HIGH-GRADIENT BREAKDOWN IN NORMAL-CONDUCTING RF CAVITIES

W. Wuensch, CERN, Geneva, Switzerland

Abstract

Over the last few years it has become apparent that RF breakdown and the damage that it can cause are critical issues for normal-conducting high-energy linear colliders. Substantial efforts to address RF breakdown issues have been launched within the linear-collider community. The ideas about the physics of breakdown, experimental results, methods to increase achievable gradients and methods to avoid damage that have emerged from the studies are reviewed.

1 INTRODUCTION

In order to set a scale for this discussion, some of the RF parameters of the NLC, JLC and CLIC linear-collider designs are summarized in Table 1 [1,2].

Table 1: Selected RF parameters

NLC/JLC 500 GeV	11.424 GHz 55 MV/m average loaded accelerating gradient 85 MW section input power 267 ns RF flat top 23 J total RF pulse energy
CLIC 500 GeV and 3 TeV	29.985 GHz 150 MV/m average loaded accelerating gradient 240 MW section input power 100 ns RF flat top 25 J total RF pulse energy

Input and unloaded gradients are typically 10 to 20 % higher than the average loaded accelerating gradient. Surface electric fields are a factor of typically 2.5 higher still. The destructive potential (total energy) of a single RF pulse is sufficient to liquefy more than five cubic millimetres of copper for either machine.

Such field and power levels are much higher than those used in existing, lower-frequency, normal-conducting RF structures. Gradients in 3 GHz linacs are in the range of 20 to 30 MV/m for example. However it has long been predicted that higher gradients become possible at higher frequencies. The prediction is based on the assumption that the frequency dependence of RF breakdown level observed at low frequency continues to higher frequencies. Some early experiments, at SLAC and CTF1 (CLIC Test Facility 1) [3,4], appeared to have confirmed the expectation of higher gradients at higher frequencies, and consequently parameters similar to those shown in Table 1 were adopted. More recent, and more comprehensive, tests at 11 and 30 GHz have proved to be much less successful. Design gradients were not achieved and significant damage to the structures was observed. Left unresolved, these problems would undermine the feasibility of normal-conducting linear colliders.

As a consequence, substantial efforts to address RF breakdown issues have been launched by the JLC, NLC and CLIC studies. Attempts to resolve these problems have greatly exploited the experience gained in the domains of lower frequency and of superconducting RF. It has however, become apparent that the character of breakdown in the high frequency and high field regime needed for linear colliders is sufficiently different that a dedicated research and development effort is required. This paper attempts to summarize the ideas about RF breakdown and about progress towards higher gradients that have emerged from these studies

The experimental work described in this paper has been made in the NLCTA (11 GHz) [5] and CTFII (30 GHz) [6]. Although sometimes limited by the performance of available power sources, progress has been substantial. Diagnostic tools have been established, our understanding of breakdown is improving, new technologies are being implemented and computational tools are being developed. Demonstrated gradients are going up and damage is going down. The NLC has operated test structures for extended periods above an accelerating gradient of 70 MV/m and CLIC has achieved gradients above of 100 MV/m. Further progress is expected based on ideas already in the development pipeline. Nonetheless, one recurring theme in the high-frequency-RF breakdown story has been that new problems are uncovered as testing evolves towards lifetime, full power and full pulse length and using prototype structures with all features (damping manifolds or waveguides). Excluding the SLC, no (normal-conducting) linear-collider study has yet made a complete test, so a definitive version of this paper cannot be written.

2 GENERAL FEATURES OF RF BREAKDOWN

Identifying the measurable quantities that carry useful information and developing appropriate diagnostics has been one of the first priorities for the RF breakdown studies. Finding common features in breakdown data has arguably been the main source of progress towards higher gradients. The main diagnostics used during high-gradient tests and the common features of breakdown are summarized in this section.

The high-power RF systems used for high-gradient testing are equipped with directional couplers before and after the structures so that the incident, transmitted and reflected power pulses can be measured. Examples of such measurements taken during breakdown at 11 and 30 GHz are shown in Figures 1 and 2 respectively [7,8]. One common, and consequently important, feature that can be derived from these signals is that there is energy missing from the balance of incident, transmitted and reflected powers. Measured missing energies can be over 50% at both 11 and 30 GHz, corresponding to well over a Joule at 11 GHz and about a half a Joule at 30 GHz. Reflected power usually remains below a quarter of the input power. The time for the transmitted power to fall is of the order of 50 ns at 11 GHz and 10 ns at 30 GHz [9].

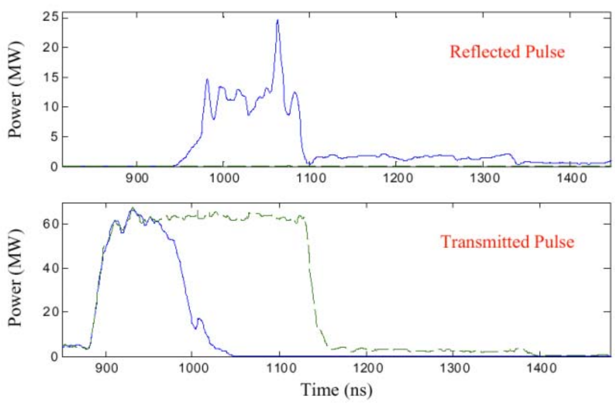


Figure 1: RF power pulse shapes during a breakdown at 11.4 GHz.

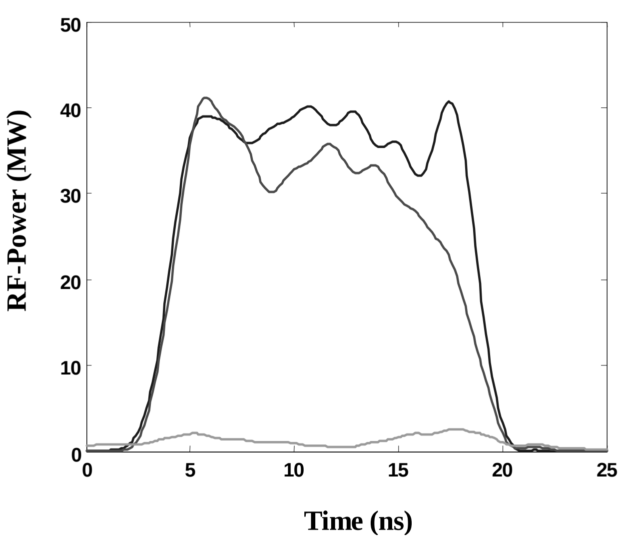


Figure 2: RF power pulse shapes during a breakdown at 30 GHz. The incident power is shown in blue (highest trace), transmitted power in red (middle trace) and reflected power in green (lowest trace).

RF breakdowns produce current bursts that are emitted through the beam pipes of the accelerating structures. It should be emphasized that these current bursts are not 'dark currents' which are emitted regularly on every pulse. Breakdown currents are also much higher than dark currents and can reach nearly an ampere. Current pulses are one of the most reliable indicators of breakdown. Even events with low missing energy can produce easily measurable emitted currents. So far, only the currents emitted out of the ends of the structures have been measured. However, there is strong reason to believe, as described in section 3, that the currents within the structures are *much* higher. Internally absorbed currents should produce X-rays measurable outside the structure. Attempts to measure X-rays have not yet yielded useful information mainly because of the absorption in the copper walls of the structure and background.

Breakdowns also produce visible light that can be observed through the beampipe of the structures. A surprising feature of the light produced in copper structures is that it lasts for nearly a microsecond after RF has left the structure. Possible origins of the light are excited plasmas of desorbed gas, copper ions that have been vaporized from the structure surface and blackbody radiation from a heated structure surface.

Acoustic waves are produced by the large powers deposited during breakdowns. Measurement with an array of piezoelectric sensors of the timing of acoustic waves allows the position of a breakdown to be localized within the structure. Figure 3 shows the output from an azimuthal array of acoustic sensors placed around an 11 GHz accelerating structure [10]. This data shows a sequence of breakdowns on either side of a symmetric input power coupler.

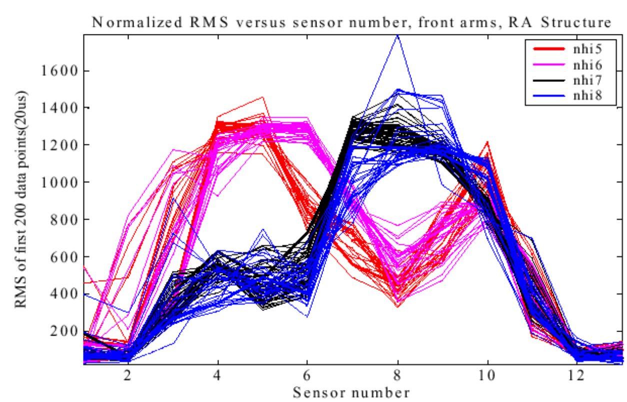


Figure 3: Output from an azimuthal array of acoustic sensors. The traces are produced over many breakdowns.

Breakdowns can also produce substantial increases in vacuum level. Vacuum signals provide a useful indicator of breakdown activity when conditioning starts, but care should be taken since the signal fades as processing proceeds.

Because of the importance of RF frequency on linear collider design, a dedicated experiment has been made to measure directly the frequency dependence of maximum achievable gradient. The experiment was made by testing six exactly-scaled single-cell standing-wave cavities resonant at 21, 30 and 39 GHz (two at each frequency). Each cavity was conditioned for 5×10^5 pulses. The astonishing result, shown in Figure 4, is that there is no discernable frequency dependence. In addition, one of the cavities was cooled to liquid nitrogen temperature and heated to 300 °C. The breakdown level was measured as the cavity heated and cooled. Here again with no discernable gradient change [11].

Nearly all of the CLIC structures have conditioned to a maximum surface electric field in the range of 300 to 400 MV/m. These include two 11.4 GHz structures tested with 150 ns pulses [12,13], numerous 30 GHz structures [9] tested with 16 ns pulses and the standing wave cavities mentioned above. The only exceptions have 30 GHz travelling wave structures tested with 3-5 ns pulses, which attained a surface field of over 600 MV/m.

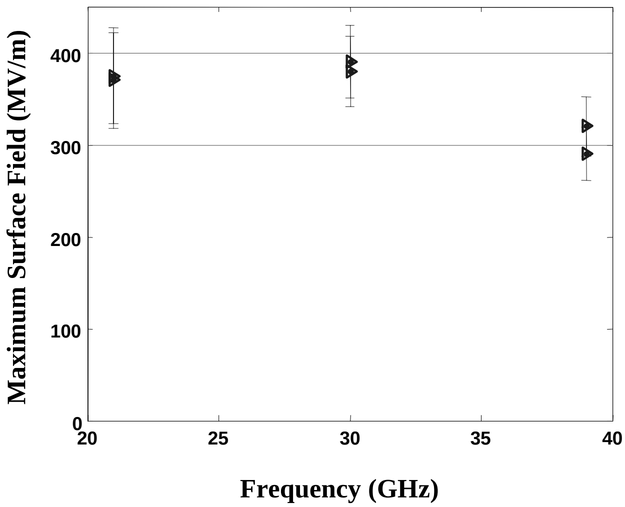


Figure 4: Final maximum surface electric field as a function of frequency achieved in six scaled single cell cavities.

3 DAMAGE

If it does not limit the achievable gradient below a desired value, RF breakdown is often merely a nuisance - conditioning a structure up to its operating gradient may be laborious but straight-forward. RF breakdown becomes most dangerous when it causes damage. Damage to both 11 and 30 GHz accelerating structures has been a serious concern.

Damage to 11 GHz structures, which have been conditioned into the 50 to 70 MV/m range, has manifested itself by a change in the phase advance per cell. In early tests, accumulated phase advance errors of many tens of degrees over a structure length were observed. Phase shift error as a function of position inside the structure is shown in Figure 5. The phase error has been determined to be caused by the removal of up to 20 μm of material from the tip of the coupling irises.

Damage to 30 GHz structures, here also operated in the range of 70 MV/m, has manifested itself through removal of cubic tenths of a millimetre of copper from the iris that separates the input coupler from the first cell. A picture of the cross section of a damaged iris is shown in Figure 6. The input coupler had only a single feed and consequently a highly asymmetric field profile. This produced a surface electric field with an over-voltage factor of 1.4 compared to the maximum surface field in the downstream iris. The damage occurred in the highest surface electric field region. Intriguingly, an iris tested with 4 ns pulses and to double the surface field (600 MV/m) showed no damage.

Damage to both 11 and 30 GHz structure appears to have occurred during the conditioning process with no obvious effect during operation. The stable operating gradient increased even as structures were damaged.

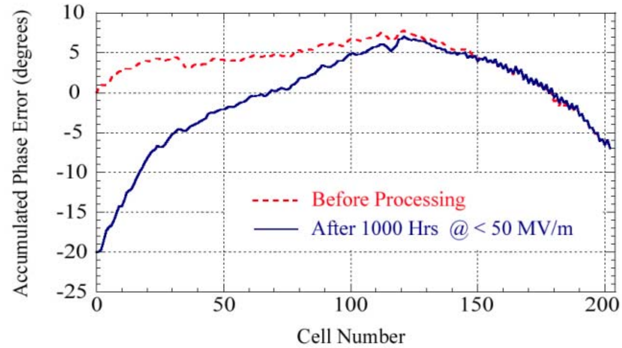


Figure 5: Phase error as a function of position introduced by conditioning an 11 GHz structure.

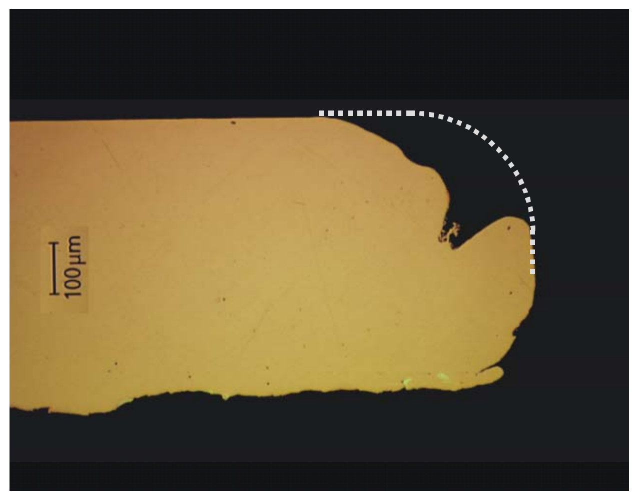


Figure 6: Cross section of coupling iris damaged by RF breakdown. The dotted line shows the original shape of the iris. The bottom of the iris was roughened when it was cut from the accelerating structure.

4 THE PHYSICS OF BREAKDOWN AND DAMAGE MECHANISMS

An attempt to explain observations described in the previous sections can be organized by posing the following questions. What triggers a breakdown? How can so much RF power be absorbed once the breakdown has started? What produces damage? How can we be sure we have the correct explanation? It should be clear to the reader that the physics of breakdown is not perfectly understood, so as a consequence, this section contains some speculation.

The reasons that breakdowns start are probably numerous. Explosive heating of dust particles and high-β (the Fowler-Nordheim microscopic electric field enhancement) factor surface features and the fieldamplifying effect of desorbed gases are breakdown triggers that have been identified for DC, lower-frequency RF and superconducting RF. Experience conditioning high-frequency/high-gradient structures shows that the dominant character of the triggering probably changes as conditioning proceeds. The decrease of vacuum activity mentioned in section 2 could be taken as evidence that dust and desorbing gas are involved mainly in the earliest breakdowns and are cleaned away as conditioning proceeds. The reason for later breakdowns is more mysterious, but an answer is essential since this is what ultimately limits field level. A hint may be found by observing that 300 to 400 MV/m surface fields have been obtained with the CLIC structures. The β factors derived from field emitted currents are typically around 30, thus giving local surface fields of the order of 10 GV/m. At such field levels 'static' electric-field forces exceed the tensile strength of copper, the binding potential of copper atoms to its crystal is exceeded and field-emission currents directly melt the copper. Any of these effects could trigger a breakdown.

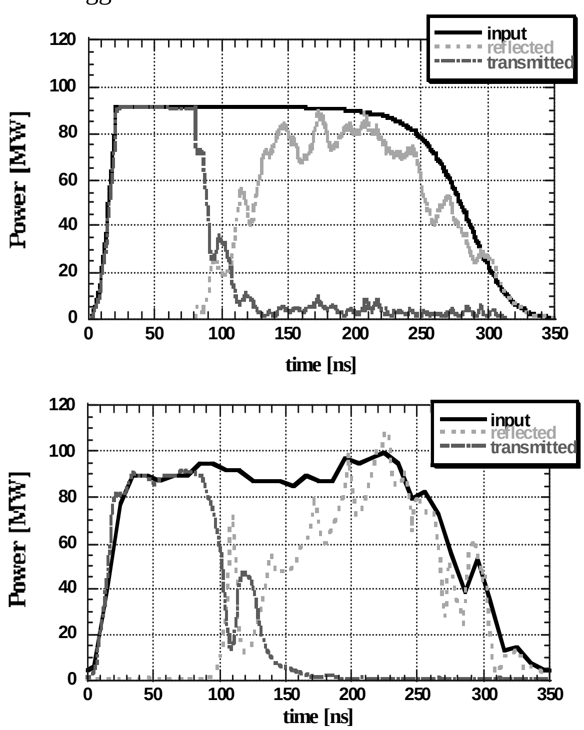


Figure 7: Measured RF signals from an 11 GHz waveguide breakdown is shown in the upper plot. Computed 11 GHz waveguide breakdown is shown in the lower plot.

Once a breakdown has been initiated, a discharge, or arc, begins. One of the most striking features of this discharge is the tremendous power it is capable of absorbing with little reflection. Absorbed RF powers can easily exceed 50 MW. This power is probably absorbed by electron currents that collide with the structure walls. Ions of any kind probably do not directly absorb RF power because they have oscillation amplitudes well below a micron when driven by fields of the order of 100 MV/m, at 11 or 30 GHz. If RF power-absorbing current is focused onto the structure surface in any way, either by the RF field pattern or by interaction with ions that are liberated during the discharge, the potential for damage is enormous. If this explanation is correct, it means that damage only occurs during conditioning

Evidence of damage caused by the impact of currents can be found in the notch in the coupler iris shown in Figure 6. Damage here appears to have been due to impact, rather than erosion of high-surface-field regions, because the damage has clearly propagated into a region of ever lower surface field. SEM photographs of the bottom of the notch show clear signs of melted copper and the surfaces opposite the damage are sprayed with copper droplets.

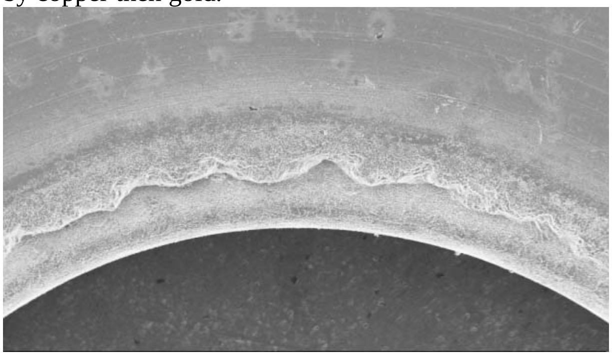
Due to the complexity of RF breakdown and the difficulty of experimentally determining the validity of many of these arguments, it becomes quite desirable to be able to simulate breakdown. Although many arbitrary input parameters are still required, efforts to simulate breakdowns have started. An example of a measurement of breakdown in a waveguide at 11 GHz and a simulation are shown in Figure 7 [14].

5 TECHNICAL AND DESIGN SOLUTIONS FOR HIGHER GRADIENTS

The aim of all this measurement and theorizing is of course to finally produce higher performance accelerating structures. Here there are three main objectives: a high (and stable) operating gradient, preferably no damage and a short conditioning period. The last point is a goal in itself, of course, but it may also play an important role in reducing damage.

Based on the evidence that damage is caused by melting during the breakdown arc, the use of high melting point materials has been proposed as a way of avoiding damage. Tungsten is clearly a prime candidate since it has the highest melting point of any metal and a reasonable DC conductivity (only about a factor of three worse than copper). A test has been made to make a direct comparison at 30 GHz of the arc resistance of tungsten and copper by replacing the damaged iris shown in Figure 6 with irises made of tungsten and copper. Each iris in turn was clamped onto the end of a copper accelerating structure, conditioned to its maximum gradient and then run for 5×10^5 RF pulses. As shown in Figure 8, the clear result is that while the copper iris was severely damaged, the tungsten iris was not. The tungsten iris was also sprayed with copper removed from the downstream iris, which had a lower surface field than the tungsten iris (the coupler iris has a 40% over-voltage factor as mentioned in section 3). The structure with tungsten iris also went to a higher accelerating gradient, although the structure was finally limited in gradient by the (copper) output coupler. These results indicate that the surface-electric-field limit may also be a function of material, and that tungsten can support a higher field than copper.

A comparison of the high-gradient performance of copper, gold and stainless steel waveguides has been made at 11 GHz [14]. A material dependant behaviour was also observed in this experiment with final conditioned gradients: highest in stainless steel, followed by copper then gold.



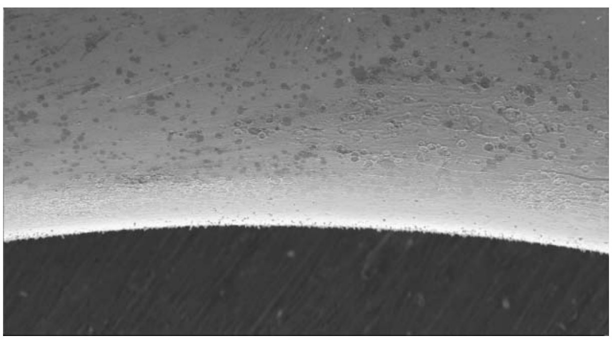


Figure 8: Direct comparison between the arc resistance of copper (upper) and tungsten (lower). The tungsten iris is shown with a higher magnification.

Changes to the RF design of accelerating structures are another path to higher gradient that is being investigated. One way to a higher ultimate gradient is by designing for reduced surface field. Surface field to accelerating gradient ratios near two can be achieved by reducing the iris aperture, by profiling the secondary radius and by choosing a lower phase advance. Power couplers often contain the highest surface fields in a structure but this can be reduced with appropriate designs [15].

It is also believed that changes to the cell geometry could result in less tendency to damage. There are currently two main ideas. One holds that the damaging mechanism represents a constant, and very low, impedance [5]. The match of the RF power to this impedance is better in higher group velocity structures. Lower group velocity should show less tendency to damage. The behaviour of 11 GHz structures has inspired the group velocity argument, although the evidence is not unambiguous. Higher phase advance can be used to maintain iris aperture and this will be tested at 11 GHz.

The other idea is based on the argument that the currents that are absorbing the RF power are responsible for the damage, as described in section 4. Since there is more than enough missing energy in breakdowns to produce the observed damage, the key issue becomes the extent to which the breakdown currents are localized. If the presence of ions (which are certainly present, as demonstrated by the observation of light) do not greatly influence trajectories, a small aperture structure would be better. This evidence comes from previous dark-current capture simulations [16]. If ion focusing plays an important role in focusing breakdown currents, more experiments and eventually simulations will be needed for guidance on design changes.

6 ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the contributions to this review from so many colleagues. From SLAC I would particularly like to thank C. Adolphson, V. Dolgashev and M. Ross for helping me understand their work. I am indebted in this work to my CERN colleagues, particularly H. Braun S. Döbert, W. Schnell, I. Syratchev, M. Taborelli and I. Wilson, for all their efforts, ideas, discussion and goodwill.

7 REFERENCES

[1] “2001 Report on the Next Linear Collider” SLAC-R-571, Fermilab-Conf-01-057-E.

[2] G. Guignard ed., “A 3 TeV e+e- Linear Collider Based on CLIC Technology”, CERN 2000-008.

[3] G. A. Loew, J.W. Wang SLAC pub. 4647.

[4] I. Wilson, “CLIC Test Beam Facilities, Status and Results” CERN/SL 96-60.

[5] 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.

[6] H.H. Braun, “Achievements and Future Plans of CLIC Test Facilities”, Proc. Heacc2001, Tsukuba.

[7] C. Adolphson, private communication.

[8] S. Doebert, private communication.

[9] H. Braun, S. Doebert, L. Groening, I. Wilson, W. Wuensch, “Status of CLIC High Gradient Studies”, CERN/PS 2001-045 (RF), Proc. PAC2001.

[10] M. Ross, private communication.

[11] C. Achard, H.H. Braun, S. Döbert, L. Groening, I. Wilson, W. Wuensch, “A 30 GHz Beam Driven High Gradient Single Cell Cavity Test”, PS/AE note 2001-010.

[12] 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.

[13] 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.

[14] V. Dolgashev, private communication.

[15] J.Y. Raguin, I. Syratchev, W. Wuensch, “Coupler Studies for CLIC Accelerating Structures”, these procedings.

[16] G. Bienvenu, P. Fernandes, R. Parodi, “An Investigation on the Field Emitted Electrons in Travelling Wave Accelerating Structures”, NIM A320 (1992).