Present activities on Coherent beam-beam

Tatiana Pieloni and Werner Herr

Present studies:

- We know: coherent modes suppressed by symmetry breaking and damping mechanisms
  - Different phase advances
  - Bunch Intensity and emittance variations
  - Machine asymmetries

- How does suppression change with multi bunch beams?
  - Different collision schemes
  - Pacman and Super-Pacman bunches
  - Bunch Coupling $\Rightarrow$ different Landau damping properties
  - Etc….

Motivations:

- Produce Tune spectra for the LHC
  - Tune measurements (bunch to bunch differences, studies on measurement kick effect, single bunch vs averaging, etc.)
  - Feedback system

- Understanding of coupled bunches beam-beam coherent modes

Models for coherent bb studies

1. Matrix formalism: One Turn Map model OTM

2. The Rigid Bunch Model RBM in COMBI

3. The Multi Particle Model MPM in COMBI

1. Matrix Model OTM

Particle distribution: Gaussian with fixed RMS (s) defined constant for all bunches of a beam and all times

Transfer Matrix:

$$T = \begin{pmatrix}
\cos(\Delta\mu_x^{b_1}) & \sin(\Delta\mu_x^{b_1}) & 0 & 0 & \dots & 0 & 0 & 0 & 0 & \dots \\
-\sin(\Delta\mu_x^{b_1}) & \cos(\Delta\mu_x^{b_1}) & 0 & 0 & \dots & 0 & 0 & 0 & 0 & \dots \\
0 & 0 & \cos(\Delta\mu_y^{b_1}) & \sin(\Delta\mu_y^{b_1}) & \dots & 0 & 0 & 0 & 0 & \dots \\
0 & 0 & -\sin(\Delta\mu_x^{b_1}) & \cos(\Delta\mu_y^{b_1}) & \dots & 0 & 0 & 0 & 0 & \dots \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
0 & 0 & 0 & 0 & \dots & \cos(\Delta\mu_x^{b_2}) & \sin(\Delta\mu_x^{b_2}) & 0 & 0 & \dots \\
0 & 0 & 0 & 0 & \dots & -\sin(\Delta\mu_x^{b_2}) & \cos(\Delta\mu_x^{b_2}) & 0 & 0 & \dots \\
0 & 0 & 0 & 0 & \dots & 0 & 0 & \cos(\Delta\mu_y^{b_2}) & \sin(\Delta\mu_y^{b_2}) & \dots \\
0 & 0 & 0 & 0 & \dots & 0 & 0 & -\sin(\Delta\mu_y^{b_2}) & \cos(\Delta\mu_y^{b_2}) & \dots \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots
\end{pmatrix}$$

- $\Delta\mu_x^{b_1}$ Phase advance
- b_x Linearized HO or LR B-B kick
- k Coupling factor

Beam-Beam Matrix:

Beam-beam interaction (HO+LR): the bunch receives a linearized bb kick b

$$B = \begin{pmatrix}
1 & 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 & \dots \\
-b_x & 1 & k & 0 & \dots & b_x & 0 & 0 & 0 & \dots \\
0 & 0 & 1 & 0 & \dots & 0 & 0 & 0 & 0 & \dots \\
k & 0 & -b_y & 1 & \dots & 0 & 0 & b_y & 0 & \dots \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
0 & 0 & 0 & 0 & \dots & 1 & 0 & 0 & 0 & \dots \\
b_x & 0 & 0 & 0 & \dots & -b_x & 1 & k & 0 & \dots \\
0 & 0 & 0 & 0 & \dots & 0 & 0 & 1 & 0 & \dots \\
k & 0 & b_y & 0 & \dots & 0 & 0 & -b_y & 1 & \dots \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots
\end{pmatrix}$$

BEAM 1

BEAM 2

$$\begin{pmatrix} x_{1b_1} \\ x'_{1b_1} \\ y_{1b_1} \\ y'_{1b_1} \\ \dots \\ x_{1b_2} \\ x'_{1b_2} \\ y_{1b_2} \\ y'_{1b_2} \\ \dots \end{pmatrix}_{s_0+C} = M_C \begin{pmatrix} x_{1b_1} \\ x'_{1b_1} \\ y_{1b_1} \\ y'_{1b_1} \\ \dots \\ x_{1b_2} \\ x'_{1b_2} \\ y_{1b_2} \\ y'_{1b_2} \\ \dots \end{pmatrix}_{s_0}$$

bunch1 beam1

bch2, ...

bunch1 beam2

bch2, ...

One Turn Matrix:

$$M_C = T_1 * B_1 * T_2 * B_2 * \dots$$

The eigenvalues of M_C give the frequencies of the beam-beam modes

OTM Advantages and Disadvantages

Advantages:

- **Fast** calculation speed (for both HO and LR)
- **Moderate flexibility** to changes in the collision and bunch schemes
- Get **ALL mode frequencies**

Disadvantages:

- non-linear terms are not treated (**linear approx**)
- **No Landau damping** (rigid bunches, no tune spread)
- **No higher order modes**; cannot be evaluated
- does **not** use a **self-consistent field calculation**

2. The Rigid Bunch Model

- Particle distribution: Gaussian with time-independent transverse sizes for all bunches of a beam and all times in both planes x and y
- Beam-beam HO and LR interactions: bunch at (x,y) receives a coherent beam-beam kick from the opposite bunch at (X,Y) and with fixed transverse sizes σ_x and σ_y. A correction factor relates coherent and incoherent kick
- Between the BBI: normally linear transfer, but can also be anything else

Fourier analysis of the bunch barycentres turn by turn gives the tune spectra of the dipole modes

RBM Advantages and Disadvantages

Advantages:

- **Very high flexibility** to change collision and bunch filling schemes
- **Good** calculation **speed**
- **Non-linear effects** taken into account

Disadvantages:

- **No Landau damping** (rigid bunches, no tune spread)
- **No higher order modes;** cannot be evaluated
- does **not** use a **self-consistent field** calculation (fixed bunch transverse sizes)

3. The Multi Particle Model

- Particle distribution: Bunches consist of a distribution of N_{tot} representative macro particles
- Beam-beam HO and LR interactions: all particles of interacting bunches receive an incoherent beam-beam kick where the opposite bunch barycentres (X and Y) and sizes (σ_x and σ_y) are changing and re-calculated from the particle distribution just before a BBI, self-consistent (strong-strong)
- Between the BBIs: normally linear transfer, but can be anything else

A Fourier analysis of the bunch motion turn by turn gives the tune spectra of the dipole or higher order modes

MPM Advantages and Disadvantages

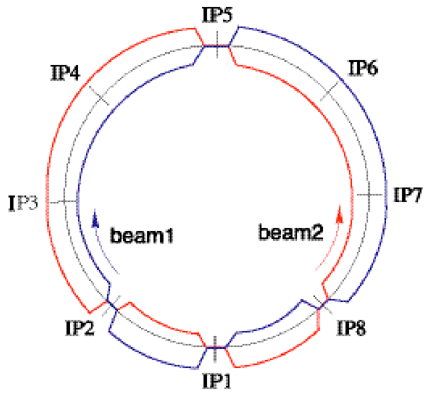
Advantages:

- non-linear effects are properly treated (**tune spread**!)
- **Landau damping** can be reproduced
- **Higher order modes** can be reproduced
- **Self-consistent field** calculation (depending on the field solver used)
- **High flexibility** to different collision patterns and beam filling schemes
- **Incoherent effects** can be studied (emittance growth, beam life time...)

Disadvantages:

- **Time consuming** (concrete results for the LHC only in parallel mode)
- does **not give ALL mode** frequencies

One Turn Map vs Rigid Bunch Model (a)



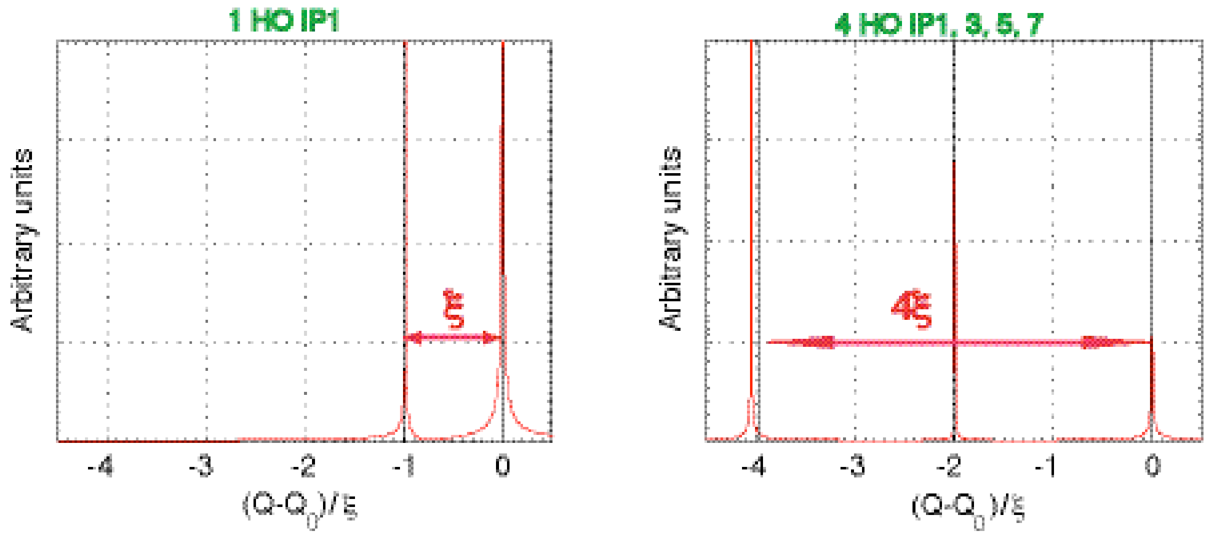
Geometrical layout

Inputs:

- 4 bch beam1 vs 4 bch beam 2 equi-spaced
- Different collision schemes (only HO)

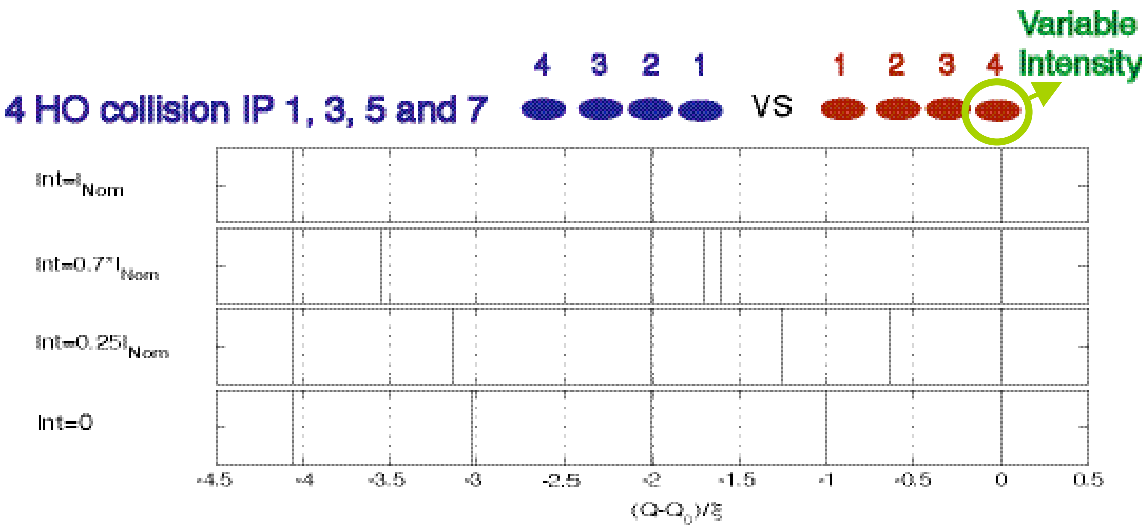
$$\Delta Q_{bb}^{max} = N_{IPs} * \xi_{bb}$$

MULTI HO collisions



- Same number of modes
- Same tune shifts

One Turn Map vs Rigid Bunch Model (b)



Inputs:

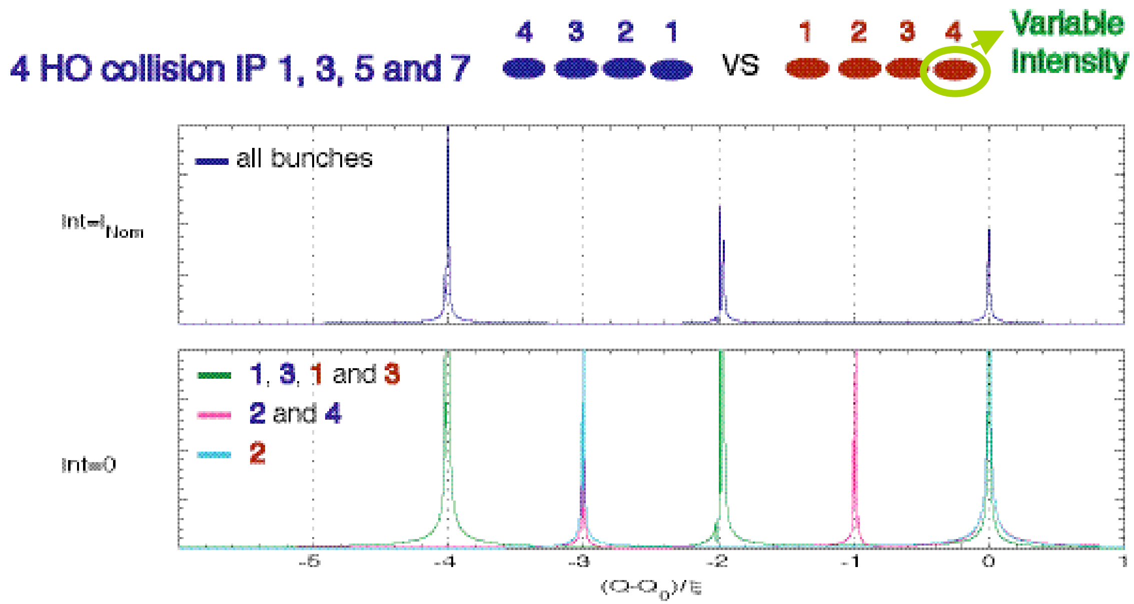
- 4 bch vs 4 bch
- same collision scheme
- intensity variation of b_4

OTM:

- **All modes** visible
- **Sliding** of modes with the intensity variation

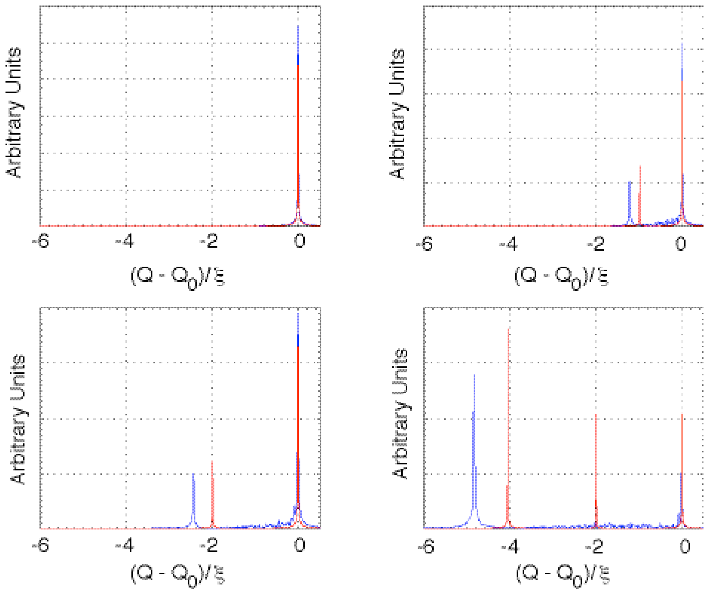
RBM:

- Evidence of **direct and indirect coupling** to b_4
- **Different frequencies and sliding of coherent modes** with the intensity variation of b_4



Rigid Bunch Model vs Multi Particle Model (a)

Multi HO collisions



Inputs:

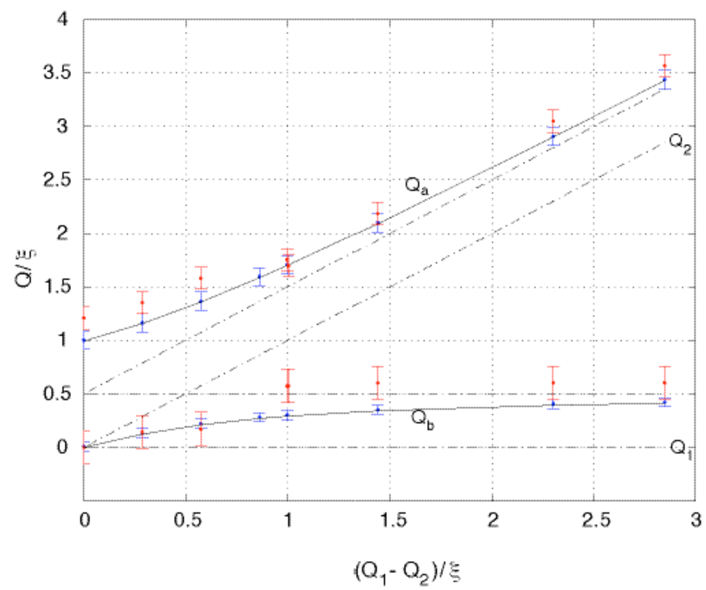
- 4 bunches beam1 vs 4 bunches beam2
- 0-1-2-4 Head-on collisions

RBM vs **MPM**

$$\Delta Q_{bb}^{max} \approx Y * N_{IPs} * \xi_{bb}$$

Landau damping of modes inside the incoherent spectrum

Q dependence



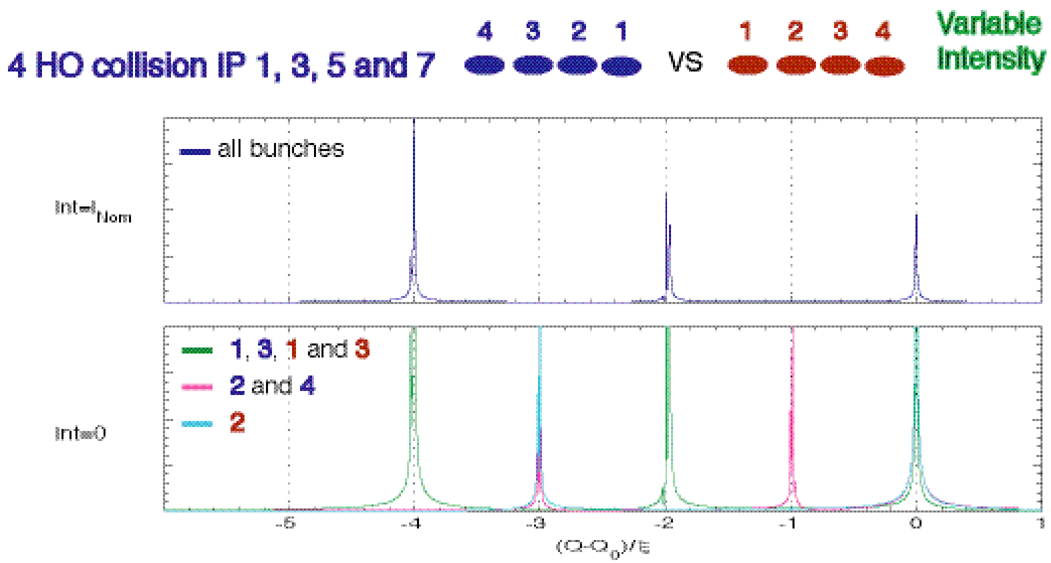
Inputs:

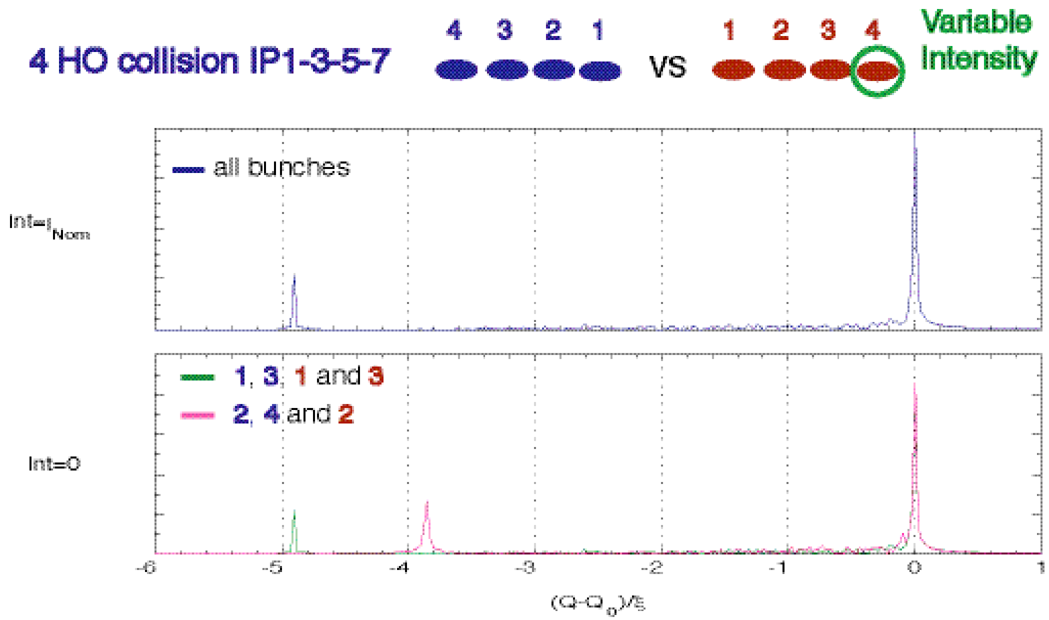
- 1 bunch beam1 vs 1 bunch beam2
- 1 Head-on collision
- $Q_{beam1} \neq Q_{beam2}$

RBM vs **MPM** vs **Analytical solutions**

Agreement in within the different approx

Rigid Bunch Model vs Multi Particle Model (b)





Inputs:

- 4 bch vs 4 bch
- same collision scheme
- intensity variation of b_4

RBM:

- Evidence of **direct and indirect coupling** to b_4 ⇒ **different tune spectra**
- **Different frequencies** and **sliding of coherent modes** with b_4 intensity variations
- **Landau damping** of bunch modes inside their **different incoherent spread**

Rigid Bunch Model vs Multi Particle Model (c)

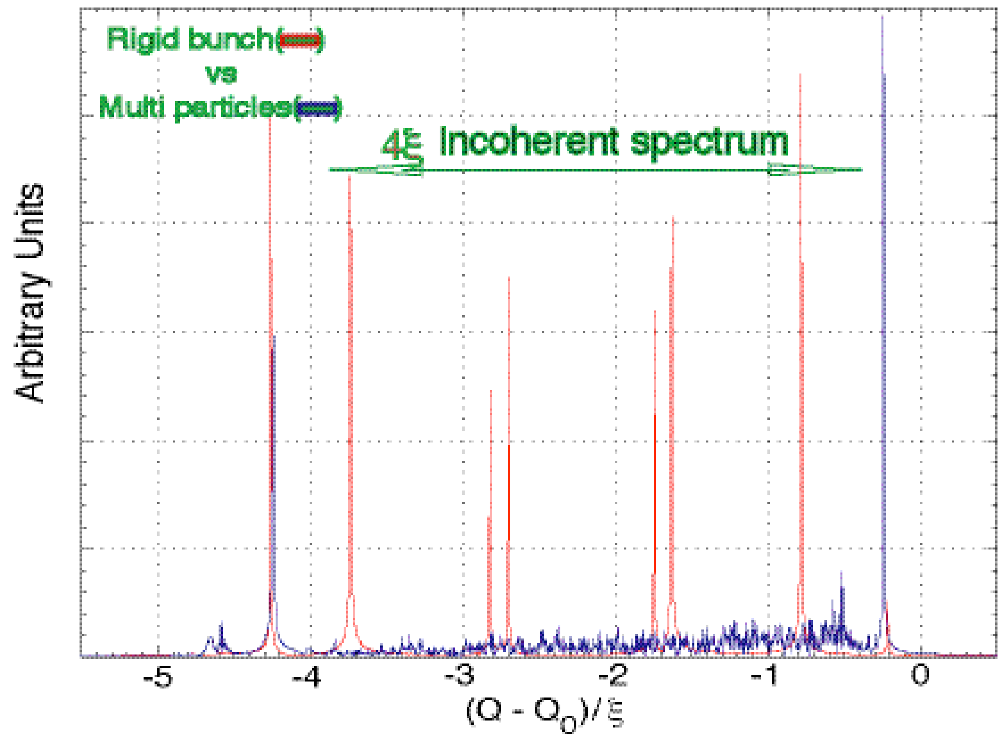
More complicate: the LHC example….

```
# Beam filling scheme #
```
4 Trains 9 bunch each

```
9 1 71 0     9 1 71 0
9 1 71 0     9 1 71 0
```

```
# Collision Scheme #
```

		$\Delta\mu_x$	$\Delta\mu_y$
1(IP1)	HO		
41	LT	8.046	6.940
81(IP2)	HO		
202	LT	23.015	21.821
321(IP5)	HO		
441	LT	23.533	20.689
561(IP8)	HO		
601	LT	7.716	7.870



- **Consistent tune** spread and multi-peak picture
- **Landau damping** of intermediate modes
- **Further studies** on multi-bunch coupling with **LR interactions**

Open Questions and future extensions

- Extensive **simulations** with **OTM, RBM and MPM**
- MPM Gaussian approximation gives **larger** than expected $\Rightarrow$ $\mathbf{Y_{factor}}$ closer to theoretical value
- **HFMM** extension for quantitatively correct field calculations

- **HFMM** $\Rightarrow$ much too slow (MPM 10 vs HFMM 32 msec/turn)
- **PARALLEL processing** mode to gain in time: to simulate LHC full batch (min.72-max.846 bunches, min.40-max.124 BBIs per turn, min.2^{14} turns, min.10^4 macro-particles).

  Some numbers with min. LHC scheme:
  - Not parallel weeks-month
  - Parallel mode day(s)

$\Downarrow$

4. HFMM solver in parallel mode

4. The HFMM Solver in Parallel mode

Starting points:

- Bunch represented 10^4-10^5 macro-particles
- Each bunch described by 1,5-2 Mbyte
- Each BBI field calculation(most of the computing time)

Strategies to parallelize COMBI code:

- Each **bunch of beam 1 resident** on a single node
- **Beam 2** bunches "**move**" from node to node
- **BBI** can be computed independently **in parallel**
- **Dedicated node** acts as a **dispatcher** to assign bunch beam 2 and action to a node

Proposal to EPFL

Proposal submitted (W. Herr, F. Jones and T. Pieloni) to **EPFL Lausanne** (A. Bay and A. Wrulich) for using IBM BlueGene

BlueGene machine:

IBM parallel system operative at EPFL

- 4 racks with 1024 bi-processor nodes ⇒ **8192 processors**
- Each node has 512 MB for a total active memory of 2TB
- Bi-processors can both used in calculations and/or one used for calculus the other for data transfer

Allows simulation of complete LHC batch (72, 432 and 864 bunches) each represented by 10^4-10^5 macro-particles undergoing up to 124 BBIs for min. 2^{14} turns