

Methods for full coupling operation in a synchrotron light source

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Several synchrotron light sources are currently designing a lattice upgrade to reach low (sub-nm) emittances, which inevitably entails a significant beam lifetime reduction. In view of the ALBA lattice upgrade, it was decided to evaluate different methods using the current ALBA storage ring to reach large betatron coupling as a way to increase the lifetime. In a first attempt, coupling was introduced by means of static skew quadrupolar magnets and by tuning the working point onto the resonance $Q_x = Q_y$, but in a realistic scenario, some kind of tune feedback is required to counteract the unavoidable tune drifts and fluctuations that would drive the system out of resonance. Furthermore, the condition $Q_x = Q_y$ constrains the linear optics resulting in an important lack of flexibility. Therefore a second method is proposed, based on the excitation of the coupling resonance with an ac skew quadrupole driven at the frequency $f_{\text{rev}}(Q_x - Q_y)$. In this case, we used the existing four-electrode tune excitation stripline recabled as a skew quadrupole. A fast tune tracking system was implemented to drive the skew quadrupole exactly on the resonance despite the tune fluctuations. This work goes over the collected results and experiences, aiming to put into light pitfalls and limits of the application of coupling to achieve round beams in a synchrotron light source.

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I. INTRODUCTION

Short Touschek lifetime is a critical aspect of low emittance electron storage rings. To ensure an acceptable lifetime, many new machine designs rely on some kind of blowup of the vertical emittance. For example, the ESRF-EBS and Diamond rings successfully implemented a vertical beam blowup using different excitation strategies [1,2]. While such a choice could seem to be working against the key requirement of low emittance, a small blowup of the otherwise tiny vertical beam size can improve substantially the lifetime, at cost of a marginal reduction of brilliance.

Alternatively, a vertical emittance blowup can be produced by sharing the relatively large horizontal emittance with the vertical plane by means of betatron linear coupling. Coupling allows the betatron action to flow between the horizontal and vertical planes, and when the lattice is tuned exactly onto the coupling difference resonance, emittances are fully shared resulting in a round beam. The main benefit of this approach is an effective reduction of the horizontal emittance, therefore mitigating

the loss in performance due to the increase in vertical emittance.

Although coupling in storage ring has been studied in great details in the past [3,4], several open questions lead to second guess the compatibility of full coupling with the normal operations of a synchrotron light source. Unavoidable tune drifts and fluctuations can easily pull the lattice out of the coupling resonance resulting in a sudden beam size change. By increasing the coupling strength the resonance can be made wider, thus reducing the sensitivity of the system to tune variations. On the other hand, an excessively strong coupling can result in optics distortion and substantial limitations to the off axis injection process.

In view of the future upgrade of the ALBA storage ring [5], several beam experiments were carried out on the present machine to evaluate different methods to achieve full coupling with special attention to the compatibility with operations [6,7]. The first round of experiments intends to achieve full coupling by tuning the working point onto the resonance $Q_x = Q_y$. Next, our second attempt is based on the excitation of the coupling resonance with an ac skew quadrupole driven at frequency $f_{\text{rev}}(Q_x - Q_y)$, with f_{rev} the ring revolution frequency. For this approach, we recable the existing tune excitation stripline into a skew quadrupole, but the limited available power allowed to produce only a small hint of coupling. In order to increase the stripline's effective kick and to enlarge

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the width of the resonance, we reconfigure the stripline as an electric deflector by removing the resistive terminations and allowing us to drive the electrodes to higher voltage. In addition, a test with an optics with higher β -function at the stripline location was carried out.

Both methods were limited by the unavoidable small fluctuations of the tunes, which did not allow us to keep a stable beam size. This was finally circumvented using an active measurement system based on the existing bunch-by-bunch electronics, which generates a real-time reference of the tunes and drive the ac skew quadrupole. This system allows us to maintain the resonant condition despite any tune fluctuations and permits us to produce a stable and strong excitation of the coupling resonance.

II. COUPLED BETATRON MOTION

Neglecting coupling and nonlinearities, the horizontal and vertical positions of a particle in a synchrotron at turn n are described by the betatron oscillations:

$$x, y = \sqrt{2J_{x,y}\beta_{x,y}(s)} \cos[2\pi Q_{x,y}n + \psi_{x,y}(s)], \quad (1)$$

where $J_{x,y}$ represents the betatron actions, $Q_{x,y}$ is the betatron tunes, $\beta_{x,y}$ and $\psi_{x,y}$ are the betatron amplitudes and phases at the observation point s . The phenomena of periodic energy exchange are commonly observed in a system of two coupled harmonic oscillators. The horizontal and vertical betatron modes in a synchrotron are not an exception, skew quadrupoles or solenoids can be introduced in the lattice to serve as a linear coupling between the two transverse planes providing a path for the betatron action to flow from one mode to the other. The presence of strong coupling can produce a substantial distortion of the optical functions, with a consequent reduction of the storage ring performance. Therefore, we restricted ourselves to the case of weak coupling. In this regime, the Courant-Snyder parameterization is still a valid representation of the beam envelope, saving ourselves the burden of dealing with a heavier but exact parameterization of the optical functions such as the one provided in [3].

The action exchange process, described in detail in [4], is made evident by observing the turn-by-turn evolution of a particle after having excited the betatron motion in only one of the two transverse planes. As shown in Fig. 1, part of the initial action of the horizontal betatron mode gets transferred to the vertical plane, after which the process inverts and goes on periodically. In general, the periodic action fluctuation on each plane assumes the form:

$$J_{x,y}(n) = J_{x,y}^{\min} + \frac{\Delta J}{2} \left[1 + \cos\left(\frac{2\pi n}{T} + \mu_{x,y}\right) \right], \quad (2)$$

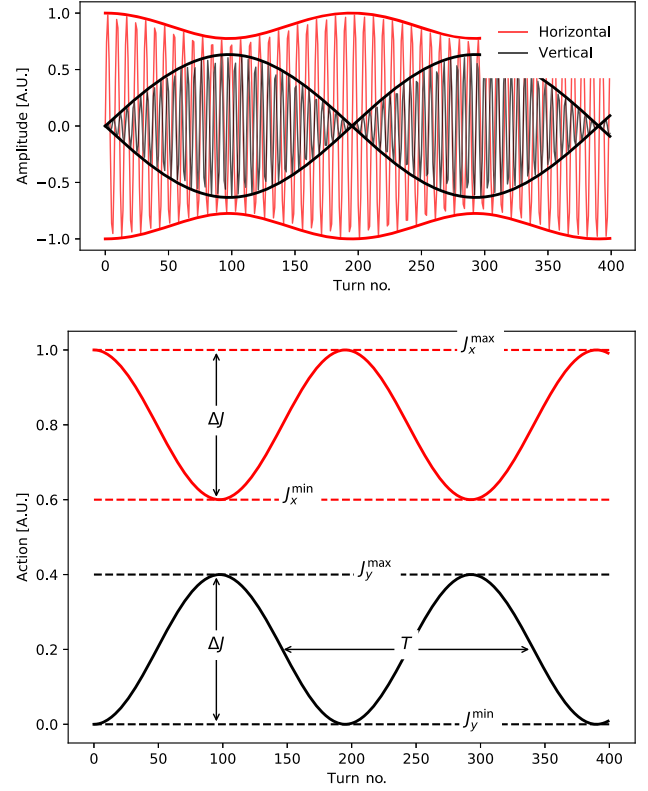


FIG. 1. After the beam gets kicked in the horizontal (red) plane, the betatron action (bottom) periodically is transferred to the vertical plane (black). In the turn-by-turn beam position (top), as would be measured by a beam position monitor, the effect is shown as a wobble of the envelope of the betatron oscillation. In this particular case, the transfer is only partial since the system happens to be not on resonance: $Q_x \neq Q_y$.

where the action exchange period T depends on the strength of the coupling term C and the distance from the difference resonance $\Delta = Q_x - Q_y$:

$$T = \frac{1}{\sqrt{(2\pi\Delta)^2 + |C|^2}}. \quad (3)$$

A full action exchange can only take place when the resonant condition $\Delta = 0$ is met exactly, otherwise, only a fraction of the action is transferred:

$$\frac{J_{\min}}{J_{\max}} = \frac{(2\pi\Delta)^2}{(2\pi\Delta)^2 + |C|^2}, \quad (4)$$

The coupling strength C for a skew quadrupole is defined as

$$C = \oint_s \sqrt{\beta_x(s)\beta_y(s)} K(s) e^{i[\psi_x(s) - \psi_y(s)]} ds, \quad (5)$$

where $K(s)$ represents the strength of the skew quadrupolar field along the ring defined as

$$K(s) = \frac{1}{B\rho} \frac{\partial B_x}{\partial x}. \quad (6)$$

Note that while the definition of C can be extended to include solenoids, for simplicity, we limit the discussion to the case of skew quadrupoles only, since in the ALBA ring no solenoids are available for experimentation.

At resonance, the dynamics induced by the action exchange process is such that on a time scale longer than the exchange period, particles exhibit on average the same amount of horizontal and vertical action independently of the initial state. When considering the statistical distribution of a bunch the overall behavior is a beam with the identical horizontal and vertical emittance. Due to the negligible vertical natural emittance of an electron ring, coupling can be considered the only source of vertical emittance. In this condition, the ratio of the emittances is equal to the fraction of exchanged action. For a detailed analysis of the equilibrium emittances in the presence of coupling and including the effect of damping (which has been neglected up to this point), we refer to the work done by Kuske [8]. For ease of reading, here we report only the main results, which will be useful for the next discussion:

$$\frac{\epsilon_x}{\epsilon_x^0} = \frac{\frac{1}{4}|C|^2 \sqrt{e^{\frac{-1}{\tau_x} + \frac{1}{\tau_y}}} \left(1 + \frac{\tau_y}{\tau_x}\right) + \left(\frac{1}{\tau_x} + \frac{1}{\tau_y}\right)^2 + (2\pi\Delta)^2}{\frac{1}{4}|C|^2 \sqrt{e^{\frac{-1}{\tau_x} + \frac{1}{\tau_y}}} \frac{(\tau_x + \tau_y)^2}{\tau_x \tau_y} + \left(\frac{1}{\tau_x} + \frac{1}{\tau_y}\right)^2 + (2\pi\Delta)^2}, \quad (7)$$

$$\frac{\epsilon_y}{\epsilon_x^0} = \frac{\frac{1}{4}|C|^2 \sqrt{e^{\frac{-1}{\tau_x} + \frac{1}{\tau_y}}} \left(1 + \frac{\tau_y}{\tau_x}\right)}{\frac{1}{4}|C|^2 \sqrt{e^{\frac{-1}{\tau_x} + \frac{1}{\tau_y}}} \frac{(\tau_x + \tau_y)^2}{\tau_x \tau_y} + \left(\frac{1}{\tau_x} + \frac{1}{\tau_y}\right)^2 + (2\pi\Delta)^2}, \quad (8)$$

where ϵ_x and ϵ_y are the horizontal and vertical emittances in the presence of coupling, ϵ_x^0 is the uncoupled horizontal emittance, τ_x and τ_y are the horizontal and vertical betatron damping times expressed in turns. When $\Delta = 0$, the equilibrium emittance is determined by the damping times and the coupling strength C only.

Whenever the horizontal emittance diffusion rate toward the vertical plane due to the coupling is dominant over the vertical damping time (i.e., strong coupling), the previous equation can be approximated as

$$\frac{\epsilon_x}{\epsilon_x^0} = \frac{\epsilon_y}{\epsilon_x^0} = \frac{\tau_y}{\tau_x + \tau_y}. \quad (9)$$

The equilibrium emittances now depend only on the damping times, and are half of the uncoupled horizontal emittance (ϵ_x^0) only if the horizontal and vertical damping times are exactly the same. In the case of ALBA, because of

TABLE I. Parameters of the ALBA storage ring in the nominal configuration and all the optics variations used for the various coupling experiments described in this work.

	Nominal	$Q_x = Q_y$	Double β
Circumference (m)	269	269	269
f_{rev} (MHz)	1.115	1.115	1.115
ϵ_x^0 (nm)	4.6	4.9	9.5
Energy spread (%)	0.1	0.1	0.1
τ_x/τ_y (turns)	4500/5800	4500/5800	4300/5900
Q_x/Q_y	0.155/0.366	0.155/0.155	0.410/0.290

a small difference in the transverse damping rates (see Table I), the fully coupled emittance is 0.57 of the uncoupled horizontal one.

By reducing the coupling strength, a choked regime is approached. Now, the small coupling limits the diffusion of the horizontal emittance toward the vertical plane compared to the vertical damping, and therefore the condition $\epsilon_x = \epsilon_y$ cannot be reached.

The emittance sharing process is also inhibited when the condition $\Delta = 0$ is not fulfilled. From Eq. (4), it is possible to derive a simple expression for the resonance width neglecting damping:

$$\Delta_{1/2} = \frac{1}{2\pi} |C|, \quad (10)$$

where $\Delta_{1/2}$ represents the distance from the resonance where the emittance exchange ratio drops down to one half. To obtain a stable emittance exchange and avoid beam size fluctuations due to tune fluctuations, it is crucial to fulfill the condition $\Delta \ll \Delta_{1/2}$, ensuring that the system is always close to resonance.

III. ALTERNATING SKEW QUADRUPOLEAR FIELD INDUCED COUPLING

The resonant condition $\Delta = 0$ imposes a strong limitation in terms of optics flexibility, adding a new constraint to the already difficult task of designing a low emittance optics. Furthermore, an active feedback over the quadrupole currents would be required to counteract the unavoidable tune drifts induced, for example, by the motion of insertion devices, as required by the experimental needs of beamlines. The complexity introduced by this approach encouraged the search for a different mechanism to produce coupling. As described in [9–12], the coupling resonance can be excited in a lattice with $Q_x \neq Q_y$, when a skew quadrupole field is pulsed at the frequency $\pm f_{\text{rev}}(Q_x - Q_y - n)$, with f_{rev} the ring revolution frequency and n an integer number. To keep the excitation frequency to a small value and simplify the hardware it was chosen to work with $n = 0$.

The kick produced by a static skew quadrupolar field on one plane due to the natural betatron motion on the other one is

$$dp_{y,x} = K_{dc} \sqrt{2\beta_{x,y} J_{x,y}} \cos(2\pi Q_{x,y} n + \psi_{x,y}), \quad (11)$$

where K_{dc} is the skew quadrupolar gradient, $J_{x,y}$ and $\psi_{x,y}$ are the betatron action and phase at the skew quadrupole, and n is the turn number. As previously discussed, a resonant action transfer arises only when the frequency of the driving force $Q_{x,y}$ coincides with the natural oscillation frequency $Q_{y,x}$ of the excited plane. If the field K_{dc} is substituted for an oscillating one $K_{ac} \cdot \cos(2\pi Q_k n)$, we obtain after some manipulation:

$$dp_{y,x} = K_{ac} \sqrt{2\beta_{x,y} J_{x,y}} \left\{ \frac{\cos[2\pi(Q_{x,y} + Q_k)n + \psi_{x,y}]}{2} + \frac{\cos[2\pi(Q_{x,y} - Q_k)n + \psi_{x,y}]}{2} \right\}. \quad (12)$$

By choosing the value of $Q_k = Q_x - Q_y$, it is possible to excite the coupling resonance without imposing the condition $Q_x = Q_y$. Of the sum and difference terms of Eq. (12), only one at a time can be resonant, and the nonresonant one will barely affect the beam motion. The previously discussed theory also applies to this new case, except that now K_{dc} should be substituted with $K_{ac}/2$, where K_{ac} represents the peak intensity of the oscillating skew quadrupolar gradient.

Even though this solution requires some sort of dedicated ac skew quadrupole, such as a stripline or a magnetic shaker, it gives complete freedom regarding the choice of the working point. Furthermore, the intrinsically wide bandwidth nature of such devices simplifies greatly the implementation of a fast feedback.

IV. COUPLING EXPERIMENTS WITH A STATIC SKEW QUADRUPOLE FIELD

In order to drive the machine onto the skew difference resonance $\Delta = 0$, it was decided to keep the horizontal tune fixed and move only the vertical one in an attempt to preserve the horizontal linear optics and not to affect the horizontal off axis injection. Table I collects the relevant machine and optics parameters in the various configurations described in this paper.

Thirty-two skew quadrupolar correctors allow control of the coupling in the ALBA storage ring. During normal operations, the skew correctors are usually turned off, resulting in an emittance ratio $\approx 0.5\%$. Whenever required, optics and coupling corrections are carried out using closed orbit response matrix approach (LOCO [13]), which during

many years of operations of the ALBA ring provided stable and reliable results.

Three different skew quadrupole settings have been prepared for the experiments, and for each setting, the coupling strength C has been measured using LOCO: (i) Weak ($|C| = 8.3 \times 10^{-4}$): LOCO was used to drive the skew quadrupoles to minimize coupling as much as possible. (ii) Nominal ($|C| = 5.9 \times 10^{-3}$): All skew quadrupoles are turned off, as during normal operation. (iii) Strong ($|C| = 1.8 \times 10^{-2}$): Skew quadrupoles settings computed for the weak coupling optics are applied with opposite sign to increase coupling.

Diagnostic wise, the storage ring is equipped with 120 turn-by-turn beam position monitors. A horizontal and a vertical fast kicker (pinger magnet) allow us to excite the betatron motion in one single turn [14]. Two independent pinhole cameras allow us to measure the beam cross section [15] from x-ray radiation collected from bending magnets. To provide a reliable readout, the cameras require an exposure time between 100 ms and 1 s depending on the beam intensity, limiting the time response of this diagnostics.

The effect of the tune stability when operating onto the coupling resonance is one of the key points under investigation in this work. Tunes have been measured and the distribution of Q_x , Q_y , and $\Delta = Q_x - Q_y$ is shown in Fig. 2. These results are consistent with what already observed in 2017 [16].

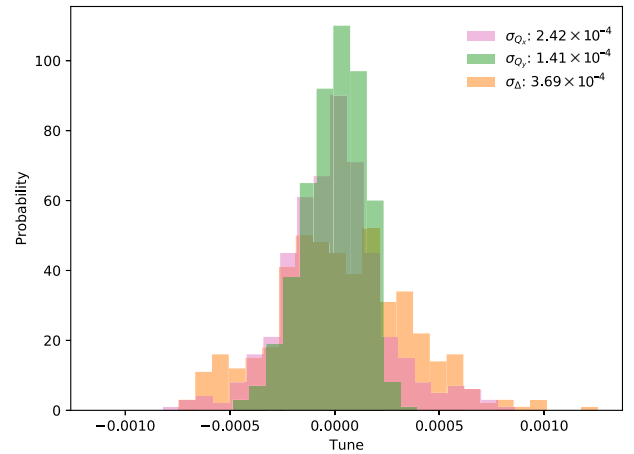


FIG. 2. Distribution of the horizontal (pink), vertical (green) tunes, and difference of the tunes (orange) derived from the spectral analysis of 500 measurements of the horizontal and vertical betatron motion. The average value of the tunes has been removed to align the three distributions and make evident the fluctuations. The fluctuation of the difference of the tunes Δ is close to the sum of the fluctuations in Q_x and Q_y pointing to an anticorrelation between the horizontal and vertical tune changes. An effect compatible with electrical noise in the quadrupole circuit.

A. Turn-by-turn action exchange measurements

As described previously, the magnitude of the coupling C can be derived from turn-by-turn beam position measurements, by observing directly the action exchange process. One of the pinger magnets was used to excite a coherent betatron motion of the beam. Provided that the lattice is tuned to low chromaticity, the coherence of the betatron motion is preserved over thousands of turns, allowing us to observe the action exchange process by means of turn-by-turn beam position monitors. This type of measurement is inherently fast, requiring only a few hundred turns. Furthermore, the same turn-by-turn data allow us to determine precisely the tunes by combining the data collected from all the beam position monitors and performing a spectral analysis using the technique presented in [17]. For these reasons, the turn-by-turn technique is particularly convenient to study coupling in the presence of fast tune fluctuations. Figure 3 shows the raw turn-by-turn beam motion after a pinger kick sampled by one of the 120 beam position monitors and the computed action.

To evaluate the fraction of action exchange, we proceed by decomposing, using a Fourier analysis, the turn-by-turn beam position measured on the excited plane, here generally indicated as x , as the sum of two terms with frequencies Q_1 and Q_2 :

$$x = a_1 \cos(2\pi Q_1 n + \mu_1) + a_2 \cos(2\pi Q_2 n + \mu_2). \quad (13)$$

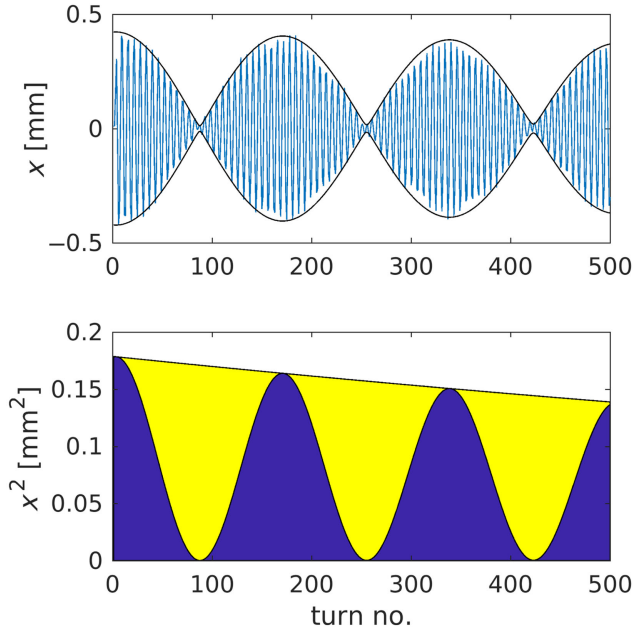


FIG. 3. Turn-by-turn measurement showing almost 100% action transfer. The upper plot shows the turn-by-turn readings (light blue line) and the amplitude (black line) obtained from spectral analysis. The lower plot shows in blue the squared amplitude (proportional to the action) and the transferred squared amplitude (yellow area).

Taking the square of the previous expression, which is proportional to the action, and comparing to Eqs. (2) and (4), it is possible to express the periodic action fluctuation as

$$J(n) \propto a_1^2 + a_2^2 + 2a_1a_2 \cos[2\pi(Q_1 - Q_2) + \mu_1 - \mu_2] \quad (14)$$

and

$$1 - \frac{J_{\min}}{J_{\max}} = \frac{2a_1a_2}{a_1^2 + a_2^2}. \quad (15)$$

For each acquisition, the analysis is repeated independently for each beam position monitor and the outcome is averaged.

Figure 4 shows the results of the measurements for the three different coupling configurations, along with the expected value computed from Eq. (4) using the value of C measured with LOCO. In the nominal and strong coupling cases, a good agreement with respect to the predicted value is observed, while the larger discrepancy in the weak case is likely due to LOCO struggling to measure the small value of C . In the weak coupling case, the small number of points with action exchange close to one is a symptom of the tune fluctuations: even when the machine is driven exactly on the resonance, only a few lucky acquisitions happen to have the correct tunes and show a large value of action exchange.

B. Pinhole emittance exchange measurements

A measure of coupling strength can be derived by observing the transverse emittance exchange using a pinhole camera. In practice, the large vertical emittance of the

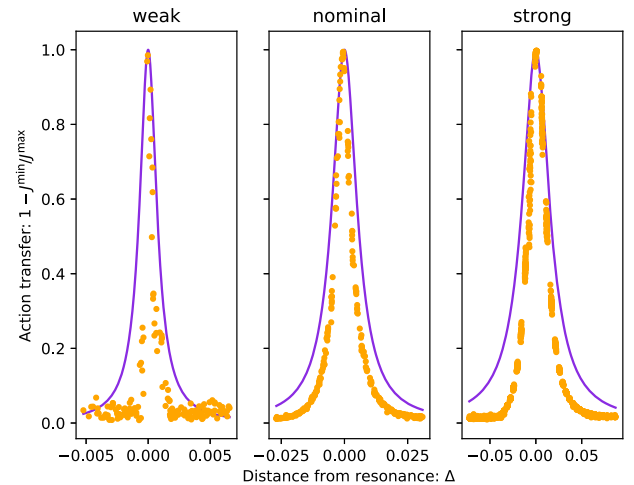


FIG. 4. Dots show the value of action transfer determined from turn-by-turn beam position measurements for the three different coupling configurations. The value of Δ was scanned around 0, and for each value the measurement was repeated 10 times. The solid line represents the theoretical value computed from Eq. (4) with the value of C measured with LOCO.

coupled beam made it difficult to acquire accurate measurements of the vertical beam size. In fact, the two pinhole cameras installed in ALBA were designed to operate with two orders of magnitude smaller vertical emittance. To avoid systematic errors related to the pinhole setup and the optical functions measurement, it was decided to rely only on the relative variation of the horizontal emittance ϵ_x/ϵ_x^0 , as a measurement of coupling rather than a direct measurement of ϵ_y/ϵ_x . With the advantage that being ϵ_x and ϵ_x^0 measured in the same conditions, the contribution of the aforementioned systematic errors is mostly eliminated. The equilibrium horizontal emittance ϵ_x^0 is obtained by acquiring some measurements far away from the resonance, where the effect of coupling is negligible.

Nevertheless, an attempt at measuring the ratio ϵ_y/ϵ_x in the nominal machine condition is shown in Fig. 5. Particular effort was made to tune accurately the optics and calibrate the pinhole camera in order to remove as much as possible systematic errors. While the curve shows an overall correct behavior, the peak value falls short of meeting the theoretical peak value of ~ 1 , probably due to a wrong estimation of the vertical emittance. More reliable results have been obtained instead from the observation of ϵ_x/ϵ_x^0 . A comparison of the measurements with the theoretical values for the three coupling configurations, as done previously for the turn-by-turn method, is presented in Fig. 6. The observed agreement is similar to the turn-by-turn case, and only the nominal and strong coupling cases show a minimum value close to ~ 0.57 as predicted by the theory.

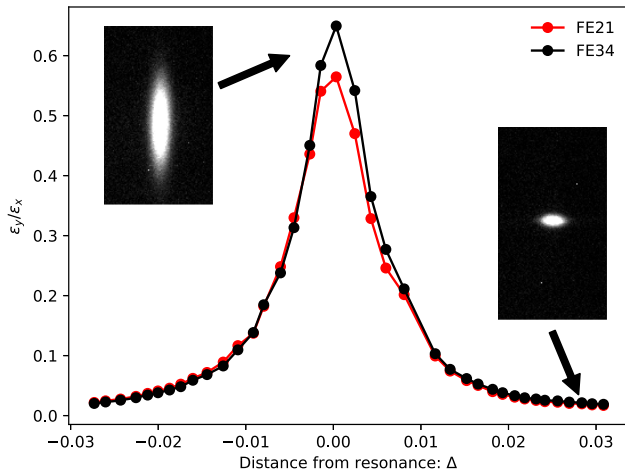


FIG. 5. Ratio of the emittances is derived from pinhole images acquired at two different locations: frontend-21 and frontend-34. The measurement was carried out with the nominal optics. Despite the effort to calibrate the pinholes and correct the machine optics the peak value falls short of meeting the theoretical value of ~ 1 . The observed large vertical emittance is far from the design parameters envelope of the pinhole system, and is likely a cause of systematic errors.

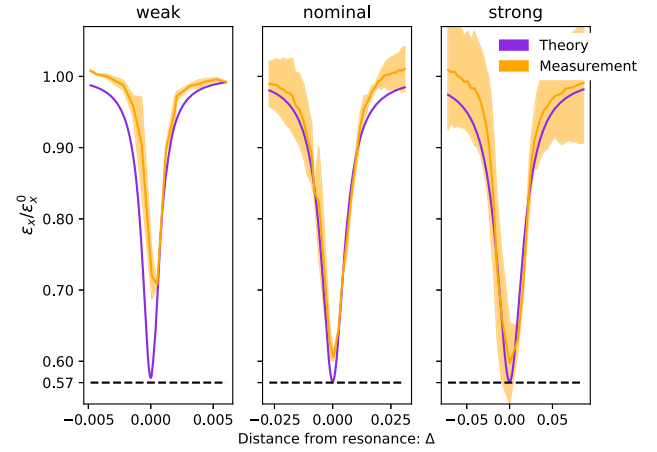


FIG. 6. Pinhole camera measurements of the emittance exchange for the three coupling configurations. The solid yellow lines represent the average over results from the two pinholes, while the shaded area shows the maximum deviation between the two. The solid purple lines represent the theoretical value computed from Eq. (4) and using the value of C measured with LOCO.

The behavior is to be attributed to the resonance width, which in the weak case is thinner than in the nominal and strong cases, and comparable to the tune fluctuations. Since the exposure time of the cameras ranges between ~ 100 ms and 1 s, the pinhole camera integrates the beam size changes as the system moves in/out of the resonance and results in a smaller measurement of the coupling peak value.

C. Injection studies

Reliable and efficient injection is a basic requirement to operate a light source in top-up mode. Two main issues have been identified as potential limitations to off axis injection in a coupled lattice: (i) losses due to large induced vertical oscillations and (ii) reduction of the dynamic aperture due to optics aberration effects.

During normal operation, insertion devices reduce the vertical physical aperture down to a few millimeters. In ALBA, a vertical scraper is positioned strategically to intercept large orbit electrons before they can reach the jaw of an insertion device and produce any damage. Therefore, the aperture imposed by such scraper defines the maximum admissible vertical action. Indeed, in coupled optics, the large horizontal action of the injected beam can leak to the vertical plane resulting in the partial or complete loss of the injected beam onto the scraper.

The horizontal dynamic aperture was measured in the three coupling cases by exciting the beam with one out of the four injection kickers. The strength of the excitation was ramped progressively up to the point where the stored beam is lost. Turn-by-turn beam position monitors located in the injection straight section were used to infer the maximum betatron oscillation amplitude. Injection

TABLE II. Measured dynamic aperture and injection efficiency for the three coupling settings for both vertical scraper positions. The values in parentheses correspond to the simulated dynamic aperture.

Scraper	Dynamic aperture (mm)		Injection efficiency (%)	
	Closed	Open	Closed	Open
Weak	14.6 (15.4)	14.8 (15.4)	84	91
Nominal	14.6 (10.0)	14.6 (15.1)	70	91
Strong	6.3 (6.3)	14.8 (15.0)	5	87

efficiency was also observed by comparing direct measurements of the current transformers located in the storage ring and in the booster ring, while the current in the storage ring was topped up from 0 to 20 mA.

Every measurement was repeated with two different configurations of the vertical scraper: at the usual operation position (± 4.75 mm) and at the open position (± 10.0 mm).

Table II shows the measured dynamic aperture and injection efficiency for the three coupling cases, along with results of simulations obtained by tracking electrons with the code AT [18]. Both measurements and simulations show that a substantial reduction of the dynamic aperture and injection efficiency is observed only in the case of strong coupling.

To better understand the mechanism, it is useful to observe the turn-by-turn beam position after kicking the beam in one plane for a few different strengths. Figure 7 shows the results of the experiment carried out using the nominal coupling optics. At small amplitude, the coupling allows the action to freely flow from one plane to the other, therefore, the same action is observed always in both planes independently of the excitation plane. At high amplitude, the action exchange mechanism gets degraded and almost stops for the strongest excitation strength. The cause of such behavior is to be attributed to the detuning with amplitude, which at high amplitudes produces a tune shift sufficient to bring the system out of the coupling resonance, inhibiting the action exchange process. Figure 8 shows a measurement of the betatron tunes as a function of the horizontal and vertical actions. From the measurement, it appears how the action required to pull the system out of the coupling resonance is comparable to what was observed in the previous measurement.

V. COUPLING EXPERIMENTS WITH AN AC SKEW QUADROPOLAR FIELD

As previously described, an alternative to constant field skew quadrupoles to induce coupling is represented by an ac field. This solution provides full flexibility regarding the choice of the machine working point, furthermore, it makes easier to implement an active system to track the tunes and keep the system on resonance despite the optics variations.

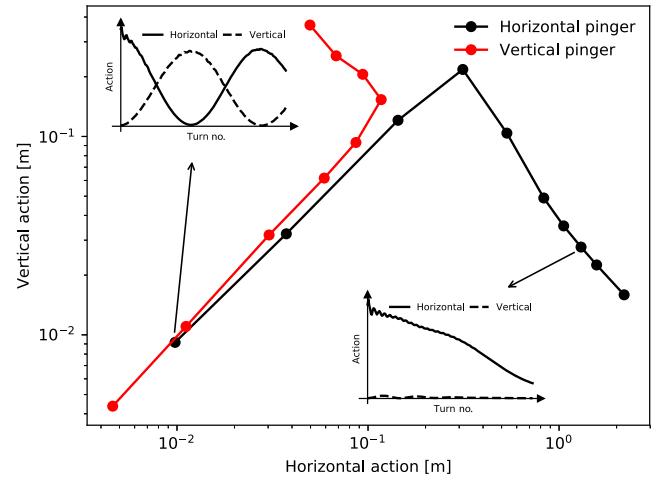


FIG. 7. Characterization of the action exchange process for different values of action in the nominal coupling case. One pinger magnet excites the betatron motion in one plane, and the action exchange process is observed during 200 turns by means of spectral analysis of the turn-by-turn beam position monitor data. Up to an action of ~ 0.1 m the exchange process takes place and therefore the same action is observed in both planes. For stronger excitations, the action is confined to the excited plane. For completeness, the experiment was repeated exciting in the horizontal (black) vertical (red) plane. The measured evolution of the action during 200 turns is shown for a couple of cases, highlighting how for strong excitations no action exchange takes place. This last case also shows a somewhat anomalous damping, which is to be attributed to the decoherence induced by lattice nonlinearities.

Before embarking in the time consuming design of a dedicated ac skew quadrupole, it was decided to carry out a first campaign of experiments relying solely on the existing hardware installed in the ALBA storage ring,

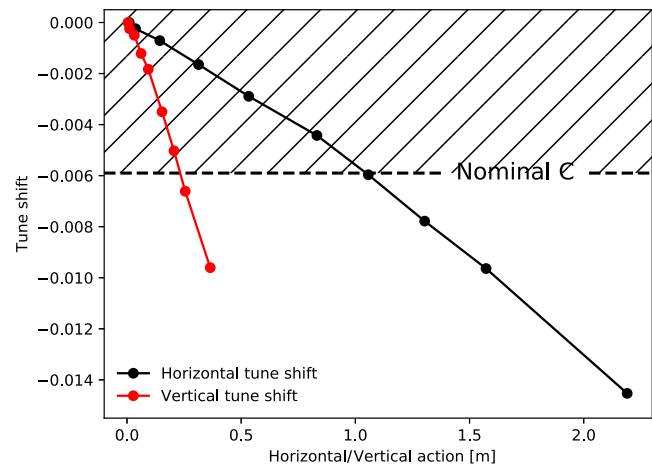


FIG. 8. Horizontal and vertical tunes were measured for the different values of the betatron action. For this measurement, the technique shown in [17] was used to observe the tune. The hatched region represents the coupling resonance width for the nominal coupling lattice.

aiming to gain some experience and to identify the requirements for an optimal solution. The only piece of equipment installed in the ALBA storage ring able to provide an ac skew quadrupolar field is the tune excitation stripline [19]. This device was designed originally to provide a horizontal or vertical dipolar field, but by changing the cabling that connects the four stripline's electrodes to the power amplifiers, it was in fact possible to turn the field to a skew quadrupolar configuration. The stripline is driven by a couple of power amplifier delivering up to 100 W. The signal provided by each amplifier is split and sent to the stripline, such that each electrode receives a power of 50 W. In this condition, the equivalent peak integrated field gradient of the stripline has been evaluated as $K_{ac} \sim 1.0$ mT.

Figure 9 shows the result of a measurement carried out with this setup and using the nominal optics with $Q_x = 0.155$ and $Q_y = 0.366$. The excitation frequency of the stripline was scanned around the resonance $Q_x - Q_y$, and a clear signature of emittance exchange was observed using the two pinhole cameras installed in the storage ring. Even though the maximum achieved coupling was small compared to what was observed in the previous experiments, the results are still in line with the theoretical model if the effects of tune noise are considered. Turn-by-turn measurements in this condition were not possible since the time exchange constant T is too long, making the signals hard to distinguish from decoherence and damping, therefore, only pinhole measurements were acquired.

To achieve stronger coupling three different paths have been considered: (i) increase the stripline field K_s ; (ii) manipulate the optics to increase $\sqrt{\beta_x \cdot \beta_y}$; and (iii) use

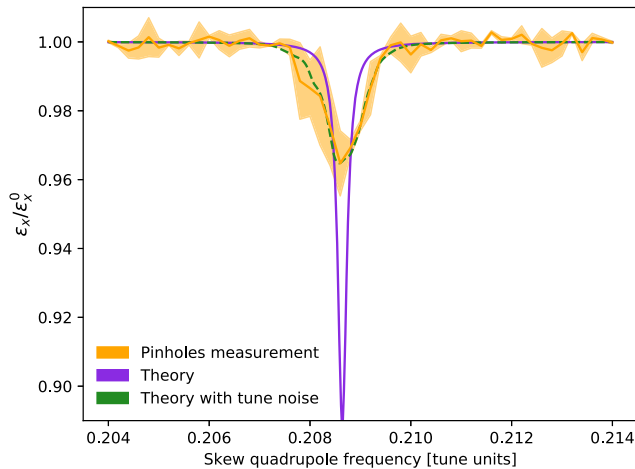


FIG. 9. Coupling evolution measured with the two pinhole cameras while scanning the stripline frequency around the resonant condition $Q_x - Q_y$. The purple line represents the theoretical value assuming no fluctuations of the tunes, instead the green dashed line is obtained including in the theoretical model the measured tune jitter.

a feedback to track the machine tunes and keep the resonant condition despite the tune jitter.

VI. FROM STRIPLINE TO ELECTRIC DEFLECTOR

Stripline kickers are designed to provide an extremely wide bandwidth response, which extends up to GHz. To ensure the wide bandwidth operation, a stripline needs to have its output port terminated on an impedance equal to the stripline characteristic impedance. When power is applied to the input port, a current is established across the stripline's electrodes and the resulting magnetic and electric fields produce an equal kick onto the beam. The power which flows from the amplifier through the stripline is finally dissipated in a dummy load. Since the power scales as the square of the kick strength a substantial upgrade of the power amplifier system would have been required to reach an amount of coupling comparable to what was achieved with the static excitation, therefore, this option was discarded.

On the other hand, our particular use case does not require the extreme bandwidth, which a stripline is capable of. Taking advantage of this condition, the dummy load was disconnected allowing us to drive the stripline as an electric deflector. In this configuration, the electrodes behave as a small capacitive load and the driving amplifier needs to provide enough current to charge and discharge the electrodes to the required voltage every cycle. Therefore, the required power can be reduced as long as the overall capacitance and frequency are kept low.

A high voltage amplifier was designed for this purpose (Fig. 10). A 50 W low output impedance linear amplifier is followed by a step up transformer with two independent secondary windings, which drive the stripline electrodes with the required phases. To keep the stray capacitances to a minimum, the amplifier is installed just below the stripline to limit leads length, and particular care is required to minimize the transformer winding to winding capacitance (Fig. 11). The new system allows us to reach the maximum stripline operating voltage of 1 kV peak-to-peak at the required frequency of $f_{rev}(Q_x - Q_y) = 230$ kHz providing a field gradient 5 times stronger than what was obtained with the previous setup (i.e., equivalent to

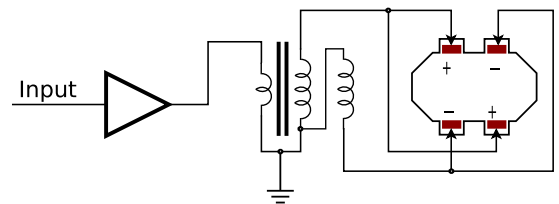


FIG. 10. Signal from a function generator is fed to a 50 W power amplifier, which drives the high voltage transformer. Two independent secondaries provide the required polarities for the stripline electrodes.

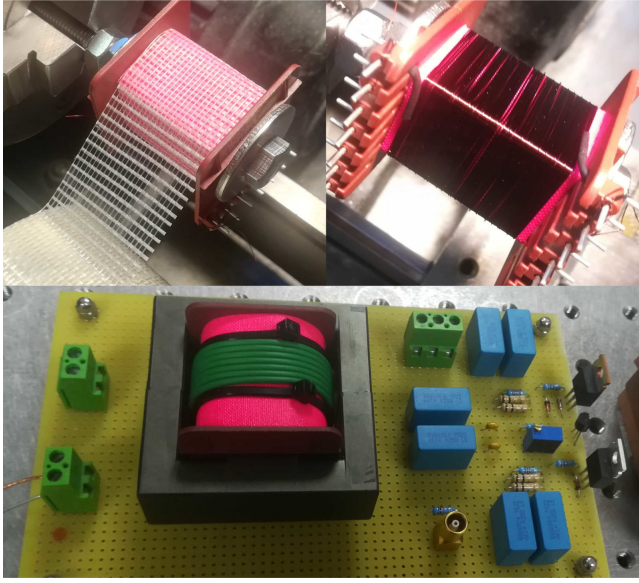


FIG. 11. High voltage transformer was prepared on purpose, the two secondary windings (top right) are interleaved with fiberglass mesh (top left) to reduce interwinding capacitance and minimize the required driving power. The bottom picture shows the complete transformer together with the power amplifier.

$K_{ac} = 5$ mT) while operating with four times lower power. A similar result could be obtained by driving the stripline electrodes as a magnet (swapping the dummy loads for a short circuit). However, this option was discarded, since the maximum current rating of the stripline connectors would have limited the field strength to a lower value respect to the electric deflector configuration. Experiments are carried out following the same procedure used previously, the frequency of the stripline is scanned around the resonance

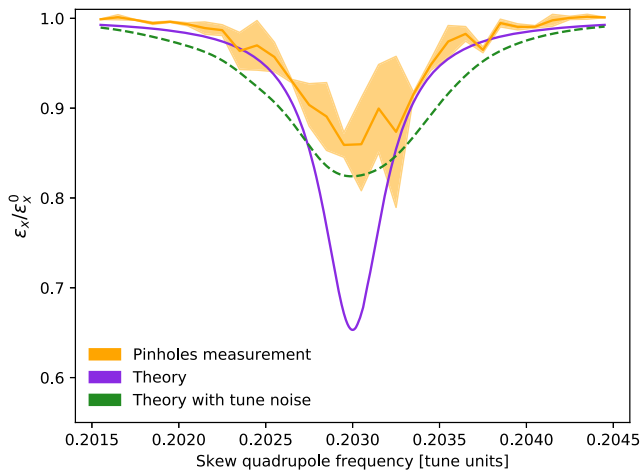


FIG. 12. Coupling evolution measured with the two pinhole cameras while scanning the stripline frequency around the resonant condition $Q_x - Q_y$. The measurement was carried out with the modified stripline, an amplitude of 1 kV peak-to-peak and nominal beta functions.

$Q_x - Q_y$, while the horizontal emittance is measured using the two pinhole cameras installed in the storage ring. Figure 12 shows the result of the scan carried out with an excitation strength of 1 kV peak-to-peak. Coherently with the increased excitation strength, coupling shows an increase, unlike the resonance width, which is still dominated by the tune noise.

VII. HIGH BETA OPTICS

An attempt to increase the coupling strength was carried out using a special lattice with high beta functions at the stripline location (Fig. 13). With the new optics, the term $\sqrt{\beta_x \cdot \beta_y}$ from Eq. (5) is increased by a factor 2.1, therefore, a similar increase in the coupling resonance strength is expected. Measurements are carried out following exactly the same process discussed previously.

Figure 14 shows the result of the scan obtained with the new optics and a stripline excitation amplitude of 1 kV peak-to-peak. An increase in maximum achieved coupling is observed again, but more importantly, the peak width also increases because now the coupling resonance width starts to dominate over the tune noise.

VIII. TUNE TRACKING WITH A PLL

As previously described, increasing the excitation strength results in a wider resonance and reduces the sensitivity to tune fluctuations. On the other hand, to meet the stability level compatible with machine operation would require a dramatic increase of the excitation power, rendering this solution not practical. A different strategy consists in employing a fast feedback system acting onto the skew quadrupolar field frequency, in order to keep the

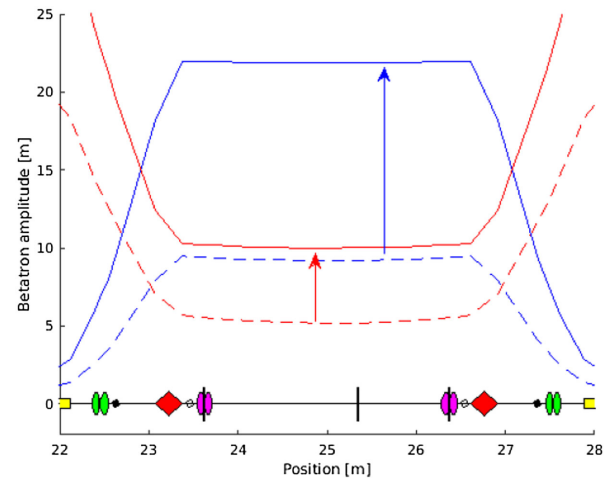


FIG. 13. Horizontal (blue) and vertical (red) betatron amplitudes at the stripline location, for the nominal optics (dashed lines) and the special optics tuned to enhance the stripline kick (solid lines). By changing the beta functions, the factor $\sqrt{\beta_x \cdot \beta_y}$ is increased from 6.9 to 14.8 m.

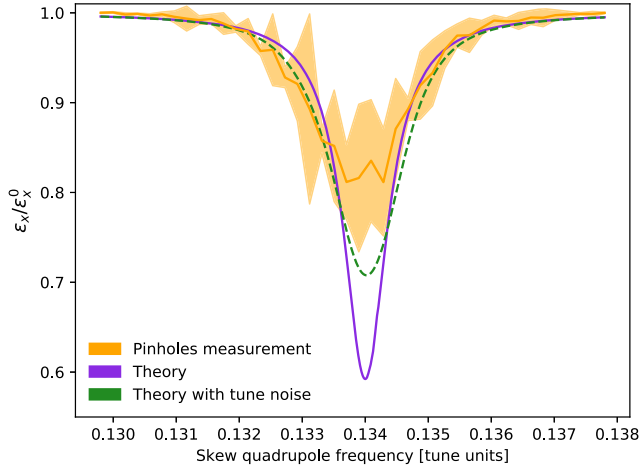


FIG. 14. Coupling evolution measured with the two pinhole cameras while scanning the stripline frequency around the resonant condition $Q_x - Q_y$. The measurement was carried out with the modified stripline, an amplitude of 1 kV peak-to-peak and high beta functions.

resonant condition. To this end, a phase-locked loop (PLL) can be used to track real time the tunes [20], provided a sufficient bandwidth in the PLL feedback loop, the PLL oscillator creates a reference signal which follows faithfully the machine tune.

To test this approach, the horizontal and vertical bunch-by-bunch feedback systems currently in use in ALBA [21] were reconfigured to work as PLL (Fig. 15). This system is a commercial unit made by instrumentation technologies [22] with a heavily modified firmware developed at Diamond [23]. The horizontal and vertical tune reference signals were obtained by tapping directly into the output of the two PLL, and were fed to an analog multiplier followed by a low pass filter to generate a signal with frequency equal to the difference of the tunes, and therefore suitable to drive the stripline. The stripline power amplifiers or the very same high voltage amplifier previously described were used to boost the signal and drive the stripline up to 1 kV peak-to-peak.

The PLL was tuned to achieve a stable lock while producing a small excitation of the betatron motion of around $1 \mu\text{m}$, better tuning of the PLL could provide similar performance with even smaller beam excitation, but for the sake of simplicity and the limited amount of time available for testing, it was chosen to work in this condition. The PLLs were locked onto the harmonic 20 of the tune frequency instead of the fundamental, the choice of a harmonic allows us to derive correctly the signal required to drive the stripline and at the same time makes the system immune to the strong perturbation at the tune frequency produced when firing the injection kickers.

Since the setup did not allow us to drive the stripline other than at the frequency equal to the difference of the tunes, all the measurements were acquired on the resonance

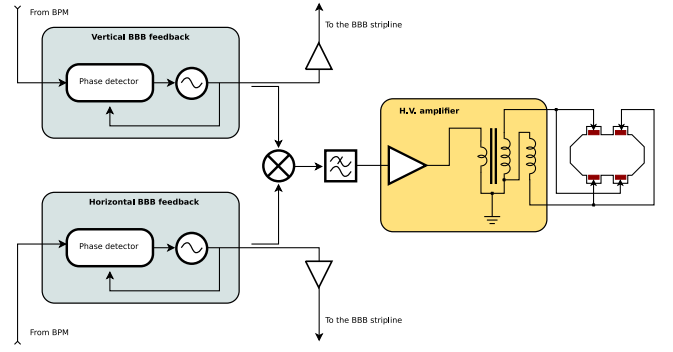


FIG. 15. Horizontal and vertical bunch-by-bunch feedback systems have been reconfigured to run as a PLL locked onto a harmonic of the tune frequency. Part of the tune excitation signals coming from the bunch-by-bunch is diverted and sent to an analog multiplier to produce a difference, which in turn is used to drive the skew quadrupolar stripline through the very same high voltage amplifier described in the previous section.

($\Delta = 0$). Figure 16 shows the distribution of the coupling measured with the pinholes during roughly 250 acquisitions. The measurement is repeated for four different amplitudes of the stripline field. A fifth measurement with a fixed excitation frequency (no PLL) is also shown for comparison. The improvement in terms of emittance stability due to the ability of the PLL to track the tunes and thus maintain the resonant condition for various stripline excitation strengths is resumed in Table III. At the maximum excitation, which corresponds to an emittance ratio of 69% an rms emittance fluctuation of only 0.24% is observed.

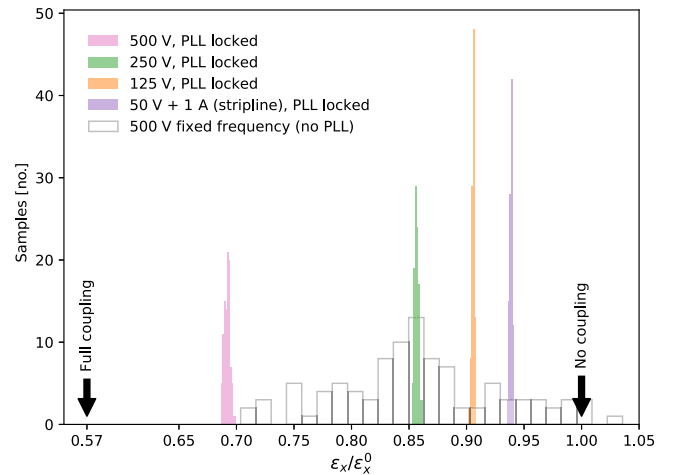


FIG. 16. Distributions of the betatron coupling measured roughly 250 times with the two pinhole cameras. The measurement is repeated for three different strengths of the stripline field. For comparison, the measurement at maximum field strength is repeated with fixed frequency excitation (no PLL). The remarkable improvement in terms of stability due to the tune tracking is quantified by the standard deviation of each distribution shown in the legend.

TABLE III. Results summary for the four measurements carried out with the PLL system. In the first measurement, the excitation was obtained terminating the stripline on a 50 Ω load, while in the other three the high voltage amplifier was used. For each measurement, the average measured and theoretical values for ϵ_x/ϵ_x^0 are given together with the rms fluctuation.

Excitation	C	ϵ_x/ϵ_x^0 theory	ϵ_x/ϵ_x^0 measured	ϵ_y/ϵ_x extrapolated
50 V + 1 A	6.0×10^{-5}	0.94	$0.94 \pm 1.1 \times 10^{-3}$	0.090
125 V	7.4×10^{-5}	0.91	$0.91 \pm 1.2 \times 10^{-3}$	0.13
250 V	1.5×10^{-4}	0.78	$0.86 \pm 1.9 \times 10^{-3}$	0.21
500 V	3.0×10^{-4}	0.65	$0.69 \pm 2.4 \times 10^{-3}$	0.61

IX. CONCLUSIONS

Experimental work has been carried out in the ALBA storage ring investigating different methods to introduce strong betatron coupling with particular attention to compatibility with operation. Tuning the optics to the $Q_x = Q_y$ resonance allowed us to drive easily the beam into full coupling, relying just on the coupling error naturally present on the machine. Quadrupolar skew correctors were then used to investigate a configuration of stronger and weaker coupling. Even though at first this approach appeared simple and viable, not requiring special hardware other than what was already present in a storage ring, it was quickly realized that some kind of tune feedback would be required in order to counteract the unavoidable tune drifts present in operation due to insertion device motion. Furthermore, the added burden due to the constraint on the working point and the complexity related to coupling error control and correction made this approach less attractive. Nevertheless, these experiments allowed us to investigate the dynamics of the injection process in the presence of strong coupling. In particular, it was shown that detuning with amplitude can be an effective strategy to avoid the large horizontal oscillation of the injected beam to be transferred to the vertical plane, where the narrow aperture imposed by the insertion devices could result in unacceptable injection losses.

A second method, based on the use of an alternating skew quadrupolar field tuned at the frequency, $f_{\text{rev}}(Q_x - Q_y)$ was investigated. This solution solves the previously mentioned issues, in fact, no particular constraint on the working point is required anymore and the design of a feedback system is simplified by requiring the tuning of a single parameter: the skew quadrupole field frequency instead of a global tune feedback. Using the existing stripline originally designed for tune excitation, it was possible to achieve a substantial field strength but still smaller compared to what was previously observed in the experiments carried out with static skew correctors. In this regime, the small tune jitter due to the noise in the storage ring quadrupole circuit was enough to pull the system out of the weak coupling resonance resulting

in a fluctuating beam size. Finally, stable excitation was achieved when a PLL tune tracking system was used to keep the system in resonance despite the tune fluctuations and the small skew quadrupolar field of the stripline. Furthermore, it was demonstrated how by modulating the coupling strength while keeping the system on resonance thanks to the PLL system, it is possible to control the emittance diffusion rate from the horizontal to the vertical plane allowing us to control precisely the vertical beam size.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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