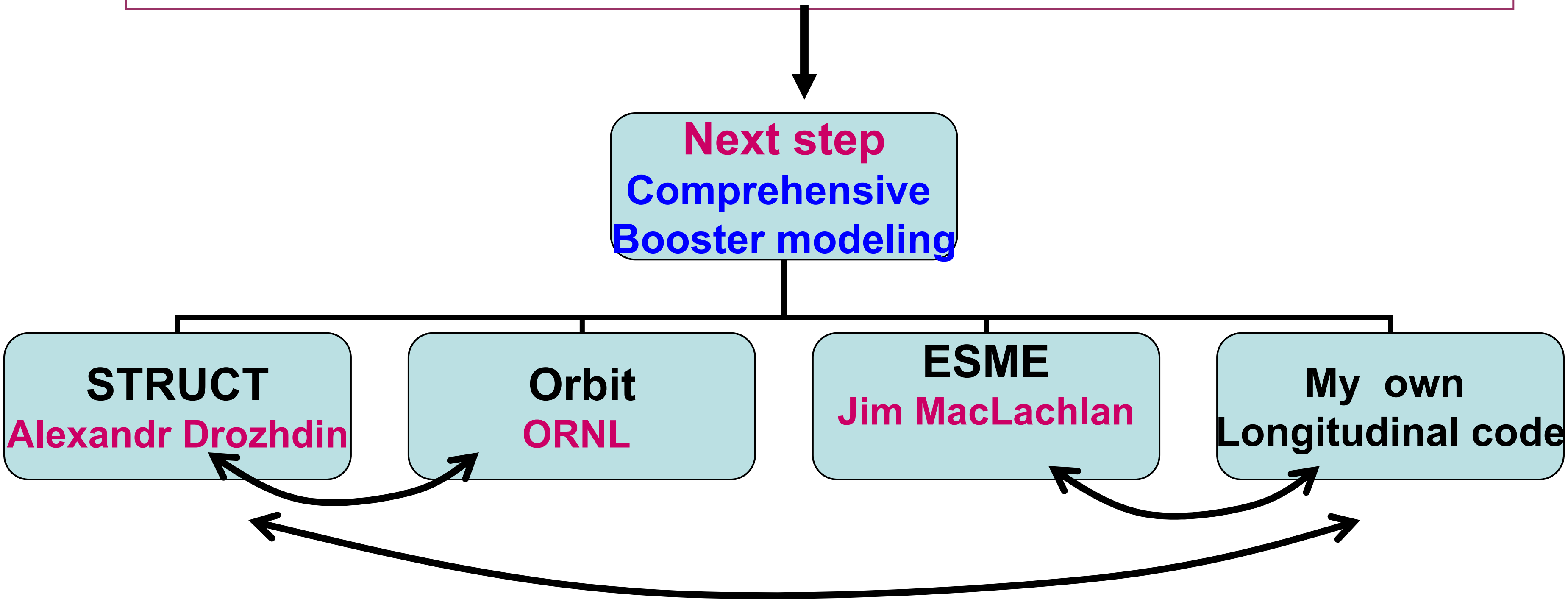
Proposal of RF manipulation in Booster

at injection and transition

X. Yang and W. A. Pellico

AEM on 03/12/07

The work is in the early stage using my own code, and the goal is to find whether or not we can benefit from having 3rd RF harmonic at injection and transition.



Acknowledgements

Valeri Lebedev for voltage jump scheme at transition,
Francois Ostiguy for Orbit code,
David Wildman, Chuck Ankenbrandt and Eric Prebys for useful discussions and supporting this work

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	5.0×10^{12}	1.278	0.3	1.85-3.2	6.12-33.69

•**the injected beam is uniformly distributed along the RF phase.**

Why 3rd RF harmonic at injection?

V(rf) only

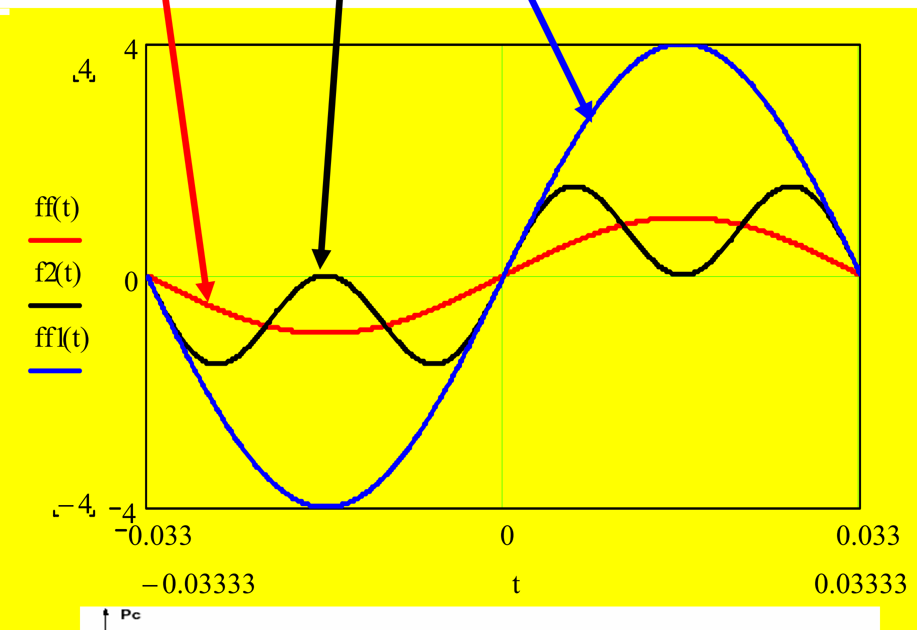
$$ff(t) := 1.0 \cdot \sin(w \cdot t)$$

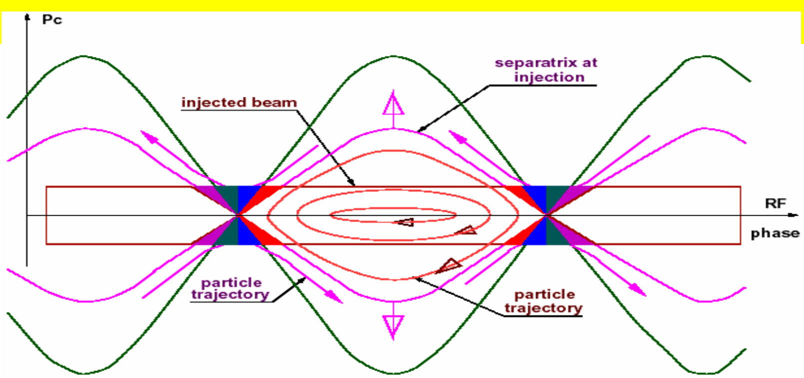
V(rf) +V(3rf)

$$f2(t) := 1.0\sin(w \cdot t) + 1.0\sin[3 \cdot w \cdot (t) + \pi \cdot 0.]$$

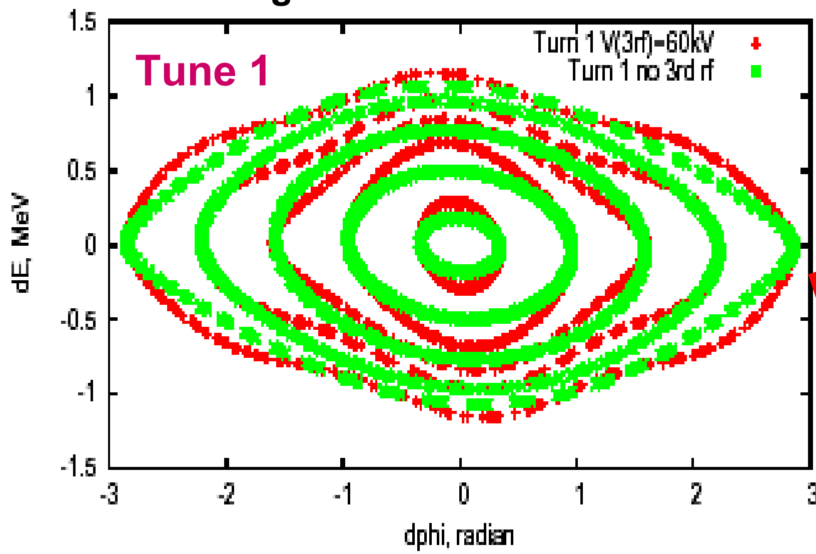
$$ff1(t) := 4.0 \cdot \sin(w \cdot t)$$

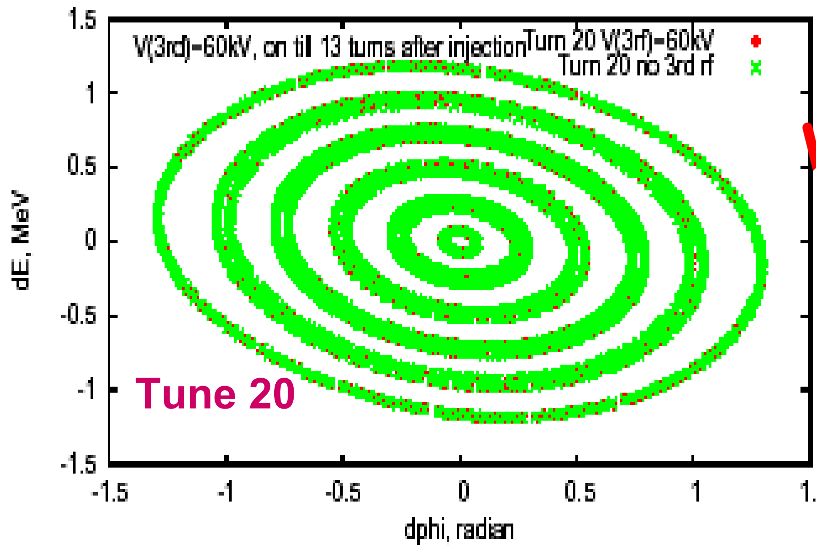
*4*V(rf)*





Red ones and green ones are with and without 3rd RF

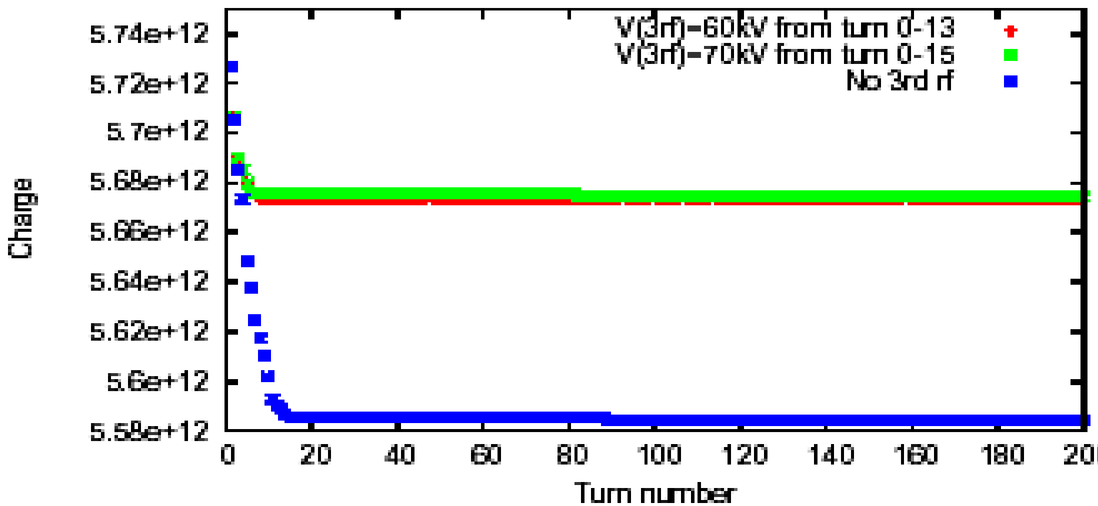


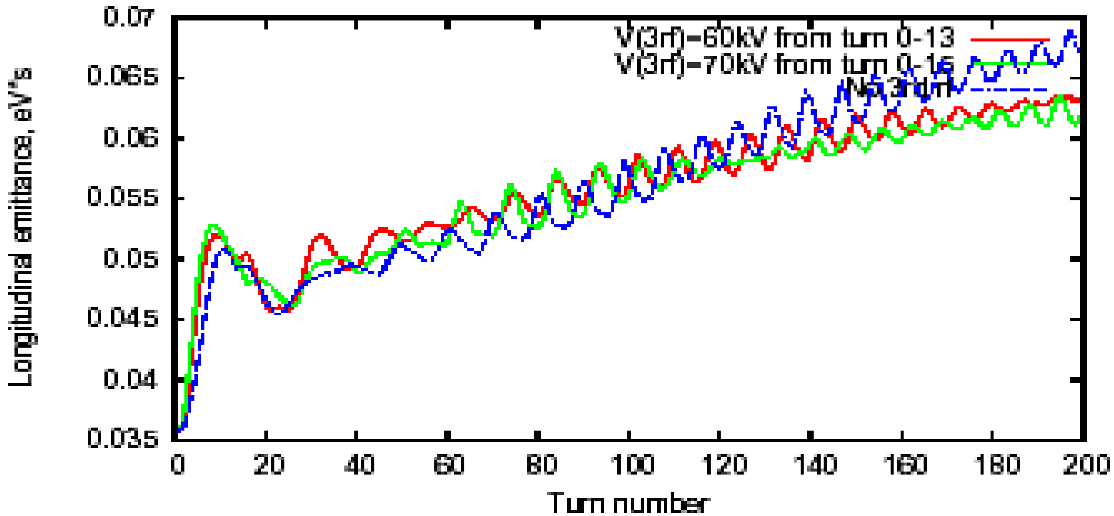


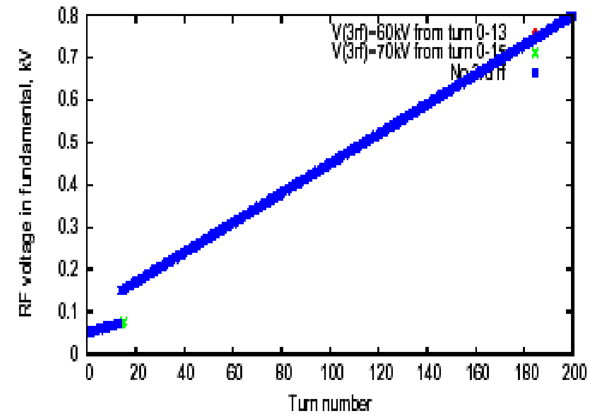
Smooth transition from 3rd rf on to off.

Long. phase contours at turn 1 (top) and turn 20 (bottom)

Results







Fundamental RF Voltage *vs.* turn number.

Comparing with 3rd RF harmonic: *V(3rf)=60 kV till 13 turns after injection (red)* and *V(3rf)=70 kV till 15 turns after injection (green)* to with fundamental RF only (blue), charge and 95% longitudinal emittance *vs*. turn number are shown at the top and bottom.

Because of using 3rd RF harmonic, there is *a factor of two reduction in particle loss* and *~8% reduction in the longitudinal emittance* till turn 200.

Why 3rd RF harmonic at transition?

Transition crossing is space charge dominated in Booster. Longitudinal space charge force induces a *mismatch before and after transition* since it's *defocusing* before transition and it becomes *focusing* after transition.

- $\gamma = 0.4/\text{ms}$ at *transition*

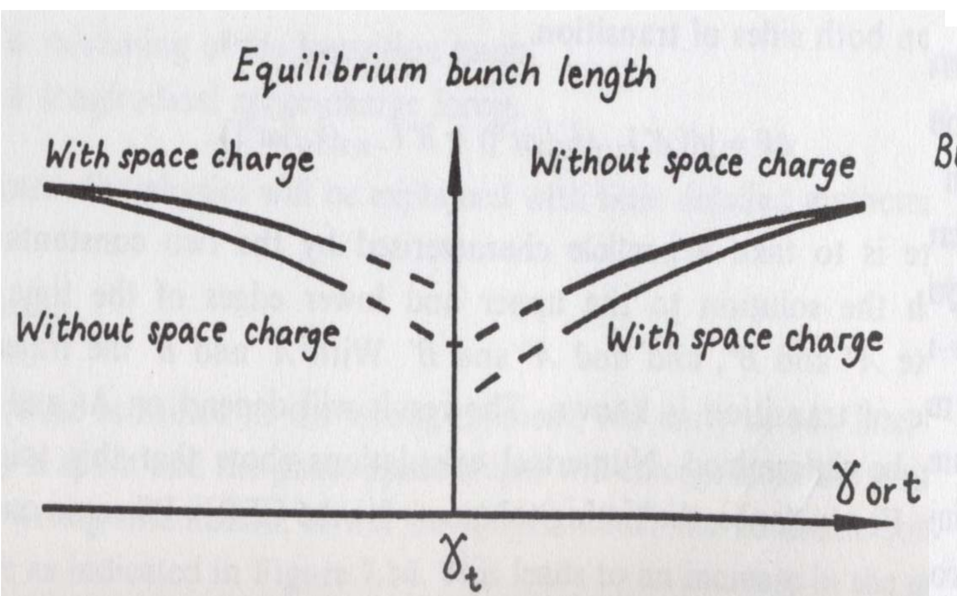
  Nonlinear chromatic effect can be removed by adjusting *sextupole corrector settings*

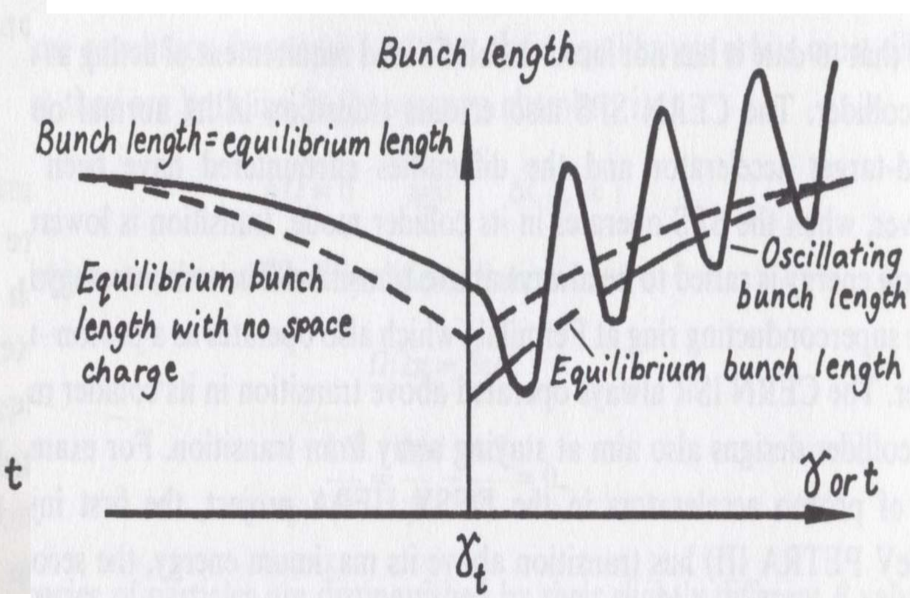
  see next page

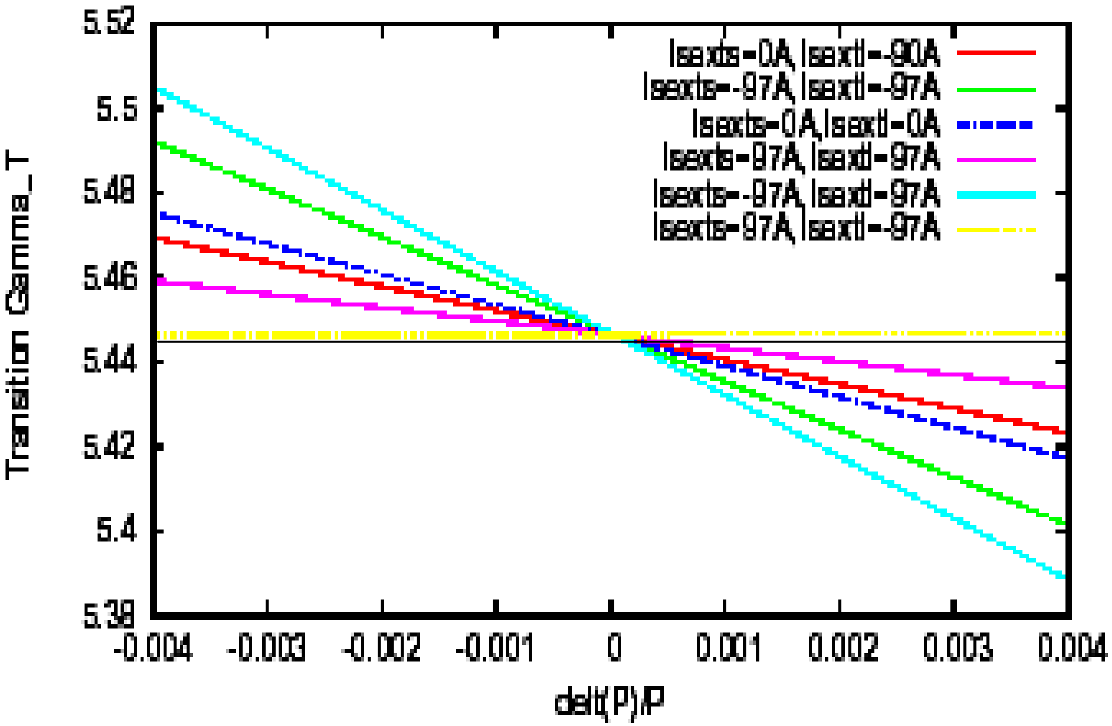
  $T_c \approx 0.25ms --- nonadiabatic\ time$

  $when\ \ the\ \ synchrotron\ \ motion\ \ is\ \ \ freezing \sim 150\ turns$

Ref: The Principles of Circular Accelerators and Storage Rings
Philip J. Bryant and Kjell Johnsen



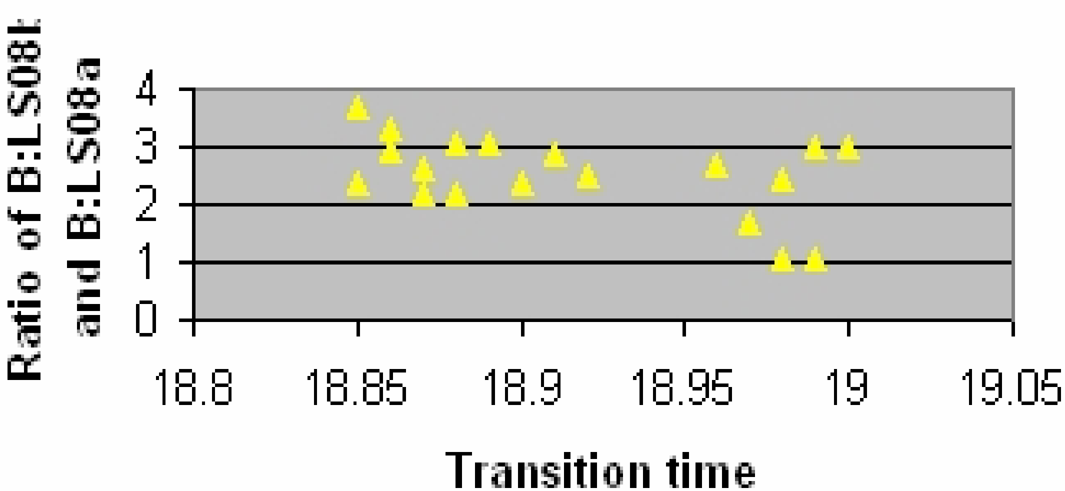




By changing the sextupole corrector settings, we can change the dependence of transition energy upon the momentum deviation of a particle (top).

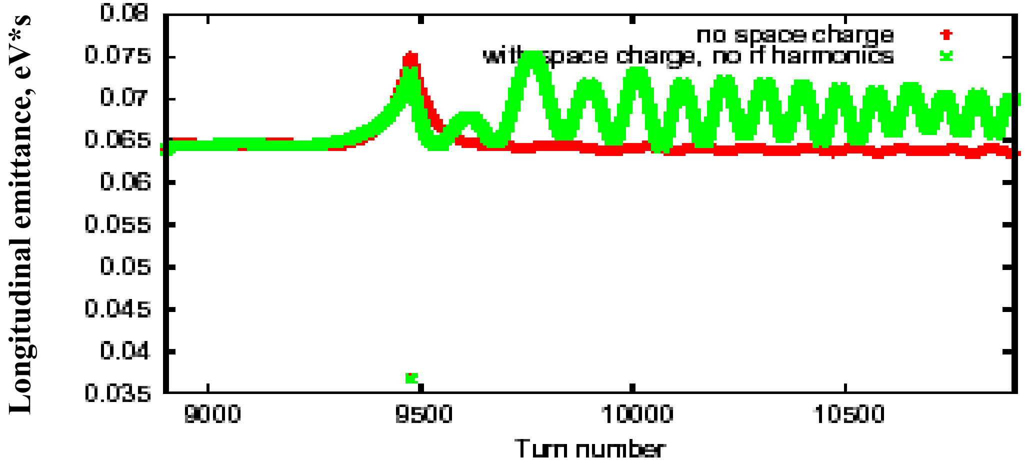
At **Isexts≈97A**, **Isextl≈-97A, we can remove such a dependence (nonlinear chromatic effect).**

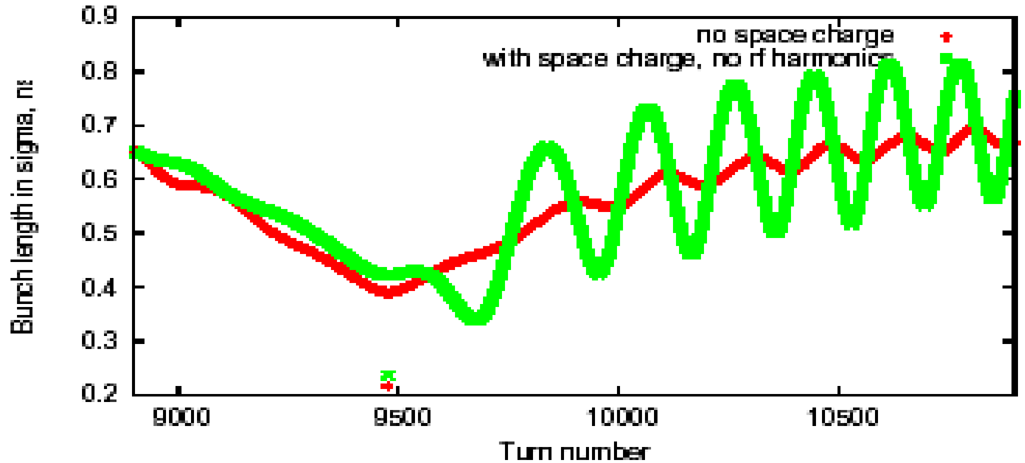
1 turn injection

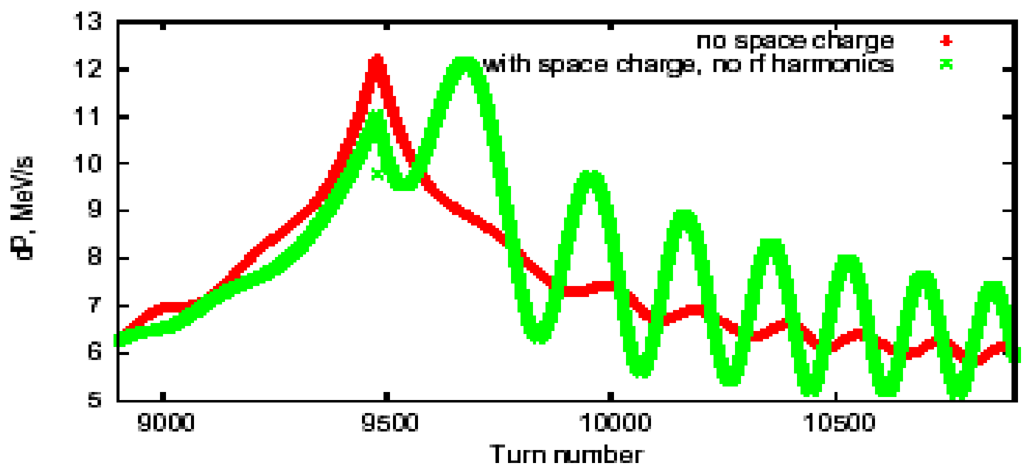


We experimentally approved that we could measure the dependence of transition energy upon momentum deviation of the particle in Booster (left). Afterwards, we can find the sextupole setting whch can remove the nonlinear chromatic effect (if it will do any good).

Arden Warner, Kent Triplett, and I are doing the study.



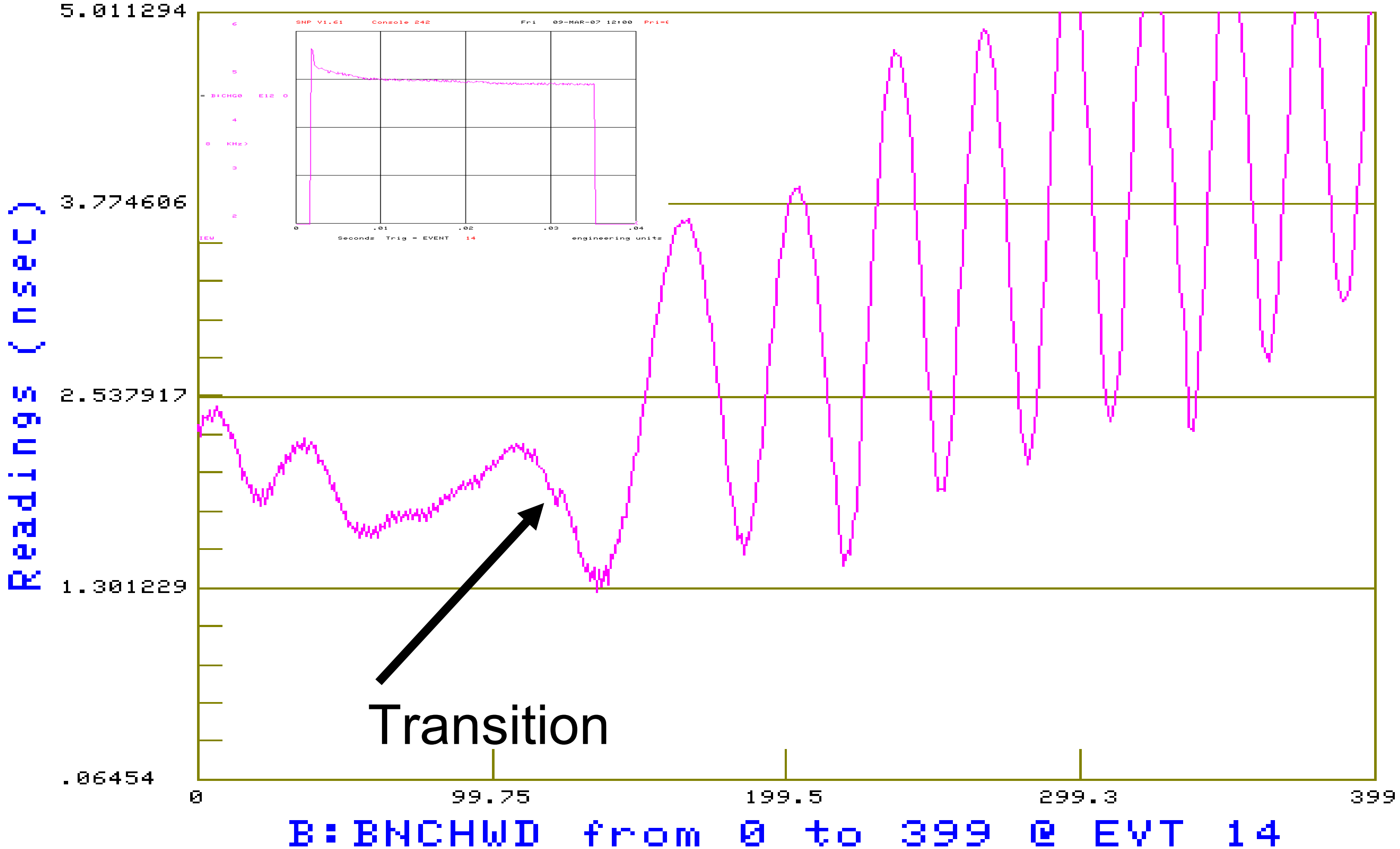




At the Booster batch intensity of 5e12, without (red) and with (green) ***space charge effect***, 95% longitudinal emittance (top), bunch length (middle), and momentum spread (bottom) *vs*. turn number.

The space charge induced mismatch during transition causes the bunch length oscillation after transition and longitudinal emittance growth.

Compare simulation with the experiment → next page



Plot is at $14 with a batch size of 5e12, bunch length in 4sigma.
The minimum bunch length in sigma is 0.42ns, and it matches with the simulation within 14%.

How to avoid such a mismatch in the beginning?-Voltage jump scheme

The naive explanation – since **before transition** ***space charge force*** is defocusing and it **decreases the momentum spread by ($-\Delta_1$)**, and **after transition** it becomes focusing and it **increases the momentum spread by ($+\Delta_2$)**, we scale such a **mismatch** at the time right before transition by **$-(\Delta_1+\Delta_2)$**, the compensation is done by **focusing the beam right before transition** by a amount of ($\Delta_1+\Delta_2$) to **cancel such a mismatch *via*. increasing the RF slope**.

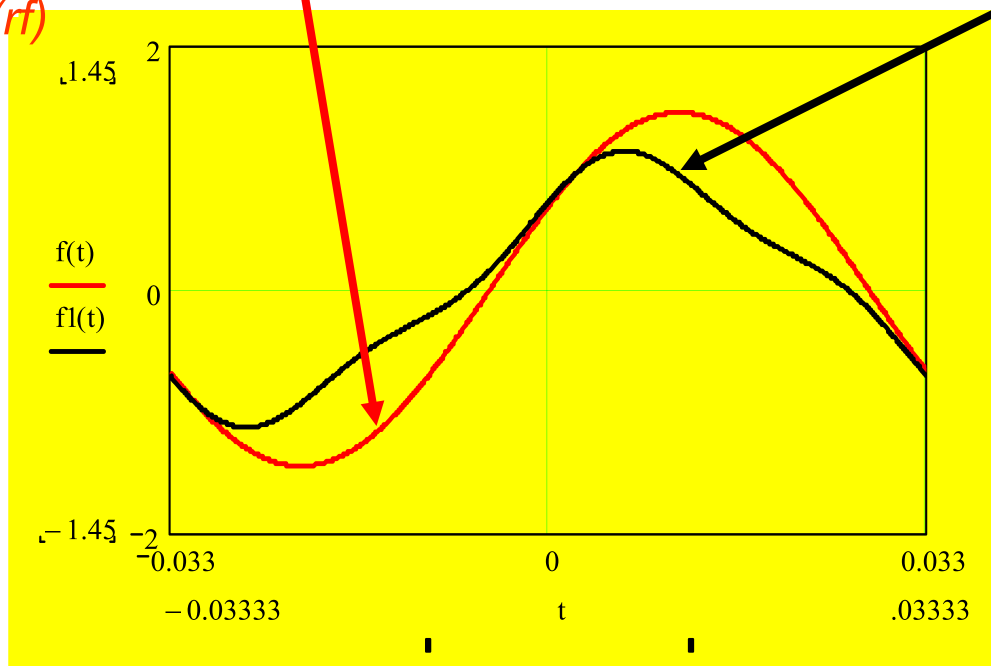
$$f(t) := 1.45 \cdot \sin\left[w \cdot (t) + 28. \cdot \frac{\pi}{180} \right]$$

$$f1(t) := 1.0 \sin\left(w \cdot t + 46 \cdot \frac{\pi}{180} \right) + .15 \sin\left[3 \cdot (w \cdot t) + (0) \cdot \frac{\pi}{180} \right]$$

*V(rf)+a*V(rf)*

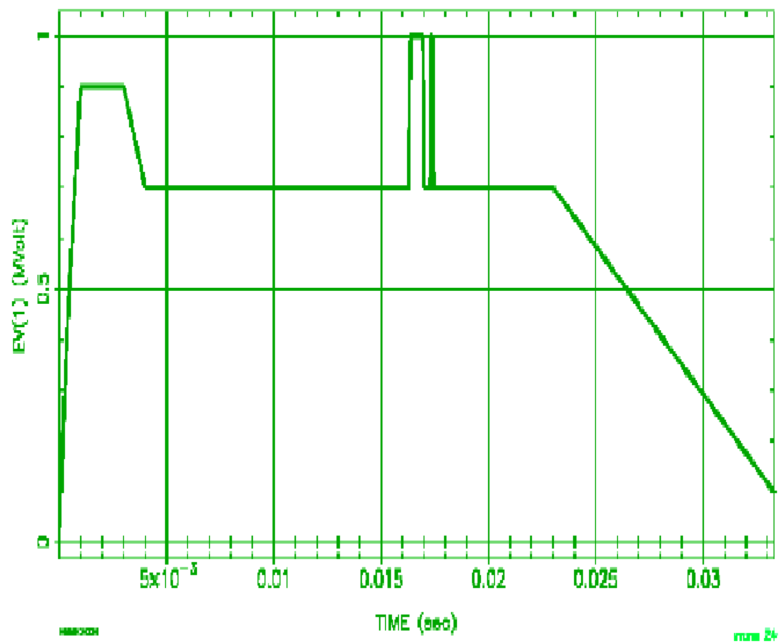
*V(rf) + (a/3)*V(3rf)*

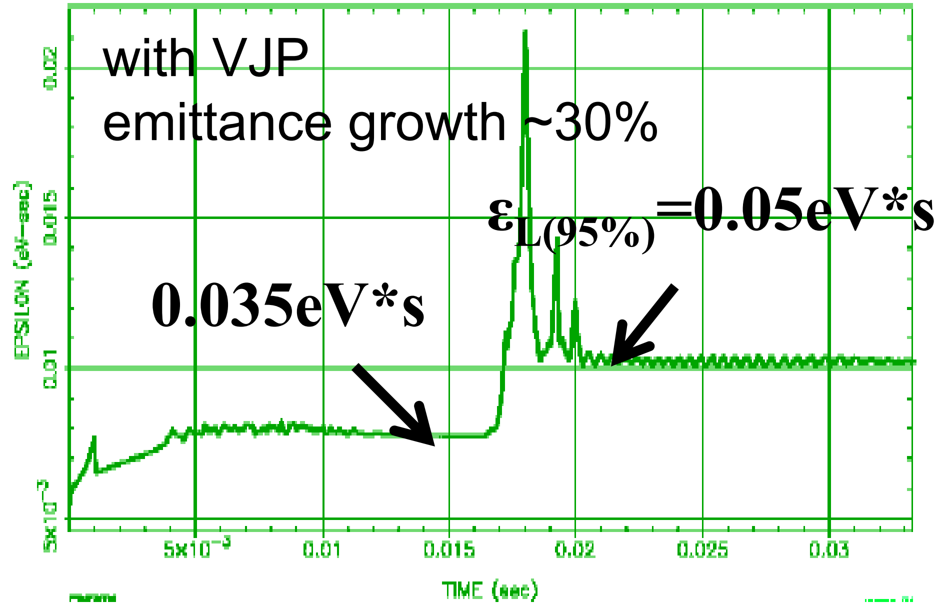
Here, a=0.45

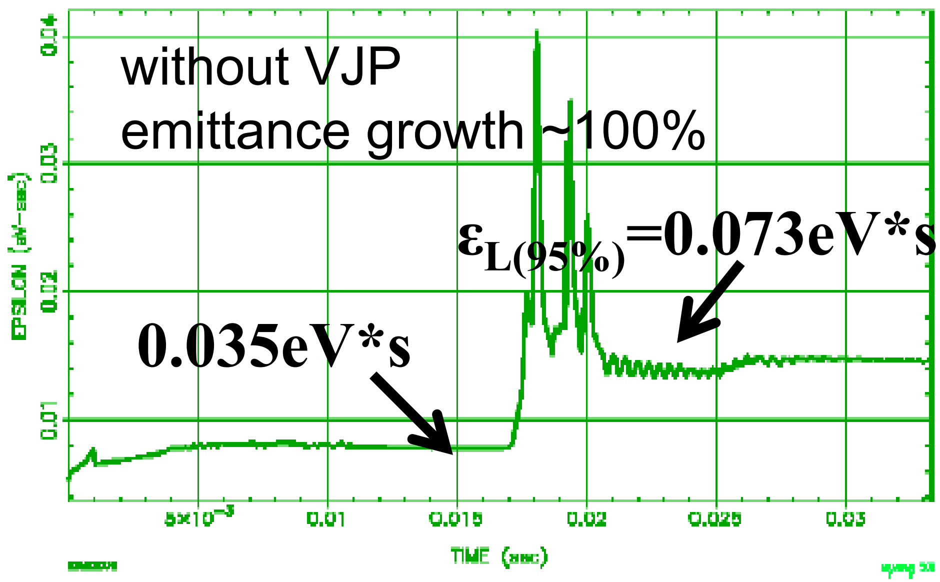


Increasing the same amount of rf slope, it takes ~ 1/3 of the rf voltage using 3rd rf harmonic compared to using the fundamental rf.

Voltage Jump using fundamental rf





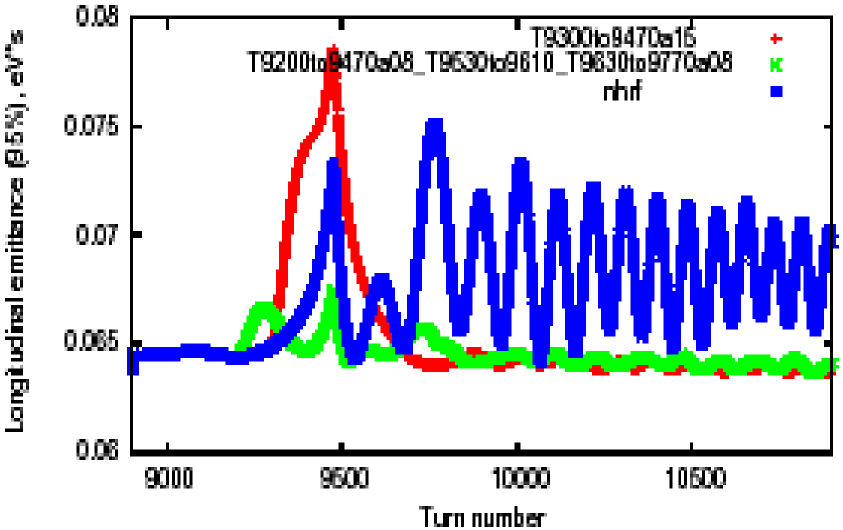


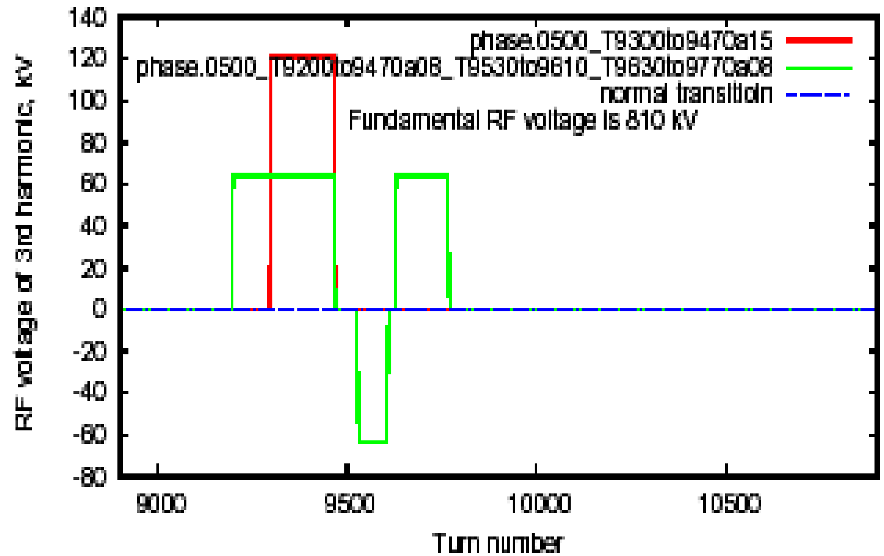
At the batch intensity of 4.e12, in order to reduce the longitudinal emittance growth to ~25%, ~300kV fundamental rf voltage increase is needed.

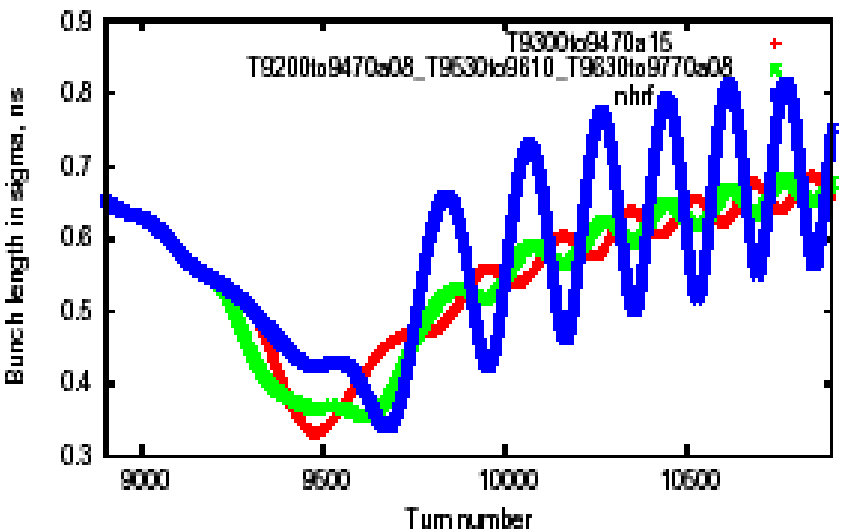
The simulation code is ESME.

Ref: FERMILAB-FN-0770-AD

Voltage Jump using 3rd rf harmonic
Since the bunch is so short at transition, we don't need to phase 3rd rf harmonic precisely (~10-20° jitter is OK)





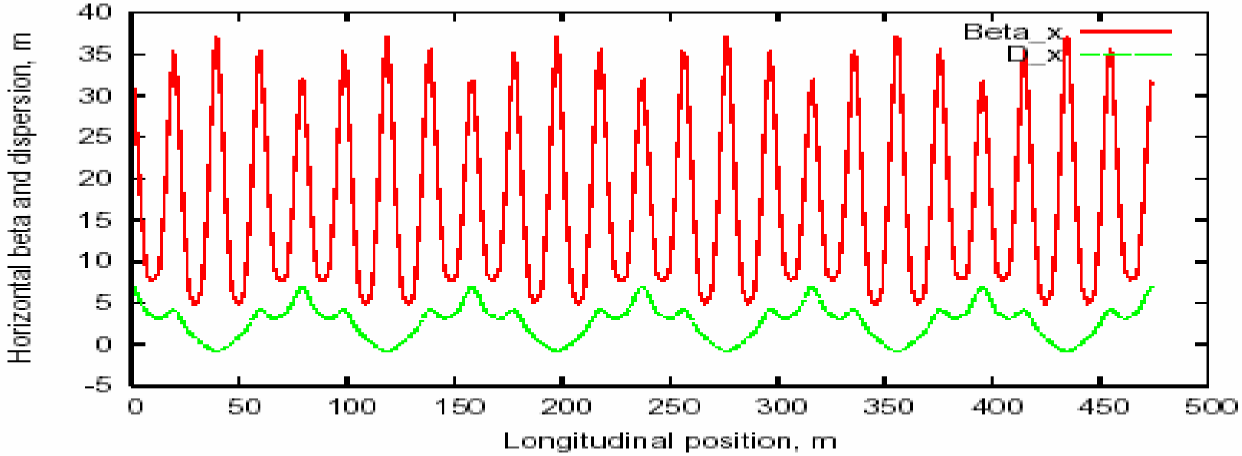


With 3rd rf harmonic: ***V(3rf)=120 kV(red)*** and ***V(3rf)=60 kV(green)***, and ***without 3rd rf harmonic (blue)***, longitudinal emittance (top left), bunch length (top right) and 3rd rf voltage (top right) are plotted. *At transition, if we have enough 3rd rf voltage (120kV), the mismatch during transition can be removed;* ***likely we have the 3rd rf voltage (60kV), the mismatch are largely removed, plus post-transition pulses, it can be as good as the red case***.

Conclusions

At the injection, *3rd rf harmonic provides a more squared bucket shape without increasing the bucket height. It can help in reducing the injection loss about a factor of two.*

During transition, *we wish to remove the source of the emittance growth instead of relying upon quad-damper after transition. We should have both voltage jump system and quad damper in order to reduce bunch length oscillation and emittance growth ---* ***this can be key to slip stacking efficiency in MI****!!*



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.