# ADVANCES IN HIGH-GRADIENT ACCELERATING STRUCTURES AND IN THE UNDERSTANDING GRADIENT LIMITS

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*Abstract*

Significant progress has been made over the past decades by studies of normal-conducting linear colliders to raise achievable accelerating gradient from the range of 20-30 MV/m up to 100-120 MV/m. The gain has come through a greatly increased understanding of high-power rf phenomena, development of quantitative high-gradient rf design methods, refinements in cavity fabrication techniques and through development of high peak rf power sources. This report will describe these new results and their impact on the understanding of the physics of breakdown and of conditioning, and on the phenomena which limit ultimate gradient in metallic rf structures.

## INTRODUCTION

Normal conducting radio frequency (rf) systems are used in many different accelerator applications, especially linacs. The numerous benefits of normal conducting rf technology include relatively simple, robust and inexpensive infrastructure, extremely high efficiency in the case of fully loaded acceleration and the potential for very high accelerating gradients. High-gradient acceleration can be important for applications which require high beam energies, for example linear colliders and X-ray XFELs, but also those seeking compact, often single-room, facilities for example Thompson scattering sources and hadron therapy linacs.

A high accelerating gradient is particularly important for the CLIC linear collider [1,2]. A high gradient reduces the overall length of the facility, maximizing energy for a given site, and minimizes costs associated with linac length. In order to realize such benefits, the CLIC collaboration has set the ambitious goal of developing prototype accelerating structures capable of operating at 100 MV/m. In addition to the import parameter of gradient, CLIC accelerating structures are also subject to a number of efficiency and beam-dynamics driven constraints. These include wakefield-driven constraints such as a lower limit on beam aperture, strong higher order mode damping and micron-level mechanical precision. The structures must also have high rf-to-beam efficiency to minimize total facility energy consumption, while maintaining a sub-percent level bunch energy spread. The efficiency requirement implies a high level of beam loading which increases the peak to average accelerating gradient. This effect has recently been measured [3]. All of these constraints make achieving the accelerating gradient much more challenging. Finally the structures must operate with a very tight, of the order of $10^{-7}$/pulse, limit on breakdown rate. The definition of the breakdown rate is the fraction of rf pulses in which a vacuum arc occurs. This requirement is to limit the luminosity loss in the 3 TeV version of CLIC due to breakdown to less than 1%.

Breakdown, also known as vacuum arcing, is one of the main physical effects which limit the gradient in the normal conducting accelerating structures. A breakdown suppresses the transmission of power through a travelling wave accelerating structure (CLIC structures are travelling wave) downstream of the cell in which it occurs and collapses the field in a standing wave accelerating structure. A breakdown results in three main negative effects on the beam. A breakdown results in the formation of a plasma spot which causes kA-level electron current emission which in turn generate complex transverse kicks to the beam which deflect it and cause emittance dilution. This transverse kick has been directly measured [4] and references therein. The breakdown also results in a decreased acceleration, changing the energy of the beam in the linac downstream of the breakdown. Finally there is a transverse effect relevant for low-emittance beams related to this energy loss. The transverse kick due to angular misalignment of accelerating structures in the CLIC linac is compensated by quadrupole offsets fixed by the active alignment algorithms [1]. A change in the acceleration of a structure, results in a changed transverse kick, a loss of compensation so an induced emittance growth.

In order to put the 100 MV/m CLIC goal into perspective, the highest operational gradients in the latest generation of XFEL linacs - SACLA, SwissFEL and the Pohang light source - are in the mid-30 MV/m range or less. During the NLC/JLC study the 55 MV/m accelerating target was achieved in prototype structures. A review of this program and summary of results can be found in [5]. 100 MV/m for the 3 TeV version of CLIC study was seen as an ambitious but realistic development goal and reachable on the decade-range timescale needed for a proposal consistent with the potential next-generation high-energy physics facilities. The feasibility stage of the development program is now complete and roughly a dozen prototype CLIC structures have been successfully built and tested at gradients in excess of 100 MV/m. A summary of results is given in the “High-gradient test results” section of this report. This accumulation of results indicates that a 100 MV/m-range linac, even subject to the beam dynamics and efficiency constraints described in the previous two paragraph, is realistic. The study now seeks to validate that gradient can be achieved with a high yield and investigate long term performance. In addition new ideas that can reduce cost or raise performance are being considered as well.



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The high-gradient accelerating structure development program has also included as an important element a broader and more fundamental study of the effects which limit gradient. Very generally, these are effects which occur when metal surfaces are subject to high surface fields, and include vacuum arcing (aka breakdown), the nefarious effects which have been described above, and surface fatigue due to pulsed surface heating. The latter will not be discussed further in this report but a review can be found in [6]. Vacuum arcing is a complex process and involves the interplay of many phenomena including field emission, dislocation dynamics, atomic field-assisted atomic evaporation, electro-plasticity, electrodynamics and plasma dynamics. The basic study of the gradient limits was undertaken to complement the prototype development program. It has for example provided quantitative tools for the rf design and linac optimization process. A specific original result was the introduction of $S_c$, which is a quantity related to local complex power flow and is one of the most important quantities which determines the achievable accelerating gradient [7]. The fundamental study has also provided a theoretical framework for carrying out and analyzing of experiments and the basis for defining and optimizing procedures for manufacture and operation of the structures.

Vacuum arcing is present in many devices and applications. Sometimes it is desired, for example in plasma coating devices or arc-based thrusters for satellites, and sometimes it is a limitation, for example in high-voltage systems and rf systems in accelerators. Vacuum arcs have been extensively studied, especially in the so-called burning stage when the plasma has been formed. The unique feature of the research advanced by the CLIC study is the focus on the mechanisms related to the initiation the breakdowns (due to the importance of breakdown rate in the CLIC accelerator) and in particular processes which dominate at the very high fields in CLIC accelerating structures - peak surface electric field is in excess of 200 MV/m.

Figure 1: One cell of a CLIC high-power test accelerating structure. The part is made from OFE copper using a diamond tool and has micron-level tolerances. The four waveguides provide higher-order-mode damping (although no terminating loads are present here) and the outer cell wall is formed by four convex segments to minimize enhancement of surface current.

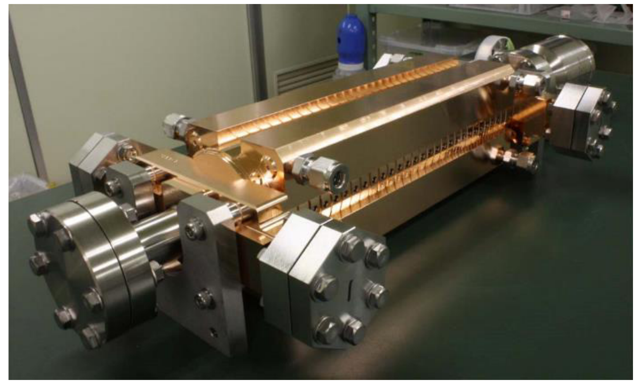

Figure 2: Fully assembled CLIC high-power test accelerating structure. This structure was designed by CERN, fabricated and tested at KEK and bonded at SLAC.

The different aspects of the CLIC high-gradient accelerating structure program and their interrelation are described in the following sections of this report by covering in sequence structure fabrication, testing infrastructure and then testing results.

## STRUCTURE FABRICATION

A photograph of one cell of a CLIC baseline prototype structure is shown in Fig. 1 and an assembled structure is shown in Fig. 2.

The prototype development program adopted a "baseline" technology for structure manufacture. This was done to give an initial priority to raising gradient through rf design, for example based on the criteria described in [7], and not immediately mixing in the extra variables given by fabrication technology. The main features of the baseline fabrication include:

- Structures are made from micron-precision diamond machined disks, a technology used in earlier stages of both, the CLIC project and the NLC/JLC projects.
- The main cells of the structures are bonded at 1040 °C following the procedure developed in the NLC/JLC project. More details can be found in [5].

This baseline technology has been used to produce the prototype structures summarized in the results section. The results from different rf designs validated the dependence of gradient on rf design. Subsequently a phase of investigating alternative fabrication techniques has begun. The primary motivation is to reduce the cost of the structure without compromising performance. Cost estimate studies have shown that assembly represents an important part of the total cost of the structures. The two new main directions being investigated are replacing bonding with brazing and constructing the structures from milled halves.

The advantages of brazing over bonding mainly stem from the reduced temperature, in the range of 850 °C rather than 1040 °C. This makes it easier to maintain micron-level tolerances through the heating cycle and results in less softening of the copper. The key open question is if the high-gradient performance of the bonded CLIC prototypes




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could be maintained with a brazed version. In order to investigate the potential of using brazing for high-gradient structures a collaboration with the SwissFEL at PSI has been established. The C-band linac of the SwissFEL consists of over 100 accelerating structures which are assembled by brazing using a silver brazing alloy (heating in the range of 850 °C) [8]. PSI has gained considerable experience during this rather large series construction project.

Two so-called T24 X-band structures have been built by PSI and delivered to CERN. The structures were designed to have the correct rf phase advance through sufficiently tight tolerances and to not require tuning. Both structures achieved this demanding requirement. The first of the two structures has been installed in XBox-3, which is described below, for high-gradient testing. At the time of this writing the structure is under conditioning and is running at a gradient of over 100 MV/m. The PSI-built structures and ongoing testing are further described in [9]. The success opens the way for a brazed version of a fully-feature CLIC prototype structure. The result also already indicates that the full 1040 °C of the baseline fabrication procedure is not necessary to achieve high gradients.

Another path to alternative design is to construct accelerating structures out of milled halves or quadrants rather than disks. In this way the separations of structure into parts lie along longitudinal symmetry planes and in the plane of the fundamental mode currents. This means that the joints between parts of the structure do not carry current flow, so a wide range assembly techniques can be used including clamping and welding. The separating planes intercept dipole mode currents which gives the possibility for slotted iris damping. Another major advantage is that the number of parts per structure is significantly reduced, reducing cost. The accelerating structures must be made entirely by milling. Numerous firms are now capable of carrying out the micron-precision milling necessary for these structures. The expected gradient is slightly lower than an equivalent structure made from disks due to field enhancement at the iris near the joint.

Early high-gradient tests of structures made from quadrants were not successful [10]. However recently a test of a structure made from halves has been successful. It was made in a collaboration between CERN and SLAC. The structure operated very well at 100 MV/m and a 200 ns pulse length. This is the expected gradient when the field enhancement at the iris is taken into account. In particular, the level of $S_c$ is the same as in structures made from disks. More details of the structure and test is reported in [11].

The expertise needed to build high-gradient X-band structures is spreading over a number of laboratories. CERN, KEK, SLAC and now PSI have collectively produced numerous structures over the course of the years. More recently the accelerator group at Tsinghua University has assembled and successfully tested a prototype CLIC accelerating structure at over 100 MV/m [12].

## TESTING INFRASTRUCTURE

In the CLIC baseline designs for all energy stages, the approximately 200 MW/m of required peak 12 GHz power for the main linac is produced by decelerating a high-current, bunched drive beam. The CTF3 test facility has successfully demonstrated many crucial aspects of this drive beam scheme [13] and specifically relating to the subject of this report, 140 MV/m acceleration has been demonstrated in the two-beam test stand in CTF3. However, CTF3 has too limited availability and repetition rate to support the high-gradient development program on its own.

In order to test prototype accelerating structures in sufficient numbers, at high gradient, at low breakdown rate and for long periods of time, three X-band, klystron-based test stands have been constructed at CERN. They are collectively known as the "XBoxes." A photograph of the klystron modulator unit of XBox-2 is shown in Fig. 3 and a view inside the test bunker is shown in Fig. 4. An extensive program in testing CLIC accelerating structures is also being carried out at the NEXTEF facility at KEK. Additional X-band high-gradient testing with a program outside the scope of this report is carried out at SLAC.

At CERN, XBox-1 and 2 are each equipped with a 50 MW, 1.5 µsec klystron manufactured by CPI, a solid state modulator manufactured by ScandiNova and a SLED-type pulse compressor [4]. Currently each test stand powers a single accelerating structure, which typically requires around 50 MW for 100 MV/m, at a pulse length of about 200 ns and a repetition rate of 50 Hz. In the future, two structures will be tested at each of these test stands after upgrading the waveguide network and high-power diagnostic system to going to the full pulse capability of the klystron/modulator units.

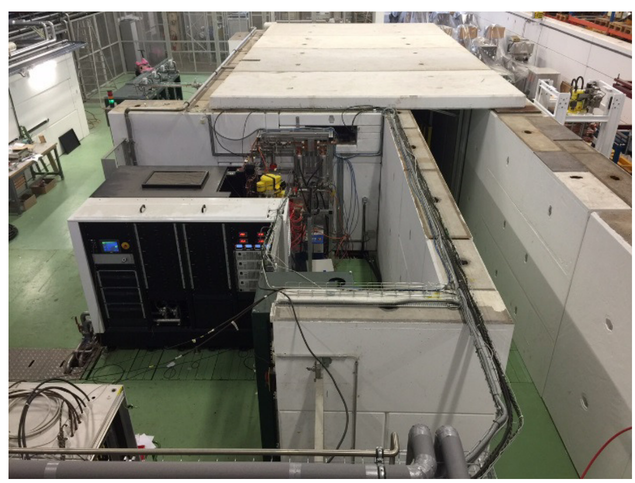

Figure 3: Klystron, modulator and pulse compressor unit of XBox-1. The modulator is in the foreground and the shielding of the klystron collector appears in yellow in the right rear corner of the modulator. The cavity pulse compressor is mounted on the bunker wall behind the klystron modulator unit.

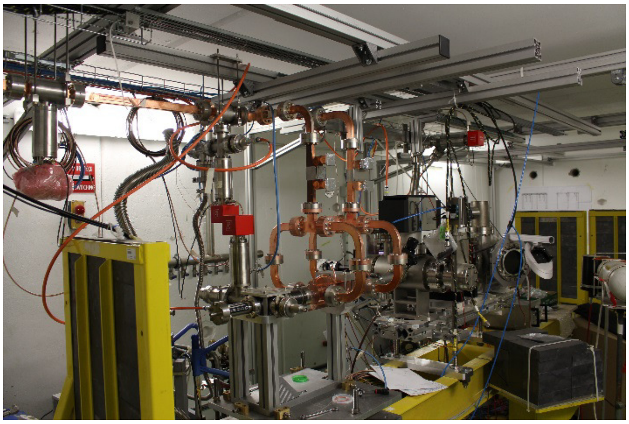

Figure 4: Inside the XBox-2 bunker. The so-called “structure in halves” is under test. The high-power waveguide network can be seen above the structure.

An additional capability of XBox-1 has been that power could be transported via low loss, over-moded waveguide to the CTF3 drive beam linac area. There the accelerating structure under test was supplied with beam from the CTF3 drive beam injector. The beam could reach over 2 A, well in excess of the 1.2 A of the CLIC main linac, which allowed high-gradient, low breakdown rate regime testing in the strong beam loading conditions of the CLIC main linac. CTF3 has now ended its experimental program and final results of the beam loading test are described in [3].

A new test stand, XBox-3, with a significantly different set of parameters is now operating. It is composed of four power units, each based on a 6 MW, 5 µsec klystron manu–factured by Toshiba, a ScandiNova solid-state modulator and a SLED-type pulse compressor. The units are combined in pairs to give the 60 MW-range input power needed for testing CLIC prototypes at 100 MV/m.

The average power capability of the klystrons in XBox-3 makes it possible to “multiplex” between two accelerating structures with each klystron pair. Specifically, the klystron/modulator units can operate at 400 Hz, but the accelerating structures are limited to around 100 Hz due to average heating at 100 MV/m gradient and 200 ns pulse length. Two structures are connected at the output of the combining hybrid and power is directed to one and then the other structure by flipping the relative phase of the two klystrons. During early stages of conditioning, when the structures have not yet achieved full gradient and pulse length and average heating is lower, various strategies of exploiting increasing repetition rate are possible. This can significantly reduce conditioning time since it appears that conditioning progresses with the number of rf pulses [14]. A summary of the system, commissioning and initial operation of the system can be found in [15].

In addition to their direct role in testing accelerating structures, the XBox test stands also represent rf system prototypes for both a klystron-driven 380 GeV version of CLIC [2] and for other electron linac applications such as XFELs and Compton sources. A test stand is equivalent in all important aspects to the rf units which would make up a klystron driven linac. Consequently the experience gained in building and operating the test stands is directly relevant for other projects. They form the basis for accurate cost and reliability estimates. It is important to note that the klystron, modulator and pre-amplifiers are all commercial products and many of the waveguide components are ordered as assembled units from industry. Finally the differences in parameters of the klystrons in XBox-1 and 2 compared with XBox-3 - 50 MW/50 Hz and 6 MW/400 Hz respectively - means that concrete examples exist for rf units for a wide range of applications with differing parameters.

## HIGH-GRADIENT TEST RESULTS

A summary plot of high-gradient tests carried out on CLIC prototype structures is shown in Fig. 5. The plot shows BDR (BreakDown Rate) in units of per pulse per meter of active length vs. the unloaded accelerating gradient. Each square represents the measured performance of a structure. Because testing was made under differing pulse lengths and breakdown rates (due to practical considerations) the results are scaled, using well established scaling laws [7], in order to be able to directly compare them. Squares to circles is pulse length scaling and circles to crosses is gradient scaling.

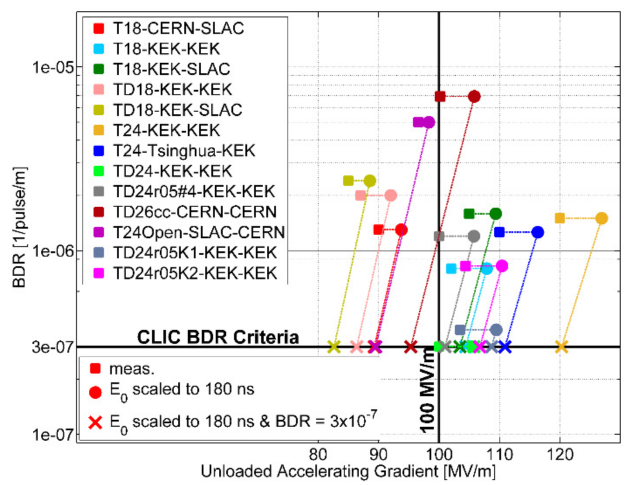


Figure 5: A summary of the high-gradient tests of CLIC prototype structures. The explanation of the details of the plot is in the text above. All results shown here are without beam loading.

The structures come in two pairs of groups. The “T” structures are undamped and have a purely circular cell geometry while the “TD” structures include HOM-damping waveguides (the plus-sign features seen in Fig. 1). The structures with the suffix ”-18” and “-24 (or 26)” differ in the number of cells and degree of iris tapering; the former are an early, heavily tapered design while the latter an improved second-generation design.

One can distinguish a number of features from the plot. The first is that a gradient above 80 MV/m - at very low breakdown rate - has been achieved in a significant number of structures, with the second generation “-24 (26)” design consistently achieving over 100 MV/m. 120 MV/m has




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even been achieved for an undamped version of this structure. The results are very significant since they show that a 100 MV/m gradient for a linear collider is feasible.

An important issue for CLIC which is highlighted by the tests is that the damping features present in the "TD" structures result in a decrease of around 15% in achievable gradient. It is not yet clear whether this is due to a fundamental effect or if it is due to a fabrication issue introduced by the increased complexity of making structures containing damping waveguides. One possible origin of the gradient decrease is that the damping waveguides result in increased surface currents on the outer cavity walls. This causes increased pulse surface heating [6] for example. On the other hand, post mortem analysis of the joints between the cells indicates that they are not uniform on the few to tens of micron level. Since this scale is larger than the 0.7 µm skin depth it causes a locally enhanced heating above the values of an ideal cell. The mechanical design of the disks in newer structures have been modified with the expectation of producing a more uniform bonding joint and such structures should be tested in the near future. In addition the cell geometry has been optimized further to reduce current density as described in [16]. The reference also describes a number of other changes to improve performance and reduce cost.

Another important insight which has been gained during the high-gradient testing program is the importance of the conditioning process. When structures are first powered they must be operated at reduced parameters; the gradient level which initially results in a BDR of $10^{-5}$ is in the range of 30 to 40 MV/m with rather short pulses of 70 ns. Gradient and pulse length are then ramped and the structure progresses to its full performance. This so-called conditioning process proceeds steadily but is rather lengthy. Fig. 6 shows the conditioning history of three similar rf design structures tested at KEK and CERN. The longest test took nearly half a year. A detailed comparison of the conditioning of different structures has shown that conditioning appears to progress as a function of the number of pulses rather than the number of breakdowns [6].

This insight has important consequences for optimizing the conditioning strategy, and suggests that an initial operation period at very high repetition rate could reduce the time required. This is possible because the average power load on the structure is lower at the beginning of the conditioning since field and pulse lengths are lower. The effective cost of conditioning structures is potentially high, so optimizing the pre-conditioning (i.e. before installation), in-situ conditioning and beam turn-on scenarios is very important. XBox-3 can operate at up to 400 Hz, so the fundamental idea of high-repetition rate conditioning will be tested there.

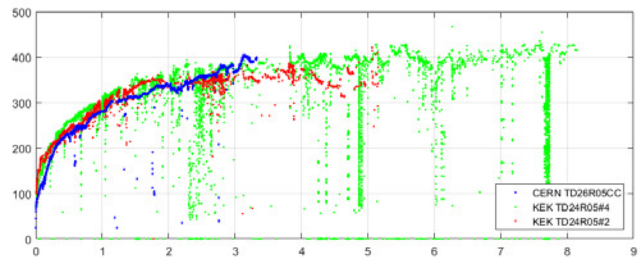


Figure 6: The conditioning histories of three similar rf design accelerating structures tested at KEK and CERN, normalized gradient vs number of pulses/$10^8$. The gradient is normalized for BDR and pulse length in order to compare tests made under different conditions.

## CONCLUSION

A significant number of prototype X-band accelerating structures have now been built and tested at low breakdown rate, in the range of $10^{-7}$, and high accelerating gradient, in excess of 100 MV/m. The high-gradient effort is now addressing cost reduction through rf design, fabrication technology and operational scenarios. X-band and high-gradient technology appears to be important for a wide range of applications. We can expect that a number of facilities operating with gradients above 70 MV/m or so are built in the coming years.

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