

# CALIBRATION OF THE ACCELERATION VOLTAGE OF SIX NORMAL CONDUCTING CAVITIES AT ALBA

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## Abstract

ALBA is a 3GeVsynchrotron light source located in Barcelona and operating with users since May 2012.The ALBA storage ring uses six room temperature cavities; each one fed by combining two 80kW IOTs amplifiers at 499.654 MHz.

An accurate calibration of the RF voltage is required for the right adjustment of the RF phase with respect the beam. In addition, since the ALBA the ring accommodates several RF cavities, these may not be optimally phased with respect to each other, complicating the calculation of the total RF voltage. In this paper, the steps to calibrate the accelerating voltage of the SR will be presented and different methodologies to cross-check these calibrations.

## INTRODUCTION

ALBA is a 3 GeV, 400 mA, 3rd generation Synchrotron Light Source in Cerdanyola, Barcelona, Spain, operating with users since May 2012.

The RF System, formed out of six RF plants, provides up to 3.6 MV of effective voltage and restores up to 540 kW of power to the electron beam. A cavity combiner add the power of two 80 kW IOTs to produce the more than 150 kW needed for each DAMPY cavity, a normal conducting HOM damped cavity developed by BESSY and based in the EU design cavity [1].

The total RF voltage seen by the beam depends on the relative RF phase between cavities which means that it is important to properly adjust RF field phase of each cavity with respect to the beam. To optimize the performance of the system, the RF voltage and phase of each cavity is controlled independently via a digital low level RF (DLLRF) [2].

## OPERATION WITH SEVERAL RF CAVITIES

When several cavities are in operation the net accelerating voltage per turn is:

$$V_{acc} = |V_{cav,1}| \sin(\phi_{s,1}) + |V_{cav,2}| \sin(\phi_{s,2}) + \dots, \quad (1)$$

where  $\phi_{s,i}$  is the RF phase respect to the beam of each cavity.

The total effective voltage can be represented as the vector sum of the cavity voltage of each RF station:

$$\overline{V_{eff}} = \overline{V_{cav,1}} + \overline{V_{cav,2}} + \overline{V_{cav,3}} + \dots \quad (2)$$

If the RF phase of the cavities with respect the beam is not the same the  $|\overline{V_{eff}}|$  is reduced, as shown in figure 1 and 2.

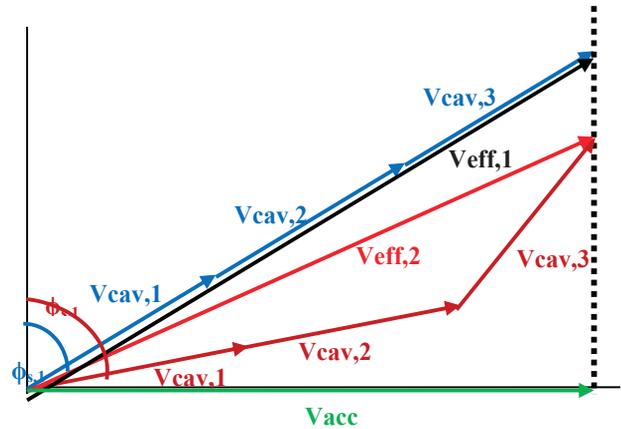


Figure 1: The effective voltage,  $V_{eff,1}$  is the sum vector of three cavity voltage in phase and  $V_{eff,2}$  is the sum when two cavities are in phase and one not  $\phi_{s,1} = \phi_{s,2} \neq \phi_{s,3}$ .

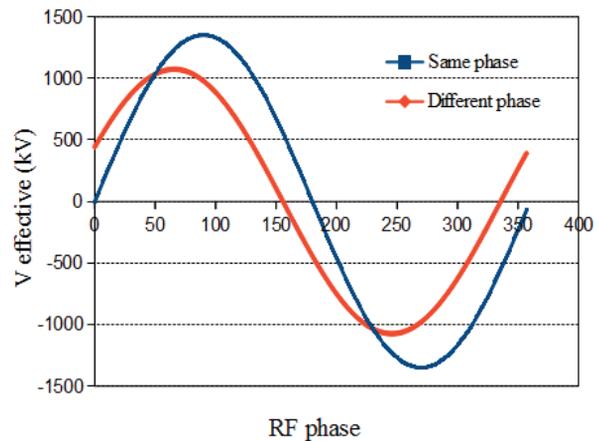


Figure 2:  $\overline{V_{eff}}$  when RF phases between the three cavities are the same and when  $\phi_1 = \phi_2 \neq \phi_3 = \phi_1 + 80$ .

## RF CALIBRATIONS

### Forward and Reflected Power

RF power in the transmission lines is measured by means of directional couplers, device that couples a small amount of the power flowing through the line, in a given direction, towards one port.

There is a bidirectional coupler installed at the RF input of each cavity, which provides signals proportional to the forward and reflected power to the cavity. These signals are later digitalized for monitoring purposes.

The amount of power that is coupled to each port is factory calibrated, but the losses introduced by cables, connectors and front ends before the signals digitalization are not easily calibrated, so a reference signal has to be used to compare the measurements with the actual power values.

In order to calibrate the whole system without having to calibrate each individual component, we rely on the calibrated output power of the transmitters. This calibrated signal is used as reference to calibrate the bidirectional couplers signals of the input cavity. To do so, the measurements of the cavity bidirectional coupler are fitted making the following assumptions:

The coupling factor of the ALBA cavities was set to  $\beta = 2.6$ , this means that in the absence of beam ( $i_{beam} = 0$  mA), 20% of the incident power is reflected.

So, when the beam current is 0mA, then:

Forward power cavity = output power of the transmitter.

Reverse power cavity = 0.2. (output power of the transmitter).

Since electronic parameters change with temperature and time, the calibration factors have to be checked after a certain period of time, so it is necessary to have a method that could be done remotely and without dismounting any equipment.

A Matlab script has been developed for varying the output power of the transmitters and measure all the relevant cavity signals, so that recalibration of the digitalized measurements of the directional couplers is automatically done.

### Cavity Voltage

The cavity voltage is measured by a pickup loop installed in the cavity that sample the cavity voltage and permit to measure its amplitude and phase.

In addition, the cavity voltage can be calculated from the dissipated power of the cavity and the shunt impedance.

$$P_{dissipated\ cavity} = \frac{V_{cav}^2}{2R_s} \quad (3)$$

Assuming that the dissipated power is equal to the forward power of the transmitter minus the reflected power, we can establish a correlation (coupling) between the actual cavity voltage and the digitalized measurement of the pick-up loop signal.

$$Coupling\ Pick\ up = 10 \cdot \log \left( \frac{V_{Pickup}^2 / 2.50}{V_{Cav}^2 / 2.Rs} \right) \quad (4)$$

### RF Phase Respect to the Beam

During beam operation, and using the previous calibrated signals, some dynamic attributes are used to calculate the RF phase with respect to the beam.

The power delivered to the beam ( $P_{beam}$ ) is obtained invoking the conservation of energy:

$P_{beam} = P_{forward\ cavity} - P_{reverse\ cavity} - P_{dissipated\ cavity}$ .

The RF phase respect to the beam  $\phi_s$  is induced from the next formula:

$$P_{beam} = V_{cav} i_{beam} \sin \phi_s \quad (5)$$

Using this method it is possible to know the RF phase respect to the beam at any moment of the operation.

### Theoretical calculations

The generator power,  $P_g$ , as a function of coupling coefficient can be expressed as:

$$P_g \left( 1 - \left( \frac{1 - \beta - \beta_{beam}}{1 + \beta + \beta_{beam}} \right)^2 \right) = P_{dissipated\ cav} (1 + \beta_{beam}) \quad (6)$$

The required generator power for different beam currents and cavity voltages were theoretically calculated and compared with the RF calibrated measurements. The results show a deviation of around 3% between both.

Table 1: Comparison Between the Generator Power Calculated Using the Formula (6) and the RF Calibrations

$i_{beam}$ (mA)	$V_{cav}$ (kV)	$P_g$ theoretical(kW)	$P_g$ calibration(kW)
50	350	30	29
100	450	51	49

### ADJUSTMENT OF RELATIVE PHASE BETWEEN STATIONS

At ALBA there are six RF cavities. During beam operation, the RF phase of the cavities are set so that all of them have the same phase with respect the beam,  $\phi_s$ , as calculated using the RF calibrations explained before.

To check the reliability of this method, the synchrotron tune, the bunch length and the lifetime of the stored electron beam of the ring were measured with respect to the RF cavity phases.

The synchrotron tune and the longitudinal beam size follow the next equations:

$$Q_s = \sqrt{\frac{\alpha_c h \left( \sum_{i=1}^n |V_{cav,i}| \cos \phi_{s,i} \right)}{2\pi E}} \quad (7)$$

$$bunch\ length = \frac{\alpha_c h}{2\pi f_s} \frac{\sigma_E}{E} \quad (8)$$

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where  $\alpha c$  is the momentum compaction of the ring,  $h$  is the harmonic number,  $E$  is the energy of the beam,  $n$  is the number of operational cavities,  $f_s$  synchrotron frequency,  $\sigma_E / E$  is the energy spread.

The total effective voltage is the vector sum of the cavity voltage of each RF station. If the relative phase is not optimized, the total effective voltage is reduced and hence the synchrotron tune and lifetime are reduced and the beam size is increased.

During the test only three cavities were in operation in order to reduce the number of parameters while maintaining enough overvoltage factor.

The RF phase with respect to the beam of one of the cavities was varied using the DLLRF. As a consequence the other two cavities changed their  $\phi_s$  to provide the needed accelerating voltage, i.e. 1 MeV to compensate the energy loss per turn, as it is shown in figure 3.

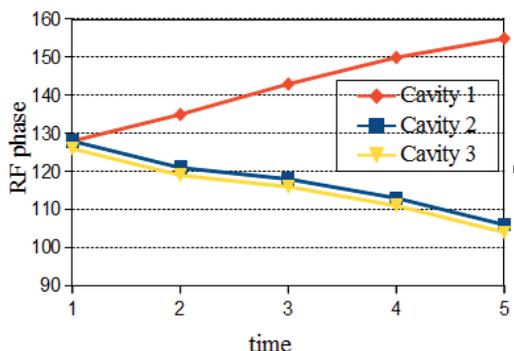


Figure 3: The RF phase respect to the beam of the cavity 1 is changed, the other two cavities varies their phase to provide the total accelerating voltage necessary for the stored beam.

The synchrotron tune, lifetime and bunch length were measured as a function of the phase deviation of one cavity respect to the optimum point (see figures 4, 5 and 6). The optimum phase is obtained when the synchrotron tune and lifetime are maximized and the longitudinal beam size is minimized.

The synchrotron tune and the bunch length were also calculated using the formulas given by (7) and (8). The theoretical results and the measurements show a deviation around 4%, demonstrating that the calibration method used is reliable.

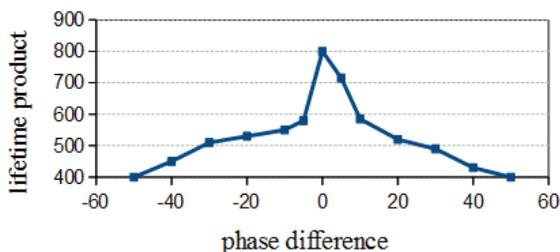


Figure 4: Lifetime versus the phase deviation of one of the cavities. The maximum is gotten for in phase operation.

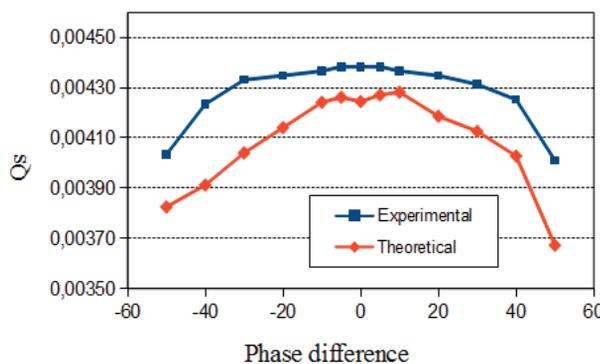


Figure 5: Synchrotron tune versus the phase deviation of one of the cavities. The maximum is gotten for in phase operation.

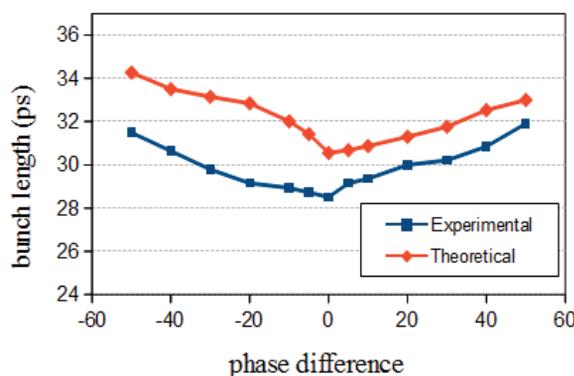


Figure 6: Bunch length versus the phase deviation of one of the cavities. The maximum is gotten for in phase operation.

## CONCLUSION

An automatic process has been implemented at ALBA to calibrate the RF cavity voltage, the power delivered to the beam per cavity and the RF phase respect to the beam. The main advantage of this method is that no external hardware or additional instrumentation is needed. The reliability of this calibration has been crosschecked with theoretical and experimental results.

This process provides a straightforward method for adjusting the relative phases between cavities. It was tested that if the relative phases between the cavities was moved from the optimum point calculated with this calibrated data, the lifetime got decreased and the bunch length increased. This proves the viability of the calibration process to adjust the RF phase between cavities.

## REFERENCES

- [1] M.Langlois, M.Cornelis, F.Perez and D.Einfeld: RF measurements on variations of the 500 MHz ALBA Dampy cavity. IPAC 2009.
- [2] A.Salom, F. Perez: Digital LLRF for ALBA storage ring. EPAC 2008.