COMMISSIONING OF THE ALBA INJECTOR WITH 67 MEV SINGLE KLYSTRON LINAC

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Abstract

The 3 GeV ALBA booster normally accelerates an injected beam of 110 MeV, delivered by the linac operating with two independent klystrons. On 2014, the linac waveguide system was upgraded and commissioned to allow operating with either klystron and providing a reduced beam energy of 67 MeV. The commissioning of the booster to capture the beam at a reduced energy and ramp it up to 3 GeV has required a long set-up process of the magnets at 67 MeV beam energy. Due to the dominant effect of the remnant magnetic field in the low energy regime, the scaling of the magnet settings at the beginning of the ramp did not allow to capture the beam, and more precise calibrations were measured on spare quadrupoles to ease its fine tuning. The effect of higher eddy currents induced when the dipoles start ramping, combined with the lower beam rigidity, has been also an issue to tune the dipole waveforms for the 67 MeV - 3 GeV cycle. The encountered problems and their solutions to commission the ALBA injector in this new mode of operation are presented in this paper.

INTRODUCTION

The ALBA light source uses a full energy injector working at 3.125 Hz and comprising a 110 MeV linac and a 3 GeV booster ring [1–3]. The injector system requires a high level of reliability and continuous operation for the top-up mode, which in turn creates much more wear on the linac klystrons which are systems with limited lifespan. The possibility of operating the linac with a single klystron provides a extra mode of operation if one of the two klystrons fails and needs to be replaced or if we want to reduce the use of the klystrons to enlarge their lifespan.

The commissioning of the new linac waveguide system was performed in 2014 with a final beam energy of 67 MeV in single klystron mode. The tuning of the booster from 67 MeV to 3 GeV has taken a long time. In fact, at the beginning all the tests to capture the lower energy beam into the booster failed, because at low beam energy the remnant field of the magnets had a strong effect and the gradient versus current quadrupole calibrations were not precise enough to set the tunes close to the right working point. This problem could not be solved by trial and error adjustments or by scanning the quadrupole settings, since in a booster with four quadrupole families as in ALBA there are too many possible combinations. The second problem arose when we started ramping the energy and a very fast tune variation was killing the beam on the half integer resonance. This effect was understood and cured by compensating the distortion of the dipole field produced by the eddy currents.

LINAC AND TRANSFER LINE SETUP

Linac with Single Klystron

The ALBA linac consists of a pre-bunching, a bunching and two accelerating sections, which under nominal conditions provides a 110 MeV electron beam. The linac cavities are driven by two TH2100 klystrons that deliver 5μs pulses at a frequency of 3 GHz. Each klystron generates a maximum output of 35 MW with a repetition rate of 3.125 Hz.

An S-band switching system implemented in the linac waveguide allows running the linac with either klystron [4]. The energy of the linac beam using one single klystron is 67 MeV, nonetheless, the delivered beam has an increase of the energy spread and of the emittance with respect to the linac beam at 110 MeV. Parameters of the linac beam measured using either klystron are shown in Table 1.

Table 1: Comparison of the Beam Parameters at the Linac Exit Measured at 110 and 67 MeV.

	110 MeV	67 MeV
σ_E/E (%)	0.13	0.14
$\epsilon_{n,x}$ $(\mu m \cdot rad)$	12.3	13.1
α_x	0.4	1.1
β_x (m)	10.1	7.6
$\epsilon_{n,y}$ $(\mu m \cdot rad)$	12.2	18.9
α_y	-0.7	0.6
β_y (m)	32.6	16.2

Linac to Booster Transfer Line Matching

Several tests have been carried out to choose a fast and reliable procedure to switch the transfer line quadrupoles from the 110 MeV to the 67 MeV mode. The best way merely consists in scaling the quadrupole setting. The cycling of the magnets is also crucial for the injector reproducibility at low energy.

BOOSTER SETUP

After several tests to capture the lower energy beam into the booster in DC mode (no ramping) without success, we understood that a better calibration of the quadrupoles at low energy was needed to fix the right settings. In fact, if the dipole settings can be finely adjusted independently of the quadrupoles by maximizing the number of turns of the injected beam into the booster, for the four quadrupole families a characterization of the field better than 1% also in the 67 MeV range was necessary. In fact, an error of 1% in the gradient of the strongest family QH02 leads to

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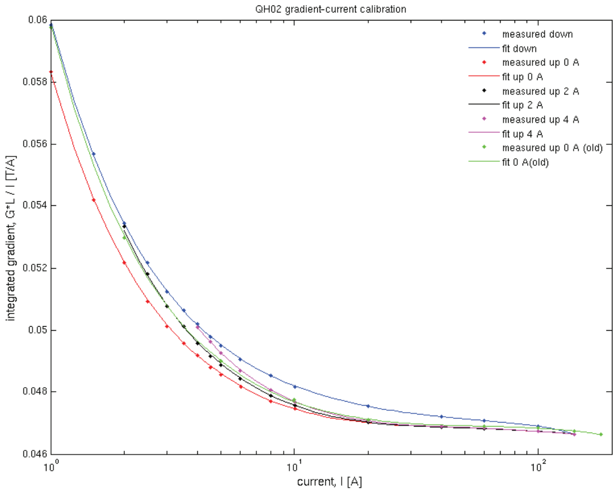

Figure 1: Calibration of the quadrupole QH02 gradient against the excitation current. The integrated gradient divided by the current, $\int G(z)dz/I$, is shown for different rising curves from a minimum of 0 A, 2 A and 4 A compared with the old calibration. The descending curve is common to all the cycles and is used for the quadrupole waveform definition.

a horizontal tune error of 0.15 and makes it impossible to capture the beam.

Magnetic Calibration of the Quadrupoles

The magnetic measurements on the booster quadrupoles, performed in 2007 before the installation, were carried out measuring only two points in the range from 2 to 5 A where the quadrupoles are set at the start of the booster ramping. This implied that the behaviour of the field in the range of low beam energy was know with an accuracy worse than 1%, too rough to guess the wanted working point of the ring.

In 2015 we decided to repeat the magnetic measurements on one spare quadrupole of the QH02 family. The integrated field was measured with the rotating coil bench of the ALBA magnetic measurement laboratory [5].

The gradient measurements were performed along a descending curve from the maximum value of 140 A to zero, and in three different ascending curves from a minimum value respectively of 0 A, 2 A and 4 A to the maximum of 140 A. From zero to 4 A corresponding to the beam energy range up to 110 MeV, the powered current was varied in steps of 0.5 A.

With these sets of magnetic measurements, a 5^{th} order polynomial fit of the integrated gradient versus the excitation current was performed for each curve to calibrate the quadrupole as shown in Fig. 1. The descending excitation curve is common to all the hysteresis cycles and must be used to fix the minimum of the magnet waveform for the digital power supplies. A detailed comparison of the different ascending curve close to 2.5 A, which is the QH02 settings corresponding to 67 MeV, pointed out that, depending on the minimum of the cycle, the remnant field can lead to a variation of the gradient larger than 1%.

For the other three quadrupoles the magnetic measurements could not be repeated and at low energy we assumed the same behaviour as QH02 just scaling the calibration to match the curve measured in 2007.

Commissioning in DC Mode

Using the new quadrupole calibrations, the capture of the beam at 67 MeV was straightforward. Small adjustments of the quadrupole settings were performed for the fine tuning of the working point to $(Q_x, Q_y) = (12.37, 7.24)$ by scaling all together the four families in steps of 0.1%. Cycling the magnets after any change was always needed to obtain a reproducible machine. Finally the steering magnets were set only by scaling the values from 110 to 67 MeV.

Effect of the Dipole Eddy Currents on the Tunes

The booster ring ramps the beam energy by increasing the strength of the dipoles and quadrupoles with sinusoidal curves with a period of 320 ms. When we started ramping the magnets, we could capture the beam with the same tunes as in the DC mode, but we lost the beam during the first 8 ms (10000 turns) hitting the second order resonance $2Q_x = 25$. After several tests we supposed that this rise of the horizontal tune was due to the fast distortion of the bending field produced by the vacuum chamber eddy currents at the beginning of the dipole ramp. An estimate of the eddy current field distortion is given by the following formula [6]:

$$\Delta B = \frac{\mu_0 k D a^2 F}{h} \dot{B}; \qquad (1)$$

where μ_0 is the permeability of vacuum, k the stainless steel conductivity, D the vacuum chamber thickness, a the horizontal semi aperture, h the half height of the magnet

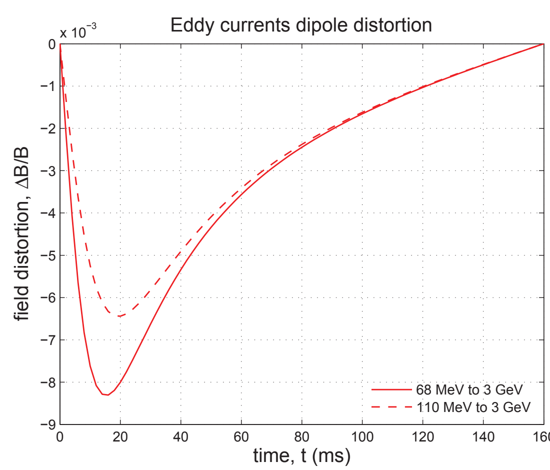

Figure 2: Estimation of the distortion of the dipole field due to the eddy currents in the dipole vacuum chamber of the ALBA booster according to Eq. 1. The comparison between the ramping from 67 MeV (solid line) and from 110 MeV (dotted line) is depicted.

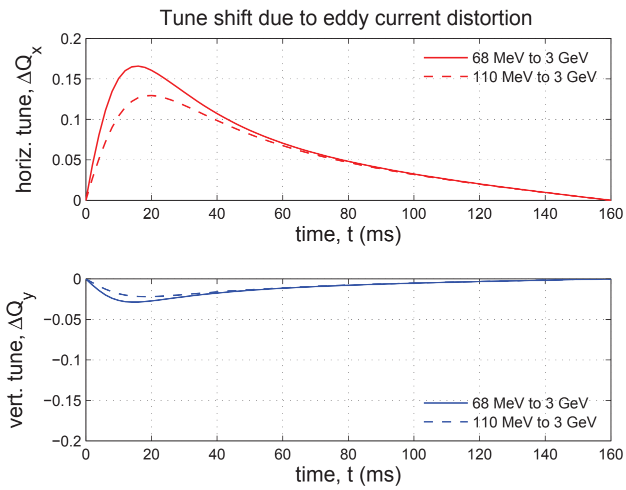

Figure 3: Horizontal and vertical tune change due to the eddy currents effect. In the 67 MeV case the Q_x peak is higher and reached earlier than in the 110 MeV case, which taking into account the lower beam rigidity makes the eddy currents effect armful for the beam.

gap, F a geometric factor of the beam pipe cross section and $\dot{B}$ the time derivative of the field. The dipole field (and the corresponding beam energy) changes by 0.85% in the first 15 ms (Fig.2), that was enough to increase Q_x up to 0.17 (Fig.3) and hitting the half integer resonance.

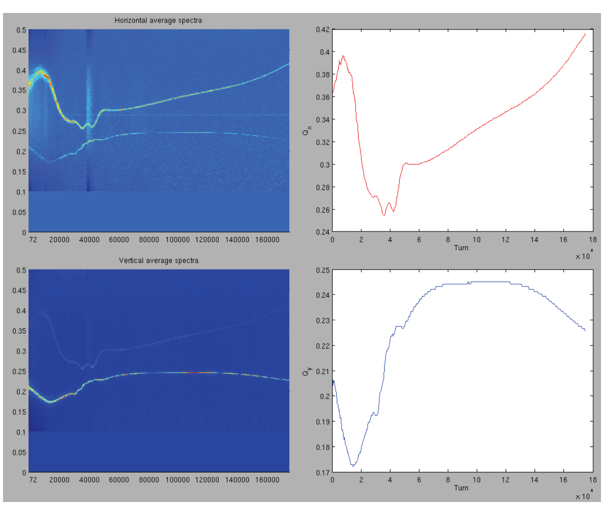

Figure 4: Measured tunes along the ramping from 67 MeV to 3 GeV. The horizontal (top) and the vertical tune (bottom) are shown against the number of turns.

Commissioning in Ramping Mode

A new booster dipole waveform was created by applying an eddy current compensating factor $(1 - \Delta B/B)$. After this

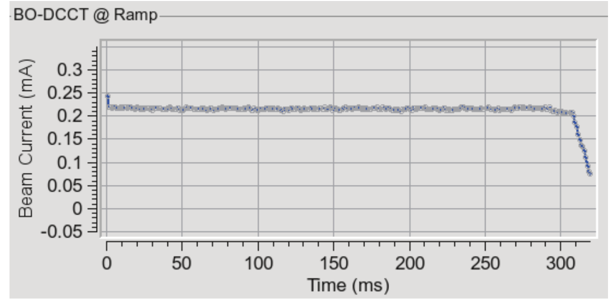

Figure 5: Measured stored current in the booster in the 67 MeV-3 GeV mode. The extraction is switched off and the beam survives in the full 320 ms long accelerating-decelerating cycle.

correction, the ramping of the beam from 67 MeV to 3 GeV was achieved very easily with sinusoidal waveforms of the magnets based on the minimum values of the DC mode and the same maximum values of the standard 110 MeV-3 GeV ramping mode. The measured tunes up to 3 GeV are shown in Fig. 4 while the stored current along the 320 ms of the accelerating and decelerating cycle is shown in Fig. 5.

CONCLUSIONS

The commissioning of the ALBA injector with a 67 MeV single klystron linac has been completed in 2015. To capture the lower energy beam and ramping it up to 3 GeV, required a fine calibration and tuning of the quadrupoles at low current and the compensation of the dipole eddy currents effect. This second mode of operation will be introduced in the standard start-up procedure after any long shut down to be always available in case one of the linac klystron fails.

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