A Radio-frequency Transfer Structure for the CERN Linear Collider

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Abstract The results from experimental and three dimensional computational studies of a radio-frequency structure for use in a linear collider are presented. The structure would perform the function of converting beam energy from an UHF accelerated drive beam to 30 GHz radiation for powering the high gradient cavities of a second parallel beam, which would be accelerated to an energy of 1 TeV. Design considerations of this unusual component are discussed along with the results of low power radio-frequency tests on a scaled model which reveal the electrical characteristics of the structure. In addition a comparison of the experimental findings with 3-D computations, performed with the MAFIA codes, is given and good agreement is found. The results of tests with the structure excited by beam from the LEP pre-injector linac are also presented. The transfer structure is found to satisfy many of the requirements needed for the role it would play in a two-beam accelerator.

1 Introduction

CLIC (CERN linear collider) is the study of a high gradient, high energy (1 TeV) e^+e^- colliding linac[1]. The necessity to operate such linacs at frequencies higher than is customary for electron linacs has been discussed adequately in existing literature[2] The absence of high frequency (30 GHz) power tubes with appropriate power levels ($\sim$ 100 MW) for achieving acceleration in colliding linacs has prompted the use of two-beam accelerators (TBA). In a TBA a primary (or drive) beam of relatively high current and relatively low energy is used to produce the necessary high frequency power for accelerating the secondary (or driven) high energy, low current beam[3]. The high frequency radiation is generated during the interaction of the primary beam with some 'extraction' structure (e.g. wiggler magnet or microwave cavity). The properties of the CLIC drive beam have been discussed in detail elsewhere[4] and so this paper will be concerned primarily with the results of studies of the extraction cavity, or CLIC transfer structure (CTS).

2 Description of the CTS

It is intended that the CLIC drive beam will be fully relativistic ($\sim$5 GeV) and accelerated at 350 MHz using superconducting cavities such as those planned for LEP. Generation of the desired 30 GHz power for the secondary beam will be by direct deceleration of the tightly bunched ($\sigma_z < 1$ mm) primary beam in the CTS. The structure itself will consist of short sections of loaded travelling waveguide connected to the main linac cavities via matched waveguide. A possible geometry for such a travelling wave structure has been proposed by one of us (Schnell) and is shown in Fig. 1. It consists of rectangular waveguide loaded by a comb-like structure. The teeth of the combs do not extend across the full height of the guide and so cell to cell coupling is through both electric and magnetic fields. The smooth wall spacing is chosen to ensure that the E_{01} mode is cut off at the RF frequency. A fundamental requirement of the CTS is that it should exhibit a very low shunt impedance[5].

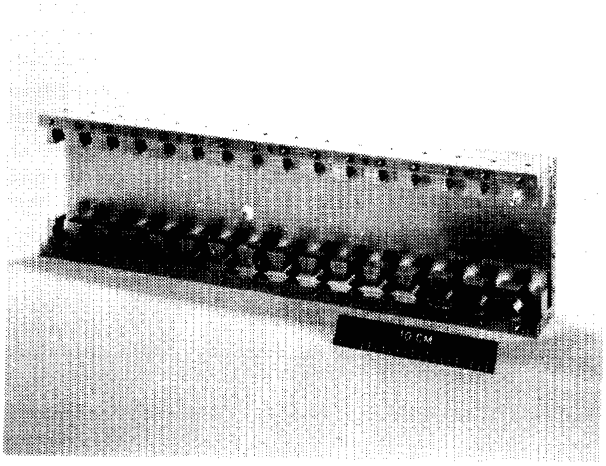

Figure 1: The Transfer Structure

This is achieved by having opposite faces of the combs relatively far apart. (Note that although this could be achieved by employing a round guide with very weak disk loading , such a structure would suffer strongly from mode competition and would have such a high group velocity that inordinately long structures would be required to obtain the correct filling time, 11.4 ns, necessary for the CLIC design.) The structure can thus be considered to consist of two weakly coupled combs which support surface waves which decay as they propagate out towards one another. The resonant frequencies of the device depend primarily on the dimensions of the combs and little on the comb separation distance and in this respect the CTS retains to some extent the features of a "lumped element circuit". As operation is in $\pi/2$ mode the cell spacing is $1/4\lambda_0$ (where λ_0 is the free space wavelength). Note that Fig. 1 shows a 10$\times$ scaled model of the required structure, i.e. it is designed to operate at 3 GHz, and has 16 cells with full cell terminations. Fine tuning of this model was achieved by employing small tuning posts inserted through the comb walls into each cell of the structure.

3 Measurements

The first measurements performed on a model of the CTS have been reported previously[6] . These included standard perturbation measurements on a 12 cell brass model operated in standing wave mode and tuned for a $\pi/2$ mode, hereafter referred to as the fundamental mode, frequency of 2 GHz. Gross tuning was achieved by machining the structure's teeth a little longer than was anticipated to be necessary and then gradually trimming the teeth for the correct frequency. It was observed that the frequency changed at a rate of 60 MHz/mm at the correct length and the variation appeared to be going non-linear. This dependence of frequency on tooth length would scale as the square of the frequency for which the structure is intended to operate. In addition measurements of the phase variations from cell to cell

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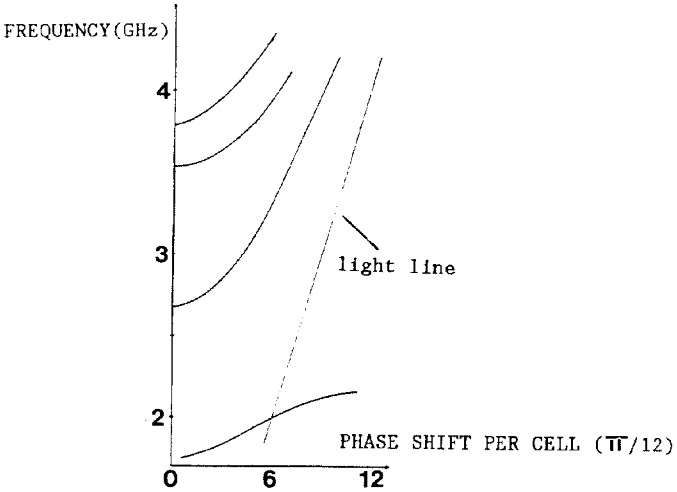

Figure 2: Brillouin plot for the CTS

of the normal mode frequencies (obtained by swept frequency reflection tests) revealed the dispersion characteristics of the structure. The dispersion of the first passband and some points from higher passbands are shown in Fig. 2. In addition to the curves plotted on Fig. 2 there exist "transverse" branches to the dispersion which correspond to the opposite combs resonating in "pull" rather than "push" mode and so producing transverse electric fields at the mid-plane of the strucure.

Each normal "longitudinal" mode has a corresponding transverse partner with a slightly lower frequency (e.g. the $\pi/2$ longitudinal mode is at 1.992 GHz while the corresponding transverse mode is at 1.98 GHz)[6]. The separation of the transverse and longitudinal branches decreases of course with increasing comb separation distance. Although the transverse modes are not believed to be a problem it has been demonstrated in any case that they can be severely damped by the inclusion of a longitudinal slot running along the centre of the broadwall of the structure, so preventing the wall currents responsible for them from flowing . In addition to the foregoing low power RF tests a pulsed co-axial wire measurement was attempted to try to get an estimate of the beam loading enhancement (B) of the structure by comparing the loss factor with the shunt impedance of the fundamental mode. However it appeared difficult to get a reliable figure for B and this was later determined by computation (see below). In addition to the various low power RF measurements the CTS has been studied under beam excitation conditions. The 3 GHz copper model of the structure was mounted on the LEP injection linac and measurements of the beam excited spectrum of the cavity were made using capacitive probes inserted in the structure. Probe signals, observed on a spectrum analyser, illustrated the relative amplitudes of the the various modes as well as demonstrating their sensitivity to beam displacement errors during beam steering exercises.

Figure 3 shows the response of the cavity to beam excitation over a broad frequency span. This was obtained with an electron beam pulse from the linac which was nominally 20 ns wide and contained a train of bunches seperated by the linac period (333 ps) and of 20 ps duration (FWHH).

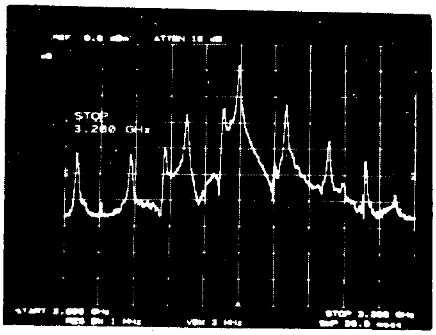

Figure 3: Spectral response of CTS to beam excitation

Although a knowledge of the probe coupling factor for each mode is required for quantitative analysis one can see that the logarithmic plot of amplitude is indicative of a high efficiency of energy transfer to the fundamental mode relative to the other modes. Indeed Fig. 3 is taken with a small (~1 mm) vertical displacement of the beam from the structure axis (vertical displacements being towards the comb of the structure) and we have demonstrated that by proper alignment of the beam with the axis of the structure half of the modes shown (the "transverse" ones) can be completely suppressed. A search for excitation of the modes of the higher passbands of the structure has shown them to be absent. The beam pipe into and out of the structure is of 20 mm diameter and starts to propagate at a frequency of 9 GHz and so no search for modes was conducted above this frequency. A rigorous investigation of the dependence of transverse mode amplitude with vertical displacement revealed a symmetrical distribution with a sharp minimum corresponding to zero displacement. In contrast the longitudinal modes appeared completely insensitive to vertical offsets and only weak variations in transverse or longitudinal mode amplitudes were found with horizontal displacements. Beam steering studies were limited to excursions of ± 5 mm before the beam pipe became a limiting aperture to the approximately round beam of $2\sigma_r = 5$ mm.

4 Computations

For comparison with the programme of measurements calculations of the RF properties of the structure were made with 3-D MAFIA codes[7]. Figure 4 shows the computed and measured dispersions of the 2 GHz model structure and it can be seen that the difference in frequencies is less than 1.5% for all modes. The same agreement for the transverse modes branch of the dispersion plot was found but this is not shown for the sake of clarity. The ratio of shunt impedance per unit length (R') to quality factor (Q) was 33 Ohms/m for both measurement and calculation (although the individual R' and Q had measured values less than their theoretical values). Figure 5 shows the distribution of the fields for the $\pi/2$ mode in the mid-plane of the structure. This was produced by the MAFIA post processor code, P3.

Although the CLIC parameters may impose a requirement for an even smaller R'/Q it has been demonstrated on MAFIA simulations that this can be easily achieved by increasing the distance between the opposing combs. In addition to verifying the measured RF parameters of the structure the MAFIA codes have been used to calculate the longitudinal loss factor of the structure at 30 GHz and hence to calculate the beam loading enhancement factor by comparing the total loss to the fundamental. The efficiency of the structure was calculated,for the traversal of a single bunch with $\sigma_z = 1$ mm, to be 75%. Computations with the geometry of the structure slightly altered (smaller tooth gap and smaller diameter) have indicated that this might be increased to 90%. As the drive beam will consist of a train of "bunchlets"[4]

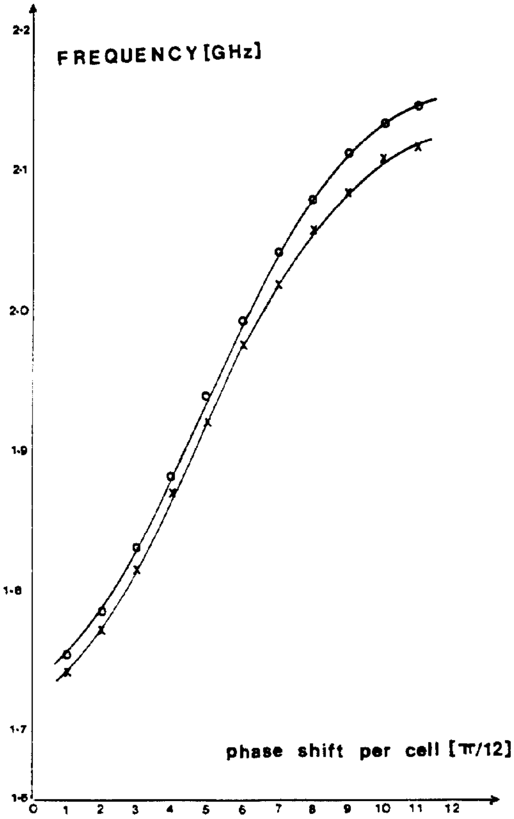

Figure 4: Comparison of computed (x) and measured (∘) mode frequencies of the CTS

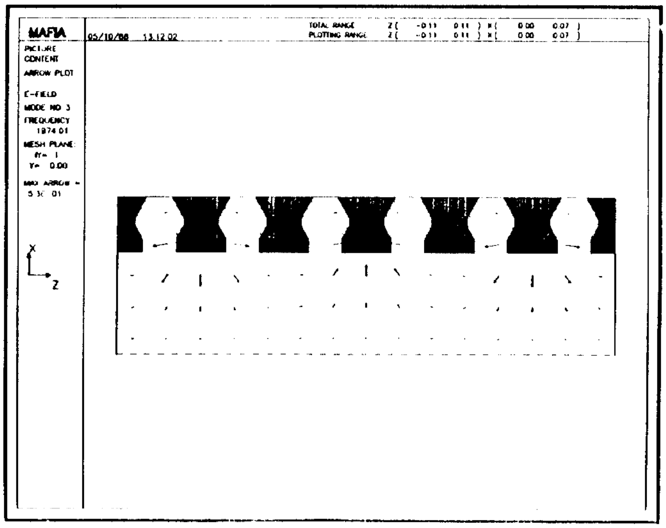

Figure 5: MAFIA output showing $\pi/2$ mode field distribution

it is hoped that the effective efficiency will be enhanced over that predicted for the single bunch case. Note, however that these efficiency figures pertain to the active part of the structure (the combs) taken in isolation. Additional energy loss into beam-induced wake fields will be due to the resistivity of the smooth and flat walls which form the cut-off pipe surrounding the beam[8] . These losses may be alleviated by means of semi-circular recesses in the walls where they are nearest to the beam. Serious energy loss will also occur at any variation of the beam pipe's cross-section. Such cross-section variations will have to be avoided as much as possible.

5 Conclusions

We have presented experimental and computational results of studies on a novel RF cavity for use as a transfer structure in a TBA colliding linac. Both low power RF tests and and studies with beam excitation have demonstrated that the structure geometry, or some close variant of it, will be suitable for this role. The computations have confirmed the results of experimental measurements (eigen-mode frequencies, R'/Q) and allowed computation of parameters less accessible to measurement (beam loading effects) as well as facilitating predictions of parameter changes following alterations in the structure geometry.

6 Acknowledgements

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