Space Charge Simulations for LHC Injector Upgrade

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In collaboration with

- LHC injector upgrade group and PS2 design study group (C. Carli, R. Garoby, E. Metral, H. Bartosik, Y. Papaphilippou et al.), CERN
- G. Franchetti, I. Hofmann, GSI
- U. Wienands, SLAC

Outline

- Introduction
- Computational models
- Space-charge simulations of PS2
- Space-charge simulations of PS
- Future work

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}).

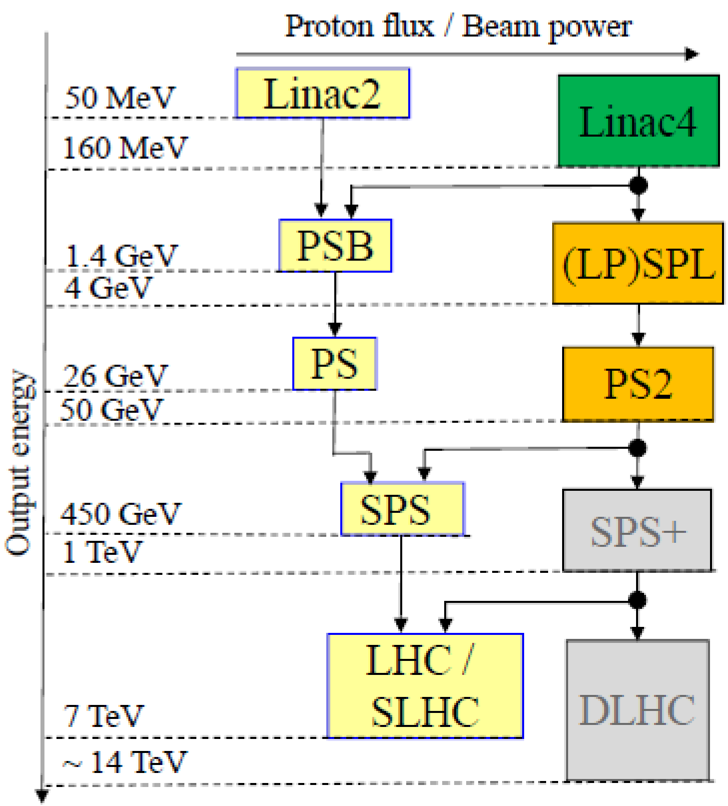


Figure 1: Overview on the CERN injector complex upgrade programme: stage 1 (green), stage 2 (orange).

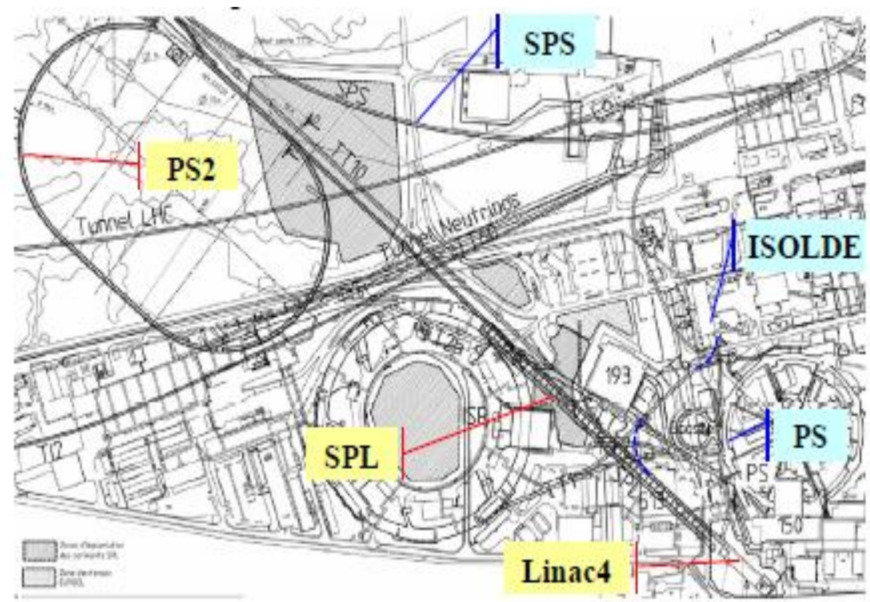
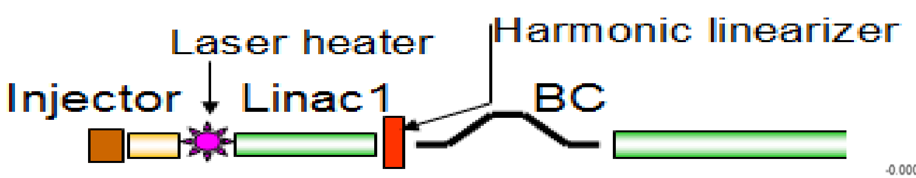


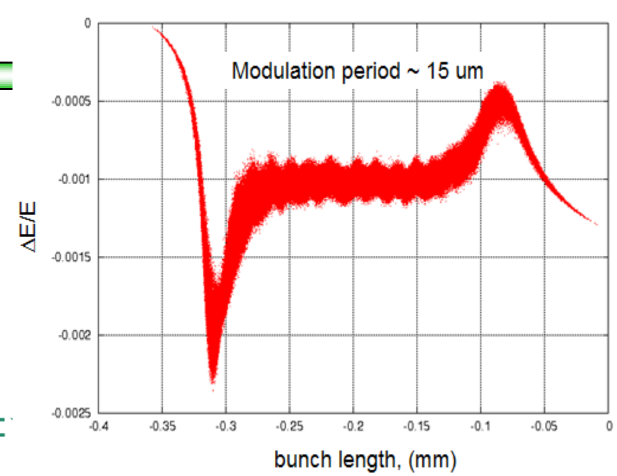
Figure 2: Integration of PS2 within the existing and future CERN accelerator complex.

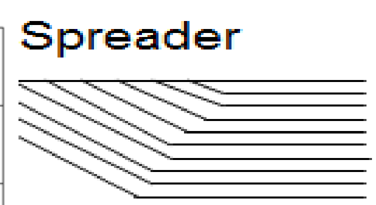
M. Benedikt, et al., PAC09, WE1GRI03

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







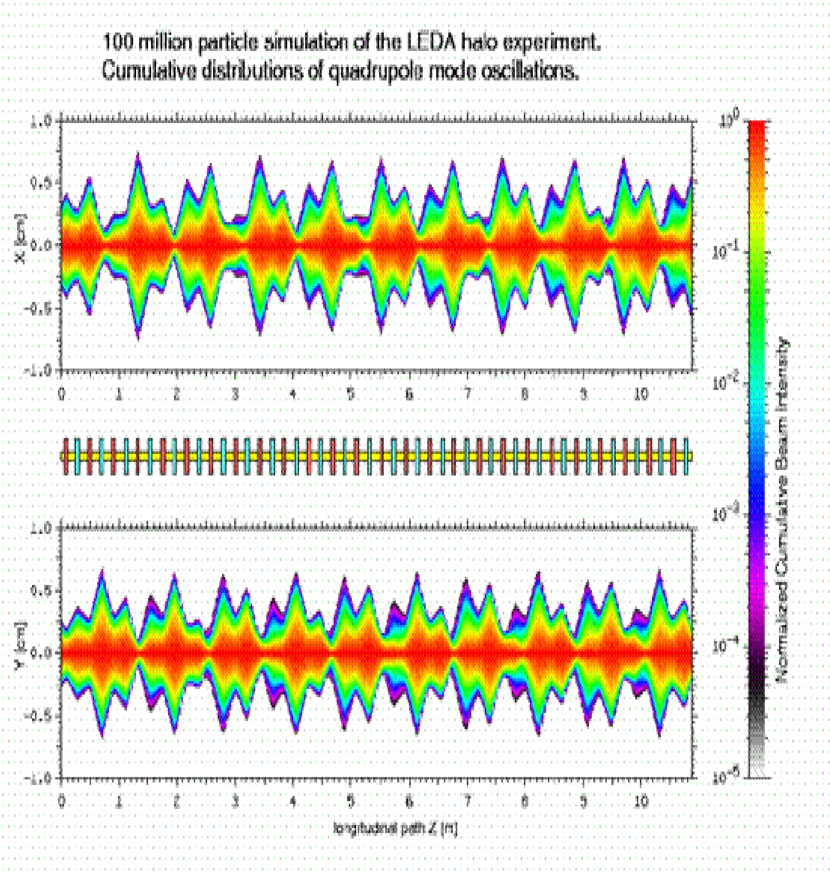
One Billion Macroparticle Simulation of an FEL Linac

(~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

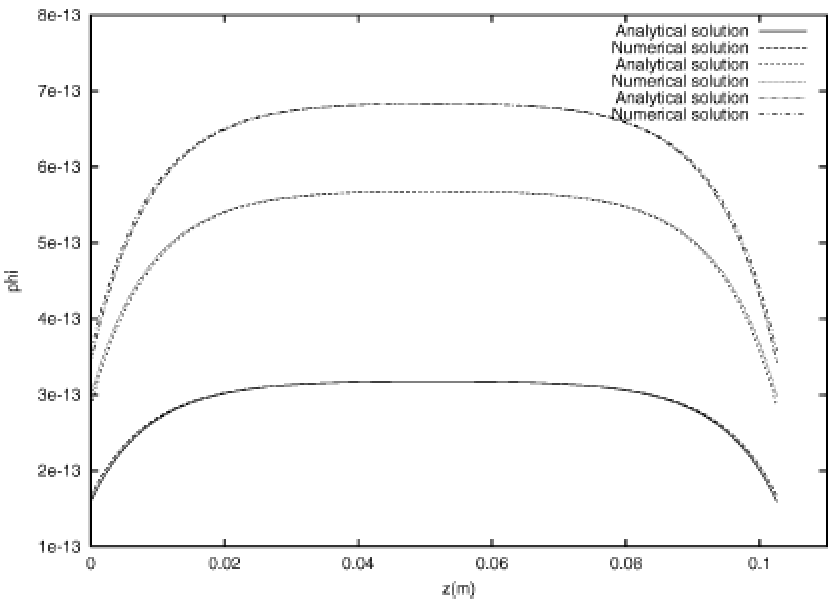
$$\rho^{lm}(z) = \frac{4}{ab} \int_0^a \int_0^b \rho(x,y,z) \sin(\alpha_l x) \sin(\beta_m y),$$

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

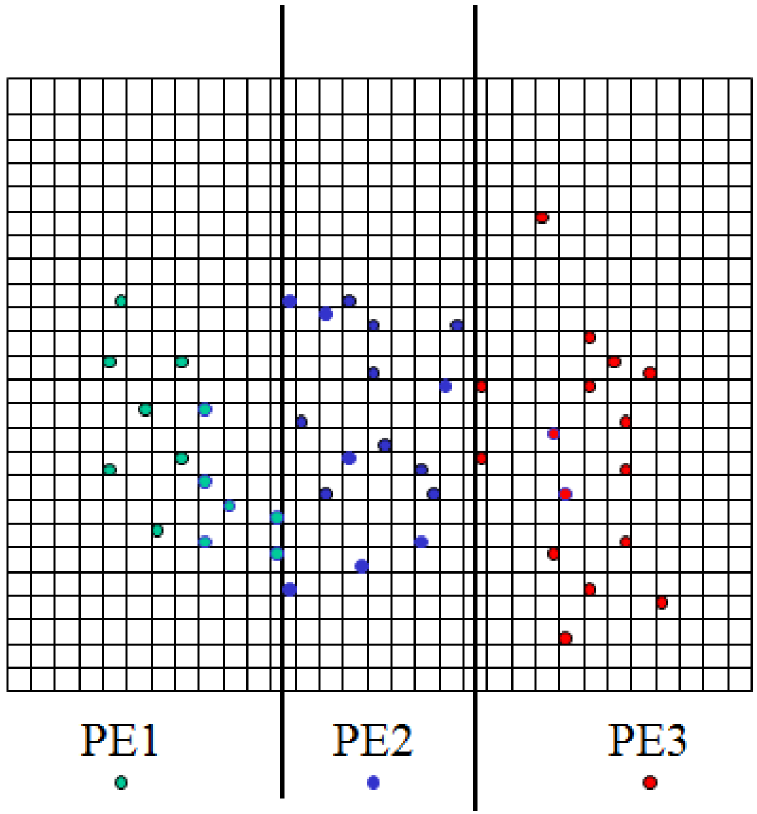
$$\frac{\partial^2 \phi^{lm}(z)}{\partial z^2} - \gamma_{lm}^2 \phi^{lm}(z) = -\frac{\rho^{lm}(z)}{\epsilon_0},$$

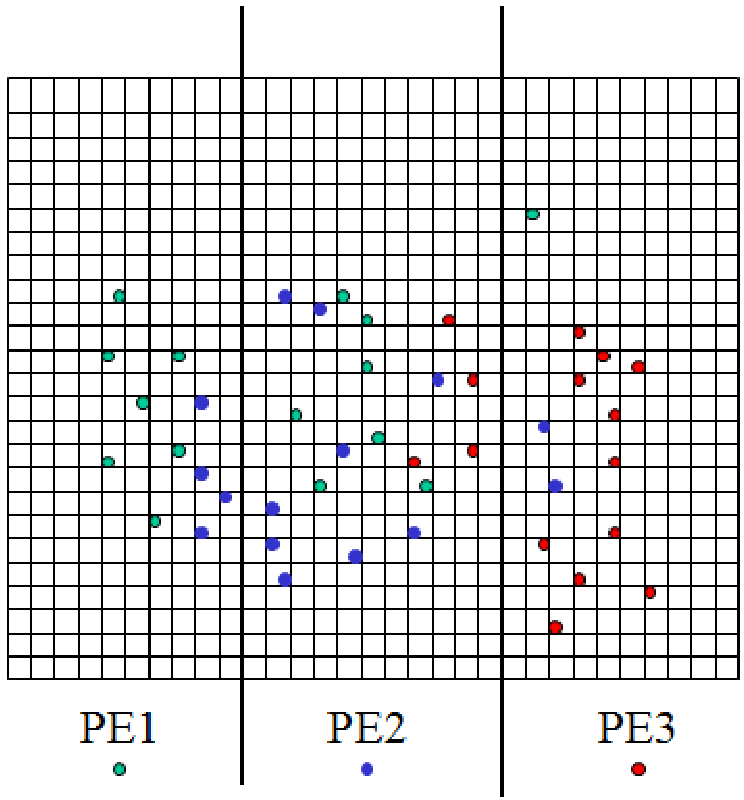
$$\frac{\phi_{n+1}^{lm} - 2\phi_n^{lm} + \phi_{n-1}^{lm}}{h_z^2} - \gamma_{lm}^2 \phi_n^{lm} = -\frac{\rho_n^{lm}}{\epsilon_0},$$

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



Space-Charge Simulation Needs Optimal 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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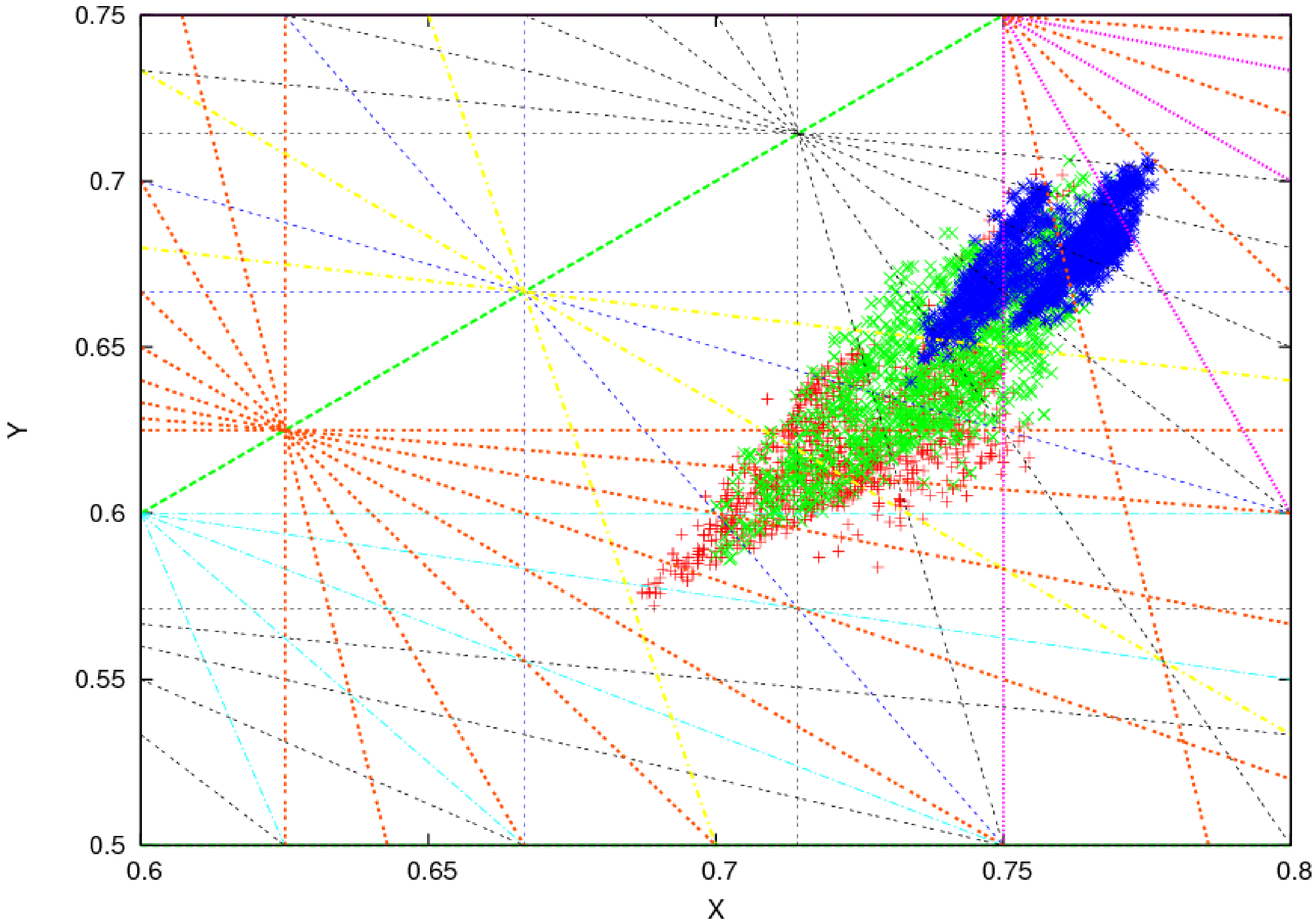
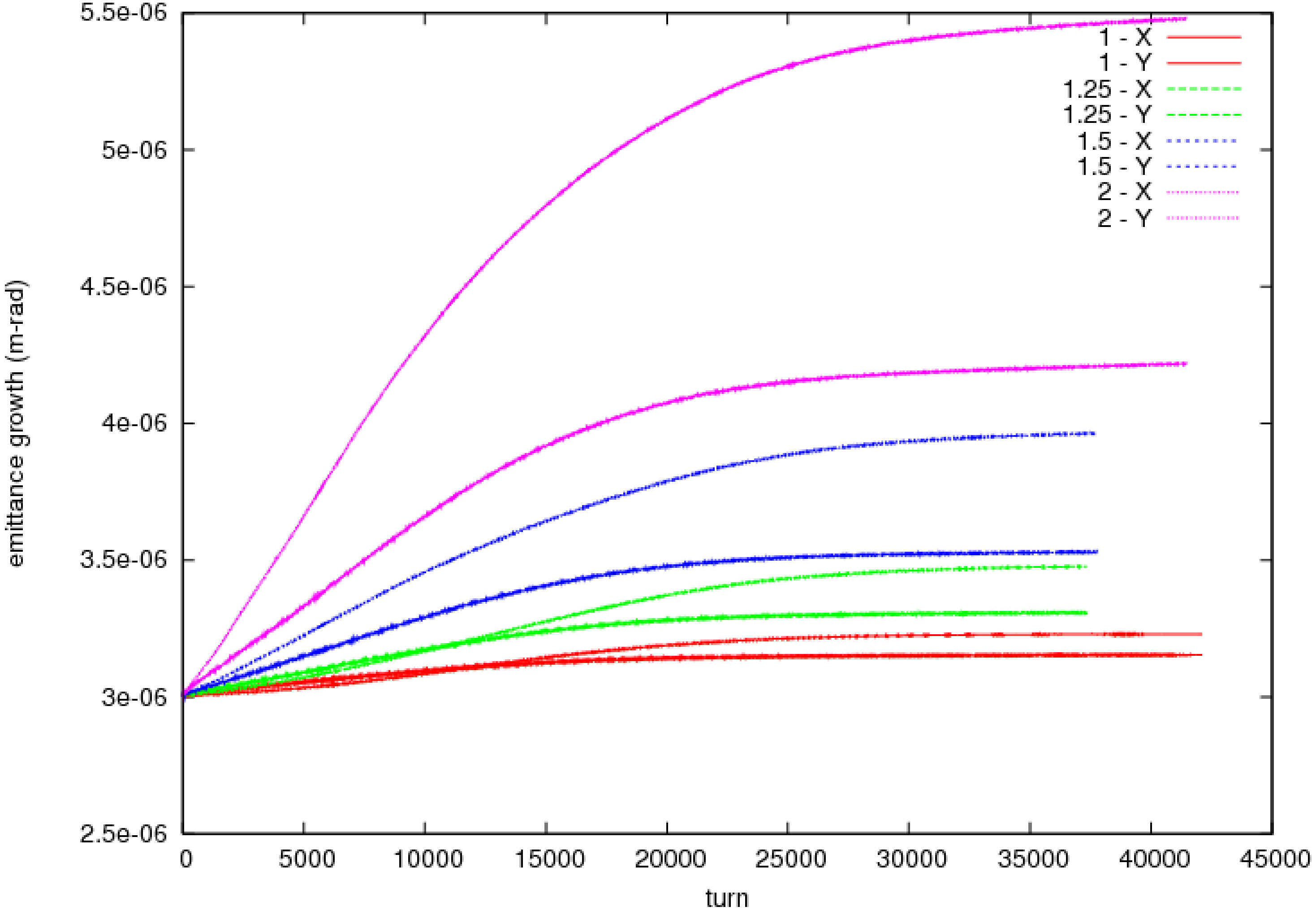
70 SC per tur
65x65x128 grid points
939,000 macroparticles

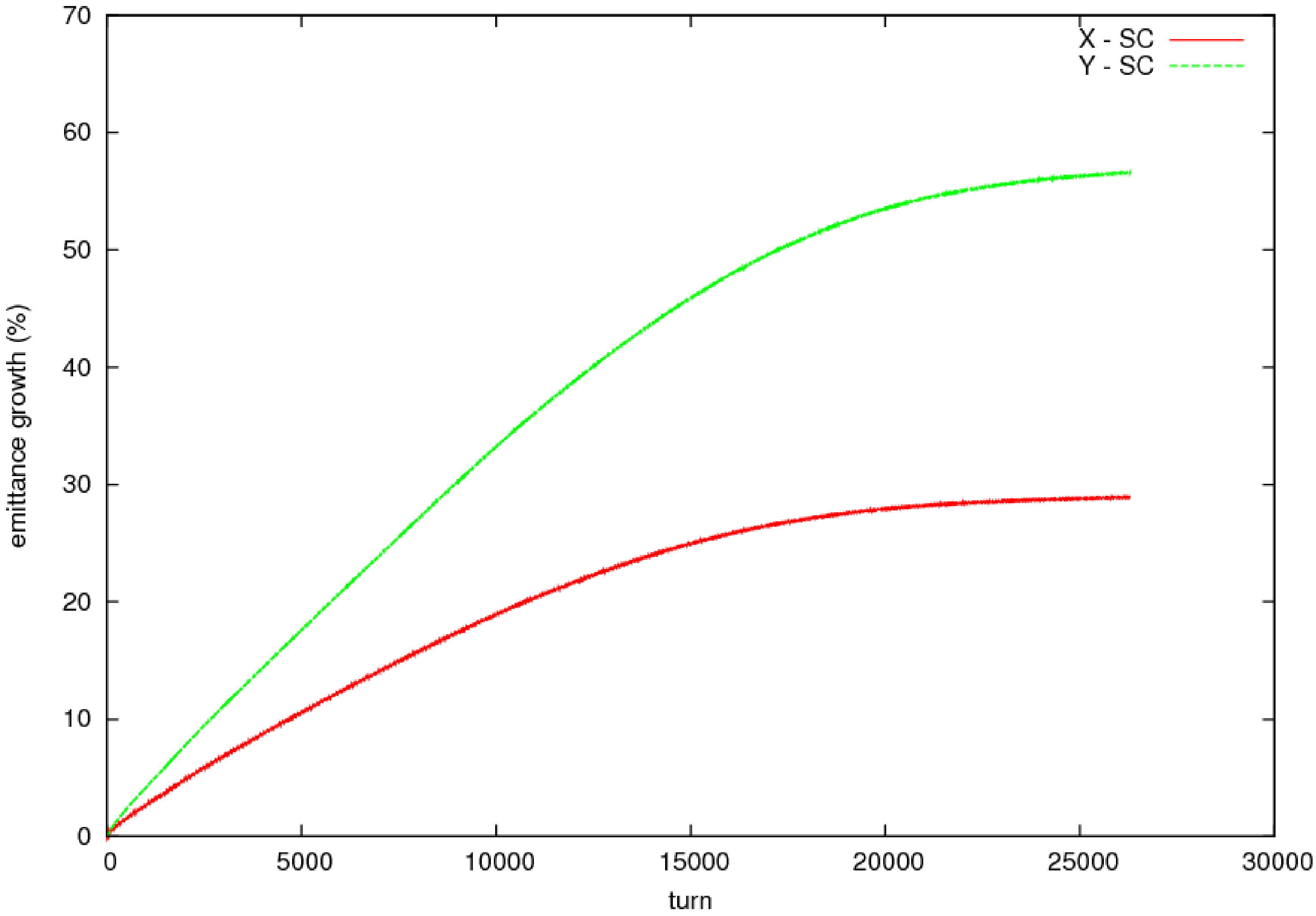
Tune Footprint around 4 GeV, 6 GeV and 8 GeV Energy



Transverse Emittance Evolution with Different Proton Intensity



Transverse Emittance Evolution with Machine Nonlinear Errors



Summary of Space-Charge Simulations in PS2

- Space-charge effects together with nonlinear machine errors can cause significant beam emittance growth in 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

Contribute to the PS2 CD Report

Conceptual Design of the PS2

PS2 WG/LARP Collaboration

GENEVA
2011

http://paf-ps2.web.cern.ch/paf-ps2/http://paf-ps2.web.cern.ch/paf-ps2/

Direct Space Effects Studies Suggested by CERN Colleagues

Present: G. Arduini, C. Carli, R. Garoby, K. Hanke, E. Metral, G. Rumolo
(S. Gilardoni and F. Schmidt could not participate)

Proposal for a LIU-LARP collaboration:

- As a starting point, we would prefer studies allowing some benchmarking comparisons with experimental observations:
  - The easiest option is to start simulations similar to the ones made some years ago in the scope of a benchmarking effort (Elias can provide more information)
  - Booster with resonance excitation based on present compensation settings (note that blow-up at low energy is difficult to be measured and thus not suitable for comparisons between simulations and measurements).
- Later-on, all topics mentioned above

Studies of beam dynamics with strong direct space charge effects is an issue for all synchrotrons in the LHC injector chain. In detail:

- Study of beam dynamics with strong direct space charge forces and lattice imperfections (quadrupolar and higher order multipoles) in the PS Booster:
  The interest is to improve understanding in view of efficient setting up during Booster recommissioning of resonance compensation at 160 MeV after Linac4 connection and possibly optimization of the working point. Comparisons with experience with the present resonance compensations at 50 MeV would allow some benchmarking.
- Study of beam dynamics with direct space charge in the PS:
  The motivation is to better understand the direct space charge limit in the PS in order to judge the need and benefit of the proposed increase of the PSB to PS transfer energy. Note that benchmarking measurements and comparative simulations with ORBIT have been made a couple of years ago.
- Study of beams with strong direct space charge effects in the SPS:
  Whereas it is planned to mitigate direct space charge effects in both the PSB and the PS by increasing the injection energy, this is not possible for the SPS in the scope of the present LIU. A better understanding of direct space charge effect and, whether this can become the performance limitation of the whole chain, is important to estimate performance reach with LIU.

PS Montague Resonance Studies

- Montague Resonance: 2 Qx – 2 Qy = 0
- can cause particle due to unequal aperture size in horizontal and vertical dimensions.

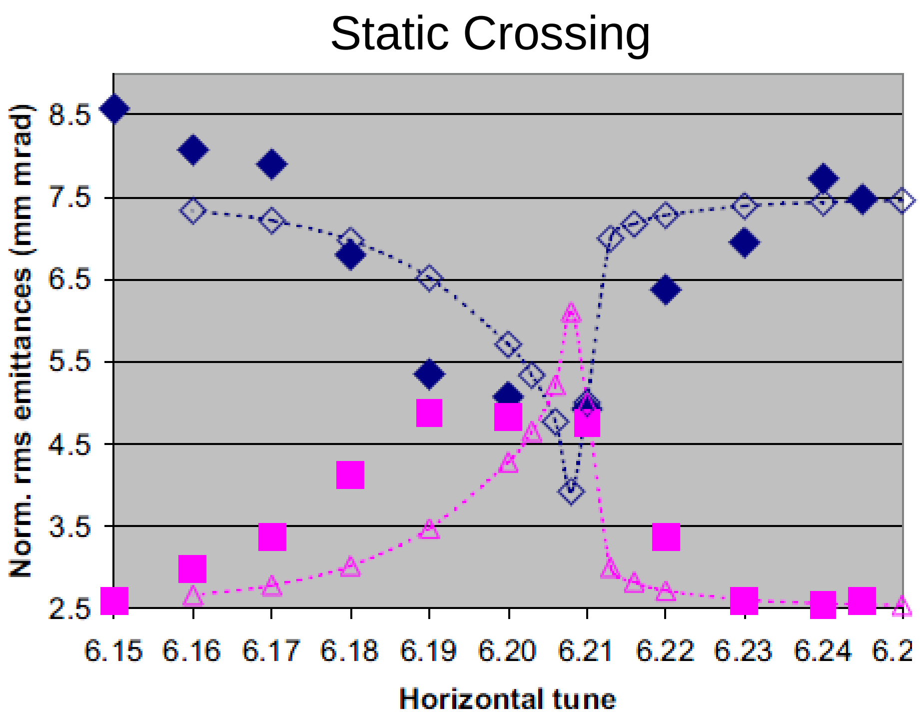
Physical parameters:

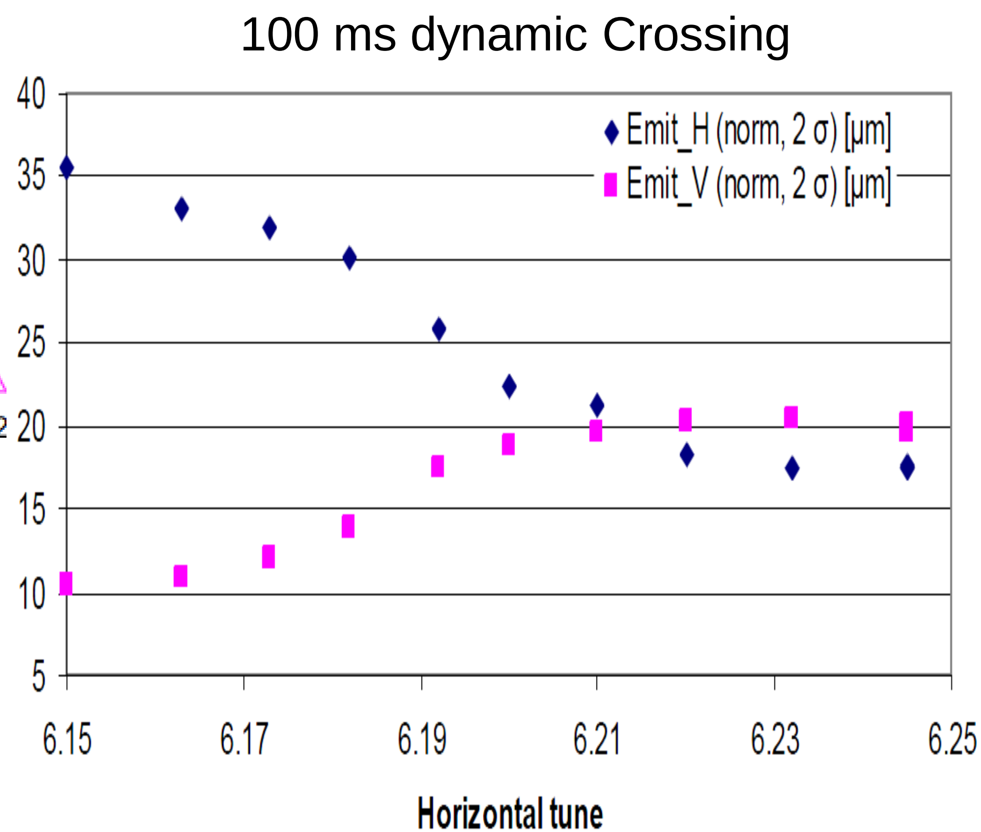
Vrf = ramping with f = 39.5 MHz
Ek = 1.4 GeV
Emit_x = 7.5 mm-mrad
Emit_y = 2.5 mm-mrad
Rms bunch length = 45 ns
Rms dp/p = 1.7 x 10^{-3}

Horizontal tune: 6.15 – 6.245
Vertical tune: 6.21
Synchrotron period: 1.5 ms
Half Aperture = 7cm x 3.5cm
I = 1.0×10^{12}

Refs: B. W. Montague, CERN-Report No. 68-38, CERN, 1968.
E. Metral et al., Proc. of EPAC 2004, p. 1894.
I. Hofmann et al., Proc. of EPAC 2004, p. 1960.

Static and Dynamics Montague Resonance Crossing at PS





Courtesy of E. Metral et al., Proc. EPAC04

IMPACT Simulations of Emittance Exchange with Constant Focusing

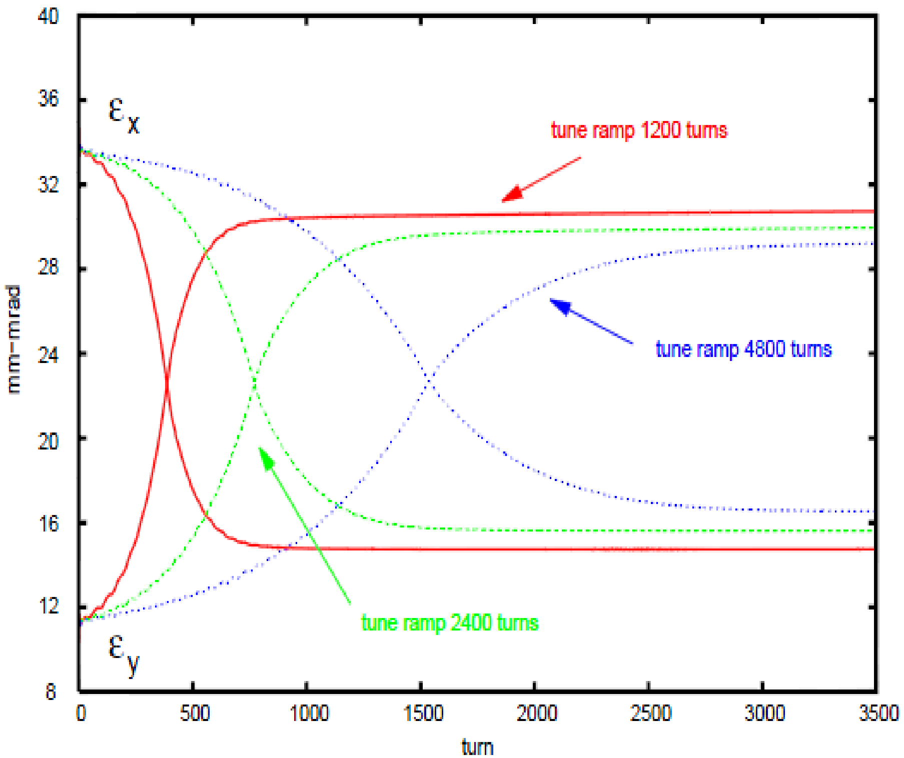


Figure 5: Rms emittances in 3D bunched beam for different tune ramps and fixed synchrotron period (100 turns).

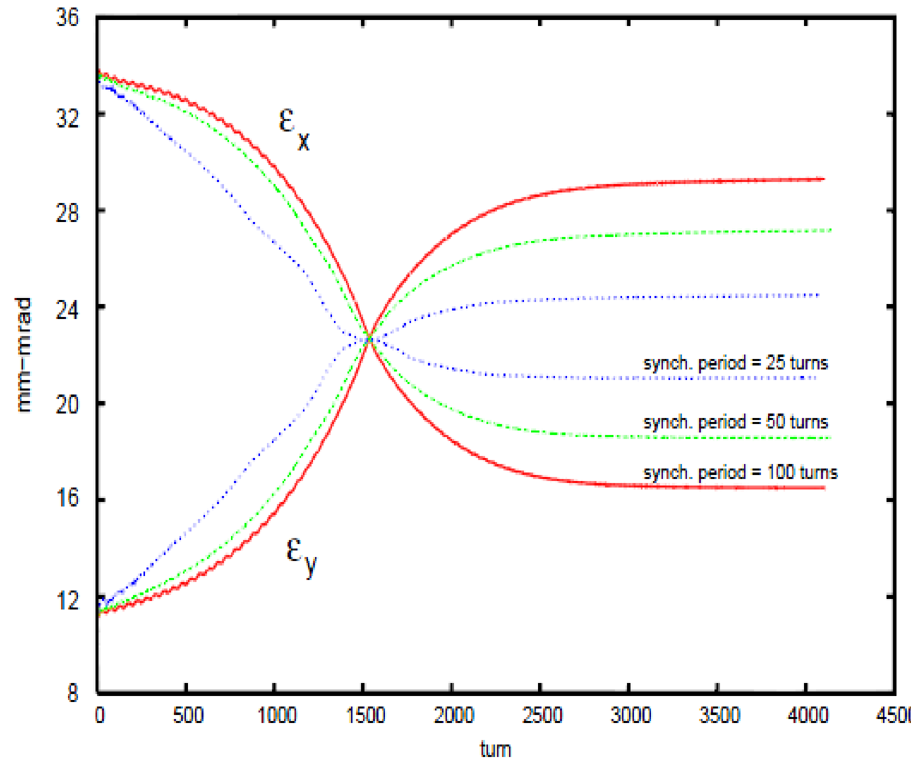
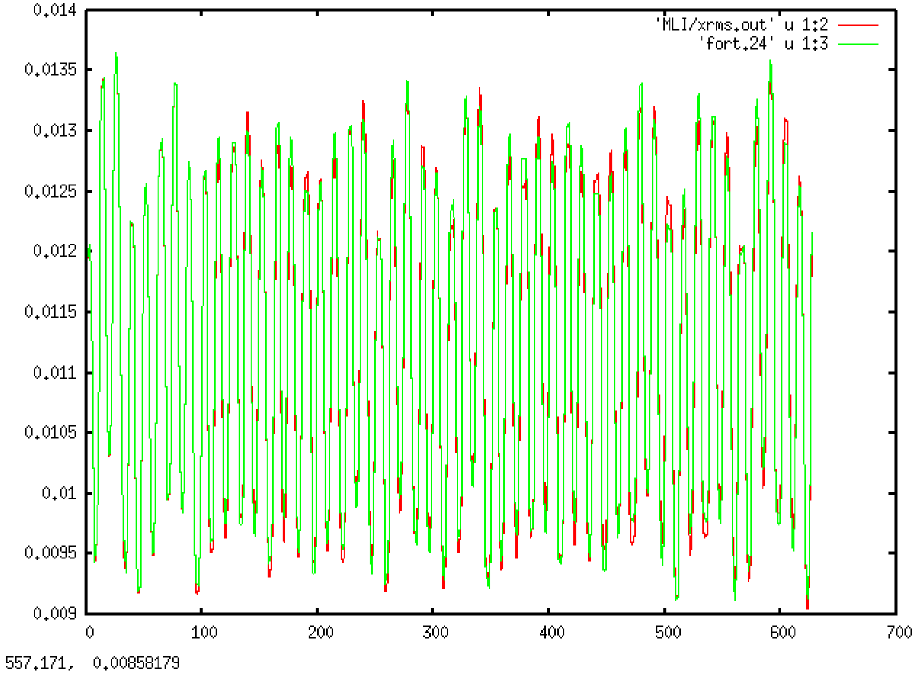
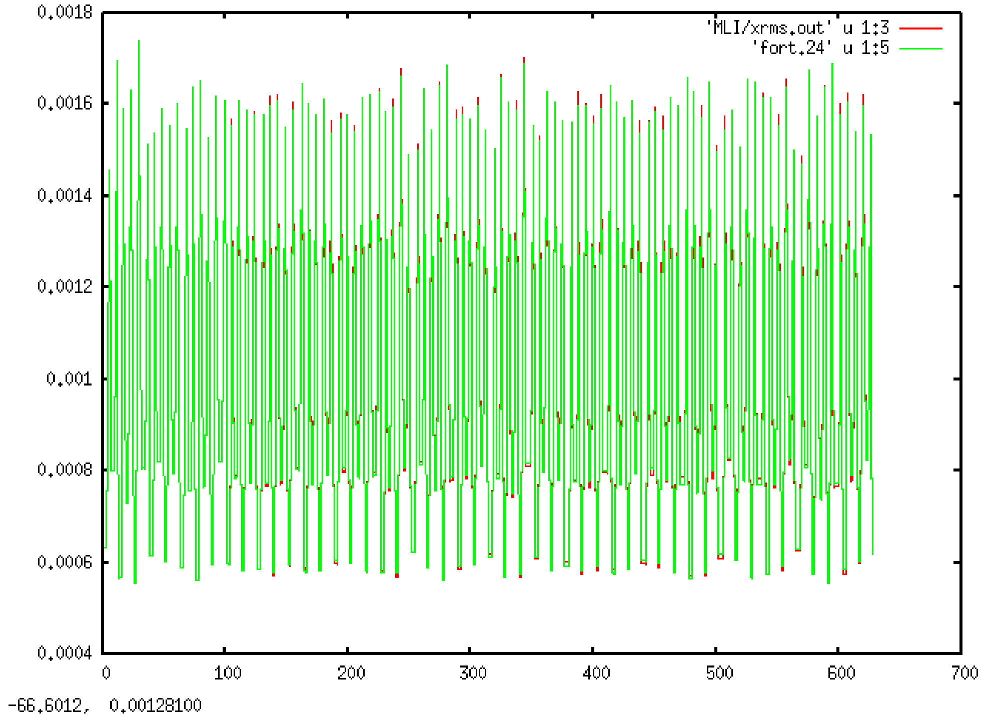


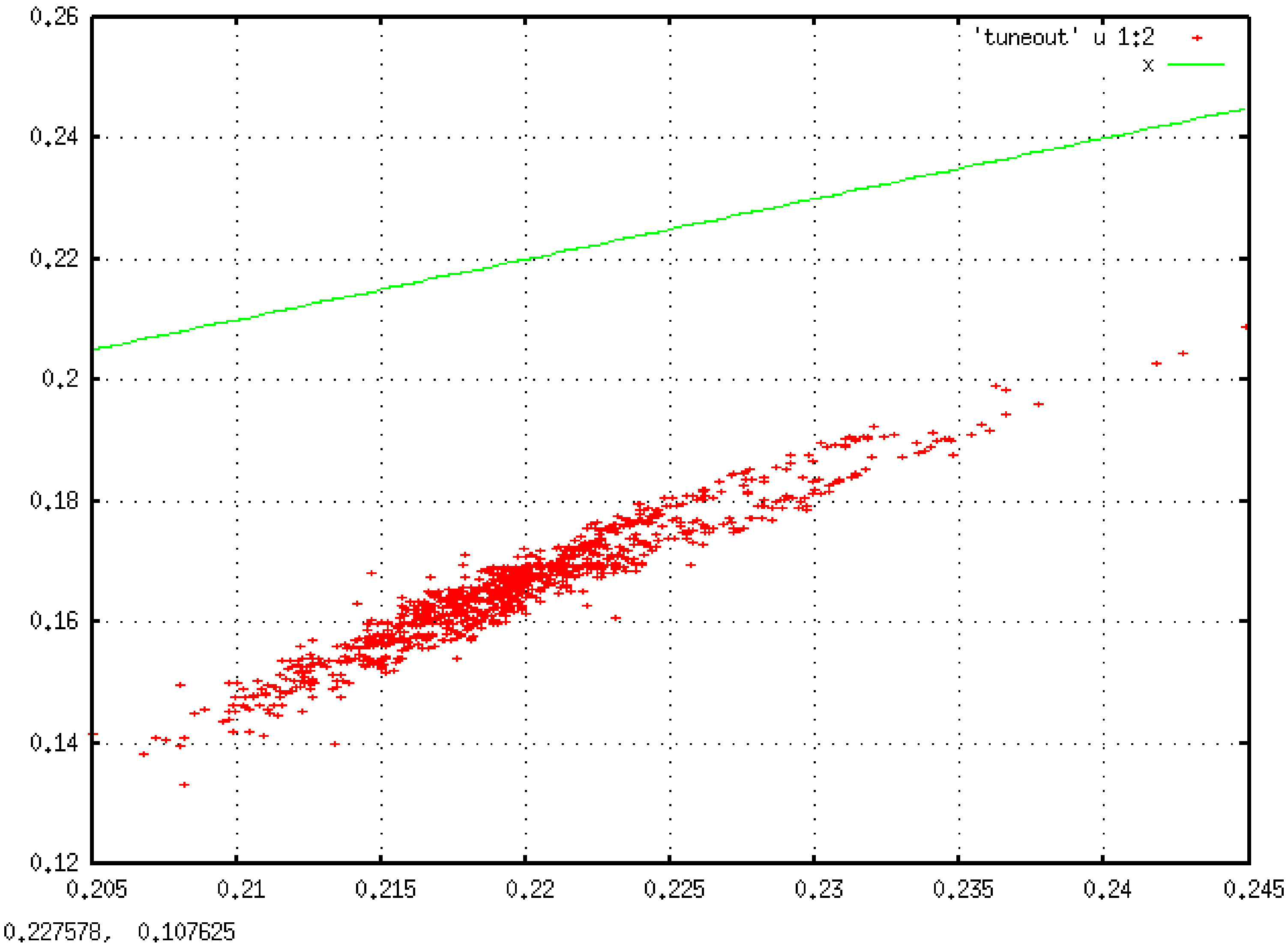
Figure 6: Rms emittances in 3D bunched beam for given tune ramp, but doubled and quadrupled synchrotron frequency.

A Comparison between the IMPACT and ML/I (0 current)

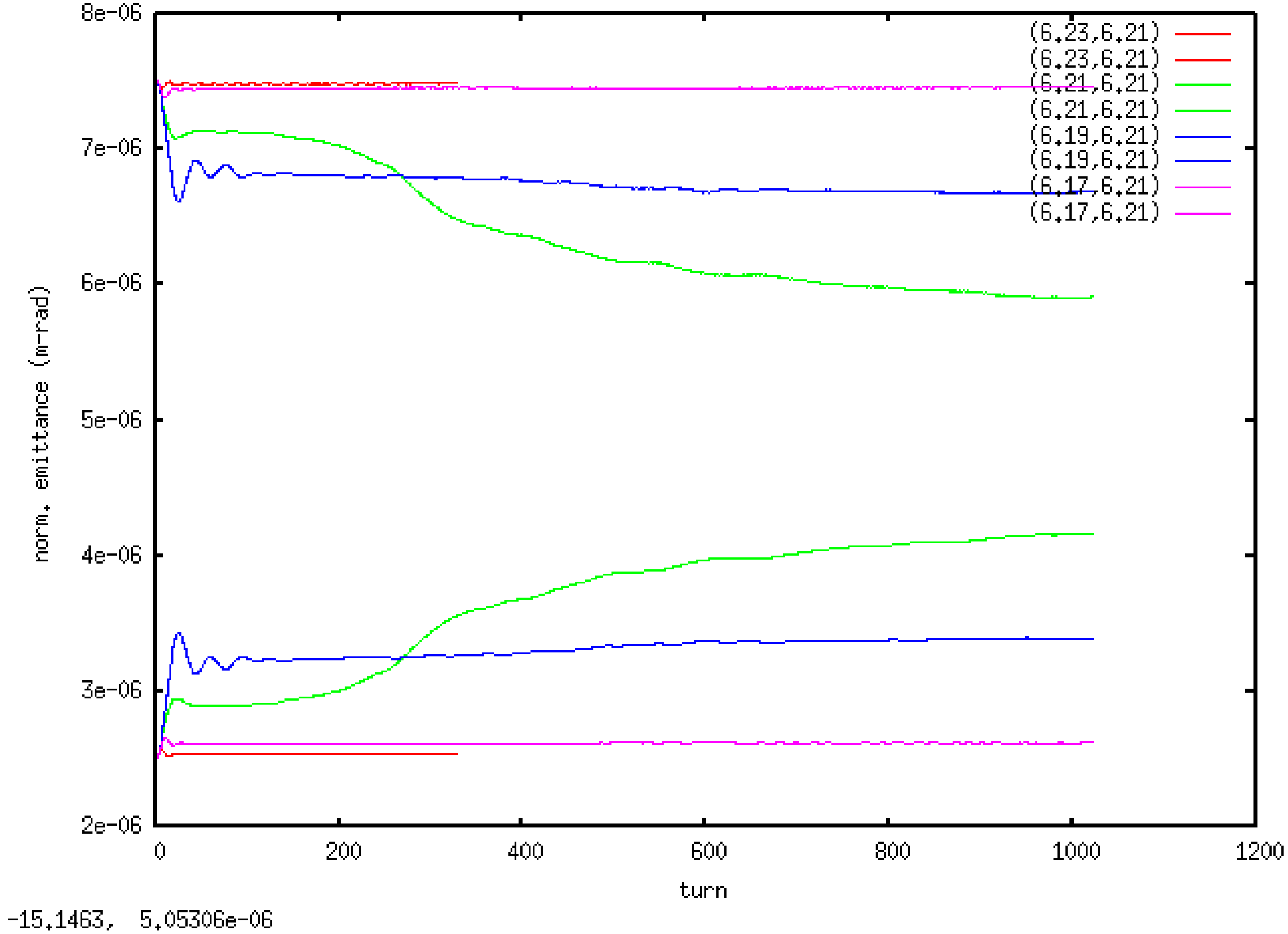




Tune Footprint with Frozen Longitudinal Dynamics



Emittance Exchange with the Longitudinal Frozen Beam



Future Work

- Benchmark static resonance crossing with realistic PS2 lattice and proton beam
- Benchmark dynamics resonance crossing with realistic PS2 lattice and proton beam
- Benchmark space-charge driven resonance at PSB
- Study space-charge effects at PSB, PS and SPS