Longitudinal manipulations with intensity effects in SIS-100

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Outline

- Introduction
- Choice of key parameters: rf voltage ramps, phases and merging time
- Intensity effects: Longitudinal space charge and cavity beam loading
- Simulation of longitudinal manipulation of proton bunches with optimized parameters (two examples)
- Simulation of heavy ion (U^{28+}) bunch manipulation including fast bunch rotation with optimized parameters
- Summary

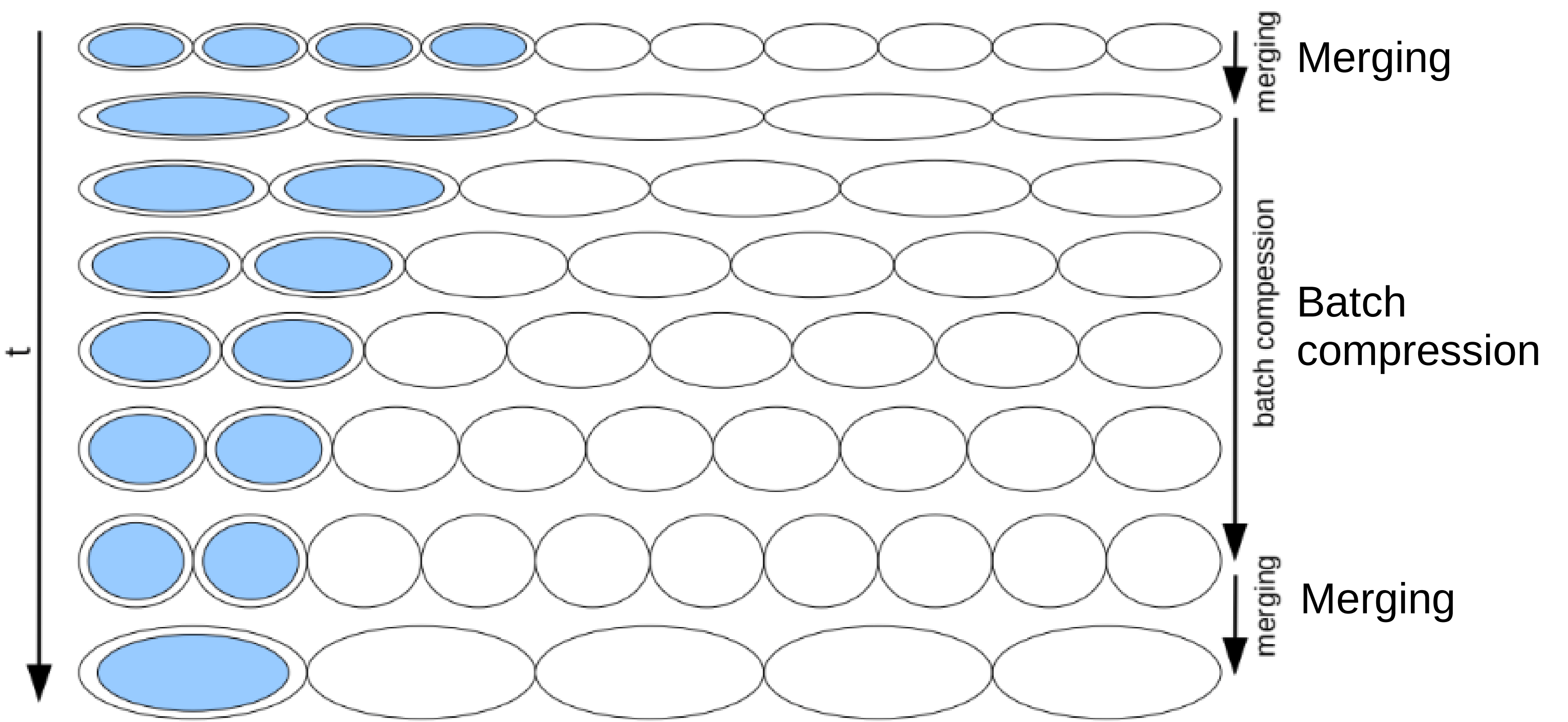
Introduction

- 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)

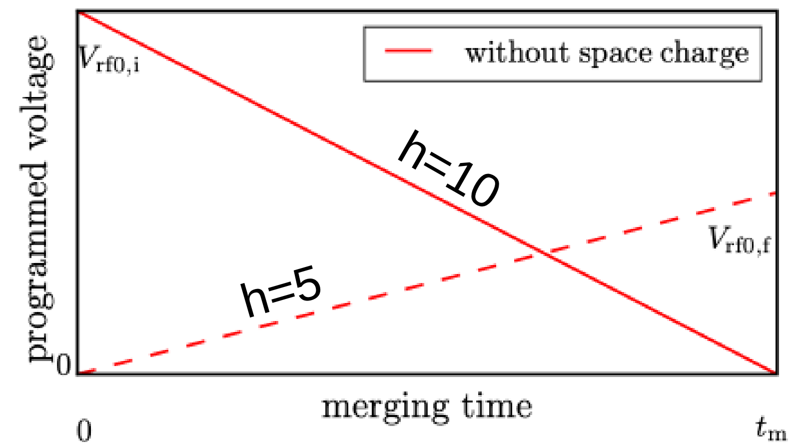
  3) Second merging: 2 bunches (h=10) → 1 bunch (h=5)



Choice of key parameters

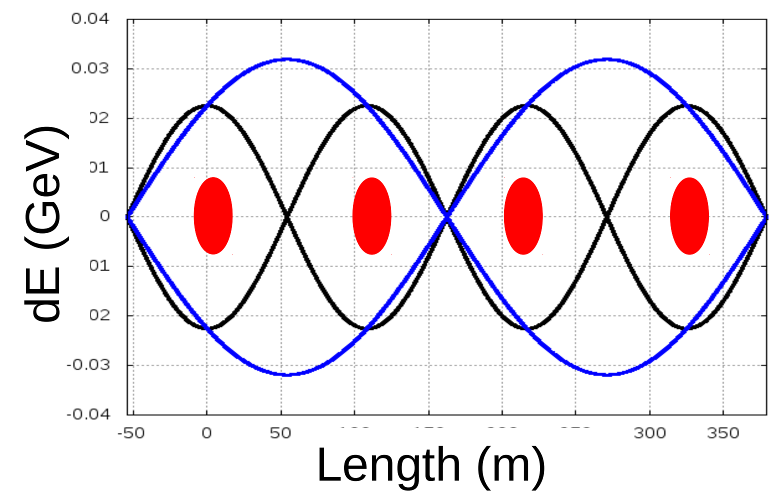
- Bunch merging with constant bunching factor
  - Bunching factor defined as $B_f = \dfrac{\text{bunch length}}{\text{bucket length}}$

Longitudinal emittance	$\epsilon_{L,f} = 2\epsilon_{L,i}$
Bunch length	$\hat{l}_f = 2\hat{l}_i$
Momentum spread	$\hat{\delta}_f = \hat{\delta}_i$



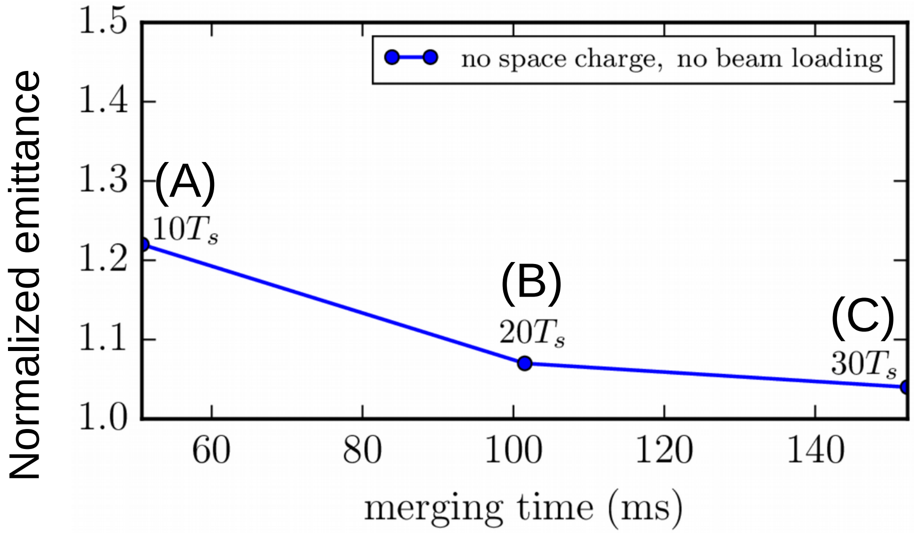
- Matched RF voltage $V_{\mathrm{rf,i}} = 2V_{\mathrm{rf,f}} = 66kV$

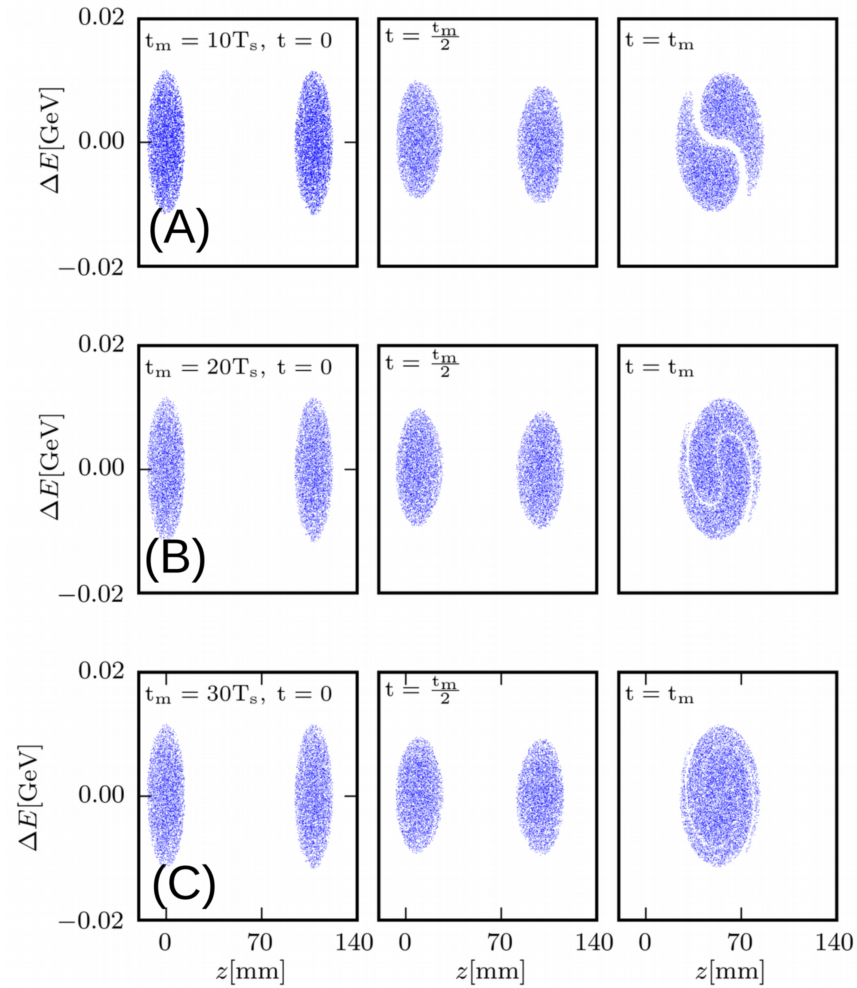
- RF phase $\phi_1 = 0, \phi_2 = 90^\circ$



Choice of parameters for bunch merging

- Merging time can be determined via simulation results
  - ~100 ms (20Ts) can ensure a good emittance conservation



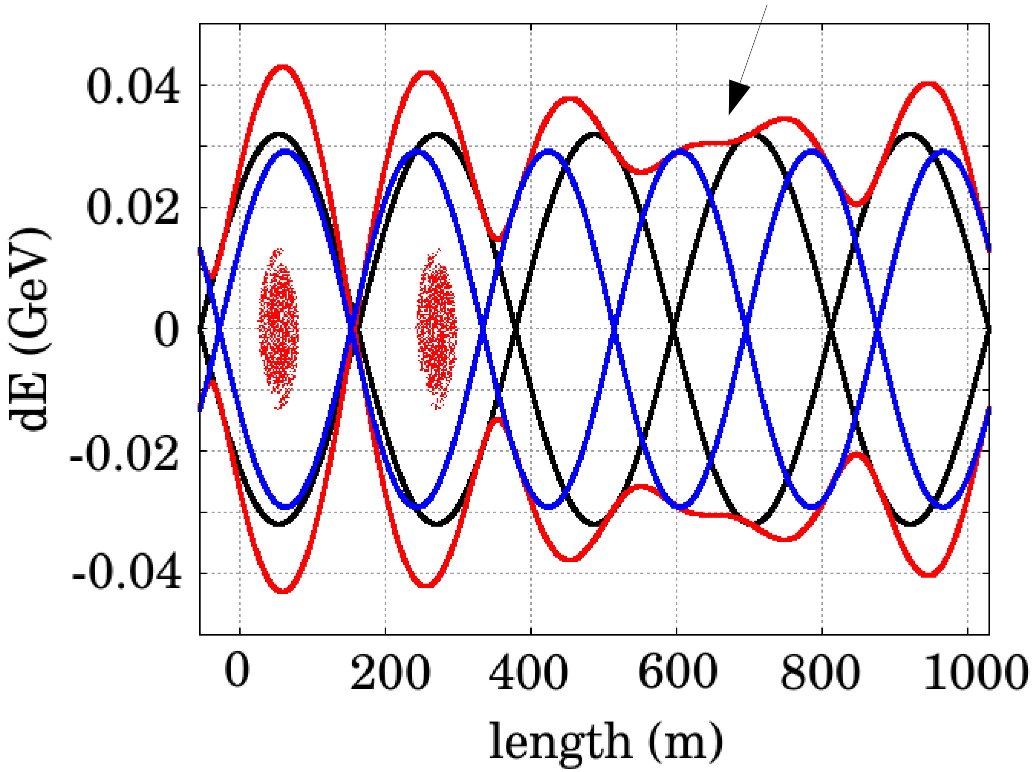


Case	Synchrotron period (T_s)	Turns (n)	time (t_m, ms)
A	10	6650	50.8
B	20	13300	101.6
C	30	26600	203.2

pyORBIT is employed for the simulation

Choice of parameters for batch compression

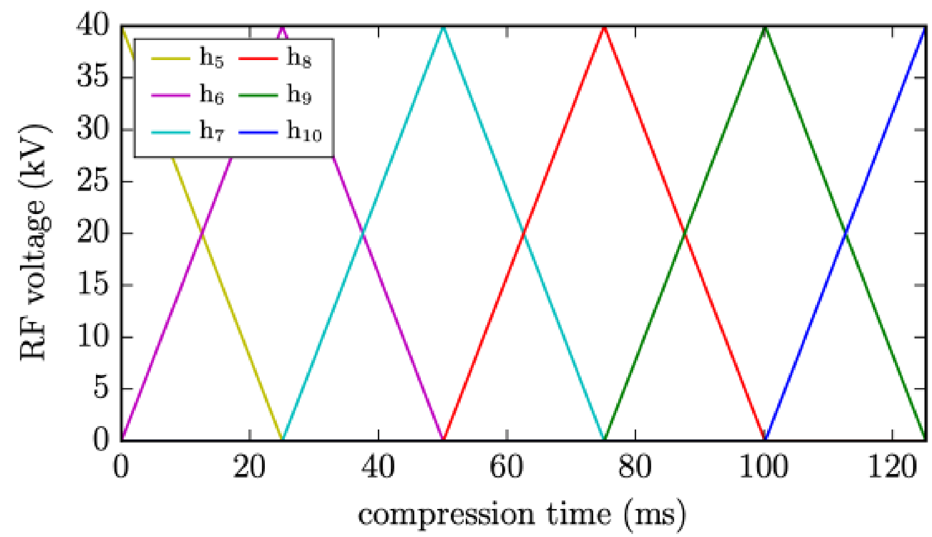
- For short bunch train, modulation effect is not a problem



Batch compression with harmonics on h =5 and h =6 (at V5 = V6)

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

- The emittance growth is less sensitive to the rf voltage than during bunch merging. Equal voltage amplitude on harmonic is chosen.



rf voltage ramps for batch compression

Intensity effects – longitudinal space charge

- Space charge can be well-compensated via increasing external rf voltage

- Space charge parameter $$\Sigma_{\mathrm{sc}} = \frac{V_{\mathrm{sc}}}{V_{\mathrm{rf}}}$$

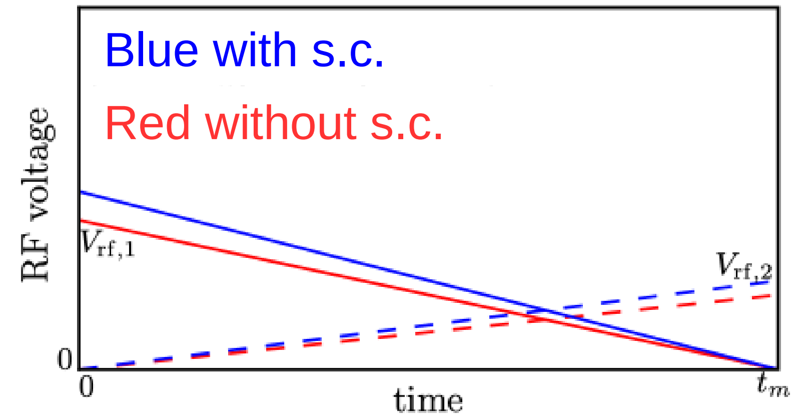
➔ e.g. For bunch merging on SIS-100, (rms emittance 6.26 m × 0.0011)

s.c.voltage

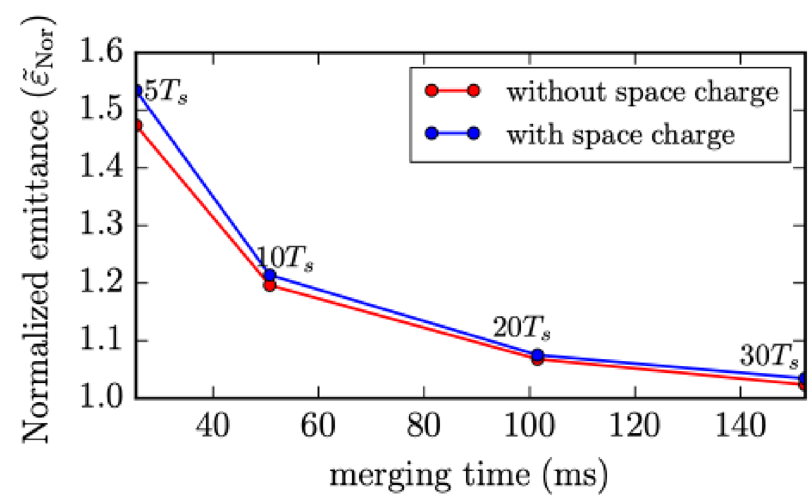
$$V_{\mathrm{rf,sc,i}} = 66.0 + \boxed{12.7} = 78.7\ \mathrm{kV}$$

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

$$\Sigma_{\mathrm{sc}} = 0.19$$



Matched rf voltage ramps without/with s.c.



Final emittance under different merging time without/with s.c.

Intensity effects – cavity beam loading

- Beam loading can be evaluated by RLC model
  - e.g. Initial beam loading voltage of four bunches on SIS-100,

$$V_{\mathrm{bl0}} = 7.61, 9.79, 15.1, 16.2\ \mathrm{kV}$$

- Beam loading matching shifts

$$\Delta\phi_{\mathrm{bl}} = \mathrm{asin}\left(\frac{V_{\mathrm{bl0}}}{V_{\mathrm{rf0}}}\right)$$

- Beam loading parameter

$$\Sigma_{\mathrm{bl}} = \frac{V_{\mathrm{bl0}}}{V_{\mathrm{rf0}}}$$

to evaluate the contribution of the beam loading

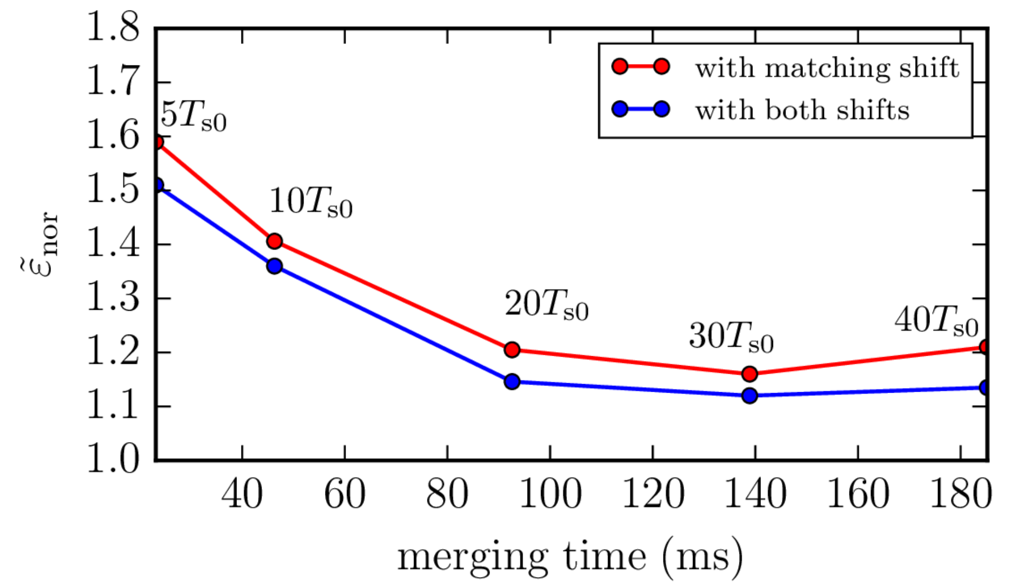
Parameters [unit]	Symbols	Initial value
Resistance [Ω]	R_{sh}	2000
Resonant freq. [Mhz] on h=10	$f_{res,h=10}$	2.72
Resonant freq. [Mhz] on h=5	$f_{res,h=5}$	1.36
Quality factor on h=10	$Q_{h=10}$	10.6
Quality factor on h=5	$Q_{h=5}$	5.3

Beam loading parameters in SIS-100

- The cavity number should be as few as possible to minimize the beam loading effect

Bunch merging with intensity effects

- Choice of merging time
  - Longer merging time
    - Better merged
    - Longer beam loading effect
  - Preferred: **100 ms**



Final emittance growth with beam loading and space charge

- Two beam loading compensation shifts
  - "Matching shift" for initial matching

$$\Delta\phi_{\rm bl} = {\rm asin}(\frac{V_{\rm bl0}}{V_{\rm rf0}}) = {\rm asin}(\Sigma_{\rm bl})$$

  - "Symmetry shift" for keeping the merging to be symmetrical

Red: with initial matching shift

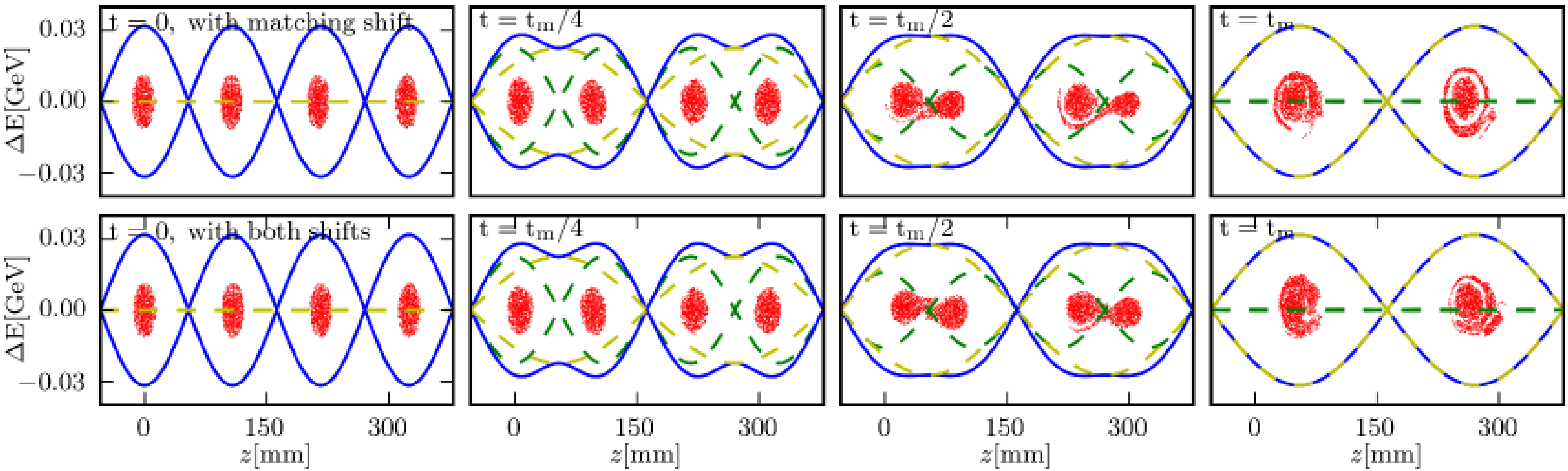
Blue: with both shifts (reduced emittance)

$$\Delta\phi_{\rm h} = \frac{1}{n_b}\sum_{j=1}^{n_b}\Delta\phi_{\rm bl,j}$$

(A physics paper to be submitted.)

Bunch merging with intensity effects

- Simulation results



Upper: with matching shift

Lower: with both shifts

- The emittance growth reduces with the symmetry shift.

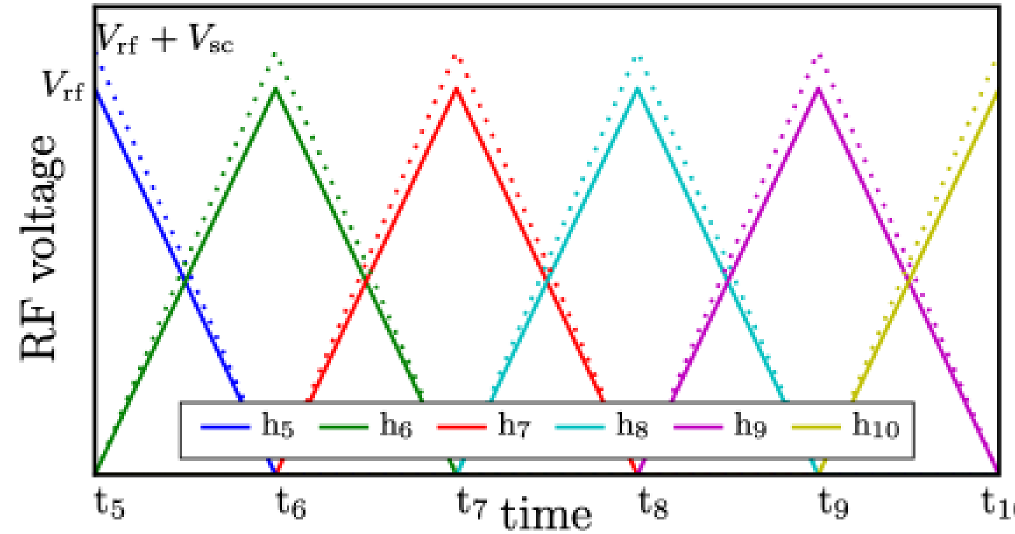
- Merging time: 100 ms

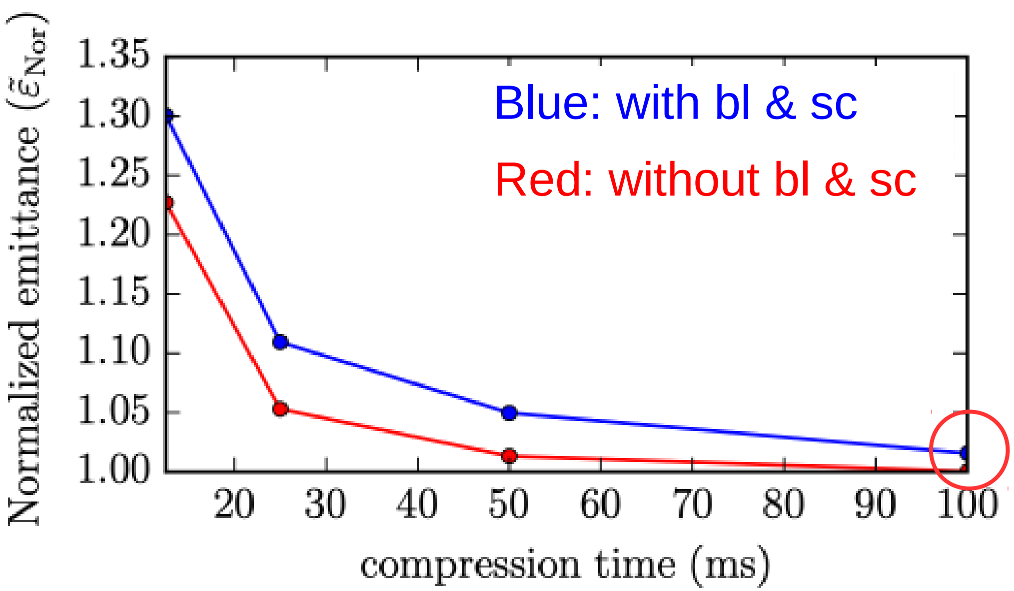
Batch compression with intensity effects

Rf voltage ramps with space charge matching for batch compression

$V_{\mathrm{rf}} = 33\ \mathrm{kV}$ Solid line

$V_{\mathrm{rf,sc}} = 39.4\ \mathrm{kV}$ Dashed line

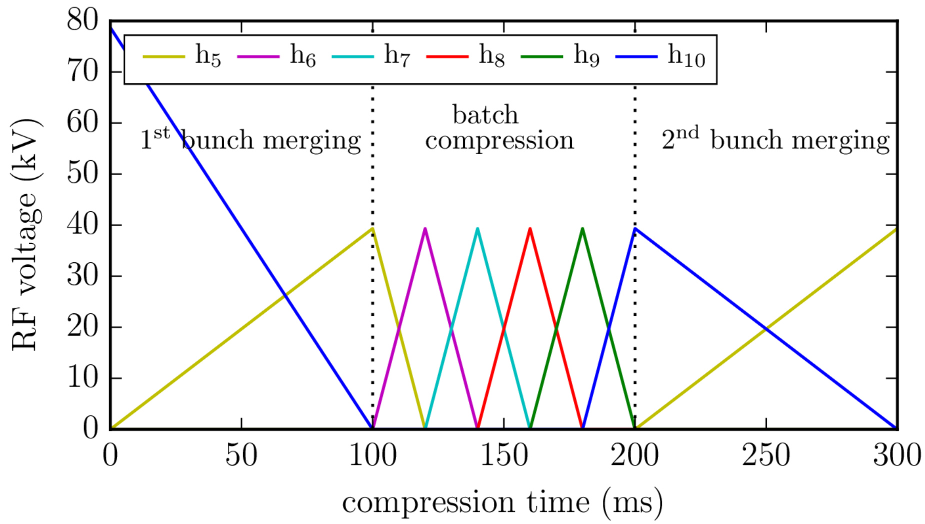




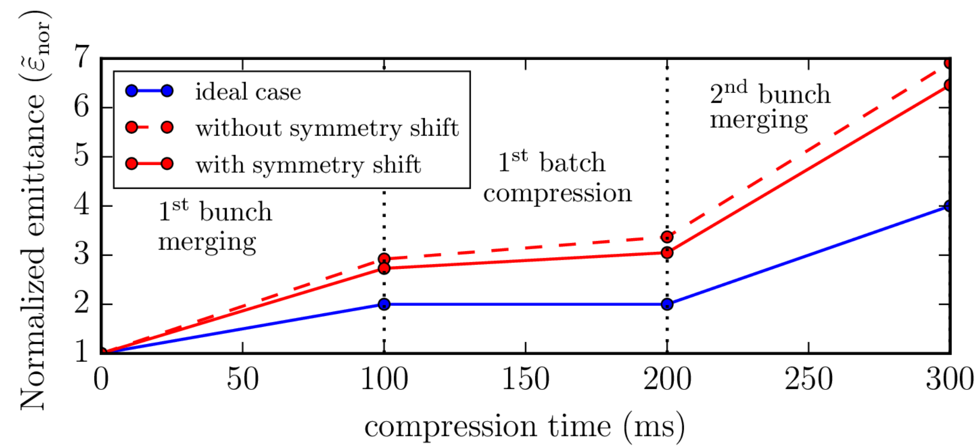
Emittance growth with different compression time

- During batch compression the beam loading effect is weaker (~2% emittance growth) than in bunch merging (~ 20%)

An example of proton bunch manipulation



Example rf voltage amplitude ramps



Emittance growth

Red: with both compensation shifts

Dashed red: without symmetry shift

Blue: ideal case

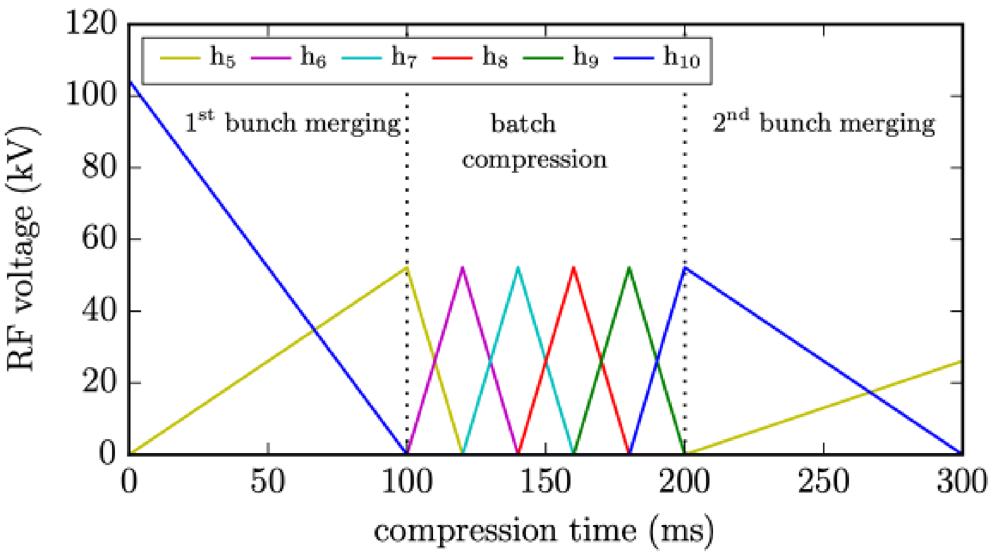
Parameters [unit]	Initial value	End of first merging	End of batch compression	End of second merging
Total emittance growth	-	36.5%	44%	59%
Bunching factor	0.18	0.21	0.34	0.37
rms bunch length [m]	6.25(*4)	13.4, 14.1	12.1, 13.9	23.5
rms momentum spread($\times10^{-3}$)	1.11(*4)	1.31, 1.42	1.52, 1.58	1.89

An example of proton bunch manipulation

Parameters [unit]	Initial	End of first merging	End of batch compression	End of second merging
rf voltage [kV]	78.7	39.35	39.35	39.35
Harmonic number	10	5	10	5
Bare synchrotron tune [$\times 10^{-4}$]	8.0	4.0	5.6	4.0
Compression time[ms]	-	100	100	100
Phase on h_{10}	0	0	180+180	0
Phase on h_9	-	-	144+162	-
Phase on h_8	-	-	108+144	-
Phase on h_7	-	-	72+126	-
Phase on h_6	-	-	36+108	-
Phase on h_5	90+4.2	0	0+90	90
Cavity numbers	8	8	6	6

Main parameters for the proton bunch manipulation

Second example of proton bunch manipulation



Proposed rf voltage ramps for the second case.

Doubled emittance

Reference emittance

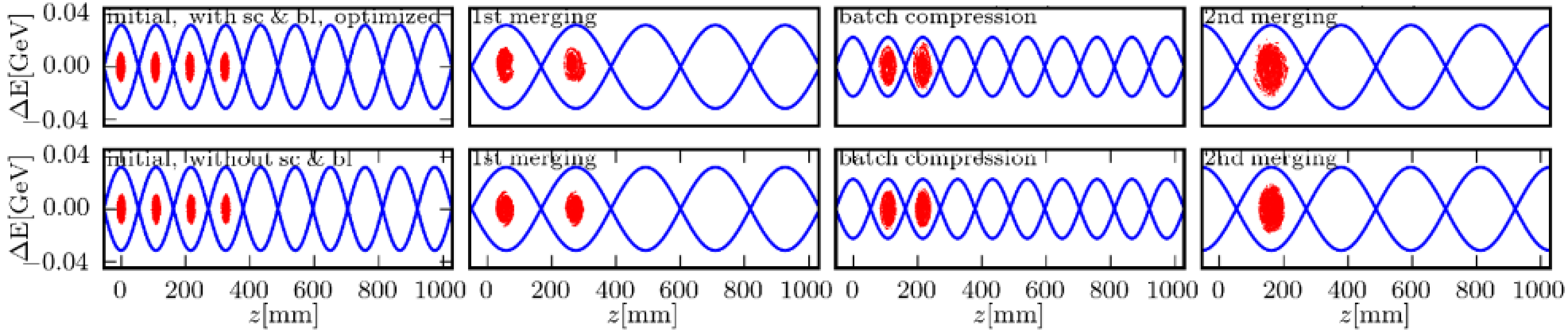
Parameters [unit]	First example	Second example
Initial rms bunch length [m]	6.25	4.42
Initial rms dp_p [10^{-3}]	1.11	0.78
Matched Voltage [kV]	78.7	104.3
beam loading voltage [kV]	12.2	20.6
Space charge voltage [kV]	12.7	38.3
Σsc	0.192	0.58
Σbl	0.154	0.197

Comparison of the parameters in two examples

Second example of proton bunch manipulation

- Simulation result

Initial | *1st merging* | *Batch compression* | *2nd merging*



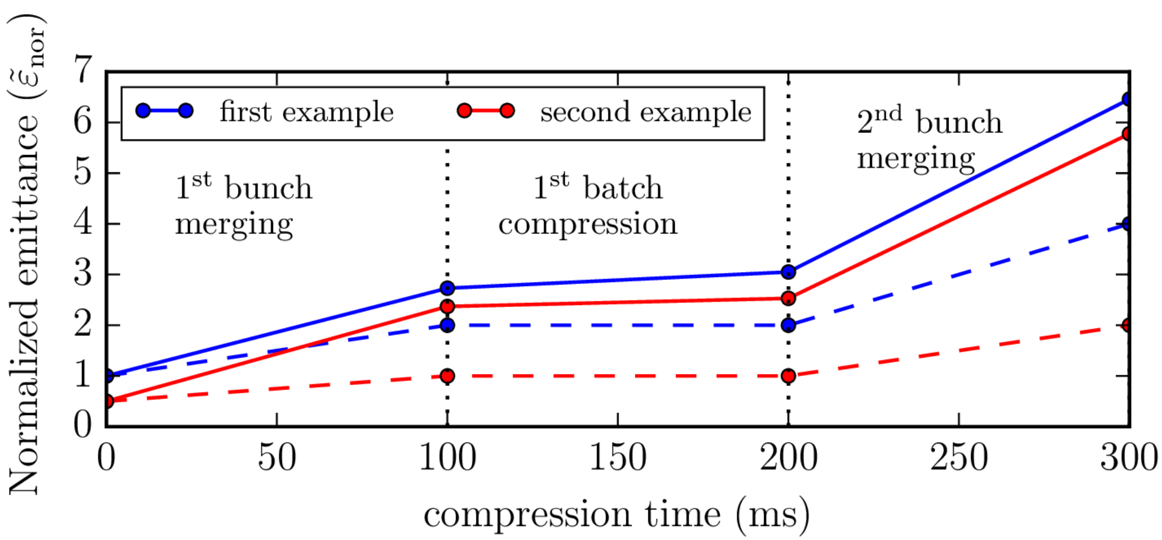
Particle distribution in the phase space during bunch manipulation

Red: Second example

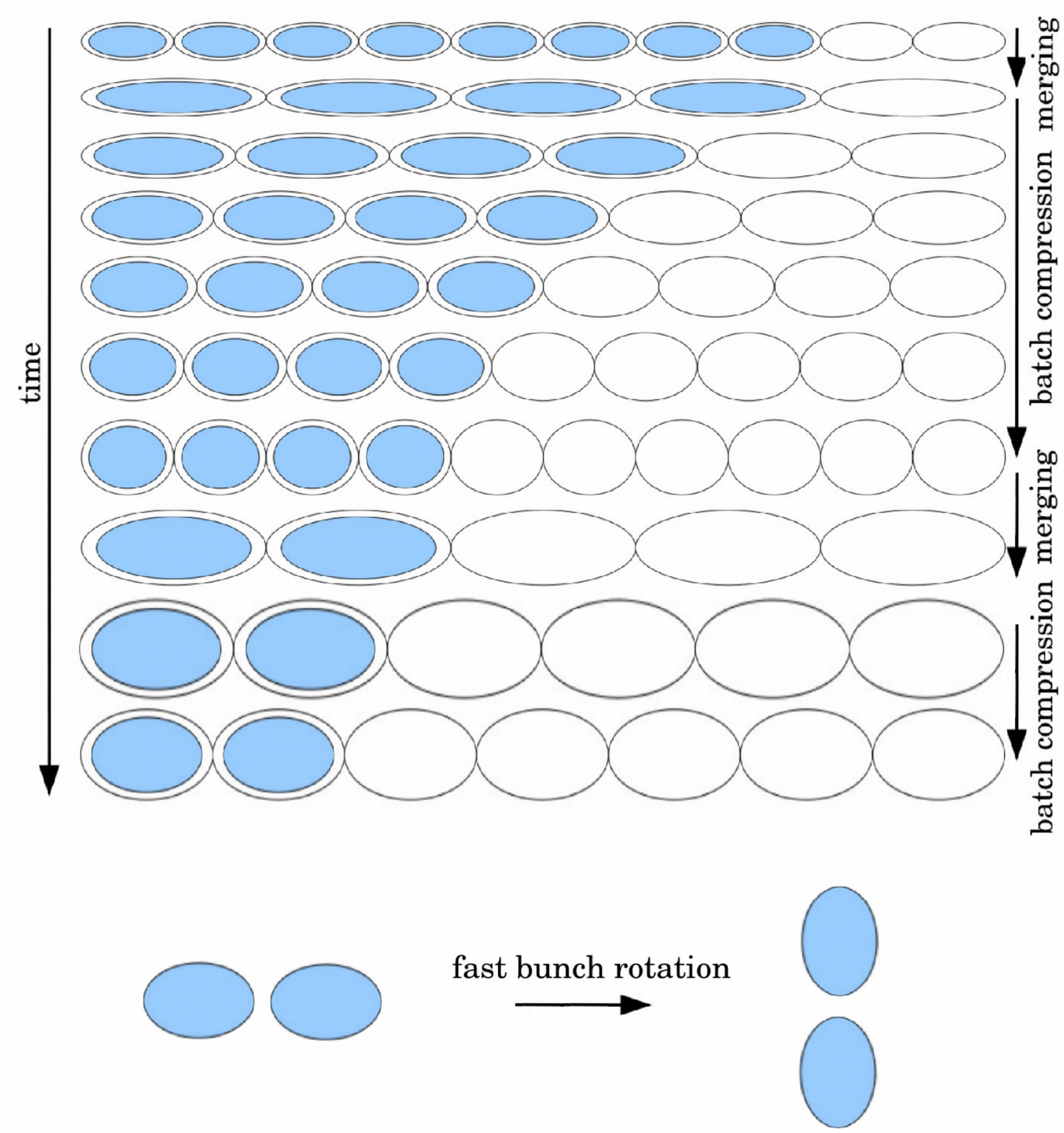
Blue: First example

Dashed line: ideal case
Solid line: with intensity effects

- The emittance growth is not sensitive to the initial emittance



Proposed schemes for heavy ion (U^{28+}) bunch manipulation



First merging (h= 10 to 5)

First batch compression (h = 5 to 10)

Second merging (h= 10 to 5)

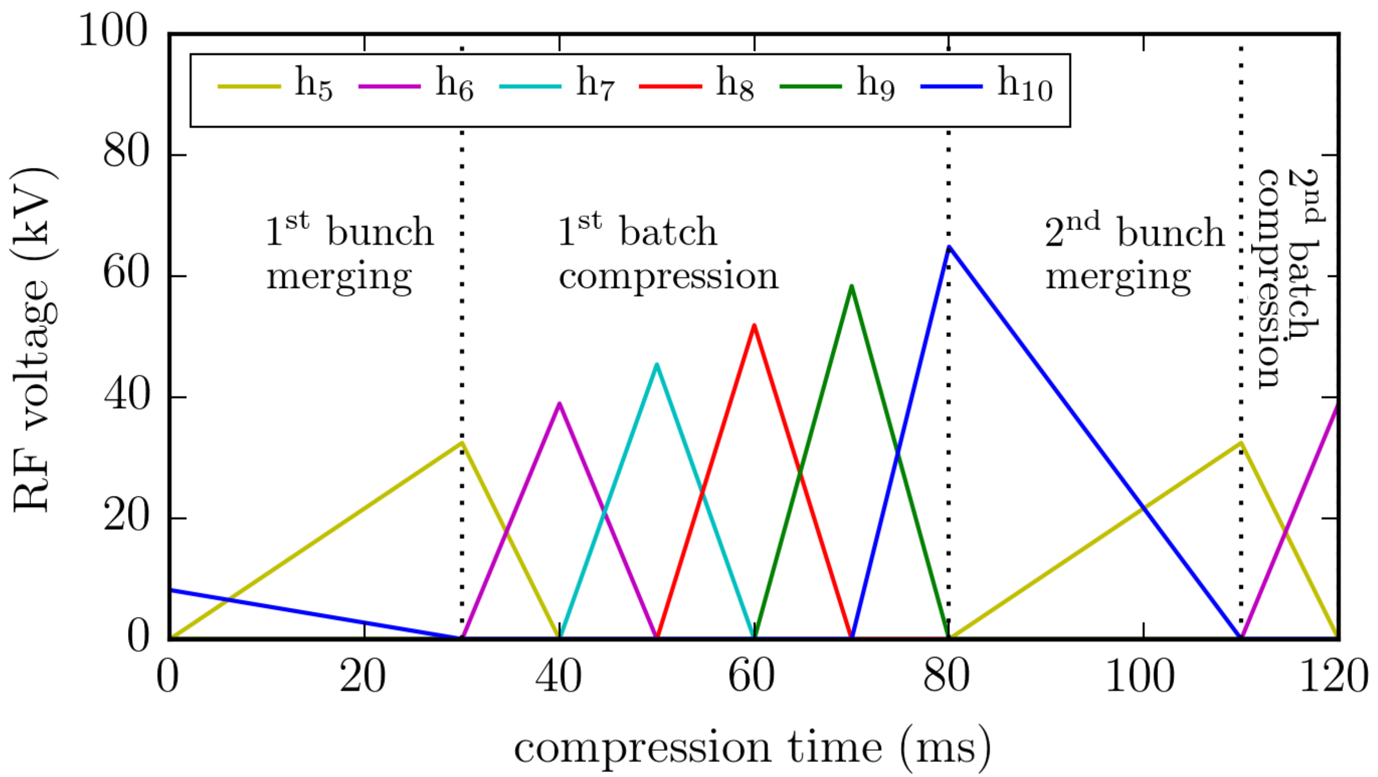
Second batch compression (h= 5 to 6)

Fast bunch rotation

Proposed heavy ion manipulation scenario after optimization

Proposed rf voltage ramps for heavy ion manipulation

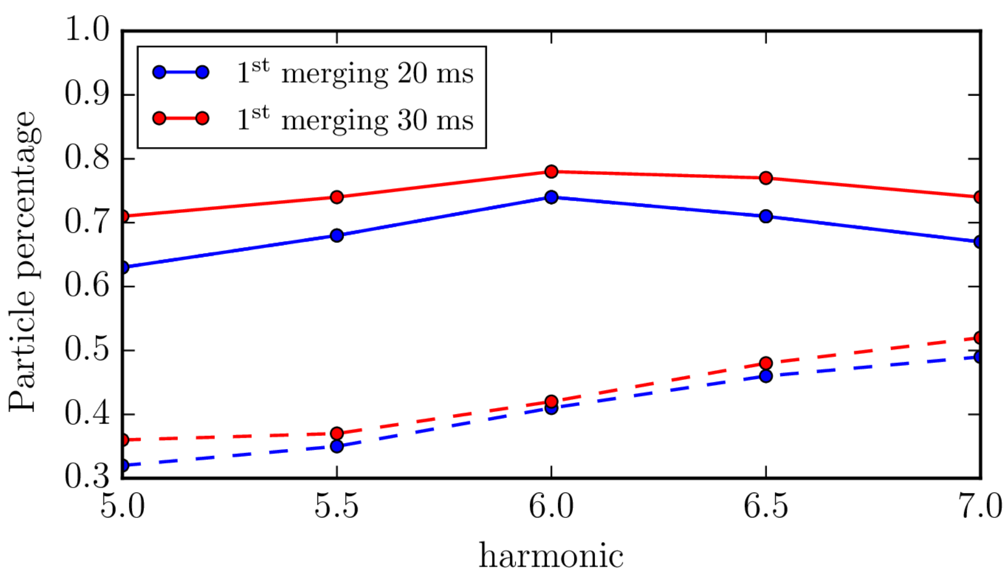
- For 1st merging and batch compression: voltages in h=5 increase fast to provide a large bucket area (acceptance).
- For 2nd merging, voltages in h=5 halved to generate a longer bunch length
- For 2nd batch compression h=5 to 6, distance decreased



Design of fast bunch rotation

- Large distance leads to large filamentation (limited voltage 360 kV)

  ➡ Rotation of two bunches after batch compression



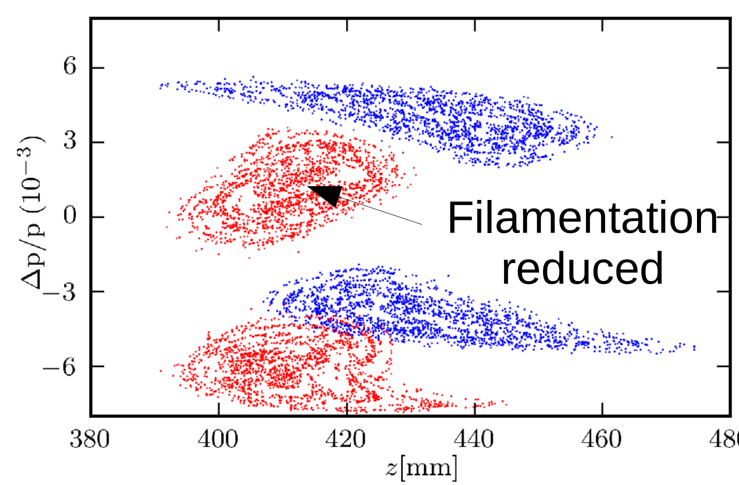
- Beam loading can dampen the filamentation

  ➡ Beneficial effects

  (Deserves a further study)

Parameter [unit]	Symbol	Value
Q-factor	Q	2
Shunt impedance [Ohm]	R_{sh}	1000
Cavity number	n_{cav}	9
Maximum voltage [kV]	V_{rf}	40
Harmonic	h	2
Rotation voltage	$V_{rotation}$	360

Model of bunch compression cavity



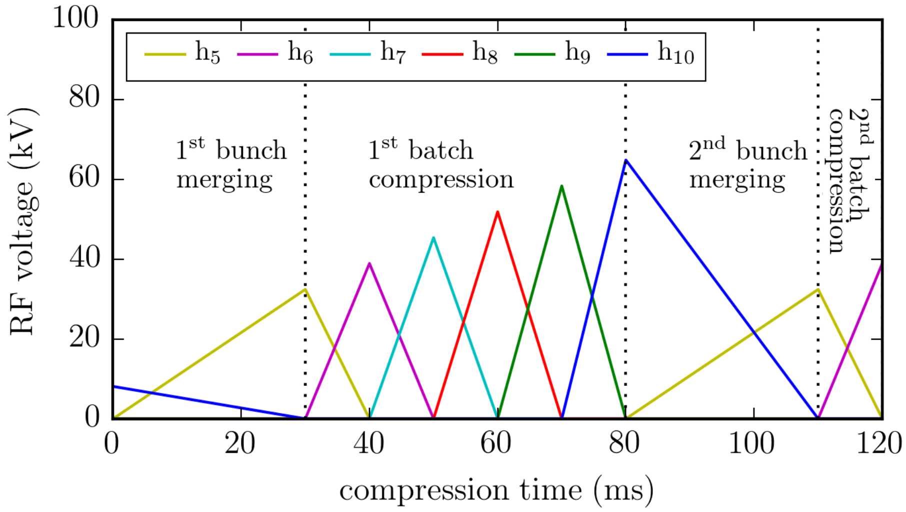
Design of fast 90° bunch rotation

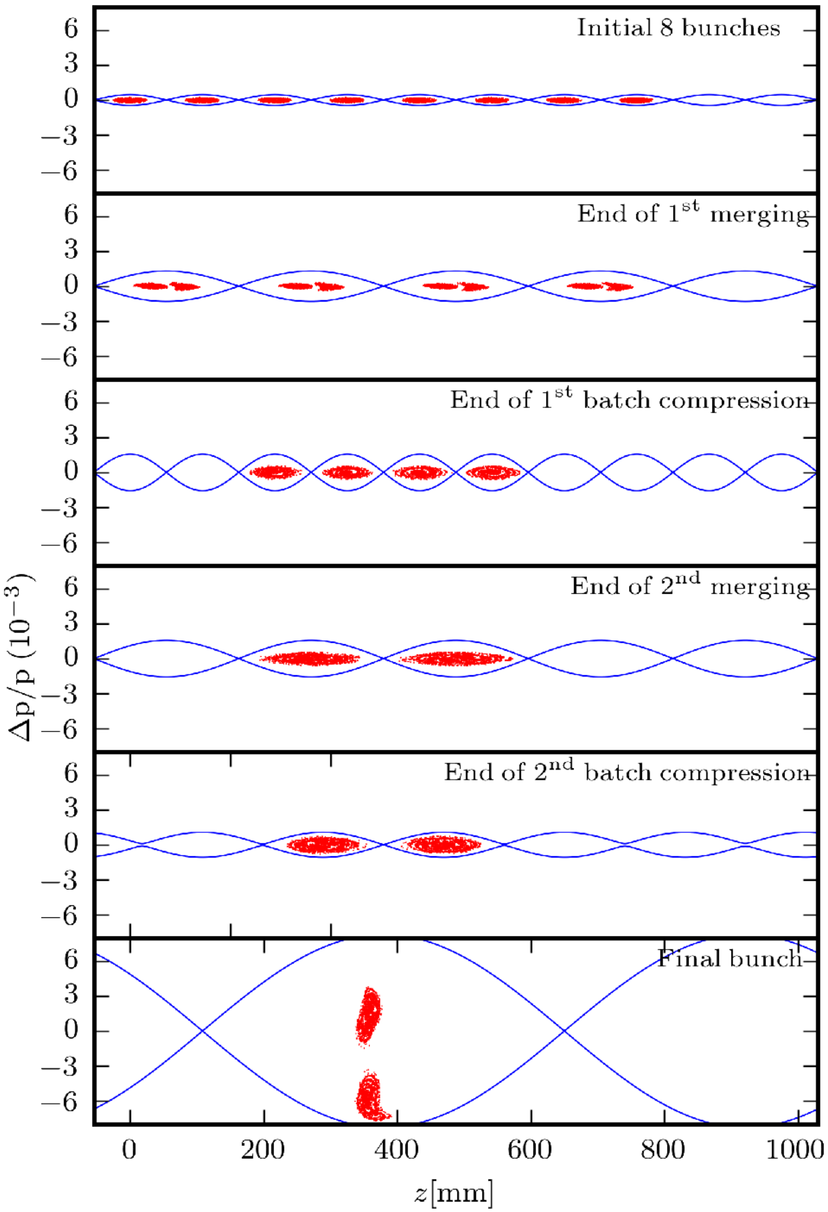
- Main parameters for the fast bunch rotation

Parameters [unit]	Initial	1st bunch merging	1st batch compression	2nd bunch merging	2nd batch compression	Fast rotation
rf voltage [kV]	8.1	32.4	64.8	32.4	38.9	360.0
harmonic	10	5	10	5	6	2
cavity numbers	3	3	5	5	4	9
rms bunch length [m]	11.6	25.6	21.4	25.3	24.2	6.1
rms momentum spread [$\times 10^{-4}$]	1.1	1.4	2.0	3.3	4.1	37.5

More detailed parameters can be found in the technical report

Simulation results of fast bunch rotation





Parameters [unit]	Value
particle percentage within 70 ns window	87%
(2σ) bunch length [m] (target / simulation)	9.7 / 8.74
(2σ) momentum spread (target / simulation)	5×10^{-3} / 3.75×10^{-3}

Designed final bunch parameters

An important criteria: compression time as short as possible

Summary

- Longitudinal bunch manipulation (bunch merging and batch compression) in SIS-100 including high intensity effect are investigated.

- Bunch merging scenario with tolerable emittance growth are demonstrated

- Manipulation of four proton bunches towards a single bunch in SIS-100 is shown, using an example ramp.

- Manipulations of eight U28+ bunches towards a single bunch, including fast bunch rotation: an optimized scenario to meet the user requirements

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

The report available at https://repository.gsi.de/record/238378

Thanks for your attention!

Appendix I Space charge calculation (Elliptical model)

- Space charge voltage is calculated based on the **elliptical model**

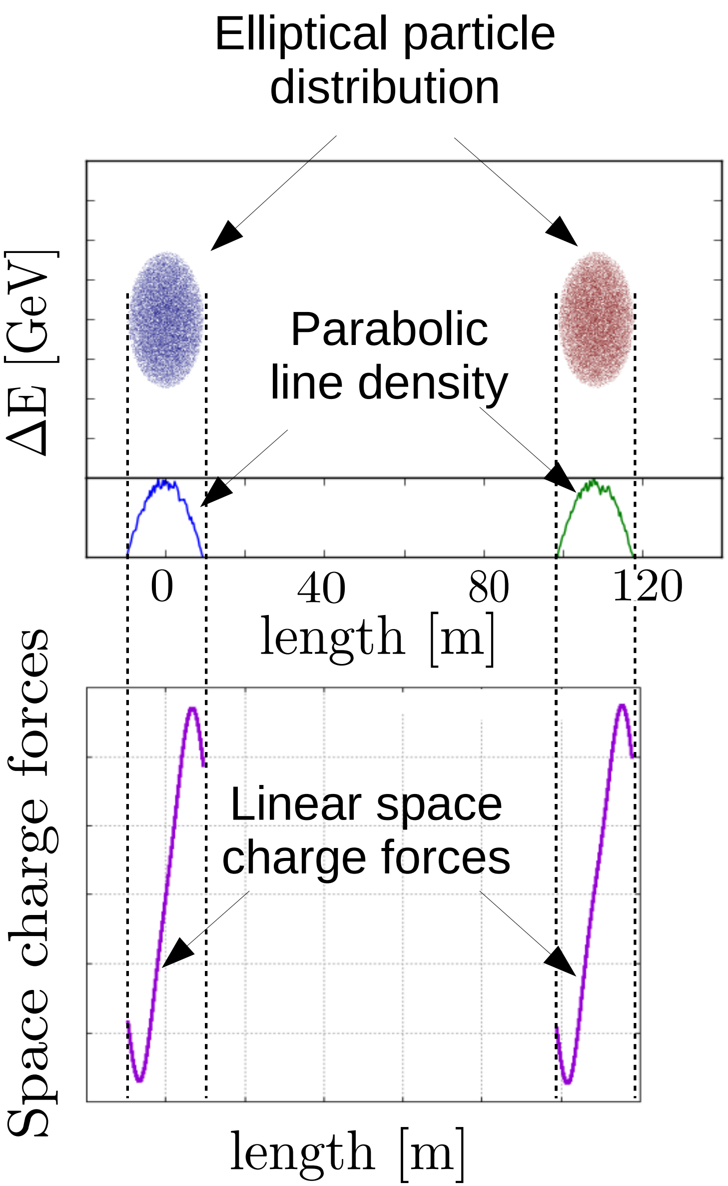
  - Elliptical model

    ↓

    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

Shunt impedance

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

Q-value

Resonant frequency

  - Beam loading Induced-voltage

beam current spectrum

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

Appendix III Beam loading shifts

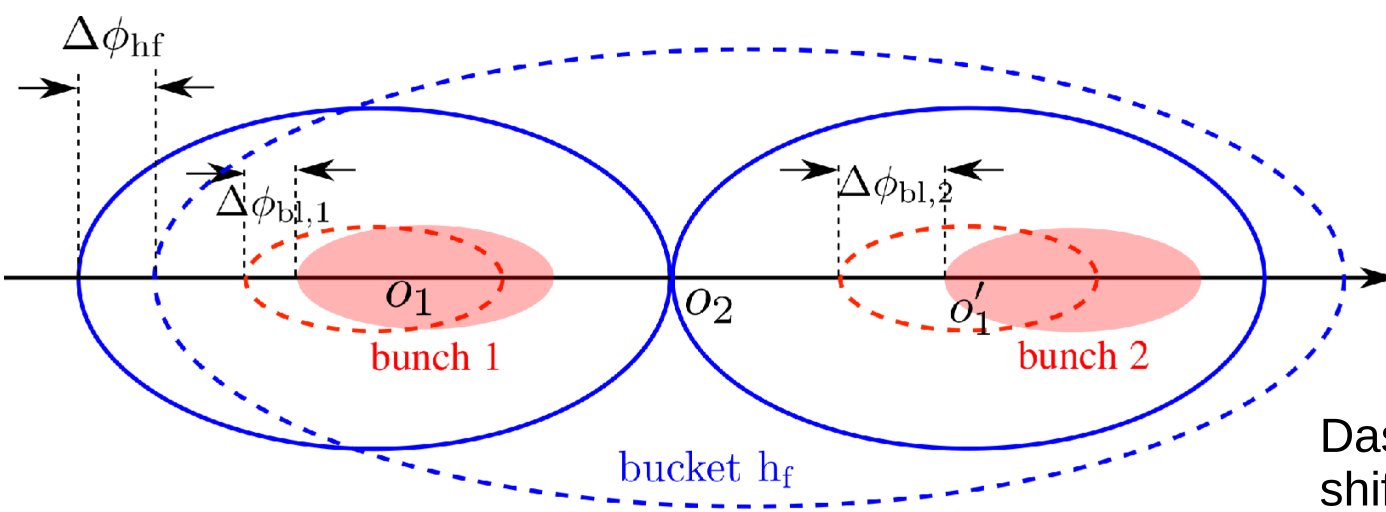
- The **matching shifts** $\Delta\Phi_{bl,i}$ for bunches are different, since the b.l. voltage depends on the positions

- 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

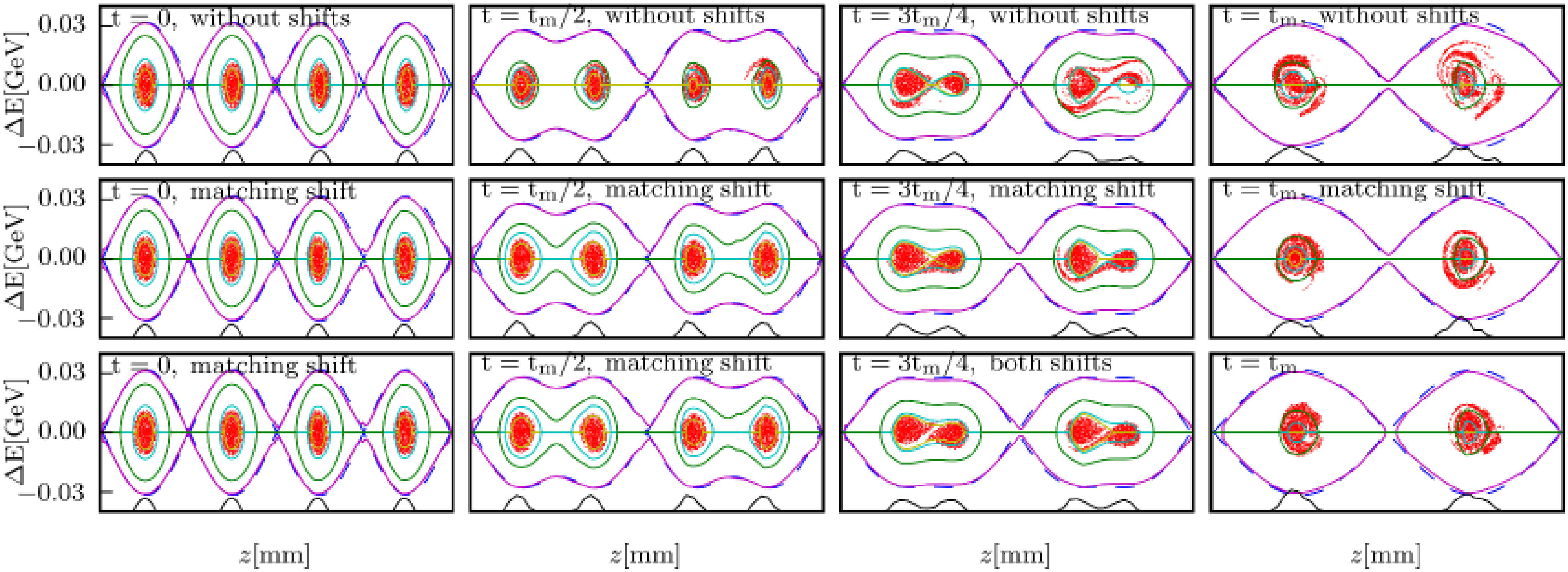
$$\Delta\phi_{\rm hf} = \frac{1}{2}(\Delta\phi_{\rm bl,1} + \Delta\phi_{\rm bl,2})$$

Symmetry shift

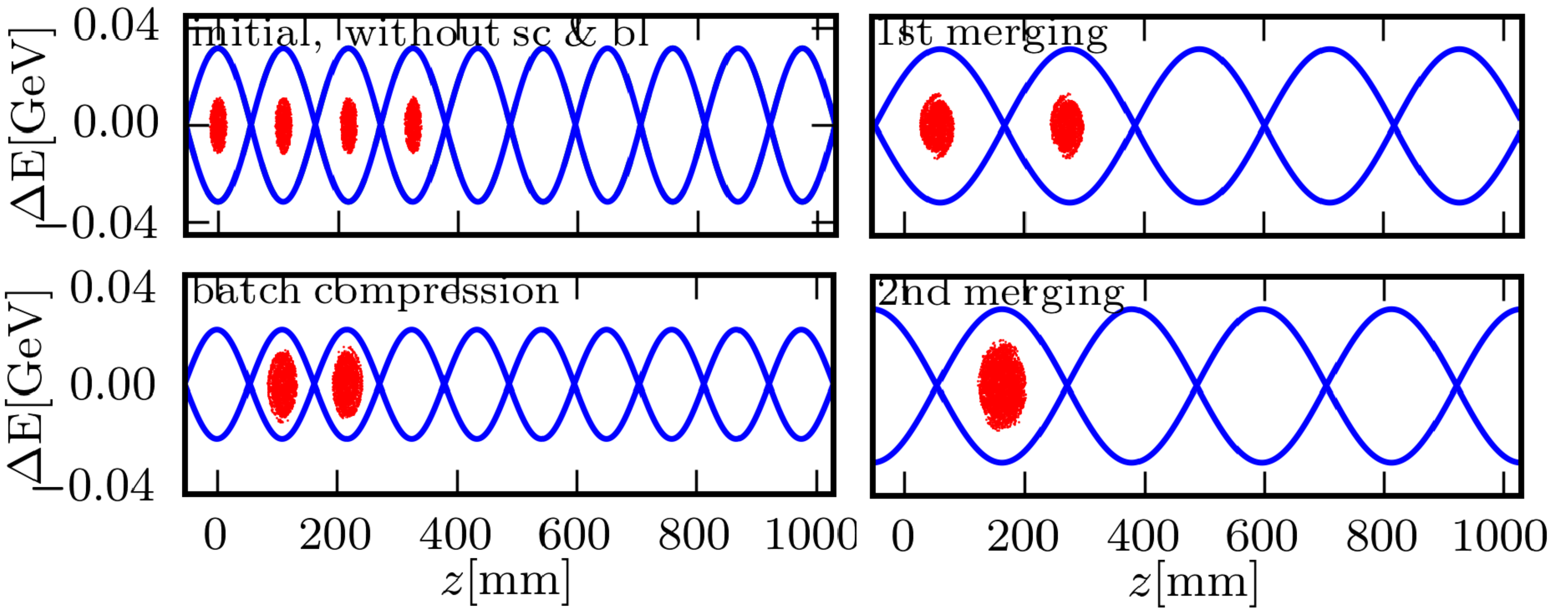


Dashed line: shifted harmonic

Appendix IV Beam loading matching



Appendix V Simulation of proton bunch manipulation without intensity effects



- The emittance growth is < 3% with total time of 300 ms.

  1st bunch merging:100 ms

  Batch compression:100 ms

  2nd bunch merging:100 ms