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DESIGN AND BEAMLOADING-SIMULATIONS OF A PRE-BUNCHING CAVITY FOR THE CLIC DRIVE BEAM INJECTOR

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Abstract

The CLIC project is developing a multi-TeV center-ofmass electron-positron collider based on high gradient, room-temperature accelerating structures and a novel two-beam RF power generation scheme. The RF power for the CLIC accelerating structures is provided by the socalled drive beam, which is a low energy, high current electron beam. The drive beam will be generated from a high current (up to 5 A) pulsed (0.142 ms) thermionic electron gun and then followed by a bunching system.
The bunching system is composed of three sub-harmonic bunchers operating at a frequency of 499.75 MHz, a prebuncher and a traveling wave buncher both operating at 999.5 MHz. The pre-buncher cavity, which has a great importance on minimization the satellite population, should be designed with special consideration of the high beam loading effect due to the high current beam crossing the cavity. In this work, we report on RF design, analytical beam loading calculations and simulations forthe CLIC drive beam injector pre-buncher cavity.

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INTRODUCTION

The beam dynamics study of the CLIC drive beam injector shows that the presence of a pre-buncher cavity before the traveling buncher has a great importance in minimization of satellite population [1]. This pre-buncher cavity will be operated at a frequency of 999.5 MHz and zero crossing RF phase. The length and acceleration voltage for this cavity are indicated from beam dynamics optimization to be 50 mm and 60 kV respectively [1]. Since the 5 A electron beam which is crossing this cavity is a periodic bunched beam with a frequency of 499.75 MHz, it will induce an additional voltage in the cavity which is referred to as the beam loading voltage V_b [2]. Therefore, in our cavity we would have two different sources for the total induced cavity voltage (V_c), the external generator $\left(V_g\right)$ and the beam loading voltage (V_b). Figure 1 shows the different type of cavity voltages and their superposition in a complex phasor diagram. We supposed that when the beam has arrived in the cavity centre, the generator voltage is out of phase by θ with respect to the beam while the beam loading voltage is out of phase by 180 ° with respect to the beam. From this diagram, we can determine the cavity voltage (V_c) and its phase relative to the beam (φ) as following:

$$V_c e^{i\varphi} = V_g e^{i\theta} + V_b e^{i\pi} \tag{1}$$

For the cavity design itself, it is ideal to have a cavity with coupling factor equal to one and higher values for shunt impedance and quality factor to minimize the input power. However, in presence of beam loading effect, any inappropriate selection for these values can result in very huge beam loading voltage and then higher necessary generator input power. In this work, we first want to calculate analytically the beam loading voltage and then try to find an optimum structure to have minimum necessary input power.

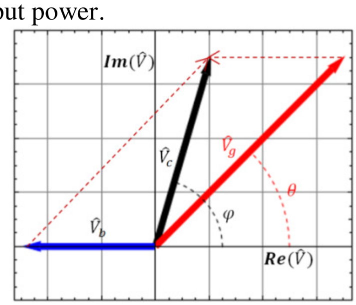

Figure 1: superposition of different cavity voltages in Complex plane as phasors.

BEAM LOADING CALCULATIONS

When a bunch of particles is crossing a cavity, the total bunch energy change is equal to [4]:

$$\Delta\varepsilon_b = q_b V_0 T F_b, \tag{2}$$

where q_b, T, F_b and V_0 are bunch charge, transit time factor, bunch form factor and electric field integral on the cavity axis respectively. To explain the beam loading effect in a simple way, we consider an empty thin lens cavity that is crossed by a beam composed of several identical point like bunches marked with numbers: 1, 2, ... respectively. Since the current has a sinusoidal time dependence with the beam frequency of ω_b, so according to Fourier transformations it can produce several harmonic electromagnetic field components. The n-th harmonic has a frequency of $\omega_n = n\omega_b$ [3]. Only one of these components, which has a very close frequency to the cavity resonant frequency ω_r, can be exited dominantly. To have a steady state in presence of a generator this frequency should be equal to generator frequency ω. Now we suppose at $t = 0$, the first bunch induces a voltage $-v_1$ in the cavity. From this time up to the arriving of the second bunch, the induced voltage inside the cavity $(\hat{V}^{(1)}(t))$ is equal to $-v_1 e^{(i\omega - \frac{1}{\tau_f})t}$. Where τ_f is the cavity filling time [4]. In addition, this bunch can interact with self-induced field and changes its energy by $\Delta\varepsilon^{(1)}$ which is equal to $\frac{1}{2} q_b \Re\{\hat{V}^{(1)}(0)\}$ [2]. Also according to conservation of energy, the electromagnetic energy stored inside the cavity from this

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time to the arrival of the second bunch ($U^{(1)}(t)$) would be equal to $-\Delta\varepsilon^{(1)}e^{-\frac{2}{\tau_f}t}$. In the other hand according to definition of shunt impedance (R_{sh}) and unloaded quality factor (Q_u), we should have [4]:

$$\frac{\left|\hat{V}^{(1)}(0)\right|^2}{U^{(1)}(0)} = \frac{\omega_r R_{sh}}{Q_u} \tag{3}$$

Therefore v_1 should be equal to $\frac{q_b\omega_r R_{sh}}{2Q_u}$. When the second bunch is crossing the cavity, it will induce the same field in the cavity like as the first bunch, but additionally it will interact with the remaining field produced by the first bunch. Again, with same approach we can find the voltage v_2 for this crossing. This method can be repeated to any desired order and at the end by generalization to real problem (from definition of bunch form factor and transit time factor), we arrive at the following formula for the beam loading voltage [4]:

$$V_b \cong \frac{Tq_bF_b\omega R_{sh}}{4\pi(1+\beta)\sqrt{1+\frac{2Q_u}{1+\beta}\delta(\omega)}}, \tag{4}$$

where β is cavity-waveguide coupling factor and $\delta(\omega) = \frac{\omega-\omega_r}{\omega_r}$ called detuning angle. This relation contains all information that we need to compensate the beam loading effect. Since shunt impedance is inversely proportional to square root of conductivity, so to have lower beam loading voltage it is better to use more resistive material for cavity construction. As an example according to this formula, the beam loading voltage for a cavity constructed with copper is 7 times bigger than a structure with the same coupling factor but made from stainless steel. Since we are not looking to maximize the shunt impedance, the simple pillbox shape seems appropriate. Moreover, if we design our cavity in over-coupling mode ($\beta > 1$), or detuned resonant frequency ($\omega_r \neq \omega$), it decreases the beam loading voltage. However, each one of these approaches can increase the necessary input power [4]. The amount for necessary generator power to induce net cavity voltage $\hat{V}_C$ is equal to [4]:

$$P_g = \frac{(1+\beta)^2\left(1+\left(\frac{2Q_u\delta(\omega)}{1+\beta}\right)^2\right)\left|V_c e^{i\varphi}+V_b\right|^2}{4\beta R_{sh}} \tag{5}$$

This relation can be minimized for any selection of cavity structure with respect to the coupling factor and detuning. During the minimization, we should pay attention that the detuning angle and the coupling factor cannot be very far from their resonant values ($\delta(\omega) = 0,\ \beta = 1$) because it will degrade the power delivered to the cavity. The amount of power delivered to the cavity before arrival of the beam (P_d) can be calculated from [5]:

$$P_d = \frac{\frac{4\beta P_g}{(1+\beta)^2}}{1+\left(\frac{2Q_u}{1+\beta}\cdot\delta(\omega)\right)^2} \tag{6}$$

For this minimization we used constraints $|\delta(\omega)| < \frac{(1+\beta)}{2Q_u}$ and $\beta < 6$ to keep P_d more than half of its maximum. After the minimization, we can compare all results to find the optimum cavity working point.

DESIGN AND SIMULATIONS

To design the pre buncher cavity, according to discussion in previous section we chose a pillbox structure with stainless steel material. In addition, to eliminate undesired higher order modes, we open a second aperture coupled to a load symmetrically with respect to the cavity axis. Figure 2 shows the geometry for this structure. To feed the structure from a generator we used WR975 standard waveguide that is connected to the cavity through a racetrack aperture. For this structure, we can minimize the generator power according to the approach that was mentioned in the previous section. Figure 3 shows the analytical minimum value for P_g versus different βs. According to these calculation the minimum P_g can be obtained with $\beta = 2.5$ and $\delta(\omega) = 0$. However, there is still one other important point that the selection of the coupling factor can affect the beam loading voltage stability. Improper selection of β can induce a transient beam loading voltage in the structure. Particle tracking codes like as CST Particle Studio can be used for beam loading simulations. We tracked in CST a 5 A, 140 keV beam of electrons with the same characteristics determined from the beam dynamics optimization [1]. According to CST simulations for several cavity structures with the same geometry but different coupling factor near the analytical minimum 2.5, the most stable situation can be obtained for the structure with $\beta = 3.738$. We preferred the stability in comparison with the minimum input power chose the latter. Figure 4 shows the time signal, which can be observed at the waveguide output. According to this diagram, after 600 ns, which corresponds to 300 bunches we will arrive at steady state. Figure 5 shows the CST simulation result for longitudinal phase space of particles in place of the pre-buncher. According to this diagram, the beam loading voltage (V_b) should be around 20 kV. With this value for beam loading voltage and relation (5), we can calculate the total generator power needed to induce net voltage of 60 kV inside the pre-buncher as follows:

$$P_g = 66.4\text{ kW}\cdot\left(1-\frac{3}{5}\cos\varphi\right) \tag{7}$$

According to this relation, in case of zero crossing phase, we need only 66.4 kW input power while in maximum phase difference ($\varphi = \pi$) we need 106.24 kW.

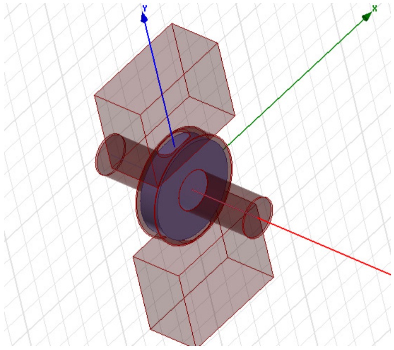

Figure 2: HFSS model for Pre-Buncher structure.

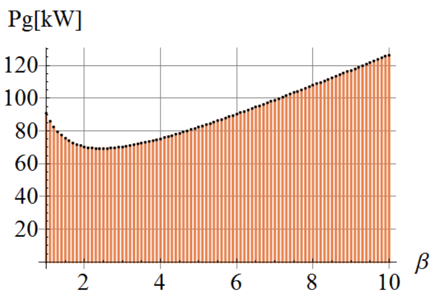

Figure 3: Analytical minimum value for P_g versus β.

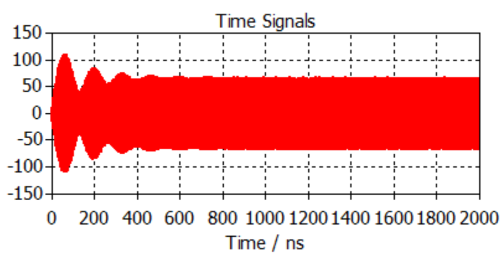

Figure 4: CST simulation results for time signal in the waveguide output port.

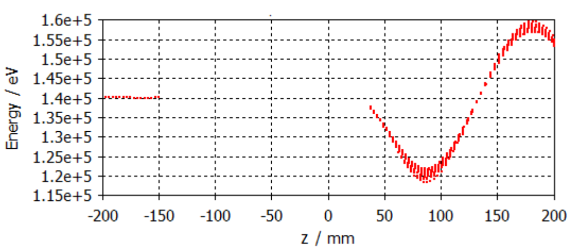

Figure 5: CST simulation results for longitudinal phase space of particles in the stationary state for two subsequent bunches. The first bunch has crossed the cavity while the second bunch is entering.

According to HFSS simulations, the optimum value for the coupling factor ($\beta = 3.738$) can be achieved by 119.055 mm cavity radius and a race-track coupling aperture with $39 \times 84\ mm^2$ area. Figure 6 shows the results obtained from HFSS simulation for the fraction of generator power, which can be delivered to this structure for different frequencies around 999.5 MHz. For this structure, all important cavity quantities are presented in Table 1.

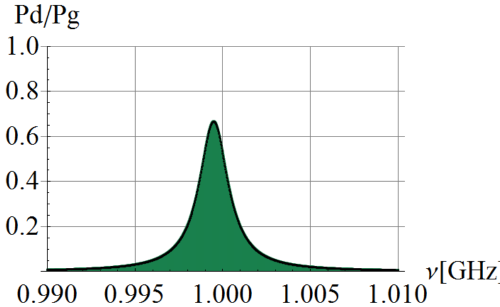

Figure 6: HFSS simulation results for relative power delivered to the cavity versus frequency.

Table 1: HFSS simulation results for cavity quantities

Quantity	*Value*
Q_u	2372.560
β	3.738
τ_f (μs)	0.159
R_{sh} (kΩ)	89.698
T	0.494

CONCLUSION

A pre-buncher cavity is designed for the CLIC drive beam injector with special consideration of the high beam loading effect. The cavity design is based on the beam loading theory and CST simulations with the goal of having minimum input power and sufficient beam loading voltage stability. The simulation results for this optimized structure show that the beam loading voltage is around 20 kV and to compensate it and produce 60 kV net voltage in the optimized pre-buncher we need only 66.4 kW input power.

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