# EXPERIMENTAL STUDY OF THE EFFECT OF BEAM LOADING ON RF BREAKDOWN RATE IN CLIC HIGH-GRADIENT ACCELERATING STRUCTURES

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*Abstract*

RF breakdown is a key issue for the multi-TeV high-luminosity e+e- Compact Linear Collider (CLIC). Breakdowns in the high-gradient accelerator structures can deflect the beam and decrease the desired luminosity. The limitations of the accelerating structures due to breakdowns have been studied so far without a beam present in the structure. The presence of the beam modifies the distribution of the electrical and magnetic field distributions, which determine the breakdown rate. Therefore an experiment has been designed for high power testing a CLIC prototype accelerating structure with a beam present in the CLIC Test Facility (CTF3). A special beam line allows extracting a beam with nominal CLIC beam current and duration from the CTF3 linac. The paper describes the beam optics design for this experimental beam line and the commissioning of the experiment with beam.

## INTRODUCTION

RF breakdown is the main effect which limits the achievable gradient in the accelerating structures of a normal conducting linear collider. A breakdown anywhere in either of the two opposing linacs of such a machine can result in a transverse kick to the beam, resulting in luminosity loss on that pulse. In order to limit luminosity loss due to this effect to less than 1%, a breakdown rate of less than $3 \cdot 10^{-7}$ BD/(pulse·m) is specified for CLIC at 3 TeV, at the operating gradient of 100 MV/m [1]. Extensive studies of the breakdown rate in prototype CLIC accelerating structures indicate that such low breakdown rates are indeed achievable [1, 2].

All low breakdown rate high-gradient tests so far have been made with structures without the presence of an accelerated beam. In order to obtain a high rf-to-beam efficiency, the CLIC linac is designed to run with a high level of beam loading where approximately 30% of the incoming rf power is converted to beam kinetic energy. This is accomplished by accelerating a high beam current of approximately 1 A. The corresponding power extraction by this high-current beam has a significant effect on the field profile in the travelling wave accelerating structures. For the same total acceleration, a structure with beam requires higher input power, has higher upstream fields and lower downstream fields than the structure without beam. This is shown in Fig. 1.

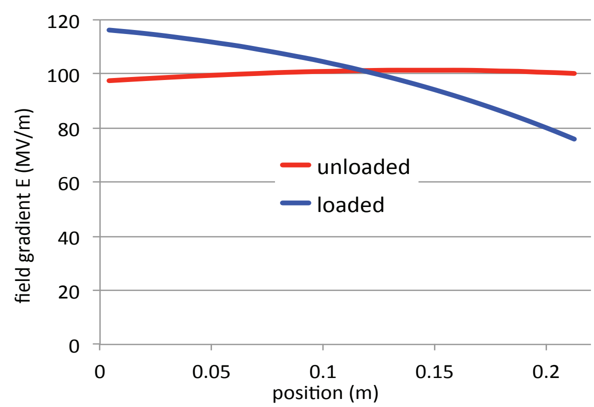


Figure 1: Steady state electric field gradient profiles along the CLIC_G accelerating structure for an average gradient of 100 MV/m. The red line represents the unloaded structure and the blue line the case for the presence of an 1.2 A beam.

The effect of the changing field profile on breakdown rate is hard to predict. The whole-structure breakdown rate varies approximately as $E_{\mathrm{acc}}^{30}$ when input power is varied [2]. On the other hand the breakdown rate along the length of a given structure varies approximately linearly with surface electric field [3]. The strong difference between the two dependencies could be due to the relative conditioning states of the cells along the length of the structure.

In order to directly measure the effect of beam loading on breakdown rate, an experiment is being prepared in CTF3, which will measure the breakdown rate in a CLIC accelerating structure fed by the 12 GHz klystron test stand (Xbox-1) [4] in presence of beam provided by the CTF3 drive beam linac.

## TEST AREA INSTALLATION

Earlier in 2000, a special dog-leg beam line was installed branching off midway the CTF3 3 GHz drive beam linac. It was used to divert the drive beam and send it through a special power production structure (PETS) to generate 30 GHz RF pulses [5]. The produced RF power was conveyed to the structure test area (CTF2) via a special low-loss RF transfer line. The existing environment is re-used for this experiment. A 12 GHz CLIC accelerating structure (CLIC_G) [6] was installed at the location of the former 30 GHz PETS,




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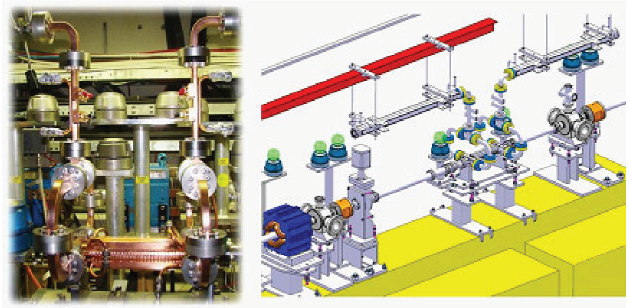

Figure 2: CLIC_G accelerating structure installed in the CTF3 dog-leg experimental area.

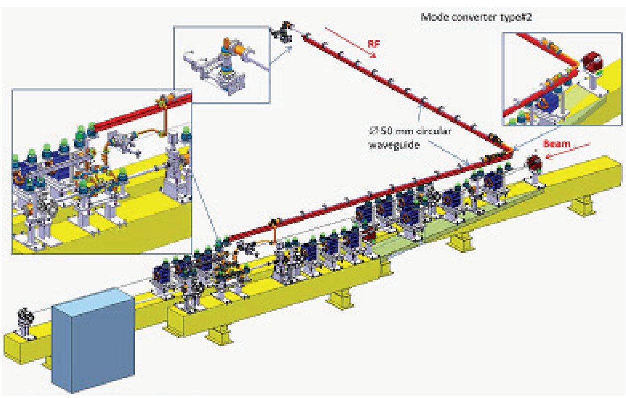


Figure 3: General layout of the dog-leg test area and low-loss RF transfer line.

see Fig. 2. The first stage of this experiment is to establish routine beam transport through the structure without losses and to integrate RF signal acquisition.

Later the structure will be connected to the 12 GHz klystron (Xbox-1) test area via the modified RF transfer line, see Fig. 3. All the necessary RF components to convert the transfer line to be compatible with operation at 12 GHz have already been fabricated [7]. The line modification is scheduled to be done in June/July 2013. Afterwards the actual experiments with beam loading will start.

## BEAM OPTICS DESIGN

The beam optics was designed to achieve proper conditions of the beam inside the accelerating structure and good beam transmission along the beam line. For this purpose, the relative differences between the beam size and the aperture along the tapered accelerating structure (from 6.3 to 4.7 mm diameter) are maximized. This results in a beam waist towards the downstream end of the structure, as the structure diameter becomes smaller there. It ensures the maximum clearance inside the structure and reduces the probability of beam losses. Additional constraints were imposed to cancel the dispersion in the straight part of the dogleg line. To achieve these goals, MAD-X [8] and OPA [9] were used to design and cross-check the required optical properties. Both results were compatible, Fig. 4 shows the results for a part of the linac and the dogleg line.

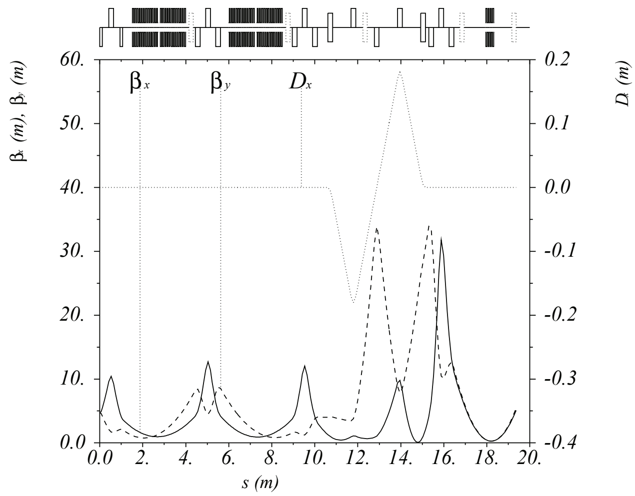


Figure 4: Beta functions and dispersion along the linac and the dogleg line.

The longitudinal positioning of an 8 mm aperture collimator was optimized to protect the structure from beam losses.

## SIGNAL ACQUISITION AND TREATMENT

The structure is equipped with directional couplers which allow the measurement of the input and output RF power of the cavity, both forward and reflected. From the couplers, the RF signal is transported trough coaxial cables and converted to a DC signal by a diode. A 250 Mhz 12-bit ADC (SIS3320) clocked at 192 MHz synchronized with the RF and beam trigger is used to digitize the RF signals. An acquisition software was developed to calibrate, visualize and analyze the digital signals in real time. The calibration is made using a step-by-step approach which accounts for the attenuation of each component and non-linear effects of the diode. The total attenuation including couplers and cables is in the range from 79 to 87 dB.

The RF reflected signal of the structure input is used to identify breakdowns by means of a threshold cut for the signal peak. In order to avoid damages to the structure in the case of a high breakdown rate, the program is able to stop the beam.

## EXPERIMENTAL SETUP

The experiment requires a lower beam current of the order of 1 A and a shorter beam pulse up to 250 ns, compared to 4 A and 1120 ns for the standard operation of CTF3. In order to maximize the beam energy, the RF pulse compression has been set up for 400 ns pulses with a higher compression ratio. In combination with the lower beam-loading in the accelerating structures, the energy of the beam could be doubled compared to the nominal beam, and an energy of 132 MeV was reached.

Instead of sending the beam into the dogleg line, the beam can be sent further down the linac, where the Twiss



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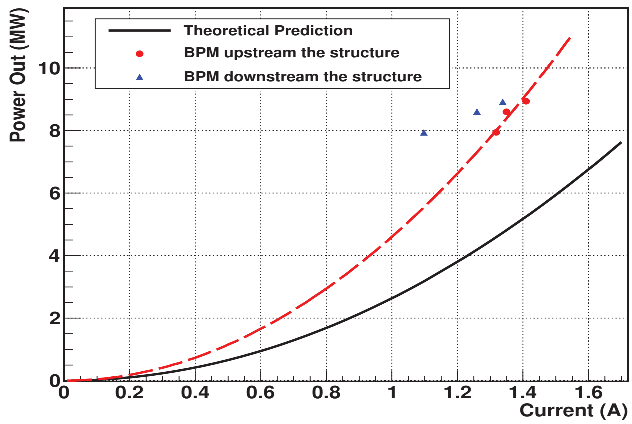


Figure 5: Steady-state forward RF output power of the accelerating structure as a function of beam current, for the theoretical prediction and based on current measurements upstream and downstream the accelerating structure.

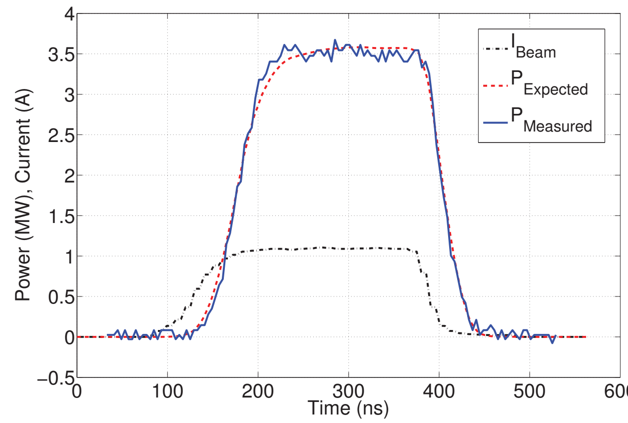


Figure 6: Forward RF output power of the accelerating structure calculated from the measured beam current profile along the pulse together with measurement (scaled in power level).

parameters can be measured by a quadrupole scan. The result of the measurement was used to calculate the optics in the linac upstream the dogleg line. Based on the measurement, the optics in a part of the linac and in the dogleg line was matched to the nominal optics, and the beam was sent into the dogleg line. After an optimization of the steering, a partial transmission trough the line could be established. After further empirical changes of the settings, a relative good transmission through the structure could be achieved, though there were still beam losses of the order of 5-15%.

First RF signals observed from the forward power of the output of the structure showed saturation for the acquisition, and the attenuation level was adjusted to achieve the proper signal level.

The expected steady-state output power as a function of beam current can be calculated and is shown in Fig. 5. The measured RF signals were analyzed for several levels of beam current on a BPM upstream and downstream the structure. Comparing them to the expected power level, it is clear that there is a calibration error of the order of 2.5 dB in the power acquisition. Another source of uncertainty is the measured beam current. As there are beam losses, the beam current measurement downstream can underestimate the current inside the structure. From the data this seems to be the case, as the power scales like expected only for the upstream BPM measurement.

The measured beam current on the BPM was used to calculate the time evolution of the forward power at the output of the accelerating structure based on the formalism introduced in an analytical beam-loading model [10]. Figure 6 shows that the measured signal (scaled to the same power level) follows very well the expected time structure.

## CONCLUSION

A dedicated experiment is planned to measure the breakdown rate in the presence of beam-loading. As a first step, the beam transport through the structure has been established and the RF signal acquisition has been set up. Further work is foreseen on the calibration of the signal acquisition and on the optimization of the beam transport through the structure. A collimator at the beginning of the dogleg line could be used to improve the beam quality in the line. The structure will be connected to the 12 GHz klystron from July 2013 when the conditioning of the structure with RF will start.

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## REFERENCES

[1] "A Multi-TeV linear collider based on CLIC technology: CLIC Conceptual Design Report", edited by M. Aicheler, P. Burrows, M. Draper, T. Garvey, P. Lebrun, K. Peach, N. Phinney, H. Schmickler, D. Schulte and N. Toge, CERN-2012-007

[2] A. Grudiev, S. Calatroni, W. Wuensch, Phys.Rev.ST Accel.Beams 12 (2009), Erratum-ibid. 14 (2011)

[3] W. Wuensch, HG2012 ICFA mini workshop, http://indico.cern.ch/conferenceTimeTable.py?confId=165513

[4] J. Kovermann et al., "Commissioning of the First Klystron-Based X-Band Power Source at CERN", CERN-ATS-2012-131, THPPC060, Conf. Proc.: C1205201 (2012)

[5] H. Braun, CTF3 Collaboration meeting 2004, http://cern.ch/clic-meeting/CTF3_Techn_Mtgs/2004/Presentations/pdf/HBraun.pdf

[6] A. Grudiev, "T24_vg1.8_disk 12WNSDVG18 CLIC_G undamped 12 GHz", http://edms.cern.ch/document/1068314

[7] I. Syratchev, "Beam Loading experiment planning", CLIC Workshop 2013

[8] http://cern.ch/mad

[9] http://people.web.psi.ch/streun/opa/

[10] A. Lunin, V. Yakovlev, and A. Grudiev, Phys. Rev. ST Accel. Beams 14 , 052001 (2011)