Booster simulations with Synergia

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Fermilab

Collaborators:

J. Amundson, E. Stern, P. Spentzouris, V. Lebedev

Outline

- Motivation
- Synergia
- Wake fields in laminated magnets
- Simulation results
    - Coherent tune shift
    - Multi-bunch instability
- Conclusions

Combined functions magnets

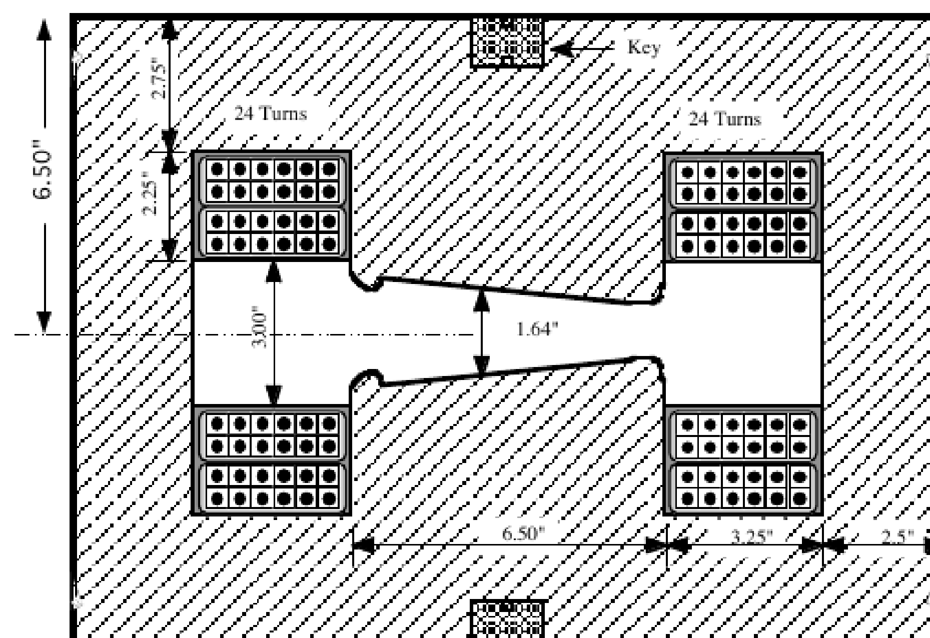
- **60 % of the machine length consists of combined-function (dipole & quadrupole) magnets.**
- **Parallel-plane geometry (or close to it).**
- **Beam exposed to laminations.**

  ➔ **Large wake field**
- **Non-ultrarelativistic effects are important, injection energy 0.4GeV (γ =1.42).**
- **Large space charge effects.**

focusing

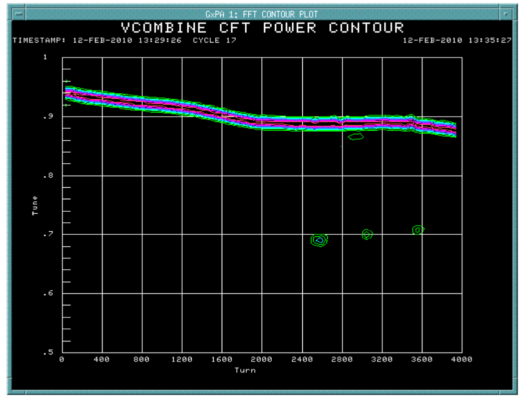
defocusing

Focusing Magnet

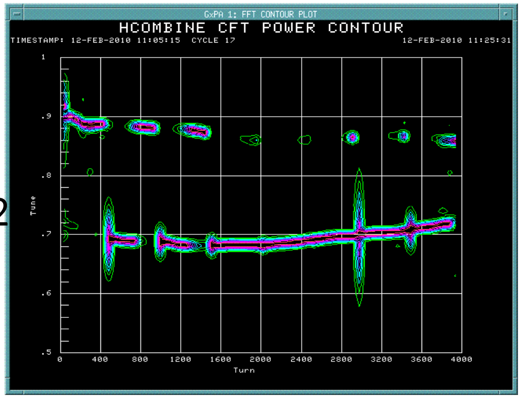


Coherent tune shift measurement

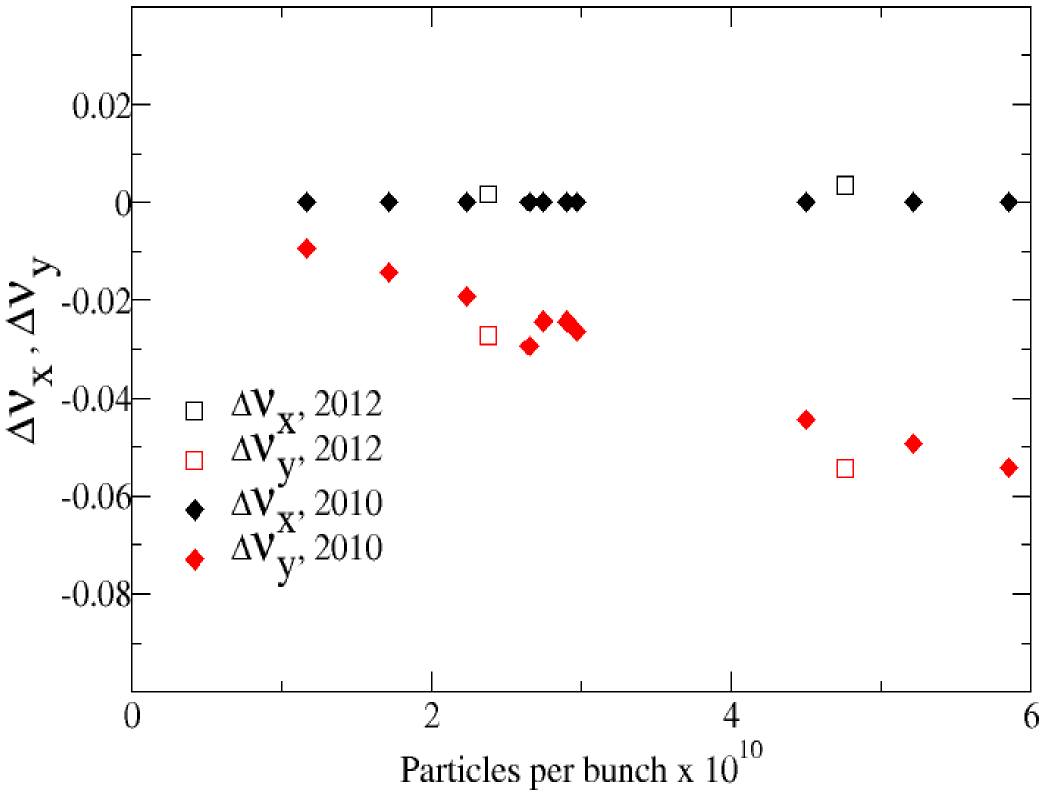
- **Data at injection**
- **Large decrease of the vertical tune**
- **Small increase of the horizontal tune**
- **Large wake field**
- **Chamber geometry is important**



Evolution of V. and H. tune monitored over time for intensities from 2 to 15 injected turns



Daniel McCarron, PhD thesis



Horizontal instability near injection

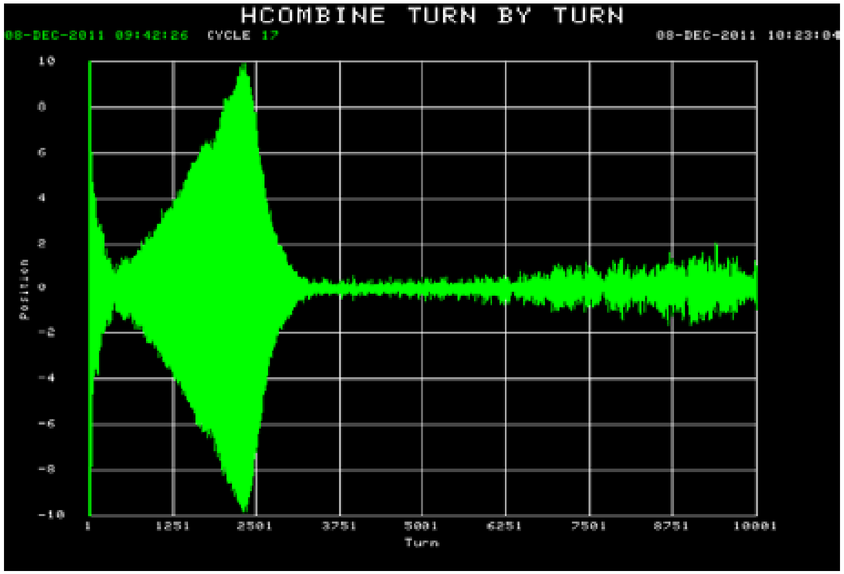


Figure 1: Combined TBT signal from HBPMs (arbitrary units) at $N_p = 4{\cdot}10^{12}$ after coupling correction.

- Horizontal instability at injection for chromaticity $\left(\frac{\omega_{\xi x}}{\beta c}, \frac{\omega_{\xi y}}{\beta c}\right) = 2\pi \times \left(0.06\,m^{-1}, 0.025\,m^{-1}\right)$

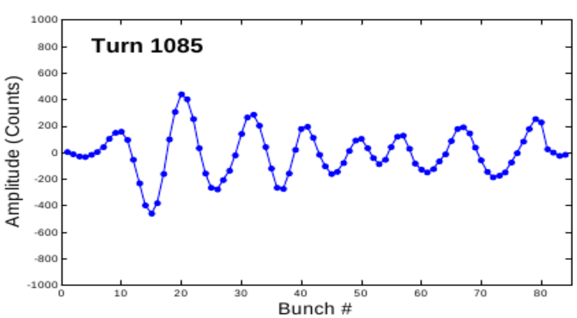
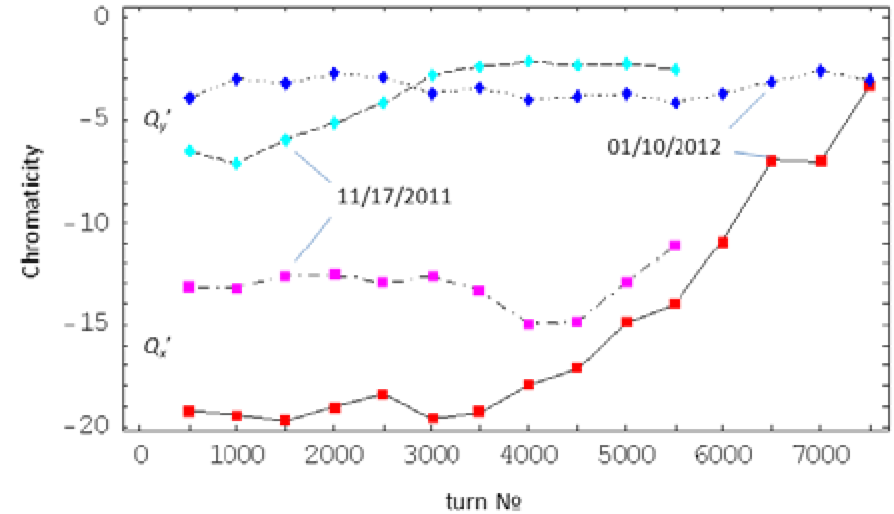


Figure 3: Bunch-by-bunch horizontal positions at the onset of horizontal instability

Y. Alexahin, et al., IPAC-2012



- Stability achieved after the increase of the horizontal chromaticity to

$$\left(\frac{\omega_{\xi x}}{\beta c}, \frac{\omega_{\xi y}}{\beta c}\right) = 2\pi \times \left(0.091\,m^{-1}, 0.023\,m^{-1}\right)$$

Synergia

Accelerator simulation package

- **Single-particle physics (provided by CHEF)**
  - linear or nonlinear
  - direct symplectic tracking (magnets, cavities, drifts, etc.)
  - (and/or) arbitrary-order polynomial maps
  - many advanced analysis features

- **Apertures** (circular, elliptical, polygon, Lamberston, phase space)

- **Collective effects** (single and multiple bunches)
  - space charge (3D, 2.5D, semi-analytic, multiple boundary conditions)
  - wake fields (can accommodate arbitrary wake functions)

URL for download, building instructions and tutorial

https://cdcvs.fnal.gov/redmine/projects/synergia2

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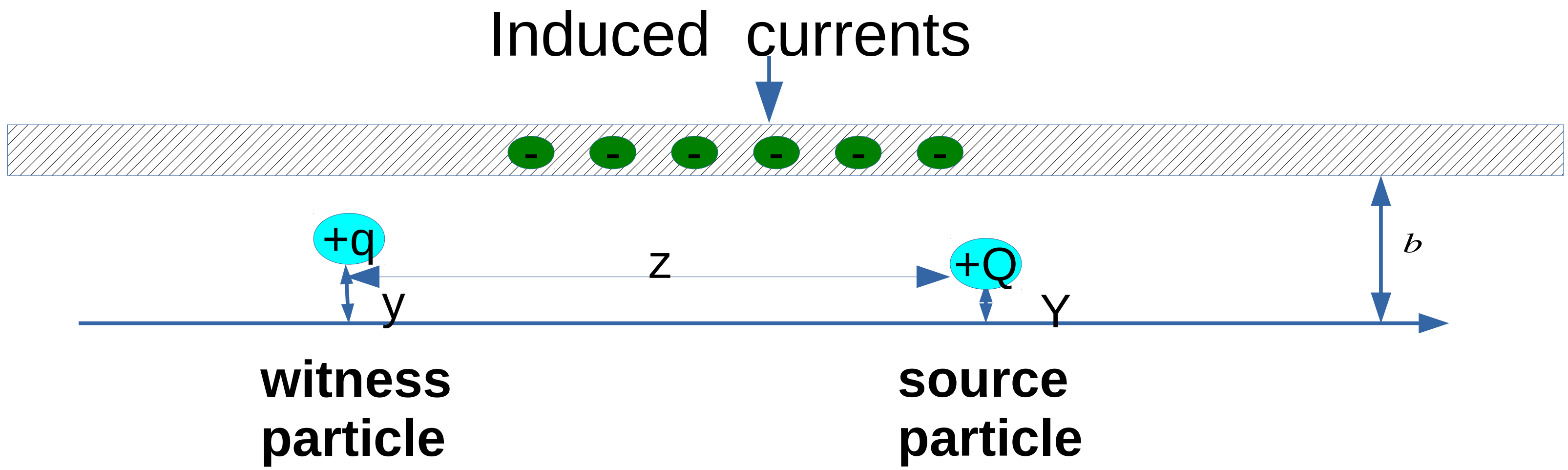
Wake field



$$\beta c \Delta p_z = -qQW^{\parallel}(z)$$

$$\beta c \Delta p_x = -qQ\left(W_X^{\perp}(z) X + W_x^{\perp}(z) x\right)$$

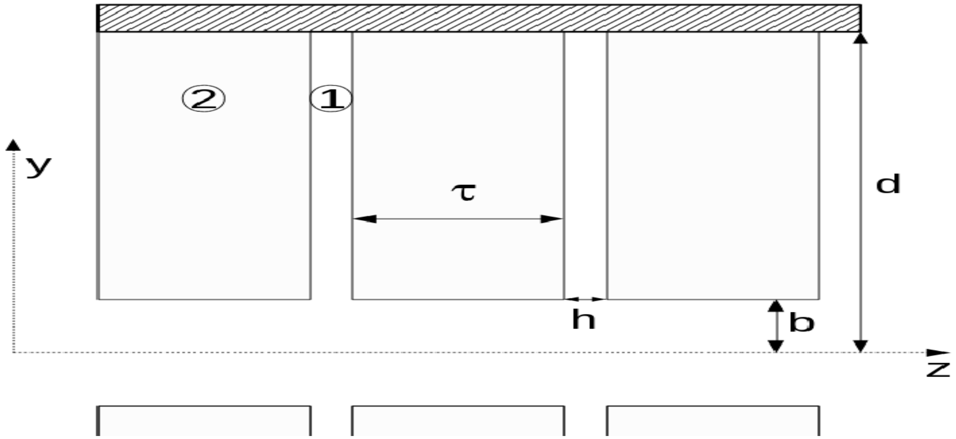
$$\beta c \Delta p_y = -qQ\left(W_Y^{\perp}(z) Y + W_y^{\perp}(z) y\right)$$

- q,Q - **charge of the source and witness particle**
- **X,Y** - **displacements of the source particle**
- ***x,y*** - **displacements of the witness particle**
- ***z*** - **distance between the source and the witness particles**

For simulations we need: $W^{\parallel}(z)$, $W_X^{\perp}(z)$, $W_x^{\perp}(z)$, $W_Y^{\perp}(z)$, $W_y^{\perp}(z)$

Wake and impedance calculation

- **Solve the Maxwell's equations in the frequency domain for a point source moving with speed βc.**
- **The impedance Z(ω) is proportional to the force acting on the witness particle.**
- **The wakes are obtain via Fourier transforms.**

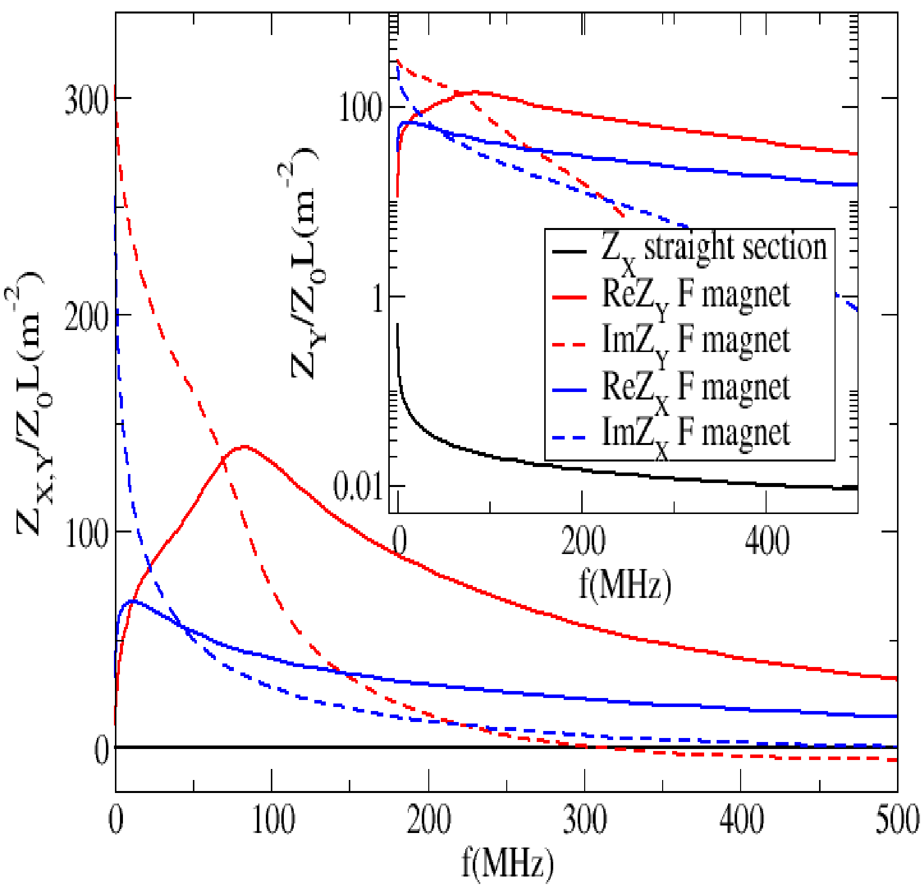


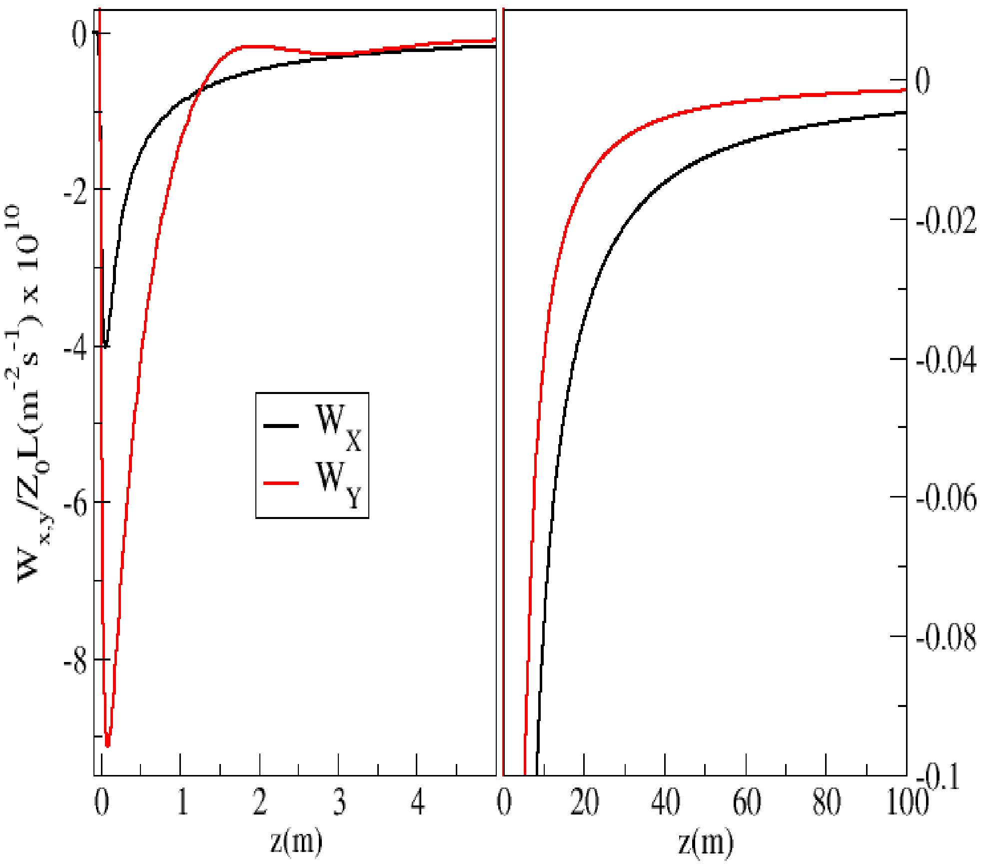
$$W^{\parallel}(z)=\frac{1}{2\pi}\int d\omega Z^{\parallel}(\omega)e^{-i\frac{\omega z}{\beta c}}$$

$$W^{\perp}_{x,y}(z)=\frac{i}{2\pi}\int d\omega Z_{x,y}(\omega)e^{-i\frac{\omega z}{\beta c}}$$

A. Macridin, et al., PRST-AB 14, 061003 (2011)
A. Macridin, et al., PRST-AB 16, 121001 (2013)

Wake and impedance in Fermilab Booster





- The impedance in the laminated magnets is much larger (10^3~10^4 times) than in the straight section.
- The horizontal impedance is larger than the vertical one at low frequency.
- The vertical wake ≈ 2 times larger than the horizontal wake at small distance (<< 1 bucket length).
- At larger distance the horizontal wake is larger (≈ 2.5 times) than the vertical one.

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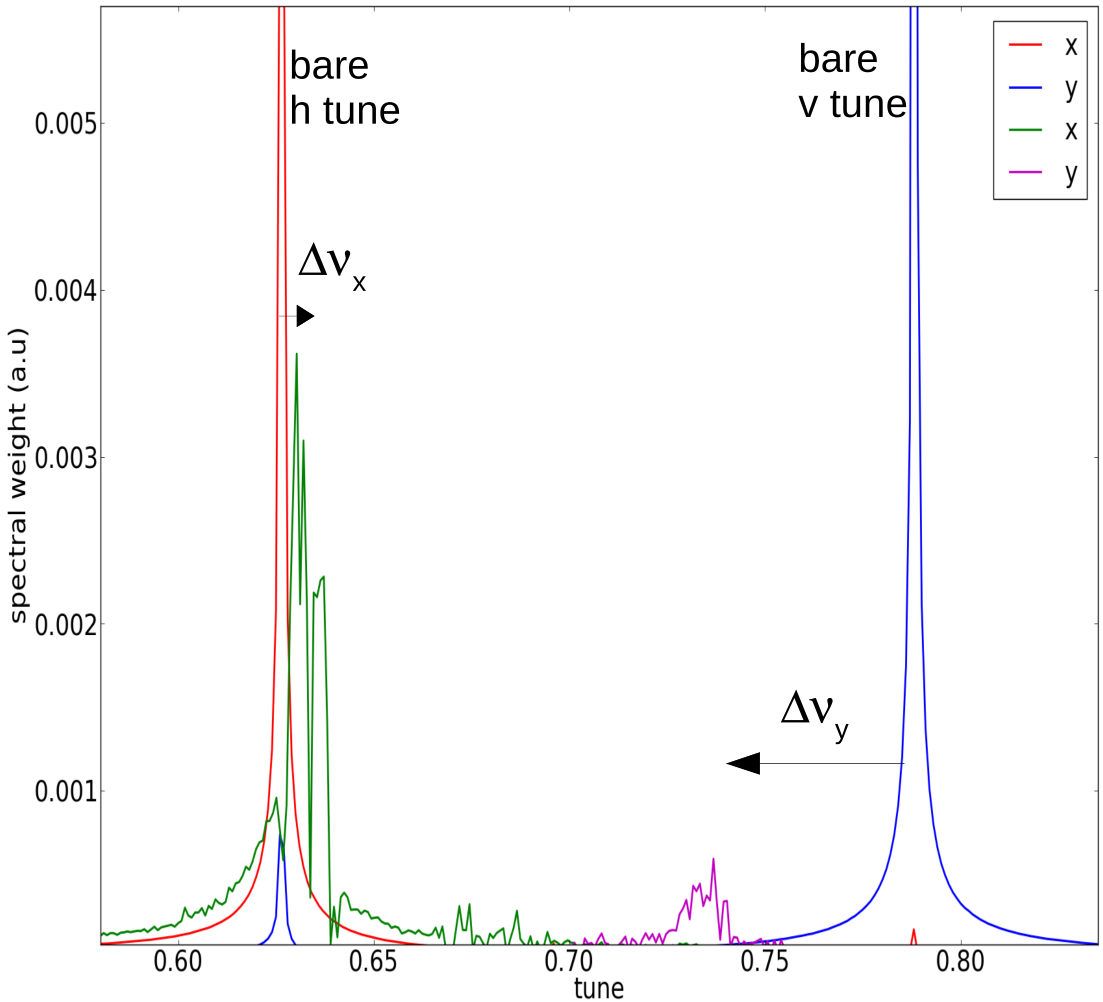
Coherent tune shift

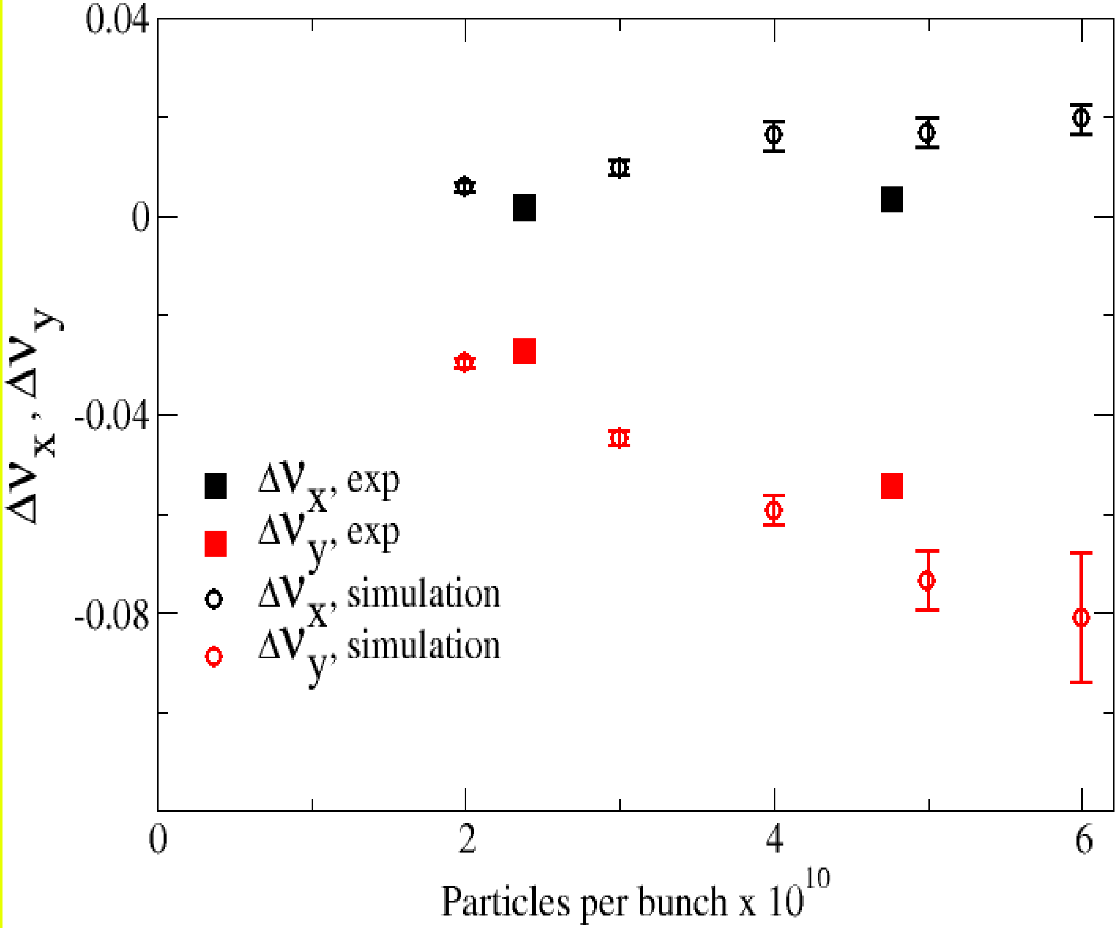
4 x 10[10] p per bunch $\left(\frac{\omega_{\xi x}}{\beta c}, \frac{\omega_{\xi y}}{\beta c}\right) = 2\pi \times \left(0.091\, m^{-1}, 0.023\, m^{-1}\right)$



- **Fourier transform of the centroid displacement**
- **Wide spectral features**
- **Large negative shift of the vertical tune**
- **Small positive shift of the horizontal tune**

Coherent tune shift

$$\left(\frac{\omega_{\xi x}}{\beta c}, \frac{\omega_{\xi y}}{\beta c}\right) = 2\pi \times \left(0.091\, m^{-1}, 0.023\, m^{-1}\right)$$



- **The simulation shows slightly larger tune shift than the measurement**

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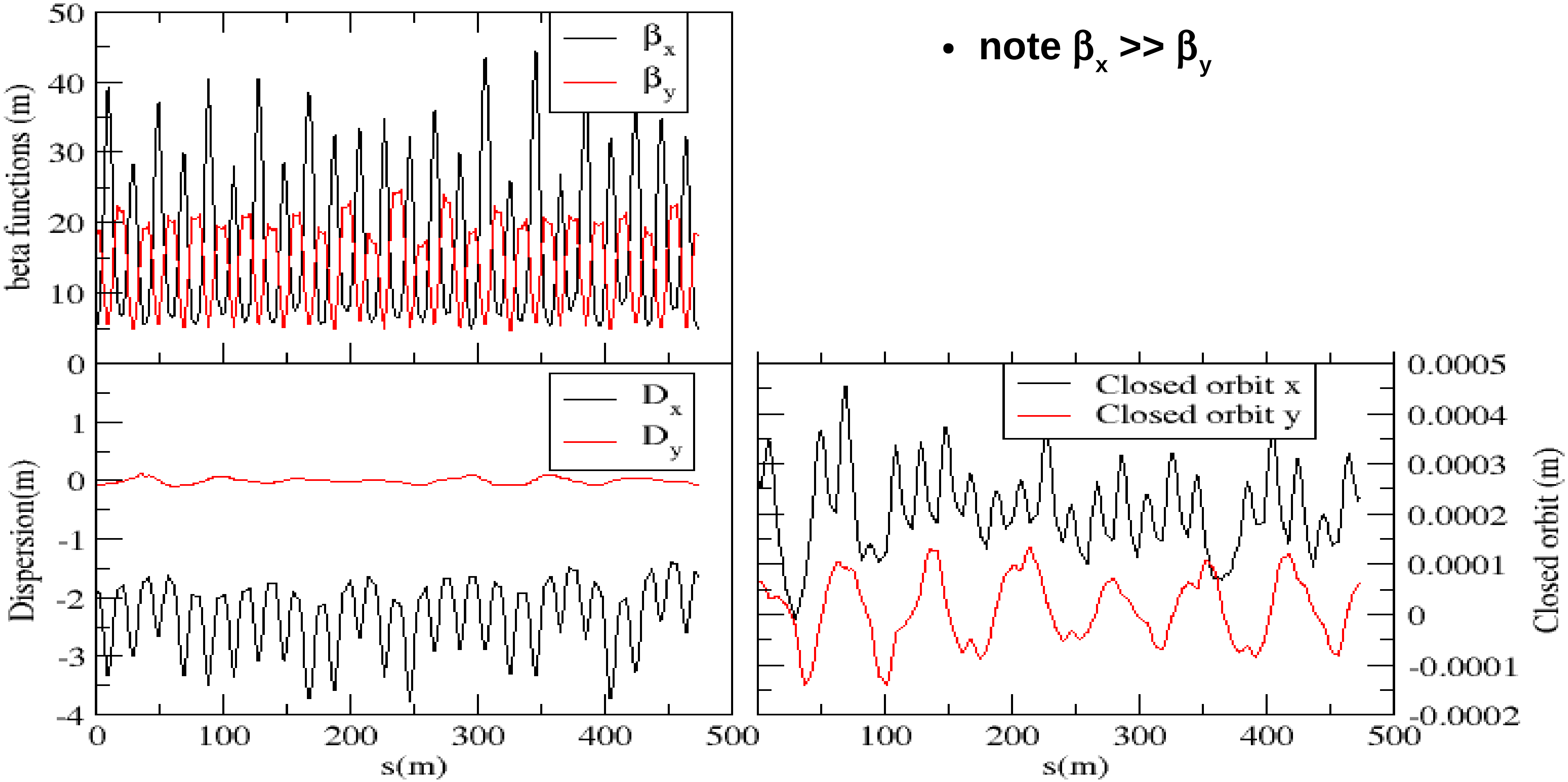
Lattice model

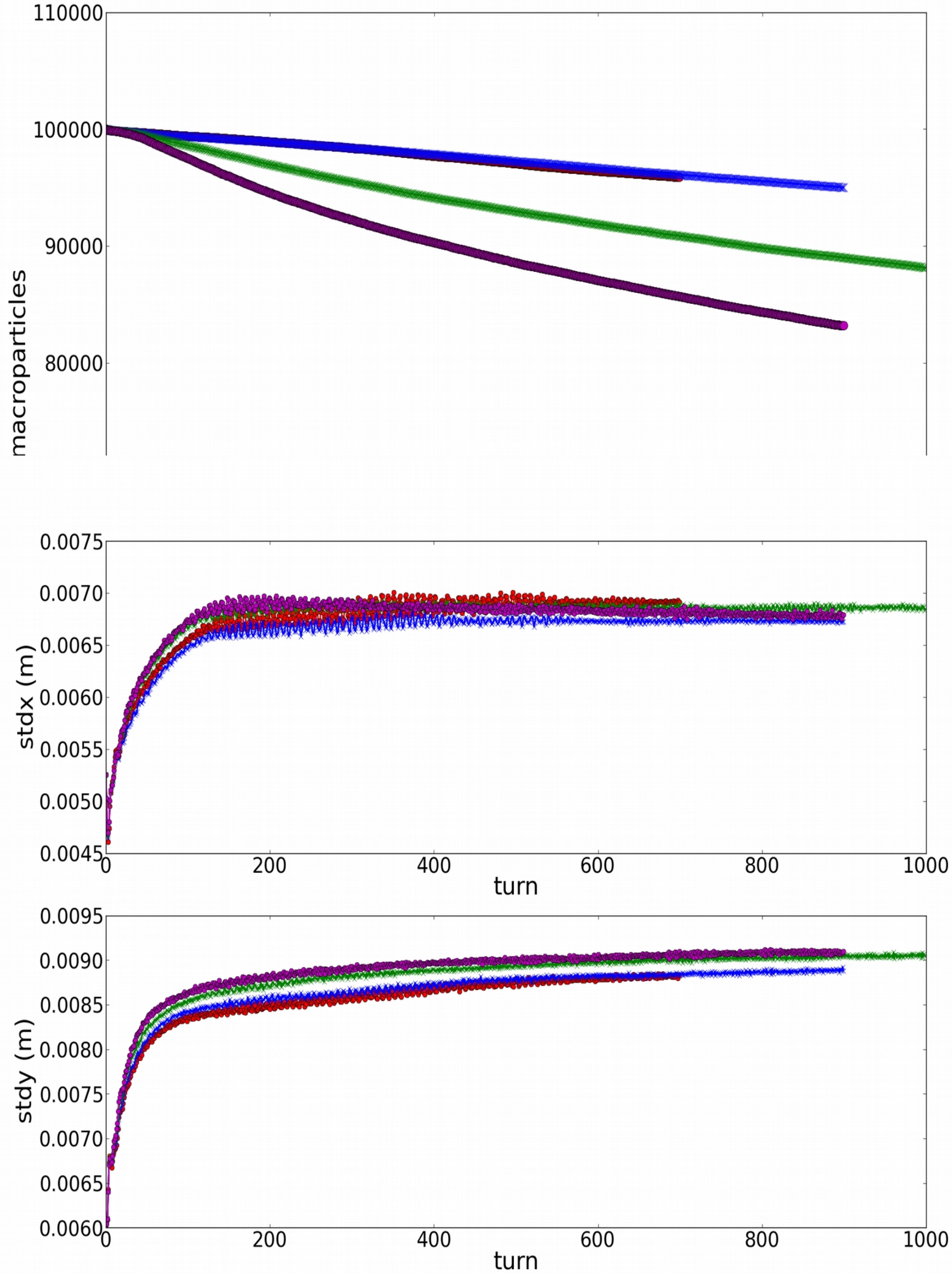
Orbit Response Measurement fitting (M. McAteer, A. Petrenko)

- **dipole and quadrupole correctors to ensure agreement with the measured lattice functions**



- **note $\beta_x >> \beta_y$**

Single bunch simulation



$$\frac{\omega_{\xi x}}{\beta c} = 2\pi \times 0.009\, m^{-1}$$ *red*

$$\frac{\omega_{\xi x}}{\beta c} = 2\pi \times 0.023\, m^{-1}$$ *blue*

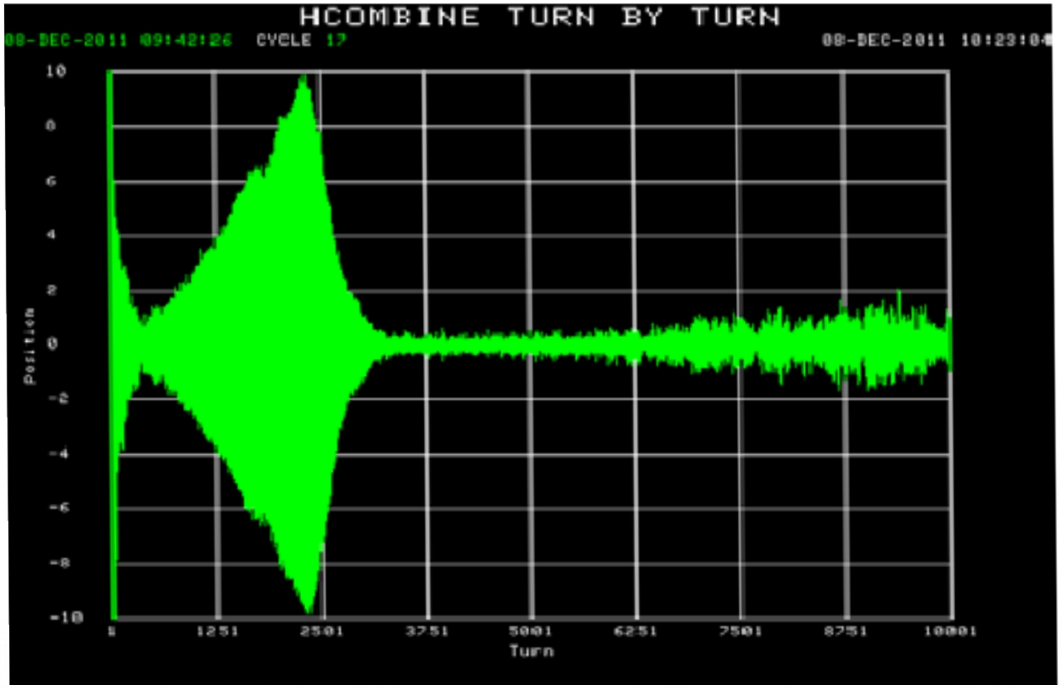
$$\frac{\omega_{\xi x}}{\beta c} = 2\pi \times 0.091\, m^{-1}$$ *green*

$$\frac{\omega_{\xi x}}{\beta c} = 2\pi \times 0.12\, m^{-1}$$ *magenta*

5 x 10^{10} p per bunch

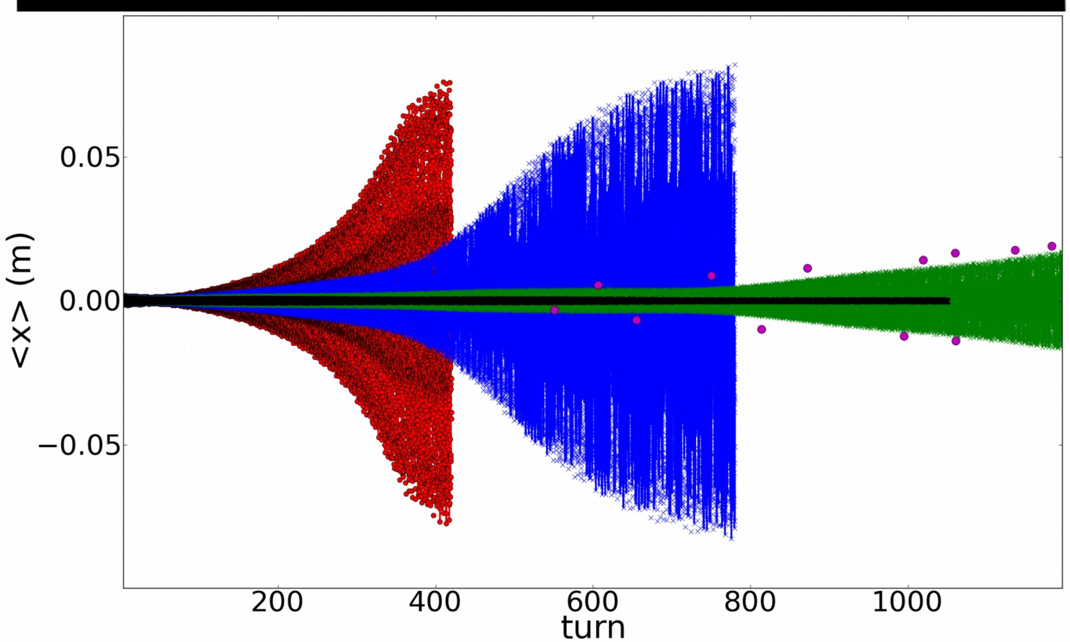
- **Beam loss increases with increasing chromaticity due to the increase in the transverse size**
- **Small chromaticities,** $\frac{\omega_{\xi x}}{\beta c} \leq \approx 2\pi \times 0.023\, m^{-1}$ **are favorable when the bunches do not interact**

84 bunch simulation, horizontal instability



experiment, Y. Alexahin, *et al. IPAC 2012*

$$\left(\frac{\omega_{\xi x}}{\beta c}, \frac{\omega_{\xi y}}{\beta c}\right) = 2\pi \times \left(0.06\,m^{-1}, 0.025\,m^{-1}\right)$$



$\frac{\omega_{\xi x}}{\beta c} = 2\pi \times 0.023\,m^{-1}$ *red*

$\frac{\omega_{\xi x}}{\beta c} = 2\pi \times 0.046\,m^{-1}$ *blue*

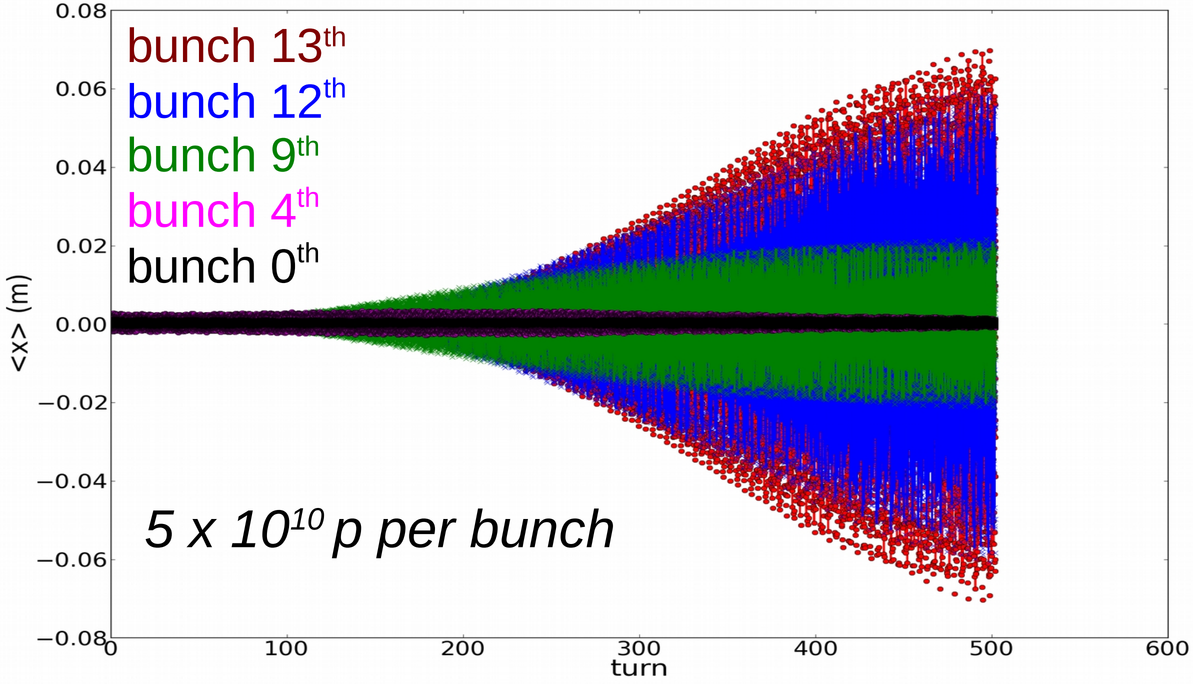
$\frac{\omega_{\xi x}}{\beta c} = 2\pi \times 0.069\,m^{-1}$ *green*

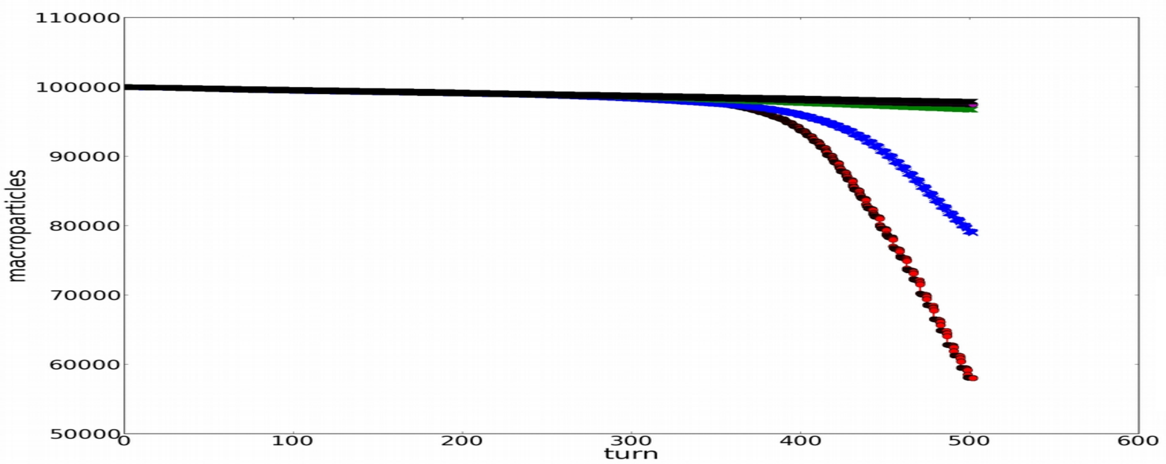
$\frac{\omega_{\xi x}}{\beta c} = 2\pi \times 0.091\,m^{-1}$ *black*

Large horizontal chromaticity (*similar value to that observed in the experiment*) needed to stabilize the beam

14-bunch train simulation

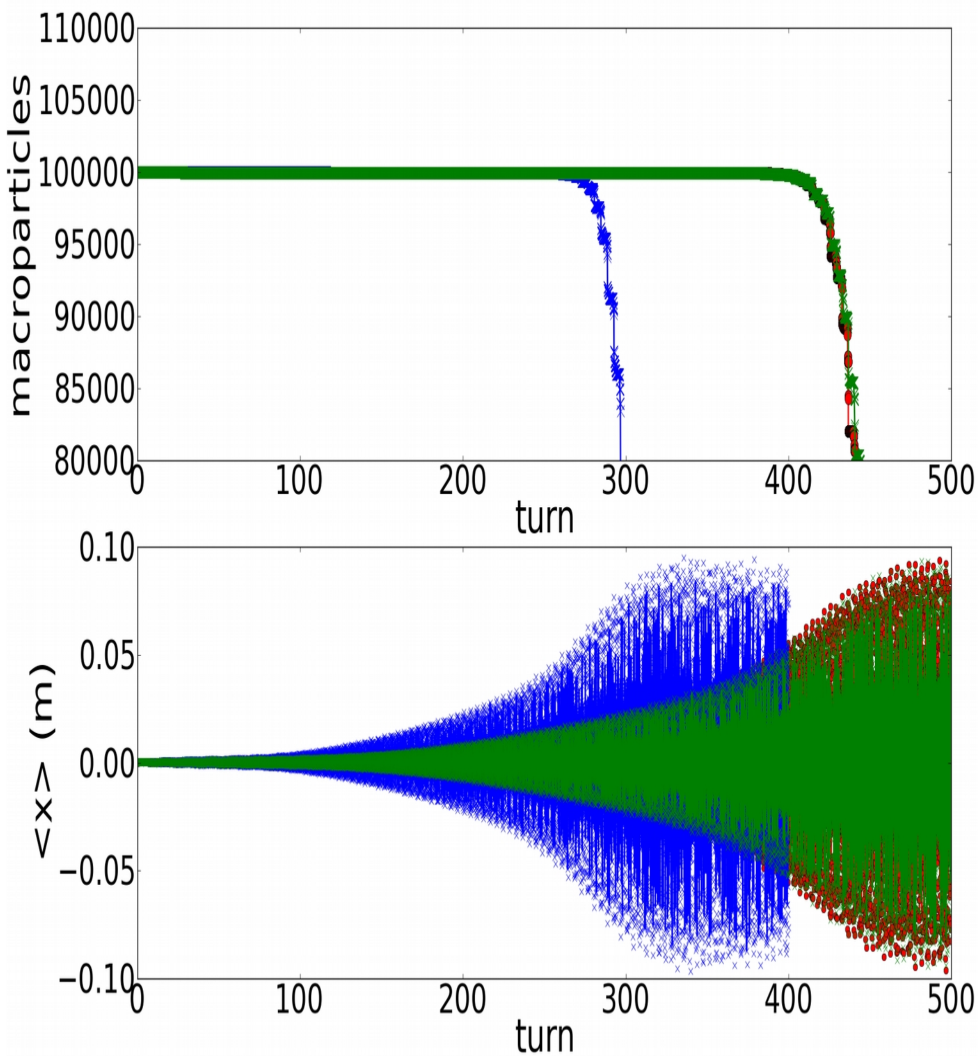
the 0th bunch leads





- **Horizontal instability**
- **The instability is caused by short range bunch-bunch interaction rather than by a coupling to a resonant element**

Simulations with modified wakes



- ***direct space-charge neglected***
- ***red - original wake, 1 x W_X, 1 x W_Y***
- ***blue - increased horizontal wake, 1.5 x W_X, 1 x W_Y***
- ***green - increased vertical wake, 1 x W_X, 2 x W_Y***

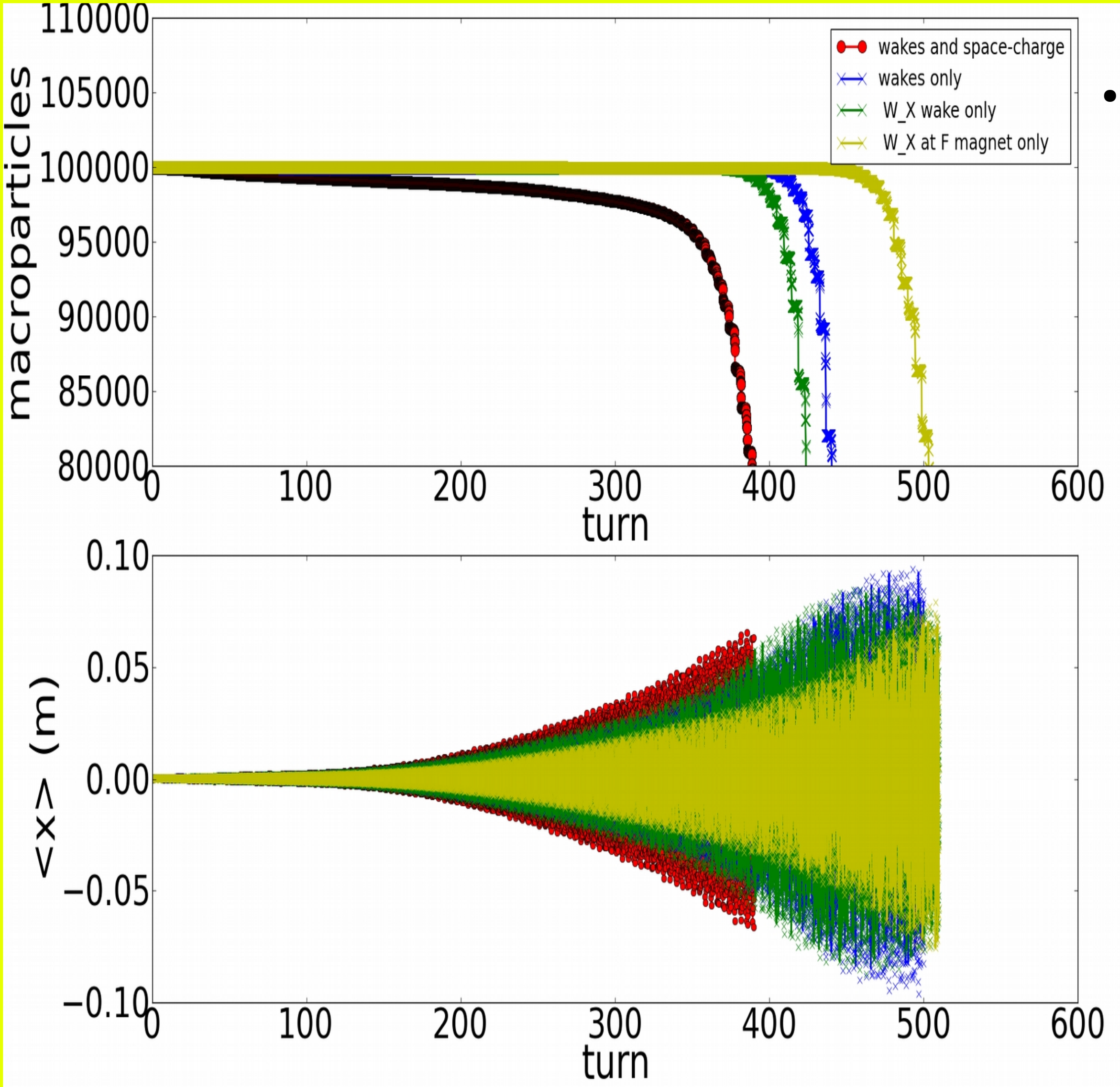
$$\beta c \Delta p_x = -qQ\left(W_X^{\perp}(z) X + W_x^{\perp}(z) x\right)$$

$$\beta c \Delta p_y = -qQ\left(W_Y^{\perp}(z) Y + W_y^{\perp}(z) y\right)$$

responsible for the instability

The instability is caused by the dipole horizontal wake

Simulations with modified wakes



- **The dipole horizontal wake at the location of the F magnets is enough to cause instability.**

$$\tau^{-1} \propto \int ds\, \beta(s) \int dz\, W^{\perp}(s-z)$$

- instability growth rate

$\langle \beta_x \rangle_F = 27.758$

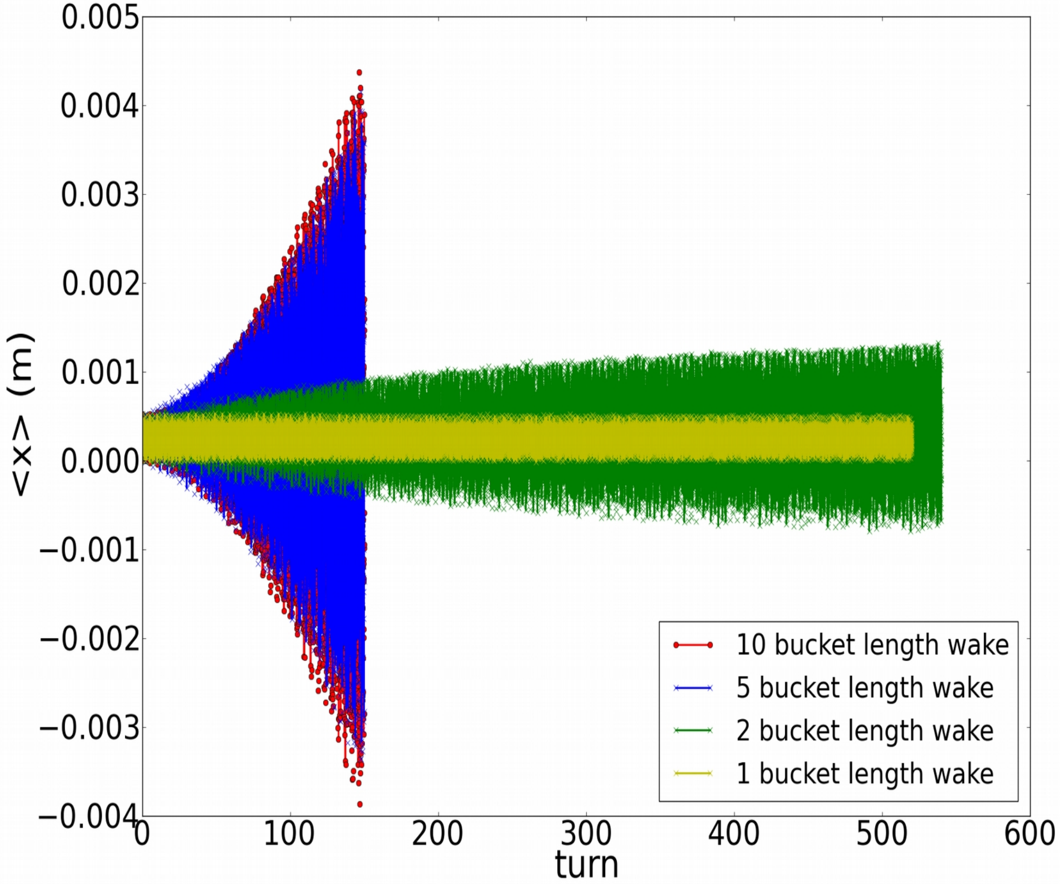
$\langle \beta_y \rangle_D = 16.78$

$\langle \beta_x \rangle_D = 12.784$

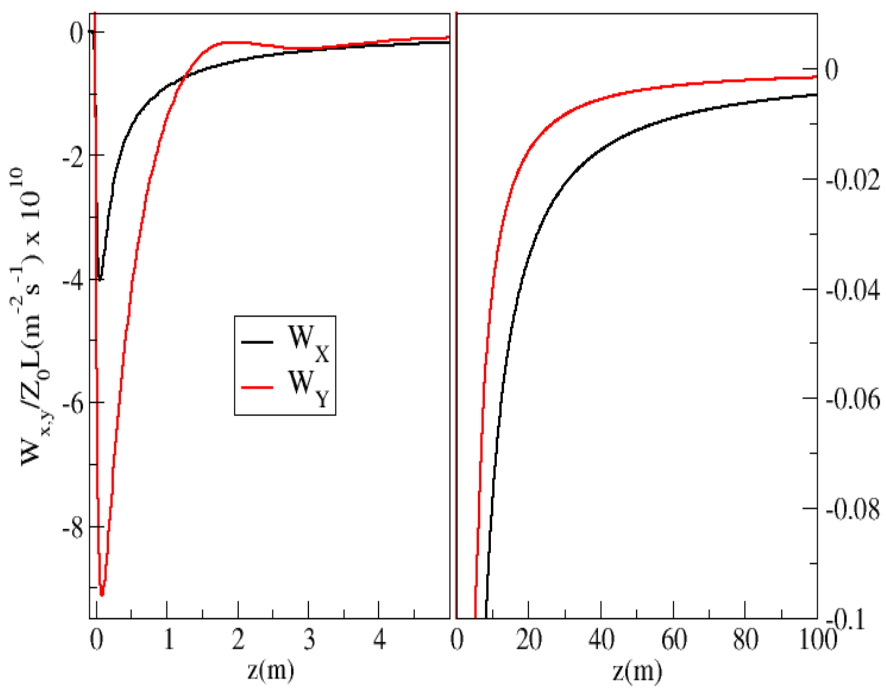
$\langle \beta_y \rangle_F = 8.15$

The lattice beta function is largest at the F magnets location in the horizontal plane

Simulation with short wakes



1 bucket length=5.654 m



- **only the dipole horizontal wake at the F magnets is turned on**
- **instability is seen for wakes longer than 2 bucket length**

At the relevant distance for the instability the horizontal wake is larger than the vertical wake

Conclusions

- **The presence of the laminations yields large and non-conventional wake fields in the Fermilab Booster.**
- **We ran single and multi-bunch Synergia simulations with realistic lattice model, space charge and wake fields.**
- **The simulation of the coherent tune shift and transverse instabilities are in good agreement with measurements.**
- **The instability is caused by short range (** *[2,5] bucket length* **) bunch-bunch interaction via dipole horizontal wake.**
- **The reason for the horizontal instability is twofold:**
    - **large horizontal lattice beta function at F magnets locations.**
    - **larger horizontal wake field at the relevant interaction range.**

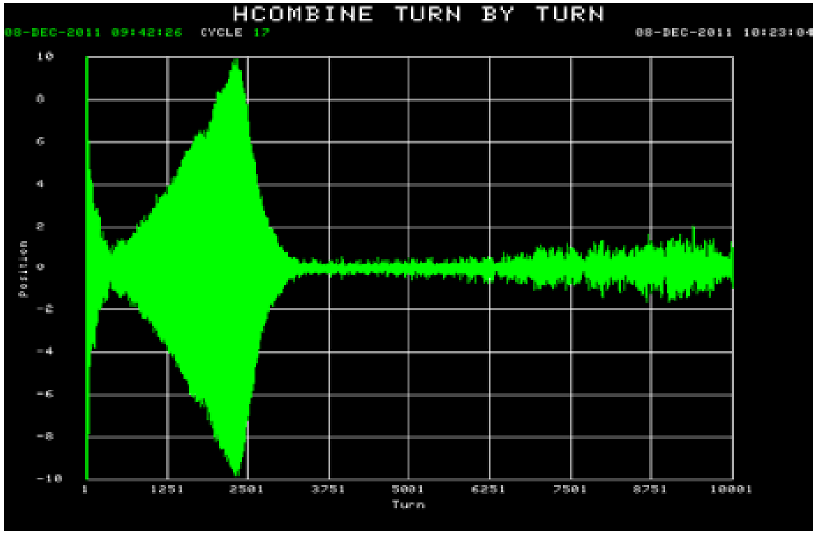
emitx= 4.54482918192e-06 meters*GeV/c = 4.7626595642e-06 meters*rad (synergia units)= 1.51600162381e-06 pi*meters*rad
emity= 1.87488822392e-06 meters*GeV/c = 1.96475026322e-06 meters*rad (synergia units)= 6.25399432664e-07 pi*meters*rad
emitz= 0.000325560118091 meters*GeV/c = 0.00108595166224 eV*s = 0.000232142587981 meters*GeV = 0.000478453292186 [cdt*dp/p] (synergia units)

* 95%emitx= 8.9639356764e-05 meters*rad = 2.85330934491e-05 pi*meters*rad
* 95%emity= 3.69791179534e-05 meters*rad = 1.17708188269e-05 pi*meters*rad
* 95%emitz= 0.0204390020255 eV*s
* Normalized emitx= 4.8438289074e-06 meters*rad = 1.54183862821e-06 pi*meters*rad
* Normalized emity= 1.99823522813e-06 meters*rad = 6.36058028036e-07 pi*meters*rad
* Normalized 95%emitx= 9.11670678286e-05 meters*rad = 2.90193789842e-05 pi*meters*rad
* Normalized 95%emity= 3.76093479071e-05 meters*rad = 1.19714272518e-05 pi*meters*rad

* xrms= 0.005 meters
* yrms= 0.006 meters
* zrms= 0.4 meters= 1.87118041835 ns
* pxrms= 0.000913323118096 GeV/c, dpx/p= 0.000957098035919
* pyrms= 0.000312583086879 GeV/c, dpy/p= 0.000327564968614
* prms= 0.000819420101319 GeV/c, dp/p= 0.000858694315327
* Erms= 0.000584292400675 GeV, deoe= 0.000436602116443
* pz= 0.954262869444 GeV/c

* total energy= 1.33827203 GeV, kinetic energy= 0.4 GeV
* L=474.203 m
* Tunes (x,y,z): 6.6265, 6.788, 0.0735
* w_0=2.832 MhZ
* head-tali phase =0.01325[m^-1] *chrom/slippage * z [m]
* slip factor=-0.44
* voltage per RF V=0.6/18.0, "RF cavity voltage in MV”

84 bunch simulation, horizontal instability



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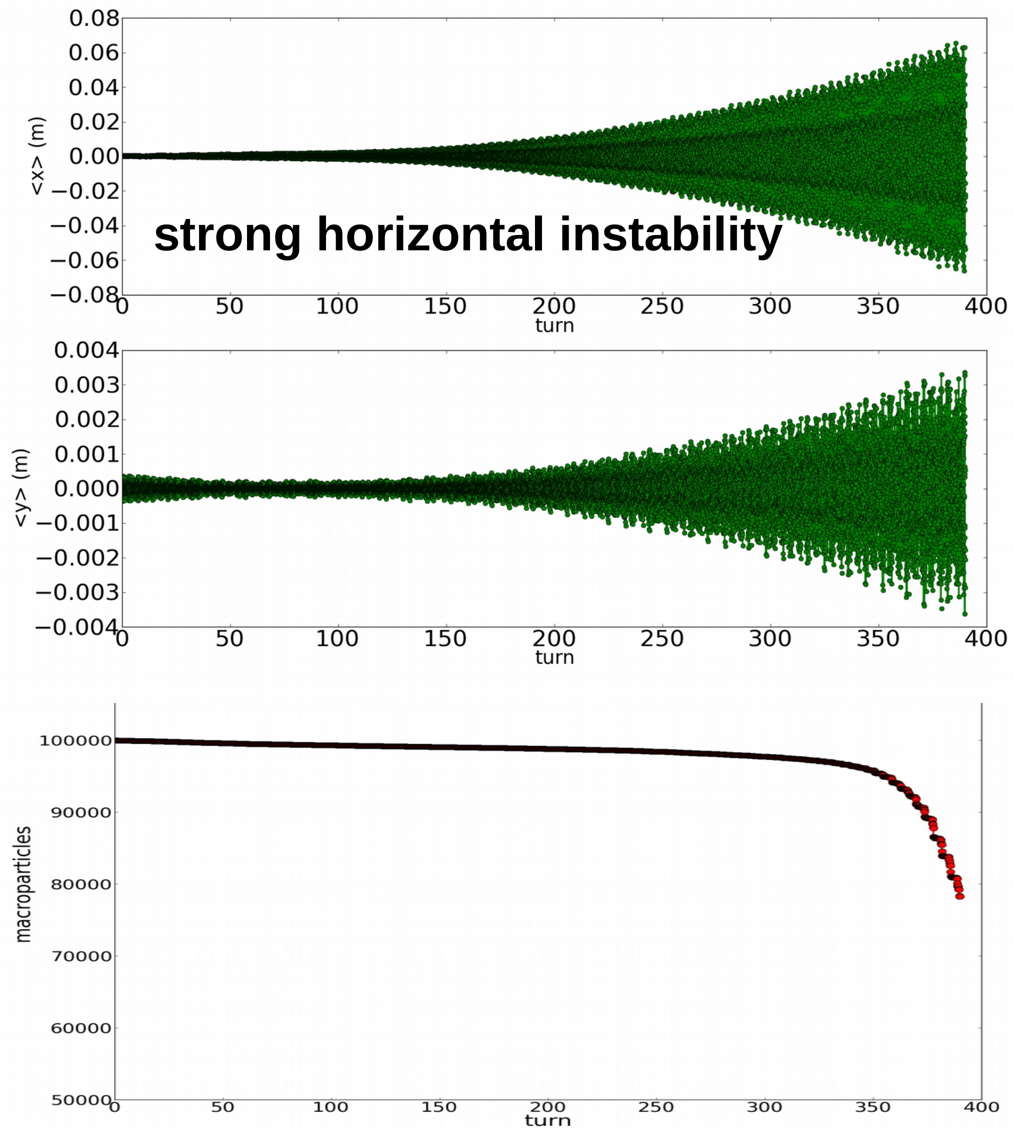
experiment, Y. Alexahin, *et al. IPAC 2012*

$$\left(\frac{\omega_{\xi x}}{\beta c}, \frac{\omega_{\xi y}}{\beta c}\right) = 2\pi \times \left(0.06\, m^{-1}, 0.025\, m^{-1}\right)$$

simulation

$$\left(\frac{\omega_{\xi x}}{\beta c}, \frac{\omega_{\xi y}}{\beta c}\right) = 2\pi \times \left(0.023\, m^{-1}, 0.023\, m^{-1}\right)$$

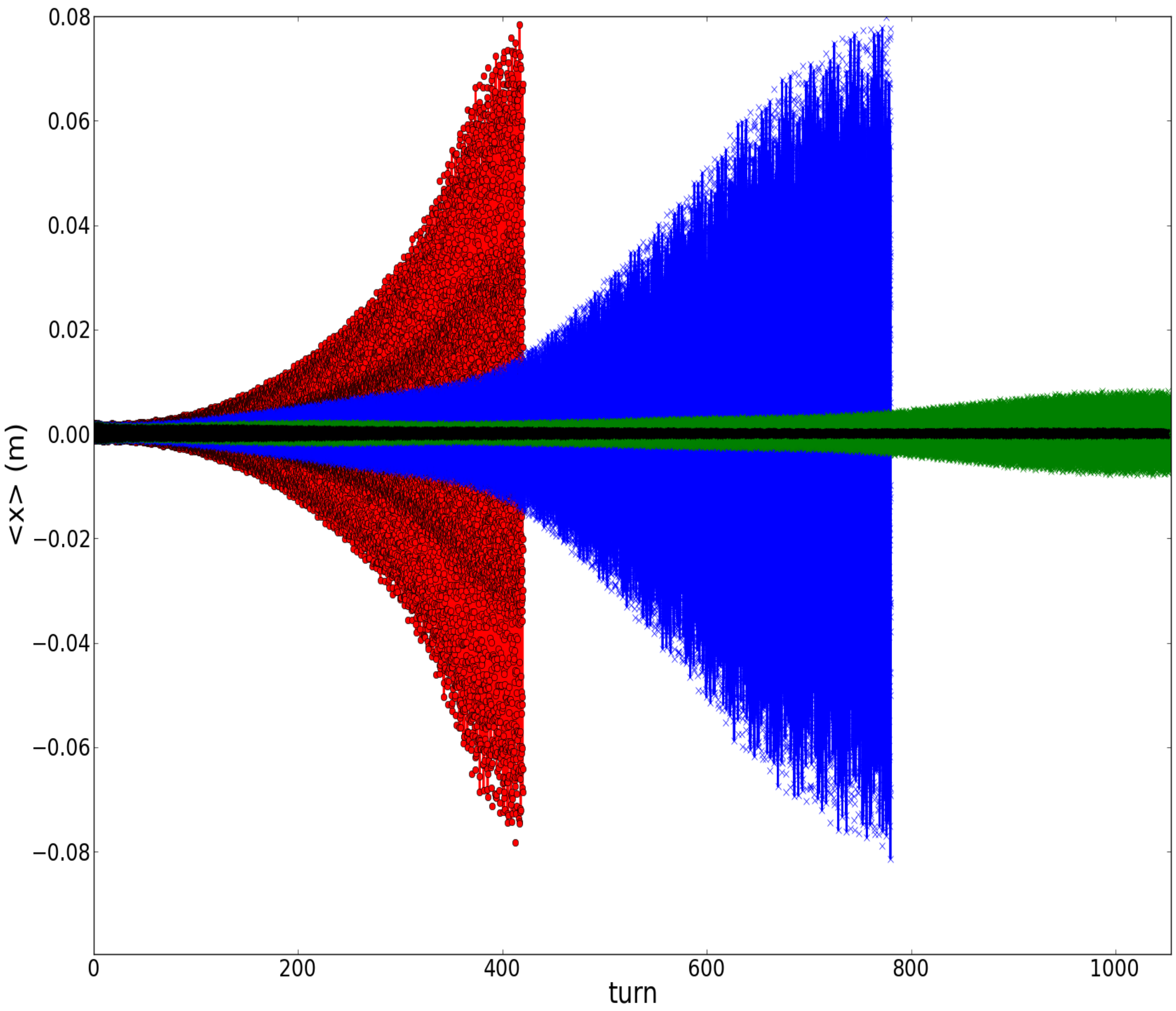
5 x 10^{10} p per bunch



Horizontal instability

5 x 10^{10} p per bunch

$$\frac{\omega_{\xi y}}{\beta c} = 2\pi \times 0.023\, m^{-1}$$



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- **Large horizontal chromaticity (*similar value to that observed in the experiment*) needed to stabilize the beam**

84 bunch simulation, the 14^{th} bunch

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