Mode coupling instability of the colliding beam

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Supervised by Dr. Xavier Buffat

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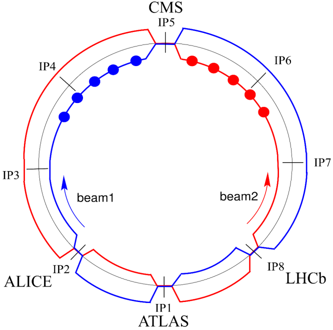
...and thanks to EPFL for providing parallel computing resources

Monday 11th September, 2017 - HSC Meeting - CERN, Geneva

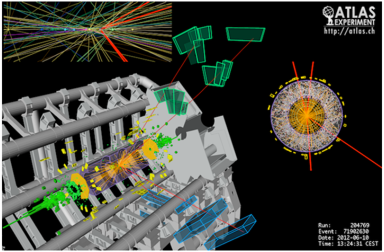
Introduction - the Large Hadron Collider (LHC)

- The purpose of this machine is to guide, **accelerate** hadron close to the speed of light and **collide** them.



- Hard Collision event rate p, noted $\frac{dR}{dt}_p$, is link to the luminosity $\mathcal{L}$ and the cross section of the event :

$$\frac{dR}{dt}_p = \mathcal{L}\sigma_p$$

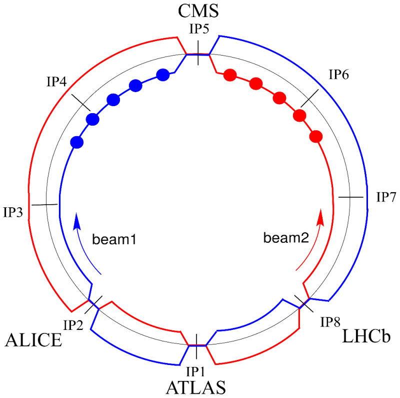


$H^0 \rightarrow ZZ \rightarrow 4\mu^-$ event

$$\mathcal{L} = \frac{n_b \omega_0 N^2}{4\pi\sigma^2}$$

Introduction - High Luminosity upgrade

- The goal of the High Luminosity Large Hadron Collider is to **increase the Luminosity by a factor 10**.

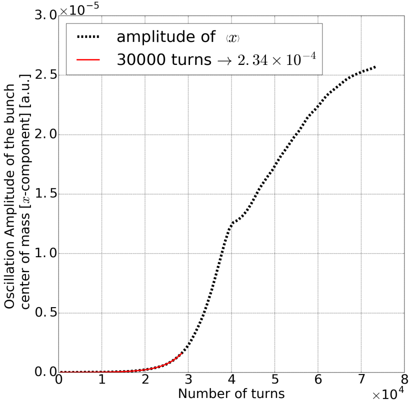


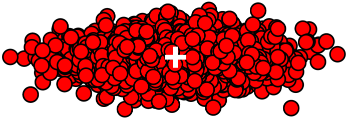
$$\mathcal{L} = \frac{n_b \omega_0 N^2}{4\pi\sigma^2}$$

- This incresing will be realised by **reduice the size** of the beam at the IP and **increase the intensity**.
- This reduicing of the size will be reached by **upgrading the final focusing magnets**.
- This incresing of the intensity will be reached by **upgrading the injector**.

Introduction - Instability

- The **electromagnetic interaction** of the beam with the **surroundings** and with the **opposite beam** could be made the beam **instable**.

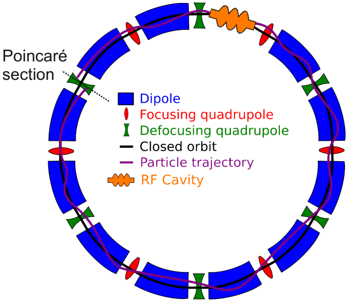




- This coherent instability can **increase the beam size and reduce the Luminosity**.
- The incoherent motion of the particle of the beam can, on particular condition, **stabalize the beam and prevent this instability**.

The effect of magnetic lattice and the electromagnetic cavity (RF cavity) could be describe :

$$\underline{x} = m_{dip} \circ \ldots \circ m_{RF} \circ \ldots \circ m_F \circ m_D \underline{x_0} = M_{oneturn} \underline{x_0}$$



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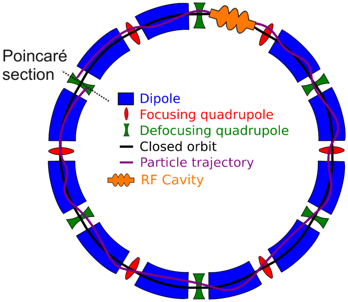
- The **closed orbit** is defined by :

$$\underline{x_c} = M_{oneturn} \underline{x_c}$$



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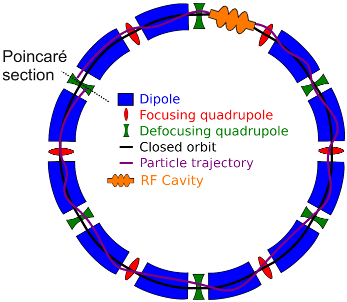
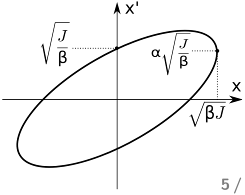
- The particle **oscillate transversely** around this closed orbit ot the normalize frequency, called **betatron tune** :

$$Q_\beta = \frac{\omega_\beta}{\omega_0}$$





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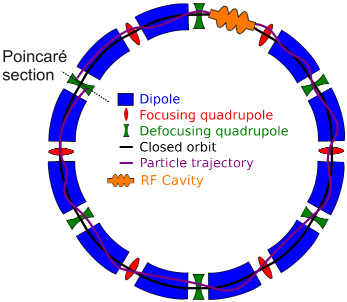

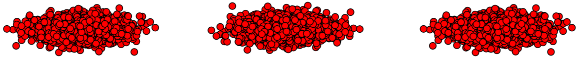

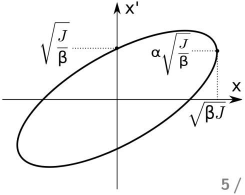

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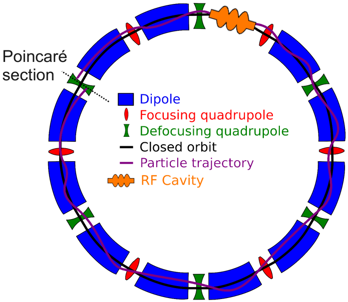

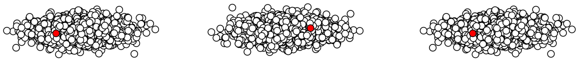

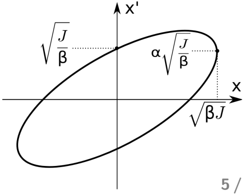

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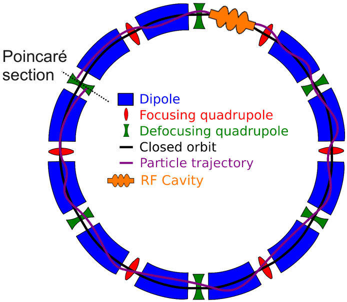
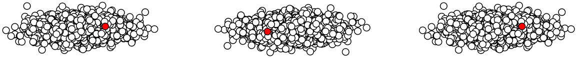
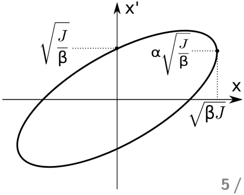
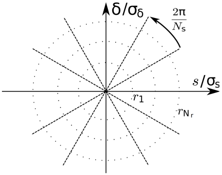






The **Circulant Matrix Model** is the discretisation of the **longitudinal phase space** of the bunch



$$\begin{pmatrix} x_1^1(s,\delta) \\ x'^1_1(s,\delta) \\ \cdots \\ x_{N_r}^{N_S}(s,\delta) \\ x'^{N_S}_{N_r}(s,\delta) \\ y_1(s,\delta) \\ y'_1(s,\delta) \\ \cdots \\ y_{N_r}^{N_S}(s,\delta) \\ y'^{N_S}_{N_r}(s,\delta) \end{pmatrix} = M \begin{pmatrix} x^{0\,1}_{\,1}(s,\delta) \\ x'^{0\,1}_{\,1}(s,\delta) \\ \cdots \\ x^{0\,N_S}_{\,N_r}(s,\delta) \\ x'^{0\,N_S}_{\,N_r}(s,\delta) \\ y^{0}_{\,1}(s,\delta) \\ y'^{0}_{\,1}(s,\delta) \\ \cdots \\ y^{0\,N_S}_{\,N_r}(s,\delta) \\ y'^{0\,N_S}_{\,N_r}(s,\delta) \end{pmatrix}$$

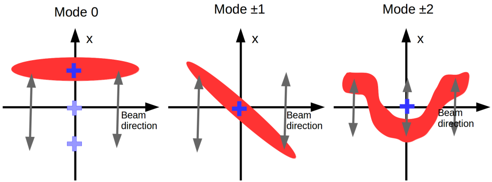
$$M = W^{-1}DW$$

$$\lambda_n = e^{-2\pi i Q_{\mathbf{coh},n_a}}$$

$Re(Q_{\mathrm{coh},n_a})$: the **frequency** of the mode
$Im(Q_{\mathrm{coh},n_a})$: the **growth rate** of the mode

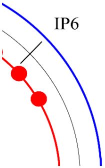
If we consider $M = M_{oneturn}$, the degenerate spectrum have this form :

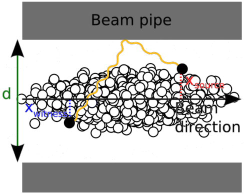
$$\mathbf{Q} = \left\{ Re(Q_{coh,n}) = \pm(Q_\beta + n_a Q_s) : n_\alpha \in \mathbb{Z}, n_a < \left| \frac{N_s - 1}{2} \right| \right\}$$

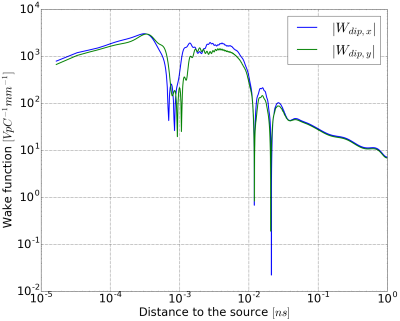


This is the so called **head-tail mode basis**
The dipolar moment : $\langle x \rangle_\tau = \frac{1}{\tau N} \sum_\tau \sum_{bunch} x$

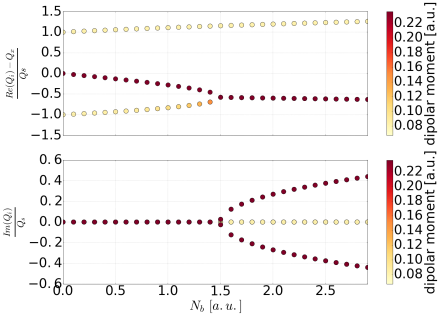
- The particle of the **head** of the bunch could became **coupled** with the particle of the **tail** due to the **electromagnetic interaction** with the surroundings



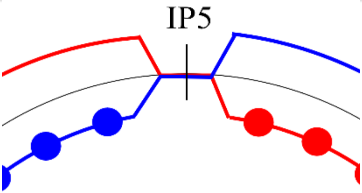


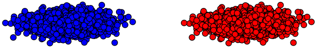


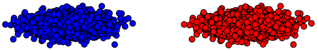
- This wake **deform** the head-tail basis of normal oscillation of the bunch



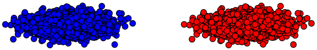
- The **TMCI** is the **coupling** between the **0 and -1** head-tail mode


IP5





$$\Delta x'_{coh}(x,y) \underset{\text{linearized}}{=} \Delta x'_{coh}(x_0,y_0) + \frac{\partial \Delta x'_{coh}}{\partial x}(x_0,y_0)\Delta x$$



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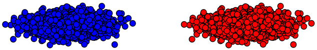
- The two bunch colliding are coupled by this coherent force and the system has two mode of oscillation



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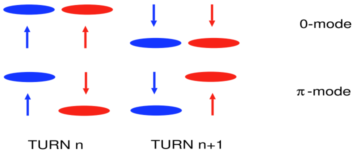
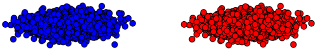
$$\begin{cases} Q_\sigma = Q_\beta \\ Q_\pi = Q_\beta + \dfrac{\beta^* \frac{\partial \Delta x'_{coh}}{\partial x}(x_0,y_0)}{2\pi} = Q_\beta + \xi \end{cases}$$





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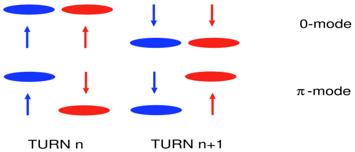

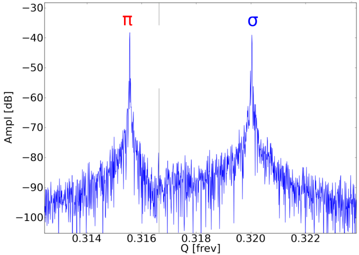

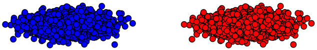

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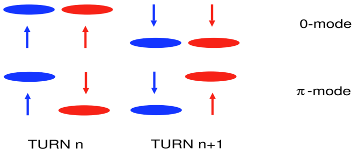
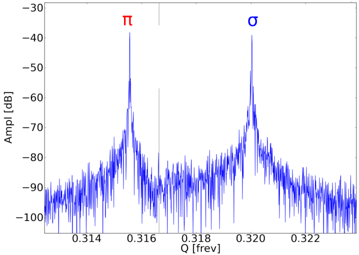
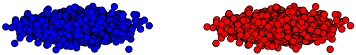




- This two mode could be **coupled** with oscillation mode driven by the wake field to create the so-called mode coupling instability of the colliding beam.

Incoherent tune spread



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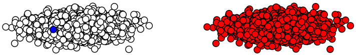

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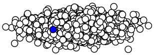

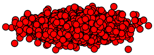

$$\Delta r'(r) \underset{Head-on}{=} \frac{2Nr_0}{\gamma r}\left[1 - e^{\left(-\frac{r^2}{2\sigma^2}\right)}\right] \underset{r\to 0}{=} -\frac{N_b r_0}{\gamma\sigma^2} r$$

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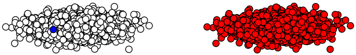

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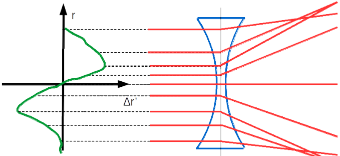
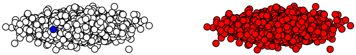
The **beam-beam parameter** is defined as :

$$\xi = \Delta Q_{bb} = \frac{1}{4\pi}\frac{\beta^*}{f} = \frac{N_b r_0 \beta^*}{4\pi\gamma\sigma^2}$$



Beam-Beam Lense (beam of identical charge)

Incoherent tune spread



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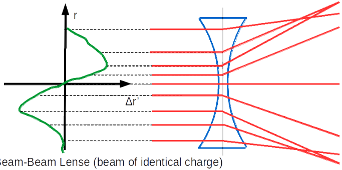
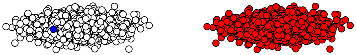


Beam-Beam Lense (beam of identical charge)

- Due to the **non linearity** of the beam-beam force the particle experienced a different kick **depending of their amplitude** generates a **tune spread** of frequency of the **incoherent motion** of the particle.

Incoherent tune spread



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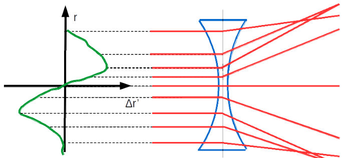

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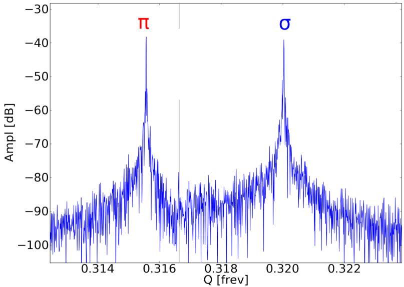

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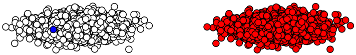
Incoherent tune spread

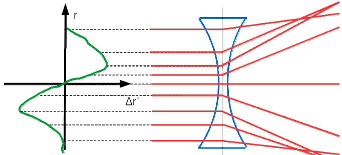


$$\Delta r'(r) \underset{Head-on}{=} \frac{2Nr_0}{\gamma r}\left[1 - e^{\left(-\frac{r^2}{2\sigma^2}\right)}\right] \underset{r\to 0}{=} -\frac{N_b r_0}{\gamma\sigma^2} r$$

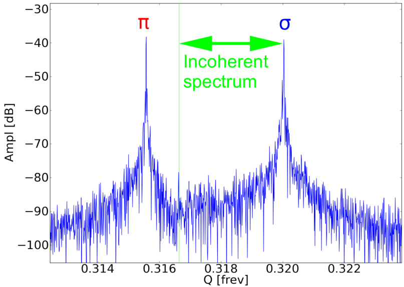
$$Q_\pi = Q_x + \Lambda_{yokoya}\xi$$

The **beam-beam parameter** is defined as :

$$\xi = \Delta Q_{bb} = \frac{1}{4\pi}\frac{\beta^*}{f} = \frac{N_b r_0 \beta^*}{4\pi\gamma\sigma^2}$$

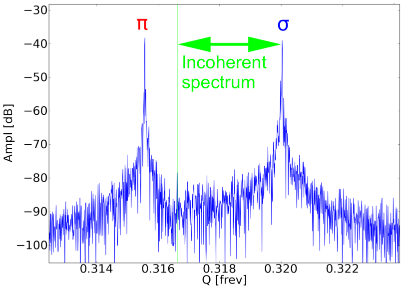


Beam-Beam Lense (beam of identical charge)



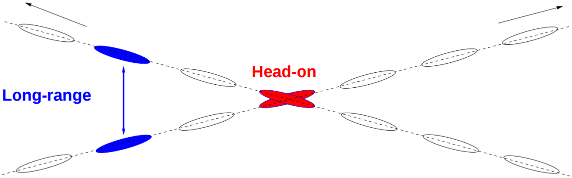
- Due to the **non linearity** of the beam-beam force the particle experienced a different kick **depending of their amplitude** generates a **tune spread** of frequency of the **incoherent motion** of the particle.

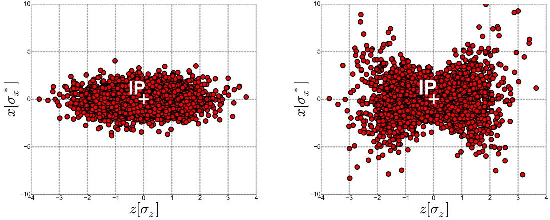
Landau Damping



- This incoherent motion can stabilize and prevent instability thanks to the **Landau Damping mechanism.**
- This mechanism is similar to Landau Damping in Plasma physics.
- The Landau Damping is strongly dependant to the distribution of the incoherent motion.

Interaction Point Configuration

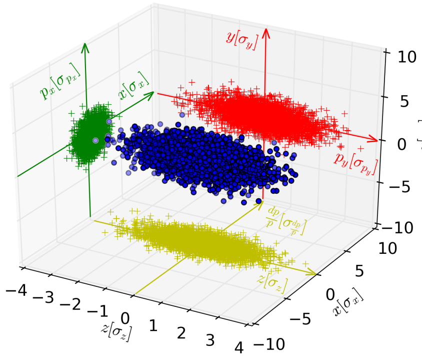




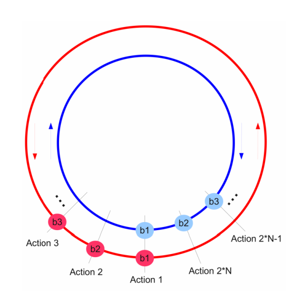
- Due to the long range effect and to have only **one-one bunches colliding**, a crossing angle are induce at the IP.
- The focusing of the bunch at the IP **deform longitudinally** the bunch, this phenomenon is called **hourglass**

- The large crossing angle and hourglass effect allow **synchrobetatron coupling** : **modulation** of the incoherent tune spread (transverse) by the synchrotron tune (longitudinal)

COMBI, a 6D macro-particle code

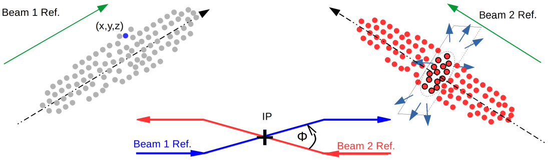


Actions



- Lattice Action already implemented
- Wake field Action already implemented
- 4D beam-beam kick already implemented

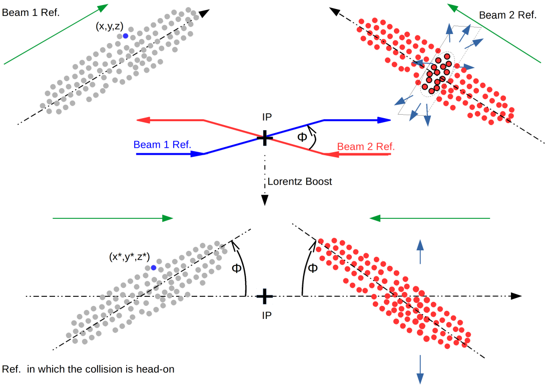
Boost - 6D kick - Anti boost



Steps of simpletic 6D soft gaussian action

$$(x, p_x, y, p_y, z, \frac{dp}{p})$$

Boost - 6D kick - Anti boost



Steps of simpletic 6D soft gaussian action

$$(x, p_x, y, p_y, z, \frac{dp}{p})$$

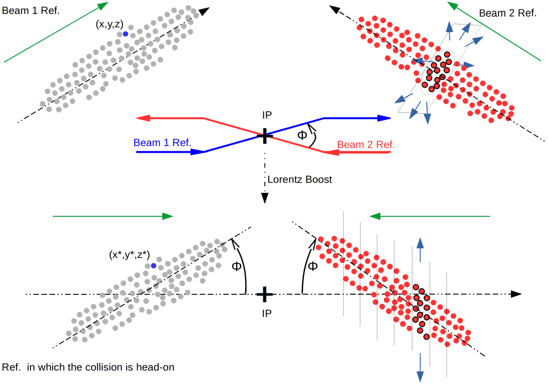
|

Lorentz Boost

↓

$$(x^*, p_x^*, y^*, p_y^*, z^*, \frac{dp}{p}^*)$$

Boost - 6D kick - Anti boost



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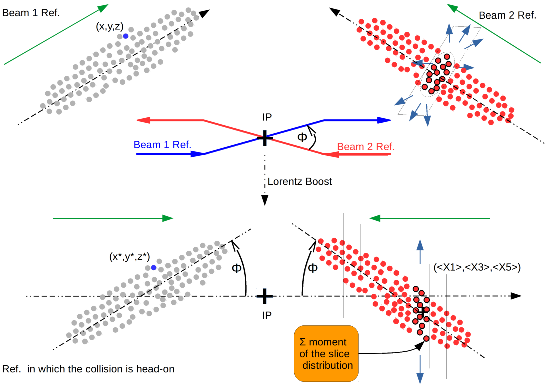
|

Longitudinal Slicing

Boost - 6D kick - Anti boost



Steps of simpletic 6D soft gaussian action

$$(x, p_x, y, p_y, z, \frac{dp}{p})$$

Lorentz Boost

$$\downarrow$$

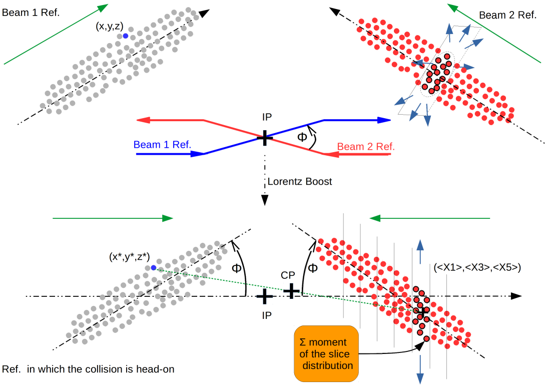
$$(x^*, p_x^*, y^*, p_y^*, z^*, \frac{dp}{p}^*)$$

Longitudinal Slicing

$$\downarrow$$

$$\left(\left\langle X_i^k \right\rangle, \Sigma_{ij}^k\right)$$

Boost - 6D kick - Anti boost



Steps of simpletic 6D soft gaussian action

$$(x, p_x, y, p_y, z, \frac{dp}{p})$$

Lorentz Boost

$$(x^*, p_x^*, y^*, p_y^*, z^*, \frac{dp}{p}^*)$$

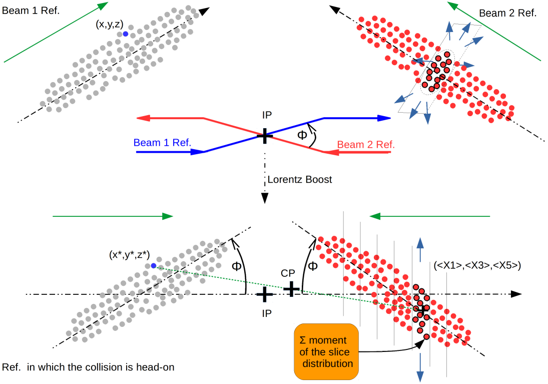
Longitudinal Slicing

$$\left(\left\langle X_i^k \right\rangle, \Sigma_{ij}^k\right)$$

electromagnetic interaction between the macroparticles and the slices

$$(x^*_{new}, p_x^*{}_{new}, y^*_{new}, p_y^*{}_{new}, z^*_{new}, \frac{dp}{p}^*_{new})$$

Boost - 6D kick - Anti boost



Steps of simpletic 6D soft gaussian action

$$(x,\, p_x,\, y,\, p_y,\, z,\, \tfrac{dp}{p})$$

|

Lorentz Boost

↓

$$(x^*,\, p_x^*,\, y^*,\, p_y^*,\, z^*,\, \tfrac{dp}{p}^*)$$

|

Longitudinal Slicing

↓

$$\left(\left\langle X_i^k \right\rangle,\, \Sigma_{ij}^k\right)$$

|

electromagnetic interaction between the macroparticles and the slices

↓

$$(x^*_{new},\, p^*_{x\ new},\, y^*_{new},\, p^*_{y\ new},\, z^*_{new},\, \tfrac{dp}{p}^*_{new})$$

|

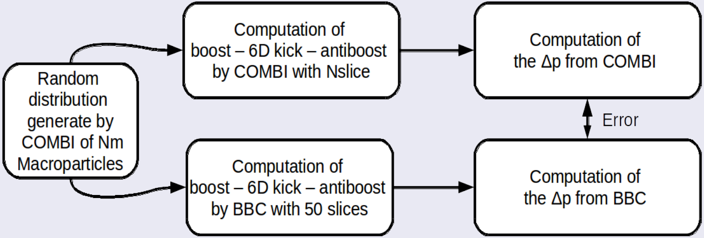
Anti-Lorentz Boost

↓

$$(x_{new},\, p_{x\,new},\, y_{new},\, p_{y\,new},\, z_{new},\, \tfrac{dp}{p}_{new})$$

Convergence method

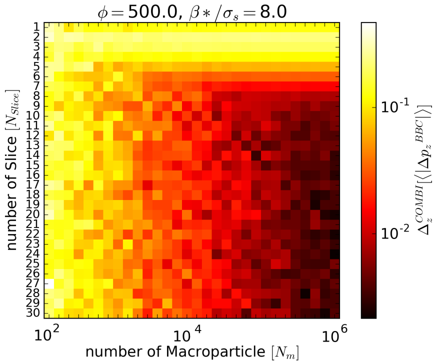
Benchmark method

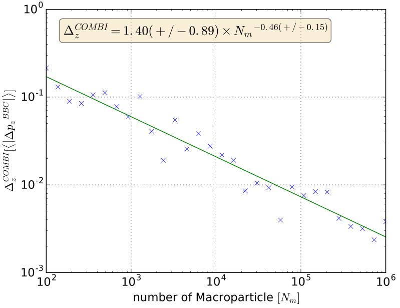


Error Definition

$$\Delta_i^{COMBI} = \frac{\langle |\Delta p_i{}^{\mathrm{COMBI}} - \Delta p_i{}^{\mathrm{BBC}}| \rangle}{\langle |\Delta p_i{}^{\mathrm{BBC}}| \rangle}$$

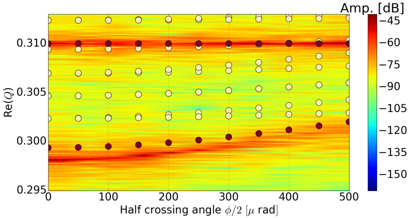
Global view of the convergence



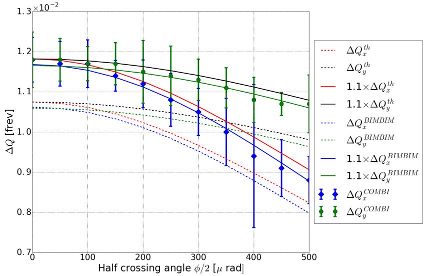


- Statistical convergence in term of Macro-particles (in $\frac{1}{\sqrt{n}}$)
- For more than 10 longitudinal slices, we reach the statistical convergence

Spectogram COMBI and Modal decomposition from BIMBIM

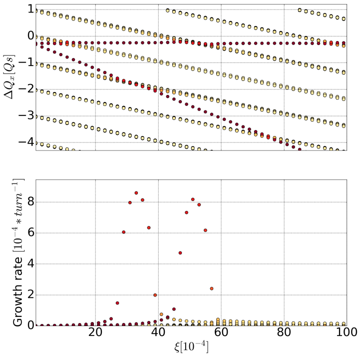


x-component



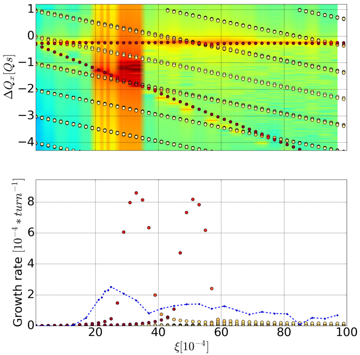
- $\Lambda_{Yokaya} \approx 1.1$ in agreement with the theory for soft gaussian kick approach
- For more than $\frac{\phi}{2} = 300$, we observe a decrease of this Yokoya factor, meaning the π-mode become closer of the incoherent spectrum
- The possible crossing of the *pi*-mode and the incoherent spectrum enable the Landau Damping of this mode

Mode coupling instability of the colliding beam in 4D approach



- Mode coupling between the beam-beam mode and the mode of oscillation driven by the wake field
- Strong coupling instability between the -1 mode with the π-mode and the 1 mode with the σ-mode

Mode coupling instability of the colliding beam in 4D approach



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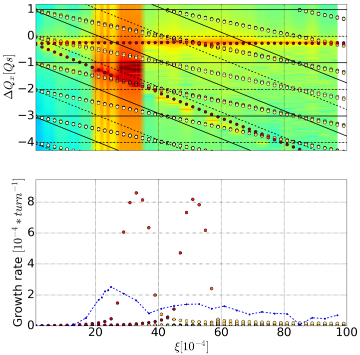
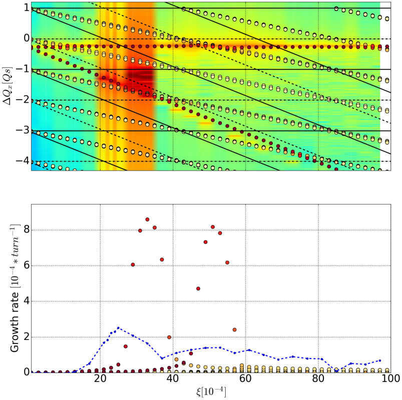
- The shifting between the modal and macro-particle approach could be explain by the non linearity and taking to account of the Yokoya factor

Mode coupling instability of the colliding beam in 4D approach

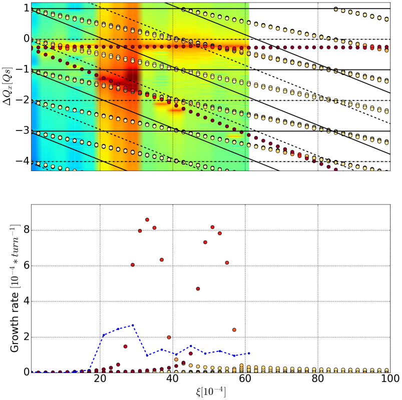


- Mode coupling between the beam-beam mode and the mode of oscillation driven by the wake field
- Strong coupling instability between the -1 mode with the π-mode and the 1 mode with the σ-mode
- The shifting between the modal and macro-particle approach could be explain by the non linearity and taking to account of the Yokoya factor
- Damping by the first sideband incoherent spectrum is not enough strength to completely dump the instability
- The high order coupling instability (for $\xi > 0.006$) observed only in the macro-particle approach

Comparaison 4D and 6D soft gaussian kick



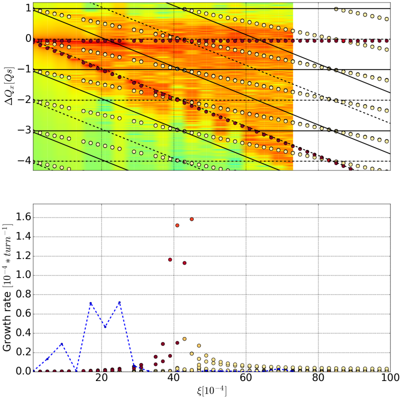
4D approach



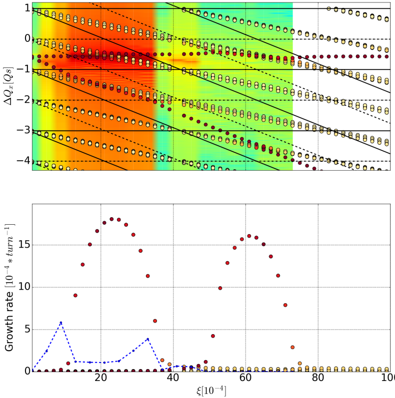
6D approach

- In the case of low hourglass effect the 6D approach must follow the 4D approach

Influence of the strength of the Wake field



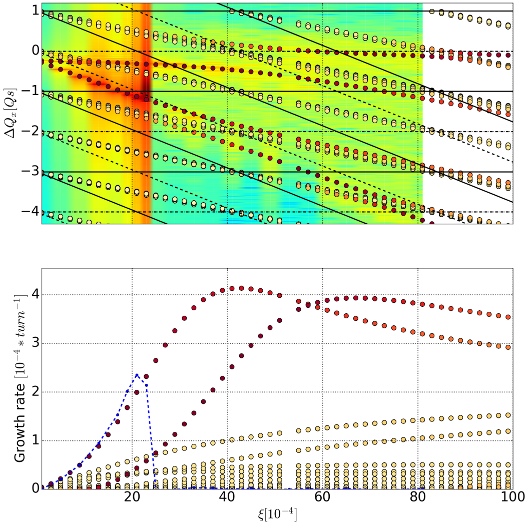
weak wake - 0.5 × 10^{11} p/b



strong wake - 4.5 × 10^{11} p/b

- For low intensity, the damping due to the incoherent spectrum of the main side-band is not enough efficient because the σ-mode is at the border of the side-band
- For high intensity, the damping of this side-band is efficient of the σ-mode due to the large tune shift due to the strong intensity of the wake.

Impact of the hourglass, $\beta^* = 0.2m$

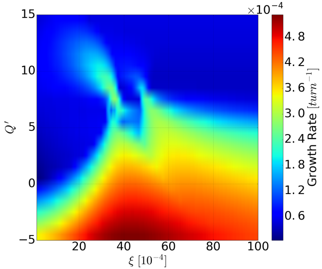


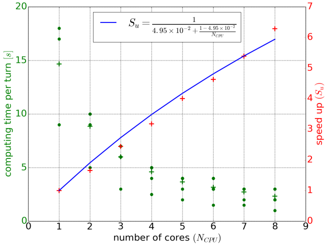
- In case of hourglass effect, the mode coupling instability of colliding beam start for a low ξ
- The behaviour of the growth match for the two approach, in case of low ξ
- When the σ and π mode enter on the respective incoherent spectrum of the first side band the Landau Damping is efficient to damp completely the instability for $\xi > 0.0021 \approx Q_s$

Conclusion

- The 6D soft-Gaussian kick was implemented and bencharked (statistical convergence against BBC, Yokoya factor and similarity with 4D) in COMBI
- A damping mechanism for intense wake have been observed due to a large tune shift of the σ mode in the main side band
- A efficient damping mechanism by the first sideband was observed in case of strong hourglass

Outlook



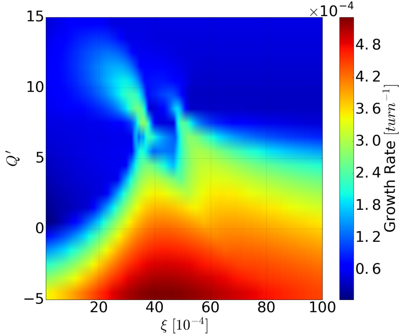


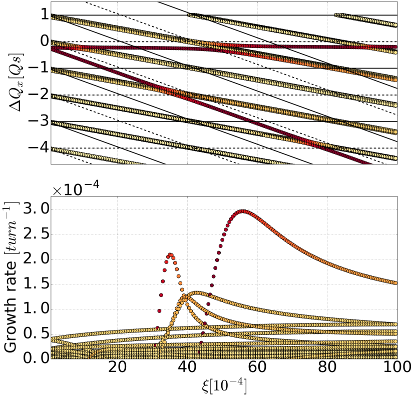
- For high chromaticity, the mode coupling stay unstable
- For $G > 2 \times 10^{-3}$, the main mode coupling are efficiently damped
- For large crossing angle, the strong betatroncoupling deform the head tail basis and allow high order coupling.
- The modeling of the very low instability (like with high gain or chromaticity) will be a computational problem to model with the macroparticle approach
- The convergence issue of the high order coupling in the modal approach need to be investigated

Any Questions ?

Thank you for your attention

Influence of the chromaticity

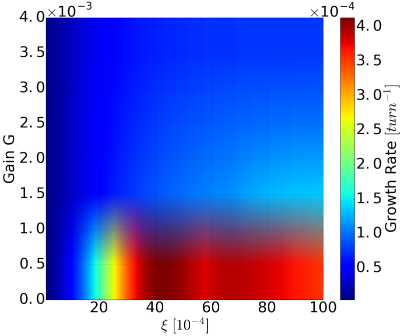


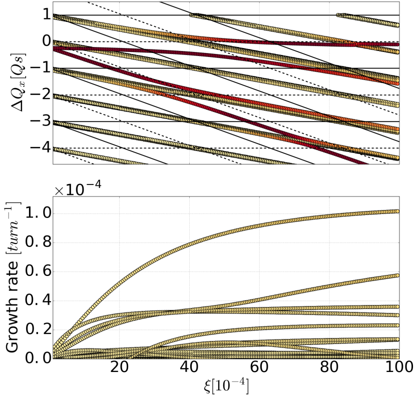


for $Q' = 5$

- For negative chromaticity, the head-tail mode are unstable (single beam theory)
- For large positive chromaticity, we reach a area of stability
- Nevertheless, the two mode coupling are shifted for larger ξ and stay unstable even for high chromaticity

Influence of the gain

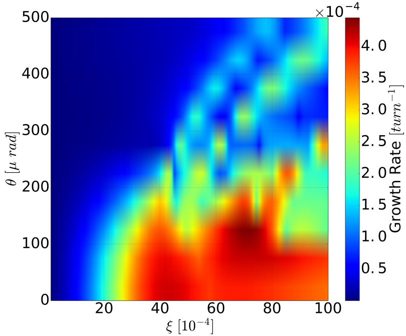


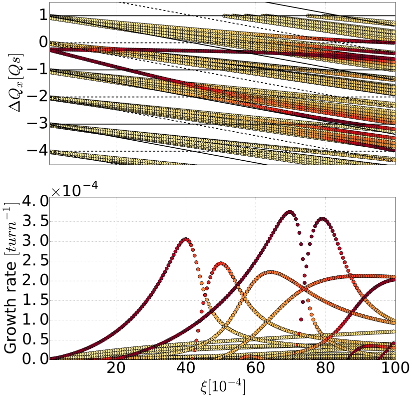


for $G = 1 \times 10^{-3}$

- For $G > 2 \times 10^{-3}$, all unstable instability seem efficiency damped
- For $G = 1 \times 10^{-3}$, the two mode coupling with dipolar componante are damped.

Influence of the crossing angle

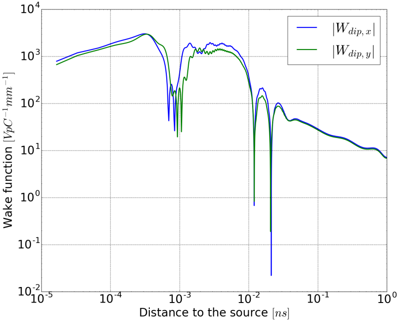


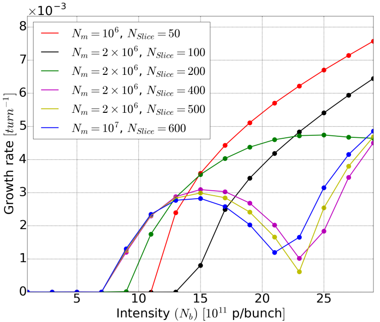


for $\phi = 150\mu$rad

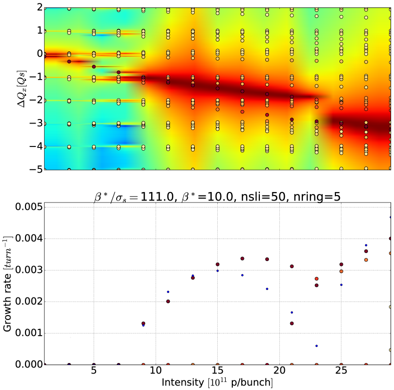
- For large crossing angle, the mode coupling instability are shifted for granter ξ
- A strong synchrobetatron coupling deform the head tail basis and the radial mode become spited
- The convergence of the modal approach need to cheked for high order coupling

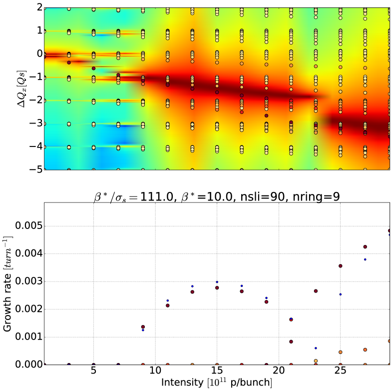
TMCI convergence



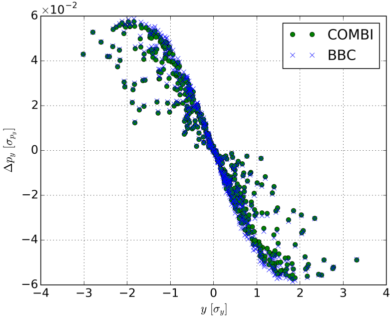


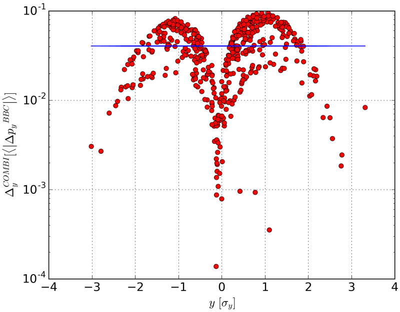
TMCI convergence



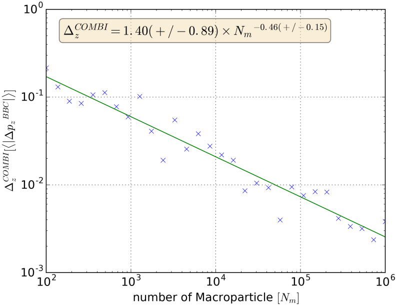


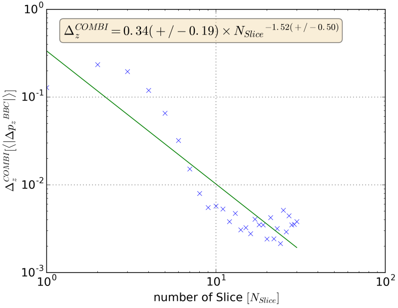
6D Kick convergence





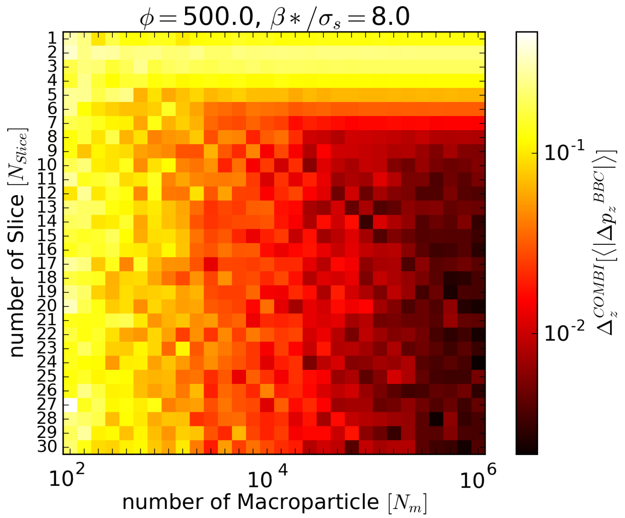
Result of convergence



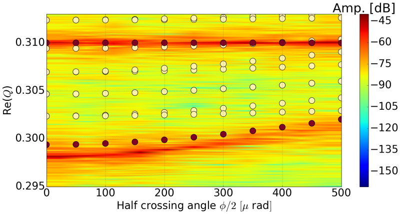


- Statistical convergence in term of Macro-particles (in $\frac{1}{\sqrt{n}}$)
- For more than 10 longitudinal slices, we reach the statistical convergence

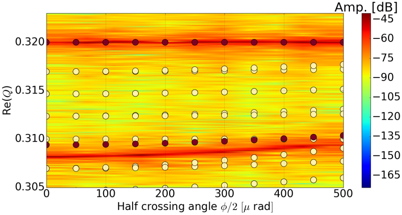
Global view of the convergence



Spectogram COMBI and Modal decomposition from BIMBIM



x-component

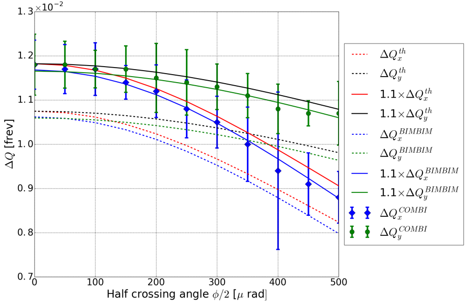


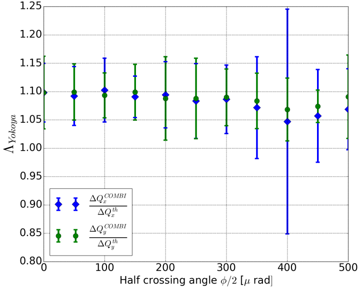
y-component

Comparaison with theoretical tune spread

$$\Delta Q_x^{th} = \frac{N_b r_0 \beta_x^*}{2\pi\gamma\sigma_x^0\sqrt{1+{P_x}^2}\left(\sigma_x^0\sqrt{1+{P_x}^2}+\sigma_y\right)}$$

Yokaya Factor Observation

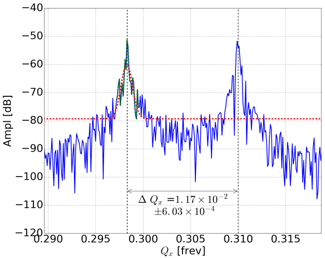




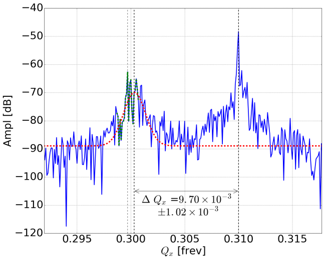
Conclusion of Yokoya Factor observation

- $\Lambda_{Yokaya} \approx 1.1$ in agreement with the theory for soft gaussian kick approach
- For more than $\frac{\phi}{2} = 300$, the error bar increase

This increasing of the error bar could be explain by ...



100 μrad



300 μrad

Hypothesis of the widening of the π-mode

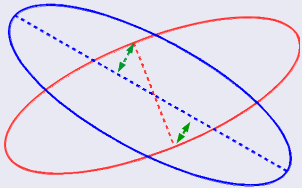
- π-mode seem outside the tune spread according the computation of Q^{th}
- Computation of the ΔQ^{th} could be not correct for the large crossing angle
- Possible Landau Damping due to the tune spread

Landau Damping in Accelerator Physics

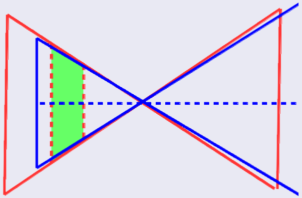
$$\langle x \rangle (t) = \frac{A}{2\omega_{\text{unp}}} \left(cos(\omega_c t) P.V. \int_{-\infty}^{+\infty} \frac{\rho(\omega_i)}{\omega_i - \omega_c} d\omega_i + \pi \rho(\omega_c) sin(\omega_c t) \right)$$

- The Landau damping depend of the distribution of the incoherent spectrum of the particle.
- More the density of incoherent spectrum of the particle is high near to the coherent frequency, more efficient is the damping.

Crossing Angle



Hourglass



Synchrotronbetatron coupling

- Oscillation of one bunch could influencing the longitudinal motion of the opposed bunch
- possible modulation of the spread (transverse) by the synchrotron tune (longitudinal)