HIGH-GRADIENT RF DEVELOPMENT AND APPLICATIONS

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Abstract

The CLIC collaboration has made significant progress in understanding the phenomena which limit gradient in normal-conducting accelerating structures and to increasing achievable gradient in excess of 100 MV/m. Scientific and technological highlights from the CLIC high-gradient program are presented along with on-going developments and future plans. I will also give an overview of the range of applications that potentially benefit from high-frequency and high-gradient accelerating technology.

INTRODUCTION

The CLIC collaboration has been developing the technology necessary for a multi-TeV range electron-positron collider [1]. A priority of this effort has been to increase the gradient achievable in normal-conducting accelerating structures to above 100 MV/m. Such gradient gives a 3 TeV center of mass energy collider with a total length of 50 km and allows optimization of gradient for cost and power consumption for lower energies. For example the 380 GeV initial energy stage of CLIC has an optimum gradient of around 70 MV/m [2].

The underlying strategy has been to take "classical" rf accelerating technology, so that a post-LHC facility can be proposed and built in a timely fashion, understand its fundamental limits, design optimized accelerating structures and demonstrate feasibility with high-power test prototypes. Many other technological challenges have been addressed by the CLIC collaboration - including rf power generation using a drive beam, micron-precision alignment and nano-meter level vibration stabilization - but this report restricts itself to the issue of gradient in the accelerating structures.

The effort to increase gradient has to take into account the numerous requirements given by the overall design of the CLIC facility. These include that accelerating structures must preserve quality of very low emittance beams, operate with high rf-to-beam power efficiency (high beam-loading), contain features which suppress higher-order-modes (HOMs) and run very stably with a breakdown (vacuum arcing) rate of the order of 10^{-7} 1/m or below [1]. These requirements impose many constraints on the accelerating structures which make the gradient more difficult to achieve.

A photograph of one cell of a prototype structure is shown in Fig. 1 and an assembled structure is shown in Fig. 2. The CLIC collaboration has now successfully operated a number of prototype accelerating structures in the range of 100 MV/m, and the results will be summarized in the section on test results. Most importantly, the accumulated results demonstrate that a 3 TeV CLIC is feasible in terms of accelerating gradient. But the results also show that high-gradient X-band accelerating systems can be useful in a wide variety of applications beyond linear colliders. These applications include XFELs, compact Compton sources and hadron therapy linacs. I will return to applications in towards the end of the report.

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 wave-guides 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.
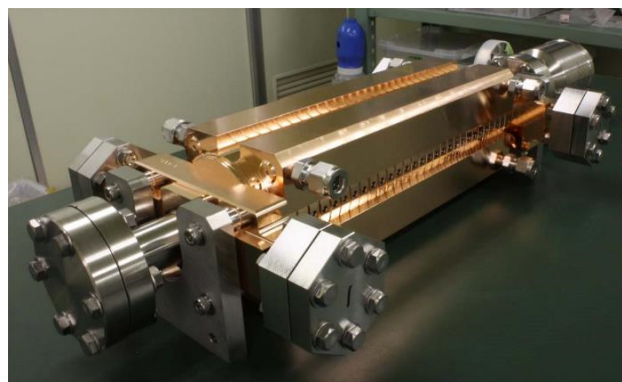

Figure 2: Fully assembled CLIC high-power test accelerating structure. This structure was designed by CERN, fabricated and tested at KEK and bonded at SLAC.

This report covers some of the main themes of the CLIC high-gradient accelerating structure development program and highlights of progress which has made. The different areas of the program can be summarised as follows:

- **Dynamics of metal surfaces under high electromagnetic fields** – Normal conducting rf structures are limited by a number of effects including vacuum arcing and pulsed surface heating. Important insights into these phenomena have come from material science and have given important input to establishing high-

gradient rf design and optimizing fabrication technology. This investigation is being done both experimentally and theoretically.

- **High-gradient performance as a function of rf design** – The performance of accelerating structures is highly dependent on rf geometry. This dependency has been quantified which, for example, allows gradient to be maximized while maintaining beam quality and allows an overall optimization for cost and power consumption of the facility to be made.

- **High-power test capability** – Increasing gradient, and learning how to operate structures at high-gradient, requires extensive testing of many structures. To this end the CERN has established three klystron-based test stands and testing has been carried out at KEK and SLAC.

- **Prototype fabrication and technology optimization** – The performance of an accelerating structure is highly dependent on the fabrication technology and on quality control. Another aspect of accelerating structures for CLIC is that they must have micron-level tolerances, primarily for beam stability but also because of the high frequency. Fabrication technology has a significant impact on cost.

I will now extend the discussion of some of these different themes and give some highlight results. However for narrative clarity I will begin by describing our testing capability and fabrication technology, then cover high-gradient test results. Finally I will address some of the applications which may benefit from high-gradient technology.

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 [3] 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 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.
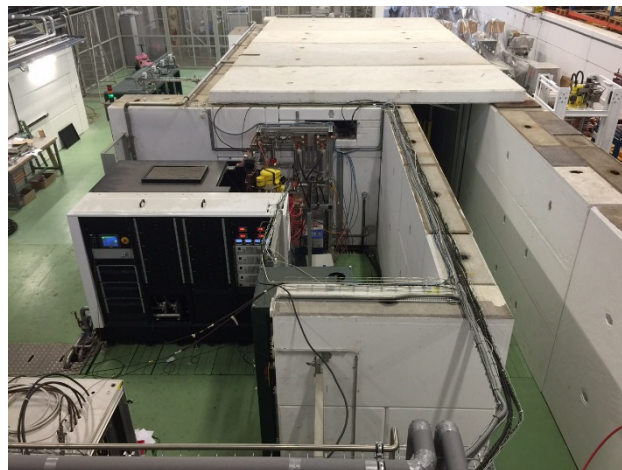

Figure 3: Klystron, modulator and pulse compressor unit of XBox-1. The modulator is in the foreground and the shielding of the klystron collector appears in yellow in the right rear corner of the modulator. The cavity pulse compressor is mounted on the bunker wall behind the klystron modulator unit.
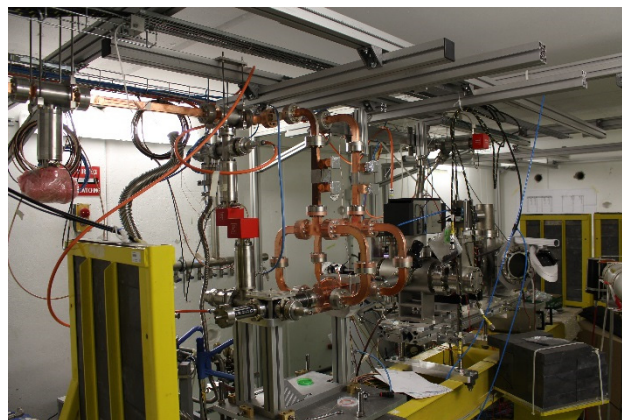

Figure 4: Inside the XBox-2 bunker. The so-called "structure in halves" is under test. The high-power waveguide network can be seen above the structure.

An additional capability of XBox-1 is that its power is transported via low loss, over-moded waveguide to the CTF3 drive beam linac area. There the accelerating structure under test is supplied with beam from the CTF3 drive beam injector. The beam can reach over 2 A, well in excess of the 1.2 A of the CLIC main linac, which allows high-gradient, low breakdown rate regime testing in the strong beam loading conditions of the CLIC main linac [5].

A new test stand, XBox-3, with a significantly different set of parameters is currently being commissioned. It is composed of four power units, each based on a 6 MW, 5

μsec klystron manufactured 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 [6].

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 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 order 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.

STRUCTURE FABRICATION

The approach to raise gradient which was given initial priority was to understand and quantify the dependence of achievable accelerating gradient on rf design [7]. This dependence also plays a crucial role in the optimization of the whole CLIC facility along with a number of other parameters which are dependent on rf design such as wakefields, peak power and rf-to-beam efficiency. In order to quantitatively compare the performance of structures with differing rf designs, they should be made using the same technology. For this reason we early on adopted a "baseline" technology for structure manufacture. The main features of the baseline include:

- Structures are made from micron-precision diamond machined disks, a technology used by both in earlier stages of 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 [8].

The baseline technology has been used to produce nearly twenty prototype structures which have run with accelerating gradients in the range of 80 to 120 MV/m, depending on the rf design. The test results are described in more detail in the next section.

With the dependence of gradient on rf design now well established, we have begun a phase of investigating alternative fabrication techniques. 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. We are carrying out this phase of the work by now fixing the rf design of the structure and comparing results from different fabrication techniques. The two new main directions using brazing and constructing the structures from milled halves.

In order to investigate the potential of using brazing for high-gradient structures we have established a collaboration with the SwissFEL at PSI. 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) [9]. PSI has gained considerable experience during this rather large series construction project. In order to benchmark their technology, PSI will build two T24 X-band structures which will be tested in the CLIC XBoxes. They will then be tested according to the standardized protocols and the results directly compared to T24 structures made by the CLIC baseline bonding technique. If the performance is equivalent, there is a good chance that the cost of CLIC accelerating structures can be reduced.

Another path to lower cost is to construct accelerating structures out of milled halves rather than disks. One major advantage of this approach is 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. Another major advantage is that the number of parts per structure is significantly reduced, reducing cost. On the other hand, the accelerating structures must be made entirely by milling, but numerous firms are now capable of carrying out the micron-precision milling necessary for these structures. Also, early high-gradient tests of structures made from quadrants (which has the same separation of parts along the longitudinal symmetry plane of the structure) were not successful [10]. However recently a recent attempt of a test of a structure made from halves is working very well, above 90 MV/m, and is reported in this conference [11]. The structure was made in a collaboration between CERN and SLAC.

The expertise needed to build high-gradient X-band structures is spreading over a number of laboratories. CERN, KEK and SLAC have successfully produced numerous structures over the course of the years. More recently the accelerator group at Tsinghua University has assembled and test a prototype CLIC accelerating structure [12]. SINAP and CIEMAT will be producing accelerating structures in the coming years.

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, in order to be able to directly compare them. Squares to circles is pulse length scaling and circles to crosses is gradient scaling.
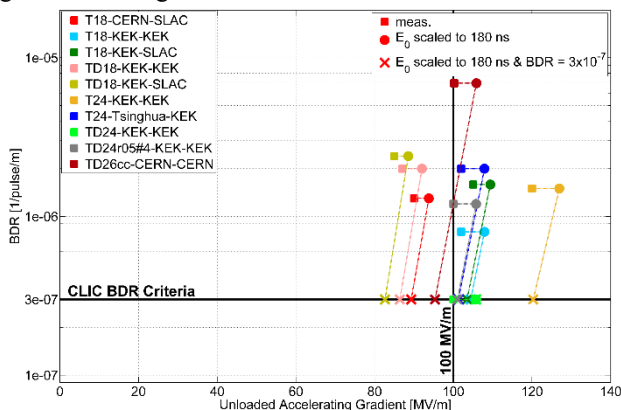

Figure 5: A summary of the high-gradient tests of CLIC prototype structures. The explanation of the details of the plot is in the text above. All results shown here are without beam loading.

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 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 [13] 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 enhance 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 [14]. 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, 70 ns. Gradient and pulse length are then ramped and the structure progresses to its full performance. This so-called conditioning process, it 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 length 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.
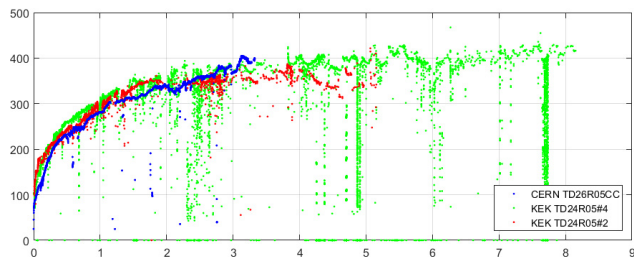

Figure 6: The conditioning histories of three similar rf design accelerating structures tested at KEK and CERN, normalized gradient vs number of pulses/10^8. The gradient is normalized for BDR and pulse length in order to compare tests made under different conditions.

All of the results presented above are for structures without beam. In an application such as CLIC, which requires high rf-to-beam efficiency, the fields and power flows inside the structure are modified by the presence of the beam. A dedicated test of the effect on BDR of beam-loading has

been carried out using the CTF3 drive beam injector and the XBox-1 power source. Initial results are reported in [5].

APPLICATIONS

I close this report with an overview of potential applications of high-gradient and X-band technology. The development effort described in this report has been carried out in the context of the CLIC study, which has had the goal of 100 MV/m acceleration for a TeV-range electron-positron collider. Maximum gradient is a clear priority for such a high-energy physics application, where the goal is maximum possible energy but where the length of a facility is limited. In general, high-gradients reduce the cost of an accelerator, since it becomes shorter and many costs scale with length. However the cost reduction associated with length is offset by the increased cost of generating the necessary peak rf power. A full cost optimization is complex and the optimum gradient is not necessarily the highest one possible but rather depends on the application itself.

Following such considerations, a number of applications have emerged as potential users of high-gradient acceleration including: linear colliders, XFELs, Compton scattering X-Ray sources and medical linacs for proton and carbon ion therapy. For example, XFELs require electron beam energies in the range up to about 9 GeV. Existing normal-conducting XFELs use S and C-band with gradients below 40 MV/m. The Australian Light Source and SINAP laboratories are considering building XFELs. In both cases, 70 MV/m-range X-band linacs would allow them to obtain their target beam energy and still construct the facilities on their existing sites [15,16]. X-band also opens the possibility of repetition rates approaching 1 kHz.

Another, very different, area of application of high-gradients is in linac-based proton and carbon ion cancer treatment. Existing facilities use cyclotrons and synchrotrons but linac-based machines have potential advantages in their high repetition rate pulsed time structure (which allows so-called tumour painting) and in smaller, and possibly less expensive, facilities which are easier to integrate in a hospital environment. The CLIC high-gradient team has received funding from the CERN KT fund to construct a high gradient structure for proton acceleration. The structure has been integrated in the TULIP concept developed by the TERA foundation. This work is summarized in [17].

CONCLUSION

A significant number of prototype X-band accelerating structures have now been built and tested at low breakdown rate, in the range 10^{-7}, and high accelerating gradient, in the range 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.

ACKNOWLEDGEMENT

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