STATUS OF VERY HIGH-GRADIENT CAVITY TESTS

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Abstract

Accelerating gradients in excess of 100 MV/m are essential for future multi-TeV linear colliders in order to limit their overall length and cost. Experience has shown that to obtain such high gradients with normal-conducting (nc) structures requires operation at a relatively high frequency. A brief review of the very high gradient test work being carried out around the world will be presented with special emphasis being placed on the effect of frequency on the maximum achievable gradient. In the framework of the CLIC study at CERN, evidence has been found during high gradient tests at 30 GHz that part of the limitation on gradient is due to the choice of copper as the standard cavity fabrication material. To support this hypothesis, a breakdown mechanism leading to material destruction is presented together with a review of results and experience obtained with alternative materials.

1 INTRODUCTION

One of the big present-day challenges in accelerator physics is to cope with the increasing demands of the high-energy physics community for lepton collisions in the TeV energy range. A figure of merit in this context is the accelerating gradient since the cost will depend on the overall length of such an installation. Accelerating fields up to 30 MV/m are achieved routinely today for nc structures at S-band and up to 25 MV/m for super-conducting (sc) cavities at L-band. Exploring the multi-TeV energy range however will require gradients around 100 MV/m. Since the current sc technology has a fundamental limit at about 50 MV/m, the most promising way to obtain very high gradients is to use nc cavities at frequencies well above S-band. Although on-going studies based on visionary technology like laser- and wakefield-acceleration are progressing well and have the potential to reach gradients in the GV/m range, it is most unlikely that this technology will be ready for the next generation of high-energy physics machines. This paper will therefore concentrate on the feasibility of obtaining gradients in the 100 MV/m range using nc RF accelerating structures and will focus on the choice of RF frequency and cavity material. Although only the CLIC-study [1] is proposing accelerating gradients in excess of 100 MV/m (the unloaded design gradient is 170 MV/m at 30 GHz), the issues of very high-gradients and RF-breakdowns, are being studied in many laboratories. SLAC and KEK, in the framework of the NLC/JLC collaboration [2], have the most-extensive high-gradient test program with the aim of obtaining an unloaded gradient of 70 MV/m at 11.4 GHz.

2 HIGH-GRADIENT TESTING AND RF BREAKDOWN PHENOMENOLOGY

High-gradient test cavities are built covering a wide range of designs from single-cell standing-wave (SW) geometries to multi-cell travelling wave (TW) geometries. High-gradient tests are performed at different frequencies using, as a consequence, different types of power sources and different criteria for the conditioning procedure. These differences make it difficult to compare results, draw conclusions or even to extract scaling laws. It is therefore useful to adopt a phenomenological approach, and to ask the following fundamental questions.

- What is a high-gradient test ?

A typical high-gradient test consists of a cavity equipped with directional couplers on the input and output RF transmission lines to facilitate the calculation of the power balance. Missing energy in the power balance is a very good indicator of RF breakdown. Traditionally a huge input reflection was an indicator for breakdown but measurements with short pulses at 30 GHz have as well as long pulses at 11 GHz showed that missing energies of up to 50 % are possible without an increase in the reflected signal. Fig. 1. shows an example of a 16 ns RF pulse at 30 GHz measured in the CLIC Test Facility (CTF II) [3].

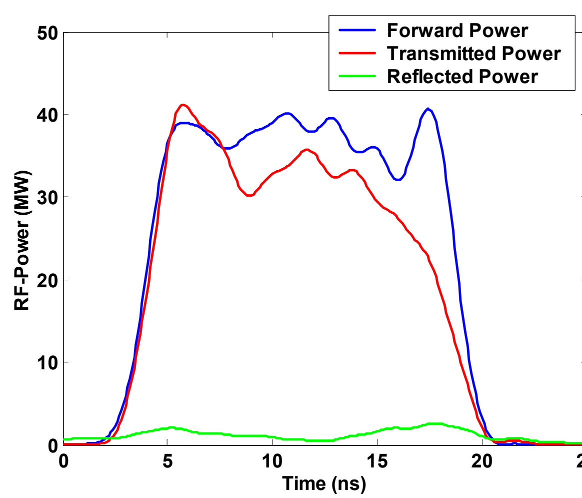

Figure 1: Typical RF-pulse with breakdown and a missing energy of about 10 % at 30 GHz.

This missing energy is dissipated in the cavity and leads to a broad variety of phenomena associated with breakdowns that can be observed by appropriate diagnostics. Fast current-pick-ups can be used to detect bursts of electrons with peak currents in the Ampere range. In our set-up these current monitors were found to be the most sensitive indicator of a breakdown. Acoustic sensors can be used to locate the position of a breakdown event by detecting mechanical shock-waves initiated most likely by fast material expansion due to local heating [4]. Optical light diagnostics such as CCD's, PMT's or spectrometers can be used to investigate the temporal and spectral characteristics of the light emitted during a breakdown. At SLAC and CERN light signals lasting much longer than the RF pulses have been found. Spectral information showed that neutral and ionised copper gas is responsible for the light emission, which is a direct hint that copper is vaporized during breakdown. A typical copper spectrum measured on a single 16 ns RF-pulse with a segmented PMT and filters is shown in Fig. 2.

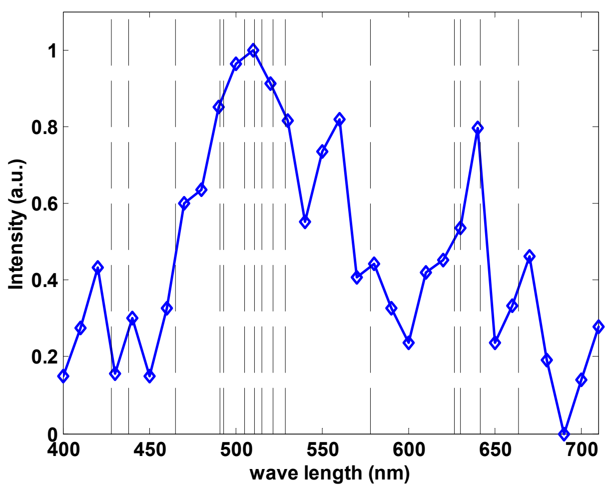

Figure 2: Example of a light spectrum emitted during breakdown at 30 GHz. Some spectral lines from neutral and ionised copper vapour (Cu I, II, III) are also shown.

Vacuum gauges located close to the cavity can monitor the gas activity, which usually decreases with conditioning time in contrast to the other above-described phenomena, which do not diminish with time. This could indicate that gas desorbtion is less relevant. Finally it is important to stress that having a probe beam to make a direct measurement of the effective accelerating field is a big advantage since RF calibrations tend to be delicate at high frequencies and high attenuation levels. In addition the beam-induced signal of such a probe beam can be used to obtain important in situ information about damage or degradation of RF parameters during the conditioning procedure.

- What is a damaged cavity?

Damage in high-gradient cavities is a hot topic at the present time, but what is actually the difference between a damaged cavity and a conditioned surface, which is empirically required to reach high gradients? Figure. 3 gives to examples. The presence of local craters and discoloured surface areas is not unusual. However a continuous degradation of the phase profile along the

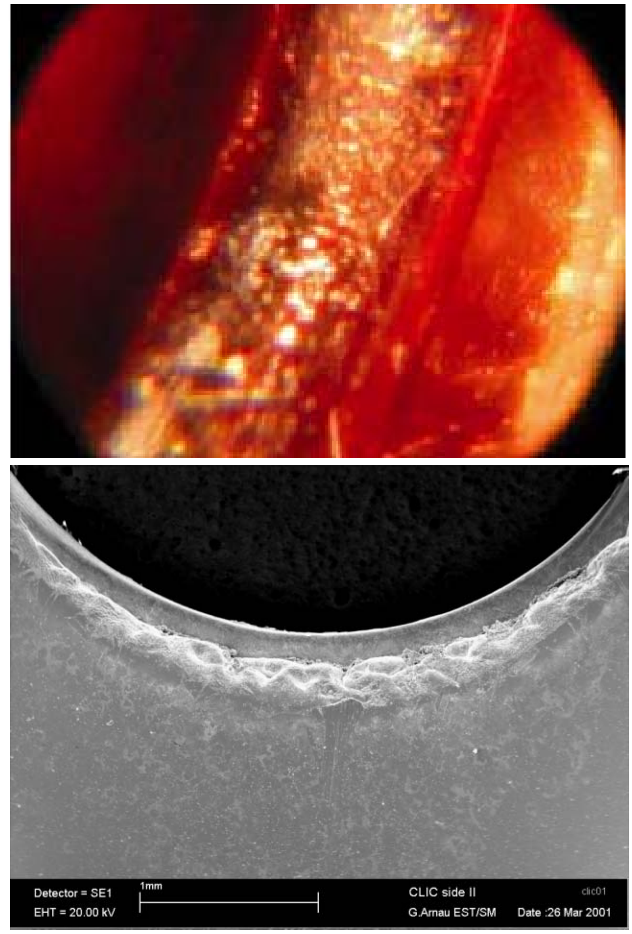

Figure 3: Boroscope image from the input coupler iris of a NLC test structure at 11.4 GHz (T53VG5R) (upper) and electron microscope image of the input coupler iris of a CLIC prototype structure (30 GHz) (lower).

structure or huge geometrical changes leading to a measurable change in the performance as an accelerating structure are much more worrying. Pure imaging often fails to catch the relevance of the viewed features with respect to the cavity performance. One of the critical issues is the ability to observe and quantify the damage during a long and time-consuming high-gradient experiment. This has not been a problem for the CLIC prototype structures where the clearly eroded surfaces indicate unmistakeably where the problems are.

- What is an RF breakdown?

In this paper an RF breakdown event is characterized as an RF pulse with some missing energy that is dissipated very quickly and locally in the cavity. These energy dissipations limit the achievable RF fields, disturb the normal operation of the accelerator if they occur at too high a rate, and they can lead to severe material erosion. Even with this very limited definition, a still somewhat speculative picture emerges as a result of intensive cavity testing. Breakdown initiation is a surface phenomenon, most likely starting with field emission due to very high surface electric fields. The field emission currents can be amplified by secondaries, by desorbed or evaporated ions. The amplification leads to local melting on the emission site due to ohmic losses, or to surface erosion by energy deposition on the impact region of these currents. Secondary ion bombardment could also be relevant to erosion. The amount of damage caused by a breakdown event is a function of the temporal and spatial RF field configuration. Correlations of damage with the maximum surface electric ($\hat{E}_s$) and magnetic field ($\hat{H}_s$) have been found as well as a dependence on the energy flow along the structure characterized by the structure group velocity (v_g) [2,5,6].

- How to avoid RF breakdown and damage?

At present there seem to be two main ways to avoid damage. First, to optimise the RF configuration of the structure by minimizing parameters like $\hat{E}_s$, $\hat{H}_s$, v_g and the very important ratio of maximum surface field to average accelerating gradient ($\hat{E}_s/\langle E_{acc}\rangle$) [7]. Second, to work on the surface in order to reduce primary emission, or to increase the damage resistance. The latter implies surface treatments to reduce field emission as well as the use of materials other than copper to increase the damage resistance.

3 FREQUENCY DEPENDENCE

The choice of frequency for present linear collider studies is based on RF power consumption as well as the assumption that the RF voltage holding capabilities increase with frequency. This assumption was based on interpolations from measured data at lower frequencies. Already in 1957, Kilpatrick found a square-root dependence between DC and 3 GHz that he explained with an ion acceleration mechanism [8]. Although later the actual spark-limits predicted by his famous criterion were found to be by far too low, the frequency dependence was considered to be still valid. This square root, or at least a cube-root dependence, was confirmed by measurements made in the range 3 - 11 GHz at SLAC [9,10]. In a more recent experiment at CERN, an attempt was made to address this frequency dependence question for the range 20 - 40 GHz in a dedicated experiment using for the first time cavities with the same geometry exactly scaled in frequency [11]. A total of six single-cell cavities (two for each of the frequencies 21,30 and 39 GHz) were tested in CTF II. A short 3 GHz drive-beam pulse excited each cavity and the subsequent decay of the field in the cavity was monitored. The maximum achievable surface field showed no significant frequency dependence (see diamonds in Fig. 4). Fig. 4 also includes the above-mentioned SLAC data and scaling [10] (circles and cube-root fit), as well as high gradients results at 3 GHz from KEK [12] (plus signs), at 11.4 GHz from SLAC (single-cell data, squares [13], NLC test program, right triangles [14]) and CERN (cross [15]), at 17 GHz from MIT (star [16]) and at 30 GHz from CERN (triangles [17]).

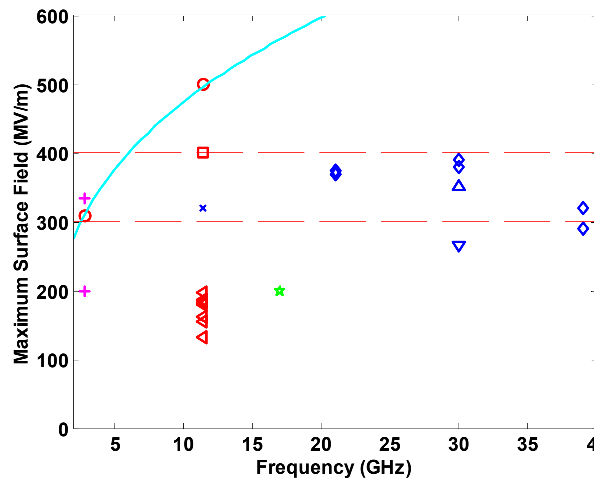

Figure 4: Frequency dependence of maximum surface field. The data is explained in the text.

The data shown in Fig. 4 comes from very different cavities tested with a variety of pulse lengths, however there is no evidence for an increase of the maximum achievable surface field with increasing frequency. Any attempt to apply pulse length scaling would indicate rather a decrease of surface field with frequency since the very high frequency data points were obtained with shorter pulses. The reason why the extrapolation of the square-root scaling which was well established at lower frequencies, fails at higher frequencies, is probably due to a change in the physics mechanism that limits the achievable performance. Ion acceleration is clearly less relevant at higher frequencies. Field emission following the frequency-independent Fowler-Nordheim (FN) theory [18] is one candidate to explain these limits. Note that the effective FN levels are obtained by multiplying the surface field by an assumed surface enhancement factor $\beta_{FN.}$ At an effective surface field of about 10 GV/m the field-emitted current will melt copper directly due to ohmic losses in about 10 ns. In Fig.4 the two dashed lines corresponds to a β_{FN} of 25 and 33. Another important field limitation comes from RF pulsed heating. For this a flat frequency dependence of $f^{1/8}$ is calculated for a pulse length scaling of $f^{-3/2}$ but will be not discussed further in this paper since only very few data is presently available.

4 CHOICE OF MATERIAL

High-gradient tests with CLIC prototype accelerating sections at 30 GHz [19] revealed not only local craters but also large eroded areas of the copper surfaces, which were correlated with the location of the highest surface fields but showed also sharp edges (see Fig. 3). Scanning electron microscope imaging identified melted and even vaporized copper zones as well as copper droplets deposited all over the cavity. The structures were found to be limited to a maximum surface field of 265 MV/m. A field enhancement factor β_{FN} of about 30 was calculated from dark-current measurements made during the high-power test. These results suggest that the limitation is due to the choice of copper as the structure material. Tungsten was an obvious alternative because it has a much higher melting point than copper and its conductivity is not too bad. Tungsten is also known for its arc resistance in industrial applications such as high voltage switching. For a first series of tests, the input coupler including the coupling iris that was heavily damaged, was machined away, and a new coupler with test irises made out of different materials was clamped on. Iris materials tested included tungsten as received, tungsten electro-polished, tungsten/copper, and OFHC copper as a reference. The experiment, which is described in detail in [17], demonstrated that tungsten (independent of the surface treatment) could survive the conditioning procedure without damage while the copper iris was again damaged in exactly the same way as in the original brazed structure. Confirmation of this material hypothesis was obtained when the copper parts melted out of the tungsten/copper-matrix material.

Encouraged by this result, two completely new accelerating structures were designed. The RF design was optimised to reduce the $\hat{E}_s/\langle E_{acc}\rangle$-ratio by reducing the iris diameter and increasing the iris thickness. One structure was all copper and the other had all irises made of tungsten. In addition a new mode-launcher coupler was used which has lower surface fields than the first cell in the structure [20]. The tungsten-iris structure consisted of copper disks (forming the cells) with tungsten inserts (forming the irises) as shown in Fig. 5.

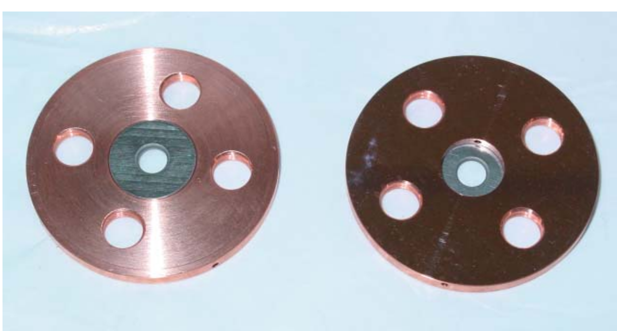

Figure 5: Tungsten irises and copper disks combined together to form the cells of the accelerating structure.

The short 30-cell 2π/3 copper-tungsten accelerating structure was clamped together and tested in a vacuum vessel. The all copper structure using the same cell geometry provided a reference for the new material and geometry. Here copper cells were brazed together in a vacuum oven while the mode-launcher couplers were again clamped onto the structure. The detailed parameters of these two new structures and the old CLIC prototype structures are given in [17]. The new structures were installed without bake-out and high-power tested in CTF II with 16 ns pulses. Fig. 6 compares the conditioning histories of the two new structures with the old CLIC prototype. The improvement from an average accelerating gradient of 60 MV/m to 102 MV/m for the copper structures is clearly due to the optimised geometry

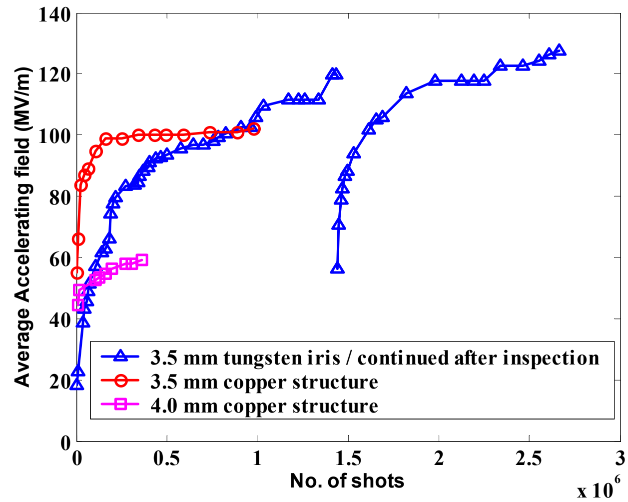

Figure 6: Comparison of the conditioning histories of the new-geometry all copper and tungsten-iris structures (3.5 mm) with the old-CLIC-prototype structure (4 mm).

($\hat{E}_s/\langle E_{acc}\rangle$: 4.4 → 2.5 and v_g: 8.2 %→ 4.2 %) since they both reached the same maximum surface field (265 MV/m).

Both copper structures after inspection showed severe surface erosion in the region of maximum surface field. The tungsten-iris structure has the same cell-geometry as the copper structure, but due to the lower Q the $\hat{E}_s/\langle E_{acc}\rangle$-ratio is less favourable (2.7). This structure reached an average gradient of 125 MV/m (152 MV/m in the first cell) which was confirmed by acceleration measurements. This corresponds to a maximum surface field of 340 MV/m. Inspection of the inner surface revealed a conditioned but undamaged tungsten surface. The conditioning was stopped because of time constraints in the CTF II schedule. A clear difference can be seen in the conditioning times. The clamped tungsten-iris structure conditioned much slower than the brazed-copper version, and after venting to air, it took much longer to reach the old values again. One reason might be that the copper was heavily degassed during brazing while the tungsten was not heat-treated at all. The fact that the tungsten-irises survived these high fields suggests that the damaging mechanism is particle bombardment rather than explosive field emission. Although tungsten's higher melting point is an advantage for heating due to particle impact, its lower conductivity makes it less favourable for heating due to ohmic losses (see Table 1 below). The klystron industry has already experimented with materials like tungsten, molybdenum, GlidCop® and stainless steel in the collector regions of their devices [21]. Titan inserts were already used to reduce dark currents [12]. In recent tests at SLAC [5] on high-power wave-guides made from stainless steel, gold and copper at X-band, the best performance was obtained with stainless steel. Tungsten is not necessarily the best choice of material for a series production of structures because of machining difficulties, further experiments are clearly needed to show which combination of material parameters has to be optimised.

Some relevant parameters might be the energy needed to melt a given volume (see Table 1, second line), or the power to melt a surface area via particle impact within one pulse length (last line, Tp = 16 ns), and the current to melt a surface by ohmic losses within the pulse length (third line, Tp = 16 ns). Table 1 lists these parameters for some typical materials. The CLIC study has foreseen to test a clamped molybdenum-iris structure at the end of this year (2002) to gain further insight into this problem.

Table 1: Material parameters considered relevant for limiting the maximum surface field for various materials.

Units	*Cu*	*W*	*Mo*	*Au*	*Nb*	*Stainless*
J/mm^3	6.64	14.97	11.46	4.66	9.07	9.41
A/µm^2	3	2.8	2.3	2.48	1.3	0.6
W/µm^2	0.2	0.31	0.22	0.15	0.12	0.05

5 CONCLUSIONS

Since the first concerns about the feasibility of achieving very high gradients for future nc linear colliders were voiced in 1999, a lot of progress has been made in understanding RF breakdown, and as a consequence, in actually achieving very high gradients. The CLIC study has now produced three structures which exceed an accelerating gradient of 100 MV/m, one at 11.4 GHz and two at 30 GHz. The later two were used to accelerate an electron beam in CTF II using a maximum average acceleration gradient of 120 MV/m (with a 16 ns pulse length), and 152 MV/m (with an 8 ns pulse length).

There are still many serious issues that are not well understood and need further study. It is still not known why single-cell structures generally perform better than multi-cells structures. The frequency and pulse length dependence on breakdown limits is still not clear, and RF pulsed heating (hardly mentioned in this paper) will create its own limitations.

First attempts to model RF breakdown with particle in cell codes started [5] but more theoretical efforts are clearly needed to understand the complicated processes involving RF, electrons and ions.

More rapid progress in resolving these outstanding issues could be made by the research teams involved by having common well-defined test and analysis criteria, and by performing frequency-scaling experiments preferably within a global framework of collaboration.

6 ACKNOWLEGMENT

I would like to thank C. Adolphsen, W. Brown, J. Haimson, T. Higo and T. Shintake who kindly provided me with their latest results. The CLIC results presented here are the fruits of the efforts of the CTF II and 30 GHz structures team members, and thanks are due to them, in preparing this review paper, for the very many useful discussions and suggestions.

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