RESULTS OF THE BEAM-LOADING BREAKDOWN RATE EXPERIMENT AT THE CLIC TEST FACILITY CTF3*

E. Senes† [1], N. Catalan-Lasheras, R. Corsini, D. Gamba, A. Grudiev, G. McMonagle,
I. Syratchev, F. Tecker, W. Wuensch, CERN, Geneva, Switzerland
T. Argyropoulos[2], J. Giner-Navarro[2,3], IFIC (CSIC-UV), Valencia, Spain
R. Rajamaki, Aalto University, Espoo, Finland
X. Stragier[2], TU/e, Eindhoven, The Netherlands
[1]also at University of Torino, Torino, Italy, [2]also at CERN, Geneva, Switzerland,
[3]present affiliation, UCLA, Los Angeles, CA, USA

Abstract

The RF breakdown rate is crucial for the luminosity performance of the CLIC linear collider. The required breakdown rate at the design gradient of 100 MV/m has been demonstrated, without beam presence, in a number of 12 GHz CLIC prototype structures. Nevertheless, the beam-loading at CLIC significantly changes the field profile inside the structures, and the behaviour with beam needs to be understood. A dedicated experiment in the CLIC Test Facility CTF3 to determine the effect of beam on the breakdown rate has been collecting breakdown data throughout the year 2016. The complete results of the experiment and the effect of the beam-loading on the breakdown rate are presented.

INTRODUCTION

The CLIC project [1] aims to collide electrons and positrons accelerated in two opposing linacs using normal-conducting high-gradient accelerating structures. A major limitation for the achievable gradient are RF breakdowns (BD) which cause luminosity loss due to the transverse kick of the beam. A maximum breakdown rate (BDR) of $3 \cdot 10^{-7}$ BD/(pulse·m) is specified for a 3 TeV CLIC at the nominal average gradient of 100 MV/m in order to limit luminosity loss due to this effect to less than 1%. An intense testing program has been carried out, and results demonstrate that such low breakdown rates are achievable [2]. Precedent tests have been carried out without the beam inside the structure. Initial attempts of measurements with the beam presence are [3, 4], and this work is their prosecution. CLIC is designed for a high RF-to-beam efficiency requiring a high level of beam loading. This is accomplished with a high beam current of approximately 1 A, unavoidably modifying the longitudinal field profile. The input power to the structure needs to be increased accordingly to maintain the same average field inside the structure.

The effect of the field profile modification is hard to predict. When input power is varied, the whole-structure BDR varies approximately as

$$BDR \propto E_{acc}^{30} \tag{1}$$

where E_{acc} is the accelerating field [2], while the longitudinal distribution of the breakdown position with the electrical field is approximately linear [5].

In order to experimentally measure the effect of the beam loading on the BDR, an experiment has been set up [6] in the CLIC Test Facility (CTF3) at CERN [1]. The RF power is provided using a 12 GHz klystron and the beam is supplied by the electron linac of the facility.

EXPERIMENT LAYOUT

In the CTF3, a dogleg line branching off halfway the Drive Beam linac is used to send the beam to a TD26CC CLIC prototype structure (Tapered, Damped, 26 cells, compact coupler) [7]. The structure is supplied with high power RF by a 12 GHz source.

The optics is designed to provide minimum beam size and maximum transmission in the structure under test [3]. The beam parameter used are reported in Table 1.

The 12 GHz test stand, called XBOX1 [8], consists of driving systems for the klystron, XL-5 klystron [9], SLED-I pulse compressor [10] and overmoded waveguides network, able to deliver the RF power to the accelerating structure under test. This system provides a 250 ns-long high power RF pulse. The forward, reflected and transmitted power is measured by directional couplers before and after the structure. These signals are acquired by logarithmic detectors. Two beam position monitors (BPMs) are installed up- and downstream the structure in order to measure the beam current and transmission.

A National Instruments PXIe-8133 controller equipped with high-performance NI FlexRIO FPGA-based digitisers (NI5761−250 MSa/s−4ch) [11] performs the power signal reading and interlocking complemented with serial buses, digital IO and the CERN control system, all controlled and interfaced to the user with an adapted version of the Labview program used in the test stand [12]. The acquisition system

Table 1: Beam Parameters Used for the Experiment

Beam current	1.6 A
Pulse length	250 ns
Energy	130 MeV
Repetition Frequency	25 Hz

* Founding for accelerating structure provided by the Swiss National Science Foundation Grant 135012.
† eugenio.senes@cern.ch

checks all signals pulse-by-pulse and stores events periodically as well as breakdown-like events based on conservative trigger criteria where only ~10% of the events passing it are real breakdowns. The breakdown identification is based on the observation of the increase of reflected RF power and the loss of transmitted signal through the structure compared to the incident pulse [13]. The stored breakdown events use a buffer which contains the two previous pulses in addition to the breakdown pulse itself. This approach allows the breakdowns to be compared with normal events and to check for potential evidences of breakdown triggers. A more detailed description of the setup is reported in [3, 4, 6].

EXPERIMENTAL RESULTS

The prototype structure was installed in the dogleg line in May 2015. By the beginning of 2016, the conditioning of the structure had saturated in the last 10^8 pulses [14]. This saturation simplifies the comparison of long measurements at different gradients and configurations.

The breakdown rate for an RF pulse with the shape and pulse length of 180 ns of the nominal CLIC RF pulse was measured for different conditions – without beam and with a beam current of 1.6 A. The nominal CLIC current is closer to 1 A and the higher value was chosen to increase the level of beam loading and thus the effect of the beam on the BDR. For this reason a higher beam current and a longer beam pulse compared to the CLIC design parameters have been used.

The beam presence causes a modification of the accelerating gradient profile, which is shown in Fig. 1. When the beam is present, adjusting the relative RF-to-beam phase it is possible to pass from the *loaded* condition, when the beam is accelerated, to the *antiloaded* condition, when the beam is decelerated. In the last case the beam will produce RF power during the deceleration process. In the loaded case the beam presence results in a lower average accelerating gradient, which depends on the beam current.

Beam Effect on the Breakdown Rate

During 2016 the structure was operated for over 313 million RF pulses, using alternatively different input power levels and switching frequently between operation with and without beam. The effect of the beam on the breakdown rate has been considered in three running periods at the same input power. During these timespans, the input power level was maintained at a constant level, while the operation was done with about three consecutive days with beam per week. The measured BDRs are presented in Fig. 2.

The measurements show that, using the same input power, the breakdown rate is up to a factor 10 lower when the beam is present inside the cavity. The data support the correlation of the BDR to the peak gradient inside the accelerating structure, rather than the average gradient [6]. According to Eq. 1, a lower BDR is expected during loaded operation compared to the unloaded case, because of the smaller contribution of the regions of the structure where the gradient is lower.

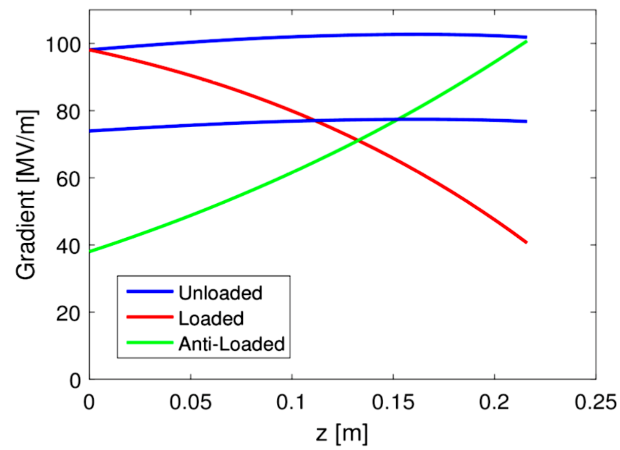

Figure 1: Longitudinal accelerating profile for the structure under test: unloaded (blue lines) 43.3 MW and 24.6 MW input power, loaded (red line) with 1.6 A of beam current and 43.3 MW input power, and anti-loaded (green line) with the same current and 6.5 MW input power.

The expected difference using the average gradient would be about four orders of magnitude. It has to be stressed that there is a large fluctuation of the BDR both for loaded and unloaded runs. This fluctuation might be amplified by the short duration of the periods in the same test conditions.

Breakdown Position

Locally, the breakdown probability depends on the surface electric field, that overall follows the trend of the longitudinal gradient profile. This implies that a region where the gradient is higher is more likely to breakdown. In the case of this experiment, considering the gradient profile in Fig. 1, the distribution of the breakdowns along the structure is expected to be relatively flat in the unloaded case; densely populated at the beginning in the loaded case; and more populated at the end in the antiloaded case.

The measured breakdown distribution for the different cases is plotted in Fig. 3.

It has to be noted that the central part of the structure showed an unexpected higher number of BDs for both unloaded and loaded case. The origin of this anomaly is not known. It appeared after a long period of antiloaded operation. This anomaly makes it impossible to deduce the precise scaling law for the longitudinal distribution of the BDs.

The breakdown distribution in the three cases is nevertheless compatible with the precedent reasoning, showing a different breakdown distribution according to the gradient profile.

To deduce the scaling law ruling the longitudinal distribution of the breakdowns, a new data acquisition unbiased by the more active zone in the centre of the structure would be necessary.

Beam Effect on the RF Power After the BD

A particularity of the operation with beam is the production of RF power after the breakdown. The breakdown

ISBN 978-3-95450-182-3

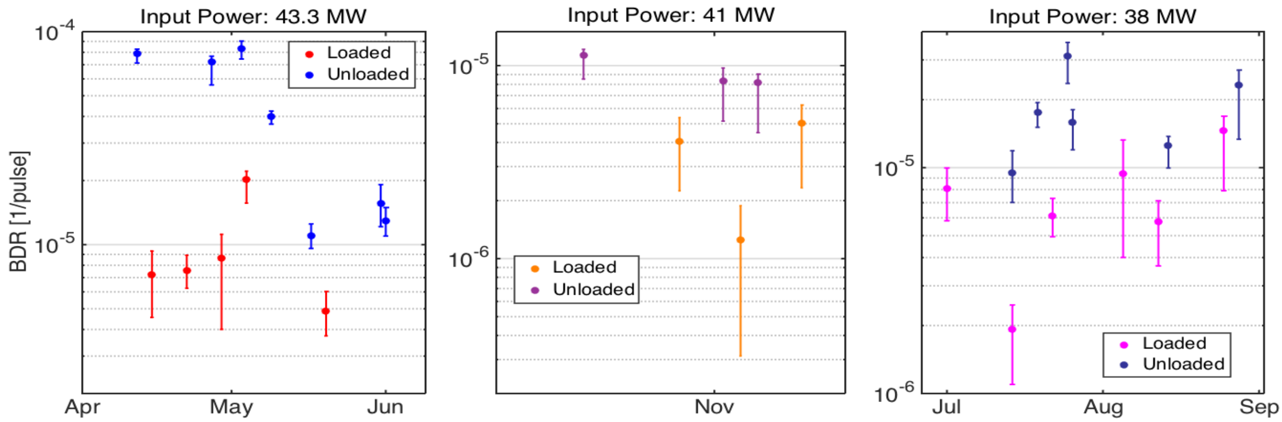

Figure 2: Measured BDR with alternating beam presence at different input power: 43.3 MW (left), 41 MW (center) and 38 MW (right).

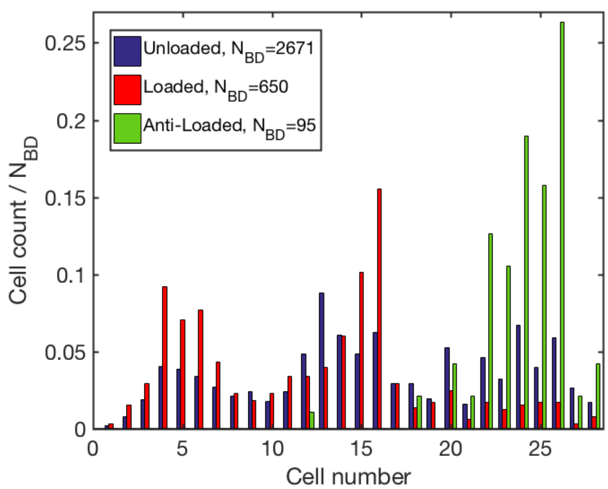

Figure 3: Breakdown distribution in the unloaded (blue), loaded (red) and antiloaded (green).

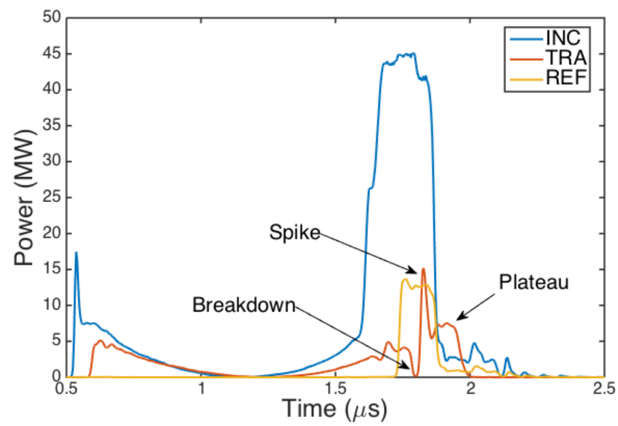

Figure 4: RF power signals in the case of a breakdown with beam. Incident (INC), transmitted (TRA) and reflected (REF) power signals are reported.

causes a reflection of the RF power, causing a quick drop to zero of the transmitted power. When the beam is present, a spike in the transmitted power is visible after the breakdown. If the beam pulse has a sufficient length afterwards, a constant power level establishes up to the end of the beam. The RF production after the BD can be explained by the beam generating RF downstream the BD location, though the origin of the spike is still object of investigation(Fig.4).

CONCLUSIONS

The beam effect on the breakdown rate has been measured in the TD26CC structure. These results complement past experiments [4] with much higher statistics and precision, and show the effects of the anti-loading operation. Breakdown rate reduction by the beam loading up to an order of magnitude has been measured.

The results complement the hypothesis of the BDR dominated by the peak gradient. In view of this, the reduction of the BDR seems to be provoked mainly by the modification of the gradient profile induced by the beam. Additional support to the peak gradient effect is given by the distribution of the breakdowns inside the structure. More data have to be collected to deduce the correct scaling law for the breakdown longitudinal distribution.

These results suggest that a modified structure tapering could result in a structure with a lower overall breakdown rate while operating with beam. More details of the analysis can be found in [15].

ACKNOWLEDGEMENT

We would like to thank the CERN CTF and PS operators for their invaluable help with beam setup and supervision.

REFERENCES

[1] M. Aicheler *et al*, "A Multi-TeV Linear Collider Based on CLIC Technology: CLIC Conceptual Design Report," CERN, Geneva, Switzerland, Rep. CERN-2012-007.

[2] A. Grudiev, S. Cialatroni and W. Wuensch, "New local field quantity describing the high gradient limit of accelerating structures," in *Phys. Rev. STAB, vol 12, p. 102001,* 2009 and Erratum-ibid, vol 14, p.099902, 2011.

[3] F. Tecker *et al*, "Experimental Study of the Effect of Beam Loading on RF Breakdown Rate in CLIC High-Gradient Accelerating Structures," Conf. Proc.: IPAC2013, Shangai, China.

[4] F. Tecker *et al*, "Effect of Beam-Loading on the breakdown rate of high gradient accelerating structures," Conf. Proc.: LINAC2014, Geneva, Switzerland.

[5] W. Wuensch, "Status and objectives of the CLIC X-band activity," in *HG2012 ICFA mini workshop,* Tsukaba, Japan, `http://indico.cern.ch/event/165513`

[6] F. Tecker *et al*, "Beam-Loading effect on Breakdown Rate in High-Gradient Accelerating Structures," Conf. Proc.: IPAC2016, Busan, Korea.

[7] A. Grudiev and W. Wuensch, "Design of the CLIC main linac accelerating structure for CLIC conceptual design report," Conf. Proc.: LINAC2010, Tsukaba, Japan, paper MOP068, p. 211.

[8] J. Kovermann *et al*, "Commissioning of the First Klystron-Based X-Band Power Source at CERN," Conf. Proc.: IPAC2012, New Orleans, USA, paper THPPC060, p. 3428.

[9] D. Sprehn *et al*, "A 12 GHz 50 MW klystron for support of accelerator research," SLAC, Stanford, CA, USA, Rep. SLAC-PUB-14377.

[10] A. Bogdashov *et al*, "A 12 GHz pulse compressor and components for the CLIC test stand," Proc. of *RuPAC-2010*, Protvino, Russia, paper TUPSA005.

[11] National Intruments, `http://www.ni.com/`.

[12] N. Catalan-Lasheras *et al*, "Experience operating an X-band high-power test stand at CERN," Conf. Proc.: IPAC2014, Dresden, Germany, paper WEPME016, p. 2288.

[13] A. Degiovanni *et al*, "Diagnostics and analysis techniques for high power X-band accelerating structures," Conf. Proc.: LINAC2014, Geneva, Switzerland, paper TUPP029, p. 290.

[14] J. Giner-Navarro *et al*, "High-gradient structure performances: ongoing tests and summary," Proc. of *CLIC Workshop 2016*, Geneva, Switzerland.

[15] E. Senes, "Test of the beam effect on vacuum arc occurrence in a high-gradient accelerating structure for the CLIC project," Master's thesis, Phys.Dept., University of Torino, Torino, Italia, 2017. Rep. Num. CERN-THESIS-2017-029.

ISBN 978-3-95450-182-3