European Organization for Nuclear Research

SLAC NATIONAL ACCELERATOR LABORATORY

BERKELEY LAB

Simulation of Space-Charge Effects in the Proposed CERN PS2

Ji Qiang, Robert Ryne, LBNL
Uli Wienands, SLAC
H. Bartosik, C. Carli, Y. Papaphilippou, CERN

HB2010, Sept. 27-Oct. 1, Morschach/Switzerland

Office of Science
U.S. DEPARTMENT OF ENERGY

Outline

- S0: Introduction
- S1: Computational models
- S2: Initial benchmark with 0 current
- S3: Space-charge simulations of PS2 with effects:
  - Synchro-betatron coupling
  - Initial painting schemes
  - RF ramping schemes
- S4: Summary

S0: 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}).

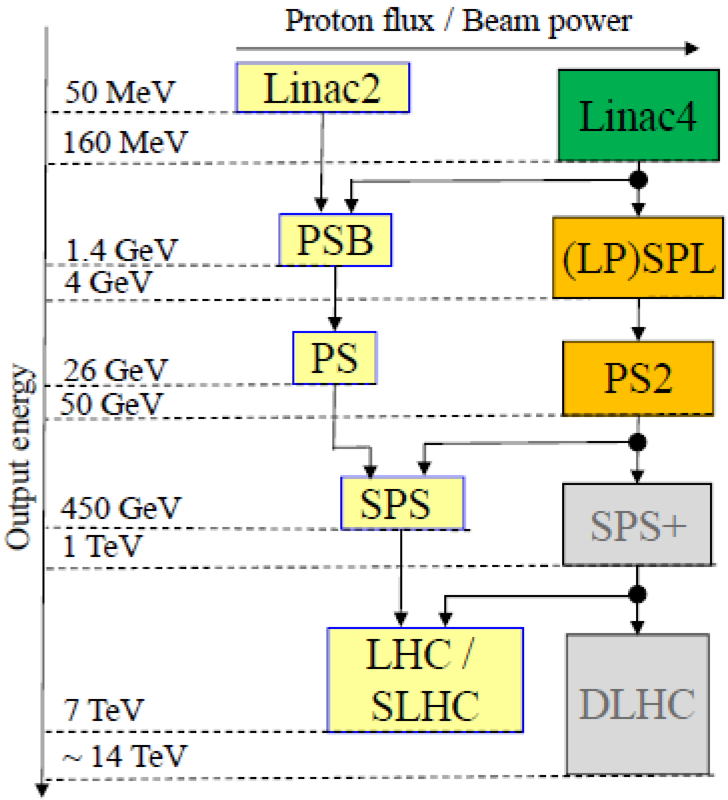


Figure 1: Overview on the CERN injector complex upgrade programme: stage 1 (green), stage 2 (orange).

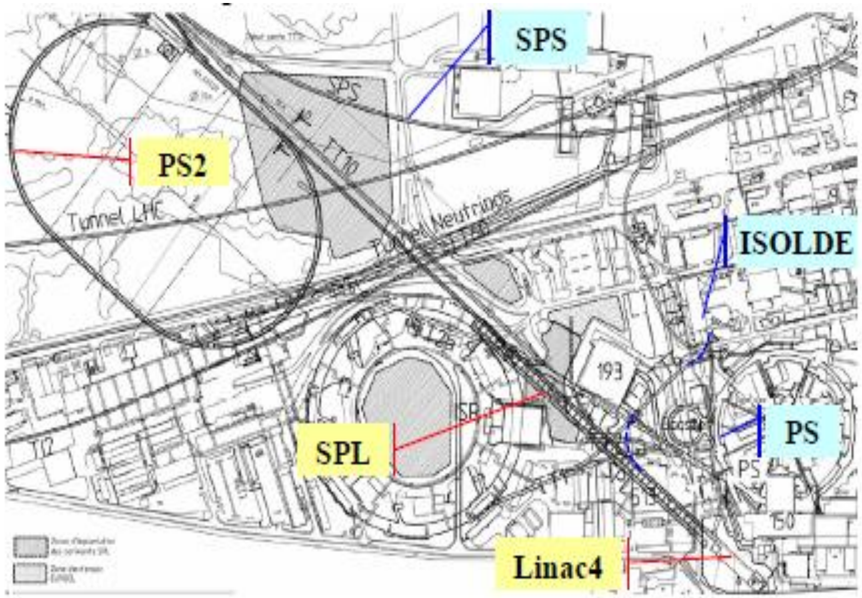


Figure 2: Integration of PS2 within the existing and future CERN accelerator complex.

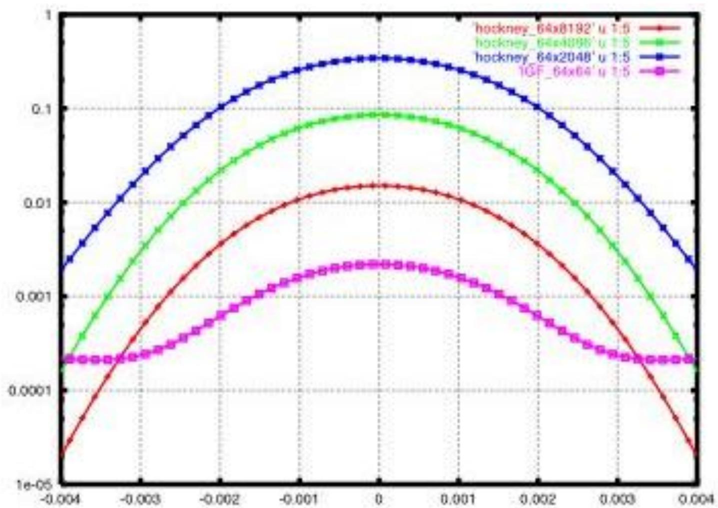
M. Benedikt, et al., PAC09, WE1GRI03

S1: Computational Models

MaryLie/IMPACT (ML/I)

- Combines capabilities of MaryLie code (A. Dragt, U Md) with IMPACT code (J. Qiang, R. Ryne, LBNL) + new features
- Multiple capabilities in a single unified environment:
  - Map generation
  - Map analysis
  - Particle tracking w/ 3D space charge
  - Envelope tracking
  - Fitting and optimization
- Recent applications: ERL for e-cooling @ RHIC; CERN PS2

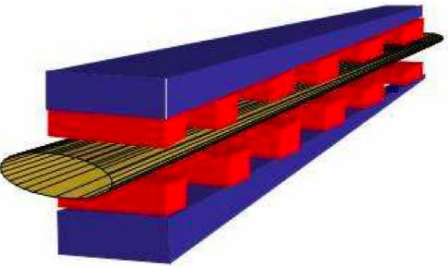
- Parallel
- 5th order optics
- 3D space charge
- 5th order rf cavity model
- 3D integrated Green func
- Photoinjector modeling
- "Automatic" commands
- MAD-style input
- Test suite
- Contributions from LBNL, UMd, Tech-X, LANL,…



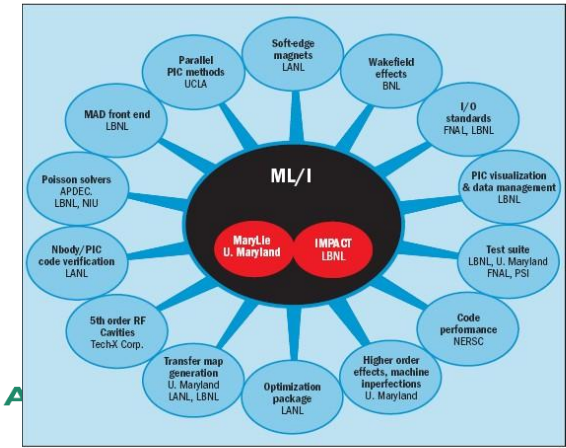
Error in E-field computed w/ different algorithms applied to a 2D Gaussian elliptical distribution w/ 500:1 aspect ratio

Integrated Green Function on 64x64 grid is more accurate than Hockney on 64x2048, 64x4096, 64x8192.

Map computation from surface data

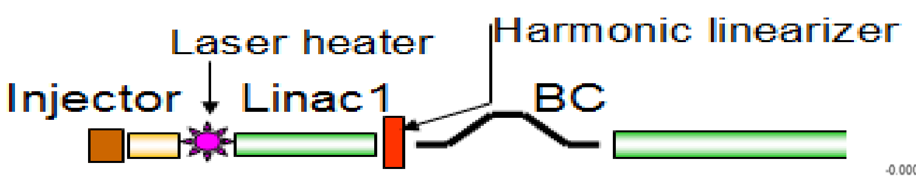


Alex Dragt, U. Md.



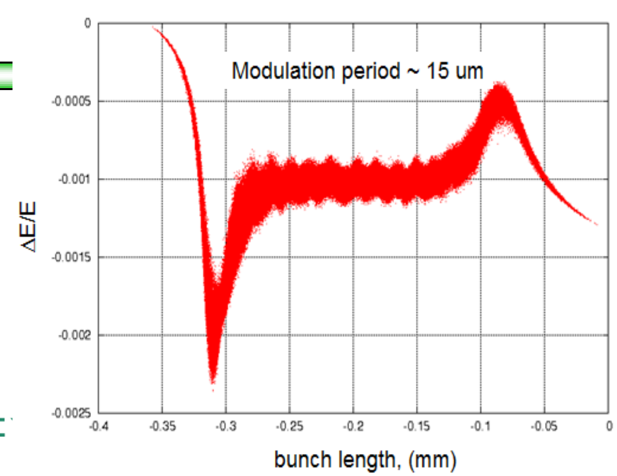
IMPACT code suite

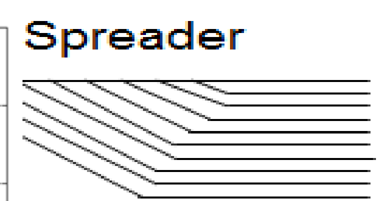
- IMPACT-Z: parallel PIC code (z-code)
- IMPACT-T: parallel PIC code (t-code)
- Envelope code, pre- and post-processors,…
- Optimized for parallel processing
- Applied to many projects: SNS, JPARC, RIA, FRIB, PS2, future light sources, advanced streak cameras,…
- Has been used to study photoinjectors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



One Billion Macroparticle Simulation of an FEL Linac

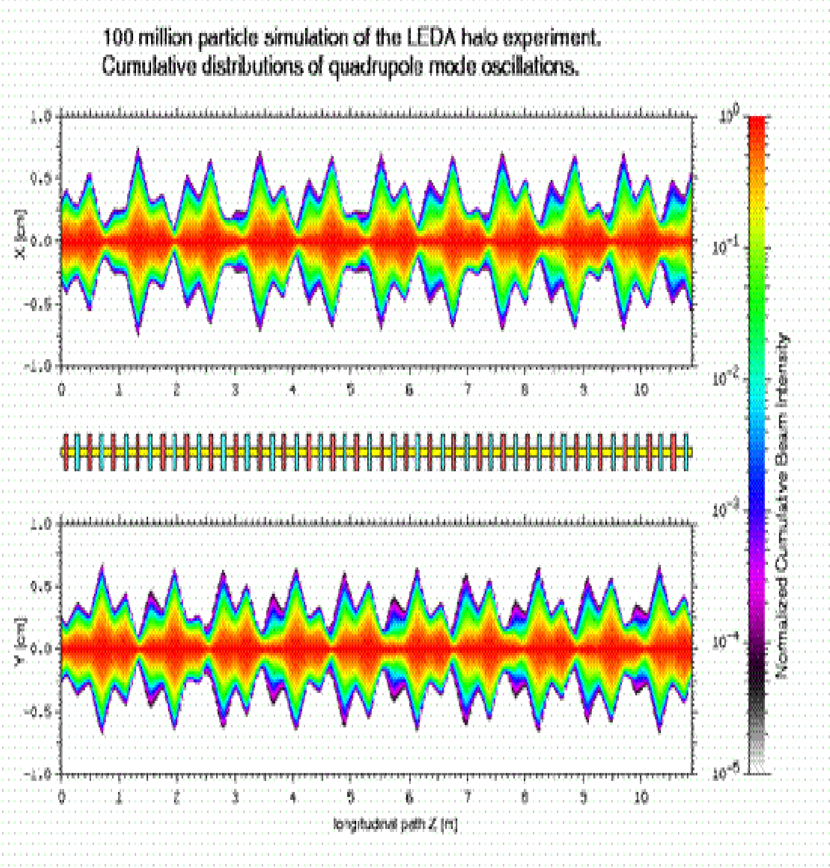
(~2 hrs on 512 processors)





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



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

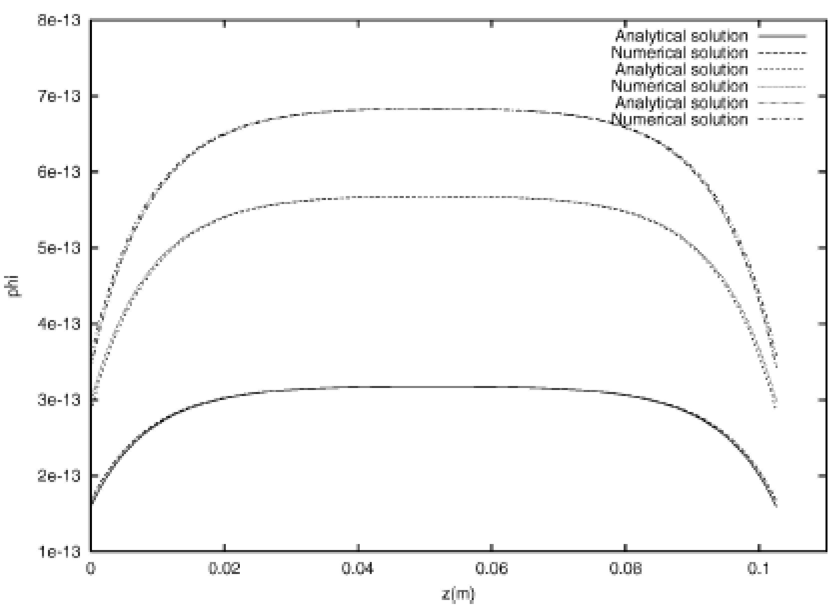
$$\rho^{lm}(z) = \frac{4}{ab} \int_0^a \int_0^b \rho(x,y,z) \sin(\alpha_l x) \sin(\beta_m y),$$

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

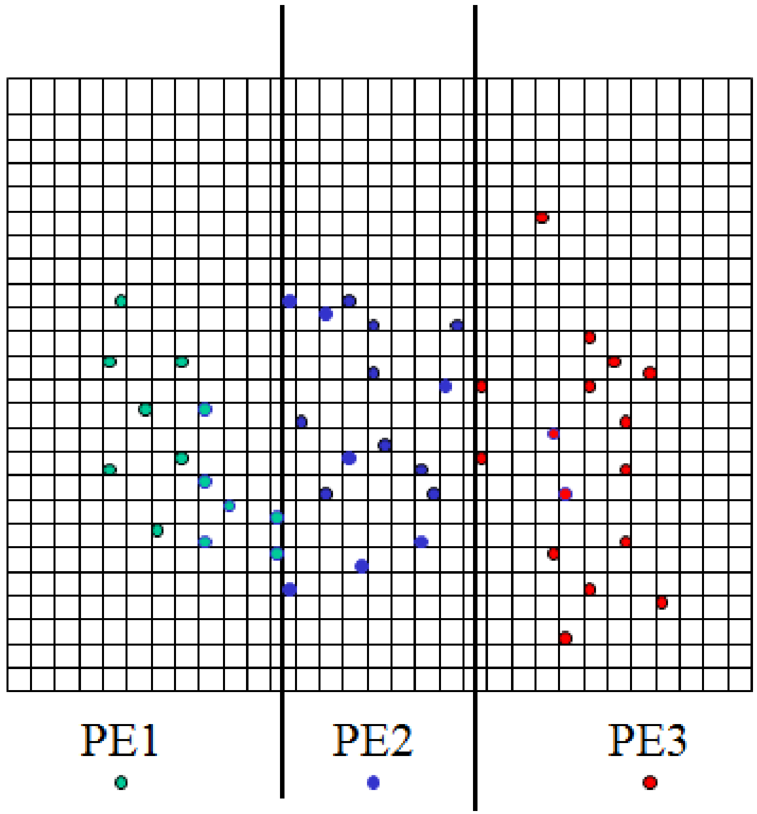
$$\frac{\partial^2 \phi^{lm}(z)}{\partial z^2} - \gamma_{lm}^2 \phi^{lm}(z) = -\frac{\rho^{lm}(z)}{\epsilon_0},$$

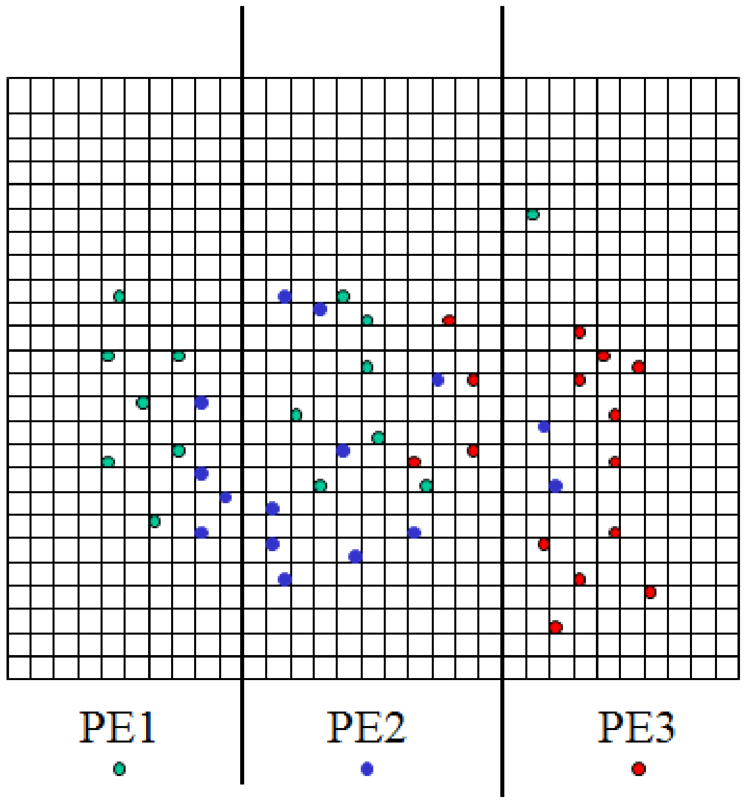
$$\frac{\phi_{n+1}^{lm} - 2\phi_n^{lm} + \phi_{n-1}^{lm}}{h_z^2} - \gamma_{lm}^2 \phi_n^{lm} = -\frac{\rho_n^{lm}}{\epsilon_0},$$

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



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.

S2: Initial Benchmark with 0 Current

Parameters of Simulations for 2010 PS2 Lattice

Physical Parameters:

Vrf = ramping with f = 39.3 MHz
Ek = 4 GeV
Emit_x = Emit_y = 3 mm-mrad
Emit_z = .098 eV-sec

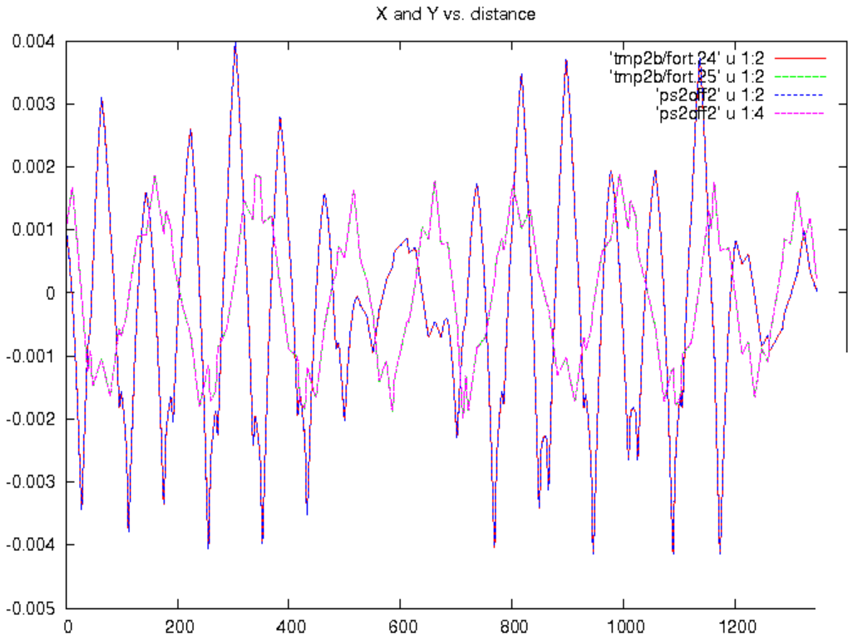
Half Aperture = 6.3cm x 3.25 cm
$I = 4.0 \times 10^{11}$

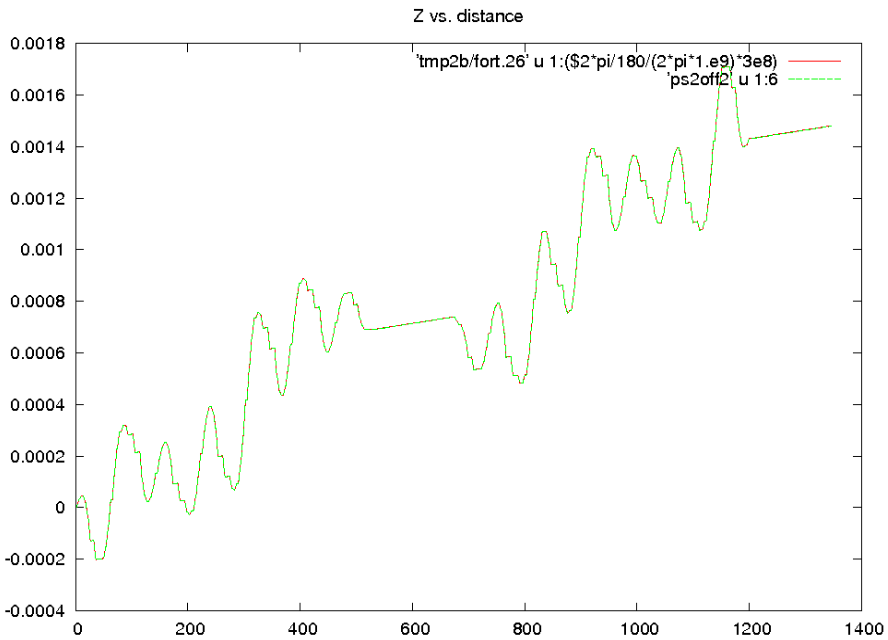
Numerical Parameters:

----

70 SC per turn
65x65x128 grid points
939,000 macroparticles

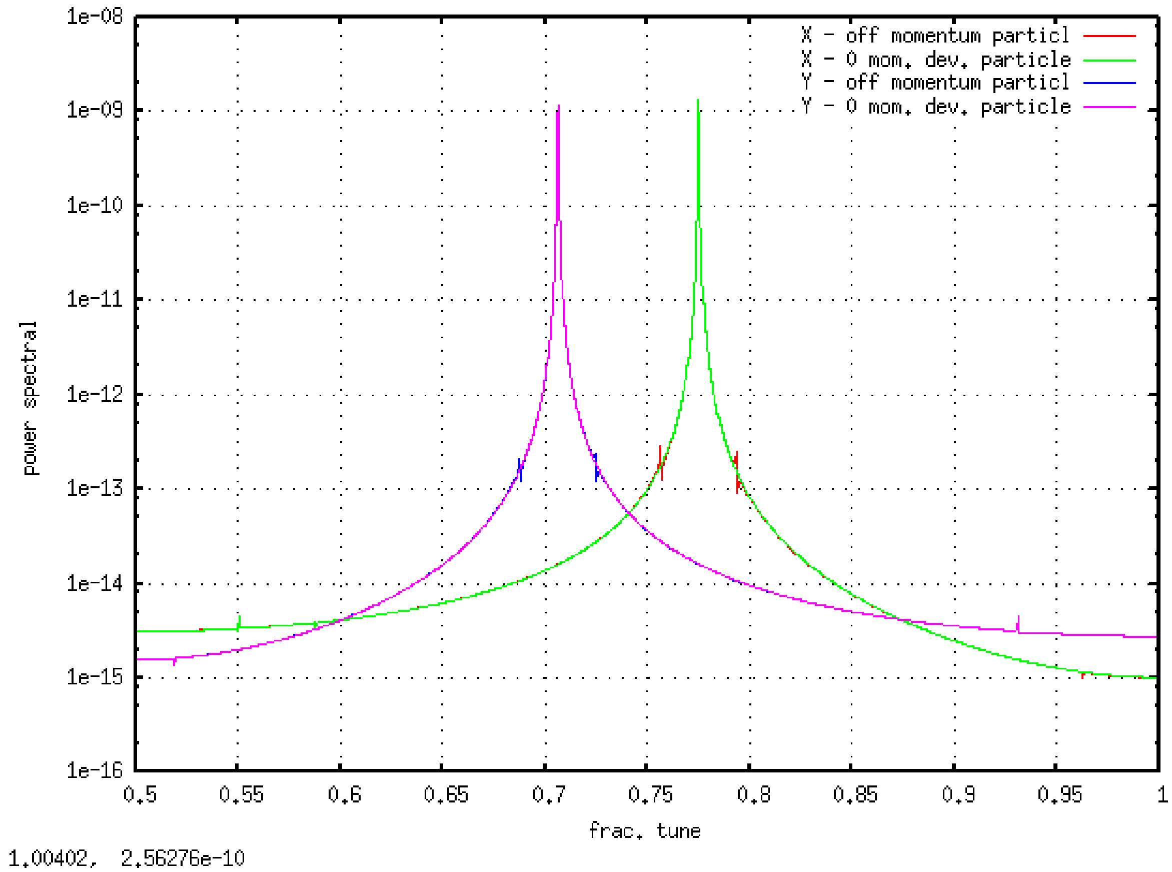
IMPACT and ML/I agreed on single-particle trajectories





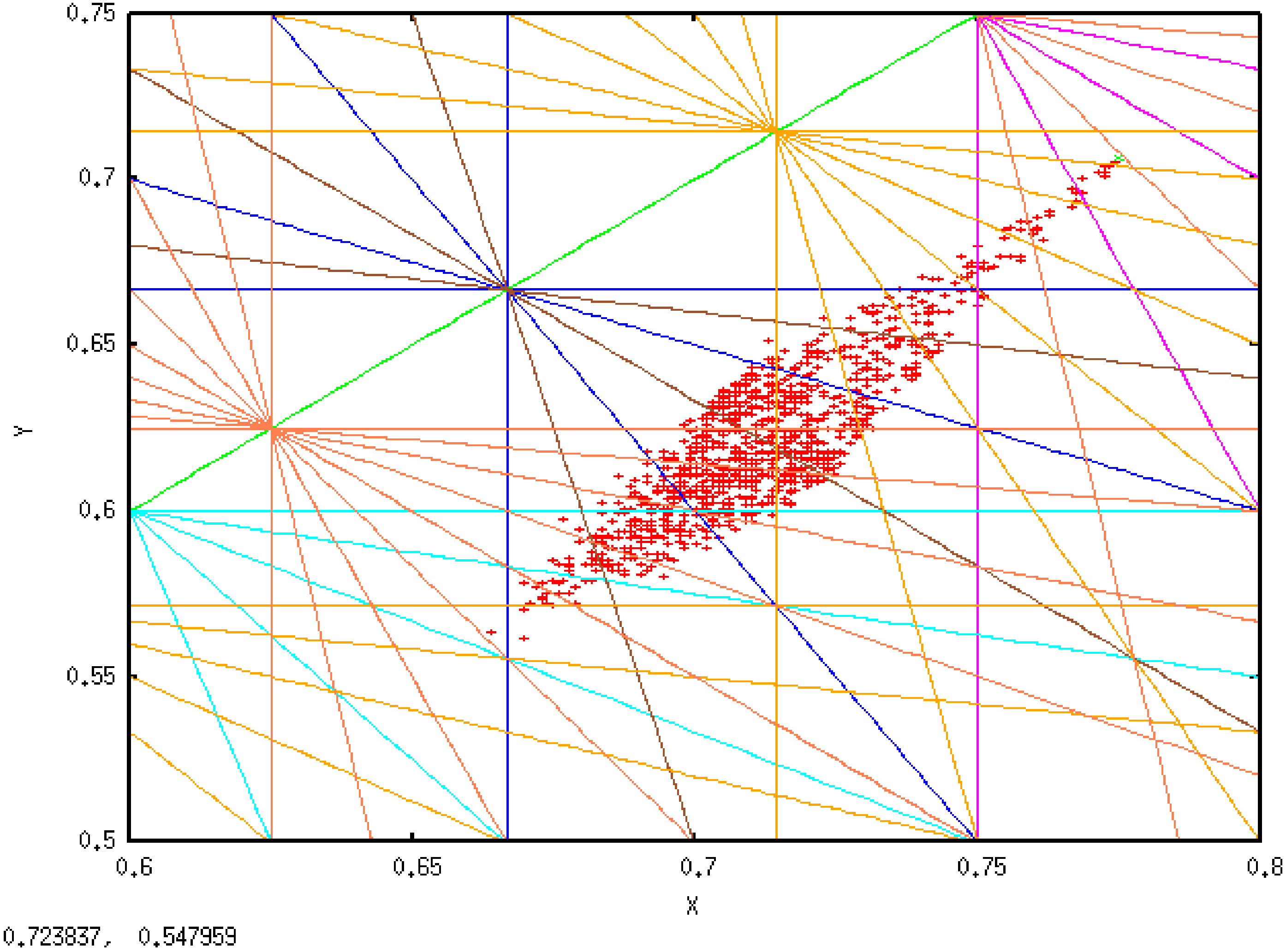
Power Spectrum of 0 mom. Dev and off mom. Particle Trajectories

- Single particle calculation to reproduce the machine lattice bare tunes
- Off-momentum particle shows the same tune as the 0 momentum particle due to 0 chromaticity

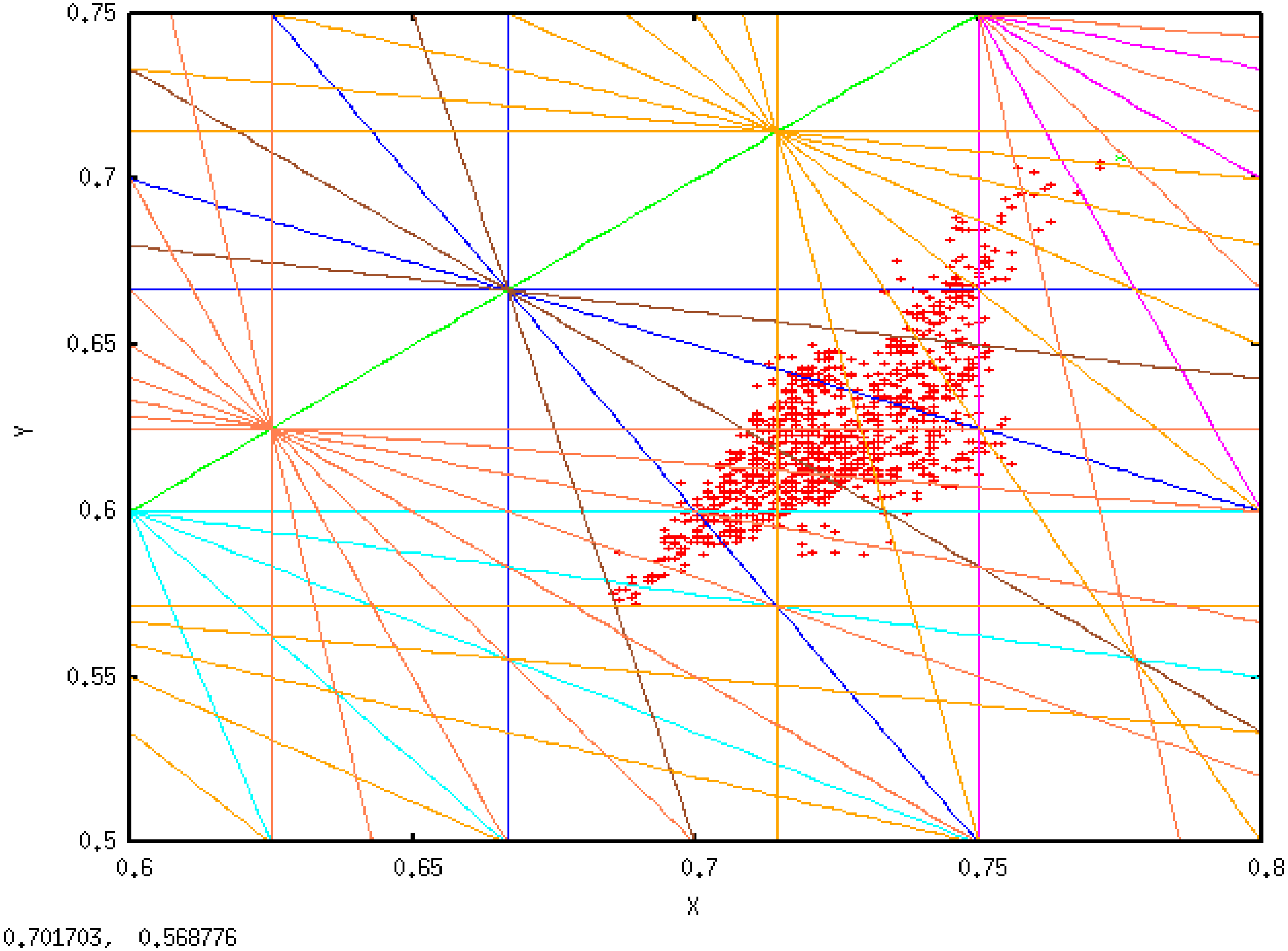


S3.1: Effects of Synchro-Betatron Coupling

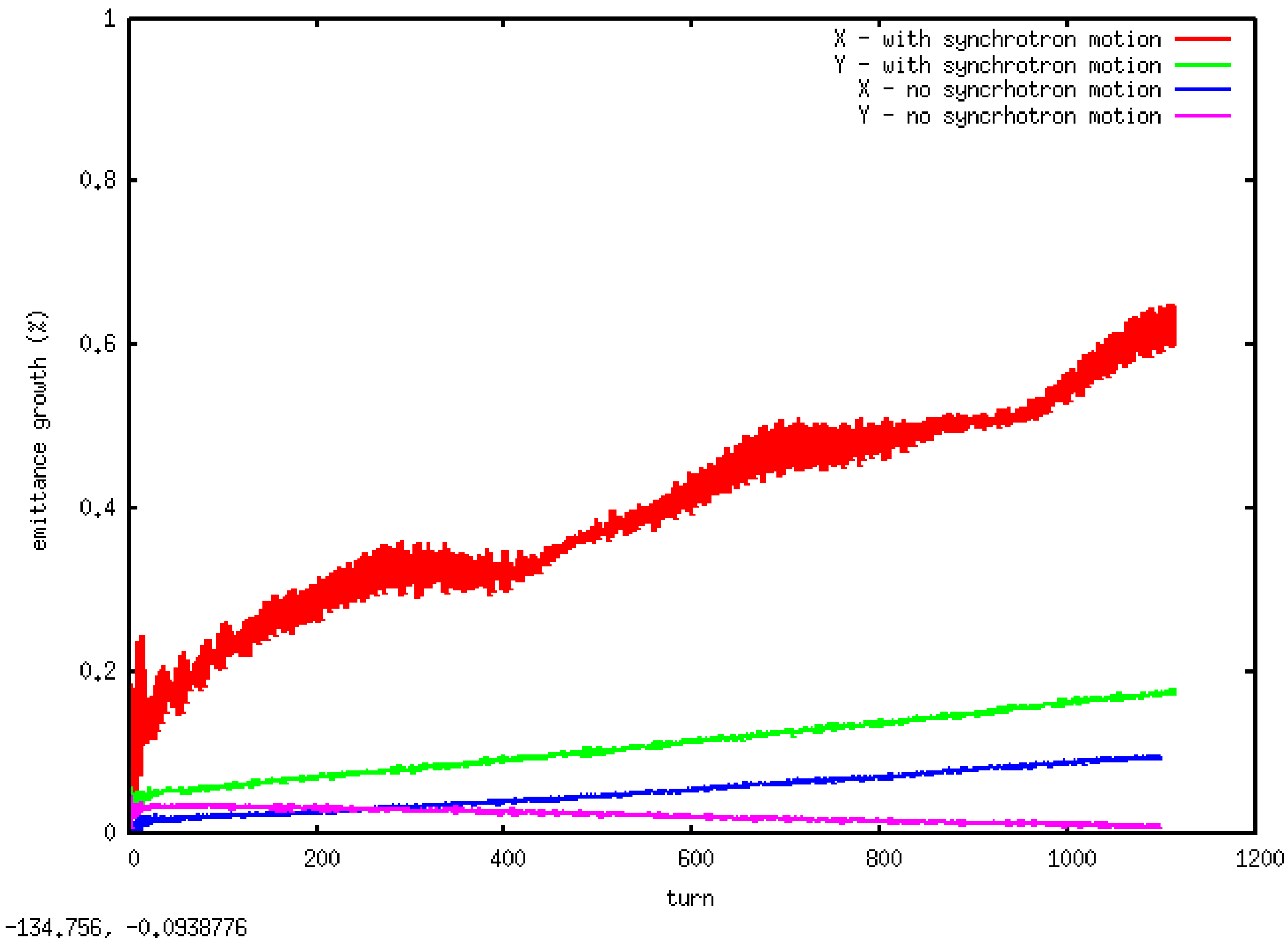
Betatron Tune Footprint with 0 Current and with SC but no Synchroton Motion



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

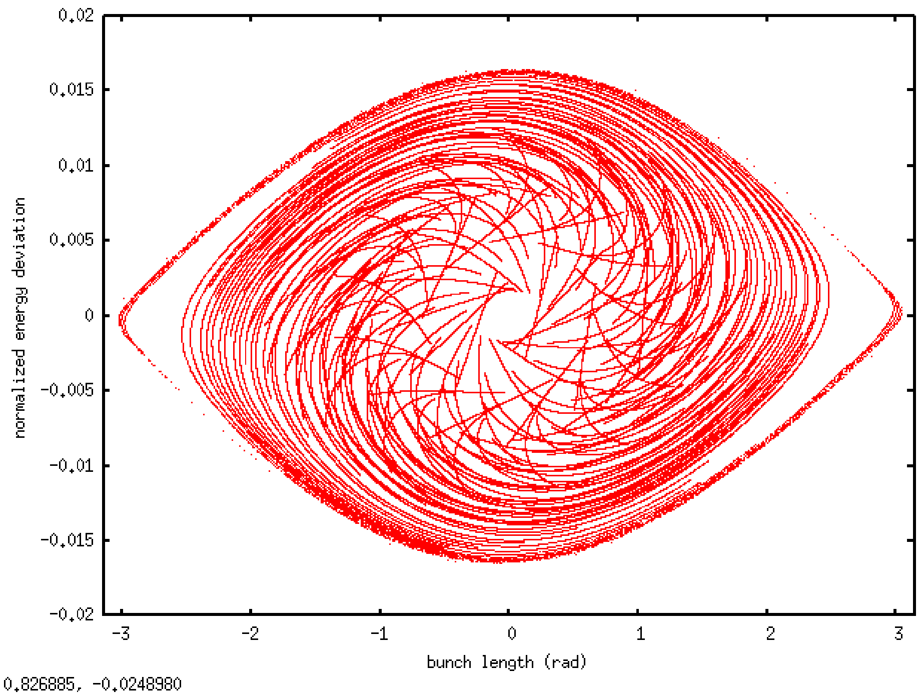


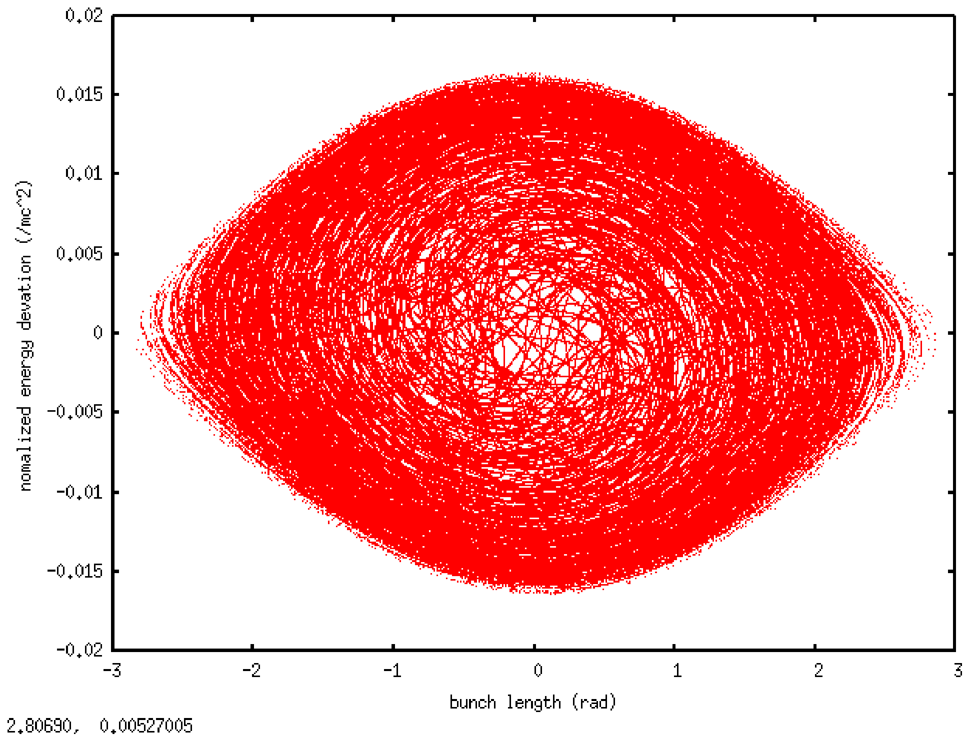
Transverse Emittance Growth with/without Synchrotron Motion



S3.2: Effects of Initial Painted Distribution

Initial Longitudinal Distribution from Painting





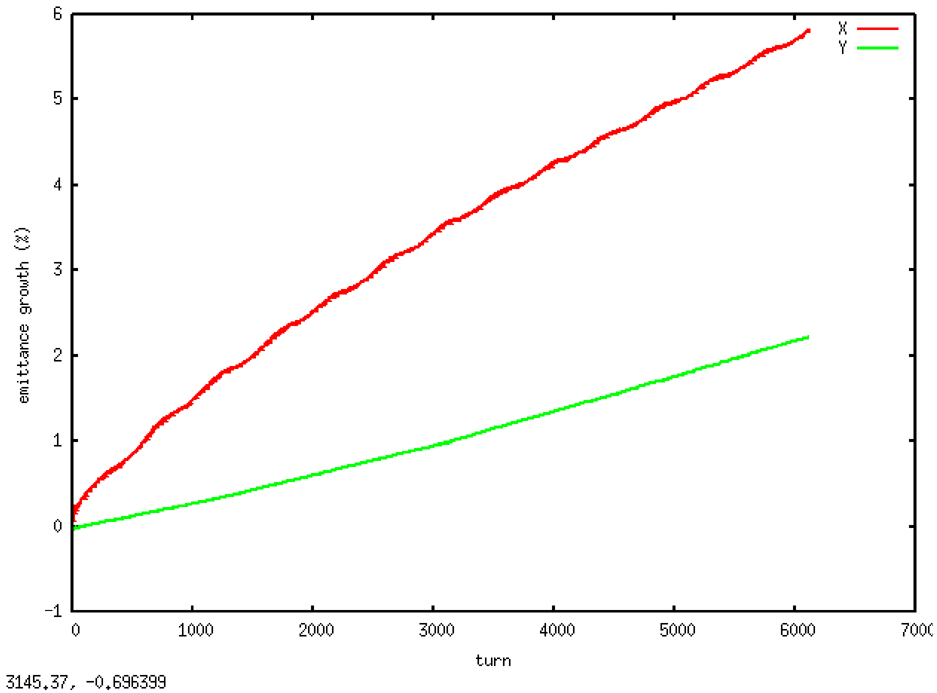
Hallow Current Profile

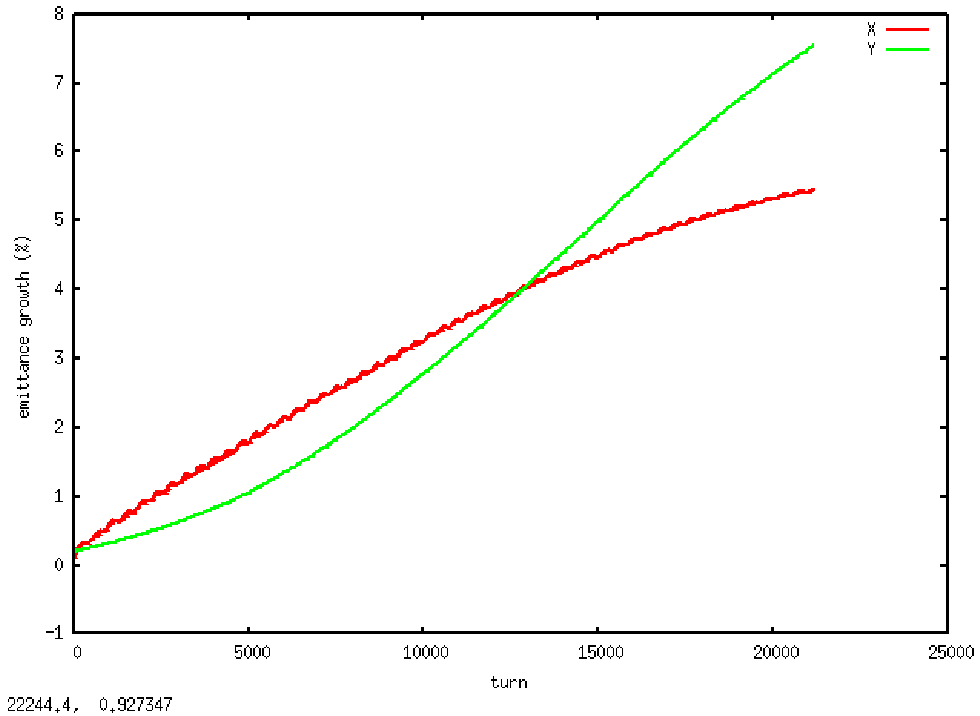
Parabolic Current Profile

Transverse Emittances vs. Turns

- A few percentage emittance growth after **6k** turns using an initial hallow painted distribution

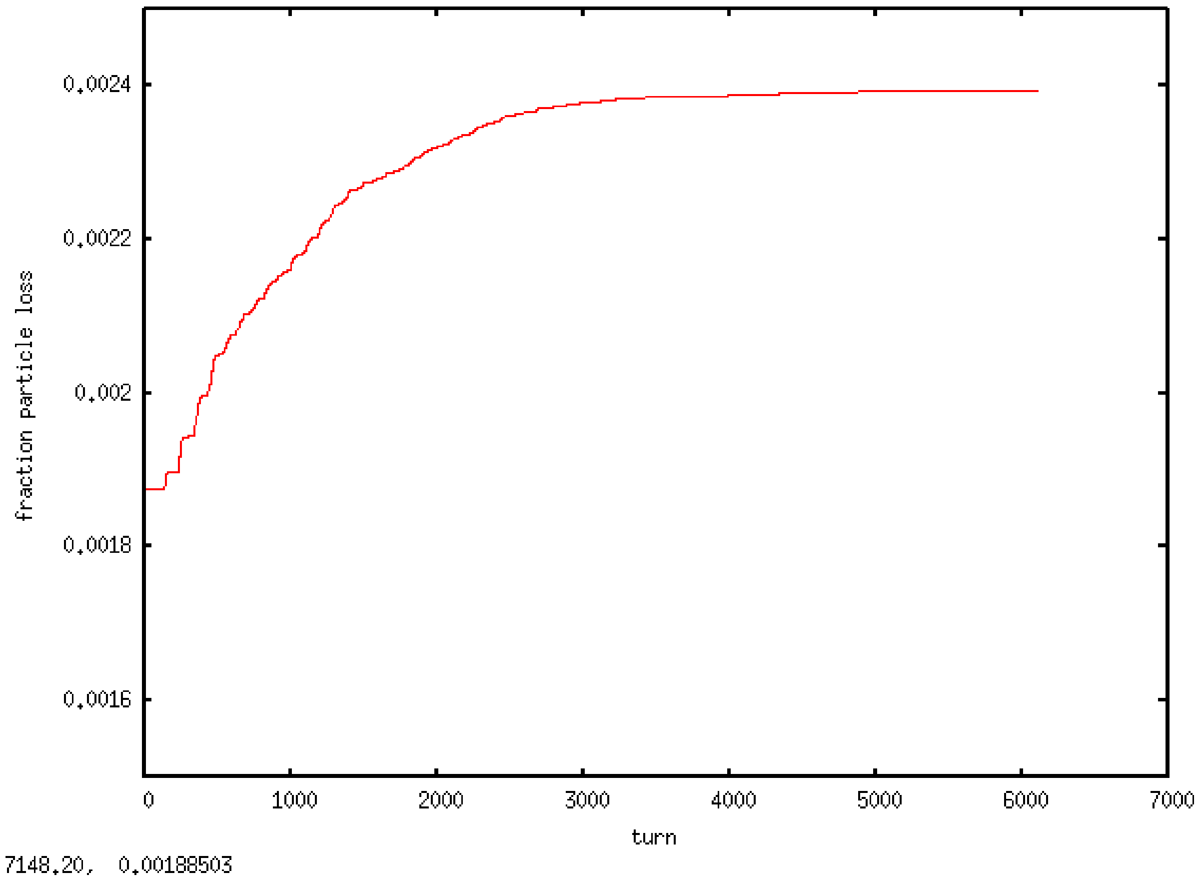
- A few percentage emittance growth after **21k** turns using parabolic painted distribution





Fraction of Particle Loss vs. Turns

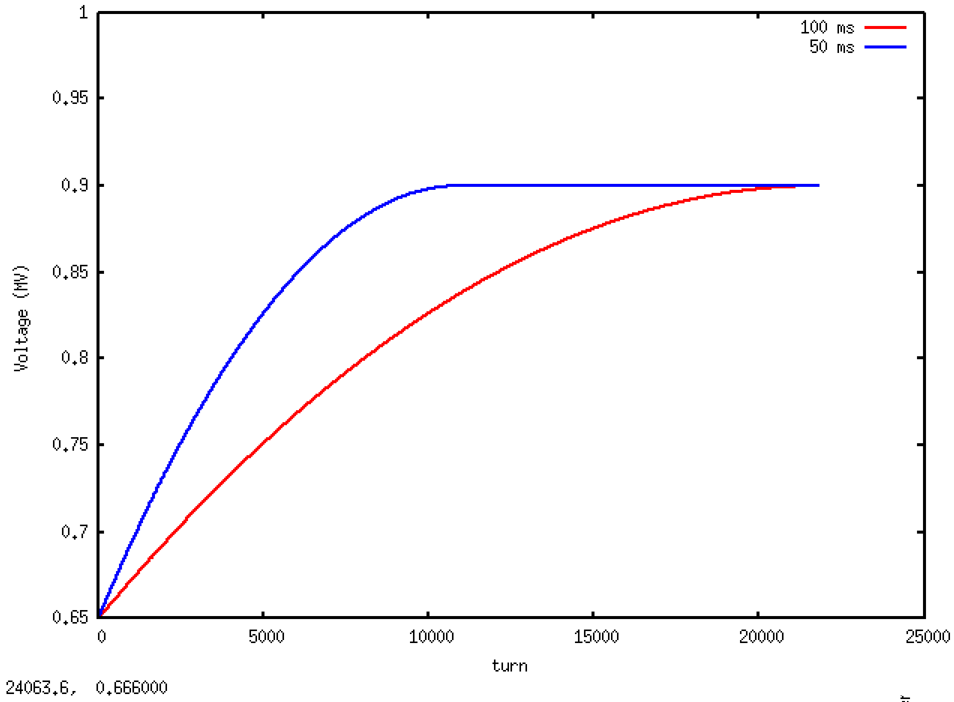
- About 0.24% particle loss after 6k turns using an initial hallow painted distribution

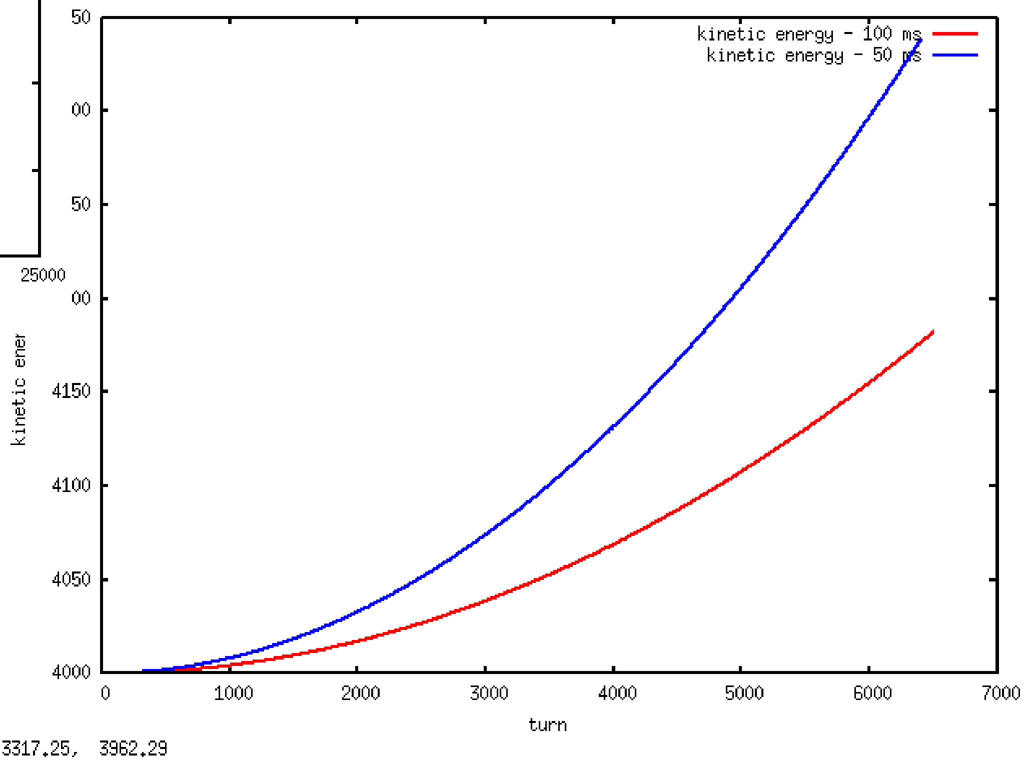


- Only 1 particle out of a million lost in 21,000 turns using the parabolic painted distribution.

S3.3: Effects of RF Ramping

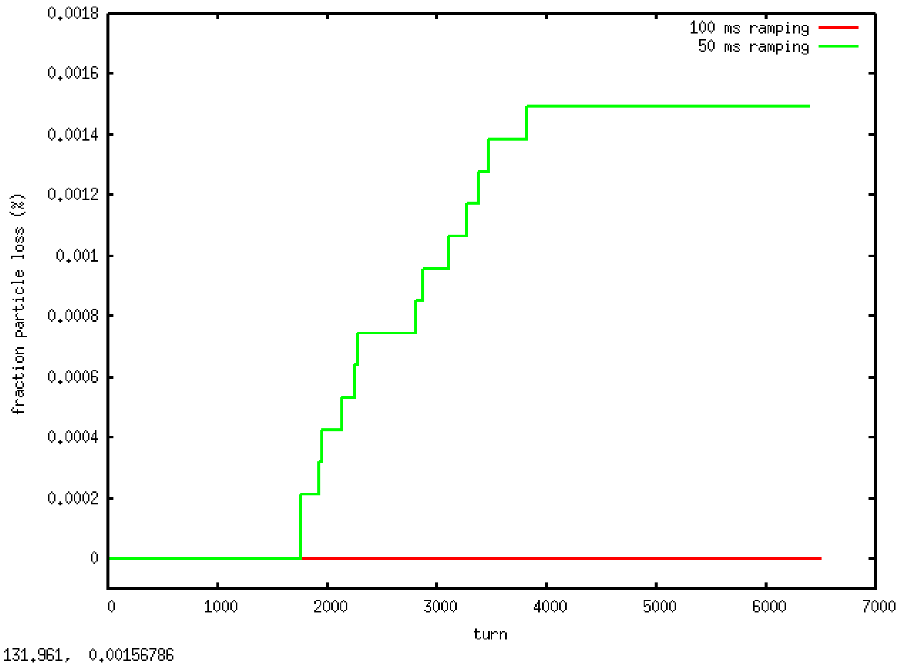
RF Voltage Ramping and Beam Kinetic Energy Evolution
100 ms vs. 50 ms RF Ramping

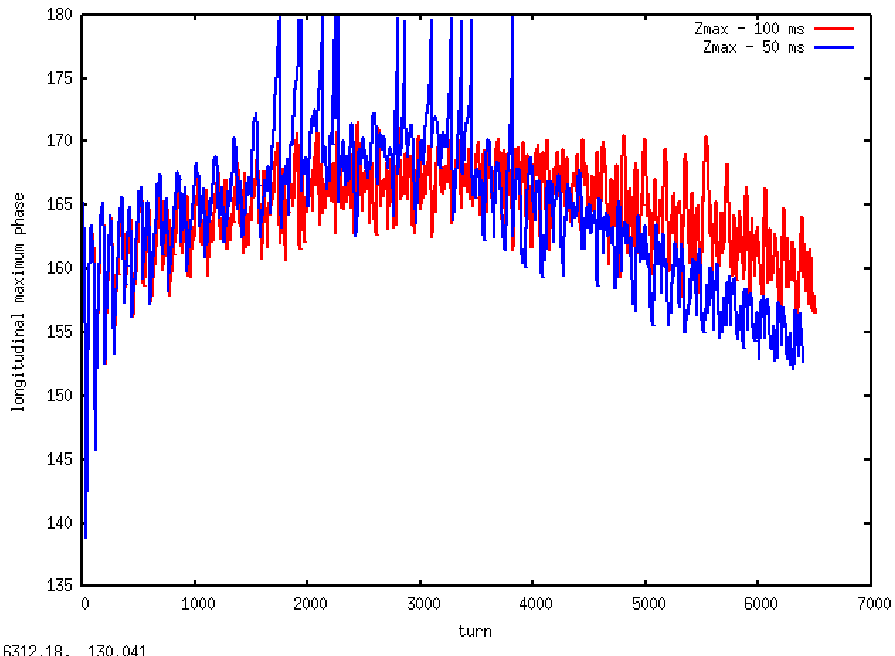




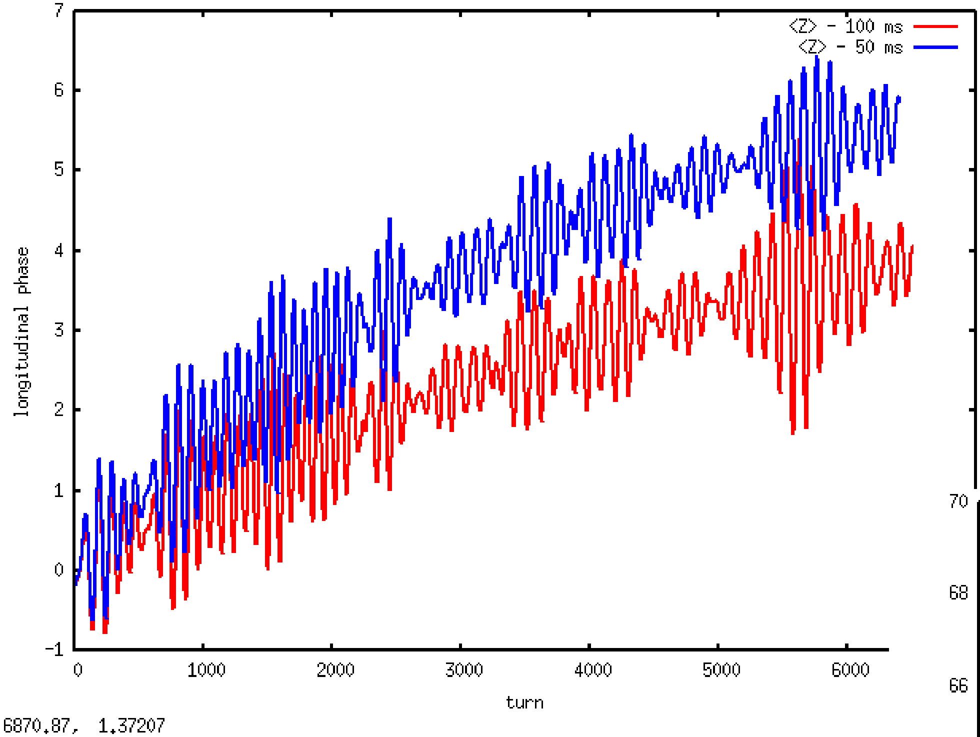
Fractional Particle Loss and Maximum Phase Amplitude
100 ms vs. 50 ms RF Ramping

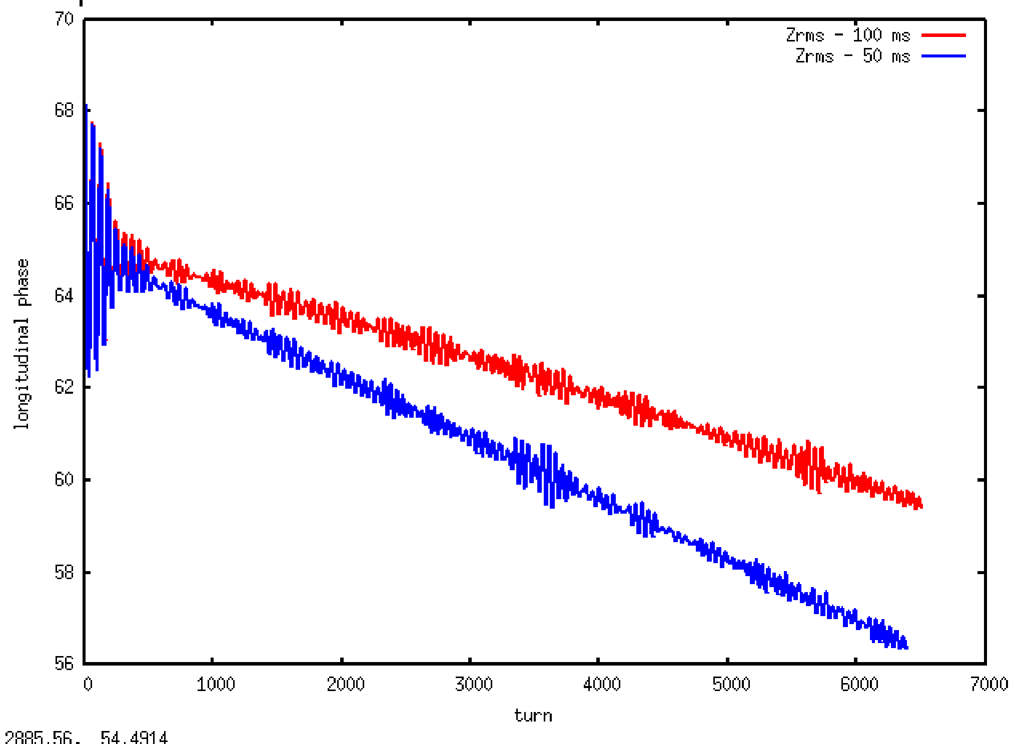
- Faster RF ramping causes more particles lost out of RF bucket





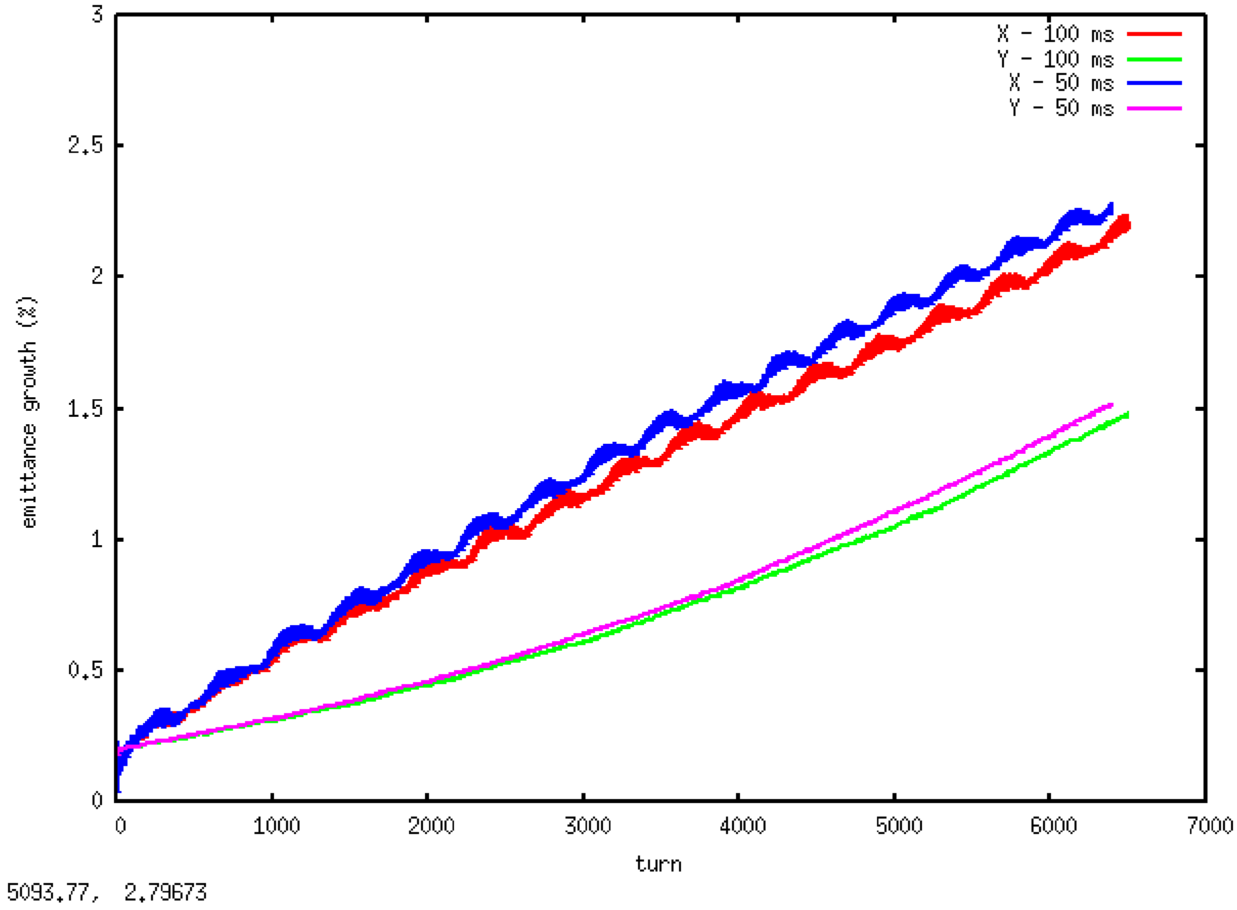
Evolution of Longitudinal Centroid and RMS Size with 100 ms and 50 ms RF Ramping



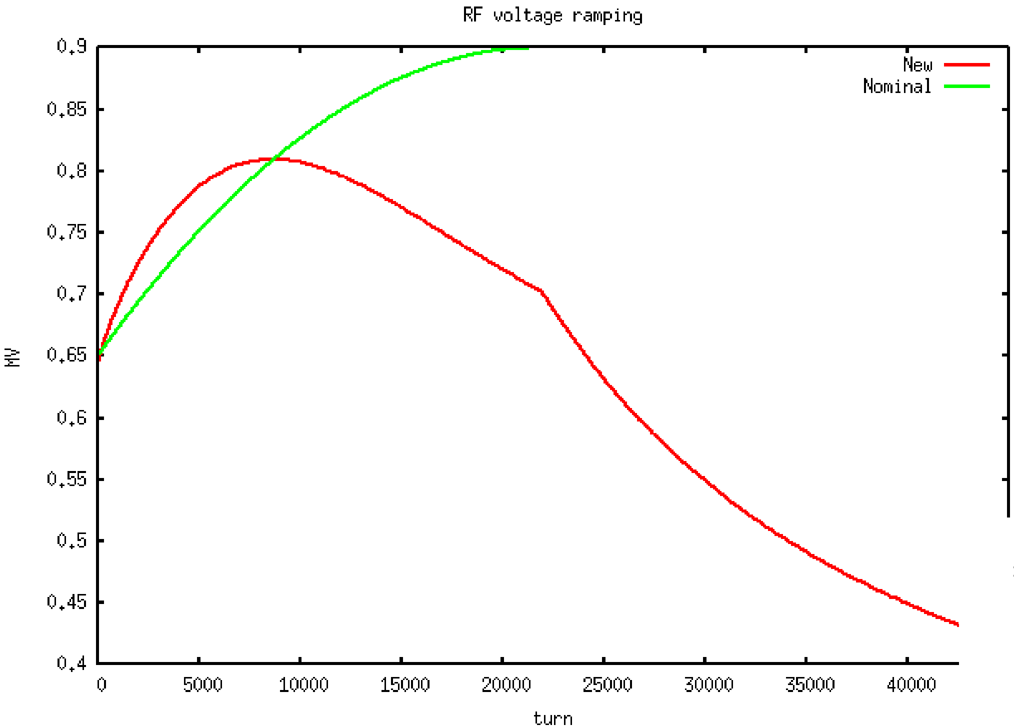


Transverse Emittances with 100 ms and 50 ms RF Ramping

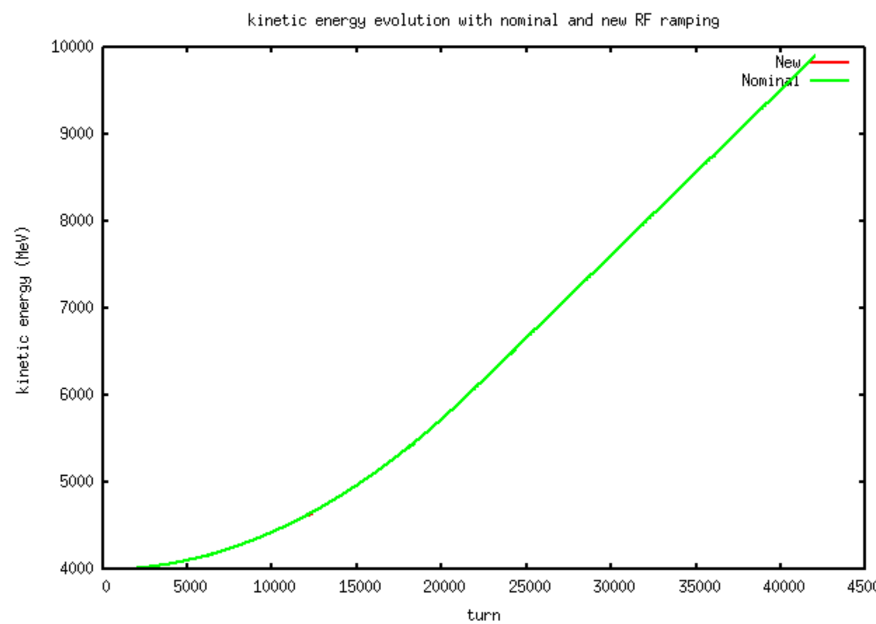
- Slightly larger emittance growth with faster RF ramping



Nominal and New RF Voltage Ramping

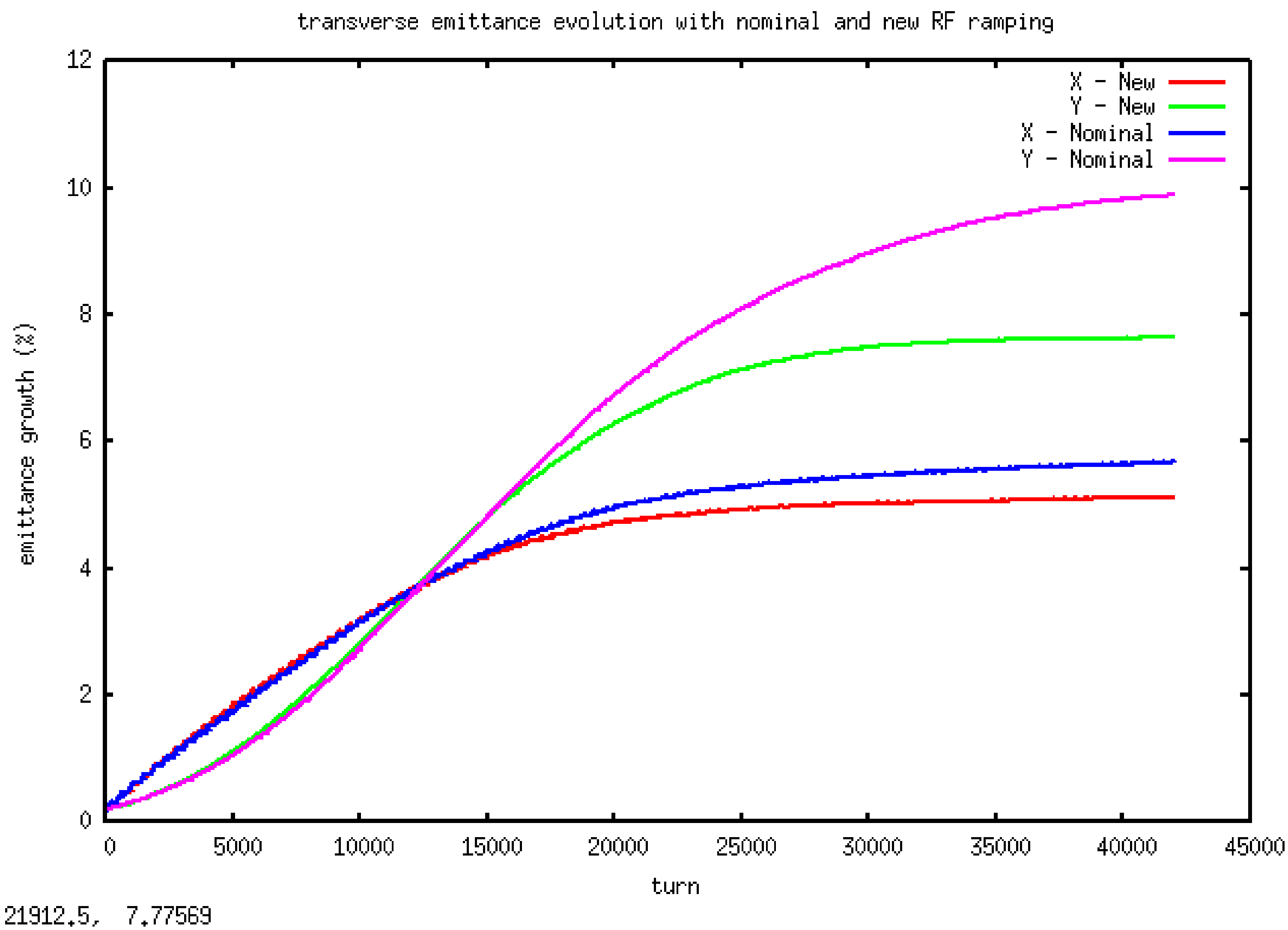


34485.5, 0.612810

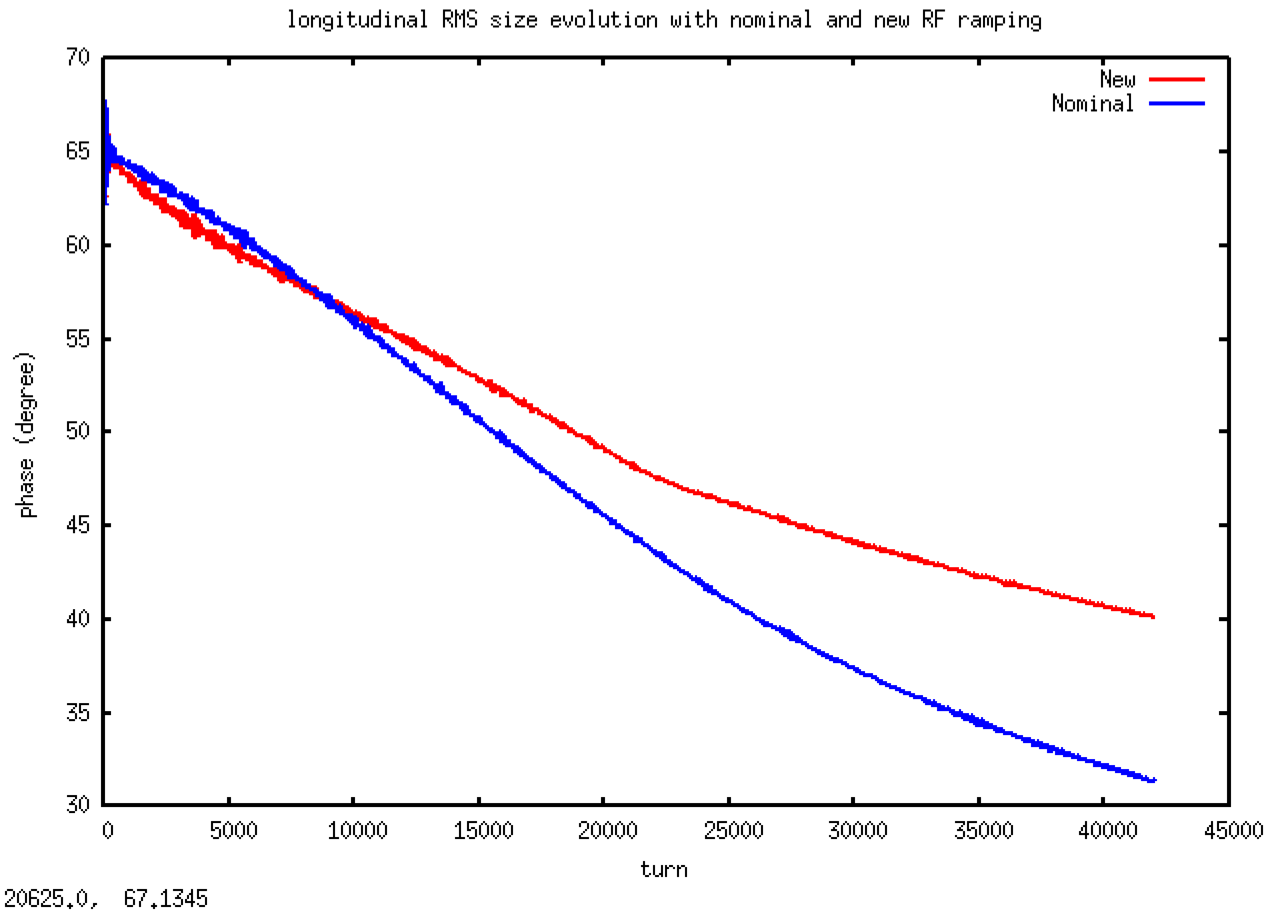


14754.3, 3459.86

Transverse Emittance Growth with Nominal and New RF Ramping



Longitudinal RMS Size Evolution with Nominal and New RF Ramping



S4: 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
- Better painted longitudinal distribution help reduce emittance growth and particle losses
- Optimizing RF voltage and phase ramping help reduce emittance growth and particle losses