SUB-HARMONIC BUNCHER DESIGN FOR THE CLIC DRIVE BEAM INJECTOR

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Abstract

The CLIC (Compact LInear Collider) is based on two beam concept where a high current drive beam provides the energy needed for acceleration of the main beam. The CLIC drive beam accelerator starts with a high current injector using a sophisticated sub-harmonic bunching system. This paper will focus on the design of the Sub Harmonic Bunchers (SHBs) the first RF components of the injector. A backward traveling wave structure has been optimized for this task. It will be shown also how to avoid asymmetrical fields inside the coupler cells and how to compensate beam loading by changing the phase velocity in comparison to the beam velocity.

INTRODUCTION

CLIC is a future TeV scale electron-positron linear collider. High RF input power (270MW per metre) is needed to achieve high gradient on-axis electric field in the CLIC main beam accelerator (100 MV/m). Because of economical and technical reasons the usage of thousands conventional klystrons are avoided and replaced by a high current drive beam facility in parallel to the main beam. High current electron bunches are produced in the CLIC drive beam and decelerated in PETS (Power Extraction and Transfer structure) to produce the necessary 12 GHz high power. Sub Harmonic Bunchers (SHBs) are the first RF components of the CLIC drive beam after the electron gun. The electron gun produces a continuous beam with about 140 µs pulse length, 50Hz repetition rate, 140 KeV energy and about 5A current. Inside SHBs the continuous beam is bunched and subdivided in 576(24x24) sub-trains with 243.7ns length. At the beginning of each sub-train, RF source phase is flipped by 180° as needed for further combination process in delay loop and combiner rings [1].

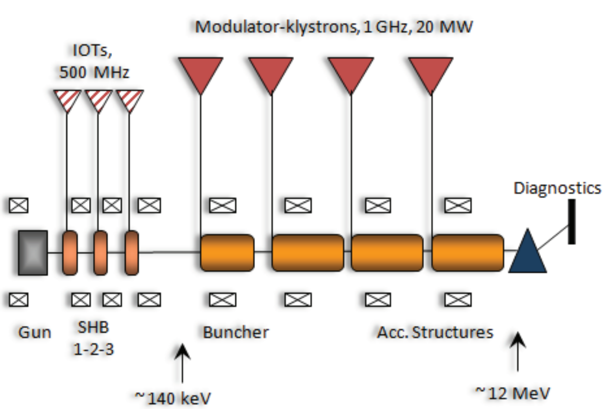

Figure 1: CLIC drive beam front-end layout.

Therefore, wide-band RF sources and SHBs is needed with fast 180° phase switching capability in 10 ns. For the combination process the SHBs resonant frequency (499.75 MHZ) should be half of the following RF accelerating structures resonant frequency (999.5 MHz). Figure 1 shows a layout of drive beam front-end as a first stage of the CLIC drive beam. At the moment, wide-band IOT seems to be the best option for SHBs RF sources.

SHB DESIGN

Band-Width Requirement Calculation

Equation 1 and Figure 2 shows a simple model of smooth 180° phase switching in 10ns from section A to C. It shows two half amplitudes $\omega_0 \pm \Delta\omega = 499.75 \pm 50$ MHz RF wave is needed in transit section (B).

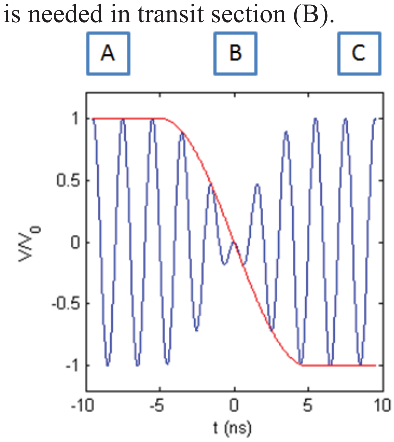

Figure 2: Smooth 180° phase switching model.

$$V = V_0 \begin{cases} \sin(\omega_0 t) : A \\ \frac{1}{2}\left[\cos(\omega_0 + \Delta\omega)t - \cos(\omega_0 - \Delta\omega)t\right] : B \\ -\sin(\omega_0 t) : C \end{cases} \quad (1)$$

Equation 2 shows the relation between field amplitude (a), band-width (B_w) and difference between resonant and driving frequencies ($\Delta\omega$). This equation shows the required bandwidth for $\Delta\omega$=50 MHz as necessary for 10ns phase switching is about 58MHz. Direct measurement with an 800 MHz IOT approved this equation [2].

$$\mathrm{a} \propto \frac{1}{1 + j\dfrac{2\Delta\omega}{B_w}} \overset{a=\frac{1}{2}}{\Rightarrow} B_w = \frac{2\Delta\omega}{\sqrt{3}} \quad (2)$$

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Cell-to-Cell Magnetic vs. Electrical Coupling

The first design of CLIC type SHBs was done by L. Thorndahl for CTF3 (CLIC Test Facility 3) [3]. They are traveling wave structures with cell-to-cell electrical coupling via beam apertures. These structures have 1.5 GHz resonant frequency, 20 KV gap voltage and about 10ns filling time. Their RF sources are TWTs with 40KW output peak power, 1.5 µs pulse length and about 160 MHz bandwidth. The CLIC drive beam injector beam dynamic study [4] shows 22,28 and 34 KV gap voltage is needed respectively for three CLIC SHBs. CTF3 SHBs rescaling calculation for 0.5 GHz resonant frequency and 10ns filling time shows a peak power of 430-1040 KW is needed which is too high. Equation 3 shows the relation between peak power (P), gap voltage (V), angular resonant frequency (ω), filling time (τ) and total R/Q factor. To keep the peak power low enough the R/Q factor should be increased then the electrical coupling via beam apertures should be avoided that reduces the R/Q factor. Therefore, a magnetic cell-to-cell coupling was chosen because it has much less influence on the R/Q factor. This selection reduces required RF peak power to 34-82 KW.

$$\mathrm{P} = \frac{V^2}{\omega\tau \frac{R}{Q}} \tag{3}$$

Cell Design

Figure 3 shows the SHBs cell design layout. The left side shows the cell structure and the right side shows the magnetic coupling hole between cells. Each coupling holes are rotated 90° related to the previous one. The cell is roughly optimized to achieve maximum R/Q according to equation 3 [5]. Coupling hole dimension is chosen to achieve 10ns filling time for a structure with four cells. The R/Q factor in this design reaches to about 500Ω. Table 1 shows the geometry dimension for the first SHB. For next SHBs, the dimensions can be changed a little to achieve different phase velocity. The difference between phase and beam velocities is needed to compensate beam loading as will be described in the next section.

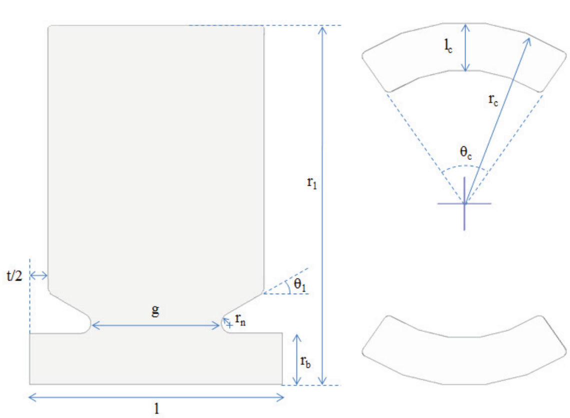

Figure 3: CLIC SHBs cell design layout.

Table 1: Geometry Dimension for First SHB Cells

g	50 mm
r_b	45 mm
r_n	4 mm
θ_1	25°
t (disk thickness)	15 mm
Frequency	499.75 MHz
l	100.00 mm
r_1	186.8 mm
r_c	157 mm
l_c	54 mm
θ_c	79.4°
Phase/Beam velocity	0.609c/0.62c
R/Q per cell	123 Ω

Beam Loading Compensation

Beam loading effect is not negligible for SHBs structures because of high current beam operation (about 5A). It should be mentioned that this kind of beam loading is different from the well-known beam loading in traveling wave structures that bunches travel on the crest. In our case bunches travel near zero crossing. At first glance, there is a similarity between this case and the beam loading in a prebuncher with one cell standing wave structure [6]. But the definition of detuning is not so obvious for a traveling wave structure. It was shown in another paper [7] that by using proper definition for detuning in a traveling wave structure, similar result to a SW case could be reached. Equation 4 shows the relation between detuning (Δω) and phase (v_p), group (v_g) and beam (v_e) velocities when bunches travel on zero crossing. F is the bunch form factor and I is the beam current. Table 2 shows these parameters for three SHBs. In our case the group velocity is negative because the structures are backward traveling wave structures. These parameters for the second and third SHBs are not finalized yet then the R/Q factor could be reduced a little to have less detuning so that the required peak power doesn't exceed 100 KW.

Table 2: Geometry Dimension for First SHB

	SHB1	SHB2	SHB3
Beam velocity (v_e)	0.62c	0.62c	0.62c
Group velocity (v_g)	-0.13c	-0.13c	-0.13c
I (A)	5	5	5
Average bunch form factor (F)	0.058	0.57	0.73
Total R/Q (Ω)	474	474	474
Frequency (MHz)	499.75	499.75	499.75
Detuning (Δf) (MHz)	1.6	12.1	12.7
V (KV)	22	28	34
V_b (V)	432	4248	5440
Phase velocity (v_p)	0.609c	0.545c	0.542c

$$\frac{\Delta\omega}{\omega}=\frac{\frac{1}{v_e}-\frac{1}{v_p}}{\frac{1}{v_g}-\frac{1}{v_e}}=\frac{1}{2\pi}\frac{V_b}{V},V_b=-\pi FI\frac{R}{Q} \quad (4)$$

Coupler Design

A high coupling between the structures and RF power source is needed then a waveguide coupling is used. The waveguide coupling has a tapered shape for a smooth transfer to a WR1800 waveguide. Figure 4 shows the entire structure with waveguide couplings. This figure also shows short-ended waveguides in the opposite side of feeding waveguides. They are used to reach symmetrical field near axis – as much as possible - to reduce the transverse beam kicking.

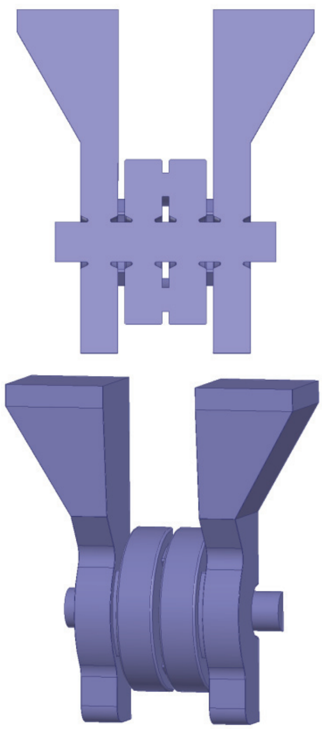

Figure 4: SHB final design.

Coupler Tuning

To tune the couplers, coupler cell radius and coupling slot length was varied to reduce s_{11} as much as possible. In the same time we should look at on-axis field pattern to be sure there is no local reflections. After each tuning, average phase velocity and asymmetrical field around axis should be checked for the proper magnitude and if is not correct the cell outer radius (r_1 in Figure 3) and short-ended waveguide lengths should be changed and coupler tuning should be repeated. This time-consuming iteration will continue to reach the proper magnitudes. Figure 5 shows the final s_{11} result and the on-axis electric field pattern at 499.75MHz.

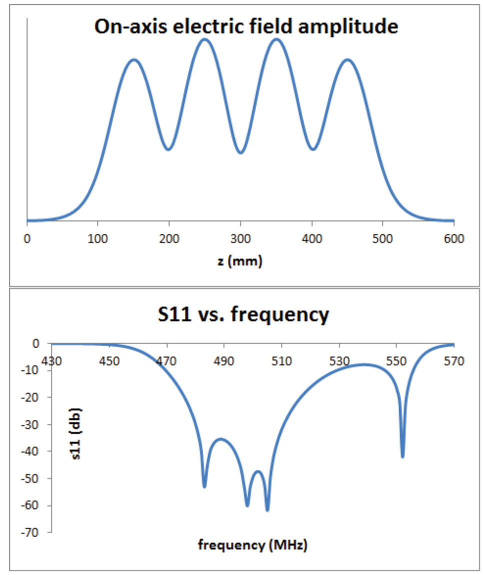

Figure 5: On-axis electric field amplitude and s_{11} with a tuned coupler.

CONCLUSION

For CLIC drive beam injector three SHBs are needed with low filling time (10ns) and between 22-34 KV gap voltages. It was showed that wide-band RF sources are needed with 34-82 KW output peak power and about 58 MHz bandwidth. Cell-to-cell magnetic couplings were chosen for higher R/Q factor that results a backward travelling wave structure. Tapered waveguide coupling is chosen for its higher coupling and short-ended waveguides is used to avoid asymmetrical field around axis. Because of high beam current operation, beam loading compensation was required. This compensation was done by cell detuning or in another word by proper difference between phase and beam velocities. Also the Fabrication of a prototype for the first SHB has been launched.

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