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PROGRESS IN UNDERSTANDING THE HIGH-GRADIENT LIMITATIONS OF ACCELERATING STRUCTURES

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INTRODUCTION

One of the main objectives of the CLIC study is to demonstrate that an accelerating gradient of 100 MV/m or higher is feasible using realistic accelerating structures under practical operating conditions. There are two main effects which limit achievable accelerating gradient: rf breakdown and fatigue cracking due to pulsed surface heating. This report considers mainly the limit due to rf breakdown which is currently the most severe. Dark current capture may also become a limitation in a high-gradient accelerator.

There are a number of issues which define 'realistic' which are quite specific to accelerating structures for linear colliders. One issue is that the structures must produce an rf to accelerated-beam efficiency as high as possible since this is one of the key efficiencies which define the overall efficiency of a linear collider complex and the power capacity which must installed. Another issue is that the beam aperture be sufficiently large so that the beam emittance growth driven by short-range wakefields be limited to acceptable values. Yet another is that the accelerating structures must contain features which suppress long-range wakefields so that bunch-to-bunch driven instabilities do not create relative offsets which give a train emittance growth. These efficiencies and emittance growths can all be determined from the geometry of the accelerating structures through electromagnetic and beam dynamic simulations. On the other hand, the achievable gradient is strongly affected by the geometry and this dependence is only approximately known. This creates one of the principle complications in optimizing and demonstrating the feasibility of a linear collider design.

One of the most important aspects of the 'practical' operating conditions is that the breakdown probability of the individual accelerating structures must be of the order of 10^{-6} to 10^{-7}. Breakdowns in the accelerating structures induce random kicks on the beam which can lead to either emittance growth or even loss of the beam if the kick is large enough. The acceptable breakdown probability is a function of the emittance loss caused by an individual kick, the number of structures in the linear collider (in the range of tens of thousands) and the acceptable emittance loss budgeted for this effect. After conditioning to certain gradient, accelerating structures become more stable as the gradient is reduced. The breakdown probability falls exponentially with gradient but many tens of percent are typically required to make the structures sufficiently stable. The cause of the breakdown rate and its dependence on field is not well understood, but initial ideas are presented below. Other aspects of practical operating conditions include: sufficiently fast rf (surface and heat treatments during production are being studied to reduce this time to a minimum or even to eliminate it) conditioning, acceptable surface modification caused by the conditioning process and the accumulated number of breakdowns over the lifetime of the linear collider and a vacuum level inside the structure during the rf pulse which is sufficiently low. All of these conditions depend on the length of the rf pulse and a longer pulse is worse for all of them. However the rf pulse length also influences the rf to beam efficiency mentioned in the previous paragraph where for this the longer pulse is better,

This objective of this report is to elaborate on the some of the effects which have been mentioned in this introduction to give the reader an idea, and the motivation, of the areas which are being pursued by the CLIC accelerating structure development program.

THE EFFECT OF SRUCTURE GEOMETRY

Very generally it has been observed that different accelerating structure designs result in a different accelerating gradient potential, all other parameters such as material, preparation and conditioning strategy being equal – although there are statistical variations between structures. The aspects of the structure design which appear to be relevant for the high gradient performance include the transition region between the input (and output) waveguide and the periodic part of the structure, the periodic part of the structure itself and its profile and the geometry of damping features. With modern three-dimensional electromagnetic field solving programs, the complete fields patterns and functions of the fields, including electric and magnetic fields, local power flow group velocity, energy density, of the structures can be determined.

What is less clear, however, is exactly how the gradient depends on these quantities, or indeed if the gradient can even be determined from the field pattern calculated without considering the fields perturbed by the currents and plasmas that are known to form during a breakdown. In fact, it appears that a fairly accurate prediction of gradient can be determined from the unperturbed fields.

The accelerating gradient limit for traveling-wave accelerating structures has been observed to depend on surface electric field, and lowering the peak surface electric field to accelerating gradient ratio has been used to improve the performance of structures [1]. There is clear evidence however, in data from both CLIC and NLC [2,3,4] which covers structures with a wide range of rf parameters, that a simple constant surface field limit is insufficient to predict the performances of different structures. In general the data shows that larger aperture and higher group velocity structures tolerate lower surface electric fields. They do on the other hand support much higher power flows. An attempt to explain this and to quantify the limit has led to the suggestion that traveling wave structures have a material dependent limit which is given by,

$$\frac{P\tau^{\alpha}}{C} < Const$$

where P is the power flow, τ is the pulse length, α gives the pulse length dependence (observed to be about 1/3 for copper and 2/3 for molybdenum) and C is the smallest circumference of the structure [2]. A refined physical explanation for this power limit scaling and expanded data is presented in this report. The subsequent arguments will be made for constant pulse length and the pulse length dependence will be addressed again below. The variation of the value of the constant with frequency is also considered.

The proposed limit is an extension of the ablation limit of $P\tau^{½}$ described in [4]. The physical reasoning for a power over *circumference* limit begins with the observation that the melted spots observed on structures after rf conditioning have a typical diameter of 100 µm independent of frequency and structure parameters, and are thus small with respect to the features of structures in the frequency range of 30 GHz and below. The power available to feed a discharge which produces such a small but fixed width spot is proportional to the power density, which is given by the total power flow through the structure divided by the circumference of structure.

During the conditioning process, the cumulative effect of breakdowns is to improve the field holding capacity of the structure surface. Above a certain threshold in discharge power however, the detrimental effect on surface geometry from a breakdown, surface roughening or even erosion and eventually ‘damage’, is greater than the improvement in field holding capacity. This surface roughening raises the local peak surface electric field. Conditioning saturates under these conditions and the power limit of the structure is reached. What is added by this proposed scaling is that the power available to the discharge is related to the geometry of the structure through the quantity *P/C*.

The pulse length dependence of the originally proposed $P\tau^{½}$ scaling is given by one dimensional heat diffusion during the breakdown. Observed pulse length dependencies, generally α≈1/3 for copper [5] and α≈2/3 [6] for molybdenum, differ somewhat. The lower value for copper may indicate that the heat diffusion is in more than one dimension or that another cooling process, such as radiation, is occurring. The higher value for molybdenum may be because of its lower thermal conductivity.

The validity of the scaling has been tested by considering data from a number of data sets for a series of very different geometry 30 GHz structures tested under comparable conditions, figure 1. The value of $P\tau^{⅓}/C$ for the three 30 GHz structures is remarkably consistent even though the values of group velocity differ by an order of magnitude, the surface electric field differs by over a factor of two and the total power flow differs by a factor of three in the opposite direction.

It is likely however that the parameter $P\tau^{⅓}/C$ is not the final word. Rather, the fundamental quantity must be a function of local electric and magnetic field which scales like $P\tau^{⅓}/C$ as the aperture is changed. If such a function is the true limit it would be frequency independent, and one would then expect that the limiting value of $P\tau^{⅓}/C$ would scale linearly with frequency. Using this assumption, 30 GHz and X-band data can be plotted together, as shown in figure 1. The data is plotted on a log-log scale, so if the quantity $fP\tau^{⅓}/C$ is the correct invariant, the data should lie on a straight line with a slope of one. The data indeed shows the validity of the constant for over an order of magnitude range in power. Deviation from the line indicates that other parameters than just circumference must be included. For example, the HDS (Hybrid Damped Structures which are assembled from quadrants and have slotted irises [7]) fall below the line and appear to have a reduced power handling capacity due to the damping features. Finding the correct function of local fields is being actively pursued.

Table 1: 30 GHz copper periodic structure data [8,9,10,11]. For structures at the conditioning limit. 2*a* refers to iris diameter.

	f [GHz]	V_g/c	E_{acc} [MeV/m]	E_{surf} [MeV/m]	P [MW]	τ [ns]	2a [mm]	$\frac{P\tau^{1/3}}{C}$
Accelerating	30	0.047	116	253	34	70	3.5	13
CTF2 PETS	30	0.5			240	16	16	12
CTF3 PETS	30	0.40	30	116	100	50	9	13

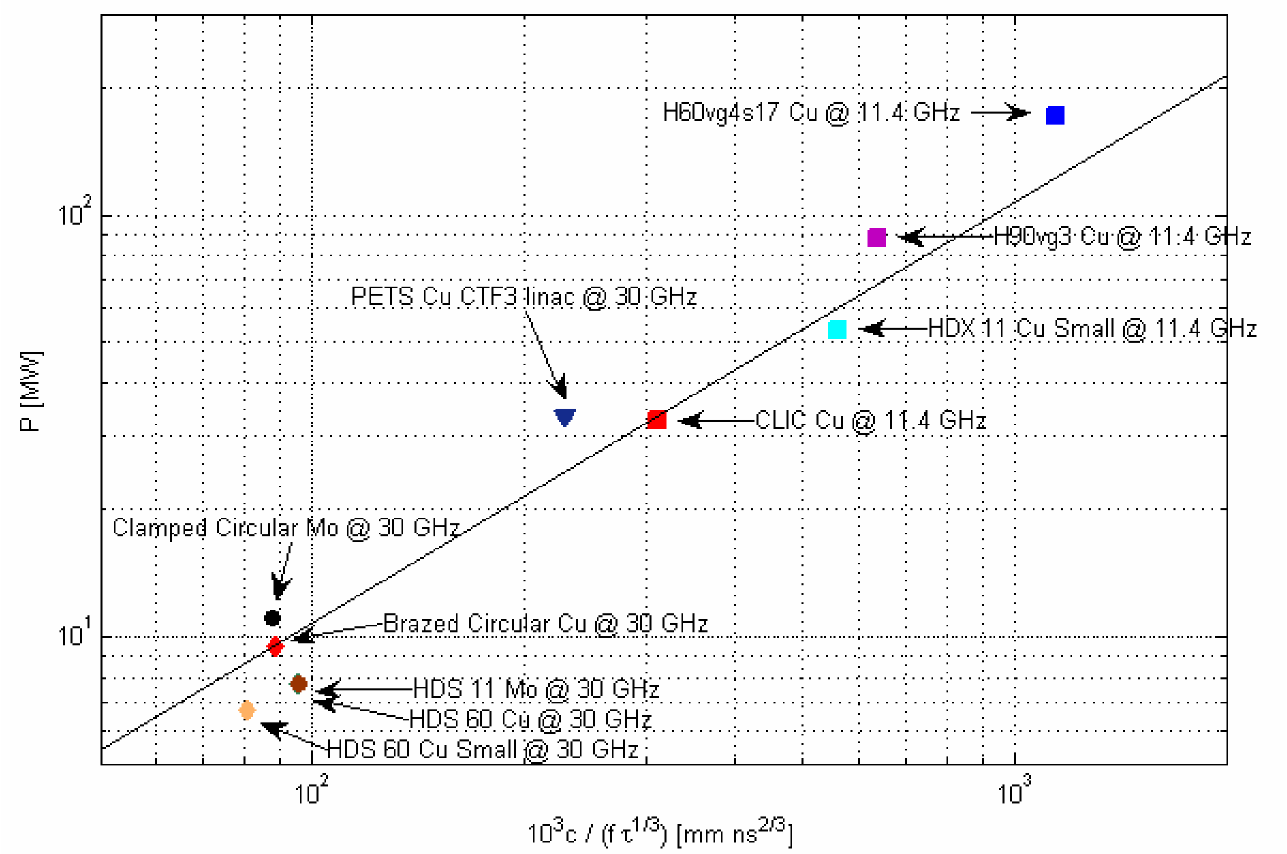

Figure 2: Data from 30 GHz and X-band structures [12]. In order to be able to compare the data from the different experiments, the power is given for a breakdown rate of 10^{-6} and a pulse length of 70 ns. The line has a slope of one.

The validity of the $P\tau^{1/3}/C$ limit applied to rectangular waveguide has been investigated using an experiment made at SLAC [13]. In the experiment two different width copper waveguides were investigated and data taken from the reference is presented in table 2. The circumference taken in the $TM_{0,1}$ structures has been replaced by twice the width of $TE_{1,1}$ mode of the rectangular waveguide, the part of the waveguide circumference with normal electric field. The relative consistency of the power over circumference limit for the waveguides is again remarkable despite the large differences between the other parameters.

Table 2: Copper waveguide data taken from [20]. *a* is the waveguide width.

	f [GHz]	V_g/c	E_{surf} [MeV/m]	P [MW]	τ [ns]	a [mm]	$\frac{P\tau^{1/3}}{2a}$
WR-90	11.424	0.82	60	56	750	22.9	11.2
Reduced width	11.424	0.18	45	32	750	13.3	10.8

MATERIAL AND BREAKDOWN PROBABILITY

Alternative materials to copper have been investigated by the CLIC study, initially in response to the observation of surface damage caused by the conditioning process. Early tests showed that refractory metals could be conditioned to significantly higher gradients than copper. These results have been duplicated in dc spark experiments. The question of material choice is significantly complicated when considerations of breakdown probability are included.

Breakdown induced transverse kicks have been measured to be about 10 KeV in X-band accelerating structures in the NLCTA [3]. A simple order of magnitude estimate for an acceptable breakdown probability for CLIC, based on the assumptions that all luminosity is lost on a pulse with a breakdown and that not more than 10% of total luminosity should be lost, gives that the breakdown probability for a structure should be 10^{-6} since there will be approximately 10^{5} accelerating structures in CLIC. This is a very low probability which has serious consequences on a practical operating gradient of a linear collider.

Breakdown probability data from tests of four structures is shown in fig. 1. The data are from an NLC structure [5] and a series of tests of identical geometry CLIC structures: a 30 GHz molybdenum iris structure [6], a 30 GHz copper structure [8] and an X-band molybdenum iris structure [14]. The data have been taken at different pulse lengths and also conditioning state in the case of the 30 GHz copper data. In all the three structures the breakdown probability at a given gradient could only be improved by conditioning the structure. No long term improvement in breakdown rate was observed during the low breakdown probability operation which lasted for about one hundred hours.

The breakdown probability of a structure appears in all cases to fall off exponentially as the gradient is reduced. The data are fit with two groups of lines on the linear/log plot in Fig. 1, one group for copper and another group for molybdenum. Each individual line is fit with a single parameter $E(10^{-1})$, the gradient giving 10^{-1} breakdown probability. The slope of each fit line, in units of decades of probability per MeV, is given by $1/0.09E(10^{-1})$ for molybdenum data and $1/0.06E(10^{-1})$ for copper data.

That the data can be fit in such a way gives insight into two major effects. One is that there appears to be a dependence of the slope on material. The other is that the breakdown probability, for a given pulse length, is determined entirely by the highest gradient at which the structure can be conditioned to, independent of frequency, structure geometry and conditioning state.

There are a number of consequences of these effects. The first is that while a material like molybdenum has a clearly higher peak gradient capability compared to copper, the lower breakdown probability slope means that at a certain probability it will be no better. Intriguingly the cross over point for copper and molybdenum appears to be at around 10^{-6}, which corresponds to the estimated requirement for CLIC. This implies that the dominant effect considered in material studies for linear colliders should be breakdown rate. On the other hand, other applications which do not require such a low breakdown probability may be able to profit from molybdenum. Another effect is that the breakdown probability is determined by the ultimate gradient, the value of which is explained by the arguments of and referred to in the previous section. The inverse proportionality of the slopes to gradient at fixed probability also implies that the pulse length dependence is constant for all breakdown probabilities – probability lines of different pulse length converge at lower gradient so as to maintain the same pulse length dependence.

Although the data provides very compelling evidence for the arguments which have been presented, the understanding emerged after the data was taken. As a consequence further tests are required to verify their validity and to address possible errors. One of the main questions is the effect clamped irises (rather than brazed) have on the molybdenum data, since both the 11 GHz and the 30 GHz were clamped iris structures. In addition the initial surface finish of the irises of both structures was quite poor. Another question is whether the breakdown probability dependence is really exponential down to low values. This will require long and stable running periods.

A possible explanation for the origin of a breakdown rate and its functional dependence is fatigue due to local cyclic tensile stress. It has been proposed that the ultimate gradient is determined when the electrostatic pull caused by the local electric field, including the Fowler-Nordhiem derived field enhancement factor β, exceeds the material tensile strength limit [15,16]. In this model rf breakdown is initiated when a the pulling force of a local electric field site exceeds the tensile strength of the material and a clump of material is broken off. A logical extension of this argument is that the breakdown probability below the ultimate gradient is given by fatigue, the accumulation of defects, under the cyclic tension. The curves of fatigue as shown for example in [17] give qualitatively the correct functional form to fit the breakdown probability data. Fatigue data of molybdenum is planned for the fatigue test to determine if the same relationship holds as for the rf breakdown probability data.

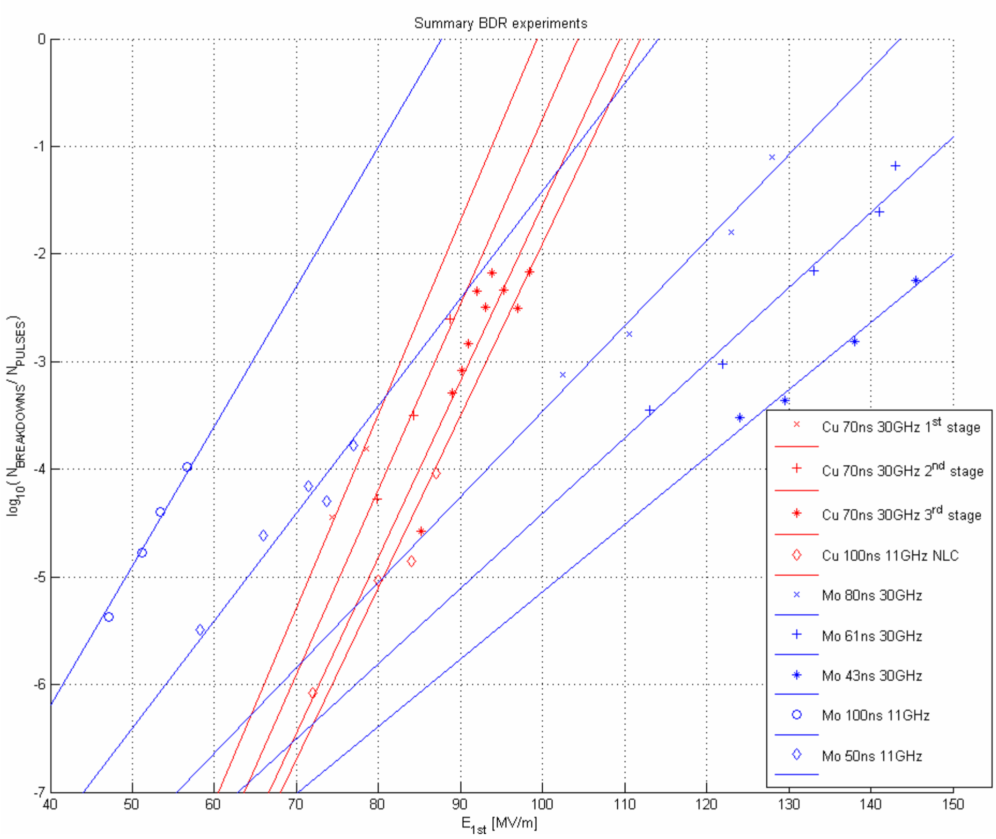

Figure 2: Breakdown rate measurements. The copper data is plotted in red and fit with $1/0.06E(10^{-1})$ and the molybdenum is plotted in blue and fit with $1/0.09E(10^{-1})$. The three 30 GHz copper data sets were taken at successive moments in the conditioning process, hence the improving breakdown probability at fixed gradient.

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