Transverse Space-Charge Coupling in the Fermilab Booster

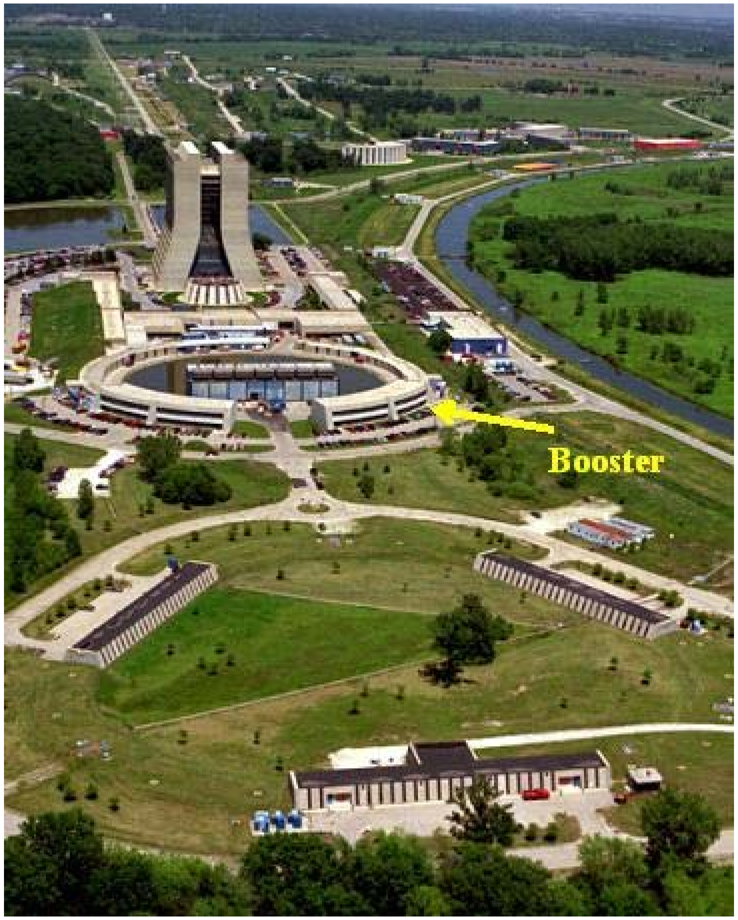
1. The 'Plight' of the Booster

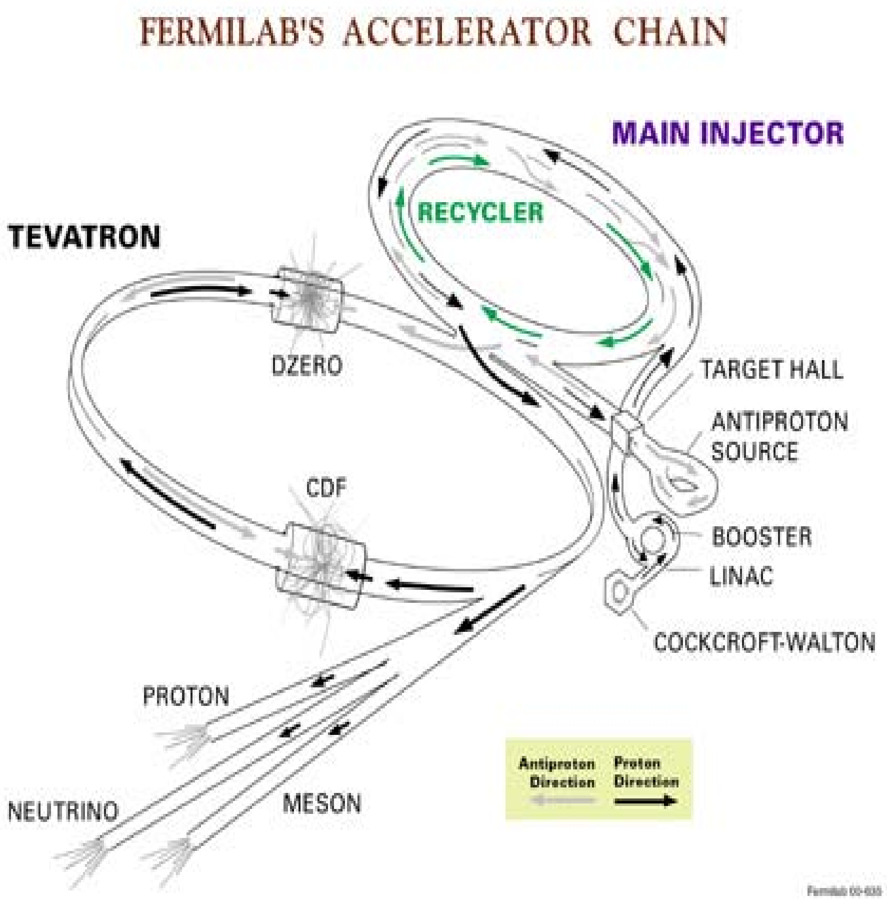
2. Coupling due to external fields (how to measure it)

3. Coupling due to space charge (we DID measure it)

4. Simulations – what we can reproduce (and what we can't yet)

The Booster, present-day photo

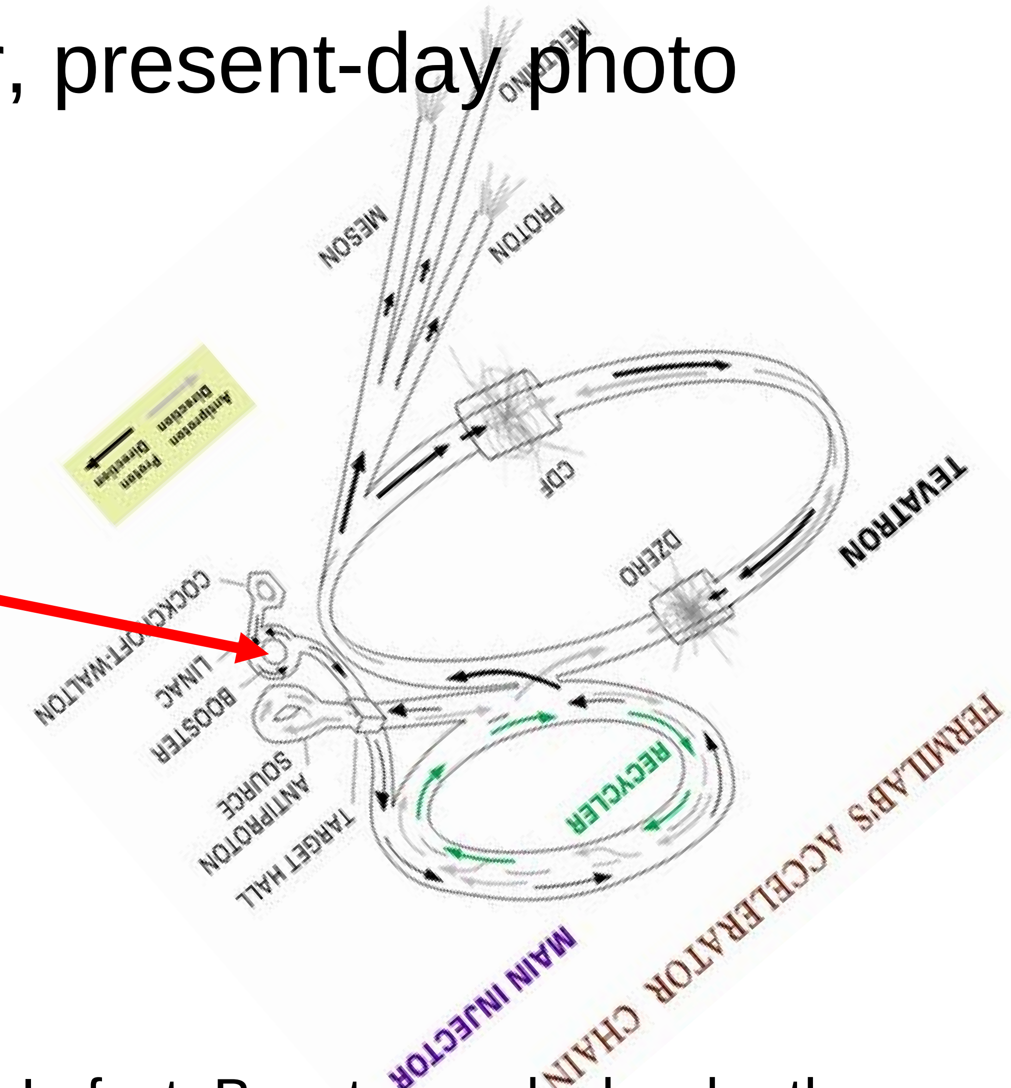




Old, but not winding down. In fact, Booster works harder than ever!

Accelerators don't get any retirement benefits.

The Booster, present-day photo



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Accelerators don’t get any retirement benefits.

A “short history” of Booster’s march to higher intensity

1. (~1993) Injection-energy upgrade (200MeV to 400Mev)

   - More beam to the Tevatron!
2. (~1993) Main Injector commissioned

   - More beam to the Tevatron!
3. (last couple of years) NuMi and MiniBoone Experiments

   - More beam needed, longer runtimes necessary

4. Space-charge effects are *maximized* at low energies. γ=1.4~9.4

   - Booster is the FIRST (circular) accelerator in the mix

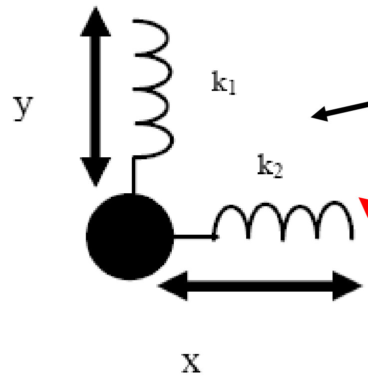
Booster is operating at intensities well above its design!
(and nobody else can pick up the slack)

Bunch intensities ~10^8 (1970’s) → $3\text{x}10^9$ (1992) → $6\text{x}10^{10}$ (today)

Classic coupling

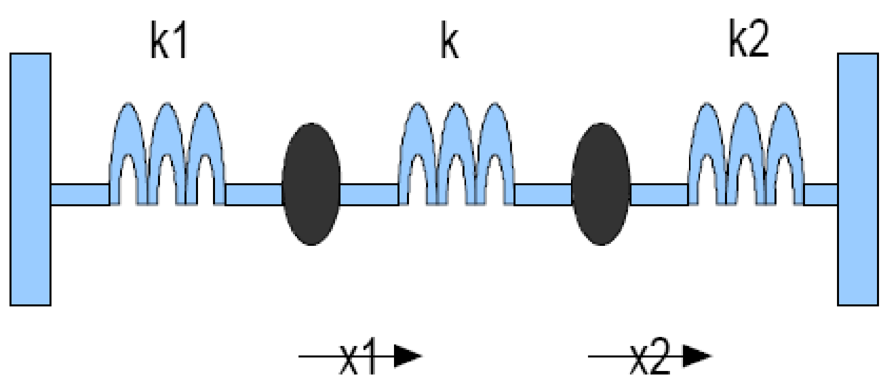
A familiar analogy

Cannot really draw the "coupling" between them



A coupled 2D oscillator

$$\omega_{\pm} = \frac{1}{2}\left[\omega_1^2 + \omega_2^2 \pm \sqrt{\left(\omega_1^2 - \omega_2^2\right) + 4q^2}\right]$$

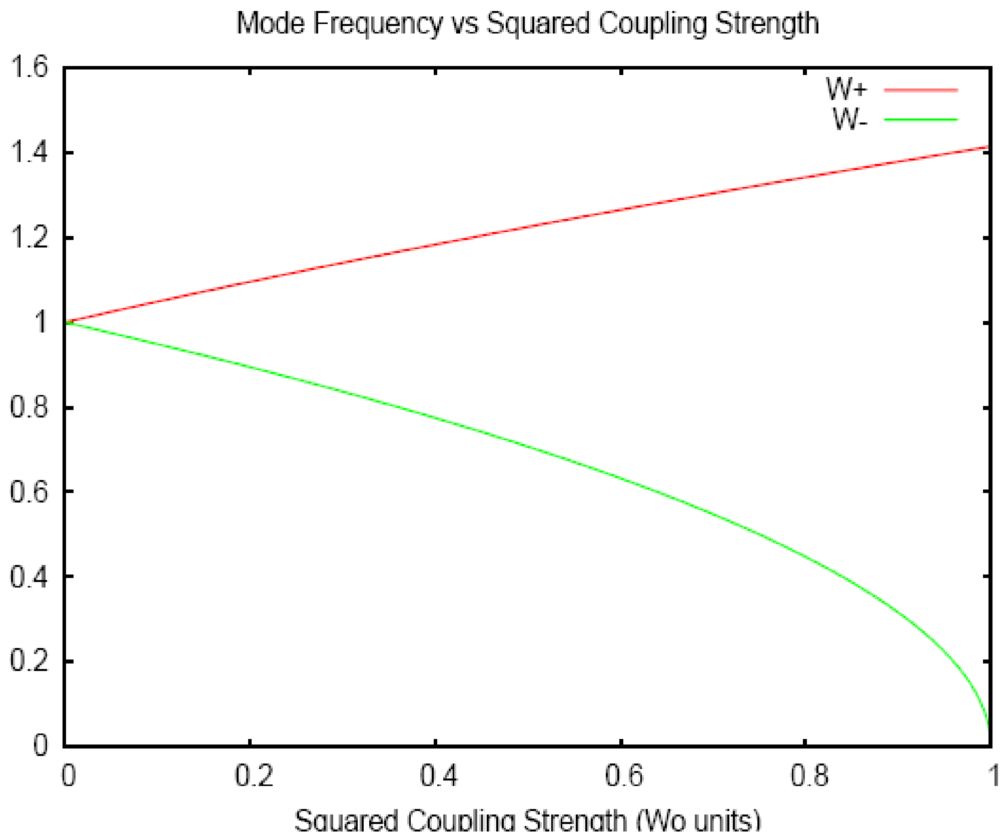


A pair of 1D oscillators with coupling between them (equivalent)

Consider the degenerate case (identical oscillators)

$$\omega_{\pm} = \frac{1}{2}\left[\omega_1^2 + \omega_2^2 \pm \sqrt{\left(\omega_1^2 - \omega_2^2\right) + 4q^2}\,\right] \longrightarrow \boxed{\sqrt{\omega_0^2 \pm q^2}}$$

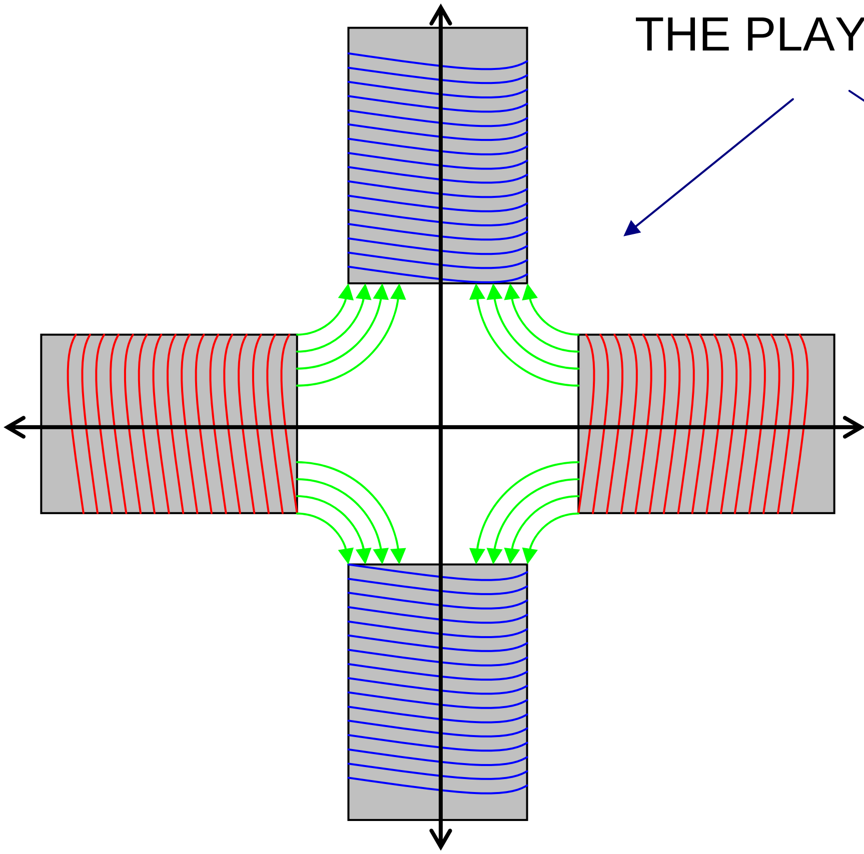
Normal modes of oscillation



Splitting depends on coupling strength q

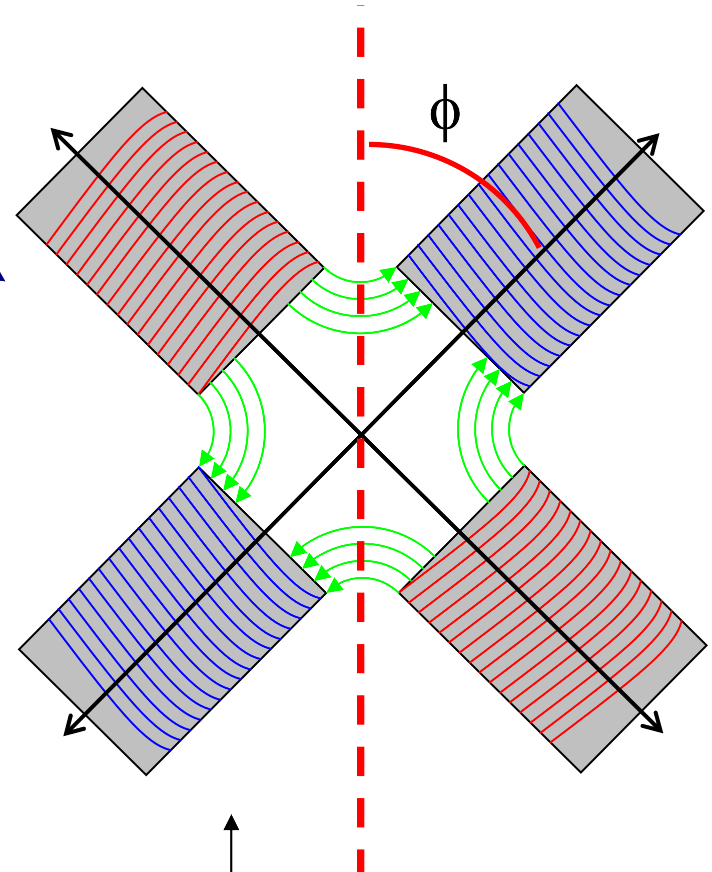
So you are probably wondering how this applies to a particle beam

THE PLAYERS



Normally Oriented Quadrupole

$$B_x = \frac{\partial B_x}{\partial y} y, \qquad B_y = \frac{\partial B_y}{\partial x} x$$



Skew-Quadrupole

$$B_y = \frac{\partial B_y}{\partial x}\left[x \cos 2\phi + y \sin 2\phi\right], \quad B_x = \frac{\partial B_x}{\partial y}\left[y \cos 2\phi - x \sin 2\phi\right]$$

So, again, *how* does this apply to a particle beam?

$$B_x = \frac{\partial B_x}{\partial y} y, \qquad B_y = \frac{\partial B_y}{\partial x} x$$

Quadrupole fields provide the “spring” in the two planes

(Machines are designed to have independent motion in each plane)

$$B_y = \frac{\partial B_y}{\partial x}\left[x\cos 2\phi + y\sin 2\phi\right], \quad B_x = \frac{\partial B_x}{\partial y}\left[y\cos 2\phi - x\sin 2\phi\right]$$

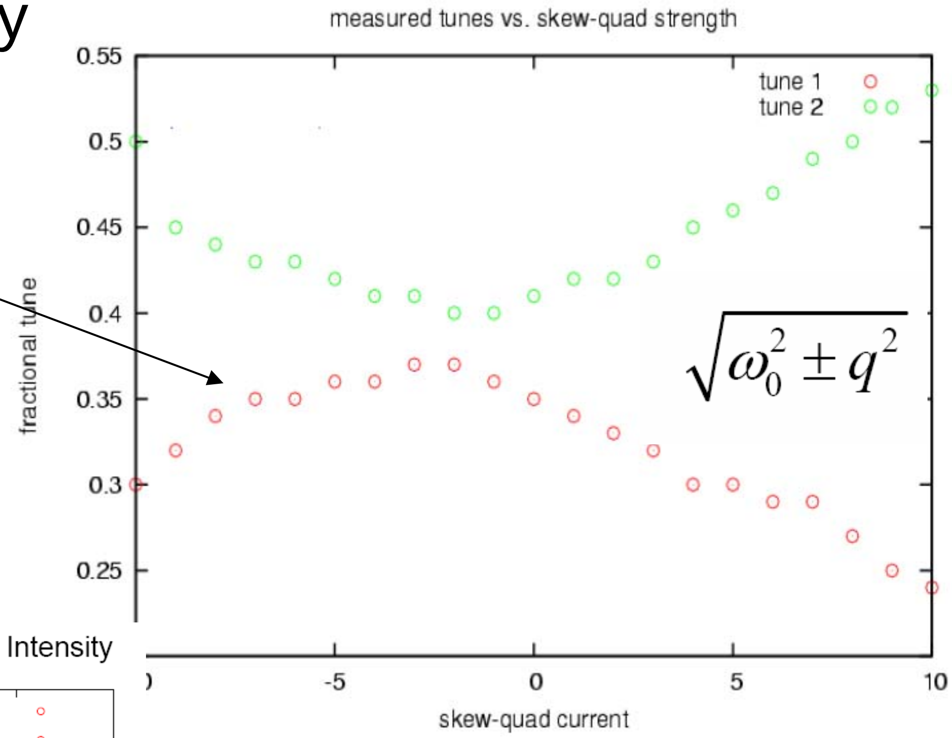
Alignment *errors* in the normal quadrupoles can couple the two degrees of freedom

“Skewed” quadrupoles are used to correct for this (Φ=±45° for a skew-quad).

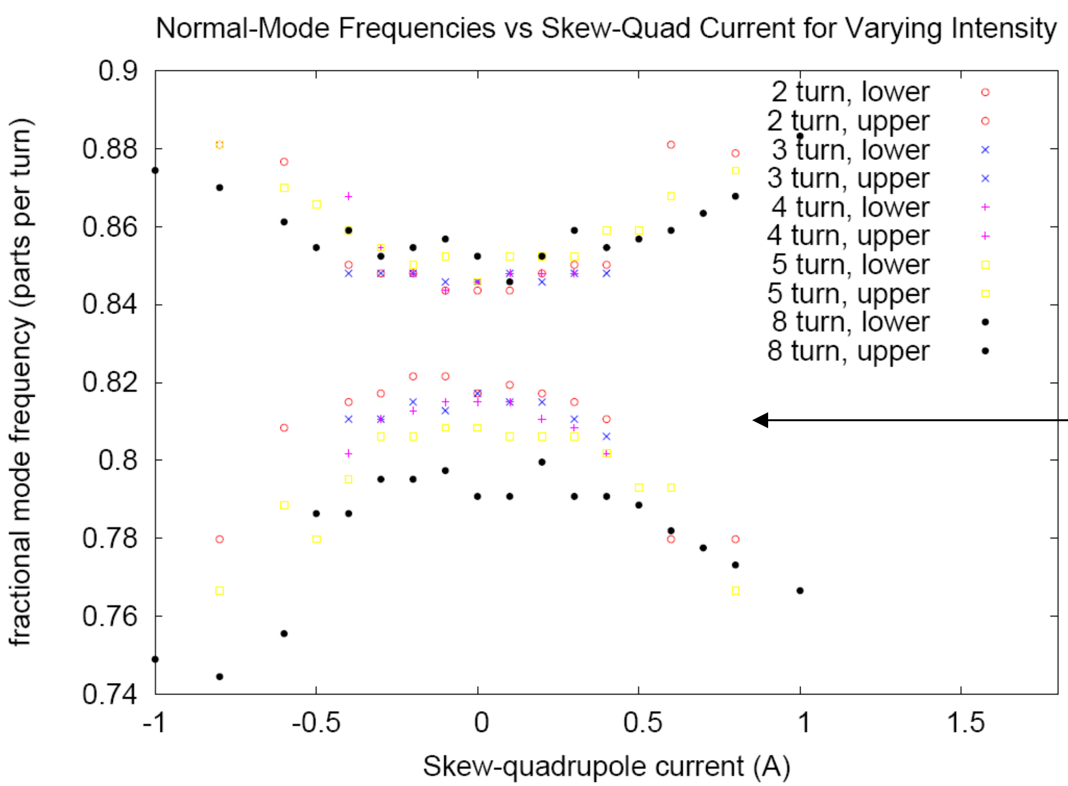
Or, they can be used to *increase* the coupling, if desired

Coupling scan at varying intensity

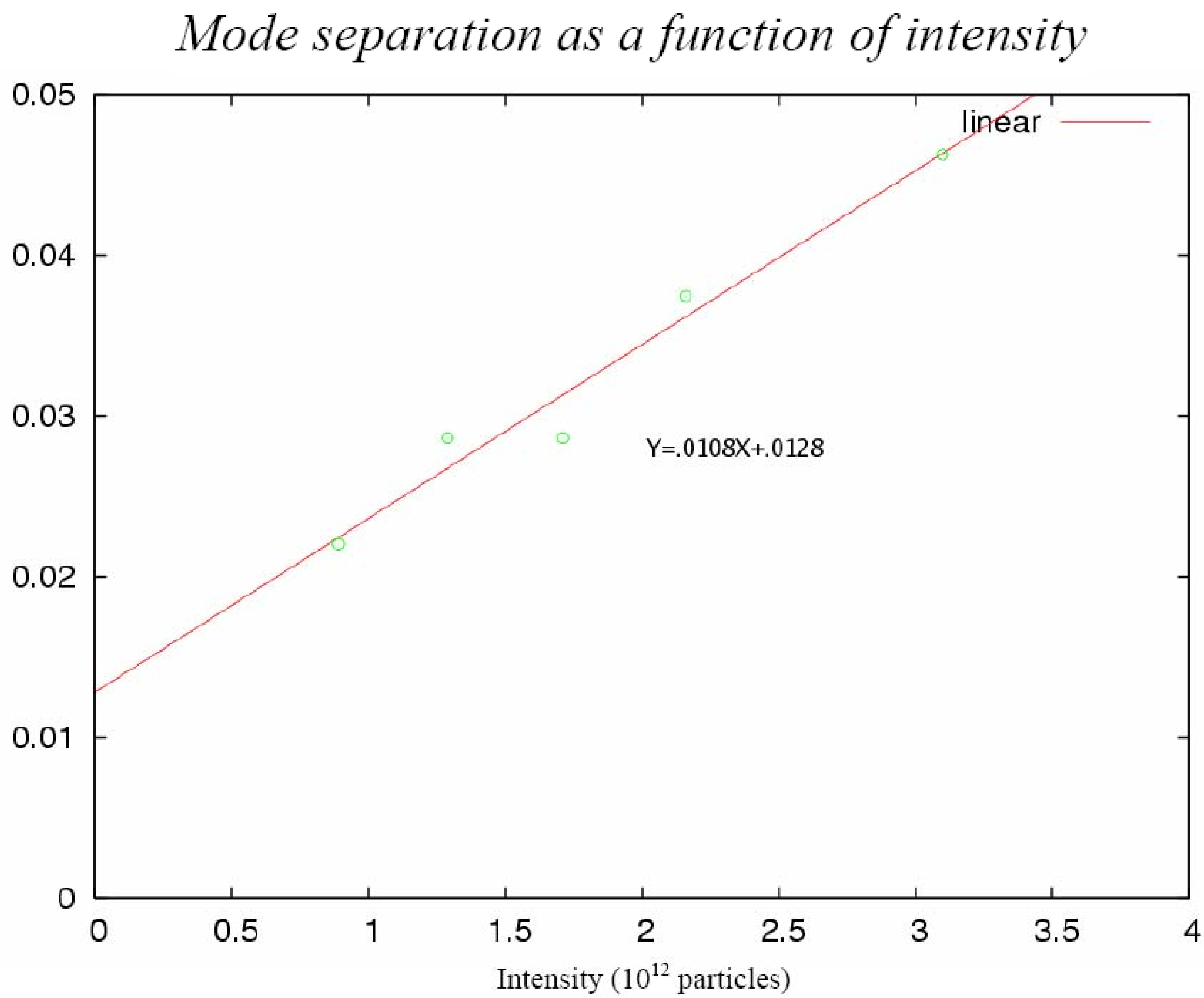
Here we use them to scan the coupling minimum at varying intensity



Coupling may not be completely eliminated!



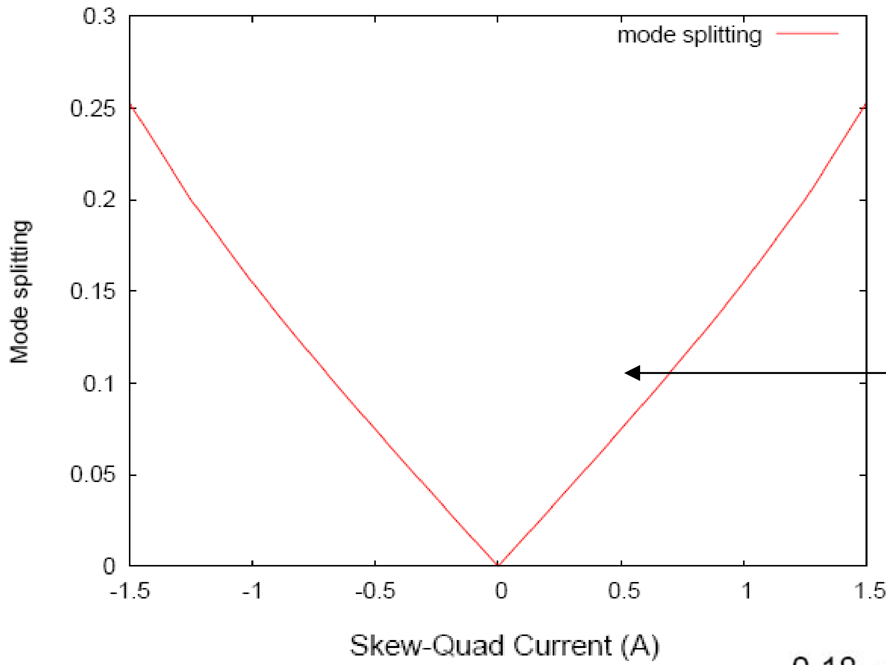
Data taken for increasing intensity show increasing coupling



We observe a linear increase in the coupling strength with intensity

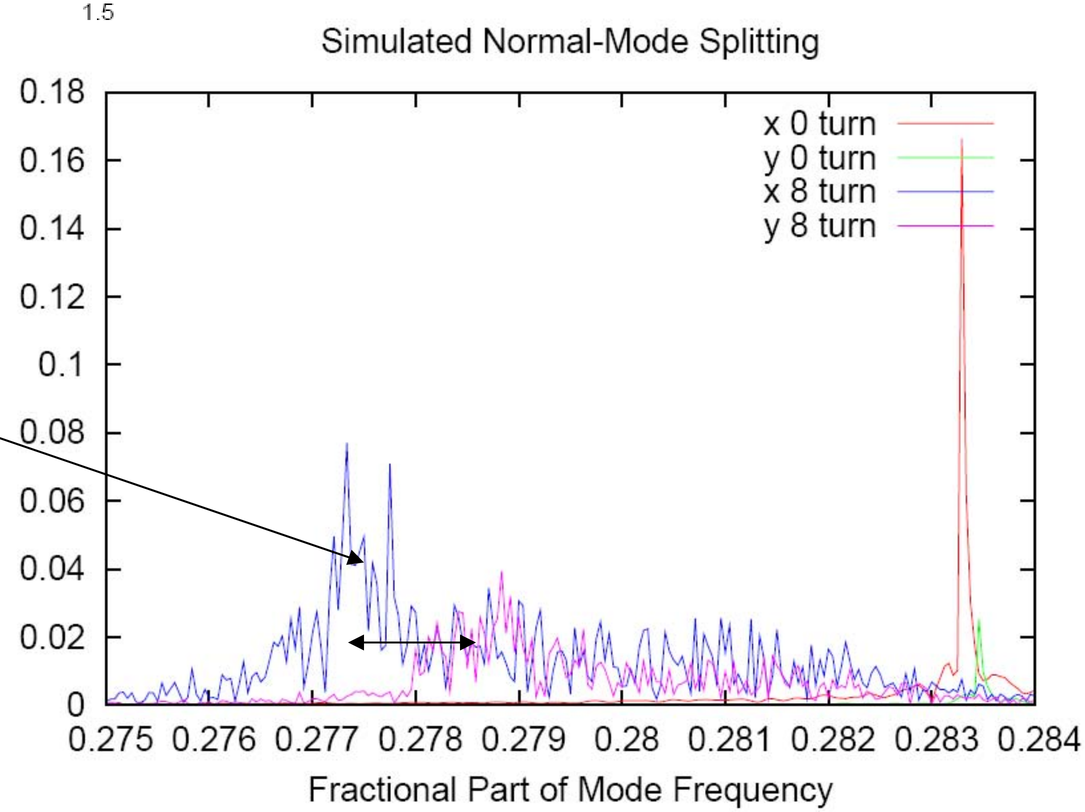
Space charge affects noticeably the correlation between the two planes

Simulation of the S.C. Coupling



Good agreement at zero intensity (skew-quad behavior fits measurement)

Intensity-dependent shift not as appealing – though we have qualitative agreement



So far, no match between simulation and measurement!

What to do next:

Repeat the coupling study at higher/lower intensities (for better understanding of limiting behavior)

Develop a mechanism for space-charge coupling

Get the simulations to reproduce this result