Strong-Strong Beam-Beam Simulations

Tatiana Pieloni
CERN - ABP
R&D and LHC Collective Effects section

Overview

- Introduction and motivation
  - Beam-beam Interactions
  - Why a new BB code for the LHC?
- The COherent Multi Bunch multi BB Interaction code
  - Analytical Linear Model
  - Rigid Bunch Model
  - Multi Particle Simulations
- Need for parallel computing
- Conclusions and Outlooks

Beam-Beam Interactions

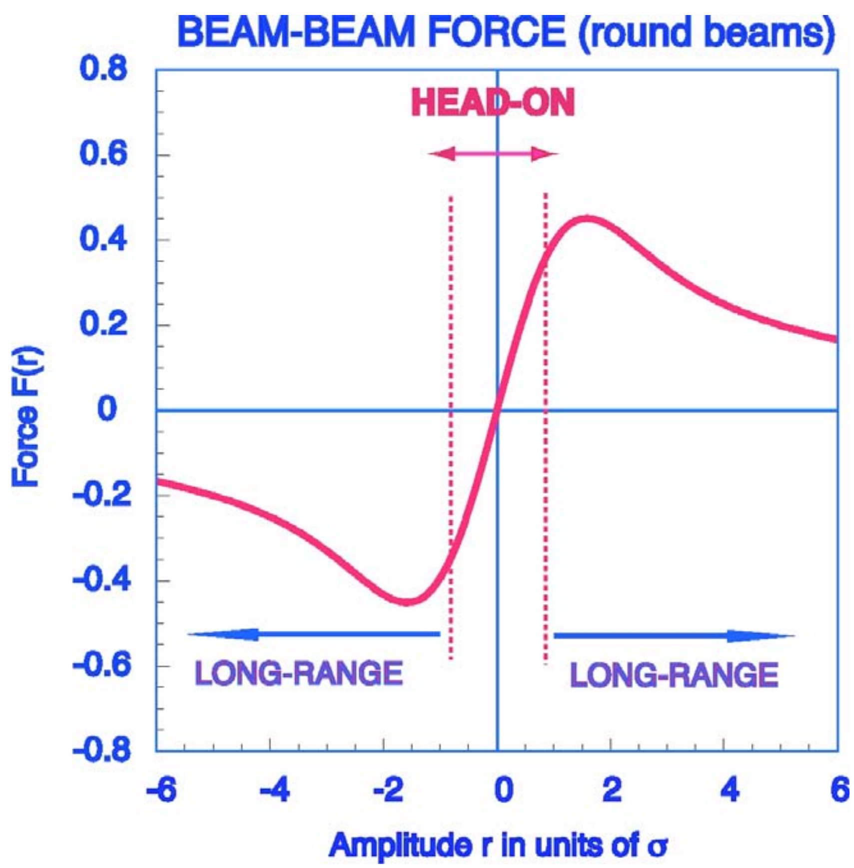
- Beam: **relativistic moving charged particles**
- Beam acts on other beam as electromagnetic lens, but:
  - It is **not** expressed by a **simple form**

$$f_{dip} \propto const \qquad f_{quad} \propto x$$

$$f_{sext} \propto x^2 \qquad \ldots$$

$$f_{bb} \propto \frac{1}{x} e^{\frac{-(x-x_0)^2}{2\sigma^2}}$$

  - Very **non-linear force** depending on particle distribution
  - Can change distribution as result of interaction (**time dependent**)

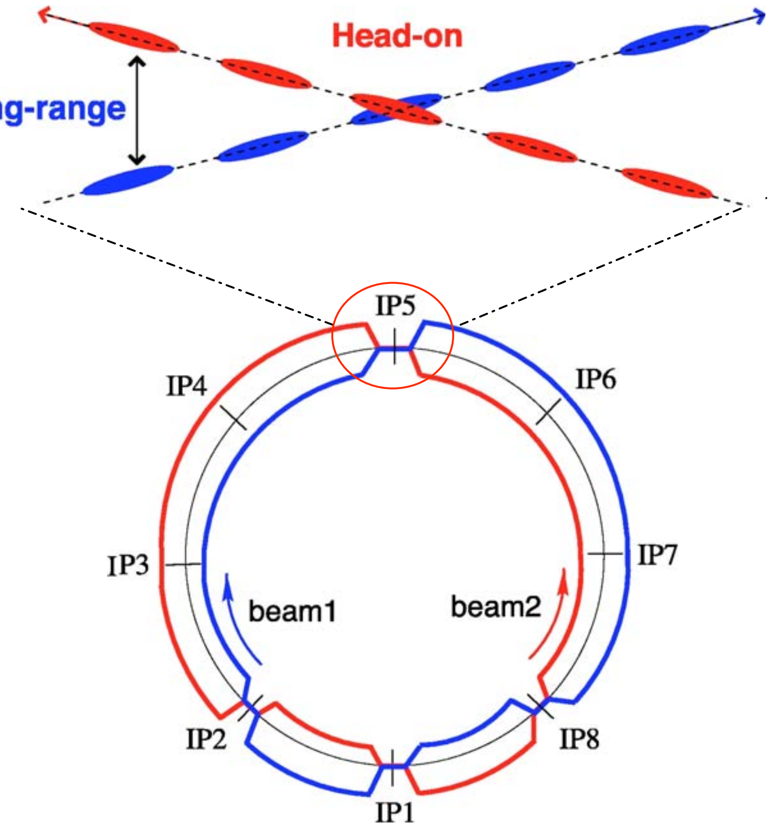


Why a new BB code for the LHC?

❑ Luminosity in a collider:

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$

N_i = bunch charge
N_b = num. of bunches
f = Repetition freq.
σ_i = beam sizes

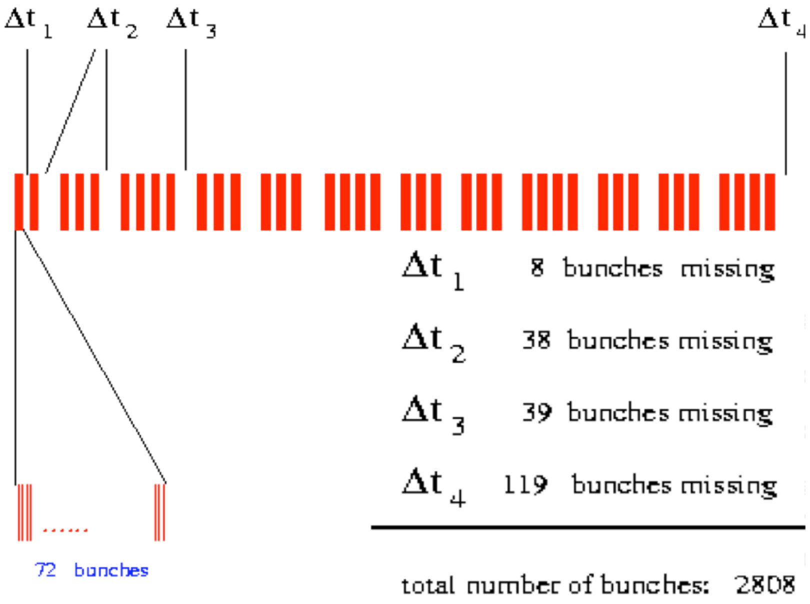


❑ Beam-beam interactions:

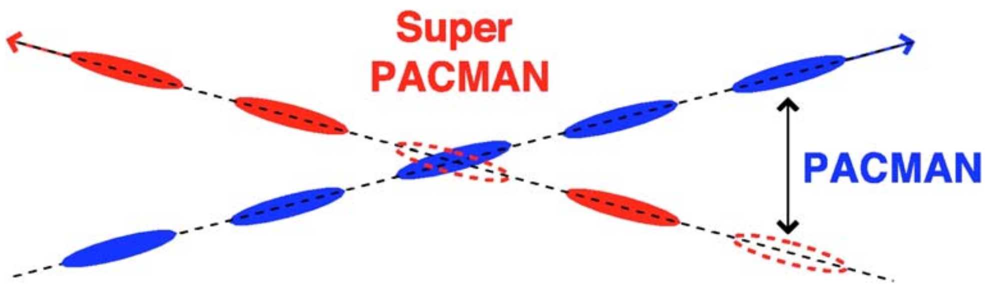
- Strong effects (high intensity 10^{11} p/bch and/or small beam sizes 10^{-6} m)
- Multi bunch beams lead to multiple BBI (LHC 2808 bunches and up to 120 BBI per turn)
- Beams and collisions not regular: different damping properties due to presence of PACMAN and Super PACMAN bunches

PACMAN and Super PACMAN bunches

Time structure of the LHC beam



Bunch crossing at the interaction region



- **PACMAN bunch:** misses one or more long range interactions
- **Super PACMAN bunch:** misses a head-on collision

For the LHC, we need a *new BB code* that CAN:

- ♥ **Predict** bunch to bunch differences (diagnostic)
- ♥ **Investigate** BB effects for different filling schemes and collision patterns

How do we proceed?

(1) Simulation type: Strong-Strong

- Only one beam affected **(weak-strong)**:
  - BBIs affect and change only weak beam, strong beam static
  - Examples: SPS collider, Tevatron, HERA…

- Both beam affected **(strong-strong)**:
  - BBIs affect and change both beams
  - Examples: LEP, RHIC, LHC …

How do we proceed?

(2) Methods

- Could solve Vlasov equation **but**:
  - Analytical solution not always possible (perturbation theory needed)
  - Numerical solutions difficult (may not converge)
  - Very difficult to apply to multi bunch beam and multi interactions

- COherent Multiple bunch Beam-beam Interactions code (COMBI) :
  - Analytical Linear Model (ALM)
  - Rigid Bunch Model (RBM)
  - Multi Particle Simulation (MPS)

Analytical Linear Model

Solve eigenvalue problem of 1 turn map

Beam-Beam Matrix:

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

BEAM 1

BEAM 2

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

bunch1 beam1

bch2, ...

bunch1 beam2

bch2, ...

Bunches: Rigid Gaussian distributions

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

One Turn Matrix ➡ $M_C = T_1 * B_1 * T_2 * B_2 * \dots$

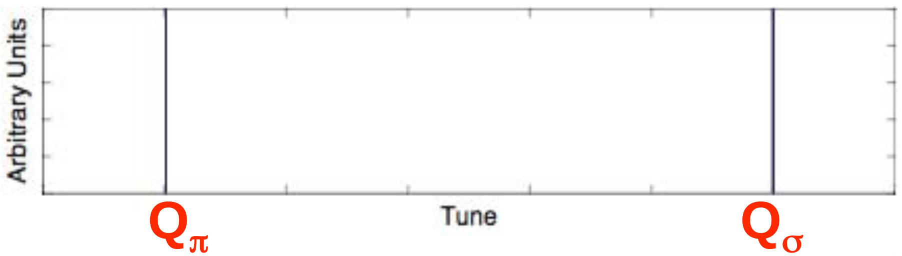
Analytical linear model

Solving the eigenvalue problem, like for a system of coupled oscillators:

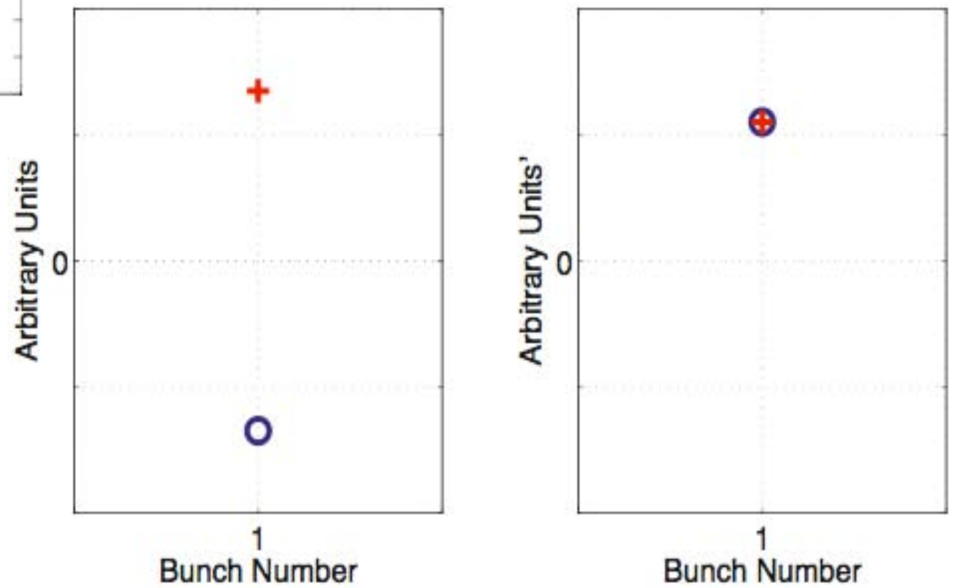
- **eigenvalues** give the system eigenfrequencies of dipolar modes (**tune**):

$$Q_i = \frac{\arccos(\lambda_i)}{2\pi}$$

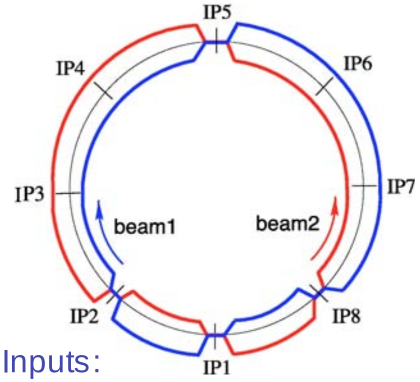
  - Mode frequencies calculations for bunches
  - Stability studies



- **eigenvectors** give the system oscillating patterns:
  - To understand bunches oscillation patterns
  - With other simulations to understand bunch to bunch differences



ALM: more bunches

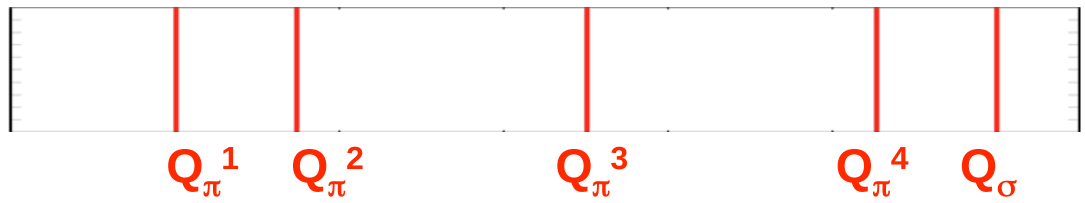


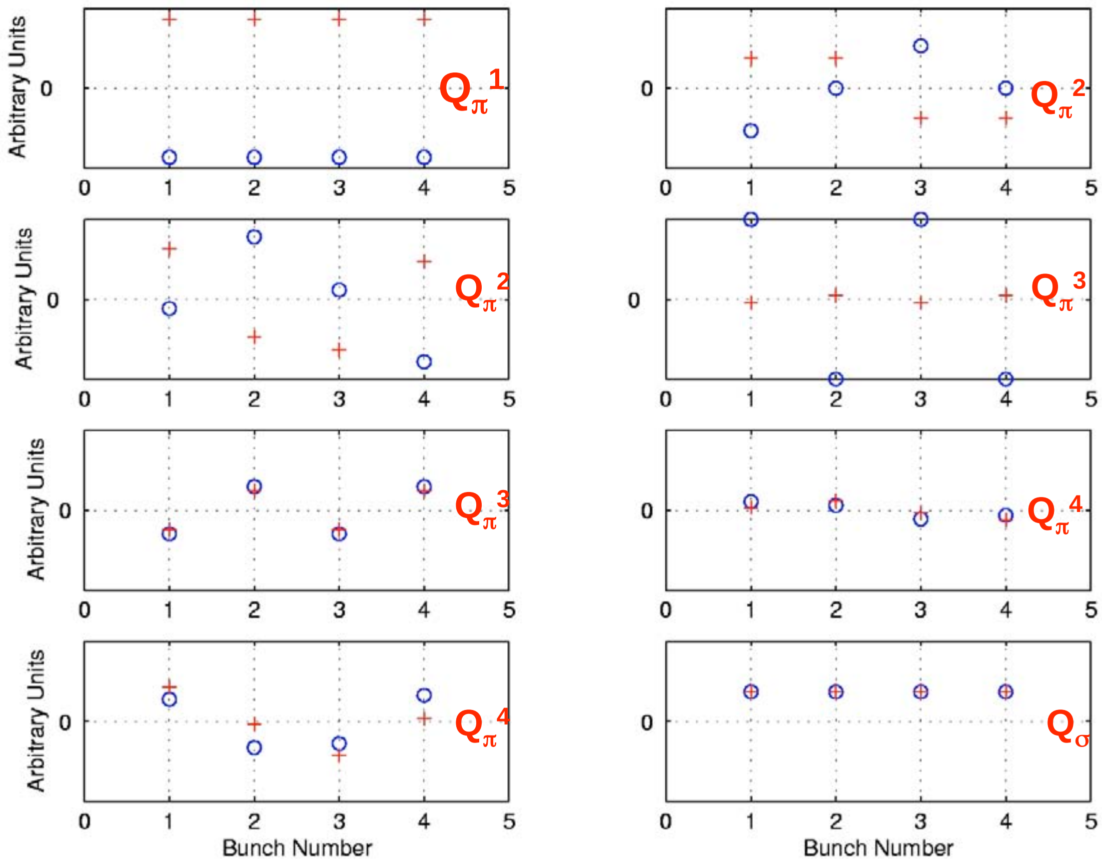
Inputs:

- Beam 1 = 4 equispaced bunches
- Beam 2 = 4 equispaced bunches
- HO collision in IP1-2 and LT

5 different Eigen-values

8 different Eigen-vectors





Q_π^1-mode:

all bunches exactly out of phase

$Q_\pi^{2,3,4}$-mode (intermediate modes):

Q_σ-mode:

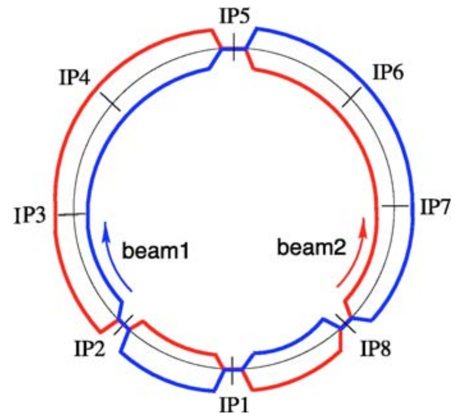
all bunches exactly in phase

ALM: Adv & Disadv

- Advantages:
  - Easy definition of any beam filling scheme and collision patterns
  - Fast calculation speed
  - Get all modes frequencies (eigenvalues)
  - Give information on bunch pattern (eigenvectors)

- Disadvantages:
  - Non-linear terms not treated
  - Landau damping cannot be included
  - Higher order modes cannot be evaluated

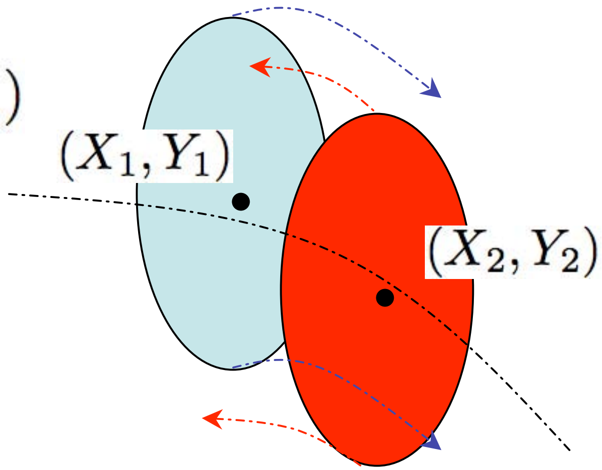
Rigid Bunch Model



- **Bunches:** Gaussian with varying barycentres (X,Y) and fixed (σ_x,σ_y)

- **At BBI** bunch at **(X_1,Y_1)** receives a transverse **kick** from the opposite bunch at **(X_2,Y_2)** and transverse sizes **(σ_x,σ_y)** and vice versa

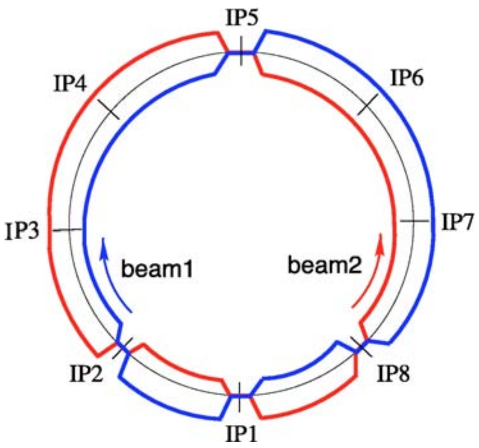
$$\Delta(X_1)' = \frac{2r_pN_p}{\gamma}\frac{\beta_x}{\sigma^2_{X_2}}F_{X_2}(X_1 - X_2, Y_1 - Y_2, \sigma^2_{X_2}, \sigma^2_{Y_2})$$



- **Between BBI:** linear transfer (rotation in phase space) and can be anything else (transverse kick from kickers, collimators,…)

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

ALM vs RBM: multi BBIs

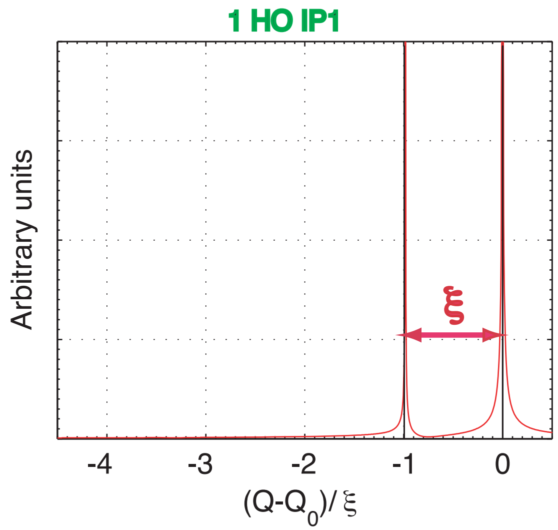


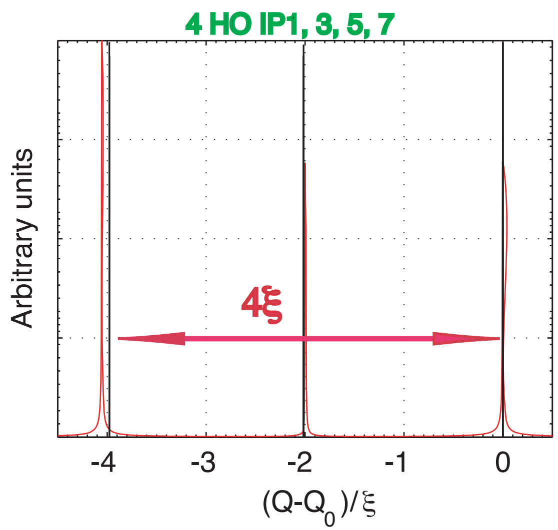
Inputs:

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

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

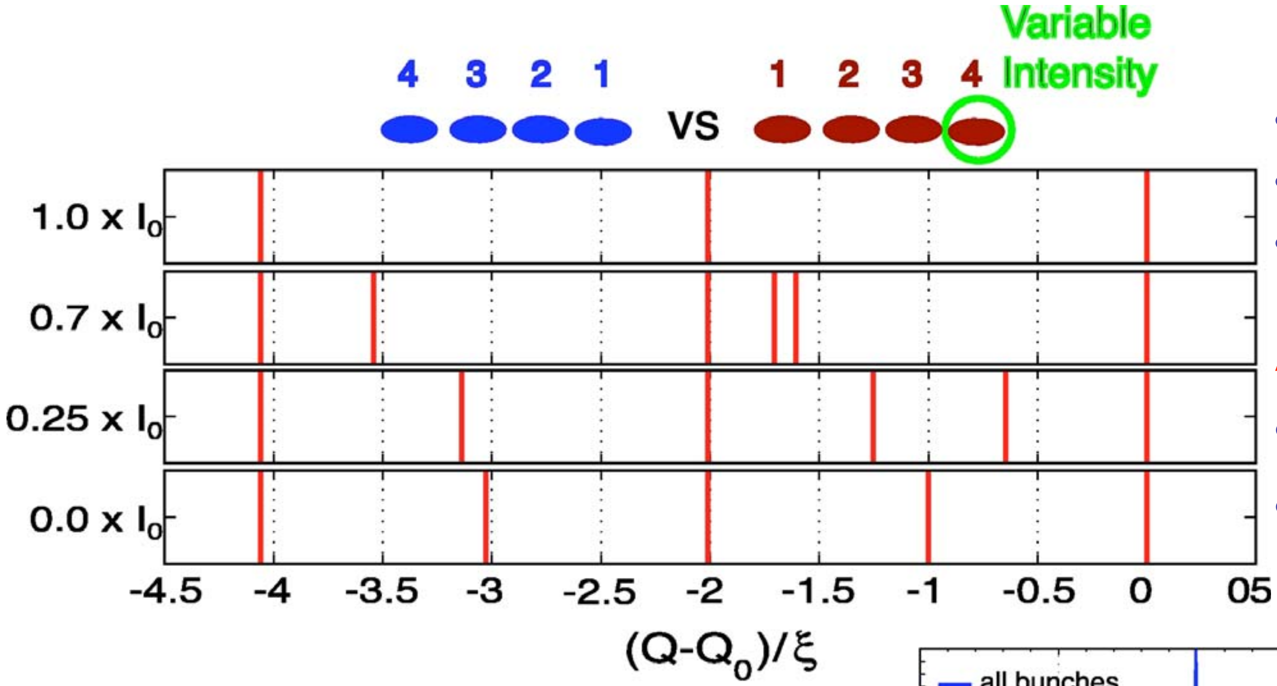
MULTI HO collisions





- Same number of modes
- Same tune shifts

ALM vs RBM: intensity effects



Inputs:

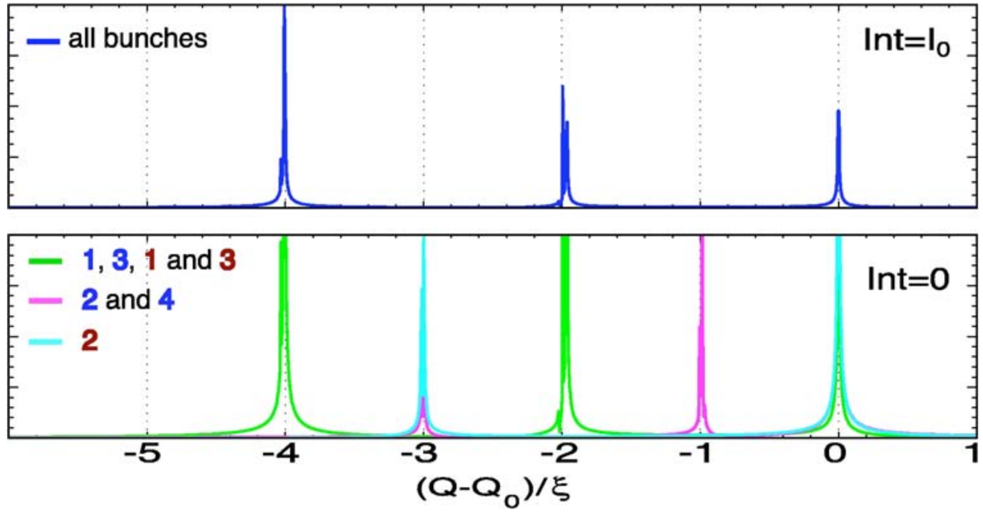
- 4 bch vs 4 bch
- same collision scheme
- intensity variation of b_4

ALM:

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

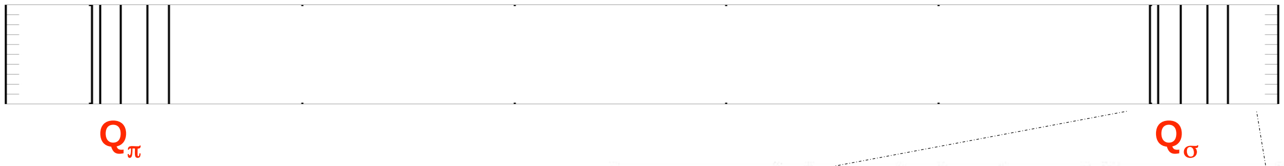
RBM:

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

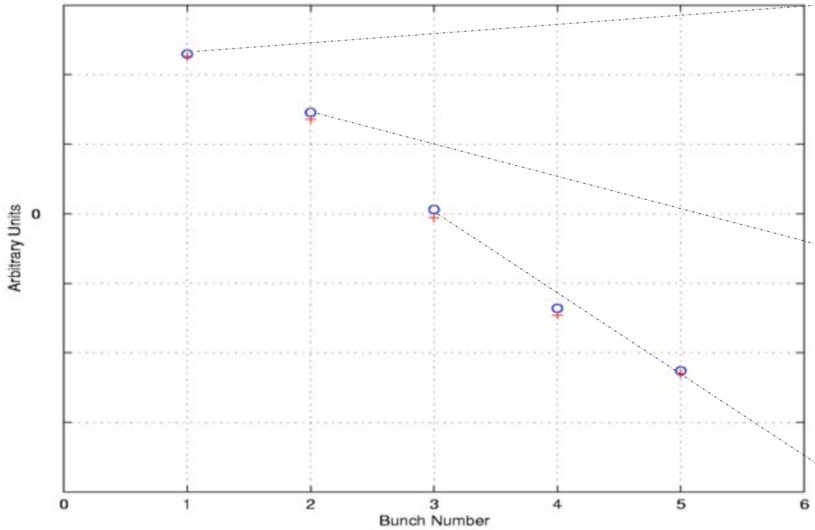


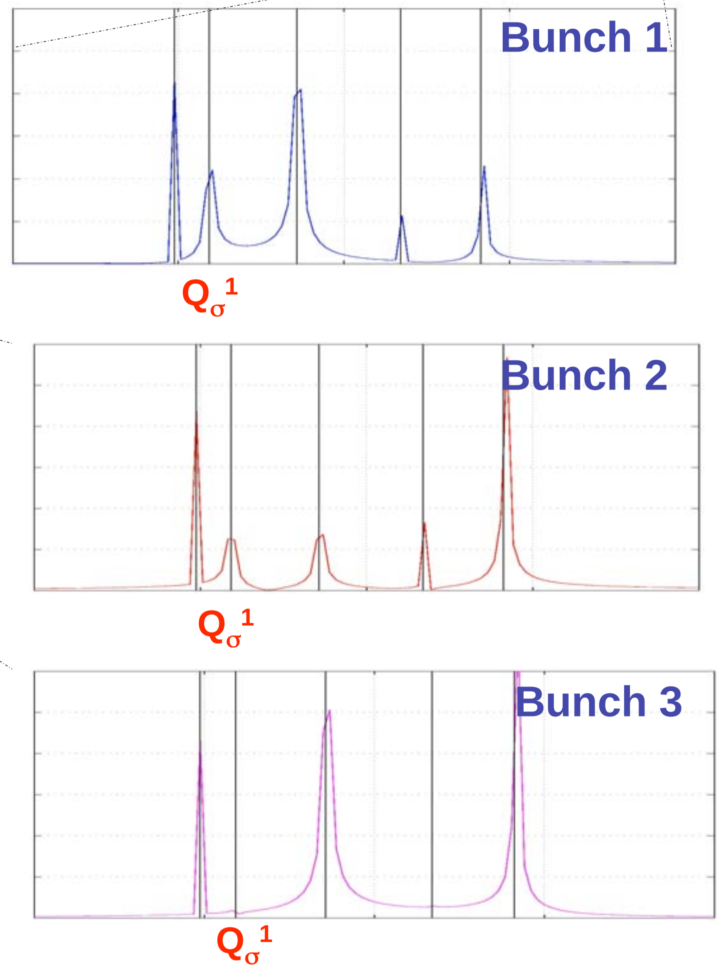
ALM vs RBM: bch to bch differences

- 5 bch train
- 1 HO 1 LR



Example Q_σ^1





The eigenvector associated to the Q_σ^1 shows that the total effect on the 3 bunches varies from bunch to bunch and for bunch 3 is zero

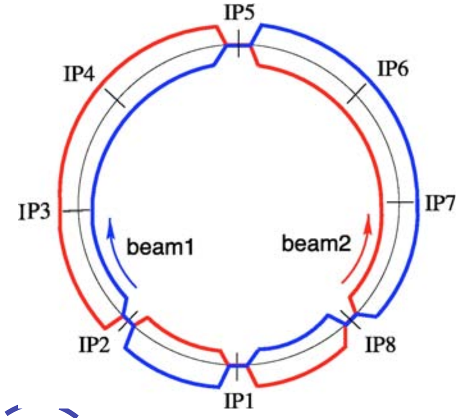
✓ **We can predict bunch to bunch differences in the tune spectra**

RBM: Adv & Disad

- Advantages:
  - Easy definition of any beam filling scheme and collision pattern
  - Bunch to bunch differences can be predicted
  - Good calculation speed
  - Non-linear effects treated only for Gaussian bunches

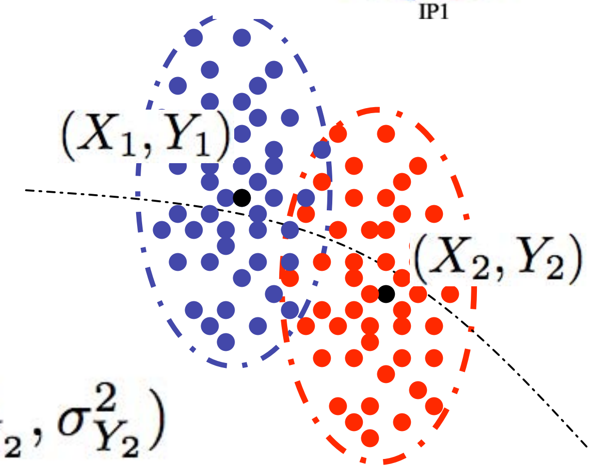
- Disadvantages:
  - Non-linear terms partially treated (field calculation not correct)
  - Landau damping cannot be included (rigid bunches)
  - Higher order modes cannot be evaluated

Multi Particle Simulations



- **Bunches: N_{tot}** (10^4-10^6) macro particles

- At BBI each particle of bunch **(X_1,Y_1)** receives a traverse **kick** from bunch **(X_2,Y_2)** and vice versa. Barycentres **(X,Y)** and sizes **(σ_x,σ_y)** change and are calculated from the particle distribution (assumed Gaussian) just before a BBI



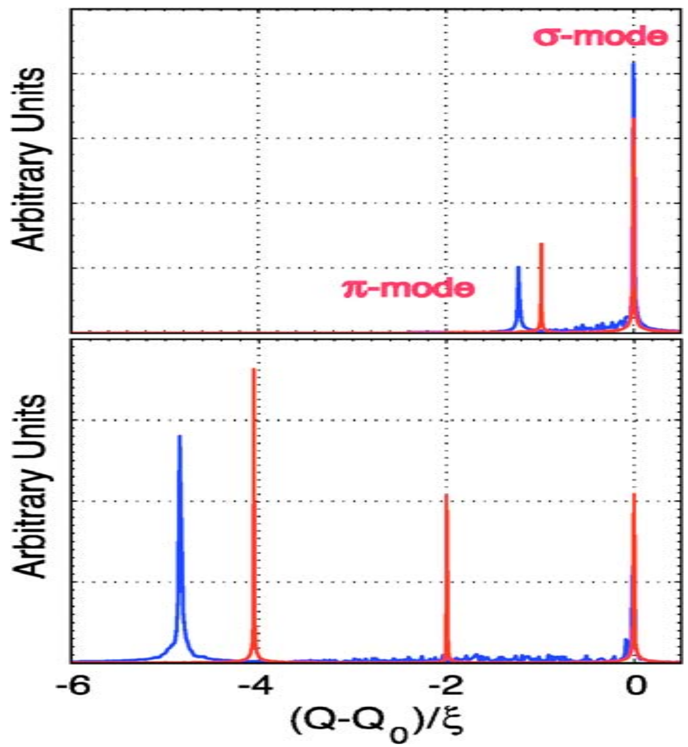
$$\Delta(x_1)' = \frac{2r_p N_p}{\gamma} \frac{\beta_x}{\sigma^2_{X_2}} F_{X_2}(x_1 - X_2, y_1 - Y_2, \sigma^2_{X_2}, \sigma^2_{Y_2})$$

- Between the BBIs: linear transfer (rotation in phase space) and anything else (transverse kick from kickers, collimators, etc)

MPS outputs:

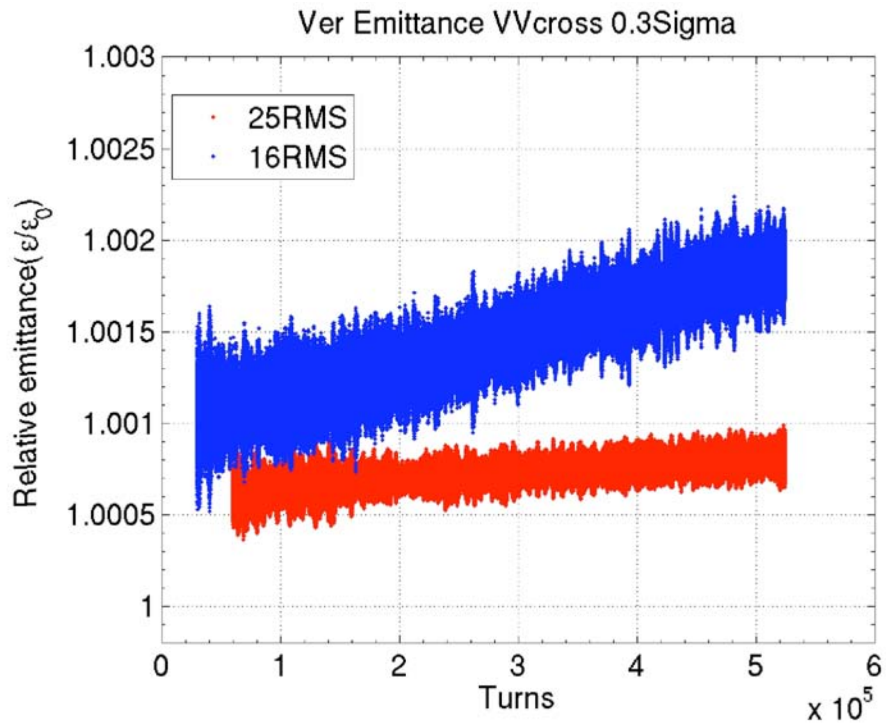
❑ Coherent effects: Fourier analysis bunch barycentres turn by turn gives tune spectra of dipolar modes

- 4 bunches 10^5 macroparticles
- 2-4 HO collisions
- Run of 32000 turns



Landau damping of modes

❑ Incoherent effects: studies of emittance behavior in different conditions

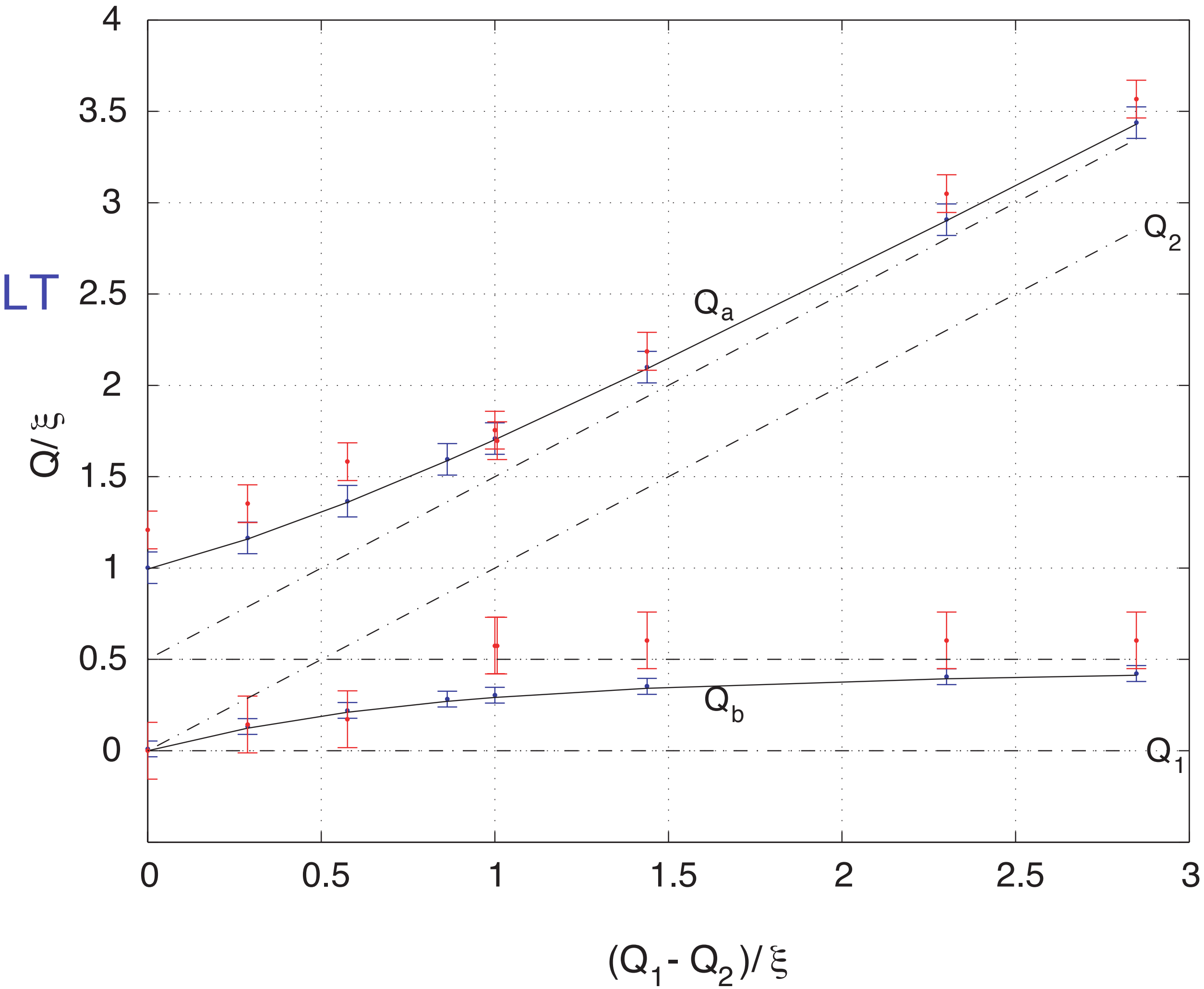


$$\Delta Q_{bb}^{max} \approx Y * N_{IPs} * \xi_{bb}$$

RBM vs MPS vs Analytical solutions

Inputs:

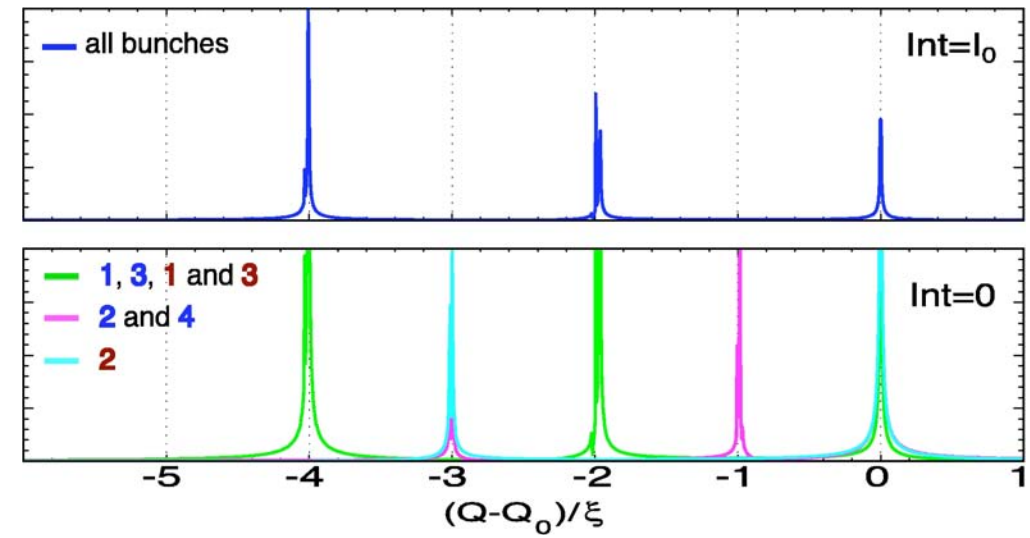
- 1 bunch beams 10^5 macroparticles
- 1 Head-on collision, 1 LT
- $Q_{beam1} \neq Q_{beam2}$
- Run of 32000 turns

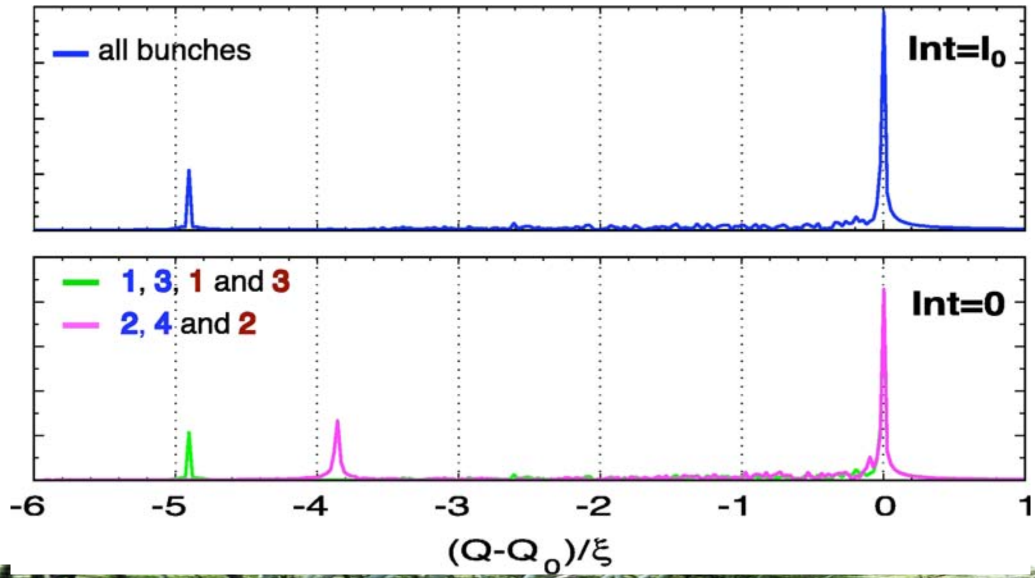


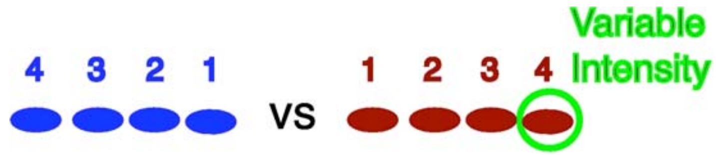
✓ Benchmark with analytical solutions of simple cases

Agreement within the different approx

RBM vs MPS: Super-pacman bunches







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**

MPS: Adv & Disad

- Advantages:
  - Easy definition of any beam filling scheme and collision patterns
  - Non linear terms properly treated
  - Landau damping can be reproduced
  - Higher order modes can be reproduced
  - Correct field calculation (depending on field solver used)
  - Incoherent effects can be studied (emittance growth, beam lifetime

- Disadvantages:
  - Does not give all mode frequencies due to damping
  - **Time consuming**

Need for Parallel Computing!!

Simplified LHC example….

- **36 bunches** per beam each $\mathbf{N_{tot}=10^4}$
- **4** Head-on collisions per turn
- **64000** turns run (only 5-6 s of LHC)

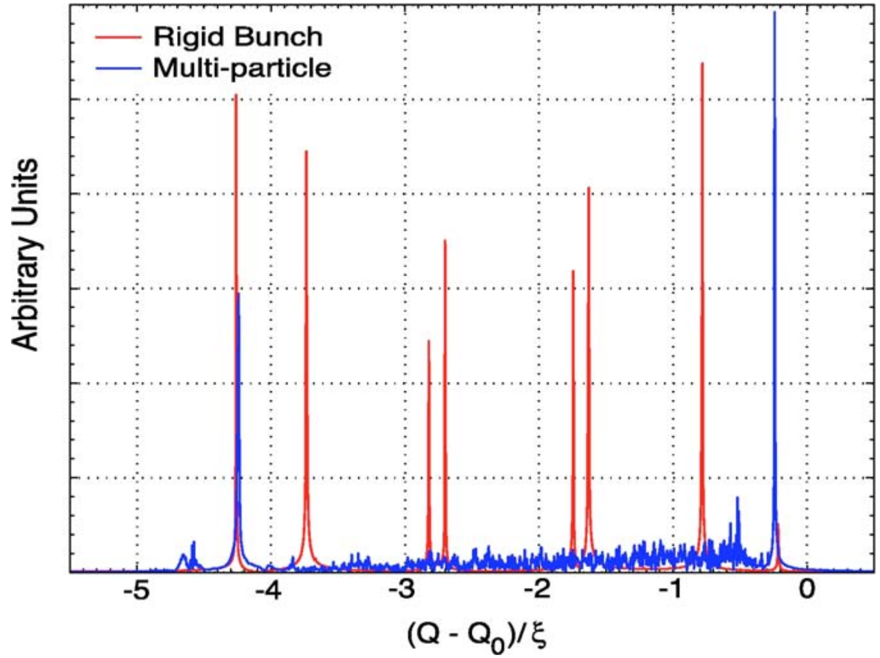
Beam filling scheme

4 Trains 9 bunch each

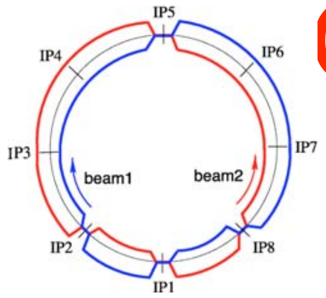
```
9 1 71 0    9 1 71 0
9 1 71 0    9 1 71 0
```

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



- ❑ **More than 1 week CPU time and**
  - ❑Few bunches and only 10^4 macroparticles
  - ❑No parasitic interactions included
  - ❑Only 5-6 sec of LHC (not enough for emittance studies)



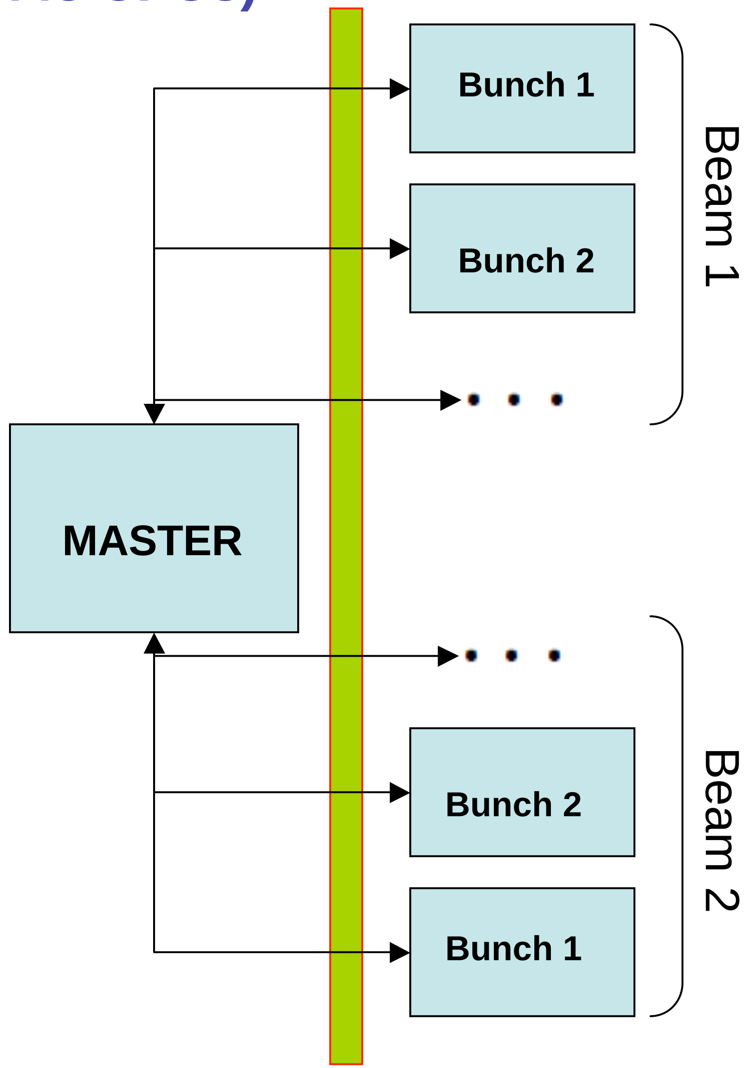
COMBI MPS to Parallel mode

Cluster: EPFL MIZAR (448 CPUs)

- MASTER:
  - Steps the bunches through the machine
  - Check which action must be done and send command to involved bunches

Slaves:

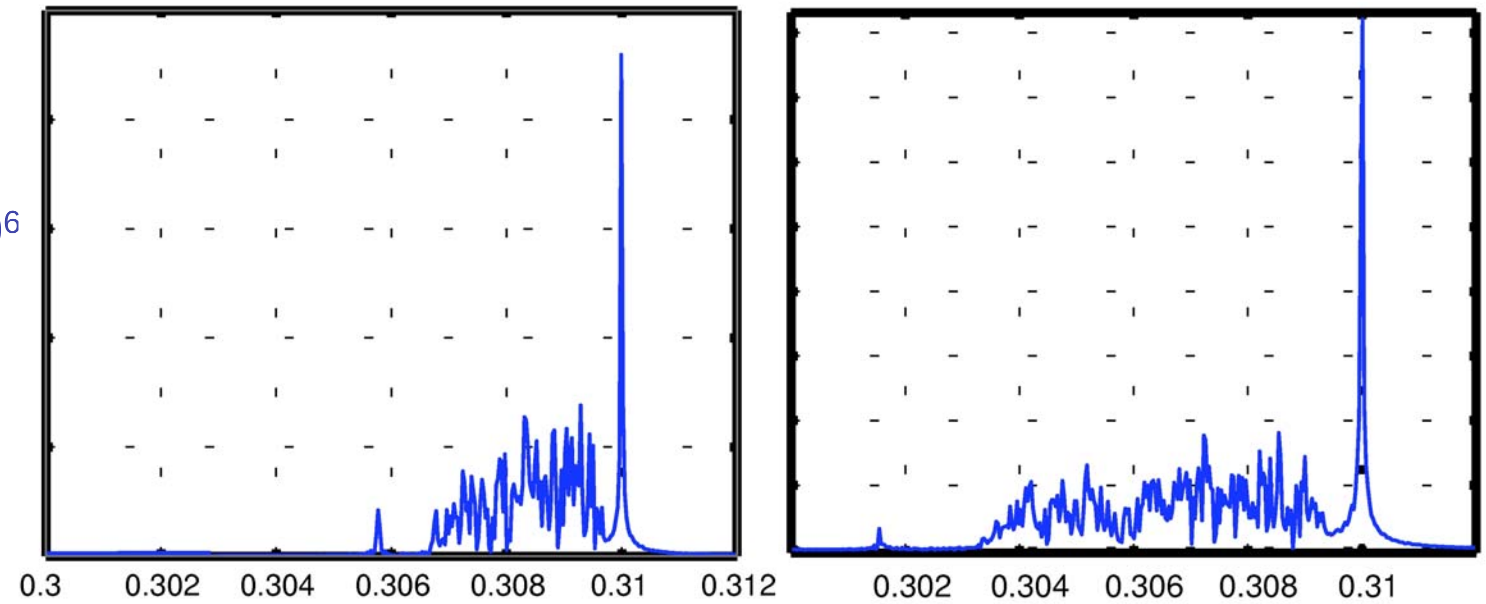
- **Store the macro-particle parameters** and **perform calculation** when an action is required from the MASTER :
  - **Single bunch action**: do not need information from opposite bunch (i.e. LT)
  - **Double bunch action**: need information (barycentre position and distribution) opposite bunch.



COMBI MPS in Parallel mode preliminary results

Inputs:

•8 bch beams 10^6 macroparticles
•1-2 HO BBIs
•64000 turns



Preliminary Results:

✓ **Good results** for simple cases (up to max 16 bch of 10^6 macroparticles on 16 CPUs for runs of 64000 turns)

➢ **Scalability studies on-going** no numbers jet…

CONCLUSIONS:

- **COMBI: flexible to any beam filling and collision scheme!**
  - Analytical Model (qualitative correct results)
  - RBM (qualitative correct results)
  - MPS (qualitative and quantitative correct results)
    - Dipolar modes in complex multi bunches coupling cases
    - Allows predicting bunch to bunch differences in tune spectra
    - Incoherent effects like emittance behavior can be addressed
    - Damping properties of bunches can be studied
    - Kickers, instrumentation devices and collimator transverse kick are implemented
    - Higher order modes can be evaluated

- **COMBI PARALLEL MODE:**
  - Same features as COMBI-MPS but faster!!!
  - HOPE for a good scalability but still UNDER CONSTRUCTION !

OUTLOOKS:

- **ON-GOING**
  - Scalability studies of the COMBI MPS in parallel mode
  - Change field solver from Gaussian approximation to HFMM solver for fully self consistent BBIs
  - Massive simulation campaign with COMBI to study multi bunch BB coupling for different beam filling schemes, collision patterns and different beam parameters
  - Benchmark of simulation results with experiments where possible (with RHIC on going, maybe HERA and Tevatron?)

- **IN FUTURE**
  - Longitudinal motion to be included
  - If MPS scalability proved then move to EPFL BlueGene machine for “realistic” LHC simulations

Acknowledgements:

MANY MANY THANKS TO MANY MANY PEOPLE

☺ CERN : Dr. Werner Herr

☺ TRIUMF: Dr. Fred Jones

☺ EPFL: Professors A. Bay, A. Wrulich and L. Rivkin

☺ LBL: Dr. J. Qiang and M. Furman

☺ RHIC: Dr. W. Fischer and Dr. R. Calaga

☺ EPFL MIZAR Team: J. Menu and J.C. Leballeur

Mizar - Central Compute Server