Space Charge Simulations for LHC Injector Upgrade: Montague Resonance at PS

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In collaboration with

- G. Franchetti, I. Hofmann, GSI
- LHC injector upgrade group (C. Carli, R. Garoby, S. Gilardoni, E. Metral, F. Schmidt, et al.), CERN

Outline

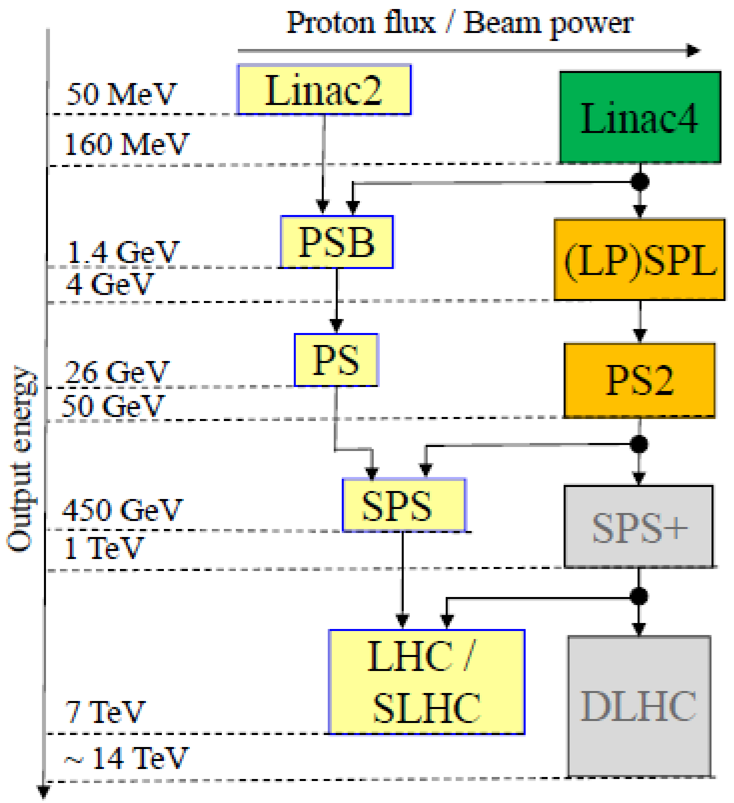
- Introduction
- Computational model
- Simulation of Montague resonance experiment at PS
- Summary and future plan

Introduction

- Proton-Synchrotron (PS) is amongst the LHC injectors the oldest, and will continue to serve the LHC at least for the next 25 years.
- Space-charge effects is a dominant factor limiting the bunch intensity.
- Montague Resonance:

  $$2\,Q_x - 2\,Q_y = 0$$

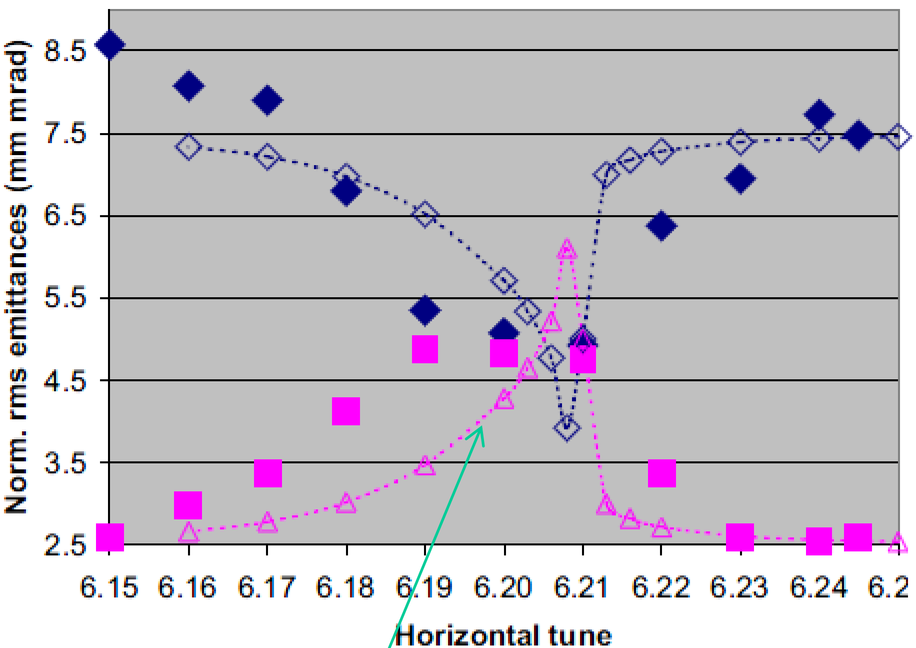
- can cause particle due to unequal aperture size in horizontal and vertical dimensions.
- benchmark space-charge codes



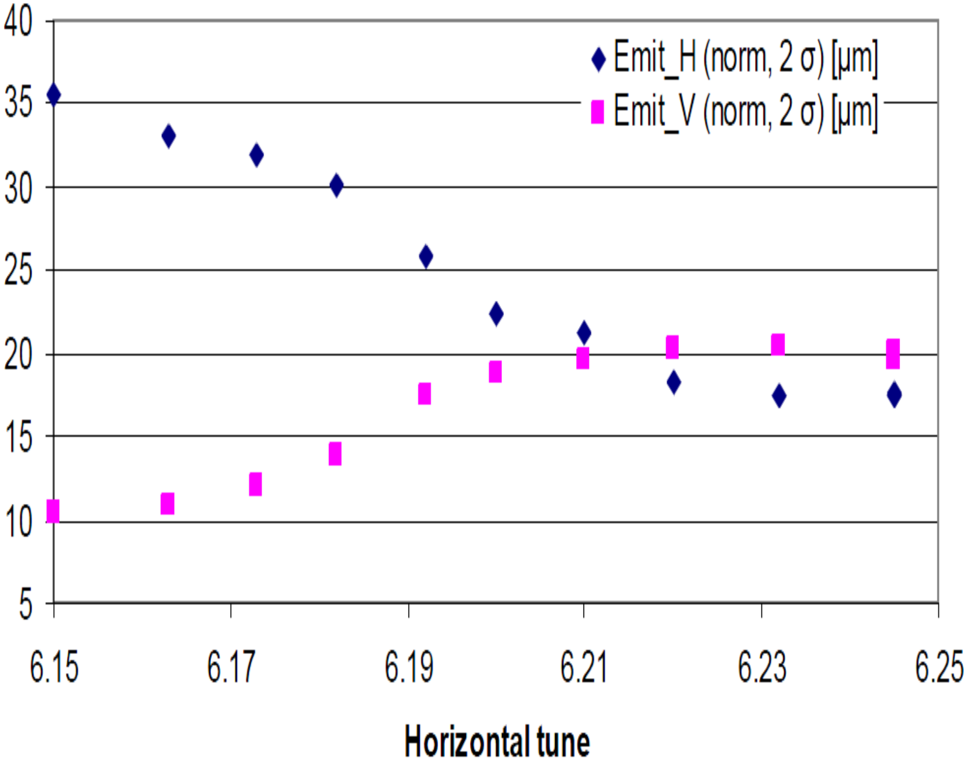
Refs: B. W. Montague, CERN-Report No. 68-38, CERN, 1968.
E. Metral et al., Proc. of EPAC 2004, p. 1894.
I. Hofmann et al., Proc. of EPAC 2004, p. 1960.

Static and Dynamics Montague Resonance Crossing at PS

Static Crossing



100 ms dynamic Crossing

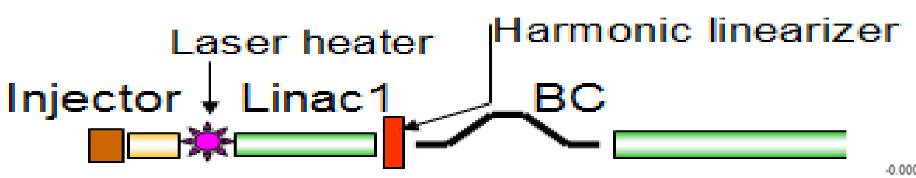


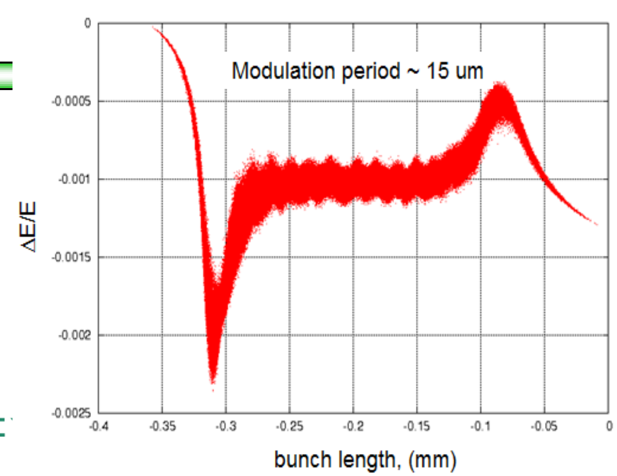
Simulations using constant focusing

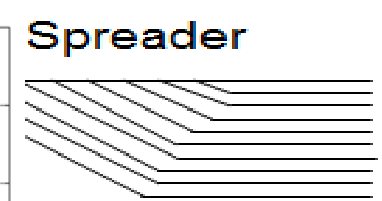
Courtesy of E. Metral et al., Proc. EPAC04

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





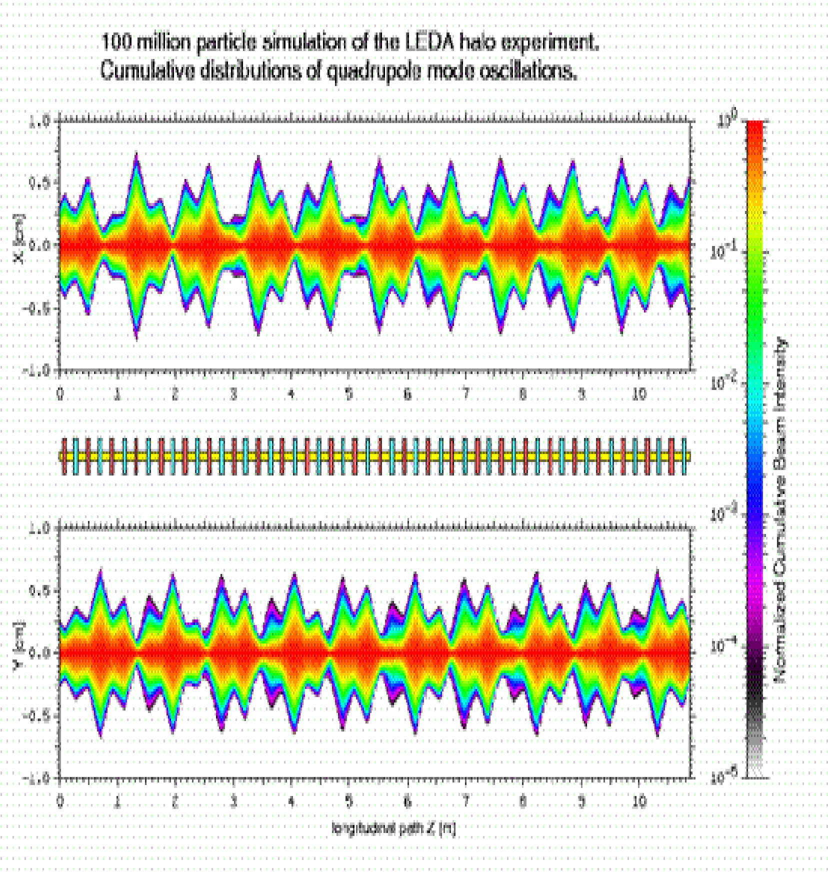


One Billion Macroparticle Simulation of an FEL Linac

(~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

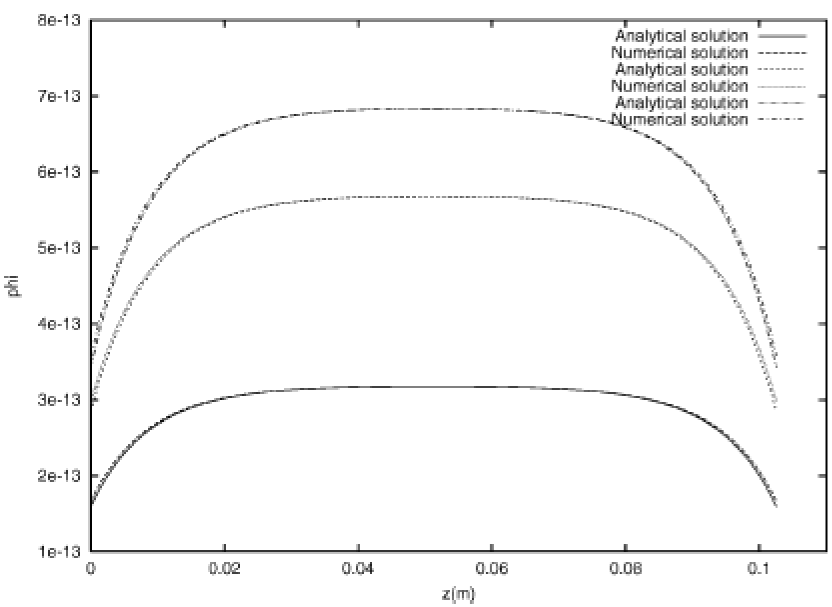
$$\rho^{lm}(z) = \frac{4}{ab}\int_0^a\int_0^b \rho(x,y,z)\sin(\alpha_l x)\sin(\beta_m y),$$

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

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

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

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



Physical Parameters of PS

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}

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Generation of Initial Matched Distribution

- Zero current match found using MaryLie normal form capabilities:
  - Normalize 1-turn map: $M=ANA^{-1}$

    A is the normalizing map

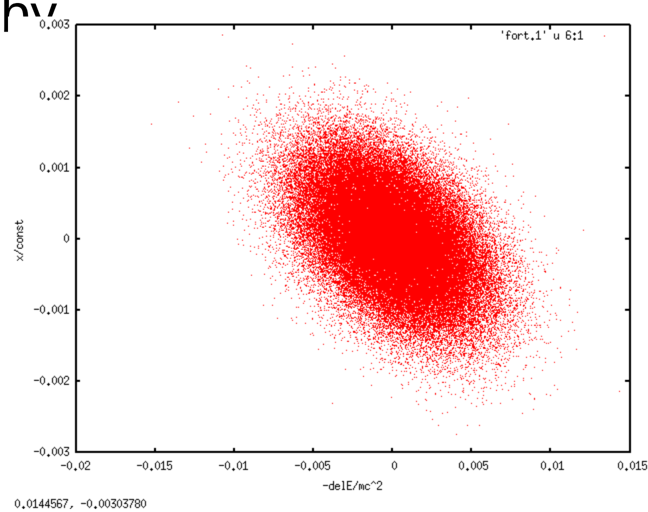
    N is the normal form which causes only rotations in phase space
  - Consider a function $g((x^2+p_x^2),(y^2+p_y^2),(t^2+p_t^2))$
  - Then $f(\zeta)=g(A\,(x^2+p_x^2),(y^2+p_y^2),(t^2+p_t^2))$ is a matched beam.

Proof: The distribution after one turn is given by

$f(M^{-1}\zeta)=g(AN\,A^{-1}A\,(x^2+p_x^2),(y^2+p_y^2),(t^2+p_t^2)) =$

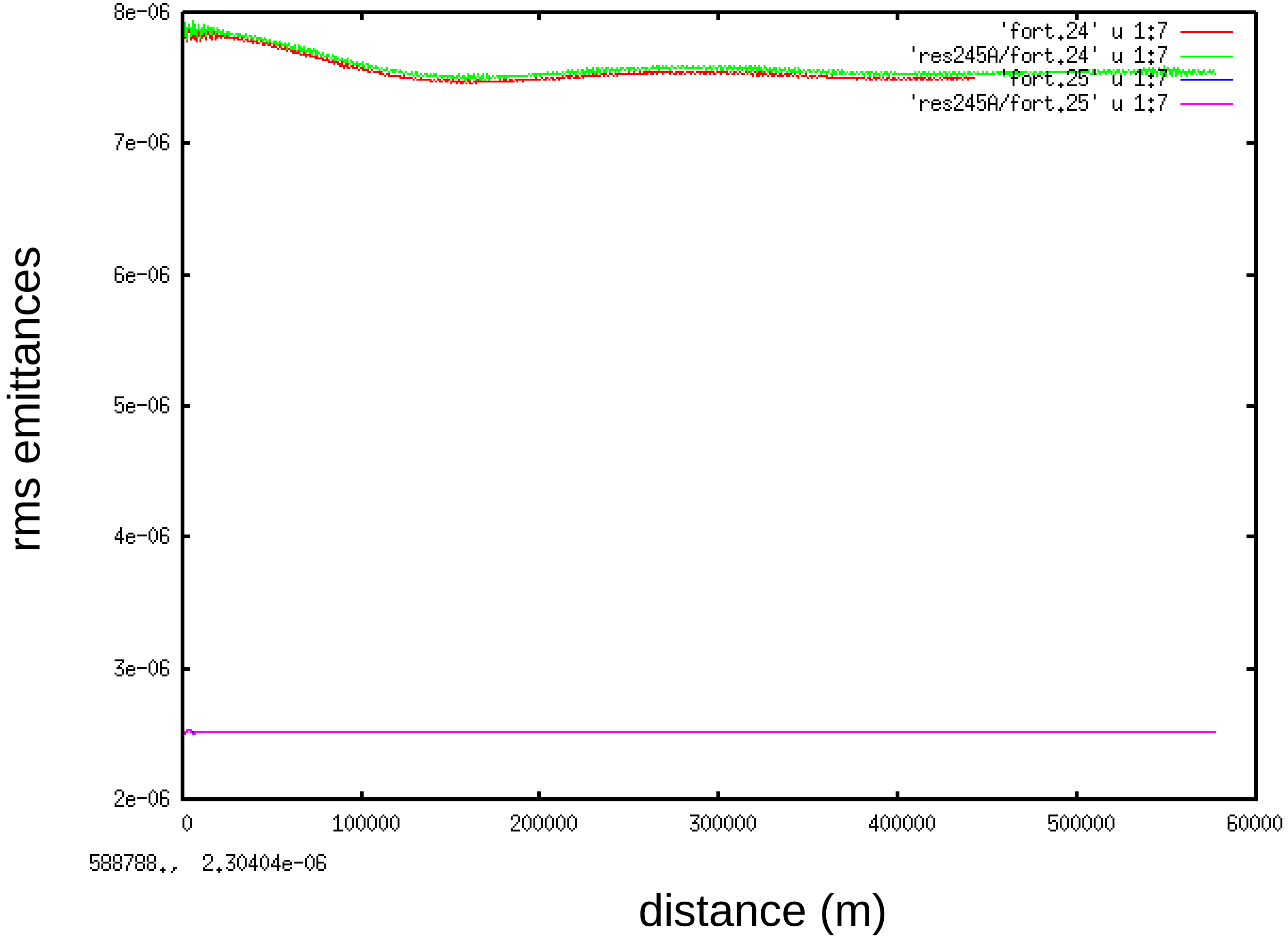
$g(AN\,(x^2+p_x^2),(y^2+p_y^2),(t^2+p_t^2))=$

$g(A\,(x^2+p_x^2),(y^2+p_y^2),(t^2+p_t^2))$



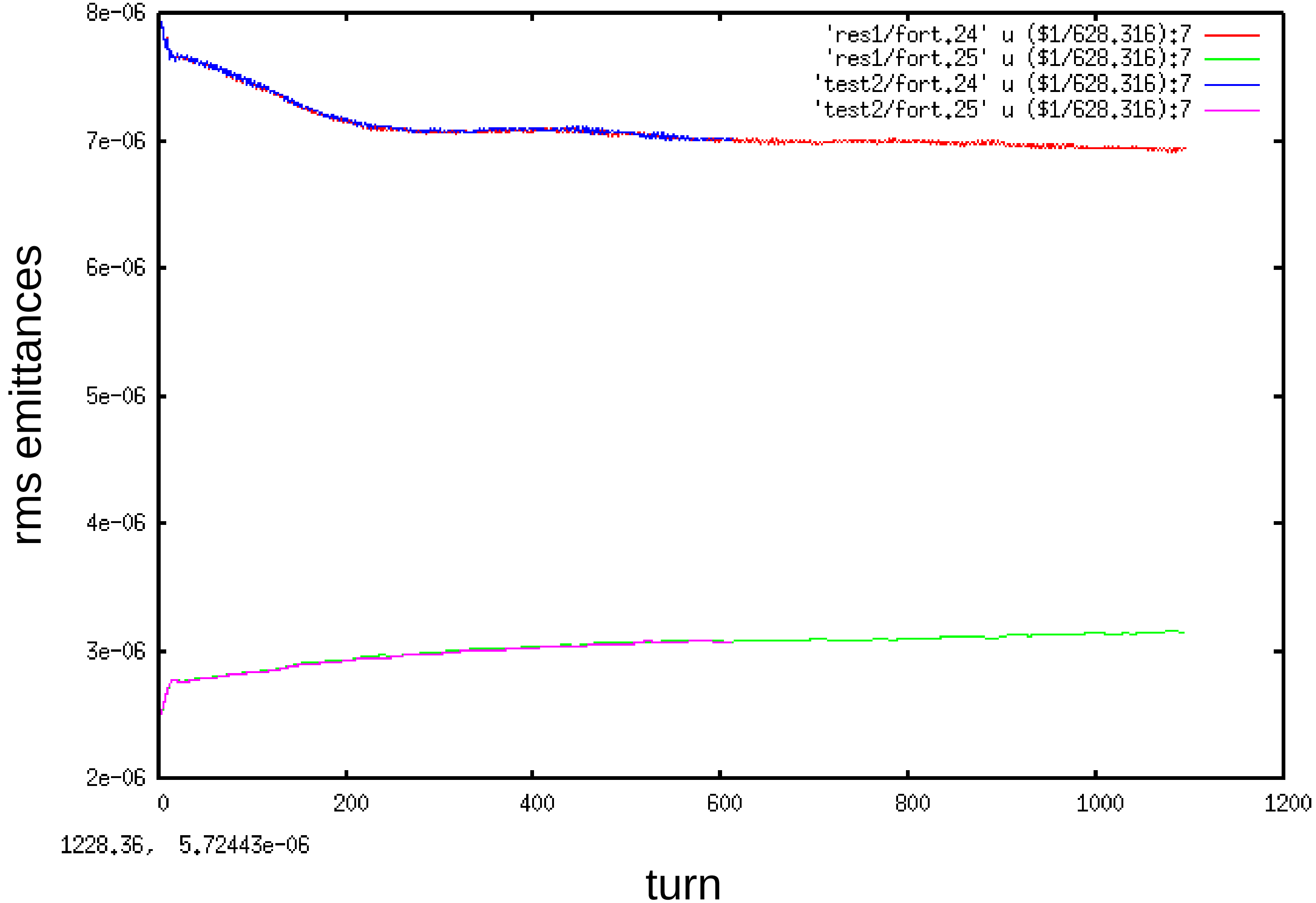
Numerical Parameters: Test of Convergence (1)

100k vs. 200k marco-particles

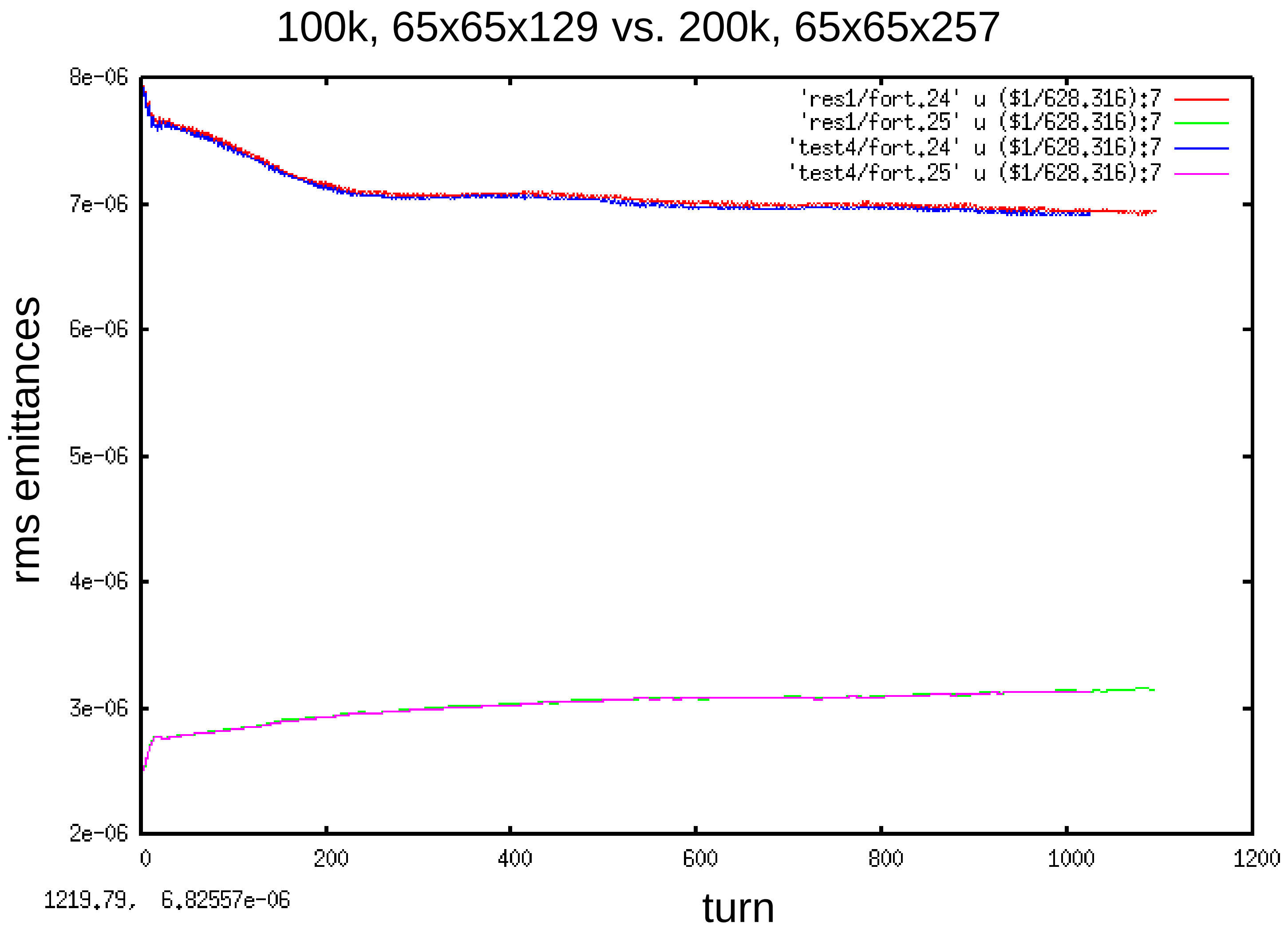


Numerical Parameters: Test of Convergence (2)

60 sc vs. 120 sc

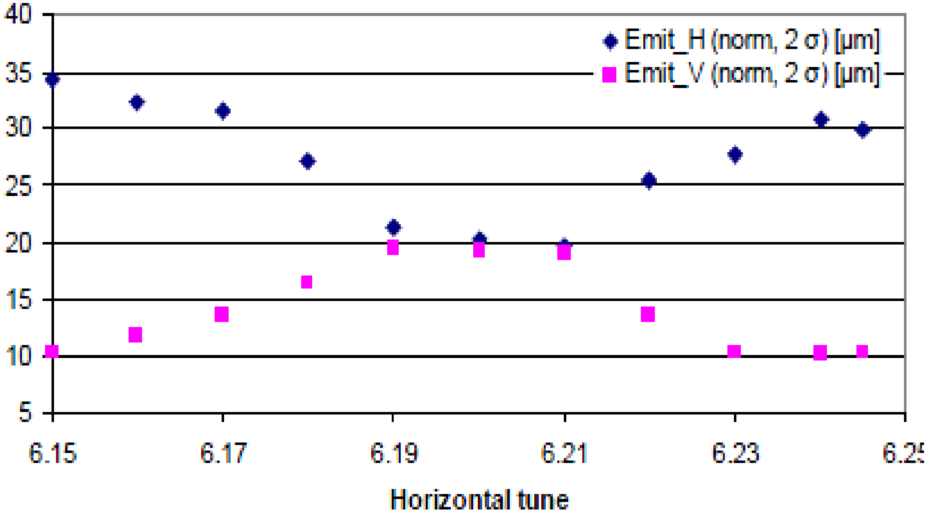


Numerical Parameters: Test of Convergence (3)

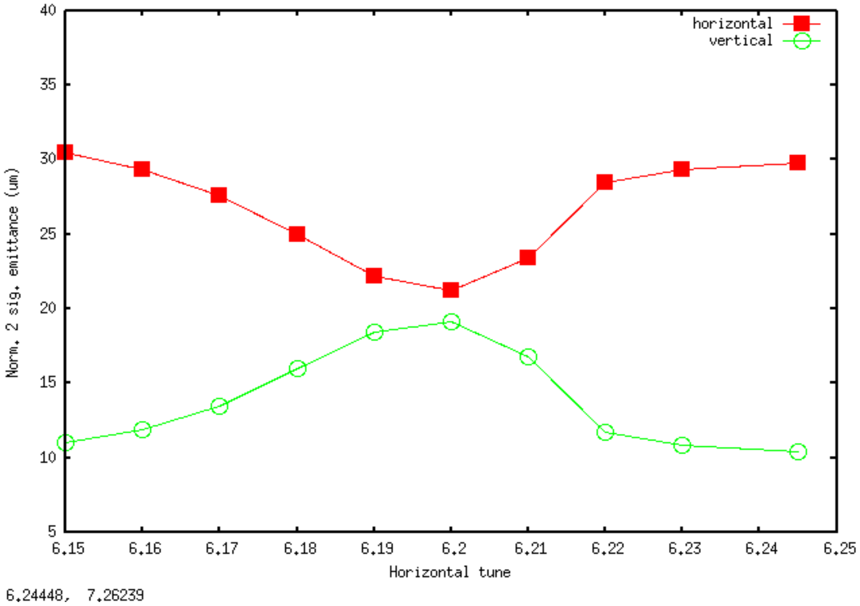


Static Montague Resonance Crossing at PS

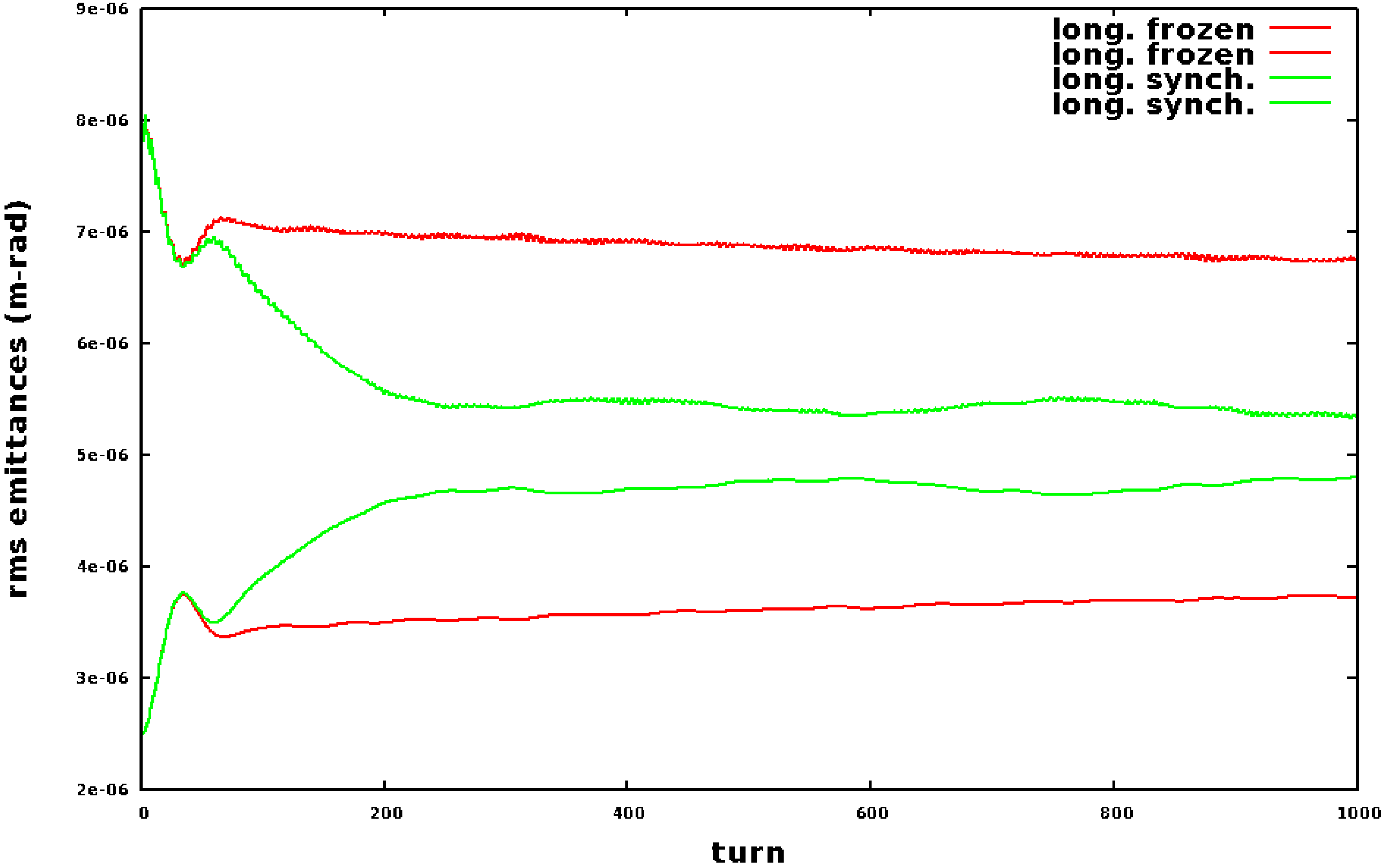
measurements



IMPACT simulation

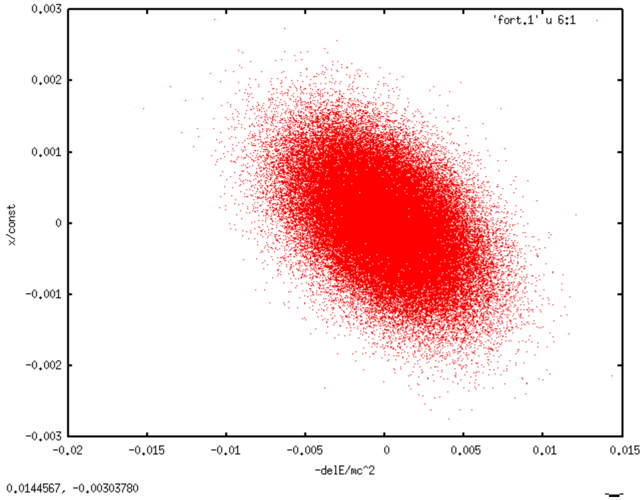


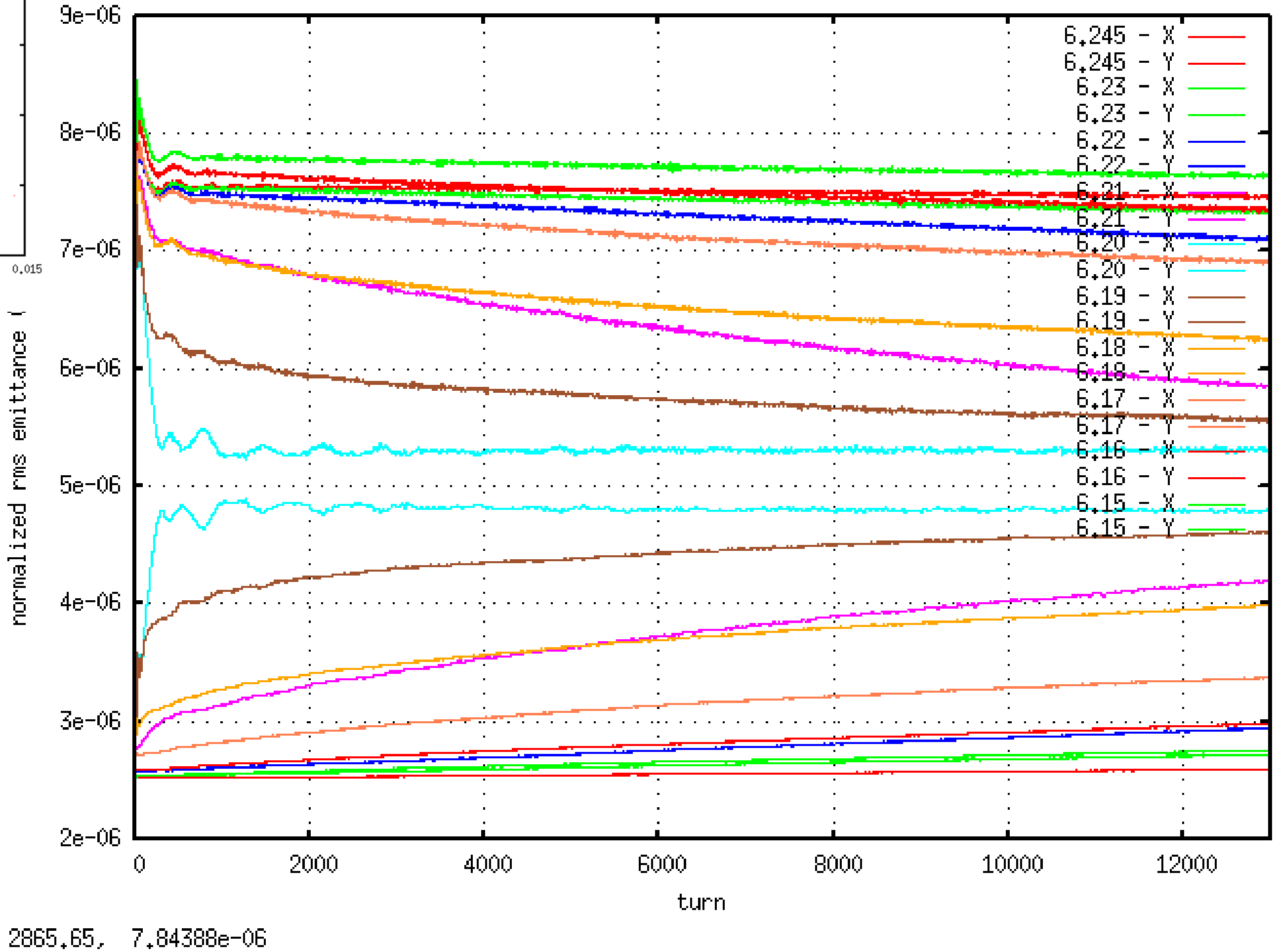
Emittance Evolution w/o Longitudinal Synchrotron Motion (6.197,6.21)



Synchrotron motion enhances the emittance exchange !

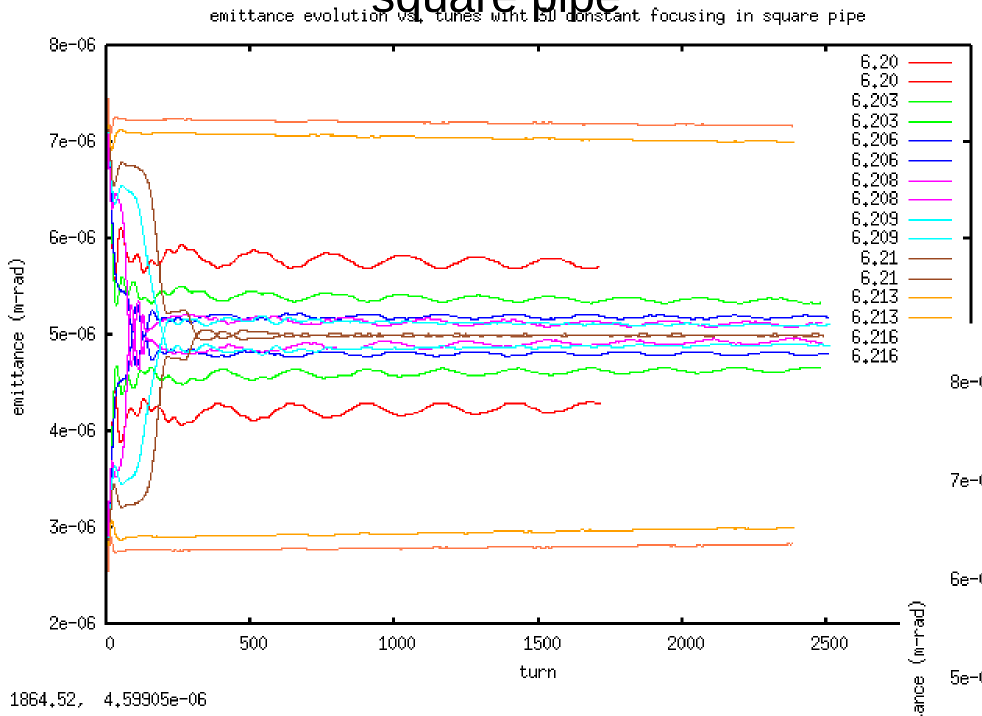
RMS Emittance Evolution with Different Horizontal Tunes



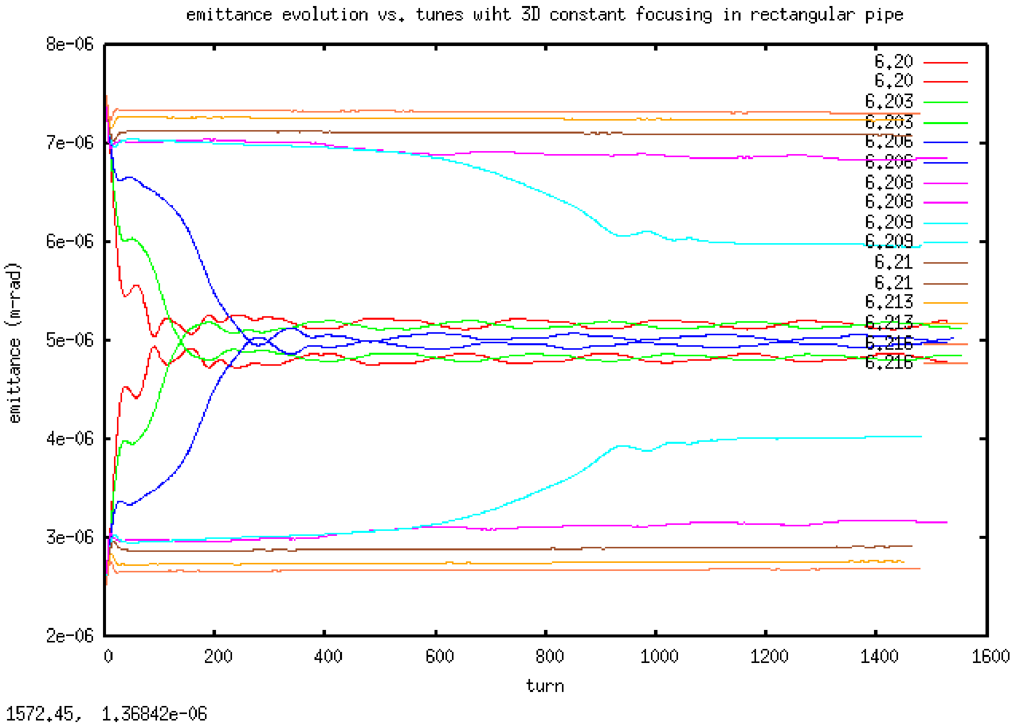


emittance exchange with constant focusing channel: square pipe vs. rectangular pipe

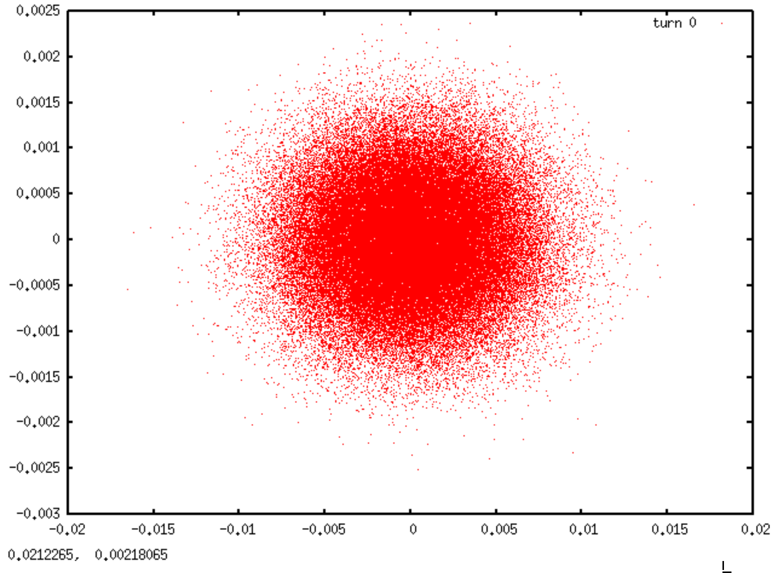
square pipe

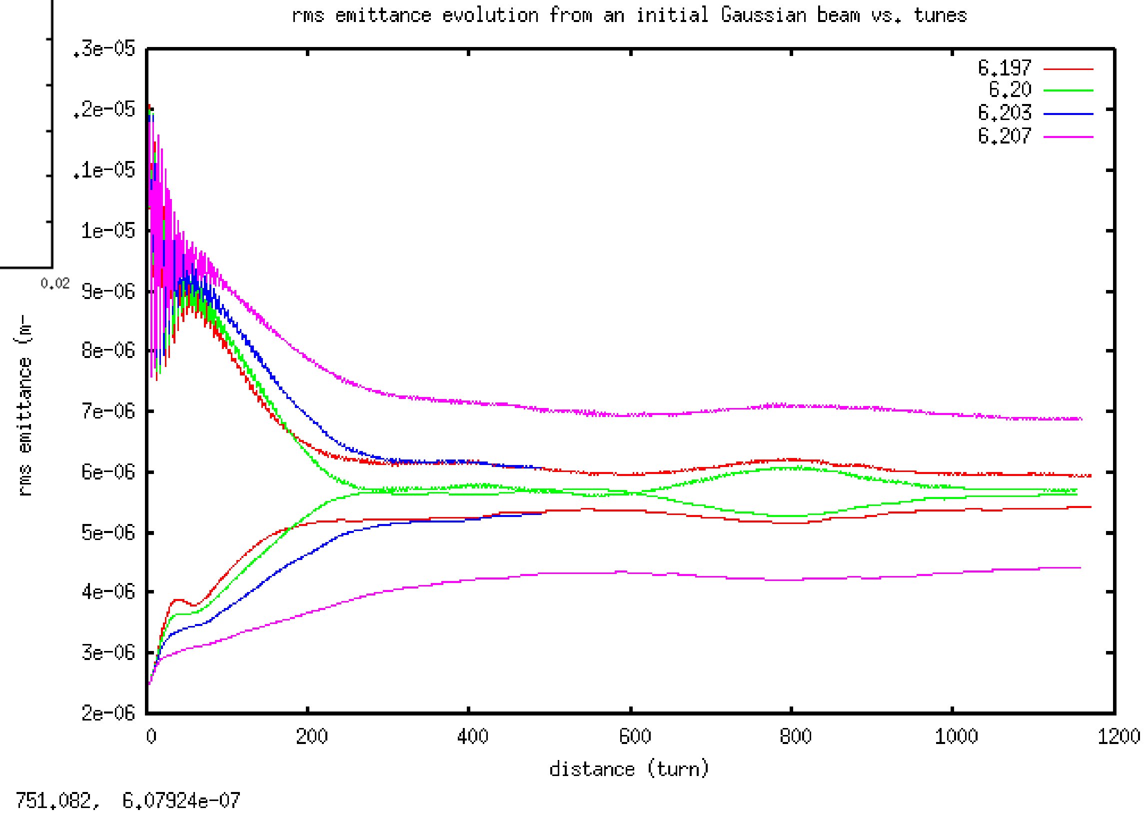


rectangular pipe



RMS emittance evolution of an initial upright Gaussian beam (with different horizontal tunes)

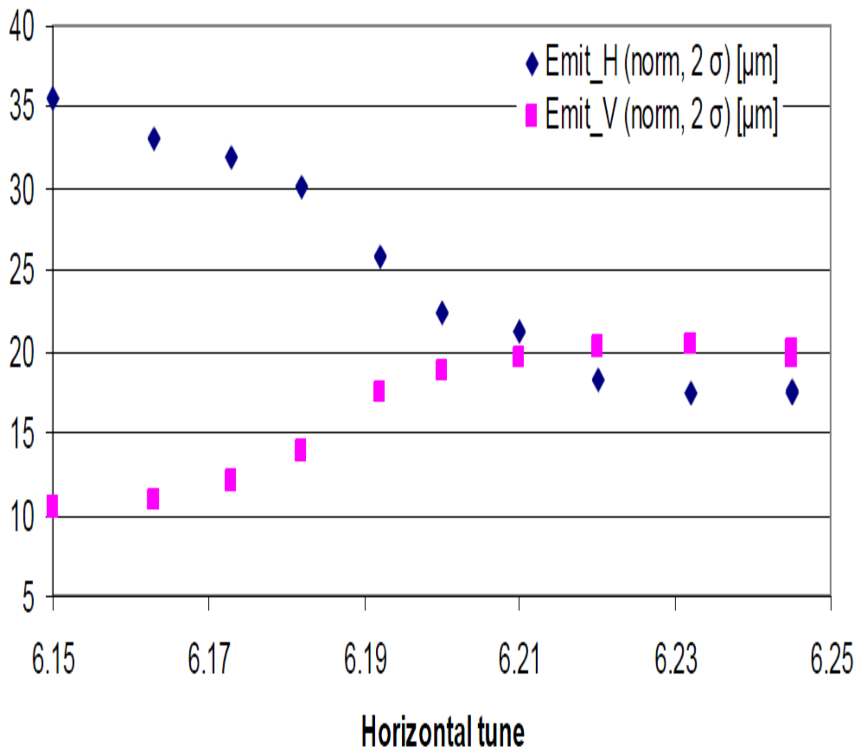




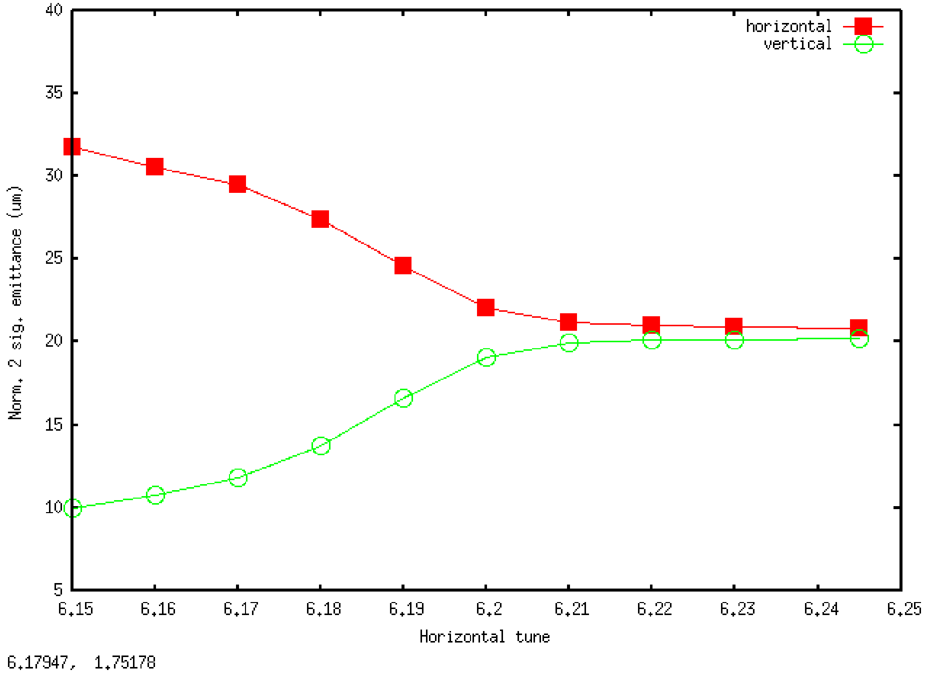
Dynamics Montague Resonance Crossing at PS (1)

100 ms dynamic Crossing

measurements

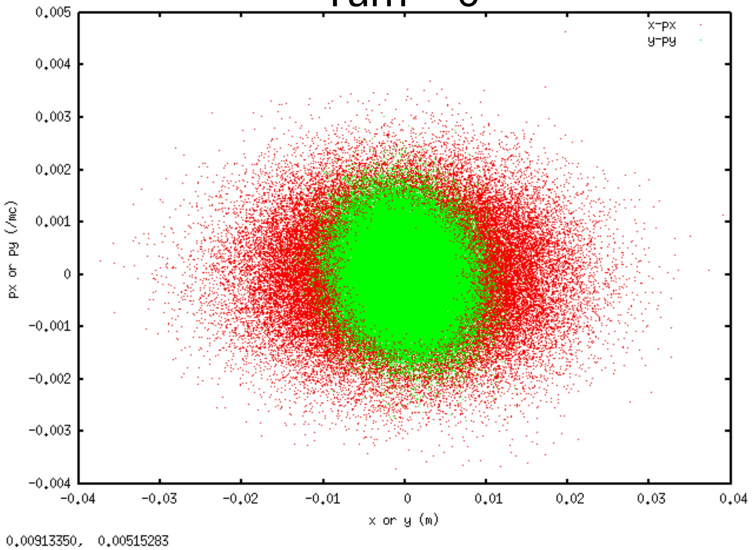


IMPACT simulation: fully 3D+nonlinear lattice

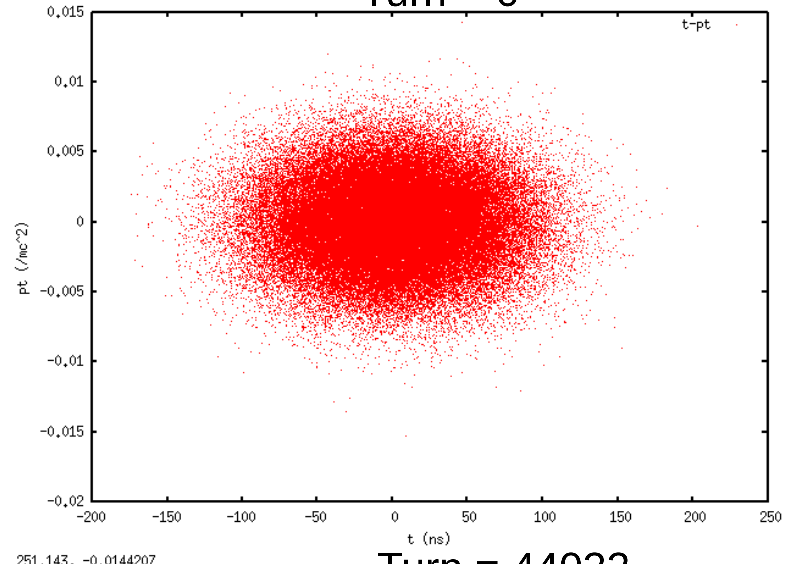


Initial and the Final Phase Space Distribution of the Dynamic Resonance Crossing

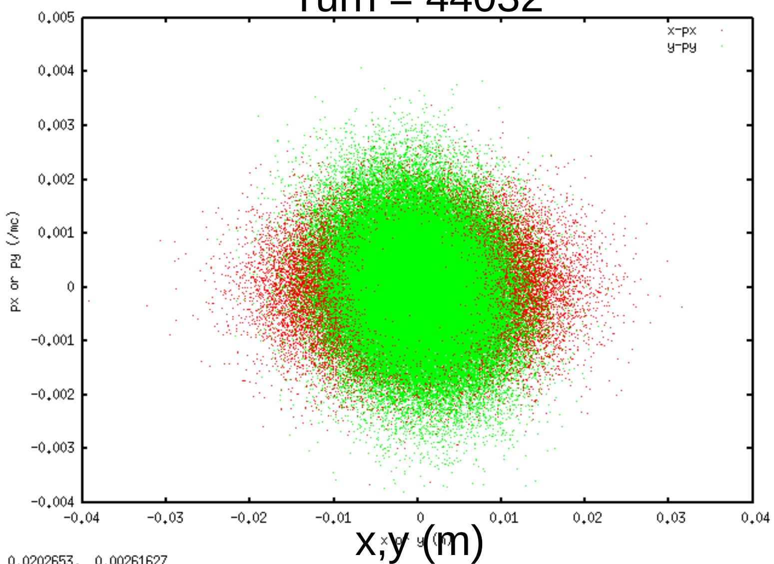
Turn = 0



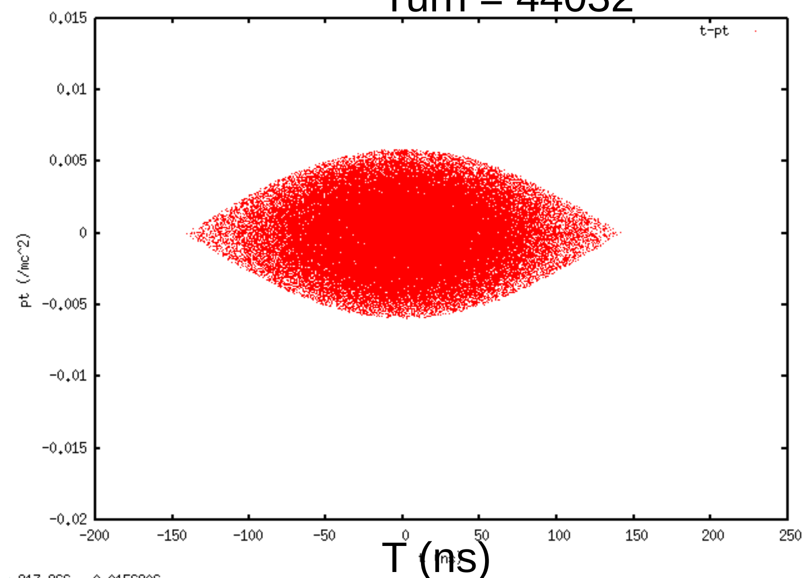
Turn = 0



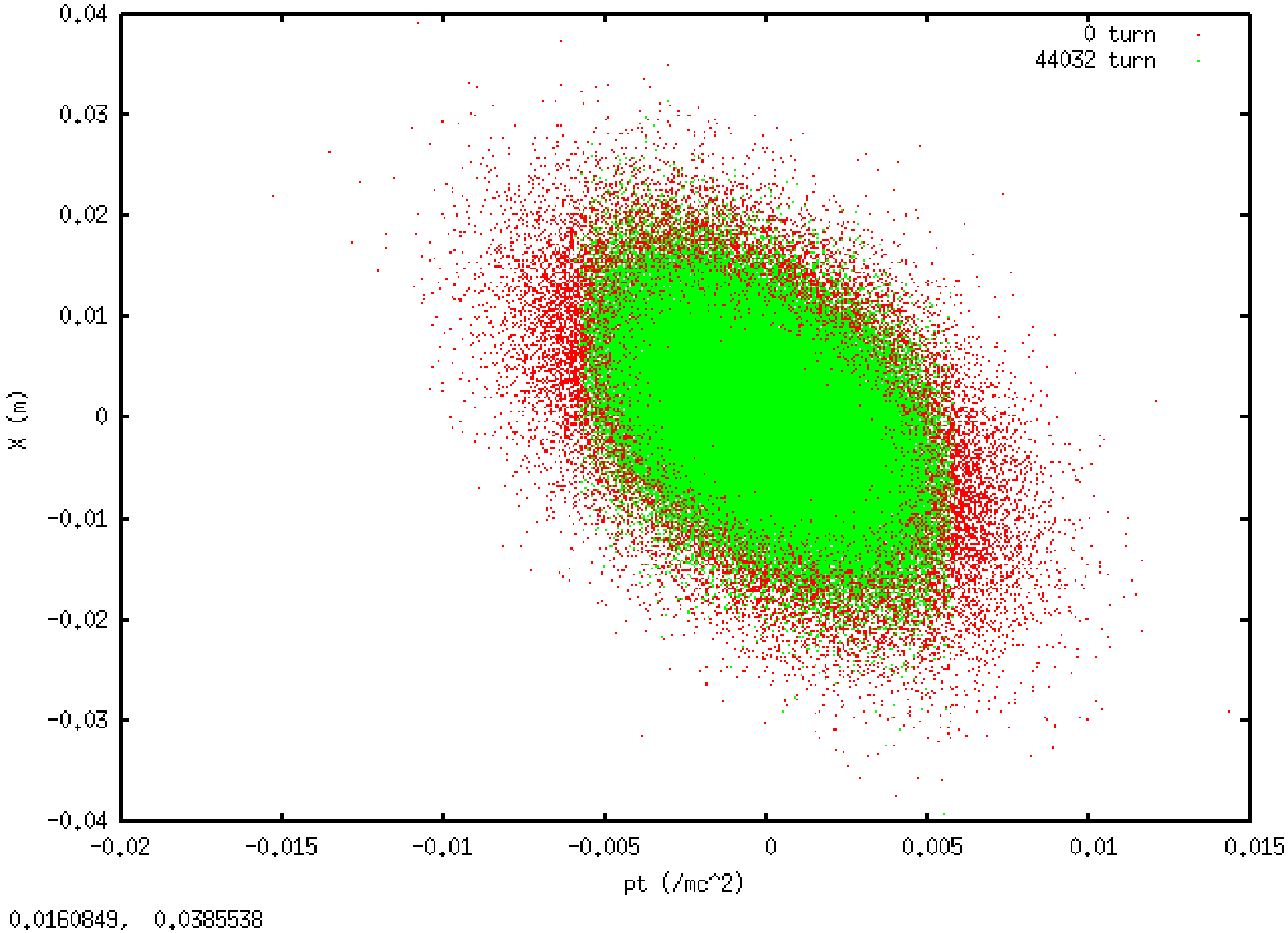
Turn = 44032



Turn = 44032



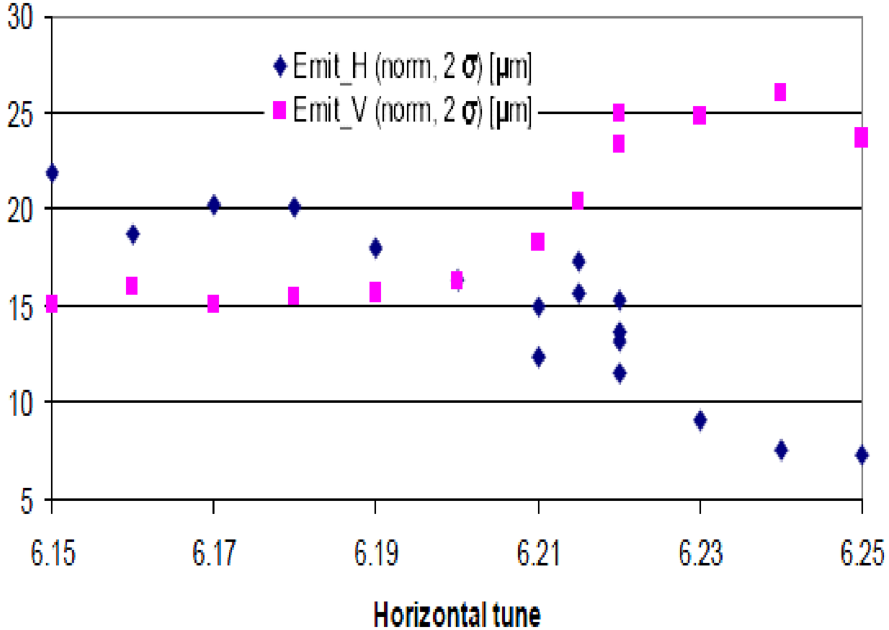
X-delE phase space correlation at the beginning and the end of 44032 turns



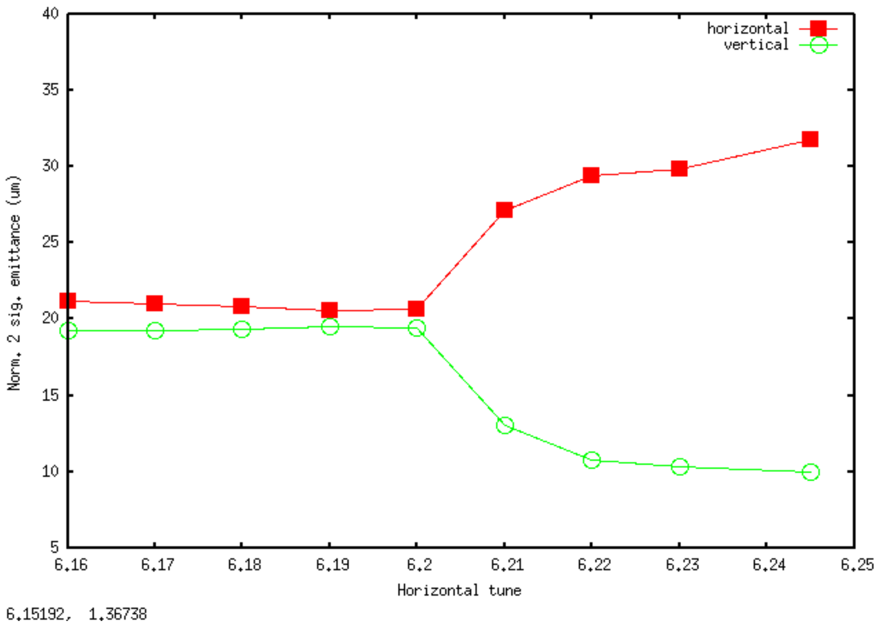
Dynamics Montague Resonance Crossing at PS (2)

100 ms dynamic Crossing

measurements



IMPACT simulation



Summary and Future Plan

- 3D self-consistent space-charge simulation reproduce the experiment data reasonably well
- Dynamic Montague resonance crossing shows no symmetry around the resonance stopband
- Longitudinal synchrotron motion helps the emittance exchange inside the resonance stopband
- Study the space-charge effects at PS with higher injection energy
- Write a paper