STREAK CAMERA MEASUREMENTS AT ALBA: BUNCH LENGTH AND ENERGY MATCHING

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Abstract

This report describes the electron beam longitudinal studies performed at ALBA Storage Ring using the streak camera. We first show the usual studies involving precise bunch length measurements and related beam parameters like energy spread. Next, the studies to match the injected beam in energy and phase are reported and compared with simulations.

INTRODUCTION

Since the beginning of the ALBA Storage Ring commissioning in March 2011, a beam diagnostics beamline (BL34) is operational. It uses the visible part of the synchrotron radiation and is mainly devoted for longitudinal beam studies using the Streak Camera (SC), an Optronis SC-10 model, with synchroscan frequency working at 250 MHz to distinguish the beam bunches spaced by 2 ns.

The SC converts the incoming photons into electrons, which are swept to transpose its longitudinal (time) structure into a transverse footprint. The sweeps are performed by a fast and a slow unit. We always use the fast sweep in the "synchroscan mode", which sweeps continuously a sinusoidal field of 250 MHz at different amplitudes, allowing sweep speeds of 15, 25 and 50 ps/mm. The slow unit provides sweep speeds from 660 ps to 5 ms/mm, triggered usually at 50 Hz and synchronized with both the storage ring (SR) revolution frequency and the injection repetition rate (3 Hz). The working principles of SC are thoroughly explained in Ref. [1].

Table 1: ALBA Storage Ring Main Parameters

Parameter	Value
energy, E [GeV]	3.0
hor emittance, ϵ_x [nm-rad]	4.6
revolution time, T [ns]	896
harmonic number, h	448
rf freq., $f_{\rm rf}$ [MHz]	499.6
dipole field, B [T]	1.42
synchrotron freq., f_s[kHz]	6.5
rf voltage (max), V[MV]	3.6

In this report, we first describe the SC characterization and its sweep speed calibration. Next, the bunch length measurements of the stored beam are reported including the energy spread measurements. Finally, we show measurements of the injected beam, including booster bunch length and longitudinal damping time. Table 1 lists the ALBA Storage Ring (SR) parameters relevant for these studies.

EXPERIMENTAL SET-UP

The light used at BL34 is extracted from the first bending after the injection section. At 8.5 m from the source, we locate an in-vacuum mirror (VMIR) whose purpose is to reflect only the visible part of the synchrotron radiation spectrum. We do so by moving up the mirror (to about 2 mrad), and so avoiding the x-ray part of the spectrum circulating in the orbit plane – see Fig. 1. The light is then directed perpendicular towards the other side of the shielding wall, already in atmospheric pressure. At this point (and at 9 m from the source), we locate a 4m lens in order to focalize the light into the experimental set-up. Next, 6 conventional mirrors direct the light through the shielding wall performing a vertical chicane to prevent radiation outside the SR tunnel. Finally, the light arrives to the experimental setup in BL34. The light optical path and optical elements are shown in Fig. 2, and more details are explained in Ref. [2].

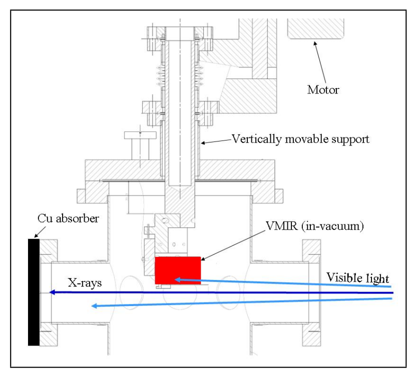

Figure 1: Sketch of the in-vacuum mirror (VMIR) and holder. The mirror is kept up around 2 mrad to avoid the x-ray part of the synchrotron radiation. The mirror is equipped with 3 thermocouples (not shown in the sketch) to prevent damages induced by possible overheating.

STREAK CAMERA CHARACTERIZATION

The "synchroscan sweep" is a sinusoidal electric field of 250MHz whose amplitude is varied to allow three different deflection speeds: 15, 25, and 50 ps/mm. The sweep is synchronized with the machine rf system working at 500 MHz. In order to crosscheck the linearity of these sweeps, we compared the bunch phase wrt sweep phase controlled by the SC. While the non-linearity is negligible for the 15 and 25 ps/mm speeds, this is not the case for the slowest vertical sweep: 50ps/mm (see Fig. 3). The total range swept with this speed corresponds to 990ps, which for the 250 MHz

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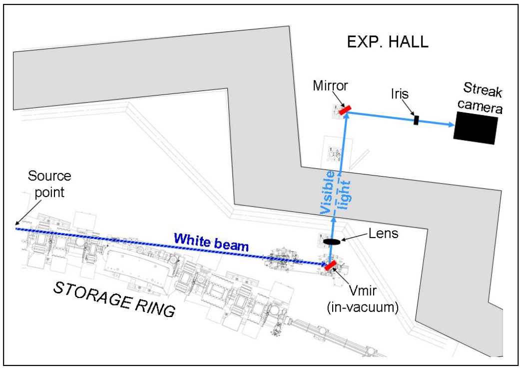

Figure 2: Optical path from the source point to the SC. Note the position of the lens (f =4 m), and the iris, that limits the incoming light aperture at the SC.

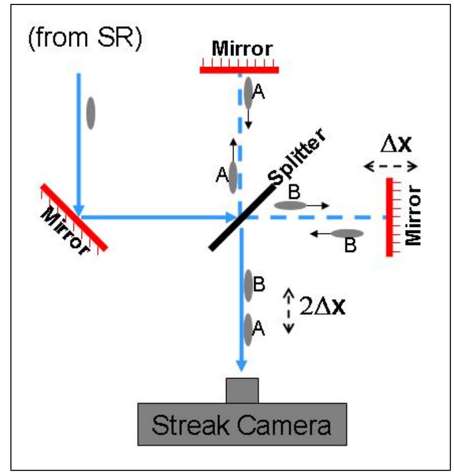

Figure 4: Calibration set-up.

synchroscan frequency corresponds to about $\pm 22^o$ in phase. In order to guarantee the linearity along the whole ramp, a multi-linear calibration is applied.

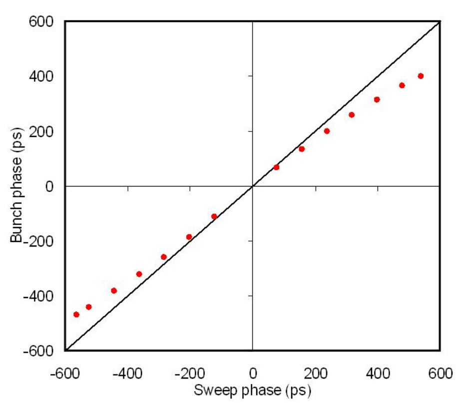

Figure 3: Linearity using the 50ps/mm sweep speed.

We also crosscheck the manufacturer time-to-space conversion factor, for which we prepared the calibration set-up shown in Fig. 4. The synchrotron light arrives at an optical splitter that divides the light into two pulses A and B going in two perpendicular branches of (initially) the same length. Each of these pulses finds a full mirror that reflects the light and sends it back to the splitter, where they are merged together and sent to the SC. By moving one of the mirrors a distance Δx from the initial length, we can see the two pulses in the SC separated by a distance $2 \cdot \Delta x$. The distance Δx is controlled with a precise micrometer, and then crosschecked with the SC result.

Because the SC frequency is 250 MHz, we sweep the odd bunches using the upward part of the sinewave (at 0^o phase), and the even bunches with the downward (at 180^o). This is why the SC images show the odd bunches in the upper half image, and the even bunches in the bottom. The image of the calibration method is shown in Fig. 5. The distance between lobes Δx is obtained by inferring the centroids distance for both even and odd bunches. We consider an experimental error bar of about 1% in the centroids measurement. The result shows that 1 mm at the optical table corresponds to 3.67 ps ±6%, which is about 10% larger than the one corresponding to the speed of light (3.33 ps). This is about a 10% larger than the theoretical value, but still acceptable if we consider the experimental error bars.

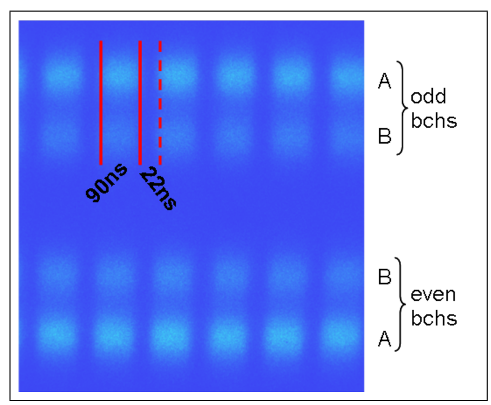

Figure 5: Images of lobes A and B for odd (top) and even (bottom) bunches. The image correspond to an almost full SR revolution. The filling pattern is composed by 8 trains of 112 ns, each train consisting in 45 consecutive bunches followed by 22 ns of gap.

STORED BEAM MEASUREMENTS

The SC settings need to be well tuned in order to perform precise bunch length measurements. First, we see enlargements of about 25% if the focusing lenses are not perfectly tuned, which we did with the help of the manufacturer [3]. The most significant effect is due to the transverse beam spot, which produces bunch length enlargements of about 50% (even by closing the SC slit). We control this beam spot with a CCD camera located next to the SC. The light

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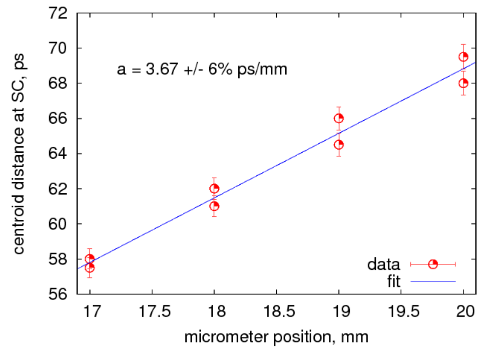

Figure 6: Linear fit to the distance between lobes for different micrometer position. The linear term provides the calibration in terms of ps/mm.

is directed to both devices using a light splitter. Figure 7 shows the image arriving at the SC as seen by a CCD camera (left), and as seen by the SC itself (right) in focusing mode (no sweeps). Precise bunch length measurements are only performed if we collimate the beam spot using the iris located in front of the SC (see Fig. 2). We suspect the reason for the peculiar shape of this spot stems in the use of conventional mirrors, whose reflection is produced by the front surface, but they can also add residual reflections at the back surface. We are currently investigating this effect.

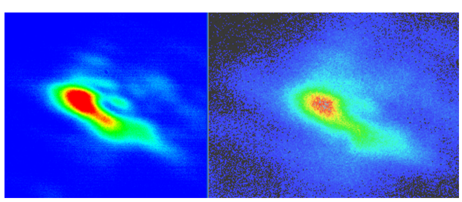

Figure 7: Transverse beam spot arriving to the SC as seen by the CCD (left) and SC itself (right). The multiple spots are suspected to be due to multiple reflections at the 6 conventional mirrors. Precise bunch length measurements are performed if we collimate the spot using the iris.

Figure 8 shows a typical example of the bunch length measurements at ALBA. The filling pattern at SR is made of 8 trains spaced by 11 buckets (22 ns), each train containing 45 consecutive bunches. The image at Fig. 8 (left) corresponds to an almost full SR turn (896 ns), where we can see almost completely the 8 trains. As usual in the streak camera, the odd bunches are at the image top, the bottom bunches are at the image bottom. The bunch length is obtained after the vertical projection of the selected ROI. As seen in Fig. 8 (right), the projection follows a Gaussian distribution, from which we obtain a beam size of FWHM=52 ps (σ_z = 22.1ps).

Figure 9 shows the evolution of the bunch length σ_z by varying the rf voltage V, which we can see it consistently follows the relation

$$\sigma_z = \sqrt{\frac{2\pi\alpha_C E\sigma_E^2}{hV\cos\phi_s\omega_{\text{rev}}^2}} \ , \tag{1}$$

where α_c is the momentum compaction factor (given by the machine optics), E is the beam energy, h is the harmonic number, ϕ_s is the synchronous phase and ω_{rev} is the angular SR revolution frequency. Both measured and modelled values are shown in Fig. 9, where the measurement errorbar considers the overestimation measured in Fig. 6.

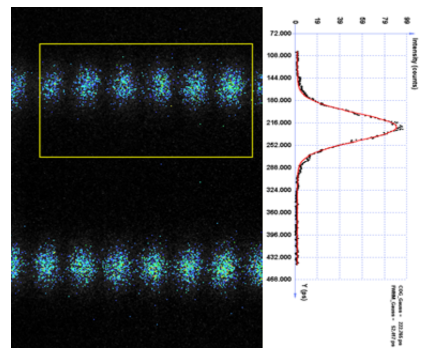

Figure 8: Example of a bunch length measurement.

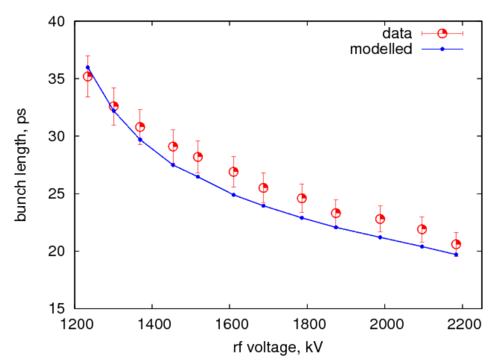

Figure 9: Measured bunch length wrt rf voltage.

A proper bunch length measurement allow the calculation of the energy spread σ_E, following:

$$\sigma_z = \frac{\alpha_C}{2\pi f_s}\cdot\sigma_E \ , \tag{2}$$

where f_s is the synchrotron frequency, controlled with the Spectrum Analyzer after varying the rf voltage. The linear relation obtained is shown in Fig. 10, with a σ_E=0.83%, consistent with the expected values.

INJECTED BEAM MEASUREMENTS

In order to perform longitudinal studies at injection, we first “unclose” the injection bump to dump the beam circulating in the machine and keep the injected beam (which arrives after the 3 Hz repetition rate from the injectors). This

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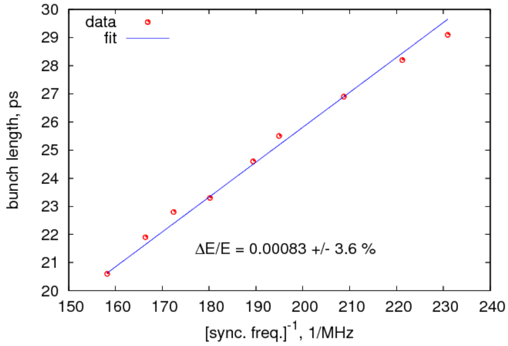

Figure 10: Energy spread measurement.

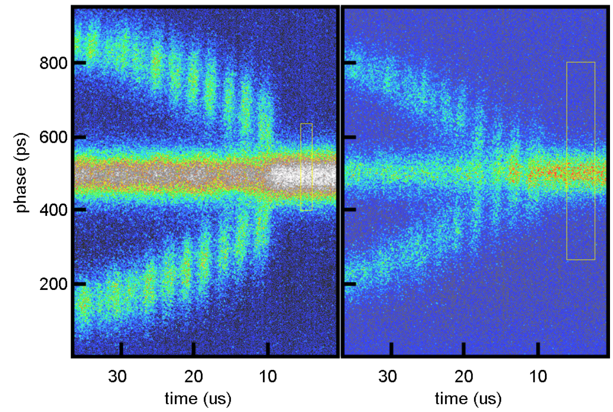

Figure 11: Streak images before/after rf phase matching. Note the time goes from right to left, and injection occurs at ∼10μs. The SC phase has been matched to superimpose the odd and even bunches at the same phase, but when the injection occurs, the injected odd bunches go upwards, injected even bunches go downwards, and the remaining stored beam remains at the same phase.

allows to keep the SR intensity ~0.2 mA and so to work with the same SC settings. In these conditions, we check the longitudinal matching between the Booster and SR by measuring and correcting the phase and energy offsets, as well as measure the injected bunch length and damping time.

Phase and Energy Match

Since the radiation damping eventually damps the injected beam to the natural SR bunch length and energy spread, the details of the longitudinal dynamics (like energy and phase match) are usually ignored as long as there is an adequate capture of the injected beam. However, in view of the future top-up operation at ALBA, we started a campaign to properly match the energy and phase from the Booster to the SR.

From the settings used in normal operation, the simplest thing is to check the rf phase. This is done by comparing the phase of the injected beam wrt the stored beam. Figure 11 shows the images of the beam before (left) and after (right) the phase matching. After injection (at ∼10μs), the left hand side pictures shows a phase jump of 139ps, corresponding to a phase offset of 25^o. After applying this phase shift to the RF system, we can see the injected beam phase is well matched with the stored beam phase, and the oscillation starting at ∼10μs are due to injection energy mismatch, which we correct next.

To correct the energy mismatch, we prepare the Booster to extract at three different energies: the setting used during normal operation (which we call hereafter "Reference"), and at ±1% of the nominal energy. We do so by editing the Booster magnets ramp curves. Because the SC images the odd and even bunches at different places, we measure then the oscillations of the odd and even bunches separately. This is then the input for a tracking simulation, which allows to identify the energy offset corresponding to the phase difference. The results are shown in Table 2. We conclude then that we were injecting with an energy offset of -18 MeV (or -0.68% in energy), and so we adjust the Booster settings to ramp at an energy of +0.68%. After several iterations with small adjustments in energy and phase, the image of the injected beam is shown in Fig. 12. It corresponds to an energy difference of 1.5 MeV and a phase difference of 10 ps (1.8^o). Note the (small) centroid oscillations wrt Fig. 11. The centroid and bunch length oscillations are explained in the next section. The phase space tracking simulations corresponding to the different energies tried in this exercise are shown in Fig. 13.

Table 2: Top/bottom oscillation at the SC for three different Booster ramps, and corresponding energy difference after the tracking simulations.

BO ramps	top/bottom osc.	ΔE
Reference -1%	353/262 ps	-43 MeV
Reference	127/111 ps	-18 MeV
Reference +1%	62/72 ps	+10 MeV

Injection Dynamics and SR Damping Time

Once we tune the injection to the right energy, we could analyze the beam coming from the Booster, which allows us to study the longitudinal damping time and the injection dynamics.

In Fig. 12, we see that the (small) centroid oscillation period coincides with the synchrotron period, while the bunch length oscillates at half this period, as it is expected because the bunch length performs two cycles for each centroid turn. Note the bunch length oscillations has different minima and maxima at different cycles, due to the non-symmetric shape of the phase space trajectory (see Fig. 13).

Following the injection, the initial beam distribution from the Booster begins to filament until it eventually damps to the natural distribution of the SR [4, 5]. Since our theoretical damping time is τ =3 ms, we record the in-

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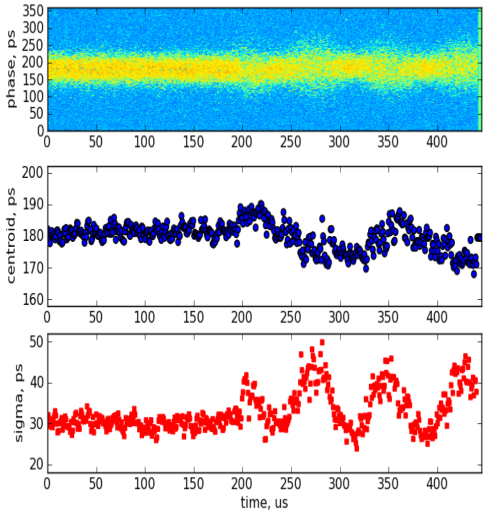

Figure 12: Injection after matching the energy and phase. Note the centroid oscillations are in the order of 10ps (middle plot), and it oscillates at the synchrotron frequency (period of ∼150μs), while the bunch length (bottom plot) oscillates at twice the synchrotron frequency (period of ∼75μs). In this case, the injection occurs at about t = 200μs.

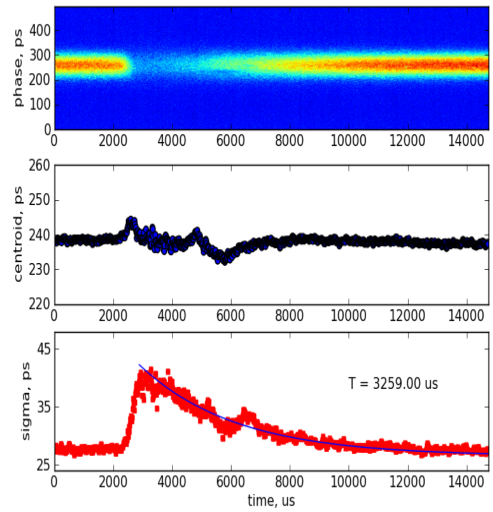

Figure 14: Streak image used to infer the longitudinal damping time (top), and evolution of centroid (middle) and bunch length (bottom). Injection occurs at about t = 2.9 ms. The bunch length is fitted to an exponential decay, the damping time obtained from the fitting results is τ =3.2 ms.

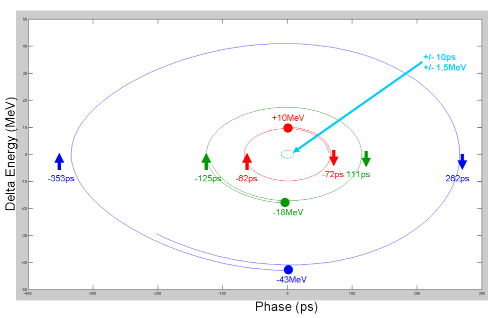

Figure 13: Matching simulations in phase space.

jection transient over 14 ms. From fitting the bunch length decay during this time we can infer the damping time – see Fig. 14. In this case, the bunch length oscillation observed in Fig. 12 cannot be resolved because the bunch length performs one oscillation over half the synchrotron period (note the different horizontal time scale at both pictures). The fitting result shows τ = 3.2 ms, consistent with the theoretical expectations [6].

CONCLUSIONS

The SC at ALBA has been operational since 1 year ago. In this time, we performed several studies to characterize the SC, with the aim of ensure the linearity and crosscheck the time to space conversion factor. All this allows us to perform precise bunch length measurements and related machine parameters like energy spread. Furthermore, we use the SC to match in energy and phase the beam coming from the Booster, which is used to obtain an insight view of the injection dynamics.

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