DESIGN AND FABRICATION STUDIES OF HIGH GRADIENT ACCELERATING STRUCTURES FOR THE CERN LINEAR COLLIDER (CLIC)

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Abstract.

An energy of 1 TeV per beam will be obtained in CLIC by classical RF acceleration using a high gradient disc loaded waveguide operating at 29 GHz. The basic parameters and resulting technical requirements of such a structure are given together with a conceptual design of a possible engineering solution. Special design features and difficulties associated with the two most likely ways of fabrication are discussed and first results from prototype tests are given. Attention is drawn to the possibility of surface damage by fatigue from induced cyclic stresses in pulsed operation for excessive electric field gradients. A beam−derived signal from a microwave position pickup incorporated into the main accelerating sections is foreseen for alignment purposes.

Introduction.

In the mid 1980's when it became clear that no major breakthrough in new acceleration techniques was imminent, attention returned to radio frequency acceleration with the hope that the principles of the classical travelling wave linac could be adapted to the requirements of linear colliders. The worldwide effort devoted to this activity over the last few years has proved to be particularly rewarding and a large consensus now believes that RF acceleration − "classical" in principle but not at all in the choice of parameters nor in the technology required − is the most promising approach to linear colliders at this time. An energy of 1 TeV per beam will therefore be obtained in CLIC by classical RF acceleration using a high gradient disc loaded waveguide (DLWG) operating at 29 GHz.

This paper describes the main parameters and resulting technical requirements of such a structure and gives a conceptual design of a possible engineering solution. Manufacturing techniques are discussed and plans for prototype test pieces are outlined. The choice and interdependence of CLIC general machine parameters is described elsewhere[1].

Basic structure parameters.

One way to obtain high accelerating gradients at acceptable RF power to beam power efficiencies is to operate at very high frequencies. Values around 30 GHz (1cm wavelength) however appear to be a limit imposed by transverse wake field problems and fabrication difficulties. The destructive effect of beam induced transverse wake fields increases with the third power of the frequency but can be held within reasonable limits in single bunch operation by adopting the rather large aperture to wavelength ratio of 0.2.

The basic cell of the CLIC structure is a variant of the usual DLWG which after investigating alternative crossbar and ladder structures[2] was found to have an overall performance which is difficult to beat.

Main parameters for phase matched structures with straight−sided discs of thickness 0.575mm as calculated by URMEL[3] are given as a function of beam hole diameter in Fig.1. It is shown later that this simple geometry is modified to suit the different fabrication techniques being investigated. One would like to have a high shunt impedance R′ to keep the peak power low, a high R′/Q to minimise average power, and a reasonably high group velocity v_g to minimise pulse distortion and maximise the length of the sections. The assumed design values for operation in the $2\pi/3$ mode at 29 GHz. are given in Table 1. Values of R′ and Q have been reduced by 5% to account for extra losses due to surface roughness.

Transverse wakefields can be stabilized by creating a large spread in the wavelengths of the transverse oscillations of the particles within a bunch by RF focussing[4]. A small fraction of the accelerating sections will therefore have an asymmetric aperture (a slot instead of a circular hole). Such sections when oriented alternatively at 90 degrees with respect to one another at suitable period lengths produce RF quadrupoles of considerable transverse focussing power without appreciable loss of shunt impedance for acceleration. The influence of slot height on effective focussing gradient (G) and effective axial electric field (Ez) has been investigated for a six cell structure using the MAFIA 3D computer code[3].

The on axis value of $G/Ez = 0.85$ found for a 3.5mm slot corresponds to a gradient of 23 T/m for an effective accelerating field of 80 MV/m and an RF phase angle of 20° from the peak. It should be noted that for maximum focussing there is no acceleration and vice versa. Although the effective energy gain for off−centre particles travelling parallel and perpendicular to the slots is different, the relative differences for a few microns of transverse displacement (typical CLIC betatron amplitudes) are negligible − values of $\Delta E/E_0$ per micron are in the 10^{-5} range.

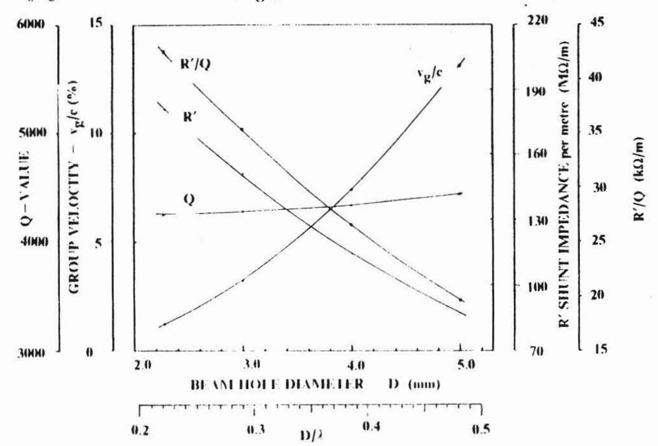

Fig.1 Variation of structure parameters with beam hole diameter.

It is seen from Table 1 that structures with 3.5 mm slotted irises have RF characteristics comparable to those of structures with 4.0 mm diameter round holes.

Table 1: Structure parameters at 29 GHz

Aperture			Round	Slotted
Dimension		mm	4.0	3.5
Shunt impedance	R′	MΩ/m	109	120.3
Quality factor	Q		4112	4950
	R′/Q	kΩ/m	26.5	24.3
Group velocity	v_g/c	%	7.4	9.2

Using the values for a 4mm circular hole and striking a reasonable compromise between peak and average power by choosing a field attenuation of 0.25 Nepers/section leads to the linac parameters given in Table 2 for a repetition rate of 1.69 kHz and a pulse length equal to the filling time τ_f.

Table 2: Main linac parameters

Gradient	80 MV/m
Section length	24.8 cm
Fill time	11.3 ns
Cells per section	72
Sections per linac	50'000
Ratio output/input power	0.61
Total peak input power	1.875 TW/linac
	150 MW/m
Total average input power	35.75 MW/linac
	2.86 kW/m
Average dissipated power	1.125 kW/m

Tolerances and surface finish.

For 50000 sections per linac and 72 cells per section it would be a great advantage if every cell did not have to be individually tuned. The level of tolerances required on main cell dimensions in order not to exceed a given phase error per cell ($\Delta\phi$) can be estimated as follows.

$v_g = \Delta\omega/\Delta\beta = L(\Delta\omega/(\Delta\phi)$ where the cell length $L = c/3f$ for $2\pi/3$ mode.

Rewriting this expression and assuming as a rough approximation that $\Delta f/f = \Delta D/D$ gives $\Delta D/D = (v_g/c)(3\Delta\phi/2\pi)$. Allowing a +/− 5° total

phase error over a section length the r.m.s phase error per cell is 0.6° for non systematic errors, and +/− 0.07° for systematic errors. The corresponding tolerances are +/− 3 μm and +/− 0.4 μm. There is a strong hope that tuning can be avoided by machining all cell dimensions to less than +/− 2 μm.
Theoretical estimates of degradation of Q as a function of surface finish and skin depth[5] indicate that for copper at 29 GHz a finish of N2 ($R_a = 0.050\ \mu$m) is required to obtain 95% of the theoretical Q value.

Transverse damping slots for multibunch operation.

Four equally spaced radial slots of rectangular cross section are foreseen to channel away higher mode energy from the centre to a dispersive sink. The slots must be wide enough to allow the lowest frequency deflecting mode (E_{11}) to propagate. This mode has a frequency about 1.5 times the fundamental and the minimum slot width ($\lambda_{11}/2$) is therefore $\simeq \lambda_{01}/3$ which is unfortunately the cell length for the $2\pi/3$ mode. There is good hope, however, that slots in every second cell will be sufficient. To be effective the slots have to cut through the discs.

Surface heating.

The highest accelerating gradient at which DLWGs can be run is limited amongst other considerations by surface heating. Although the extreme limit corresponds to the melting of the cavity walls, a more realistic limit as shown below is probably the appearance of surface damage due to fatigue cycling under thermally induced stresses.
Using the dissipated power distribution along the inside surface of a cell a maximum flux density of $P_a = 172$ kW/cm^2 was found for a single power pulse in the first cell of each section where the losses are highest (75 MW/m). For a metal surface at an initial temperature T_o with heat supplied at x=0 at the constant rate P_a per unit area for time τ_f the maximum temperature occurs at the surface (x=0) at the end of the pulse ($t=\tau_f$) and is given by

$$T_{max} = (2P_a/K)\sqrt{(\kappa\tau_f/\pi)}$$

where $\kappa = K/\rho c$, ρ is the density, c is the specific heat and K is the thermal conductivity. It can be seen from Fig.2, where the temperature increase is plotted as a function of distance from the surface, that transient effects are confined to a very small surface layer of about ten times the skin depth, and that the large temperature gradient within this surface essentially disappears after 1000 ns.

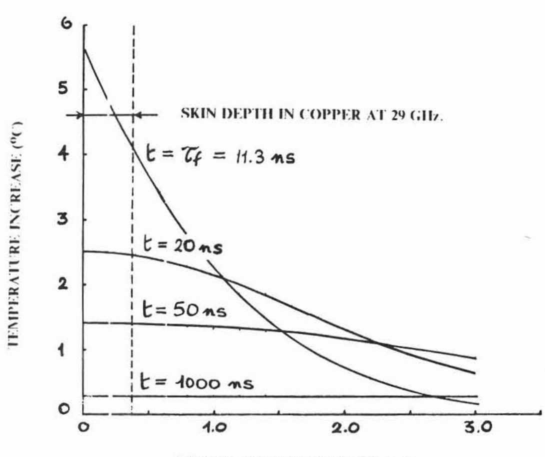

Fig.2 Temperature increase in the surface layer.

Fig.3 shows surface temperature as a function of time, the time t=591700 ns corresponds to the time between pulses. It is clear from Figs.2 and 3 that the transient problem is a single pulse problem and is essentially independent of the surrounding geometry. The resulting maximum surface temperature increases are

$$\Delta T_{max} = 5.6\ \mathrm{C^o} \quad \text{(for 80MV/m)}$$
$$\Delta T_{max} = 22.4\ \mathrm{C^o} \quad \text{(for 160MV/m)}$$

For such localised surface temperature gradients the induced thermal stresses are given approximately by

$$\sigma = -E\,\alpha\,\Delta T$$

where E is the Modulus of Elasticity, α is the coefficient of thermal expansion and ΔT is the temperature increase. The maximum induced cyclic stresses are therefore

$$\sigma = 0 \rightarrow -6.8\ \mathrm{N/mm^2} \quad \text{(for 80MV/m)}.$$
$$\sigma = 0 \rightarrow -43\ \mathrm{N/mm^2} \quad \text{(for 160MV/m)}.$$

Fatigue data for OFHC under these conditions is not readily available, but as an example for reversed cycling of +/− 50 N/mm^2 at room temperature, annealed OFHC has a lifetime of only 10^8 cycles. Tests are needed to establish whether or not this is serious problem.

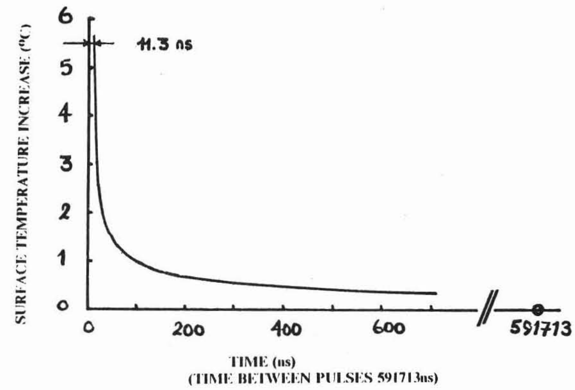

Fig.3 Surface temperature decay with time.

Transverse alignment and beam pickups.

It is foreseen to maintain the transverse alignment tolerance along the linac − calculated[6] to be about 10 μm − by active feedback using precision movers and a beam derived pickup signal. The simple circular cavity,coaxial to the beam axis and excited in E_{11} mode by an off−center beam, forms an excellent position pickup with the potential of micrometer resolution[7]. Incorporating the pickup into a rigidly supported structure with a precise reference to the movers is however essential.

Conceptual design.

A conceptual design of the CLIC main linac structure is shown in Fig.4. Four high precision accelerating sections are inserted into the central bore of a 1m long copper cylinder which provides mechanical support, water cooling, vacuum pumping, the input and output waveguide feeds and the higher mode dispersive sink. The connection between cylinders is shown in Fig.5. Higher mode energy produced at the gaps between section lengths is absorbed by lossy ceramics. The ends of adjacent cylinders − reinforced with stainless steel rings and machined to be concentric with the central bore − sit on a common V−block and gaurantee continuity of alignment.
The pickup monitor positioned at the entrance to each four section long module has two cells which are slotted for multibunch operation.

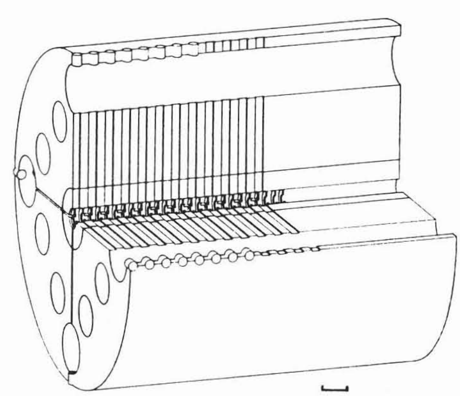

Fig.4 Conceptual design of the CLIC accelerating structure.

Fabrication by brazing copper cups.

Short test stacks of precision machined cups as shown in Fig.6 have been ordered from industry and will be brazed at CERN under slight axial compression in a free hanging position after precision alignment in the jig shown in Fig.7. This particular choice of cup geometry simplifies machining and puts the brazed joint in a corner where the electric field is low. The copper cups will be machined to the required tolerances and low. The copper cups will be machined to the required tolerances and surface finish on a Pneumo MSG−325 diamond tool lathe. This two axis machine has CNC control, closed loop laser interferometer feedback with 25 nm resolution, vibration isolation and air bearing spindle and slides.

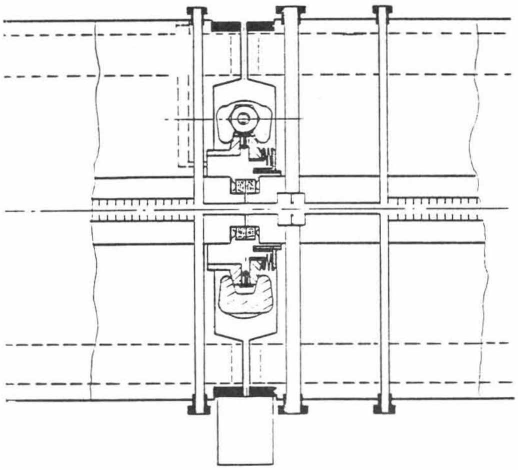

Fig.5 Connection between CLIC modules.

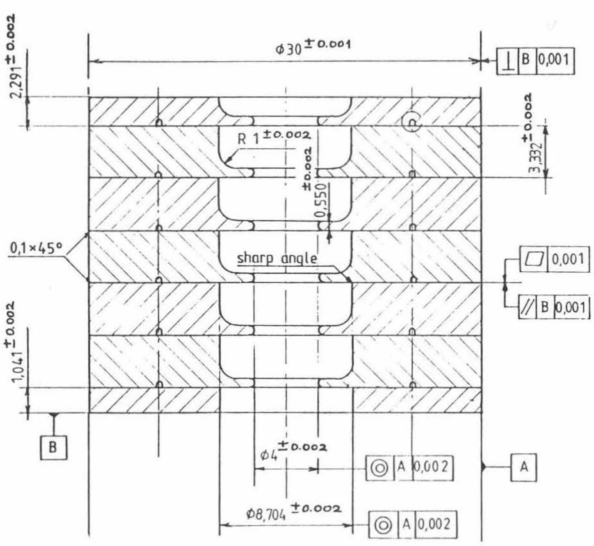

Fig.6 Short test stack of precision machined cups (29.985 GHz).

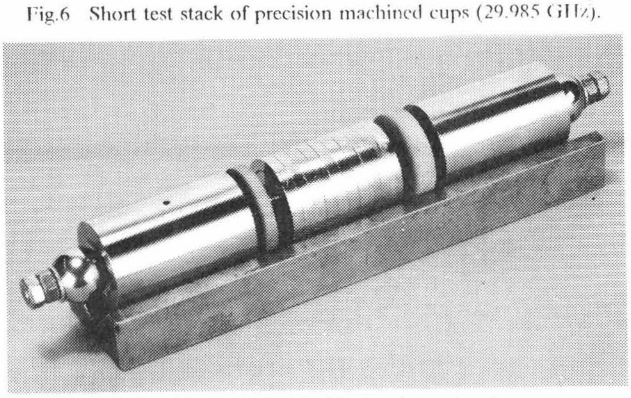

Fig.7 Alignment in V−block prior to brazing.

Fabrication by electroforming.

Prototype work has started with the aim of fabricating complete section lengths by depositing copper onto disposable precision machined mandrels of the form shown in Fig.8. It is aknowledged however that to obtain the required tolerances and surface finish on such long mandrels will not be easy. A small development program has been initiated to find ways of filling the 0.55 mm wide grooves with copper without forming voids or cracks. Ideas being considered as well as modifying the cell geometry to have rounded corners include introducing electrodes into the grooves to obtain a more favourable field distribution and jet spraying through fine nozzles onto the bottom of the grooves. Tests are underway to find appropriate ways of dissolving away the mandrel without a significant deterioration of the surface finish of the electrodeposited copper.

Both the electroforming and brazing techniques have been successfully used in important pioneering work in this field to fabricate the HGS 33 GHz structures at Livermore[8].

Wire machining of rectangular slots.

It is proposed to cut the transverse damping slots (1mm x 3.5mm) and the input and output waveguide ducts (7.1mm x 3mm) by electroerosion using a continuously running wire in demineralised water. This technique has an accuracy of about 0.01mm and produces surface finishes of N6/N7 (0.8/1.6μm). A slotted CLIC cross section is shown in Fig.9.

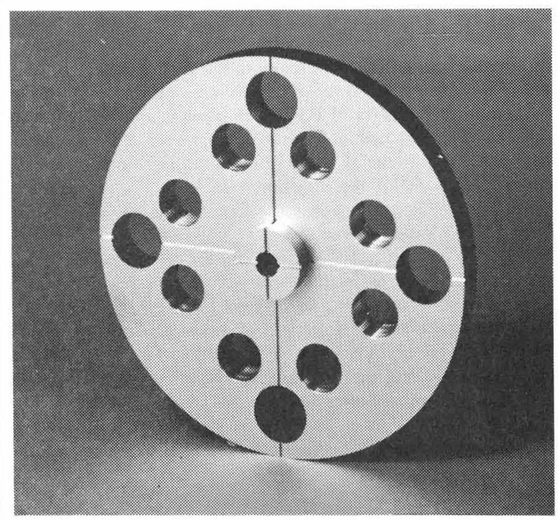

Fig.9 Cut through CLIC cross section showing transverse slots.

Vacuum.

The section lengths are pumped from four 20mm diameter manifolds via the transverse damping slots. First estimates indicate that for an assumed outgassing rate in the cells under full power of $5x10^{-10}$ Torr.l/s.cm^2 a pressure of 10^{-7} Torr should be possible.

References.

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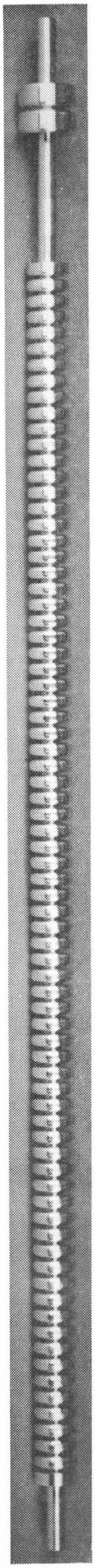

Fig.8 Aluminium mandrel (75 cells + 2 pickup cells) for 29.985 GHz.