HIGH CURRENT OPERATION OF PRE-BUNCHING CAVITIES IN THE CTF3 ACCELERATOR

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Abstract

Two single-cell pre-bunching cavities at 3 GHz have been constructed by the LAL laboratory for the injector of the CLIC Test Facility (CTF3). Although simple in appearance, special care has been taken in the design of one of the pre-bunchers for which calculations showed the destructive presence of beam-loading. We present a brief summary of the RF simulations of the pre-bunchers and of the in-situ RF conditioning. Operation with the electron beam is also reported.

INTRODUCTION

In order to test various issues related to the multi-TeV linear collider (CLIC) proposed by the CERN, prototype test facilities have been built in several stages. The latest, CTF3 is currently under development. LAL has already contributed to the preliminary phase of CTF3 with the construction of a 2 A, 90 kV thermionic gun [1]. In this paper, we report on the construction and the operation of two pre-bunching cavities for the initial phase of CTF3. The performance of the complete accelerator is described elsewhere [2].

RF DESIGN

At first glance, this stage should not be complicated as the general shape of the cavity is the well-known cylindrical pill-box. However, there are two main differences between the first cavity, PB1, and the second, PB2, downstream of PB1. Indeed, PB1 sees a CW electron beam, hence there is little concern about the interaction between the cavity and the beam. Therefore, we decided to use a normal high quality factor copper cavity. Whereas, the beam, bunched due to the field of PB1, interacts with the cavity impedance of PB2 and induces a voltage which can degrade the beam quality. The solution we adopted to reduce the beam loading in PB2 was to make an over-coupled cavity from stainless steel.

First pre-buncher

In principle, it is unnecessary to use a 3D code to calculate the dimensions of a cylindrical cavity at 3 GHz. However, one needs to inject the power into the cavity via a coupling hole and the dimensions of the coupling aperture and its influence on the resonant frequency are not easily calculable analytically. Nevertheless, it is still possible to initially estimate the dimensions of the coupling hole using analytical formulae [3] and to refine them with simulations. The aim is to find the dimensions for a coupling factor of unity, in which case the reflected RF power is near to zero. The cavity is shown schematically in figure 1. This cavity is made from copper resulting in a high Q ~ 10000, and the shunt impedance is ~ 880 kΩ. The radius of the cavity is 39.1 mm and the area of coupling aperture is 10x20.6 mm^2 with a racetrack shape.

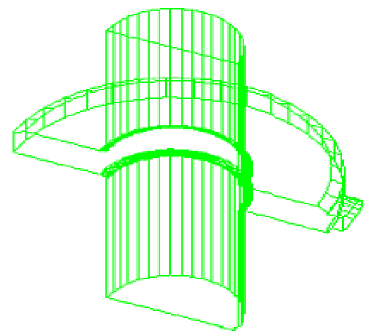

Figure 1: HFSS model of the copper pre-buncher.

Second pre-buncher

According to beam dynamic simulations [4], PB1 and PB2 must be operated at voltages of 20 kV and 40 kV respectively. Thus, in PB2, the beam is partially bunched with a bunch length of approximately 50 ps (rms). The beam loading voltage, V_{bl}, and the cavity frequency detuning, Δf, induced by the beam in PB2 can be calculated as follows:

$$V_{bl}=\frac{R_{sh}I_{harm}T^2}{1+\beta} \tag{1}$$

$$\Delta f=-f_{RF}\frac{V_{bl}\sin\phi}{2Q_L V_c} \tag{2}$$

where R_{sh} and Q_L are the shunt impedance and the loaded quality factor of the cavity, I_{harm} is the harmonic component of the current at the RF frequency, f_{RF}, T is the transit time factor, β and V_c are the coupling and the accelerating voltage of the cavity and ϕ is the phase of the bunch with respect to the RF wave.

The beam is emitted from the thermionic gun in a 1.5 µs pulse, the energy is 140 keV and the current is 6 A. The mechanical parts of this gun were provided by SLAC while the electronics, magnetic focusing coil and high-voltage power supply were built by LAL. With these parameters, and if one were to use a copper cavity, the beam loading voltage would reach 367 kV, almost 10 times larger than the applied voltage and the detuning would be 1.5 MHz which would mean total reflection of the RF power by the cavity. So, in order to avoid this situation, we built a stainless steel pre-buncher with an over-coupling of about 7 resulting in a Q_L = 125 and a bandwidth of 24 MHz. The cavity is shown schematically in figure 2. We chose to open a second aperture coupled to a load symmetrically with respect to the axis of the beam to avoid problems of RF dipole component and degradation of the emittance. However, with two apertures, we have to meet the following condition in order to minimize the reflected power: $\beta_1 = \beta_2 + 1$ where β_1 is the coupling of the first hole for the RF input power and β_2 is the coupling of the second aperture towards the load.

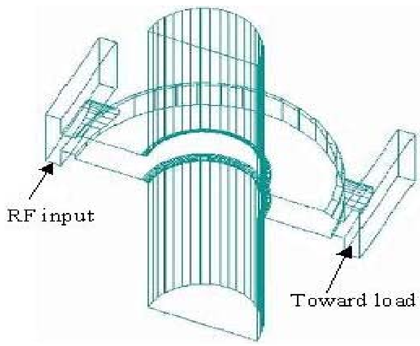

Figure 2: HFSS model of the second pre-buncher.

For the larger coupling, the apertures are 34x10 mm^2. After defining the geometries, the cavities were built proceeding by iterative steps in the mechanical adjustments and RF measurements to get the right resonant frequency and coupling. Finally, the cavities were brazed at CERN. The RF measurements showed a resonant frequency shift around 730 kHz for PB1 and almost 1 MHz for PB2. Applying a mechanical deformation along the axis of the cut-off pipes of PB1, we managed to compensate 500 kHz and as a consequence to obtain an RF reflection factor about 0.46 %. For PB2, it was impossible to use the same technique because the stainless steel is too rigid. In any case, the frequency shift is small compared to the cavity bandwidth and the reflection factor, 0.63 %, is acceptable.

RF CONDITIONING

The installation of the pre-bunchers on CTF3 was done in May 2003 and the conditioning began at the end of June 2003. In the case of PB1, in the absence of a magnetic field, the conditioning proceeded well, without breakdown, up to the nominal RF power of 500 W. An example of the measurements is shown in figure 3.

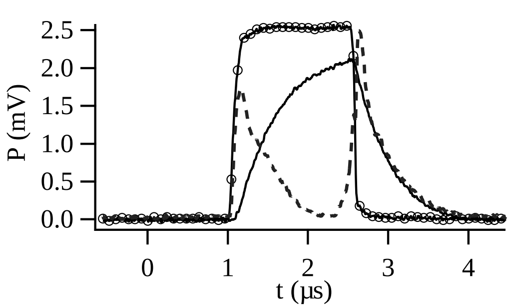

Figure 3: RF power in PB1 measured as a function of time; line with O points, incident klystron power; plain line, stored power in the cavity and dashed line stands for the reflected power at the input of PB1.

Note that PB1 is well matched as the reflected power is almost zero at the end of the pulse. The conditioning of PB2 was also successful as up to 160 kW were fed to the cavity without any problems. Measurements are shown in figure 4. The curves of the stored and reflected power are very different with respect to the previous case. Due to the very low Q, the time constant of PB2 is shorter than in PB1. Therefore, the stored power reaches the steady state in shorter time.

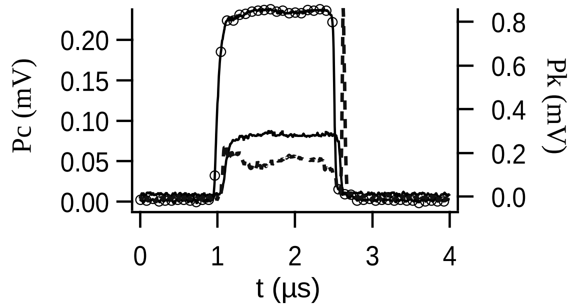

Figure 4: RF power in PB2 measured as a function of time; line with O points, incident klystron power (right axis); plain line, stored power in the cavity and dashed line stands for the reflected power at the input of PB1 (left axis).

With the residual magnetic field of a focussing solenoid, we observed multipactor, mainly in PB1. A typical measurement is illustrated in figure 5.

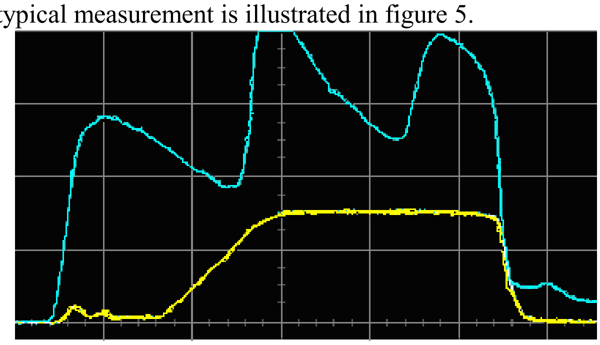

Figure 5: reflected RF power as a function of time (200 ns/div) in presence of a magnetic field; blue upper line, in PB1 and yellow lower line in PB2.

The reflected power and hence the stored energy are strongly unstable in PB1 due to the multipactor which is absent in PB2. It is possible to cancel the multipactor in PB1 if we increase the RF power to the same level as in PB2. Hence, PB1 must be operated in a range of power where the multipactor may be present but after a week of conditioning, the level was greatly reduced and the stored power was almost stable after the filling time.

OPERATION WITH BEAM

Operation of PB2 with a beam current up to 4.5 A was satisfactory at the nominal RF power. Unexpectedly, we noticed the presence of a beam-cavity interaction which seems to decrease the energy stored in PB1. And, as illustrated in figure 6, the impact on the PB1 voltage becomes stronger as the beam current is increased. In addition, the multipactor is enhanced by the presence of the beam.

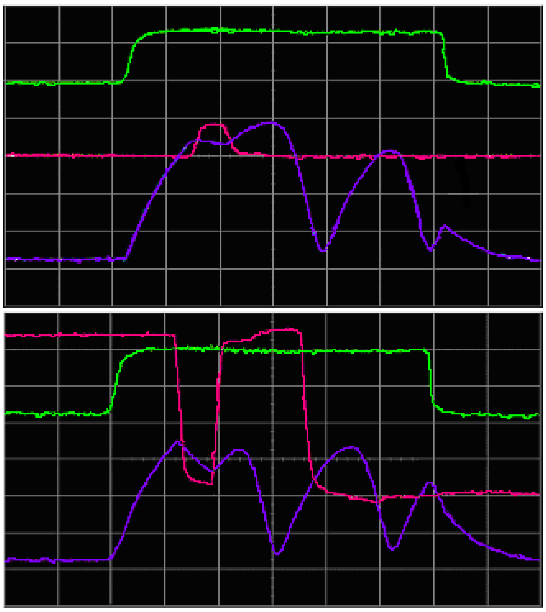

Figure 6: RF signals measured with an oscilloscope, 500 ns/div; green upper curve, klystron incident power; violet lower curve, stored power in PB1 and pink middle curve stands for the beam pulse. Upper picture is for 1.5 A beam current and lower picture for 3.9 A.

As a function of the beam current, the cavity voltage can be either flattened or decreased. It appears very similar to beam loading as was foreseen and compensated for in PB2. However, in PB1, the beam emitted by the thermionic gun at an energy of 140 keV is CW. Since there is no modulation of the current at 3 GHz, there is no way that a voltage can be induced in the cavity according to the classical mechanism of the beam loading.

Nevertheless, the beam induces a detuning of the cavity which leads to an enhancement of the reflected power and to a reduction of the cavity voltage. Indeed, during the experiments with CTF-3, we noticed that it was possible to cancel the increase of the reflected power due to the beam thanks to a change of PB1 temperature with the water cooling system. So, we measured the detuning as a function of the beam current for 1 W of forward RF power to PB1. The results are shown in figure 7.

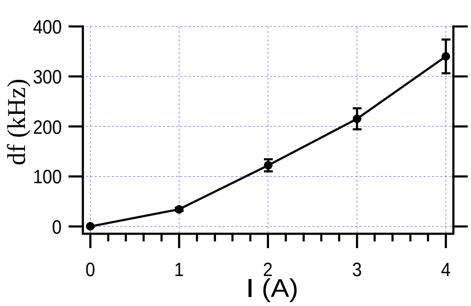

Figure 7: detuning of the pre-buncher PB1 as a function of the beam current for 1 W of input RF power.

The detuning can reach 340 kHz at I = 4 A, which is the same order of magnitude of the bandwidth of the cavity.

As the results seem to indicate the presence of beam loading, we decided to check if the beam could be sufficiently modulated at 3 GHz in PB1 itself due to the cavity voltage. It has been already observed elsewhere that a CW beam can induce a detuning due to the beam loading in the first cavity of a klystron [5]. We performed numerical simulations of the beam dynamics with PARMELA. The result is shown in figure 8.

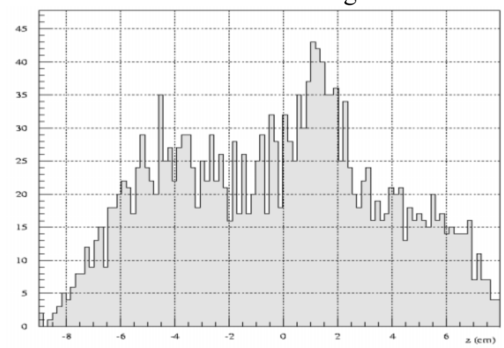

Figure 8: PARMELA simulation of the longitudinal profile (histogram) of the beam in the middle of PB1, beam energy is 140 keV and the current is 1.5 A.

Clearly, there is a small modulation of the beam current of 50 % with a bunch length approximately equal to 2.5 cm. Hence, the harmonic component of the current is I_{harm} = 0.57 A. Using (1) and (2) and assuming this modulation constant over the length of PB1, one can deduce a detuning of 300 kHz which is a factor 3 bigger with respect to the measurements shown in figure 7. But, the modulation becomes visible only in the downstream part of the cavity. Therefore, we overestimate the value of the detuning in this simple calculation. However, the beam loading is probably the cause of the detuning of PB1.

CONCLUSION

Two single cell cylindrical cavities for pre-bunching have been built by the LAL laboratory and delivered to CERN for CTF-3. In one hand, beam operation of the over-coupled stainless steel pre-buncher is quite satisfying. In the other hand, the copper pre-buncher, due to its high shunt impedance and the high current, is detuned by beam loading effect. However, CTF-3 has been operated without powering the latter and gave successful results [2].

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