Beam-beam effects

(an introduction)

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(/afs/ictp/home/w/wfherr/public/CAS/doc/beambeam.pdf)

(http://cern.ch/lhc-beam-beam/talks/Trieste_beambeam.pdf)

BEAMS: moving charges

- Beam is a collection of charges
- Represent electromagnetic potential for other charges

→ Forces on itself (space charge) and opposing beam (beam-beam effects)

→ Main limit for present and future colliders

→ Important for high density beams, i.e. high intensity and/or small beams:
for high luminosity !

Beam-beam effects

Remember:

$$\Longrightarrow \quad \mathcal{L} = \frac{N_1 N_2 f B}{4\pi\sigma_x\sigma_y} \quad = \quad \frac{N_1 N_2 f B}{4\pi \cdot \ \sigma_x\sigma_y}$$

- **Overview: which effects are important for present and future machines (LEP, PEP, Tevatron, RHIC, LHC, ...)**
- **Qualitative and physical picture of the effects**
- **Mathematical derivations in:**
  Proceedings, Zeuthen 2003

Beam-beam effects

- **A beam acts on particles like an electromagnetic lens, but:**
  - **Does not represent simple form, i.e. well defined multipoles**
  - **Very non-linear form of the forces, depending on distribution**
  - **Can change distribution as result of interaction (time dependent forces ..)**
- **Results in many different effects and problems**

Fields and Forces (I)

- **Start with a point charge q and integrate over the particle distribution $\rho(\vec{x})$.**
- **In rest frame only electrostatic field: $\vec{E}'$, but $\vec{B}' \equiv 0$**
- **Transform into moving frame and calculate Lorentz force**

$$E_{\parallel} = E'_{\parallel}, \quad E_{\perp} = \gamma \cdot E'_{\perp} \quad \text{with:} \quad \vec{B} \;=\; \vec{\beta} \times \vec{E}/c$$

$$\vec{F} = q(\vec{E} + \vec{\beta} \times \vec{B})$$

Fields and Forces (II)

- **Derive potential U(x, y, z) from Poisson equation:**

$$\Delta U(x,y,z) = -\frac{1}{\epsilon_0}\rho(x,y,z)$$

- **The fields become:**

$$\vec{E} \;=\; -\nabla U(x,y,z)$$

- **Example Gaussian distribution:**

$$\rho(x,y,z) = \frac{Ne}{\sigma_x\sigma_y\sigma_z\sqrt{2\pi}^3}\exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}\right)$$

Simple example: Gaussian

- **For 2D case the potential becomes (see proceedings):**

$$U(x,y,\sigma_x,\sigma_y) = \frac{ne}{4\pi\epsilon_0}\int_0^\infty \frac{\exp(-\frac{x^2}{2\sigma_x^2+q} - \frac{y^2}{2\sigma_y^2+q})}{\sqrt{(2\sigma_x^2+q)(2\sigma_y^2+q)}}dq$$

- **Can derive $\vec{E}$ and $\vec{B}$ fields and therefore forces**
- **For arbitrary distribution (non-Gaussian): difficult (or impossible, numerical solution required)**

Simple example: Gaussian

- **Round beams:** $\sigma_x = \sigma_y = \sigma$
- **Only components** E_r **and** B_Φ **are non-zero**

→ **Force has only radial component, i.e. depends only on distance r from bunch centre**

(where: $r^2 = x^2 + y^2$*)* **(see proceedings)**

$$F_r(r) = -\frac{ne^2(1+\beta^2)}{2\pi\epsilon_0 \cdot r}\left[1 - \exp(-\frac{r^2}{2\sigma^2})\right]$$

Beam-beam kick:

- **Kick ($\Delta r'$): angle by which the particle is deflected during the passage**
- **Derived from force by integration over the collision (assume: $m_1=m_2$ and $\beta_1=\beta_2$):**

$$F_r(r,s,t) = -\frac{Ne^2(1+\beta^2)}{\sqrt{(2\pi)^3}\epsilon_0 r\sigma_s}\left[1-\exp(-\frac{r^2}{2\sigma^2})\right]\cdot\left[\exp(-\frac{(s+vt)^2}{2\sigma_s^2})\right]$$

$$\text{with Newton's law}: \qquad \Delta r' = \frac{1}{mc\beta\gamma}\int_{\infty}^{\infty} F_r(r,s,t)dt$$

Beam-beam kick:

Using the classical particle radius:

$$r_0 = e^2/4\pi\epsilon_0 mc^2$$

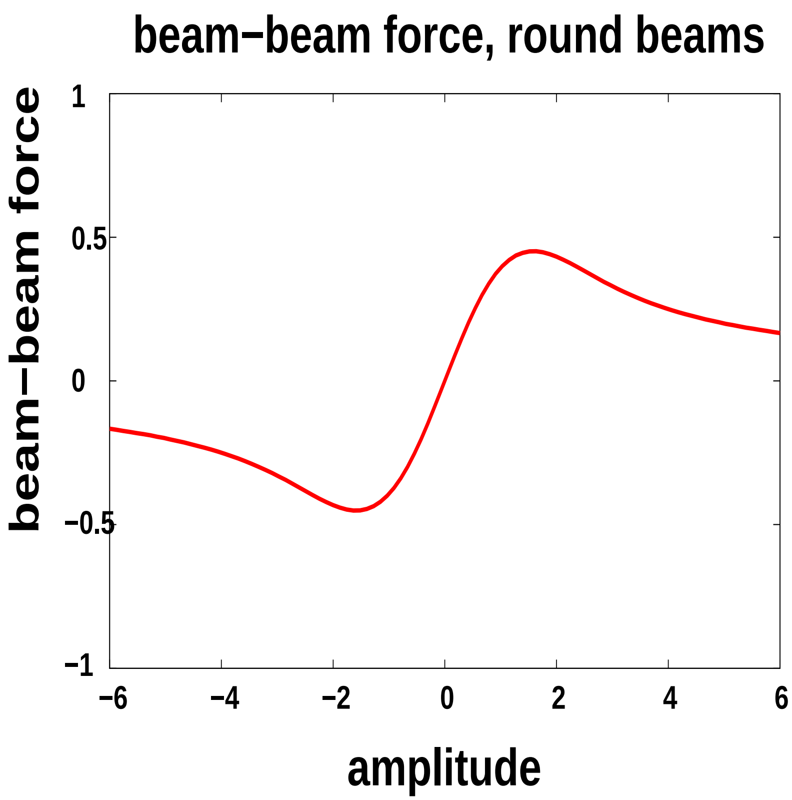
we have (radial kick and in Cartesian coordinates):

$$\Delta r' = -\frac{2Nr_0}{\gamma} \cdot \frac{r}{r^2} \cdot \left[1 - \exp(-\frac{r^2}{2\sigma^2})\right]$$

$$\Delta x' = -\frac{2Nr_0}{\gamma} \cdot \frac{x}{r^2} \cdot \left[1 - \exp(-\frac{r^2}{2\sigma^2})\right]$$

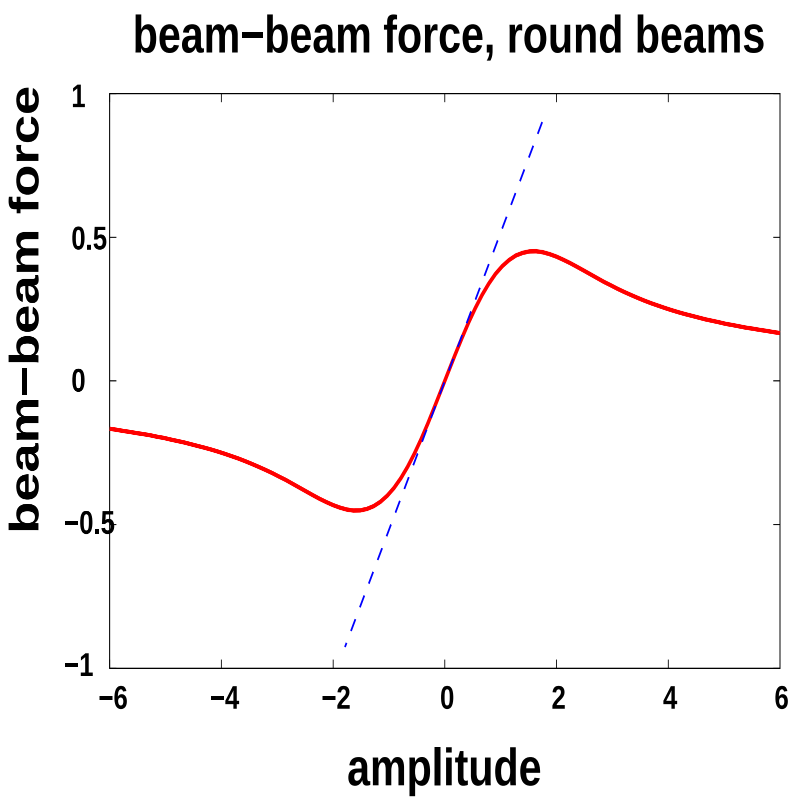
$$\Delta y' = -\frac{2Nr_0}{\gamma} \cdot \frac{y}{r^2} \cdot \left[1 - \exp(-\frac{r^2}{2\sigma^2})\right]$$

Beam-beam force



- Force varies strongly with amplitude
- Exponential function:
  - Contains many high order multipoles

Beam-beam force



- For small amplitudes: linear force
  - amplitude independent tune change (like quadrupole)

- For large amplitudes: very non−linear
  - amplitude dependent tune change (like non−linear fields)

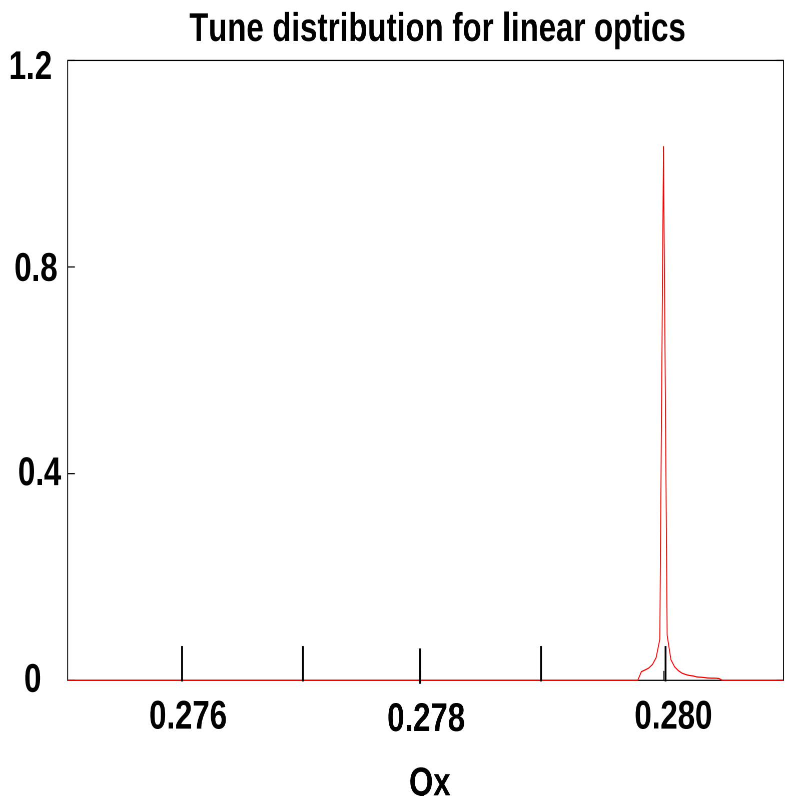
Can we measure the beam-beam strength ?

- **Try the slope of force at zero amplitude → proportional to (linear) tune shift Δ Q_{bb} from beam-beam interaction**
- **This defines: beam-beam parameter ξ**
- **For head-on interactions we get:**

$$\xi_{x,y} = \frac{N \cdot r_o \cdot \beta_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)}$$

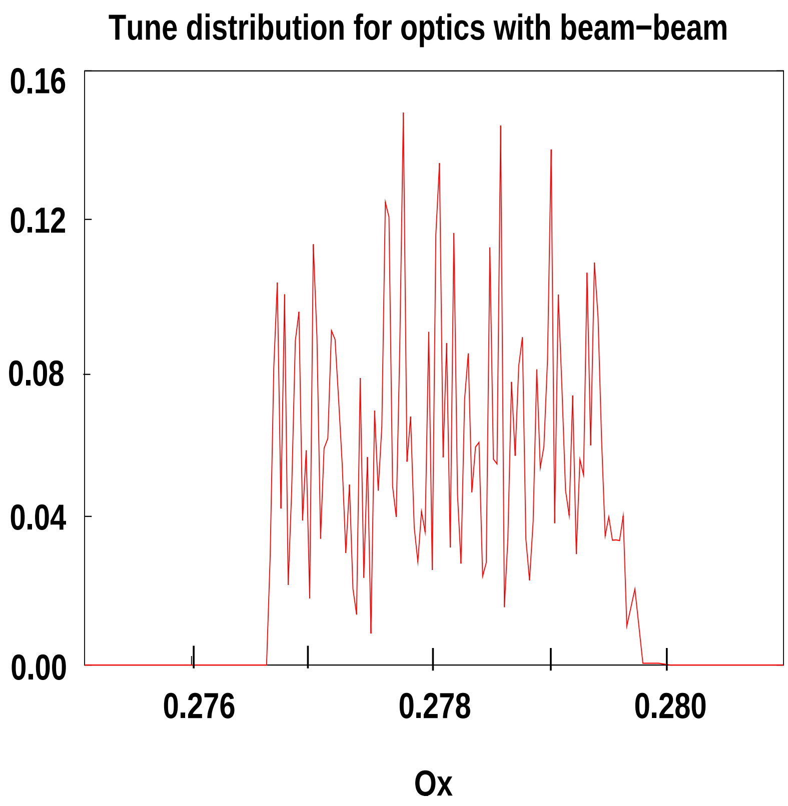
- **BUT: does not describe non-linear part of beam-beam force (so far: only an additional quadrupole !)**

Tune measurement: linear optics



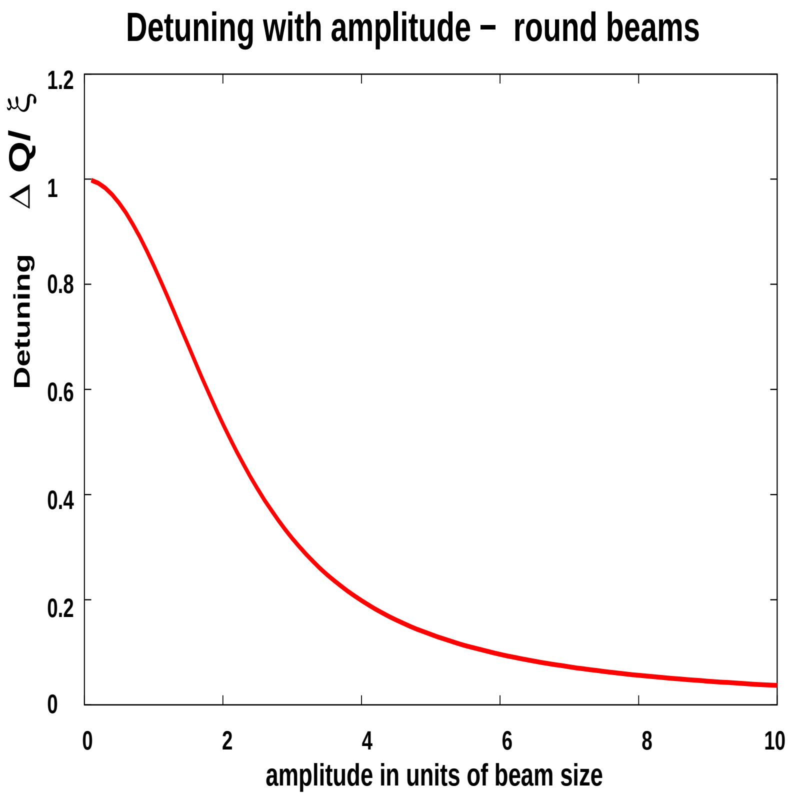
- Linear force: →
- all particles have same tune
- ▶ Only one frequency (tune) visible

Tune: linear optics with beam-beam



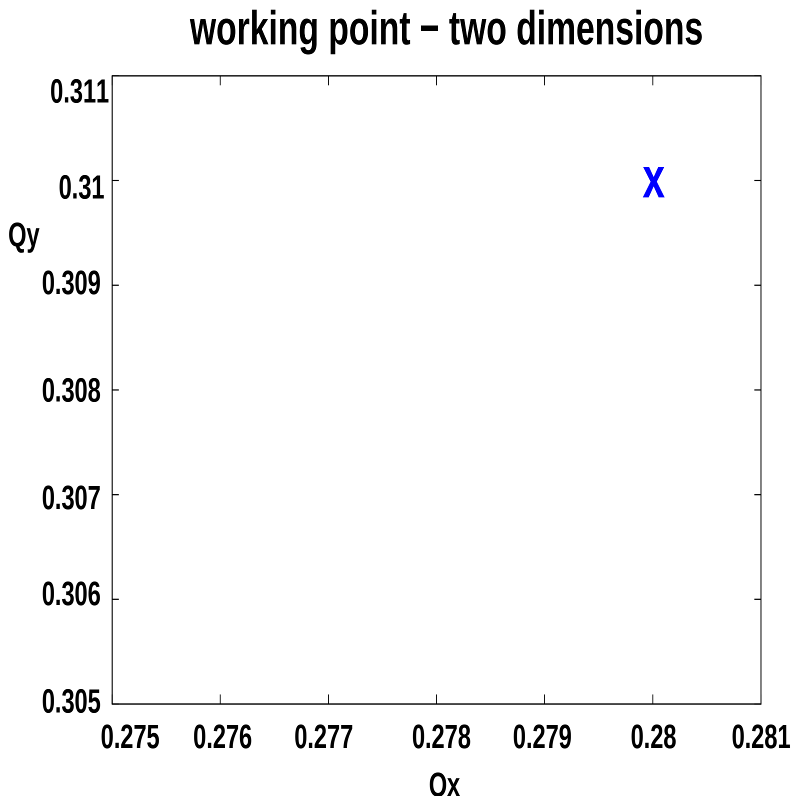
- Non−linear force: →
- particles with different amplitudes have different frequencies (tunes)
- We get frequency (tune) spectra
- Width of the spectra: about ξ

Amplitude detuning



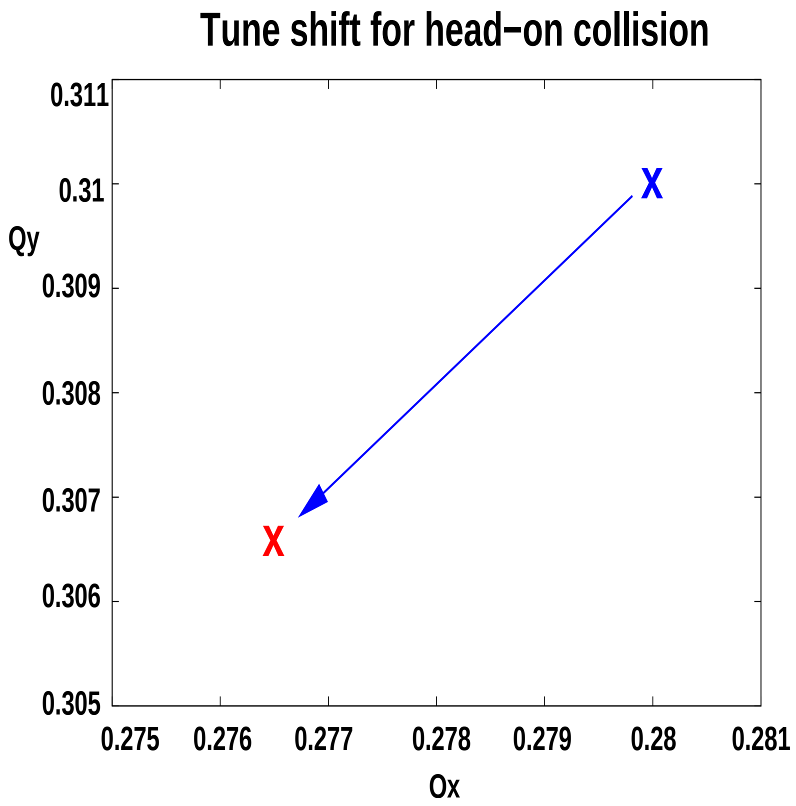
- Non−linear force: → tune depends on amplitude
- Largest effect for **small** amplitudes
- Calculation in the **proceedings**

Working point - two dimensions



- Start with standard working point
- Beam−beam will change working point

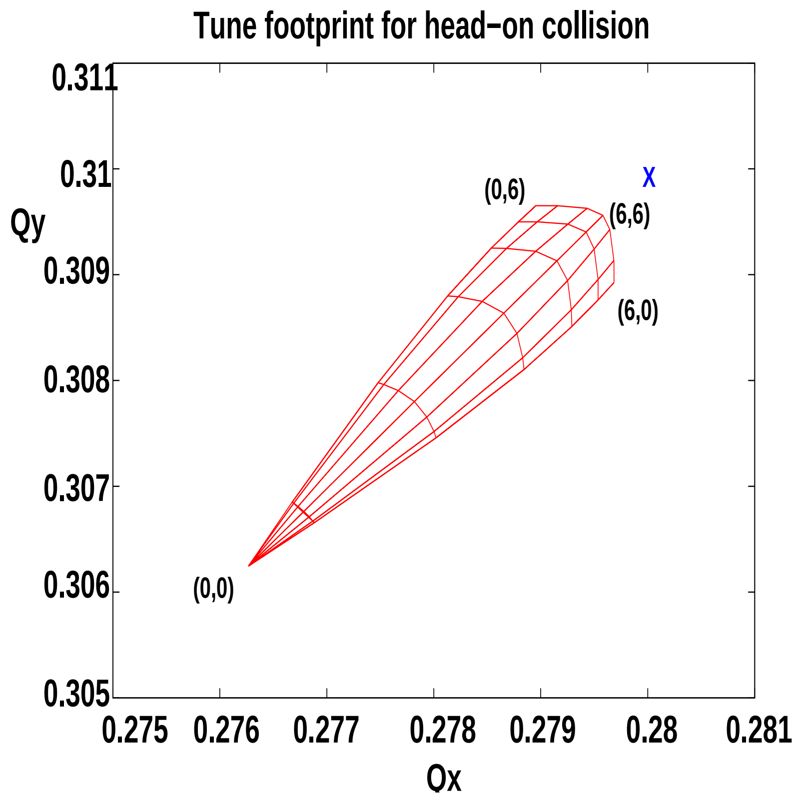
Linear tune shift - two dimensions



- Start with standard working point

- Tunes shifted in both planes

Non-linear tune shift - two dimensions



- Tunes depend on x and y amplitudes
- No single tune in the beam
- Compute and plot for every amplitude (pair) the tunes in both planes
- In 2 dimensions:
  plotted as footprint

LEP - LHC

	LEP	LHC
Beam sizes	**160 - 200μm · 2 - 4μm**	**16.6μm · 16.6μm**
Intensity N	**4.0 · 10^{11}/bunch**	**1.15 · 10^{11}/bunch**
Energy	**100 GeV**	**7000 GeV**
$\beta_x^* \cdot \beta_y^*$	**1.25 m · 0.05 m**	**0.55 m · 0.55 m**
Crossing angle	**0.0**	**285 μrad**
Beam-beam parameter(ξ)	**0.0700**	**0.0034**

Weak-strong and strong-strong

- Both beams are very strong (strong-strong):
  - → Both beam are affected and change due to beam-beam interaction
  - → Examples: LHC, LEP, RHIC, ...
- One beam much stronger (weak-strong):
  - → Only the weak beam is affected and changed due to beam-beam interaction
  - → Examples: SPS collider, Tevatron, ...

Incoherent effects

(single particle effects)

- **Single particle dynamics: treat as a particle through a static electromagnetic lens**
- **Basically non-linear dynamics**
- **All single particle effects observed:**

  $\rightarrow$ **Unstable and/or irregular motion**

  $\rightarrow$ **beam blow up or bad lifetime**

Observations hadrons

- Non-linear motion can become chaotic

  → reduction of "dynamic aperture"

  → particle loss and bad lifetime

- Strong effects in the presence of noise or ripple
- Very bad: unequal beam sizes (studied at SPS, HERA)
- Evaluation is done by simulation

Observations leptons

Remember:

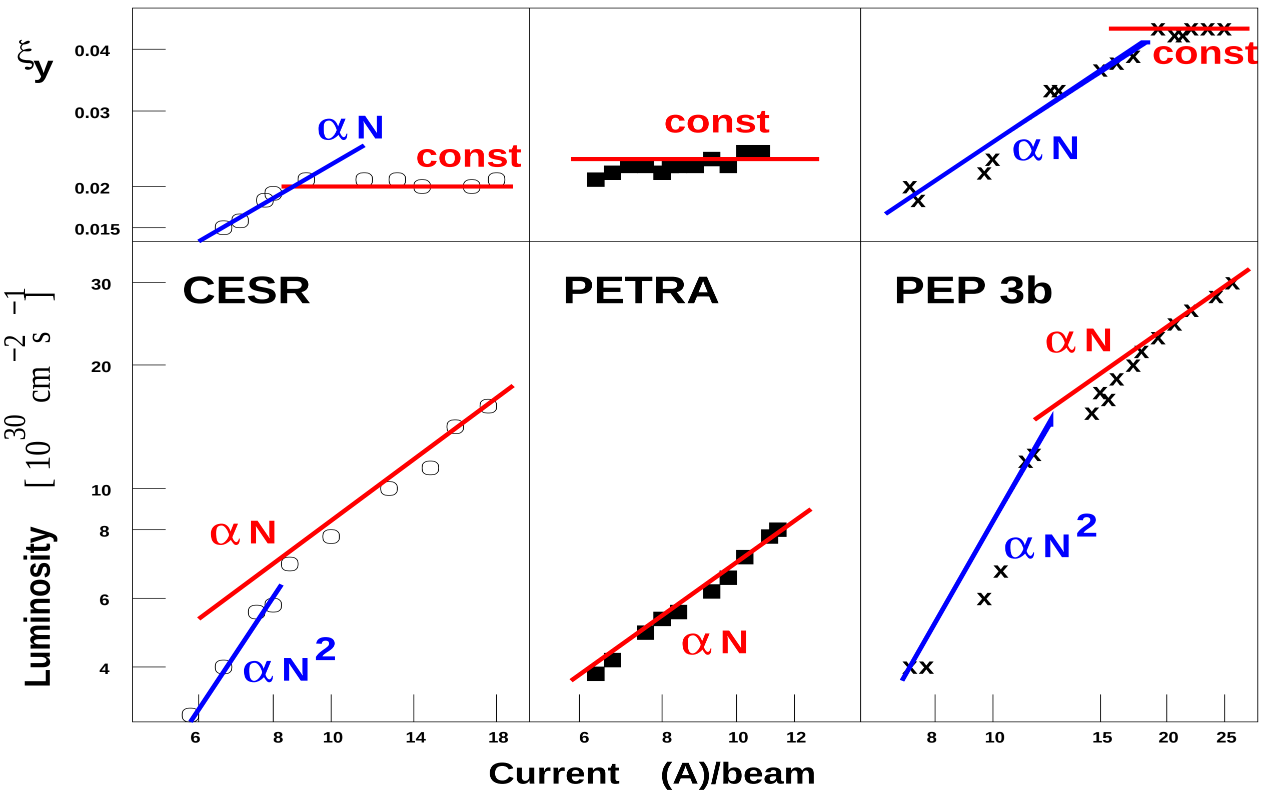
$$\Longrightarrow \quad \mathcal{L} = \frac{N_1 N_2 f B}{4\pi\sigma_x\sigma_y}$$

- **Luminosity should increase** $\propto N_1 N_2$

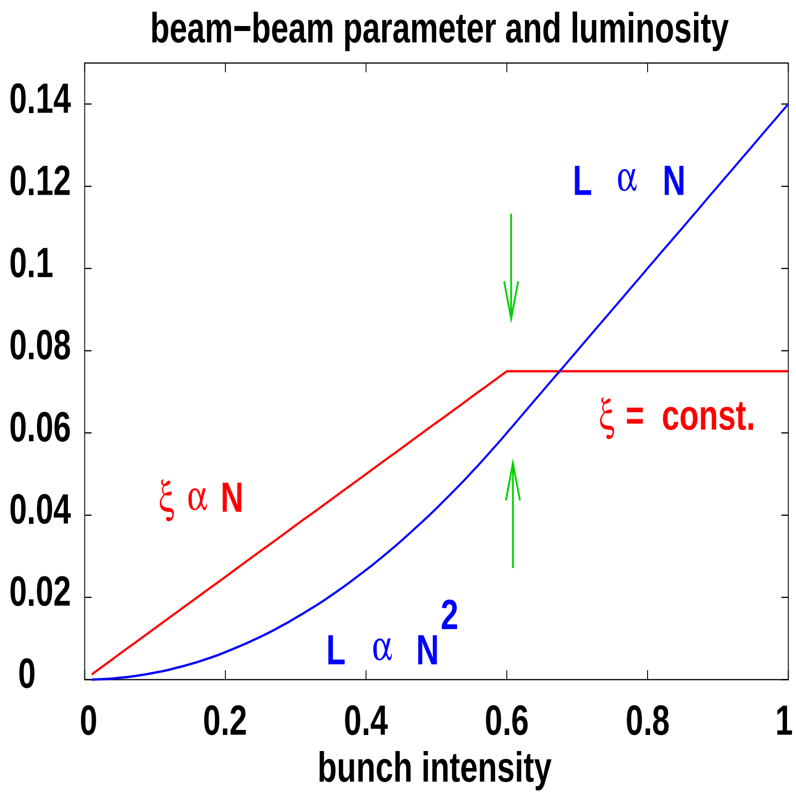
→ **for:** $N_1 = N_2 = N$ → $\propto N^2$

- **Beam-beam parameter should increase** $\propto N$
- **But:**

Examples: beam-beam limit



Beam-beam limit (schematic)



- Beam−beam parameter increases linearly with intensity
- Saturation above some intensity
- Luminosity increases linearly
- So−called **beam−beam limit**

What is happening ?

we have

$$\xi_y = \frac{N r_0 \beta_y}{2\pi\gamma\sigma_y(\sigma_x + \sigma_y)} \overset{(\sigma_x \gg \sigma_y)}{\approx} \frac{r_0 \beta_y}{2\pi\gamma(\sigma_x)} \cdot \frac{N}{\sigma_y}$$

and

$$\mathcal{L} = \frac{N^2 f B}{4\pi\sigma_x\sigma_y} = \frac{N f B}{4\pi\sigma_x} \cdot \frac{N}{\sigma_y}$$

- **Above beam-beam limit: σ_y increases when N increases to keep ξ constant → equilibrium emittance !**
- **Therefore: $\mathcal{L} \propto N$ and $\xi \approx$ constant**
- **ξ_{limit} is NOT a universal constant !**
- **Difficult to predict**

The next problem

Remember:

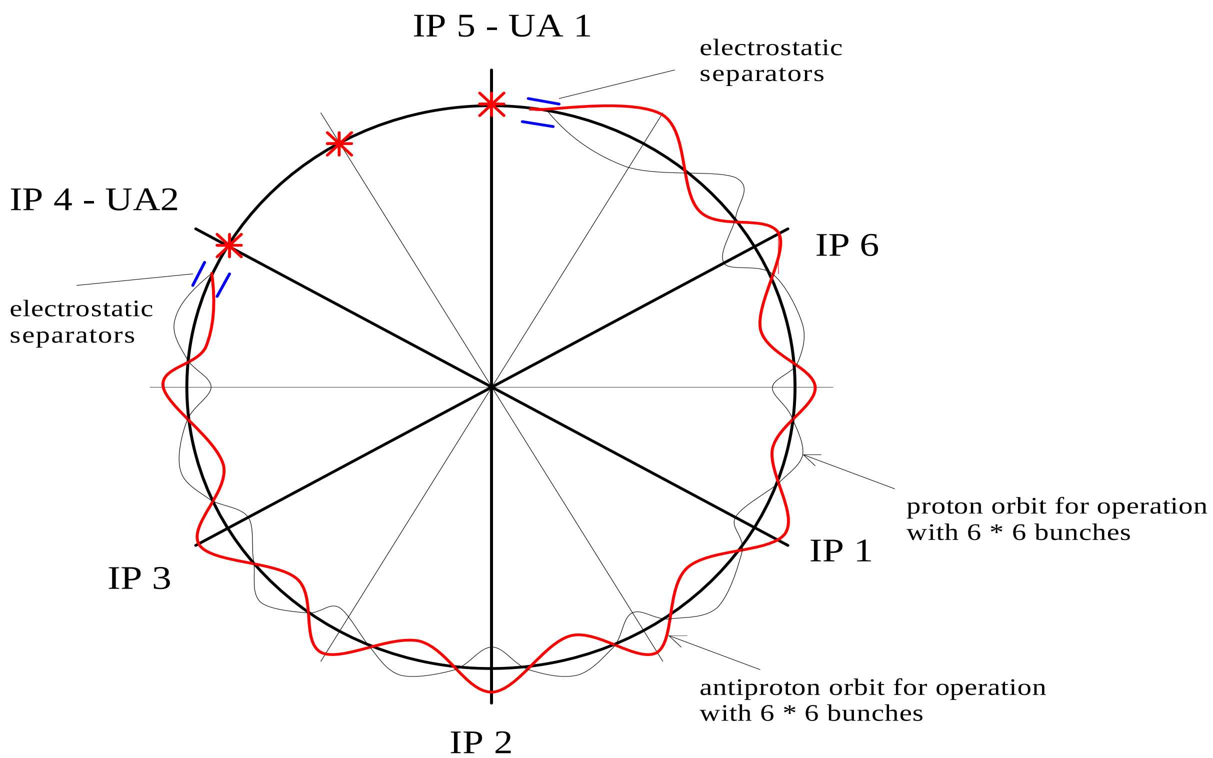
$$\Longrightarrow \quad \mathcal{L} = \frac{N_1 N_2 f \cdot B}{4\pi\sigma_x\sigma_y}$$

- **How to collide many bunches (for high $\mathcal{L}$) ??**
- **Must avoid unwanted collisions !!**
- **Separation of the beams:**
  - → **Pretzel scheme (SPS,LEP,Tevatron)**
  - → **Bunch trains (LEP,PEP)**
  - → **Crossing angle (LHC)**

Separation: SPS

- $\Rightarrow$ **Few equidistant bunches**
  (6 against 6)
- **Beams travel in same beam pipe**
  (12 collision points !)
- **Two experimental areas**
- **Need global separation**
- **Horizontal pretzel around most of the circumference**

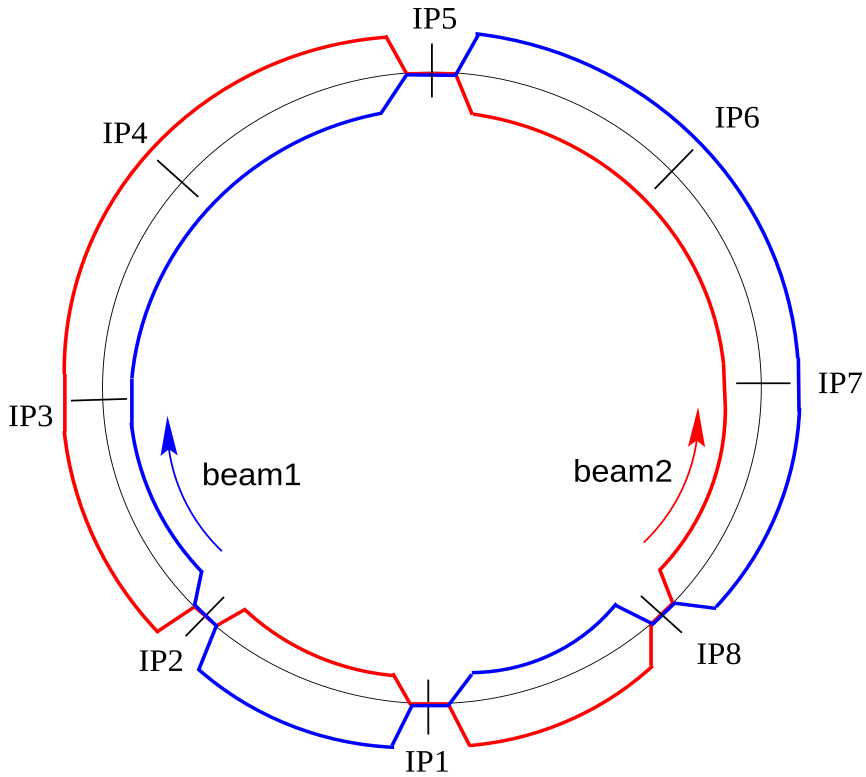
Separation: SPS



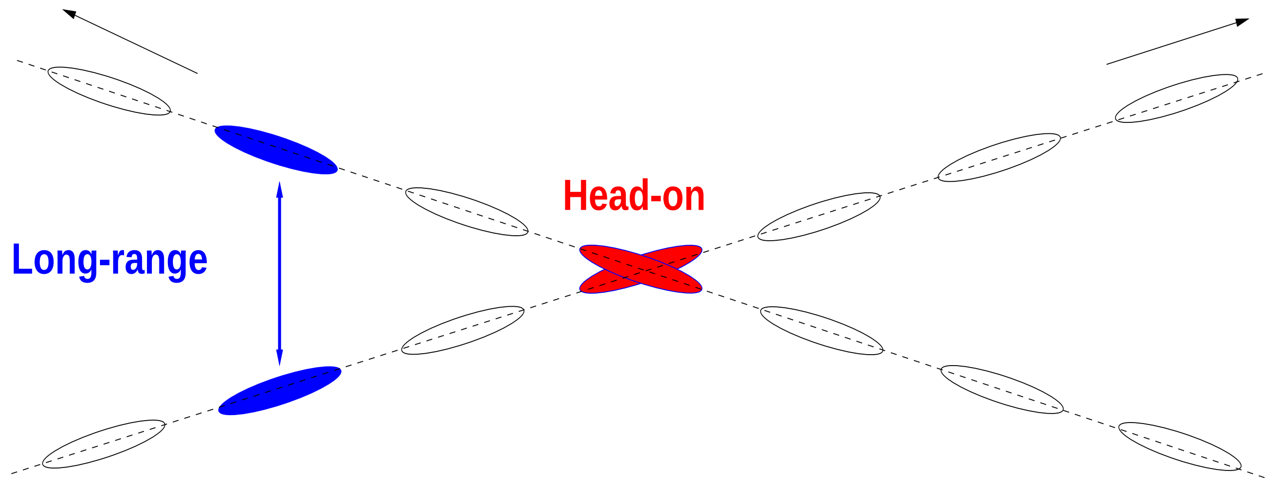
Separation: LHC

- ⇒ Many equidistant bunches
- Two beams in separate beam pipes except:
  - Four experimental areas
  - Need local separation
- Two horizontal and two vertical crossing angles

Layout of LHC



Crossing angles (example LHC)

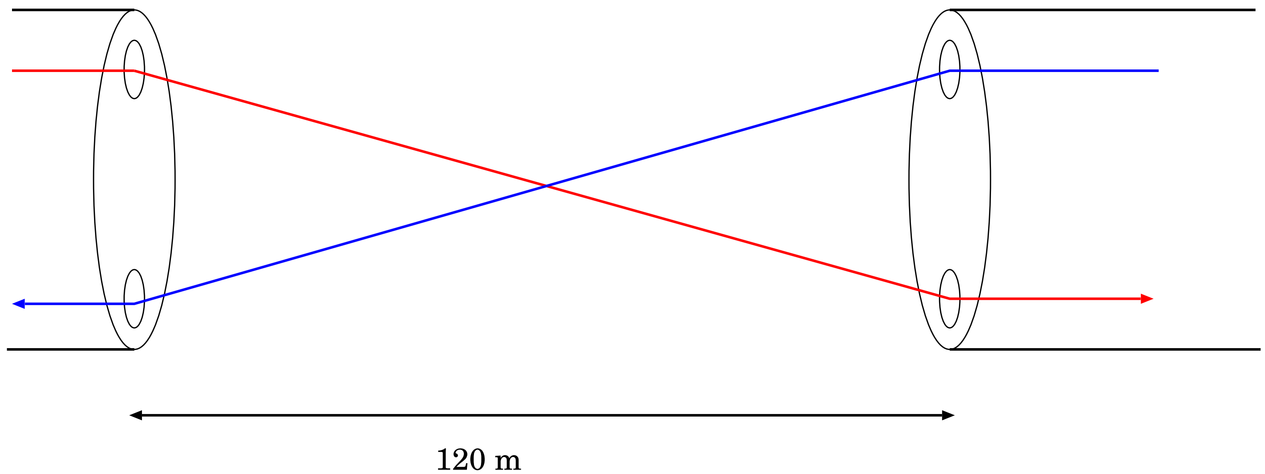


- Still some parasitic interactions
- Particles experience distant (weak) forces

→ We get so-called long range interactions

Example: LHC

- **Two beams, 2808 bunches each, every 25 ns**
- **In common chamber around experiments**

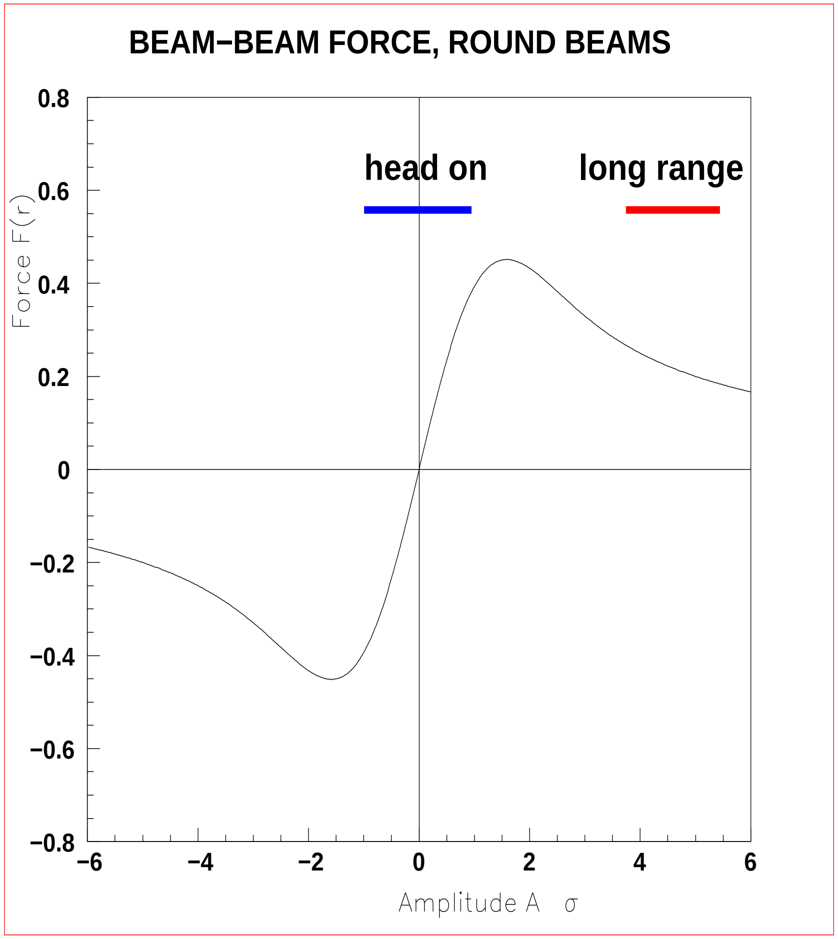


- **Around each IP: 30 long range interactions**
- **Separation typically 6 - 12 σ**

What is special about them ?

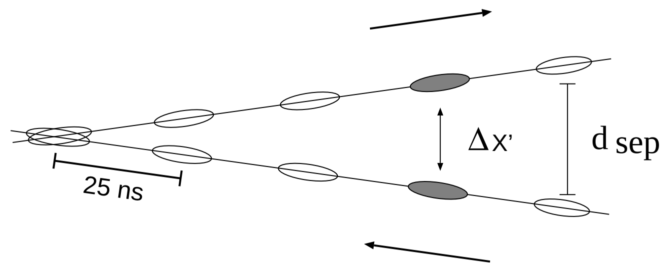
- Break symmetry between planes, also odd resonances
- Mostly affect particles at large amplitudes
- Tune shift has opposite sign in plane of separation
- Cause effects on closed orbit
- PACMAN effects

Opposite tuneshift ???



- Local slope of force has opposite sign for large separation
- Opposite sign for focusing
- Used for partial compensation

Long range interactions (LHC)

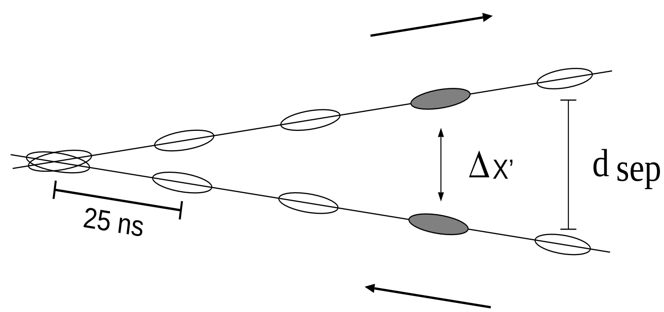


➡ **For horizontal separation d:**

$$\Delta x'(x+d,y,r) = -\frac{2Nr_0}{\gamma}\cdot\frac{(x+d)}{r^2}\left[1-\exp(-\frac{r^2}{2\sigma^2})\right]$$

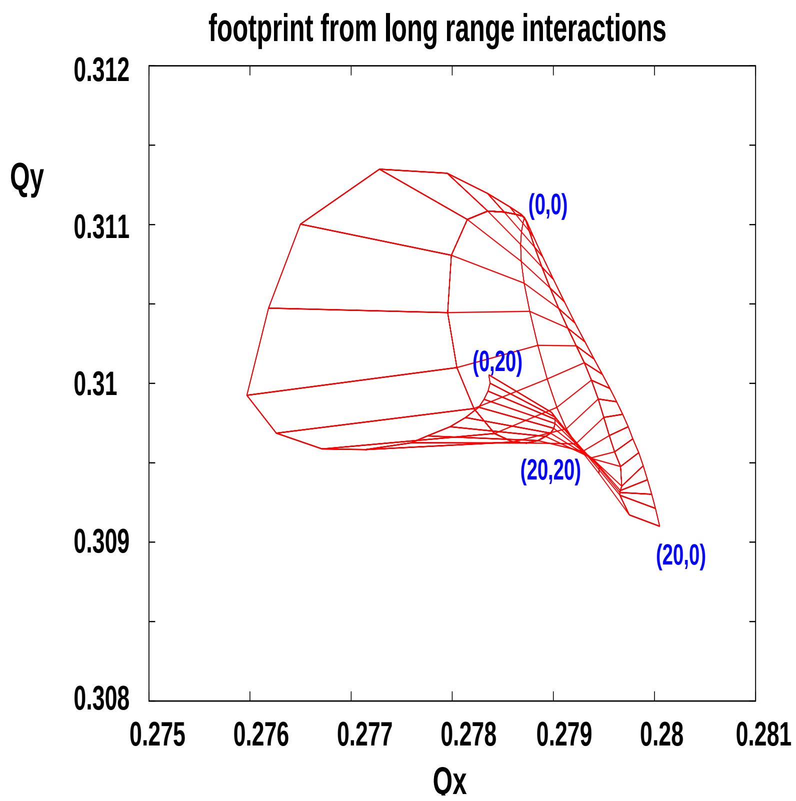
(with: $r^2 = (x+d)^2 + y^2$ ***)***

Long range interactions (LHC)



- **Number of long range interactions depends on spacing and length of common part**
- **In LHC 15 collisions on each side, 120 in total !**
- **Effects depend on separation:** $\Delta Q \propto -\frac{N}{d^2}$ **(for large enough d !)** **footprints ??**

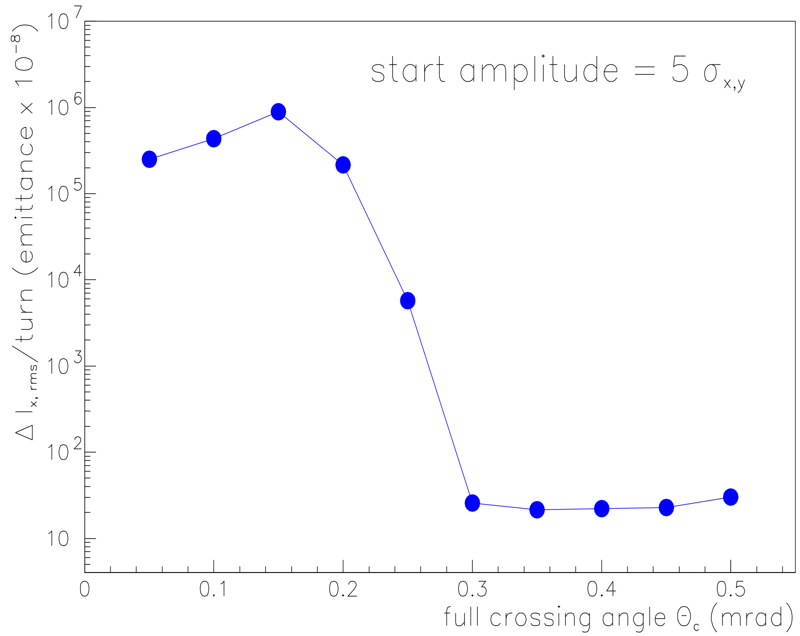
Footprints



- Large fo largest amplitudes where non−linearities are strong
- Size proportional to $\frac{1}{d^2}$
- Must expect problems at small separation
- Footprint very asymmetric

Particle losses

- **Small crossing angle $\Longleftrightarrow$ small separation**
- **Small separation: particles become unstable and get lost**



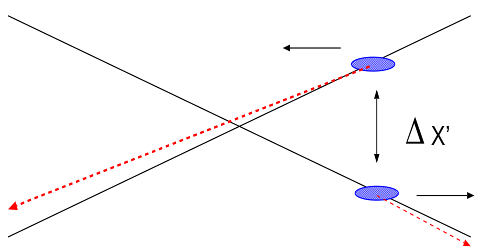
- **Minimum crossing angle for LHC: 285 μrad**

Closed orbit effects

$$\Delta x'(x+d, y, r) = -\frac{2Nr_0}{\gamma} \cdot \frac{(x+d)}{r^2} \left[1 - \exp(-\frac{r^2}{2\sigma^2})\right]$$

For well separated beams ($d \gg \sigma$) the force (kick) has an amplitude independent contribution: ➡ **orbit kick**

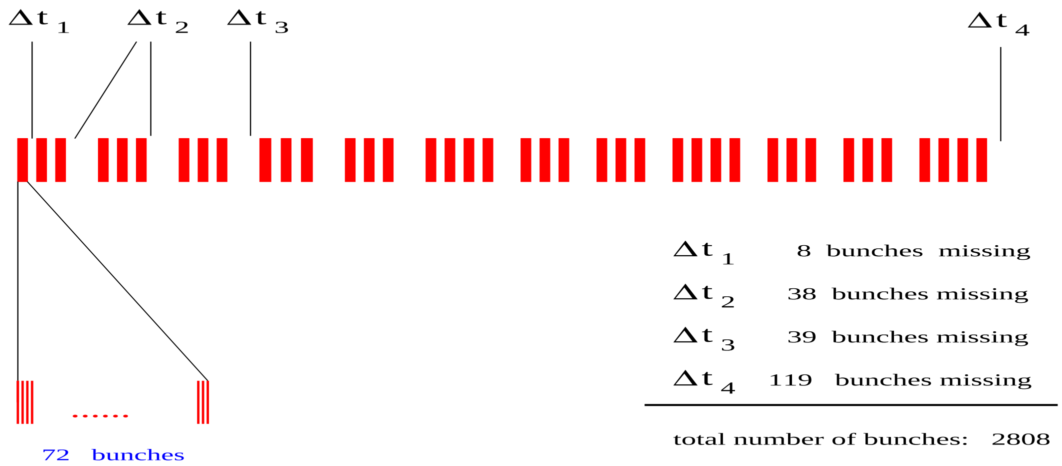
$$\Delta x' = \underbrace{\frac{const.}{d} \cdot [\ 1}\ -\ \frac{x}{d} + O\left(\frac{x^2}{d^2}\right) + \ ...$$



Closed orbit effects

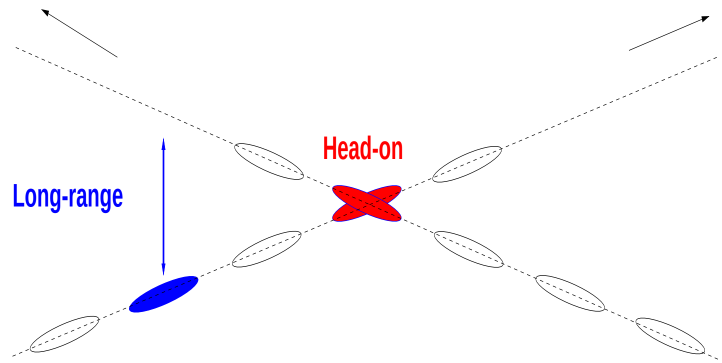
- Beam-beam kick from long range interactions changes the orbit
  - Has been observed in LEP with bunch trains
  - Self-consistent calculation necessary
  - Effects can add up and become important
- Orbit can be corrected, but:

PACMAN bunches



- **LHC bunch filling not continuous: holes for injection, extraction, dump ..**
- **2808 of 3564 possible bunches → 1756 "holes"**
- **"Holes" meet "holes" at the interaction point**
- **But not always ...**

Effect of holes

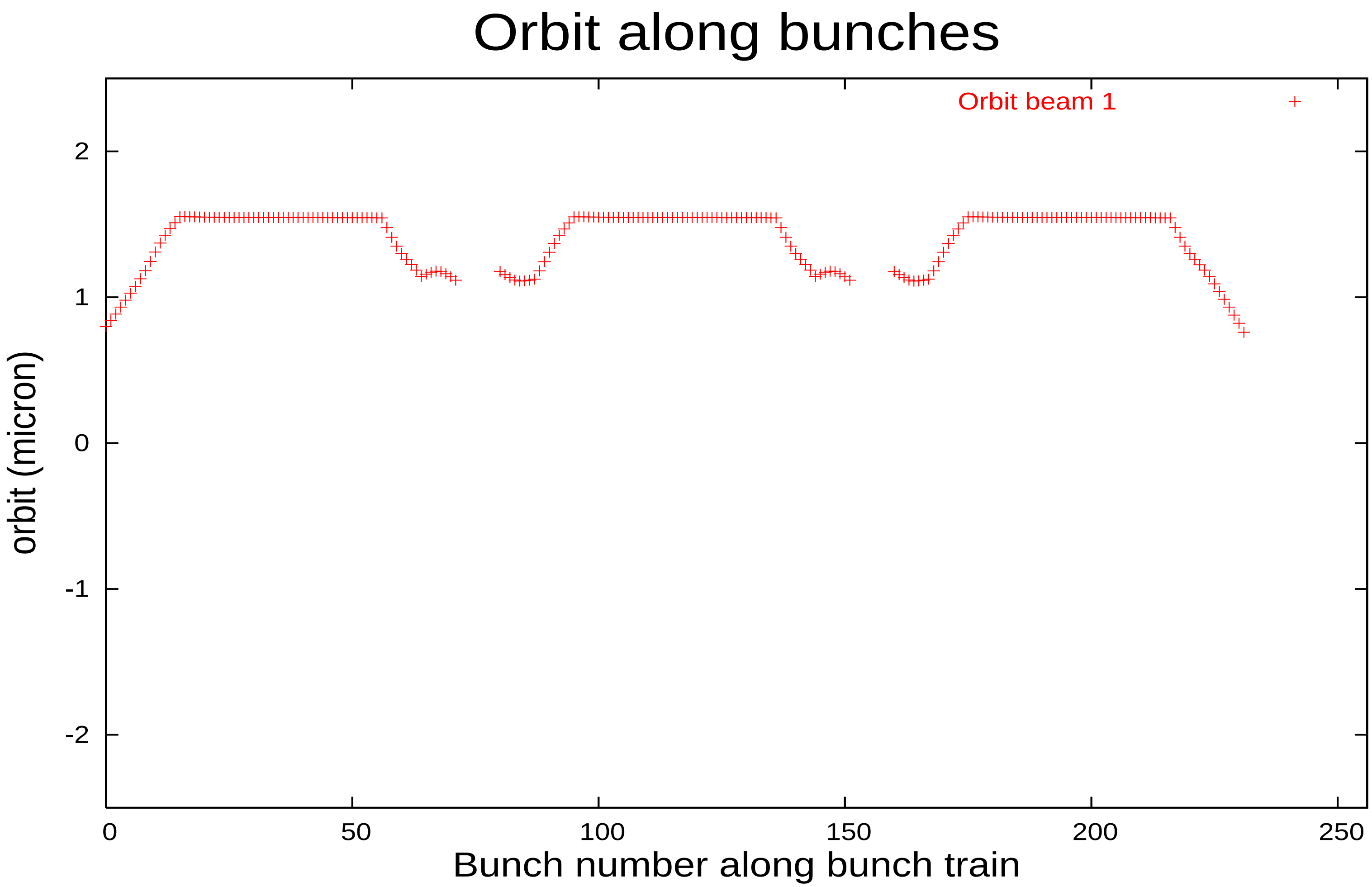


- A bunch can meet a hole (at beginning and end of bunch train)
- Results in left-right asymmetry
- Example LHC: between 120 (max) and 40 (min) long range collisions for different bunches

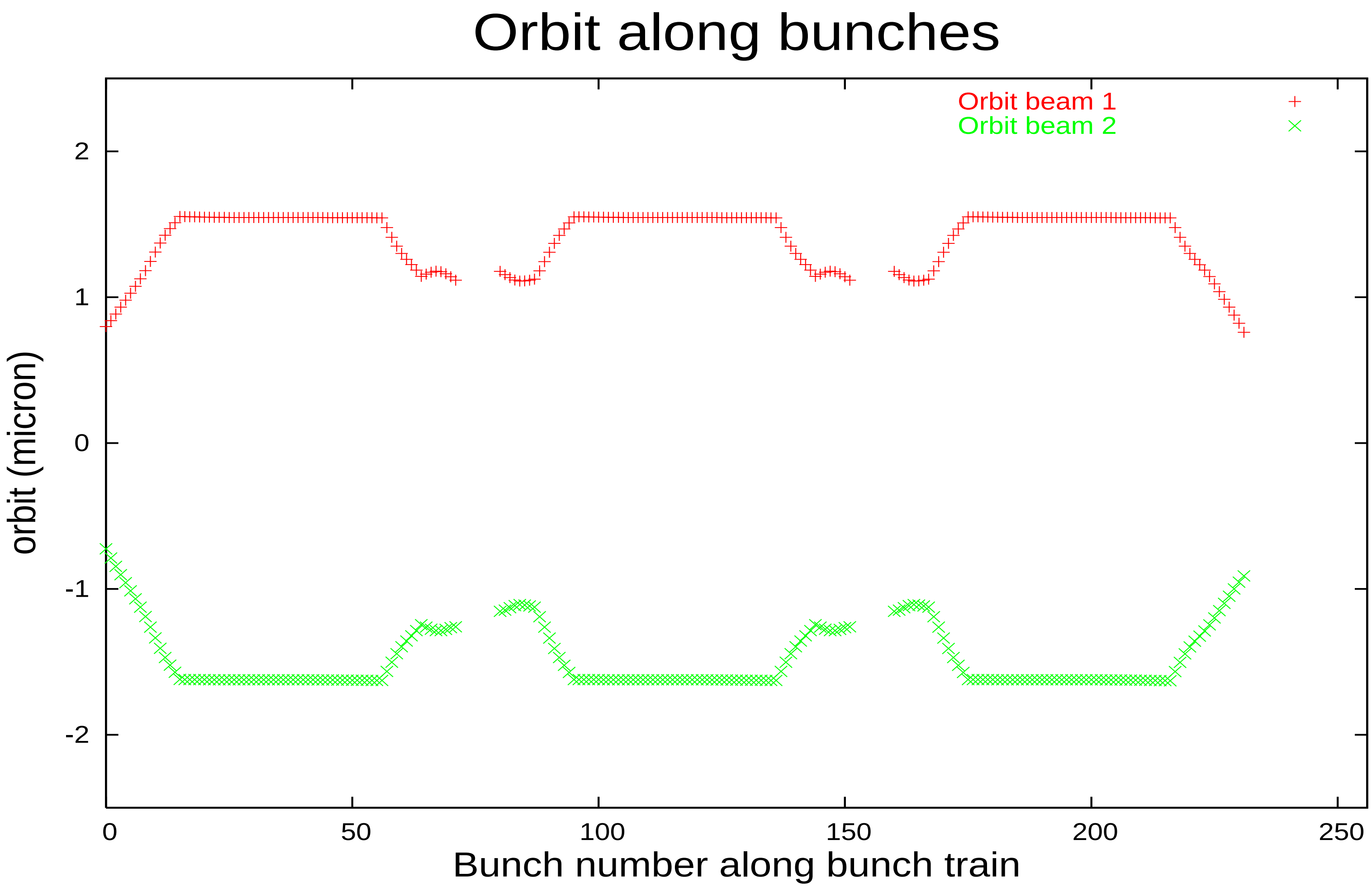
PACMAN bunches

- When a bunch meets a "hole":
  - ➡ Miss some long range interactions, PACMAN bunches
  - ➡ They see fewer unwanted interactions in total
  - ➡ Different integrated beam-beam effect
- Example: orbit and tune effects

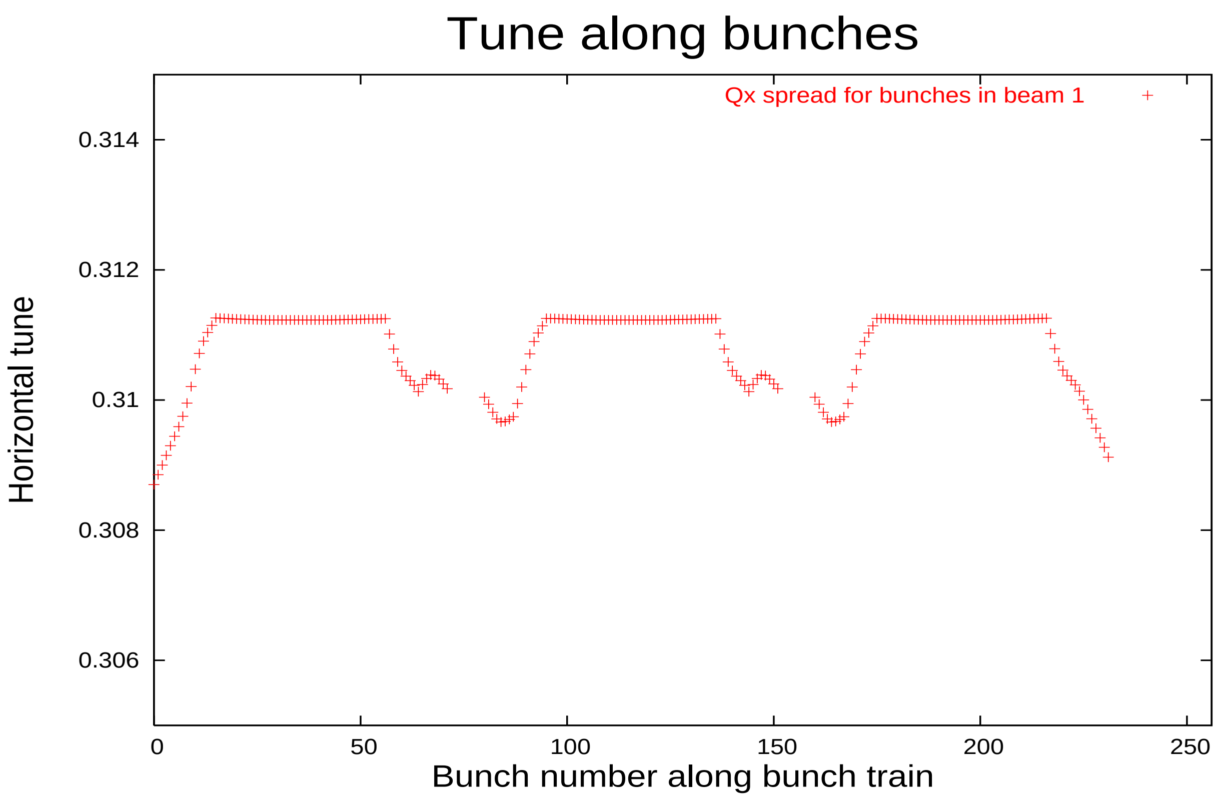
Orbit along batches: beam 1



Orbit along batches: beam 1 and beam 2



Tune along batches

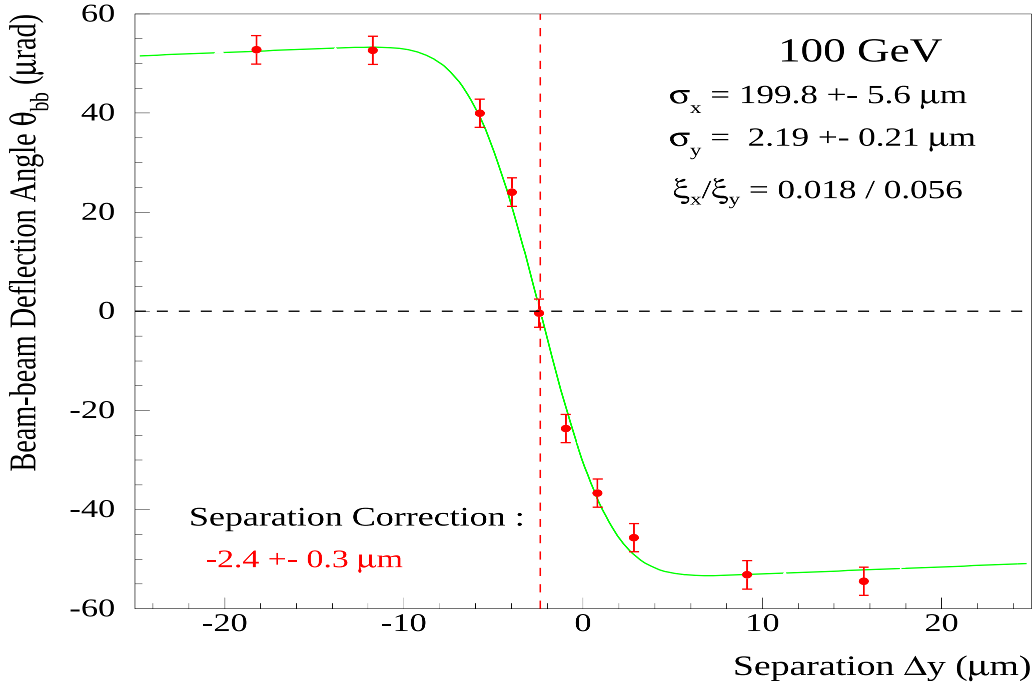


- Spread is too large for safe operation

Beam-beam deflection scan

- The orbit effect can be useful when one has only a few bunches, i.e. not PACMAN effects
- Effect can be used to optimize luminosity
- Scanning two beams against each other
- Two beams get a orbit kick, depending on distance

Deflection scan (LEP measurement)

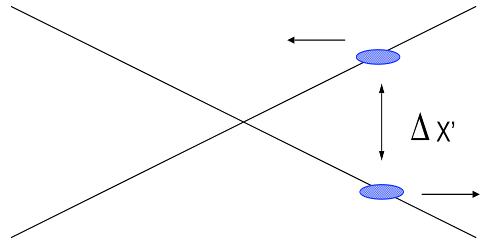


(Courtesy J. Wenniger)

Deflection scan

- **Calculated kick from orbit follows the force function**
- **Allows to calculate parameters**
- **Allows to centre the beam**
- **Standard procedure at LEP**

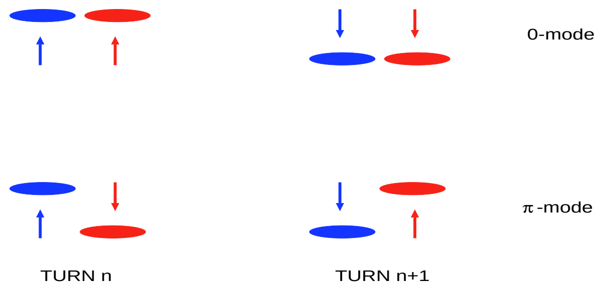
Coherent beam-beam effect



- **Whole bunch sees a kick as an entity (coherent kick)**
- **The coherent kick of separated beams can excite coherent dipole oscillations**
- **All bunches couple together because each bunch "sees" many opposing bunches: many coherent modes possible !**

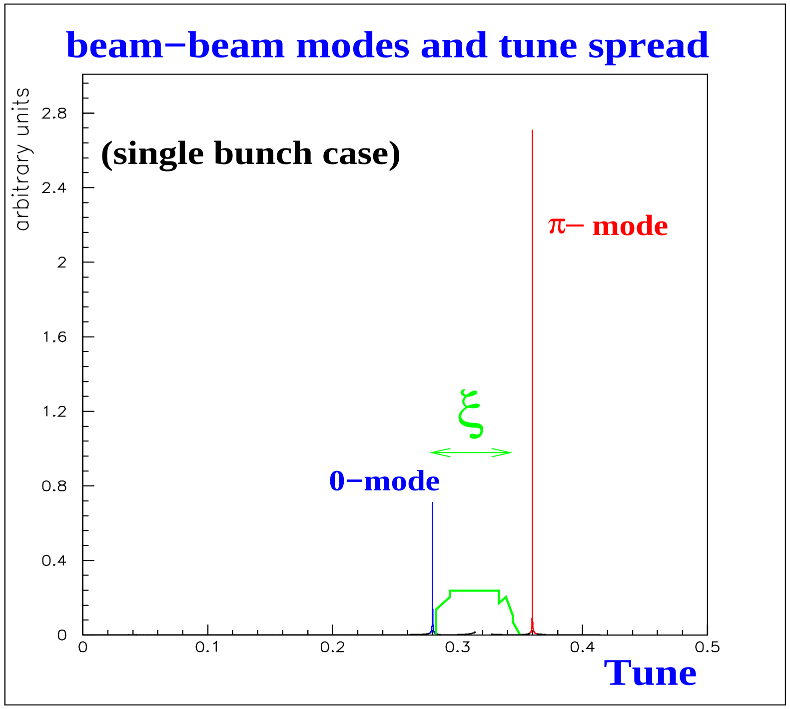
Coherent beam-beam effect

Simplest case: one bunch per beam:



- **Coherent mode: two bunches are "locked" in a coherent oscillation**
- **0-mode is stable (Mode with NO tune shift)**
- **π-mode can become unstable (Mode with LARGEST tune shift)**

Coherent beam-beam frequencies (schematic)

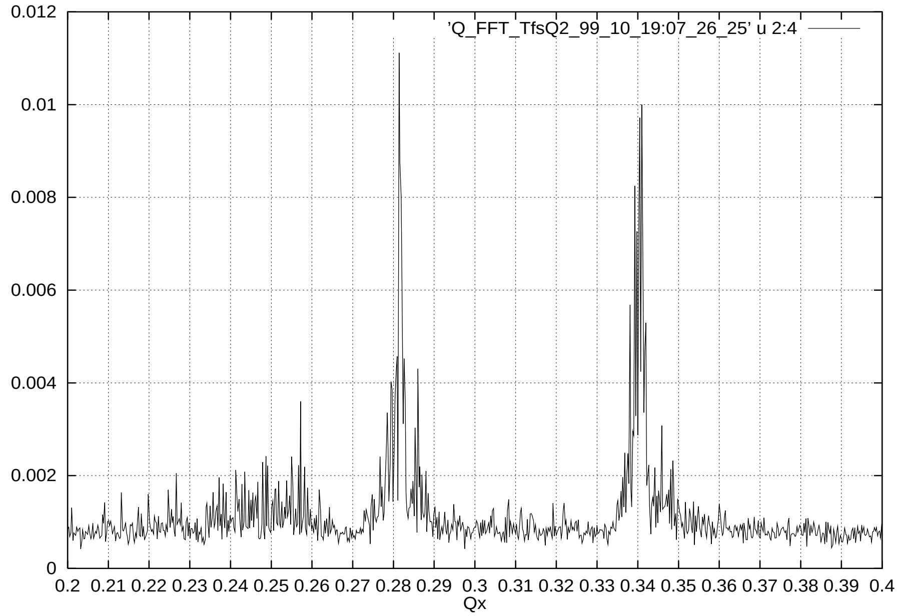


- 0−mode is at unperturbed tune
- π−mode is shifted by 1.1 − 1.3 · ξ
- Incoherent spread between [0.0,1.0] · ξ

➡ Strong-strong case: π-mode shifted outside tune spread

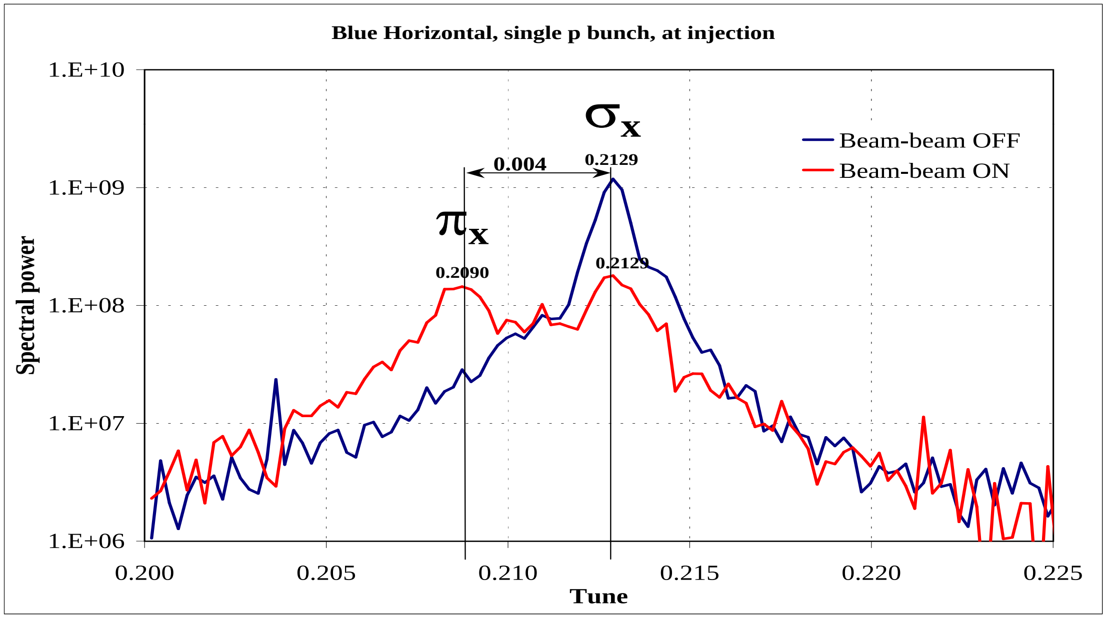
➡ No Landau damping possible

Measurement: LEP



- **Two modes clearly visible**
- **Can be distinguished by phase relation, i.e. sum and difference signals**

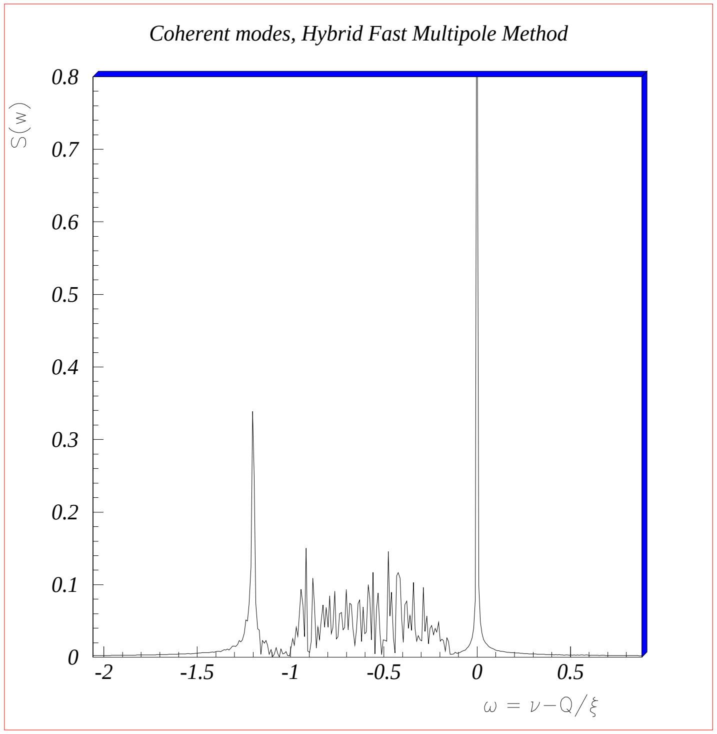
Measurement: RHIC



Courtesy W. Fischer (BNL)

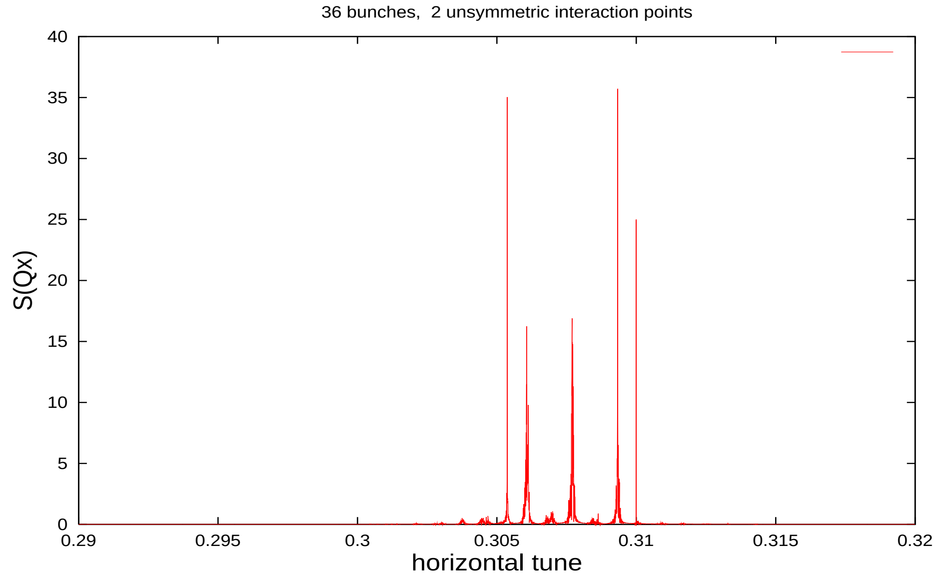
➡ **Compare spectra with and without beams : two modes visible with beams**

Simulation of coherent spectra



- Full simulation of both beams required
- Use up to 10^8 particles in simulations
- Must take into account changing fields
- Requires computation of arbitrary fields

Many bunches and more interaction points



- **Bunches couple via the beam-beam interaction**
- **Additional coherent modes become visible**
- **Potentially undesirable situation**

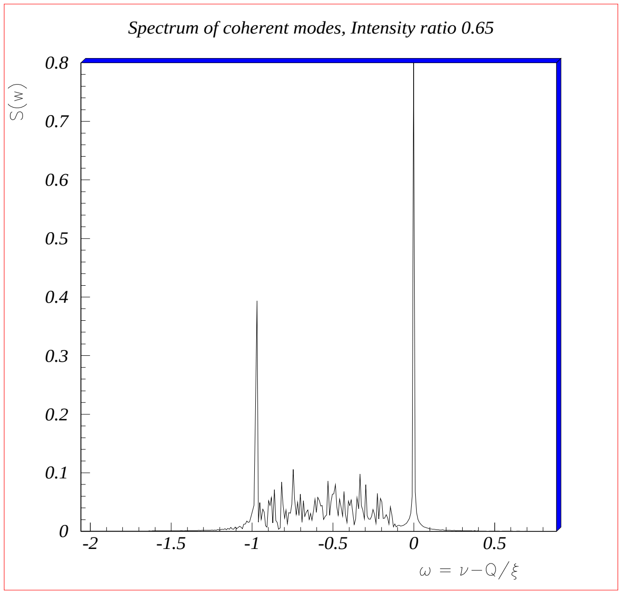
What can be done to avoid problems ?

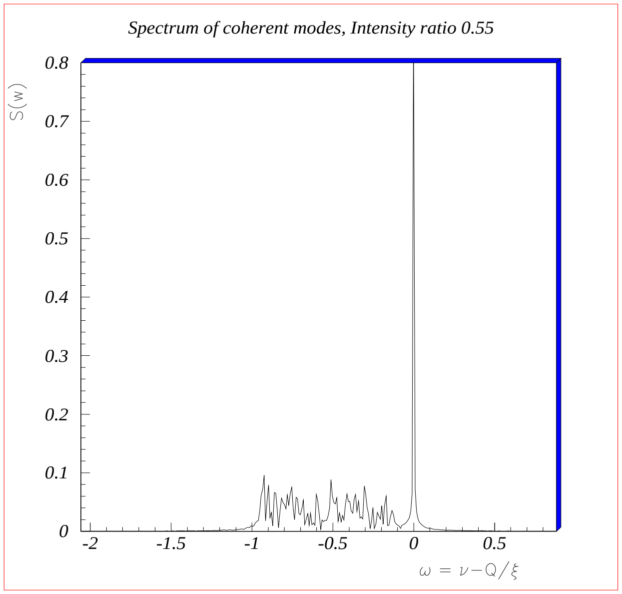
- Coherent motion requires 'organized' motion of many particles
- Therefore high degree of symmetry required
- Possible countermeasure: (symmetry breaking)

$\rightarrow$ Different bunch intensity

$\rightarrow$ Different tunes in the two beams

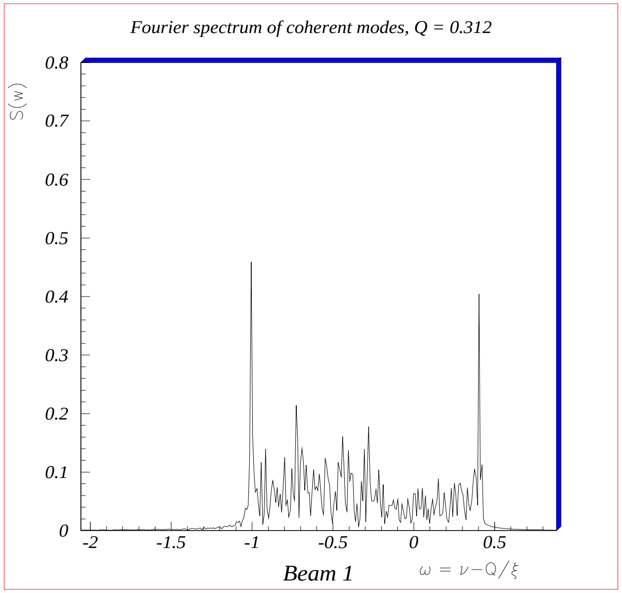
Beams with different intensity

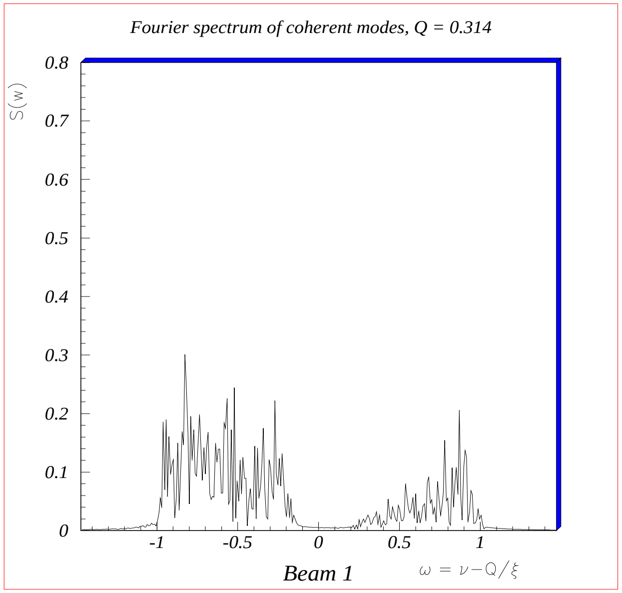




➡ **Bunches with different intensities cannot maintain coherent motion**

Beams with different tunes





➡ **Bunches with different tunes cannot maintain coherent motion**

Can we suppress beam-beam effects ?

- **Find 'lenses' to correct beam-beam effects**
- **Head on effects:**
  - → **Linear "electron lens" to shift tunes**
  - → **Non-linear "electron lens" to reduce spread**
  - → **Tests in progress at FNAL**
- **Long range effects:**
  - → **At very large distance: force is 1/r**
  - → **Same force as a wire !**
- **So far: mixed success with active compensation**

Others: Möbius lattice

- **Principle:**
  - → **Interchange horizontal and vertical plane each turn**
- **Effects:**
  - → **Round beams (even for leptons)**
  - → **Some compensation effects for beam-beam interaction**
  - → **First test at CESR at Cornell**

Not mentioned:

- **Effects in linear colliders**
- **Asymmetric beams**
- **Coasting beams**
- **Beamstrahlung**
- **Synchrobetatron coupling**
- **Monochromatization**
- **Beam-beam experiments**
- **... and many more**

Bibliography

Some bibliography in the hand-out

Beam-beam lectures:

A. Chao, The beam-beam instability, *SLAC-PUB-3179 (1983).*

L. Evans, The beam-beam interaction, *CAS Course on proton-antiproton colliders, in CERN 84-15 (1984).*

L. Evans and J. Gareyte, Beam-beam effects, *CERN Accelerator School, Oxford 1985, in: CERN 87-03 (1987).*

A. Zholents, Beam-beam effects in electron-positron storage rings, *Joint US-CERN School on Particle Accelerators, in Springer, Lecture Notes in Physics, 400 (1992).*

Beam-beam force:

E. Keil, Beam-beam dynamics, *CERN Accelerator School, Rhodes 1993, in: CERN 95-06 (1995).*

M. Basetti and G.A. Erskine, Closed expression for the electrical field of a 2-dimensional Gaussian charge, *CERN-ISR-TH/80-06 (1980).*

PACMAN bunches:

W. Herr, Effects of PACMAN bunches in the LHC, *CERN LHC Project Report 39 (1996).*

Coherent beam-beam effects:

A. Piwinski, Observation of beam-beam effects in PETRA, *IEEE Trans. Nucl. Sc., Vol.***NS-26** *4268 (1979).*

K. Yokoya et al., Tune shift of coherent beam-beam oscillations, *Part. Acc.* **27**, *181 (1990).*

Y. Alexahin, On the Landau damping and decoherence of transverse dipole oscillations in colliding beams, *Part. Acc.* **59**, *43 (1996).*

A. Chao, Coherent beam-beam effects, *SSC Laboratory, SSCL-346 (1991).*

Y. Alexahin, A study of the coherent beam-beam effect in the framework of the Vlasov perturbation theory, *Nucl. Inst. Meth.* **A 380**, *253 (2002).*

Y. Alexahin, H. Grote, W. Herr and M.P. Zorzano, Coherent beam-beam effects in the LHC, *CERN LHC Project Report 466 (2001).*

Simulations (incoherent beam-beam):

W. Herr, Computational Methods for beam-beam interactions, incoherent effects, *Lecture at CAS, Sevilla 2001*,
at http://cern.ch/lhc-beam-beam/talks/comp1.ps.

Simulations (coherent beam-beam):

W. Herr, Computational Methods for beam-beam interactions, coherent effects, *Lecture at CAS, Sevilla 2001*,
at http://cern.ch/lhc-beam-beam/talks/comp2.ps.

W. Herr, M.P. Zorzano, and F. Jones, A hybrid fast multipole method applied to beam-beam collisions in the strong-strong regime, *Phys. Rev. ST Accel. Beams* **4**, *054402 (2001).*

W. Herr and R. Paparella, Landau damping of coherent modes by overlap with synchrotron sidebands, *CERN LHC Project Note 304 (2002).*

Möbius accelerator:

R. Talman, A proposed Möbius accelerator, *Phys. Rev. Lett.* **74**, *1590 (1995).*