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Abstract

The Digital LLRF of ALBA has been implemented using commercial cPCI boards with Virtex-4 FPGA, fast ADCs and fast DACs. The firmware of the FPGA is based on IQ demodulation technique and the main feedback loops adjust the phase and amplitude of the cavity voltage and also the resonance frequency of the cavity. This paper summarizes the latest LLRF developments done to improve performance of the RF systems and beam stability, including feed-forward loops based on phase modulation to compensate disturbances due to RF trip, beam loading compensation and Power Unbalance Compensation Loop for RF amplifiers Combination.

INTRODUCTION

ALBA is a 3GeV synchrotron light source located in Barcelona and operating with users since May 2012. The 500MHz RF system of the SR is composed of six cavities, each one powered by combining the power of two 80 kW IOTs CW through a Cavity Combiner (CaCo). The main parameters of this system are summarized in Table 1.

Table 1: RF/LLRF Specifications of ALBA SR

Frequency	499.654	MHz
No of cavities	6	NC - HOM
RF Power (per cavity)	150	kW
RF Voltage (per cavity)	600	kV
Maximum Beam Current	400	mA
Nominal Beam Current	250	mA
Beam Losses per turn (U_0)	1.1	MeV
Synchrotron Frequency	5 - 9	kHz
Amplifiers type	IOT	
Main DSP of Digital LLRF	IQ mod/demodulation	
LLRF Amplitude stability	0.1	% rms
LLRF Phase stability	0.1	º rms

The Digital LLRF of ALBA was developed in 2006 using commercial cPCI boards from Nutaq with Virtex-4 FPGA, fast ADCs, fast DACs and a Windows XP CPU as host PC. The main loops implemented in this board were meant to control the amplitude and phase of the cavity voltage within 0.1% rms amplitude resolution and 0.1º rms phase resolution using the very well-known IQ demodulation technique [1].

At present, the operating current of the SR is 150 mA. This current is foreseen to be increased to nominal value (250mA) in the following months. Unfortunately, there are few interlocks per week in the RF plants, mainly caused by arcs in the IOTs, pre-drivers faults and electronics of water flow meters. The redundancy and overvoltage of the RF system makes possible the survival of the beam after one of these trips. Nevertheless, we have observed that if the SR current is increased and the RF voltage is maintained, the RF interlocks can lead to beam dumps due to the disturbance induced in the beam .

In order to improve the reliability of the RF systems the RF and pre-drivers amplifiers are being replaced by more robust models (IOTs: Thales TH-795 and L3-L4444C; Pre-drivers: SSA 500W from TTI and BTESA). Meanwhile, SW upgrades have been implemented in the LLRF to minimize the disturbances induced in the beam after RF interlocks and to prevent beam losses.

LLRF FW UPGRADES

Phase Modulation for RF Trip Compensation

After a RF interlock, the beam starts to longitudinally oscillate around the beam synchronous phase. As consequence, the voltage of the remaining active cavities drops and oscillates, as shown in Figure 1. If the remaining RF voltage is higher than the beam losses per turn (U_0), the beam survives. Otherwise, the beam is lost.

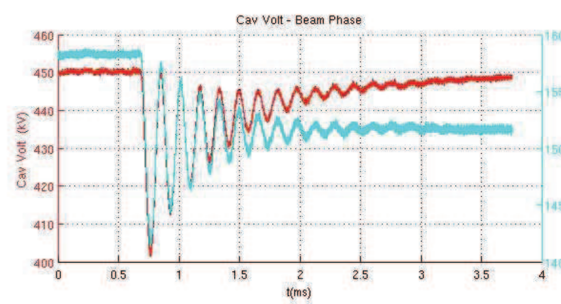

Figure 1: Response of active cavities after RF failure.

A first approach to compensate these oscillations and to prevent the voltage drop was to introduce an amplitude modulation of the RF Drive with the same frequency and amplitude of the oscillations and opposite phase. This solution was implemented and successfully tested with beam in 2015 [2]. A fake RF interlock was created in order to induce a beam was lost when no compensation was applied. On the contrary, when the amplitude modulation compensation was enabled, no beam was lost after an RF interlock.

The only drawback of this approach was the required sudden increase of RF amplifiers power to do this, increasing at the same time the probability of arcs inside the tubes. To overcome this, an alternative compensation algorithm based on phase modulation was tested. In this case, whenever an RF interlock is detected, a phase step is applied to the RF Drive anticipating the new synchronous phase required by the beam with the new RF voltage. After this, the phase is modulated in opposite direction to the natural oscillations of the beam. Doing this, the longitudinal excursion of the beam is minimized, avoiding the RF voltage drop responsible of the beam dumps.

Figure 2 and Fig 3 show the voltage amplitude and phase (respectively) of an active cavity (cavity 10A) after a RF interlock in another cavity. Before the interlock, the current of the SR was 57mA and the overall RF voltage of the SR was 1.7MV (350kV provided by 5 cavities). After the interlock, if no compensation is applied (blue line), the overall RF voltage of the remaining cavities drops due to the longitudinal oscillations of the beam, causing a beam dump. The other lines of the plot show the RF voltage of the remaining active cavities after a RF interlock when applying different settings of the phase modulation compensation. The black line shows the optimum settings of the phase modulation to fully prevent the beam loss under these conditions.

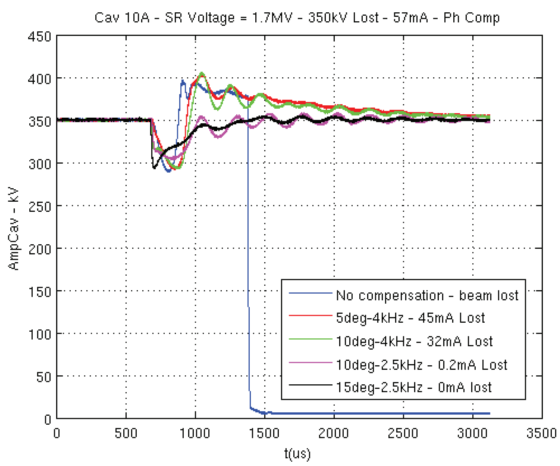

Figure 2: Cavity Amplitude after RF Trip and Ph Mod.

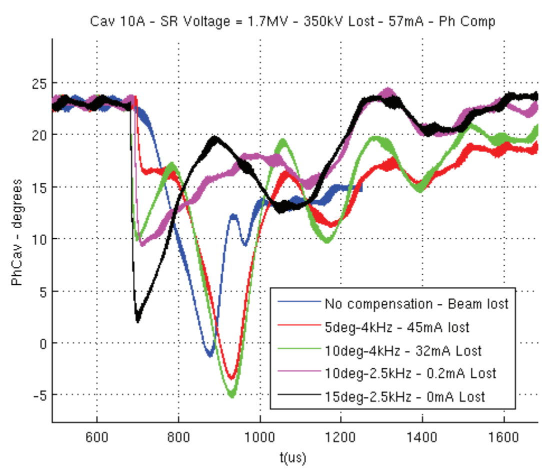

Figure 3: Cavity Phase after RF Trip and Ph Mod.

The phase modulation utility for RF Trip compensation was tested and adjusted in November 2015 and it has been enabled for operation with users since January 2016.

A combined phase and modulation compensation loop has been also implemented. For the moment, only the phase modulation is applied since it has proved to be effective enough for RF trip compensation at 150mA current in the SR. When higher SR currents are achieved, the phase compensation may not be enough to damp the longitudinal oscillation. If that is the case, the combined action of amplitude and phase modulation will be tested.

Unbalance Compensation Loop for RF Power Combination

Another source of RF interlocks in ALBA is the gain drop of the RF amplifiers pre-drivers. In ALBA, the power of each cavity comes from combining two IOT RF amplifiers with a Cavity Combiner (CaCo) [3]. These IOTs are fed by 500W Solid State Amplifier pre-drivers. The SSA combines the power of 8 LVDMOS transistors. If one of these transistors fails, the SSA output power and its corresponding IOT output power drop around 2dBs. This results in an unmatched combination of the IOTs power in CaCo, causing reverse power interlocks at the IOTs outputs.

In normal operation, the LLRF checks the phase and amplitude of the cavity voltage and computes the required RF drive to be sent to the two IOT amplifiers. To overcome the unbalanced combination of the IOTs, a second IQ loop called "master-slave IOT" loop was implemented. This second loop checks the phase and amplitude of both IOTs. One of them has to be assigned as master while the other one is the slave. The "master-slave IOT" loop will compute a "Slave Control" signal to be added to the main IQ RF Drive, so the Slave IOT always matches the phase and amplitude of the master IOT, as shown in Figure 4.

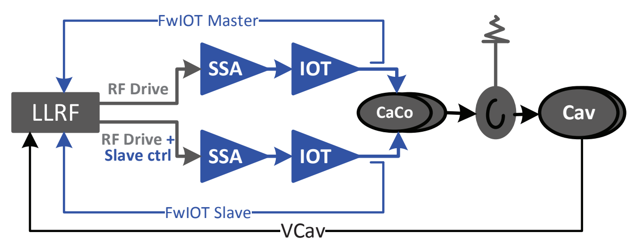

Figure 4: Master-Slave IOT Loop.

The "master-slave IOT" loop has been enabled only when problems in the SSA were detected and it has proven to be effective against gain jumps of the amplifiers. In order not to interfere with the "main cavity voltage" loop of the LLRF, the BW of this second loop was set ten times lower than the main loop.

Beam Loading Compensation

The revolution frequency of ALBA SR is around 1MHz and the current filling pattern is rather homogenous (95% filling distributed among 10 trains of pulses). As consequence, the steady beam loading effect on the cavities voltage of ALBA is negligible. In other machines with more heterogeneous filling patterns this effect can be more evident, creating disturbances in amplitude and phase of the cavity voltages, which in the end can cause

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longitudinal or phase displacements between the first and last bunches of the same train.

As part of a collaboration agreement between CELLS and CLIC/CERN, we have implemented two beam loading compensation algorithms to overcome this problem. One is based on Feed-Forward loops and another one is based on Feed-back loops.

Beam Loading Compensation based on FF Loops

Like for the RF trip compensation, a FF loop has been implemented for the compensation of steady beam loading effects. The first step was to modify the filling pattern of ALBA SR to make more evident the beam loading disturbances and to measure them with the LLRF electronics. Figure 5 shows the effect on the beam synchronous phase measured by the LLRF when one third filling pattern is applied on ALBA SR (only the first third of the SR buckets are filled) .

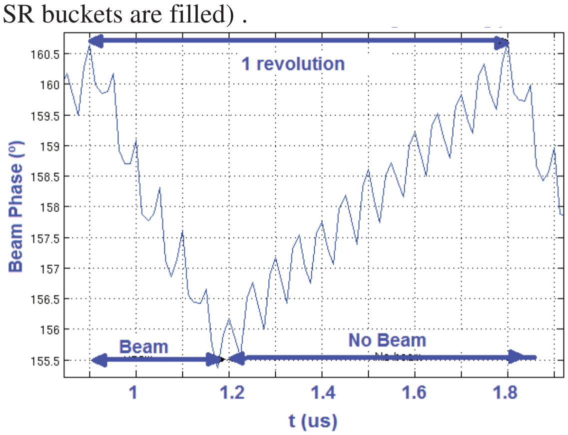

Figure 5: Beam Phase variation due to Beam Loading – 1/3 filling pattern.

Similarly to the RF trip compensation, if the disturbance is known, compensation with the same amplitude and frequency and opposite phase can be applied to reduce it. In ALBA case, the parameters of the disturbance are:

- t1: time while beam is in cavity
- t2: time while there is no beam in cavity
- Amplitude of disturbance (in phase and amplitude).

To simulate the effect of the beam loading, a voltage controlled phase shifter was installed between the RF drive of the LLRF and the ADC of the cavity voltage. This phase shifter induced a variation of 30% in amplitude of the IQ components, as shown in Figure 6. A trigger signal synchronized with the simulated revolution frequency was also connected to the LLRF. After properly adjusting the settings of the Beam Loading compensation (BLC), the 30% the voltage cavity error was reduced to 6%. Further debugging is still needed to compensate the overshoot when a new revolution trigger is received.

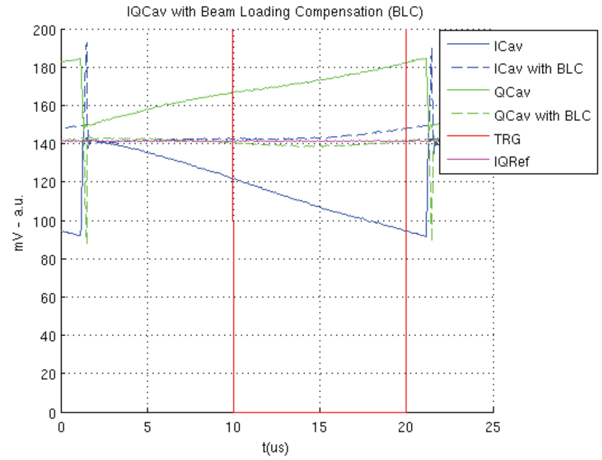

Figure 6: Beam Loading compensation based on FF Loops. Top ICav, Bottom: QCav.

Beam Loading Compensation based on FB Loops

The main drawback of the FF beam loading compensation is that their parameters have to be re-adjusted if the operating conditions are changed: SR current, voltage, filling pattern, etc. For this reason, a Feed-back loop that could be self-adjusted is preferred. On the other hand, we can assume that these disturbances will be very similar from revolution to revolution. Keeping all this in mind, the 80 samples of the LLRF corresponding to one revolution can be processed by 80 independent PI Loops and the correction of each PI Loop (clk1, clk2, clk3…) will be added to the main RF drive of the main FB loops in the next beam revolution.

To succeed in the implementation of this loop two requirements are essential: a trigger signal synchronized with the beam revolution and group delay compensation. The transit time or group delay of the LLRF correction signal up to the cavity is between 1 and 2us, and thus, in the same order of magnitude than the revolution time. The measurement and compensation of this parameter will be the most critical parameter to make the Beam Loading FB loops stable.

CONCLUSIONS

Digital LLRF systems based on FPGAs have proven to be very flexible and powerful, allowing LLRF systems to be upgraded to match new requirements of machine operations with just software modifications, and thus, at low cost.

In ALBA these upgrades have focused on increasing beam availability by minimizing effect of RF interlocks through Phase Modulation Feed-Forward Loops and secondary loops to keep the power balance of several RF amplifiers combination.

As part of a collaboration agreement between CELLS and CLIC/CERN, compensation algorithms for beam loading effects due to partial filling are being studied.

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