Design Calculations of the CLIC Transfer Structure

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Abstract

The power required for acceleration in the main linac of CLIC (CERN Linear Collider, see eg. [1]) is generated by a high current, moderate energy drive beam. The transfer structure will extract this power at 30 GHz from the drive beam. A design presently under study consists simply of a circular cylindrical beam tube of relatively large diameter (16 mm) which is coupled to the wide side of one or more rectangular output waveguides through rows of coupling holes. Output waveguide cutoff and coupling hole spacing are chosen such that the beam is synchronous with the backward TE_{10} wave of the output waveguide at 30 GHz. The RF pulse length is controlled by the length of coupling sections. By placing output waveguides on both sides of the beam tube, 160 MW/m can be extracted with section lengths of 35 cm. Numerical studies show that the desired power level can be reached with small coupling holes. Excitation and propagation of parasitic higher order modes in the beam tube limit the design. The TM_{01} backward wave in the beam tube can efficiently be suppressed using "staggered coupling."

1. INTRODUCTION

Synchronism is a necessary condition for continuous interaction of the drive beam and some electromagnetic wave in the transfer structure. In a straight cylindrical tube, synchronism is impossible. Periodic disturbances or dielectrics are necessary; we use a periodic structure. In the transfer structure, the synchronism condition determines the frequency of the output signal.

The CLIC drive beam should persist over the whole accelerator length of $\simeq$13 km. In order not to deteriorate the beam over this length, not more than the required power of $\simeq$160 MW/m should be extracted, i.e. the structure should exhibit a **low beam impedance** (the drive beam current peak value is $\simeq$20 kA!). Particularly dangerous are transverse wakefields which might cause beam break-up. They scale with the inverse 3rd power of the aperture diameter. For these reasons the transfer structure should have quite a large inner cross section, and the periodic disturbance should be very shallow.

As a third condition, the output **pulse length** should be exactly 85 RF periods, because the drive beam is accelerated at the 85th sub-harmonic (at 350 MHz), and the time gaps in the drive bunch train have to be spanned by energy storage in the transfer structure. Four of these 2.8 ns bunches make up the fill time of the CLIC main linac structure.

The most obvious type of structure satisfying the above conditions is a wide circular tube with very shallow wall corrugations [2]. We have analyzed this type of structure in some detail. The output waveguide was aligned in parallel to the beam tube and coupled to it by a series of coupling holes spaced by the structure period. It turned out that the periodic disturbance caused by the coupling holes themselves is sufficient to attain the necessary power level with a beam tube diameter of 16 mm. This makes the beam tube cylindrical.

The output pulse length T (2.8 ns) is given by

$$T = \frac{L}{v_{gr}} \mp \frac{L}{c}, \qquad (1)$$

where L is the length of the structure and v_{gr} the group velocity of the synchronous wave. The minus (plus) sign holds for the forward (backward) wave. To attain the required pulse length with a forward wave calls for a low group velocity which seems not realizable in this case. **Backward wave operation** allows for a group velocity in the order of $0.7\,c$ with a section length of 35 cm.

2. SIMPLIFIED MODEL

In a first, simplified model the excitation of modes in the beam tube is neglected. The field incident on the holes is just the TEM field around the beam. The coupling to the output waveguide is calculated by *Bethe* theory [3]. The contributions coupled through the holes are then just phase-shifted due to the output waveguide dispersion and added at the output.

The resulting amplitude of the TE_{10} wave at the output is simply

$$A(0) = \mathrm{j}\, I_0\, \frac{\sqrt{Z_0}}{2R\lambda} \sqrt{\frac{2}{ab}}\, \frac{2}{3} r_{11}^3 \left\{ \sqrt{\frac{Z_{WG}}{Z_0}} + 2\sqrt{\frac{Z_0}{Z_{WG}}} \right\} \frac{\sin(N\phi(\omega))}{\sin(\phi(\omega))}\, e^{-\mathrm{j}(N-1)\phi(\omega)}, \qquad (2)$$

the output power is $|A(0)|^2$. The other parameters are:

I_0	*Fourier* component of beam current at ω
Z_0	$c\mu_0 = 377\,\Omega$
R	beam tube radius
a (b)	output waveguide width (height)
r_{11}	coupling hole radius
Z_{WG}	$\omega\mu_0/\beta_{WG}$
N	cells per section

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$\phi(\omega)$	$(\omega/c + \beta_{WG})\,p/2$
β_{WG}	$\sqrt{(\omega/c)^2 - (\pi/a)^2}$
p	structure period = cell length

The $\sin(N\phi)/\sin\phi$-term in (2) accounts for the finite length of the structure. The proportionality of the output power to the 6th power of the coupling hole radius is due to *Bethe* theory. In a refined theory [4], where also the coupling hole depth is considered, this dependence becomes even stronger.

3. MODAL ANALYSIS

Due to its large diameter the beam tube represents a waveguide well above cutoff. The field of the beam incident on the coupling holes will not only be coupled to the output waveguide, but also be scattered back into the beam tube, exciting waves in both forward and backward direction. Also, the wave in the output guide will be coupled back into the beam tube. The field thus generated in the beam tube (the wakefield) might act back on the beam and hence must not be neglected.

To account for these effects we use as a second, refined model, a modal presentation of the total field consisting of the "space charge field" around the beam plus the "wakefield" excited by the coupling holes in both the beam tube and the output waveguide. In this representation, the fields are given by

$$\vec{B} = \sum_i A_i \vec{b}_i \,, \qquad \vec{E} = \sum_i A_i \vec{e}_i - \frac{1}{j\omega}\vec{J} \,. \tag{3}$$

$\vec{e}_i$ and $\vec{b}_i$ are the normalized electric and magnetic modal fields of mode i respectively. The last term in (3) assures that only the divergence-free part of $\vec{E}$ is expanded. It remains to determine the z-dependent amplitudes A_i.

The current density $\vec{J}$ is assumed to have only a z-component and a *Gaussian* transversal distribution. If all particles move with c it is given by

$$J_z = \frac{I_0}{2\pi\sigma^2}\exp\left(-\frac{1}{2}\left(\frac{\rho}{\sigma}\right)^2 - j\frac{\omega}{c}z\right). \tag{4}$$

The finite beam width has been introduced here not only for a more realistic model, but also substantially improves the numerical convergence.

Sections between holes: The excitation of a mode i in a straight beam tube of length z is described by

$$A_i(z) = \left[A_i(0) - \frac{I_0}{2}\,\frac{\kappa_{i0}}{j\frac{\omega}{c} - \gamma_i}\right]\exp(-\gamma_i z) + \frac{I_0}{2}\,\frac{\kappa_{i0}}{j\frac{\omega}{c} - \gamma_i}\exp(-j\frac{\omega}{c}z)\,. \tag{5}$$

The integrals for the excitation coefficients κ_{i0} can be evaluated analytically, for TM_{0i} modes they are

$$\kappa_{i0} = \frac{\chi_{0i}\,B_i}{j\omega\,R^2\sqrt{\pi}\;J'_0(\chi_{0i})\sqrt{Z_i}}\,, \tag{6}$$

where the factor B_i accounts for the transverse position and shape of the beam, for a centered beam (4) it is

$$B_i = \exp\left(-\frac{1}{2}\left(\frac{\chi_{0i}\,\sigma}{R}\right)^2\right) \tag{7}$$

for TM_{0i} modes, and zero otherwise.

The result (5) consists of a homogeneous solution with the propagation constant γ_i, and a particular solution propagating $\propto \exp(-j\omega z/c)$ with the exciting beam. The first part describes the wakefields. It is excitated only at discontinuities (at the holes) and vanishes for an infinitely long beam tube. The particular solution is just the modal expansion of the TEM field of the beam.

Coupling hole sections: The wave amplitudes A_{i2} after a (short) coupling hole section are given in terms of the amplitudes A_{i1} before it by

$$A_{i2} = A_{i1} \pm \frac{j\omega}{2}\sum_k\left\{p_e\vec{e}_k\cdot\vec{e}_{-i} + p_m\vec{b}_k\cdot\vec{b}_{-i}\right\}A_{k1}\,. \tag{8}$$

p_e and p_m are the electric and magnetic hole polarizabilities respectively. The plus (minus) sign is valid if i is a forward (backward) wave.

Matrix of a cell: If the beam is treated as another waveguide mode with amplitude I_0 and propagation constant $j\omega/c$, the results of (5) and (8) can be combined in matrix form; this is the transmission matrix of a cell of the periodic structure – its N-th power is the matrix of the transfer structure section consisting of N cells. Taking the boundary conditions into account, the overall behaviour of the structure is calculated.

4. SAMPLE RESULTS

The actual transfer structure cross section is sketched in Figure 1. Opposite coupling holes assure the suppression of unwanted dipole modes. A second pair of coupling holes is staggered by half a cell period.

Figure 2 shows as an example the inverse *Fourier* transform (time domain) output at one of the 4 output waveguides of a transfer section. The beam tube diameter is 16 mm, the coupling hole diameter 2.8 mm. The assumed drive bunch train is as foreseen for CLIC: 11 bunchlets of 160 nC each with a repetition rate of 30 GHz, repeated 4 times with a repetition rate of 350 MHz.

A power of 40 MW (76 dBW = 76 dB above 1 W) is attained. The results are in good agreement with

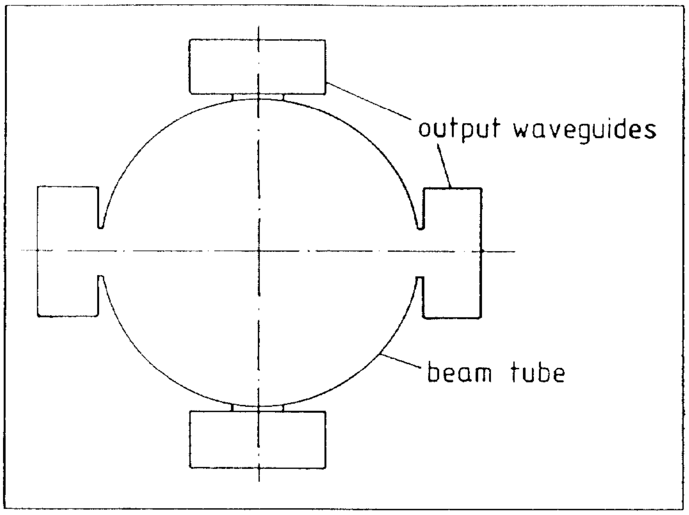

Figure 1. **Cross section of the transfer structure**. 4 output waveguides are coupled to the beam tube. One pair of coupling holes is offset from the other by half a cell length (staggered).

measurements of a scaled model [5], but predict a by about 2 dB higher output level.

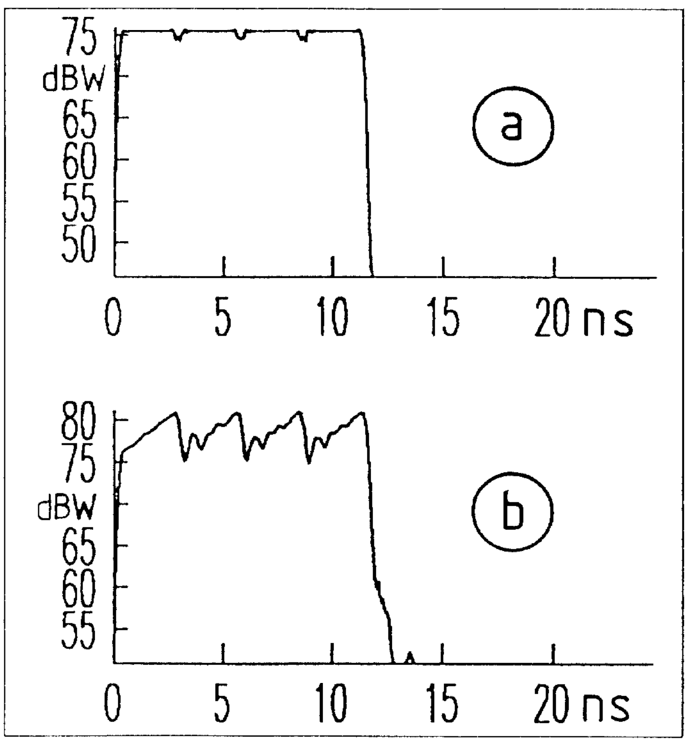

Figure 2. **Sample time domain output**. The output power in 1 of 4 waveguides is plotted versus time. Prediction by a) simplified model, and b) modal analysis.

5. STAGGERED COUPLING

The most dangerous spurious mode is the TM_{01} backward wave of the beam tube. For the considered geometry, it is synchronous at about 27 GHz. The power in this mode is lost and might destroy the beam. By staggering 2 rows of coupling holes [6] as already indicated in Figure 1, the effective structure period for monopole modes inside the beam tube is halved, thus pushing their synchronous frequencies much higher. The effect of this staggering on the spectrum of the TM_{01} backward wave is sketched in Figure 3. The peak at 27 GHz vanishes completely, the peak at 30 GHz is decreased by $\simeq$15 dB.

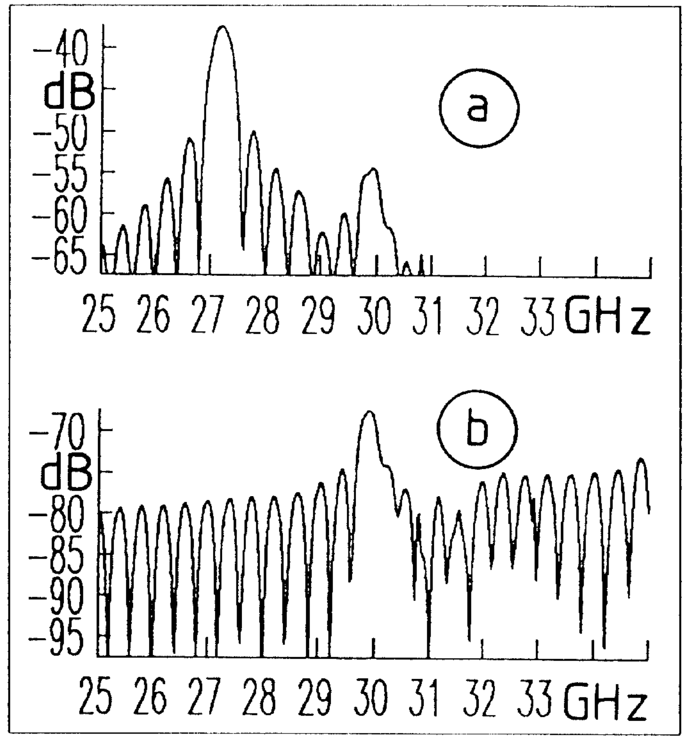

Figure 3. **Effect of staggered coupling**. The relative power in the TM_{01} backward wave plotted versus frequency. a) opposite, and b) evenly staggered coupling hole pairs.

Acknowledgement

The author wishes to thank L. Thorndahl for his help.

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