THE 30 GHZ TRANSFER STRUCTURE FOR THE CLIC STUDY*

G.Carron, A.Millich, L.Thorndahl, CERN, Geneva, Switzerland

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Abstract

In the so-called "Two-Beam Acceleration Scheme" the energy of a drive beam is converted to rf power by means of a "Transfer Structure", which plays the role of power source. In The Transfer Structure the bunched drive beam is decelerated by the electromagnetic field which it induces and builds up by the coherent interaction of successive bunches with the chosen longitudinal mode. The CLIC Transfer Structure is original in that it operates at 30 GHz and uses teeth-like corrugations to slow down the hybrid TM mode to make it synchronous with the drive beam. The beam energy is transformed into rf power, which travels along the structure and is collected by the output couplers. The 30 GHz rf power is then transported by means of two waveguides to two main linac disk-loaded accelerating structures. This report describes the CLIC Transfer Structure design, 3-D computer simulations, model construction and measurements as well as the prototype construction and testing with the low energy beam in the CLIC Test Facility. The result of this development is a compact, fully passive, relatively simple and low cost device, which offers a readily scalable solution to the problem of rf power extraction from high frequency bunched beams.

1 GENERAL DESCRIPTION AND PRINCIPLES

1.1 Definition and function of the Transfer Structure (TRS)

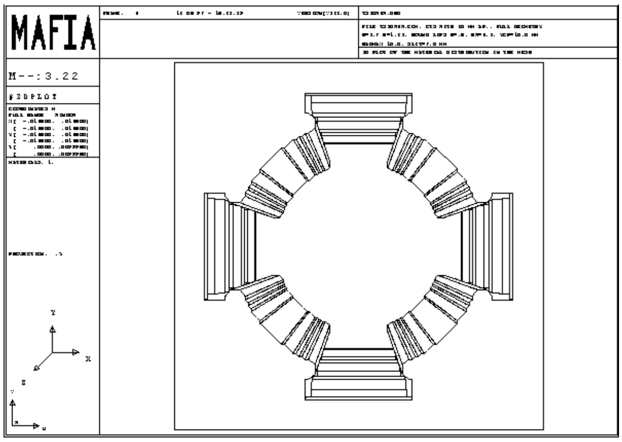

Figure 1 Three cells section of TRS

The transfer structure [1] is a passive rf device in which the bunched electron beam interacts with the impedance of periodically loaded waveguides and excites preferentially one synchronous hybrid TM mode. In the process the beam kinetic energy is converted in electromagnetic energy at the mode frequency which travels along the structure with the mode group velocity. The rf power produced is collected at the downstream end of the structure by means of couplers and conveyed to the main linac accelerating structures by means of waveguides. In its classic configuration the TRS consists of a cylindrical beam chamber, which is coupled by longitudinal slits to four teeth-loaded waveguides as visible in Figure 1. It shows our reference TRS model with beam chamber diameter 24 mm.

1.2 Principle of operation.

When a train of short electron bunches each of charge q_b traverses a section of TRS l_s meters long, it builds up a voltage across the structure of peak value

$$U_d = \frac{\omega}{2}\left(\frac{R'}{Q}\right) l_s q_d \tag{1}$$

where $\omega = 2\pi f$ is the excited mode frequency, R'/Q is the normalised longitudinal impedance per unit length (expressed in circuit Ohms/m) of the structure at frequency f, q_d is the total beam charge in one drain time T_d of the structure and l_s is the structure length. The drain time is simply the time it takes for the energy deposited by one bunch in the fundamental mode to travel out of the structure starting from the moment the bunch has left the structure itself:

$$T_d = \frac{l_s}{c}\left(\frac{1}{\beta_g} - 1\right)$$

where $\beta_g = \frac{v_g}{c}$ is the normalised group velocity.

In order for the mode excitation to be coherent and therefore constructive, the bunch spacing must be a multiple of the mode wavelength which is 10 mm and the mode phase velocity must be equal to the speed of the relativistic bunches. The bunch time separation T_b however, must be much shorter than one drain time T_d in order for several bunches to contribute to the build up of the voltage U_d. The rate of energy deposition by the beam or the rf power generated in the TRS is obtained by multiplying the voltage U_d by the average beam current in one drain time q_d / T_d:

$$P = \frac{\omega}{2}\left(\frac{R'}{Q}\right)\frac{q_d^{\,2}}{T_d} l_s F^2(\sigma) \tag{2}$$

$F^2(\sigma)$ is the power form factor which takes into account the finite length of the gaussian bunches. For a train of bunches lasting much longer than the structure drain time the peak power level in equation (2) stays constant after one drain time has elapsed provided that the charge per drain time remains constant. Expression (2) therefore gives the steady state power level at the structure output when neglecting the internal wall losses.

2 THE REFERENCE TRS.

2.1 Transfer structure parameters.

The four-waveguide TRS shape is the result of a development started several years ago, [2] [3]. The 3D simulations using MAFIA [4]. led to the determination of the main geometric and rf parameters.

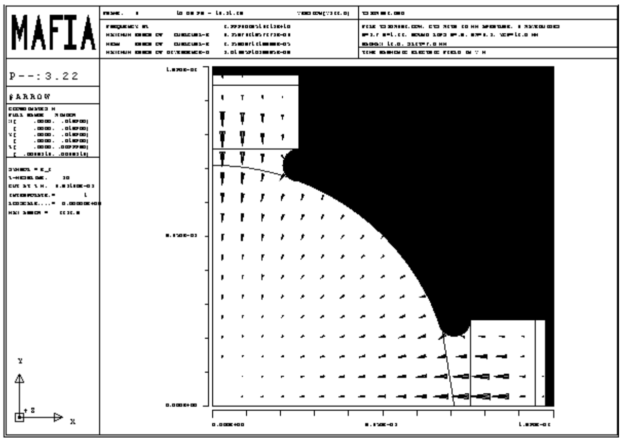

Figure 2 Transverse electric field in the TRS.

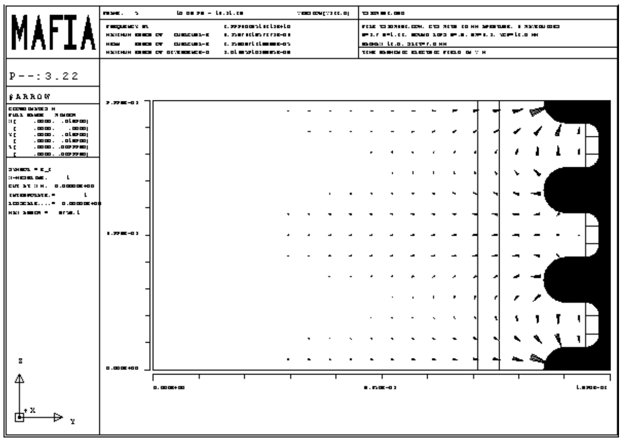

Figure 3 Electric field pattern in the longitudinal plane

The solution found for the resonant hybrid mode appears in Figure 2, which shows the transverse field pattern. The arrows length being proportional to field intensity, we see that most of the mode energy is located in the vicinity of the waveguides, a feature which favours power extraction. The mode phase advance of 2π per 3 cells is well illustrated in Figure 3. A six-cell model was used to determine the dispersion curve of the structure and to derive the R'/Q and group velocity of the $2\pi/3$ mode. Table 1 shows the main geometric and rf parameters of the transfer structure with 24 mm beam chamber aperture which has been adopted as power extracting structure for the drive beam decelerator [5].

Table 1 Parameters of the reference TRS

Beam chamber diameter	24.00	mm
waveguide width	8.60	mm
waveguide height	3.70	mm
slit aperture	7.00	mm
synch. mode frequency	29.983	GHz
synch. mode β_g	0.440	
synch. mode R'/Q	31.10	Ohm/m
peak transverse wakefield	0.42	V/pC/mm/m
effective structure length	0.80	m
nominal output power*	495.4	MW

.* The output power is computed for a train of bunches with charge 17.4 nC, σ =0.5 mm, spaced 20 mm and with $F'(\sigma)=0.9$

2.2 Wakefields in TRS

The transverse wake induced in a 24 cells section of TRS by a gaussian bunch with σ = 0.6 mm and charge one pC displaced one mm off center is shown in Figure 4 and its spectrum in Figure 5.

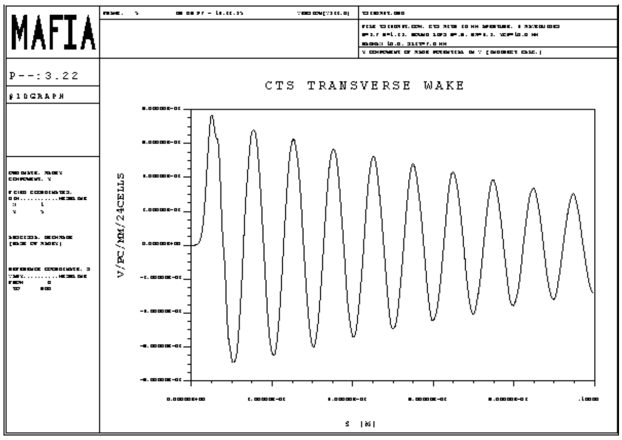

Figure 4 Transverse wakefield in 24 TRS cells

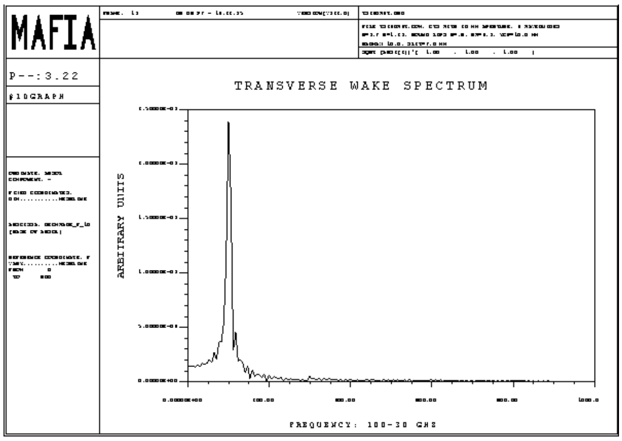

Figure 5 Transverse wake spectrum.

The wake spectrum shows almost no higher order modes. It is therefore justified to assume that practically all the transverse deflection of an off-center beam is caused by the main deflecting mode, the frequency of which is only a few tens of MHz away from the main longitudinal mode. The value of the peak transverse wakefield, which appears in Table 1, is used in the computation of the transverse stability of the drive beam.

2.3 TRS integrated longitudinal electric field uniformity.

Because of the particular geometry of the TRS, the integrated decelerating field varies as a function of the angular and radial position within the beam chamber. The plots in Figure 6 show the variation of the normalised longitudinal integrated field over a three cells section of the TRS as function of the radial position for φ=0 (towards the middle of the waveguide) and φ=45 degrees (towards the chamber wall).

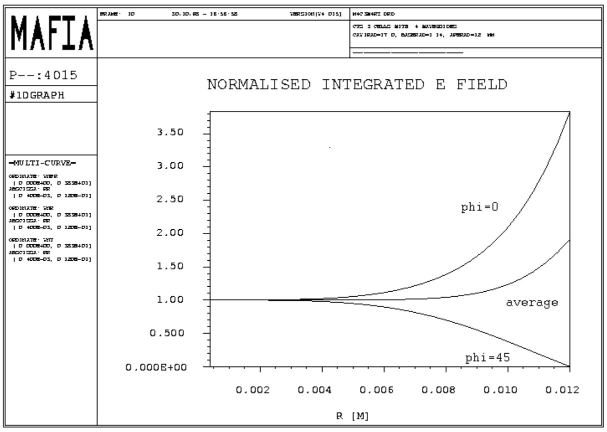

Figure 6 Normalised integrated field at φ=0, φ=45 degrees and average.

The non uniform beam deceleration causes the particles to receive transverse kicks which are a function of the particle position within the TRS chamber. The overall result found in tracking programs is that the drive beam would be unstable if no cure were found to the problem. One possible simple solution consists in rotating by 45 degrees every other TRS in the decelerating linac so that a particle off centre at φ=0 in a structure would be at φ=45 degrees in the following one, thus averaging the field non uniformity. Figure 6 also shows the normalised integrated field when averaged over two rotated structures as described above. The useful effect of the alternate TRS rotation is somewhat reduced by the betatron motion of the particles in the drive linac lattice, however tracking programs have shown that the overall result is beneficial to the transverse beam stability and worth the implementation effort [6]

2.4 Transfer structure for the test facility CTF2.

Prototypes TRS were built in 1995 and '96 for the Two-Beam tests to be performed in the CTF2 facility.. The beam charge available for the test being limited to 640 nC in 48 bunches with bunch distance 10 cm, the R'/Q of the TRS had to be increased to 550 Ω/m in order to provide the nominal output power of 80 MW. This requirement was met by reducing the beam aperture diameter to 15 mm and eliminating the lips between the beam chamber and the waveguides, see Figure 7. The reduced aperture produced an increment of the transverse wakefield which would make the low energy drive beam unstable [7]. It was found necessary to damp the main transverse mode to make the beam go through six transfer structures.

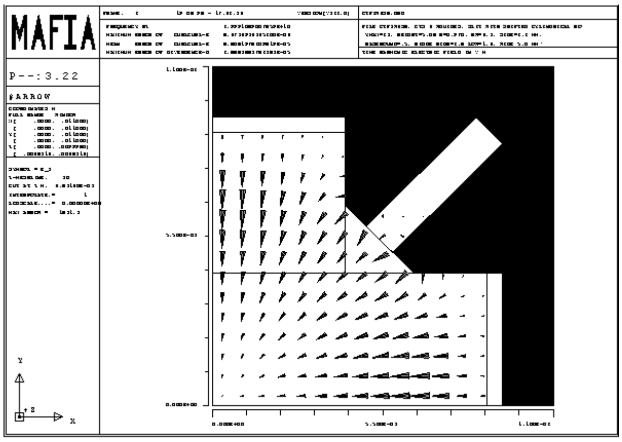

Figure 7 Longitudinal decelerating mode electric field pattern in TRS for CTF2

2.5 Transverse mode damping.

The TRS has been equipped with transverse mode dampers, which consist in four corrugated slits oriented at 45 degrees in the transverse plane in order to intercept the image current of the transverse mode. The slits are closed at their outer ends with respect to the beam chamber by rods of SiC forming rf loads. The position of the dampers is chosen in symmetry planes such that the main mode is not affected by their presence. The difference in mode coupling is well illustrated in Figures 7 and 8.

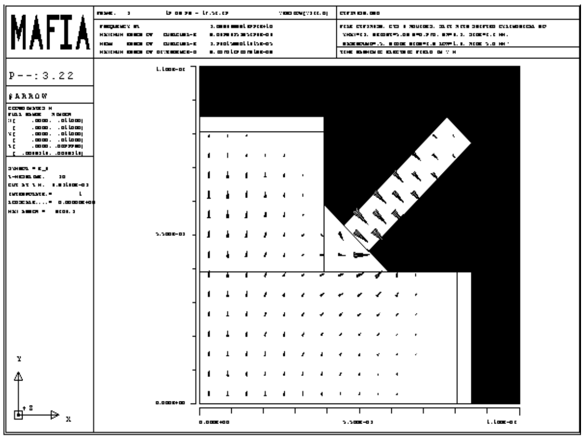

Figure 8 Transverse deflecting mode electric field pattern

Model measurements indicate that the Q value of the transverse mode is strongly lowered by the dampers.

2.6 TRS construction method

Figure 9 shows the cross-section of the damped TRS installed and tested with beam in CTF2. The structure consists of four copper racks with the periodic corrugations, which are held by four square profiles of Cu-plated stainless steel (for mechanical rigidity). The corrugated damping slits with the SiC slabs are visible. The SiC slabs are pressed into the slots by helical springs running over the whole length inside the cylindrical bore of the profiles.

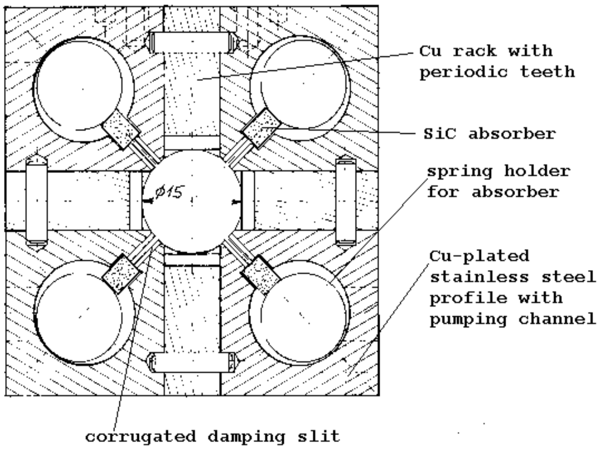

Figure 9 Cross-section of the damped transfer structure used in the CLIC Test Facility

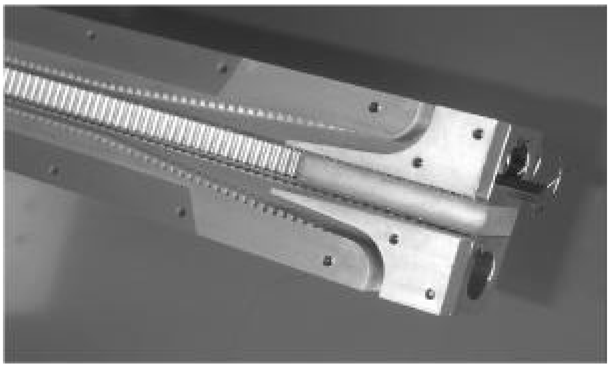

Figure 10 Extremity of open transfer structure with output couplers and channels

All metal parts are vacuum-brazed in a single operation. The power is extracted by means of output couplers visible in Figure 10. The extraction of the mode energy from the beam chamber with very high efficiency is made possible by the shape of the couplers, which present an outward ramp, where the tooth height is increased, thus slowing down the phase velocity locally. Towards the end of the ramp, inside the waveguides but before the last bends, the tooth height is slowly reduced to zero and the rf power is smoothly guided towards the output rectangular slits..

2.7 Model Work

Having met with difficulties in calculating the Q-value of damped transverse modes in the TRS because of the uncertain knowledge of the SiC properties, we attempted to measure them using short (to select the relevant mode) resonating models with the real SiC damping material. Such a model is shown in Figure 11. The model was totally encapsulated in metal and equipped with rf probes. In the case of the CTF2 structure the absorbers lowered the Q to values not measurable. In the case of our reference structure values about 60 were obtained.

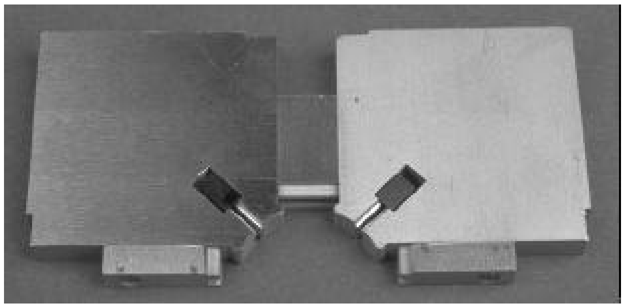

Figure 11 rf model for measurements of Q-values of transverse mode.

2.8 Beam Tests in the Clic Test Facility

The prototype four-waveguides TRS was installed in the drive beam line of the CTF2 and produced 27 MW rf power at 30 GHz.

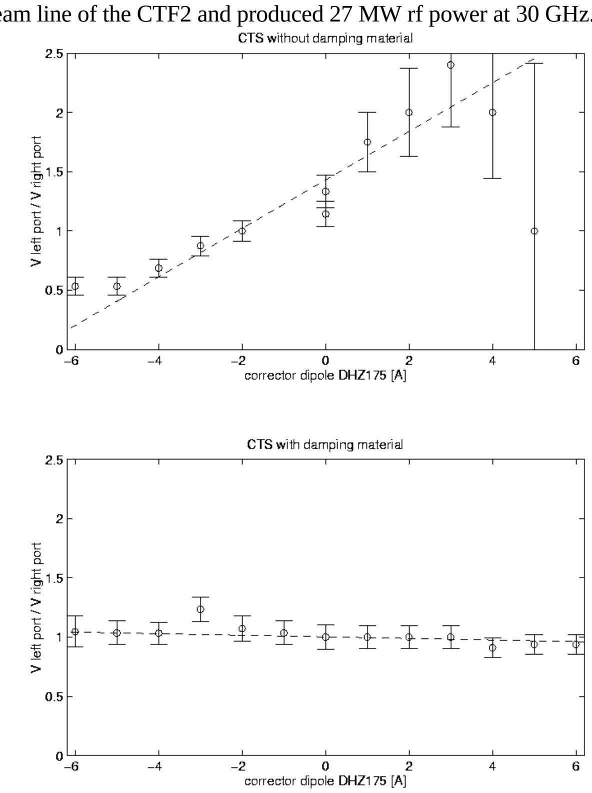

Figure 12 Results of measurements performed in CTF2.

The power was fed to a main linac disk-loaded structure, in which the probe beam was accelerated by 28 MeV [8]. The effort to produce the nominal drive beam intensity, which would provide a TRS output power of 80 MW, is being pursued. Comparisons between signals on the four output channels of the TRS when the beam is displaced laterally show a large beam-position dependence when the structure is not equipped with damping material and rather position-independent signals when the material is present [9]. In Figure 12 we see the ratio between left and right output signals when the beam is moved across the structure aperture. The upper graph is without damping material in the structure, the lower graph with damping material.

4 CONCLUSION

The development of the TRS has resulted in the construction of two prototypes which, when tested with beam, have shown to produce the amount of power predicted by calculations as function of the beam charge. The four-waveguides TRS is a rugged and relatively simple device, which warrants low cost production of large number of units. New and more sophisticated designs being explored foresee structures with six or even eight waveguides, which are more complex to build and present challenging problems for the power extraction. Ultimately the drive beam stability requirements in the decelerator linac will impose the future design choices.

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