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SINGLE BUNCH BUCKET SELECTION INJECTION MODES IN THE ALBA STORAGE RING

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The ALBA Synchrotron has been operating routinely in top-up mode since 2014, performing reinjections of multibunches every 20 minutes. Recently, the control of the timing has been upgraded to allow single bunches to be injected into any storage ring bucket and therefore to top up the stored current also in single bunch injector mode.
In addition, by means of a specific algorithm, a new injection mode called Single Bunch Bucket Selection (SBBS) has been developed to provide any kind of filling pattern in the ALBA storage ring. This mode controls independently the amount of current injected into each bucket, and injects first into those buckets with lowest charge. When used in top-up mode, SBBS keeps the charge distribution of the filling pattern with an uniformity below 10%. The improved flexibility and stability of the filling pattern increases the scope of research for the ALBA experiments and for machine studies development. The implementation of the new injection modes and their performance are presented.

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The ALBA Synchrotron has been operating routinely in top-up mode since 2014, performing reinjections of multi-bunches every 20 minutes. Recently, the control of the timing has been upgraded to allow single bunches to be injected into any storage ring bucket and therefore to top up the stored current also in single bunch injector mode. In addition, by means of a specific algorithm, a new injection mode called Single Bunch Bucket Selection (SBBS) has been developed to provide any kind of filling pattern in the ALBA storage ring. This mode controls independently the amount of current injected into each bucket, and injects first into those buckets with lowest charge. When used in top-up mode, SBBS keeps the charge distribution of the filling pattern with a uniformity below 10%. The improved flexibility and stability of the filling pattern increases the scope of research for the ALBA experiments and for machine studies development. The implementation of the new injection modes and their performance are presented.

THE STORAGE RING

The ALBA storage ring (SR) is a 3.0 GeV electron accelerator that at present provides photon beams to 8 beamlines [1]. Currently, three new beamlines are under construction. The ring has a circumference of 268.8 m and is powered by six RF cavities working at the master oscillator (MO) frequency, 499.654 MHz. Therefore, the ring has 448 buckets, each of 2 ns duration. At present, 152 mA are equally distributed in a filling pattern consisting of 8 trains of 40 buckets filled with electrons separated by 16 empty buckets. The SR current is topped up every 20 minutes.

THE INJECTOR

The top-up operation option was considered already in the design phase of the ALBA injector, which is composed of a 100 MeV linac [2] and a full energy booster that works at a repetition rate of 3.125 Hz. A 90 keV thermionic electron gun generates bunches of electrons of 1 ns length by modulating the grid voltage at the MO reference frequency. The electronics associated to the modulation makes possible the extraction of bunches in two modes, see Figure 1:

Single Bunch Mode (SBM) From 1 up to 16 single bunches are generated per shot. Each bunch is delayed by an adjustable time delay known as "Interval" which can be set between 6 and 256 ns in steps of 2 ns.

Multi Bunch Mode (MBM) One train of bunches separated by 2 ns is generated per shot. The length of the train can be set between 36 and 1024 ns.

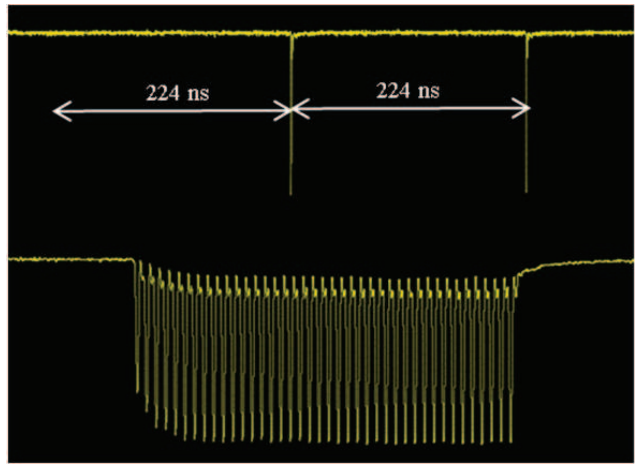

Figure 1: FCT signals taken after the gun. Above, 2 single bunches with Interval set to 224 ns. Below, one MBM of 40 bunches.

The maximum length of the pattern shot delivered by the electron gun should not exceed the 400 ns. This is the flat-top width of the kicker magnet used to inject the linac beam into the booster. On the other hand, the maximum achievable charge per bunch at the linac exit is about 0.25 nC. Using multi-bunches is possible to have up to 4nC per shot. However, due to the rise and fall times of the trains, multi-bunches have a poor charge homogeneity. Right after the linac exit the RMS of the average charge of all bunches is 30%, whereas the RMS averaging the charge of several single bunches is only 3%. Therefore, in order to create SR filling patterns with high charge distribution uniformity it is most convenient injecting in SBM. Until recently, the SR filling pattern was injected and topped up only by means of MBM shots. The use of SBM was limited to machine studies. Since January 2017, top-up injections are performed using the upgraded injection application described below.

THE INJECTION PROCESS

The SR injection process is driven automatically by an injection application written in Python and operated with a Graphical Users Interface (GUI) [3, 4]. From the GUI the desired filling pattern and the injection modes are selected. When the injection is launched, the application checks that the injection conditions are fulfilled and switches on the injector subsystems until the SR current target has been reached.

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The time duration of the top-up injections has to be set to a minimal value. The reason is that the pulsed magnets used in the injection of the beam into the storage ring produce a residual beam distortion that is too fast to be corrected by the Fast Orbit Feedback system [5]. As a consequence, the top-up injections are not completely transparent for some of the beamlines. On the other hand, the homogeneity of the filling pattern current increases when the current injected per shot is lower. So, a compromise between the time needed to inject and the current injected into the SR per shot has to be found. A reasonable time for injecting 2 mA in top-up mode in SBM has been settled to be 10 s, which corresponds to about 0.05 mA/shot. With these values, the charge distribution uniformity of the filling pattern has been measured to be lower than 10%.

Timing Upgrade

The injection application links the injector subsystems with the events-based timing generator which has a 8 ns time resolution and is synchronized with the MO frequency. To inject one shot into a determined bucket of the SR (in multi or in single bunch mode) the application calculates and sets the event at which the linac and the rest of the injector components (like the booster and the pulsed magnets) have to be activated. However, with this system it is only possible to inject into buckets that are separated by a time multiple of 8 ns starting from a reference bucket, the so-called “bucket 0”.

To overcome the 8 ns limitation, the event receiver of the linac has been replaced by a cPCI-EVRTG-300 type, which provides an extra delay to the linac trigger, called “fine delay”. The fine delay has a precision of 10 ps and is adjustable from 0 to 10 ns. So, using the new receiver, when the linac gets an event from the generator the production of the electron bunch is delayed by both the Delay (D) and the Fine Delay (FD). By adjusting the value of the FD, the injection application makes possible the injection of single bunches into any desired position of the SR. The fine delay adjustment is however not implemented for MBM injection.

In operation, at the beginning the SR is almost fully filled with MBM shots because the injections are faster. Then the injection is completed in top-up mode using SBM.

To synchronize one MBM and one SBM to the bucket 0 the following condition has to be accomplished:

$$D_{MBM} + FD_{MBM} = D_{SBM} + FD_{SBM} + Interval + 28 \quad (1)$$

D refers to the linac delay which is adjustable in steps of 8 ns and FD refers to the linac fine delay, adjustable from 0 to 10 ns in 2ns steps. To inject into bucket 0 the value of FD_{SBM} is fixed (typically to 2 ns). The Interval value is fixed as well and the 28 ns is a measured delay introduced by the electron gun electronics. Equation (1) implies that the timing settings for SBM and MBM have to be adjusted for every filling pattern.

The Single Bunch Bucket Selection

A new mode of injection, called Single Bunch Bucket Selection mode (SBBS) has been implemented in the injection application and put into operation in January 2017. This mode is operative only when working in SBM and allows controlling the amount of current injected at any of the storage ring bucket with the aim of keeping a uniform distribution of the filling pattern over time. For that, an algorithm compares the actual current in each bucket with the one of the defined pattern, decides which buckets will be topped up in the next 10 shots and then performs the injections firing one SBM per shot. This process is repeated until either the storage ring target current is achieved or the number of cycles done reaches a previously defined limit. The refilling process is more precise when the value of the current injected per shot is estimated as accurate as possible and when the data from the filling pattern is refreshed as often as possible.

The monitoring of the SR filling pattern is provided by a Time Correlated Single Photon Counting (TCSPC) or a Fast Current Transformer (FCT) [6].

A proof-of-principle test of the SBBS mode was performed in 2016 by creating a SR filling pattern where the ALBA word was written. See Figure 2.

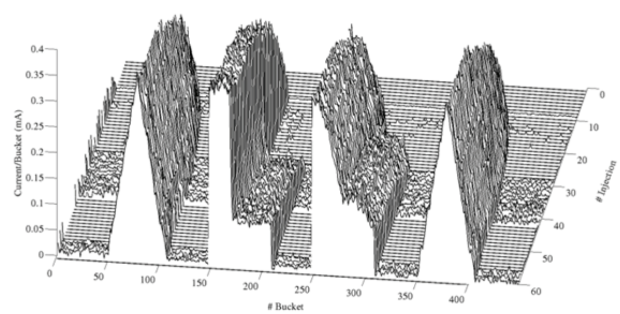

Figure 2: SR filling pattern in which ALBA has been written using the SBBS mode.

OPERATION IN SBBS

Symmetric Filling Pattern

At present, during normal operation a symmetric filling pattern consisting of 8 trains of 40 bunches filled with the same charge is used. The trains are separated each other by 16 buckets. Figure 3 presents the symmetric filling pattern after being injected in MBM and after a few hours of top-up injections in SBBS. The homogeneity of the current per bunch is clearly improved as it is shown in Figure 4. The RMS of the average charge of all the filled bunches has been reduced from 20% down to 4%. However, notice that in this case the current injected to the SR per shot was lower than 0.05 mA.

The use of a symmetric filling pattern was established during the SBBS commissioning because it is compatible with being refilled in several modes. For example, in case of failure of the SBBS system, one can switch the injector to MBM easily and keep working with the same pattern. This is also possible because all the trains of this specific

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filling pattern are injected into buckets spaced by a multiple of 8 ns with respect to the bucket 0.

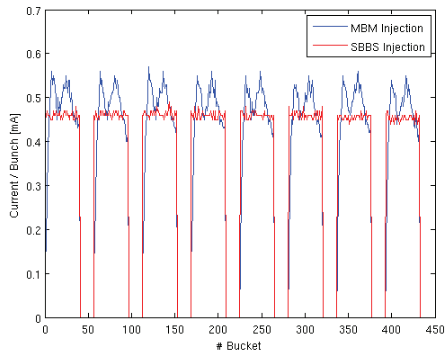

Figure 3: Symmetric filling pattern first filled using MBM shots (in blue) and after few hours of top-up in SBBS using 1SBM (in red).

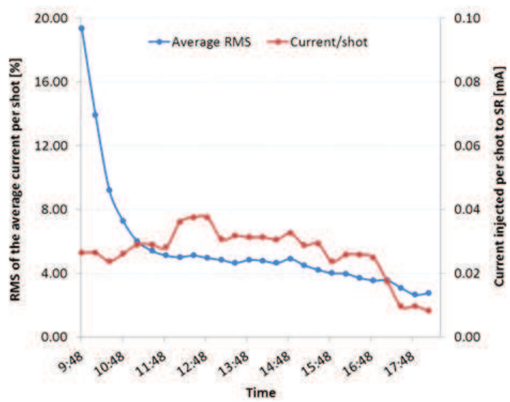

Figure 4: The charge homogeneity of the symmetric filling pattern shown in Figure 3 dramatically decreases when using SBBS mode.

Moreover, in a symmetric filling pattern it is possible to fire 2 single bunches per shot while working in SBBS. The SBBS algorithm does not take the second shot into account, but the trick works when the second single bunch is injected into the same bucket position of another train. In our symmetric filling pattern the two single bunches are separated by an Interval of 224 ns. Consequently, the first single bunch is injected into a bucket of the train *i* and the second single bunch is injected into the same bucket but from the train *i+2*.

Using only 1SBM the charge at linac is set at its maximum. Thus, injecting 2SBM increases the current injected per shot into the SR and it is used to reduce the injection time in case of low charge transmission between the linac and the SR.

Hybrid Filling Pattern

Hybrid filling patterns combining uniform multi-bunches with higher charge single-bunches have been created in SBBS, but they have not been used yet in experiments with synchrotron light. One hybrid filling pattern proposed by the CIRCE beamline is ready to be tested at the PEEM end-station, where samples will be measured by means of a gating system. The pattern, shown in Figure 5, consists of a multi-bunch part where 224 buckets are filled in a row and after a gap, 32 single bunches are filled one every 4 buckets. The total SR current is equally distributed among all the bunches. The pattern has been created in two steps. First 100 mA have been injected using 56 ns MBM trains to fill the multi-bunch part. Later SBBS has been used in 1SBM to distribute 50 mA to the rest of the buckets to be filled. The top-up mode has been left for 4 hours with a current injection rate of 0.03 mA/shot. The homogeneity of the filling pattern achieved is of 10%.

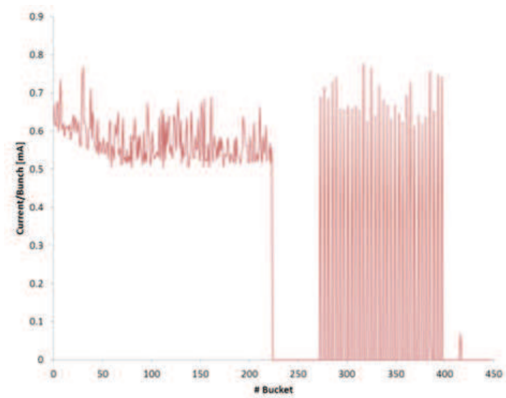

Figure 5: Hybrid filling pattern to be used with a gating system in the CIRCE beamline.

CONCLUSIONS AND OUTLOOK

The Single Bunch Bucket Selection mode controls the amount and position of the electrons injected in the storage ring with high accuracy. The SBBS has been implemented in the injection application and is currently running during user operation. Any type of storage ring filling pattern is now available in top-up mode and kept over time with high current uniformity. Still, in order to make the injection process more robust from the operation point of view and to perform even more current- and position-controlled injections a new version of the SBBS algorithm is under way.

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