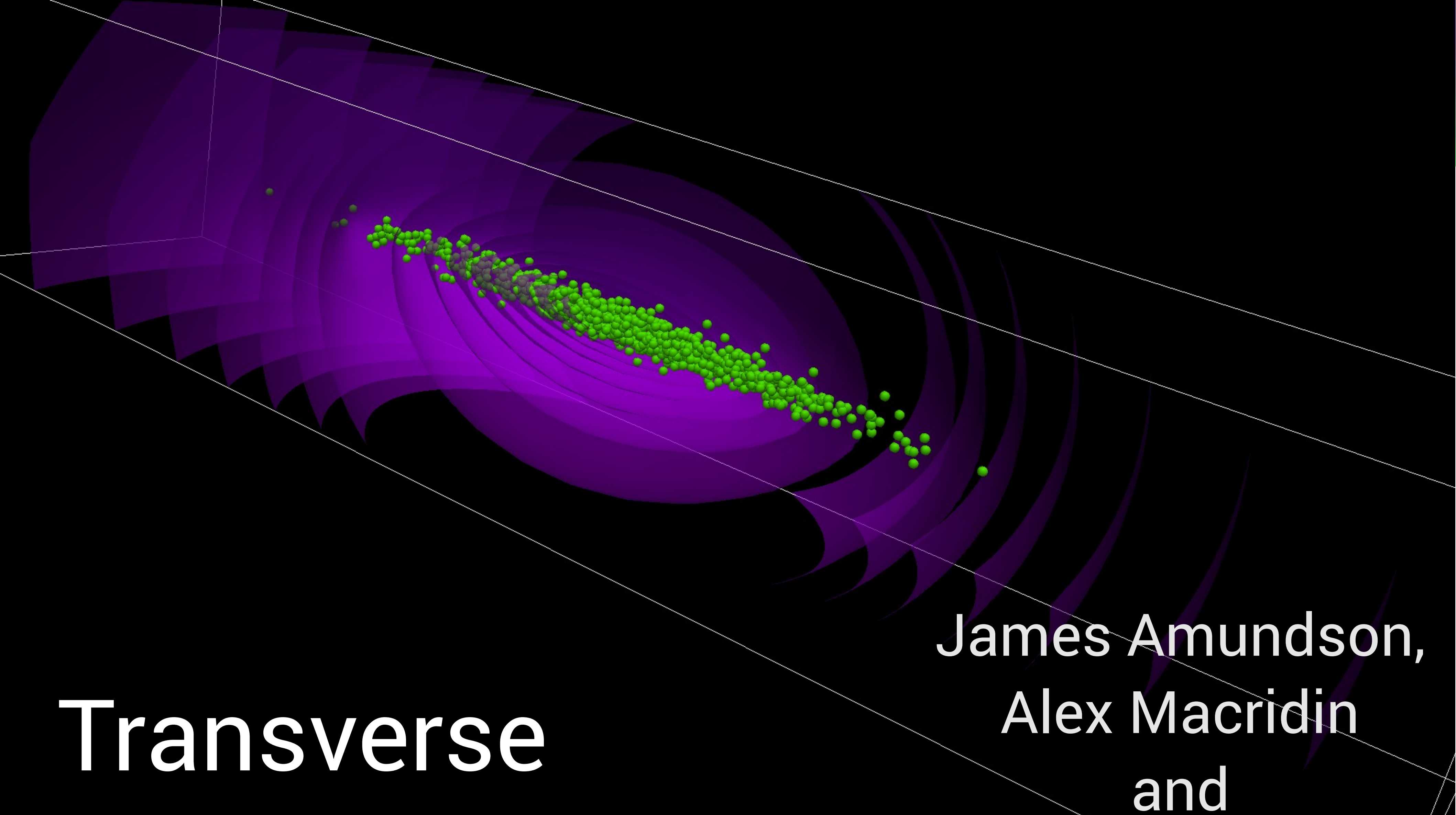
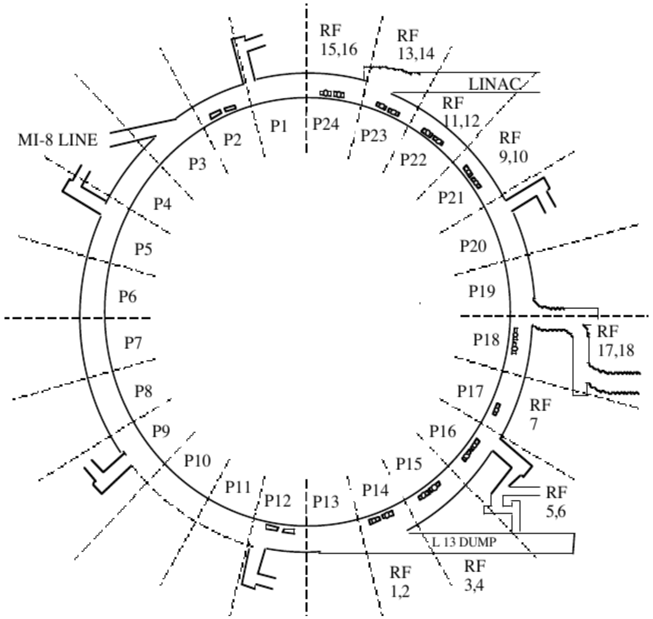


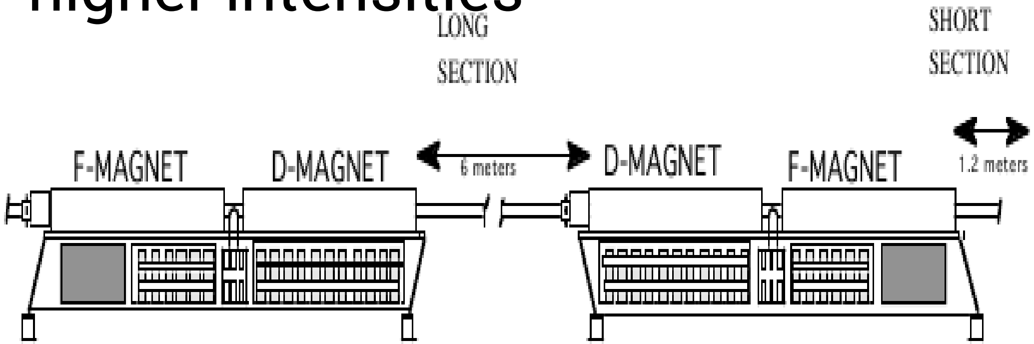
# Transverse Instabilities in the Fermilab Booster

James Amundson,
Alex Macridin
and
Panagiotis Spentzouris
***Fermilab***

# Fermilab Booster

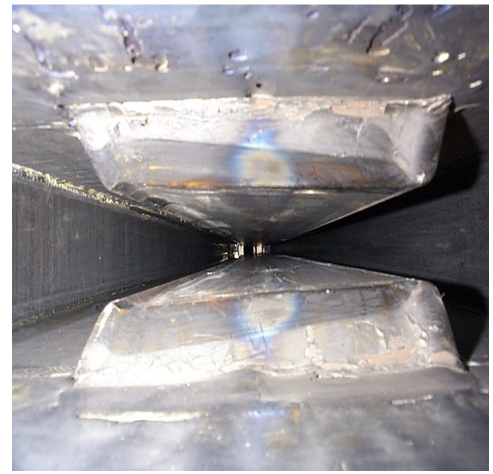
- Rapid cycling synchrotron
- Over 40 years old
- Current intensity ≈ $4.5 \times 10^{12}$ protons per batch
- 400 MeV injection energy
- Observe instability and beam loss at high intensity
  - Space charge important
  - Wake fields also important
- Future Fermilab program will require higher intensities

# Booster Combined Function Magnets

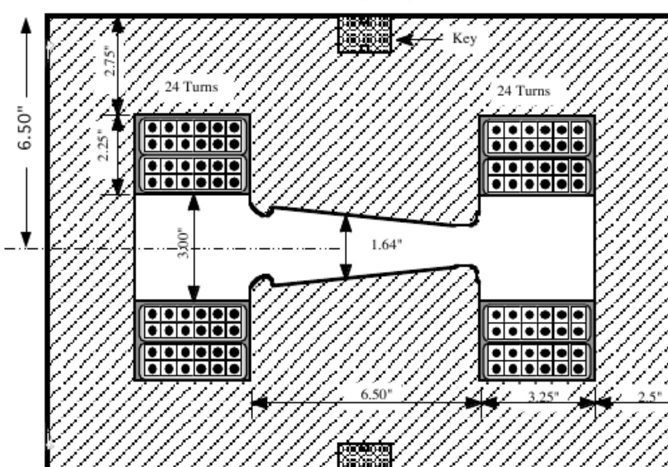
- 60% of the machine length consists of combined-function (dipole & quadrupole) magnets
- Nearly parallel-plane geometry
  - Vertical aperture much smaller than horizontal aperture
- Beam exposed to laminations
  - Large wake fields
- Non-ultrarelativistic* effects are important at injection energy of 0.4 GeV ($\gamma$ =1.42)
  - *neither nonrelativistic nor ultrarelatvistic



focusing

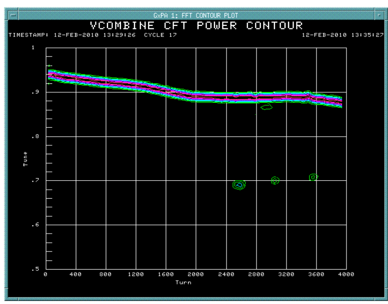
defocusing

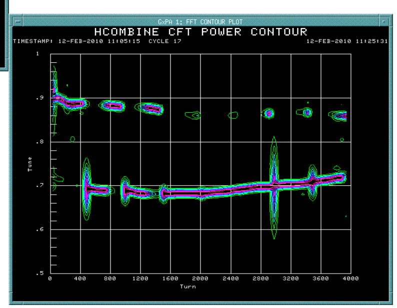
Focusing Magnet



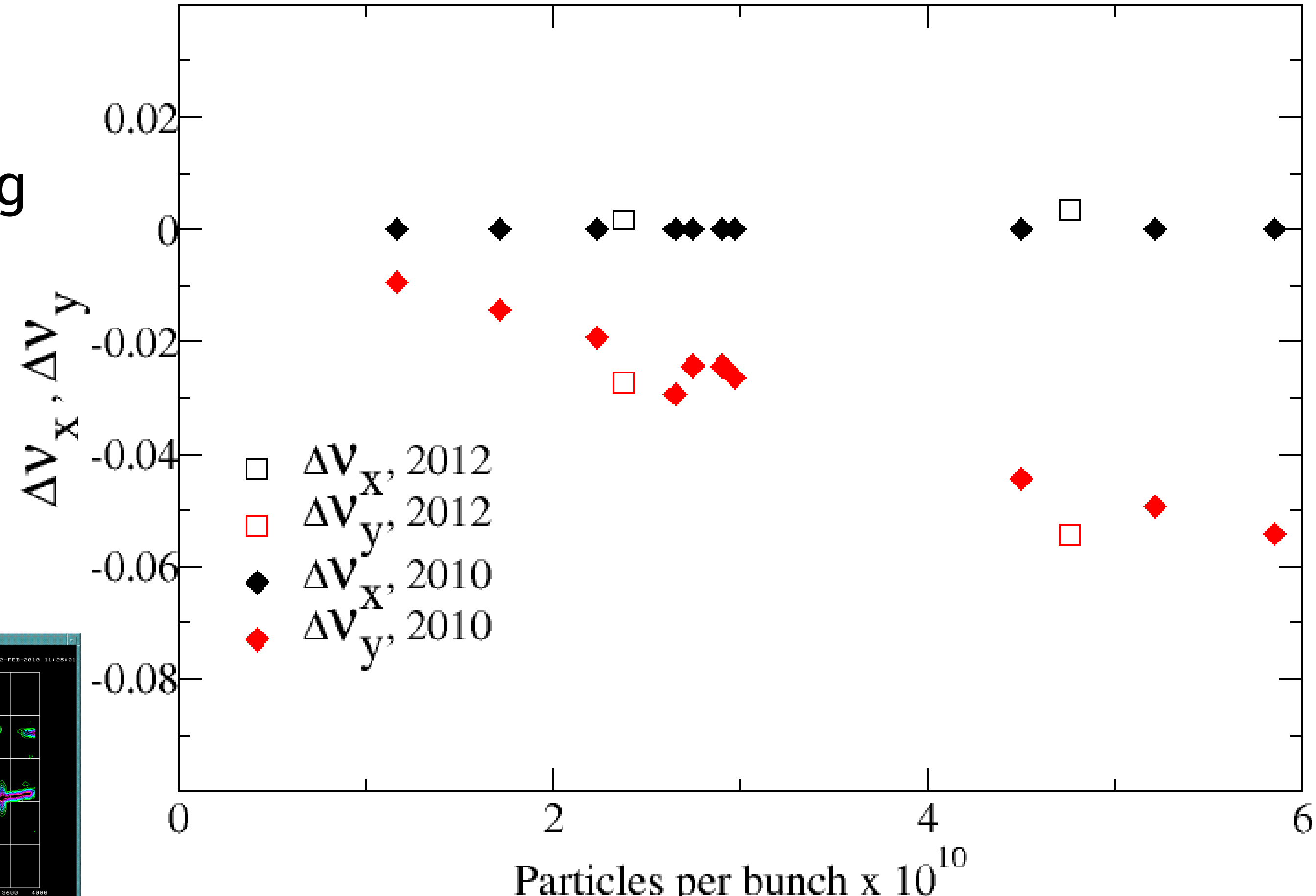
# Observed Coherent Tune Shift

- Tunes measured at injection
- Intensity varied by varying number of injection turns from 2 to 15




*Daniel McCarron, PhD thesis*




- With increasing intensity, observe
  - Strong vertical tune suppression
  - Weak (or no) horizontal tune enhancement

# Observed Horizontal Instability

## Horizontal instability observed near injection

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

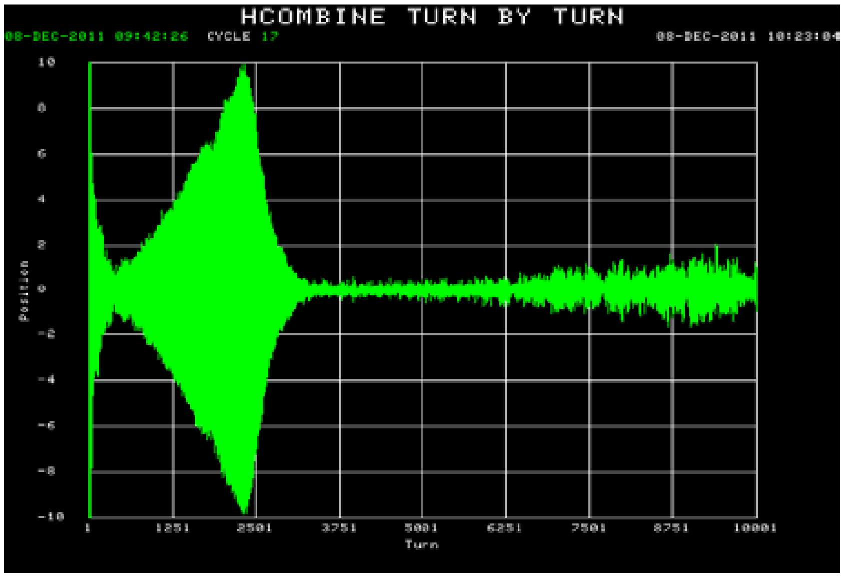



Figure 1: Combined TBT signal from HBPMs (arbitrary units) at $N_p = 4{\cdot}10^{12}$ after coupling correction.

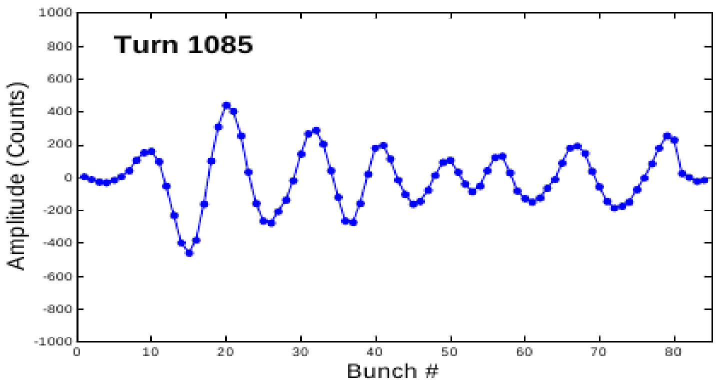
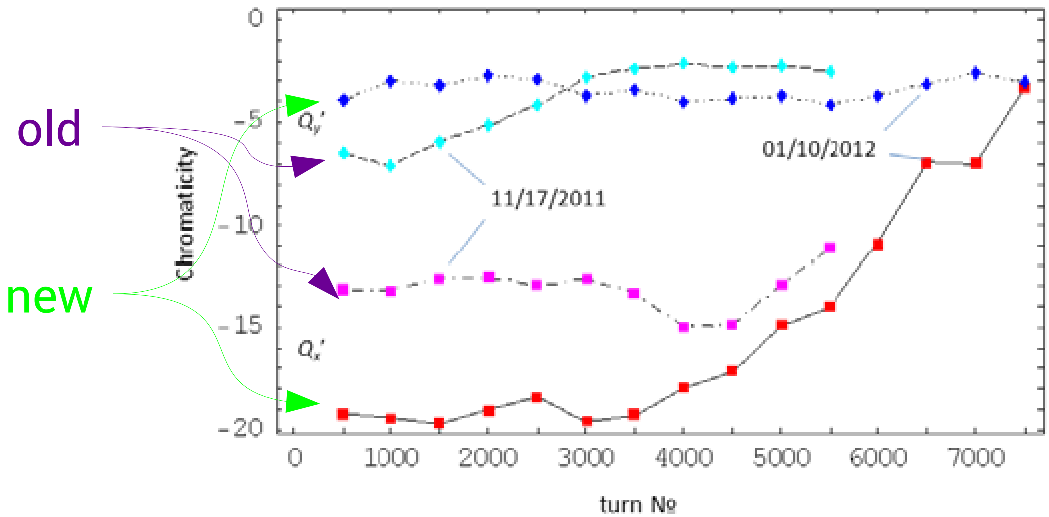



Figure 3: Bunch-by-bunch horizontal positions at the onset of horizontal instability

In operation, problem solved by modifying chromaticity



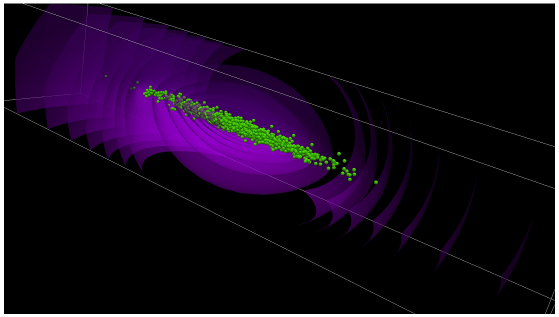

Quantitatively:

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

Changed 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



## Synergia: A comprehensive accelerator beam dynamics package

http://web.fnal.gov/sites/synergia/SitePages/Synergia%20Home.aspx


Fermilab

Accelerator Simulation Group

James Amundson, Paul Lebrun, Qiming Lu, Alex Macridin, Leo Michelotti, Chong Shik Park, (Panagiotis Spentzouris) and Eric Stern


## The ComPASS Project

High Performance Computing for Accelerator Design and Optimization

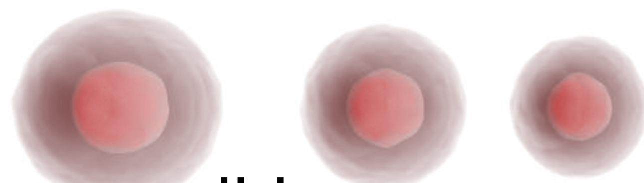
https://sharepoint.fnal.gov/sites/compass/SitePages/Home.aspx


Funded by DOE SciDAC

# Synergia Booster Model

- General wake field model
  - Wake functions calculated for Booster combined function magnets
  - Inter- and intra-bunch effects

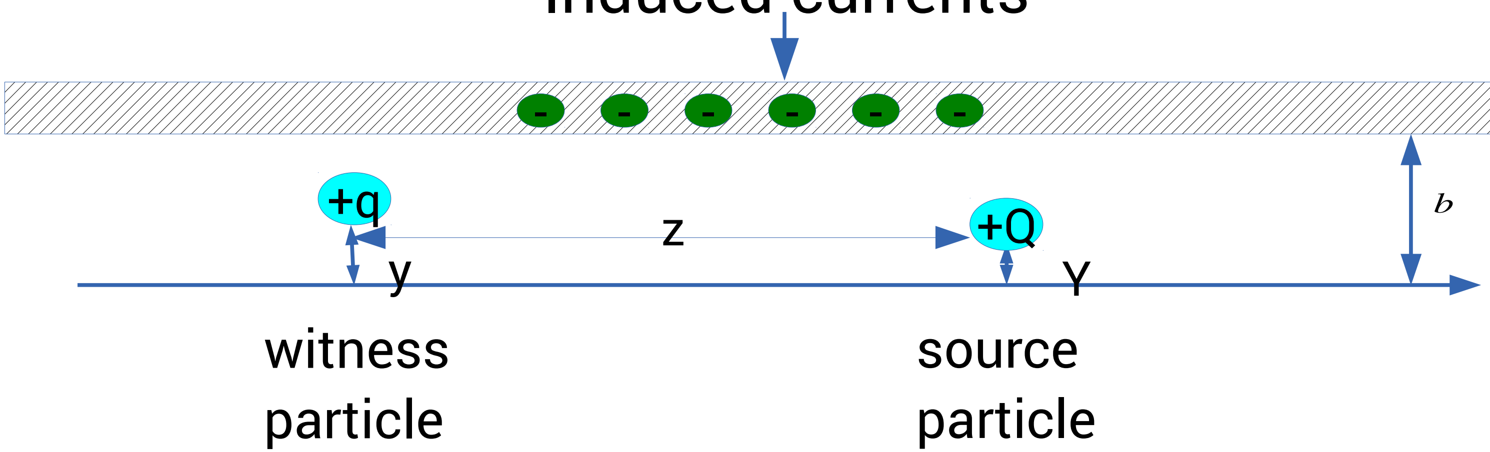
- Space charge
  - 3D



  - Rectangular conducting boundary conditions
  - Carefully avoid double-counting wake fields
- Multiple bunches

  - Communicate through wake fields

# General Wake Field Model




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

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

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

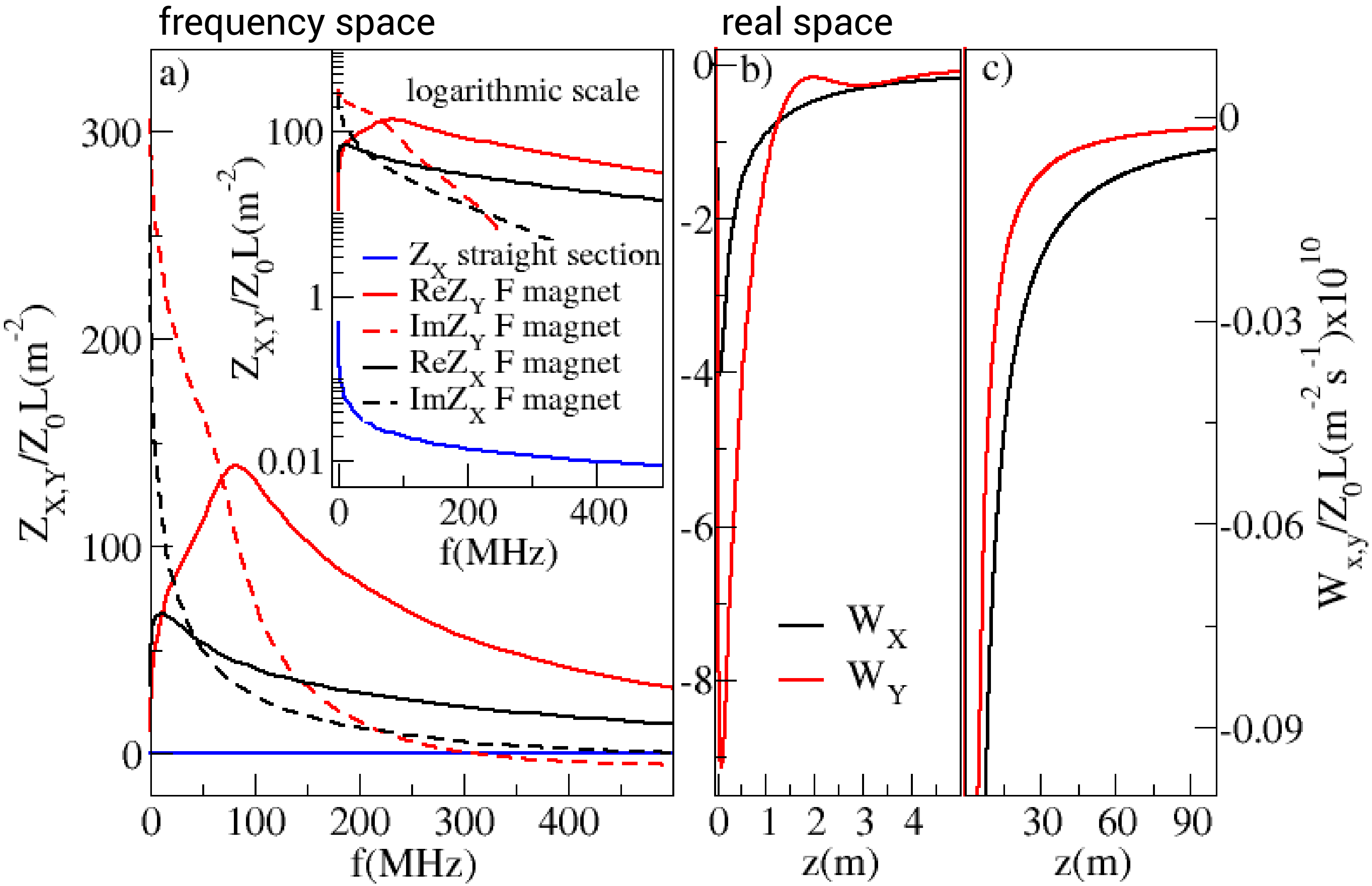
- q,Q - charges of the witness and source particles
- X,Y - displacements of the source particle
- *x,y* - displacements of the witness particle
- *z* - distance between the source and the witness particles

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

# Wake Field Calculation in the Booster

- New calculation of wake fields in Booster combined function magnets
  - *A. Macridin, et al., PRST-AB 14, 061003 (2011)*
  - *A. Macridin, et al., PRST-AB 16, 121001 (2013)*
- Results show limitation of simple geometric arguments
  - Relative magnitude of vertical and horizontal wake functions change with frequency/length scale
- General technique for wake field calculations
  - neither non-relativistic nor ultra-relativistic
  - applied to exposed lamination magnets

# Wake Field Calculation in the Booster (2)

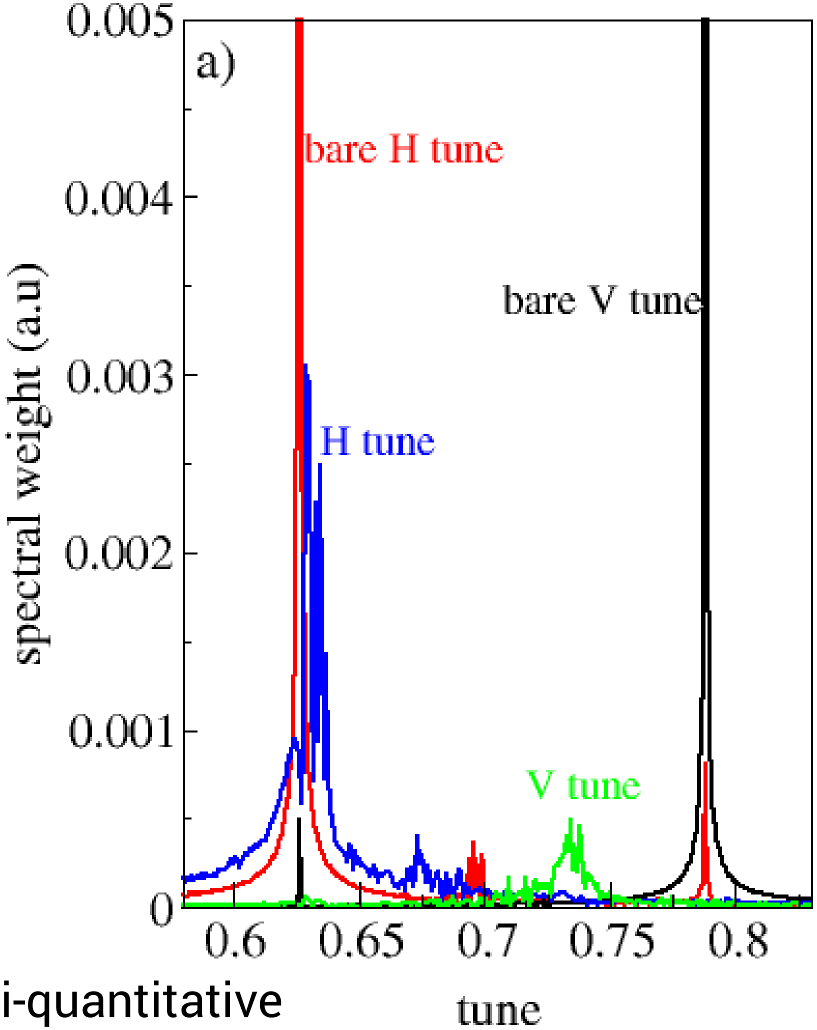



- Impedance in the laminated magnets is much larger ($10^3$~$10^4$ times) than in the straight sections
- Vertical wake dominates at short distances, horizontal dominates at long distances (note negative magnitude!)

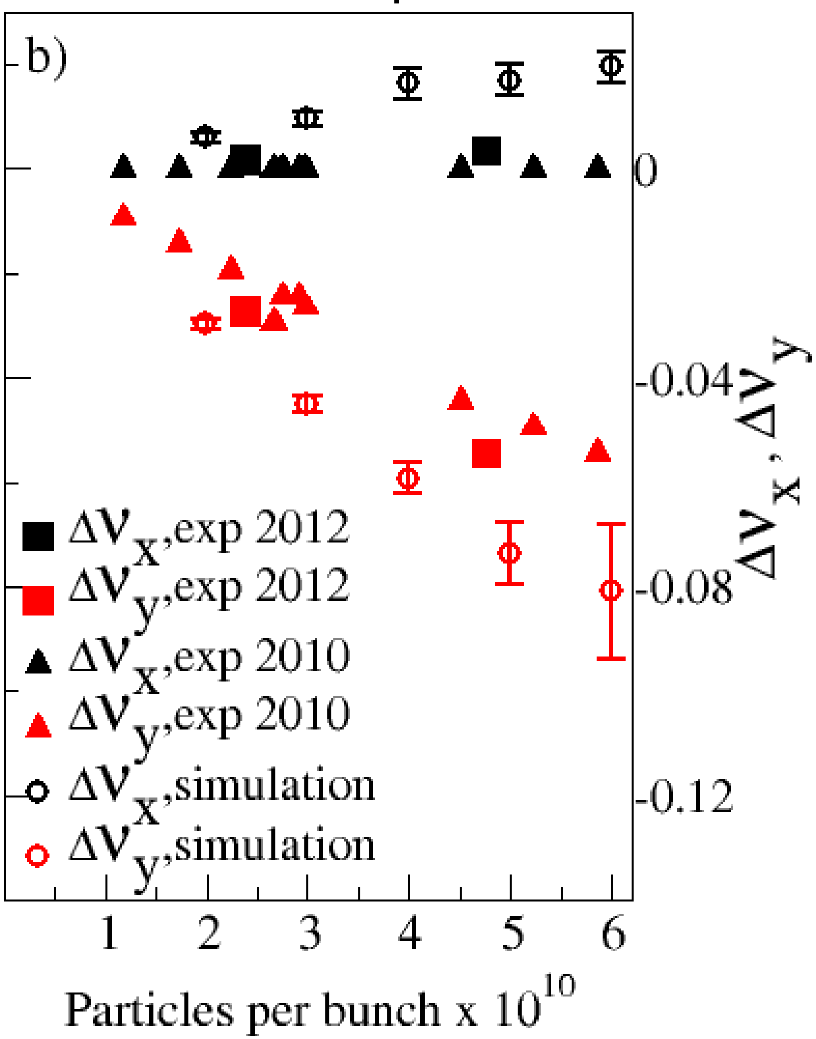
# Results: Coherent Tune Shift

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

simulation




simulation and experiment

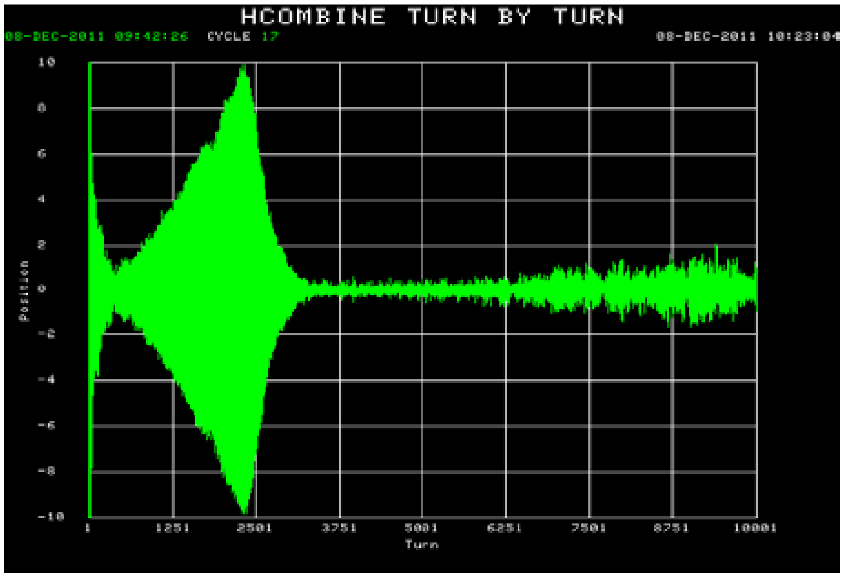



Qualitative and semi-quantitative reproduction of experimental results

# Results: Horizontal Instability

## experiment

*4 x 10^10 p per bunch* $\left(\frac{\omega_{\xi x}}{\beta c}, \frac{\omega_{\xi y}}{\beta c}\right) = 2\pi \times (0.06\, m^{-1}, 0.025\, m^{-1})$

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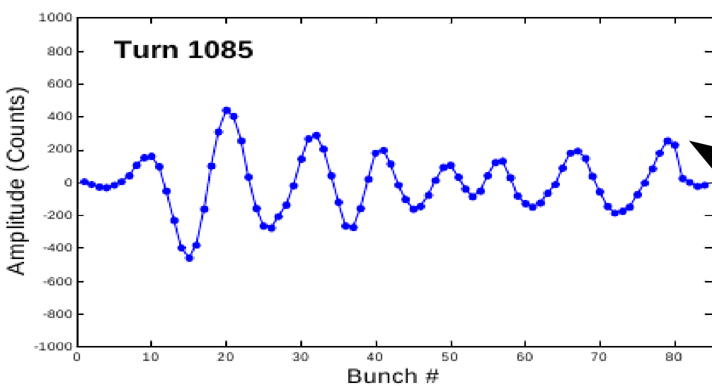
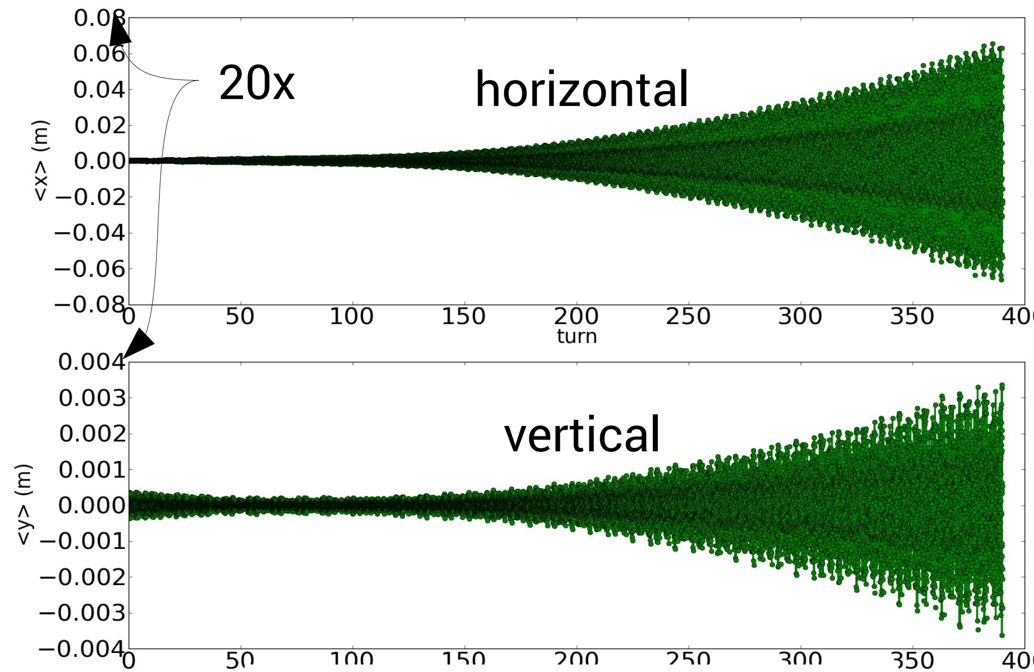


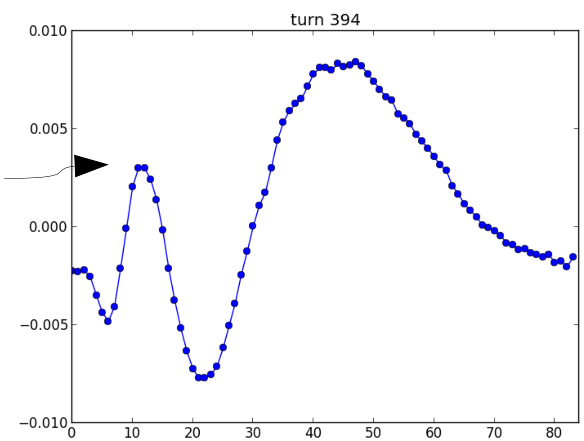

Figure 3: Bunch-by-bunch horizontal positions at the onset of horizontal instability

## simulation

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




bunch-to-bunch coupling effect




*qualitative agreement*

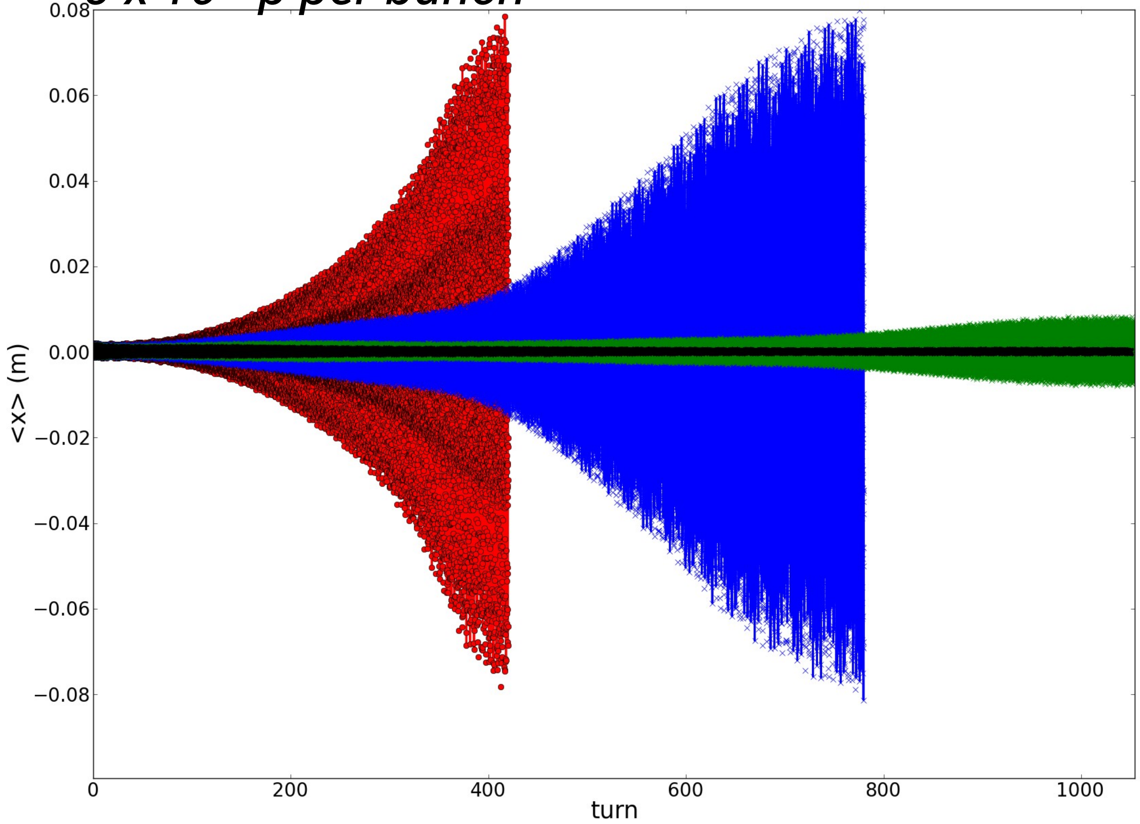
# Results: Chromaticity Dependence

experiment

*4 x 10^10 p per bunch*


simulation

*5 x 10^10 p per bunch*




Larger chromaticity works!
(Horizontal instability does not interfere with operation.)

*qualitative agreement*

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

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

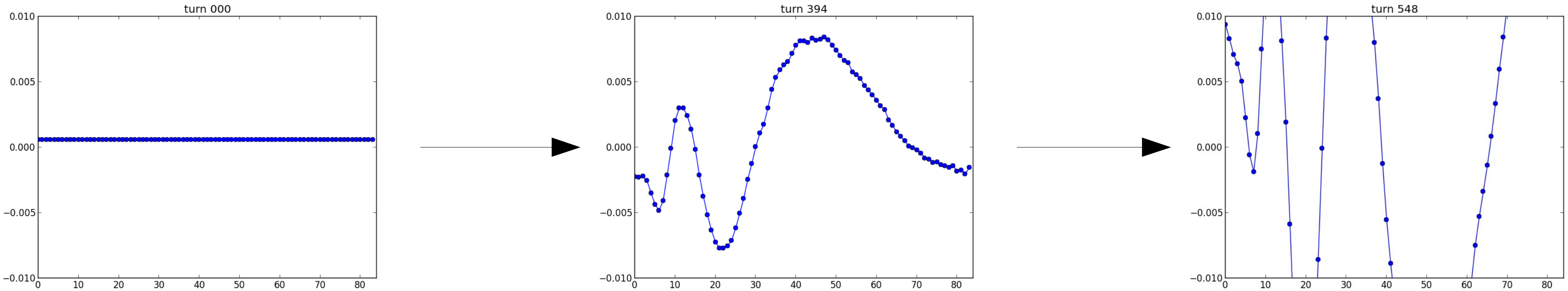
$\frac{\omega_{\xi x}}{\beta c} = 2\pi \times 0.046 m^{-1}$ *blue*

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

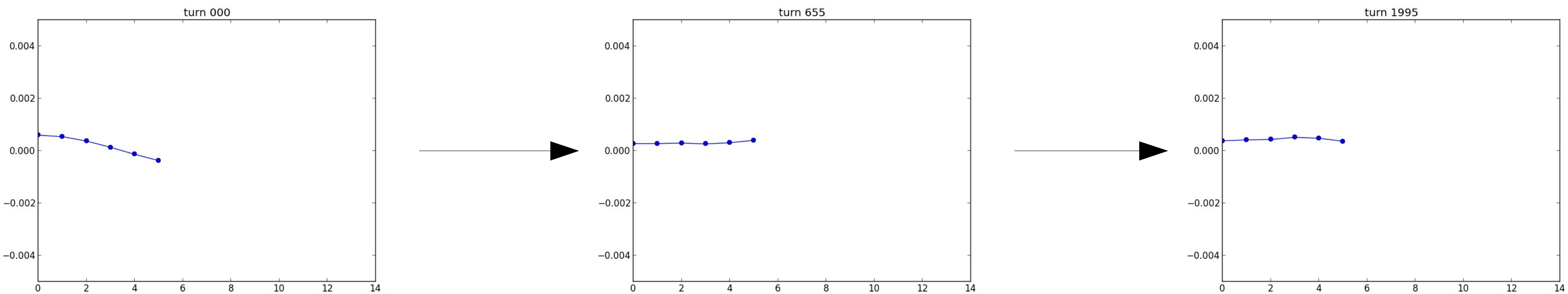
# Why? Many-bunch effect

## 84 bunches: instability

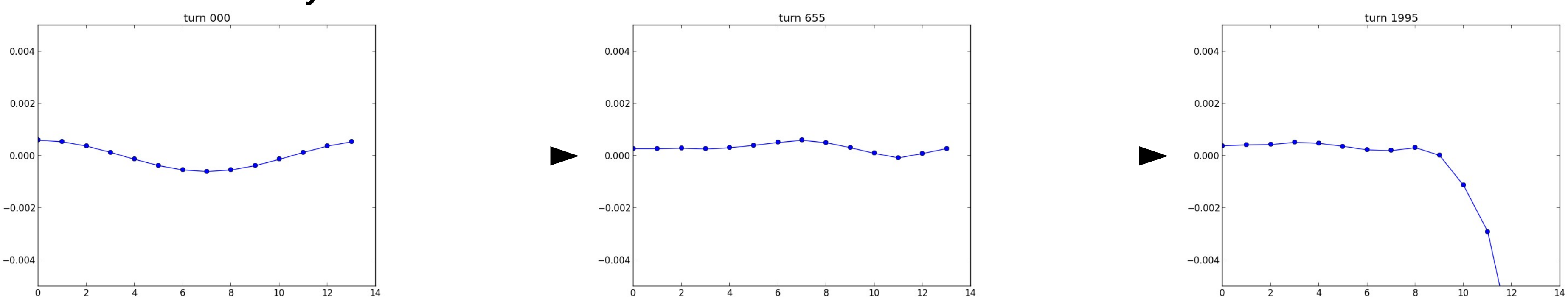
https://cdcvs.fnal.gov/redmine/projects/synergia2/wiki/Multi-bunch_animation



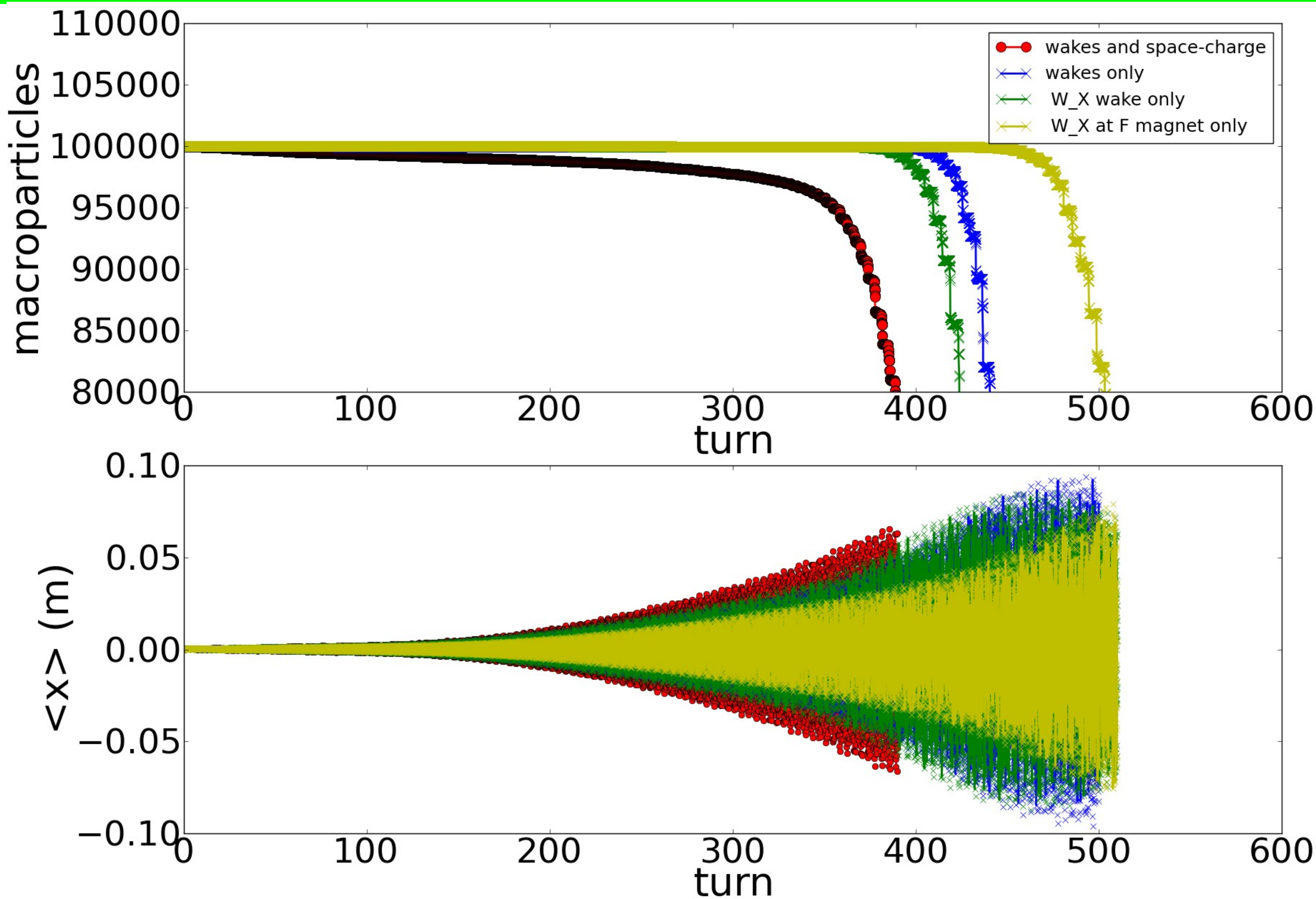

## 6 bunches: no instability




## 14 bunches: instability



# Why? Beta function enhancement



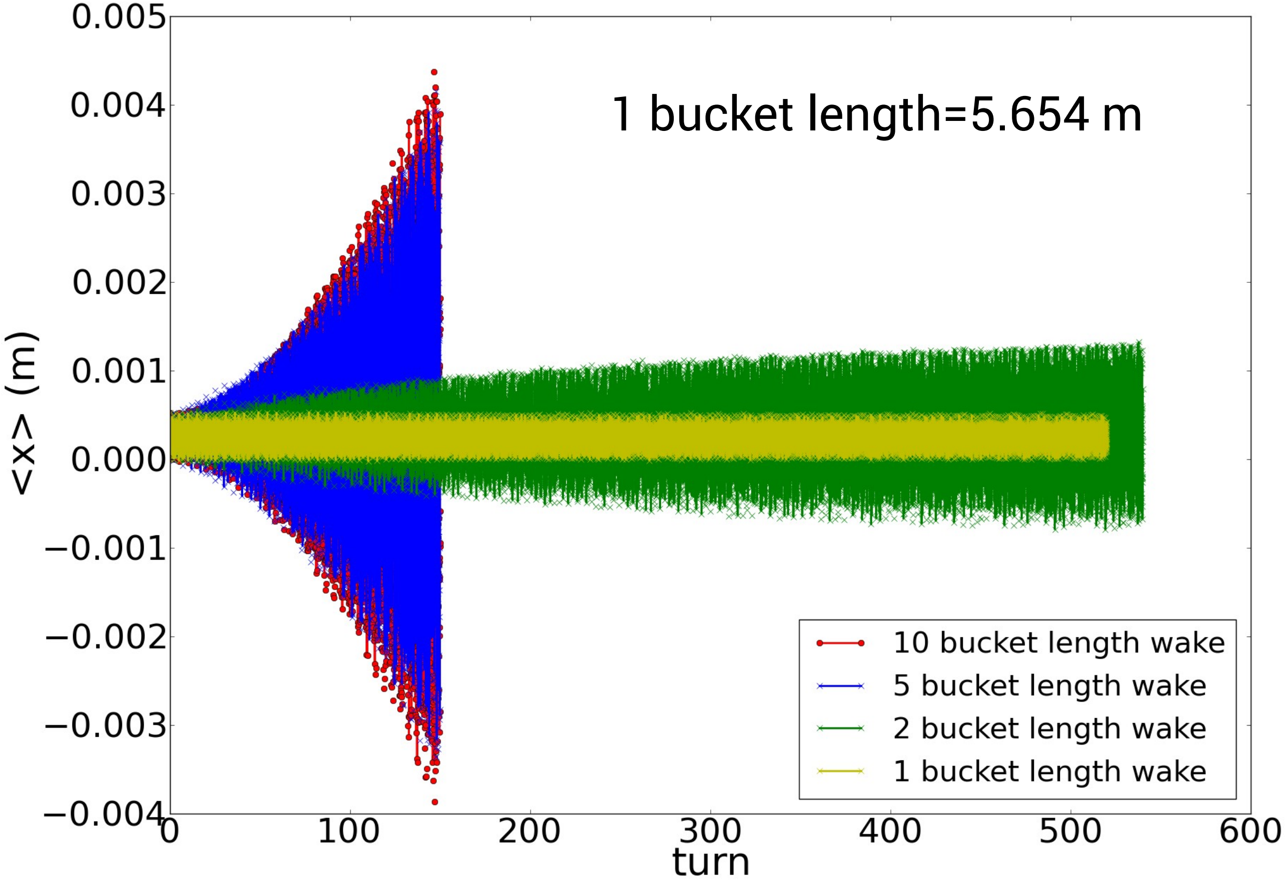

$$\langle\beta_x\rangle_F = 27.758$$
$$\langle\beta_y\rangle_D = 16.78$$
$$\langle\beta_x\rangle_D = 12.784$$
$$\langle\beta_y\rangle_F = 8.15$$

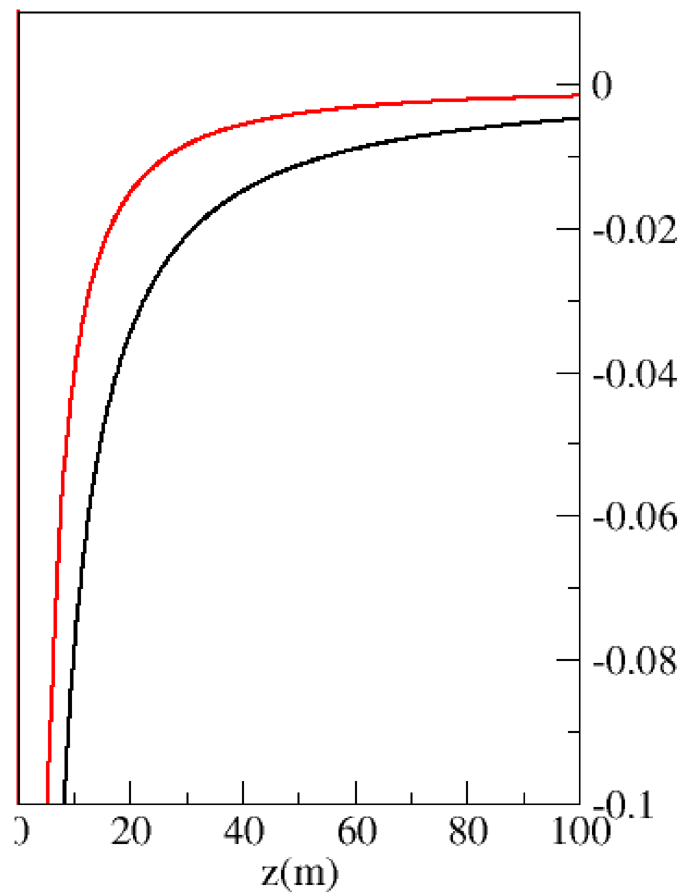
$$\tau^{-1} \propto \int ds\, \beta(s) \int dz\, W^{\perp}(s-z)$$

instability growth rate

The dipole horizontal wake at the location of the F magnets alone is enough to cause instability

# Why? Wake length scale




Scale for the instability is 2-5 bucket lengths.

Horizontal wake (black) dominates at relevant length scales (10m-30m). *Note negative magnitude!*

# Conclusions

- Exposed laminations in the Booster combined function magnets lead to large wake fields
  - ... and large headaches
    - Observe large vertical tune shift with increasing intensity
    - Observe horizontal instability at low chromaticity
- Our Synergia model of the Booster includes multiple bunches, wake fields and space charge
  - New calculation of wake fields in the Booster
    - Non-trivial structure in frequency/distance
  - Qualitatively and semi-quantitatively describe observed tune shifts and instability
- The simulation allows us to explore the reasons for the effects
  - Bunch-bunch interactions are necessary
  - The relevant length scale is 2-5 bucket lengths
  - The horizontal instability is due to two effects
    - Large horizontal lattice beta function at F magnets locations
    - Larger horizontal wake field at the relevant interaction length scale

# Gory simulation details

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] (sy

* 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"