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ENERGY LOSS MEASUREMENTS WITH STREAK CAMERA AT ALBA

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Abstract

Analyzing streak camera images of the beam injected into a Storage Ring with no RF voltage allows calculating several parameters, like the energy loss per turn and the energy mismatch between injected and stored beams. These measurements are based on the analysis of the centroid drift path of a bunch as it spirals inwards, changing its rotation period. This drift is clear and measurable in single and multi-bunch modes in several horizontal sweep speeds of the streak. With this technique we also measure the momentum compaction factor and observe its change with respect to the insertion devices' open/closed states. The obtained values are comparable with theoretical expectations, as well as with values measured by other means.

INTRODUCTION

Since its commissioning in 2011 the beam diagnostics beamline at ALBA is using the visible part of the synchrotron radiation for dedicated longitudinal studies of the Storage Ring (SR) beam. Among the tools on the optical table is the Optronis SC-10 streak camera (SC), whose details can be checked at Refs. [1,2]. In short, the SC uses two sweep units to distinguish the bunches spaced by 2 ns: the fast (vertical) unit with the synchroscan frequency of 250 MHz at different amplitudes, allowing deflection speeds of 15, 25 and 50 ps/mm (equivalent to full scales of 215, 360 and 720 ps respectively), and the slow (horizontal) unit at some trigger frequency allowing sweep speeds from 660 ps to 5 ms/mm (equivalent to full scales of 9 ns and 72ms respectively). For a proper visualization of the beam bunch, the slow sweep unit is synchronized with both the SR revolution frequency and the injection repetition rate of 3 Hz.

Measurements to characterize the bunch length and the longitudinal beam dynamics at ALBA are shown in Ref. [2], where a proper injection phase and energy matching is performed between the Booster (Bo) and the SR and how to measure it with the RF system on.

In this work we study the dynamics of a bunched beam which is injected into a machine with its RF system off. The beam revolution period changes and it starts to spiral inwards until it is eventually lost. This was described in Ref. [3] for a beam, whose injected energy was exactly the same as the equilibrium energy of the SR. In our case, we consider the possibility to have a small Bo to SR energy offset, and show that it still is possible to calculate the energy loss per turn and the energy mismatch, having the SR RF system off. Furthermore, provided that the energy loss per turn is inferred with other means, we also show how this method can be used to measure the momentum compaction factor.

For reference, we list the main parameters of the longitudinal plane of the ALBA SR in Table 1.

Table 1: Machine parameters of the ALBA Storage Ring. The energy loss per turn below corresponds to losses only due to synchrotron radiation produced by the dipoles.

beam energy, GeV	2.979
bunch spacing, ns	2
RF frequency, MHz	500
revolution time, ns	896
energy spread, %	0.105
momentum compaction factor	$0.88{\cdot}10^{-3}$
energy loss/turn, keV	990
RF voltage, MV	[2.1 - 3.1]
bunch length, σ_z	[21 - 17] ps

INJECTION MATCHING WITH RF ON

Studies with the streak camera allow to match the injection process longitudinally. First, we overview the RF phase match between the Bo and the SR, and secondly, the energy match.

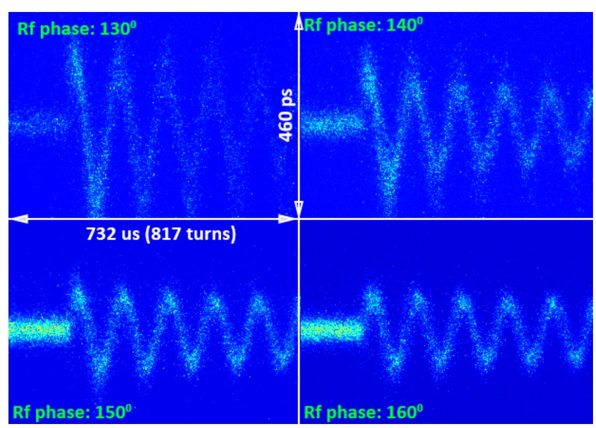

Figure 1: Injection oscillations as seen by the SC for various RF phase mismatch of the Bo and the SR.

RF Phase Matching

Despite some phase and energy mismatch between the injected and stored beam, the injected bunch eventually gets damped to the proper synchronous phase and its natural bunch length. The injection RF phase match can be checked by looking at the injection time interval with the SC, which requires a precise work with the timing and SC triggers.

Injection into the ALBA SR uses a conventional local injection bump with four dipole kickers [4]. For our studies, the best way to properly visualize this injection process is to delay kicker-1 trigger such that the Bo beam is injected but not accumulated.

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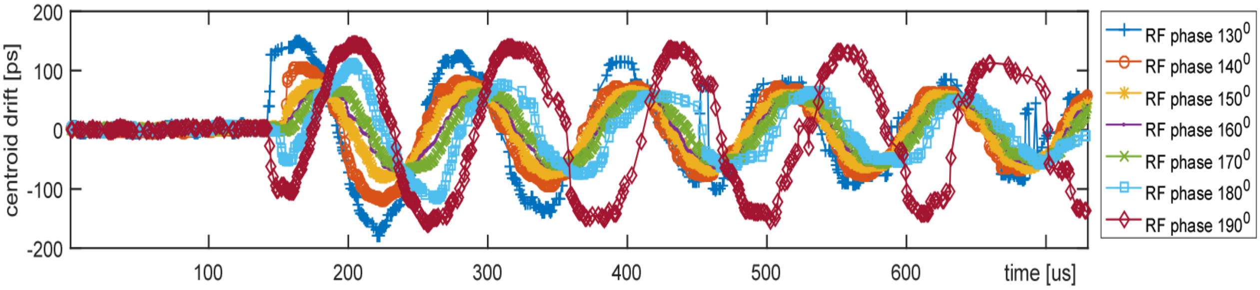

Figure 2: Longitudinal centroid oscillations of a bunch during an injection from Bo to SR with various RF phase mismatch.

Once this timing is set-up, the RF phase is clearly seen with the SC. Figure 1 shows the injection moments observed by the SC for different Bo RF phases. On each of the four images, the horizontal time axis goes from left to right, such that the first ~150 µs correspond to the stored beam circulating in the SR; then an injection occurs and the injected beam starts oscillating. On both top images we can observe two indications of higher RF phase mismatch between the Bo and the SR: the oscillations start with an offset from the stored beam position, and high oscillation amplitudes. On both bottom images the difference in phase is not evident but can be quantitatively measured it using image analysis.

Figure 2 shows tracking of the centroid motion from the different image analysis shown in Fig. 1. The injection phase match can be measured here in two different ways: one is from the maximum amplitude of the oscillations, the second is from the position at which the oscillations start. In both cases the proper RF phase match is found when the Bo RF phase is 160^0.

Energy Offset

Once the injection RF phase has been properly matched, the second step consists of analyzing the energy offset between the Bo and the SR. In stable machine configuration small energy differences between beams in both rings are eventually damped shortly after injection, and the injected beam is stabilized into the equilibrium energy.

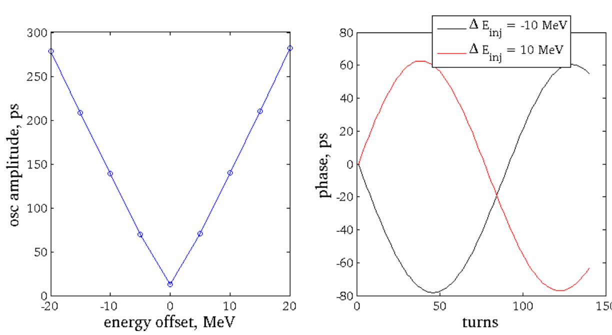

Figure 3: Left: phase mismatch (in ps) for different energy offsets between the Bo and the SR. Right: phase oscillations for energy offset of +10 (black) and -10 MeV (red).

Nevertheless, for a proper phase match, the energy offset can be inferred from the comparison between the injected beam oscillations produced during the energy damping captured with the SC, and the ones obtained from solving the longitudinal phase/energy equations of motion, which have been performed using the Matlab Accelerator Toolbox (AT).

Figure 3 (left) shows the theoretical maximum phase oscillations for different energy offsets when the Bo and SR phases are properly matched; the right plot shows the oscillations if this offset is positive or negative (first oscillation towards positive or negative phases). In case of ALBA these oscillations have an amplitude of 120 ps and they first go towards positive values. We conclude that the energy offset in this case is +10 MeV. Note that proper care should be taken to properly identify the sign, since the SC image visualization depends on the relative phases.

INJECTION WITH RF OFF

When an electron beam enters an accelerator where the RF system is turned off, the beam starts to lose energy at every turn and spiral inwards until it eventually gets lost. Its revolution time τ changes with time t according to the relation:

$$\frac{d\tau}{dt} = \frac{\Delta T}{T_0}, \tag{1}$$

where T_0 is the revolution time for beam at nominal energy E_0. The right part in Eq. (1) can be expressed as a function of energy following the expression:

$$\frac{\Delta T}{T_0} = \alpha \frac{\Delta E}{E_0}, \tag{2}$$

where α is the momentum compaction factor and $\Delta E = E - E_0$. Considering that the beam enters into SR with the energy $E_0 + \Delta E_{inj}$, and that every turn it loses the energy U_0, its energy at turn n can be expressed as:

$$E = E_0 + \Delta E_{inj} - nU_0 . \tag{3}$$

Using $n = t/T_0$, Eqs. (1) and (2) can be combined as:

$$\frac{d\tau}{dt} = \frac{\alpha \Delta E_{inj}}{E_0} - \frac{t}{T_0}\frac{\alpha U_0}{E_0} . \tag{4}$$

Integrating both sides of Eq. (4) leads to an analytical expression that describes how the revolution period τ changes with time:

$$\tau = \tau_0 + \frac{\alpha \Delta E_{inj}}{E_0} t - \frac{\alpha U_0}{2E_0 T_0} t^2 . \tag{5}$$

Note that this expression is basically the same as in [3], but also includes a linear term proportional to ΔE_{inj}. As

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an example, Fig. 4 shows parabolas described by bunches injected into the ALBA SR with energies equal to corresponding equilibrium energies of E_0 and with fixed offset of $\Delta E_{\mathrm{inj}} = \pm 20$ MeV. The data comes from simulation using the Matlab AT.

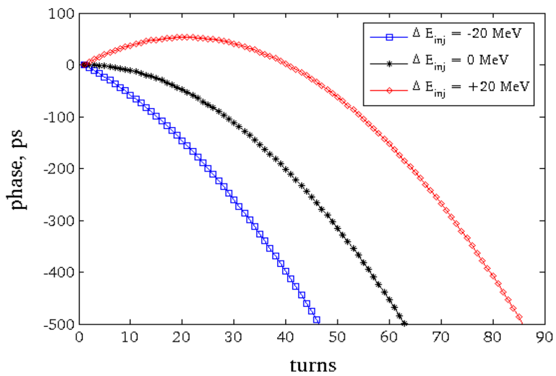

Figure 4: Simulation: bunch phase tracking after injection into SR with RF off for different beam energies.

These simulations show that when the beam is injected with an energy slightly larger than E_0, it first tends to go towards its new equilibrium orbit, which is seen as if the phase actually increases (parabola goes up). Few turns later it reaches a maximum in its phase, and then it spirals inwards (parabola goes down) until it gets lost. This is described by Eq. (5), from which it can be proved that the time τ_1 at which this maximum occurs is:

$$\tau_1 = \frac{\Delta E_{\mathrm{inj}}}{U_0} \cdot T_0 \quad . \tag{6}$$

Note that both Eqs. (5) and (6) give both U_0 and ΔE_{inj}, provided that the beam energy E_0 and the momentum compaction factor α are precisely known.

Energy Offset and Energy Loss per Turn

An experimental evidence is shown in Fig. 5, corresponding to an injection with RF off and with all SR Insertion Devices (IDs) open. The left and right images correspond to the SC at sweep speeds of 5 µs/mm and 10 µs/mm respectively. The yellow line following the streak trace corresponds to a fit using Eq. (5) to the centroid motion. From this analysis, we find that this corresponds to an energy loss of U_0=1.03 MeV (in good agreement with the theoretical values from Table 1), and an injection offset of ΔE_{inj}=18.3 MeV. This is larger than the values found in the previous section (with RF system on), but it should be mentioned that the two measurements are spaced by 8 months, so the machine conditions were certainly different.

Note that, compared with the measurements of the energy offset with RF system on, this method has the advantage that only one fitting provides both U_0 and ΔE_{inj} without the need to rely on additional simulations.

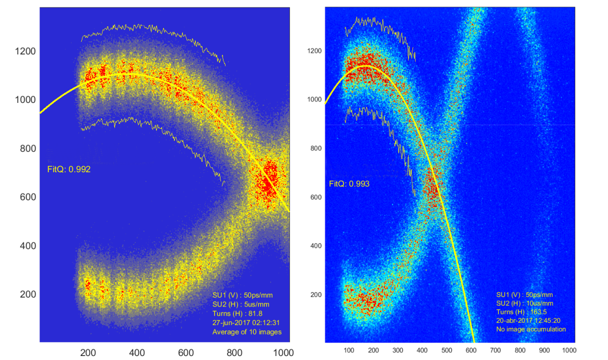

Figure 5: Streak camera acquisition of injection into ALBA SR in multi-bunch mode with RF off and IDs open. Horizontal sweep speeds of SC are 5 (left) and 10 us/mm (right).

Energy Loss for Different Configurations of Insertion Devices

To estimate the precision of this method to calculate the energy loss per turn, the above example has been further tested for different configurations of the IDs, thereby changing the energy loss per turn. Figure 6 shows parabolas, described by beam centroid drifts for three different configurations of the IDs at ALBA:

- IDs closed, SCW on (blue trace, and U_0=1.09 MeV)
- IDs open, SCW on (red trace, U_0=1.07 MeV)
- IDs open, SCW off (green trace, U_0=1.03 MeV)

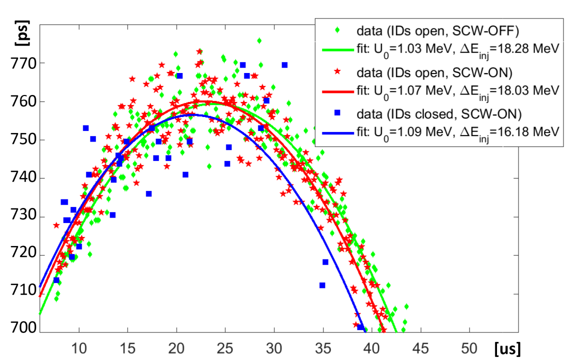

Figure 6: Measurement: Beam spiraling inwards after injection while RF system off, with IDs open, closed, and SCW on/off.

The results agree with theoretical predictions, and we can conclude that we are able to distinguish the losses down to 20 keV/turn. Nevertheless, the calculations are noisy because the SNR for low charge beams is not so good, and not all shots from the injector carry the same charge. As a consequence, we acquire around 10-20 shots for each case, but some of them need to be discarded to reduce bad data.

In order to calibrate this method to calculate the energy loss per turn, we compare the results in Fig. 6 with the ones obtained using the shift of the RF phase and with the theoretical calculations. When the energy loss per turn increases, the RF phase decreases to compensate the loss of energy due to longitudinal focusing. Therefore, by measuring the

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RF voltage and the corresponding phase shift, we can infer the energy loss per turn with precision [5]. The method is consistent with the RF measurements if we consider an error bar of 10 keV/turn, as seen in Fig. 7.

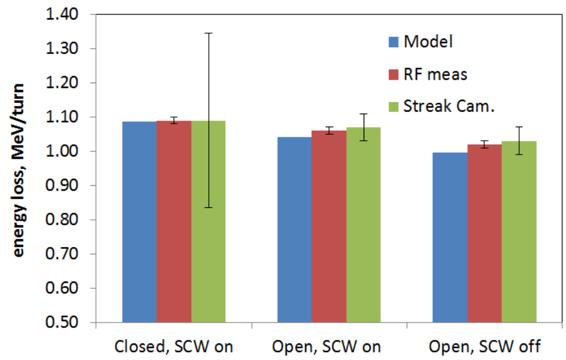

Figure 7: Comparison of the energy loss per turn in three different IDs configurations at ALBA.

CALCULATION OF MOMENTUM COMPACTION FACTOR

For the case shown in Fig. 5, calculation of the energy loss per turn assumes the theoretical value of momentum compaction factor α, shown in Table 1. Nevertheless, provided that the energy loss per turn is inferred by other means, the formalism shown in the previous section can be applied to calculate the momentum compaction factor as well.

For instance, we can calculate the energy loss per turn using the RF phase measurements, as shown in Fig. 7. This provides then a tool to infer the momentum compaction factor by leaving ΔE_{inj} and α as free parameters in Eq. (5). Moreover, since this fitting can be done for different status of the IDs, the error bar is further reduced.

Table 2: Momentum compaction factor values for different IDs states at ALBA. U_0 is inferred from RF measurements. On average, $\alpha = 0.894 \times 10^{-3}$.

IDs status	**U_0, MeV**	**$\alpha \times 10^3$**
Closed, SCW on	1.09	0.8904
Open, SCW on	1.07	0.8957
Open, SCW off	1.03	0.8952

In this case, Table 2 shows results obtained from the three cases described in Fig. 6, from where we conclude that $\alpha = 0.894 \times 10^{-3} \pm 10\%$ is in good agreement with the theoretical value from Table 1. The error bar stems from the uncertainty in the fit parameters from Fig. 6 correspond to the standard deviation between the three cases.

In order to estimate the reliability of this value, we compare it with the one calculated from the relation between the bunch length σ_z (measured by SC) and the synchrotron tune Q_s (provided by the bunch-by-bunch system):

$$\sigma_z = \frac{\alpha}{2\pi Q_s f_0} \Delta E / E \,, \tag{7}$$

where f_0 is the revolution frequency and $\Delta E/E$ is the beam energy spread (assumed the theoretical one).

Measurements for three different beam intensities at 60, 120 and 180 mA are shown in Fig. 8, where the data is linearly fit with no independent term; the momentum compaction factor measured for beam intensity is shown in the plot. On average $\alpha = 0.85\times10^{-3} \pm 2\%$, which is very similar to the value obtained with the streak camera.

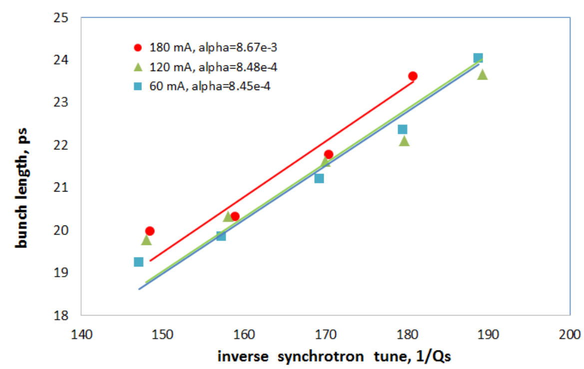

Figure 8: Bunch length measurements at 60, 120 and 180 mA while changing the RF voltage and so varying Q_s.

CONCLUSIONS

This work studies the change in the revolution time of a beam injected into the Storage Ring with the RF system off. By analyzing the motion of a beam with the streak camera, we prove that it is possible to measure both the energy loss per turn and the energy offset between the injected beam and the equilibrium energy of the Storage Ring. Furthermore, combining this method with other techniques, we have inferred the momentum compaction factor with good accuracy.

The precision of the results shown in this report is about 10%, and its limitations are related with injection jitters and low SNR of the streak images (produced by low charge beams). Nevertheless, these results are in good agreement with the ones derived by other means.

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