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ALBA INJECTOR RELIABILITY IMPROVEMENT WITH AN 80 MeV LINAC BEAM

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Abstract

The ALBA injector consists of a 110 MeV Linac, a Linac-to-Booster Transfer Line (LTB) and a full energy Booster that further accelerates the electrons up to 3 GeV. The Linac consists of two pre-bunchers (PB1 at 500 MHz and PB2 at 3 GHz) a buncher and two accelerating structures (AS1 and AS2). The whole system is powered by two pulsed 37 MW klystrons at 3 GHz. To overcome an eventual klystron failure the injector has been adapted to keep operative at lower Linac beam energy. In 2014 the injection into the Booster was optimized for a Linac beam of 67 MeV, which is the energy achieved using only one klystron. However, the procedure of switching the injector from a Linac beam of 110 MeV to a 67 MeV one is not straighforward and it requires to be periodically updated. After a recent waveguide modification the RF-power sent to the first accelerating structure is equally distributed between both accelerating structures. As a result, a Linac beam of 80 MeV is achieved using only one klystron. The injection into the Booster in this mode is expected to be efficient and stable enough to be set as the nominal Linac operation mode. Furthermore, setting the nominal Linac beam energy at 80 MeV the injector operation will be assured by the hot-spare klystron in case of klystron failure

INJECTOR VERSALITY

An overview of the whole ALBA injector [1] is shown in Fig. 1. The Linac is placed in a separate bunker whereas the Booster is placed in the same tunnel than the Storage Ring. The Booster lattice has a four-fold symmetry with a circumference of 249.6 m. On-axis injection from the Linac to the Booster is achieved by using a single septum and a single kicker.

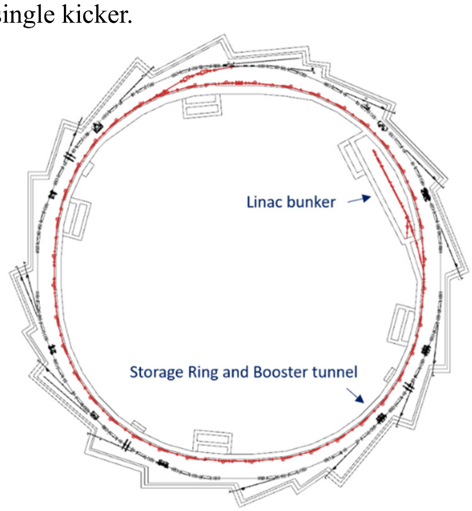

Figure 1: Schematics of the ALBA Synchrotron. All the injector elements are marked in red.

Since 2012 the nominal operation mode of the Linac is a 108.5 MeV beam consisting of 40 bunches with a total charge of 0.2 nC and 0.05 nC/bunch. In this mode klystron 1 (KA1) feeds the 3 GHz bunching cavities (PB2 and BU) and the first Accelerating Section (AS1) whereas klystron 2 (KA2) feeds exclusively AS2.

Injector operation versatility was first improved in 2014 by installing an S-band switching system in the Linac waveguide that allows using KA2 instead of KA1 in case of KA1 failure [2]. The schematics of the Linac waveguide with the implemented S-band switching system is shown in Fig. 2.

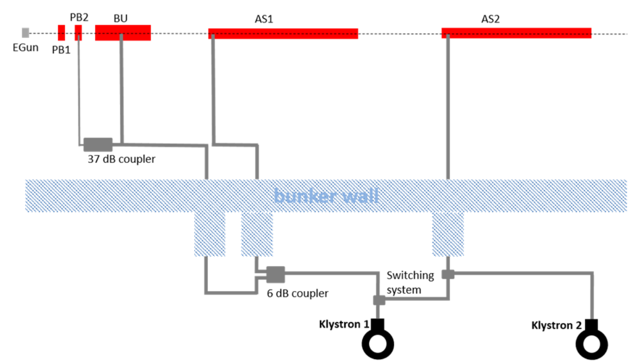

Figure 2: Schematic of the Linac RF-cavities and its waveguide system, including the S-band switching system installed in 2014.

Powering only the bunching part and AS1 with KA1 the Linac delivers a 67 MeV whereas using KA2 the beam achieved is limited to 60 MeV due to arcs in the waveguide. The power distribution of the nominal operation mode at 108.5 MeV and of the two low energy modes using only one klystron are shown in Table 1.

Table 1: RF-Power Distribution of the Current Operation Modes of the ALBA Linac

Mode	Energy [MW]	KA1 [MW]	KA2 [MW]	BU [MW]	AS1 [MW]	AS2 [MW]
Nominal	108.5	30	13	5.8	19	11.5
KA1 only	67	26		5.2	17	
KA2 only	60		22	4.5	16.2	

The whole injector (LTB, pulsed elements and Booster) was then adapted to make possible the injection (and further acceleration to 3GeV) of the low energy beam delivered by the Linac using only one klystron. Beam capture into the Booster at low beam energies was achieved despite difficulties due to non-linear effects in the Booster magnetic fields [3]. The magnetic field distortions are produced by eddy currents induced at the bending magnet vacuum chambers. These effects become more significant at lower

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beam energies because the beam requires lower magnet currents.

The injector settings to capture the beam in the Booster at 67 MeV were found first. The injection at 60 MeV was achieved later and it was more complicated due to the lower beam energy and higher beam emittance.

Injecting at 60 or at 67 MeV turned out not to be robust and stable enough to be set as a nominal mode of operation. Nevertheless, the two low energy modes have been considered and used as rescue modes. To keep them operational it is necessary to review them at least every 6 months. Switching the injector from nominal to low energy mode it can require few hours of adjustments.

Since its implementation, the low energy mode has been required and used in few occasions, mainly to overcome klystron or RF-cavity failures.

NEW WORKING MODE AT 80 MEV

A significant increase of the beam energy using only one klystron can be achieved by splitting the RF-power sent to AS1 in two equal branches: 50% to feed AS1 and 50% to feed AS2, as shown in Fig. 3.

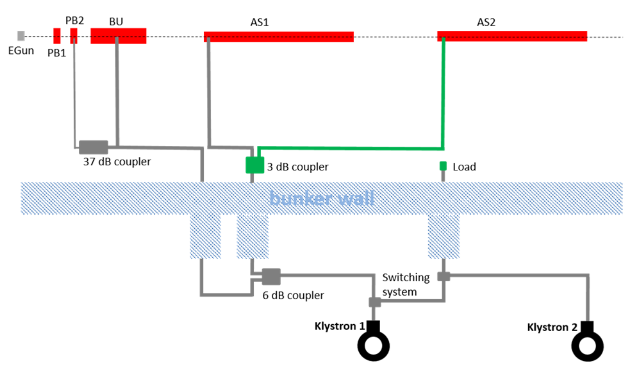

Figure 3: The modification of the Linac waveguide (shown in green) allows equally distributing the power that previously was send entirely to AS1 among AS1 and AS2. A beam energy gain of 40% is achieved.

According to the power calculation formula,

$$P = \frac{V^2}{R} \quad (1)$$

for a given klystron power P the total voltage V applied to the electron beam increases by a factor $\frac{2}{\sqrt{2}}$ since AS1 and AS2 are identical and have the same resistance R:

$$V = \sqrt{\frac{P}{2}R} + \sqrt{\frac{P}{2}R} = \frac{2}{\sqrt{2}}\sqrt{P\,R} \quad (2)$$

The beam energy gain along AS1 and AS2 will then be increased by the same factor:

$$Energy\ gain_{AS1+AS2} = \frac{2}{\sqrt{2}} * Energy\ gain_{AS1} \quad (3)$$

Based on this principle, an improved low energy mode at 80 MeV using only one klystron has been implemented at the ALBA Linac. Although using KA1 a 92 MeV beam could be achieved, a 80 MeV beam has been preferred because it is reachable by both klystrons and avoids arcs in the waveguide. The 80 MeV beam is expected to be much robust than the 67 MeV one and could be set as nominal operation mode in the close future. This new mode of operation enlarges the number of possible operation modes of the Linac and of the ALBA injector, as shown in Table 2.

Table 2: The different modes of operation of the ALBA injector. The new low energy modes at 80 MeV using one klystron are being commissioned (shown in grey).

Energy [MeV]	KA1	KA2	Cavities fed
108.5	On	On	BU + AS1 + AS2
67	On	Off	BU + AS1
60	Off	On	BU + AS1
80	**On**	**Off**	**BU + AS1 + AS2**
80	**Off**	**On**	**BU + AS1 + AS2**

Linac Waveguide Modification

The required modification of the Linac waveguide for achieving a 80 MeV beam with only one klystron is shown in detail in Fig. 4.

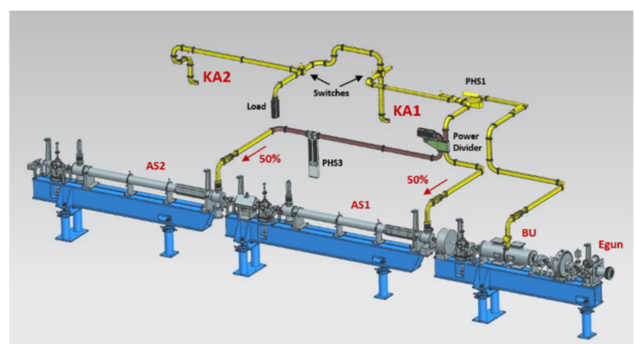

Figure 4: Schematic of the ALBA Linac and the waveguide system with the upgrade that allows feeding the full Linac with a single klystron. The new parts are drawn in brown. To switch to the previous waveguide configuration (shown in Figure 2) it takes about 2 hours.

The key elements of this upgrade are a 3 dB power divider to equally split the RF-power among the two accelerating structures and a phase shifter (PHS3) to set the phase at the AS2 entrance. To use this mode, the waveguide of KA2 is disconnected from AS2 and terminated to a load. Using the S-band switching system any of the two klystrons can be used to feed the whole Linac. The klystron that is not in use will be always kept as hot spare, ready to be used if the one in operation fails. Switching to the spare klystron is almost immediate, therefore, this new mode of operation increases enormously the time response after a klystron failure.

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Commissioning a 80MeV Beam with One Klystron

In March 2024 the Linac waveguide upgrade that allows feeding the whole Linac with only one klystron was implemented. First the Linac was feed with KA1 and the power was ramped slowly up to check and confirm that all new waveguide elements withstand the required power.

Then, the electron gun was set to on with the aim to reach a 80 MeV beam at the Linac exit. For that, the RF-phases were adjusted. In particular, the matching between the Buncher and AS1 was adjusted by means of phase shifter 1 (PHS1) and the phase between AS1 and AS2 was done by means of the new phase shifter 3 (PHS3). The magnets along the Linac were scaled to the new energy and the alignment of the beam was readjusted at each step. A similar procedure was performed powering the Linac with klystron 2.

The final beam energy and energy spread was measured at the diagnostics line using a bending magnet as a spectrometer. Figure 5 shows the measurements of the 80 MeV beams achieved by powering the Linac with either klystron. Both beams have a low energy spread and are stable, which is essential for being injected into the Booster.

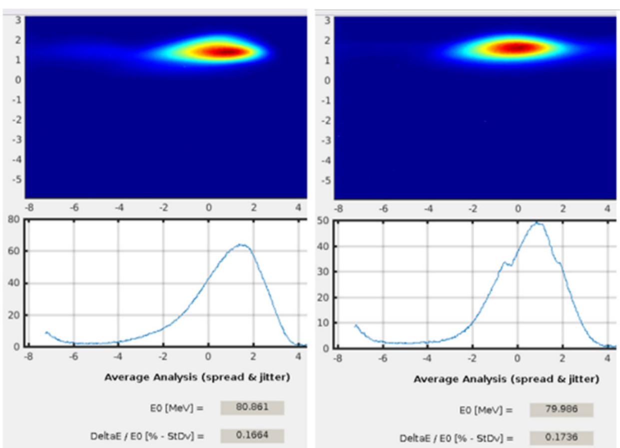

Figure 5: Energy and energy spread measurements of a 80 MeV beam using only KA1 (left) and only KA2 (right). The measurements are an average of 10 shots at 0.2 nC.

The RF-power distribution of the new single klystron operation mode is shown, for each klystron, in Table 3. The table contains the estimated and the measured power values at the entrance of each cavity. The estimation was based on the power used in the nominal 108.5 MeV mode. It is noticeable that the power that reaches AS2 is not equal to the one that reaches AS1 but lower. This is due to power losses in the waveguide, which has a longer path for AS2. The rest of the RF-power measurements are in good agreement with the estimated ones.

Table 3: RF-power distribution of the new low energy mode at 80 MeV using one klystron. In bold are measured values, in grey are estimated values

Mode	Energy MeV	KA1 MW	KA2 MW	BU MW	AS1 MW	AS2 MW
KA1 only	80	23.7		4.8	8	8
	80.9	**22.8**		**5.1**	**8.1**	**6.6**
KA2 only	80		22	4.5	8.1	8.1
	80.2		**21.4**	**5**	**8.4**	**6.9**

Booster Injection at 80 MeV

The commissioning of the injection of a 80 MeV Linac beam into the Booster is under way. First, strategies of scaling the injector settings from 108.5 MeV downwards were applied assuming that the non-linear effects in Booster magnetic fields could be overcomed at 80 MeV. After unfruitful results, the same process used to find the injector at 60 and 67 MeV is being applied. Thousand of turns have already been achieved, which indicates that the acceleration of the 80 MeV beam at 3 GeV will be available in the following weeks.

CONCLUSIONS AND OUTLOOK

The ALBA injector has been reliably running for twelve years, ten in top-up mode. Hardware upgrades, such as the single klystron working mode at 67 MeV have enhanced the Linac operation versatility. Another boost to the injection reliability will be the implementation of the single klystron working mode at 80 MeV as nominal Linac operation mode. This mode will increase enormously the time response after a klystron failure.

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