LHC Injectors Upgrade

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Slip stacking in the SPS

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LIU Day 2014

11 April 2014

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Motivation

- Increase the peak luminosity for the HL-LHC ($6\text{-}7\times10^{27}$ cm^{-2} s^{-1} at 7 ZTeV requested by the ALICE experiment)
  (D.Manglunki, RLIUP, Archamps 2013)

- Increase the number of bunches in the LHC → decrease the bunch spacing (from 100 ns to 50 ns)

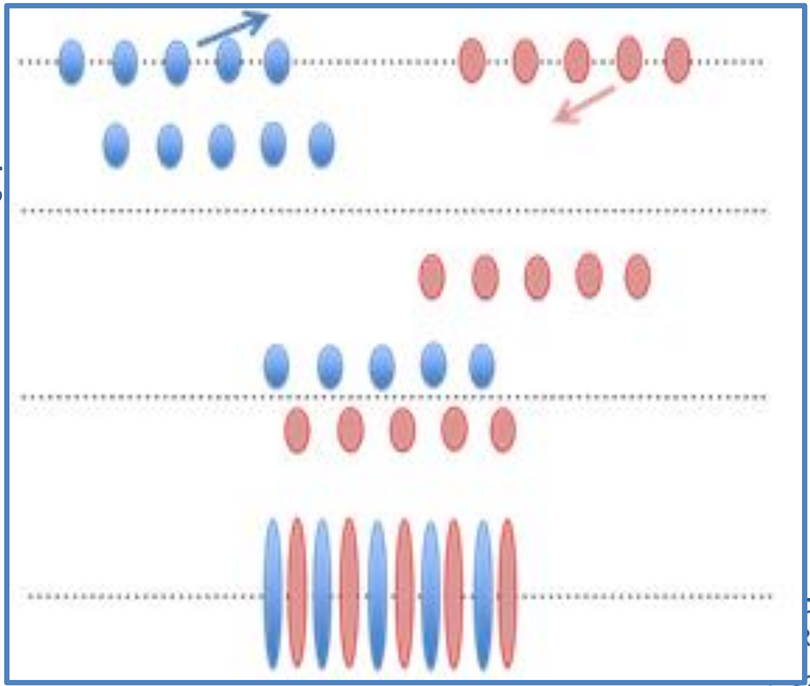
- Bunch-splitting or batch compression difficult to perform in the PS

- Alternative: momentum slip-stacking in the SPS (R. Garoby)

- Potential feasibility based on
  - Large bandwidth of the SPS 200 MHz Travelling Wave RF system
  - Relatively small initial emittances
  - Low ion intensity (no need of FB, FF, 800 MHz, …)

Procedure

- **Two super-batches injected into the SPS**:
  - **PS batch**: 4 bunches spaced by 100 ns
  - 6 PS batches injected into the SPS (batch space of 100ns)
  - **SPS super-batch**: 24 bunches spaced by 100 ns (2.3 µs)
- The two super-batches are captured by the two pairs of 200 MHz TWC → **independent beam controls are needed**
- f_{RF} variation to accelerate the first batch and decelerate the second
- Let the batches slip
- Bring them back by decelerating the first and accelerating the second
- Once the bunches are interleaved they are recaptured at average RF frequency



Basic beam dynamics concept

- The total voltage experienced by both batches

$$V_{tot} = V_0 \sin(\omega_{RF} t - \delta\omega\, t) + V_0 \sin(\omega_{RF} t + \delta\omega\, t) \Leftrightarrow$$
$$V_{tot} = 2V_0 \sin(\omega_{RF} t) \cos(\delta\omega\, t)$$

V_0: voltage amplitude of each RF system
ω_{RF}: RF angular frequency on central orbit
$\delta\omega$: RF angular frequency offset from ω_{RF}

motion of the bunches is disturbed from the other RF system

- At sufficiently large $\delta\omega$ this excitation averages within a synchrotron oscillation period → **bunches practically independent**
- For constant energy separation and equal RF voltage amplitudes V_0

$f_{s0} = f_{rev}\sqrt{h|\eta|eV_0/2\pi\beta^2\mathrm{E}}$ → small amplitude synchrotron frequency

$H_B = \sqrt{2\beta^2\mathrm{E}eV_0/h|\eta|\pi}$ → Bucket half height

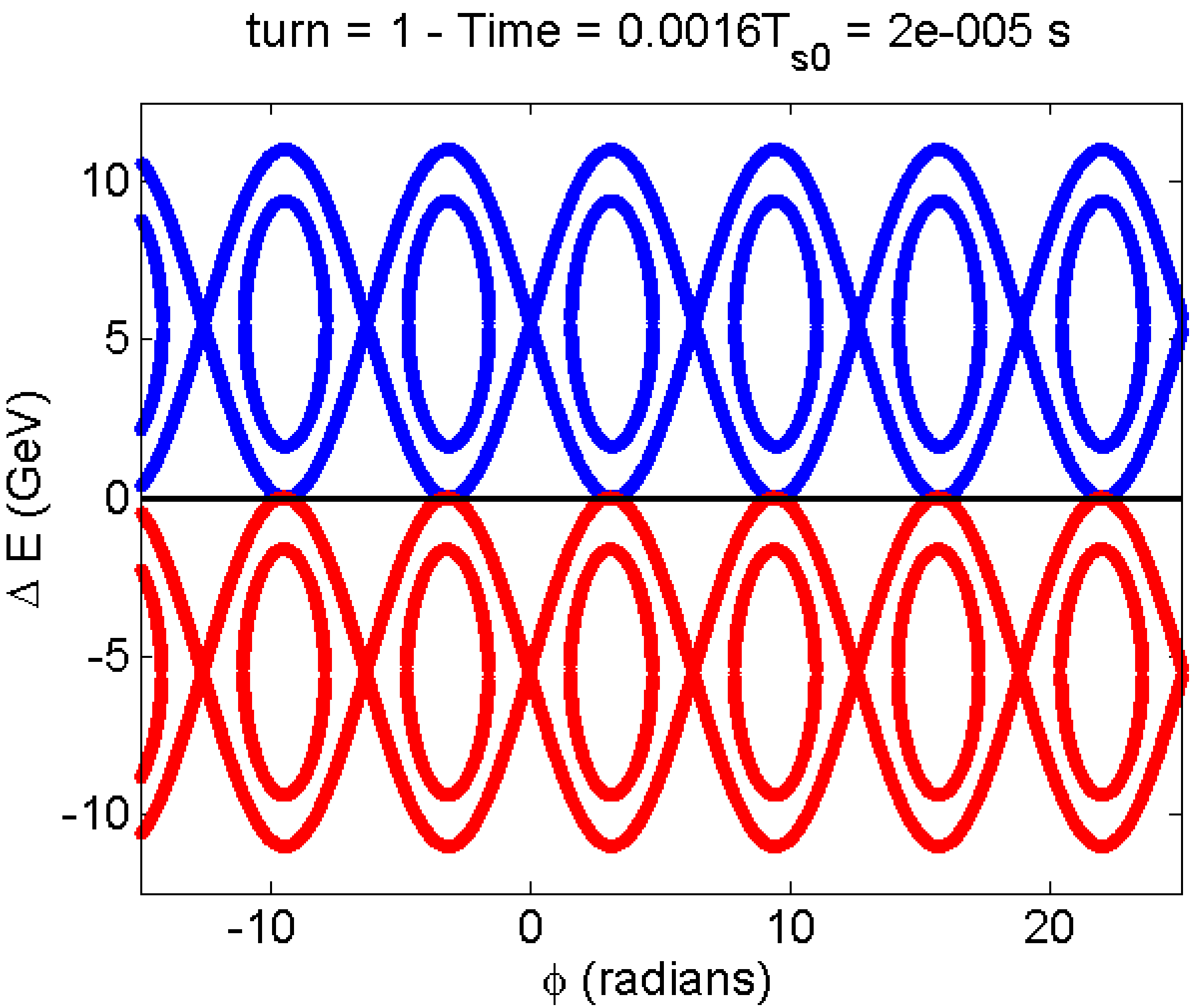
$$\frac{\Delta f_{rev}}{f_{rev}} = -\eta \frac{\Delta\mathrm{E}}{\beta^2\mathrm{E}}$$

ΔE: Energy difference between the two beams
Δf_{rev}: difference in revolution frequency between the two beams
Δf_{RF}: difference in RF frequency between the two beams

Combining the three equations we get:

$$\alpha \stackrel{\mathrm{def}}{=} \frac{\Delta f_{RF}}{f_{s0}} = 2\frac{\Delta\mathrm{E}}{H_B}$$

Basic beam dynamics concept



- $\alpha = 4 \;\rightarrow \Delta\mathrm{E} = 2H_B$: tangent boundaries for the two buckets → lower limit for stable motion (F. E. Mills)
- But, rapid effective emittance growth from tracking simulations
- Acceptable to hold bunches for several T_s when $\alpha \geq 8$: space of 1 empty bucket between the two → large emittance blow-up when recaptured
- Recapture when the 2 RF Voltages are in phase → disturbed bunch shape with empty phase-space in $\Delta\mathrm{E} = 0$

Energy consideration

- **Flat bottom**
  - Strong effects of space charge, IBS and RF noise (observed during operation)

- **Flat top**
  - Extra time for filamentation is needed
  - Uncaptured beam will be transferred into the LHC

- **Intermediate energy plateau**
  - Benefits due to high energy (no IBS, space charge)
  - Filamentation during the ramp to top energy
  - Clean beam for the LHC

Simulations presented below were performed at 300 GeV/c (proton equivalent)

Slip stacking at 300 GeV/c (proton equivalent)

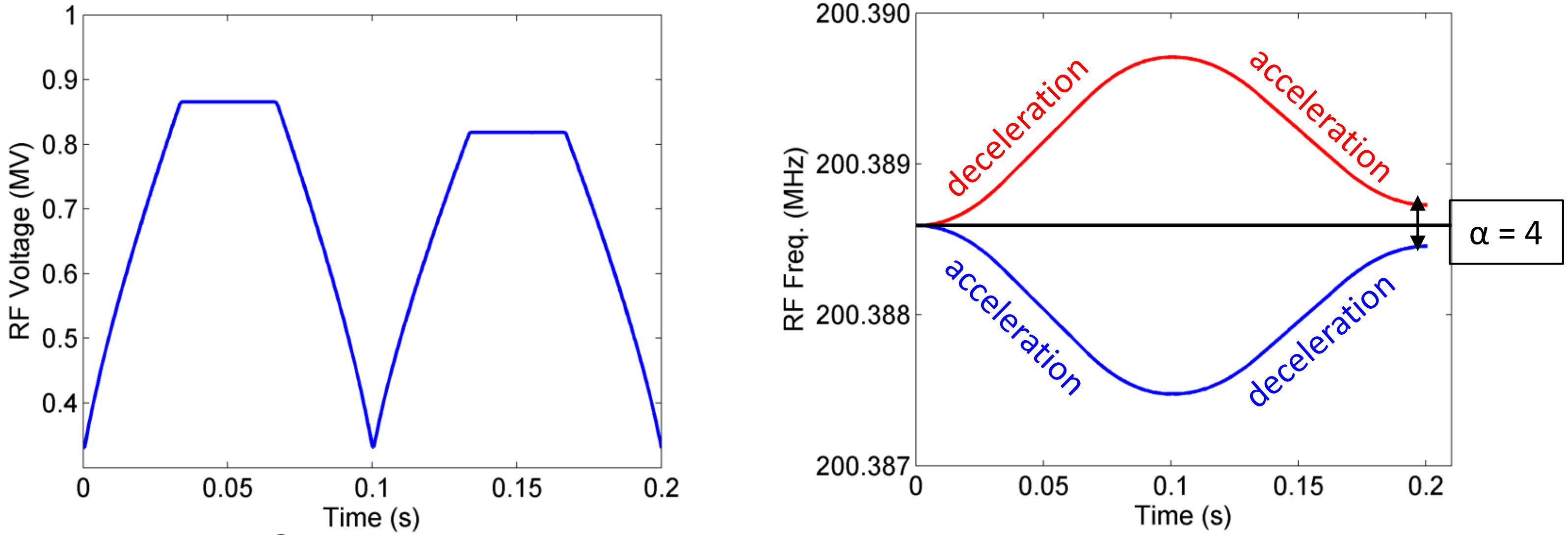
- Longitudinal emittance: **ε_l = 0.125 eVs/A**
- Initial RF Voltage: **V_{RF} = 0.34 MV** (filling factor in momentum of 0.9)
- Maximum momentum separation: **dp/p=1.84×10^{-3}** → much larger than the bucket height (0.22×10^{-3}) but within the aperture limit → **reduce slip time and minimize the mutual influence of the two beam during the slip**

Initial conditions used in the simulations for slip-stacking

Parameter	Symbol	Value	Units
Lorentz factor	γ	127	-
Slippage factor	η	3×10^{-3}	-
Longitudinal emittance	ε_l	0.125	eVs/A
RF voltage amplitude	V_{RF}	0.34	MV
Small amplitude synchrotron frequency	f_{s0}	68	Hz
Maximum momentum separation per beam	dp/p	1.84×10^{-3}	-
Maximum radial displacement per beam	ΔR	6.0	mm
Frequency offset per beam	Δf_{RF}	1116	Hz

Designed RF programs

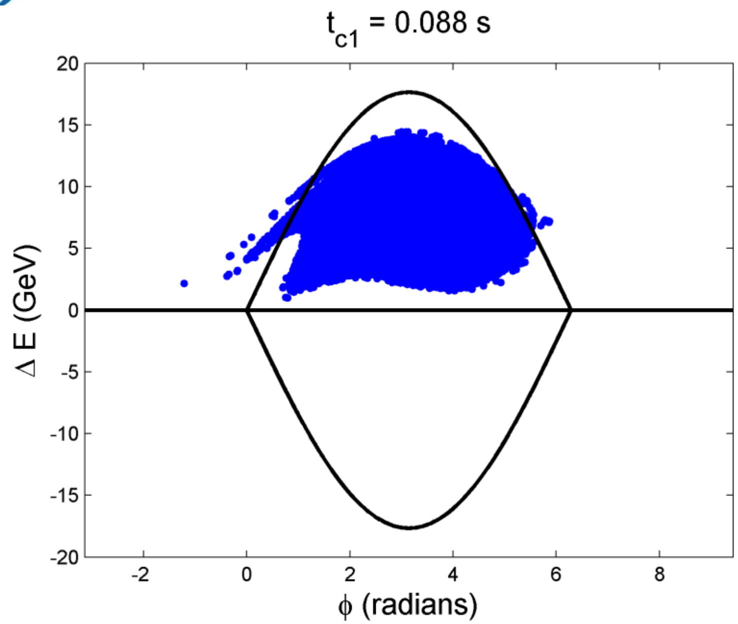
- The RF programs calculated for a single RF for constant filling factor in momentum (0.9)

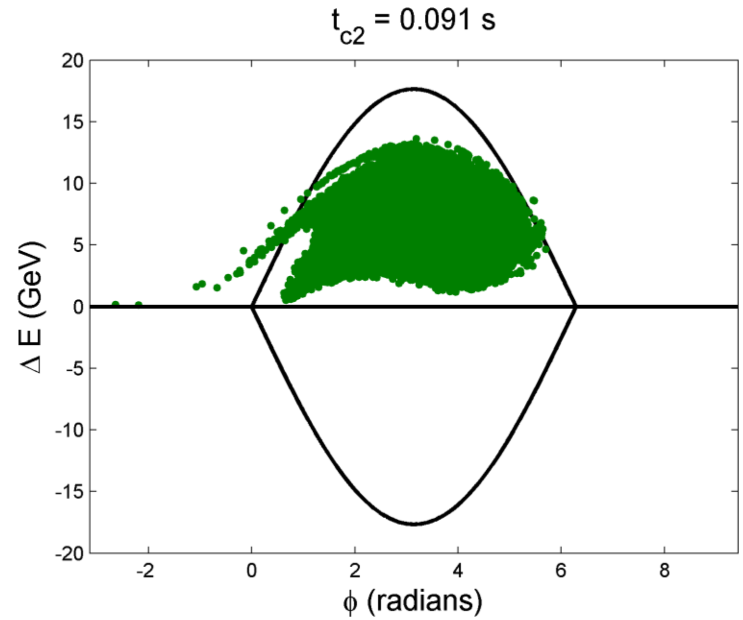


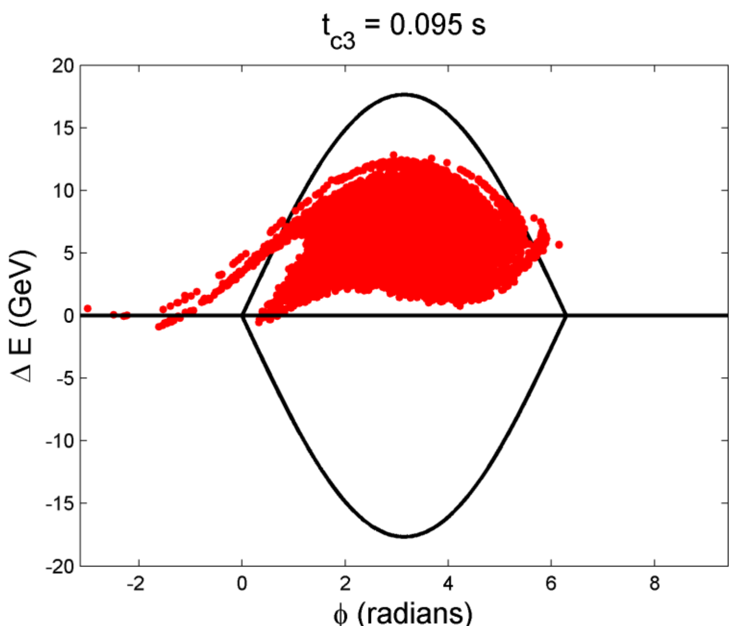
- Duration of 200 ms:
  - fast compared to the cycle (about 50 s)
  - slow enough to avoid particle losses

- Final energy corresponds to the case of α = 4 → bunches are distorted before the end → **optimization of the capture time is needed**

Capture time



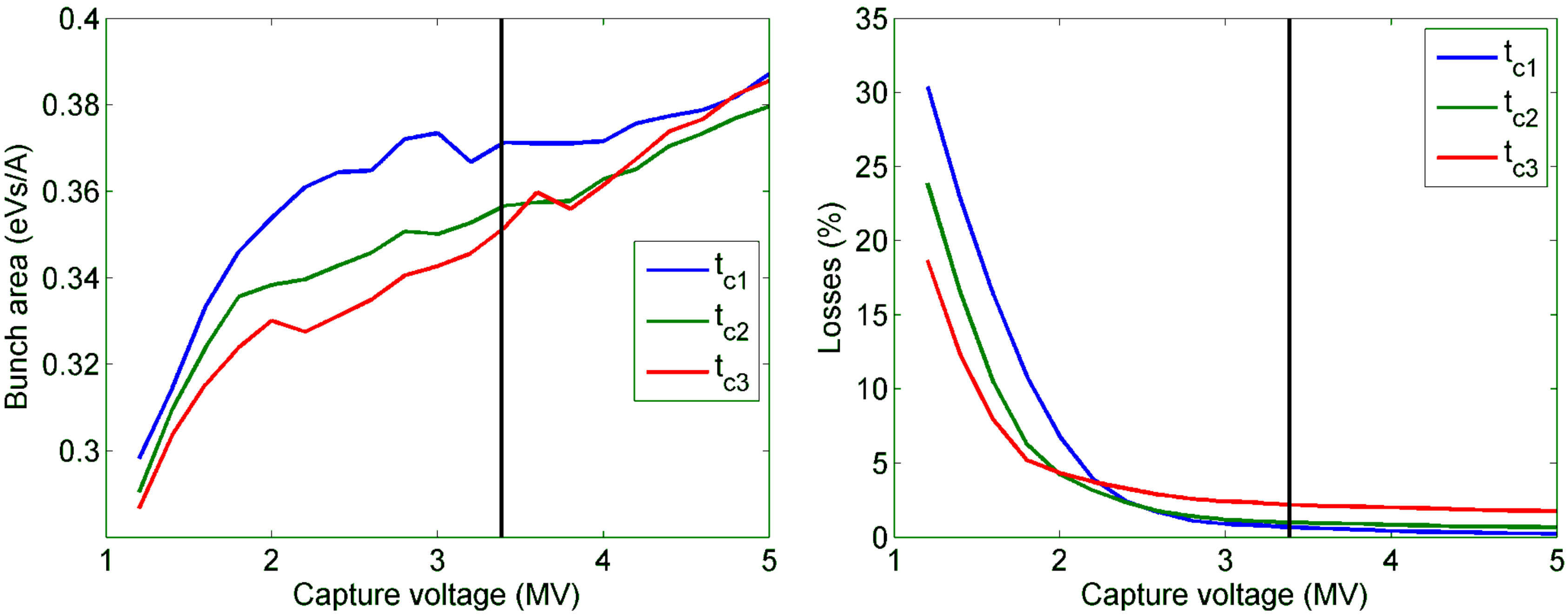




- Recapture bunches when the two RF voltages are in phase → **disturbed shape**
- While approaching each other in energy more particles are lost.

Beam capture optimization

- Optimize capture voltage and time with respect to:
  - Final emittance
  - Particle losses

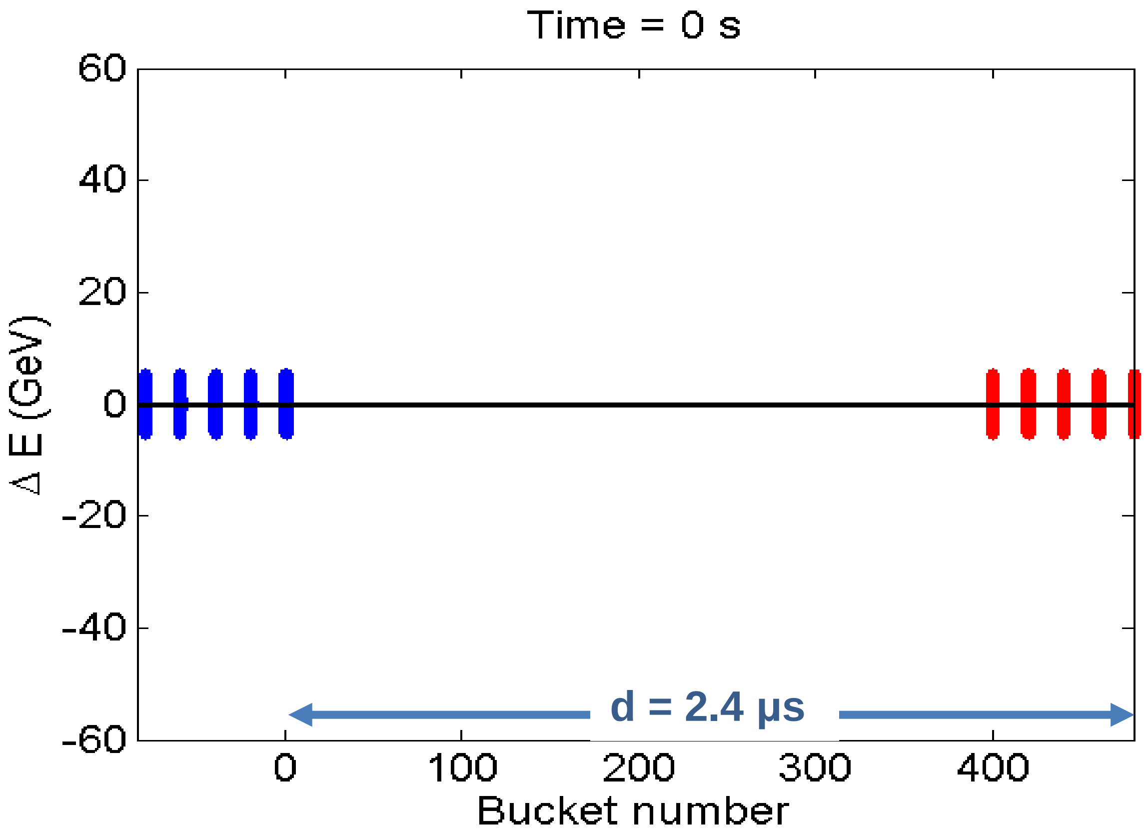


- Selection based on minimizing losses → larger longitudinal emittance
  - Capture time: t_{c2}
  - Capture voltage: 3.4 MV

➢ ε_l ~ 0.35 – 0.36 eVs/A

➢ Losses ~ 1 – 1.5 %

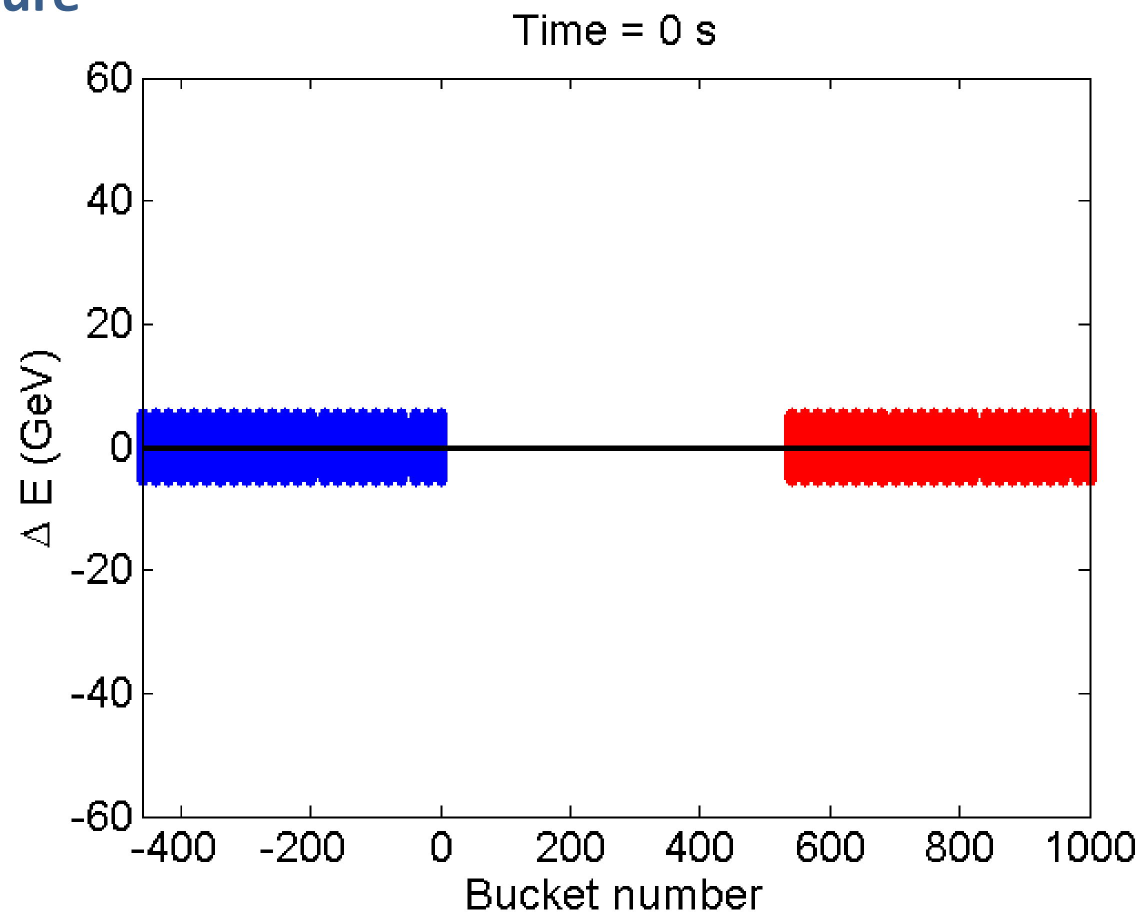
Example for selected conditions



- Using the designed RF programs (**200 ms**): distance between the last bunch of each batch **d = 2.4 μs**
- Since batch length is **2.3 μs** → **very small batch spacing (T_B=100 ns)**
- In reality T_B is **defined by the LLRF specifications**: large enough to assure that each batch is exposed only to the RF voltage of its corresponding pair of 200 MHz TWC (**T_B > 1.3 μs**)
- Extra slipping time at maximum energy separation.

Example with T_B = 2.7 μs

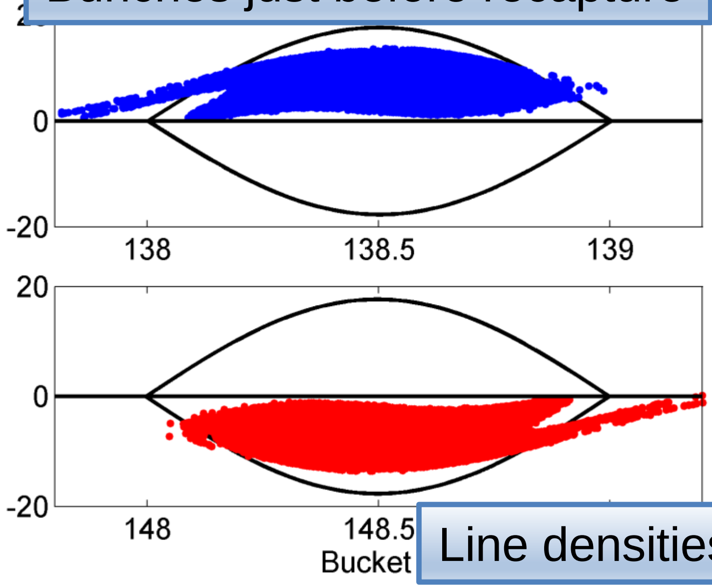
- T_B =2.7 μs large enough for RF voltage modulation → **each batch sees only the voltage of one pair of TWC during most part of the procedure**



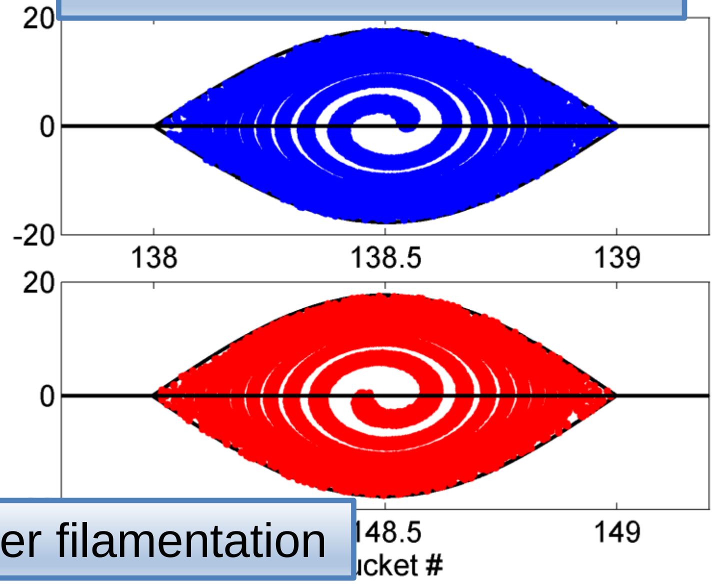
Total duration of around 300 ms

Beam parameters

Bunches just before recapture

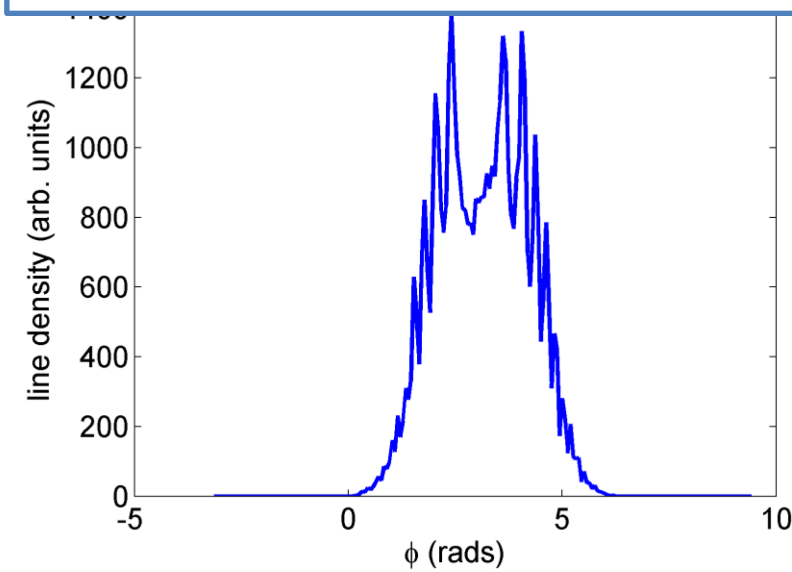


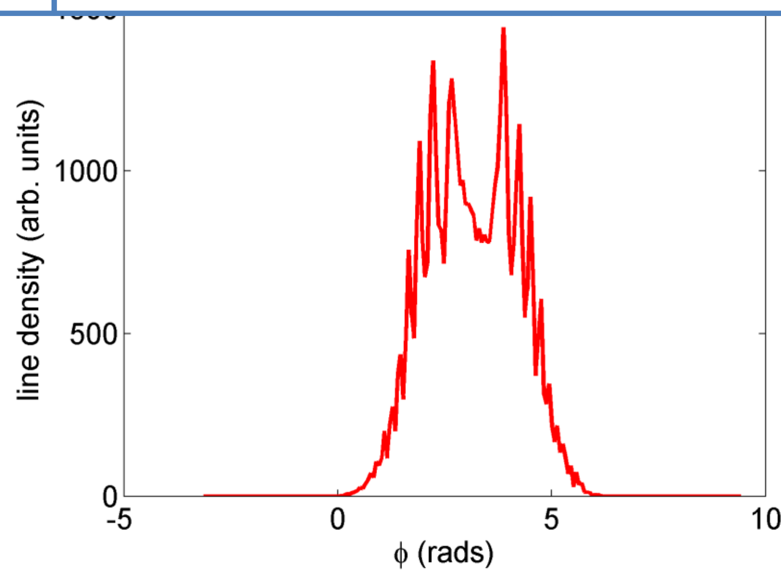
Bunches after filamentation



Line densities after filamentation

$\tau = 3.3\ ns - \varepsilon = 0.36\ eVs - losses = 1.1\%$	$\tau = 3.3\ ns - \varepsilon = 0.36\ eVs - losses = 1.0\%$

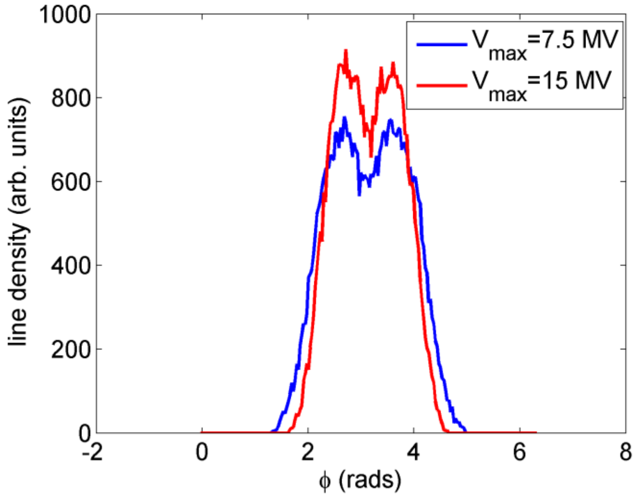




Beam parameters at flat top

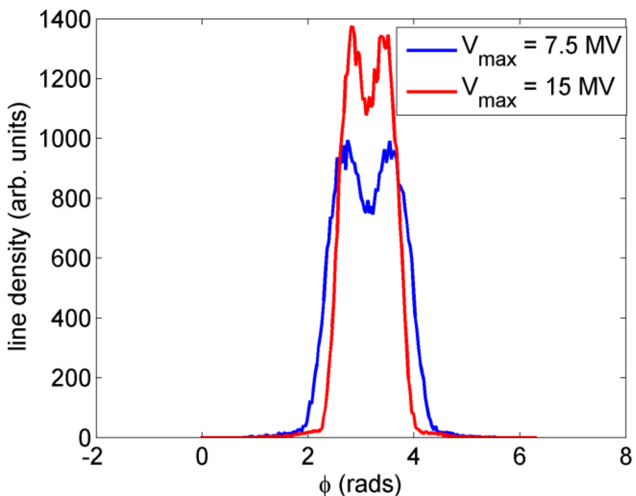
- ❑ Accelerate the beam to top energy
- ❑ Two possible schemes to provide the final bunch length at extraction

I. Adiabatic voltage increase



- ➢ V_{RF} = 7.5 MV: τ = 2.3 ns
- ➢ V_{RF} = 15 MV : τ = 1.9 ns
- ➢ Total losses = 1.2 %

II. Bunch rotation



- ➢ V_{RF} = 7.5 MV: τ = 1.8 ns
- ➢ V_{RF} = 15 MV : τ = 1.3 ns
- ➢ Total losses = 1.2 %

Implementation and tests

- **AM and FM of the RF cavities is foreseen after LS2** (LIU TDR SPS LLRF, P. Baudrenghien, T. Bohl, G. Hagmann): individual beam and cavity controllers

- Tests can be done before only with one batch (flat top, flat bottom) to:

  - Investigate the beam life time without the phase loop (PL) → unpredicted behavior of the PL during the slip stacking procedure → might be necessary to operate without PL
  - Define the aperture limitation ΔR
  - Test and optimize the designed RF programs regarding the particle losses and the final longitudinal emittance
  - …

Summary

- Momentum slip-stacking in the SPS proposed as a potential way of increasing the number of bunches for the nominal I-LHC beams
- Particle simulations performed to confirm this possibility regarding the beam dynamics (no intensity effects had been included)
- Small particle losses (~1-2 %) when recapture RF voltage is high → large emittance blow-up (factor of 3) → large bunch length
- Can be reduced by the **increase of the available RF voltage** (LS2) and by **bunch rotation** before extraction → **Acceptable beam parameters for the LHC**
- Implementation is foreseen after LS2
- Useful tests can still be performed using only one RF system.

Summary table

- **Simulations performed also with the Q26 optics**
  - More sensitive to IBS and space charge effects
  - More promising due to the larger relative bucket area for the same available RF voltage→ **provides more margin if needed**

Summary results of the slip-stacking simulations and beam parameters at extraction.

SP optics	Capture Voltage (MV)	Final emittance (eVs/A)	Losses (%)	Bunch Length at flat top (ns)			
				Bunch compr.		Bunch rot.	
				V_{RF} = 7.5 MV	V_{RF} = 15 MV	V_{RF} = 7.5 MV	V_{RF} = 15 MV
Q20	3.4	0.35 – 0.36	1 – 2	2.3	1.9	**1.8**	**1.31**
Q26	2.0	0.35 – 0.36	1 – 2	2.0	**1.7**	**1.41**	**1.05**

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