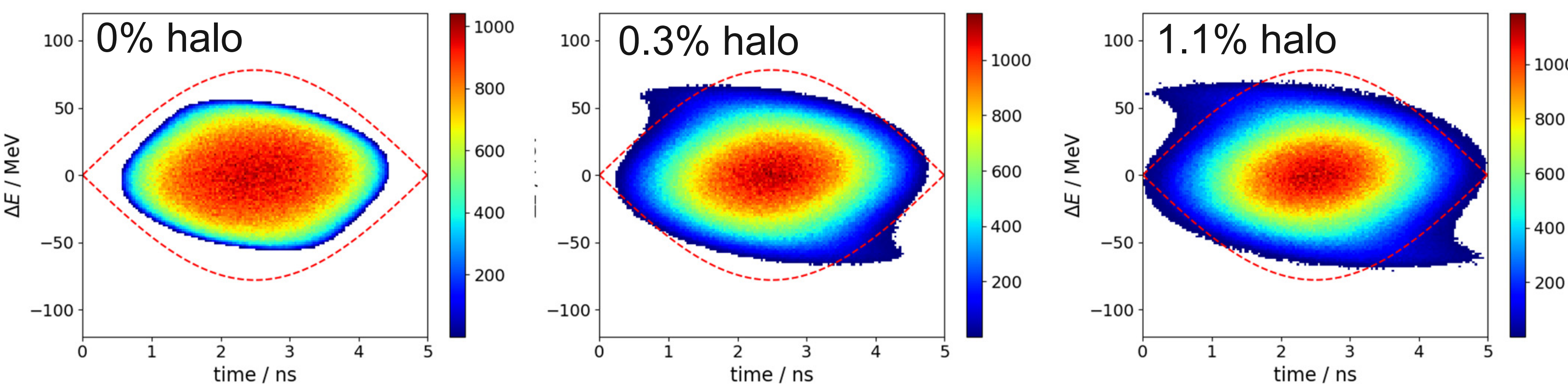


[A. Lasheen et al., Proc. Evian 2017]

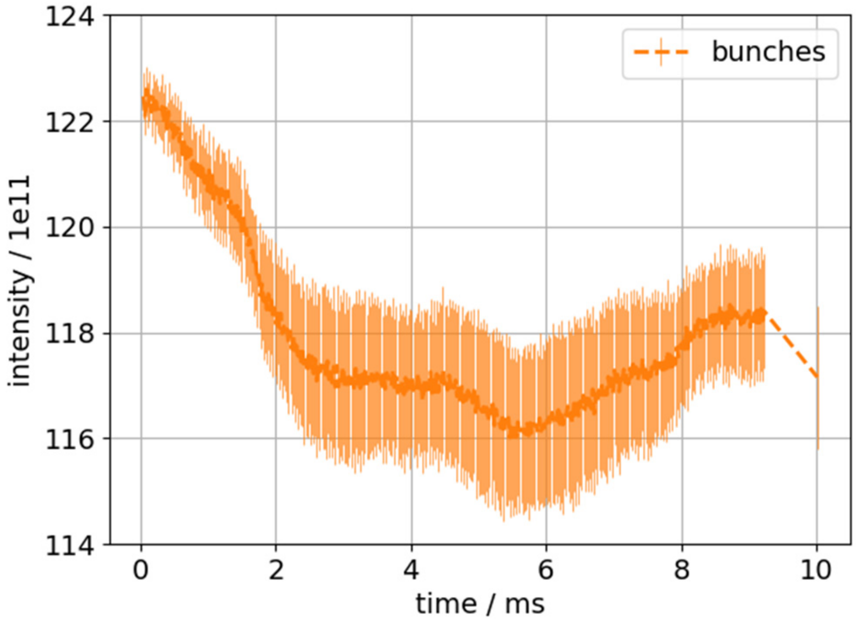
2. 4σ bunch length of 14 ns too long for 5 ns SPS RF bucket -> bunch rotation yields 4σ of 4 ns

Nonlinearities in the RF create particle halos!

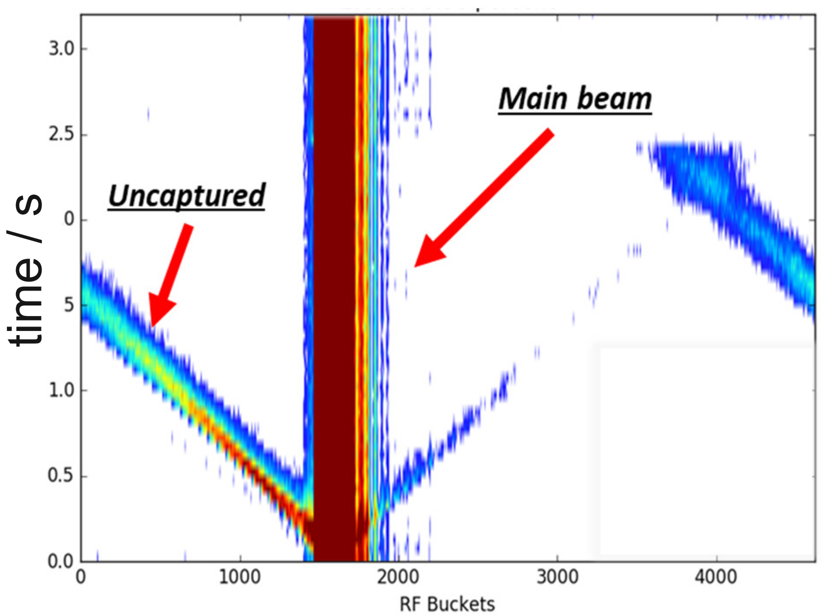
Simulated longitudinal particle distributions after splitting and rotation in PS:



Capture losses



- Intensity drop during first 2 ms: uncaptured halo particles drift away from RF bucket
- Intensity increase after ~6 ms: uncaptured particles drift above/below neighboring bunches



- Measurements with Fast BCT show that uncaptured particles have left main beam after ~500 ms

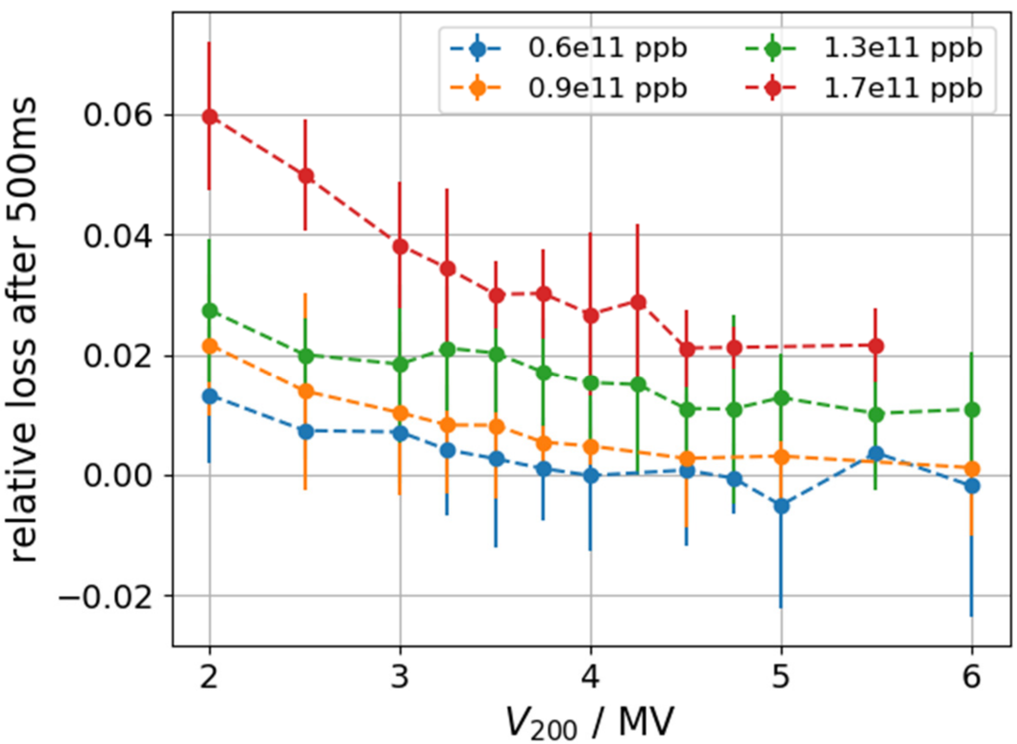
Setup:

- 72 bunches, vary intensity from 0.6e11 ppb up to 1.7e11 ppb

Aim: study if bunches injected from the PS change with intensity

Idea:

- RF-bucket area scales as $a \sim \sqrt{V}$. Voltage seen by the beam given $V = V_{RF} - V_{ind}$, where induced voltage V_{ind} depends in bunch intensity and bunch shape.
- with increasing RF-bucket area a capture losses l_{capt} decrease ($l_{capt} \sim 1/a \sim 1/\sqrt{V - V_{ind}}$) and should level off, once all beam is captured
- **IF** bunch shapes from the PS were independent of intensity, V_{ind} depends only on intensity and for different intensities **capture losses l_{capt} would just be shifted horizontally**



Observed:

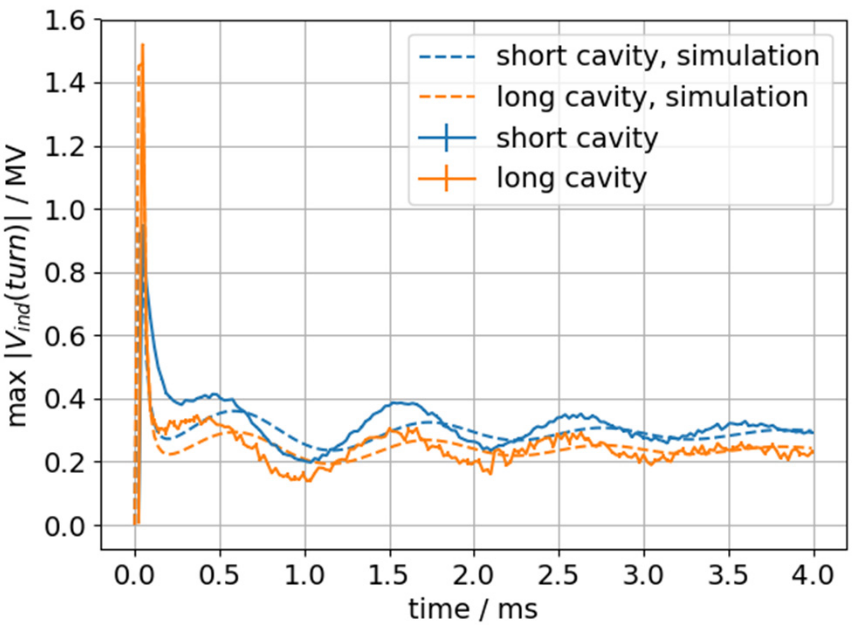
- leveling of losses for V > 4.5 MV
- **vertical offset** with intensity
  -> more halo for higher intensity

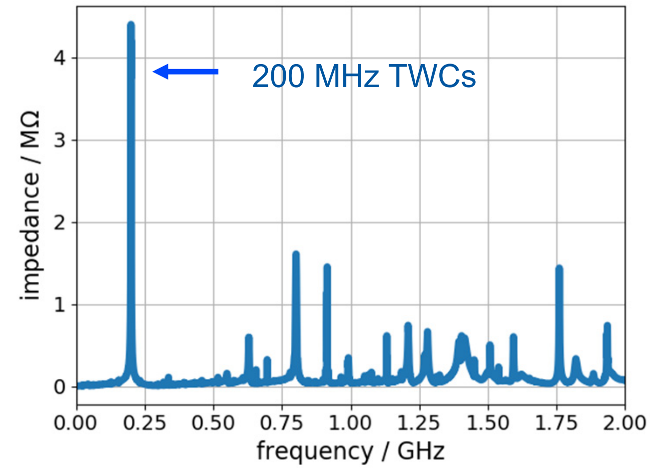
Longitudinal beam dynamics simulations

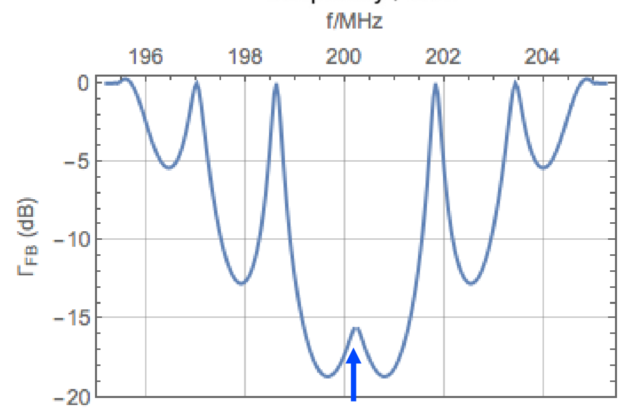
- Longitudinal tracking code BLonD [blond.web.cern.ch]
- Different distributions from PS (0% halo, 0.3% halo, 1.1% halo)
  - 1.5 million macro-particles per bunch; 72 bunches 25ns apart
- Longitudinal SPS impedance model
- Dynamic model of one-turn delay feedback under development
- Here: model effect of feedback by multiplying impedance with feedback-reduction factor [P. Baudrenghien, Charmonix X, 2001] and time-dependent attenuation:

$$Z_n = Z_{n-1}\,(\Gamma_{FB})^{S\,att(t)} \text{ with } att(t) = 1 - e^{-\frac{t-t_{start}}{\tau}}$$

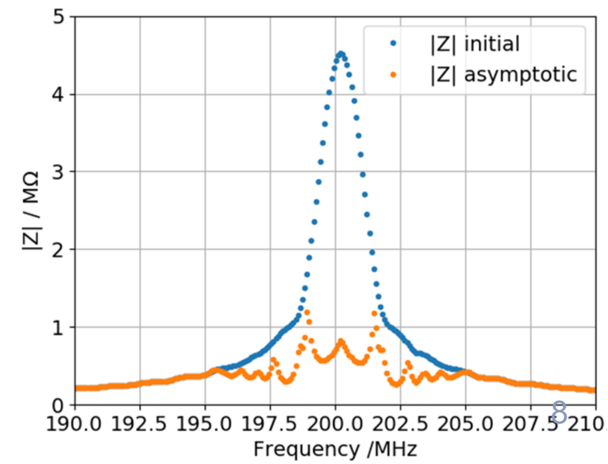
- Adjust attenuation parameters such that maximum beam loading amplitude V_{ind} at each turn agrees in simulation and measurement:





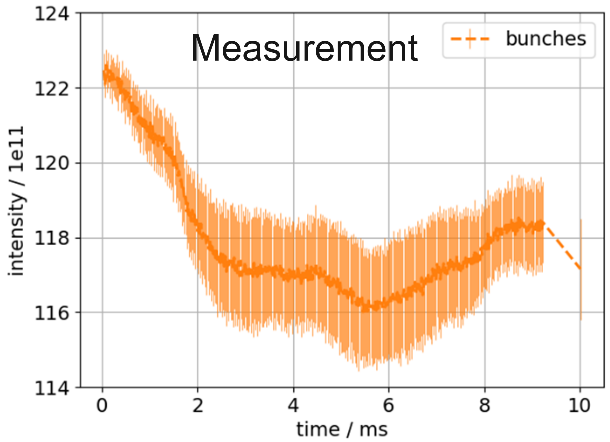


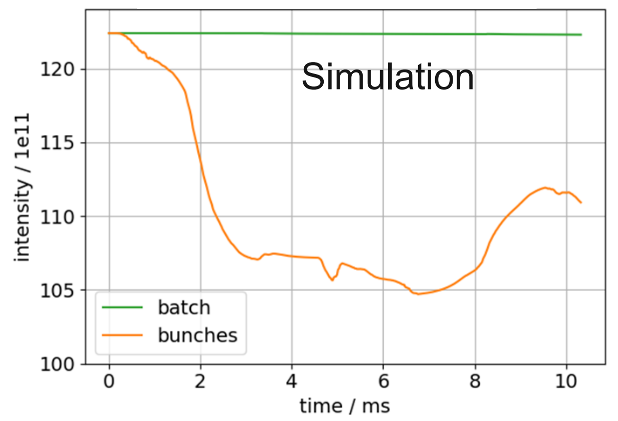
$\Gamma_{FB} = -15.5\ dB$ at f_{RF}



Measured and simulated intensity

- 72 bunches (25ns spacing), 1.7e11ppb, low V_{200} voltage (2.0MV) in both measurement and simulation

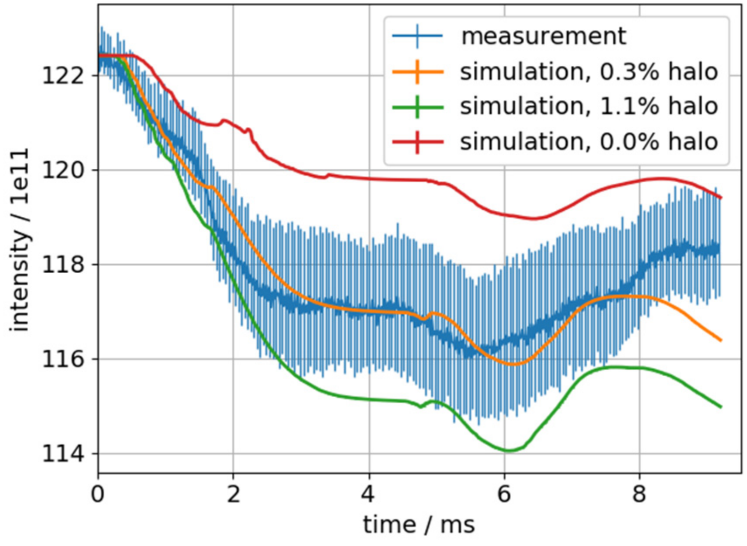




✓ Shape and time scale agree very well!

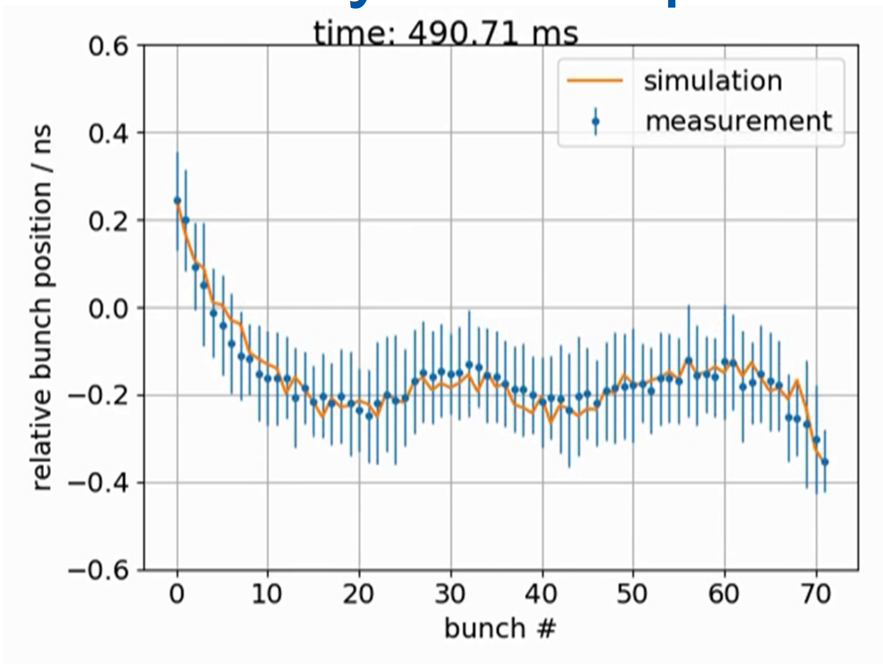
! Simulated losses to high compared to measurements…

✓ Also **using phase loop** and frequency loop in simulation gives **quantitative agreement** between simulated and measured intensity:

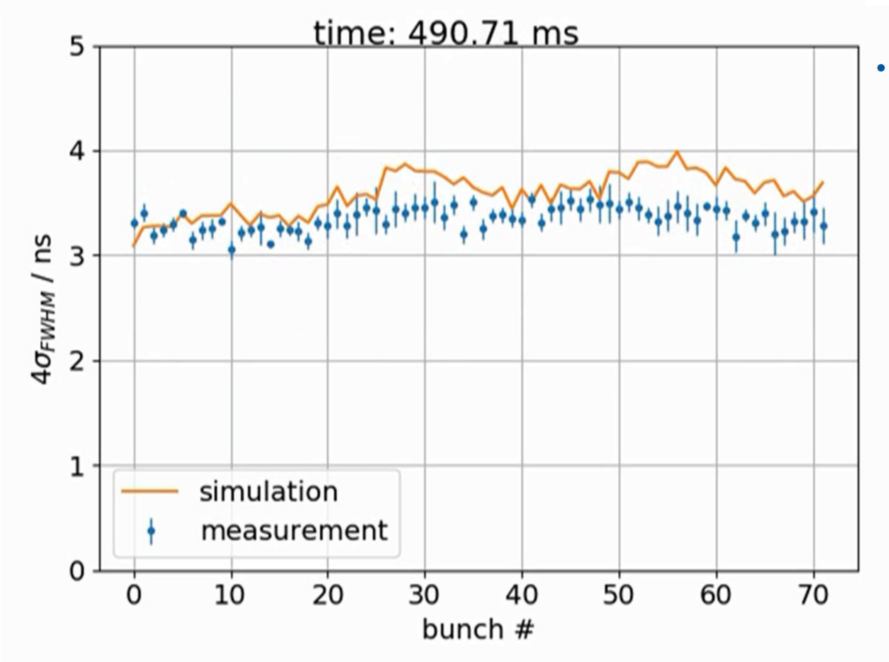


- Similar intensity curve for all halo types
- Absolute amount of losses strongly depends on initial halo

Bunch-by-bunch position and lengths

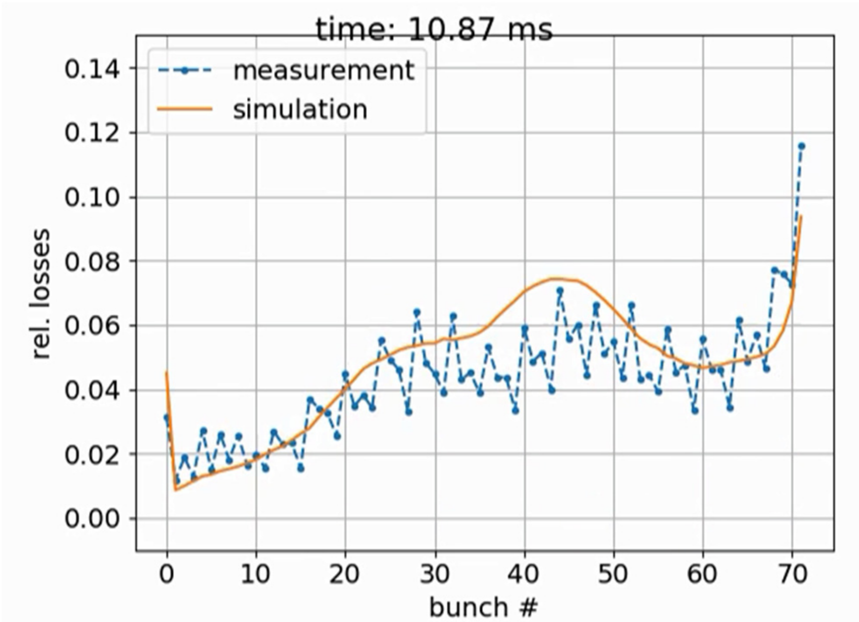


- Bunch displacement relative to 'bare' RF bucket due to beam loading



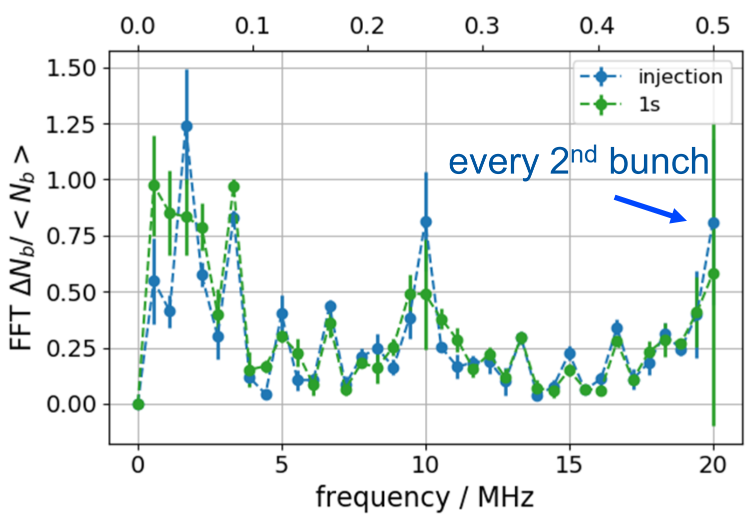
- 4σ bunch length

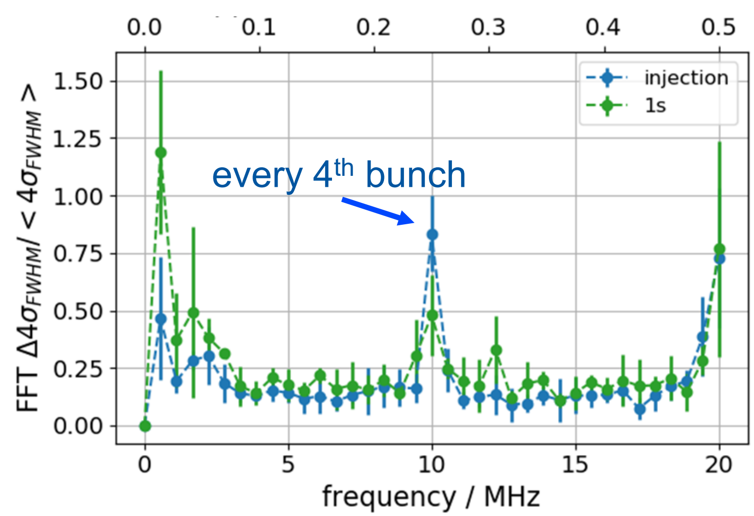
Bunch-by-bunch losses



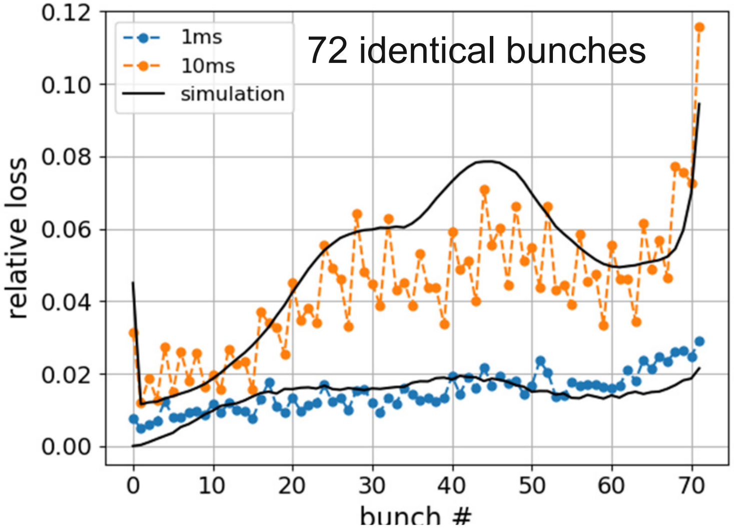
- ✓ Shape of measured and simulated bunch-by-bunch losses agrees well
- ! Measured 'loss modulation' not reproduced

Injected batch was not homogenous, but displayed intensity and bunch length modulation (due to bunch splitting in PS):



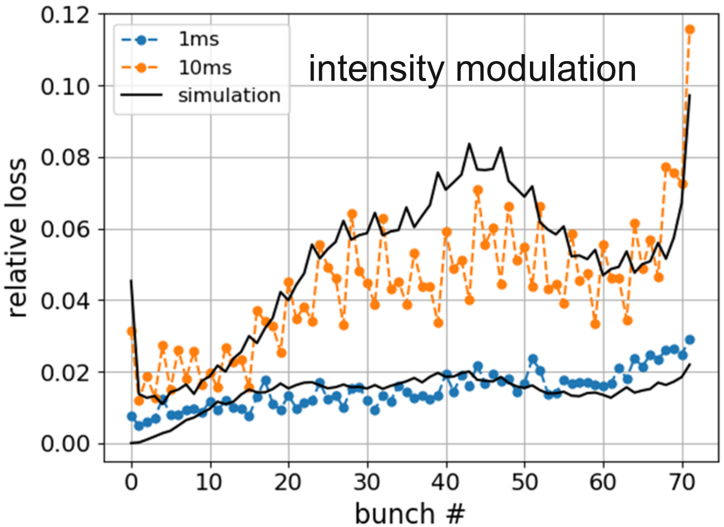


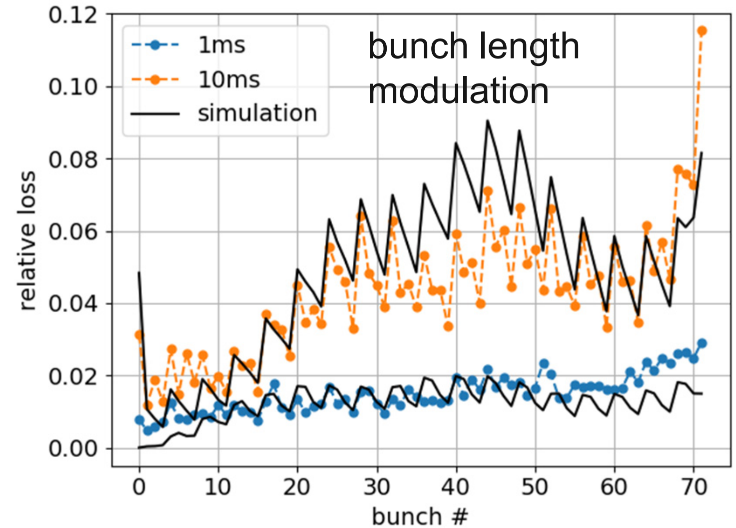
Bunch-by-bunch losses



Simulations with 72 bunches created:

- from same distribution
- from same distribution with intensity variation similar to measurement (same bunch length)
- from distributions with different bunch lengths similar to measurement (same intensity)

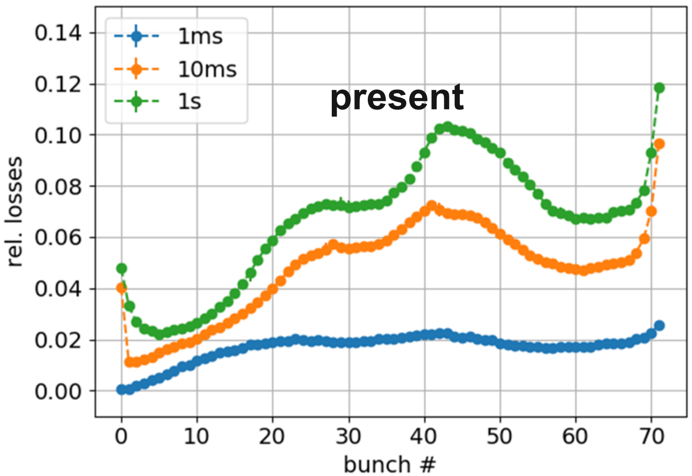




- Modulation of intensity produces small modulation in losses
- Modulation of bunch length gives correct modulation of losses -> important to control bunch length at injection

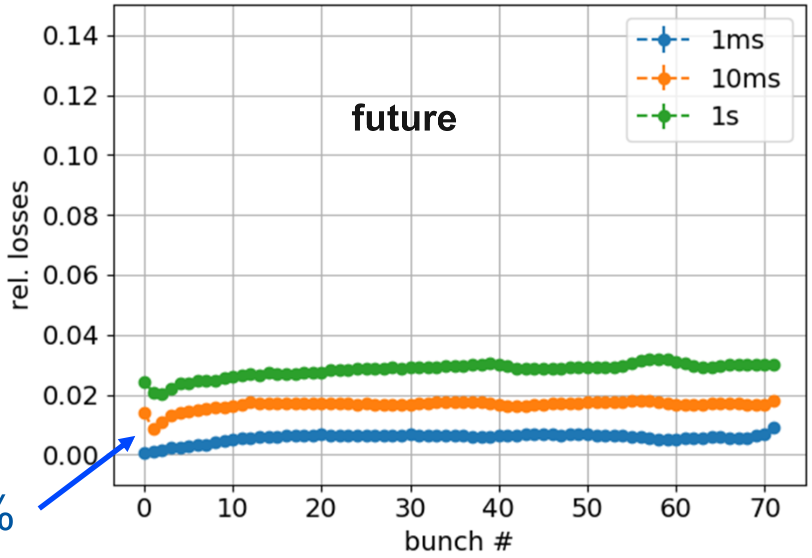
Simulated capture losses for high intensity, 2.6e11 ppb

- Simulation(*), **present** SPS parameters:
  - 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(*), **future** upgraded SPS parameters:
  - 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 (shielded vacuum flanges)

capture losses ~2%

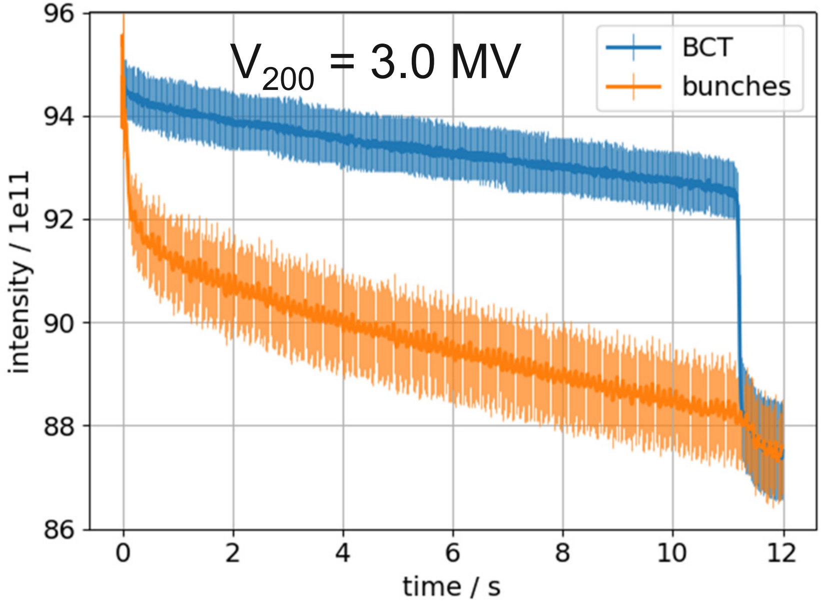


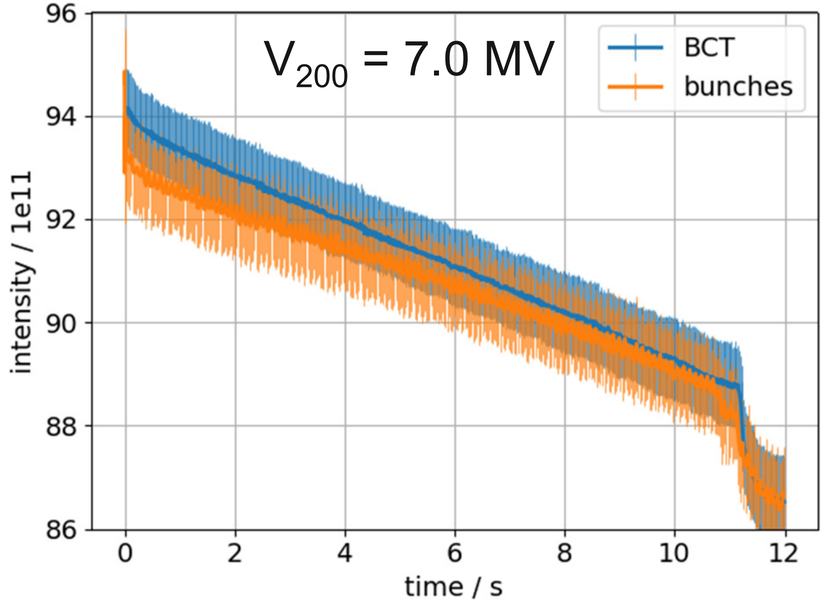
(*) based on distribution with 1.1% tails

Flat-bottom losses

Capture losses suggest to use highest voltage to capture large amount of halos, but larger capture voltage leads to large emittance due to filamentation -> problem to accelerate

- Solution? Capture in nominal V_{200} (4.5 MV) and increase V_{200} on flat-bottom after capture to prevent particles escaping from bucket





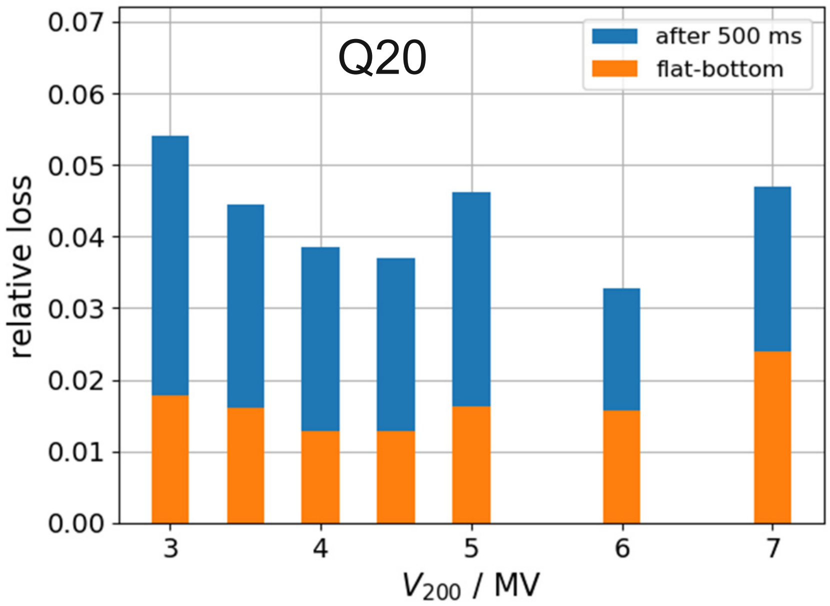
- Decreasing V200 from 4.5 MV to 3.0 MV after capture drives protons out of the RF bucket, which continue to circulate in the SPS
- Increasing V200 to 4.5 MV to 7.0 MV captures more protons initially and no uncaptured protons are present in the SPS, but loss rate from bunches is doubled! -> limited by momentum aperture

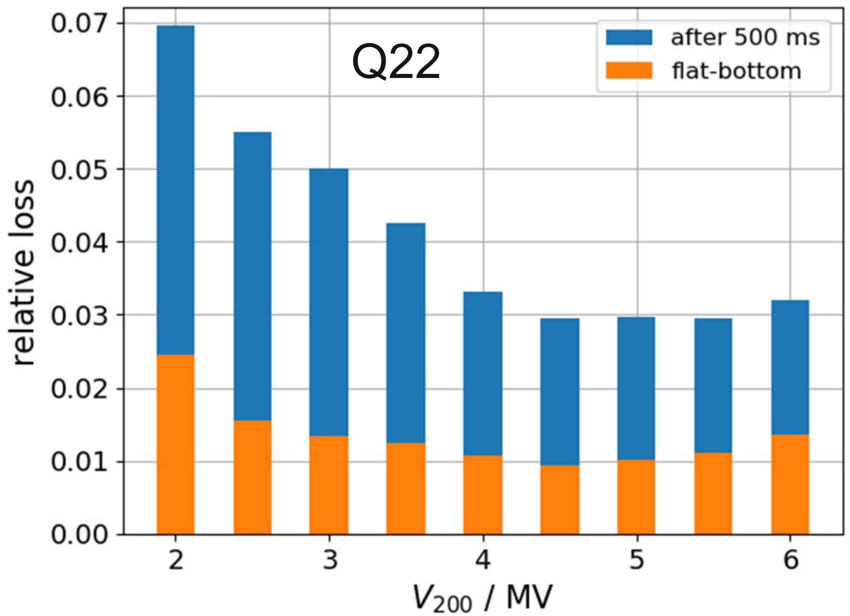
Sources of flat-bottom losses:

- limited momentum aperture
- RF noise
- …

Optics with larger momentum aperture

- Beam with 48 bunches and reduced transverse emittance, 1.35e11 ppb
- Compare nominal optics **Q20** and **Q22** optics
  - higher transition energy -> voltages that yield same RF bucket area $V_{Q22} \cong 0.81\, V_{Q20}$
  - larger momentum aperture





- Capture losses (blue) decrease with increasing RF bucket area
- Total losses show minimum at V_{200} ~ 4.5 MV because losses along flat-bottom increase for higher V_{200}
- Losses along flat-bottom (orange) for V_{Q20} = 7.0 MV in nominal optics Q20 are about twice as much as those for equivalent voltage of V_{Q22} = 5.7 MV in optics Q22 with larger momentum aperture!

Summary and conclusion

- High Luminosity LHC intensity of 2.2e11 ppb at LHC flat top requires 2.6e11 ppb at injection in the SPS and a loss budget of 10%.
- One bottleneck for these high intensities are losses in the SPS at flat bottom.
- Capture losses occur at the PS bunch to SPS RF bucket transfer
    - Caused by halo particles outside and close to the SPS RF bucket
    - Increase with intensity due to increased beam loading and larger halo
- Capture losses are reproduced in longitudinal tracking simulations that include SPS intensity effects, feedback system, and beam phase loop.
- Based on simulations, capture losses for future upgraded SPS are 2%.
- Further losses occur during the SPS flat bottom, caused among others by a limited momentum aperture:
    - Flat-bottom losses are reduced optics with larger momentum aperture
    - Beams with reduced transverse emittance have smaller flat-bottom losses

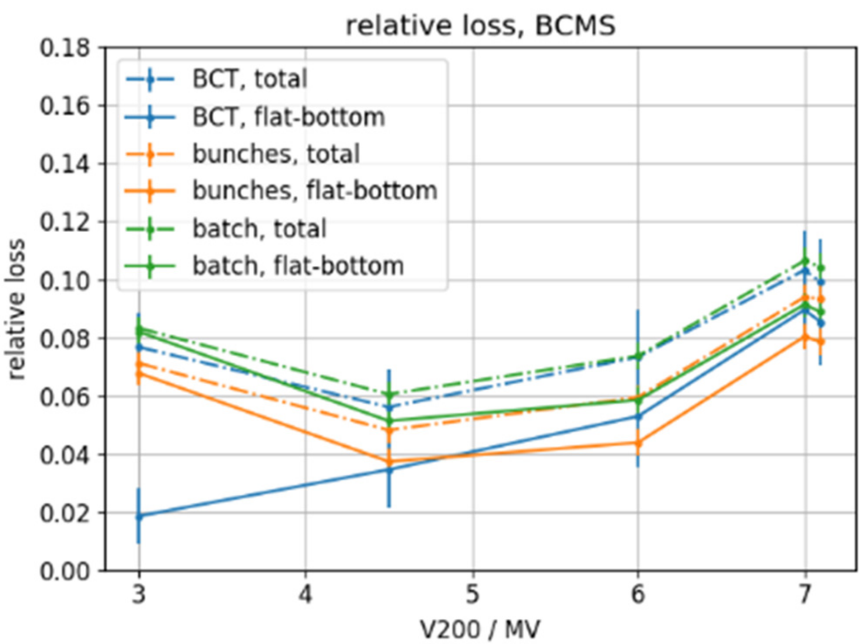
Outlook:

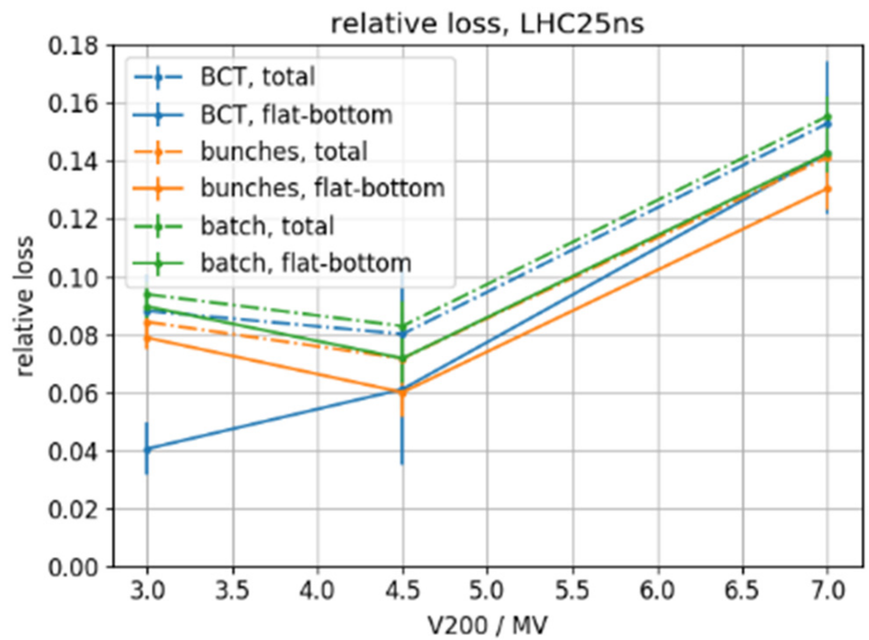
- Need to include particle loss due to momentum aperture in simulations to model larger time scales (> 1s)
- A physical aperture limitation was recently discovered [V. Kain et al., SPS injection losses review, CERN 2017] and will be fixed during upcoming long shutdown.
- RF noise (in particular feedforward system) as another contributor to flat-bottom losses is currently under investigation.

Thank you for your attention!

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

First results with dynamic OTFB

Motivation:

- Previously, SPS OTFB modeled by ‘impedance reduction’, i.e. no dynamic implementation
- Dynamic OTFB developed for BLonD (H. Timko)
- Here, present first comparisons with measurements

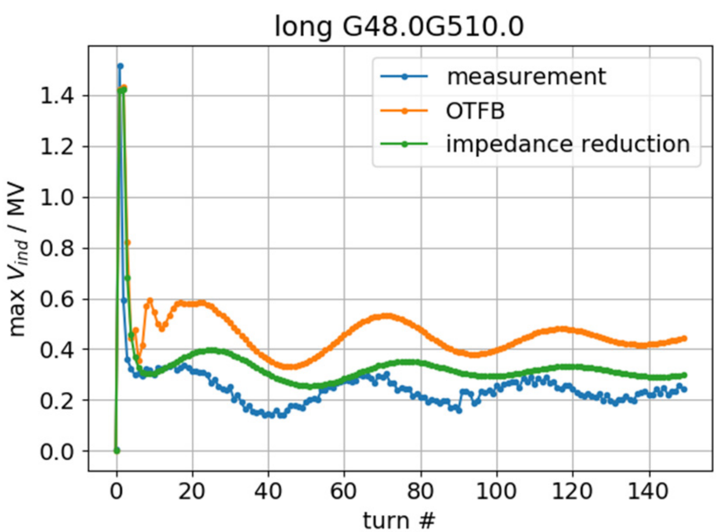
Measurements:

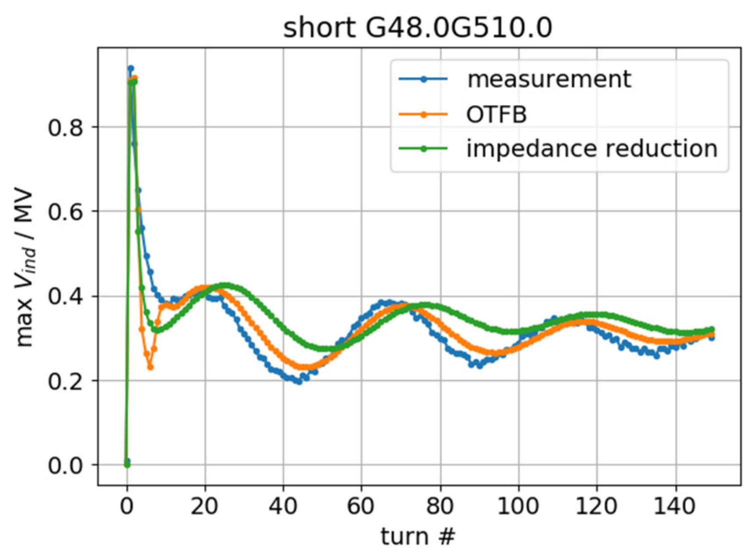
- 48 bunches, 1.48e11 ppb
- V_{200} = 4.5 MV, Q22 optic

Simulation parameters:

- 48 bunches, 1M 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)

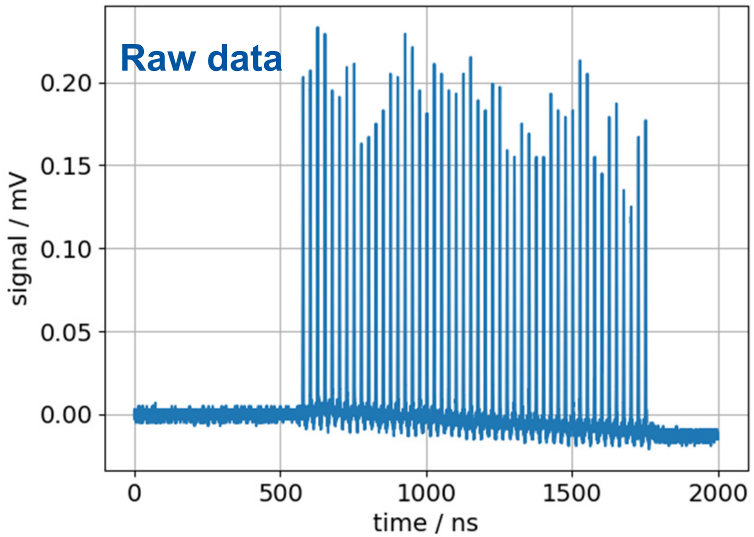




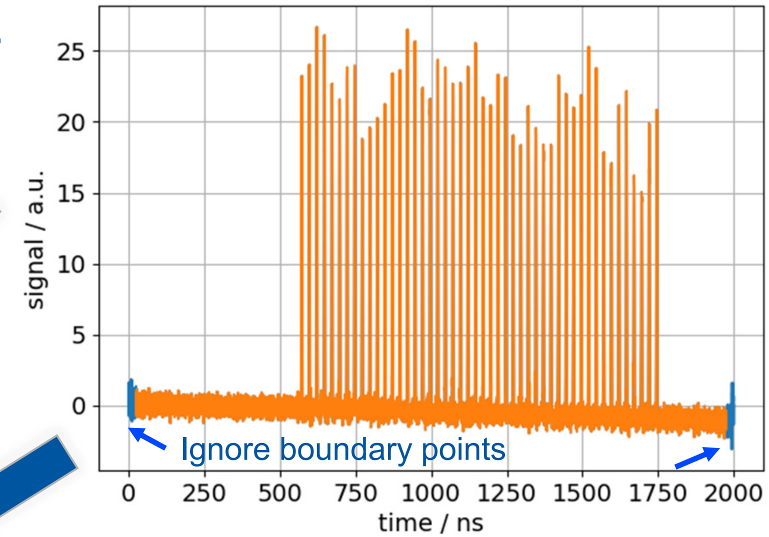
Results:

- Induced voltage in short TWC ‘undershoots’ around turn 10; asymptotic behavior represented well
- For long TWC, OTFB does not reduce induced voltage enough -> need to adjust gain margin

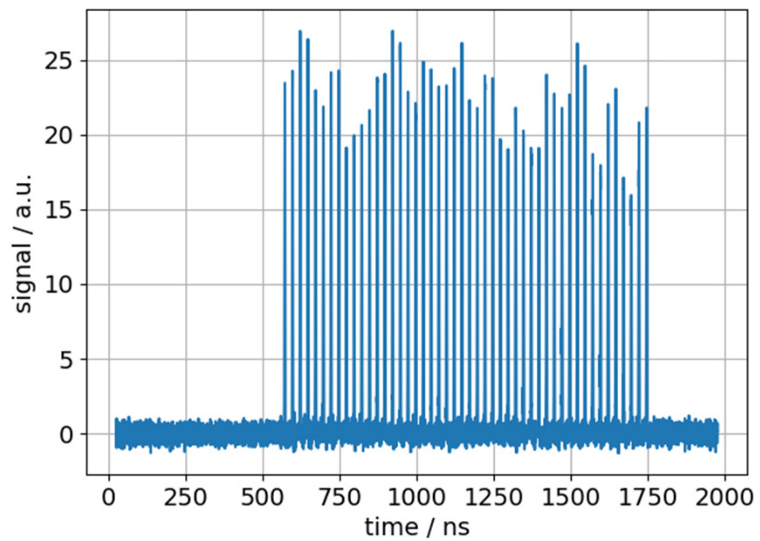
Profile analysis



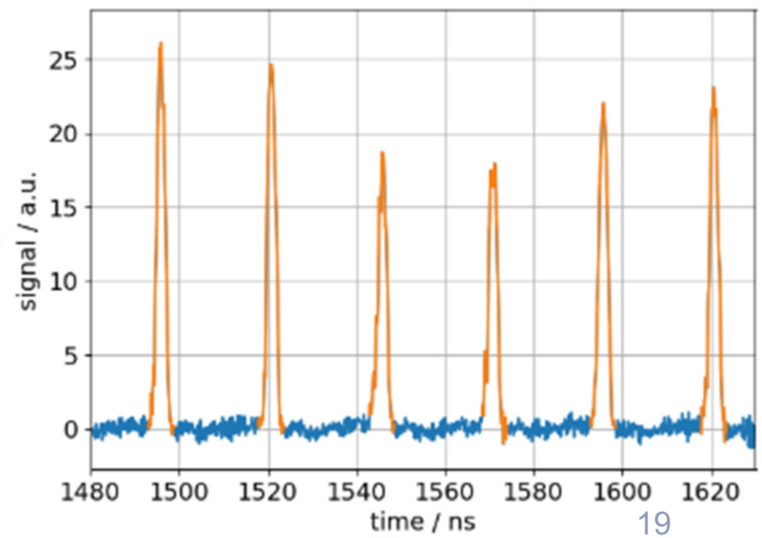
Apply transfer-function correction



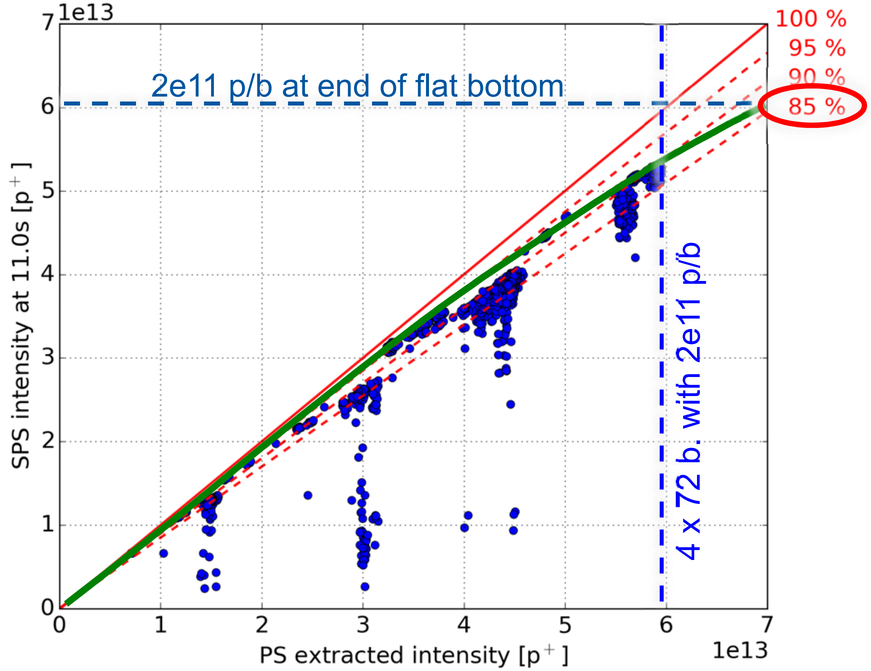
Remove baseline



detect bunches



Losses in the SPS

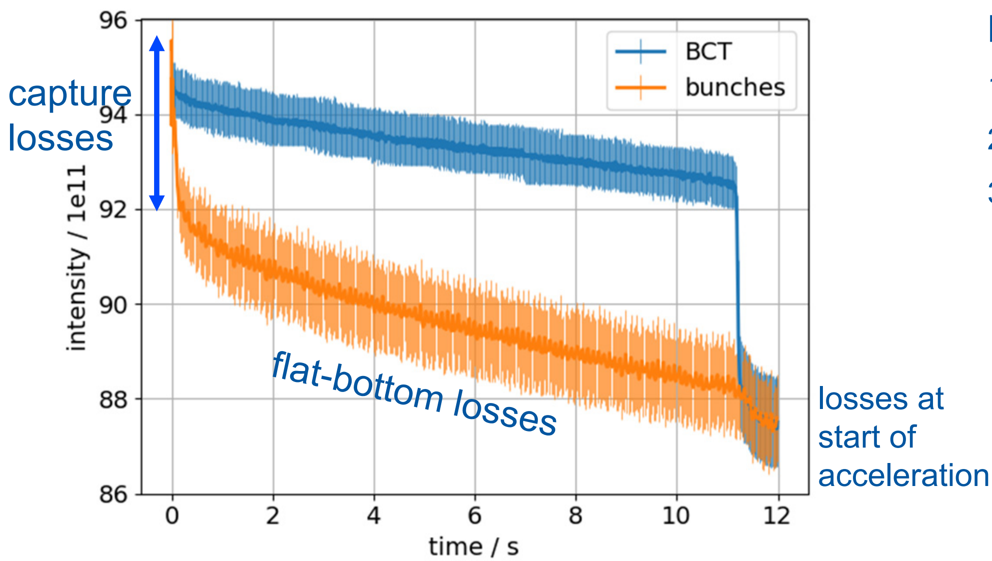


Need to 2.6e11 ppb injected into the SPS to take account for the loss budget of 10% from injection to extraction

Measurements in 2015 with injected 2.0e11 ppb already gives 15% losses at flat bottom!

[H. Bartosik et al., SPS injection loss review, CERN,2017]

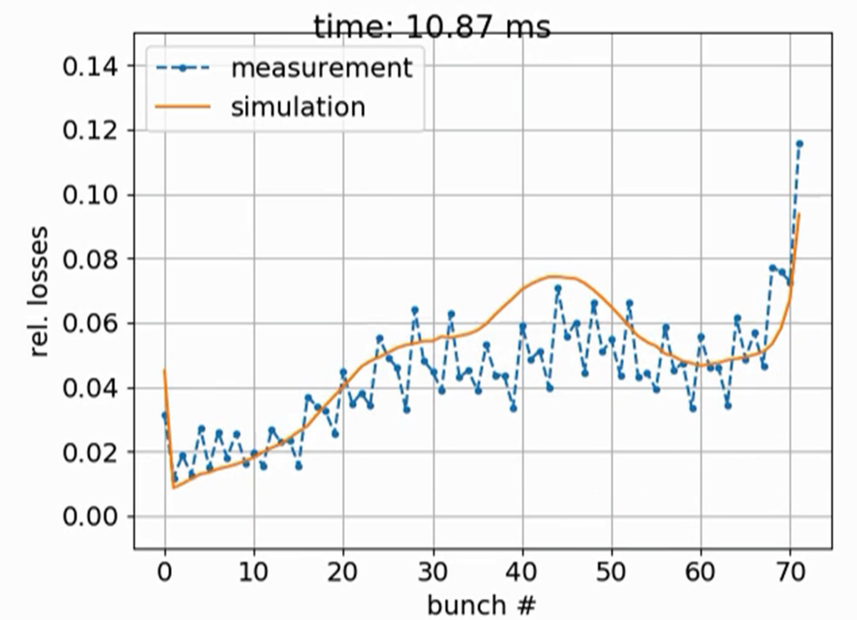
Need better understanding to control losses



Measured intensity along SPS flat bottom reveals:

1. capture losses
2. flat-bottom losses
3. losses during acceleration and flat top

Bunch-by-bunch losses



- ✓ Shape of measured and simulated bunch-by-bunch losses agrees well
- ! Measured 'loss modulation' not reproduced

Injected batch was not homogenous, but displayed intensity and bunch length modulation (due to bunch splitting in PS):