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ALBA LLRF UPGRADES TO IMPROVE BEAM AVAILABILITY

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Abstract

ALBA is a 3GeV synchrotron light source located in Barcelona and operating with users since May 2012. The RF system of the SR is composed of six cavities, each one powered by combining the power of two 80 kW IOTs through a Cavity Combiner (CaCo). At present, there are several RF interlocks per week. The redundancy given by the six cavities makes possible the survival of the beam after one of these trips. In these cases, the cavity has to be recovered with the circulating beam. An auto-recovery process has been implemented in the digital LLRF system in order to recover the faulty RF plant with circulating beam. But these trips also create perturbations to the beam stability. In order to minimize the beam perturbations induced by these RF interlocks, an additional feed-forward loop has been implemented. The functionally, main parameters and test results of these new algorithms will be presented.

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ALBA is a 3GeV synchrotron light source located in Barcelona and operating with users since May 2012. The RF system of the SR is composed of six cavities, each one powered by combining the power of two 80 kW IOTs through a Cavity Combiner (CaCo). At present, there are several RF interlocks per week. The redundancy given by the six cavities makes possible the survival of the beam after one of these trips. In these cases, the cavity has to be recovered with the circulating beam. An auto-recovery process has been implemented in the digital LLRF system in order to recover the faulty RF plant with circulating beam. But these trips also create perturbations to the beam stability. In order to minimize the beam perturbations induced by these RF interlocks, an additional feed-forward loop has been implemented. The functionally, main parameters and test results of these new algorithms will be presented.

INTRODUCTION

The RF System of the ALBA SR has been designed to provide up to 3.6MV of accelerating voltage and to restore up to 540kW of power to the electron beam [1]. 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

At present, there are several RF interlocks per week mainly due to internal arcs in the RF amplifiers. The redundancy of the RF system and the present operation of the SR at relatively low current (100mA) make possible the survival of the beam after one of these trips. An auto-recovery process has been implemented in the digital LLRF system in order to recover the faulty RF plant with circulating beam. However, when increasing the beam current in the SR, we have observed that the disturbances induced in the beam due to these RF trips can produce a partial or total beam dump. A feed-forward loop has been also implemented to compensate these perturbations and to increase the reliability of the RF systems

CAVITY AUTORECOVERY WITH BEAM

When there is a RF trip, the stopped cavity absorbs power to the circulating beam, since instants before the interlock that cavity was properly tuned. To avoid this situation, the LLRF detunes the cavity around 500kHz immediately after the interlock is detected. Besides this, the main feedback loops, amplitude and phase, get disabled and the LLRF Drive is set to a minimum level.

After clearing the interlock source, the operator sets the RF plant back into operation while the electron beam is still circulating in the SR. Then, the LLRF moves the plunger back to the position previous to the interlock detection, while keeping the LLRF drive to the minimum level and keeping the feed-back loops disabled. When the original position of the plunger is reached, the tuning loop gets enabled. In order to let the tuning loop adjust the resonance frequency of the cavity, the RF power provided by the amplifier should be high enough to overcome the beam loading effect of the circulating beam, but at the same time, it should be low enough to avoid triggering a reflected power interlock, since the cavity is completely detuned when the plant is set into operation.

After tuning the cavity, the amplitude and phase feed-back loops get enabled and the power is increased smoothly up to the nominal value set by the operator. It is important to notice that when the RF plant is set back to operation, there are no feed-back loops to adjust the phase of the cavity voltage with respect to the beam. In order to ensure the right synchronization between the LLRF drive in open loop and the phase of the beam, a digital phase shifter has been implemented at the output of the LLRF, which compensates any phase delay between the LLRF control output and the measured cavity voltage.

All the parameters for a proper cavity recovery are accessible via the LLRF control system: minimum power, detune frequency, phase delay, so that can be easily adjusted in case of changing the RF or beam conditions.

FEED-FORWARD LOOPS FOR RF TRIP COMPENSATION

Depending on the overvoltage factor of the RF and on the circulating beam current, the voltage disturbance caused by a cavity RF trip can be transparent or may cause a partial or total beam dump. The first step to compensate the perturbations caused by a RF trip is to proper characterize these disturbances.

Perturbations Analysis after a RF Trip

Figure 1 shows the evolution of the cavity voltage when another cavity trips and the beam survives as measured by the Fast Data Logger (FDL) implemented in the DLLRF [2]. Several effects are observed:

- Cavity voltage gets reduced just after the interlock and the power delivery to the beam per cavity increases.
- Synchronous beam phase starts to decrease and it oscillates with a frequency equal to the synchrotron tune until it reaches the new equilibrium point
- The higher the beam current and/or lower the RF voltage, the higher the amplitude of these perturbations and the more likely to have a beam dump.

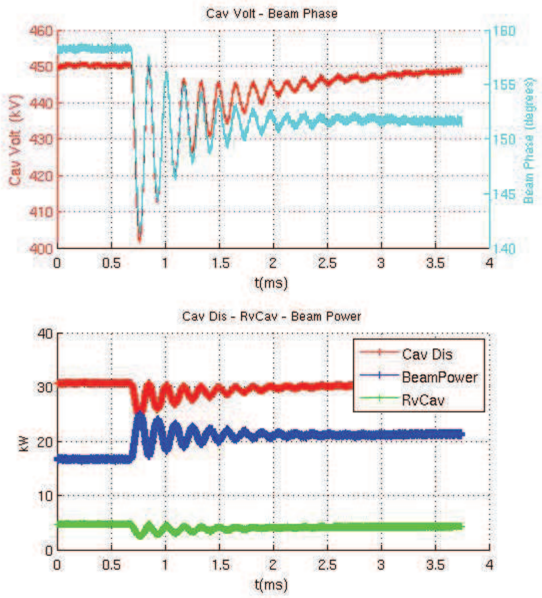

Figure 1: Response of active cavities after RF failure and beam survival.

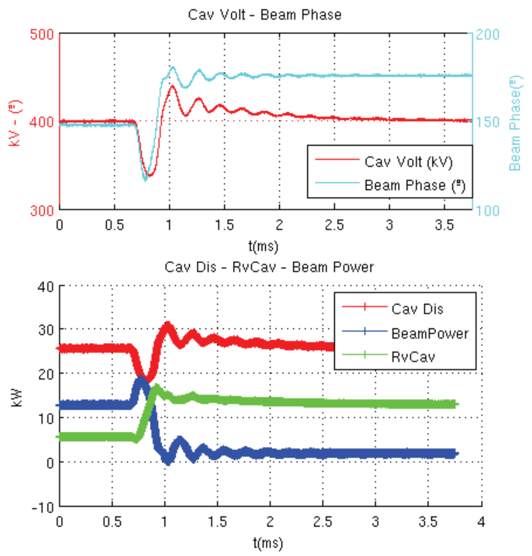

Figure 2: Response of active cavities after RF failure and partial beam loss.

On the contrary, Fig. 2 shows the RF voltage evolution of an active cavity after a partial beam loss due to an RF trip. In this case, the cavity voltage also gets reduced after the first oscillation period of the perturbation, but later there is a voltage overshoot. Similarly, the reverse power of the cavity also increases dramatically and the power delivered to the beam gets reduced. The conclusion of this phenomenon is that this extra generated power (overshoot in Cavity Voltage and higher reverse power) is coming from the beam, i.e., instead of providing power to the beam, we are extracting power from it, forcing the beam to decelerate and producing a beam dump.

In order to avoid this, the extra power required by the beam has to be provided by a compensation loop.

Main Parameters of Feed-Forward Loop

We have already seen how the voltage of the cavity decreases after an RF failure. When this failure happens, the other plants are informed about this by the timing system in less than 100ns. So, in order to prevent the voltage of the cavity to drop, the Feed-Forward loop (FF) should increase the drive just after receiving the trigger from the timing system following a sinusoidal signal, with frequency equal to synchrotron tune, but with opposite phase to the foreseen perturbation. On the other hand, the transient of the perturbation after an RF trip has a damping time of around 3ms (longitudinal damping time) and it decays following an exponential curve. Since the mathematical operations to be implemented in a FPGA are limited, the amplitude of the feed-forward loops will follow a linear decay that will last one third of the damping time of the perturbation. This implies that only the first oscillations of the perturbations will be compensated, but not the rest. Anyway, since the beam losses happen during the first period of the transient this has proven to be enough.

Simulations of FF Loop Interaction with Beam

In order to proper adjust the main settings of the Feed-Forward Loops (amplitude, phase, decay time and frequency), the interaction of the beam after a RF trip was simulated with and without active compensation. The results of the simulation showed that it was not possible to completely remove the perturbations caused by a RF trip. In fact, if an over-drive was sent by the Feed-Forward loops, the perturbations could be worsened. Figure 3 shows the evolution of the active cavities after a RF trip when different Feed-Forward amplitudes were applied.

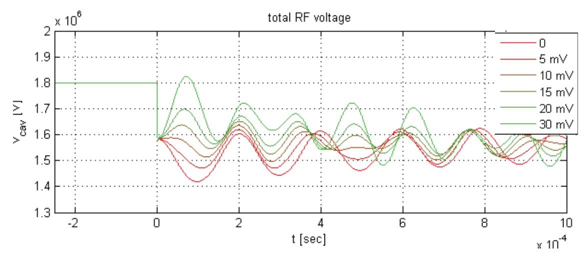

Figure 3: Simulated evolution of total RF Voltage after RF trip when different FF loop amplitudes are applied.

When the amplitude of the Feed-Forward loop is higher than 10mV (arbitrary units), the voltage of the active cavities show overshoots that in practice we have observed are translated into beam losses.

Experimental Results

Keeping in mind the simulations results, the Feed-Forward loops were adjusted to get a response where the perturbations caused by a RF trip were minimized without causing any overshoots in the RF voltages of the active cavities.

To check the viability of the Feed-Forward loop, the tests were performed with low current (60mA) to avoid high radiation doses when the beam was lost and also with low RF voltage (1.5MV). With this configuration, a fake interlock was caused, forcing the total RF voltage to get reduced from 1.5MV to 1.2MV (almost no overvoltage). When no compensation was applied, the beam was lost. After measuring the frequency of the ripples induced by this interlock, the Feed-Forward loops were enabled and adjusted. Then, the fake interlock was repeated, increasing steadily the amplitude of the compensation until we managed to fully cancel out the beam dump.

Figure 4 shows the voltage of an active cavity after a forced interlock in another cavity. First it is represented the evolution of the voltage without any compensation (red line). Magenta line shows the evolution of the same cavity voltage when the FF loops are enabled and set to send 35% overdrive to compensate the disturbances. In this case, 2mA out of 60mA were lost. Green line shows the same test but increasing the FF amplitude to 40%. In this case, only 0.5mA were lost. Finally, increasing the FF amplitude to 45%, no beam loss was produced.

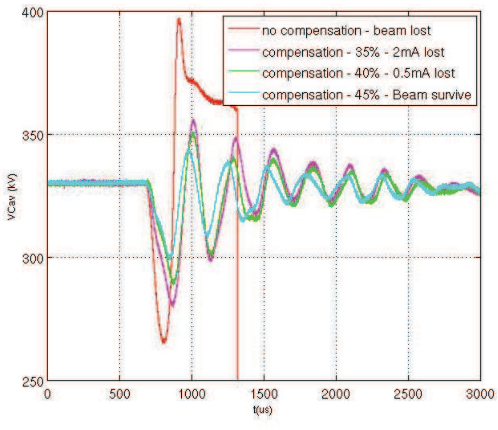

Figure 4: Comparison of different Feed-Forward Settings after a forced RF trip.

Next Steps

For the moment, the Feed-Forward loops just modulate the amplitude of the LLRF Drives to compensate the perturbations due to RF trips. While the RF amplifiers were capable to provide this extra power, this method could be used. However, this might not be the case when maximum beam current is stored in the accelerator. For this reason, the next step will be to implement a phase modulation Feed-Forward loop and to check its effectiveness. The main advantage of this approach is that in principle, the output of the amplifier would remain almost constant.

BEAM LOADING COMPENSATION

The Feed-Forward loops have proven to be able to compensate transient beam loading effects. The same strategy could be used to compensate steady beam loading effects.

Figure 5 shows the evolution of cavity voltage phase when 30mA with one third filling pattern is injected in ALBA SR. The revolution time in ALBA case is around 1us and we can observe in this plot how the cavity voltage phase varies around 0.8º per turn.

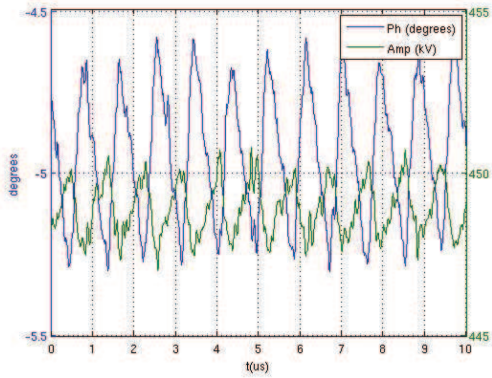

Figure 5: Cavity Voltage and Phase variations per turn due to Beam Loading.

Following the same approach presented for the RF trips compensation, an algorithm will be developed to compensate the steady beam loading effect. Although at the moment this effect is not critical for ALBA operation, it could become visible when new beamlines will be operative (i.e. infrared).

Also, this method of active beam loading compensation with a digital LLRF system is being investigated as a proposed solution for the stringent phase requirements of the CLIC damping ring.

CONCLUSIONS

An active Feed-Forward loop has been implemented to compensate the transients caused by a RF trip. Experimental and theoretical results show the viability of this method. It will also help to increase the reliability of the RF systems and the possibility to extra compensate beam loading effects for a better beam stability.

REFERENCES

[1] F. Perez et al, "New Developments for the RF System of the ALBA Storage Ring", EPAC06, Edinburgh, Scotland (2006).

[2] A. Salom et al, "Digital LLRF for ALBA Storage Ring", EPAC08, Genoa, Italy (2008).