

ANALOGUE LLRF FOR THE ALBA BOOSTER

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Abstract

ALBA Booster will inject up to 2 mA of current, at 3 Hz, in the 3 GeV 3rd generation Synchrotron Light Source ALBA, that is in the construction phase in Cerdanyola, Spain. The Booster will ramp the beam energy from 100 MeV to 3 GeV, the RF voltage will be ramped as well from <100 kV to 1 MV to improve injection efficiency and maintain the beam stable. The Booster RF System will have to provide up to 1 MV of accelerating voltage and have a high dynamic range. An Analogue LLRF prototype has been developed for the Booster 5 cell RF Cavity. The prototype is based on the IQ modulation/demodulation technique and it has been designed completely in house. The prototype has been installed in the high power RF lab of CELLS and tested to control up to 80 kW on the real Booster Cavity. The test results of the control loops (amplitude, phase and tuning) will be presented, as well as the hardware structure and the system interface.

INTRODUCTION

For the ALBA Booster a ramping electric field with a peak value of 1 MV and a repetition frequency of 3 Hz will be needed to increase the energy of the injected beam from 100 MeV to 3 GeV.

The Booster RF system includes a 5-cell PETRA type cavity supplied by a TH793-1 IOT from Thales Electron Devices and a 38 kV - 4 A High Voltage Power Supply from Thomson Broadcast and Multimedia. The RF parameters and the LLRF specifications of the ALBA Booster are summarized in table 1.

Table 1: RF parameters of the ALBA Booster

Parameter	Value	Unit
RF frequency	499.654	MHz
Repetition frequency	3	Hz
No. of cavities	1	
Cavity shunt impedance	14	MΩ
RF power (at 3 GeV)	40	kW
RF voltage (at 3 GeV)	1	MV
Beam current	2	mA
Beam power (at 3 GeV)	1.3	kW
Amplitude stability	$\leq \pm 1$	%
Phase stability	$\leq \pm 1$	°
DAC resolution	16	bits
DAC throughput	100	kHz
LLRF bandwidth	> 200 kHz	kHz
Loop delay	< 1000	ns
Dynamic range	> 23	dB

AMPLITUDE AND PHASE LOOPS

The design of the ALBA Booster Analogue LLRF (ALLRF) is based on quadrature demodulation and PID

regulation. Figure 1 presents the schematics of the amplitude/phase loops.

For cavity field regulation the probe voltage in the cavity's center cell (3rd cell) is first decomposed into in-phase (I) and quadrature (Q) components and then converted into single-ended by an in-house developed IQ demodulator board which is based on AD8348 and AD8130 from Analog Devices. The cavity I and Q components are then compared to their set values and the I and Q errors are fed into two PIDs to regulate the I and Q, hence the amplitude and phase of the cavity voltage. The outputs of the two PIDs are, in the next stage, multiplied by an adjustable gain and added to the feed-forward set values before entering the base-band phase shifter which is based on six AD835 adder/multipliers. The phase shifter -basically a rotation matrix- makes a controlled rotation of the IQ vector so that it compensates for the loops delays, hence preventing the loops from becoming unstable. The I and Q outputs of the phase shifter are converted from single-ended to differential by two AD8132 and modulated by a quadrature modulator board based on AD8345 from Analog Devices. The output of the modulator, after being pre-amplified, serves as the input of the solid-state amplifier which drives the IOT.

By choosing proper reference values for the I/Q loops (i.e. I_{FB} and Q_{FB}) the operator will be able to control the amplitude of the cavity voltage from nearly zero to the maximum affordable by the IOT and the phase from 0° to 360° thus providing full control over the cavity amplitude and phase both in DC and ramping modes.

The reason for the I_{FF} and Q_{FF} inputs is two-folded: first, it can be used as a function generator when the system is operated in open-loop; in this case the I/Q *Reg. gains* are set to 0 V to open the loops, so that the IOT is driven only by the I_{FF} and Q_{FF} inputs. Secondly, it can be used to compensate predictable errors such as arrival of the beam before these errors are sensed and compensated by the I/Q loops.

By setting proper values for the phase shifter inputs (which are marked as 'Sin θ ' and 'Cos θ ') the operator can provide an adjustable phase shift from 0° to 360° and an adjustable gain from 0 to 1.4. The operator should then select proper *Sin θ* and *Cos θ* to have both loops stable with the largest possible phase margin. This is done by first finding upper and lower stability thresholds for the phase shift and then setting the phase to the middle point. This ensures a stable operation of the I/Q loops in addition to providing the biggest stability margin from both sides. The phase shifter adjustment should be kept at the same level unless there's a change in the loop delay (ex: a cable is changed) which implies finding a new set value for the phase. The scale factor of the phase shifter could be used as another way to control the loop gain in addition to the *Reg. gain* inputs.

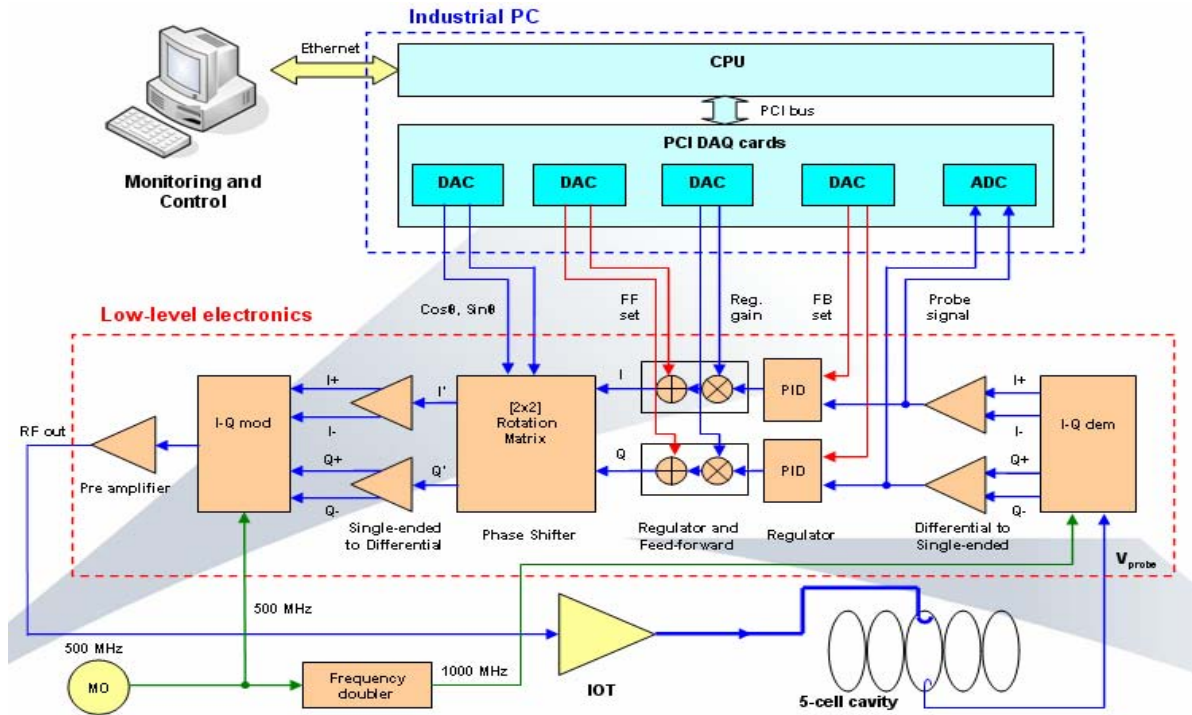


Figure 1: Layout of the IQ-based amplitude and phase loops for the ALBA booster.

TUNING AND FIELD-FLATNESS LOOPS

Tuning loop controls the resonance frequency of the cavity in order to have minimum reflected power with the presence of the beam and other disturbances such as temperature drifts. For this purpose, the two tuners of the 5-cell cavity are driven in the same direction so that the phase difference between the forward power and cavity voltage remains as close as possible to its reference value. The reference phase is the one which results minimum reflected power from the cavity and provides stable Robinson operation. A field-flatness loop has also been foreseen for the booster cavity to equalize the amplitude of the electric field in all the cells. In this case the two tuners are driven in opposite directions so that the difference of the voltage in the 2nd and the 4th cells remains as small as possible.

The design of the ALBA tuning and field-flatness loops is also based on quadrature demodulation. Four RF signals (i.e. V_{fwd} , V_{cell3} , V_{cell2} , and V_{cell4}) are demodulated by four IQ demodulator boards and sampled by an industrial PC. The first two signals are used for tuning and the last two for field-flatness. The industrial PC calculates the phase difference between the forward and 3rd cell voltages as well as the normalized amplitude difference between the 2nd and 4th cells using the following equations:

$$\Delta\theta(V_{fwd}, V_{cell3}) = \arctan 2(I_{fwd}, Q_{fwd}) - \arctan 2(I_{cell3}, Q_{cell3})$$

$$\Delta amp(V_{cell2}, V_{cell4}) = \frac{\sqrt{I_{cell2}^2 + Q_{cell2}^2} - \sqrt{I_{cell4}^2 + Q_{cell4}^2}}{\sqrt{I_{cell2}^2 + Q_{cell2}^2}}$$

Where $\arctan 2$ means 4-quadrant tangent-inverse (i.e. it can vary between 0° and 360°).

According to the $\Delta\theta(V_{fwd}, V_{cell3})$ and $\Delta amp(V_{cell2}, V_{cell4})$ values the industrial PC send pulses to the motor controller, which moves the two tuners in the right direction to have $\Delta\theta$ as close as possible to its reference value and Δamp as close as possible to zero. This is done by defining two windows with $\pm C1$ and $\pm C2$ thresholds ($C2$ resides within $C1$) centred at the desired value where the $C1$ window defines the acceptable range of the parameter and $C2$ defines the range that the parameter should be brought to when it exceeds the $+C1/-C1$ thresholds. This is illustrated in figure 2 for tuning:

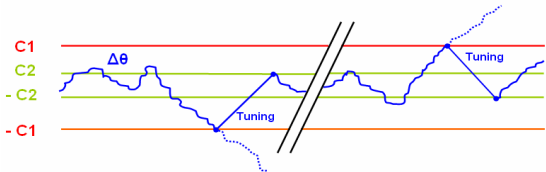


Figure 2: Tuning thresholds.

For the ALBA booster, tuning and field-flatness will be done one after another at the peak of the ramping curve as shown in figure 3:

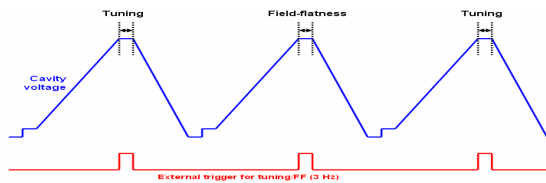


Figure 3: Synchronization of tuning and field flatness actions with a 3 Hz trigger.

After a change in the set values, the two tuners will find their right positions in a few ramping cycles so that both tuning and field-flatness conditions are satisfied.

PRACTICAL RESULTS

A disturbance was generated on the amplitude/phase of the cavity voltage by a voltage controlled attenuator/phase-shifter to investigate the performance of the IQ loops. Figure 4 and 5 show the result of the phase test in time and frequency domains respectively:

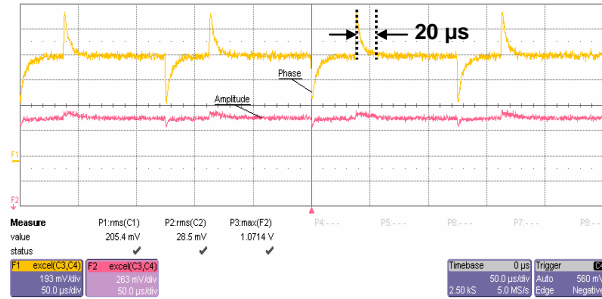


Figure 4: Time-domain performance of the IQ loops for phase disturbance rejection with a settling time of 20 μ s.

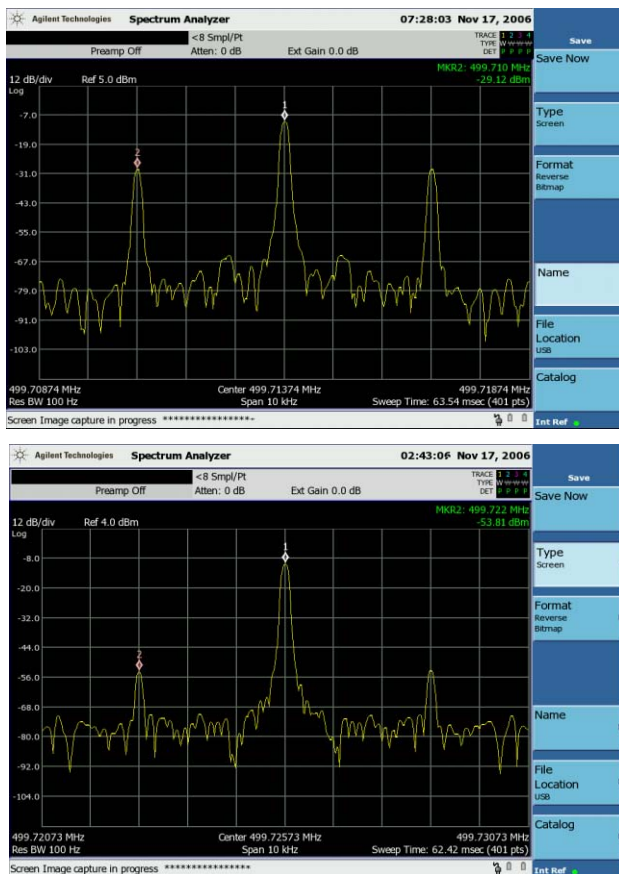


Figure 5: Frequency-domain performance of the IQ loops for 3 kHz phase ripple rejection; above: without regulation; below: 24 dB ripple reduction with regulation.

The ALLRF system was successfully tested in all the four I/Q quadrants with a dynamic range of more than 26 dB as can be seen in figures 6.

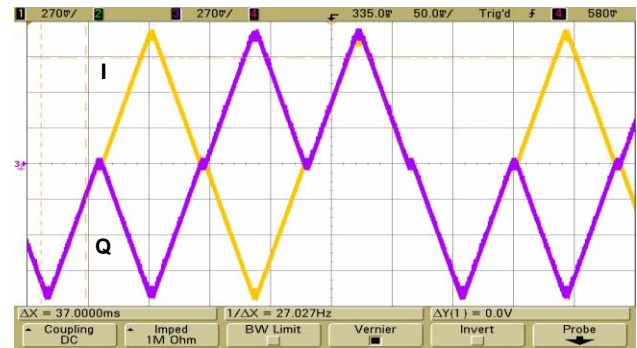


Figure 6: Measured I/Q components of the cavity voltage in ramping mode with 4-quadrant phase coverage and dynamic range of > 26 dB.

The measured peak-to-peak noise on the baseband signals was 5 mV giving a short-range amplitude and phase stability of 0.25% and 0.4° approximately. The system was also operated in a non-regulated temperature environment during several hours with no significant drift on the baseband signals.

During the tests (both DC and ramping) the cavity reflected power was always monitored by a power meter and the level was at least 25dB lower than the forward power.

SUMMARY AND CONCLUSIONS

A low cost Analogue LLRF prototype based on quadrature demodulation/modulation and PID regulation has been designed and developed at CELLS.

The system has gone through extensive tests to evaluate its performance for RF field stabilization, dynamic range, bandwidth etc. and the results were always better than the specifications.

The final Analogue LLRF for the booster is currently being built and will be installed in the ALBA booster in few months.

REFERENCES

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