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AC EXCITATION STUDIES FOR FULL COUPLING OPERATION

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Abstract

Betatron coupling resonance has been considered by many low emittance upgrade light sources as a candidate to produce round beams. Due to the limited literature on the topic, last year an experimental campaign was undertaken on the ALBA storage ring to establish limits and requirements to operate a light source in full coupling. The work highlighted how coupling can indeed produce a round beam with certain easiness but not free from shortcomings: the fractional betatron tunes must be set equal, resulting in a substantial constraint to the optics and requiring a sophisticated control of the optics itself in order to keep the resonance condition despite the movement of insertion devices and drifts. To work around these limitations, this year a different approach, based on the excitation of the coupling resonance with an A.C. skew quadrupole was tested. A first experiment was attempted by converting the existing tune excitation stripline into a skew quadrupole, but the limited available power allowed to produce only a barely perceptible coupling. The stripline was then turned into an electric deflector by removing the resistive terminations and allowing to drive the electrodes to higher voltage. Here the newly obtained results with the A.C excitation are presented.

INTRODUCTION

Full coupling can be easily achieved by selecting a working point which satisfy the resonant condition $Q_x = Q_y$ and with a minimal tuning of the skew quadrupole magnets as demonstrated in [1]. On the other hand fulfilling the resonant condition imposes a strong limitation in terms of optics flexibility. Furthermore an active feedback over the quadrupoles current would be required to ensure that the resonant condition is maintained despite the unavoidable optics drifts induced by the motion of insertion devices, as required by the experimental needs of beamlines. The added layer of complexity introduced by this approach encouraged the search of a different mechanism to produce coupling more suitable for operation. As described in [2, 3] the same resonant condition can be achieved in a lattice with $Q_x \neq Q_y$, when a skew quadrupole field (the coupling source) is pulsed at a frequency $Q_x - Q_y$ (230kHz in the case of ALBA nominal working point). Even though this solution requires some sort of dedicated A.C. skew quadrupole such as a stripline or a magnetic shaker, it gives complete freedom regarding the choice of the working point. Furthermore the intrinsic wide bandwidth nature of such devices simplify greatly the implementation of a fast feedback. Before embarking in the time consuming design of a dedicated A.C. skew quadrupole, it was decided to carry out a first round of experiments relying solely on the existing hardware installed in the ALBA storage ring, 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 A.C. skew quadrupolar field is the tune excitation stripline. By changing the cabling that connects the four stripline's electrodes to the power amplifiers, it was in fact possible to turn the stripline field from dipolar to skew quadrupolar. Encouraging results were gathered during a first test in 2022 using this setup [1]. 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, as shown in Fig. 1, the maximum achieved coupling was limited to ≃ 5%, far from the ≃ 90% observed in previous experiments carried out using skew quadrupolar magnets and tuning the lattice to $Q_x = Q_y$. Note that while in the previous work the coupling was inferred from the ratio of the vertical to the horizontal emittance, here it is inferred by normalizing the horizontal emittance by a reference measurement acquired far away from the coupling resonance, virtually in absence of coupling. This quantity is 1 in absence of coupling and drops to a minimum when full coupling is reached. The exact minimum value is 0.5 in the case of an optics with equal transverse damping times, while for ALBA is 0.56. This change in the measuring technique was made necessary by the need to run experiments with substantially different optics. By inferring the coupling from the ratio of two measurement of the horizontal beamsize, an accurate model of the optics function at the pinhole is not required eliminating a source of systematic errors. Furthermore the pinholes camera installed in the ALBA ring struggle measuring the huge vertical beamsize produced by the coupling resonance.

EFFECTS OF TUNE NOISE

The disappointing results obtained from the previously discussed simple stripline setup can be explained as a result

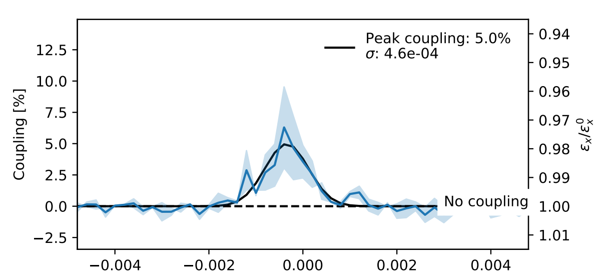

Figure 1: Coupling measurement carried out in 2022 at ALBA using using a skew quadrupolar stripline pulsed at the frequency $Q_x - Q_y$.

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of the interplay of coupling resonance and machine stability. For a complete discussion of betatron coupling theory we suggest to refer to [4], here instead we restrict our attention to the resonance width produced by a single coupling source (i.e. a single A.C. skew quadrupole) which can be expressed as:

$$\Delta C = \frac{|K_s|}{2\pi}\sqrt{\beta_x \cdot \beta_y} \quad (1)$$

where β_x and β_y are the betatron amplitudes at the source and K_s is the source strength. A substantial emittance exchange is observed only as long as $|Q_x - Q_y| << \Delta C$, which in the case of the ALBA stripline provides $\Delta C \simeq 8.5 \cdot 10^{-5}$. Many minor effects can produce a comparable tune shift, therefore a substantial reduction of the observed coupling is unavoidable. It is known that the tune stability in the ALBA storage ring is dominated by quadrupoles power supplies noise, previous studies [5] allowed to accurately assess the overall rms tune fluctuation to $\Delta Q_x = 2.3 \cdot 10^{-4}$ and $\Delta Q_y = 1.0 \cdot 10^{-4}$. To make things worse, the stated noise fluctuations are anti-correlated, therefore the tunes difference fluctuates with an amplitude equal to the sum of the two contributions. While a purposely designed magnetic shaker could easily provide the required field to excite a wide enough resonance dominating over the above mentioned tune fluctuations, at this stage of the study we prefer to rely only on the hardware already present in the storage ring. To increase the resonance width two paths are possible:

1. Increase the stripline field K_s
2. Manipulate the optics to increase $\sqrt{\beta_x \cdot \beta_y}$

FROM STRIPLINE TO ELECTROSTATIC 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 his output port terminated on an impedance equal to the stripline characteristic impedance. When power is applied to the input port, a current flows is established across the stripline's electrodes and the resulting magnetic and electric fields produce an equal kick onto the beam. The power which flow from the amplifier through the stripline is finally dissipated in the termination impedance (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, 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 to drive the stripline as an electrostatic deflector. In this configuration the electrodes behave as a 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 on purpose (Fig. 2). A 50 W linear amplifier is followed by a step up transformer with two independent secondary windings drive counter phase the stripline electrodes. To keep the stray capacitances to a minimum, short leads are used to connect the transformer output to the electrodes and particular care is required to minimize the transformer winding to winding capacitance (Fig. 3). The new system allows to reach the maximum stripline operating voltage of 1 kV peak-to-peak at the required frequency of 230 kHz providing a kick 5 times stronger than what was obtained with the previous setup operating at 200 W. A similar result could be obtained by driving the stripline electrodes as a magnet (swapping the dummy loads for a short circuit). 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 electrostatic deflector configuration. Experiments are carried out following the same procedure used previously, the frequency of the stripline is scanned around the resonance $Q_x - Q_y$ while the horizontal and vertical emittances are measured using the two independent pinhole cameras installed in the storage ring. Figure 4 shows the

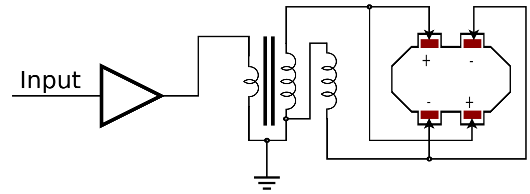

Figure 2: The signal from a function generator is fed to the 50W power amplifier which drives the high voltage transformer. Two independent secondaries provide the required polarities for the striplines electrodes.

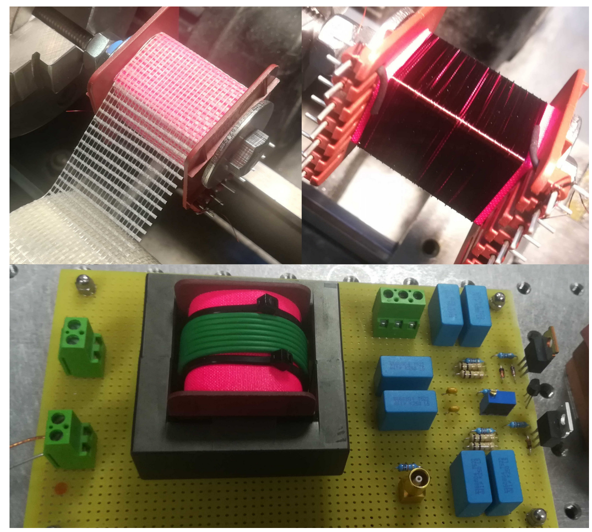

Figure 3: A high voltage transformer was prepared on purpose, the two secondaries windinds (top right) are interleaved with fiberglass mesh (top left) to reduce inter-winding capacitance and minimize the required driving power. The bottom picture shows the complete transformer together with the power amplifier.

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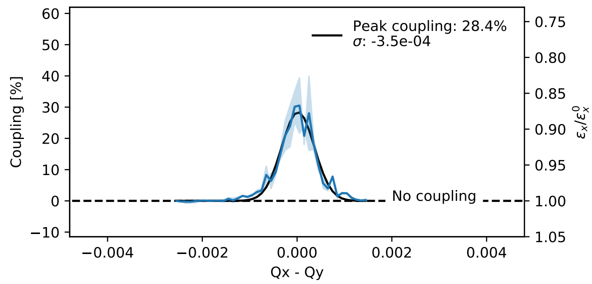

Figure 4: Coupling evolution measured with the two pinhole cameras while scanning the stripline frequency around the resonant condition $Q_x - Q_y$. The measurement was carried out with the modified stripline, an amplitude of 1kV peak-to-peak and standard beta functions.

result of the scan carried out with an excitation strength of 1kV 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.

HIGH BETA OPTICS

In the previous section it was discussed how the stripline field was increased up to the maximum design limit, a stronger field could result in permanent damage to the hardware. The only way left to enhance the effect of the stripline requires to act on the optics. A special lattice with double beta functions at the stripline position was commissioned (Fig. 5). With the new optics the term $\sqrt{\beta_x \cdot \beta_y}$ from Eq. (1)

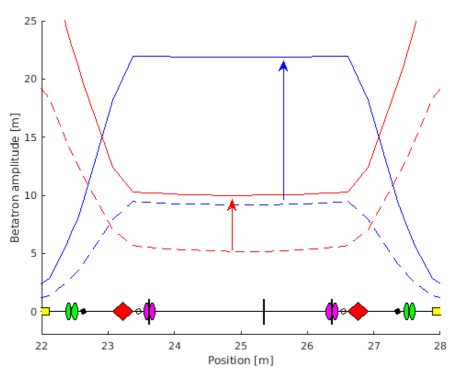

Figure 5: Horizontal (blue) and vertical (red) betatron amplitudes at the stripline location, for the nominal optics (dashed lines) and the special optics tuned to enhance the stripline kick (solid lines). By changing the betas the factor $\sqrt{\beta_x \cdot \beta_y}$ is increased from 6.9 m to 14.8 m.

is increased by a factor 2.1, therefore a similar increase in the coupling resonance strength is expected. An even more aggressive optics with higher value of the betatron amplitudes was considered at first, however the difficulties encountered during the lattice commissioning process made us desist from the attempt. Measurements are carried out following exactly the same process discussed previously. Figure 6

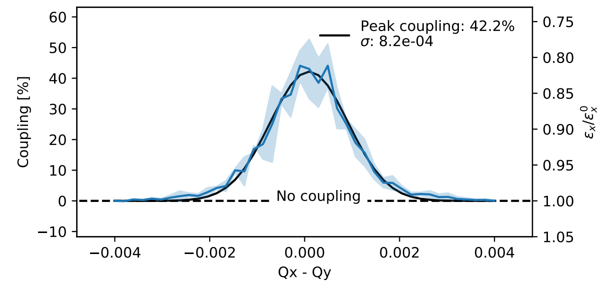

Figure 6: Coupling evolution measured with the two pinhole cameras scanning the stripline frequency around the resonant condition $Q_x - Q_y$. The measurement was carried out with the modified stripline, an amplitude of 1kV peak-to-peak and high beta functions.

shows the result of the scan obtained with the new optics and a stripline excitation amplitude of 1kV 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.

CONCLUSIONS

In view of the ALBA upgrade [6] it was decided to study the use of coupling as a mean to increase lifetime while keeping transverse emittance to a competitive level. The lack of practical experience urged to start an experimentation campaign. Several tests were carried out, first with a more traditional approach based on static skew quadrupolar magnets and by tuning the working point onto the resonance $Q_x = Q_y$, and lately employing a pulsed skew quadrupolar field tuned at the frequency $Q_x - Q_y$. This last method was strongly preferred due to the lack of any special requirements on the working point. To minimize the impact on machine operation it was decided to rely solely on the installed hardware, restricting the experimentation to the use of a short stripline originally designed for tune excitation purposes. The suboptimal design of the stripline limited drastically the maximum skew quadrupolar field that could be produced, and forced us to explore different directions in order to achieve stronger coupling. In the first experiments only a small hint of coupling was visible, later after reconfiguring the stripline as an electrostatic deflector and by using a purposely matched high betas optics it was possible to raise the coupling above 40%. The collected results line up well with theory and provide a solid ground to start the design of an optimal solution for the ALBA upgrade program.

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