CLIC ACCELERATING STRUCTURE DEVELOPMENT

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Abstract

One of the most important objectives of the CLIC (Compact Linear Collider) study is to demonstrate the design accelerating gradient of 100 MV/m in a fully featured accelerating structure under nominal operating conditions including pulse length and breakdown rate. The main issues which must be addressed and their interrelations are described along with the development and testing programs which have been put into place to accomplish this feasibility demonstration. Initial experimental results showing the feasibility of the gradient are presented.

INTRODUCTION

CLIC accelerating structures must fulfil a complex set of demanding performance criteria which are strongly coupled to one another in order to arrive at a high-performance and cost-effective linear collider design. Demonstrating that these accelerating structure performance criteria can be achieved is one of the main objectives of the CLIC study. Very generally, the demonstration process can be broken down into two steps – operating at the design goal of 100 MV/m with at least a minimally realistic structure and then operating with a structure that gives an optimally energy-efficient and cost-effective collider. And as will become apparent, there are many tradeoffs and to a large extent efficiency and gradient can be exchanged.

The current CLIC parameter set specifies that accelerating structures operate at 100 MV/m loaded gradient with a breakdown rate of the order of 10^{-7} (per structure) at a pulse length of 240 ns. The pulse length must be sufficiently long compared to the fill time of the structure to accelerate a bunch train which provides a good luminosity-to-power ratio. However the pulse length is limited by an increased probability of breakdown and by an increased level of pulsed surface heating, an effect which will be described below. A high rf-to-beam efficiency favours long structures because less power flows into loads however this increases the fill time of the structures. The length is also limited by an increasing peak to average gradient ratio, which increases as the structure length increases, and by the limit on input power flow which causes damage during breakdown.

The iris aperture and structure alignment tolerance, which is of the order of a few microns, must result in sufficiently small short-range wakefields. The structures also need significant higher-order long-range wakefield suppression in order to transport the long bunch trains needed for efficiency. These structure requirements are related through the bunch charge, dimensions and long-range wakefield level which are all determined through beam-dynamics simulations.

The wakefield suppression features however influence the pulsed surface heating level. Accelerating structure must be capable of surviving twenty years of operation which corresponds to nearly 10^{11} pulses. The main effect that limits lifetime is fatigue damage caused by pulsed surface heating, the level of which is determined by the surface magnetic-field, pulse length and material properties. The surface magnetic field is enhanced by the damping features needed for long-range wakefield suppression but the effect can be mitigated through use of high fatigue-strength copper alloys. However new materials inevitably introduce numerous new technological challenges. These can include restricting the assembly techniques that can be used (no brazing for example), excluding heat treatment procedures which may be necessary for high-gradient operation and extending the development time needed for the structures. Alternative materials to copper are also being considered as a way of mitigating the effects of breakdown although however the base-line solution of CLIC structures is fabrication from copper or a copper alloy.

Micron precision fabrication techniques must then be found which are compatible with the chosen wakefield-suppression geometry. Different damping methods, waveguides, manifolds, slots and chokes, result in very different topologies assembly concepts. Options like disks or quadrants require quite different machining and assembly techniques.

Accelerating structure and beam dynamics performance requirements also result in demanding designs for other engineering aspects of accelerating structure sub-systems such as vacuum, cooling and system integration. These areas must be investigated to be sure specifications can be met and that there are not any hidden feasibility issues.

Each of these different domains described above individually require substantial studies to acquire the basic knowledge and experience to be able to make quantitative performance predictions which are needed when addressing complexity of the overall design. The main objectives of this note are to give an overview of status of studies in three of the domains along with the main scientific and technical results: accelerating structure design and optimization, breakdown physics and quantified high-power limits and high-power rf tests. Pulsed surface heating, other aspects of breakdown research including dc spark testing and engineering aspects of subsystems are covered in [1,2,3].

The areas of expertise and the number of facilities (machining, surface preparation, high-power testing) which are needed for accelerating structure development, even just for a minimum feasibility demonstration, are numerous. To this end considerable effort has been invested in setting a large collaboration and much of the work described here comes from those collaborators.

ACCELERATING STRUCTURE AND MAIN LINAC INTEGRATED DESIGN AND OPTIMIZATION

The strong and multiple interconnections between the different performance aspects of the accelerating structure and the main beam has motivated the development of an integrated optimization procedure [4,5]. A schematic view of the optimization procedure is shown in Fig. 1. The inputs to the procedure are parameterized properties of the fundamental and dipole mode characteristics (such as dimensions, v_g, R/Q, surface fields, Q etc.) over a range of cell geometries, the relationships between gradient, beam aperture, bunch charge, wakefields and luminosity given by beam dynamics and a set of functions which give high-gradient and high-power limits. These limits are referred to as ‘rf constraints’ in Fig.1. The optimization procedure essentially systematically constructs all possible accelerating structures from the cells over the range under study. Structures are then either accepted or rejected based on whether they are consistent with the high-power rf constraints. The beam characteristics of the retained structures are determined and the luminosity to power ratio, which is the overall figure of merit of a collider, is computed. The nominal structure is then the one with the highest (or nearly highest if criteria not present in the optimization emerge as being important) figure of merit.

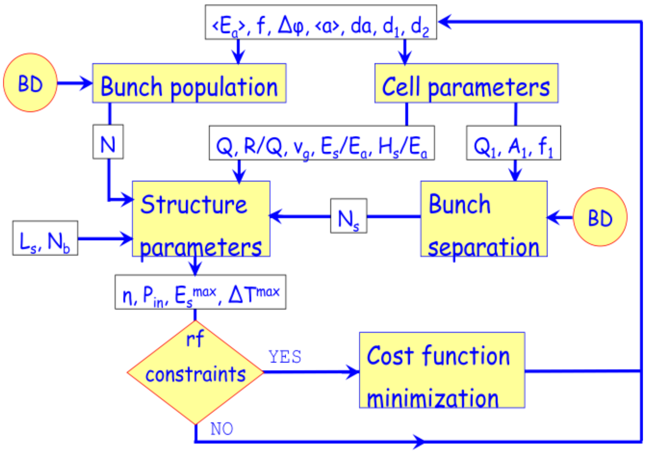

Figure 1: Schematic representation of the structure and main linac optimization procedure [5].

The basic cell geometry currently under consideration for CLIC is shown in Fig 2. The wakefield damping manifolds result in a lowest dipole-band Q of below ten. All surfaces are rounded in order to minimize peak values of surface electric and magnetic fields. This is particularly evident in the convex shape of the outer cavity wall, which is required to counteract the concentration of surface magnetic field caused by the presence of the damping waveguides.

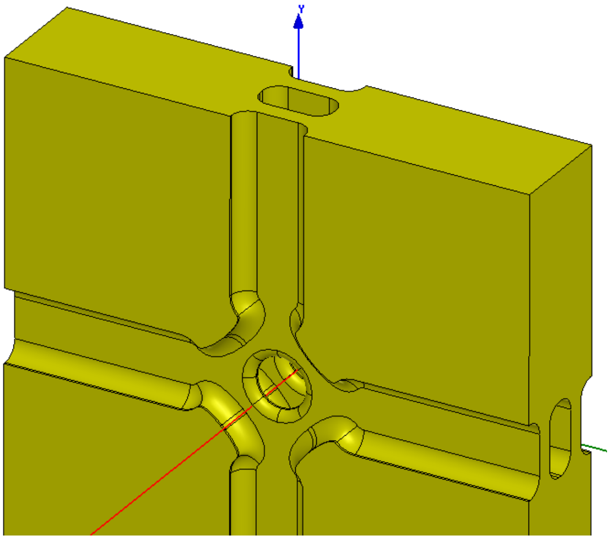

Figure 2: Basic cell geometry of the accelerating structure with strong waveguide HOM damping [5].

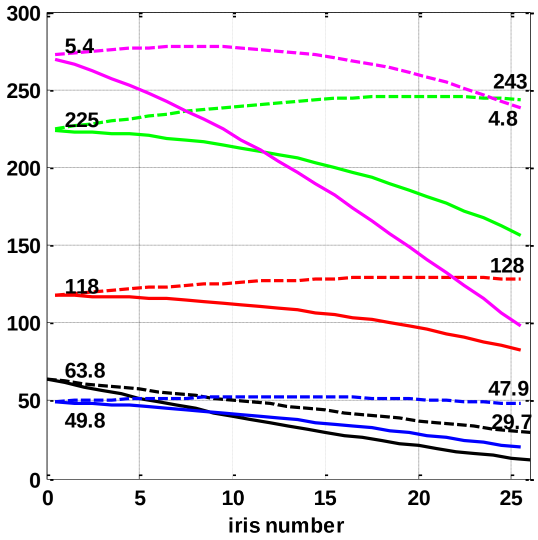

Figure 3: The fundamental mode properties the nominal CLIC accelerating structure, CLIC_G. The traces from top to bottom are: S_c *40 [W/μm^2](pink), surface electric field [MV/m](green), accelerating gradient [MV/m](red), power [W](black), pulse surface temperature rise [ºC](blue). Dashed traces are unloaded and solid are beam loaded conditions [5].

When the cells are combined the resulting structures have an which iris diameter is decreasing along the length of the structure. This tapering has benefits both for the fundamental mode properties and the higher order mode properties (other taperings such as nose cones or phase advance can also be considered). Travelling wave structures have long been designed to be ‘constant gradient' and in the case of CLIC this has been extended to being 'constant high-power limits'. The specifics of the limits will be introduced in the next section, however in optimally efficient structures, the decreasing power flow along the structure results in a geometrical tapering which maintains the levels of the limits at or near their maximum. The fundamental mode properties and constant high-power limit nature of the current nominal CLIC structure, called CLIC_G, is shown in Fig. 3.

The taping also provides detuning of the higher order modes which is an important effect even for heavily damped structures. The relative contributions of the heavy damping and detuning to the transverse wakefield spectrum is shown in Fig. 4. The transverse wake computed in time domain of the full structure is shown in Fig 5. One can see that the wake is below the 7 V/pC/mm/m at the position of the second bunch, following at 0.15 m, as required for beam dynamics.

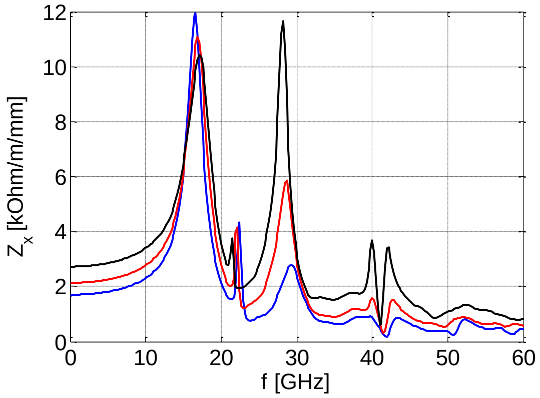

Figure 4: Transverse impedances of the first, middle and last cells of the CLIC_G structure [5].

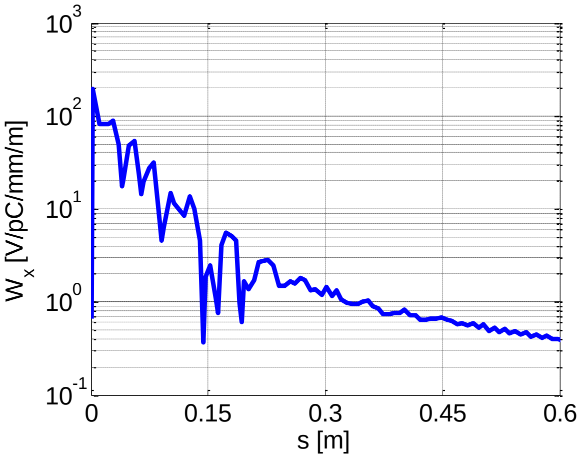

Figure 5: The transverse wake of the CLIC_G structure. The CLIC bunch spacing is 0.15 m [5].

BREAKDOWN PHYSICS AND HIGH-POWER LIMITS

One of the most important effects which limit gradient (or the more precisely, the gradient to efficiency trade-off) is rf breakdown. Rf breakdown is an extremely common effect however it is not well quantified. Technological issues such as material and surface preparation certainly influence the achievable gradient of a structure. However it has become clear in testing at CLIC and NLC/JLC that the geometry of the structure strongly influences the achievable gradient. An early attempt to quantify the limit due to breakdown was that achievable gradient is a (decreasing) function of group velocity [6].

The integrated design procedure being developed in the CLIC study strongly motivated further efforts to quantify the effect of geometry on gradient. An early attempt to establish the relationship was that the power flow in a structure is limited to a fixed value of *P/C*, where *P* is the power flow and *C* is the circumference of the smallest aperture of the structure [7]. This was derived empirically by collecting available high-gradient data and was combined with a general physical argument that the gradient is limited by a threshold in local power just above the structure surface which can feed an arc. This model worked reasonably well, however the model did not describe very low group velocity and standing wave structures, did not give the correct frequency scaling and did not have a sound physical basis.

It was clear that to go beyond *P/C* it would be necessary to increase the quantified understanding of breakdown, although this is admittedly a very ambitious objective given the complexity of breakdown. To progress the questions to be addressed have been split according to the different steps in the breakdown process: creation of emission sites and the breakdown trigger, initiation of the arc and formation of a plasma and absorption of the incoming rf. A discussion of the experimental program which has been put into place for the third stage is described in [8]. Progress in this stage could help to explain why some design of structures continue to improve with time and others deteriorate often with the appearance of visible melting and damage.

Research into the creation of emission sites is being carried out using atomistic simulations [9]. The principle idea behind these studies are that it may be that the probability of random movement of atoms at the material surface, combined with the pulling force of the strong applied electric field, around 200 MV/m, will result in a spontaneous surface roughening with features of nm size. These are expected to give the often observed Fowler-Nordheim field enhancement factors, often in the range of 30 to 100, which consequently trigger the breakdown. The statistical nature of the dynamic roughening may explain the breakdown rate dependence on applied field. The implementation of an external electric field to an existing atomistic simulation tool is now underway.

Confirmation of the nm scale of emission sites in the case of CLIC pulses comes from a classical Fowler-Nordhiem and heat-flow analysis of the time and power needed to heat emission tips [10]. The results of the calculations are shown in Fig. 6. The curves show that in order to heat a tip to a reference temperature, which in the case of Fig. 6 is the melting point of Cu, within a pulse of 200 ns, the tip must have dimensions below 100 nm. The power dissipated in the cross section of the tips under these conditions is of the order of 0.5 W/μm^2. Two proposals have been made to explain how the emission site heating evolves to an electron cascade, and in particular how this can result in a breakdown probability which decreases with decreasing applied field. The first is that the tensile force on the emission tip from the applied electric field combined with the thermal stresses induced by the resistive heating result in fatigue and fracture with subsequent ionization of the clump of material by emitted electrons. The second is that the heating causes evaporation of molecules from the tip which have a statistical probability of ionization from the emitted current which is in turn dependent on the applied external field. Ions are then back bombarded on the surface.

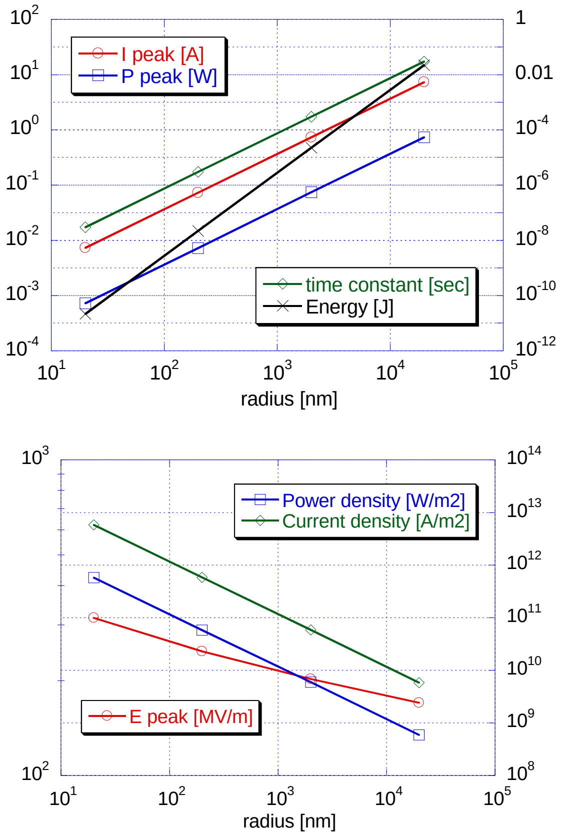

Figure 6: Parameters to attain the melting point of the tip of a Cu cylinder of given radius and beta =30.

The heating of emission sites has also been investigated from the perspective of rf power flow [11]. The underlying observation here is that a minimum level power flow is required to maintain Fowler-Nordheim type emission currents and tip heating. In an rf structure this power can only come from the rf fields. This is in contrast to a dc spark set-up [2] where power is supplied to an arc from an external energy storage device like a capacitor. There are two important considerations regarding the power flow, which is given by the Poynting vector ***S***. The first is that both the real and the imaginary part of the Poynting vector must be considered. The real part of the Poynting vector is the time averaged power flow through the structure, while the imaginary part is power flow back and forth during a cycle between predominantly electric and magnetic field regions. Both power flows are relevant for tip heating. However the coupling to the emitted currents is different due to the 90° phase difference in the relative phase between the electric and magnetic fields in the real and imaginary power flows. Taking into account this phase difference gives a difference in the effective coupling of real and imaginary power to the emission site. The resulting high-power limit is given by the maximum value of

$$S_C = \mathrm{Re}\{S\} + 0.2\,\mathrm{Im}\{S\} \qquad (1)$$

on the surface of the structure. With this function, three of the main weaknesses of *P/C* have been resolved: the quantity applies to low group velocity and standing wave structures, it gives the observed independence of gradient for geometries scaled with frequency and it has a solid physical model behind it. The function has been computed for the X-band and 30 GHz structures for which there is appropriate high-power data and the consistency is quite good [11]. The limiting value determined from this existing data is 2.5 W/μm^2 for a 100 ns pulse and 10^{-6} breakdown rate. This value is remarkably consistent with the power density from the previous calculation when the volume of field affected by the tip is considered. S_c is now being implemented in the integrated design procedure and has been used in designing high-power rf test structures.

HIGH-POWER RF TESTING

Many accelerating structures have been tested over the years in the contexts of the NLC/JLC and CLIC studies and results in the form of a comprehensive comparison can be found in [11]. The ultimate test of a predictive theory such as *P/C* or S_c is the operation of a structure which is designed using the theory and produces a higher gradient than previously tested structures. To test only the theory, it is important that such a structure be made using a well known and reproducible technology and that a number of these structures are tested to understand the variability of the results.

To this end and to make a first demonstration of low-breakdown rate operation in the range of 100 MV/m, a structure, called the T18 in this text, has been designed. It was designed using *P/C* (S_c was not mature at the time of design) and the result is a strong tapering. Four undamped disk-based structures are under production now at KEK using the technology developed during the NLC/JLC programs [12]. The first of these structures has been completed, Fig. 7, and was tested at SLAC. Damped versions of the structure will follow.

The main results from this test are shown in Fig. 8. And are very positive [13]. The first point is that the structure is operated with respectable breakdown rates in the

100 MV/m gradient range. The target value for CLIC is a breakdown rate per meter of approximately 3x10^{-7}. The overhead in gradient needed for beam loading is about 7 MV/m for this structure. The structure is actually operating above the prediction based on S_c of 93 MV/m at 4x10^{-6} and a pulse length of 230 ns. Another noteworthy point is that the structure showed a steady improvement in performance over the running period.

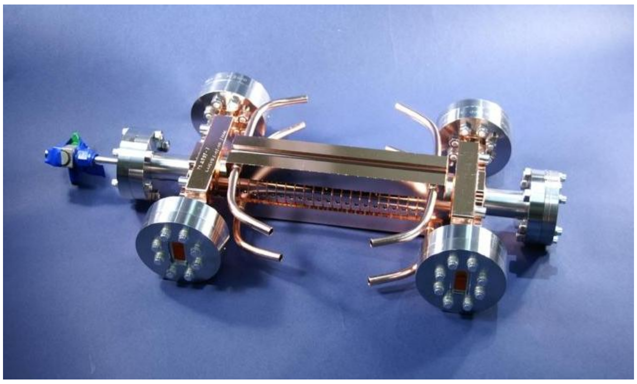

Figure 7: The first T18 test accelerating structure.

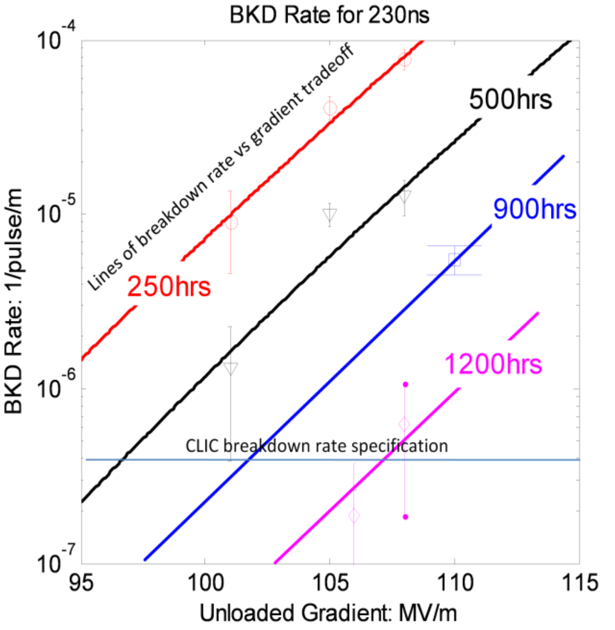

Figure 8: High-gradient results of the T18 test structure for a 230 ns pulse. The horizontal scale is average unloaded accelerating gradient [MV/m]. The vertical scale is breakdown probability per meter. The data (top to bottom) are after operation over 250, 500, 900 hr and 1200 [13].

These results are the first for a test structure designed after the switch of frequency of CLIC to X-band. A second KEK-built T-18 structure is currently being tested at NEXTEV at KEK and a CERN built version is being tested at SLAC. The objectives of further tests will be to add damping and to a test of the nominal CLIC_G structure which was designed using S_c as a criterion.

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