RF manipulations with high intensity effects in SIS-100

Yao-shuo Yuan, Oliver Boine-Frankenheim, TU Darmstadt
Vladimir Kornilov, GSI

Outline

- Introduction
- Bunch merging with constant bunching factor (because of transverse space charge tune shift)
- Key parameters: rf voltage ramps, phases and merging time
- Intensity effects: Longitudinal space charge and cavity beam loading
- Simulation of the full single bunch generation with intensity effects.
- Summary

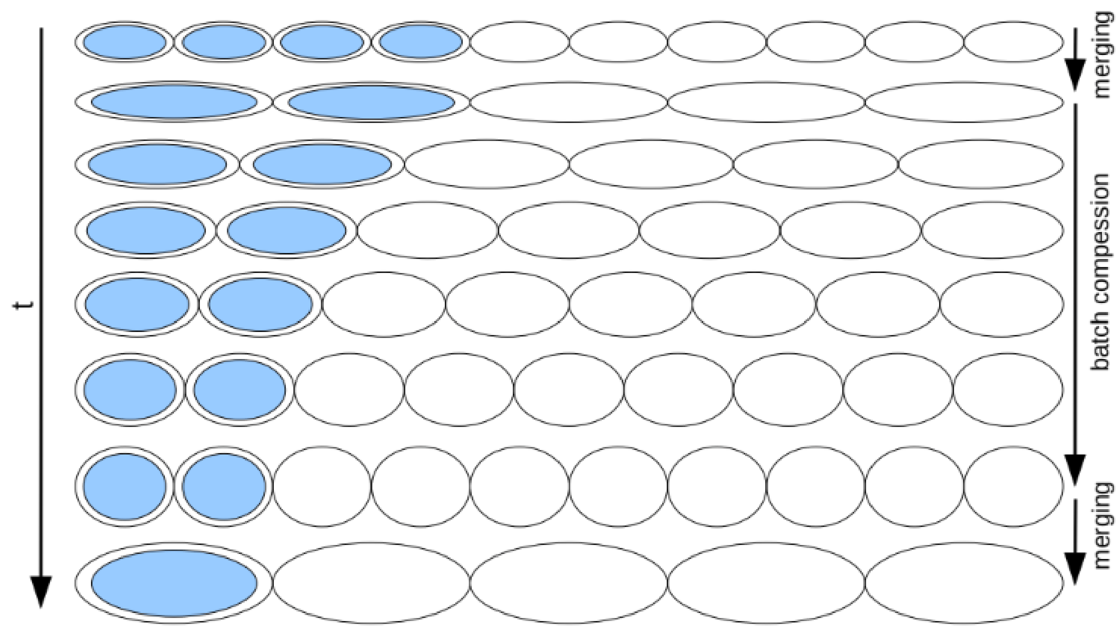
Introduction

- In SIS-100, for proton operation, four bunches are merged to one bunch:

1) First merging: 4 bunches (h=10) → 2 bunches (h=5)

2) Batch compression: 2 bunches compressed (h=5 to 10)

3) Second merging: 2 bunches (h=10) → 1 bunch (h=5)



Merging

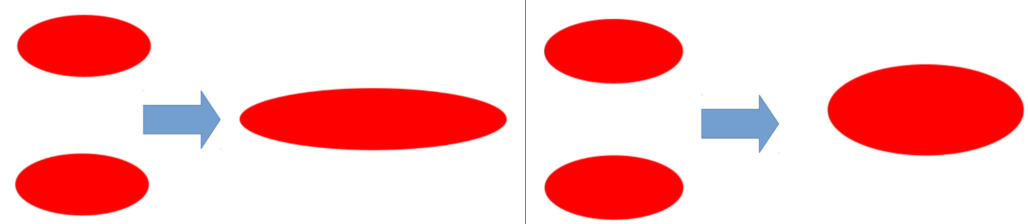
Batch compression

Merging

Bunch merging with constant bunching factor

- Bunching factor defined as $B_f = \frac{\text{bunch length}}{\text{bucket length}}$

- After bunch merging $\epsilon_{L,f} = 2_{L,i}$
  - Bunch length: $\hat{l}_f = 2\hat{l}_i$
  - Momentum spread $\hat{\delta}_f = \hat{\delta}_i$



Constant bunching factor

Constant bunch ratio

- Advantage:
  Lower tune shifts;
  Lower rf voltage ramps.

	Before merging	After merging
Constant bunching factor	0.26 (0.07, 0.12)	0.26 (0.07, 0.12)
Constant bunch ratio	0.26 (0.07, 0.12)	0.18 (011, 0.18)

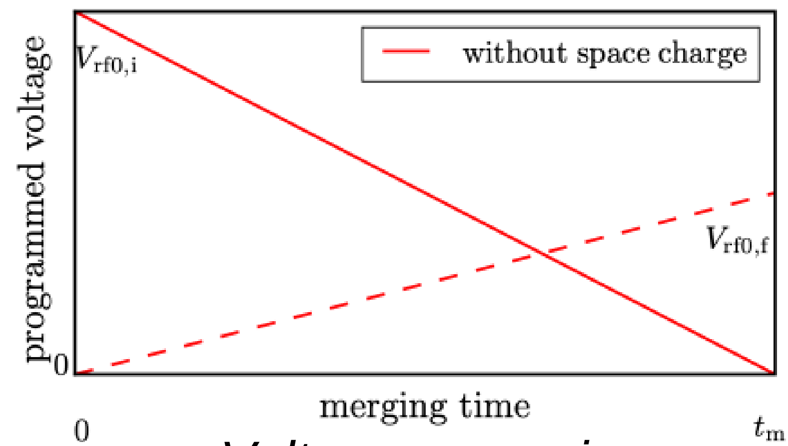
← Bf

← (ΔQx, ΔQy)

An example of bunching factor and tune shift

Longitudinal settings for bunch merging

- Three key parameters: required rf voltage ramps, phases, and merging time.

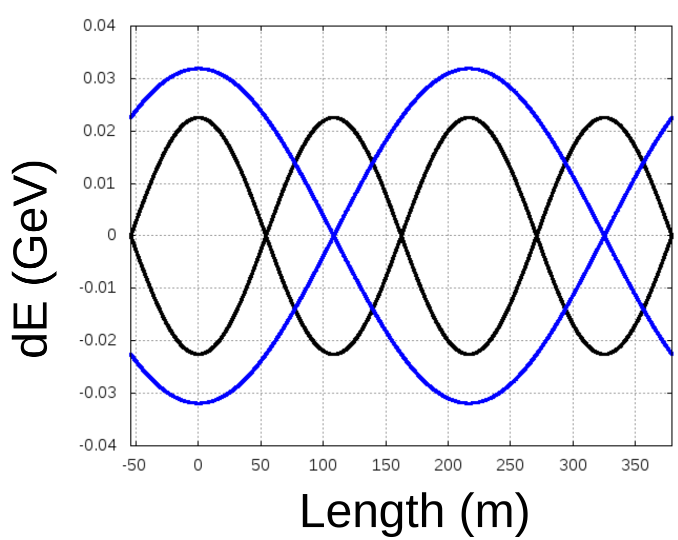


Voltage ramps in bunch merging

- First bunch merging (from h10 to h5)

$$V_{\mathrm{rf,i}} = 2V_{\mathrm{rf,f}}$$

➔ Relative phase between h=10 and h=5

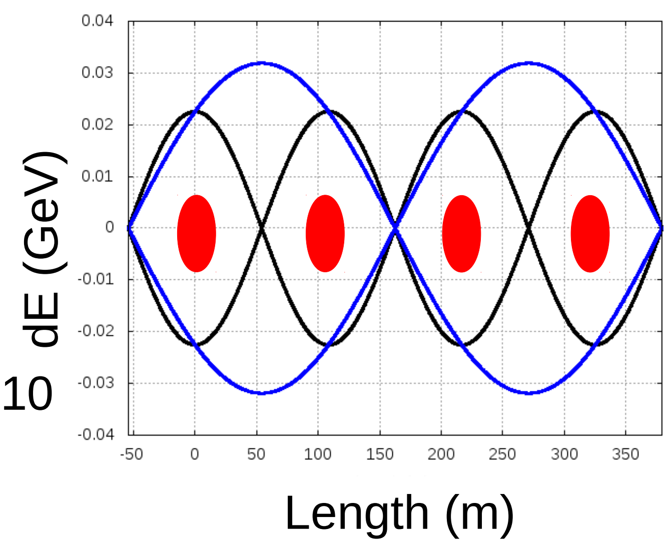


$$\phi_1 = \phi_2 = 0$$

shifted

Black = h=10

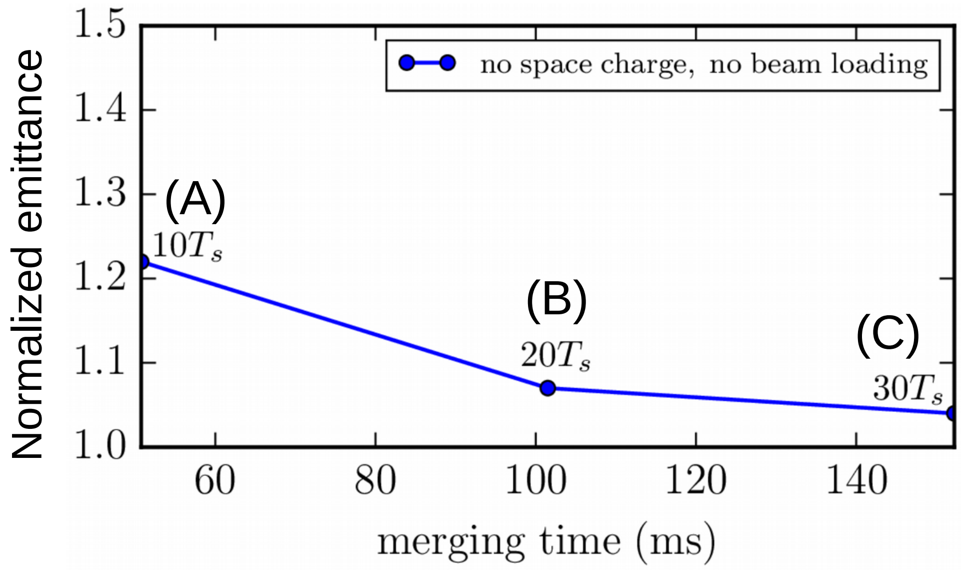
Blue h =5

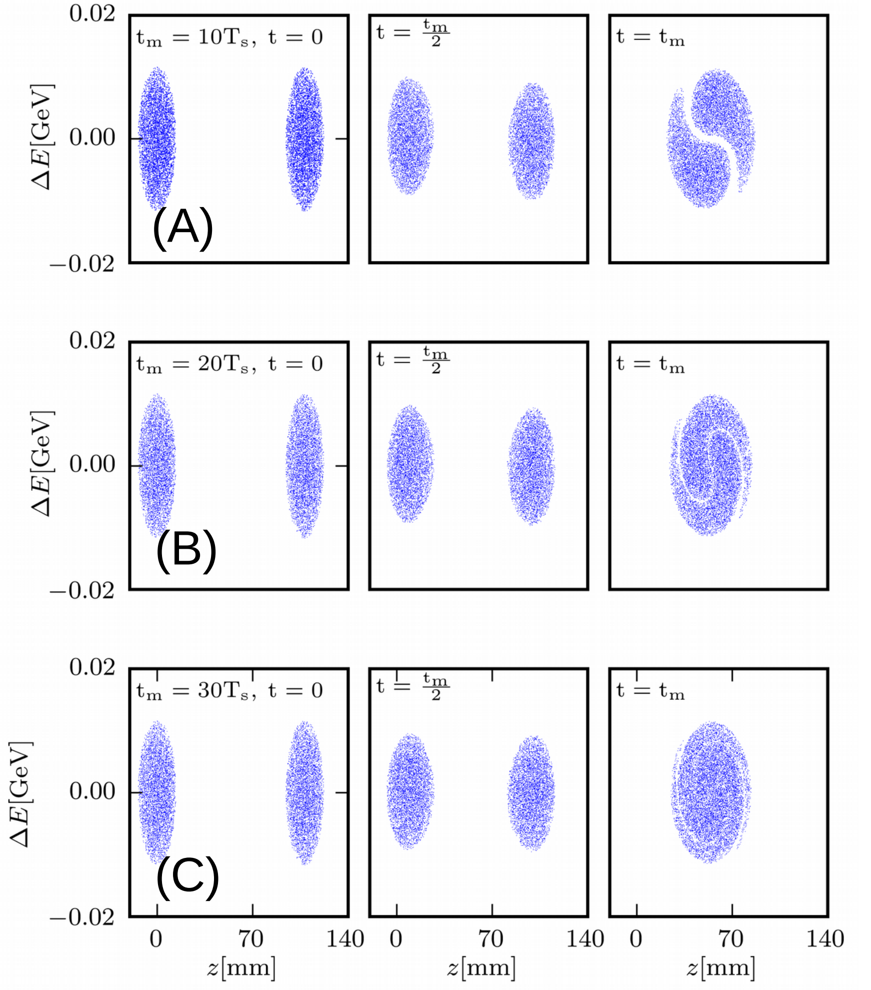


$$\phi_1 = 0, \phi_2 = 90^\circ$$

Longitudinal settings for bunch merging

- First bunch merging (from h10 to h5)
  - Simulations show that merging time of ~100 ms (20Ts) can ensure a good emittance

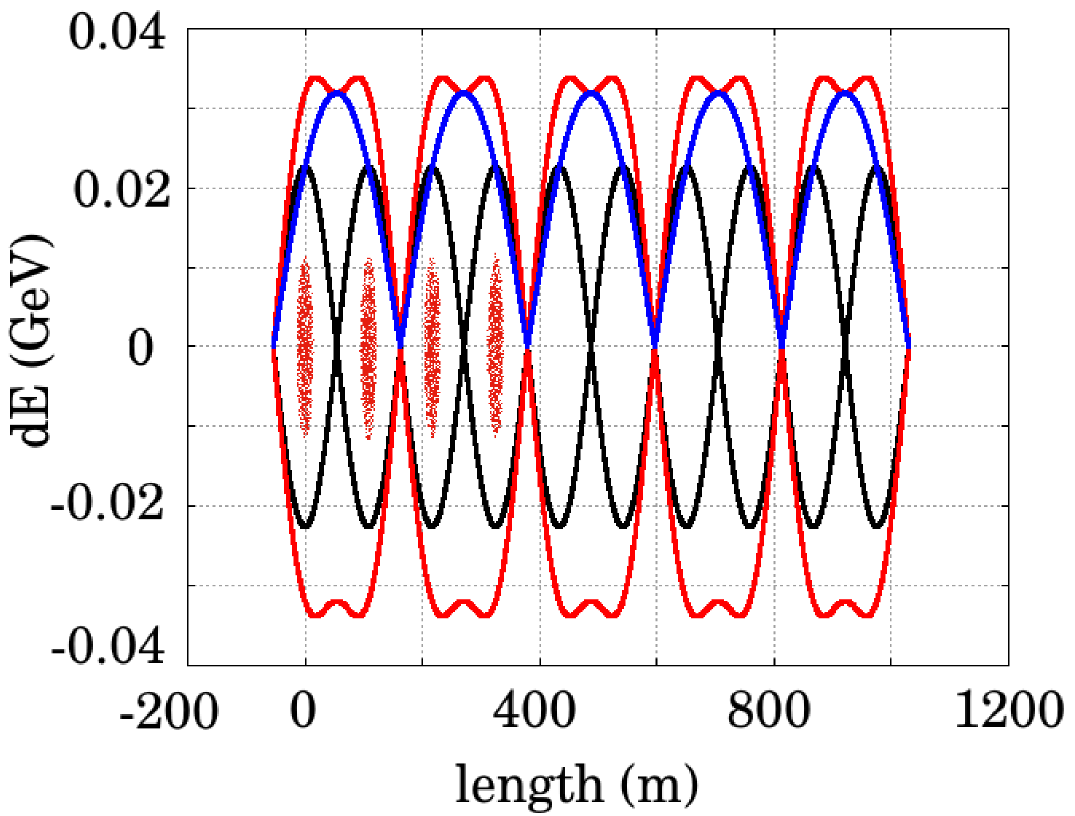




Case	Synchrotron period (T_s)	Turns (n)	time (t_m)
A	10	13800	50.8
B	20	13,300	101.6
C	30	26,600	203.2

Longitudinal settings for bunch merging

- Configuration of the first bunch merging



Initial bunch merging with harmonic on h =5 and h =10

- Simulation code pyORBIT[1] is employed for rf manipulation with high-intensity effects in SIS-100

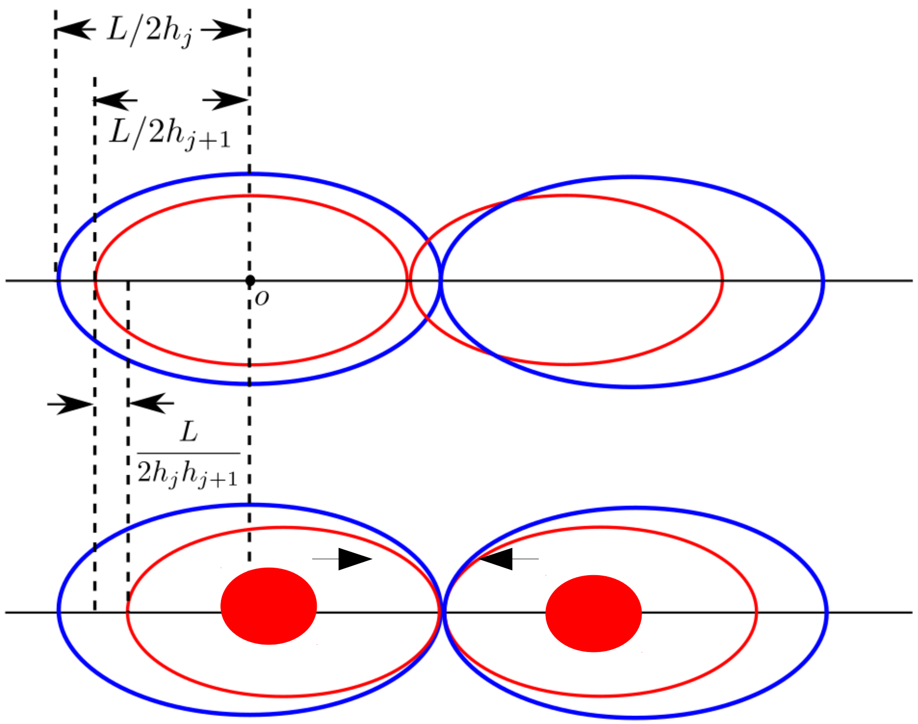
Black h=10;
Blue h=5;
Red combined

[1] A. Shishlo, S. Cousine, J. Holmes, T. Gorlov, "The Particle Accelerator Simulation Code PyORBIT", 1272, Procedia Computer Science (2015)

Longitudinal settings for batch compression

- Batch compression (from h5 to h10)
- Phases:
  (1) Since two bunches shrinking symmetrically both the harmonics should be centered to the center of bunches.
  (2) Different bunch positions.

$$\phi_k = \frac{L}{2h_j h_{j+1}}$$



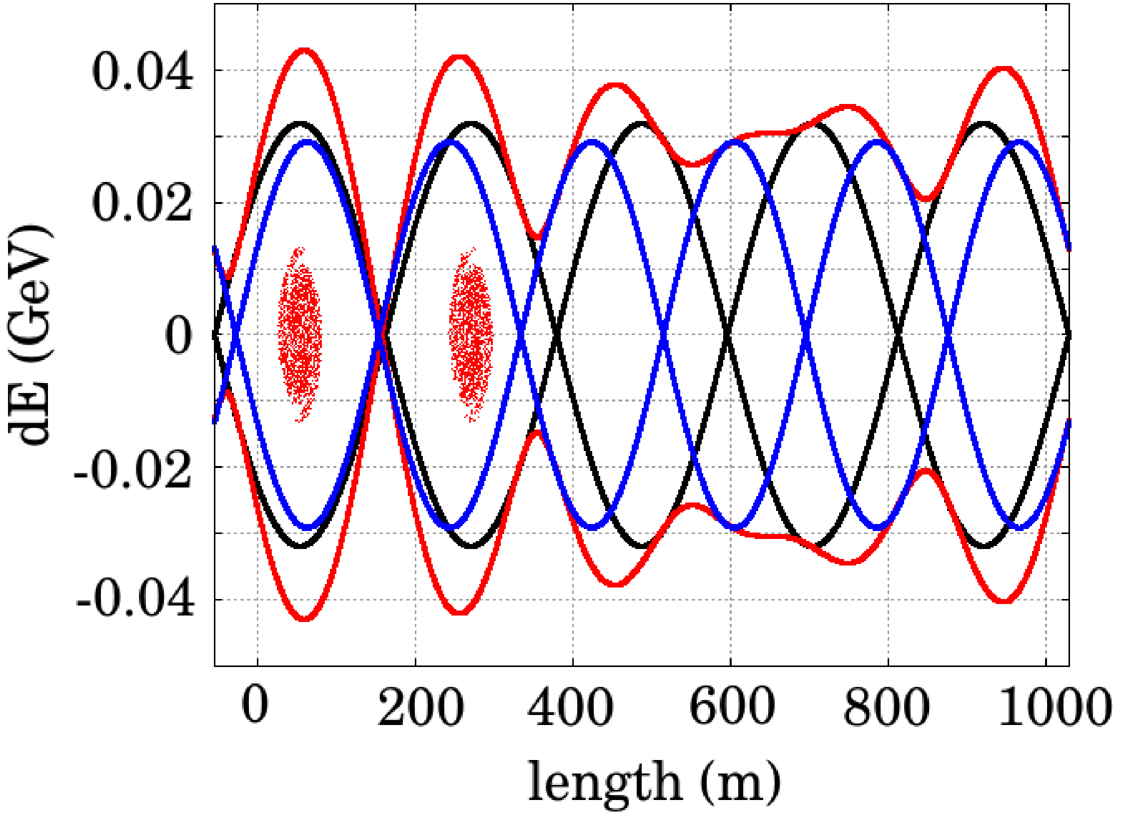
Schematic drawing of the relative phase

Phase shifts (deg)	Shift for bunch position	Shift for symmetry
Φ5	90	0
Φ6	108	36
Φ7	126	72
Φ8	144	108
Φ9	162	144
Φ10	180	180

Relative phase for batch compression in SIS-100

Longitudinal settings for batch compression

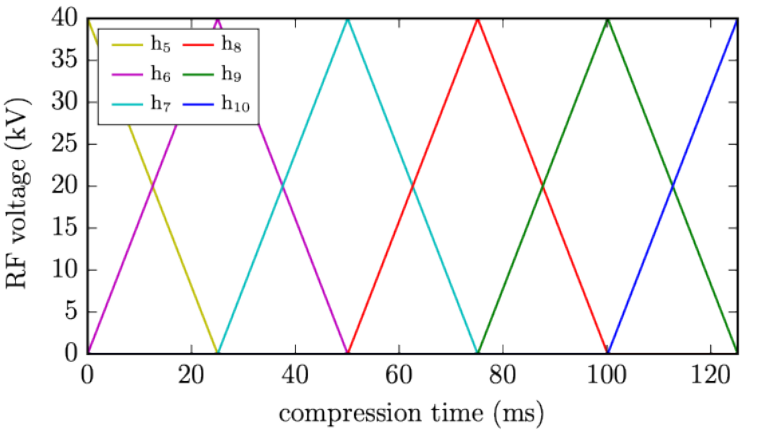
- Configuration of the batch compression (an example of h5 to h6)



Batch compression with harmonics on h =5 and h =10

Black h=5; Blue h=6; Red combined

- The emittance growth is less sensitive to the rf voltage than merging.



Longitudinal settings for second bunch merging

- Final merging (from h10 to h5)
  - Similar to the first merging, phase shifts is

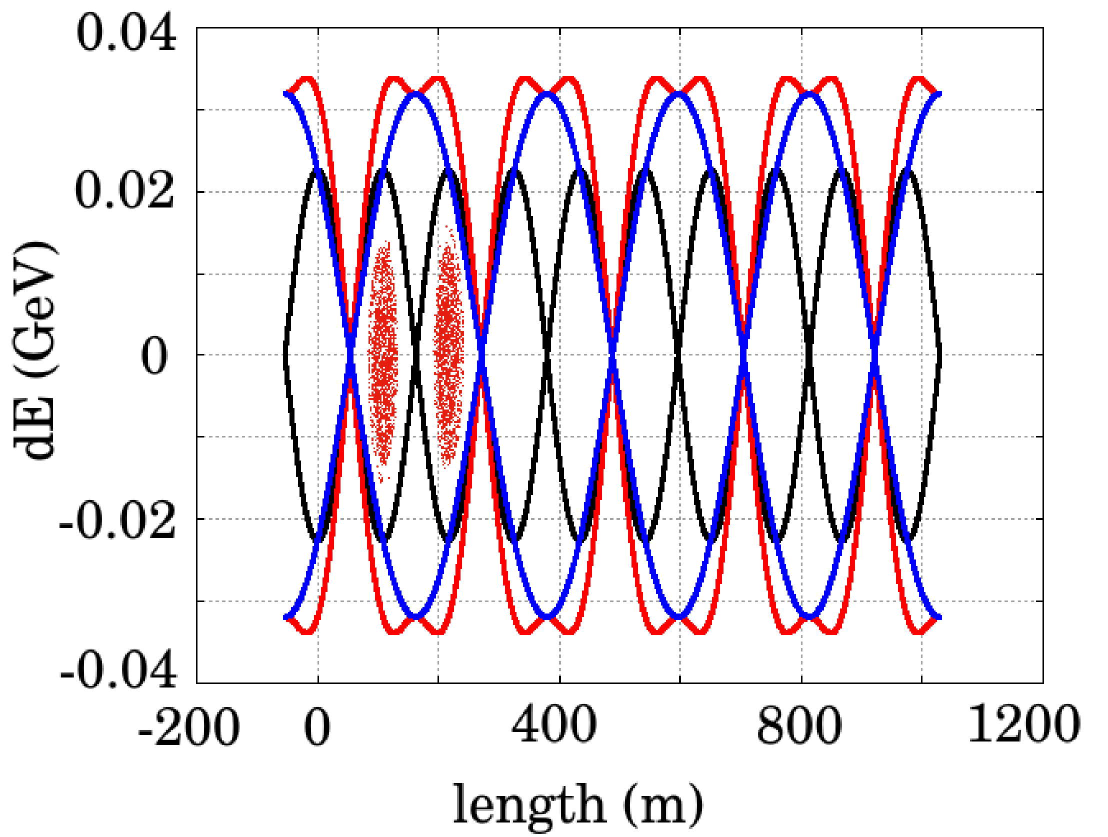
$$\phi_{10} = 0^\circ, \phi_5 = 270^\circ$$

  - The merging time

$$t_m \sim 105 \text{ ms}$$

- Configuration of the final bunch merging

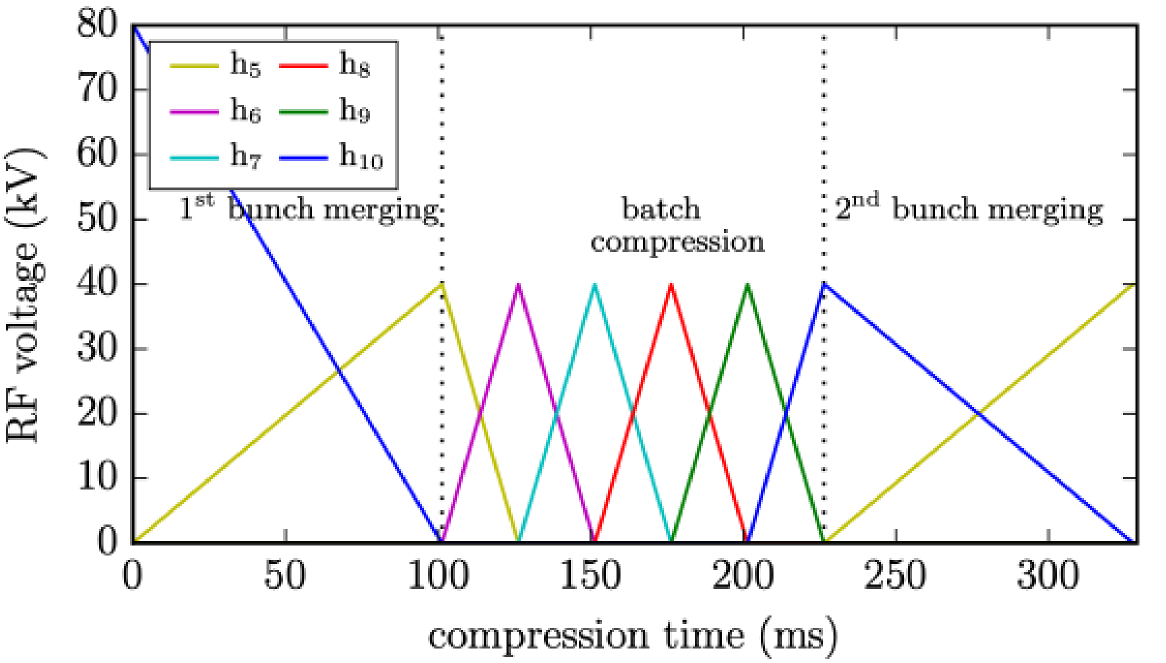
Black h=10;
Blue h=5;
Red combined



Final bunch merging with harmonic on h =5 and h =10

Full rf manipulation without intensity effects

- Proposed voltage waveform for rf manipulation



- Transverse tune shifts

	Initial value	First merging	Batch compression	Final value
Bunching factor	0.26	0.26	0.45	0.36
tune shifts (νx,νy)	(0.07, 0.12)	(0.07, 0.12)	(0.09, 0.14)	(0.11, 0.18)

Intensity effects: space charge

- s.c. force can be calculated and matched for specified intensity and emittance

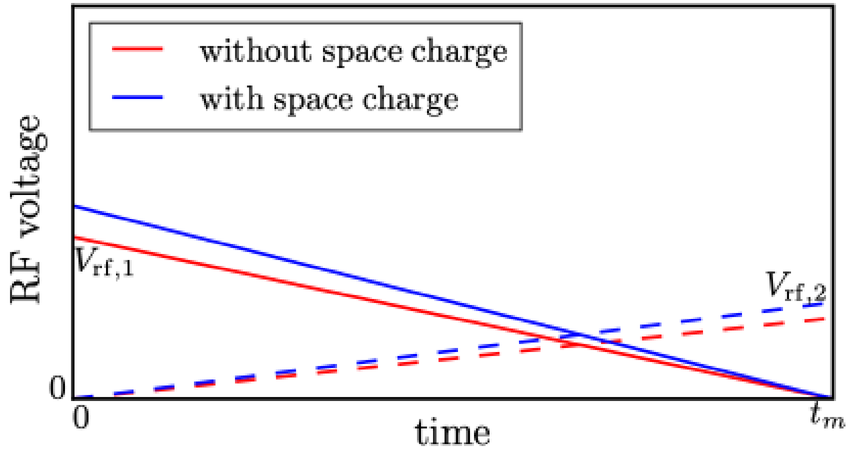
- For SIS100, initial and final s.c. matching

s.c.voltage

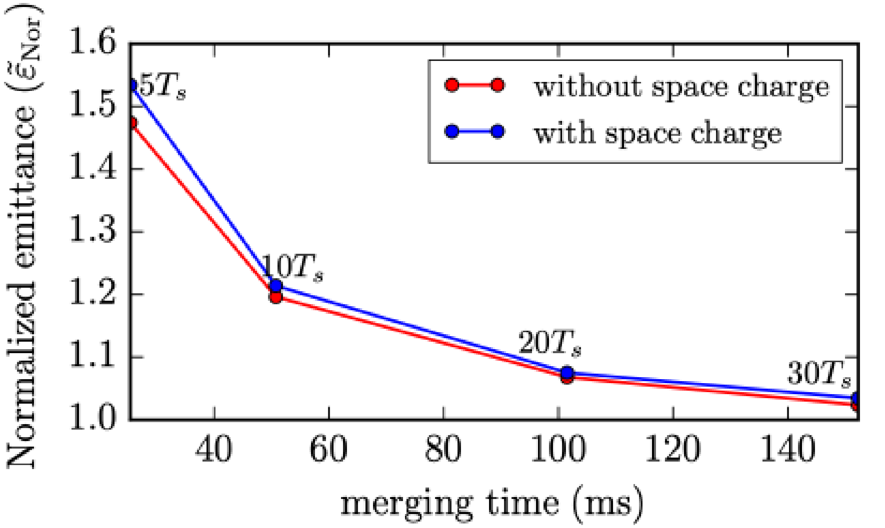
$$V_{\mathrm{rf,sc,i}} = V_{\mathrm{rf,i}} + V_{\mathrm{sc,i}} = 66.0 + \boxed{12.7} = 78.7\ \mathrm{kV}$$

$$V_{\mathrm{rf,sc,f}} = V_{\mathrm{rf,f}} + V_{\mathrm{sc,f}} = 33.0 + \boxed{6.3} = 39.3\ \mathrm{kV}$$

Space charge can be well compensated.



Designed RF voltage waveform without/with s.c.



Comparison of the final emittance under different merging time without/with s.c.

Intensity effects: beam loading

- The total impedance seen by the beam (RLC model)

$$Z_{\mathrm{bl}} = n_1 Z_{\mathrm{bl,i}} + n_2 Z_{\mathrm{bl,f}}$$

$$= \frac{n_1 R_{\mathrm{sh}}}{1 + iQ_{\mathrm{c1}}(\omega/\omega_{\mathrm{r1}} - \omega_{\mathrm{r1}}/\omega)} + \frac{n_2 R_{\mathrm{sh}}}{1 + iQ_{\mathrm{c2}}(\omega/\omega_{\mathrm{r2}} - \omega_{\mathrm{r2}}/\omega)}$$

The first harmonic   The second harmonic

Resonant freq.

$$\omega_{\mathrm{r1}} = h_1\omega_0 \quad \omega_{\mathrm{r2}} = h_2\omega_0$$

Loaded Q-value

$$Q_{\mathrm{c1}} = 10.6 \quad Q_{\mathrm{c2}} = 5.3$$

Number of cavities for constant bunching factor

$$n_1 = 4, n_2 = 2$$

Parameters [unit]	Symbols	Initial value
Resistance [Ω]	R_{sh}	2000
Harmonic number	h	10
Resonant frequency [MHz]	f_{res}	2.72
Loaded quality factor	Q_c	10.6

Main parameters for beam loading calculation in SIS-100

High intensity effects--beam loading

- The beam-induced voltage can cause dipole oscillation.

- Before merging, bunches are assumed to be matched to beam loading, via a shift of the bunch center

$$\Delta\phi_{\mathrm{bl}} = \mathrm{asin}(\frac{V_{\mathrm{bl0}}}{V_{\mathrm{rf}}})$$ (matching shift)

- The rf harmonic should be shifted to keep the merging symmetrically

$$\Delta\phi_{\mathrm{hf}} = \frac{1}{2}(\Delta\phi_{\mathrm{bl,1}} + \Delta\phi_{\mathrm{bl,2}})$$ (symmetry shift)

- Symmetry shift will dampen the emittance growth (show later)

Choice of rf cavities

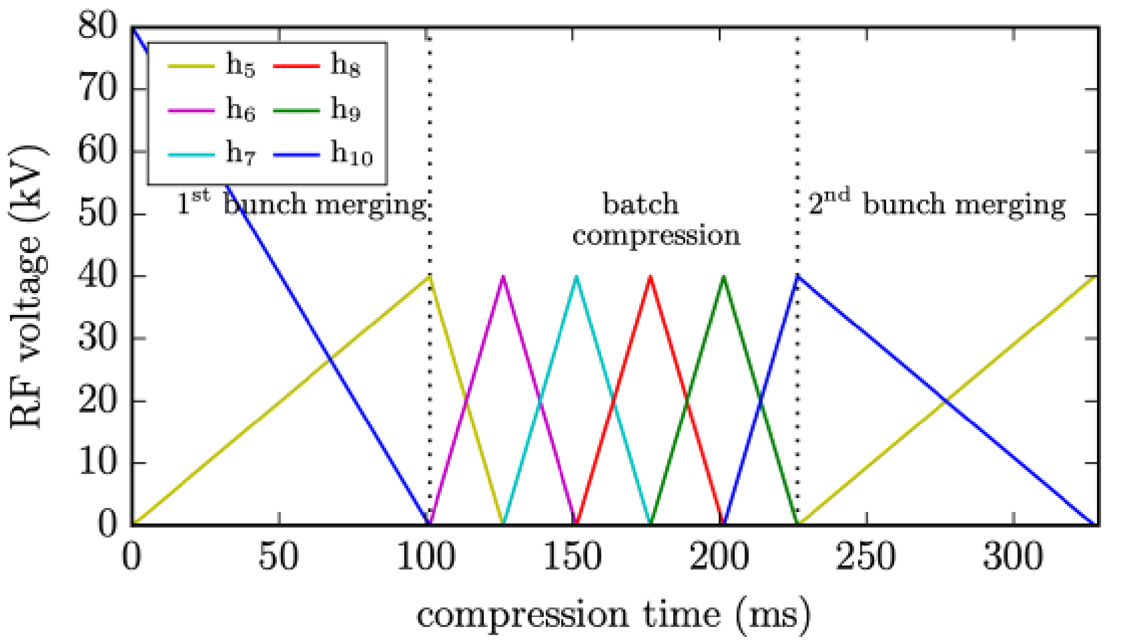
- **First bunch merging: 4 + 2 cavities** (enough for **constant bunching factor**) contributes minimum beam loading effect.
  - → 4 cavities on h10, 2 cavities on h5 (80kV, 40kV)

Comparison: constant ratio 4 + 4 cavities.

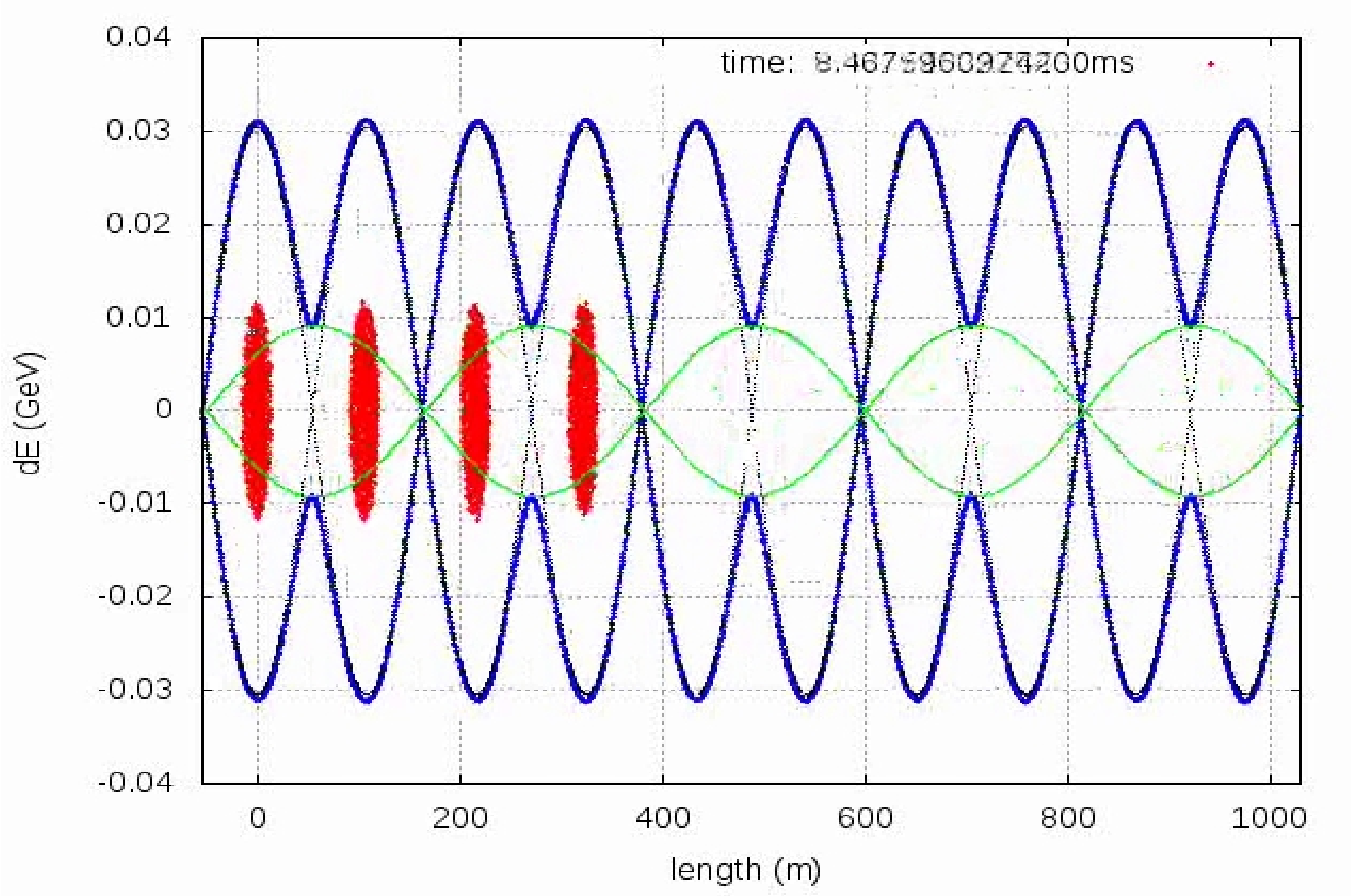
- **Batch compression:** less sensitive to beam loading
  - → 2 cavities (h5 to h10)(40 kV)

- **Final bunch merging**
  - → 2 cavities on both h5 and h10 (40 kV)

  or
  - → 2 cavities on h5 and 1 cavity on h10 (40 kV, 20 kV) (low current)

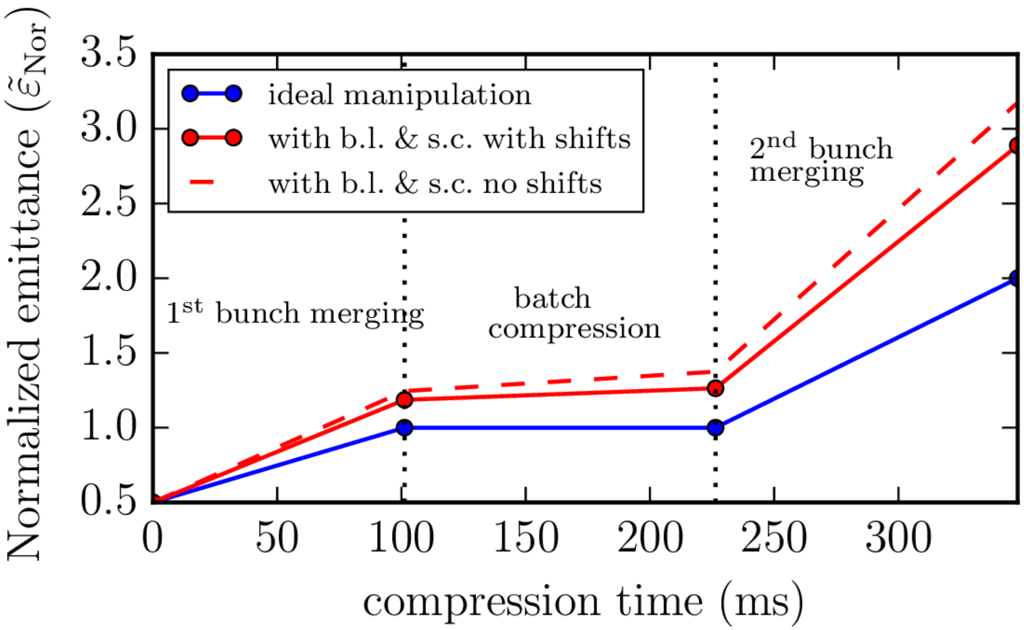


Full rf manipulation with b.l. and s.c.



Movie: Full rf manipulation with high intensity effects

Full rf manipulation with b.l. and s.c.

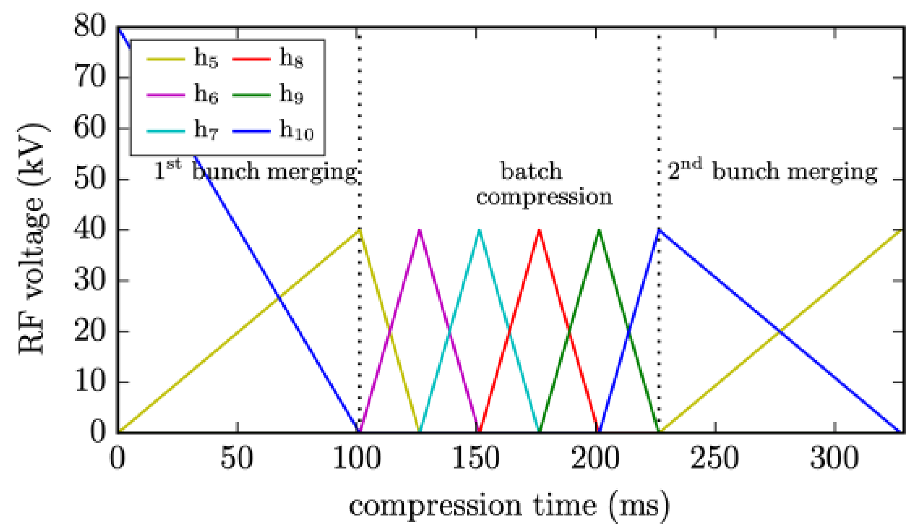


	With shifts	Without shifts
First merging	18.6%	24.5%
Batch compression	26.4%	37.4%
Second merging	44.3%	58.7%

Emittance growth ratio during rf manipulation

Comparison of normalized emittance

RF voltage waveform for bunch manipulation



Summary

- RF manipulation (bunch merging and batch compression) in SIS-100 are investigated by using the simulation code pyORBIT.

- The full rf manipulation towards a single bunch in SIS-100 is shown, using an example ramp.

- Intensity effects (s.c. & b.l.) are included.

- Optimized ramp parameters are used to minimize the emittance growth caused by intensity effects.

Thanks for your attention!

Appendix I Space charge calculation (Elliptical model)

- Space charge voltage is calculated based on the **elliptical model**, in which the space charge forces are linear

  - Elliptical model

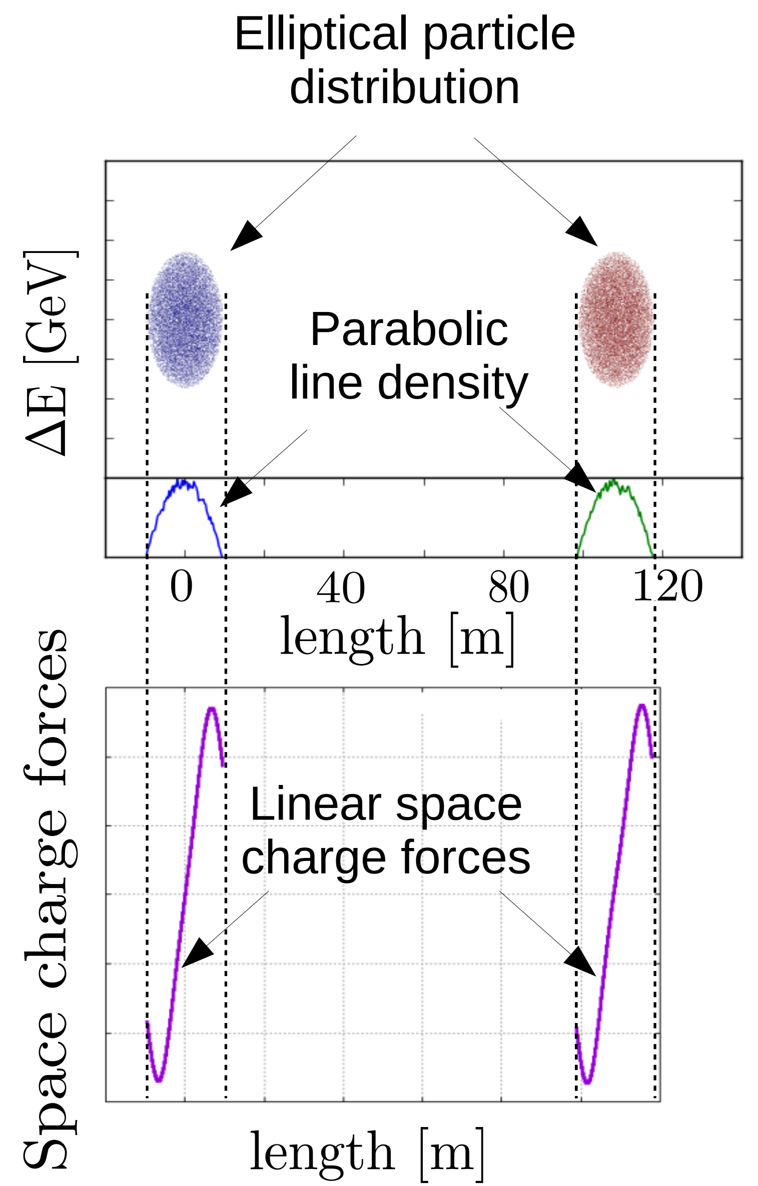
    ↓

    Parabolic line density

    ↓

    Linear space charge forces

- With space charge, the rf voltage should be increased to compensate the space charge defocusing force (voltage)



Appendix II Beam loading calculation model

- The parallel RLC circuit seen by the beam
  - Cavity impedance

$$Z_{\rm bl}(\omega) = \frac{R_{\rm sh}}{1 + iQ_c(\omega/\omega_r - \omega_r/\omega)}.$$

Shunt impedance ($R_{\rm sh}$), Q-value (Q_c), Resonant frequency (ω_r)

  - Beam loading Induced-voltage

$$V_{\rm bl}(z) = -\sum_{n=0}^{\infty} I_n Z_n e^{inz/R}$$

beam current spectrum (I_n)

Appendix III Beam loading matching

- The bunches are matched to beam loading, obtained via a shift

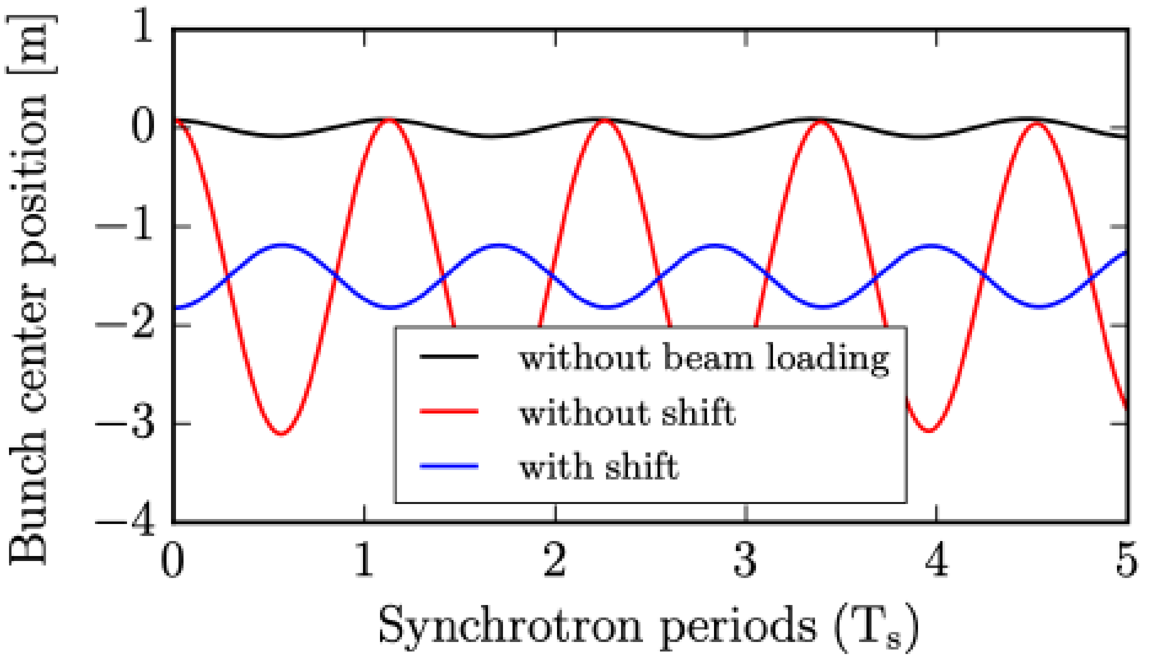
$$\Delta\phi_{\mathrm{bl}} = \mathrm{asin}(\frac{V_{\mathrm{bl0}}}{V_{\mathrm{rf}}})$$

The b.l. voltage at the bunch center

RF voltage

Matching shift

Evolution of the (bunch center) dipole oscillation



Red: b.l., without matching shift

Blue: b.l., with matching shift

Black: no b.l., for comparison

- Beam center oscillation largely reduced by $\Delta\Phi_{bl}$

Appendix IV Beam loading shifts

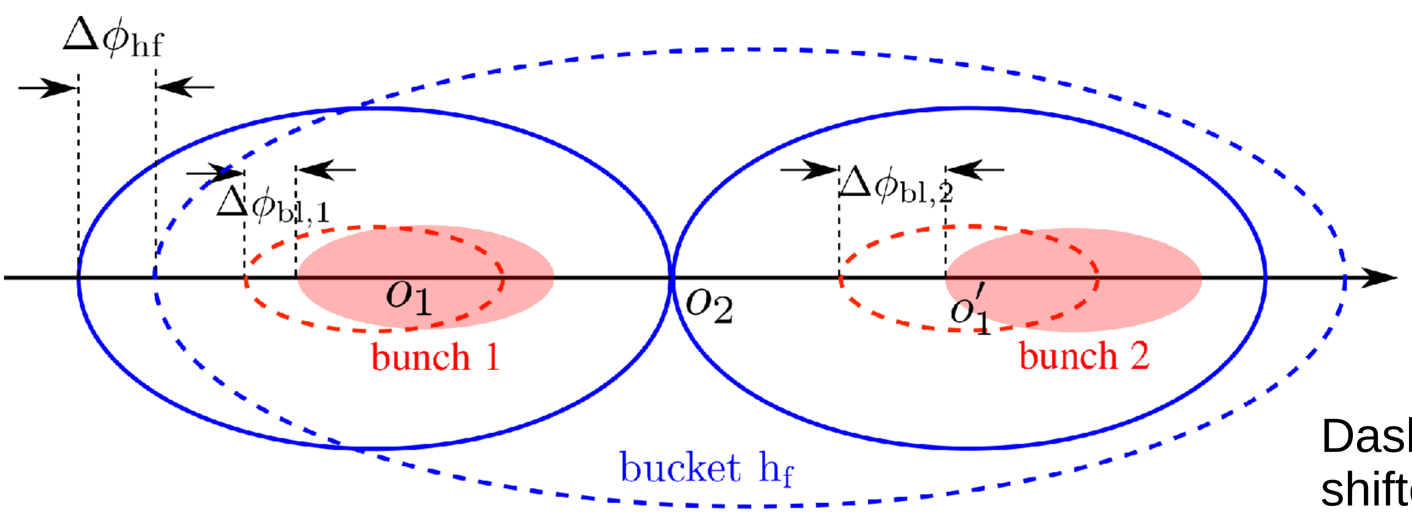
- The **matching shifts** $\Delta\Phi_{bl,i}$ for bunches are different, since the b.l. voltage depends on the positions

- However, $\Delta\Phi_{bl,i}$ break the symmetry during bunch merging

- To compensate the symmetry, the **symmetry shift** $\Delta\Phi_{hf}$ is added on the harmonics (cavities), satisfying

$$\Delta\phi_{\mathrm{hf}} = \frac{1}{2}(\Delta\phi_{\mathrm{bl},1} + \Delta\phi_{\mathrm{bl},2})$$

Symmetry shift



Dashed line:
shifted harmonic

Appendix V: Summary of the last discussion

- Bunch merging with constant bunch ratio
- Space charge can be well compensated via an matched rf voltage.
- Beam loading can be compensated partly via phase shifts.
- Beam loading can cause dipole oscillations, and more serious than space charge.