Wakes in laminated magnets and applications for Fermilab Booster

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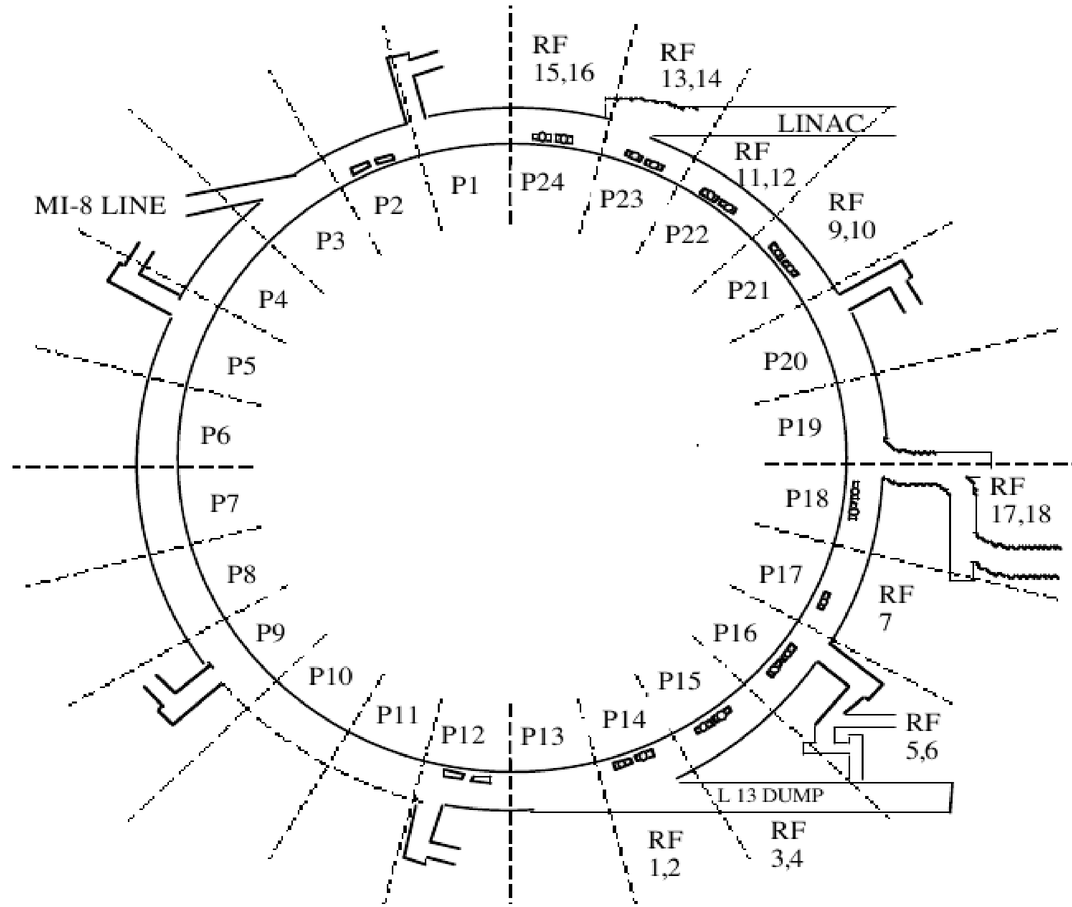
Outline:

- Introduction
- Impedance and wake in laminated magnets
- Synergia code
- Results
- Conclusions

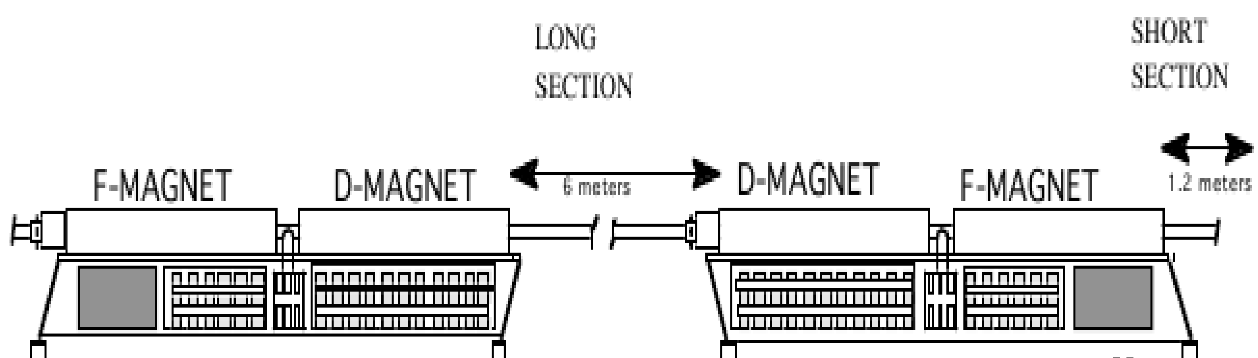
Fermilab Booster:

- Intensity ≈ 6 x 10^{12} p, much grater than the design value
- At injection, E= 400 MeV, γ=1.4
- Collective effects are important

  space-charge
  wake fields



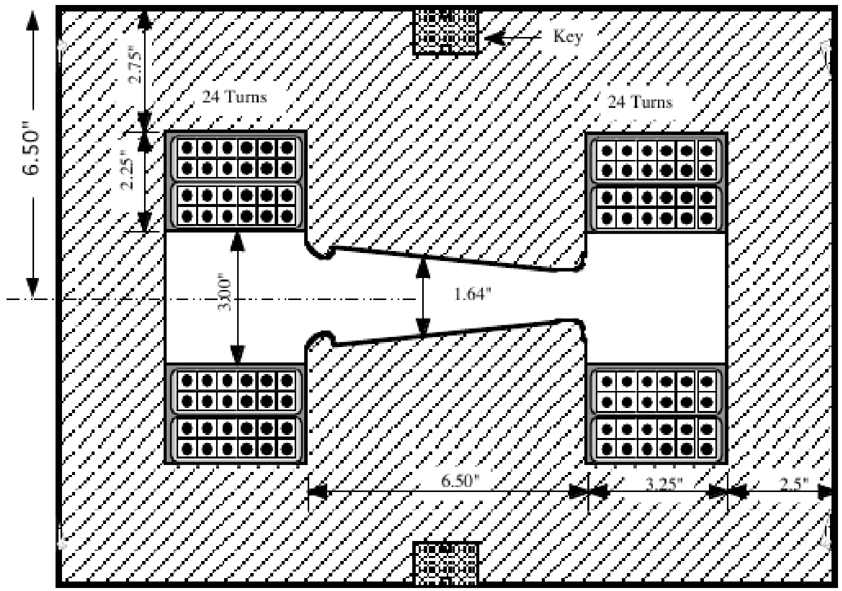
- 24 cells
- F-magnets
- D-magnets
- straight sections



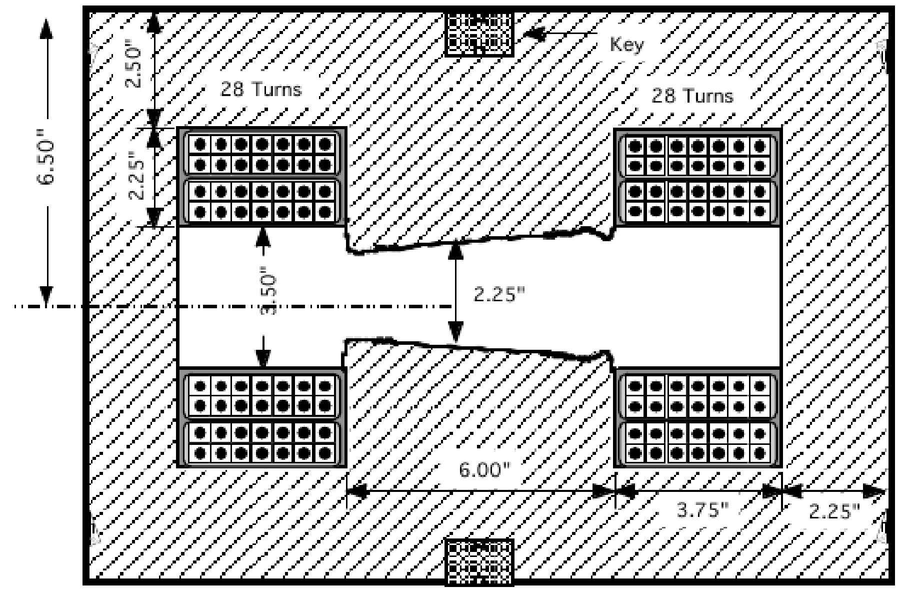
FDOODFO cell

Particularities of Booster magnets:

Focusing Magnet



Defocusing Magnet



- **Vacuum chamber geometry**

We assume parallel-planes chamber geometry is a good approximation for calculating wake fields

- **Laminations:** strong wake fields

Realistic simulations should include :

- **Single particle maps**

- **3D space-charge solvers for the parallel-planes magnets and the circular straight sections**

- **Coupling wake fields for laminated magnets**

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Wakes for chambers with parallel-planes geometry

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

$$c\Delta p_x = -qQ(W^{\perp}{}_x(z)X - W^{\perp}{}_x(z)x)$$

$$c\Delta p_y = -qQ(W^{\perp}y(z)Y + W^{\perp}{}_x(z)y)$$

quadrupole terms

Not present in circular chambers

- q,Q - charge of the trailing and the leading particle
- X,Y - displacements of the leading particle
- *x,y* - displacements of the trailing particle
- |z| - distance between the leading and the trailing particles

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

Impedance functions

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

$$W_{x,y}{}^{\perp}(z)=\frac{j}{2\pi}\int d\omega Z_{x,y}(\omega)e^{-j\frac{\omega}{c}z}$$

The impedance can be written in a good approximation as function of
the surface impedance $\mathcal{R}(\omega)$

$$Z^{\parallel}=\frac{\mathcal{R}}{2\pi b},$$

Z=Z($\mathcal{R}$)

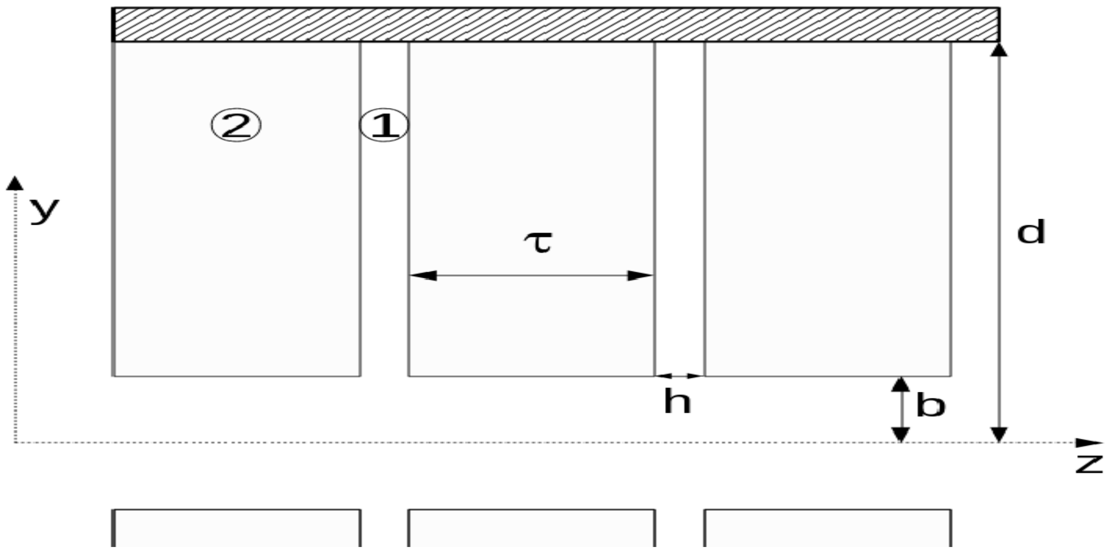
$$Z_x=\frac{\mathcal{R}}{2\pi k}\int_0^{\infty}d\eta\frac{\eta^2\operatorname{sech}^2\eta b}{1-\frac{j\mathcal{R}\eta}{Z_0 k}\tanh\eta b}$$

E_z=-$\mathcal{R}$$H_x$ at pipe's wall (y= b)

$$Z_y=\frac{\mathcal{R}}{2\pi k}\int_0^{\infty}d\eta\frac{\eta^2\operatorname{csch}^2\eta b}{1-\frac{j\mathcal{R}\eta}{Z_0 k}\coth\eta b}$$

for parallel-planes geometry

Laminated structure model



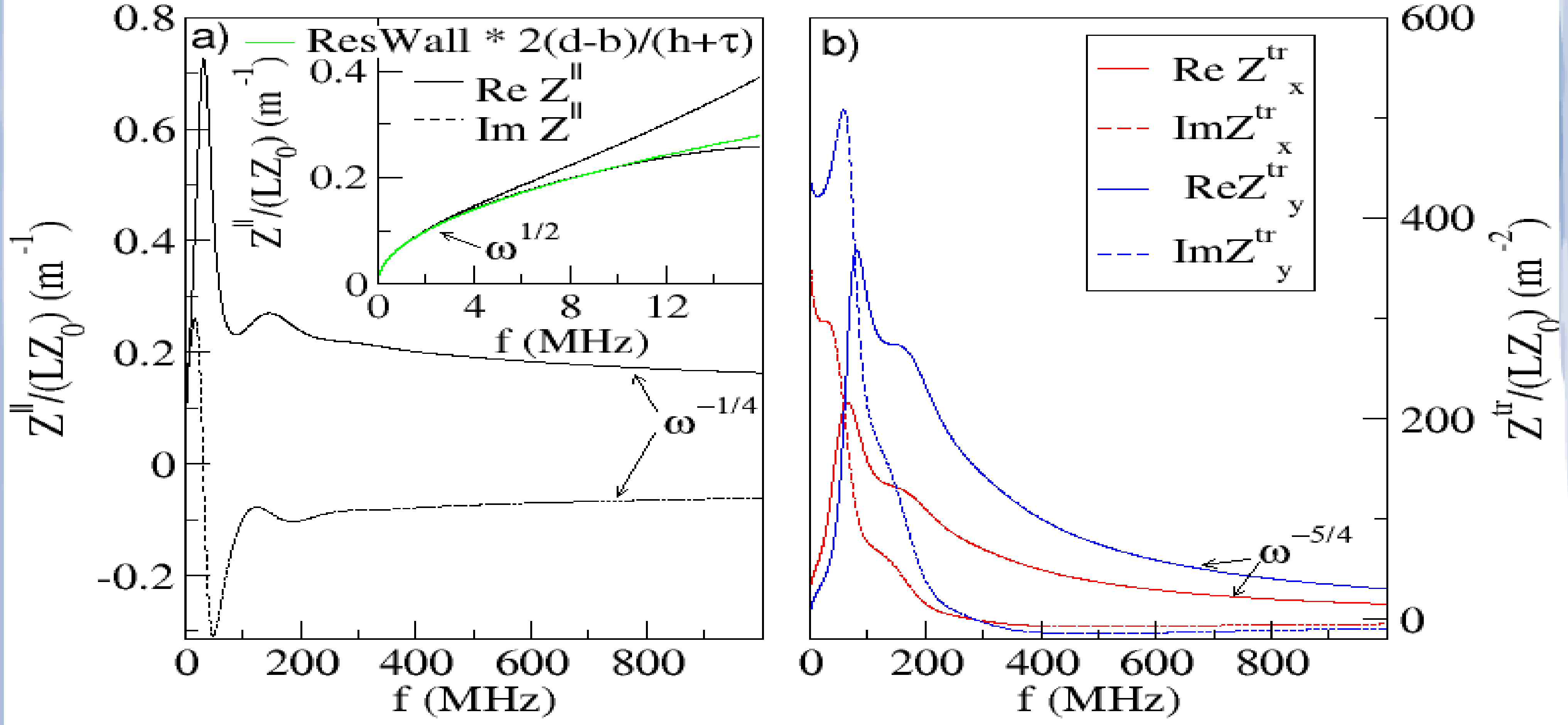
- iron laminations
- dielectric crack
- laminations are shorted

The calculation of the impedances reduces to the calculation of the surface impedance for crack, $\mathcal{R}_c$

$$R = \frac{R_c h + R_l \tau}{h + \tau} \approx \frac{R_c h}{h + \tau}$$

K.Y. Ng, Fermilab, FN-0744

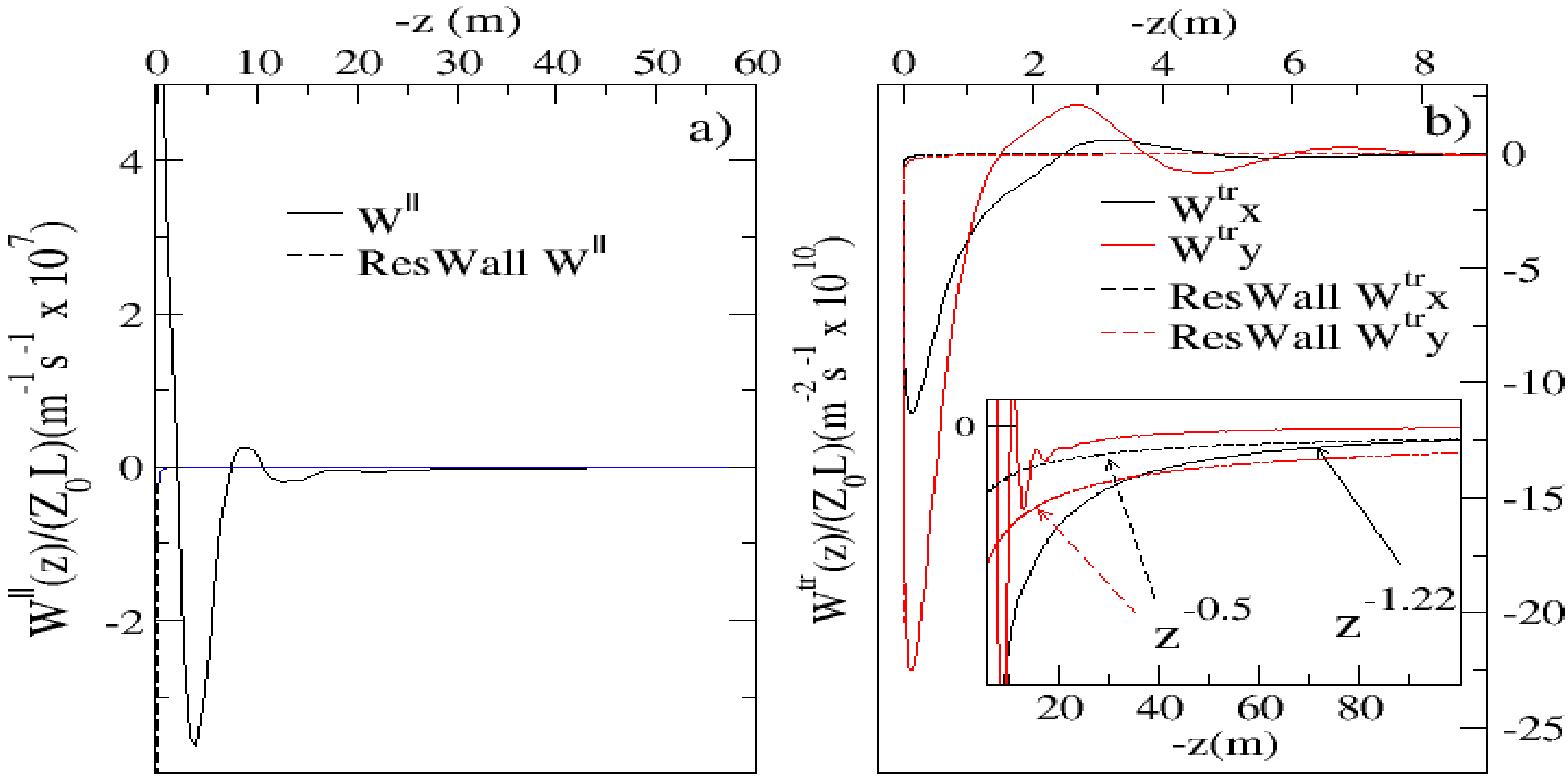
Impedance functions, F-magnet



- Low ω behavior of $Z^{||}$ is resistive-wall like $\approx \omega^{1/2}$ but $\approx$400 times larger than for an iron resistive-wall pipe

- The impedances show two peaks in the interval 20 MHz -200 MHz

Wake functions, F-magnet



- For distance of the order of meters wakes are large
- $W^{||}(z)$ oscillates in sign, is repulsive for z<2m, attractive around z ≈4m
- At large z, $W^{\perp}_{x,y}(z)$ decays faster than resistive-wall wake

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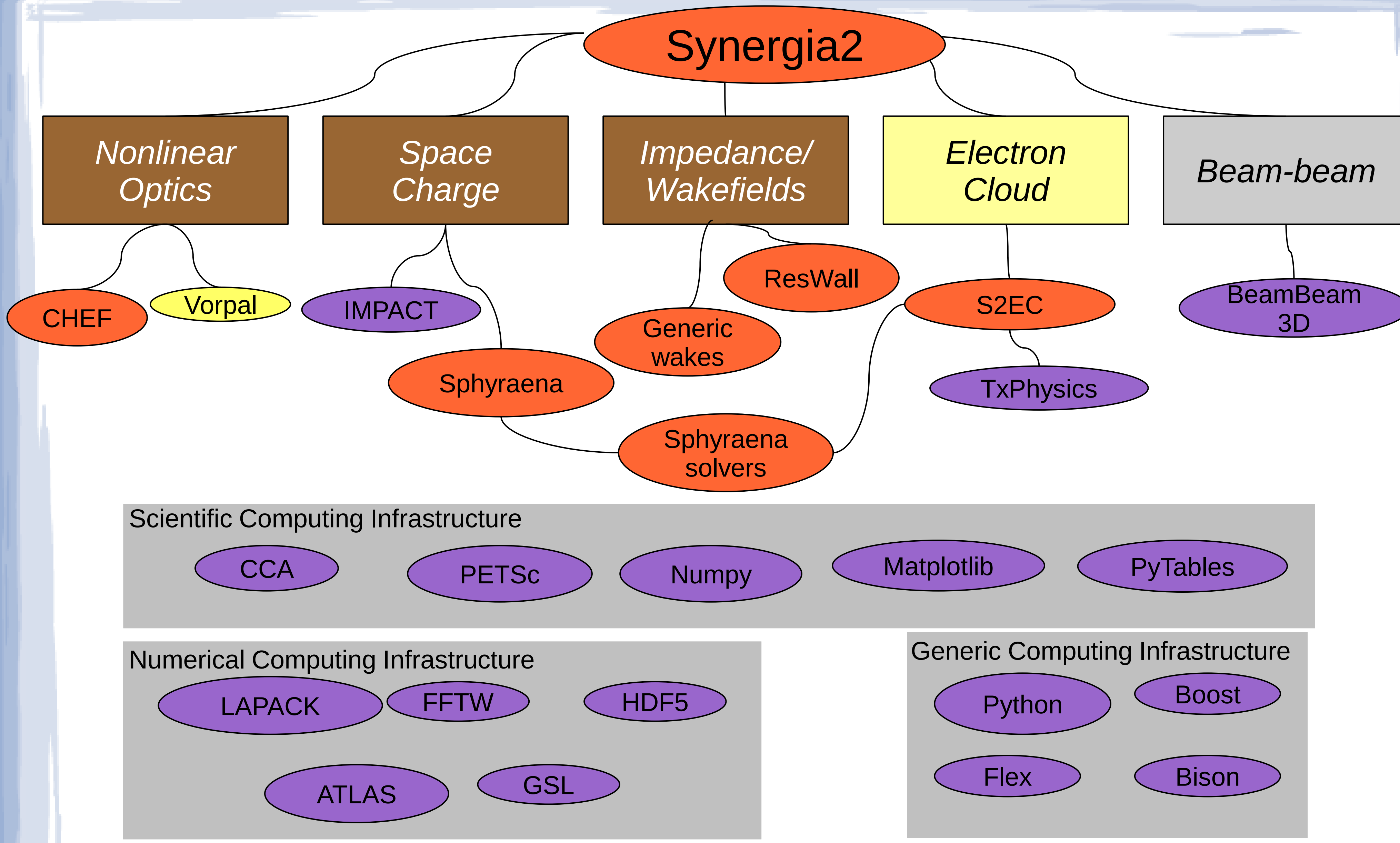

- Synergia is a composite code containing modules from several sources
- Synergia utilizes state-of-the-art numerical and general computing infrastructure

New modules for Booster simulation:

- **3D Poisson solvers (PIC) for parallel-planes and rectangular vacuum chamber geometry**
- **General impedance module, requires a file with tabulated wake functions**

Wake field simulation:

130,000 macroparticles per bunch

Example: transverse kick of the macroparticle "i"

$$c\Delta p_{xi} = -qQ\sum_j (W^{\perp}{}_x(z_{ji})X_j - W^{\perp}{}_x(z_{ji})x_i)$$

$$c\Delta p_{yi} = -qQ\sum_j (W^{\perp}{}_y(z_{ji})Y_j + W^{\perp}{}_x(z_{ji})y_i)$$

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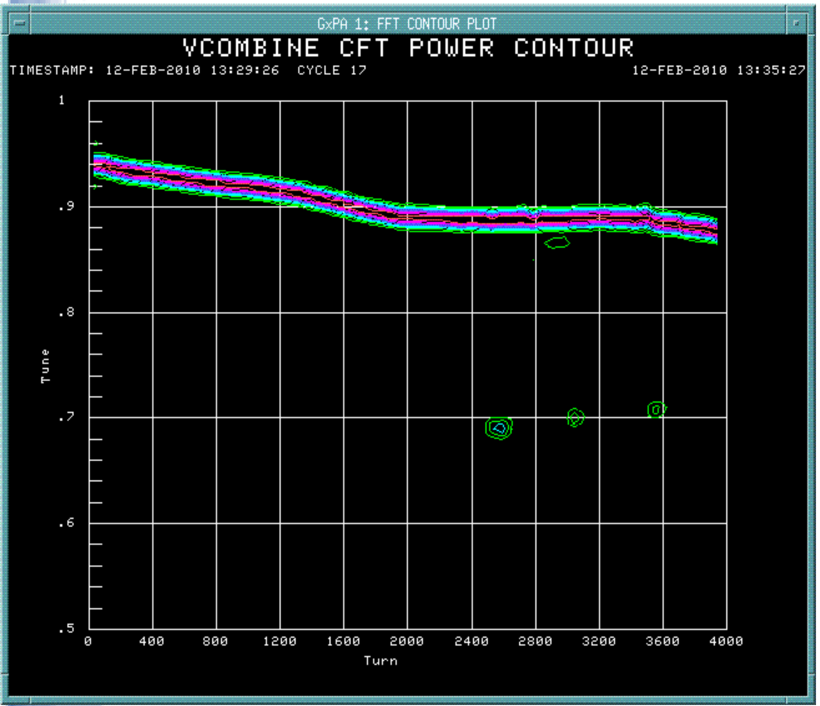
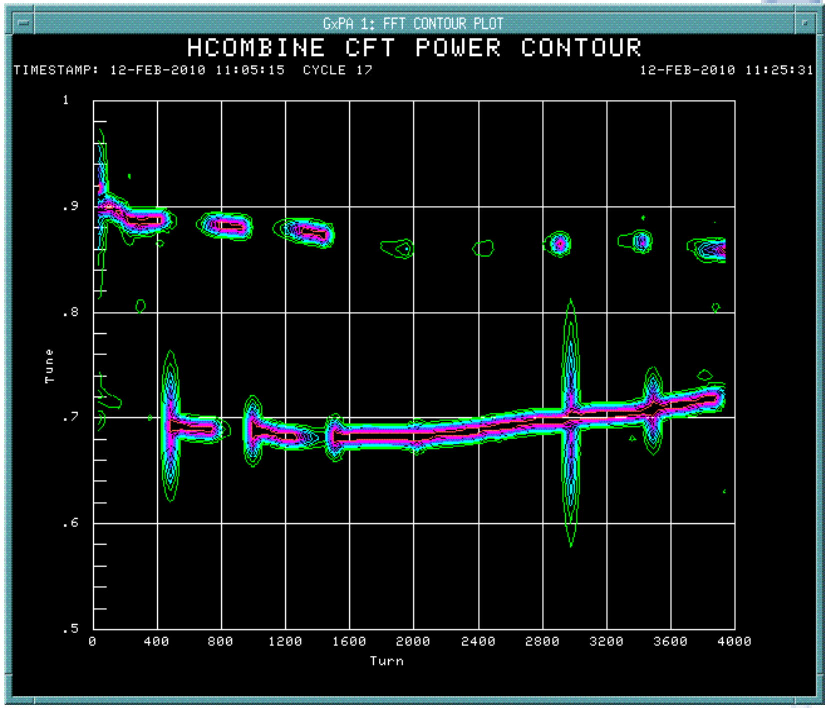
Experiment

Tunes separated to minimize coupling effect

Daniel McCarron
PhD Thesis, 2010



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

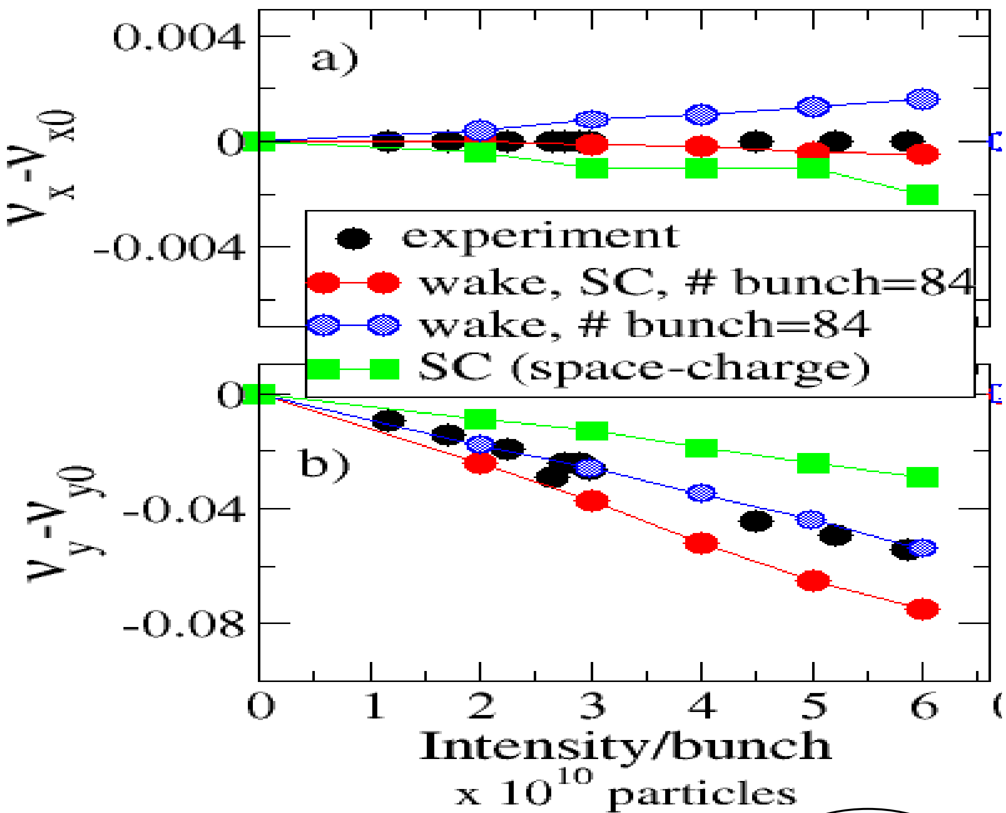


Direct measurement of tune shift with well-separated tunes

- Large tune separation to minimize coupling effect
- Tunes recorded continuously over 1st few *ms* of cycle
- Cumulative effect on tune observed
- Magnification from laminations in keeping with prediction

Chao, Heifets, Zotter PRSTAB vol. 5, 111001 2002

Coherent tune shift, comparison with experiment



- **No net acceleration**
- **Runs at injection E=400MeV**
- **Good agreement with the experiment**

$$c\Delta p_x = -qQ(W^{\perp}{}_x(z)X - W^{\perp}{}_x(z)x)$$

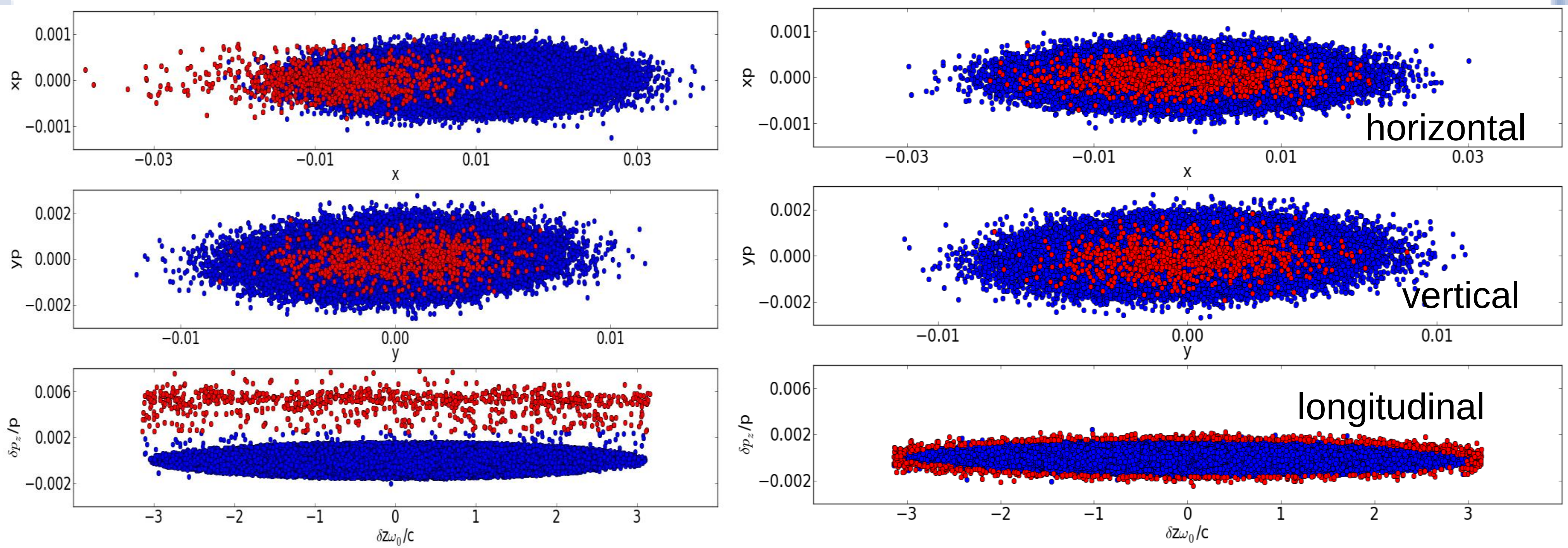
$$c\Delta p_y = -qQ(W^{\perp}y(z)Y + W^{\perp}{}_x(z)y)$$

quadrupole terms

Quadrupole wake effect:

- υ_x increases
- υ_y decreases

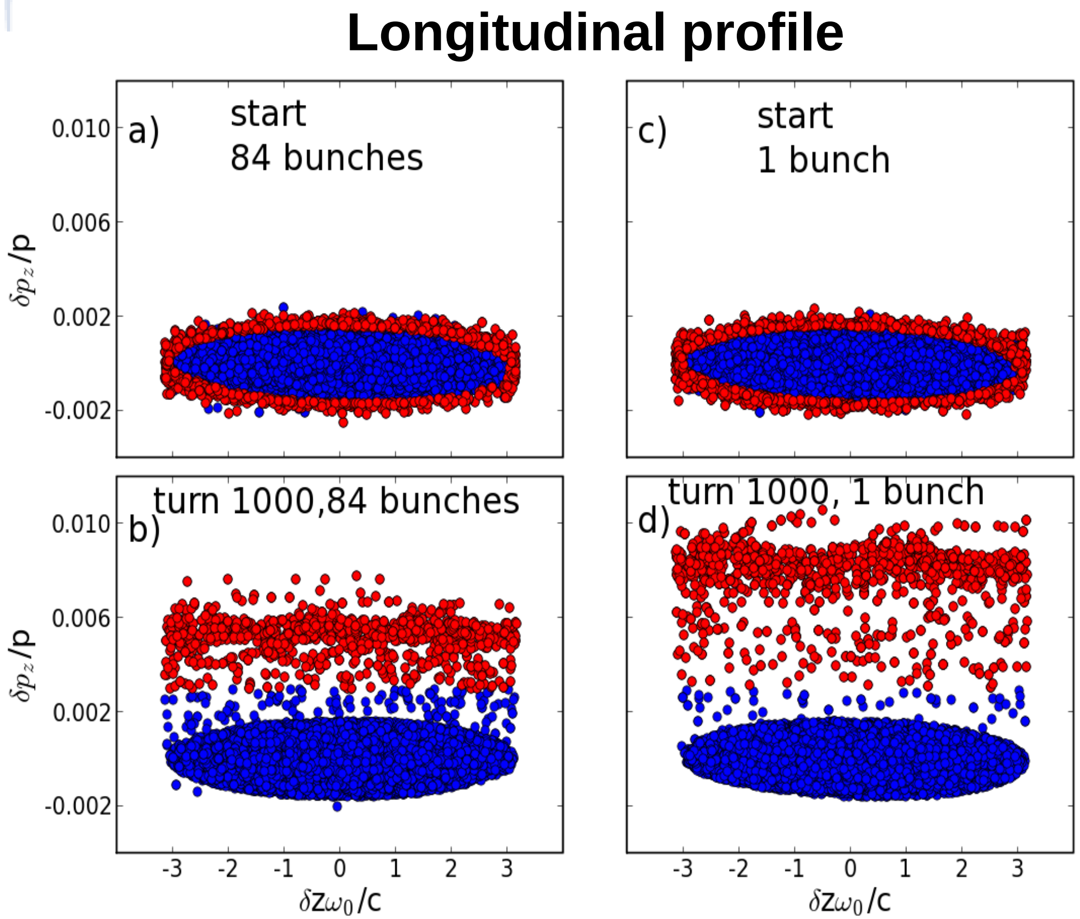
Phase space profiles

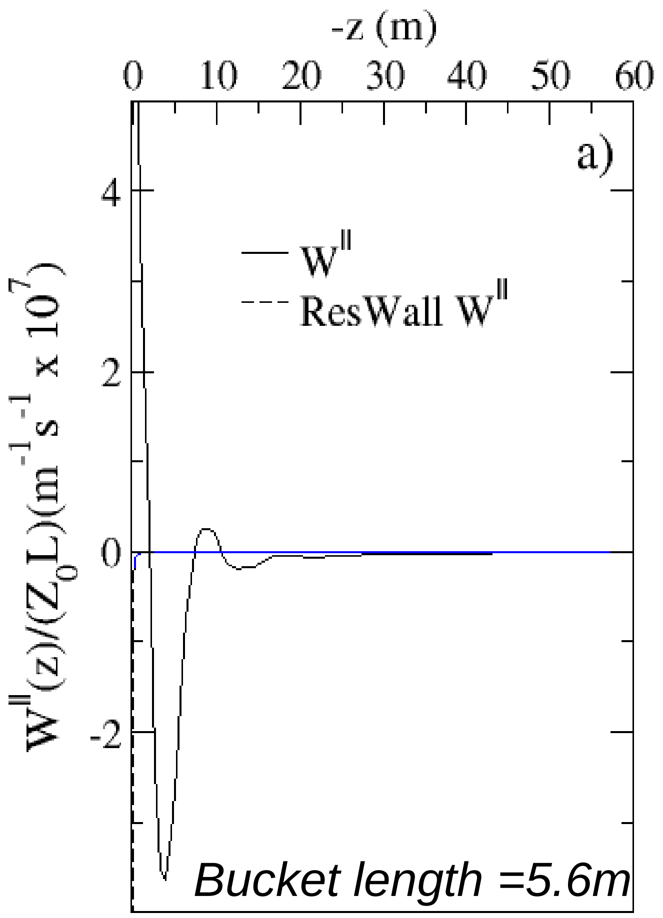


1000 turns **injection**

- **We start with a matched beam for the simulations without collective effects**
- **The departing particles after 1000 turns (red points) are traced back. At injection they are close to the separatrix**
- **Wake fields contribute to beam loss, ≈1% after 1000 turns**

Single bunch versus multi-bunch simulation





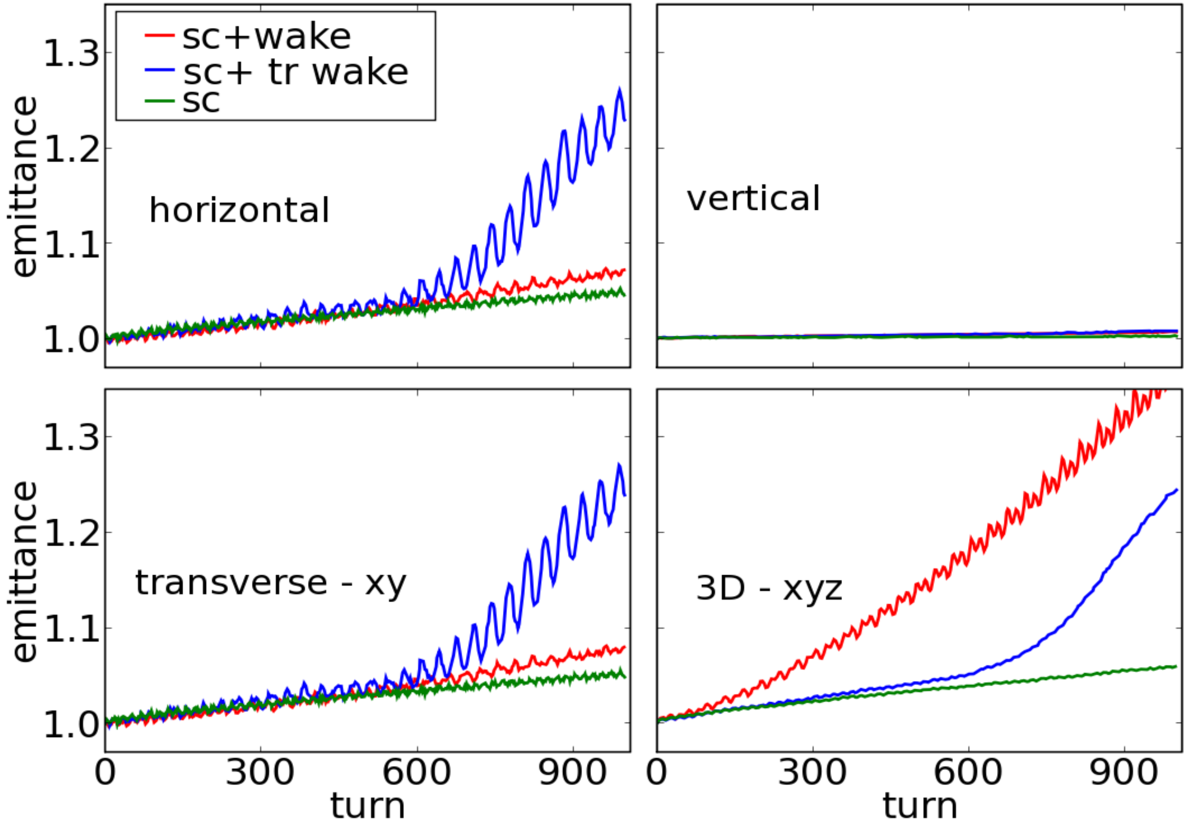
Longitudinal wake

- **Beam loss is reduced by the wake interaction between bunches**
- **The attraction between bunches reduces beam loss**

Emittance

3 simulations:

- **Space-charge and full wake**
- **Space-charge and transverse wake only**
- **Space-charge only**



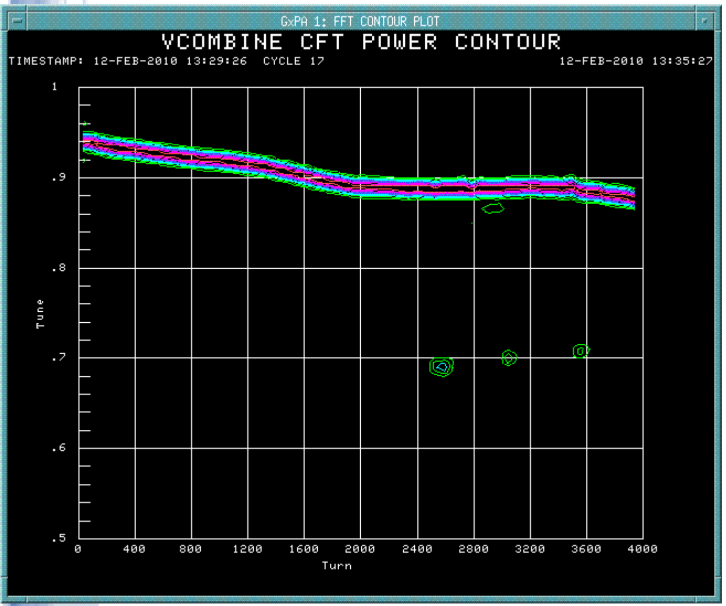
- **Wake fields increase strongly the emittance**
- **The space-charge effect on emittance is much smaller**
- **The transverse wakes increase the transverse emittance**

Conclusions:

- The laminated wake fields are large and have a very different shape then the resistive wall ones
- The coherent tune shift simulations are in good agreement with experiment
- The longitudinal wake has the potential to produce significant beam loss
- Bunch-bunch wake interaction reduces beam loss
- The wake fields increase strongly the emittance

Study 2

Tunes separated to minimize coupling effect



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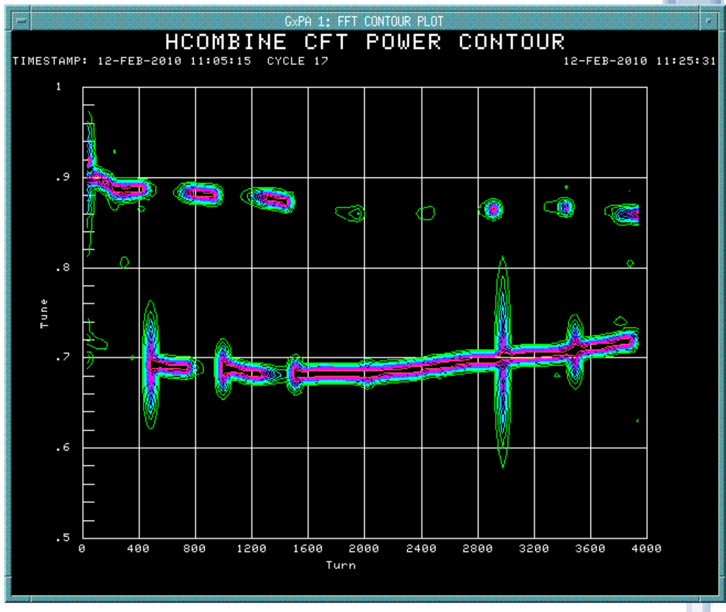
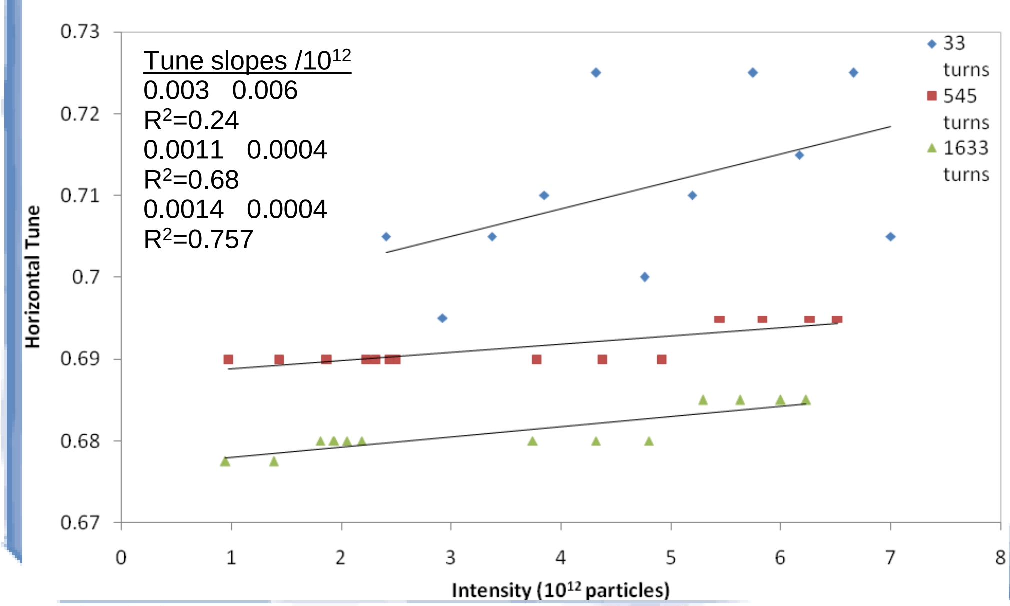


Tunes vs. intensity near injection, and later in cycle

Horizontal Tune Dependence on Intensity



Vertical Tune Dependence on Intensity