EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - PS DIVISION

CERN/PS 2002-059 (RF)
CLIC Note 532

CLIC 30 GHZ ACCELERATING STRUCTURE DEVELOPMENT

W. Wuensch

Abstract

The main effects which limit accelerating gradient in CLIC (Compact Linear Collider) main linac accelerating structures are RF breakdown and pulsed surface heating. Recent highlights of the structure development program are presented, including demonstration of higher accelerating gradients using tungsten and a complete redesign of the CLIC main linac accelerating structure, based on reduced surface electric and magnetic fields and including new power couplers and higher-order mode damping waveguides.

Presented at the Advanced Accelerator Concepts Workshop, Oxnard, California, 23-28 June, 2002

Geneva, Switzerland
10 September 2002

CLIC 30 GHz Accelerating Structure Development

W. Wuensch

CERN, Genève23, 1211 Switzerland

Abstract. The main effects which limit accelerating gradient in CLIC (Compact Linear Collider) main linac accelerating structures are RF breakdown and pulsed surface heating. Recent highlights of the structure development program are presented, including demonstration of higher accelerating gradients using tungsten and a complete redesign of the CLIC main linac accelerating structure, based on reduced surface electric and magnetic fields and including new power couplers and higher-order mode damping waveguides.

INTRODUCTION

The CLIC linear-collider design envisages the use of the rather high accelerating gradient of 150 MV/m [1], which results in an accelerating structure input power of 130 MW [2]. These fields and powers are well above those used in existing, lower frequency, RF structures. For reasons of beam stability, CLIC accelerating structures also have quite stringent limits on short-range wakefields and the requirement that long-range wakefields must be suppressed. Because of the challenges that each of these design requirements presents, programs of high-gradient studies and damped-structure studies have been carried out by the CLIC team. This has lead to a better understanding of the interplay between high-gradient, structure wakefield and RF efficiency issues. The status of this work is presented in this report. Recent progress in overcoming RF breakdown induced damage and obtaining higher gradients with tungsten is reviewed in section 2. A recent redesign of the CLIC main linac accelerating structure, which takes into account the most recent ideas about high-gradient limits, is outlined in section 3. Finally a simplified discussion of the motivation of the very high fields in CLIC, and the consequences on the required powers and pulse energies, is presented in section 4.

HIGH-GRADIENT TESTING

Accelerating gradients in the range of 150 MV/m, and with a pulse length of 150 ns, were demonstrated using two copper X-band accelerating structures, one tested at KEK and one tested at SLAC [3,4]. However, subsequent tests of prototype copper 30 GHz accelerating structures at the CLIC test facility, CTF2, with pulse lengths of only 16 ns have produced accelerating gradients of only 60 MV/m and significant damage to the structures was observed [5]. The reasons for the very different performances achieved in the tests are probably partially due to differences in RF design, the X-band structures had a very small beam aperture, $a/\lambda=0.11$, and the 30 GHz structures had highly asymmetric power couplers. In addition there were substantial differences between the conditioning procedures. The high-gradient test area in CTF2 was not, until recently, instrumented as thoroughly as the test areas at KEK and SLAC, and power production is still not interlocked to breakdown. It is clear however, that the tens of thousands of structures that must survive many decades in a linear collider must be extremely robust and cannot require heavily instrumented, lengthy and delicate conditioning and re-conditioning procedures. In this way, the conditions at CTF2 may be more representative of what may be encountered at a future linear collider. In any case, the difficulties encountered with the damage to the copper structures indicated that a very basic problem existed and that an innovative new approach to structure design and construction had to be found.

One solution to the structure damage problem is to use an arc-resistant material instead of copper in the areas of a structure where damage due to RF breakdown occurs [6,7]. The arc-resistance of a material is a well established concept at DC, and is a consequence of a high melting point and a low vapor pressure. A number of refractory metals are arc resistant, but tungsten, with a DC conductivity only three times worse than copper, is the most obvious candidate for a first test in an accelerator application. In addition to arc resistance, it is possible that the highest field a surface is capable of supporting is a function of material.

The program of testing new materials has begun with tungsten, and has had two distinct phases. In the first phase, a series of simple and rapid tests were made by re-using a copper constant-impedance structure and replacing only the damaged iris of the input coupler with a new iris. Each new iris to be tested was clamped between the coupler and the structure, giving mechanical integrity and an RF contact. Vacuum was provided by placing the clamped assembly inside a vacuum tank. In these tests only relative material properties could be tested since the geometry of the structure was unchanged. Achievable gradients were also limited because the rest of the structure was in copper. However, maintaining the single-feed coupler guaranteed that the potential for damage to the new irises under test remained very high.

The second phase of the tungsten testing program consisted of producing two entirely new 30-cell structures with identical geometries, one made entirely of copper and the other made from copper cells with all irises made of tungsten. The first objective was to demonstrate an improved accelerating gradient due to the RF design change. The second objective was to provide a direct comparison between tungsten and copper of achievable gradient.

All tests were made in the CTF2 and the results reported here were all produced using 16 ns RF pulses (unless noted otherwise) at a repetition rate of 5 Hz. To improve turn-around time, no in-situ bakeouts were made. It is clear that in-situ bakeouts, along with clean assembly conditions, are desirable for achieving high gradients, and will probably be part of an optimized linear collider assembly and installation procedure. The emphasis of these test was however to determine the effects of materials and RF design in as straight forward a way as possible. All structures were conditioned in the same way, by raising power to maintain controlled levels of emitted breakdown electron currents, vacuum activity and missing RF energy. The calibrations of field levels were always confirmed by measurement of the acceleration of a 0.5 nC probe beam.

In order to determine achievable gradient each new iris was RF conditioned after installation. The conditioning curves, which plot the maximum stable gradient as a function of number of RF pulses, for the coupler iris tests for both a copper and a tungsten iris, are shown in Figure 1. A saturation of the conditioning curve indicates that the maximum gradient has been reached.

From the conditioning curves it is clear that the tungsten iris provided an improved gradient compared to the copper iris. SEM (Scanning Electron Microscope) micrographs of both the copper and the tungsten irises are shown in Figure 2, and demonstrate quite clearly the increased arc resistance of tungsten. The peak surface electric field of the damaged copper iris was estimated to be nearly 40% higher than that of the original, un-damaged, geometry. The tungsten iris showed no change to its geometry. The micrographs also show that the tungsten iris has been sprayed with copper from the surrounding structure, probably the downstream iris. This iris had a 40% lower surface electric field than the coupler iris and was clearly damaged after the tungsten test. Microscopic zones of melted tungsten are also visible on the tungsten iris, but these zones appear to be benign and a normal consequence of conditioning. Although the tungsten iris a clearly higher surface field, it was not possible to conclude from these tests whether the tungsten went to a higher because the surface is capable of supporting a higher gradient, or whether the tungsten went to a higher gradient because it maintained its shape.

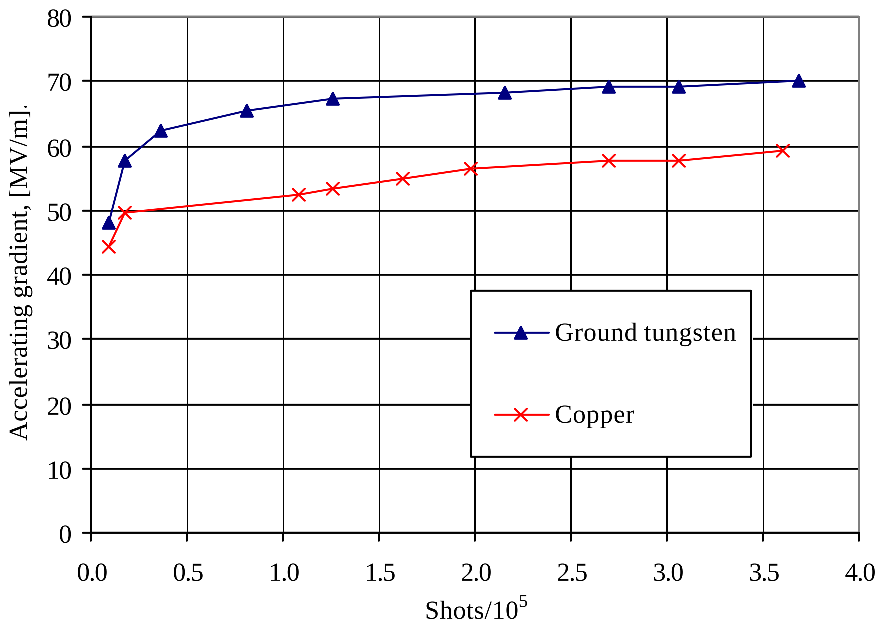

FIGURE 1. Conditioning histories tungsten and copper irises in the single-feed input coupler set-up.

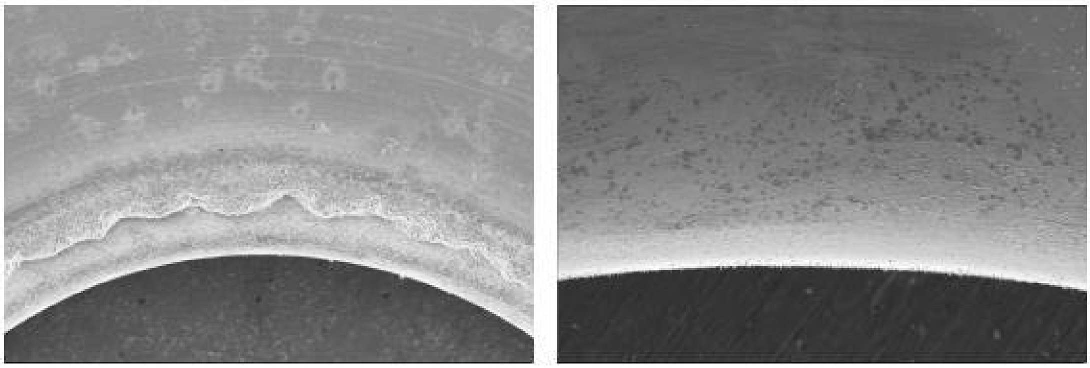

FIGURE 2. SEM images of the copper (left) and tungsten (right) irises after conditioning. The tungsten image was taken at a higher magnification – the radii are the same.

The surface electric field in the cells of the new 30-cell structures was reduced, compared the structure used in the previous tests, by reducing the iris aperture, from 4.00 mm to 3.50 mm, and by increasing the iris thickness, from 0.55 mm to 0.85 mm. RF design issues will be discussed in greater detail in the next section. The surface field enhancement in the coupler was reduced by adopting a 'mode launcher' coupler [8].

The tungsten-iris structure was composed of copper disks, which formed the cavity cell walls, and tungsten irises, which where placed in counter-bores in the copper disks. These parts are shown in figure 3. The whole structure was assembled by clamping. The all-copper structure was made from diamond turned disks and assembled by vacuum brazing, although the couplers were clamped on. The structures were tested inside a vacuum tank and each structure was mounted on a vacuum cover plate to reduce turn-around time between experiments to about an hour.

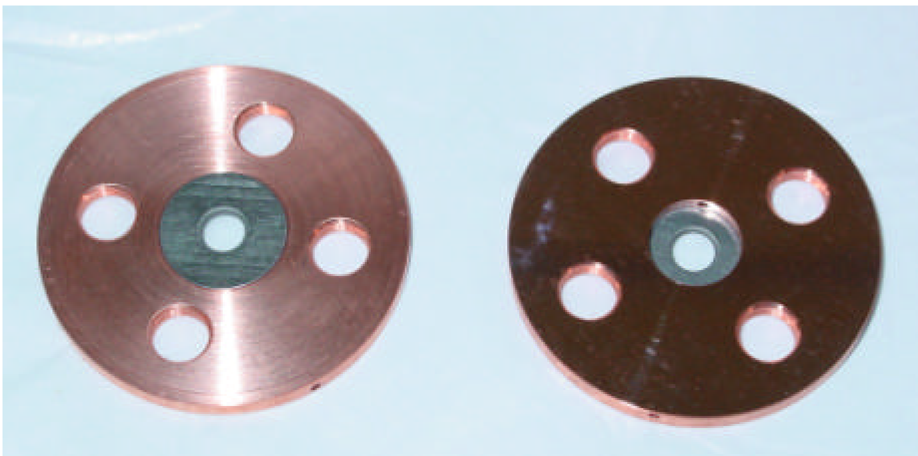

FIGURE 3. Copper cells with tungsten iris inserts.

The conditioning curves of the two new structures, along with the copper data from the previous test, are shown in Figure 3. The first feature to emphasize is that the average accelerating gradient improved from 60 MV/m to 100 MV/m due to RF design changes alone. A further improvement to 125 MV/m was obtained by the using tungsten. It should be noted that the tungsten conditioning curve may not yet have saturated, but the experiment was suspended due to lack of time in the testing program. The maximum achieved accelerating gradient in the first cell was 152 MV/m for the tungsten-iris structure and 112 MV/m for the copper structure. Corresponding peak surface fields were 340 MV/m and 270 MV/m respectively. A visual inspection of the tungsten-iris structure confirmed that the geometry of the irises was unchanged. A detailed analysis of the geometric and surface changes of the two structures will be made at a later date.

To investigate pulse length dependence, the RF pulse length was reduced to 8 ns, which corresponds to the filling time of the structure. The beneficial effect of the reduced pulse length allowed a direct measurement, using the tungsten-iris structure, of a 16.2 MeV energy gain of a 0.5 nC electron bunch. This corresponds an average accelerating gradient of 152 MV/m and a gradient in the first cell of 184 MV/m.

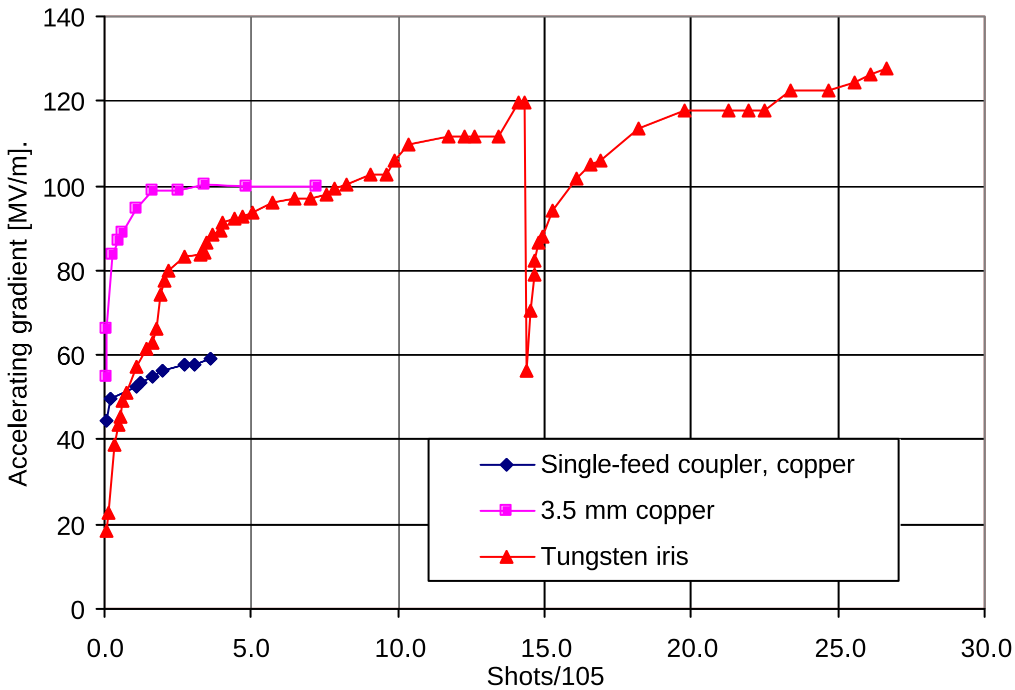

FIGURE 4. Single-feed copper structure, 30-cell copper and 30-cell tungsten iris structure conditioning curves. The dip in the tungsten conditioning curve occurred after the structure was opened to air for visual inspection for damage.

In addition to RF breakdown, fatigue damage due to pulsed surface heating represents a second serious limit to accelerating gradient [9]. A 30 GHz testing program has started in JINR, Dubna, using a free electron maser as a power source [10] to complement and eventually extend on previous work made at X-band [11]. After intentionally damaging copper test cavities in an initial series of tests, an investigation of different materials will be made.

RF-DESIGN STUDIES

The high-gradient testing program cannot yet give a definitive value of the maximum achievable surface electric field because testing has not yet been made at the full RF pulse length. However, from experience and quite reasonably, a reduced peak surface electric field appears to be a crucial design criteria. Subjectively combining the 150 ns copper X-band results and the 16 ns tungsten 30 GHz results suggests that a design limit of 300 MV/m surface electric field can be set with reasonable confidence. A definitive limit of allowable temperature rise cannot be given either, as testing is only just beginning, but it is already clear that an RF design should seek to reduce it as much as possible. For current design purposes an 'aggressive' design limit of 60°K has been chosen. The current redesign of the CLIC main linac accelerating structure is based on maximizing RF-to-beam efficiency, minimizing short-range wakefields and maintaining a high degree of long range wakefield suppression under the constraints of a maximum surface electric field of 300 MV/m and a maximum temperature rise of 60°K.

It should be noted that the geometry of the structure may also play more subtle roles, in the damage that an arc produces for example [6,11], but this is still unclear. Features in accelerating structures that can cause enhanced levels of surface electric and/or magnetic field are power couplers, higher-order-mode damping waveguides, pumping holes and tuning dimples.

CLIC accelerating structures have quite stringent constraints on wakefields caused by beam induced higher-order modes for reasons of beam stability [2]. Short-range transverse wakefields must be limited through micron-precision alignment tolerances and a limitation on the smallest beam aperture the structure can have. A large beam aperture increases the peak surface electric field which can be reduced by utilizing a relatively thick coupling iris and adopting an elliptical cross section.

Long-range transverse and longitudinal wakefields must be suppressed, by approximately two orders of magnitude in twenty fundamental mode cycles for the lowest dipole mode. This suppression is accomplished through a combination of damping via waveguides and detuning via dimensional tapering along the length of the structure. The validity of this technique has been demonstrated by direct measurement in the ASSET facility at SLAC [12]. The boundaries of the damping waveguides are, however, locations of a rather severe concentration of surface currents, which leads to enhanced pulsed surface heating [9].

A major innovation for the geometry of waveguide damped structures has been the introduction by a profiled convex outer cavity wall [2], in contrast to the usual, turned, concave outer cavity wall. The convex outer wall blends the cavity to the damping waveguides smoothly. This spreads out the surface currents so that the resulting temperature rise is only about a factor of 2.3 higher than in an equivalent undamped geometry. The convex geometry, called XDS for conveX Damped Structure, made from straight line and elliptical segments is shown in figure 4. The corresponding surface currents are shown in figure 5.

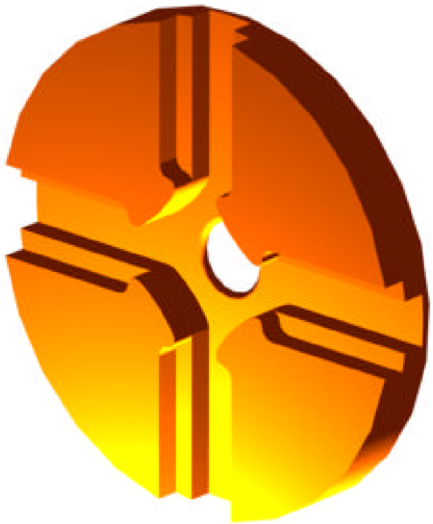

FIGURE 5. Low surface electric and magnetic field geometry, XDS. The low surface electric field is accomplished through a thick iris with an elliptical cross section. The low surface magnetic field is accomplished through the profiled convex outer cavity walls, in distinction to the usual, turned, concave outer cavity wall.

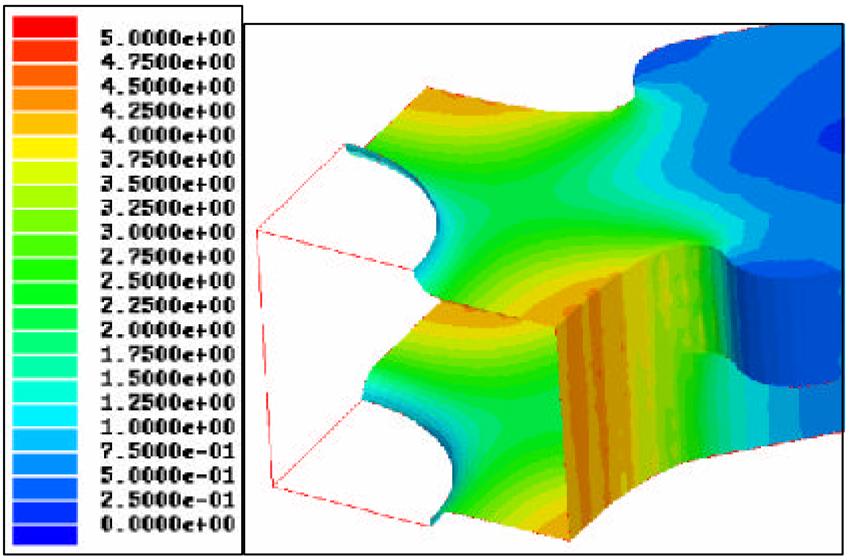

FIGURE 6. Surface currents of the XDS geometry (1/4 shown). The area of maximum temperature rise is a broad area in the cell wall situated between the damping waveguides.

The input and output power couplers are other features of a structure which are a source of a concentration of both surface electric and surface magnetic fields. Asymmetries in fields due to the input waveguide(s) result in enhanced surface electric fields. Inductive matching elements result in concentrations of surface magnetic field. An electric coupler solves both of these problems [8]. The geometry of the electric coupler is shown in Figure 6. In this coupler the maximum surface electric field is on the matching iris and is about 80% of the value for a regular cell. The magnetic field is about 5% higher than in a regular cell.

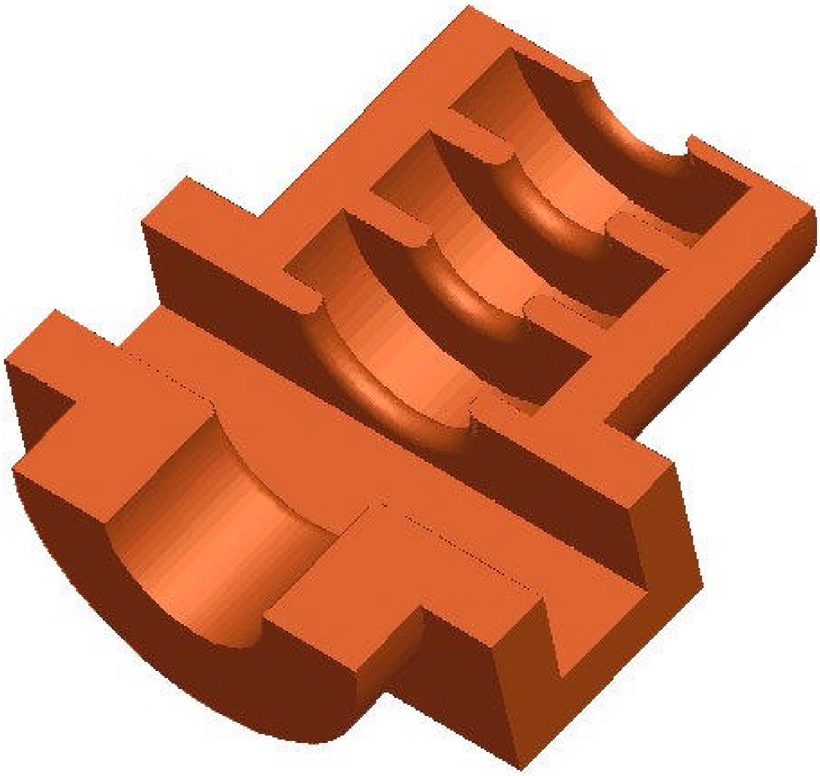

FIGURE 7. Electric coupler.

DERIVATION OF FIELD AND POWER LEVELS

In order to better understand how RF breakdown and pulsed surface heating become such important effects for CLIC accelerating structures, a simplified explanation of the scale of important accelerating structure parameters follows. A 150 MV/m accelerating gradient is required for the CLIC 3 TeV design in order to limit the over-all length of the facility to 30 km [1]. In order to achieve an adequate luminosity for physics, extremely low-emittance beam trains with an average current of about one ampere and with a 100 ns pulse length must be accelerated at a repetition rate of 100 Hz. The current is strongly influenced by the value of the lowest feasible emittance. Acceleration of a 1 A beam by a gradient of 150 MV/m requires a peak power transfer to the beam of 150 MW per meter of linac and a pulse energy of 15 J per meter of linac (ignoring inefficiency for the moment). Irrespective of the mechanism, accelerating a linear-collider beam at a gradient as high as 150 MV/m requires coping with extraordinary power and energy densities.

The peak input power required for an individual accelerating structure is determined by its R/Q, which is proportional to accelerating gradient squared divided by power flow. The main motivation for the original choice of an operating frequency of 29.985 GHz [13] was, staying with a 'classical' RF accelerating structure, to minimize peak power by maximizing *R*/*Q* with operating frequency (*R*/*Q* is proportional to f^2 for a given geometry). The upper frequency is limited by short range transverse wakes which cause an unacceptable degradation of the stability of the beam. Transverse wakefield amplitudes are fixed by fabrication and alignment tolerances of a few microns, which is considered the current state of the art of manufacturing. Another argument made in favor of a high operating frequency was that it should increase the feasibility of achieving high accelerating gradients. The result of choosing 29.985 GHz is that the peak power input to individual accelerating structures is of the order of 100 MW. With a pulse length of 100 ns this results in a pulse energy of 10 J. It is the combination of the 150 MV/m gradient combined with an associated power flow of more than 100 MW and a pulse energy greater than 10 J that define many of the design challenges of CLIC accelerating structures.

Selected RF parameters for CLIC accelerating structures [2], with losses now considered, are summarized in Table 1.

TABLE 1. Selected CLIC accelerating structure parameters.

Parameter	Value	Units
Operating frequency	29.985	GHz
Average accelerating gradient	150	MV/m
Section input power	132	MW
Total RF pulse length	130	ns
Pulse energy	16.5	J

Pulsed surface heating becomes a problem because the fraction of the more than 10 J pulse energy absorbed by cavity wall losses heats only a very small volume of material. Losses are confined to the skin depth, and initially little heat diffusion takes place because the pulse length is so short, so the corresponding temperature rise is high. Breakdown level is a problem because an accelerating gradient of 150 MV/m necessarily results in a surface electric field of about 300 MV/m. Damage due to RF breakdown is a problem because the arc that is formed during a breakdown absorbs a large fraction of incident power, often greater than 90%. A localization of this absorbed energy can be quite serious since the destructive potential (total energy) of a single 10 J pulse is sufficient to liquefy more than two cubic millimeters of copper [6].

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the role of my colleagues in this work, particularly D. Allard, C. Achard, H. Braun S. Döbert, S. Leblanc, J-Y. Raguin, W. Schnell, I. Syratchev, M. Taborelli and I. Wilson. They are thanked for all their ideas, discussion, efforts, and goodwill.

REFERENCES

1. G. Guignard ed., "A 3 TeV e+e- Linear Collider Based on CLIC Technology", CERN 2000-008.
2. J-Y. Raguin, D. Schulte, I. Syratchev, I. Wilson, W. Wuensch, "A New Damped and Tapered Accelerating Structure for CLIC", Proc. LINAC2002.
3. T. Higo, T. Taniuchi, M. Yamamoto, J. Odagiri, S. Tokumoto, H. Mizuno, K. Takata, I. Wilson, W. Wuensch, "High Gradient Performance of X-Band Accelerating Sections for Linear Colliders", Particle Acclerators, 1994, Vol.48 pp. 43-59.
4. J.W. Wang, G.A. Loew, R.J. Loewen, R.S. Ruth, A.E. Vlieks, I. Wilson, W. Wuensch, "SLAC/CERN High Gradient Tests of an X-Band Accelerating Section", CERN/SL 95-27, Proc. PAC95.
5. H. H. Braun, S. Döbert, L. Groening, I. Wilson, W. Wuensch, "Status of CLIC High Gradient Studies", CERN/PS 2001-045 (RF), Proc. PAC2001.
6. W. Wuensch, "High-Gradient Breakdown in Normal-Conducting Cavities", CERN/PS 2002-28, Proc. EPAC2002.
7. H.H. Braun, S. Döbert, I. Syratchev, M. Taborelli, I. Wilson, W. Wuensch, "CLIC High Gradient Test Results", Proc. LINAC2002.
8. J-Y. Raguin, I. Syratchev, W. Wuensch, "Coupler Studies for CLIC Accelerating Structures", CERN/PS 2002-036, Proc. EPAC2002.
9. I. Wilson, W. Wuensch, "The CLIC Main Linac Accelerating Structure". CERN/PS2000-057, Proc. LINAC2000.
10. A. Elozhov, I. Ivanov, A. Kaminsky, V. Kosukhin, E. Perelstein, S Sedykh, A.P. Sergeev, N. Ginzburg, S. Kuzikov, N. Peskov, M. Petelin, A.S. Sergeev, N. Zaitsev, "30 GHz Test Facility for Experimental Study of Accelerating Structure Damage Due to the Pulse Heating", Proc. EPAC2002.
11. D.P. Pritzkau, R.H. Seimann, "Results of an RF pulsed heating experiment at SLAC", SLAC-Pub-8554, Proc. LINAC2000.
12. C. Adolphsen, W. Baumgartner, R.K. Jobe, F. Le Pimpec, R. Loewen, D. McCormick, M.C. Ross, T. Smith, J.W. Wang, T. Higo, "Processing Studies of X-Band Accelerator Structures at the NLCTA", Proc. PAC2001, Chicago.
13. I. Wilson, W. Wuensch, C. Achard, M. Dehler, E. Jensen, M. Luong, C. Adolphsen, M. Ross, T. Slaton, D. McCormick, "An ASSET Test of the CLIC Accelerating Structure", CERN/PS2000-044, Proc. EPAC2002.
14. W. Schnell, "A Two-Stage RF Linear Collider Using a Superconducting Drive Linac", CERN/LEP-RF/86-06.