LHC Injectors Upgrade

Overview of measured capture and flat bottom losses

H. Bartosik, T. Bohl, S. Cettour Cave, K. Cornelis, H. Damerau, B. Goddard, V. Kain, A. Lasheen, K. Li, G. Papotti, J. Repond, G. Rumolo, M. Schwarz, E. Shaposhnikova, H. Timko

SPS injection losses review, 30 November 2017

Introduction

- The aim of this presentation is to give an overview of the measurements performed on flat bottom and capture losses in the last few years and present our present understanding of the underlying mechanisms

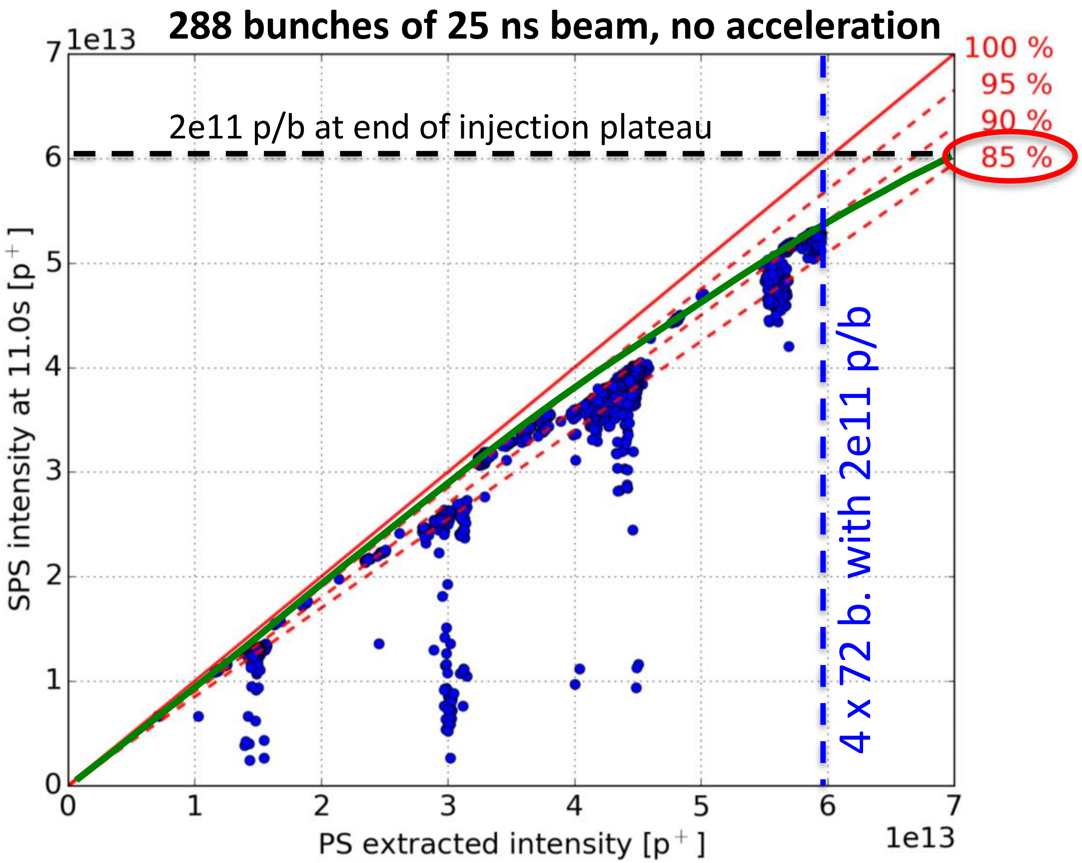
- Almost all measurements presented here were done in Q20 (unless indicated otherwise)

- Most results presented here were obtained with a single batch of a 25 ns beam (either 72 bunches standard beams or 48 bunches BCMS beams) with nominal longitudinal emittance of 0.35 eVs at PS extraction (unless stated otherwise)

The problem

- **(Relative) losses in SPS observed to increase as function of intensity**
  - Lots of studies in the past in preparation of the nominal LHC beams – back then important e-cloud effects (nowadays seems less important after scrubbing)

- **Flat bottom transmission during high intensity scrubbing run in 2015:**



Estimation from 2015:
15% losses on SPS flat bottom to reach 2e11 p/b before acceleration but LIU target is actually to reach 2.3e11 p/b at SPS extraction! …

… since then effort intensified again to better understand losses in SPS

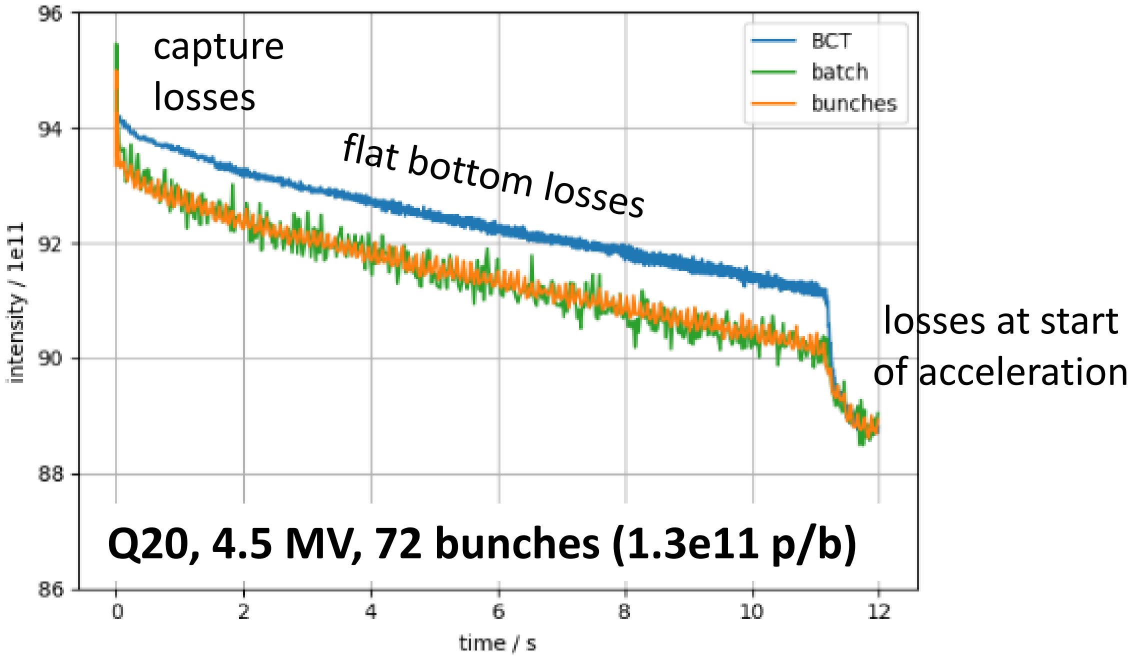
… SPS RF will be upgraded in LS2

… LIU SPS loss budget of 10%

Observed losses in SPS

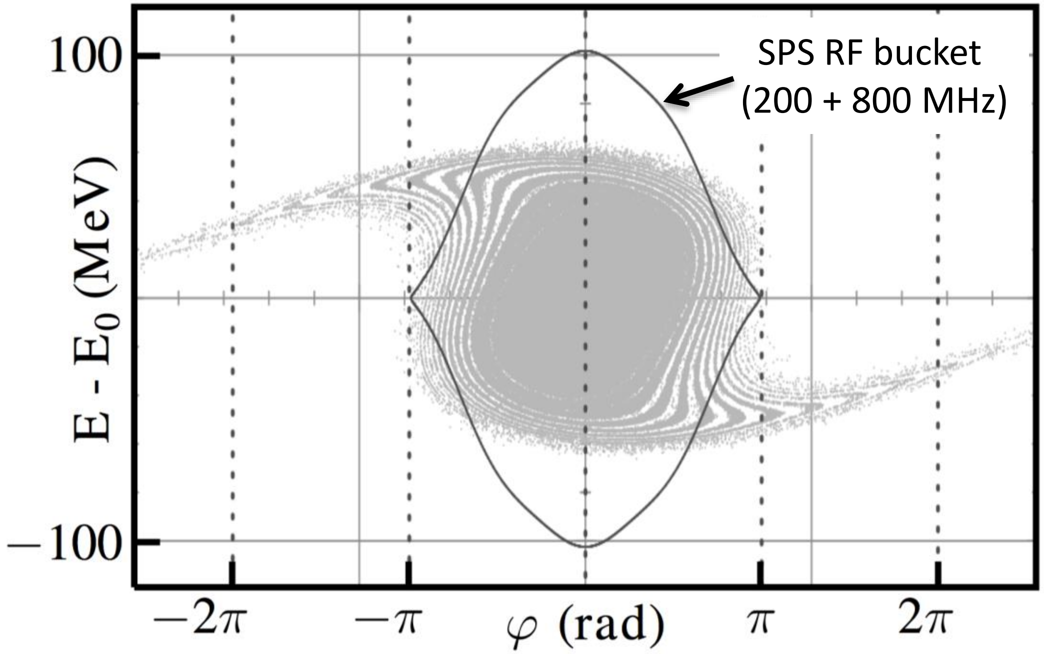
- **Capture losses**
  - Fast losses at injection + un-captured beam circulating in SPS (losses at start of acceleration)
  - Additional losses at start of acceleration

- **Continuous losses on flat bottom**
  - Particles reaching momentum acceptance (uncaptured beam, particles close to separatrix diffusing out of the bucket, …)
  - Transverse losses (e.g. losses due to betatron resonances)



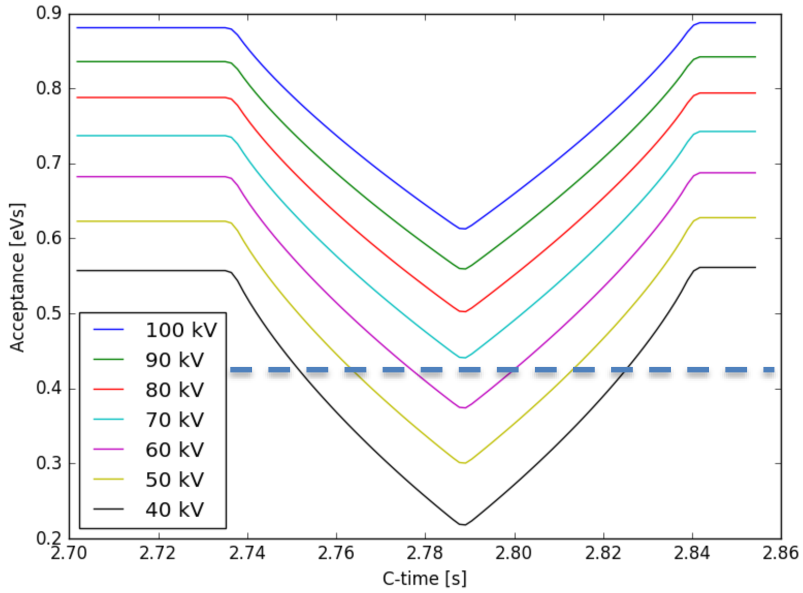
Longitudinal distribution from PS

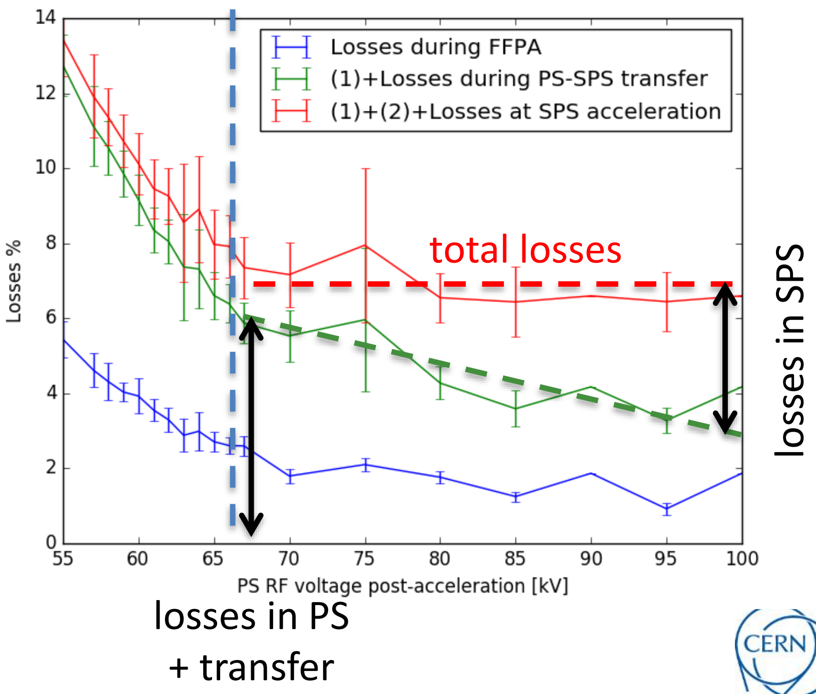
- **Transfer from PS 40 MHz to SPS 200 MHz buckets**
  - Canonical longitudinal emittance in PS before extraction at 0.35 eVs
  - Bunch rotation at PS extraction creates longitudinal tails → outside of SPS RF bucket
  - Rotated longitudinal distribution is not matched to SPS bucket
  - Expect capture losses in SPS due to “geometric effect”
  - PS would prefer large longitudinal emittance for fighting longitudinal instabilities
  - Proposals to improve shape of core of longitudinal distribution (see presentation of A. Lasheen)



Longitudinal distribution from PS

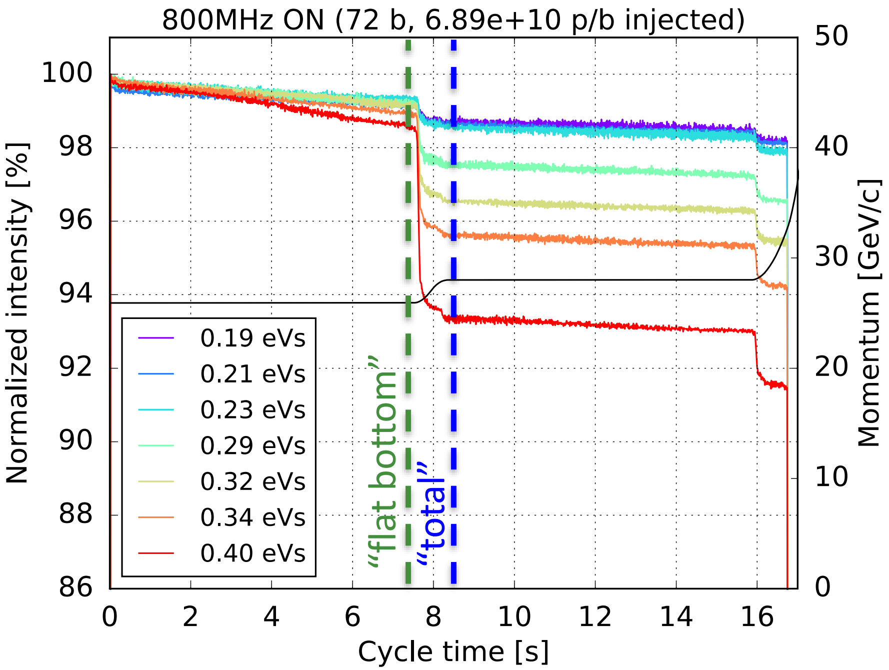
- **Studies of contribution from longitudinal halo coming from PS**
  - Longitudinal shaving is performed by keeping the RF voltage constant during a fixed frequency acceleration performed at end of PS cycle "post-acceleration" → dip in longitudinal acceptance
  - Presently only possible with limited beam intensity due to RF trips (i.e. 36 bunches, 1.2e11 p/b)
  - **For ~0.4 eVs minimum acceptance in PS, losses almost completely shifted from SPS to PS (for same total losses) … hints towards uncaptured beam and longitudinal halo from PS** (see Alexandre's presentation)

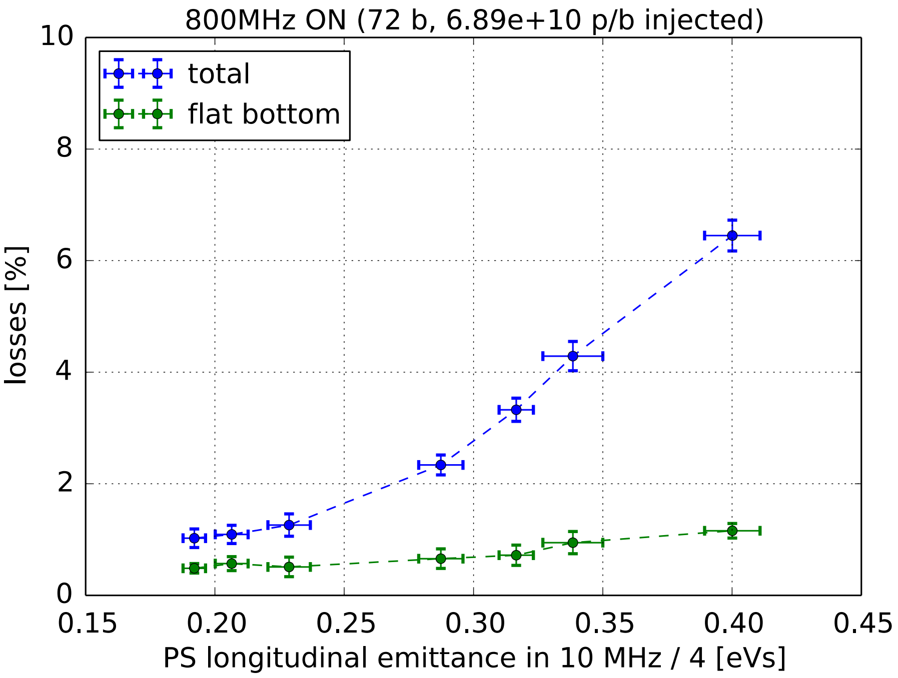




Losses as function of longitudinal emittance

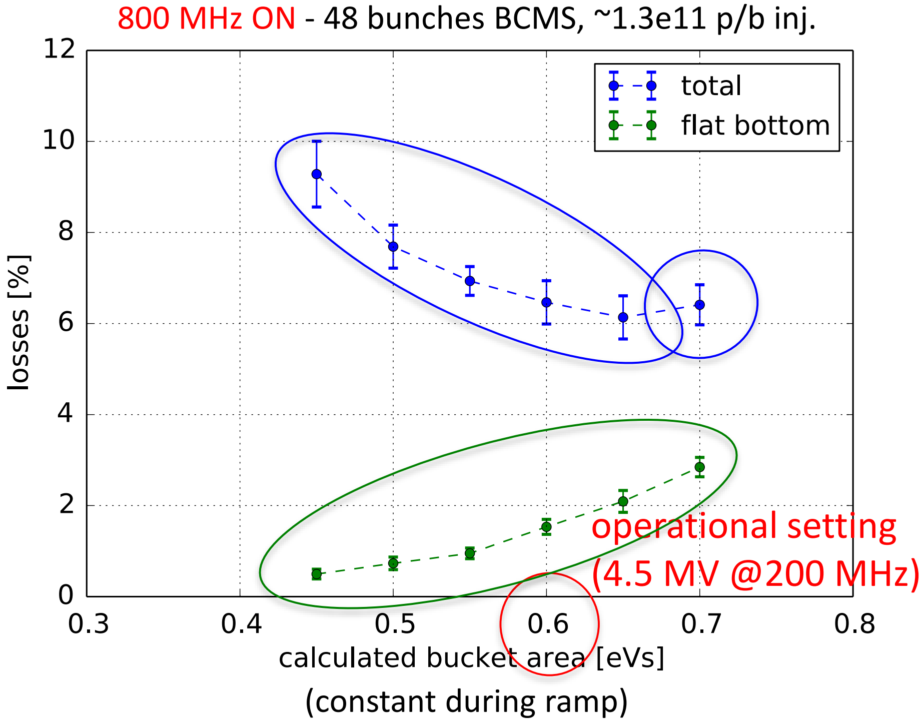
- Longitudinal emittance is varied with controlled blow-up in the PS (low beam intensity)
- Transmission degrades with larger emittance (mainly losses at start of the ramp) due to longitudinal distribution after bunch rotation in PS (S-shape)
- Small longitudinal emittance is not an option for operation due to longitudinal instability in PS

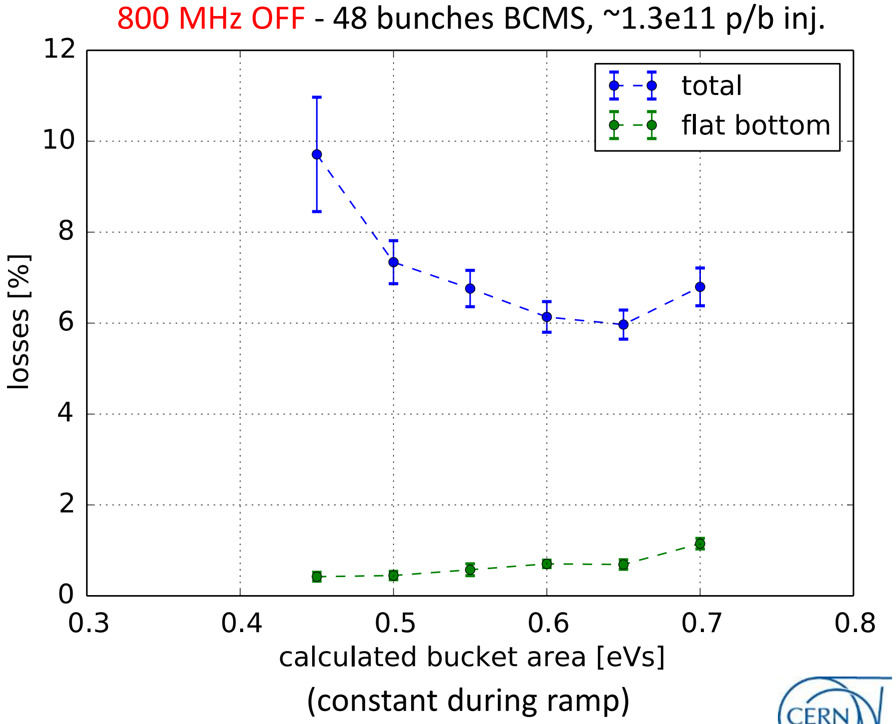




Losses as function of SPS RF voltage

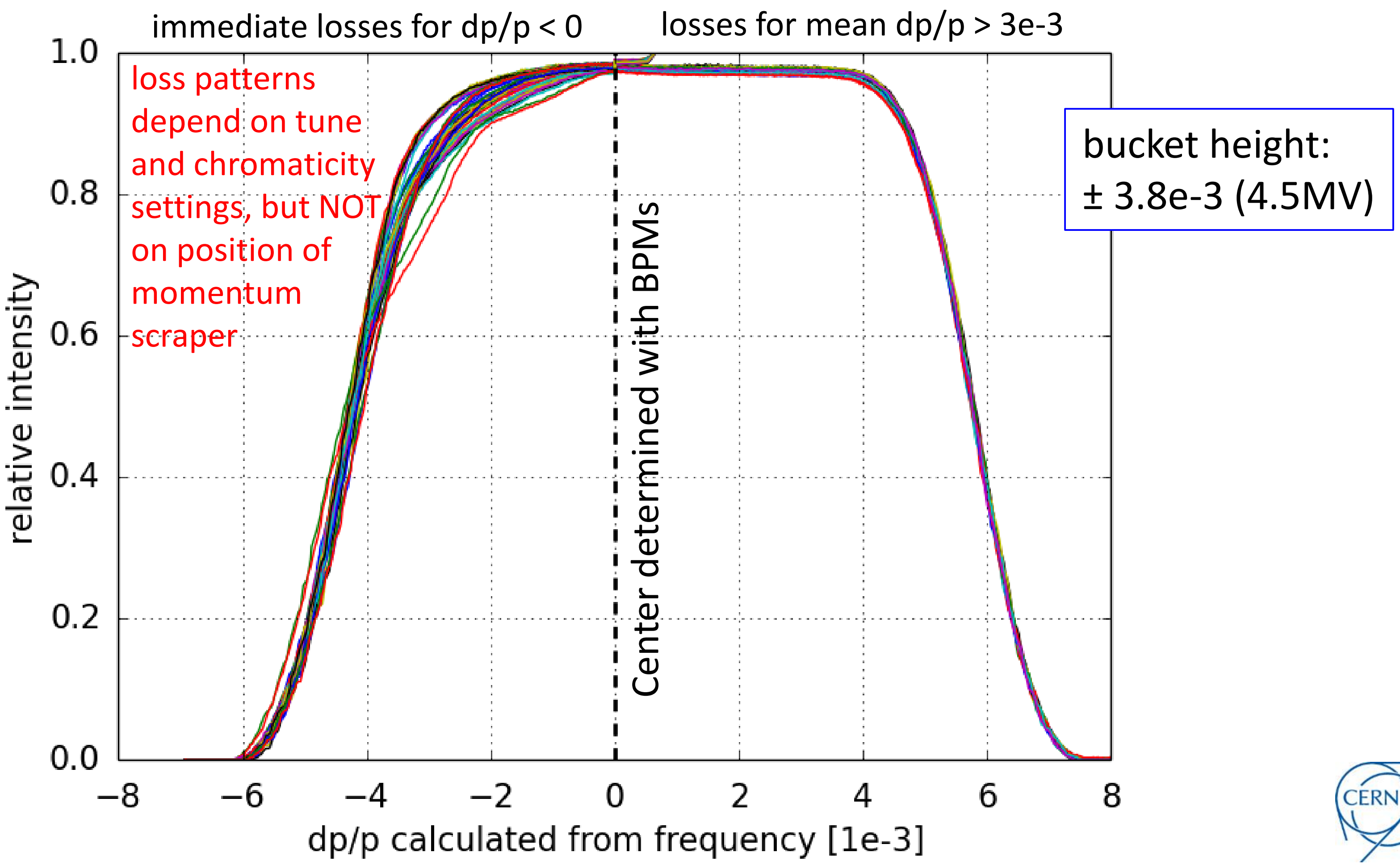
- As expected, total transmission improved when increasing bucket area in SPS
- Flat bottom losses increase with higher bucket area
- For very high bucket area losses start increasing again due to limited **momentum acceptance**
- Operational setting close to optimum
- Same total transmission without 800 MHz, but flat bottom losses significantly reduced





Momentum acceptance

- **Radial steering revealed asymmetric momentum acceptance**
  - horizontal aperture at MBB-QD transition is critical (see Verena's presentation)



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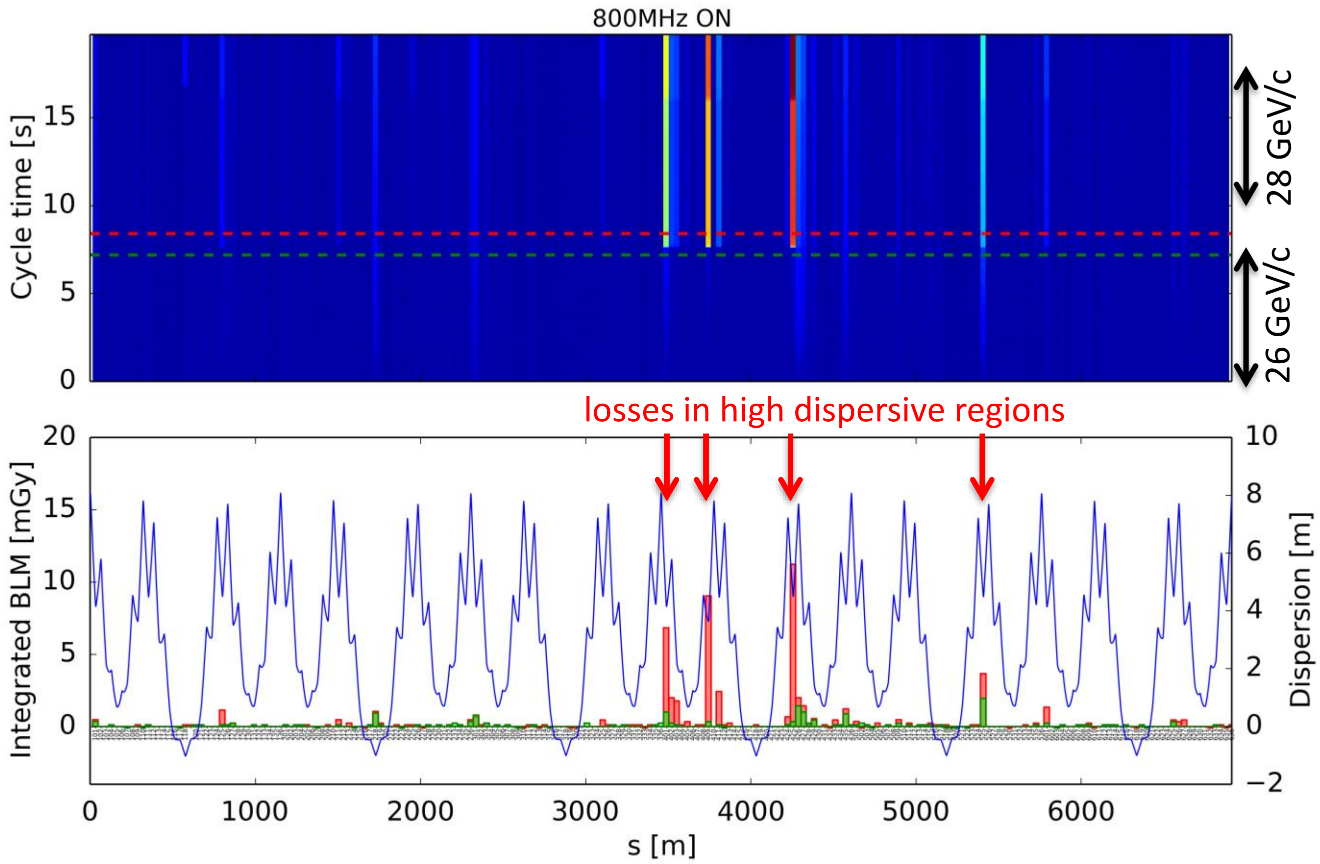
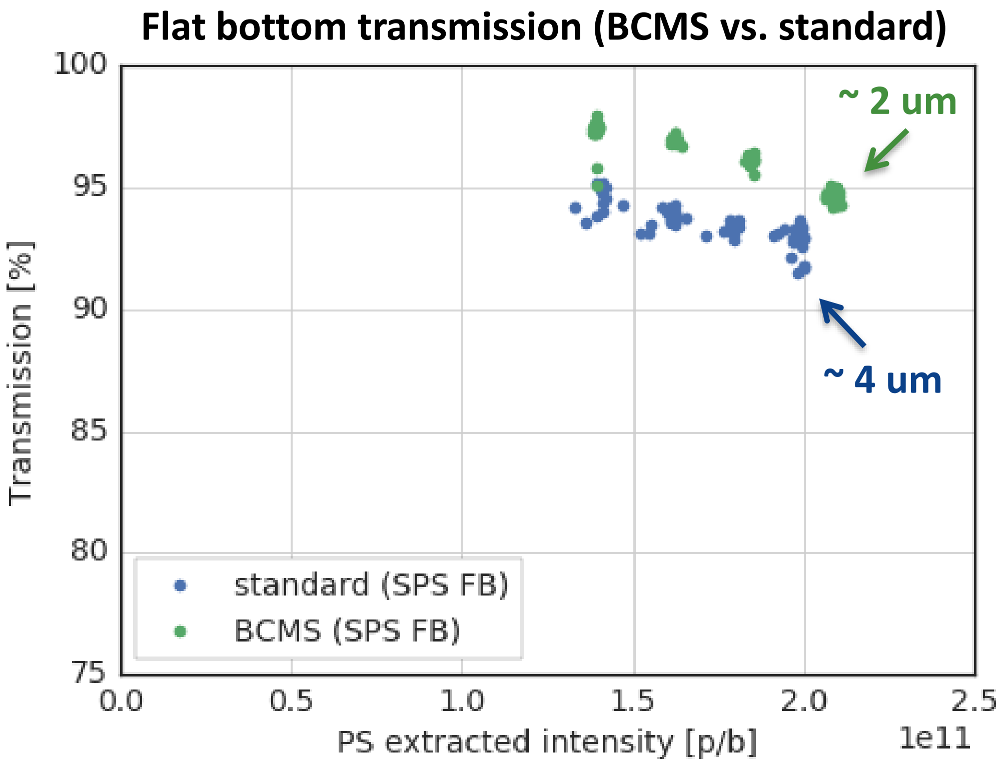
- **Flat bottom losses concentrated in high dispersive (QD) regions of the machine**



Momentum acceptance

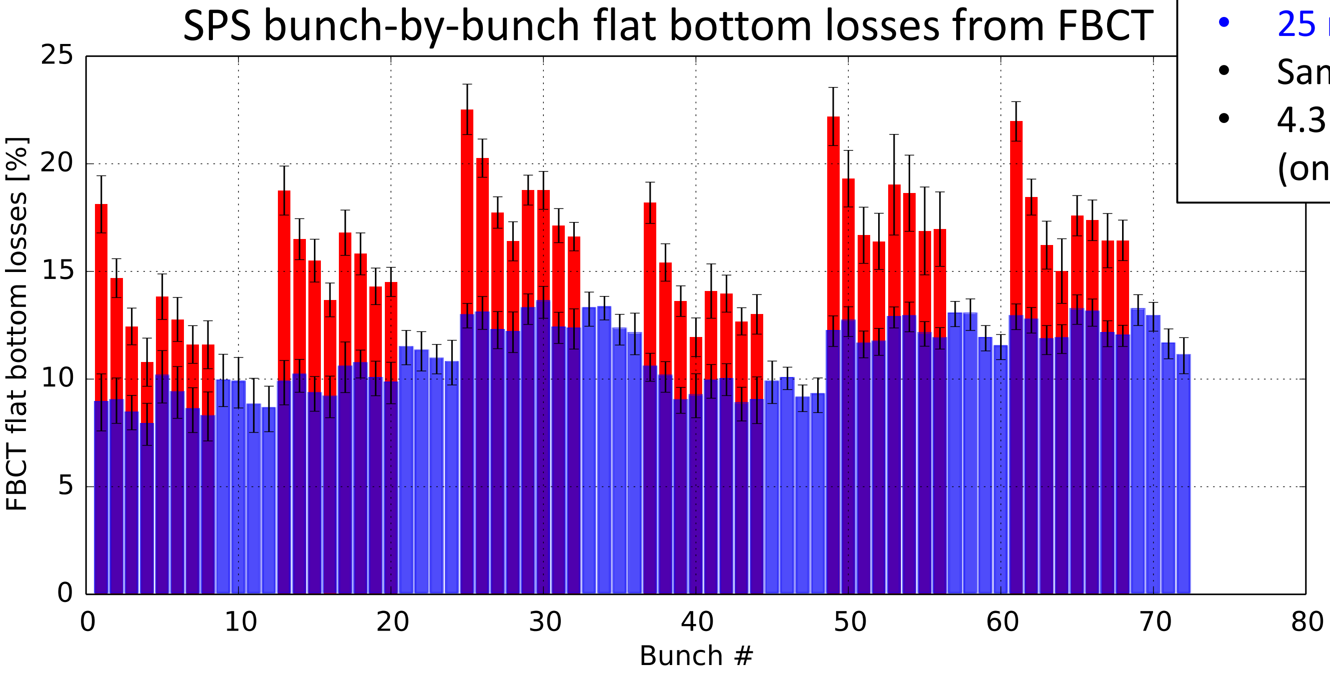
- **Radial steering revealed asymmetric momentum acceptance**
  - horizontal aperture at MBB-QD transition is critical (see Verena's presentation)
- **Flat bottom losses concentrated in high dispersive (QD) regions of the machine**
- **Flat bottom transmission improves for smaller horizontal emittance**



Therefore studies in second half of 2017 were performed with BCMS beam (similar brightness as LIU beam post-LS2)

Losses increasing with intensity not e-cloud

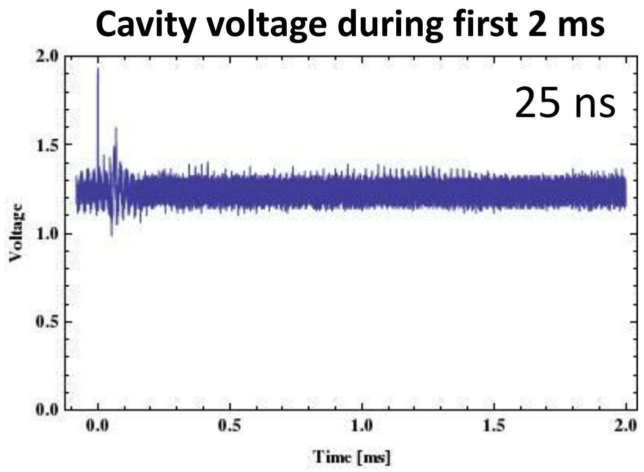
- **Direct comparison of 8b4e vs. 25 ns standard beam**
  - 8b4e bunch intensity about 3/2 compared to 25 ns beam (same total intensity)
  - Relative losses for 8b4e also about 3/2 higher compared to 25 ns beam
  - No e-cloud expected for 8b4e → **e-cloud not the main driver for increasing losses with intensity (more likely due to RF hardware limitations at least for 8b4e)!**

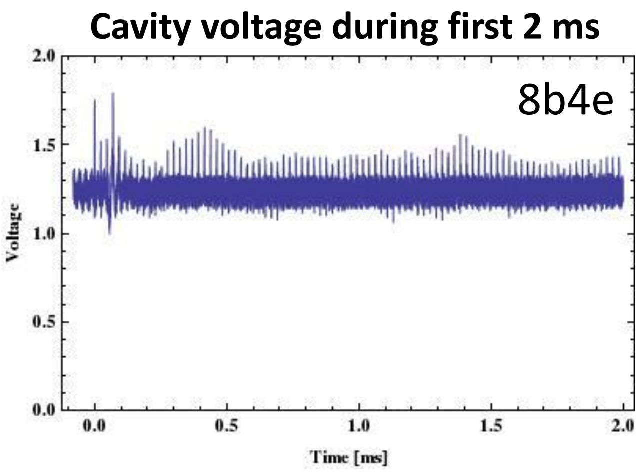


- 8b4e – 48 b. (~1.8e11 p/b inj.)
- 25 ns – 72 b. (~1.3e11 p/b inj.)
- Same total intensity
- 4.3 ns bunch length at injection (one 40 MHz cavity in PS)

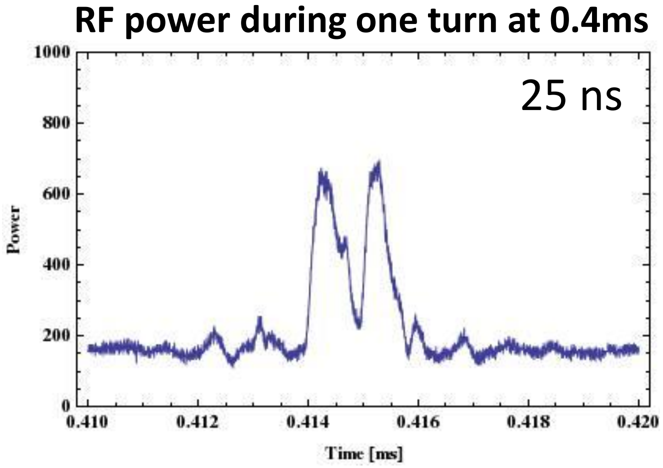
RF hardware limitations

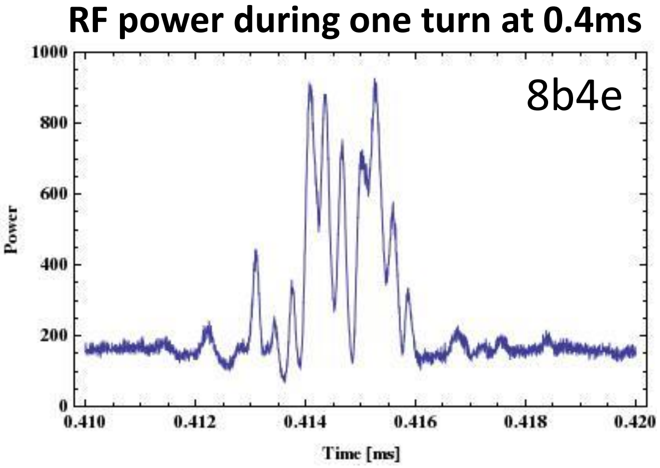
- Imperfect beam loading compensation, especially for 8b4e beam (bunch pattern)





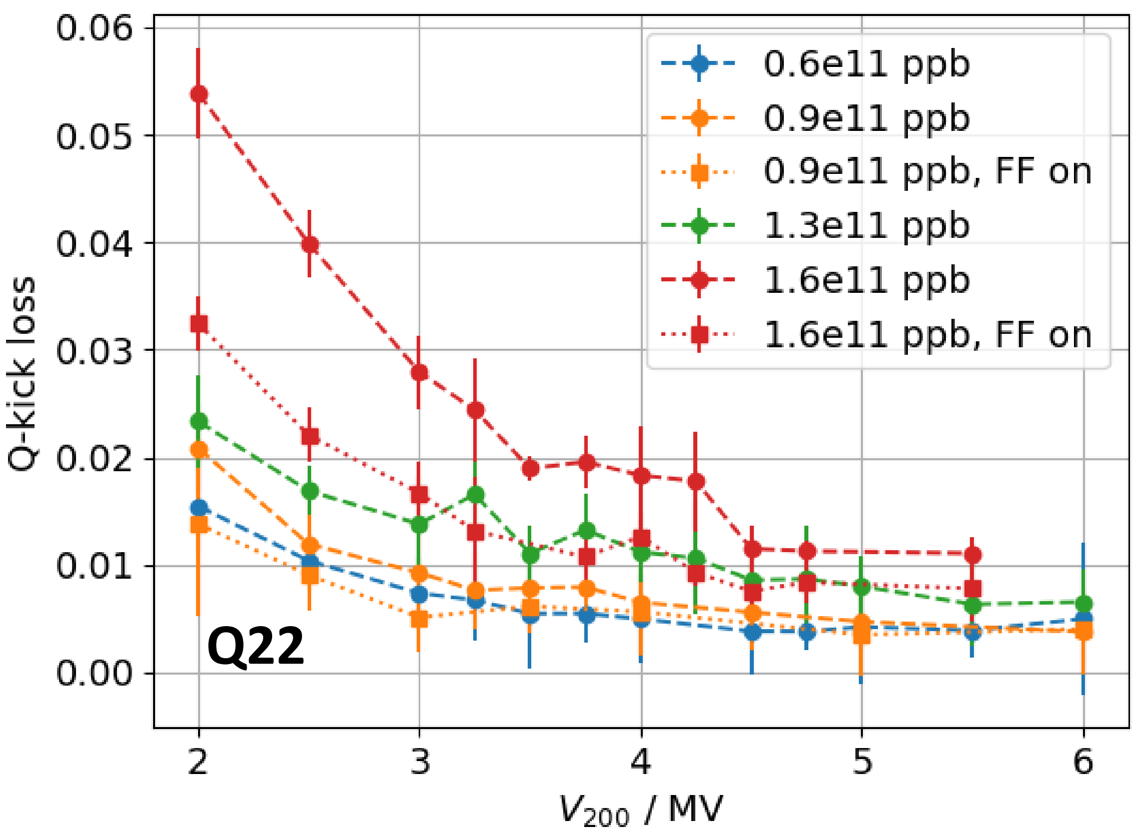
- RF power limitations with present SPS RF system





PS long. distribution vs. SPS intensity effects

- **Recent studies aiming at resolving the outstanding question if the losses with intensity are mostly driven by beam degradation in PS or by SPS intensity effects**
  - Measurement of un-captured beam as function of intensity and SPS RF settings
  - More details in Markus' presentation



Summary & Conclusions

- **Present understanding of losses in SPS**
  - Main contribution to losses from longitudinal effects
  - Capture losses mostly due to longitudinal distribution after bunch rotation in PS (transfer from 40 MHz to 200 MHz buckets …) and RF transients during first few ms in SPS
  - Minimizing capture losses by increasing RF voltage in SPS is limited due to a) unmatched distribution results in larger longitudinal emittance b) momentum acceptance and c) RF voltage for maintaining bucket area during the ramp
  - Losses out of bucket on SPS flat bottom due to particles close to separatrix (full bucket)
  - Minor contribution from e-cloud effects

- **Losses at SPS injection / flat bottom strongly coupled to PS intensity limitation**
  - PS fights with longitudinal instabilities and would profit from larger longitudinal emittance
  - SPS losses increase with longitudinal emittance

- **Open questions**
  - Why losses increase with intensity? Beam quality from PS degrading or intensity effects in SPS?
  - What is the main driving mechanism for losses out of SPS RF bucket on flat bottom?
  - Do transverse effects play an important role for flat bottom losses (concerning “good” particles)?
  - Will the SPS RF upgrade reduce losses in SPS for high intensities (e.g. due to better beam loading compensation with more RF power)?

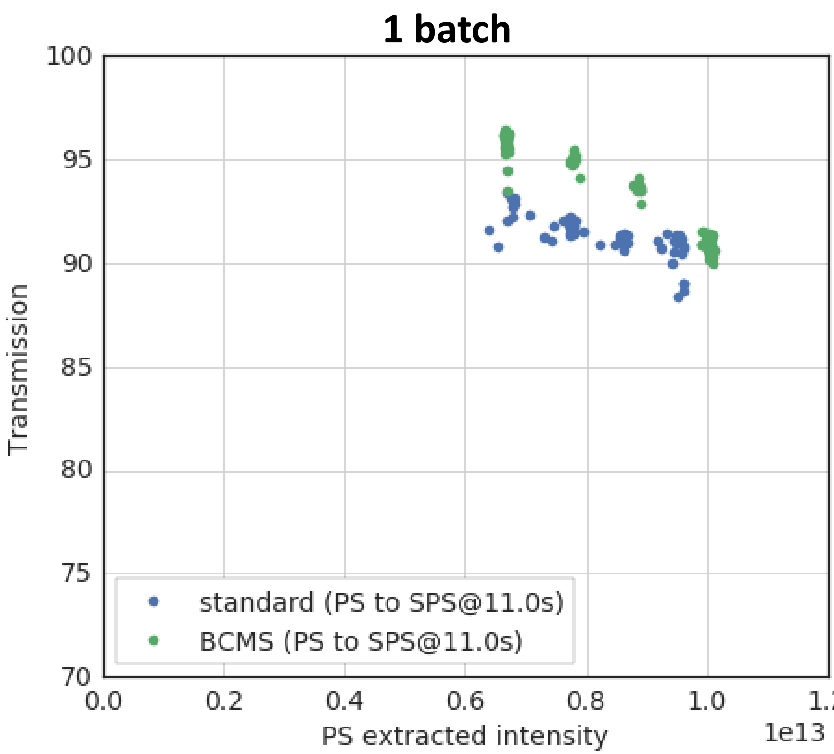
LHC Injectors Upgrade

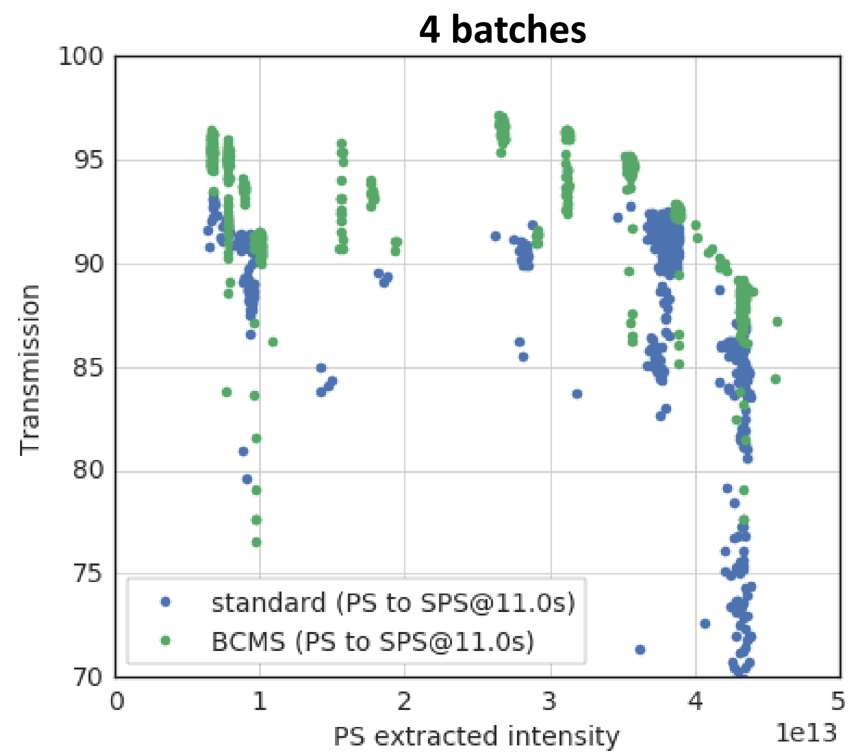
Thank you for your attention!

CERN

Transmission – BCMS vs. standard 25 ns

- **Measurements from Monday, batches of 48 bunches for both beams**
  - Generally transmission is quite OK
  - Transmission of BCMS beam better than 25 ns standard due to smaller (horizontal) emittance
  - The transmission from PS to SPS is degrading with intensity for BCMS





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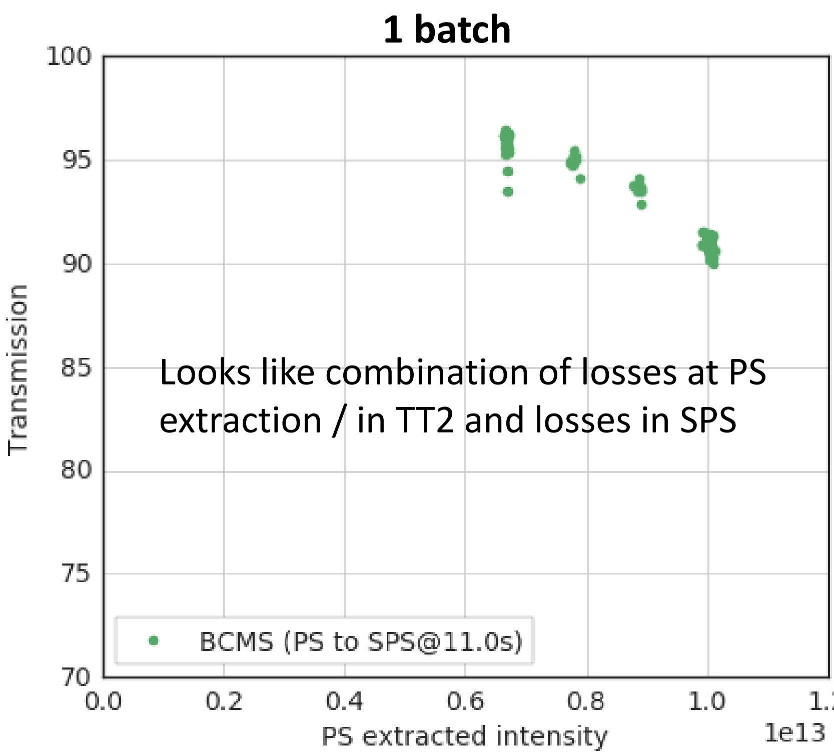

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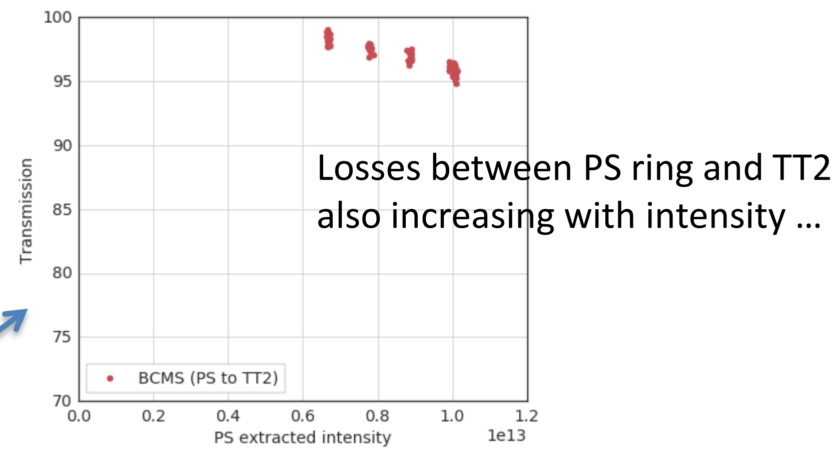

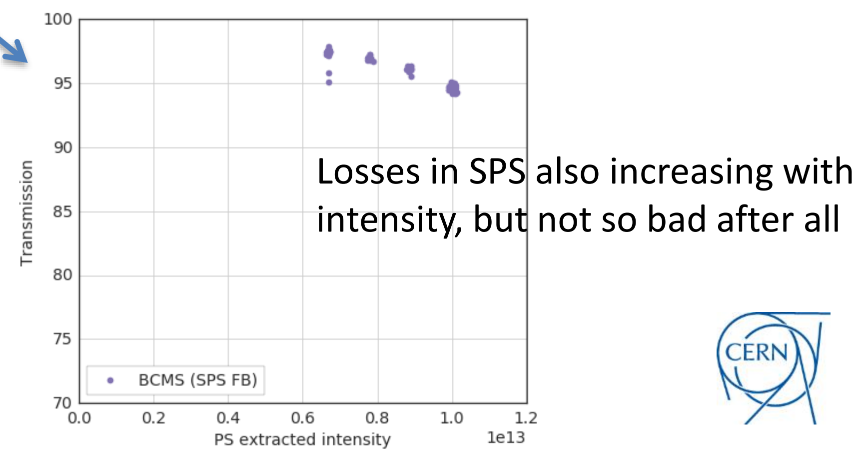

Cleaning of un-captured beam with Q-kicker

- **BCMS beam on special MD cycle (6 bp flat bottom + ramp to 28 GeV/c plateau)**
  - 48 bunches, ~1.35e11 p/b injected, 4 ns bunch length at injection
  - Vertical tune kicker on empty part of circumference for cleaning un-captured beam
  - Flat bottom losses enhanced with 800 MHz (V=1/10 of 200 MHz), no impact on total transmission
  - **3.5% losses due to uncaptured beam, 2% losses at start of acceleration, 1% at 28 GeV/c**