PS beam injected into SPS: measurements and simulations

SPS injection losses review 30/11/2017

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CPS operators, SPS operators, MD coordinators, BLonD dev team

Outline

- Introduction
- Improvement of the bunch rotation
  - Linearization of the RF voltage
- Characterization of the bunch distribution (core and tails)
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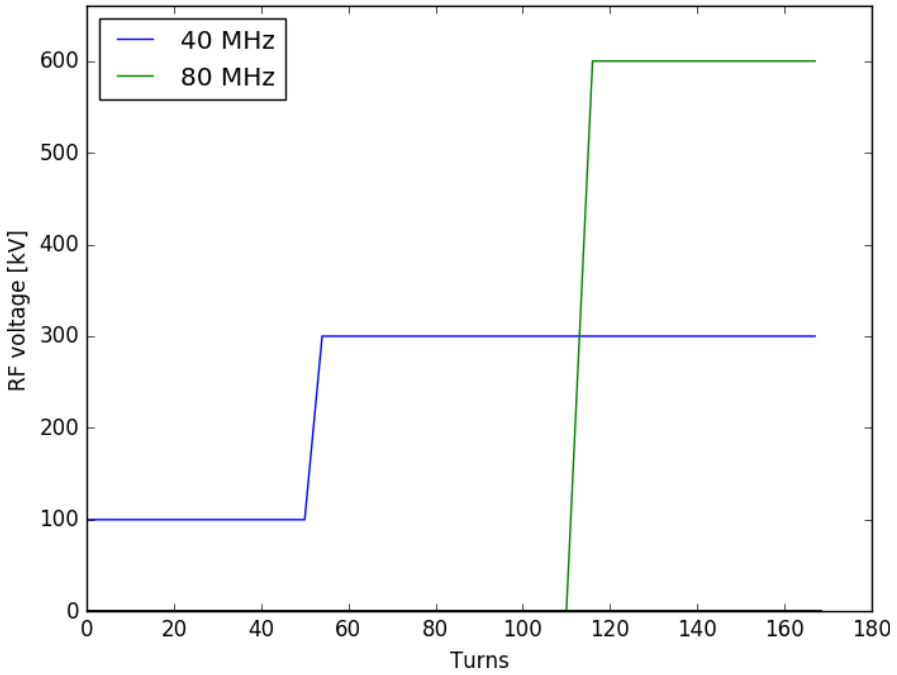
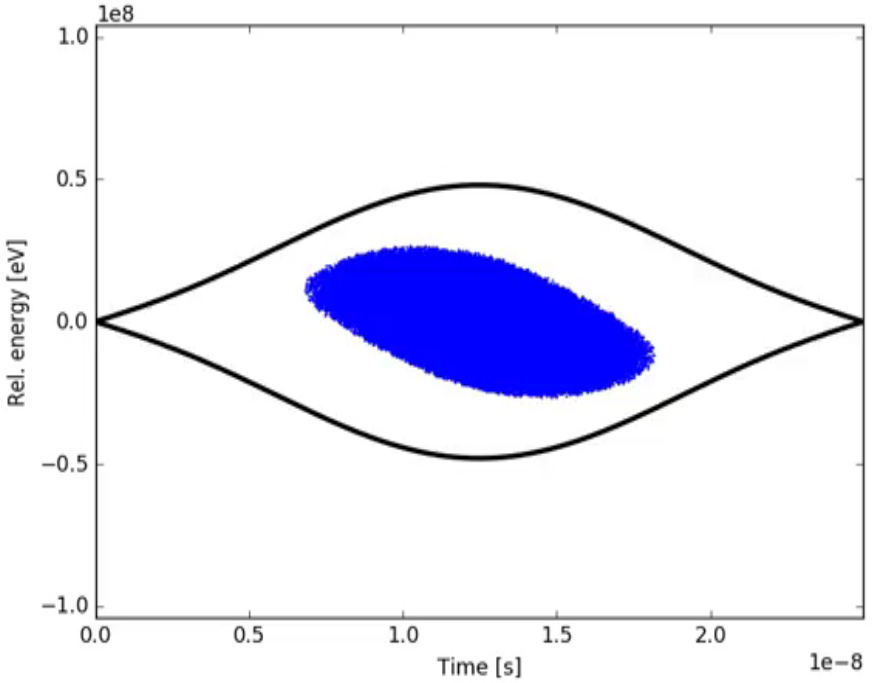
  - Post-acceleration and longitudinal shaving
- Intensity effects and emittance degradation
  - Emittance blow-up during splittings
- Conclusions

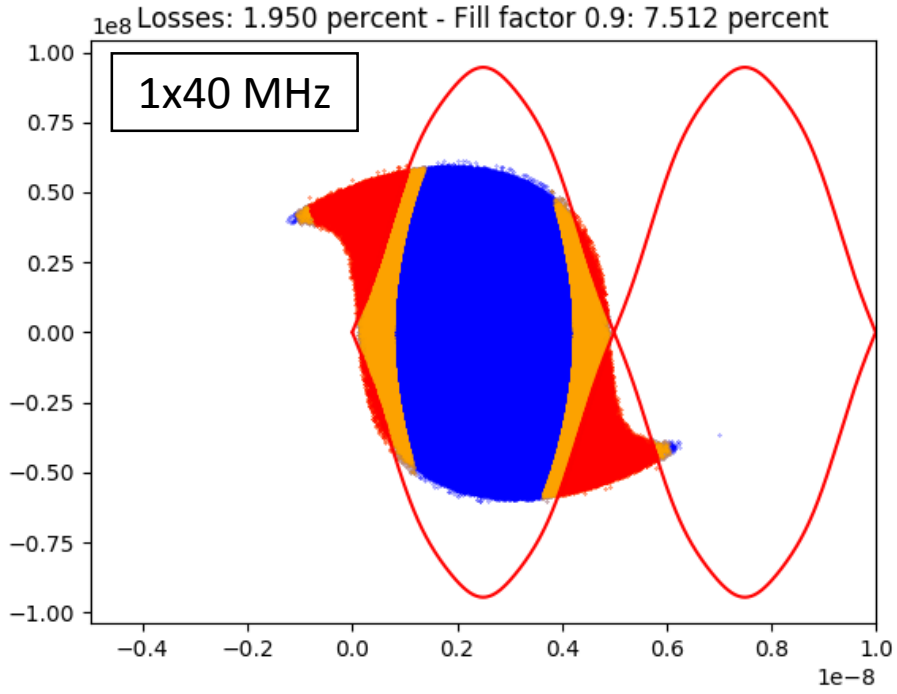
Introduction

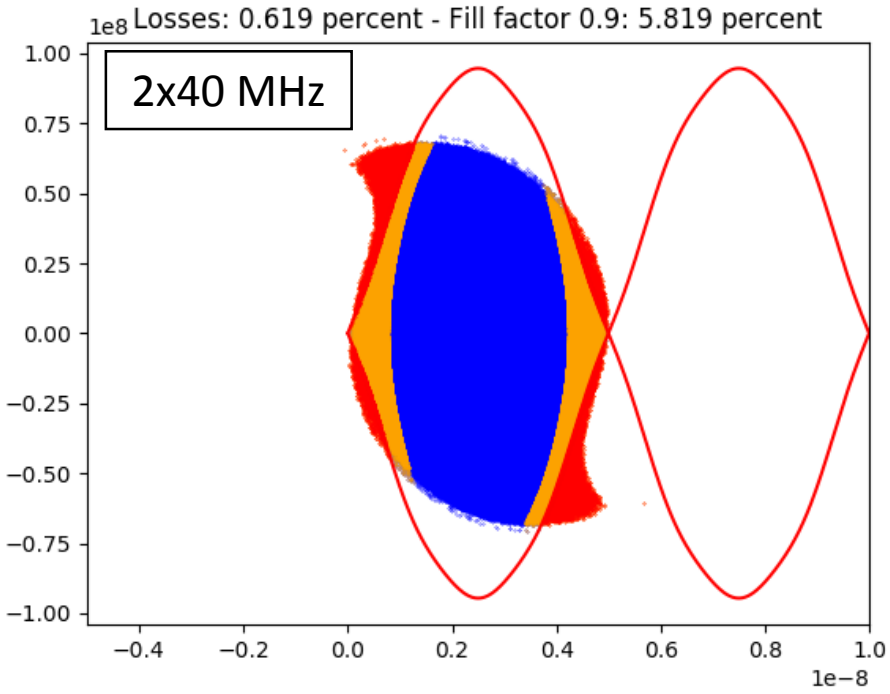




- The PS bunches after splittings are too large to fit in the SPS RF bucket
  - 16 ns bunch length for 5 ns SPS RF bucket length
- Bunch shortening performed to reduce bunch length by factor 4 before extraction
- Fast voltage increase in two steps using 1x40 MHz cavity and 2x80 MHz cavities (bunch rotation, [1] R. Garoby)

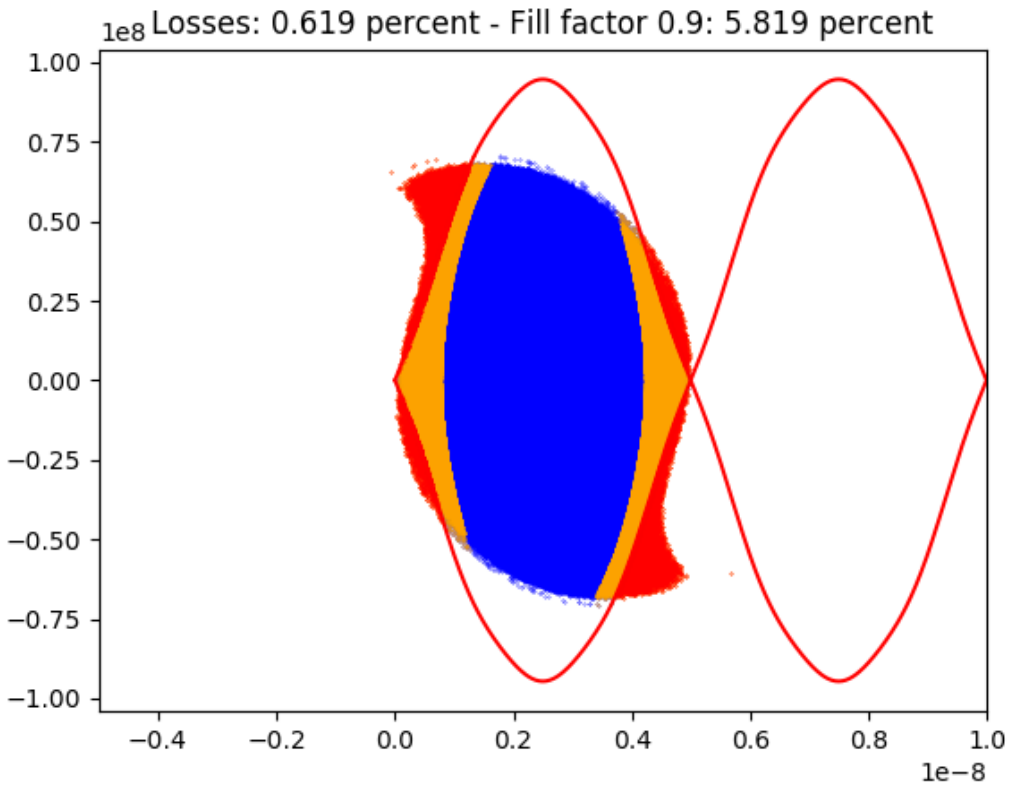
Introduction





- Studies were performed in 2013 showing that losses could be reduced by ~2% by using 2x40 MHz cavities for the bunch rotation ([2] H. Timko et al.)
- In 2016/2017, the spare 40 MHz cavity was put in operation to reduce the losses
- For high intensity, still large losses in the SPS so studies were continued to further improve the PS beam

Definition of losses



SPS RF bucket (double RF):

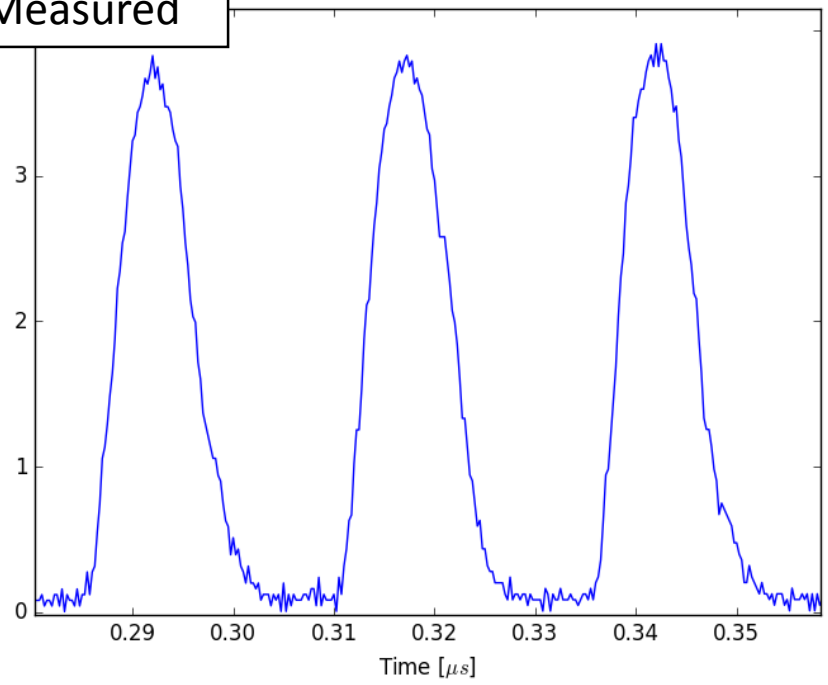
$V_{200} = 4.5$ MV

$V_{800} = 0.45$ MV

- Blue: particles captured in SPS
- Orange: Particles inside the RF bucket but too close to separatrix, criterion set to $\Delta E/E = 0.9$ filling factor
- Red: Uncaptured particles, drifts from the main beam at injection

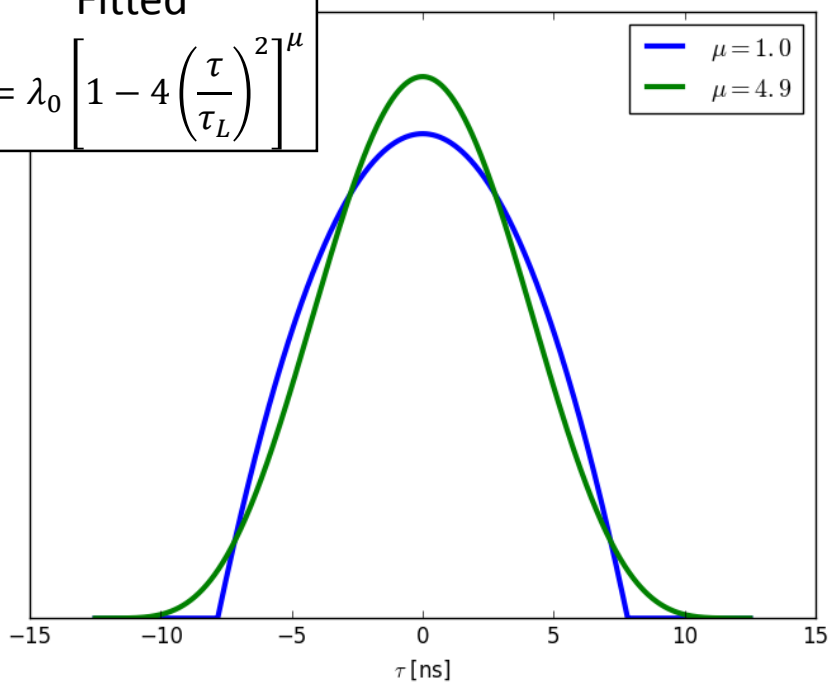
Initial bunch distribution

Measured



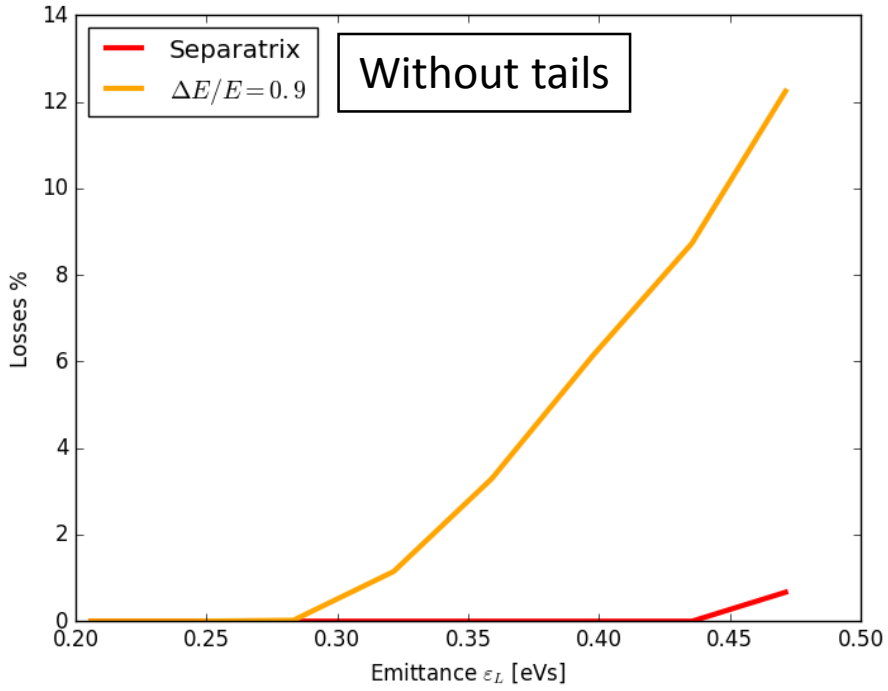
Fitted

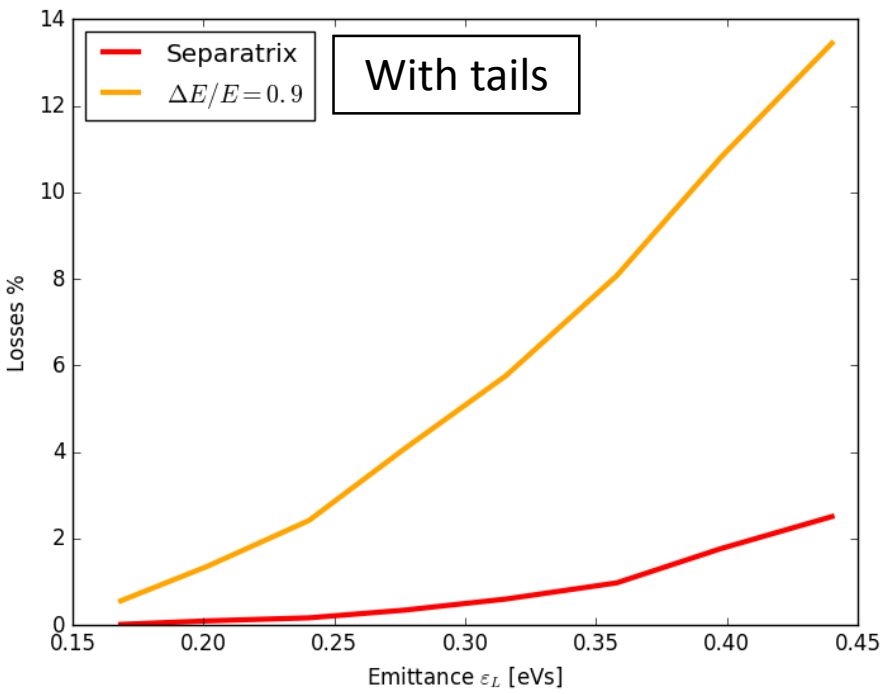
$$\lambda = \lambda_0 \left[1 - 4\left(\frac{\tau}{\tau_L}\right)^2\right]^{\mu}$$



- Starting from measured rms bunch length before bunch rotation
- Difficult to evaluate tail distribution from measured bunch profiles
- Using the binomial bunch profile with same rms bunch length but different μ to evaluate influence of tails for the losses

Influence of tails on losses





- Simulations performed for the present RF program, with different tails for the initial bunch distribution
- Without tails, below a certain emittance all particles are captured in the SPS. With tails, the bunch is never fully captured
- Overall, losses strongly depend on the longitudinal emittance

Improvement of the bunch rotation

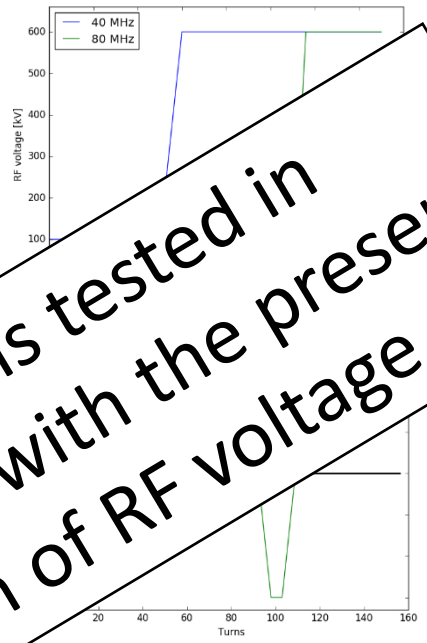
Present operation	2x80 MHz	3x80MHz
τ_L	4.0 ns	3.6 ns
ρ_{in}	97.2 %	98.7 %

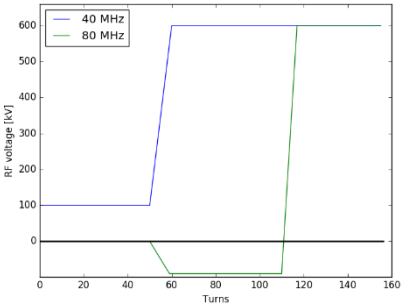
Unstable point	2x80 MHz	3x80MH
τ_L	3.9 ns	
ρ_{in}	97.4 %	

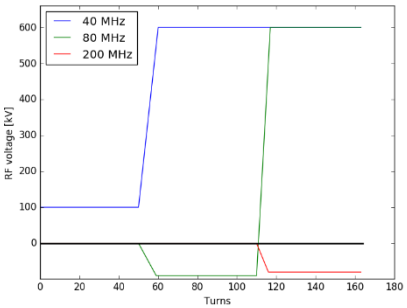
Linearized RF 1 step		
τ_L		
		99.2 %

Linea	x80 MHz	3x80MHz
	4.0 ns	3.6 ns
ρ_{in}	97.9 %	99.6 %

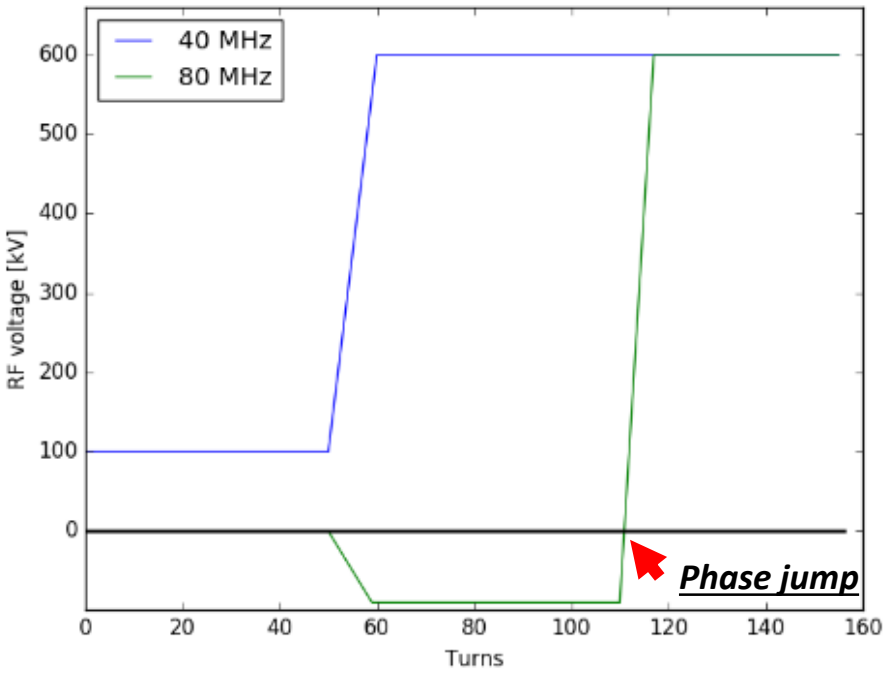
Many different configurations tested in simulations, only one possible with the present hardware -> Linearization of RF voltage

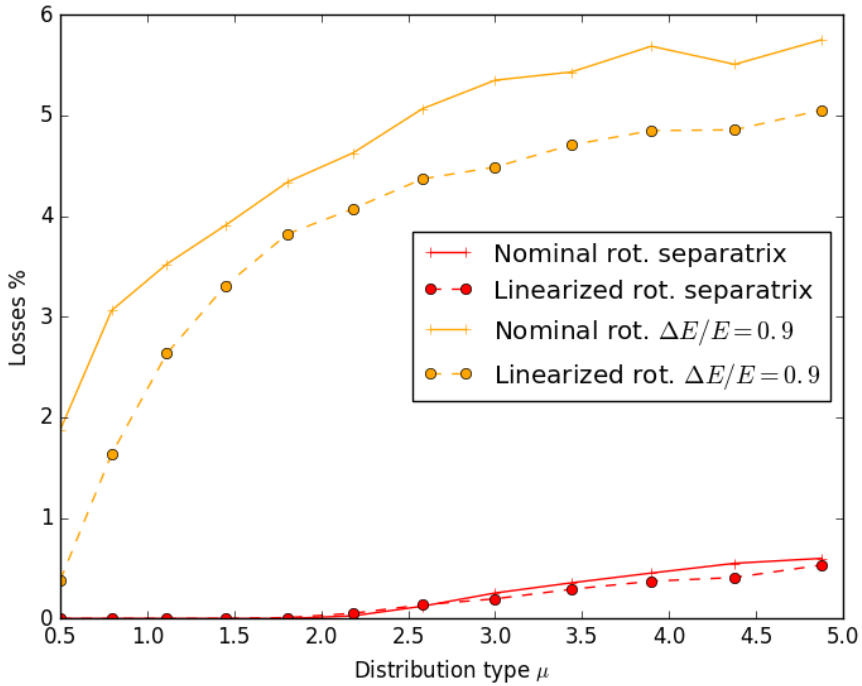






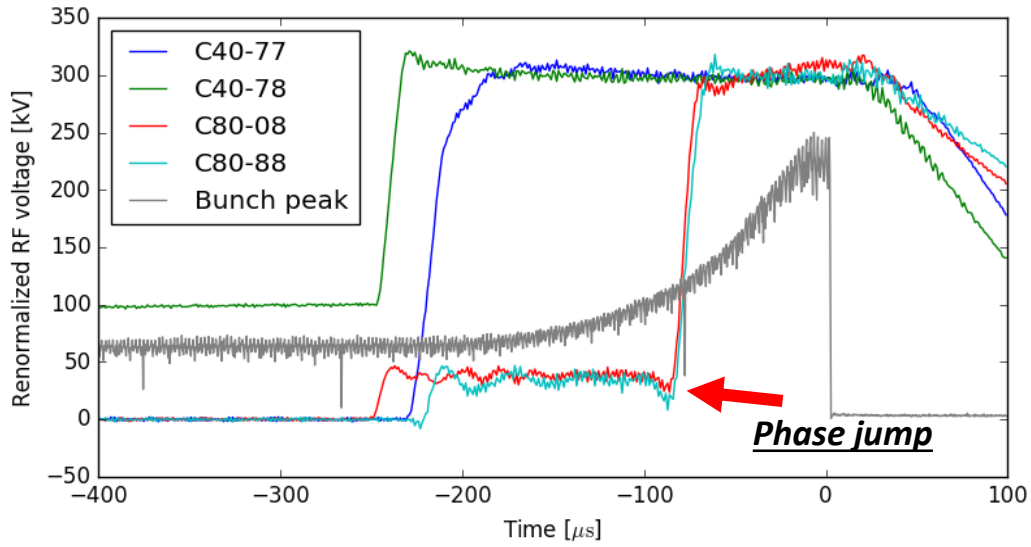
Linearization of the RF voltage (simulations)



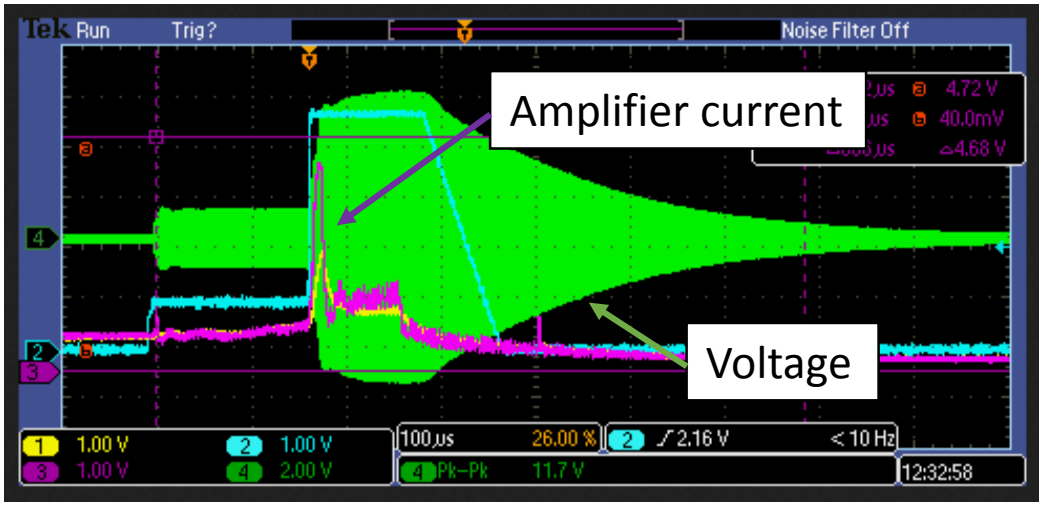


- To reduce the S-shape of the rotated bunch, the RF voltage can be linearized by a higher harmonic ([3] R. Garoby)
- Requires a fast phase jump of the 80 MHz cavity
- The linearization of the RF voltage can be very effective for bunches without tails, but less efficient for large tails

Implementation of the linearized RF program

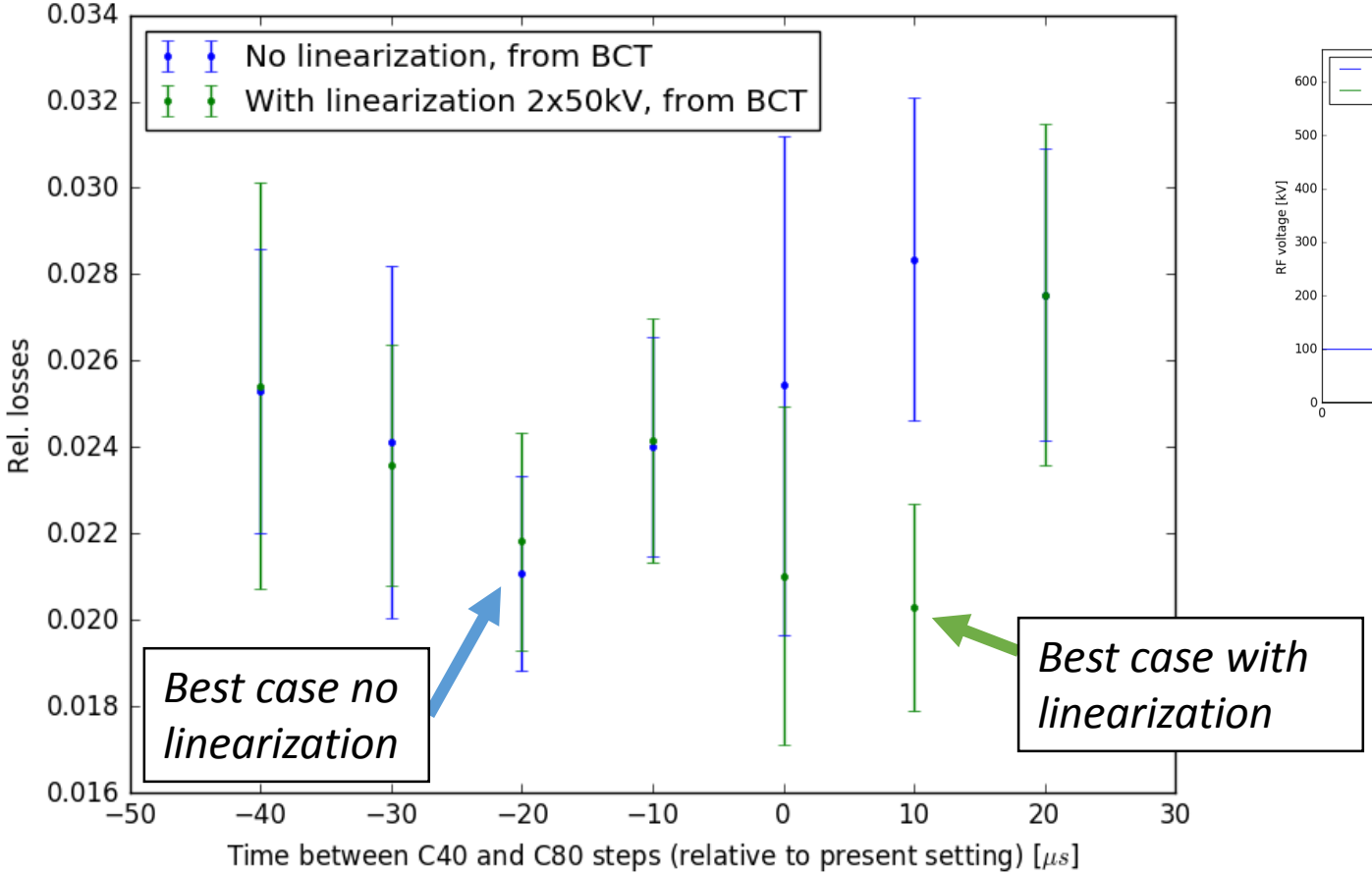


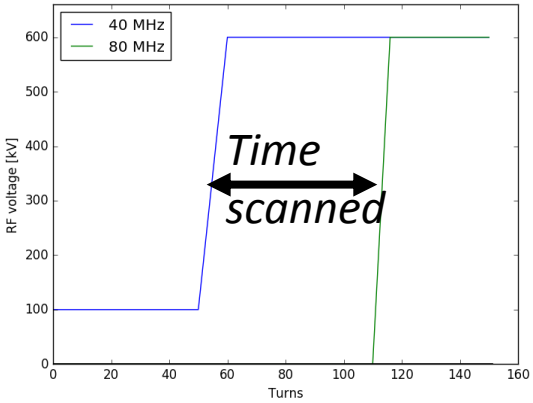
- The low-level RF was adjusted to control the phase of the 80 MHz cavities (addition of a fast phase shifter module)



- The phase jump can be done only for low voltage (e.g. ~50 kV)

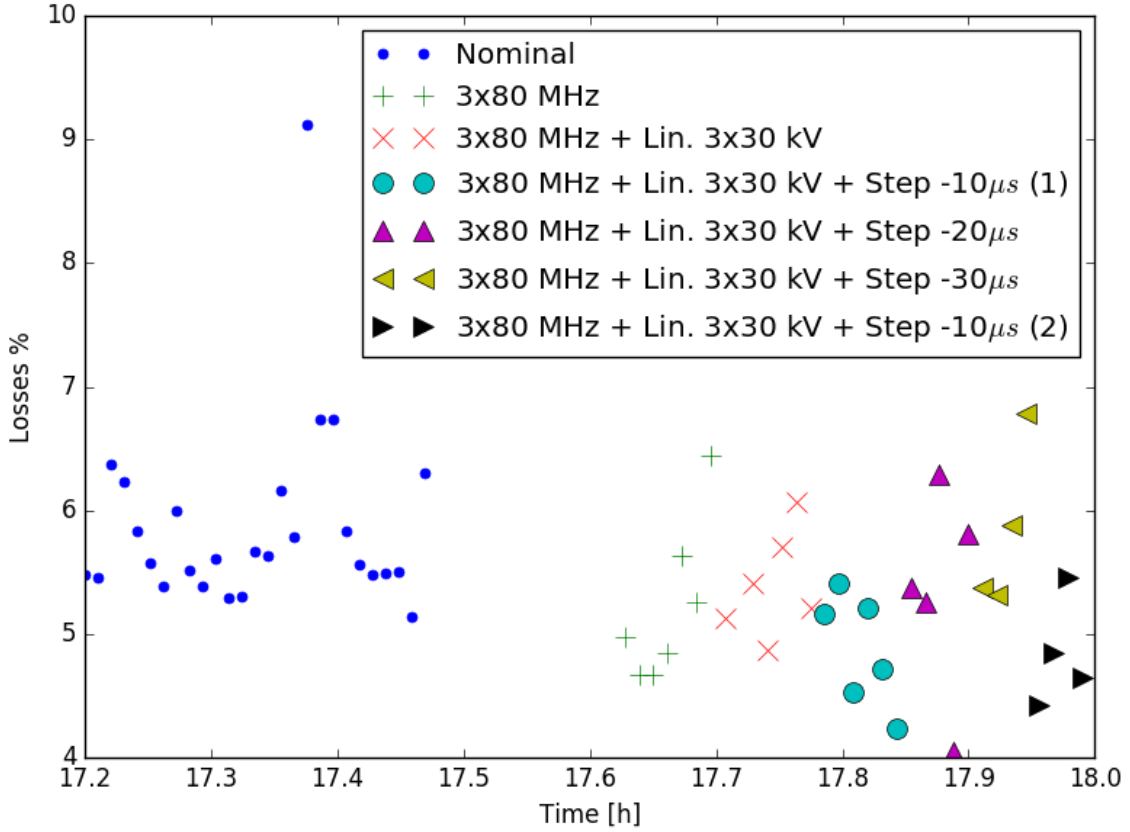
Scan of bunch rotation timings





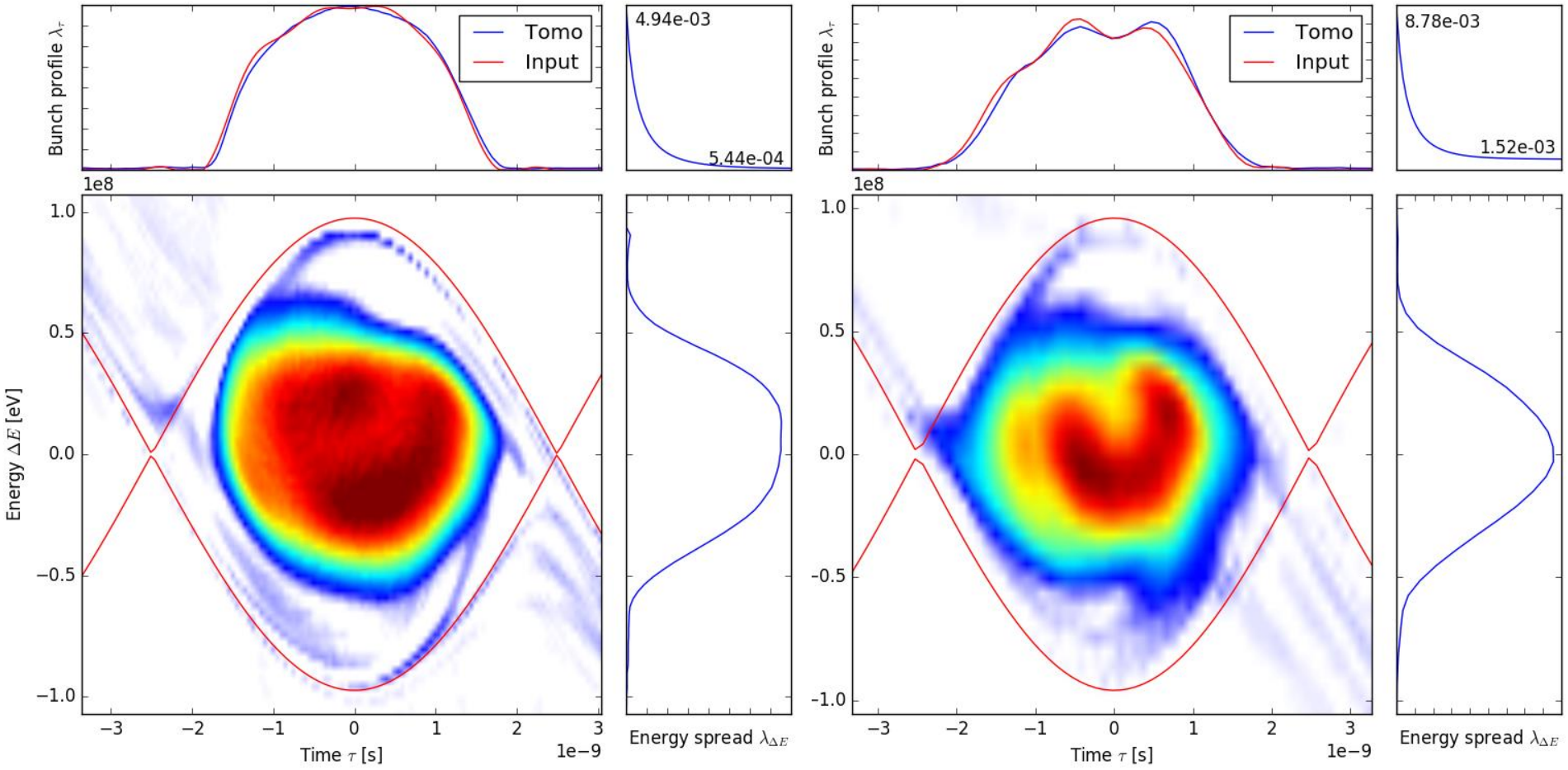
- The effect of the linearization on the losses is small, and the shot to shot variation is large
- The program with the linearization is very sensitive to adjustment errors in the phase of the cavities

Using 3x80 MHz cavities for rotation



- The gain is in the order of ~1% in terms of losses with respect to the nominal configuration.
- The small gain in transmission is a first indication that losses comes from tails
- NB: the 3x80 MHz is not compatible with high intensity at the moment due to uncontrolled emittance blow-up

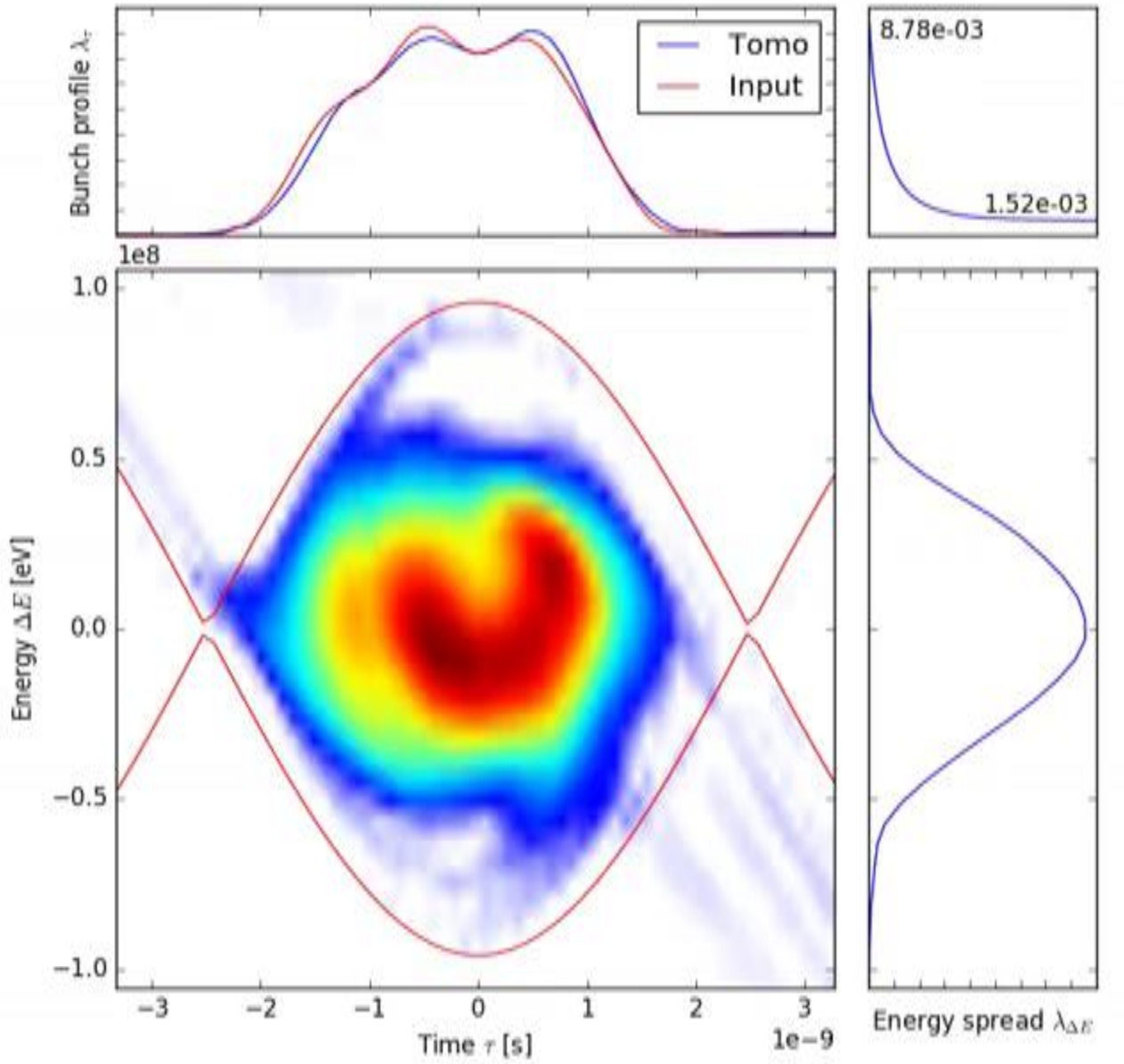
Tomography of bunches injected in the SPS



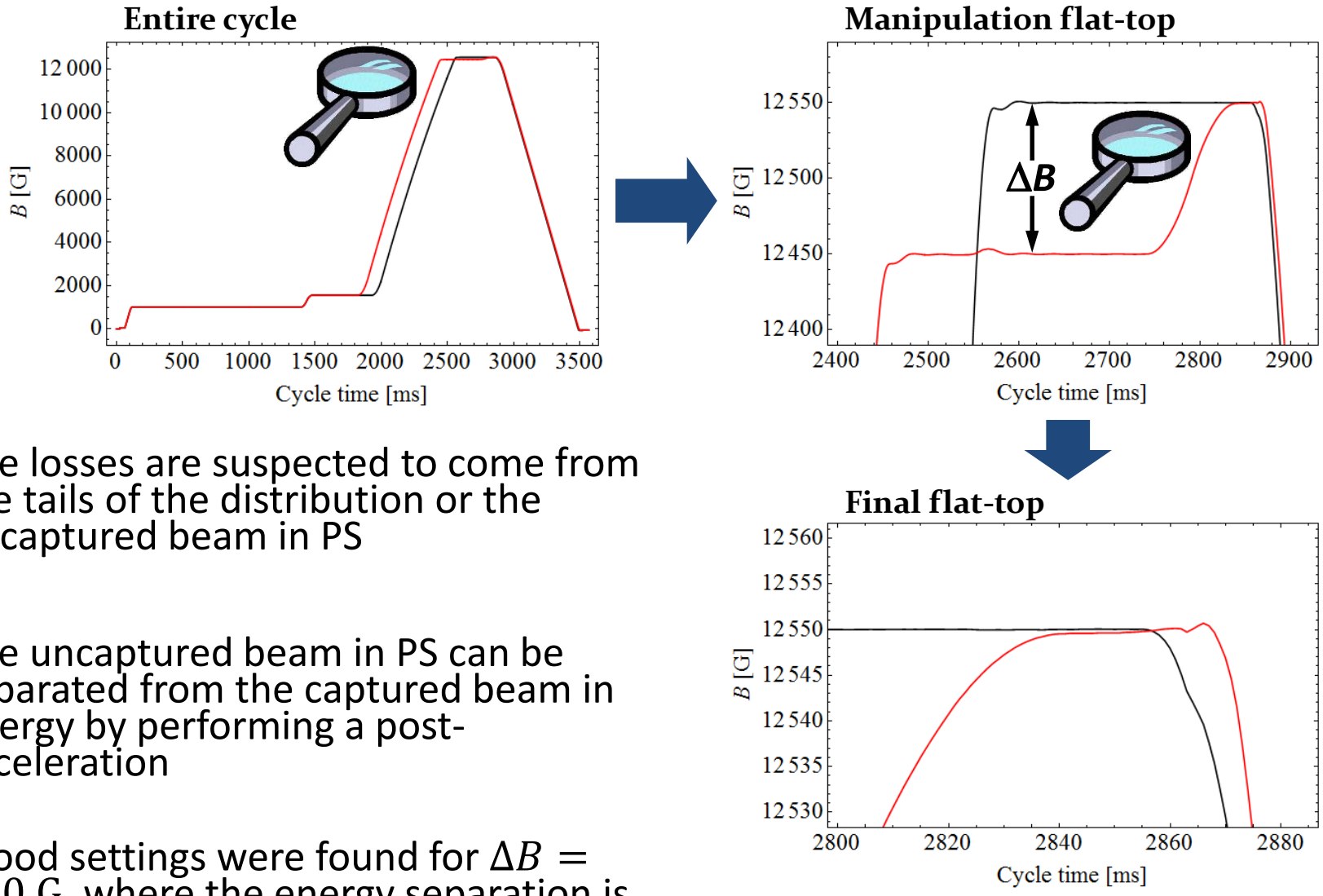
Single bunch: very dense

Multi bunch: more tails, core not very well structured

Tomography of bunches injected in the SPS

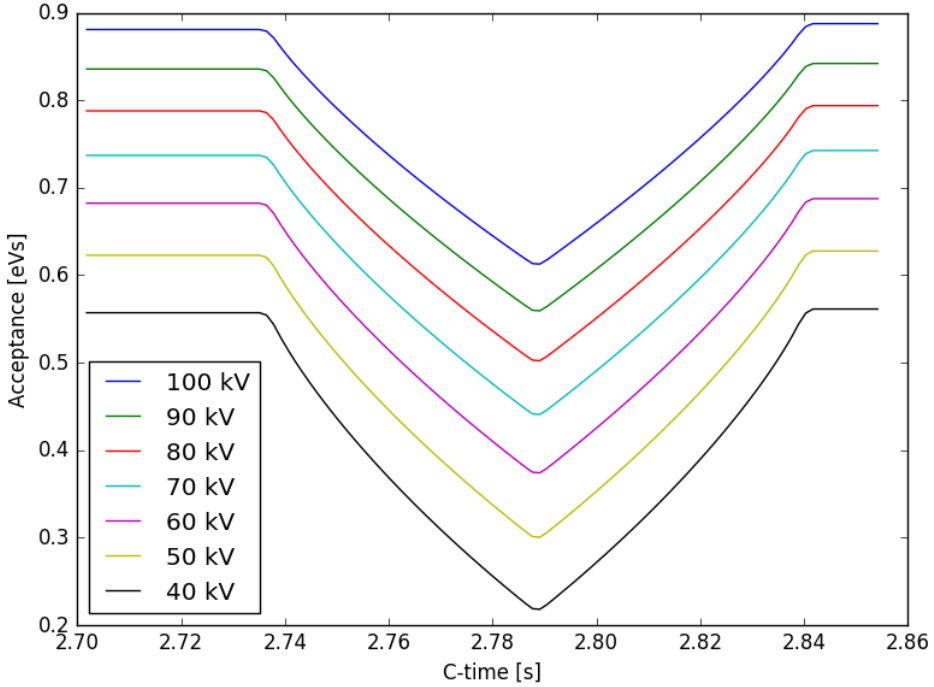


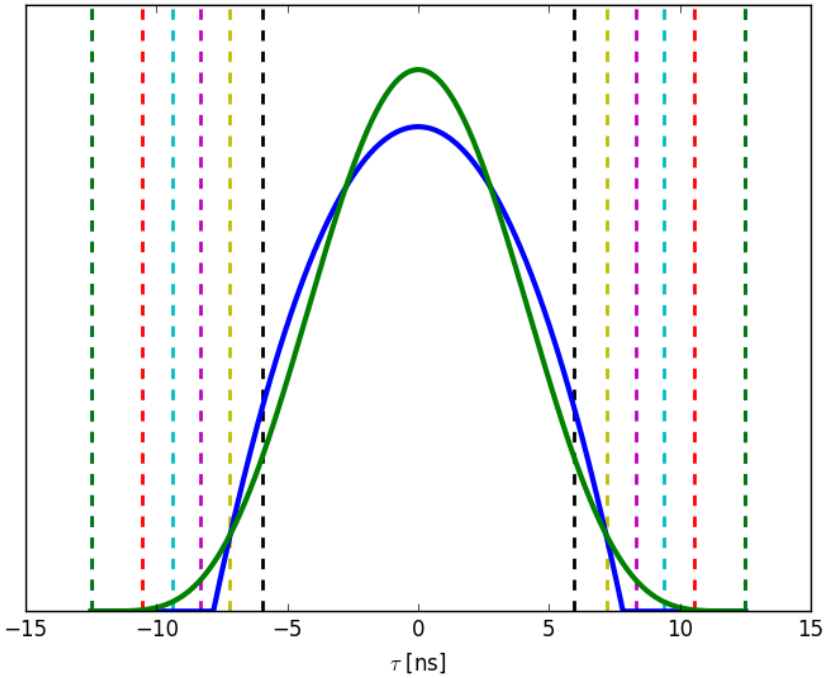
Post-acceleration



- The losses are suspected to come from the tails of the distribution or the uncaptured beam in PS
- The uncaptured beam in PS can be separated from the captured beam in energy by performing a post-acceleration
- Good settings were found for $\Delta B = 200$ G, where the energy separation is large (15 bucket heights) without scraping the beam (large orbit excursion)

Shaving during post-acceleration

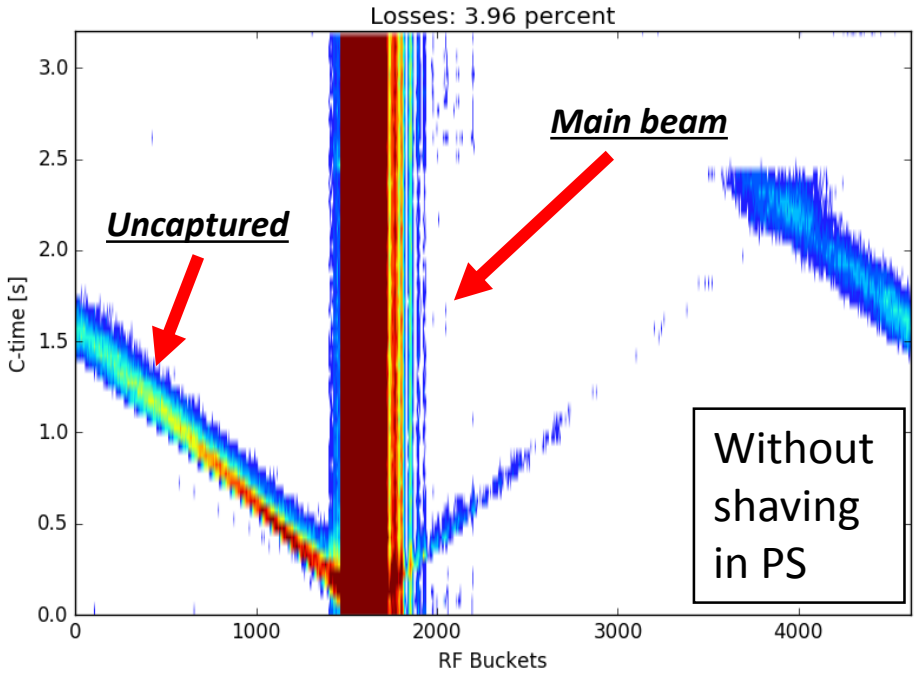


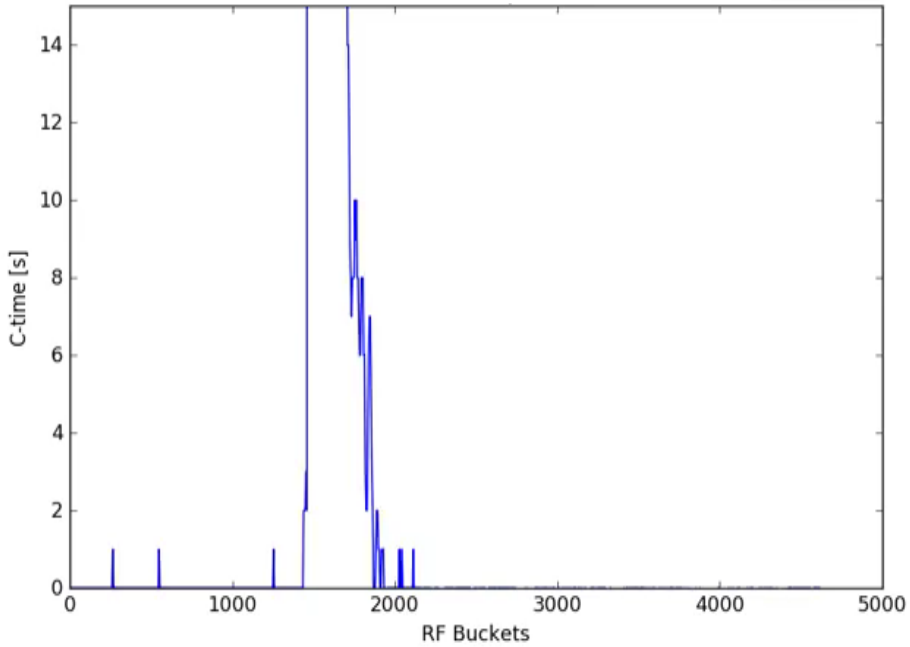


- The post-acceleration can also be used to shave the beam, by keeping the RF voltage constant (dip in longitudinal acceptance)

- Scanning the value of the RF voltage to find the optimum point where the tails are shaved and not the core of the bunch (longitudinal emittance is ~ 0.35-0.4 eVs, so ~50-60kV is expected to be the limit)

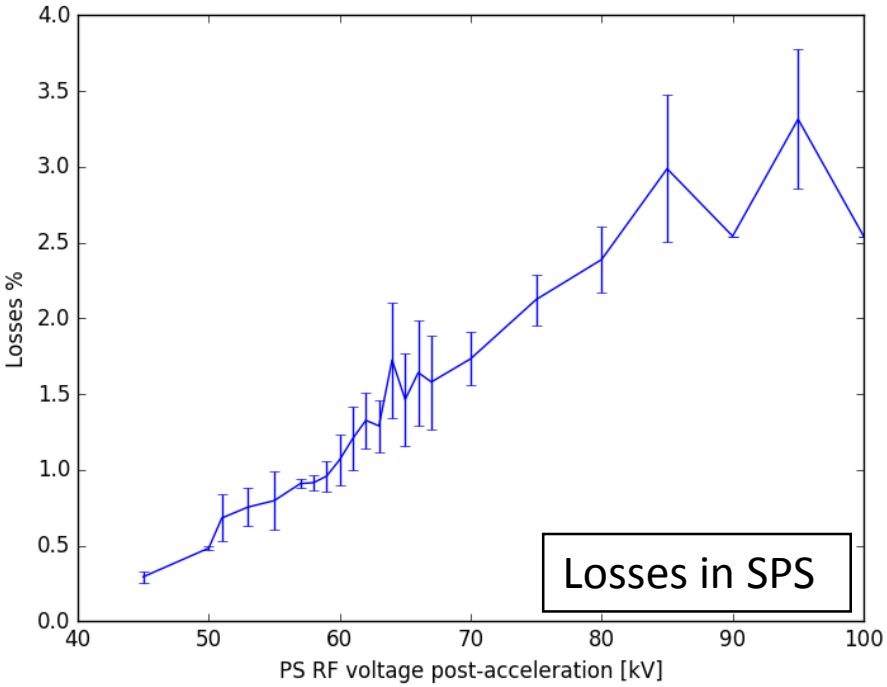
Shaving and capture losses in SPS

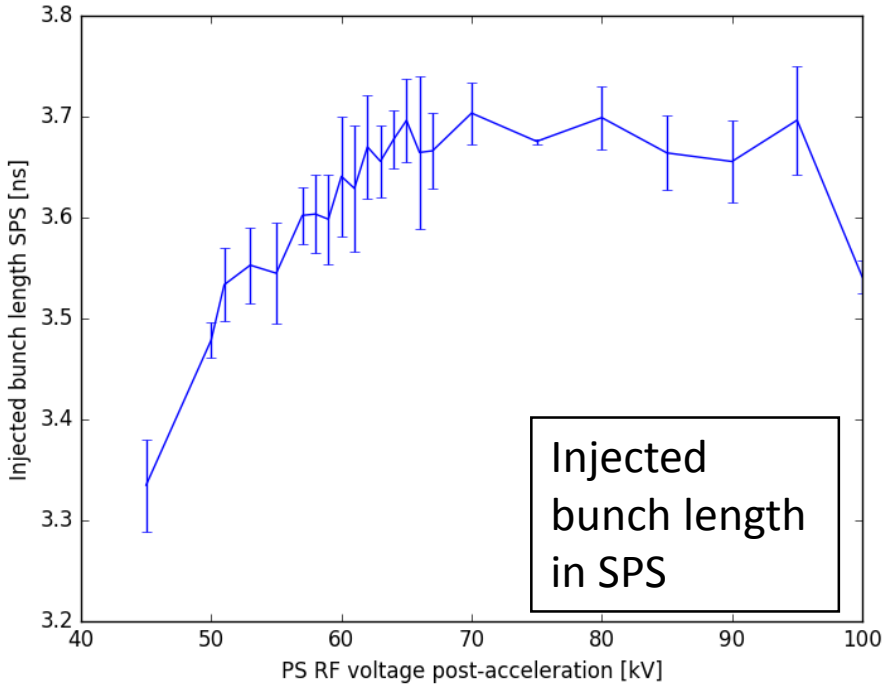




- The shaving during post-acceleration in PS is efficient and no uncaptured beam is measured in the SPS

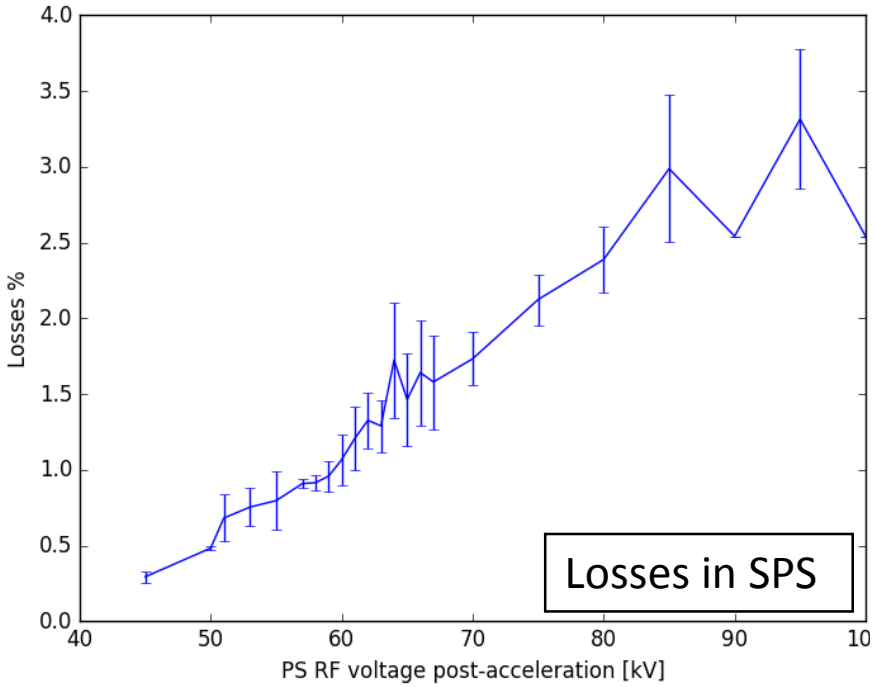
Injected bunch length and losses during ramp (SPS)

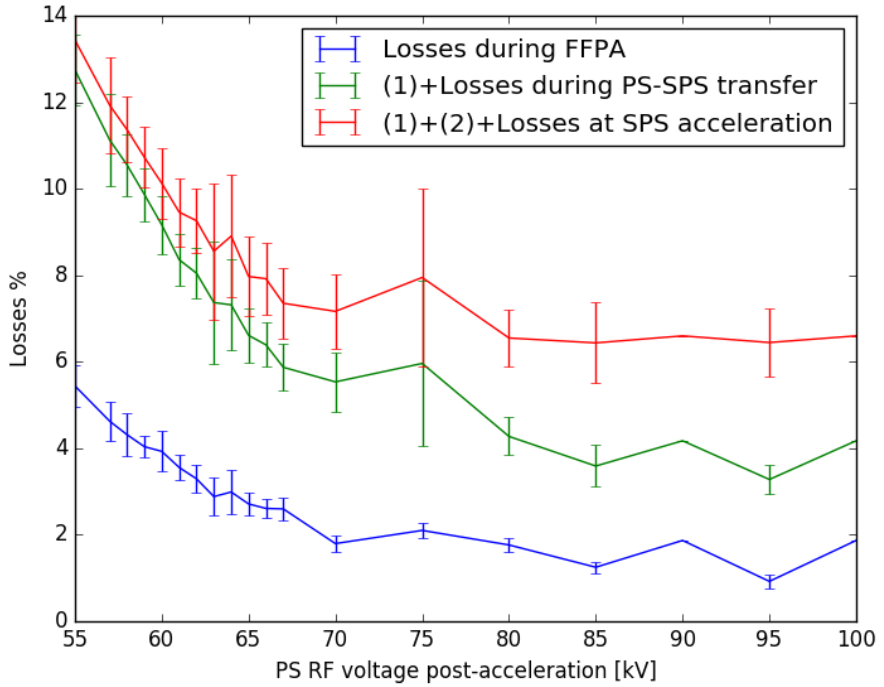




- Three regions of interest:
  - 70kV-100kV, the losses are reduced while the injected bunch length is unchanged => effectively shaving the tails only
  - 60kV-70kV, the tails are fully shaved, starting to shave the core
  - 40kV-70kV, the bunch length reduces, the core is also affected

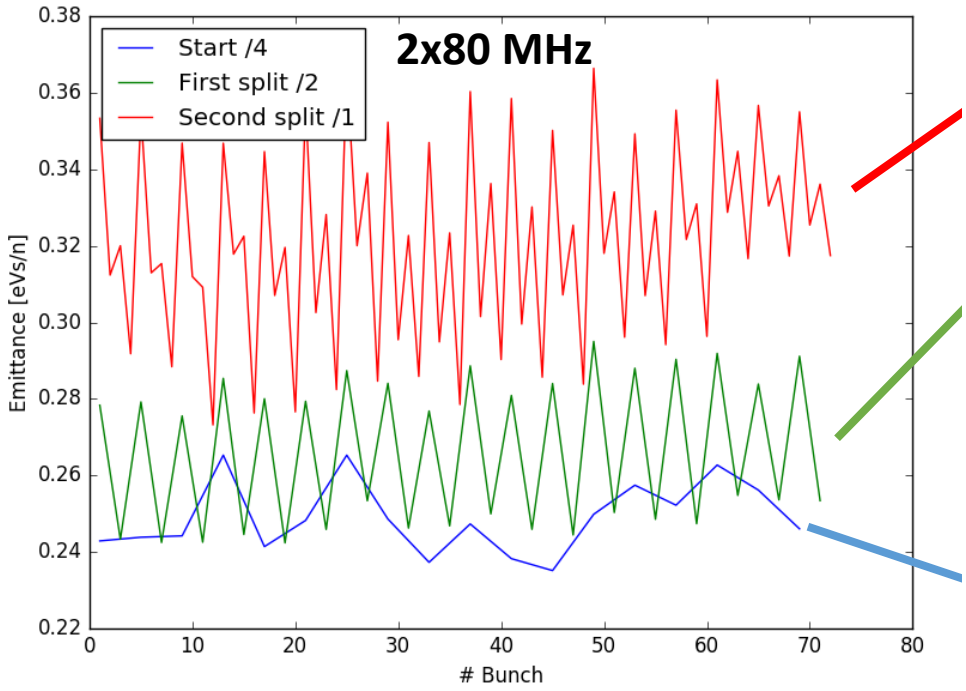
Injected bunch length and losses during ramp (SPS)

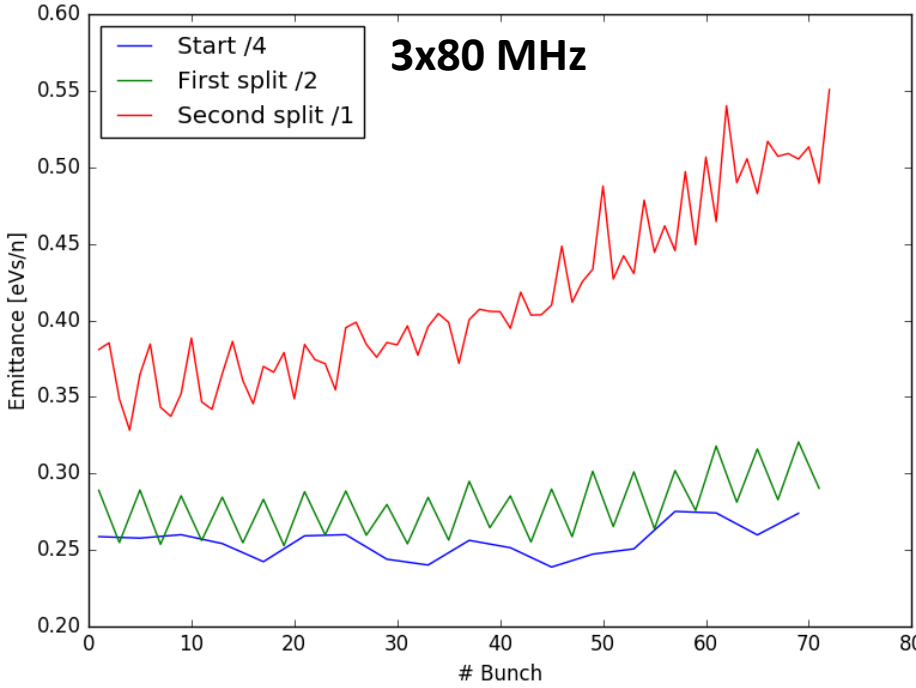




- Three regions of interest:
  - 70kV-100kV, the losses in the SPS and the tails are gradually lost in PS
  - 60kV-70kV, the tails are fully shaved, starting to shave the core and lose more in the PS
  - 40kV-70kV, the core starts to be shaved in the PS

Emittance blow-up during splittings





- Longitudinal emittance evaluated at different steps of the splittings
- Measured emittance blow-up during the double splittings for an intensity of $4 \times 2.0 \times 10^{11}$ ppb
- Longitudinal emittance blow-up along the batch during splitting with 3x80 MHz cavity gaps open
- The future Multi Harmonic Feedback should be a sufficient mitigation. Nevertheless, the sources of emittance blow-up should be minimized as much as possible (i.e. other impedance sources)

Conclusions

- Studies were performed to characterize and improve the extracted PS beam

- The tails of the PS bunch are the main contributors to the losses in the SPS

- Further improvement of the bunch rotation mainly targets the core of the bunch and is a limited solution to the problem as long as tails are the main contribution to losses

- It is necessary to minimize the sources of uncontrolled emittance blow-up, tail production and beam instability

References

[1] R. Garoby, A Non-Adiabatic Procedure in the PS to Supply the Nominal Proton Bunches for LHC into 200 MHz rf Buckets in SPS, PS/RF/Note 93-17

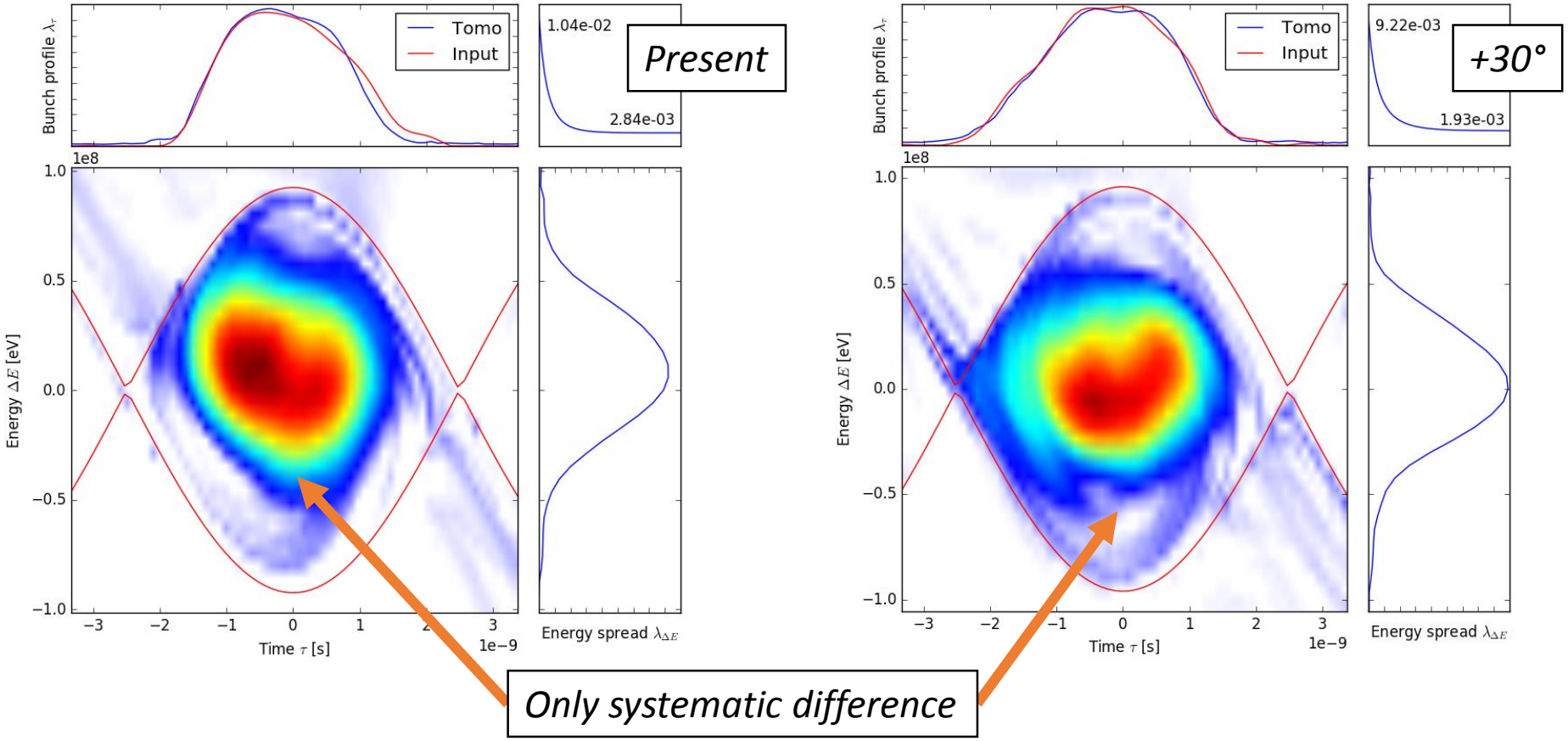
[2] H. Timko et al., Longitudinal transfer of rotated bunches in the CERN injectors, Phys. Rev. ST Accel. Beams **16**, 051004

[3] R. Garoby, Une procédure de fabrication de paquets courts dans le PS, PS/LR/Note 79-16

[4] R. Cappi et al., PRST-AB 5 (2002): 094401

Spare slides

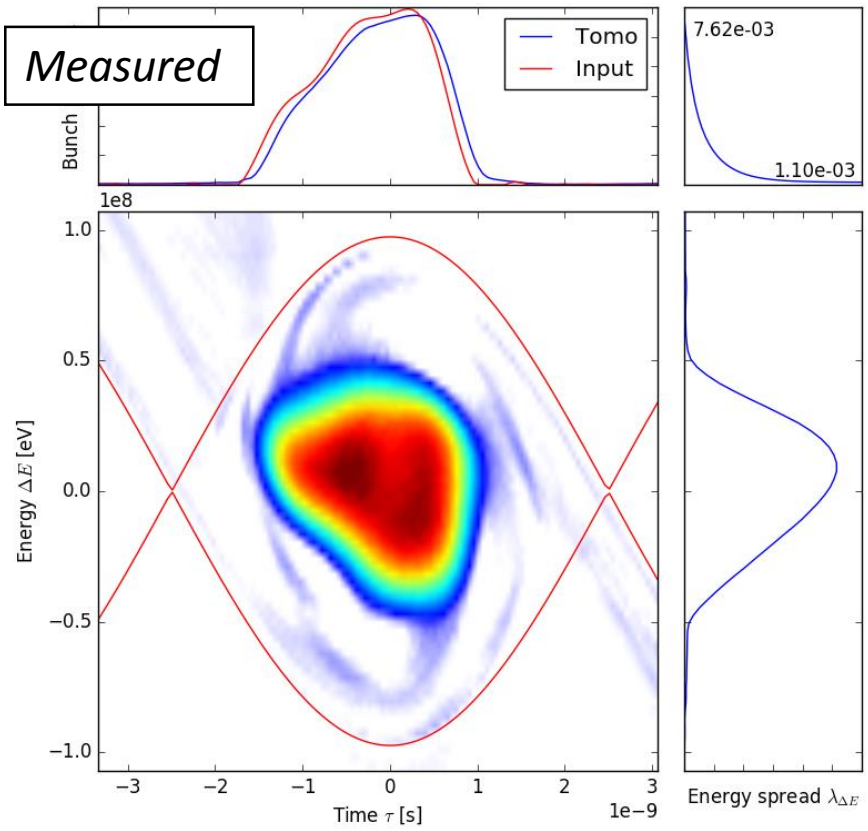
Tomography of rotated bunches in SPS

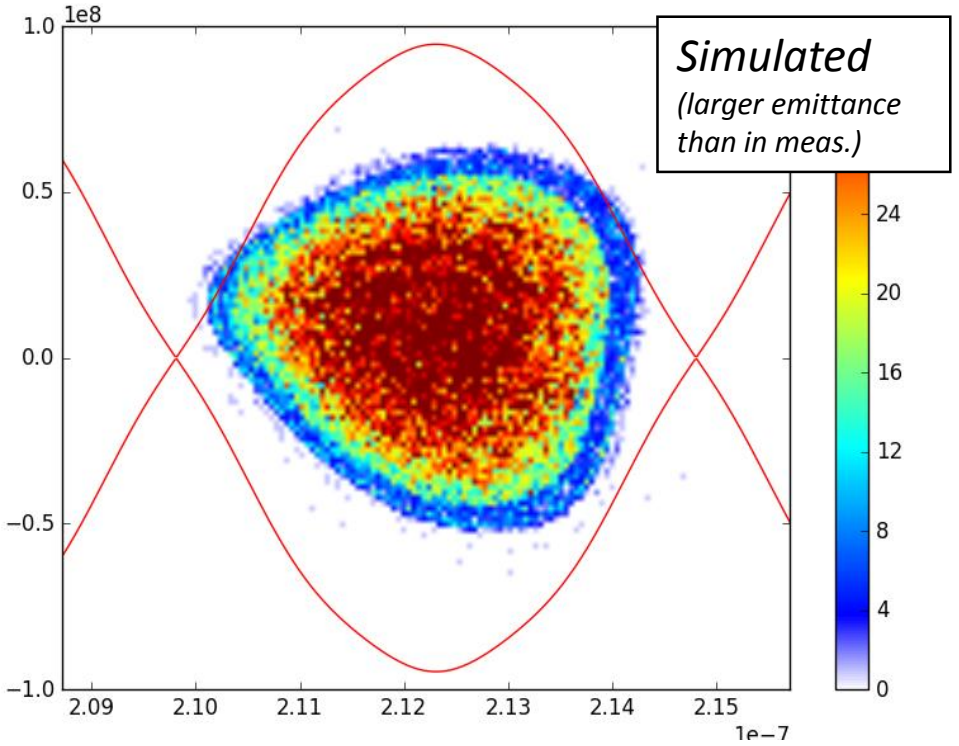


- Tomography was performed in the SPS to put in evidence the 80 MHz phase error
- The bunch is more “triangular” with the present settings, but the core of the bunch is not regular in all cases (RF variations during bunch rotation ? Intensity effects in PS ? Intensity effects to be taken into account in tomography ?)

➢ Not easy in practice…

Effective parameters of bunch rotation





- Expected ~30° phase error according to simulations (single bunch)

Simulation with int. effects (LIU intensity)