Transverse Impedance and Transverse Instabilities in the Fermilab Booster

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Fermilab

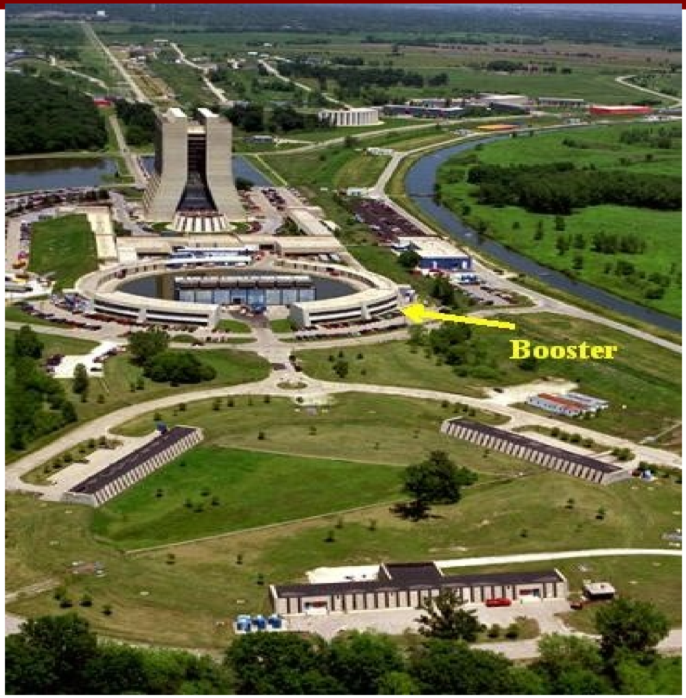
COMPASS - SciDAC

Outline

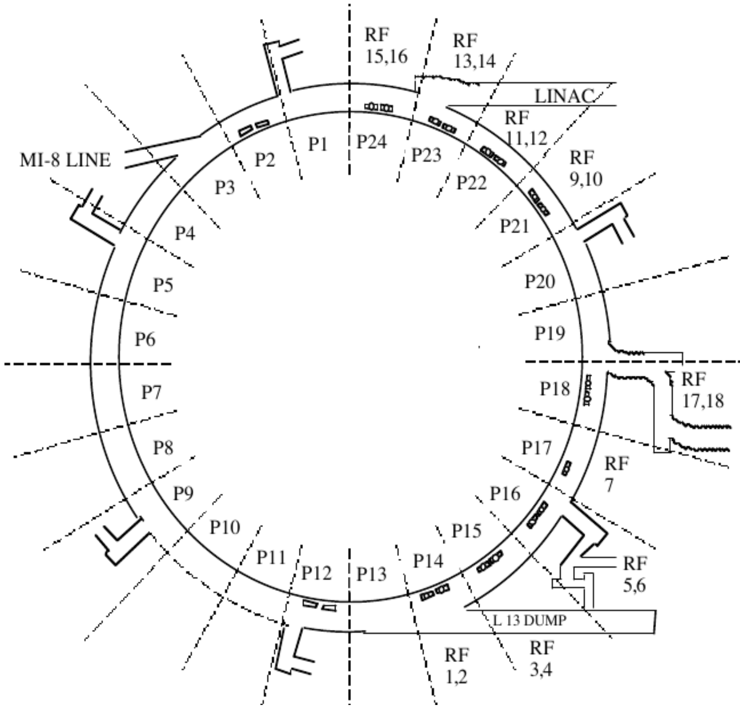
- Introduction and motivation
- Synergia code
- Wake fields in laminated magnets
- Simulation results
- Conclusions

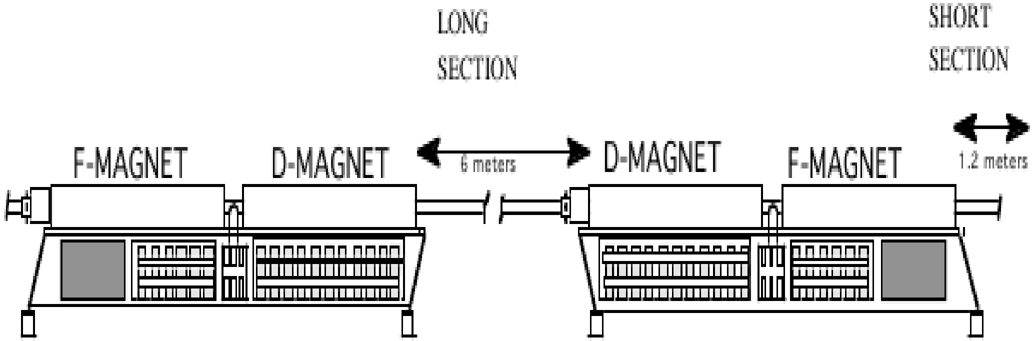
Fermilab Booster

- **Intensity ≈ 4.5 x 10^{12} p per batch**
- **Instability and beam loss at high intensity**
- **Requirement to increase intensity**



Kinetic energy (injection/final)	GeV	0.4/8
Circumference	m	474.25
Transition γ_t	-	5.48
RF harmonic number	-	84

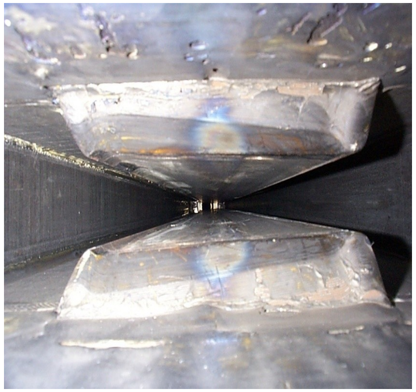




Combined function magnets

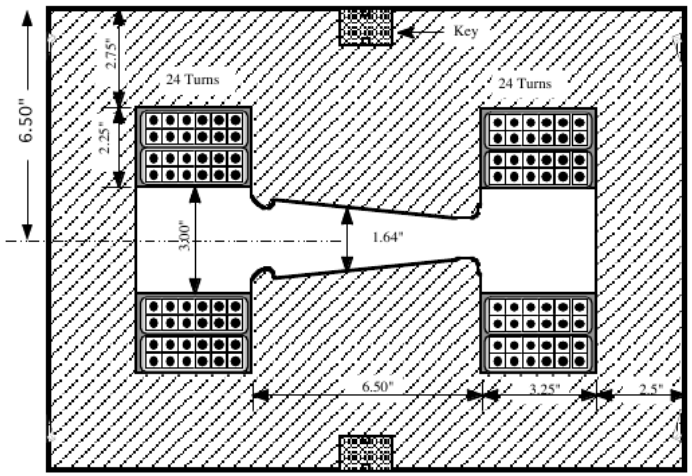
- **60 % of the machine length consists of combined-function (dipole & quadrupole) magnets**
- **Almost parallel-plane geometry**
- **Beam exposed to laminations**
    - **Large wake field**
- **Non-ultrarelativistic effects are important, injection energy 0.4GhZ (γ=1.42)**
- **Large space charge effects**

focusing



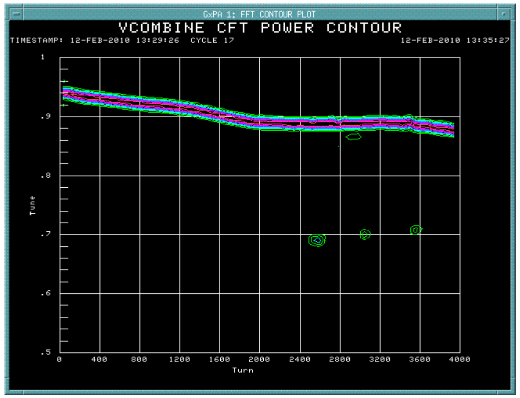
defocusing

Focusing Magnet

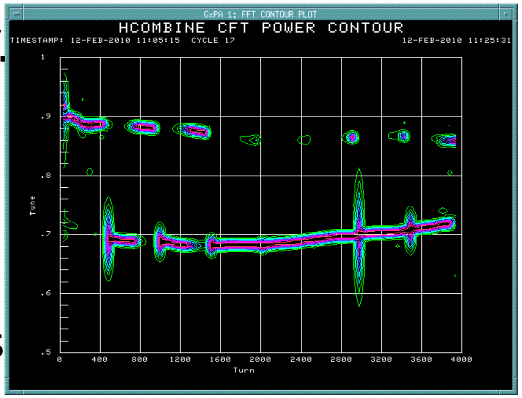


Coherent tune shift measurement

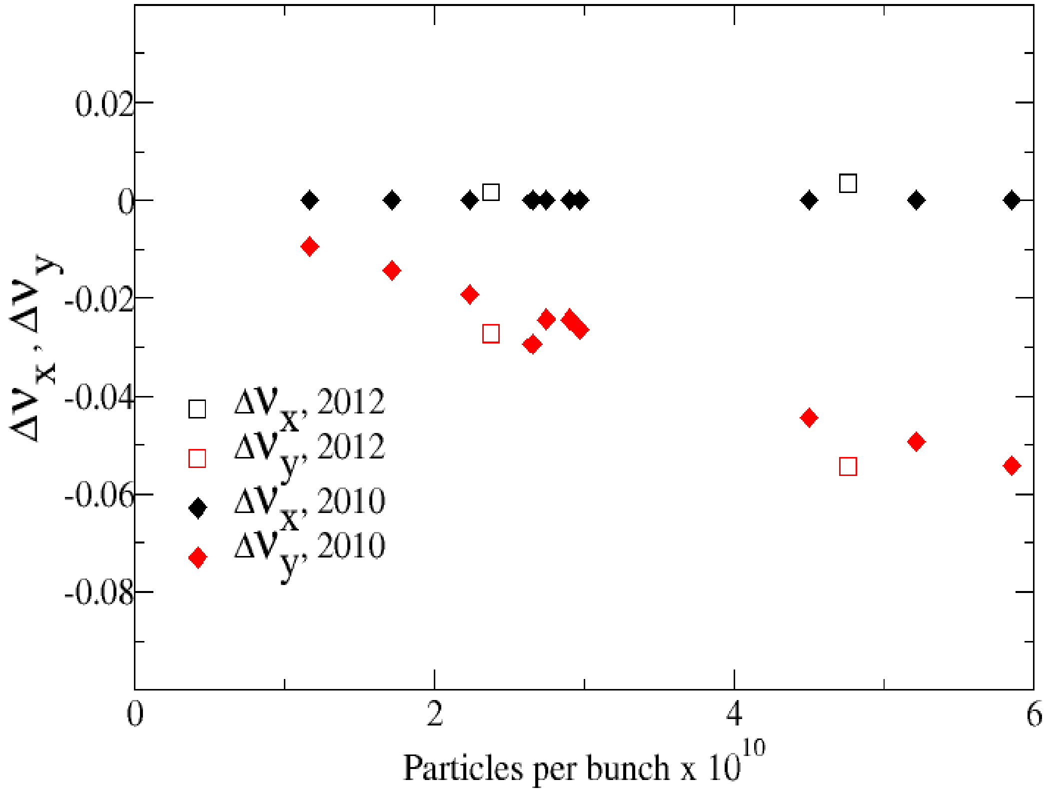
- **Data at injection**
- **Large decrease of the vertical tune**
- **Small increase of the horizontal tune**
- **Large wake field**
- **Chamber geometry is important**



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

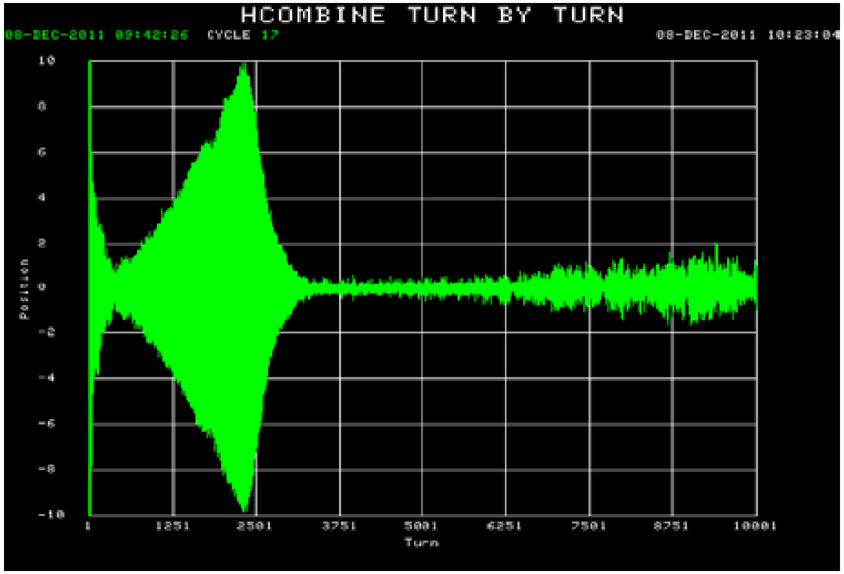


Figure 1: Combined TBT signal from HBPMs (arbitrary units) at $N_p = 4{\cdot}10^{12}$ after coupling correction.

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

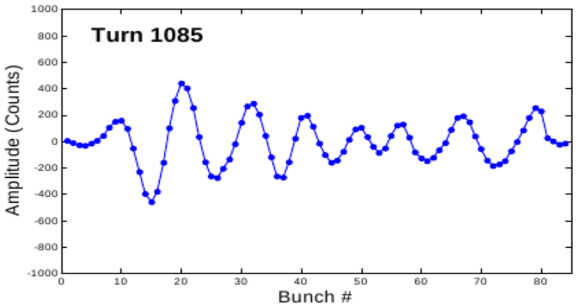
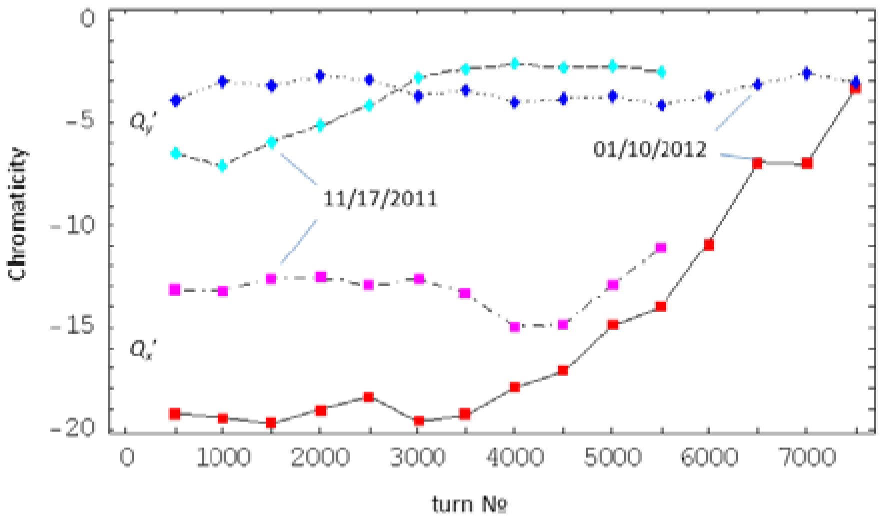


Figure 3: Bunch-by-bunch horizontal positions at the onset of horizontal instability

Y. Alexahin, et al., IPAC-2012



- Stability achieved after the increase of the horizontal chromaticity to $\left(\frac{\omega_{\xi x}}{\beta c}, \frac{\omega_{\xi y}}{\beta c}\right) = 2\pi \times \left(0.091\, m^{-1}, 0.023\, m^{-1}\right)$

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- Wake fields in laminated magnets
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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)

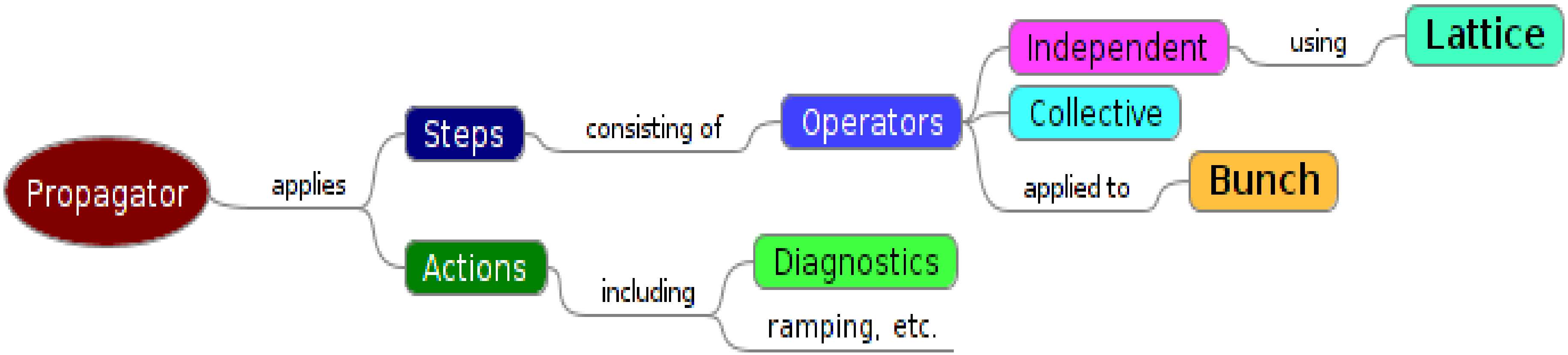
URL for download, building instructions and tutorial

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

Synergia

A simulation consists of propagating a *Bunch* (or *Bunches*) through a *Lattice*.

- **Inputs:** machine lattice, initial bunch parameters, wake fields, ...
- **Outputs:** user-selected Diagnostics (means, emittances, particle tracking, ...)



Designed for range of computing resources: laptops and desktops, clusters, supercomputers

Scalability: multibunch Synergia simulations have been shown to scale to 131,072 cores on Intrepid, a BlueGene/P supercomputer

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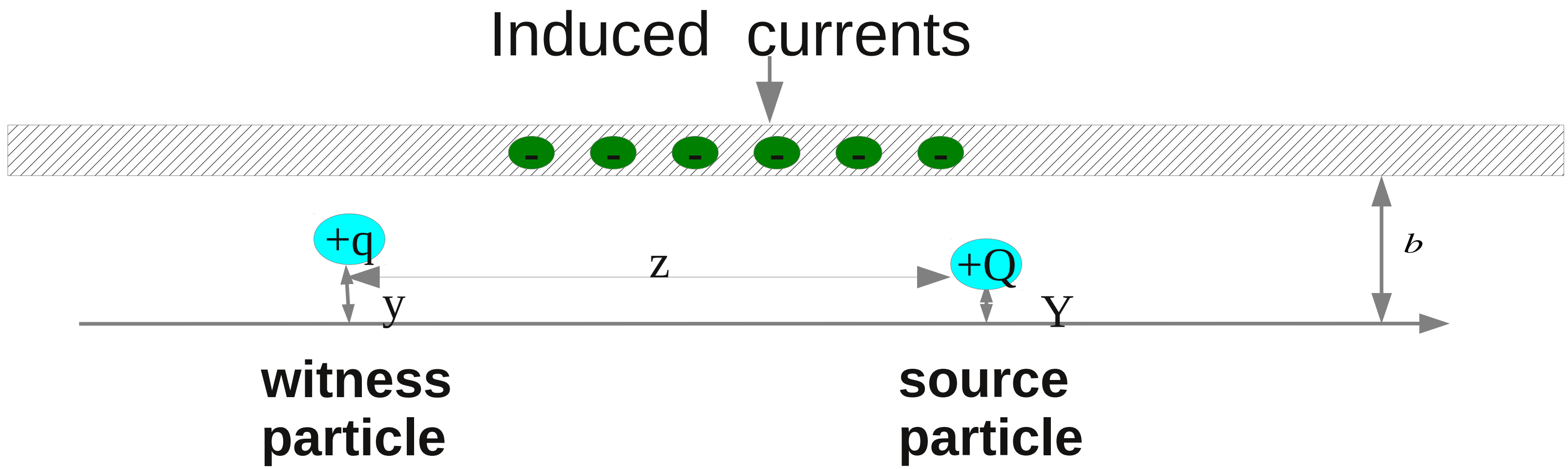
Wake field



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

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

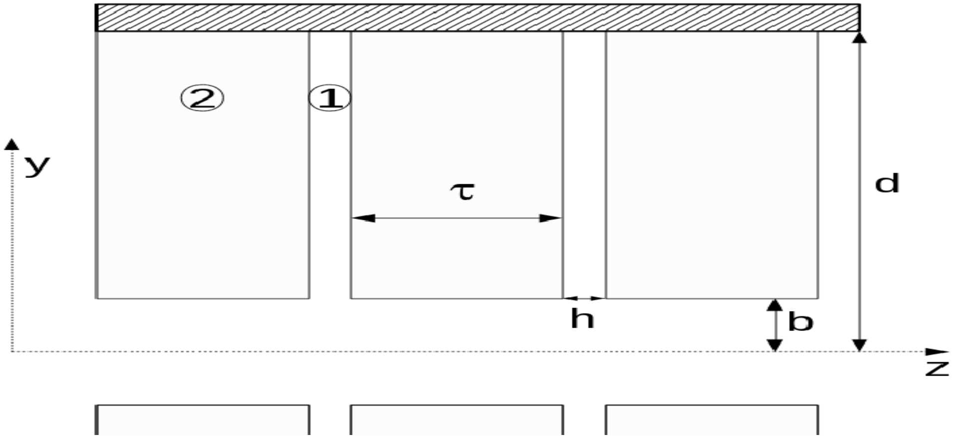
$$\beta c \Delta p_y = -qQ\left(W_Y^{\perp}(z)Y + W_y^{\perp}(z)y\right)$$

- 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: $W^{||}(z)$, $W_X^{\perp}(z)$, $W_x^{\perp}(z)$, $W_Y^{\perp}(z)$, $W_y^{\perp}(z)$

Wake field 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.**

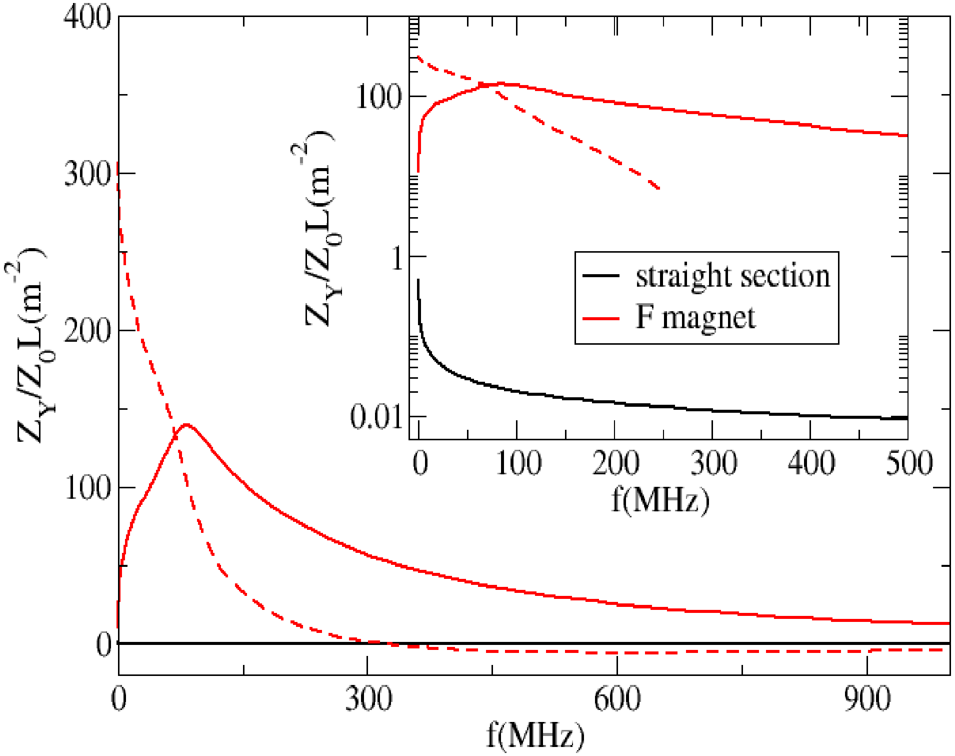


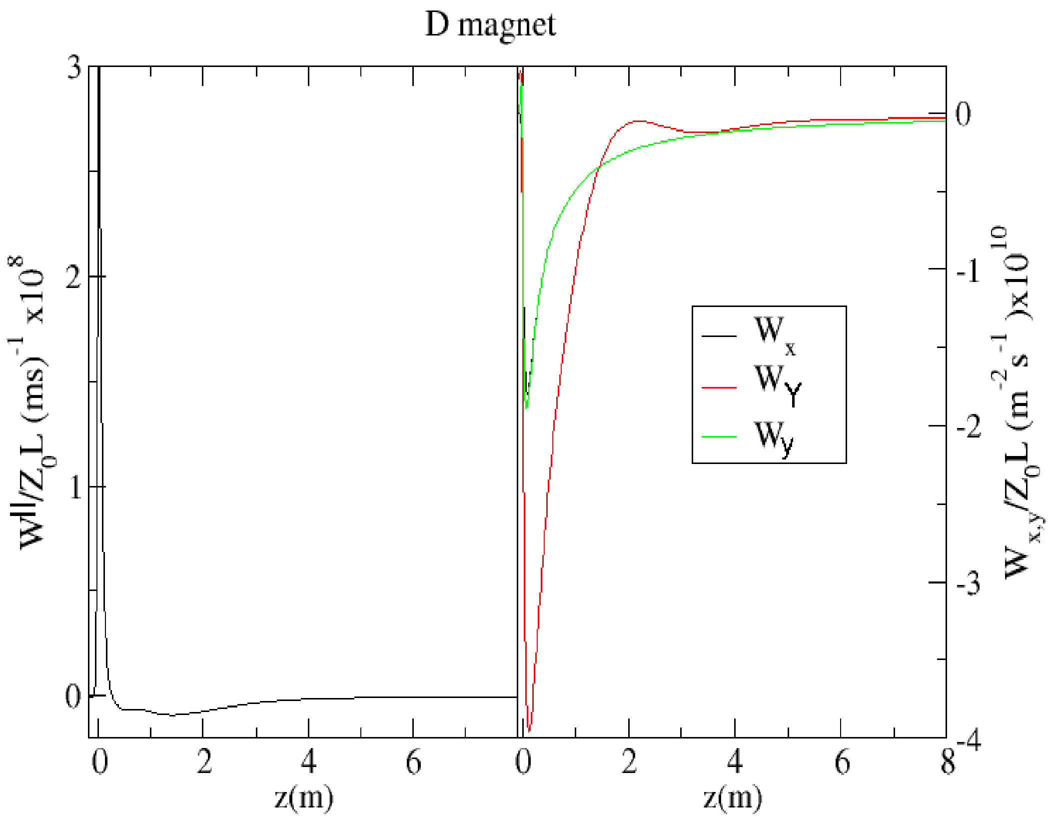
$$W^{\parallel}(z)=\frac{1}{2\pi}\int d\omega Z^{\parallel}(\omega)e^{-i\frac{\omega z}{\beta c}}$$

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

A. Macridin, et al., PRST-AB 14, 061003 (2011)
A. Macridin, et al., FERMILAB-PUB-13-390-CD, submitted to PRST-AB

Wake field and impedance in the Booster





- **Impedance in the laminated magnets is much larger (10^3~10^4 times) than in the straight section**

- **Vertical wake ≈ 2 times larger than horizontal wake**
- **Non-ultrarelativistic wake (γ =1.42)**

  Wake field is nonzero at small distance (up to ≈0.1m) in front of the source

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Computing resources

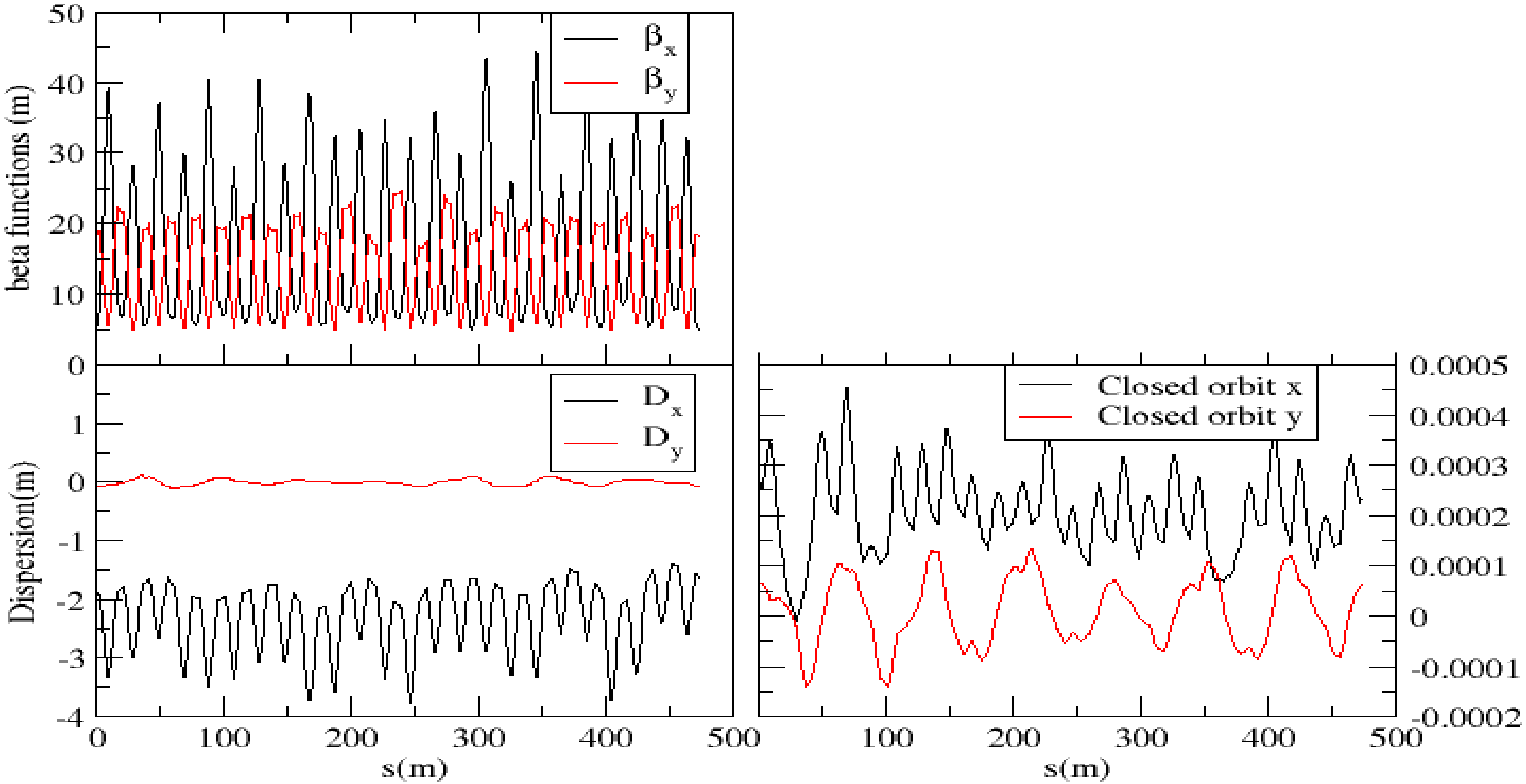
- **Simulations done on the Intrepid (Bluegene/P supercomputer) at Argonne Leadership Computing Facility**
- **Multi-bunch simulations are computationally expensive: 200 turns require 12 hours on 16000 cores**

Computing time provided by a 2013 INCITE Award

Lattice model

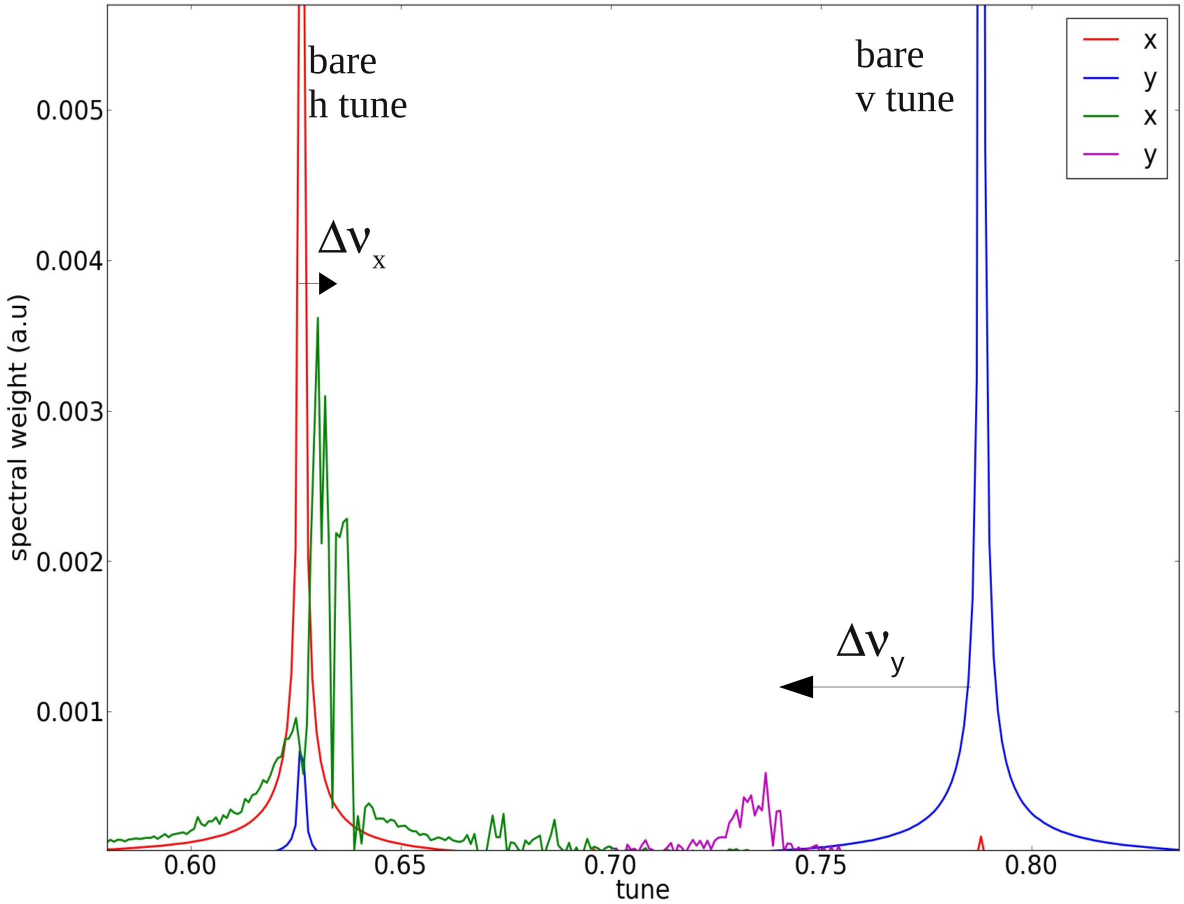
Orbit Response Measurement fitting (M. McAteer, A. Petrenko)

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



Coherent tune shift

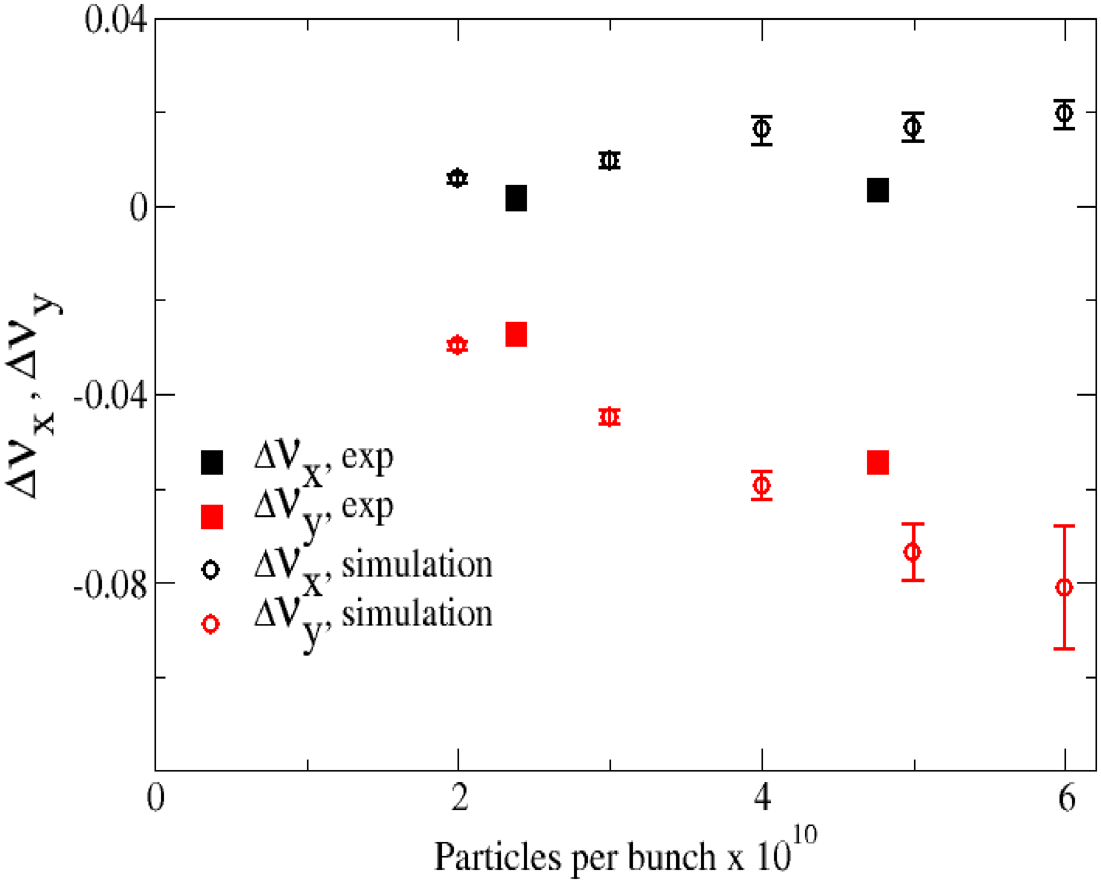
4 x 10^{10} p per bunch $\left(\frac{\omega_{\xi x}}{\beta c}, \frac{\omega_{\xi y}}{\beta c}\right) = 2\pi \times (0.091\, m^{-1}, 0.023\, m^{-1})$



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

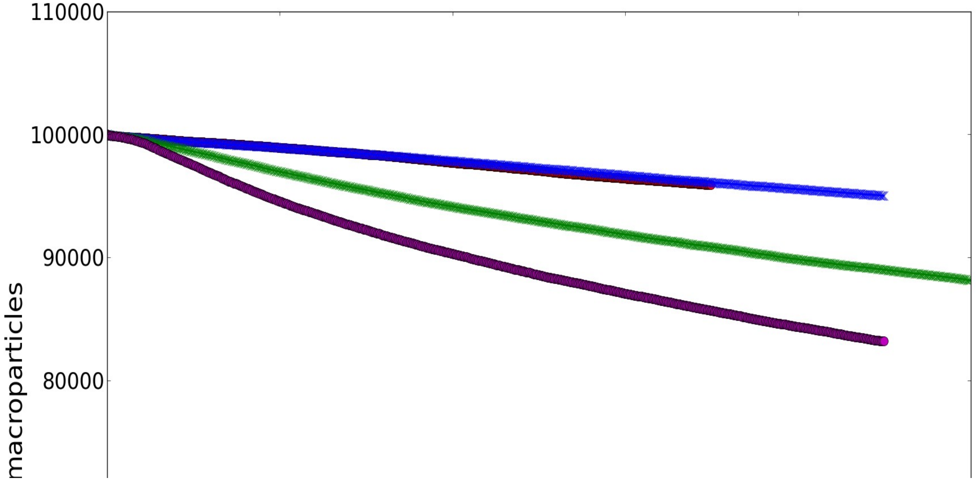
Coherent tune shift

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



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

Single bunch simulations



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

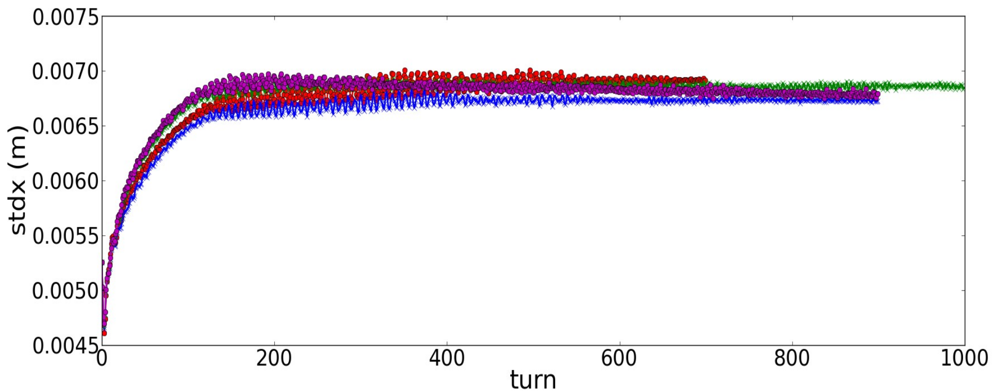
$\frac{\omega_{\xi x}}{\beta c} = 2\pi \times 0.023\, m^{-1}$ *blue*

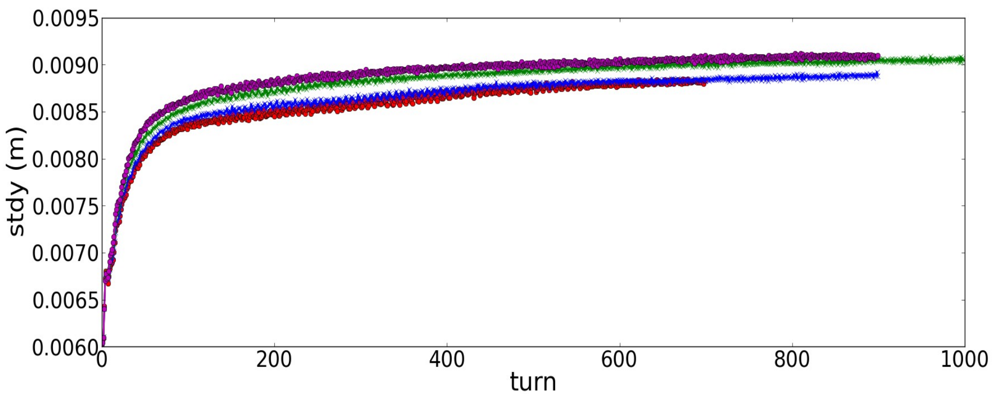
$\frac{\omega_{\xi x}}{\beta c} = 2\pi \times 0.091\, m^{-1}$ *green*

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

5 x 10^{10} p per bunch

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





- **Beam loss increases with increasing chromaticity due to the increase in the transverse size**
- **Small chromaticities are most favorable for non-interacting bunches,**

$$\frac{\omega_{\xi x}}{\beta c} \leq\ \approx 2\pi \times 0.023\, m^{-1}$$

84 bunch simulation, horizontal instability

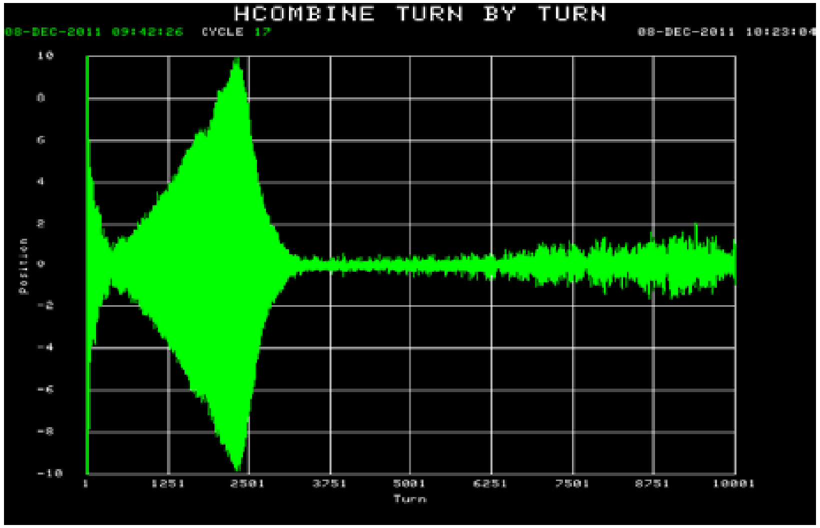


Figure 1: Combined TBT signal from HBPMs (arbitrary units) at $N_p = 4{\cdot}10^{12}$ after coupling correction.

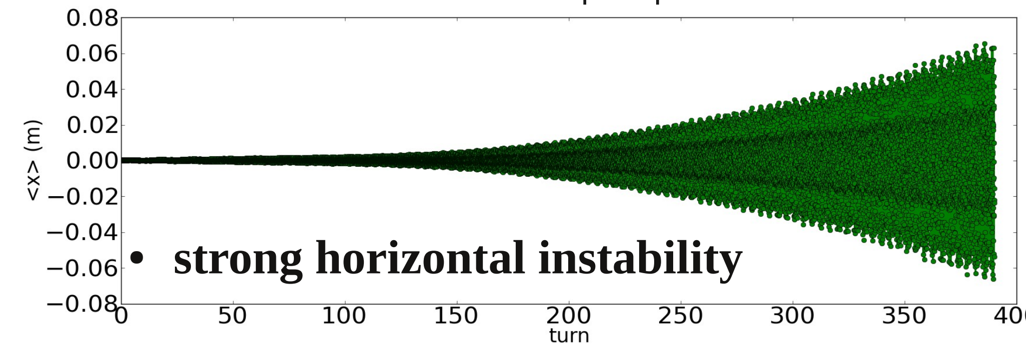
experiment, Y. Alexahin, *et al. IPAC 2012*

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

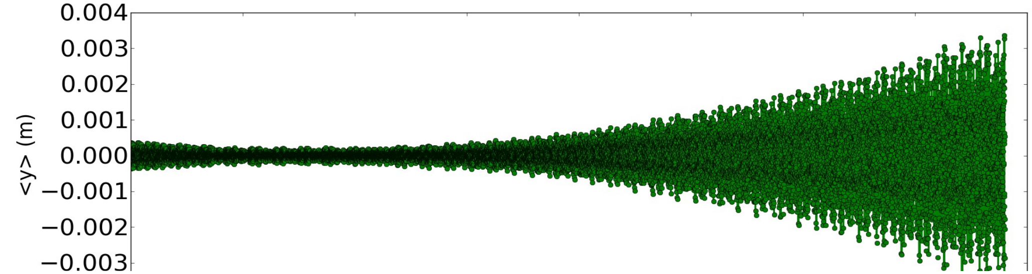
simulation

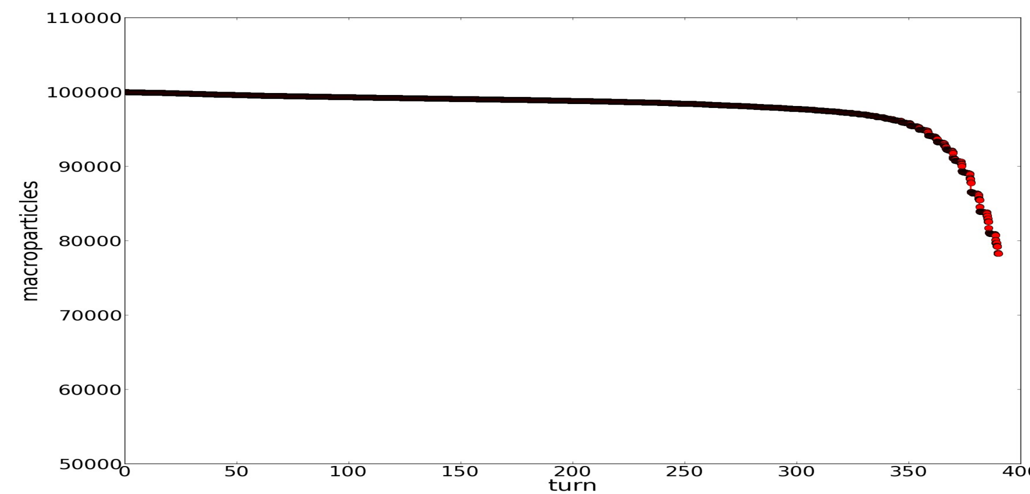
5 x 10^10 p per bunch

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



- **strong horizontal instability**

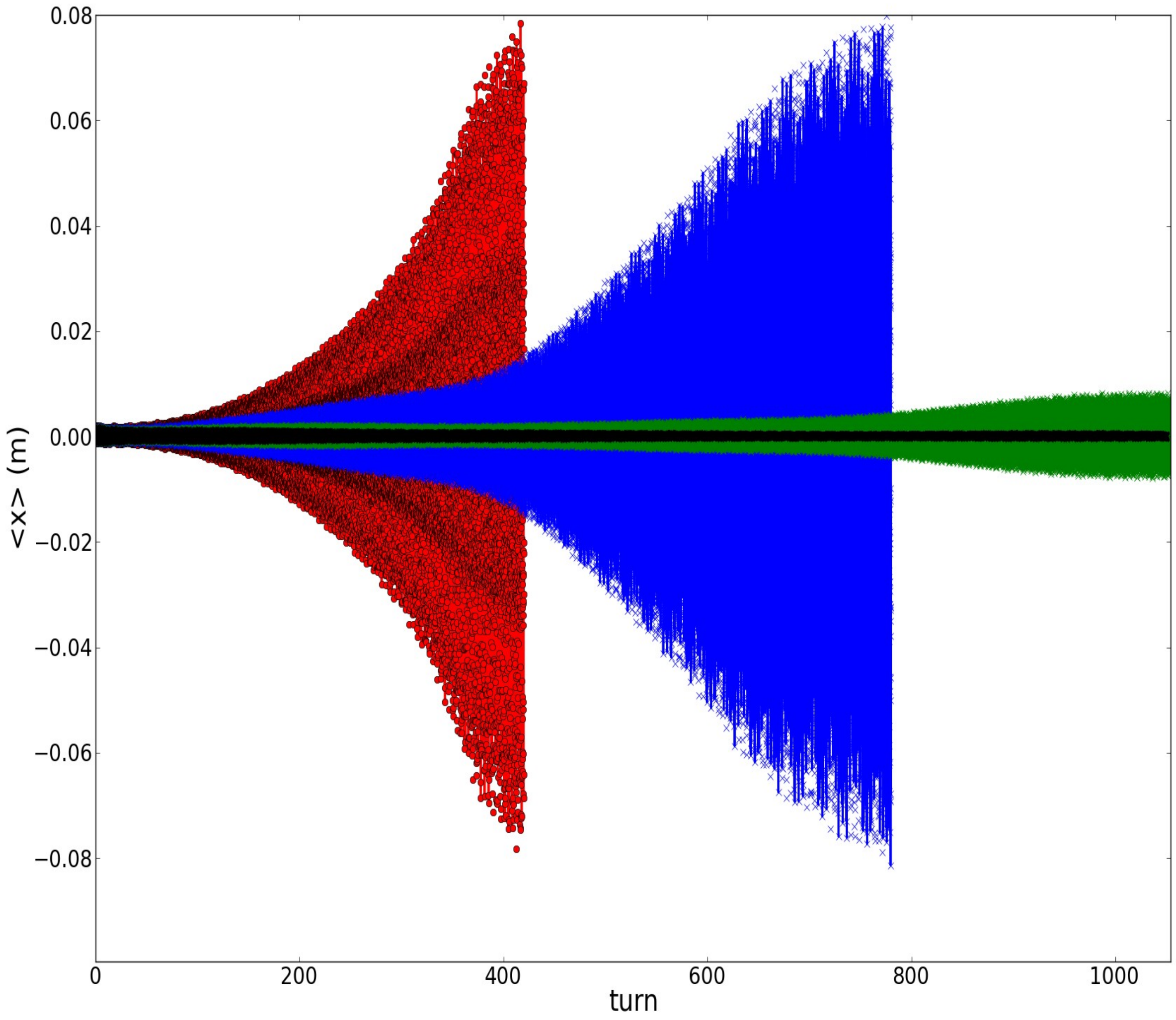




Horizontal instability

5 x 10^{10} p per bunch

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



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

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

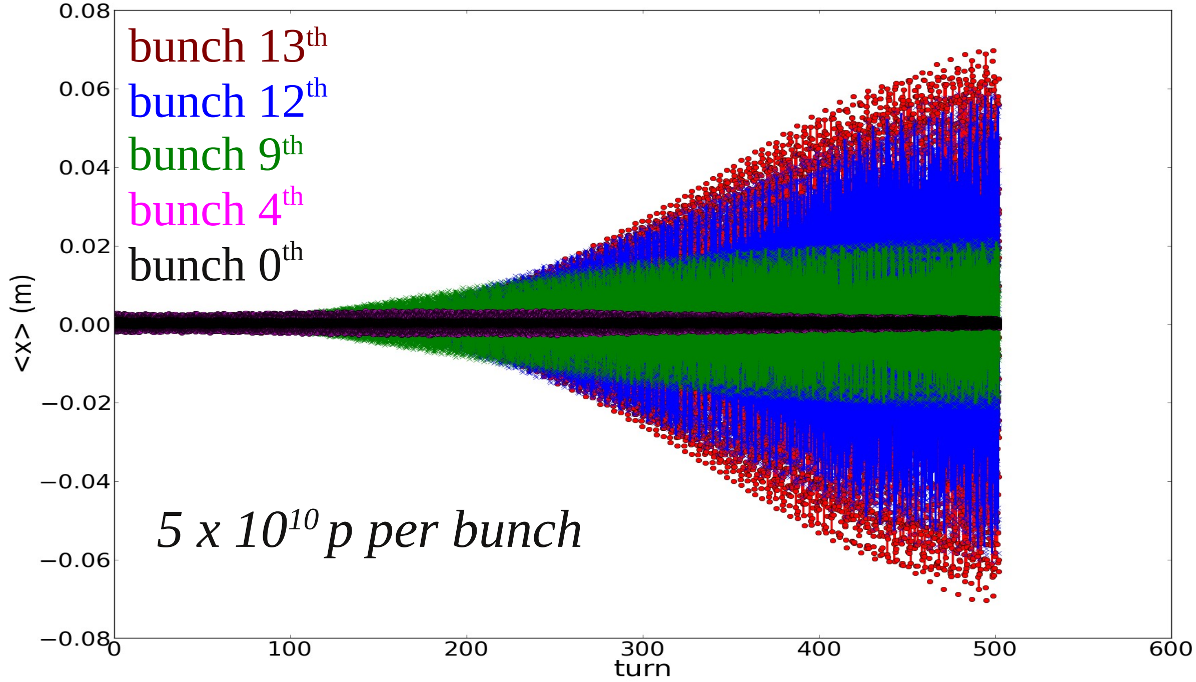
$\frac{\omega_{\xi x}}{\beta c} = 2\pi \times 0.069\, m^{-1}$ *green*

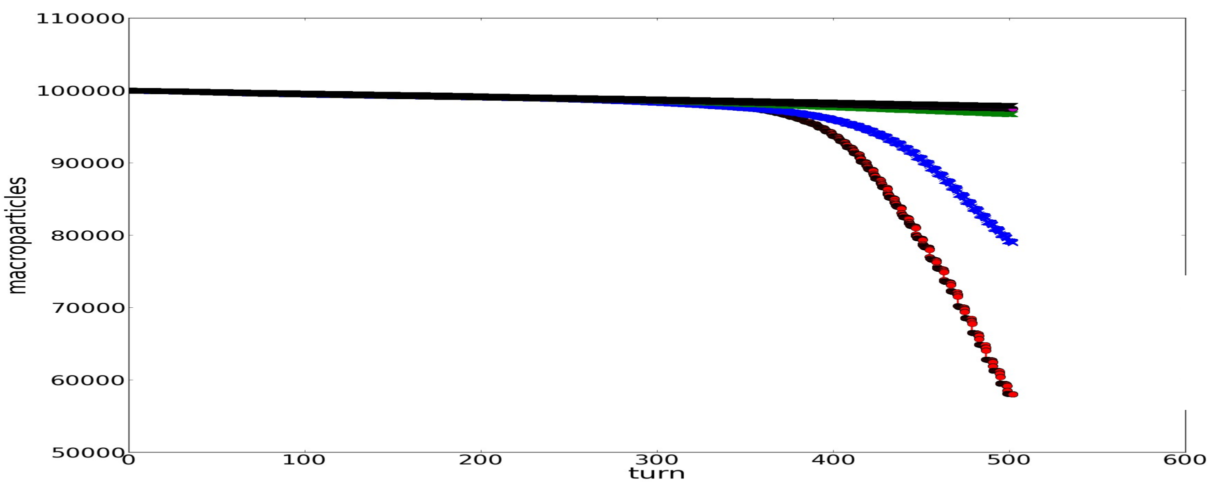
$\frac{\omega_{\xi x}}{\beta c} = 2\pi \times 0.091\, m^{-1}$ *black*

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

14 bunch simulation

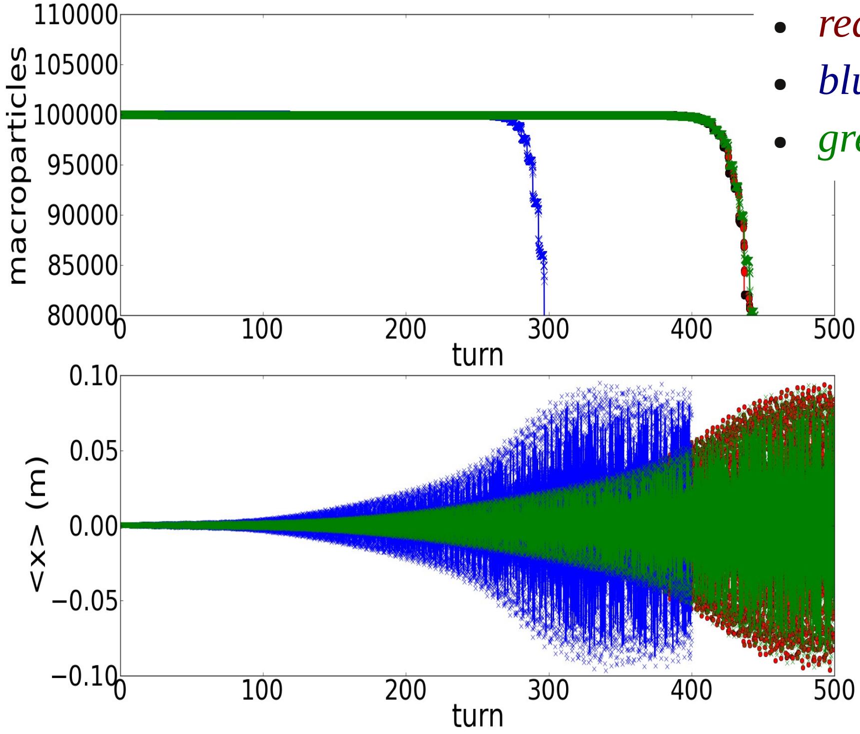
The subsequent buckets are populated, the 0th bunch leads





- **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

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

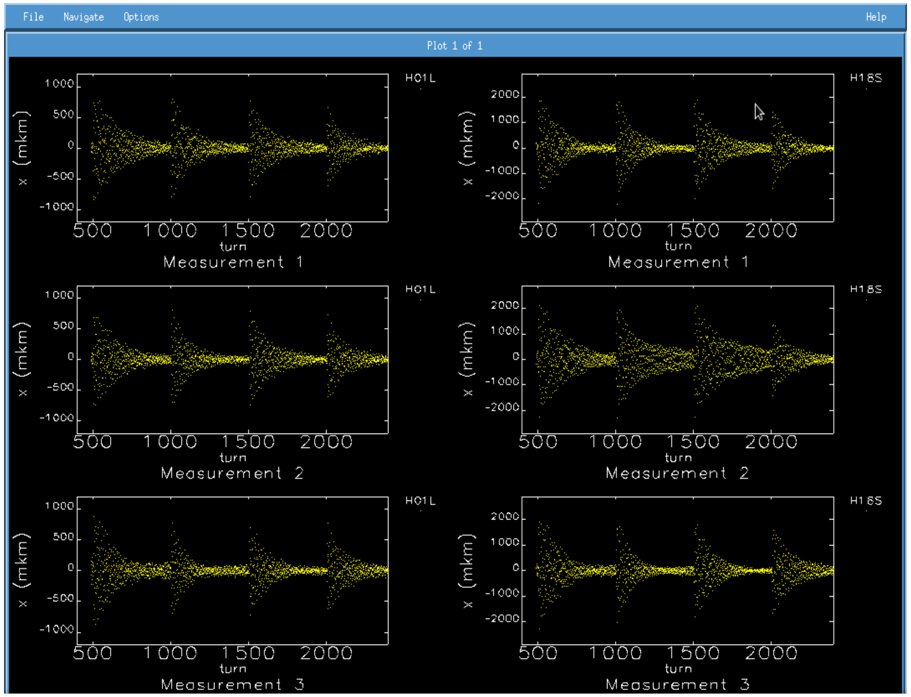
- instability growth rate

$\langle\beta_x\rangle_F = 27.758 \quad » \quad \langle\beta_y\rangle_F = 8.15$

$\langle\beta_x\rangle_D = 12.784 \quad \approx \quad \langle\beta_y\rangle_D = 16.78$

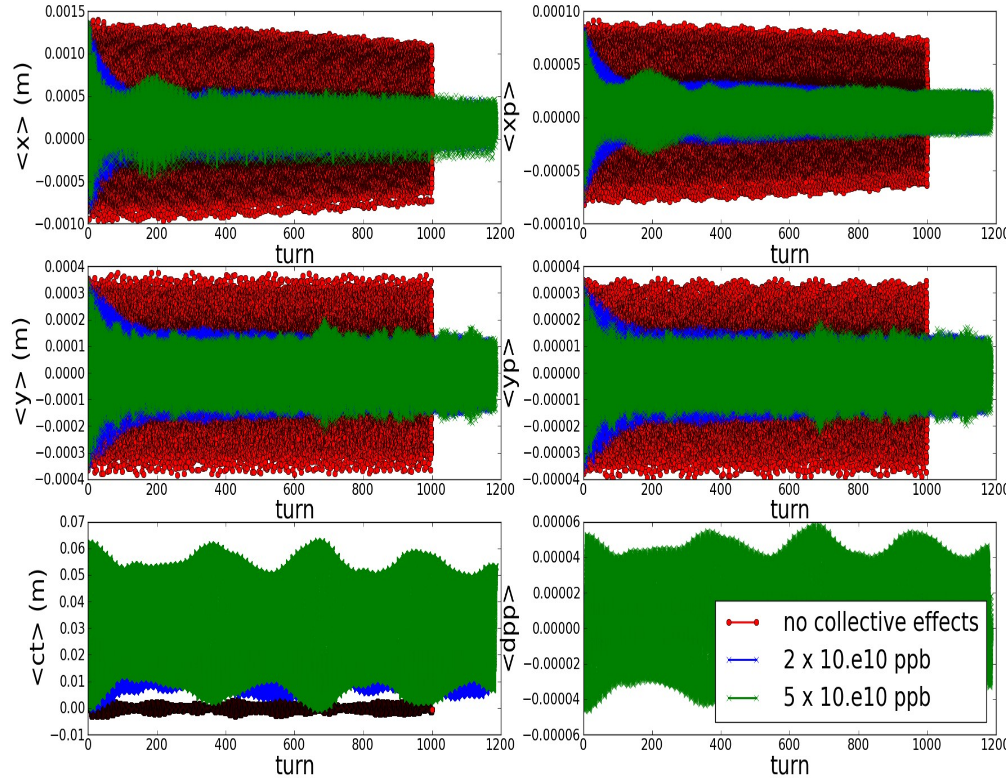
The instability is caused by the large horizontal beta-wake coupling at the F magnets locations

Kick decoherence



- **Experiment show very strong kick decoherence in both horizontal and vertical planes**

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



- **Simulation shows strong kick decoherence**
- **The decoherence increases with intensity**
- **Not a direct comparison with experiment, just an observation**
- **Future investigations planned**

Conclusions

- **The presence of the laminations causes large and non-conventional wake fields in Booster**
- **We ran single and multi-bunch Synergia simulations with realistic lattice model, space charge and wake fields**
- **The simulation results regarding coherent tune shift and transverse instabilities are in good agreement with measurements**
- **The dipole horizontal wake coupled with the large horizontal beta function at the F magnets is the main culprit for the instability**
- **The instability is caused by short range bunch-bunch interaction rather than by a coupling to a resonant element**