PS2 Space Charge Simulations

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Outline

- Introduction
- Computational models
- Space-charge simulation with RF ramping
  - Case 1
  - Case 2
- Effects of initial emittance
- Bunch intensity limit
- Space-effects in fixed target application
- Summary
- Future plans

Introduction

➢PS2 was proposed for LHC upgrade with higher injection energy (4 GeV) to mitigate the space-charge effects to reach higher number of protons per bunch (4 x 10^{11}).

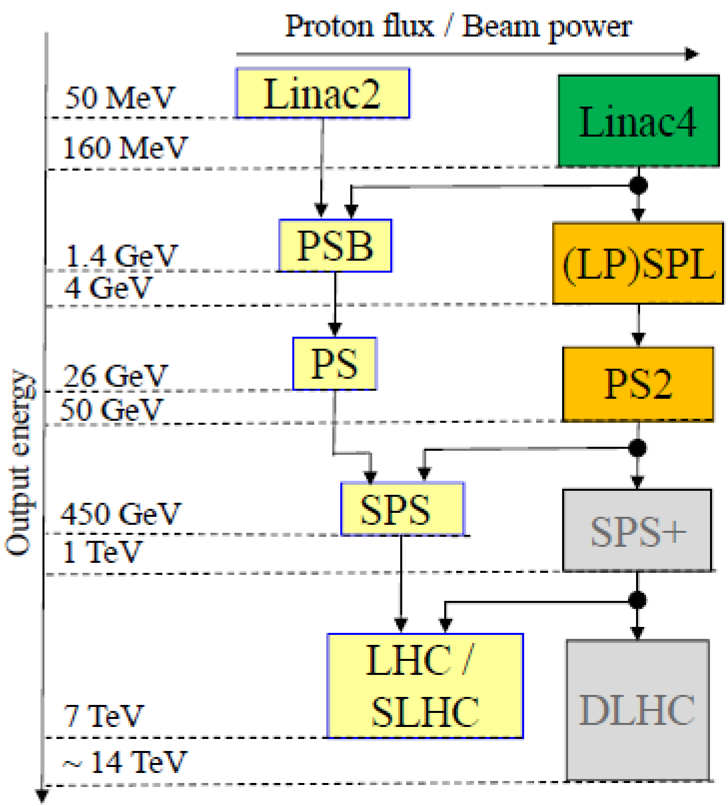


Figure 1: Overview on the CERN injector complex upgrade programme: stage 1 (green), stage 2 (orange).

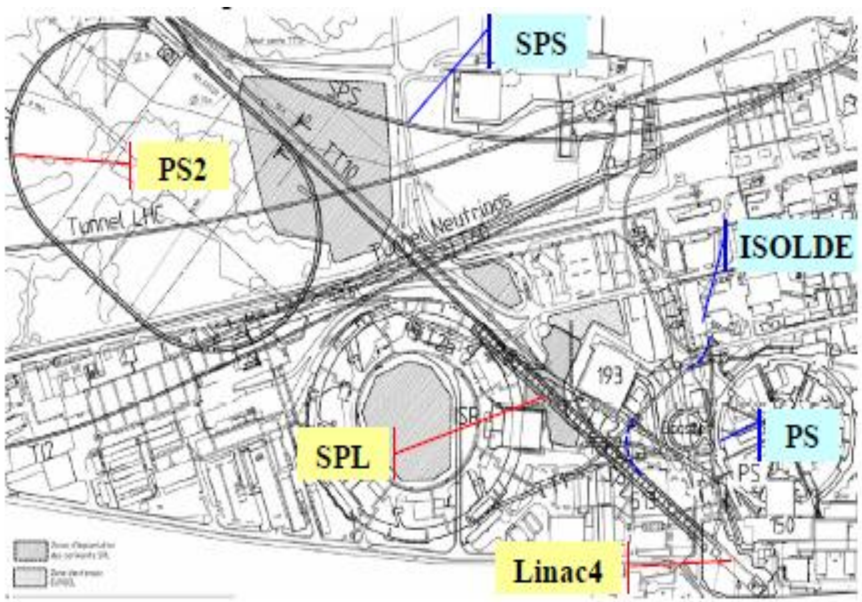
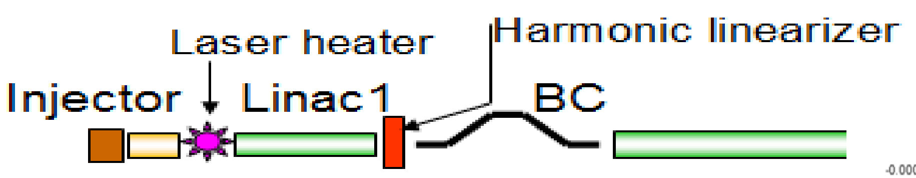


Figure 2: Integration of PS2 within the existing and future CERN accelerator complex.

M. Benedikt, et al., PAC09, WE1GRI03

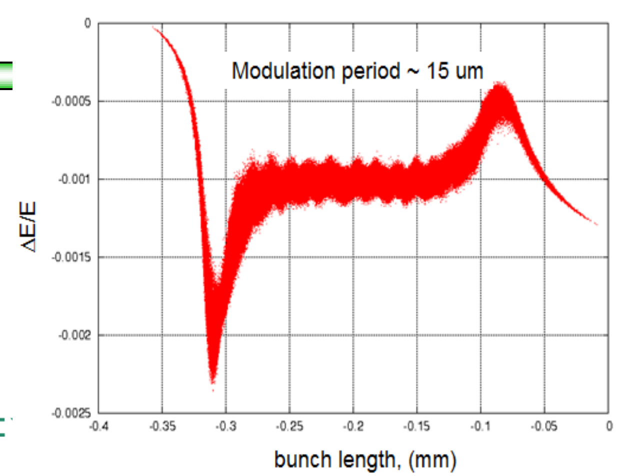
IMPACT code suite

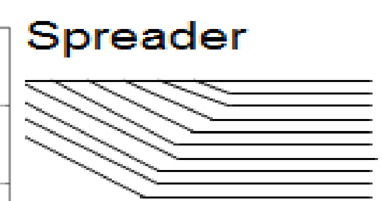
- IMPACT-Z: parallel PIC code (z-code)
- IMPACT-T: parallel PIC code (t-code)
- Envelope code, pre- and post-processors,…
- Optimized for parallel processing
- Applied to many projects: SNS, JPARC, RIA, FRIB, PS2, future light sources, advanced streak cameras,…
- Has been used to study photoinjectors for BNL e-cooling project, Cornell ERL, FNAL/A0, LBNL/APEX, ANL, JLAB, SLAC/LCLS



One Billion Macroparticle Simulation of an FEL Linac

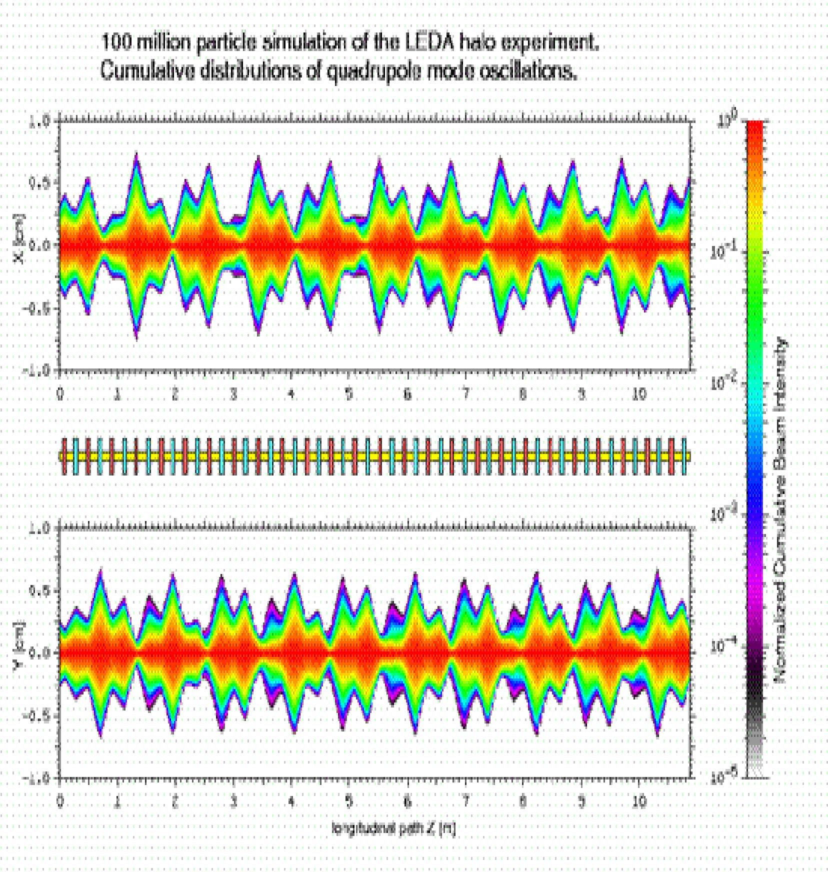
(~2 hrs on 512 processors)





IMPACT-Z

- Parallel PIC code using coordinate "z" as the independent variable
- Key Features
  - — Detailed RF accelerating and focusing model
  - — Multiple 3D Poisson solvers
    - Variety of boundary conditions
    - 3D Integrated Green Function
  - — Multi-charge state
  - — Machine error studies and steering
  - — Wakes
  - — CSR (1D)
  - — Run on both serial and multiple processor computers



IMPACT-Z for Space-Charge Study in Ring

Particle-in-cell simulation with split-operator method

- Particle-in-cell approach:
  - Charge deposition on a grid
  - Field solution via spectral-finite difference method with transverse rectangular conducting pipe and longitudinal open
  - Field interpolation from grid to particles
- Split-operator method with $H = H_{external} + H_{space\ charge}$
- Thin lens kicks for nonlinear elements
- Lumped space-charge at a number locations

Poisson Solver Used in Space-Charge Calculation

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}=-\frac{\rho}{\epsilon_0}$$

with boundary conditions

$$\begin{aligned}\phi(x=0,y,z)&=0,\\ \phi(x=a,y,z)&=0,\\ \phi(x,y=0,z)&=0,\\ \phi(x,y=b,z)&=0,\\ \phi(x,y,z=\pm\infty)&=0,\end{aligned}$$

$$\rho(x,y,z)=\sum_{l=1}^{N_l}\sum_{m=1}^{N_m}\rho^{lm}(z)\sin(\alpha_l x)\sin(\beta_m y),$$

$$\phi(x,y,z)=\sum_{l=1}^{N_l}\sum_{m=1}^{N_m}\phi^{lm}(z)\sin(\alpha_l x)\sin(\beta_m y),$$

where

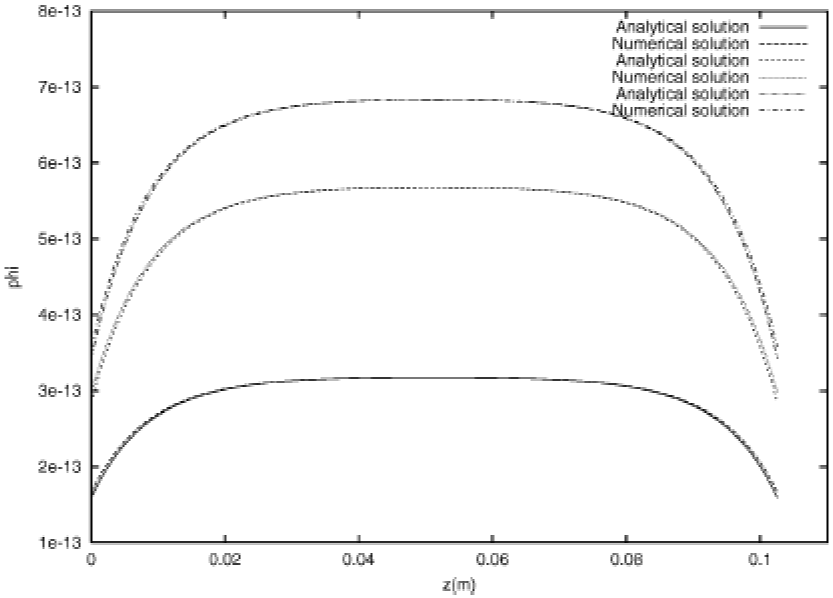
$$\rho^{lm}(z)=\frac{4}{ab}\int_0^a\int_0^b\rho(x,y,z)\sin(\alpha_l x)\sin(\beta_m y),$$

$$\phi^{lm}(z)=\frac{4}{ab}\int_0^a\int_0^b\phi(x,y,z)\sin(\alpha_l x)\sin(\beta_m y),$$

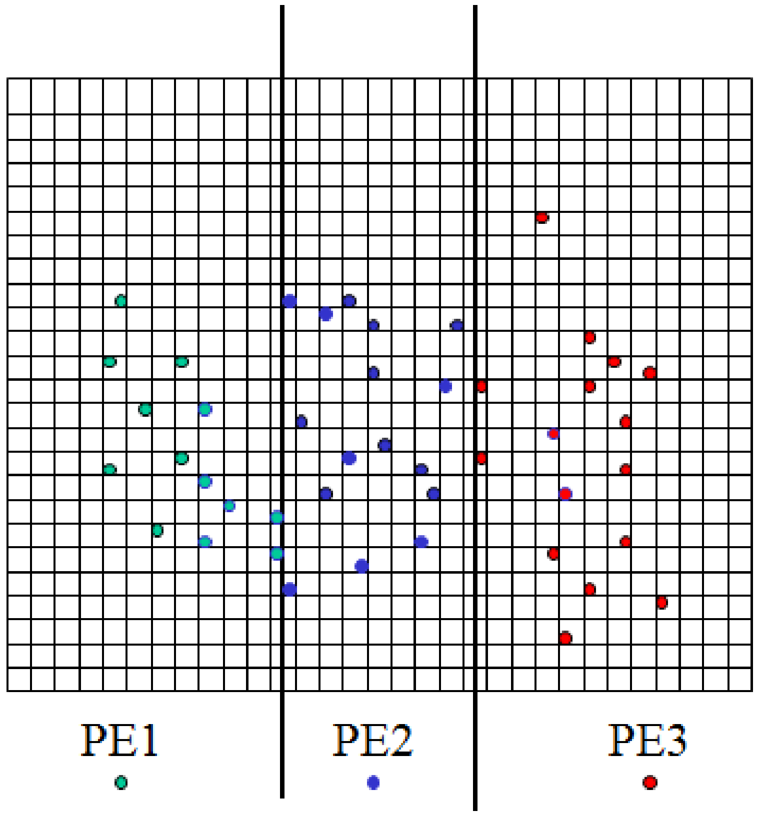
$$\frac{\partial^2\phi^{lm}(z)}{\partial z^2}-\gamma_{lm}^2\phi^{lm}(z)=-\frac{\rho^{lm}(z)}{\epsilon_0},$$

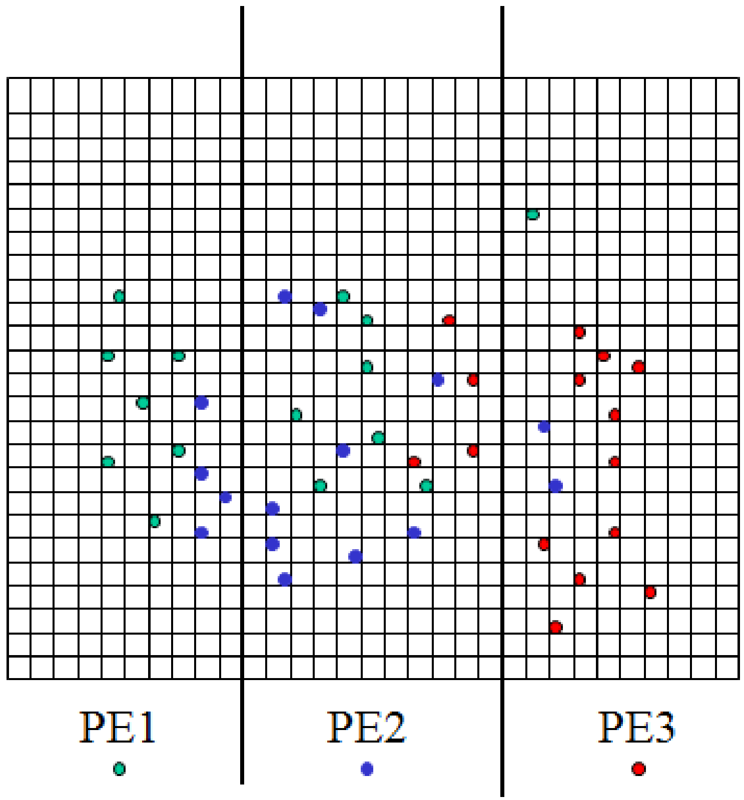
$$\frac{\phi_{n+1}^{lm}-2\phi_n^{lm}+\phi_{n-1}^{lm}}{h_z^2}-\gamma_{lm}^2\phi_n^{lm}=-\frac{\rho_n^{lm}}{\epsilon_0},$$

$$\begin{aligned}\phi_{-1}^{lm}&=\exp(-\gamma_{lm}h_z)\phi_0^{lm}, & n&=0,\\ \phi_{N+1}^{lm}&=\exp(-\gamma_{lm}h_z)\phi_N^{lm}, & n&=N.\end{aligned}$$



Parallel Implementation: Domain-Decomposition vs. Particle Field Decomposition





➢In the application where the number of macroparticles is not dominant, the domain-decomposition has a better scalability than the particle-field decomposition.

Physical Parameters for PS2 Simulations

Vrf = ramping with f = 39.3 MHz

Ek = 4 GeV

Emit_x = Emit_y = 3 mm-mrad

Emit_z = .098 eV-sec

Half Aperture = 6.3cm x 3.25cm

I = 4.0×10^{11}

Numerical Parameters:

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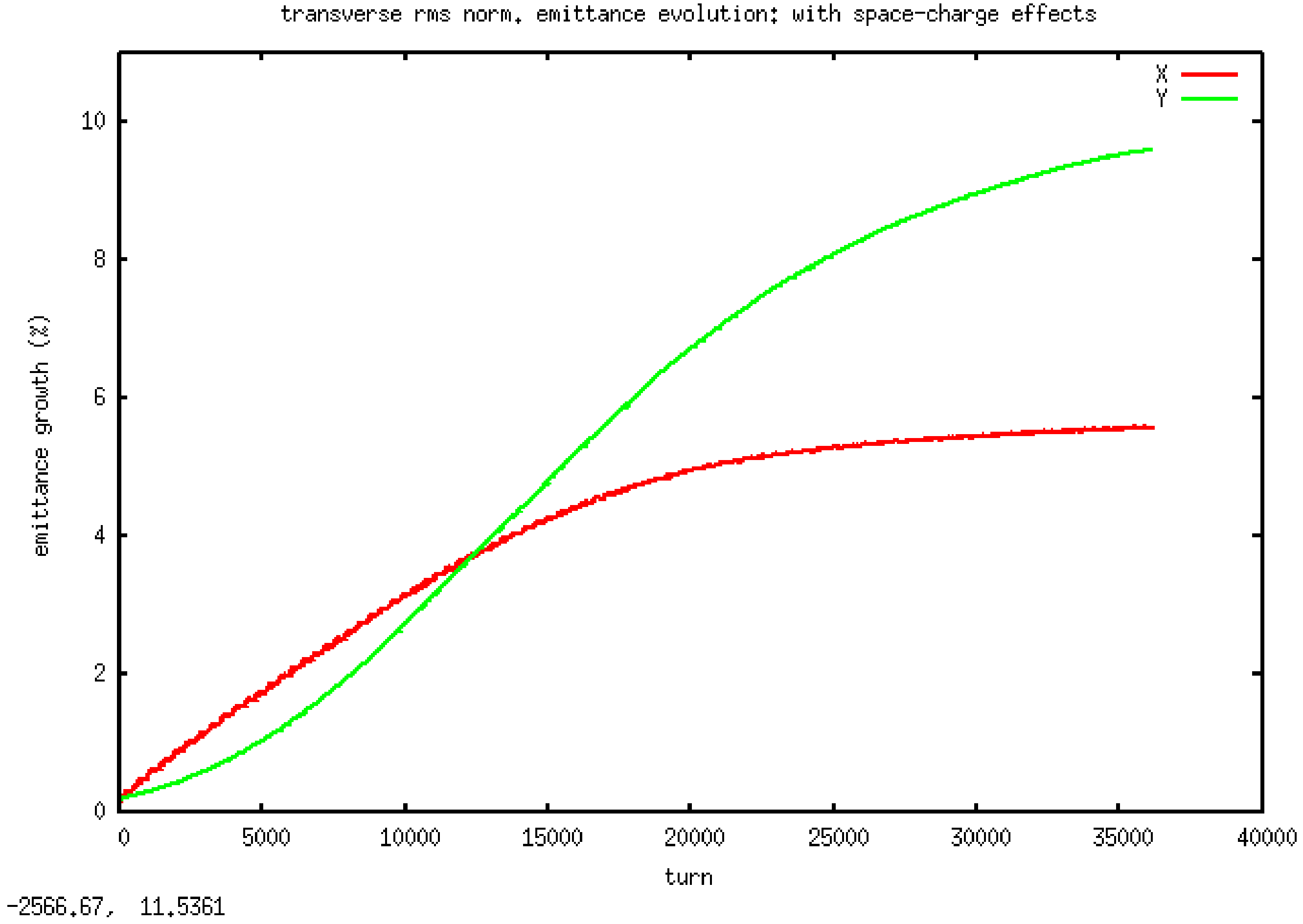
70 SC per tur

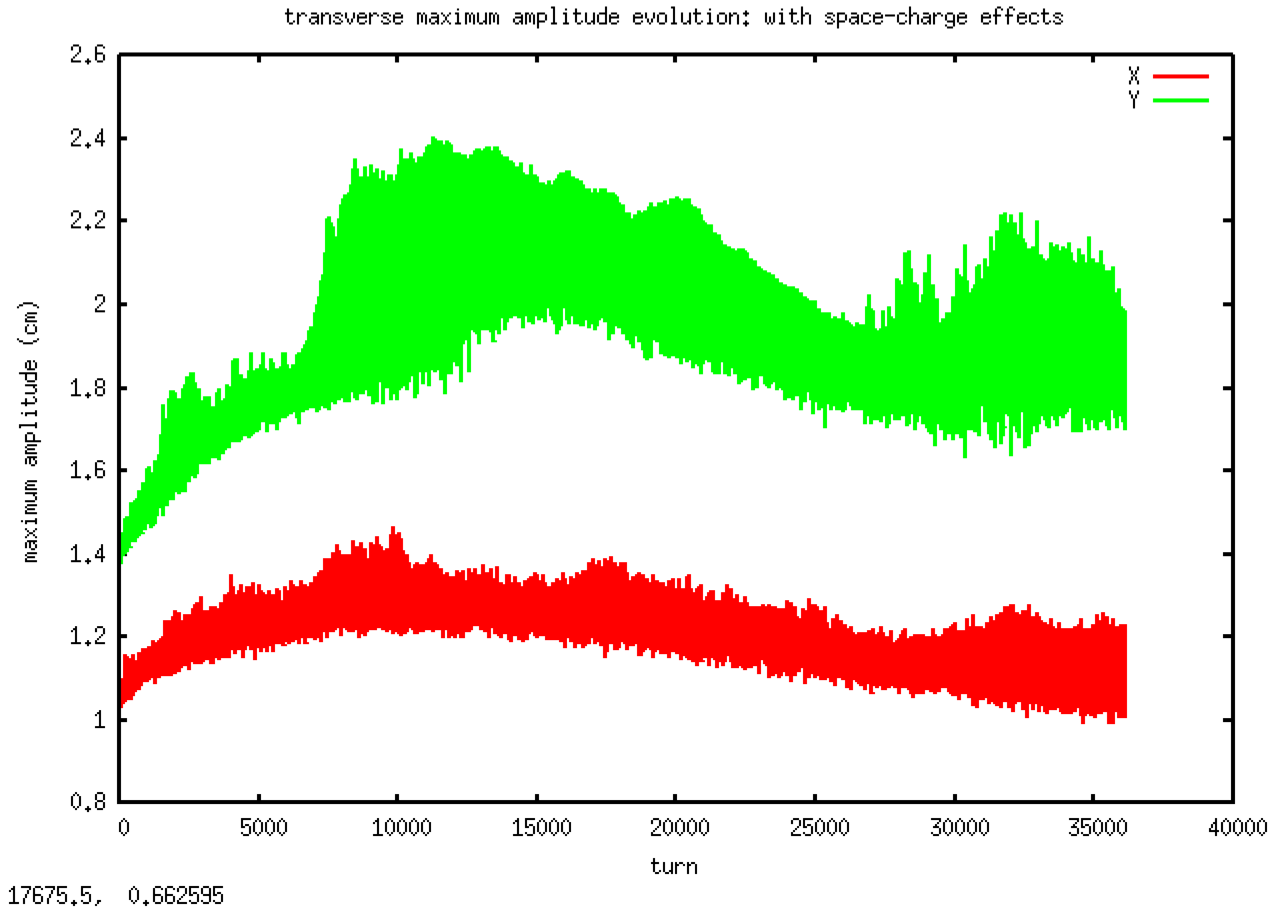
65x65x128 grid points

939,000 macroparticles

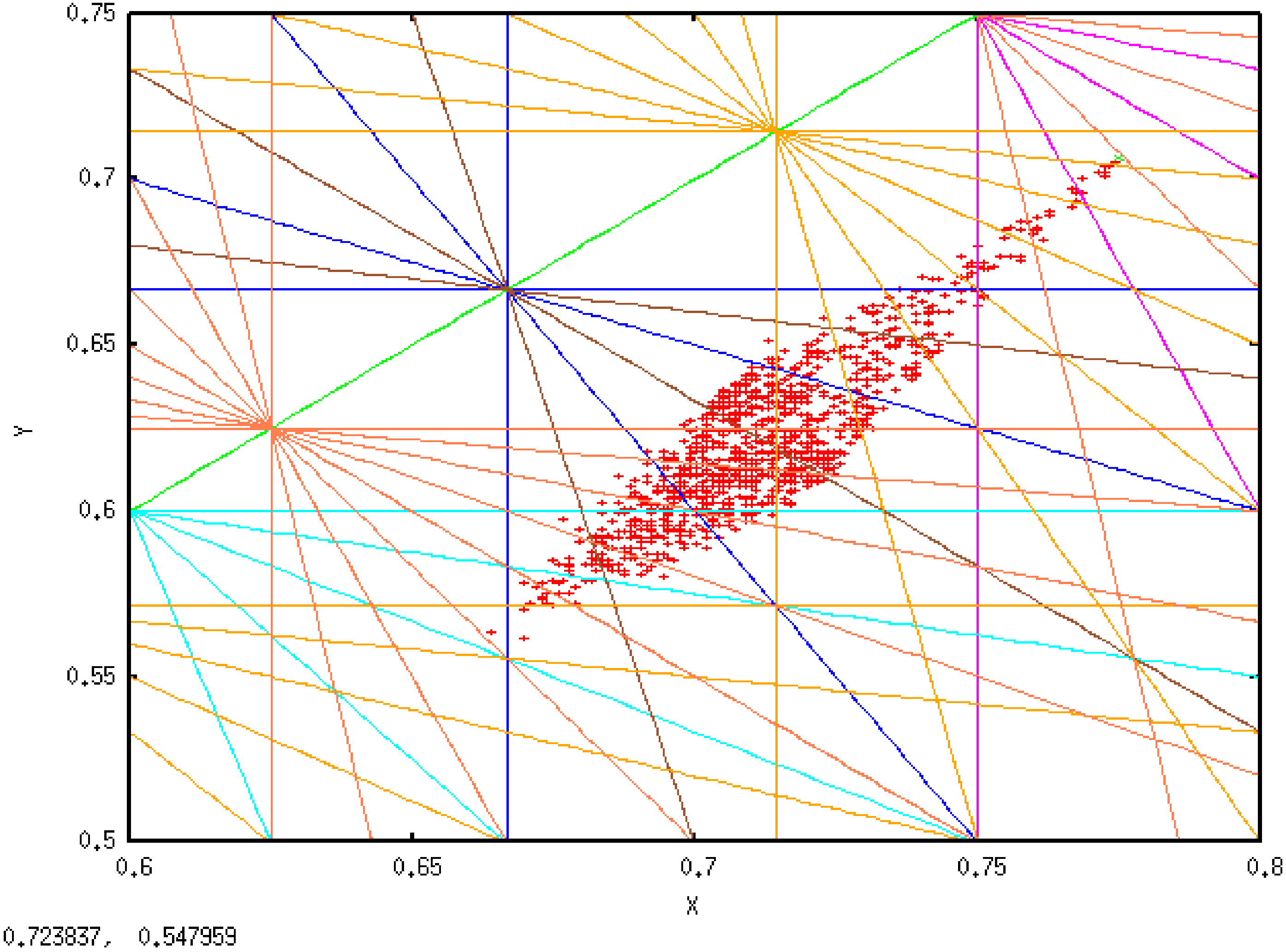
Transverse Emittance Growth



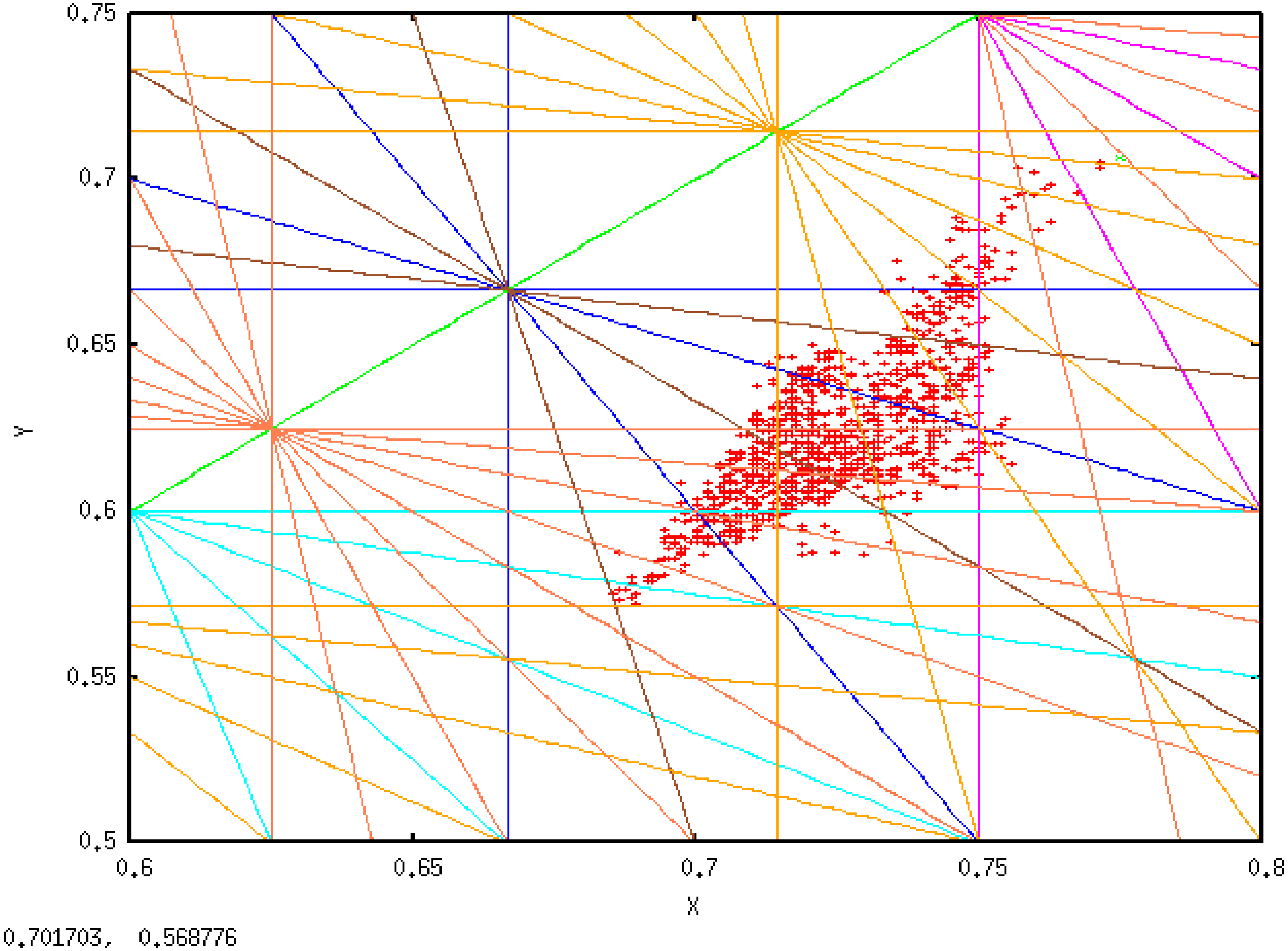
Transverse Maximum Amplitude Evolution



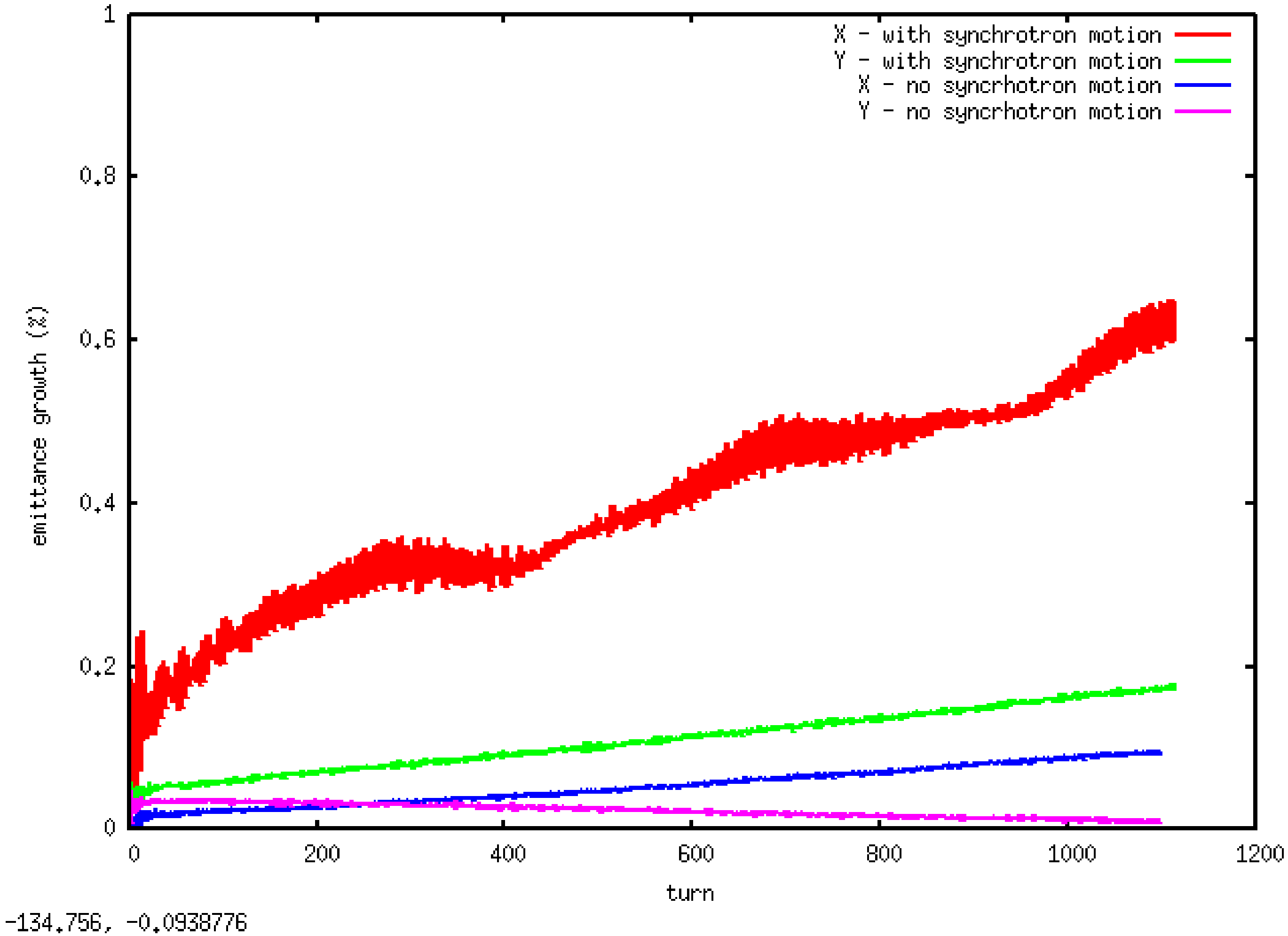
Betatron Tune Footprint with 0 Current and with SC but no Synchroton Motion



Betatron Tune Footprint with 0 Current and with SC and Synchroton Motion

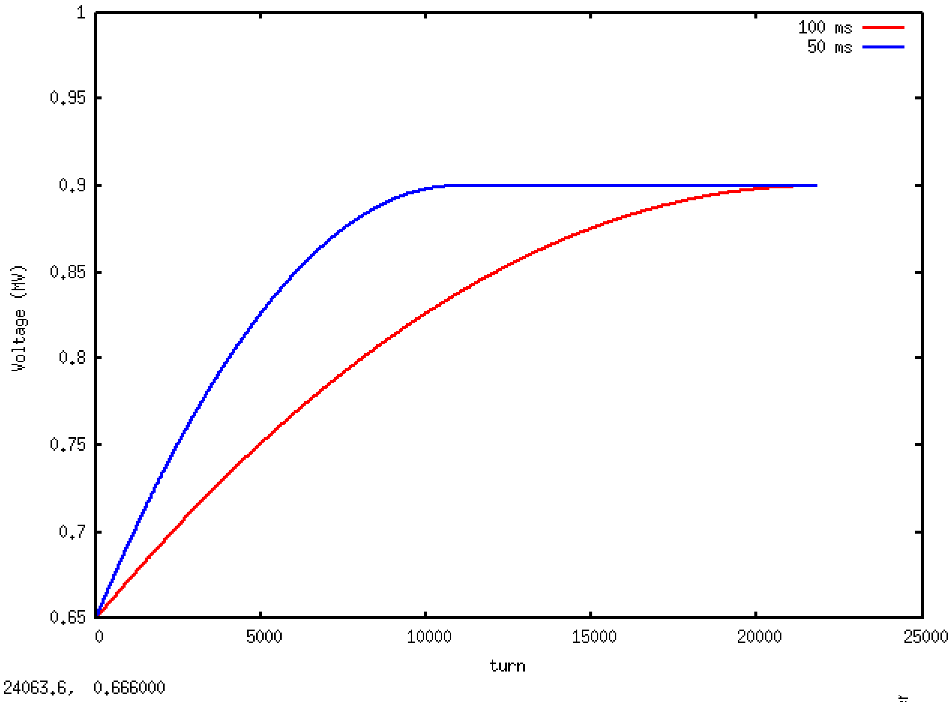


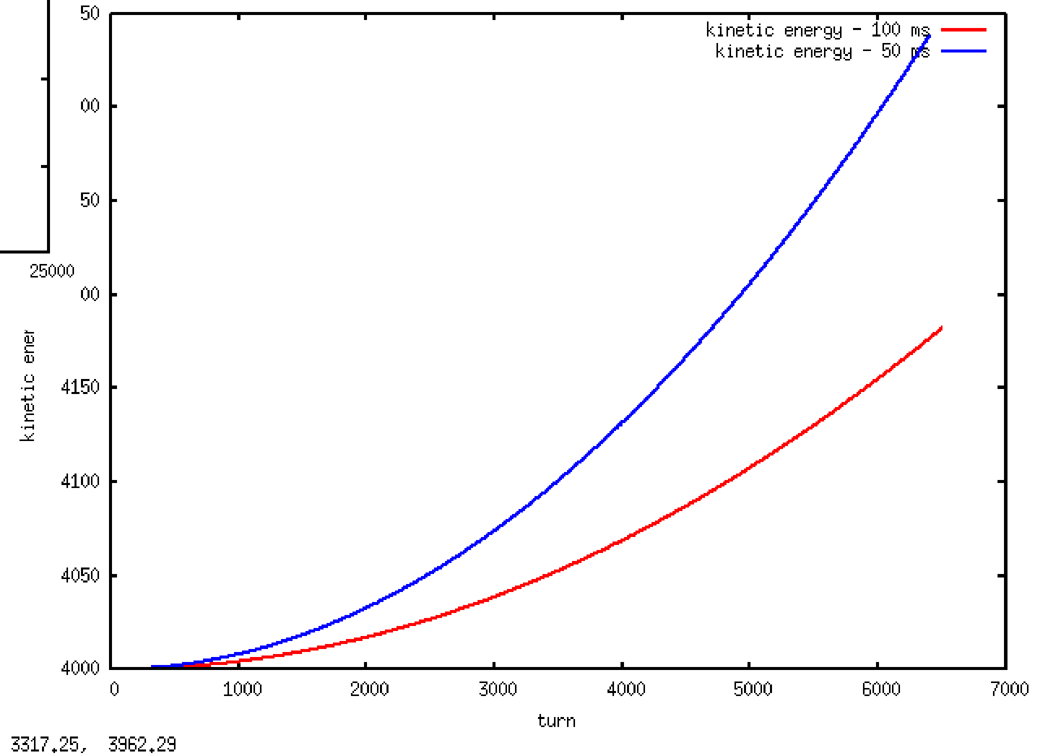
Transverse Emittance Growth with/without Synchrotron Motion



Effects of RF Ramping

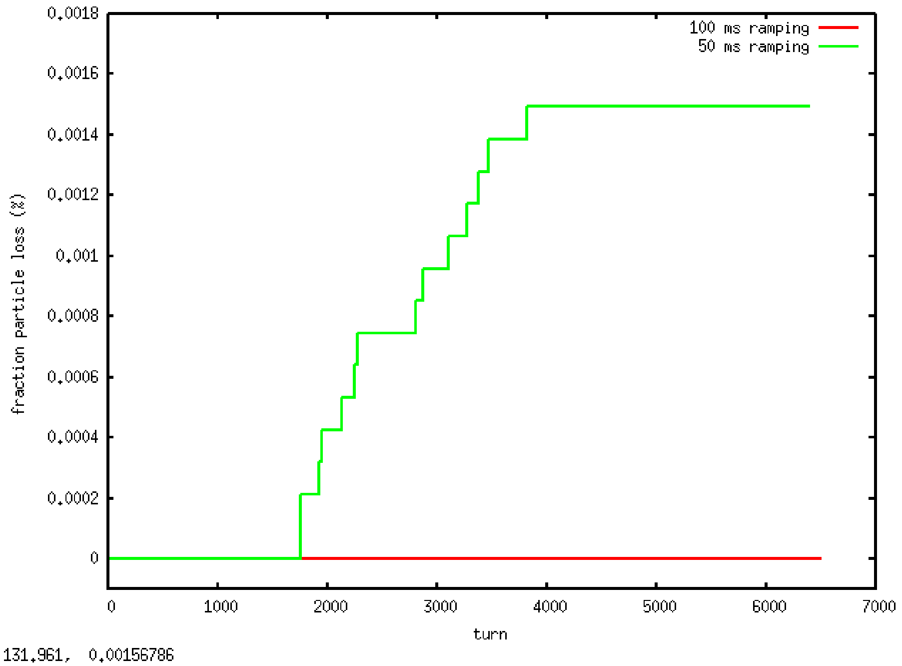
RF Voltage Ramping and Beam Kinetic Energy Evolution
100 ms vs. 50 ms RF Ramping

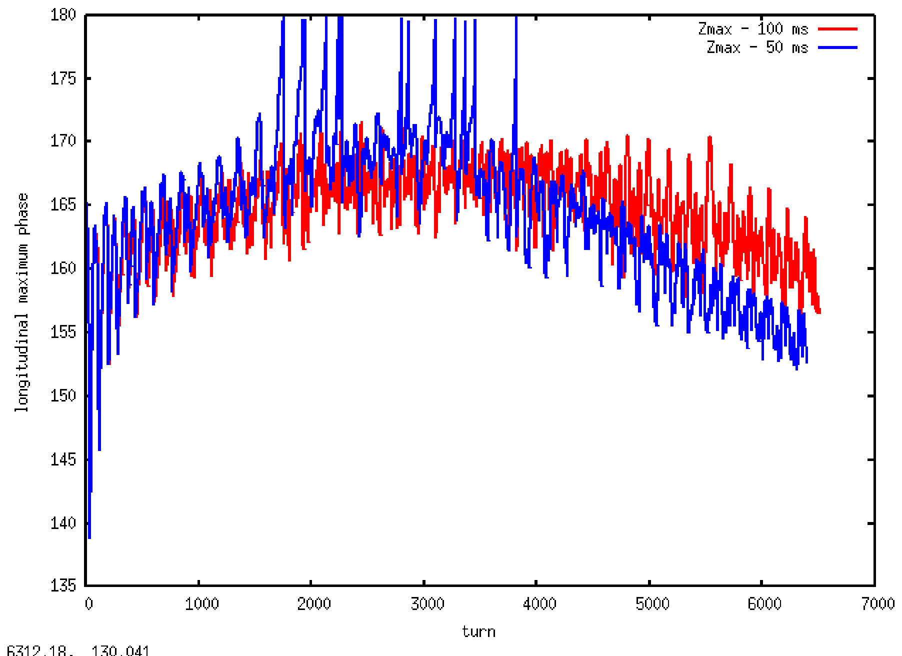




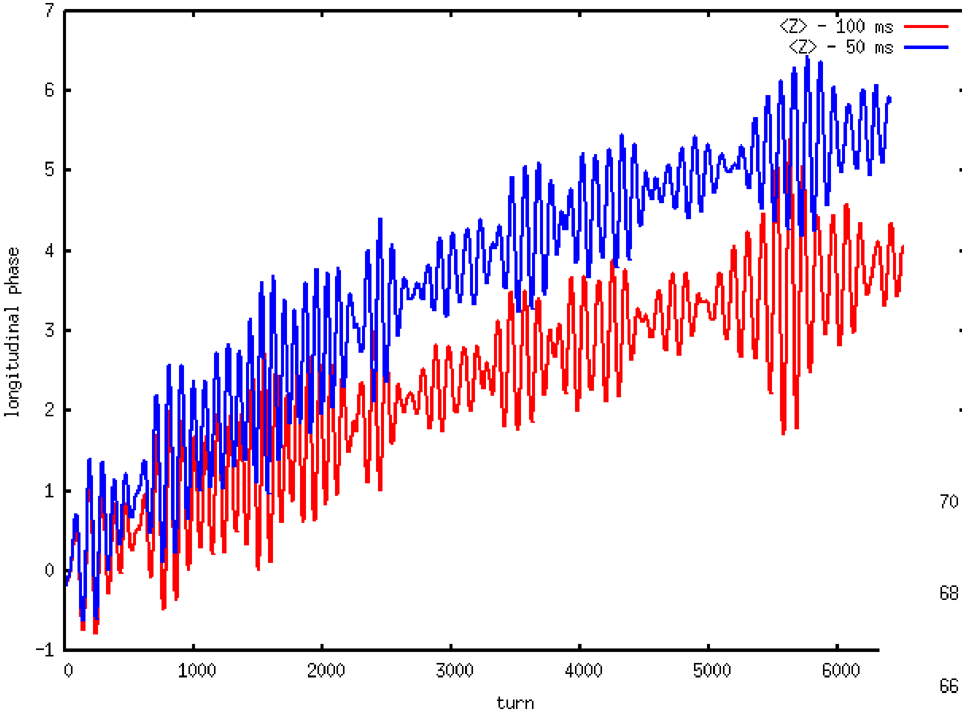
Fractional Particle Loss and Maximum Phase Amplitude 100 ms vs. 50 ms RF Ramping

- Faster RF ramping causes more particles lost out of RF bucket

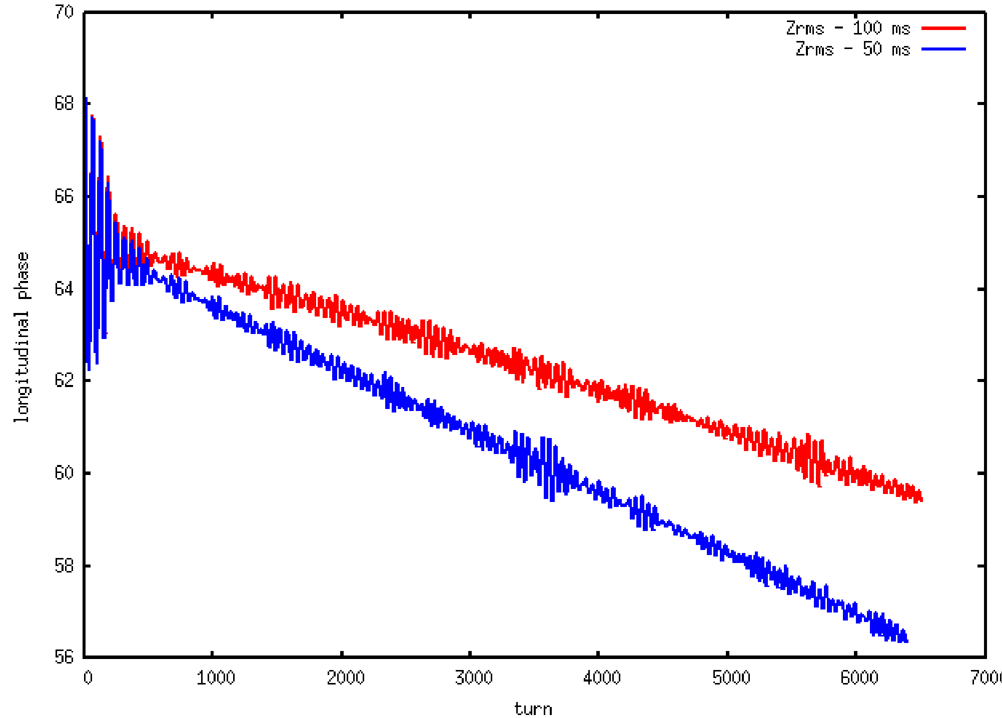




Evolution of Longitudinal Centroid and RMS Size with 100 ms and 50 ms RF Ramping



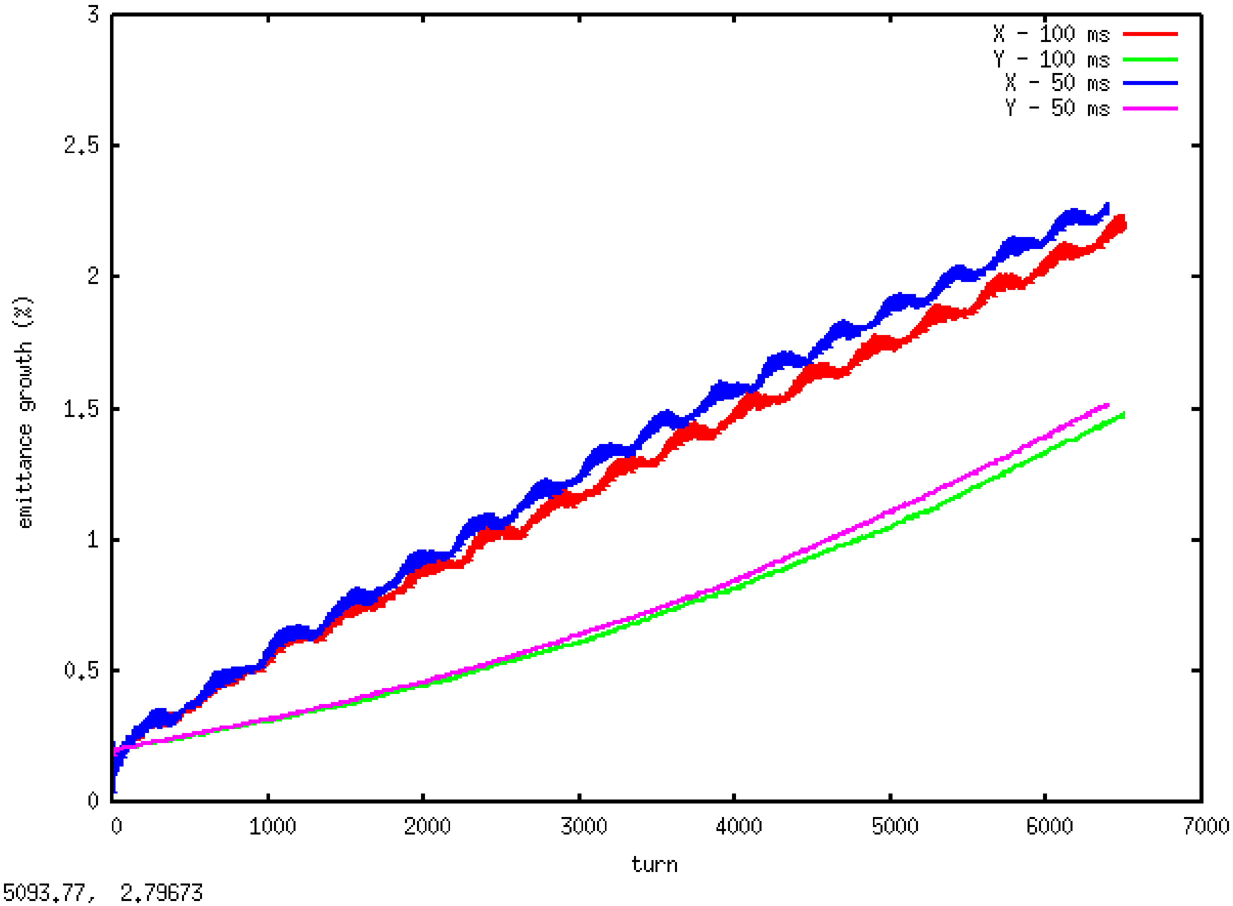
6870.87, 1.37207



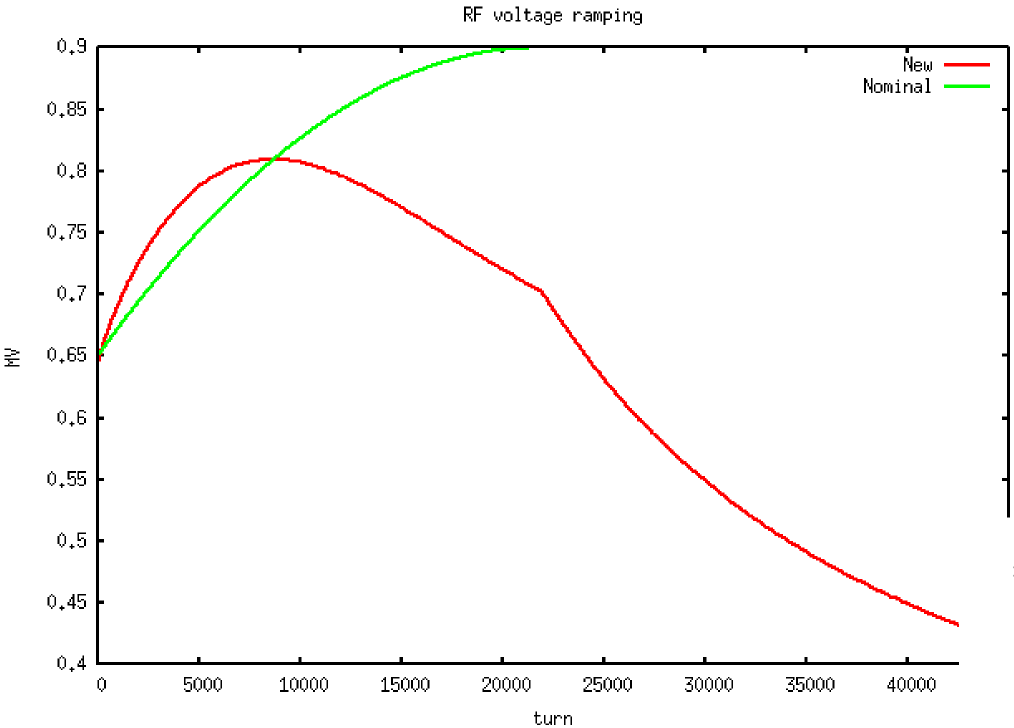
2885.56, 54.4914

Transverse Emittances with 100 ms and 50 ms RF Ramping

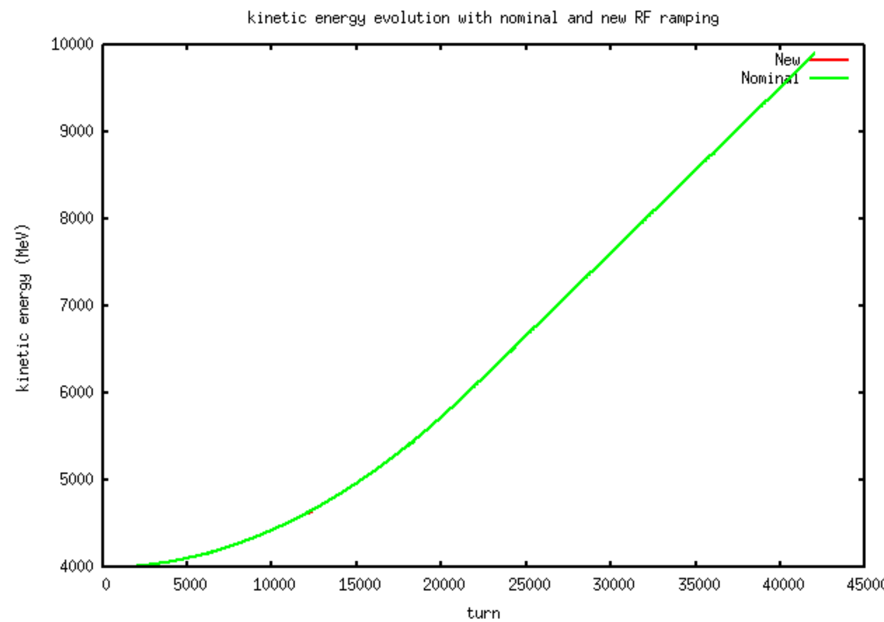
- Slightly larger emittance growth with faster RF ramping



Nominal and New RF Voltage Ramping

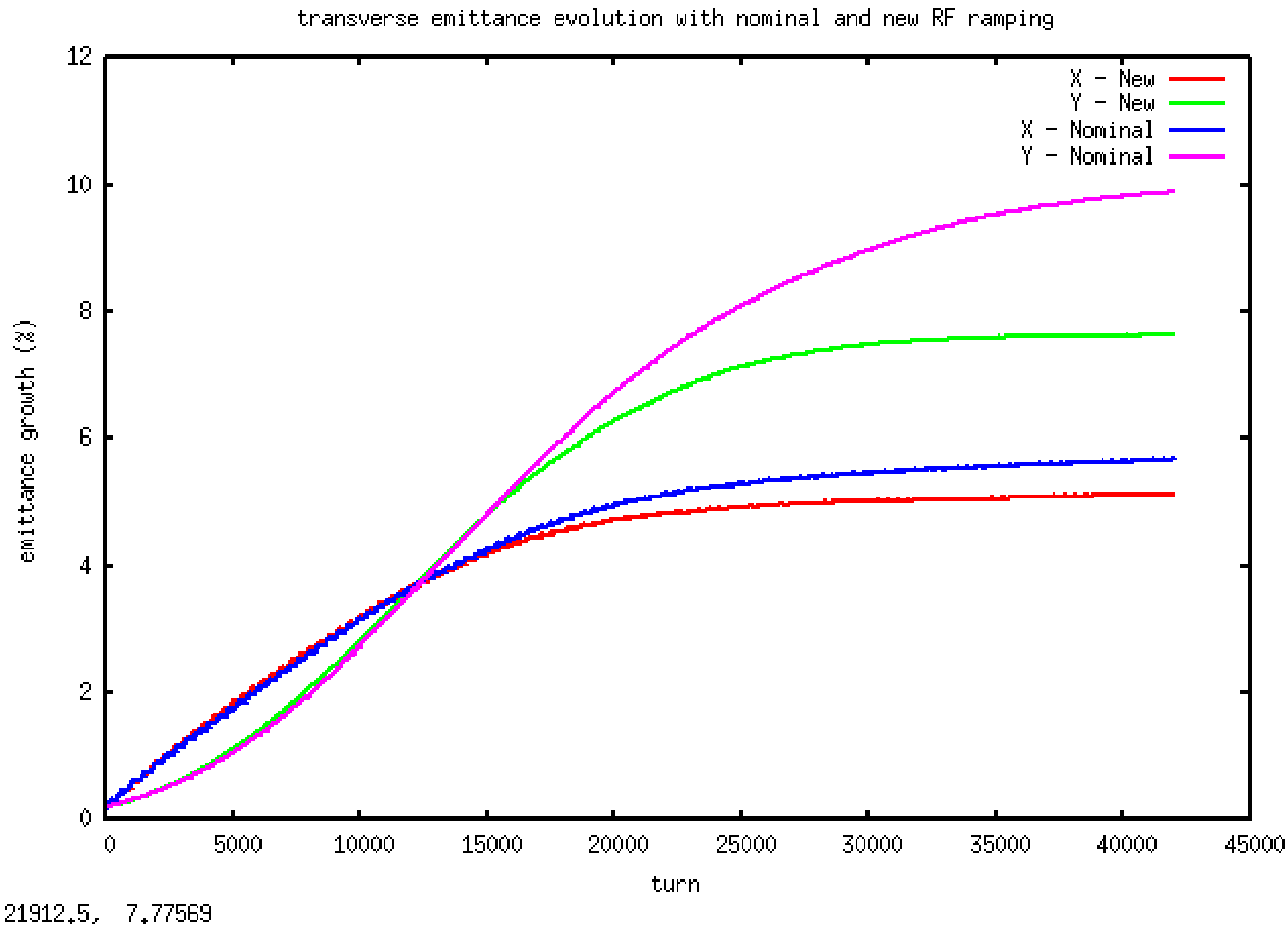


34485.5, 0.612810

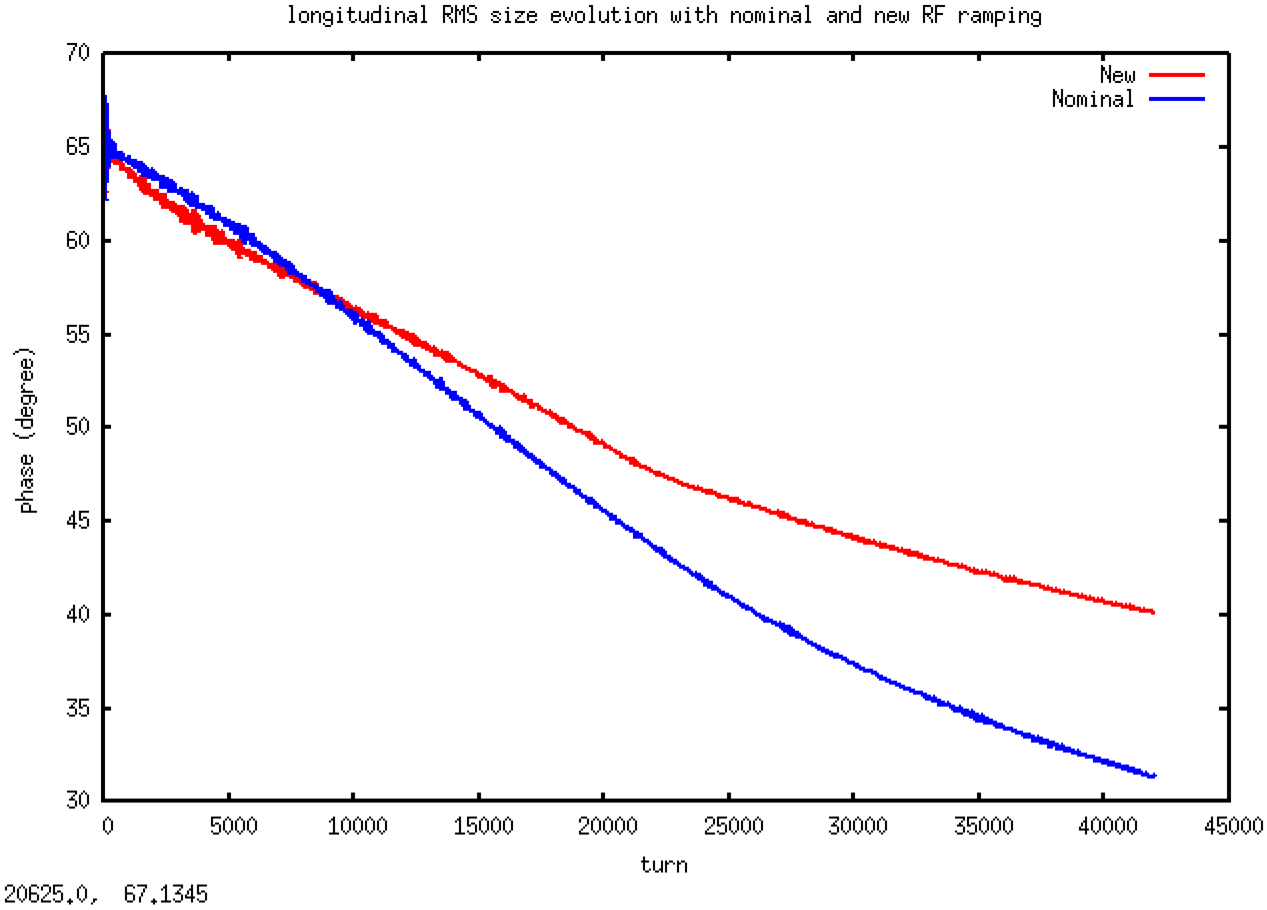


14754.3, 3459.86

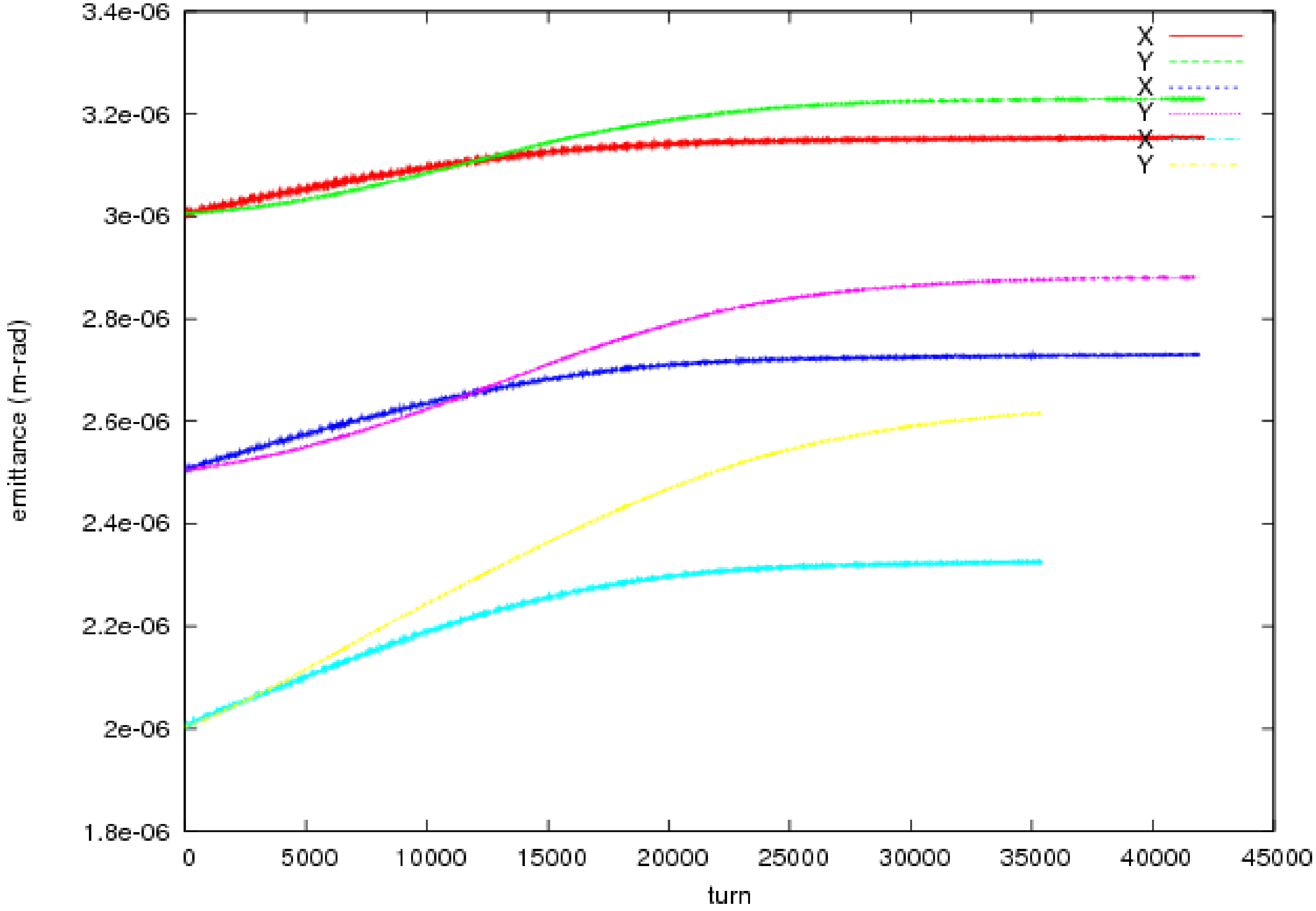
Transverse Emittance Growth with Nominal and New RF Ramping



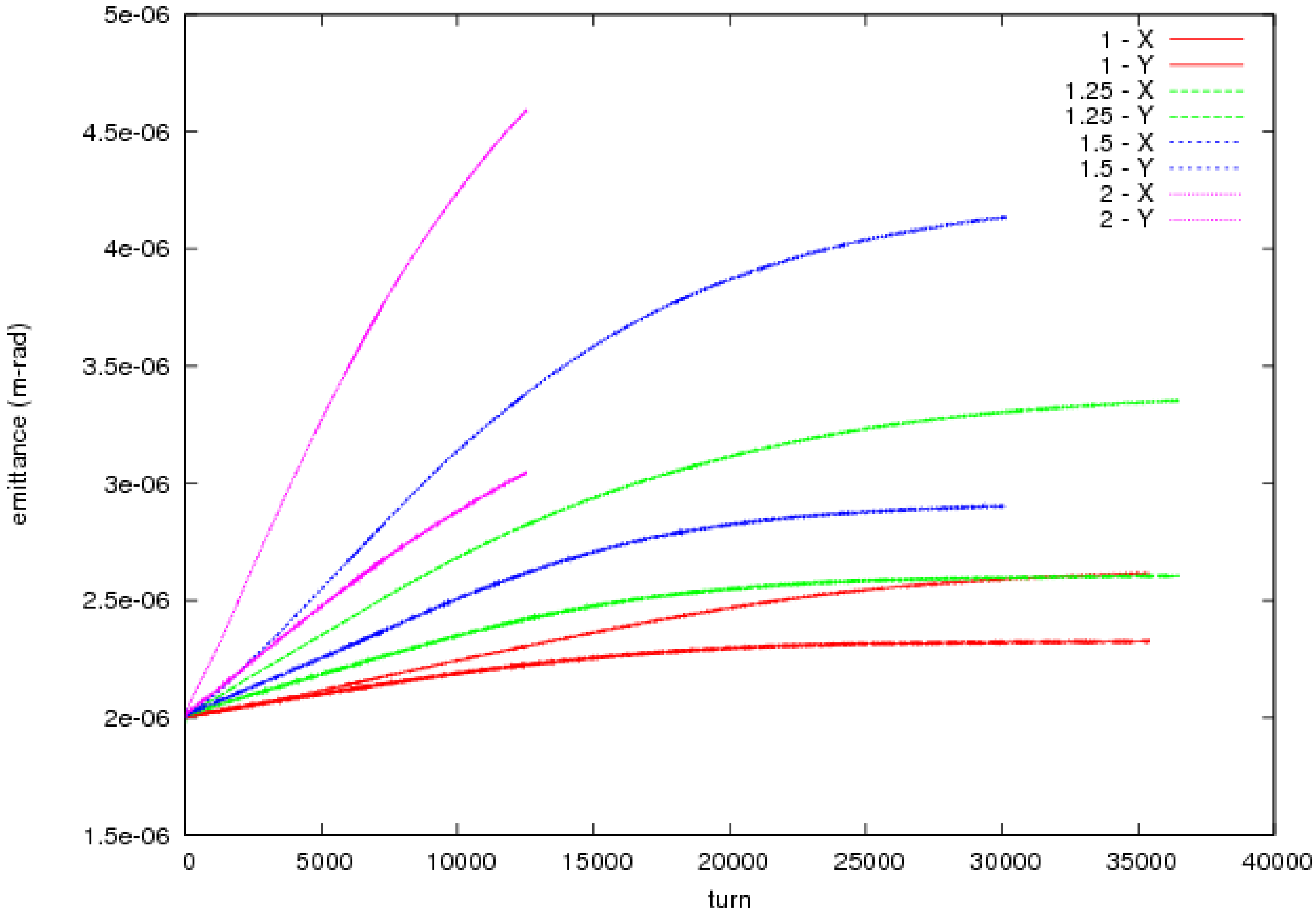
Longitudinal RMS Size Evolution with Nominal and New RF Ramping



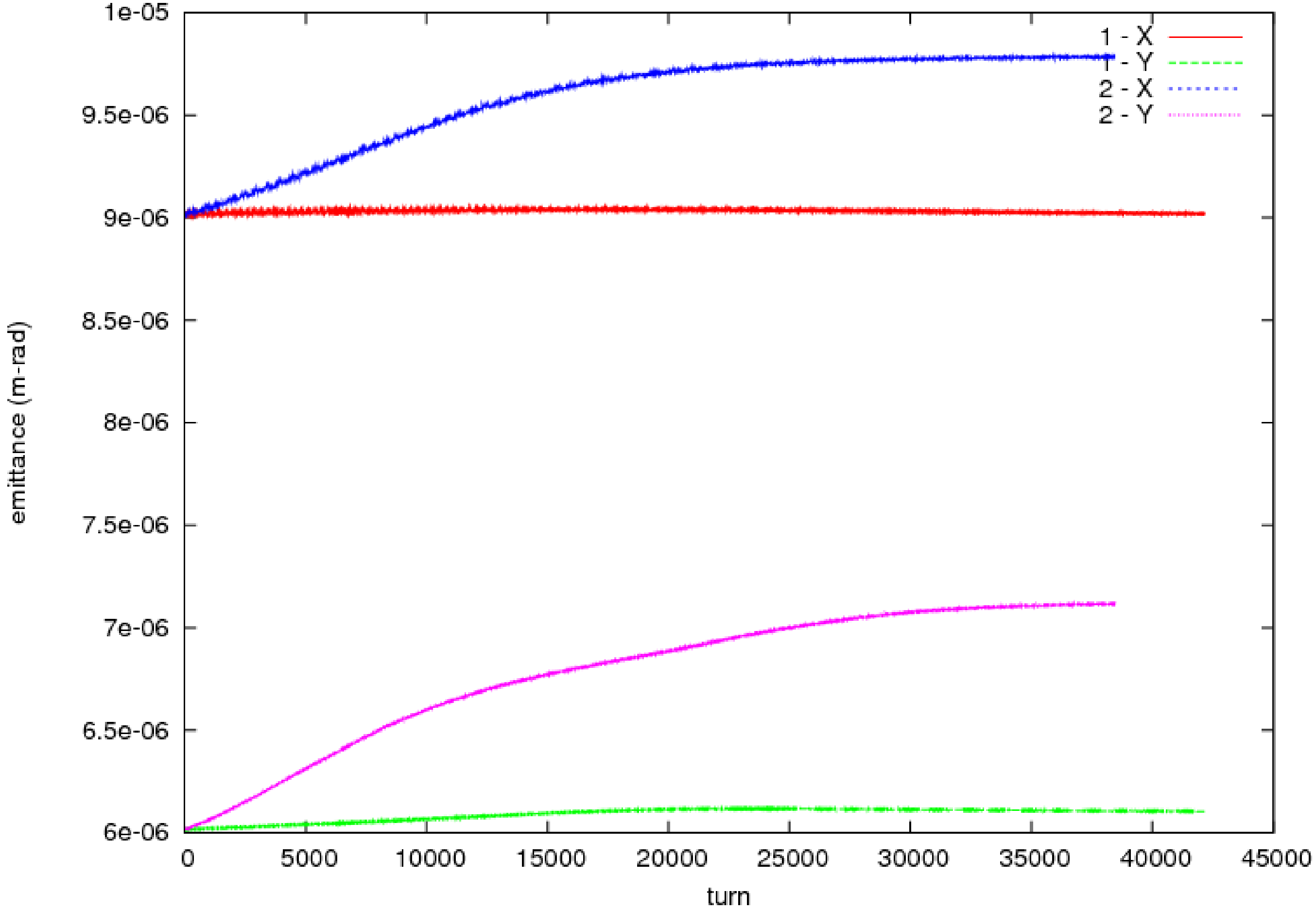
Transverse Emittance Growth with Different Initial Emittances



Transverse Emittance Growth with Different Bunch Intensities



Transverse Emittance Growth with Different Bunch Intensities for Fixed Target Application



Summary

- Space-charge effects can cause significant beam emittance growth and particle losses at PS2
- Synchro-betatron coupling with 3D space-charge forces causes extra tune spread and emittance growth
- Optimizing RF voltage and phase ramping help reduce emittance growth and particle losses
- Smaller initial emittance leads to larger relative emittance growth, but with smaller final emittance
- Nominal bunch intensity is close to the maximum boundary of designed emittance
- There is little emittance growth in the nominal design parameters for fixed target application

Future Plans

- Complete the PS2 design report
- Space charge effects at PSB
  - optimize the painting process with space-charge effects
  - study the emittance growth driven by the space-charge effects
  - study the particle losses and beam halo formation driven by the
    space-charge effects
- Space charge effects at PS
  - better understanding of the behavior/limitation of high brilliance beams experiencing significant direct space charge effects