Booster 3-D simulations

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This work has been done in collaboration with Alexandr Drozhdin

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Abstract

1. In order to have a better understanding of the FermiLab Booster ***beam loss at the injection***, ***emittance growth at the transition crossing***, and ***momentum spread reduction at the extraction***, we need a 3-D model which includes ***the longitudinal and transverse space charge effect*** and ***the longitudinal impedance effect***. After we've successfully bench marked the longitudinal motion model against the experiment (see the accelerator physics and technology seminar at 09/02/06), it has been added to the particle tracking code STRUCT. Also, a simplified transverse space charge model has been added to STRUCT.
2. Based upon our simulation, the momentum reduction at the extraction is optimized operationally to ***reduce the beam loss during Slip Stacking*** in the Main Injector.
3. We obtained a good agreement between experiment and simulation at injection and extraction.
4. We're ready to include the longitudinal impedance module and nonlinear chromatic effect at the transition in STRUCT.

Outline

- Injection – space charge effect; RF voltage ramp optimization for improving the charge transmission and reducing the beam emittance
- Transition –how the γ_t jump system, the speed and amount of phase jump at the transition influence the loss and beam stability; varying nonlinear compaction factors *via* changing sextupole current, etc.
- Extraction – optimizing the momentum spread reduction at the extraction in Booster for a better match to the stable bucket area at the slip stacking in Main Injector --- reduce the beam loss in MI.

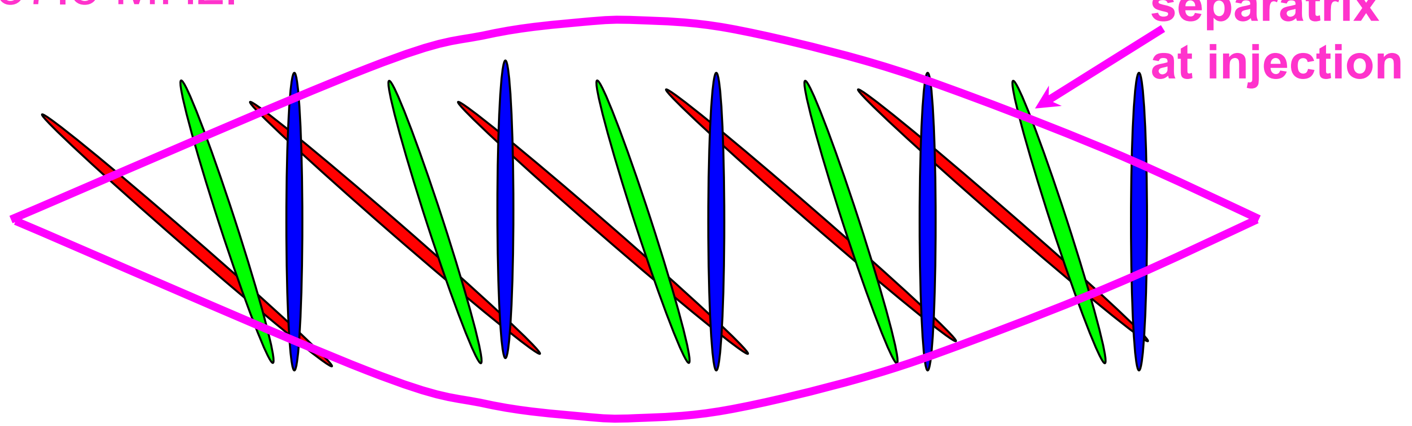
Booster parameters used in the simulation

Kinetic energy at injection (GeV)	Kinetic energy at extraction (GeV)	Repetition rate (Hz)	Batch size (number of proton at extraction)	$\varepsilon_{x,y}(1\sigma)$ (mm·mrad)	dP at injection $(\Delta P)_{1\sigma}$ (MeV)	D_x (m)	β_x (m)
0.4	8	15	4.6×10^{12}	0.01278	0.1	1.85-3.2	6.12-33.69
0.4	8	15	4.6×10^{12}	1.278	0.1	1.85-3.2	6.12-33.69

I. At the injection

- **We assume that the injected beam has a uniform distribution along the RF phase.**
- ***However, we'll do multi-turn micro-bunch injection simulations in the future.***
- ***Also we'll numerically investigate how injection errors influence the capture process.***

Example**,** **3 turn micro-bunch injection** --- 1st turn, 2nd turn, and 3rd turn. 200 MHz micro-bunches from Linac are injected to Booster with the RF frequency of 37.8 MHz.



Transverse space charge

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} \leq 1$$ **eq.1**

$$F_x = \frac{e^2 \times N \times x}{\varepsilon_0 \times \pi \times \gamma^2 \times a \times (a+b)}$$
$$F_y = \frac{e^2 \times N \times y}{\varepsilon_0 \times \pi \times \gamma^2 \times b \times (a+b)}$$

eq.2

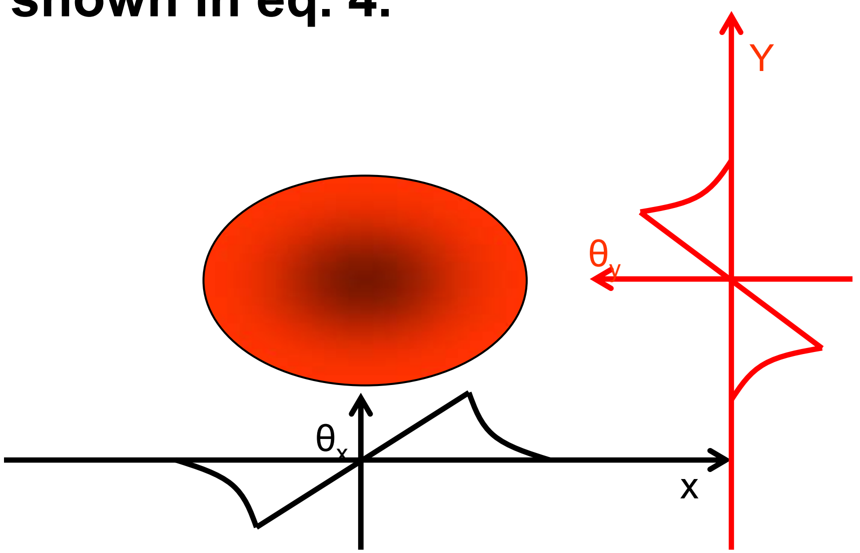
$$F_x = \frac{e^2 \times N \times x}{\varepsilon_0 \times \pi \times \gamma^2 \times 2 \times r^2}$$
$$F_y = \frac{e^2 \times N \times y}{\varepsilon_0 \times \pi \times \gamma^2 \times 2 \times r^2}$$

eq.3

$$\theta_x = \frac{F_x \times L}{\beta \times P \times c}$$
$$\theta_y = \frac{F_y \times L}{\beta \times P \times c}$$

eq.4

- **The beam is assumed to have a uniform density within the elliptical cross section defined by eq. 1. Here, $a=3\sigma_x$, $b= 3\sigma_y$.**
- **Transverse space charge forces are shown as eq. 2 when $x<=3\sigma_x$ and $y<=3\sigma_y$; they are shown as eq. 3 when**
- **$(x^2/a^2)+ (y^2/b^2)>1$**
- **The angle kick due to the transverse space charge force at a path length of *L* is shown in eq. 4.**



Longitudinal space charge

$$\frac{z_\omega}{nh} = -i \times z_0 \times g \Big/ \left(2 \times \beta \times \gamma^2\right)$$

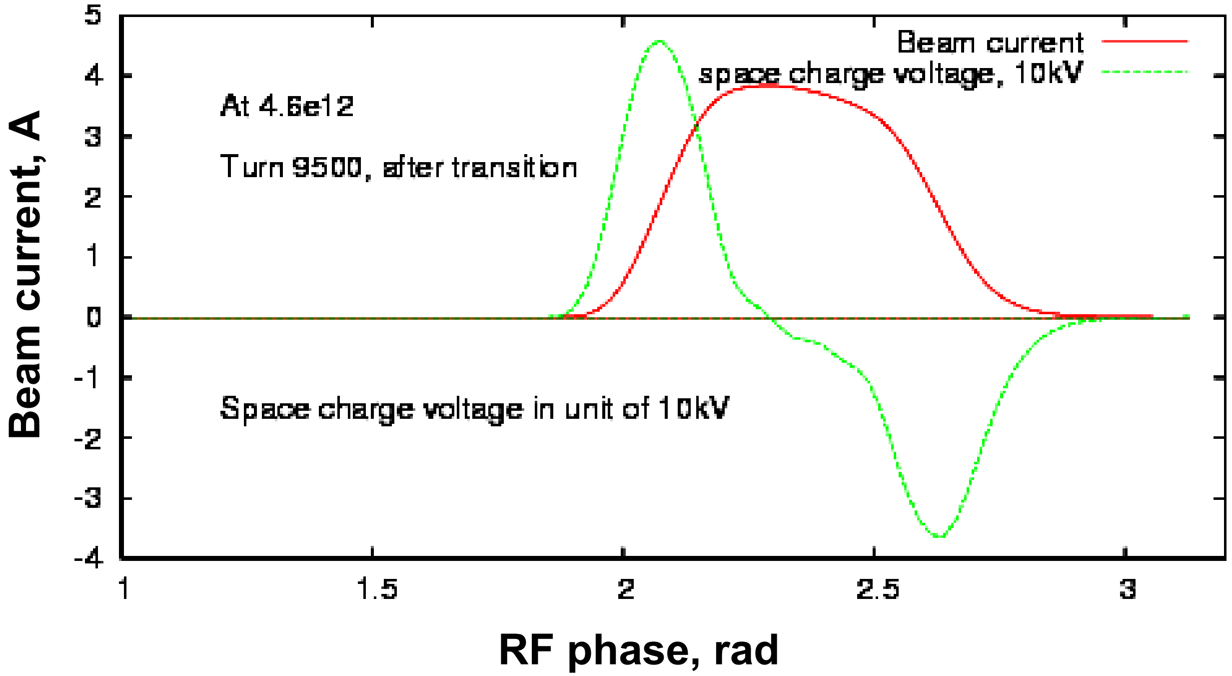
$$\omega = n \times h \times \omega_R$$

$$g = 1 + 2 \times \ln(b/a)$$

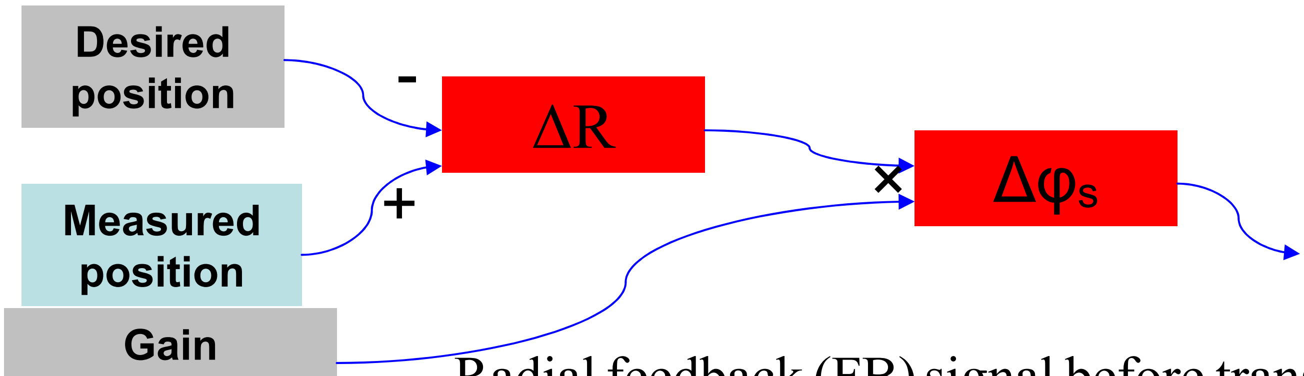
eq.(5)

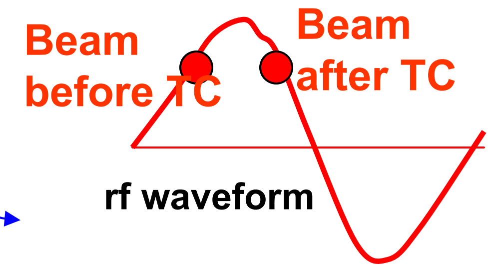
Longitudinal space charge impedance z_ω is shown as eq. 5

Here, $z_0 = 377\Omega$ is the free-space impedance, h=84 is the harmonic number, *b* and *a* are transverse radius of the beam pipe and the beam.



Radial feedback





Radial feedback (FB) signal before transition

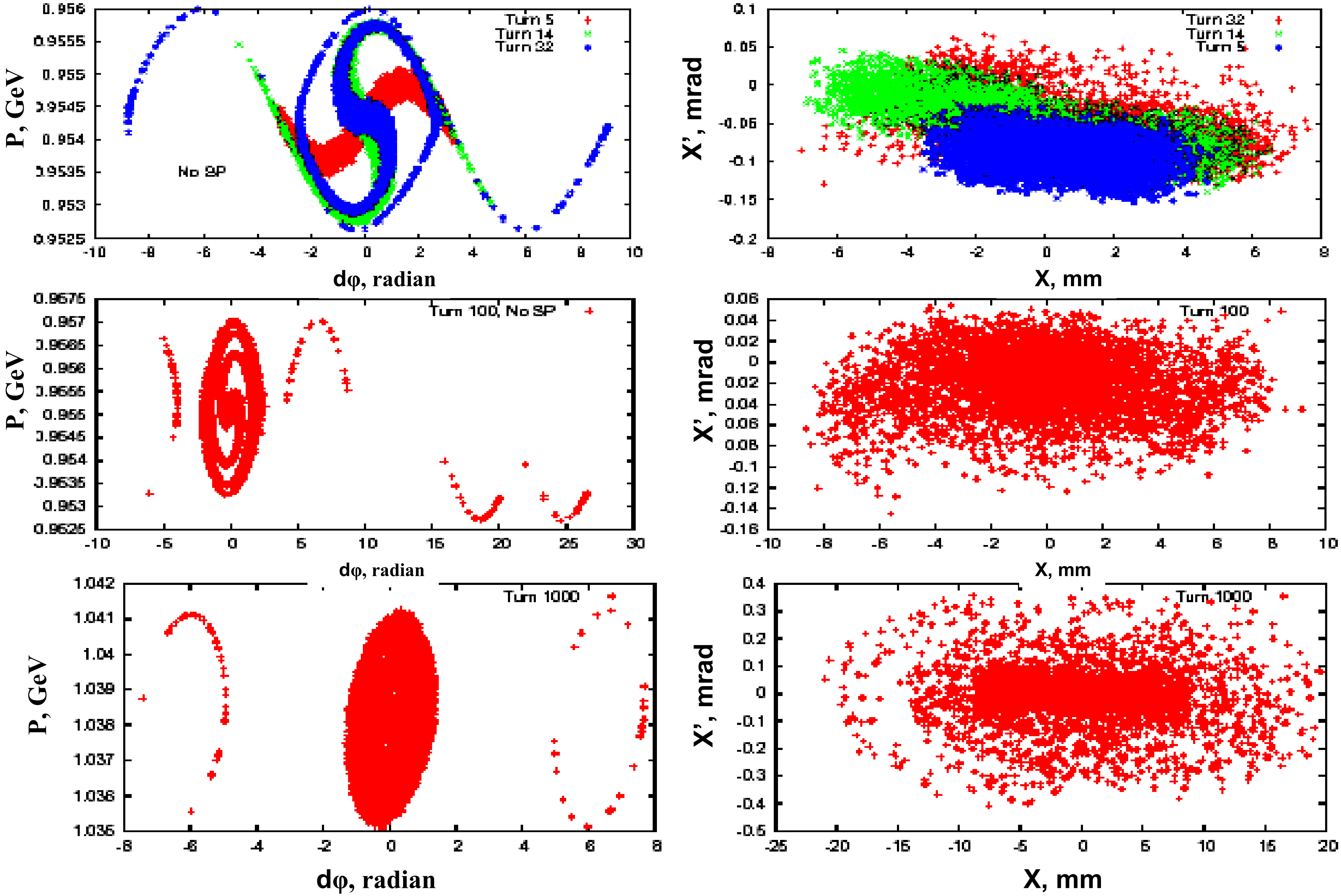
$$\Delta\varphi_s(t) = -\Delta R(t)\times r_g(t) = -R_g(t)\times\left(\Delta P/P\right) \quad (6)$$

Radial feedback (FB) signal after transition

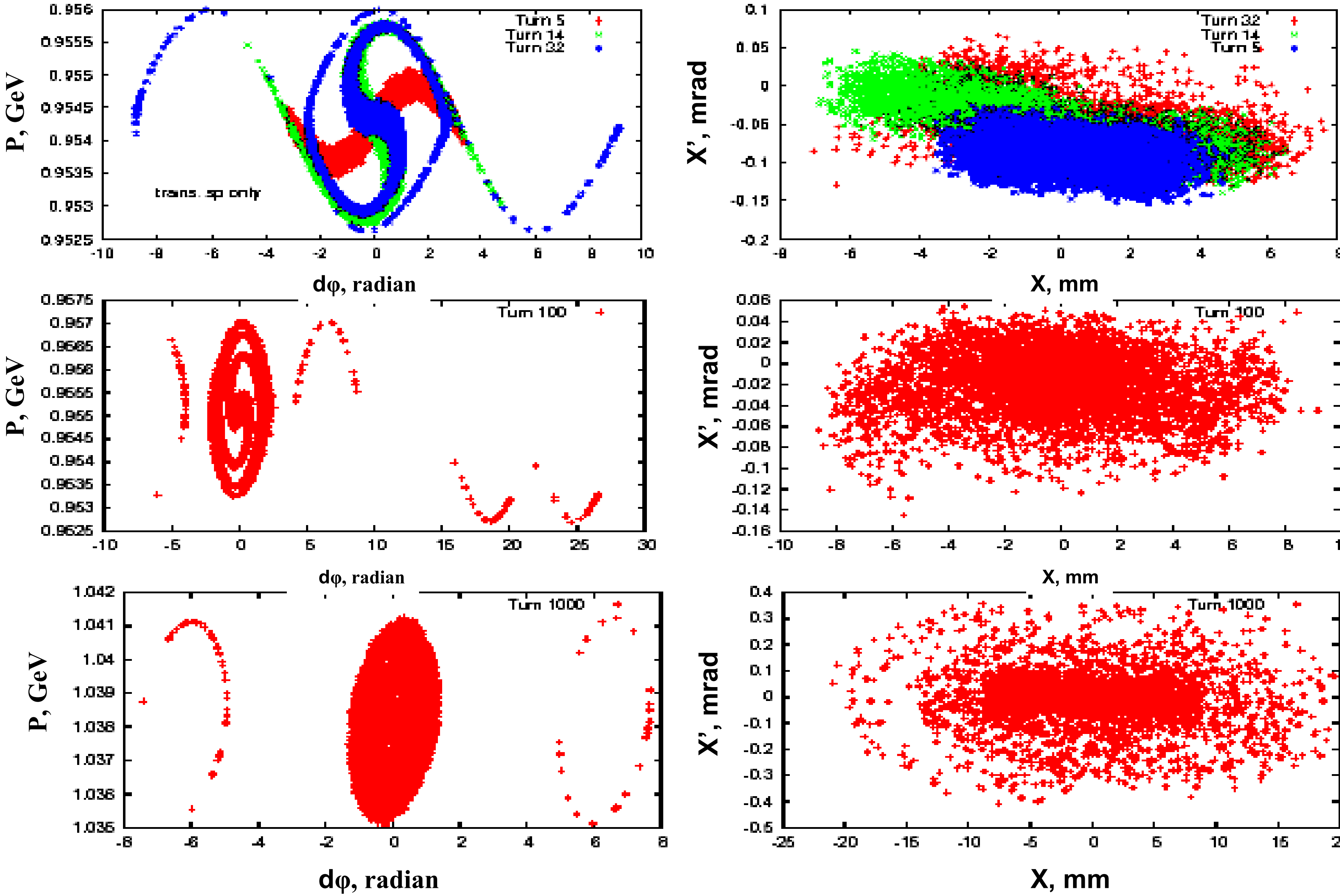
$$\Delta\varphi_s(t) = \Delta R(t)\times r_g(t) = R_g(t)\times\left(\Delta P/P\right) \quad (7)$$

The momentum deviation (Δ*P*) causes a radial position offset due to the nonzero dispersion. The radial *FB* picks up such an offset (Δ*R*), multiplies it by the *FB* gain (r_g), and sends it to shift the phase of the beam relative to the *rf* accelerating waveform ($\Delta\varphi_s$). Since φ_s is in the range of 0° to 90 ° before transition and in the range of 90 ° to 180 ° after transition; in order to get more accelerating voltage, before and after transition, the sign of $\Delta\varphi_s$ should be changed, as shown in eq. 6 and eq. 7.

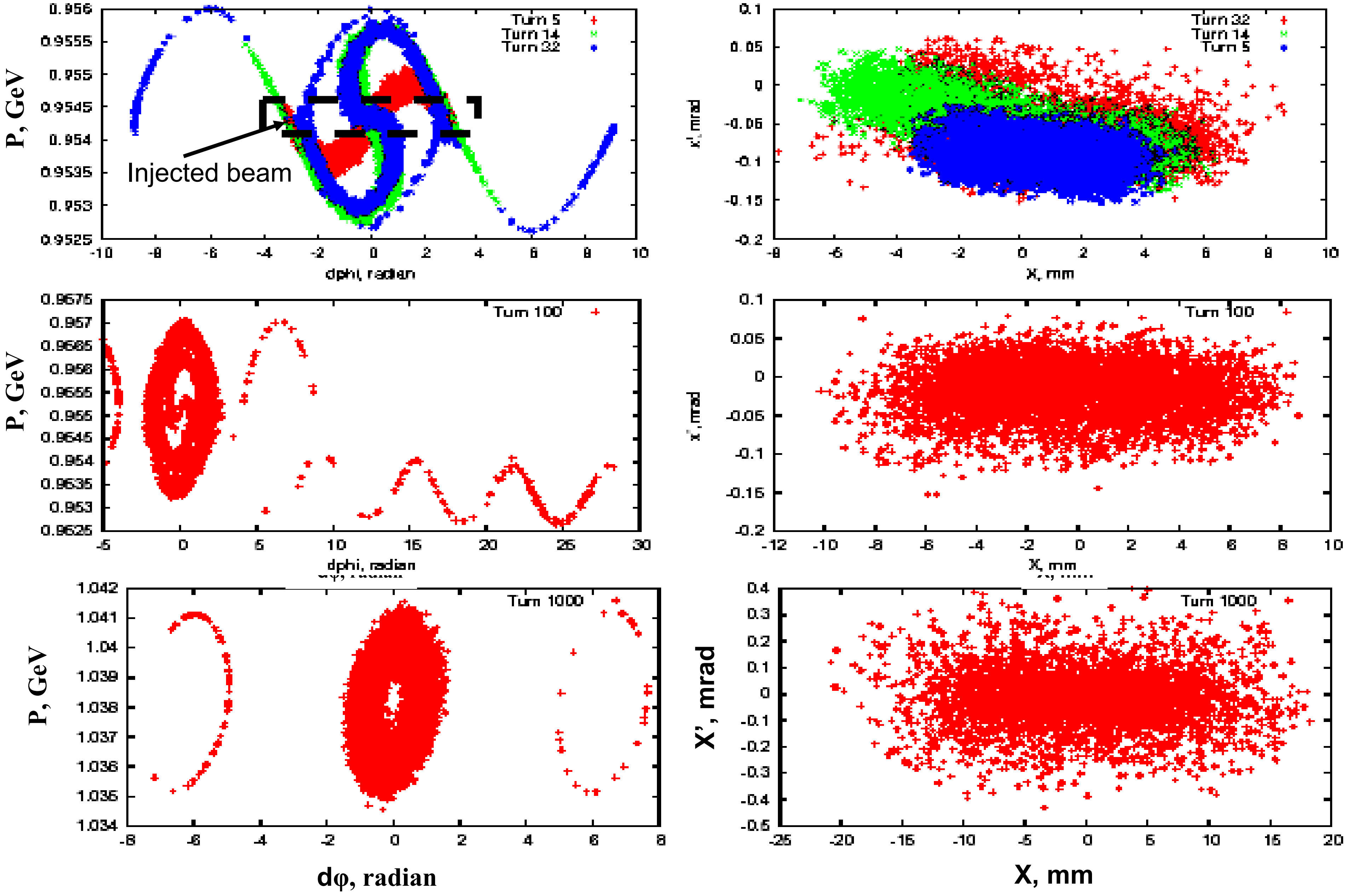
Understanding longitudinal and transverse space charge effects at injection ---- no space charge effects

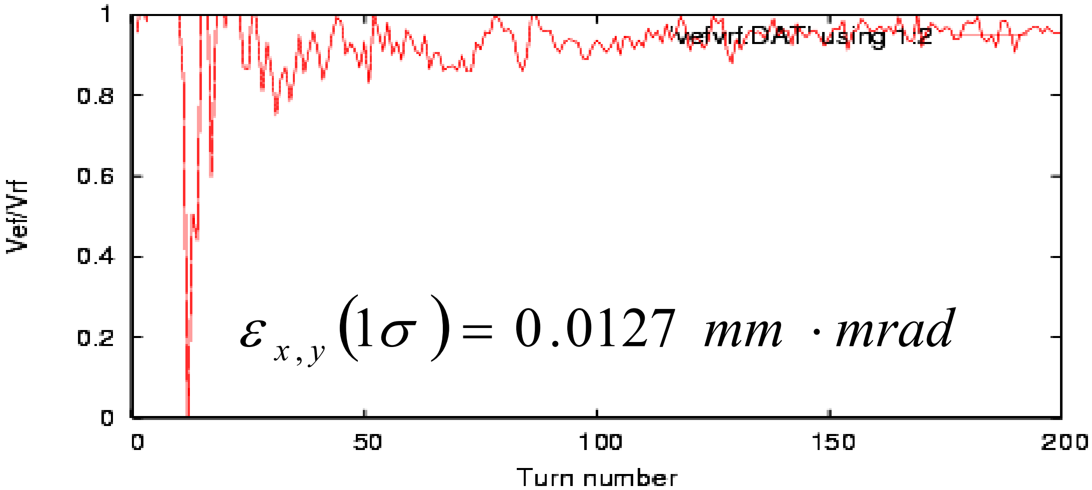


---- only the transverse space charge effect



---- only the longitudinal space charge effect



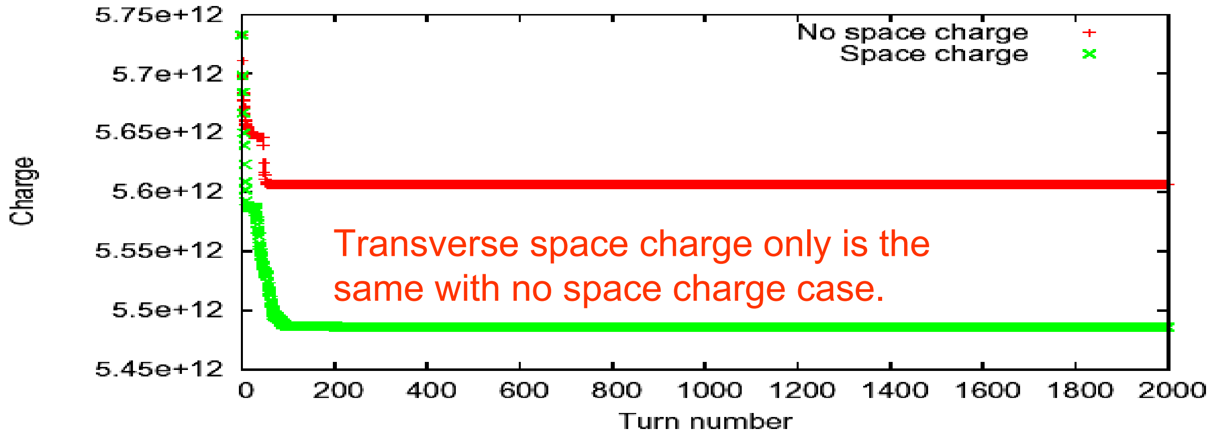


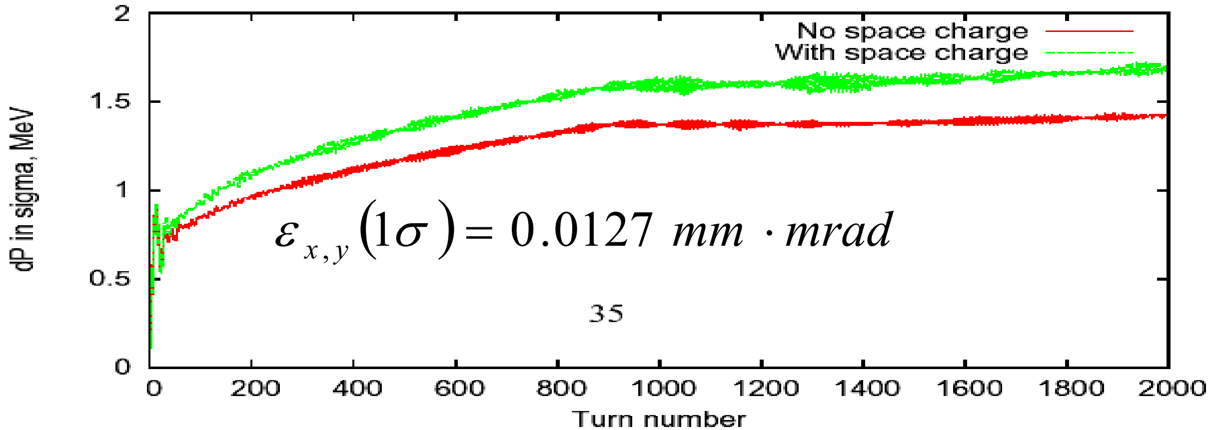
$$V_{ef} / V_{rf} = \left(V_{sp} + V_{rf}\right) / V_{rf}$$

$$V_{sp} = V_{sp}\left(+1.5\sigma_{bl}\right) - V_{sp}\left(-1.5\sigma_{bl}\right)$$

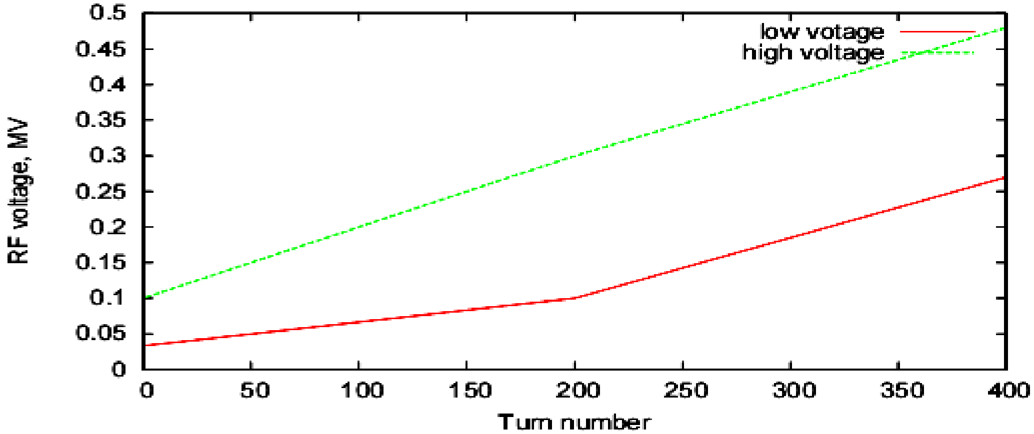
$$V_{rf} = V_{rf}\left(+1.5\sigma_{bl}\right) - V_{rf}\left(-1.5\sigma_{bl}\right)$$

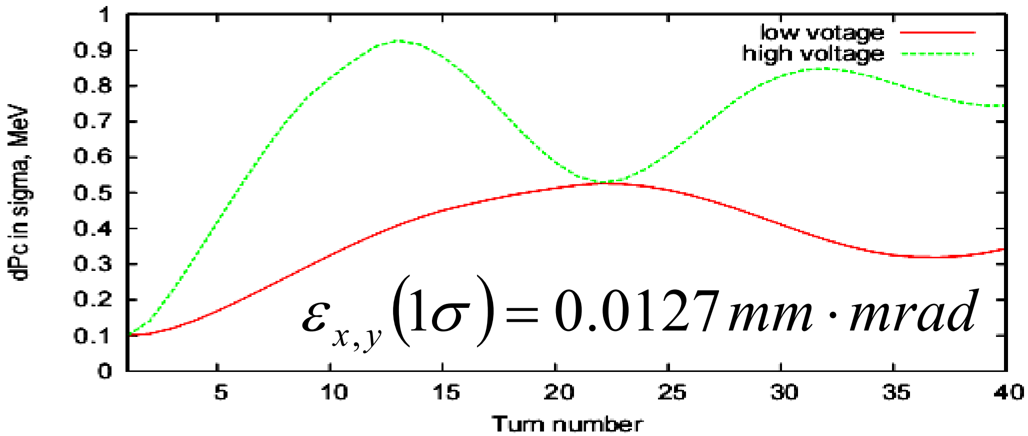
The ratio of the effective voltage and the rf voltage vs. turn number is shown in the rf voltage ramp of 0.05-0.4MV in the 1st 200 turns.

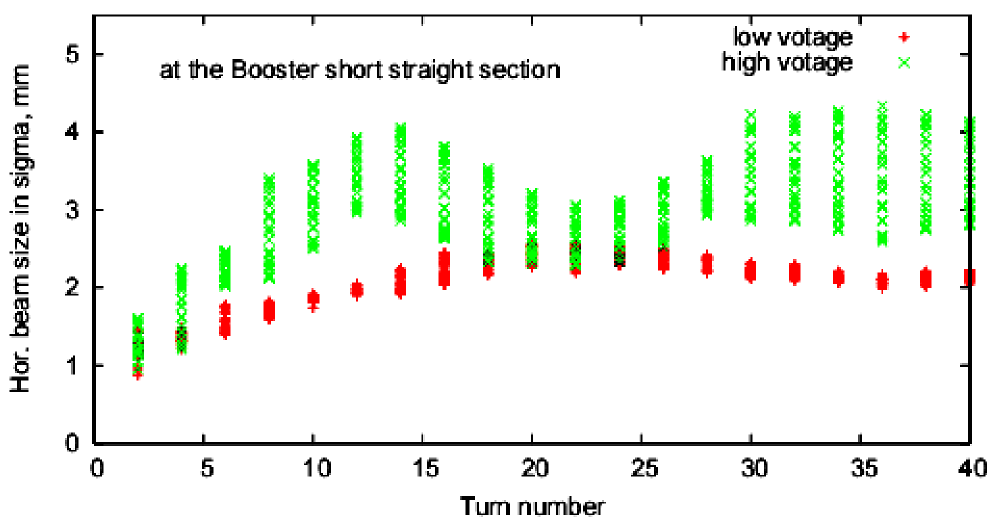




- Comparing without (red) and with (green) space charge effect, charge and momentum spread in sigma are shown at the top and bottom.
- Due to the longitudinal space charge effect, there is a factor of two more charge loss and ~20% larger momentum spread.

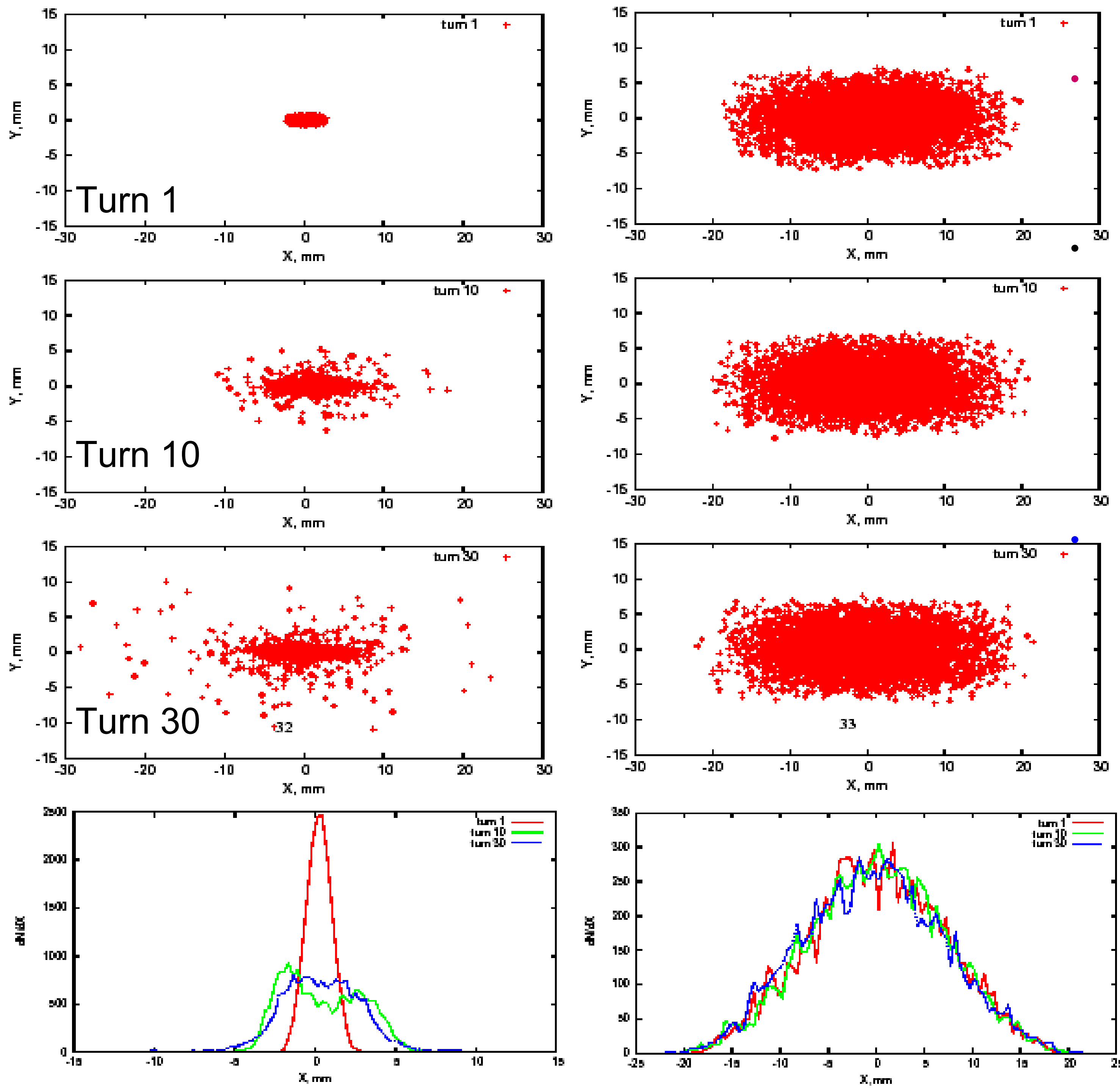




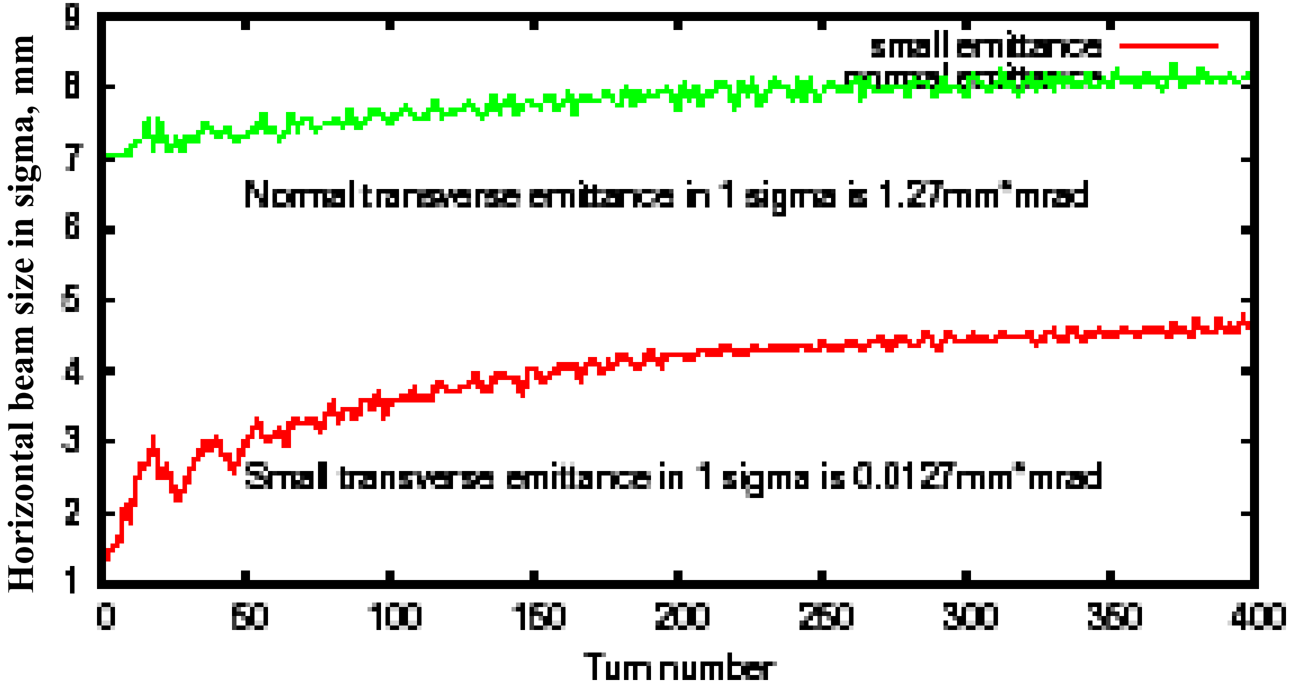


Two RF voltage ramps are shown as the red and green curves (top).

The momentum spread (middle) and the horizontal beam size (bottom) are shown. The higher the initial voltage is, the faster and higher dP grows right after the injection. Fast growth in the momentum spread and horizontal beam size till reaching their 1st maximums in 14 turns are caused by the first ¼ synchrotron oscillation after the beam is injected (see Fig. at p12).



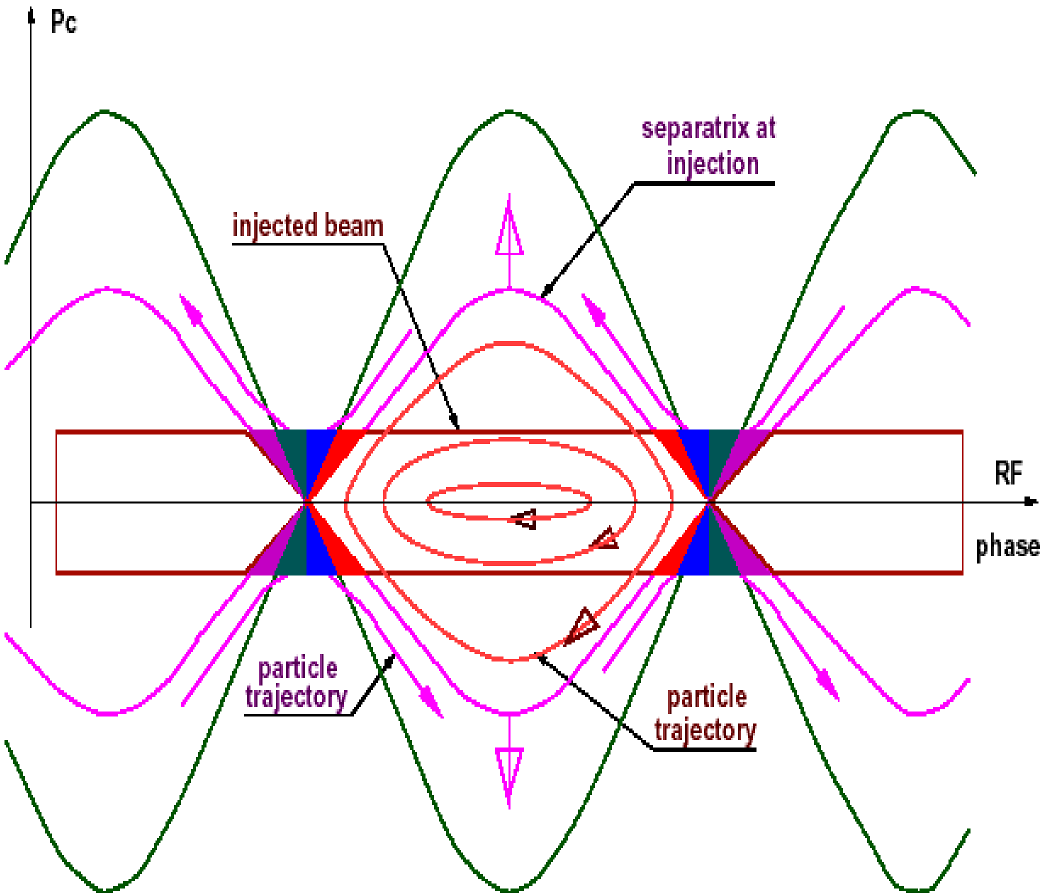
- In the transverse plane, the injected beam with two different emittances.
- Beam size in Booster at different turns after injection for small transverse emittance (0.0127mm*mrad, left) and normal emittance (1.27mm*mrad, right).
- In small emittance case, transverse space charge effect creates a small amount of halo particles, in normal emittance case, which is close to the operational condition, transverse space charge effect makes no difference.

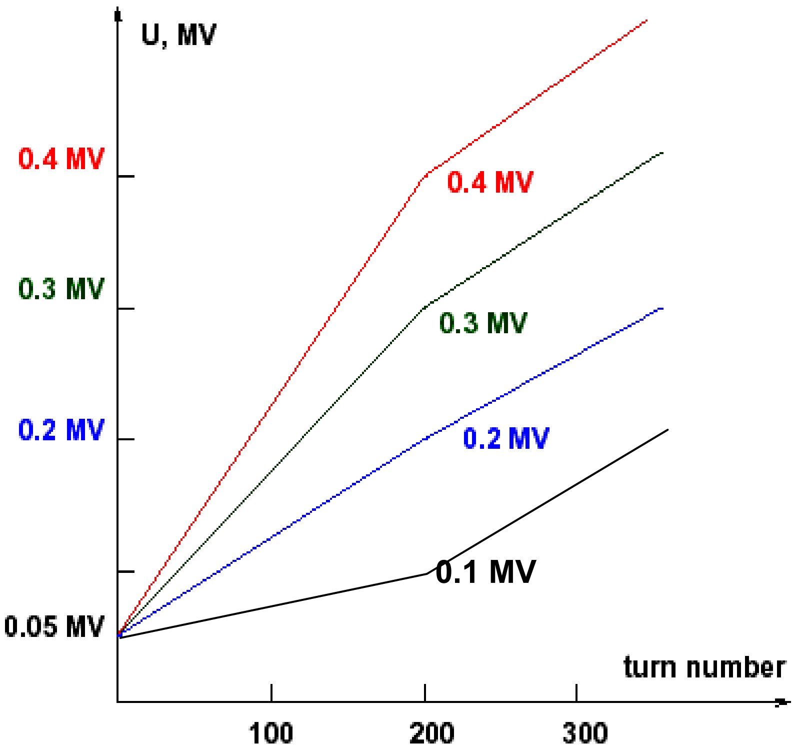


- Beam size in 1σ is 0.64 mm at the small emittance case and 6.4 mm at the normal emittance case.
- First ¼ synchrotron oscillation causes more than 0.5 MeV increase of ΔP which is ~0.1% ΔP/P, and it contributes to the beam size *via* dispersion. It's the same for both normal and small emittance cases, and it's about 3 mm.
- In the small emittance case, sqrt(0.6^2+3^2)≈3 mm, -- ***a big increase in horizontal beam size***
- In the normal emittance case, sqrt(6^2+3^2)≈6.7 mm, -- ***a small increase in horizontal beam size***

Summary-I

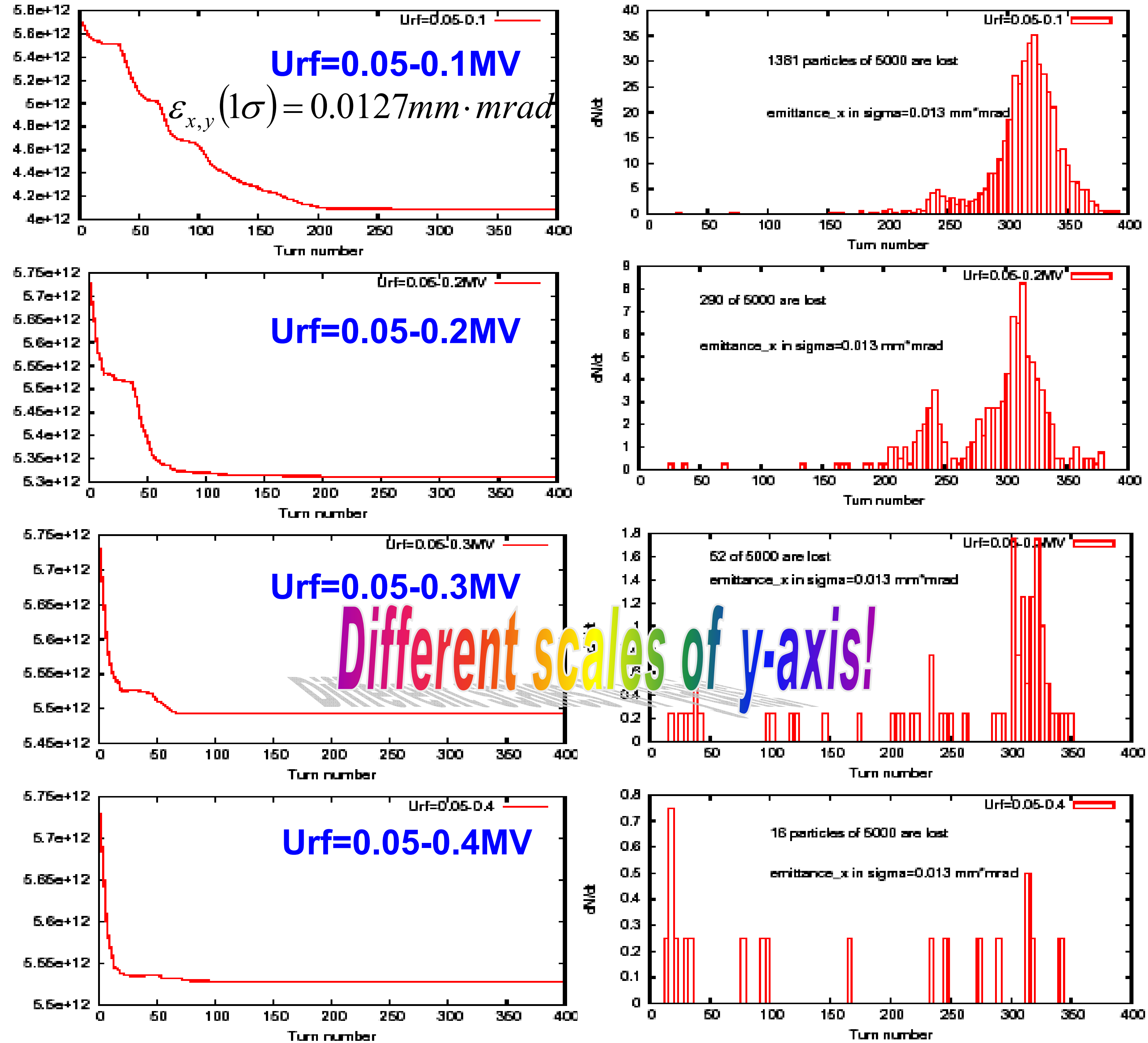
- ***The influence of the transverse space charge effect is very small without considering field errors.***
- ***The longitudinal space charge effect causes the beam loss and emittance growth at the injection.***
  Since there isn't any beam pipe in Booster main magnets, the geometric factor shown in eq. 5 is not known precisely. It's adjusted in the simulation to make the simulation match the experiment.
- ***RF voltage ramp at the injection has a great influence on the charge transmission and the emittance of the beam***. **-- It's an important parameter to be adjusted to get a higher transmission and a smaller emittance of the beam!!!**





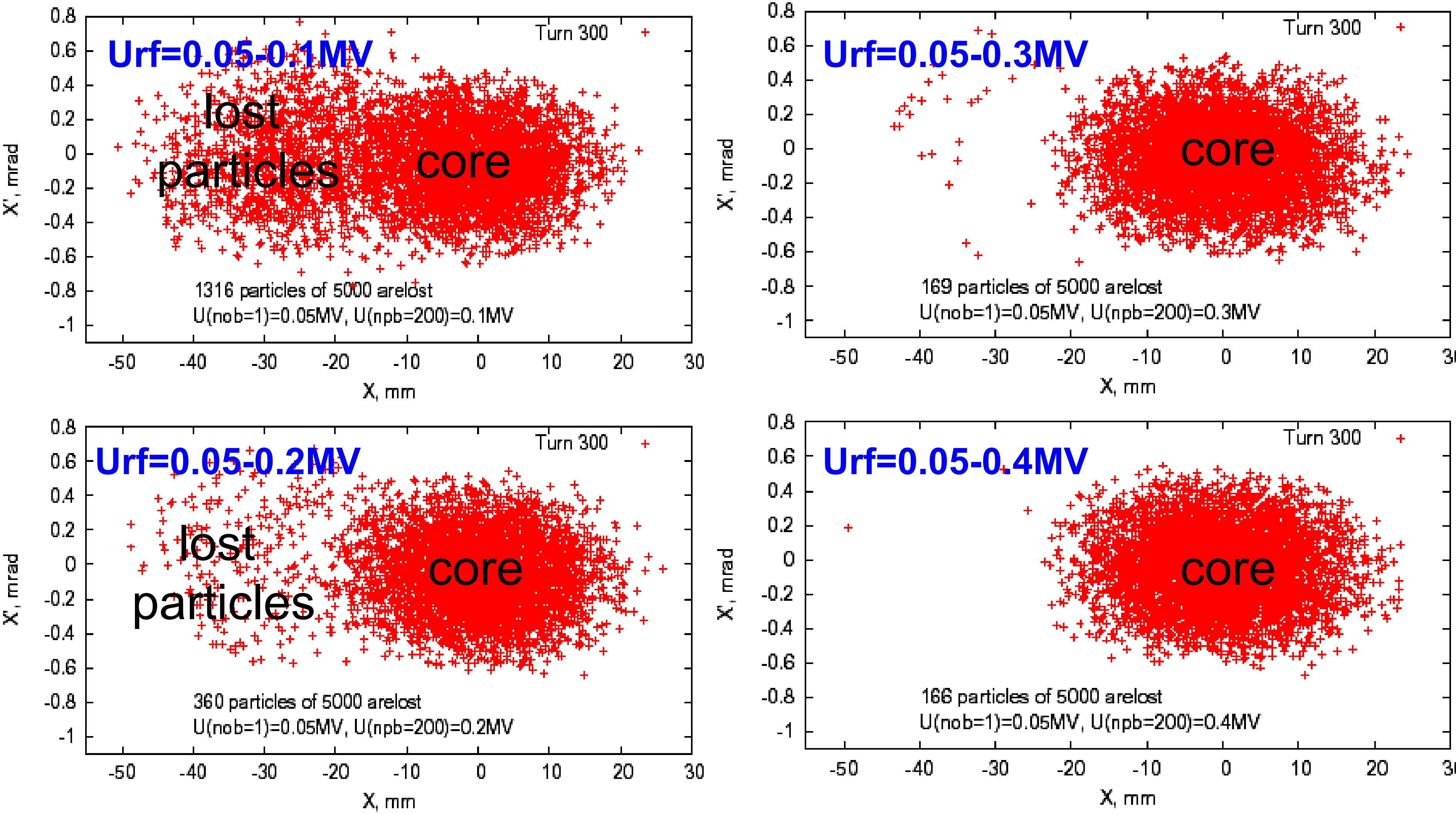
RF voltage at injection.

Longitudinal phase plane at the injection

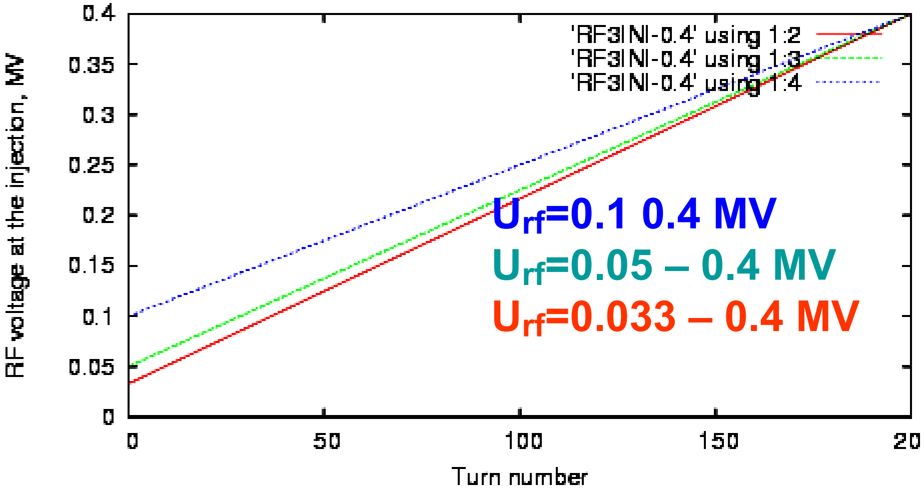


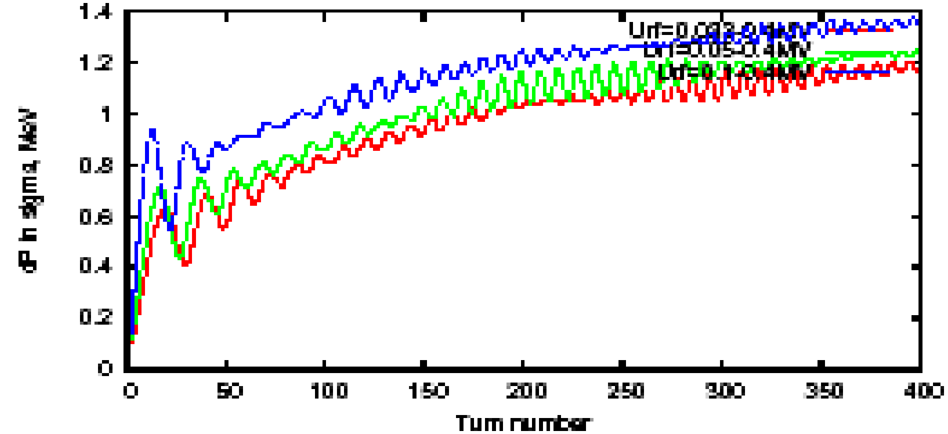
- **Injection parameters from the blue line of table 1 – small emittance.**
- **In the left, charge reduction due to particles moving out of the bucket, charge calculated in the range of [-*π*, *π*] with respect to synchronous phase (left); in the right, particle loss at accelerator aperture.**

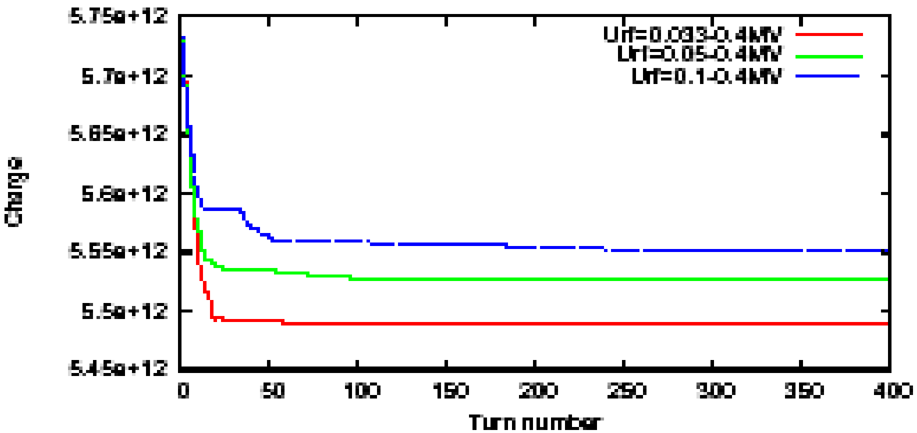
Comparing four different RF voltage ramps, losses can be largely removed by ramping up the RF voltage faster, as shown in the left column from top to bottom.

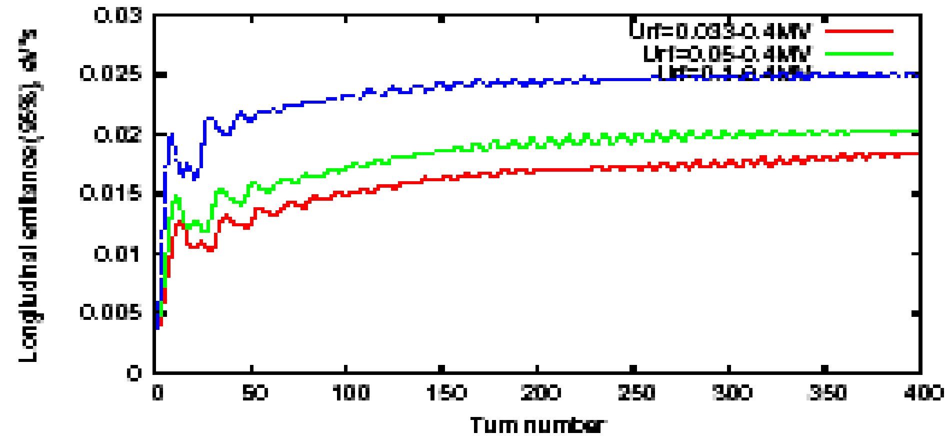


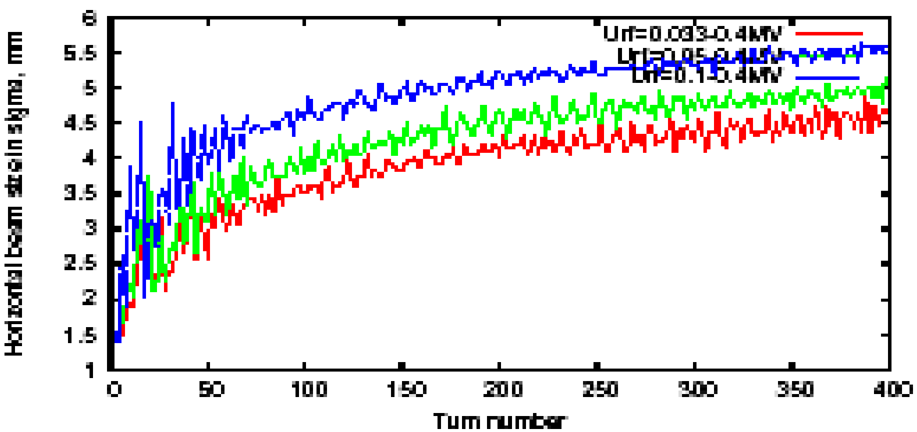
- **Transverse phase plane at Turn 300 for RF voltage ramps of 0.05-0.1MV, 0.05-0.2MV, 0.05-0.3MV, and 0.05-0.4MV in 200 turns (top to bottom and left to right).**









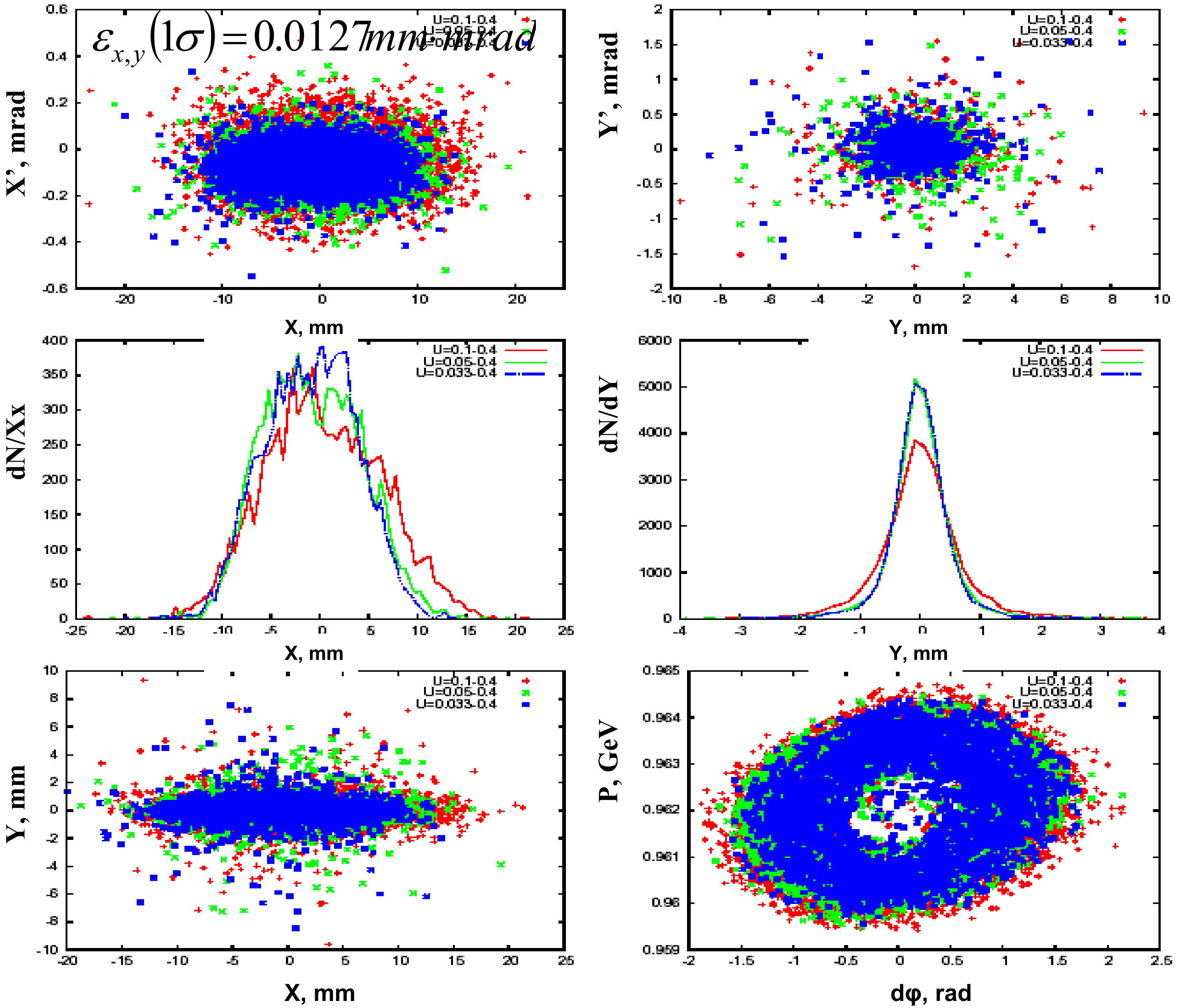


Injection parameters from the blue line of table 1 --- small emittance.

Three RF ramps with different initial values and they're linearly ramped up to 0.4MV at Turn 200.

Once the RF voltage at the injection is ramped up fast enough, the capture efficiency can be as high as 95% to 97%. However, higher the initial RF voltage, bigger the transverse beam size and longitudinal emittance of the beam are.

Comparing three linear ramps with different U_{rf} at Turn 0 and the same U_{rf} at Turn 200

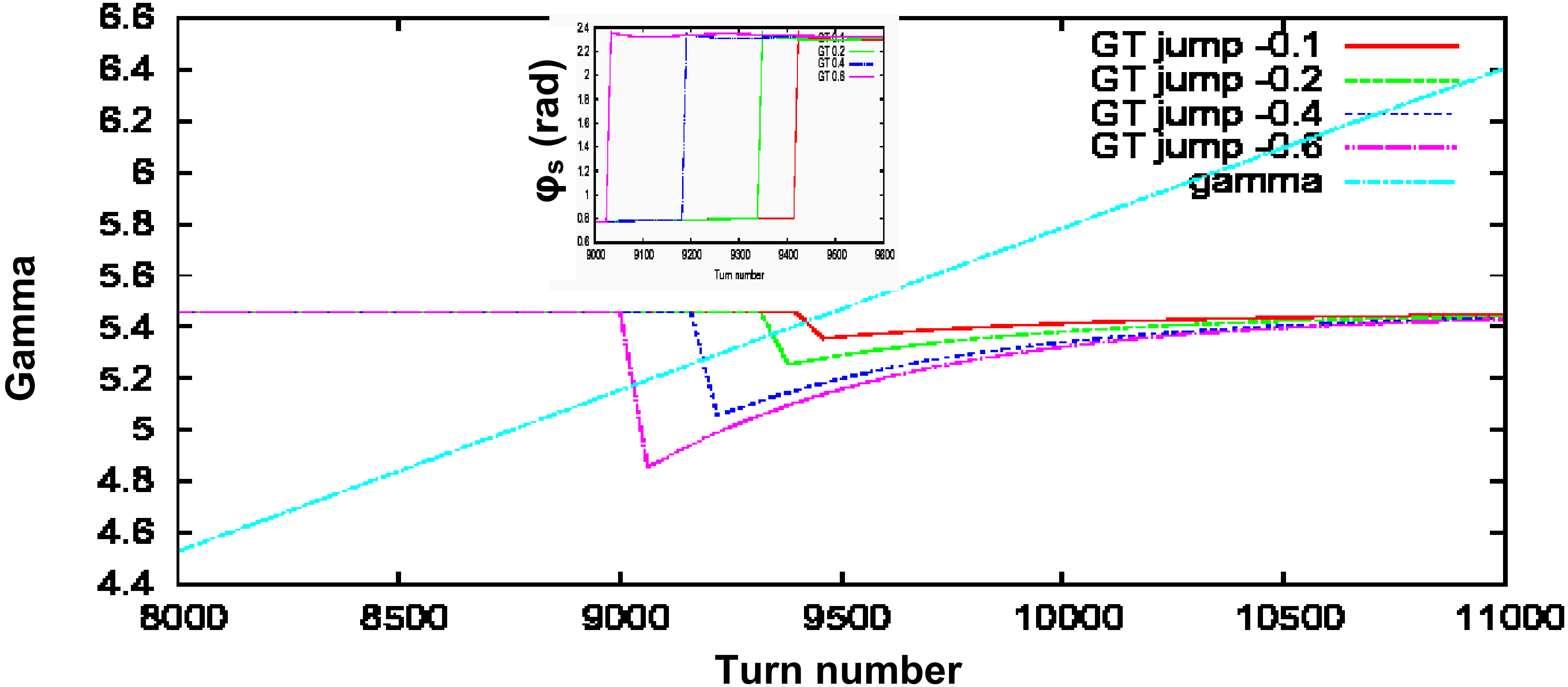


At Turn 300, three RF voltage ramps of 0.1-0.4MV (red), 0.05-0.4MV (green), and 0.033-0.4MV (blue) in 200 turns, there are differences in the transverse beam size, the momentum spread, and the bunch length.

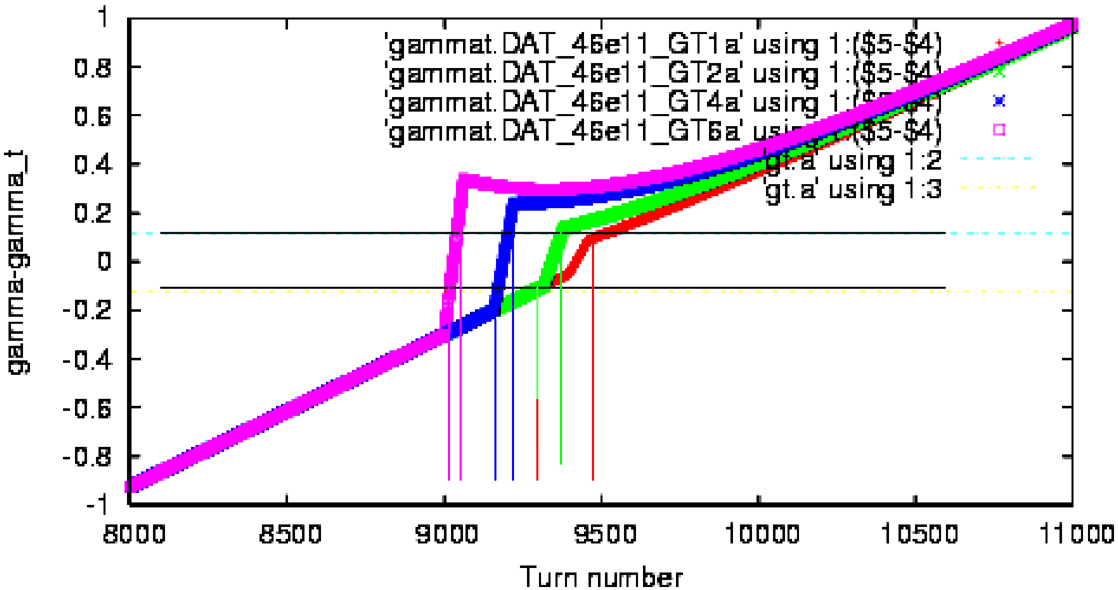
The RF ramp of 0.033-0.4MV in 200 turns has the smallest transverse beam size.

II. Transition crossing

γ_t jump system is designed to make the transition crossing faster by changing the lattice function γ_t in 1unit within 0.1 ms, for the purpose of preventing beam losses from the momentum spread growth and the beam instability from the bunch length shortening.



γ_t *vs*. turn number is plotted for $\Delta\gamma_t$=-0.1 (red), -0.2 (green), -0.4 (blue), and -0.6 (magenta), and also relativistic γ of the beam *vs*. turn number is plotted as the light blue curve. γ_t jump is done by γ_t quads excitation.

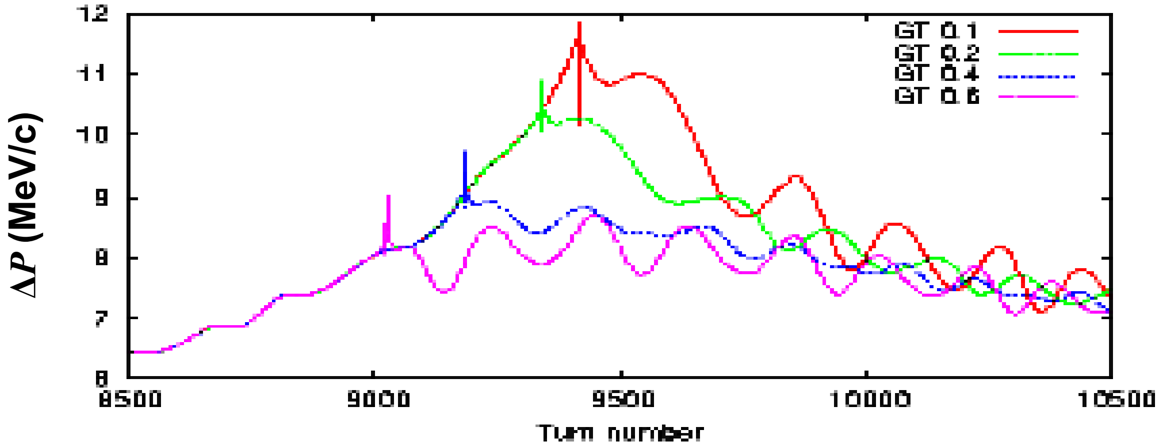


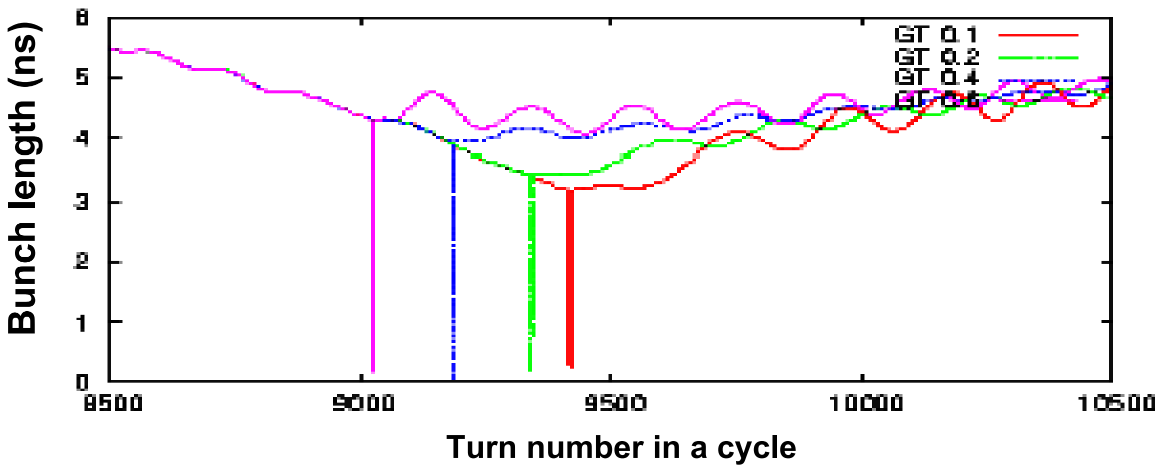
$(\gamma - \gamma_t)$ vs. turn number

$\dot{\gamma} = 0.4 / ms$ at transition

$T_c \approx 0.25 ms$ --- characteristic non-adiabatic time when the synchrotron motion is nearly freezing. ~ 150turns

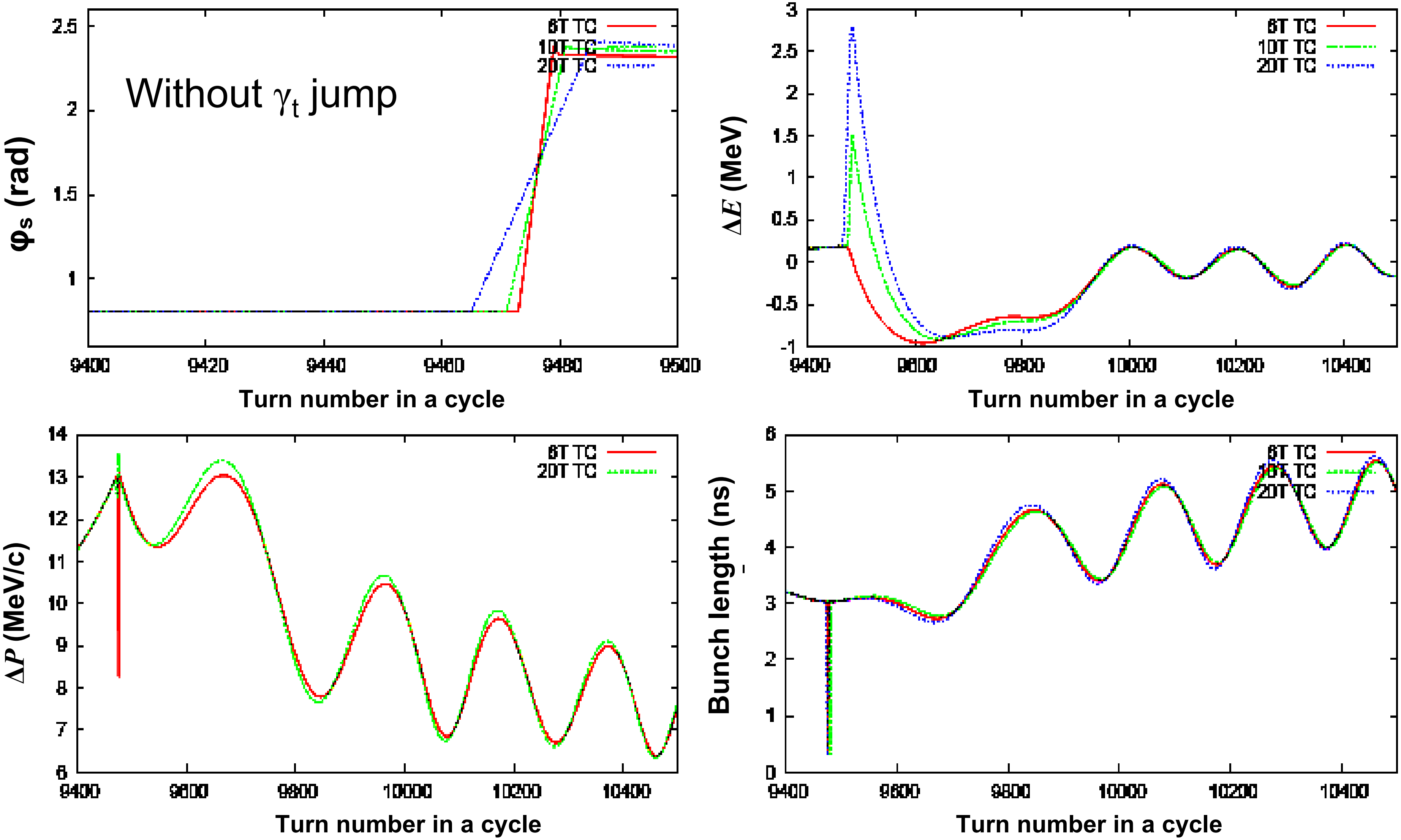
$\Delta\gamma = (\gamma - \gamma_t) >= \{(\dot{\gamma} \cdot T_c) = 0.1\}$





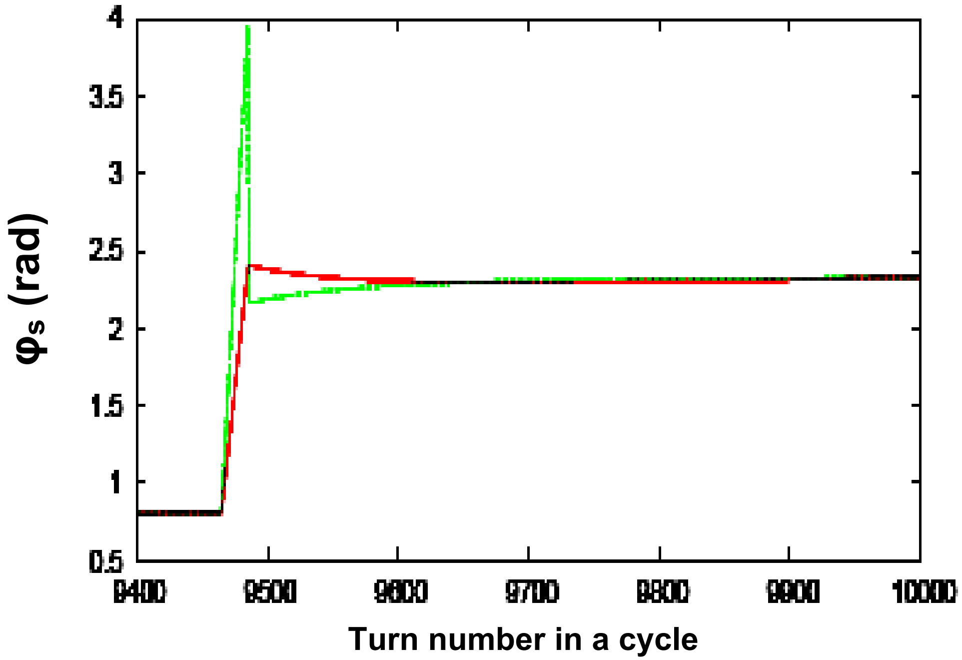
ΔP is plotted at the top for $\Delta\gamma_t$ =-0.1 (red), -0.2 (green), -0.4 (blue), and -0.6 (magenta) during transition. Bunch length in 6σ *vs*. turn number is plotted at the bottom.

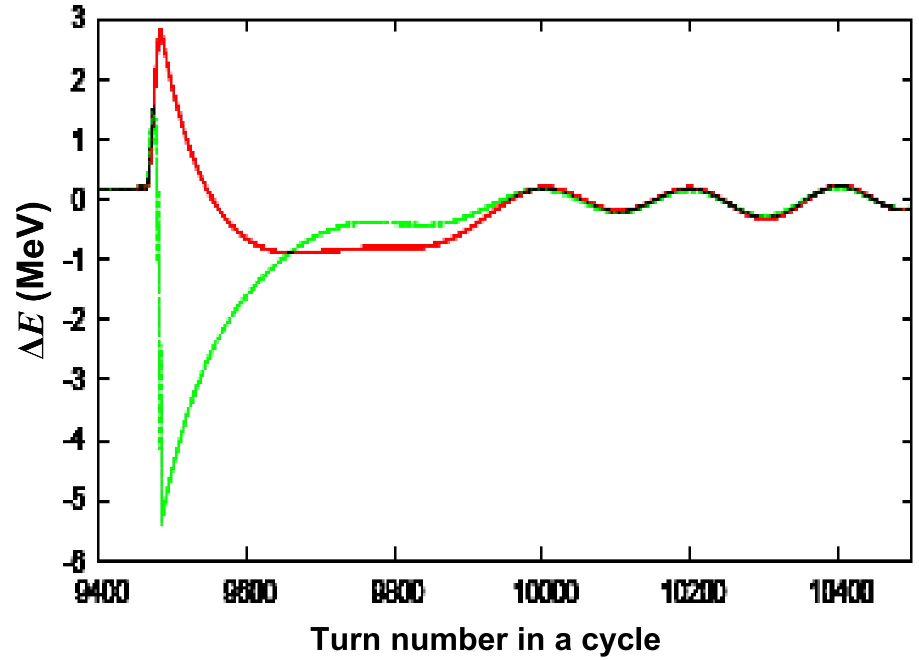
Larger γ_t jump produce longer bunch with smaller momentum spread. The advantage of having a longer bunch length is -- high frequency components of the beam current get smaller such that high frequency coupled bunch modes are excited in smaller amplitudes.



φ_s ***vs***. **turn number is plotted for taking 6 turns (red), 10 turns (green), and 20 turns (blue) to complete transition phase jump at the top left. Their corresponding energy error ΔE at the top right, ΔP in rms at the bottom left, bunch length in 6σ at the bottom right.**

It's clear that faster the transition crossing is, smaller the energy error ΔE is; so making transition crossing faster may help in reducing losses of high intensity beams. Of course, the highest speed limit of transition crossing is set by Booster RF systems.

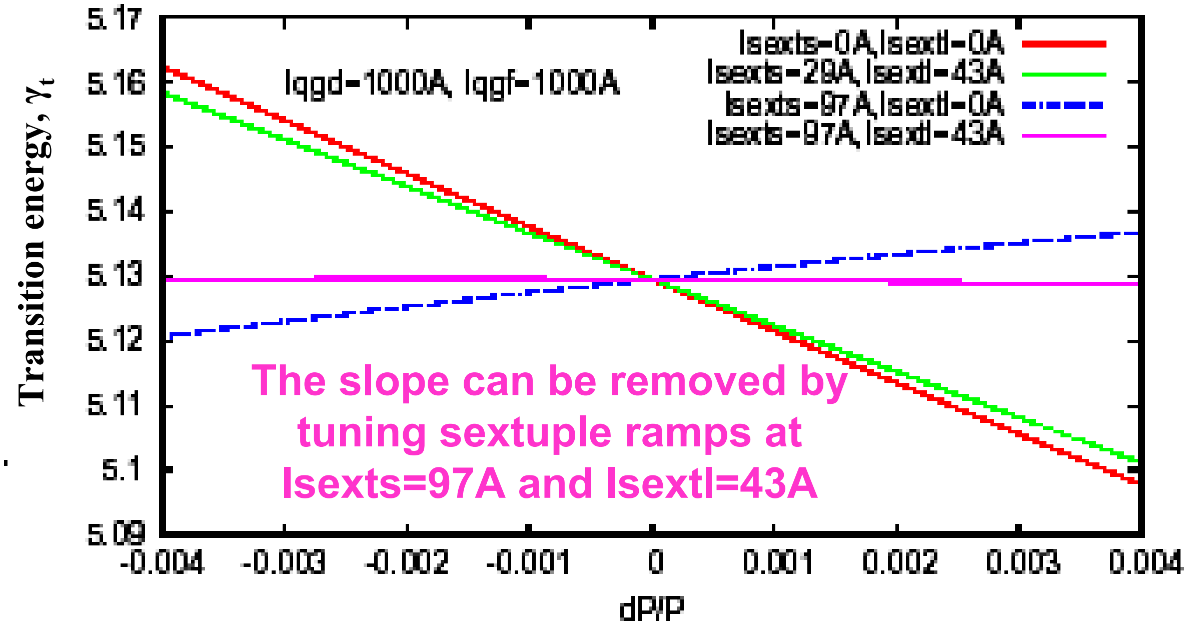




φ_s *vs*. turn number is plotted at left for 20 turns of 180°-2φ jump (red) and 20 turns of 2x(180°-2φ) jump (green). Energy error ΔE is plotted at the right.

Operationally, high intensity beams sometime prefer the phase jump in the green case, or there aren't any differences between the green case and the red case.

In order to understand this, the impedance effect and the nonlinear momentum compaction factors should be added in our 3-D model in the future!



- **Transition energy as a function of the momentum deviation evaluated from MAD at four different current settings of sextupole correctors, *Isexts*=0A, *Isextl*=0A (red); *Isexts*=29A, *Isextl*=43A (green); *Isexts*=97A, *Isextl*=0A (blue); and *Isexts*=97A, *Isextl*=43A (magenta), is plotted.**

According to J. Wei Ph.D thesis (1990), δ = dP/P

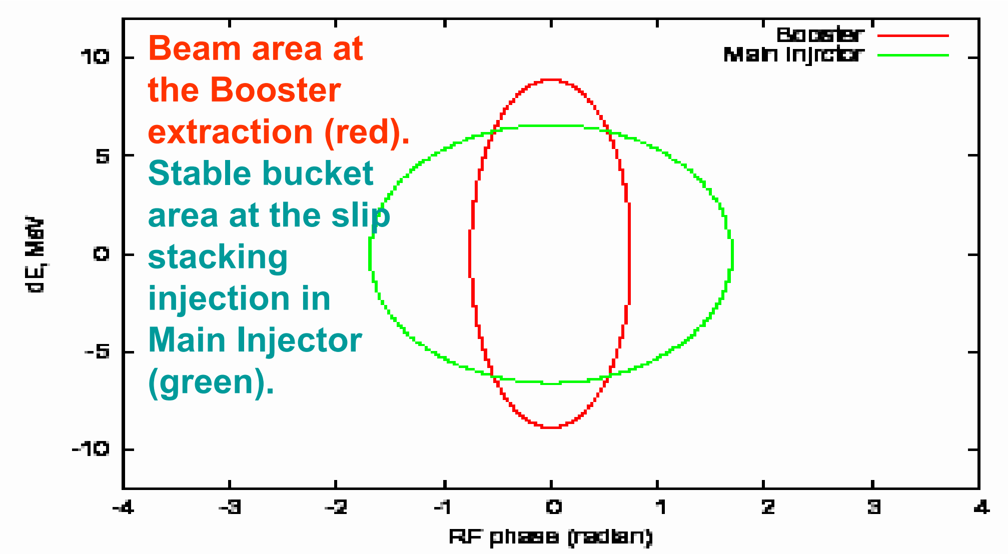
$$\eta(\delta) \approx \alpha_0 - \frac{1}{\gamma_s^2} + \alpha_0 \cdot \left(\alpha_1 + 3/2 \cdot \beta_s^2\right)\delta + \left[\alpha_0 \cdot \alpha_2 + \frac{\left(1 - 5 \cdot \beta_s^2\right) \cdot \beta_s^2}{2 \cdot \gamma_s^2}\right] \cdot \delta^2$$

$$\alpha_1 \approx -\gamma_t' \cdot \sqrt{\alpha_0} - \frac{1}{2},$$

$$\alpha_2 \approx -\frac{2}{3}\gamma_t'' \cdot \sqrt{\alpha_0} + \left(\gamma_t'\right)^2 \cdot \alpha_0 - \frac{2}{3} \cdot \alpha_1$$

We are going to insert nonlinear terms to the module.

III. At the extraction

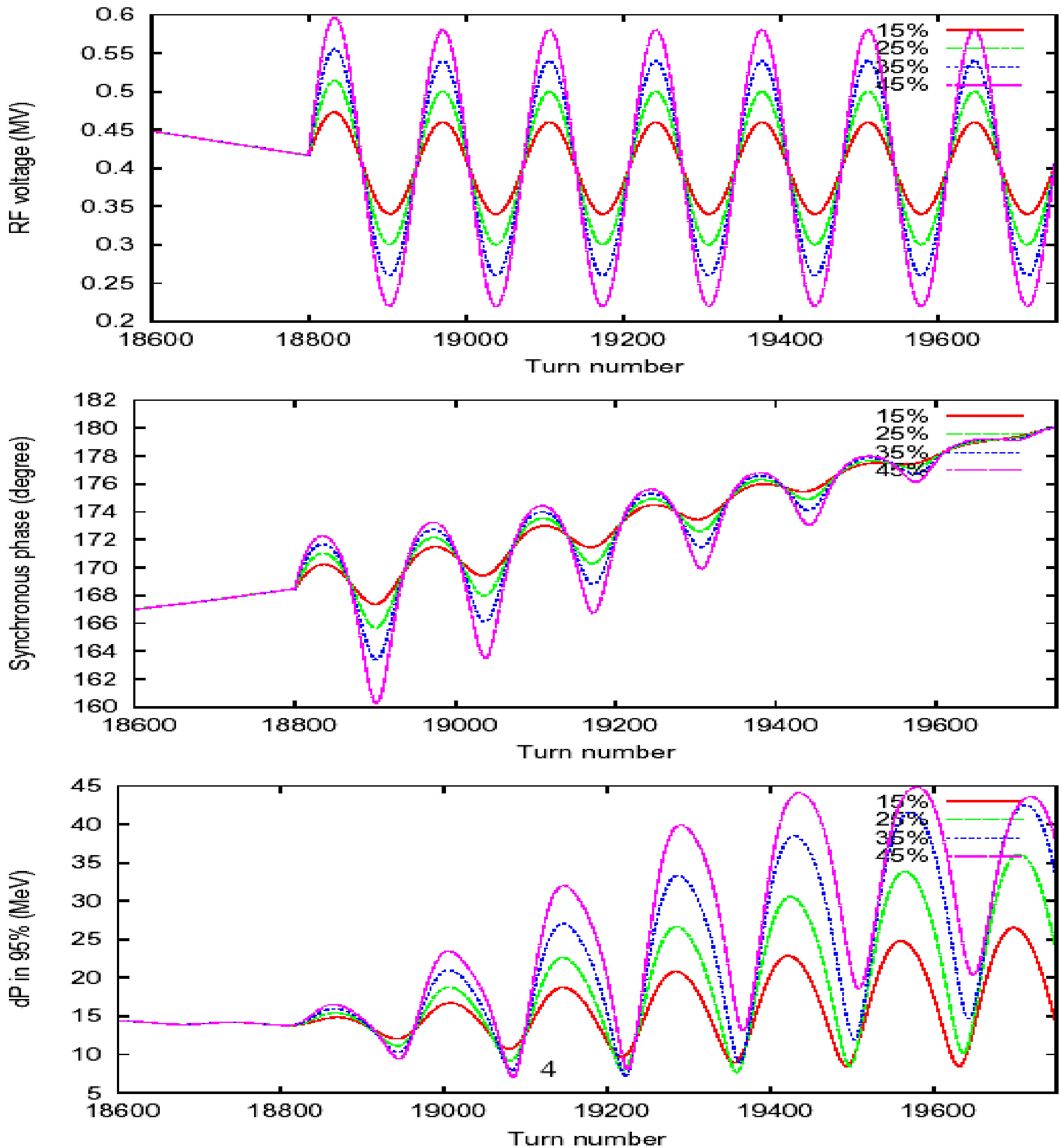


In the slip stacking cycle:

Problem --- there is a bucket mismatch between Booster and Main Injector.

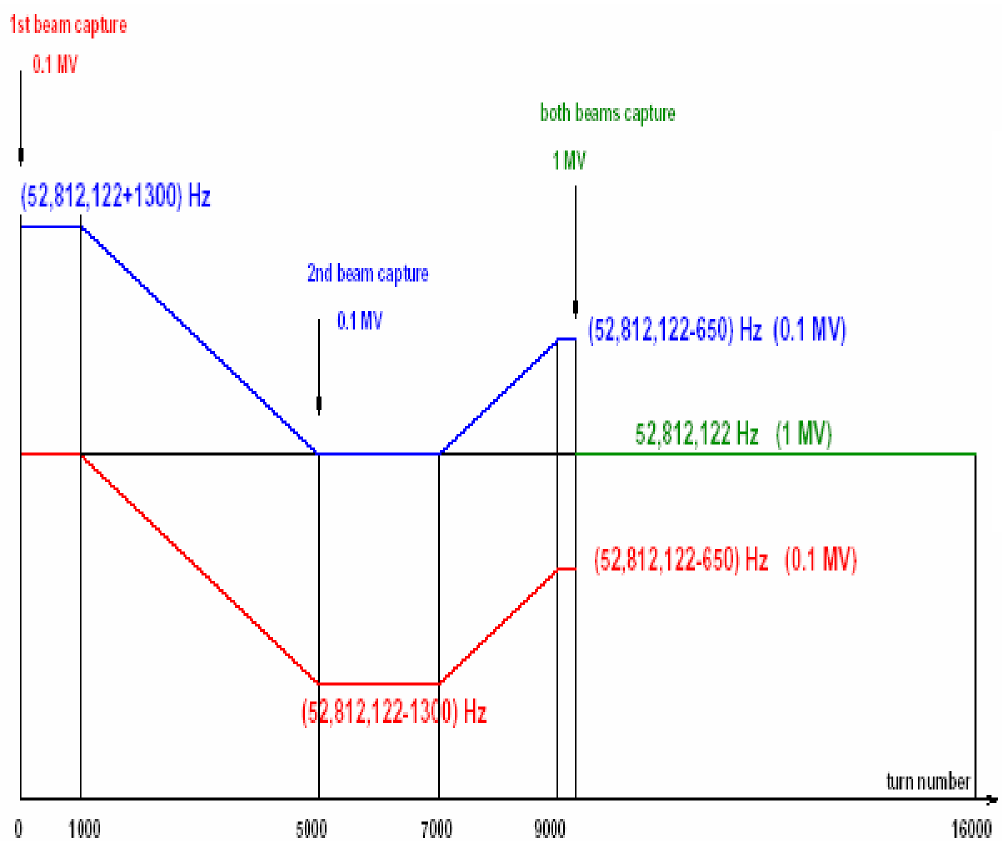
Solution --- momentum reduction *via* RF manipulation.

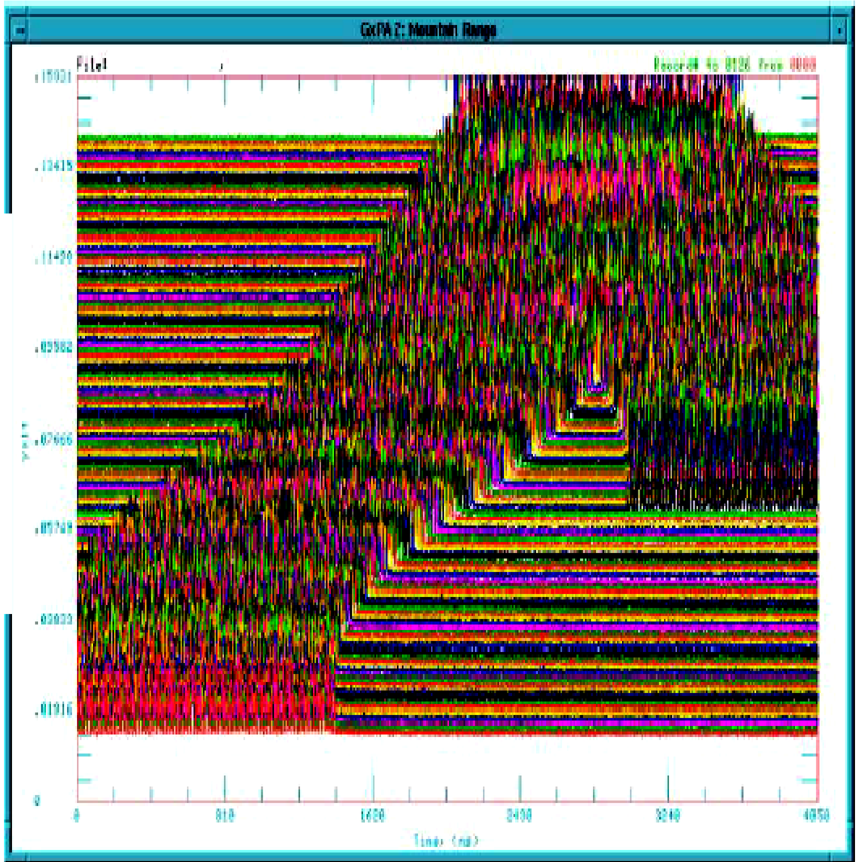
- Bunch rotation *via* RF voltage reduction was applied to reduce the momentum spread of the 8 *GeV* Booster beam below 8 *MeV* (95%) to reduce the slip stacking beam loss in Main Injector.
- However, the fast RF voltage reduction often causes beam loading issues to Booster RF stations, and reliabilities of extracted beams becomes a problem.
- An alternative solution has been numerically investigated and is now being used in the Booster operation. Modulating the RF voltage at twice the synchrotron frequency introduces bunch length oscillation at the end of a cycle, and the 8 *GeV* beam is extracted at the time when the bunch length reaches the maximum and the momentum spread becomes the minimum.



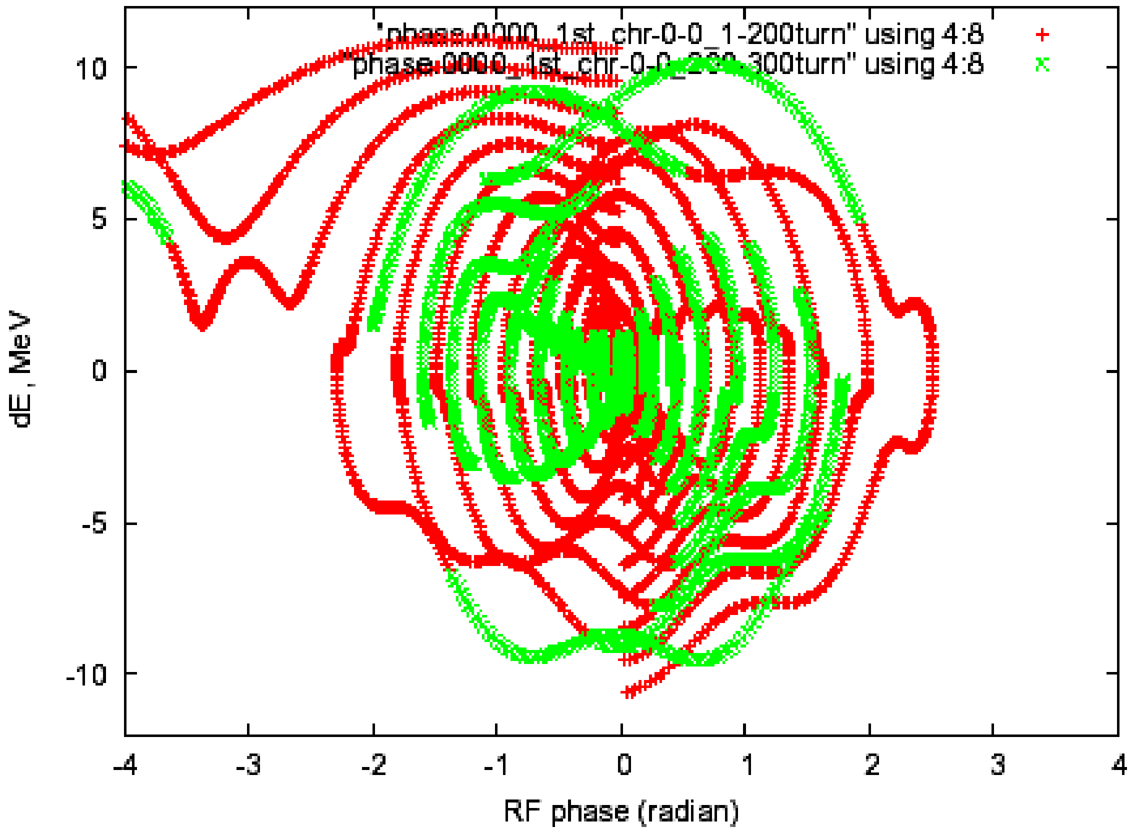
- **With the initial RF voltage of 0.4MV, four different amplitude modulations, 15% (red), 25% (green), 35% (blue) and 45% (magenta), are used in our simulation. RF voltage, synchronous phase, and 95% momentum spread *vs.* turn number are plotted from top to bottom.**
- **Beam is extracted at 2nd or 3rd minimum of the momentum spread (bottom).**

Slip stacking in the Main Injector





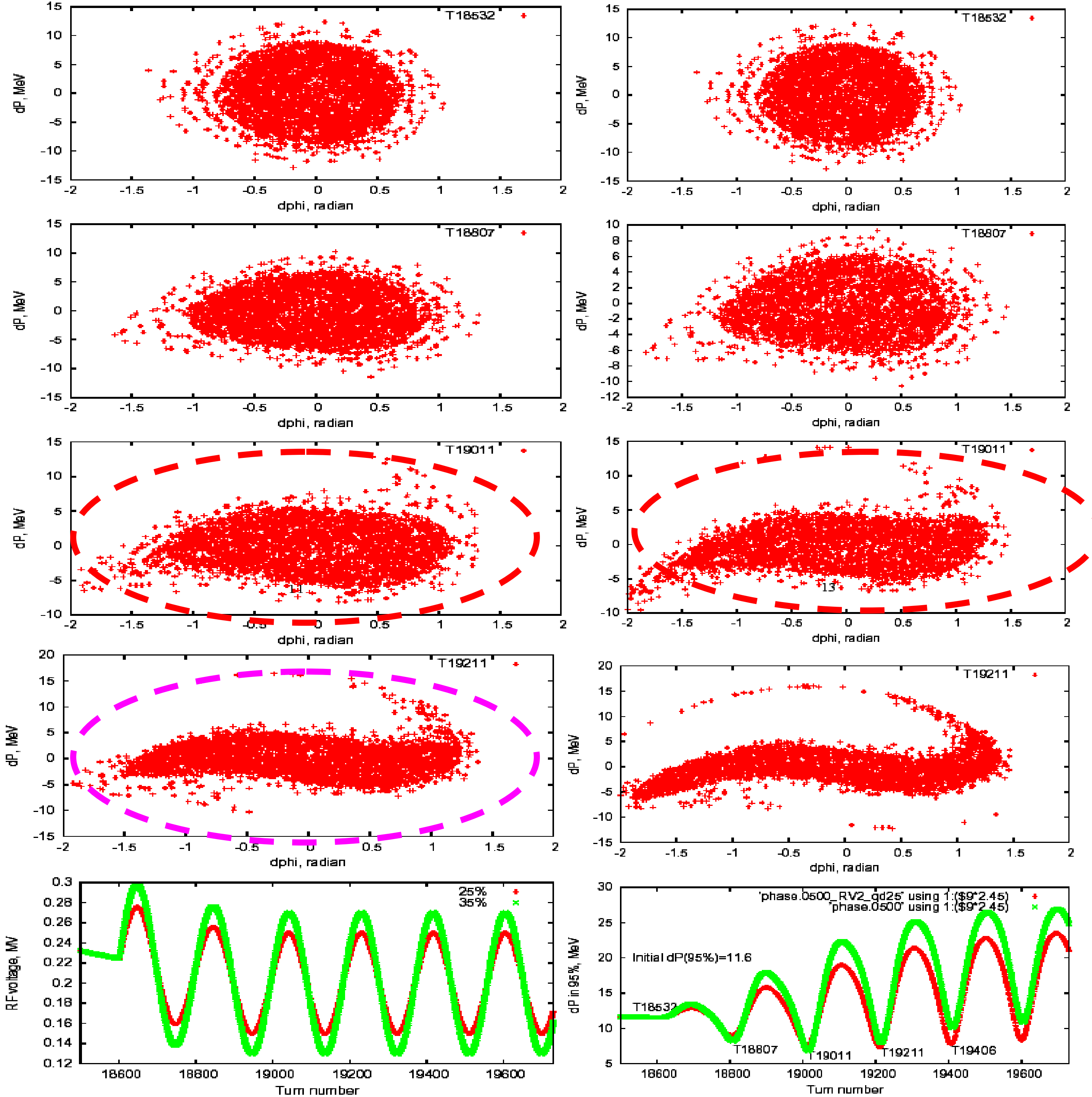
RF frequency of reference, first and second stations during slip-stacking injection at simulations



- Longitudinal phase plane for the 1st beam during 300 turns after the injection. First 3 particles of beam 1 with

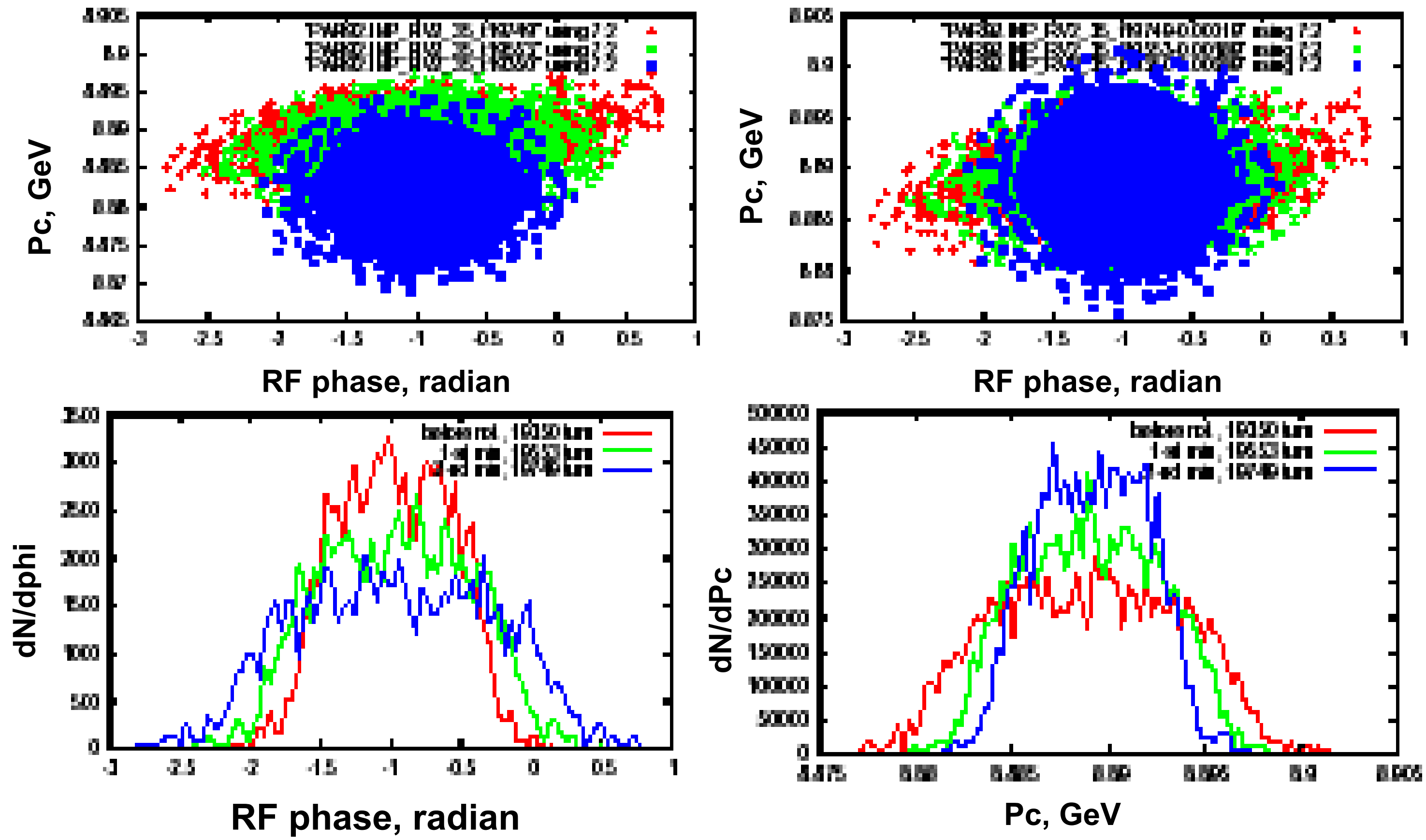
$$dE \geq \pm 8MeV$$

- are lost from the separatrix.



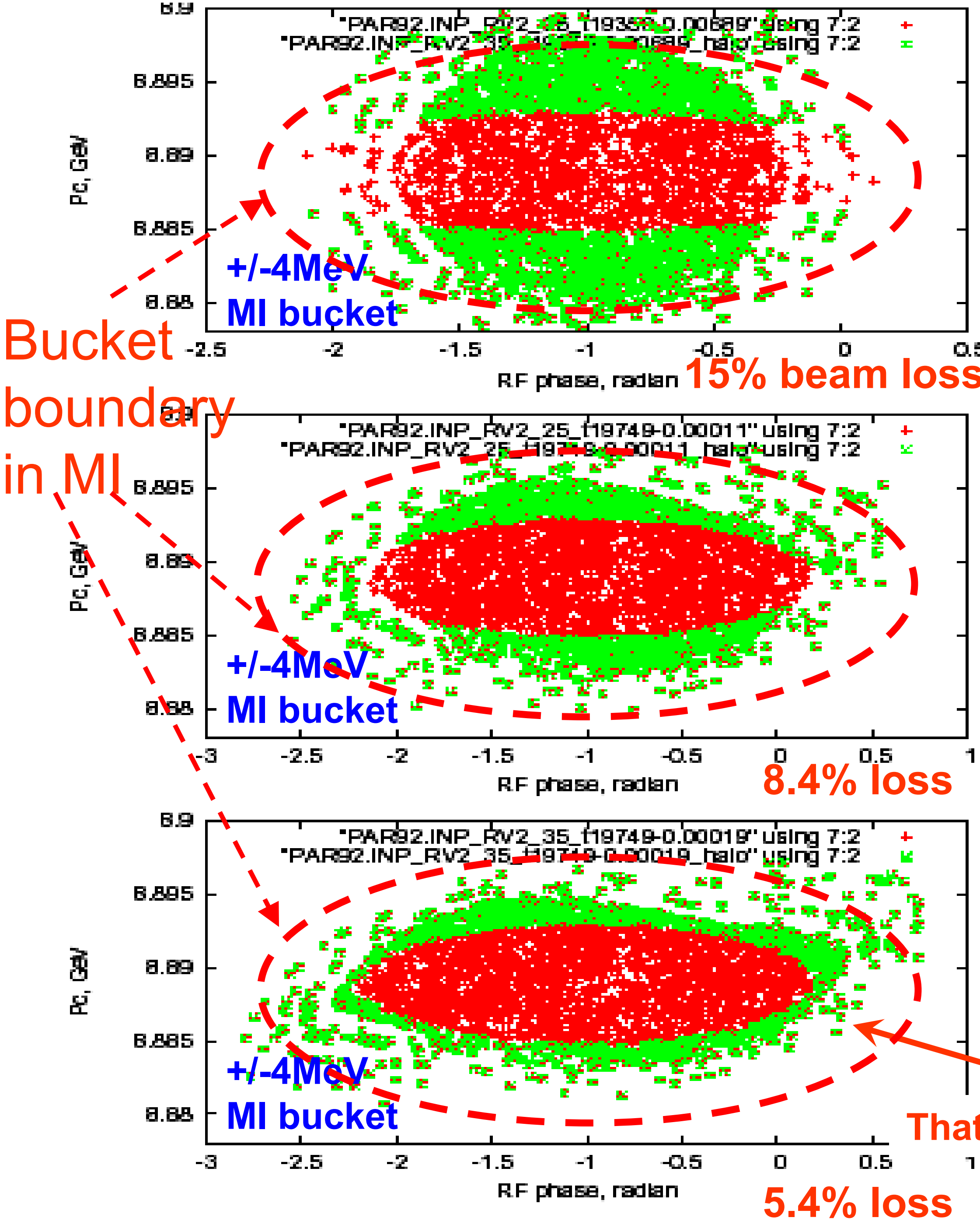
- **With the RF voltage at extraction of 0.2MV, two different amplitude modulations, 25% (left) and 35% (right), are simulated. Longitudinal phase plane at the initial, 1st, 2nd, and 3rd dP minimums are plotted from top to bottom.**

- **RF voltage and 95% momentum spread *vs*. turn number are plotted for 25% (red) and 35% (green) modulations at the bottom left and right.**



- Initial RF voltage 0.2MV, 35% modulation in Booster. Longitudinal phase plane at extraction to Main Injector without Pc correction (left) and with Pc correction to Pc=8.88889 GeV (right).

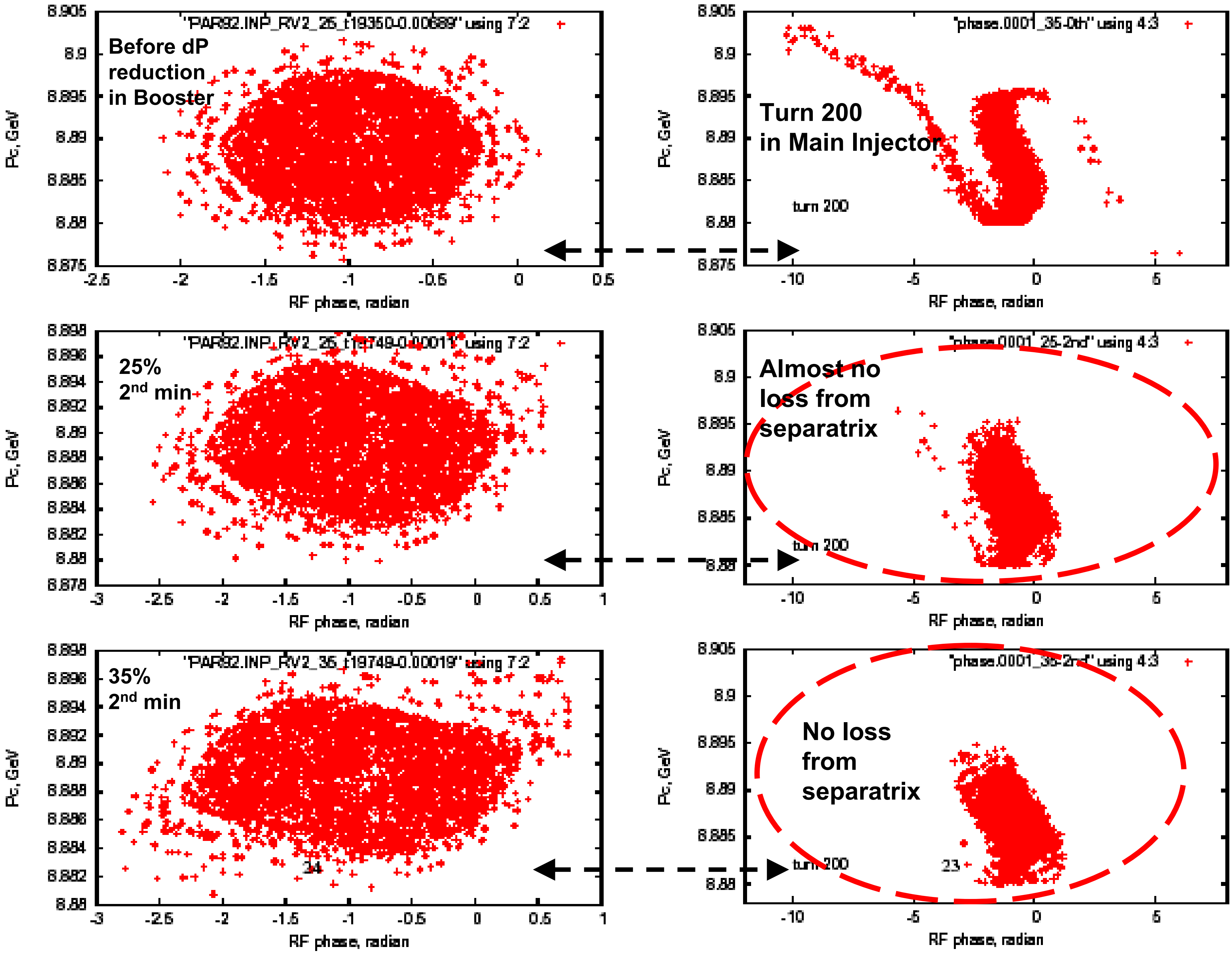
- Longitudinal distribution (left) and momentum distribution (right) of the bunch before momentum reduction, at 1st and 2nd minima.



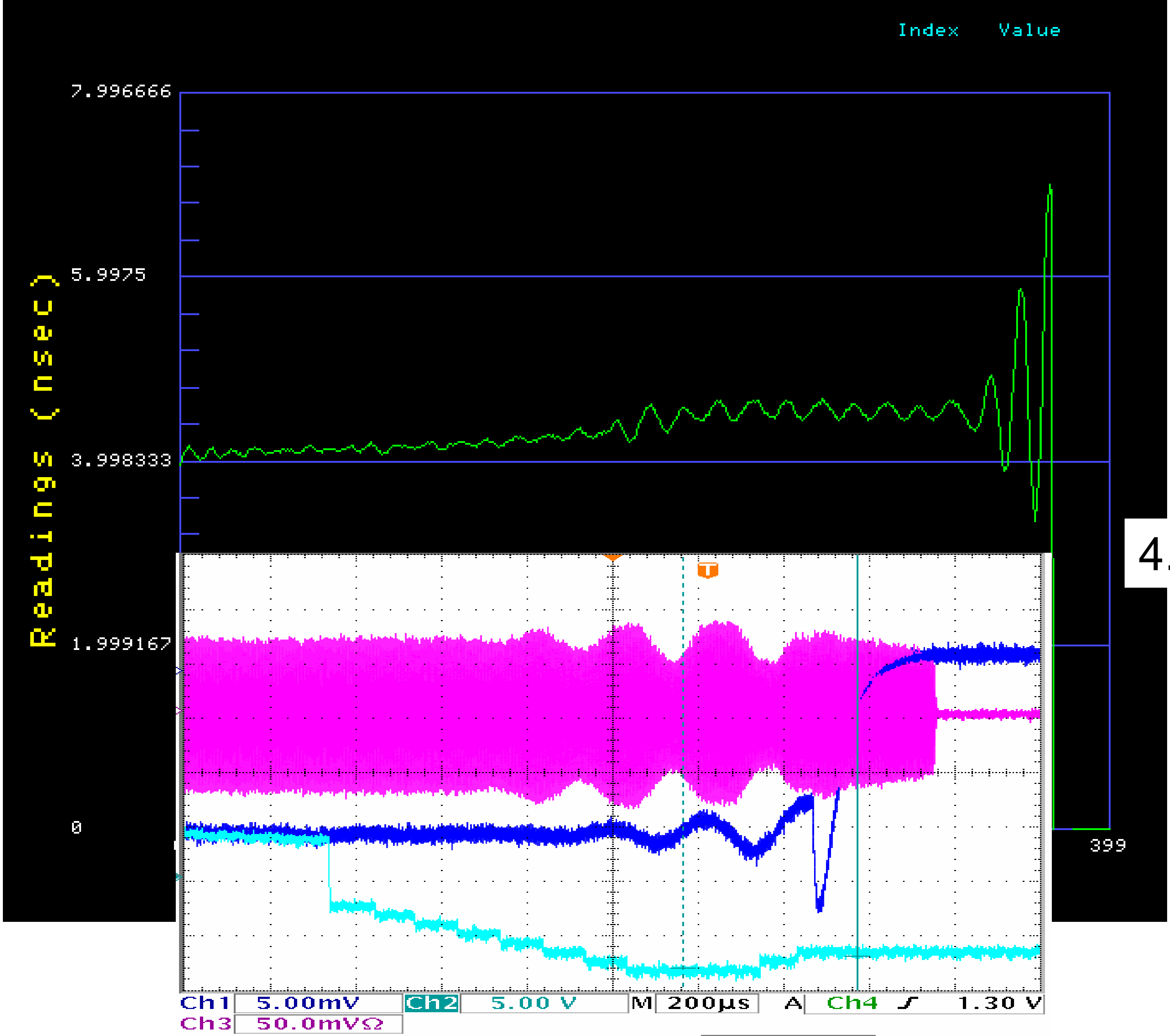
- **Longitudinal phase plane at injection to the Main Injector for Urf=0.2MV in the beginning of momentum reduction in the Booster: top – extracted before dP reduction, 2nd line – extracted at 2nd minimum with 25% modulation, 3rd line – extracted at 2nd minimum with 35% modulation.**
- **“Halo” particles, shown as greens were taken for particle loss calculations in the Main Injector during 12,000 turns after injection.**
- **Tracking 1000 particles for 12000 MI turns takes 60 hours.**

The best results are obtained at Urf=0.2MV, the modulation depth of 35%, and the beam being extract at the 2nd *dP* minimum. We are using it in the operation.

That’s why we get the best result!

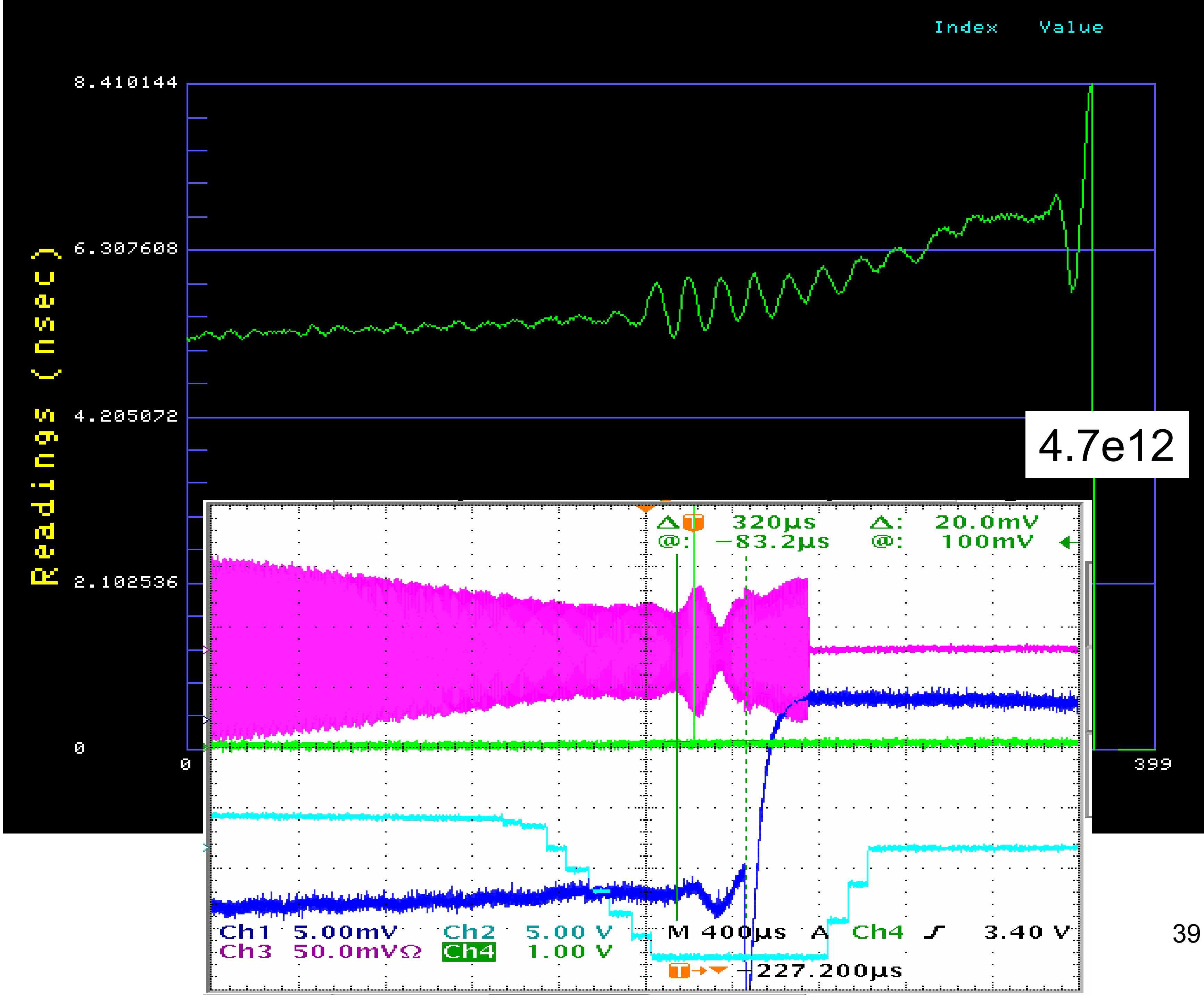


'PAR92.INP_RV2_25_t19350-0.00689' using 7:2
Before dP
reduction
in Booster
'phase.0001_35-0th' using 4:3
Turn 200
in Main Injector
turn 200
'PAR92.INP_RV2_25_t19749-0.00011' using 7:2
25%
2nd min
'phase.0001_25-2nd' using 4:3
Almost no
loss from
separatrix
'PAR92.INP_RV2_35_t19749-0.00019' using 7:2
35%
2nd min
'phase.0001_35-2nd' using 4:3
No loss
from
separatrix
Pc, GeV
RF phase, radian



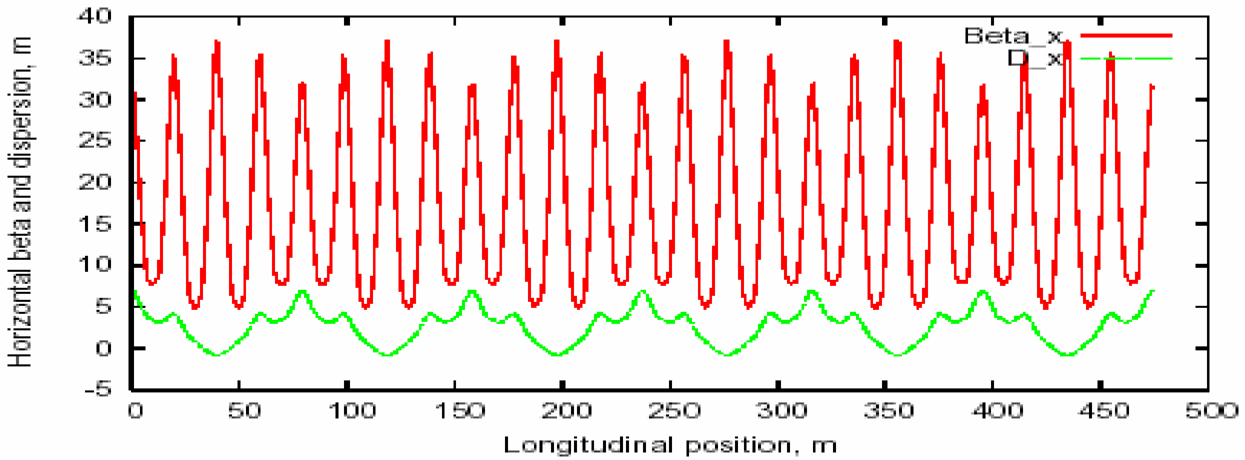
Index
Value
7.996666
5.9975
3.998333
1.999167
0
Readings (nsec)
399
Ch1 5.00mV
Ch2 5.00 V
M 200µs
A Ch4 1.30 V
Ch3 50.0mVΩ

4.2e12


Index
Value
8.410144
6.307608
4.205072
2.102536
0
0
399
Readings (nsec)
4.7e12
320µs
@: −83.2µs
Δ: 20.0mV
@: 100mV
Ch1 5.00mV
Ch2 5.00 V
M 400µs
A Ch4 3.40 V
Ch3 50.0mVΩ
Ch4 1.00 V
227.200µs

Summary

- We now have a single detailed modeling tool for the Booster in both longitudinal and transverse motions throughout the entire acceleration cycle.
- The influence of the transverse space charge effect is very small without considering field errors; the longitudinal space charge effect causes the intensity dependent beam loss and emittance growth, etc.
- It's important to inject the beam at a small RF voltage in order to reduce the beam size and the longitudinal emittance, etc., and ramp up the RF voltage quickly to capture more beam.
- At the transition crossing, 3-D simulation which includes the longitudinal impedance and nonlinear compaction factors should be done in order to have a better understanding of experimental observations.
- At the extraction, modulating the RF voltage with twice the synchrotron frequency and extracting the 8-GeV beam at the d*P* minimum have been investigated *via* varying the initial RF voltage and modulation depth, and how extracted beams in different conditions affect the slip-stacking beam loss have been numerically investigated.



Horizontal beta and dispersion in the Booster at transition ($\gamma_t = 5.13$) with γ_t quadrupoles current 1000 A (top), with qgf at short 02, 06, 10, 14, 18, and 22; qgd at short 04, 08, 12, 16, 20, and 24. Sextl arrangement is two at upstream of long 4, two at upstream of long 8, two near the middle of long 18, and one at the upstream of long 20.