Experimental demonstration of emittance coupling control via an AC skew quadrupole driven at the difference resonance $(Q_x - Q_y)$

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Let's talk about coupling, why?

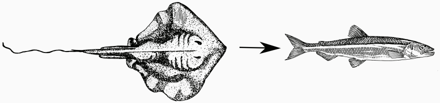
ALBA is a third generation light source located in Barcelona. As many other light sources we are venturing into the complex exercise of designing a low emittance upgrade...

We are looking into a 25 times emittance reduction: $4.6\text{nm} \rightarrow 0.2\text{nm}$ There are many difficulties operating a storage ring with such a small emittance, **lifetime remains indeed of great concern**

Electron beams in storage rings are flat:

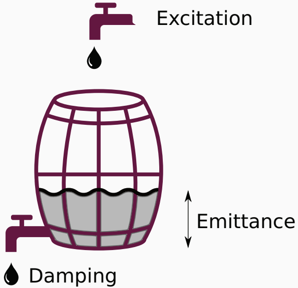
Recoil due to synchrotron radiation excite an incoherent horizontal betatron oscillation!
No excitation in the vertical plane!

- Flat beams have small transverse cross sectional area
- In a small area electrons meet frequently...
- In **ALBAII** the beam losses due to **Touschek scattering** are massive! $\rightarrow$ **lifetime** $<$ **1h**



Flat beams are bad for lifetime:
Can we turn our flat beam into a round one?

Natural horizontal emittance

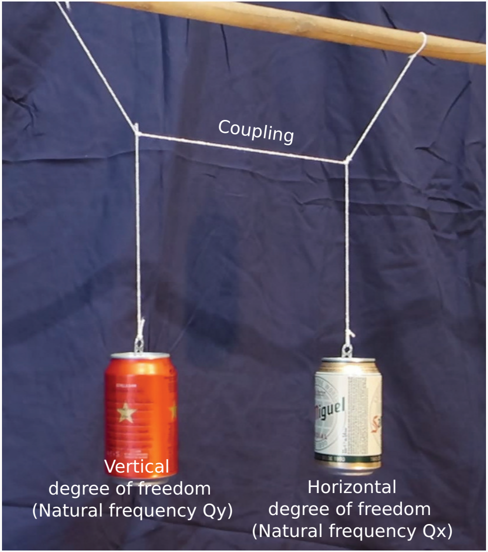


- **Recoil due to synchrotron radiation** emission results in a **horizontal betatron motion**
- Radiation emission is **stochastic**: electrons oscillate with **different amplitude and phase**
- **Oscillation damping** results from a combined effect of radiation emission and the RF field
- The **horizontal natural emittance** is the **equilibrium between damping and excitation!**

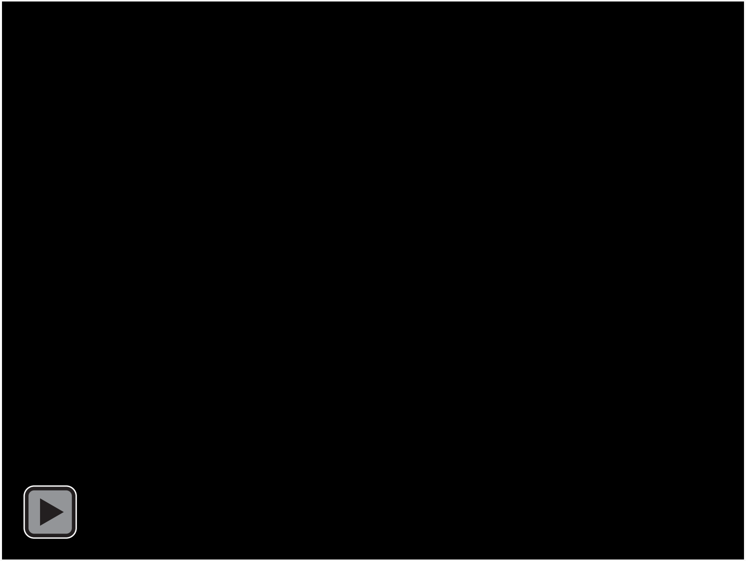
Natural vertical emittance

- If there is **no dispersion** in the vertical plane (usually is the case)
- ...the energy loss due to radiation emission **does not excite any betatron motion**
- At equilibrium the **vertical emittance is zero!**

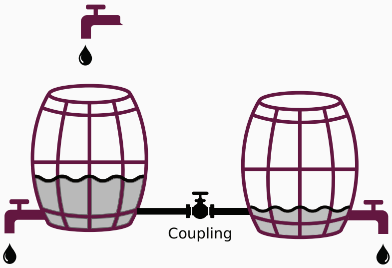
$Q_x = Q_y \rightarrow$ Betatron oscillations coupling



$Q_x = Q_y \rightarrow$ Betatron oscillations coupling



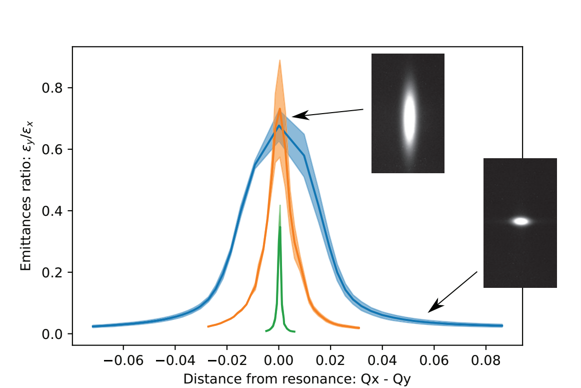
Emittances on the coupling resonance



- **Coupling** allows **exchange of betatron actions** between transverse planes
- Some of the horizontal emittance goes to the vertical plane
- **The horizontal emittance decreases!**
- **The vertical emittance increases!**
- If the **damping times are equals** $\rightarrow$ **The sum of the emittances is a constant**
- Usually damping times are close...

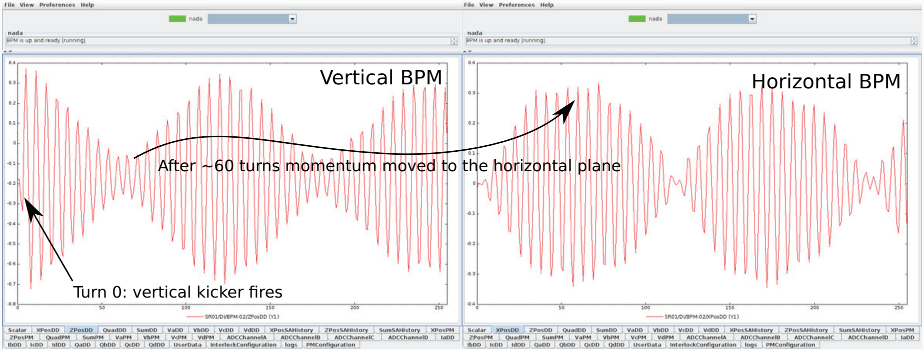
Measuring coupling with a pinhole

- **3 coupling settings:** strong $\longrightarrow$ skew on to increase the coupling
  nominal $\longrightarrow$ skew off, natural coupling
  weak $\longrightarrow$ skew on to correct the coupling



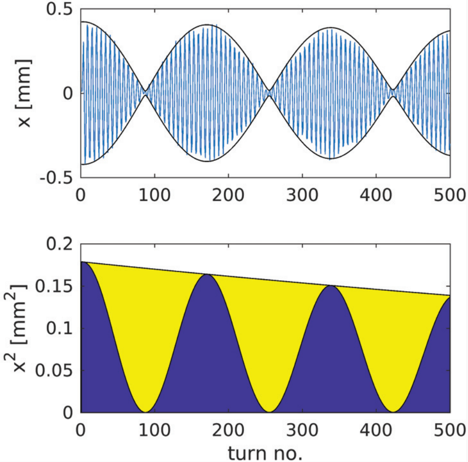
- The **tunes are scanned** around the difference resonance: $Q_x = Q_y$
- emittances are inferred from **beam size measurements at pinholes**
- Every point is the average of 2 pinholes, error bar is the difference
- **The 2 highest coupling settings reach ∼75% coupling while the weak one does not...**

Measuring coupling with turn-by-turn BPMs



- A **transverse kick** excites a coherent betatron oscillation of the beam
- The momentum transfer between the transverse planes is observed with BPMs
- **How much momentum is transferred is a direct measurement of coupling!**

Measuring coupling with turn-by-turn BPMs



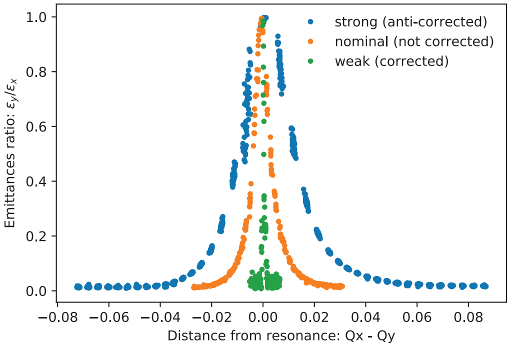
Pros:

1. Is **fast**: requires < 1000 turns ($\sim$1 ms)
2. **Does not rely on complex hardware calibration or optics models**
3. ALBA is equipped with 120 turn-by-turn BPMs, providing a very good statistics

Cons:

1. Hard to distinguish coupling from **decoherence**: chromaticity should be $\sim$0
2. Doesn't work very well when the coupling term is too weak

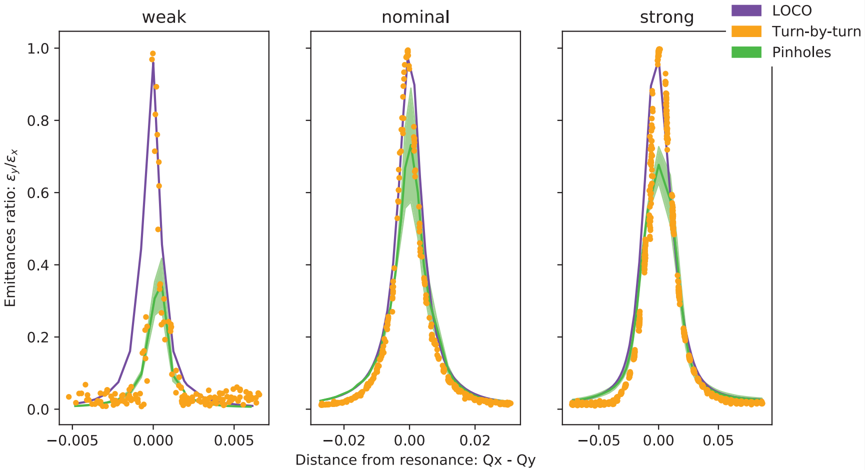
Measuring coupling with turn-by-turn BPMs



- Tune is inferred for each individual shot using a combined BPMs technique [1]
- **Every setting reach 100% coupling**
- **The width of the weak resonance is ∼4e-4, comparable to the tune stability**

[1] P. Zisopoulos et al., PRAB 22, 071002 (2019)

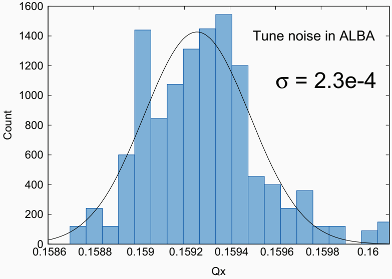
Pinholes vs Turn-by-turn vs LOCO fit model



- An **optics model** is derived from **closed orbit measurement** (LOCO)
- The model is used to **simulate coupling** along the tune scan

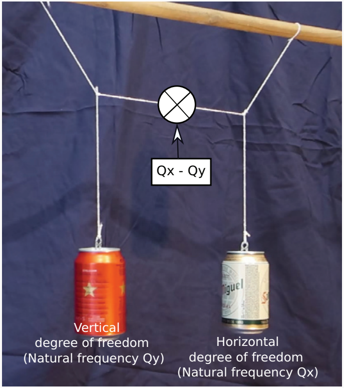
What's wrong? $Q_x = Q_y$ is actually difficult...

- Machine stability: the **tunes fluctuate** due to **power supply noise** (check picture). Will we be able to stay on the resonance?
- **Loss of optics flexibility (Qx=Qy)**
- Control of skew quadrupolar errors is important, cannot afford large errors: Optics correction is more complicated



Exciting coupling resonance far from $Q_x = Q_y$ [1]

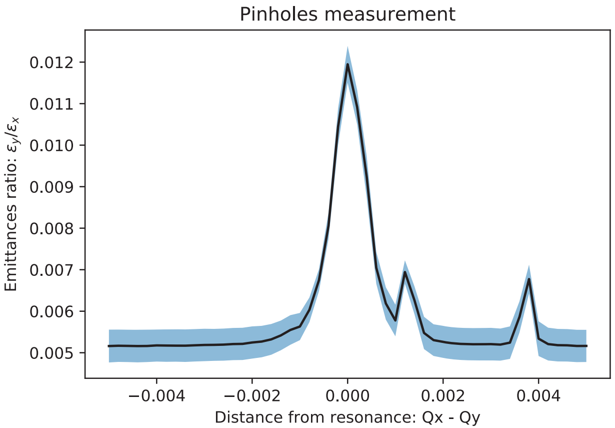
If Qx≠Qy we can "trick" each plane to "think" the other one has the same tune by pulsating coupling at frequency Qx-Qy → frequency shift the excitation



- At Alba we don't have a dedicated A.C. skew quadrupole for these studies
- Instead the tune excitation stripline was reconfigured to provide a skew quadrupolar field

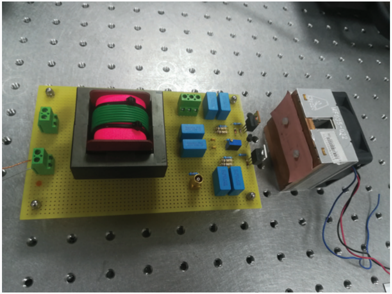
[1] P.Kuske, 8-th Low Emittance Rings Workshop, Frascati, Italy, 2020

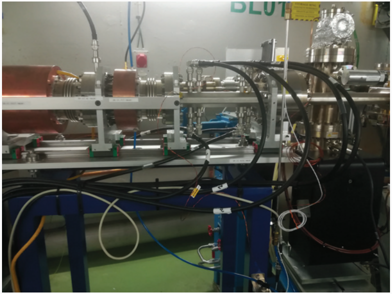
A first A.C. skew quadrupole test at ALBA



- ALBA is equipped with a short (15cm) tune excitation stripline
- The stripline was reconfigured to produce a skew quadrupolar field
- The skew stripline is driven by a **signal generator + 200W amplifier**
- This **stripline is by far not an high power design!**
- **Tune jittering is a big problem...** $\rightarrow$ $Q_x - Q_y$ **is moving continuously**

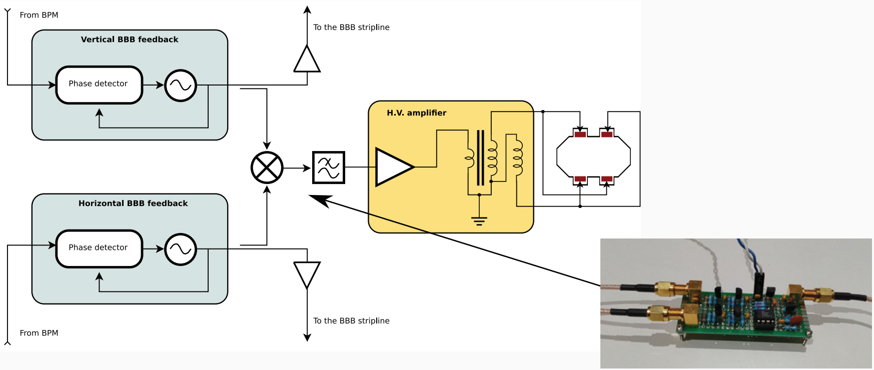
From stripline to electric deflector





- **Striplines** have wide bandwidth but **are not very power efficient**
- Most of the power gets dissipated in a dummy load at the stripline output
- We remove the 50Ohm terminations → **drive the stripline as an electric deflector**
- With a home made 50W amplifier we can get 500V on the stripline
- **5 times more kick than the 200W amplifier...** bandwidth is limited to 300kHz
- The amplifier is hung under the stripline to reduce cable capacitance

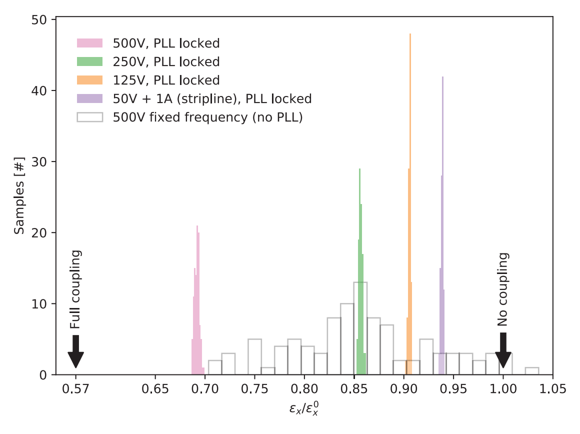
Using a PLL to lock onto $Q_x - Q_y$



- Betatron tunes are not stable! (PSU noise, ID motion...)
- The AC skew frequency needs to be locked onto $Q_x - Q_y$: A tune following system is required
- **PLL in the bunch by bunch feedback** [2]system provides a tune reference
- The **tune signals are mixed with an analog multiplier to produce the $Q_x - Q_y$ signal**
- This system has **sufficient bandwidth to track tunes fluctuations**

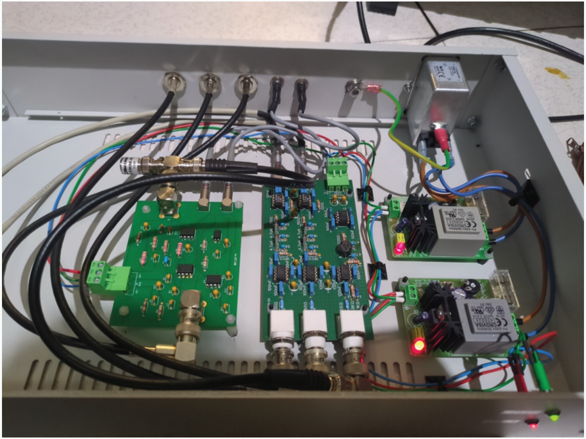
[2] M. Abbott et al. Architecture of transverse Multi bunch feedback processor at Diamond, 15th ICALEPCS

Experimental results with the PLL tune tracking



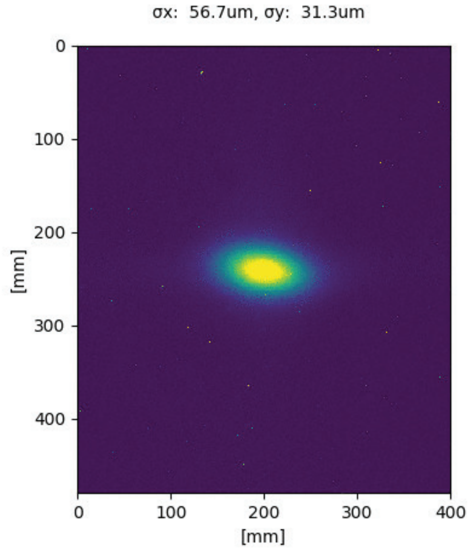
- Excitation frequency $(Q_x - Q_y)$ is obtained by beating signals from the PLLs
- The $Q_x - Q_y$ signal is amplified and fed to the electric deflector
- The amplitude of the signal is changed by adding attenuators (orange, green, pink)
- For each amplitude ~ 100 **emittances measurements** are obtained with the **pinholes**
- The same is repeated with the **PLL system off: fixed excitation frequency (white)**

Operation ready electronics

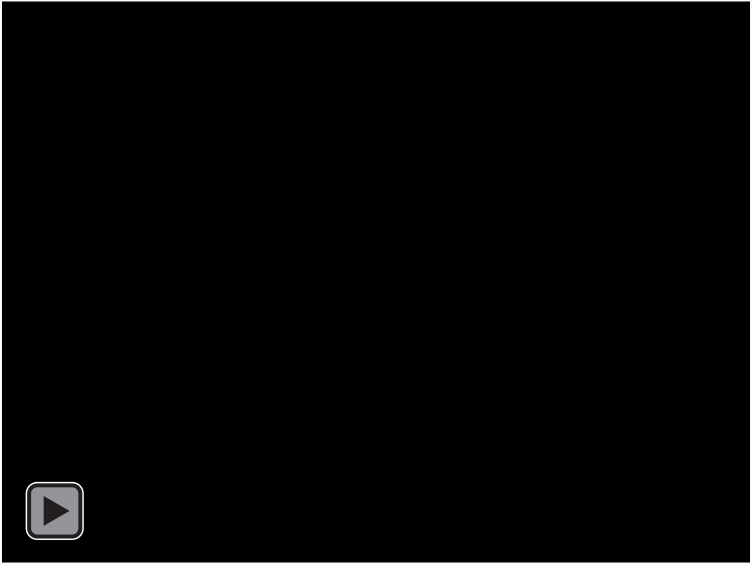


- The previous setup is **not compatible with operation...**
  cannot operate as feedback and tune reference at the same time
- We **modified the firmware of the bunch by bunch feedback** to get the tune reference
  we reconfigured an **unused serial port to get a square wave**
- The new electronics takes the two square references convert them in sinusoids, generate the frequency difference and allow to control amplitude

Coupling control



Coupling control



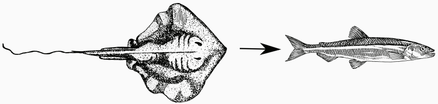
Coupling provides a way to control vertical beam size, increase lifetime with a bonus reduction of the horizontal emittance

Working on the coupling resonance $Q_x = Q_y$ is possible but:

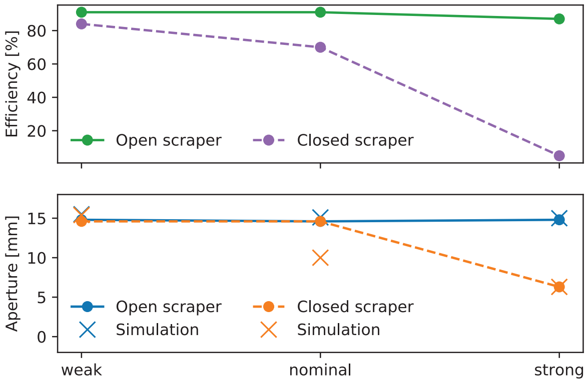
- The working point constraint is a problem for lattice optimization
- Strong skew quadrupoles are required to avoid tune jittering problems $\rightarrow$ Off-axis injection could be a problem

An A.C. skew quadrupole with frequency $Q_x - Q_y$ allows to work with $Q_x \neq Q_y$:

- We have been experimenting with a short tune excitation stripline converted to an electrostatic skew quadrupole
- In this configuration is easy to achieve large coupling values
- It is mandatory to lock the excitation frequency onto $Q_x - Q_y$
- We have been experimenting using a PLL system with very satisfactory results

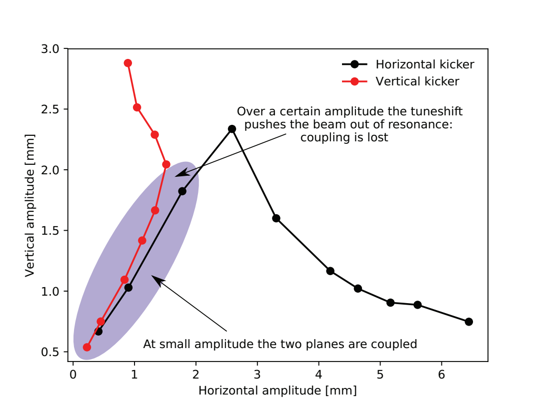


Injection efficiency and horizontal dynamic aperture



- Horizontal dynamic aperture was measured and compared against the model (LOCO)
- A substantial **drop is visible only for strong coupling and with vertical scraper closed...**

Tune shift with amplitude



- Coupling allows momentum to move from one plane to the other
- Kicking in the **vertical** plane a similar betatron amplitude is observed in the horizontal
- So as if kicking in the **horizontal** plane a similar amplitude is observed in the vertical
- But this is true only at small amplitudes
- At high amplitude the tune shift with amplitude pushes the beam out of resonance!