Status of coherent beam-beam studies

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Reminder

- We know that coherent modes can be suppressed by symmetry breaking and damping mechanisms:
  - Different phase advances
  - Bunch intensity and emittance variations
  - Machine asymmetries
- In the LHC, bunches of a train will undergo different collisions and therefore they will not be all the same.
  Can we predict the behaviour of each bunch?
  What will we see with single-bunch measurements?
  Can we suppress unwanted modes?
  - Nominal and Pacman bunch tune spectrum
  - By acting on a single and defined bunch could we break the mode symmetry and so suppress it?

Motivations:

Last time

- ~~Produce Tune spectra for the LHC and understanding the variations with respect to beam and machine parameters:~~
  - ~~Tune measurements (bunch to bunch differences, studies on measurement kick effect, single bunch vs averaging, intensity fluctuations, asymmetric beams, asymmetric phase advances, etc.)~~

This time

- Understanding of coupled bunch coherent bb modes to explain differences between bunches tune spectra:
  - Produce and study the mode pattern for different collision schemes with HO and LR interactions
  - Compare and relate to different bunch tune spectra **important for single bunch measurements**

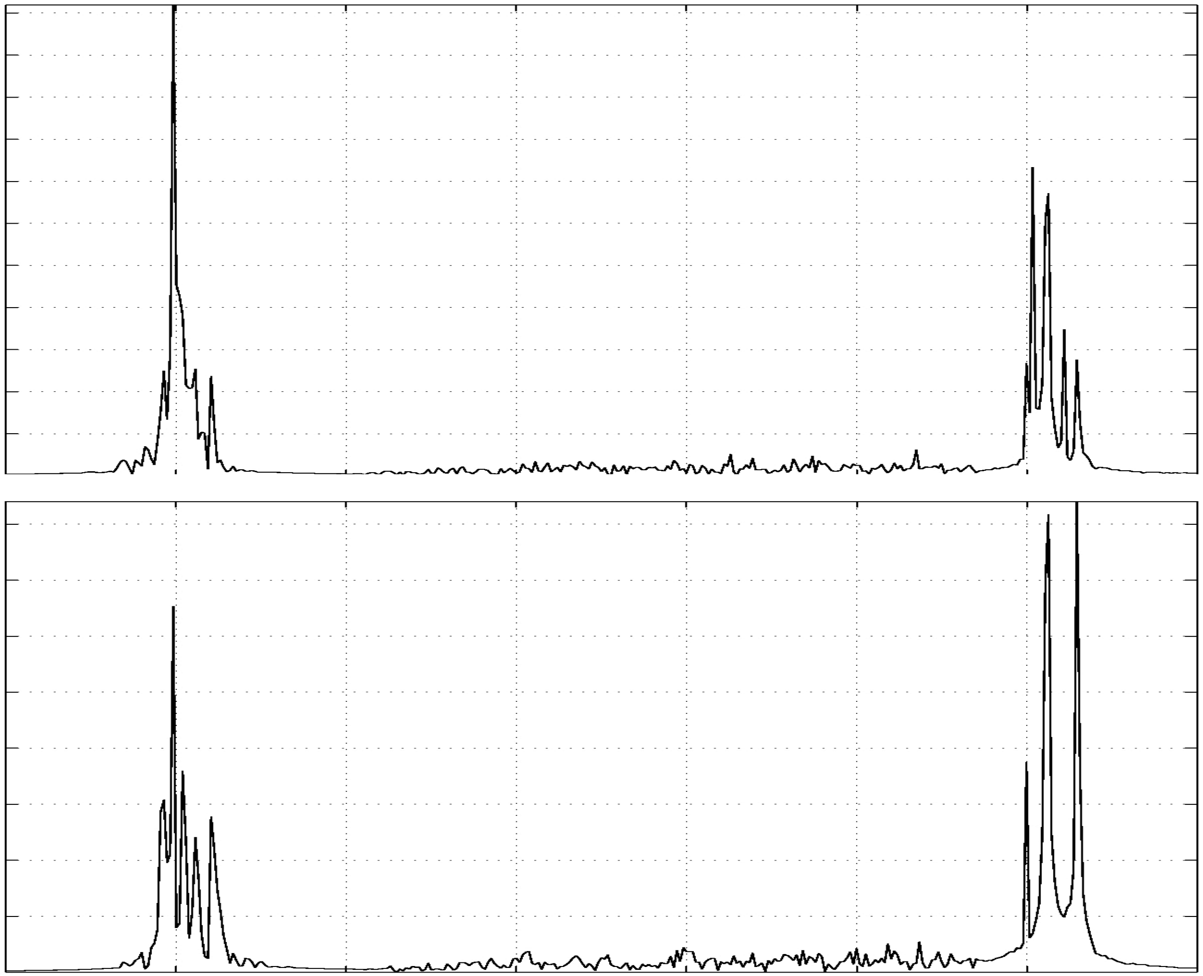
3 models used with new tools

1. Matrix formalism: One Turn Map model OTM (improved to study the eigen-modes of a system of *N* bunch beams colliding HO and LR in any collision scheme)

2. The Rigid Bunch Model RBM in COMBI (to compare tune spectra of different bunches with the eigen-freq and modes)

3 models used with new tools

3. The Multi Particle Model MPM in COMBI (to compare different bunch spectra with eigen-freq and modes including damping)



1. Reminder: OTM

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

Transfer Matrix:

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

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

Beam-Beam Matrix:

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

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

BEAM 1 / BEAM 2

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

bunch1 beam1 (bch2, ...)

bunch1 beam2 (bch2, ...)

One Turn Matrix: $M_C = T_1 * B_1 * T_2 * B_2 * \ldots$

2. OTM contains information on eigen-frequencies and eigen-modes

The eigenvalue problem:

$$\mathbf{M_C} \times \mathbf{v} = \lambda \times \mathbf{v}$$

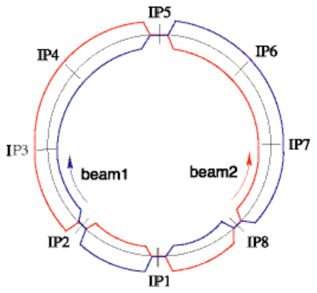
- From eigenvalues calculate the system eigenfrequencies (Piwinski, Keil, Hirata, Chao) :

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

Used for →
  - Mode frequencies calculations for few bunches
  - Stability studies

- New feature: Eigenvectors used to understand the oscillation patterns!

Simplest and known case: 2 bunches colliding HO

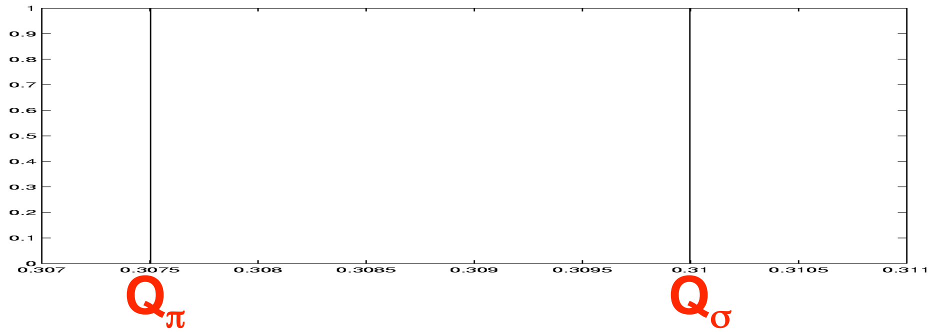


Geometrical layout

2 different Eigen-values

2 different Eigen-vectors

- Beam 1 = 1 bunch Beam 2 = 1 bunch
- HO collision in IP1 and linear transfer along the ring



2 Eigen-frequencies:

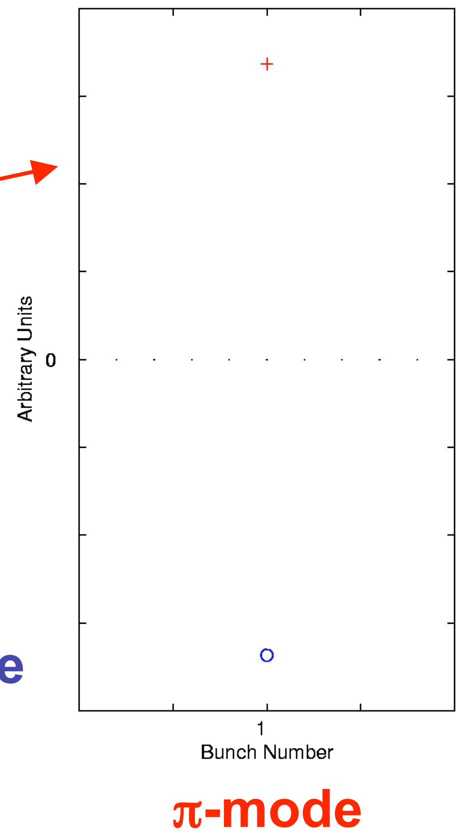
Q_π (the perturbed tune) and

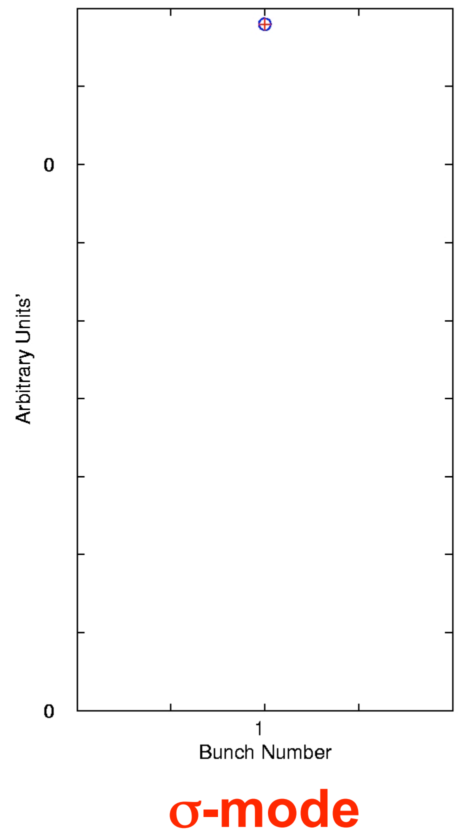
Q_σ (unperturbed tune)

2 Eigen-modes associated:

Q_π gives the π-mode while

Q_σ the σ-mode





π-mode bunches collide out of phase

σ-mode bunches collide in phase

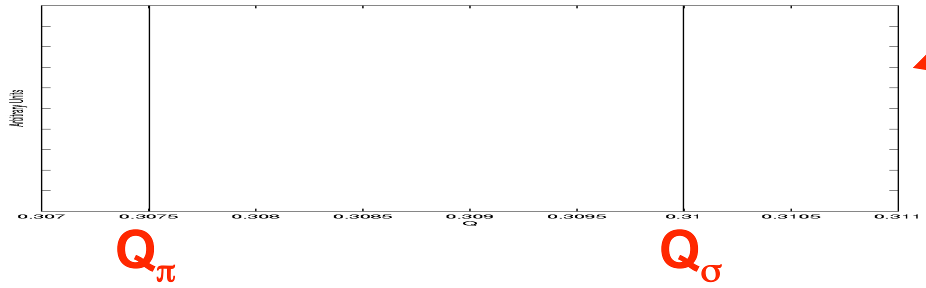
Let’s move to one more bunch per beam colliding HO

Inputs:

- Beam 1 = 2 equispaced bunches
- Beam 2 = 2 equispaced bunches
- HO collision in IP1 and linear transfer

2 different Eigen-values

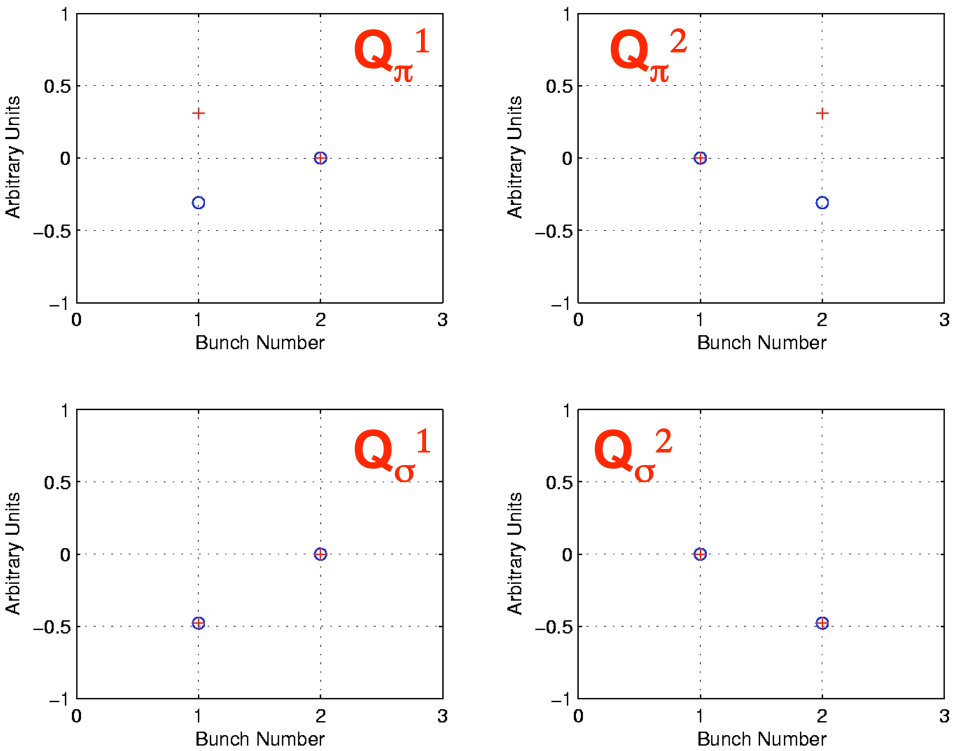
4 different Eigen-vectors



2 Eigen-frequencies:

Q_π (the perturbed tune) and

Q_σ (unperturbed tune)



4 Eigen-modes associated:

Q_π gives the π-mode while

Q_σ the σ-mode

Q_π^1 :

bch1 b1 and bch1 b2 collide out of phase

Q_π^2 :

bch2 b1 and bch2 b2 collide out of phase

Q_σ^1 :

bch1 b1 and bch1 b2 collide in phase

Q_σ^2 :

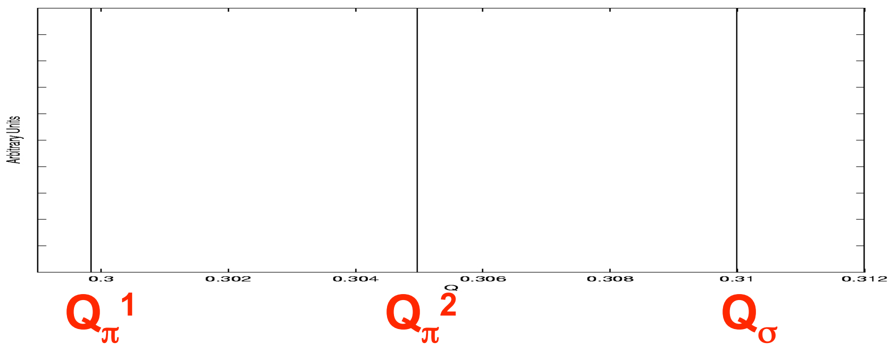
bch2 b1 and bch2 b2 collide in phase

Now if we couple them more… HO coll in 4 symm IPs

3 Eigen-frequencies:
Q_π^1 (the perturbed tune)
Q_π^2 (the perturbed tune) and
Q_σ (unperturbed tune)

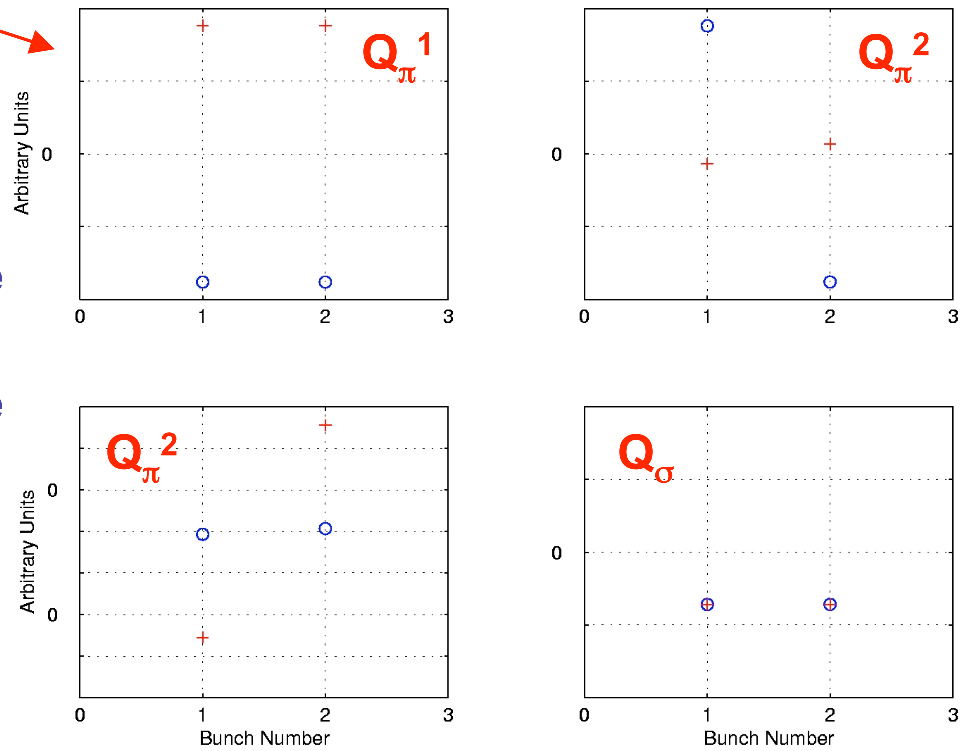
3 different Eigen-values
4 different Eigen-vectors

Inputs:
- Beam 1 = 2 equispaced bunches
- Beam 2 = 2 equispaced bunches
- HO collision in IP1-3-5-7 and LT



4 Eigen-modes associated:
Q_π^1 gives the π-mode
Q_π^2 gives the π-mode while
Q_σ the σ-mode

Q_π^1:
2bch b1 and 2bch b2 collide out of phase
Q_π^2 (intermediate mode):
bch1 b1 and bch1 b2 collide out of phase while bch1 b1 and bch2 b2 collide in phase and…
Q_σ:
2bch b1 and 2bch b2 collide in phase

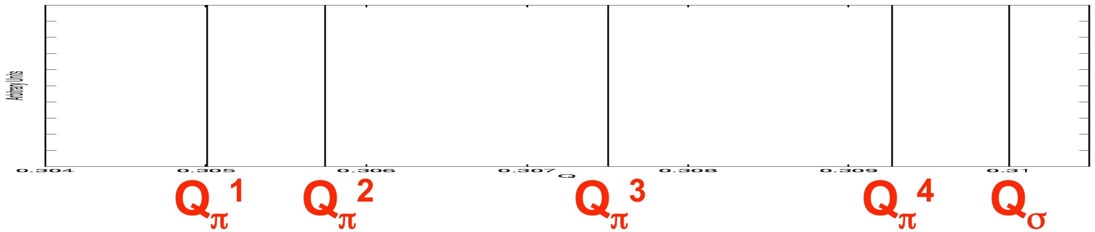


4 bunch beams… HO coll in 2 non-symm IPs

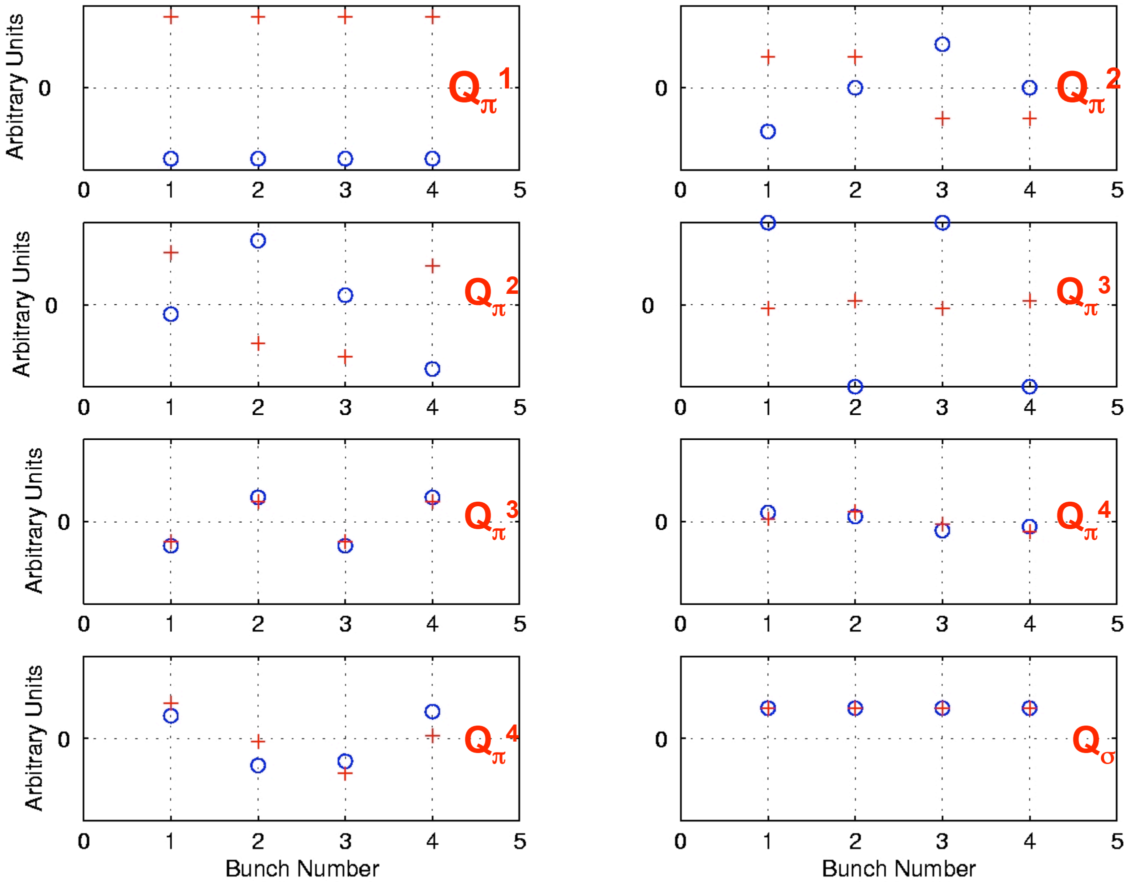
5 Eigen-frequencies:
Q_π^1 (the perturbed tune)
Q_π^2 (the perturbed tune) and
Q_σ (unperturbed tune)

5 different Eigen-values
8 different Eigen-vectors

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



8 Eigen-modes associated:
Q_π^1 gives the π-mode
Q_π^2 gives the π-mode while
Q_σ the σ-mode



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

What do we learn from this?

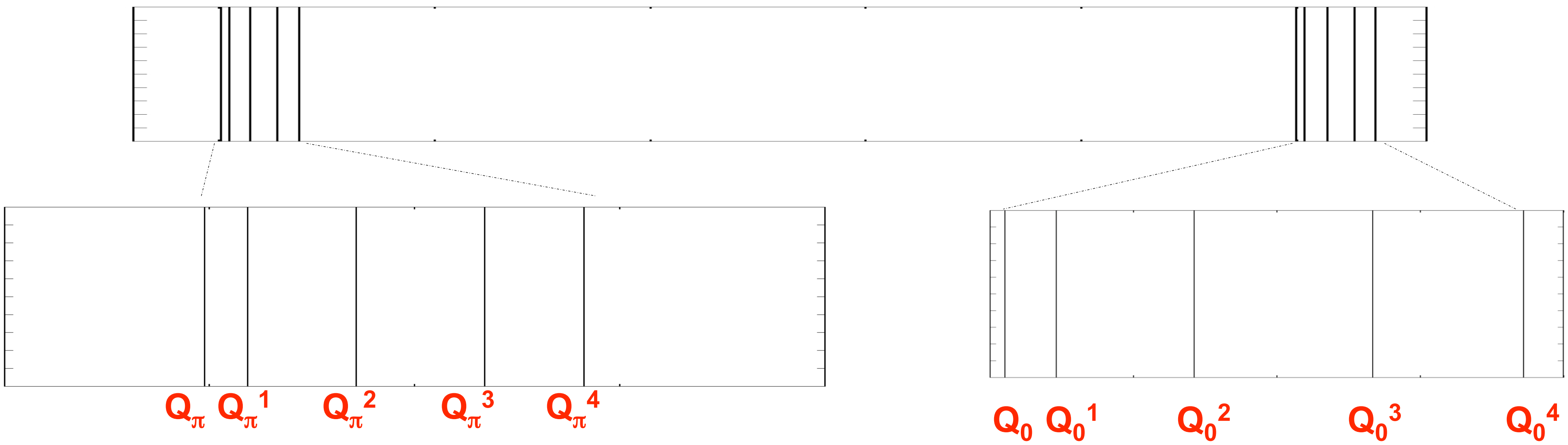
- We can now look at all eigen-frequencies and all eigen-modes, for any beam filling pattern (equally-spaced, trains…) and any collision scheme

- For each eigen-frequency we have different oscillating patterns and the number of possible patterns decreases for increasing coupling of the bunches (more coupling = less patterns, less degrees of freedom in the coherent motions)

- For a given eigen-frequency we can identify the contribution of single bunches by looking at the eigen-vectors.
  The pattern for the given frequency is a linear combination of the associated eigenvectors so it's not easy in understand

Trains of 5 bunches colliding HO in IP1 and 1 LR

1. Eigenfrequencies from OTM

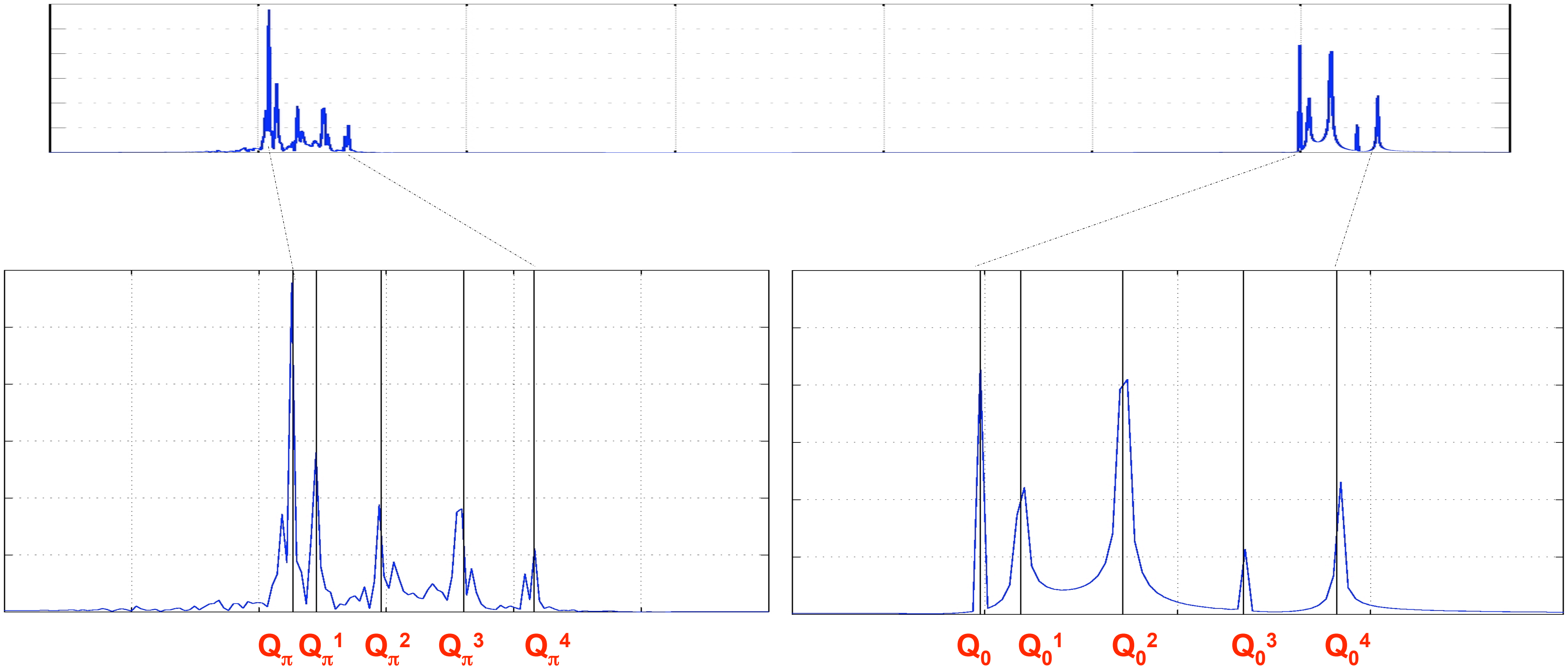


Due to the LR interaction all bunches are coupled as a result the σ and π modes split with sidebands with direction opposite with respect to the HO bb tune shift

The total number of different eigenfrequencies of the system is 10

Trains of 5 bunches colliding HO in IP1 and 1 LR

2. Tune Spectra for Bunch 1 from RBM

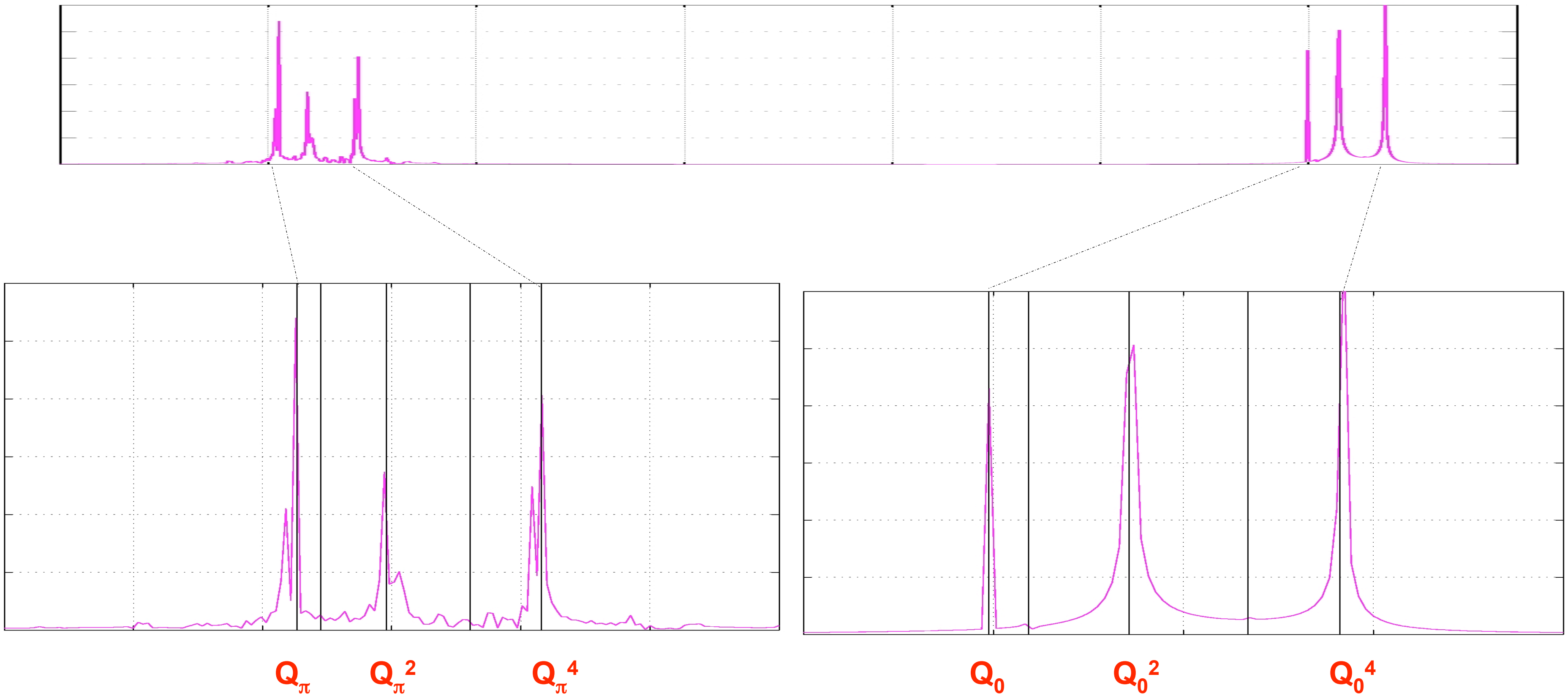


Due to the LR interaction all bunches are coupled as a result also with the RBM the σ and π modes split with sidebands with direction opposite with respect to the HO bb tune shift

The tune spectrum of bunch 1 shows all 10 frequencies

Trains of 5 bunches colliding HO in IP1 and 1 LR

3. Tune Spectra of Bunch 3 from RBM



Also for bunch 3 we see the σ and π modes split

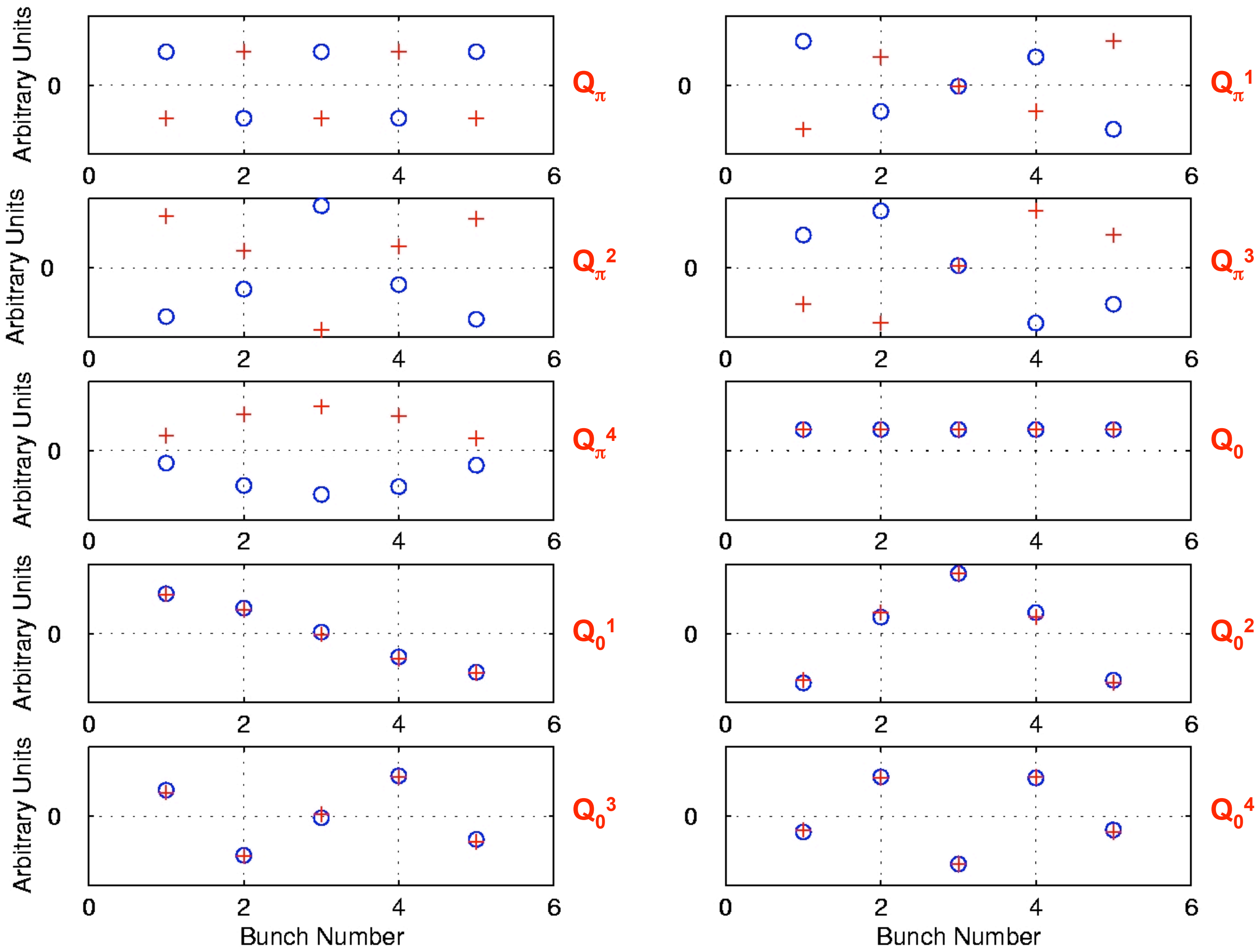
BUT

The tune spectrum of bunch 3 shows only 6 frequencies

<u>CAN WE UNDERSTAND WHY FROM THE EIGENVECTORS?</u>

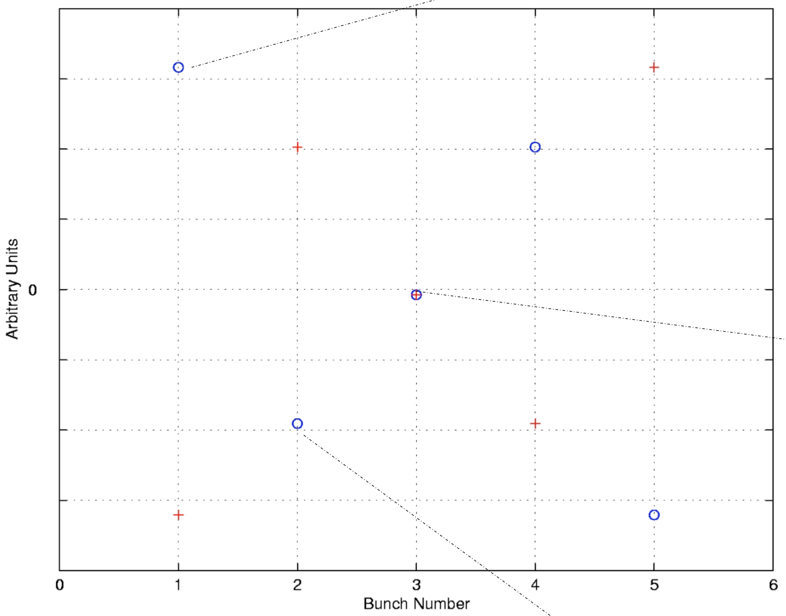
Trains of 5 bunches colliding HO in IP1 and 1 LR

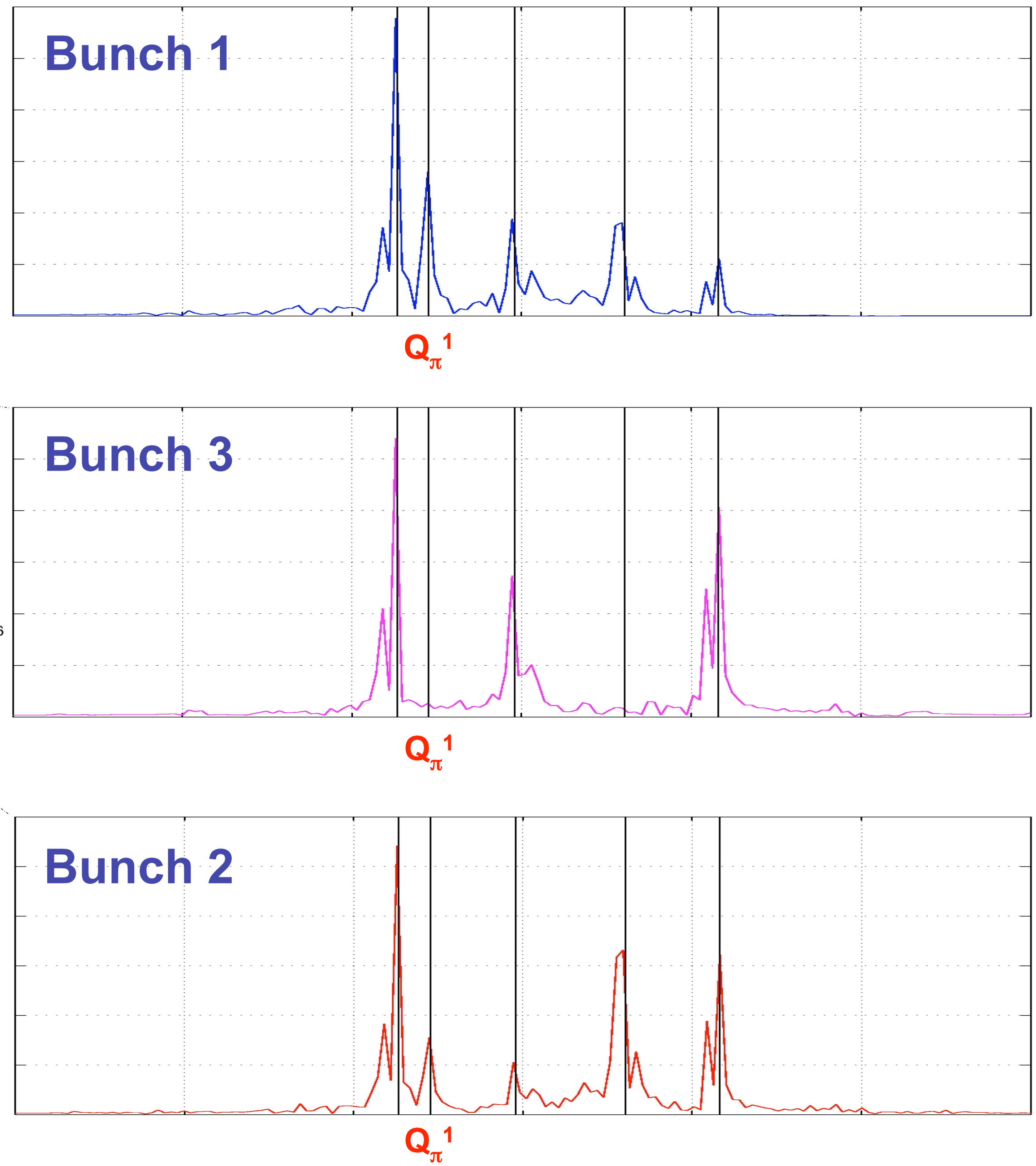
4. For each eigenfrequency the eigenvectors from OTM are:



Different bunches ⇔ different spectra

Example Q_{Π}^{1}



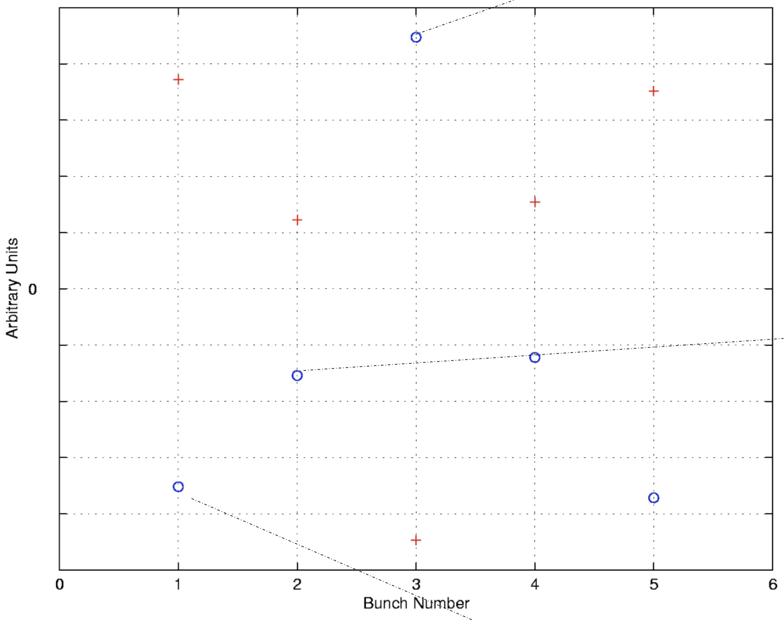


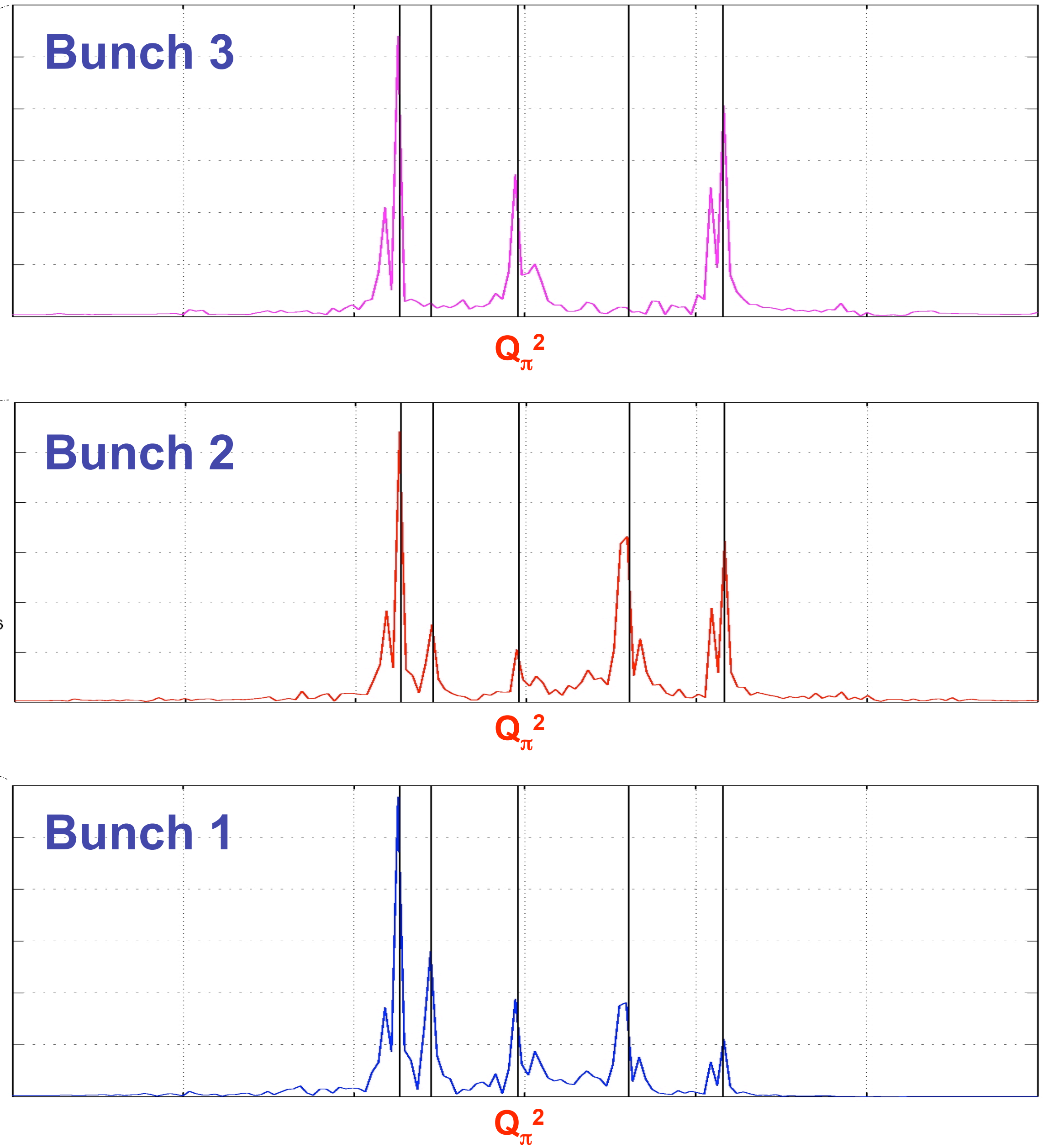
The eigenvector associated to the Q_{π}^{1} shows that the total effect on the 3 bunches varies from bunch to bunch and for bunch 3 is zero

In the spectra of bunch 1 and 2 the peak at Q_{π}^{2} changes in amplitude following the variation while degenerates for bunch 3

Different bunches ⇔ different spectra

Example Q_{Π}^{2}



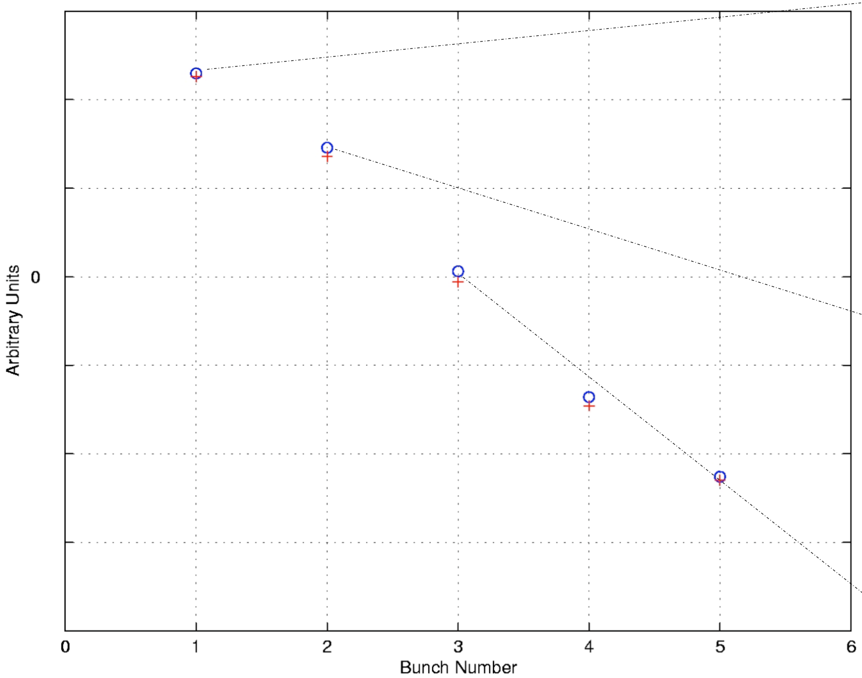


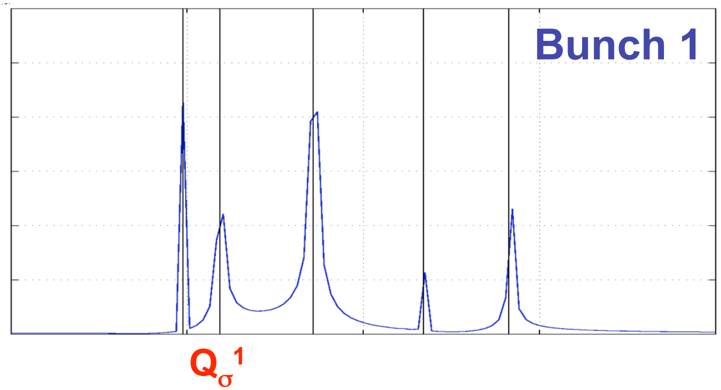
The eigenvector associated to the Q_{π}^{2} shows that the total effect on the 3 bunches varies from bunch to bunch

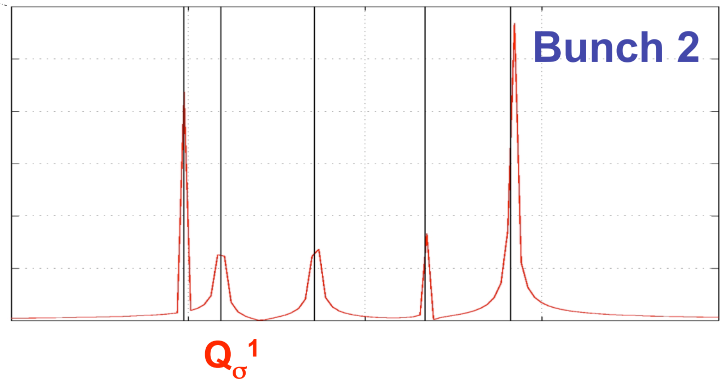
In the 3 spectra the peak at Q_{π}^{2} changes in amplitude following the variation

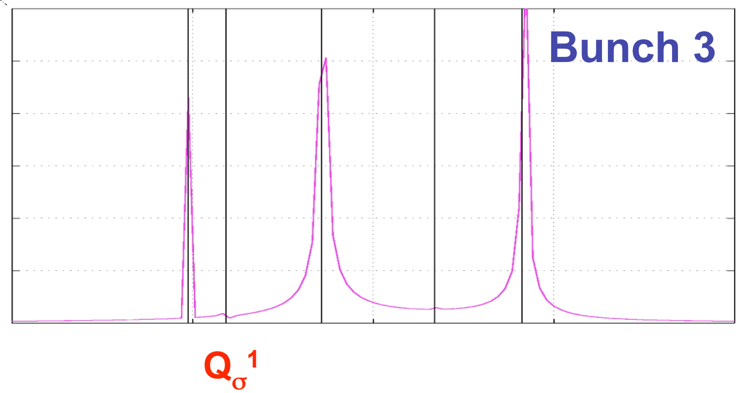
Different bunches ⇔ different spectra

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

In the spectra of bunch 1 and 2 the peak at Q_π^2 changes in amplitude following the variation while degenerates for bunch 3

SUMMARY

- We can identify all eigen-frequencies for any beam filling scheme (equally spaced, trains…) and any collision pattern

- We can identify all eigen-vectors for the same system and so have an idea of all the oscillating patterns associated with a given eigen-frequency

- Different bunches show different tune spectra, we can understand differences by evaluating the eigen-modes (degeneracy of eigen-frequencies and modes)

SUMMARY

- We can identify all eigen-frequencies for any beam filling scheme (equally spaced, trains…) and any collision pattern
- We can identify all eigen-vectors for the same system and so have an idea of all the oscillating patterns associated with a given eigen-frequency
- Different bunches show different tune spectra, we can understand differences by evaluating the eigen-modes (degeneracy of eigen-frequencies and modes)

1. Predict which modes are damped
2. Can one suppress one or more modes by acting on defined bunches that are know to be the ones that contributes to the mode????