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HIGH GRADIENT PERFORMANCE OF AN S-BAND BACKWARD TRAVELING WAVE ACCELERATING STRUCTURE FOR MEDICAL HADRON THERAPY ACCELERATORS

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Abstract

The high-gradient performance of an accelerating structure prototype for a medical proton linac is presented. The structure was designed and built using technology developed by the CLIC collaboration and the target application is the TULIP (Turning Linac for Proton therapy) proposal developed by the TERA foundation. The special feature of this design is to produce gradient of more than 50 MV /m in low-β accelerating structures (v/c=0.38). The structure was tested in an S-band test stand at CERN. During the tests, the structure reached over above 60 MV/m at 1.2 μs pulse length and breakdown rate of about $5x10^{-6}$ bpp. The results presented include ultimate performance, long term behaviour and measurements that can guide future optimization.

INTRODUCTION

The development of low-β high-gradient (HG) accelerating structures is one of the main requirements for implementation of compact and cost-effective hadron linacs for medical applications. Cancer therapy accelerator need to reach the full penetration depth of the human body and thus provide particle beams with energies in the range 70-230 MeV for protons and 100-400 MeV/nucleon for carbon ions.

To accelerate effectively to higher energies, a HG S-band structure has been designed and manufactured at CERN. An overview of the 3 GHz Backward Travelling Wave (BTW) structure, currently under test, is given in [1].

This accelerating structure is proposed as part of the TULIP project [2], a single room proton therapy facility. The prototype has been designed to accelerate protons with an energy of 70 MeV. Composed of 12 equal length RF cells, totally 189.84 mm in length, the structure has 10 regular cells and two coupling cells, whose aperture diameter is 5mm. Main parameters of the structure are shown in Table 1.

HG operation of RF cavities is limited by undesired RF breakdowns (BD) which may cause beam losses, cavity surface damage, radiation and vacuum deterioration. A maximum breakdown rate (BDR) of the order of 10^{-6} bpp/m is usually required in a hadron therapy linac in order to guarantee an acceptable number of BDs throughout the whole treatment session.

The main goal of this study is to define the HG limits of S-band cavities in terms of BDR. In this paper we present test and data analysis of the structure which includes the BD localisation within the structure and the study of BDR dependence on the RF fields and pulse parameters.

Table 1: Main Parameters of the Accelerating Structures

Operation frequency	2.9985 GHz
Number of RF cells	12
Geometric β – RF Ph. Adv.	0.38 – 150 deg
Max Es/Ea	3.9
Pin @ 50 MV/m	20.16 MW
Pout @ 50 MV/m	11.24 MW
Filling time	220 ns
Group velocity (first/last)	0.39 / 0.21 %c

HIGH POWER TEST SET-UP

The first high-power test of the BTW structure is being performed at the S-band test facility at CERN. The accelerating structure is located in the CTF2 bunker and powered by a 43 MW S-band klystron via WR-284 waveguide lines. The klystron is protected against reflected power by a high power circulator. A schematic of the high-power components of the test facility is shown in Fig. 1.

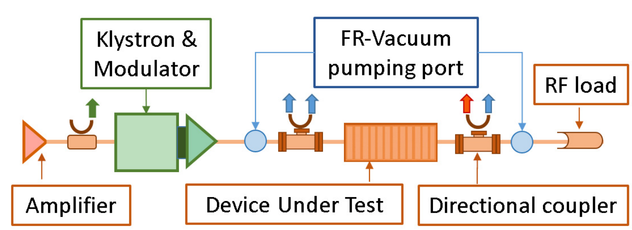

Figure 1: Schematic layout of the test setup.

Presently, the klystron MKS07 previously used in CTF3 is used to delivers RF pulses with a maximum length of 5 μs at a repetition rate of 50 Hz.

Directional couplers situated at the input and output of the structure, are used to measure the incident, reflected and transmitted RF signals. Faraday cups are placed in the upstream and downstream directions along the structure's beam axis to measure dark current and detect BD events

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in the structure. The structure is connected to an ion pump and dedicated chiller unit to adjust the cooling water temperature. An additional sensor is installed to measure the surface temperature of the structure.

The control and acquisition system are based on National Instruments electronics. A PXI real-time system performs the acquisition of RF, vacuum, temperature and water cooling signals. The detection of BD events in the structure using the acquired signals and the final data storage. The RF signals from the directional couplers are digitised in a NI-5761 ADC installed on the PXI crate and they are used as feedback to the power fed to the system. The operation of the test stand is controlled and interfaced by a simplified version of the Xbox-2 LabVIEW software [3]. In Fig. 1, the arrows show the signals that are sent to the NI PXI crate for acquisition and analysis. A photograph of the experimental setup is shown in Fig. 2.

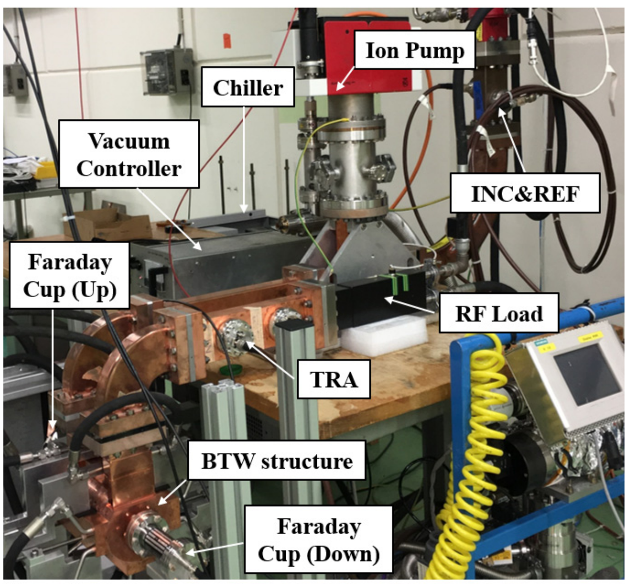

Figure 2: Picture of the test bench at S-box. Structure, diagnostics, vacuum and cooling system are labelled.

HIGH POWER MEASUREMENT

The conditioning algorithm developed on the Xboxes, was also used to test the BTW structure [4, 5]. The conditioning is carried out by increasing the input power level in a controlled manner while limiting itself by BDR of about 3x10^{-5} BDs per pulse. A small initial pulse width was used to avoid damaging the structure. The pulse length has been gradually increased from 350 ns up to 1.2 µs.

The plot in Fig. 3 represents the accelerating gradient (blue) and the cumulative number of breakdowns (red) with respect to the number of triggered pulses, at the different pulse lengths indicated on top.

The BTW structure achieved a maximum gradient above 60 MV/m with 1.2 µs pulses. The typical pulse length for medical accelerators is 2.5 µs flat-top with rise time equal to filling time of the structure. Therefore, further testing of the structure with a longer pulse length has a significant interest.

The structure is still conditioning and more data is being collected to increase the statistics and measure BDR at longer pulses.

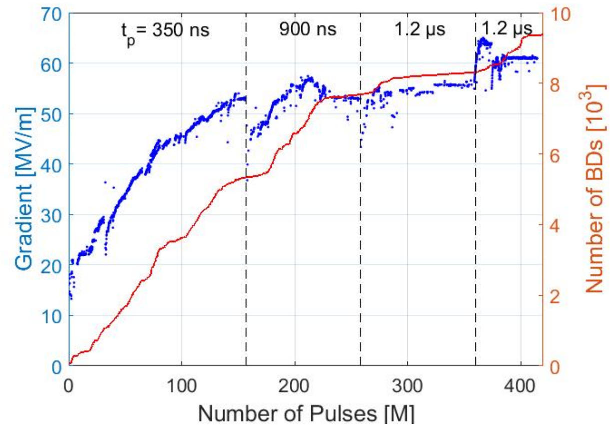

Figure 3: Conditioning history of a BTW prototype tested at Sbox.

BD localisation

The threshold detection of the reflected signal from the structure and the dark current signals, measured from the upstream and downstream Faraday cups are used to determine if a BD has occurred. The shape of these signals during a BD and the previous pulse is shown in Fig. 4

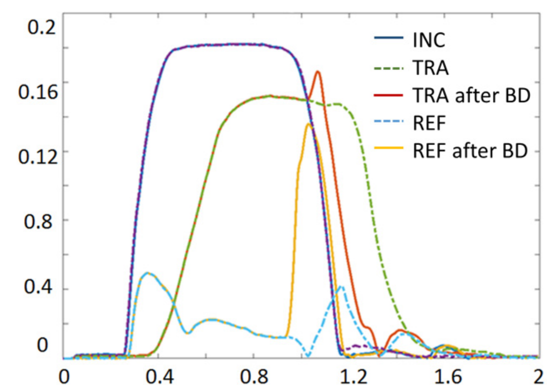

Figure 4: BD incident (INC), reflected (REF) and transmitted (TRA) RF signals in the structure during the conditioning phase with comparison to a nominal pulse before the BD event, for an RF pulse length 900 ns (amplitude of signal versus time (µs)).

The data collected by the acquisition system is analysed offline in order to characterize the behaviour of the structure. The group velocity profile of the structure used to translate the time into a measure of the length travelled by the RF wave [6]. The difference in timing between the transmitted and reflected signals have been used for BD cell localization. This measurement allows determination of the spatial distribution of the BDs along the multiple cells of the structure (see Fig. 5). We aim for the earliest detection of a 'hot spot', where BDs predominantly occur at a single point in the structure and can lead to the deterioration of the structure's performance.

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The results show that the BDs are distributed along the structure according to the design features. Indeed group velocity has a strong reduction between the input and output of the structure of a factor of two. A 'hot spot', where excessive BDs are initiated, is observed at cell number 5. Continuous monitoring of BDs localisation is required to avoid damage of the cell.

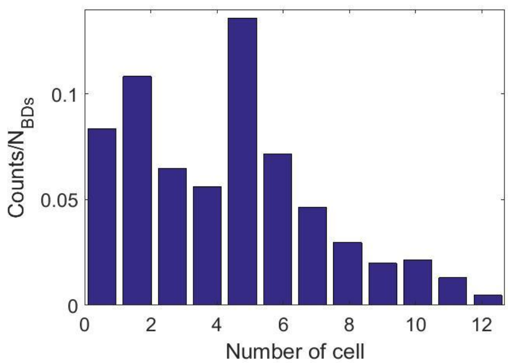

Figure 5: BD location in the RF structure.

Dark current measurement

A unique feature of this structure is that it is both high gradient, with surface fields in excess of 200 MV/m, and low beta. Consequently there may be differences in captured field emission current compared to high-gradient, high-beta structures and field emission is being studied closely. Field emission induced radiation can become an important issue for shielding in a medical facility.

During operation of the structure, field emission currents varied over time. Higher values are observed at initial conditioning of the structure due to imperfections on the surface that can lead to enhanced field emission. To quantify the quality of the surface of the structure, a power scan measuring radiation and the dark current level were performed by a radiation monitor and Faraday cup (see Fig 6).

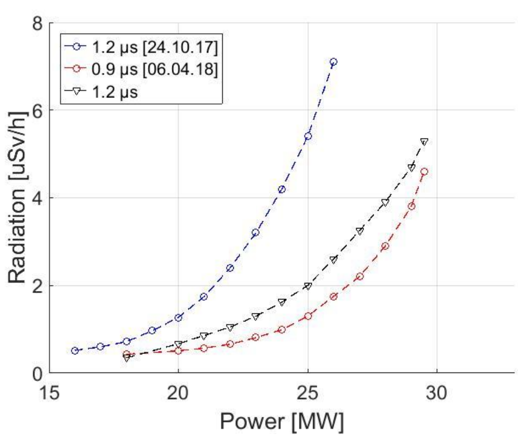

Figure 6: Dependence of radiation level on power during conditioning.

The amplitude of the dark current emitted from the structures follows the Fowler-Nordheim dependence on the surface electric fields after fitting the field enhancement factor β [7]. For BTW structures β is around 35–45 as shown in Figure 7. This value of β is similar to that of Xband accelerating structures tested at CERN.

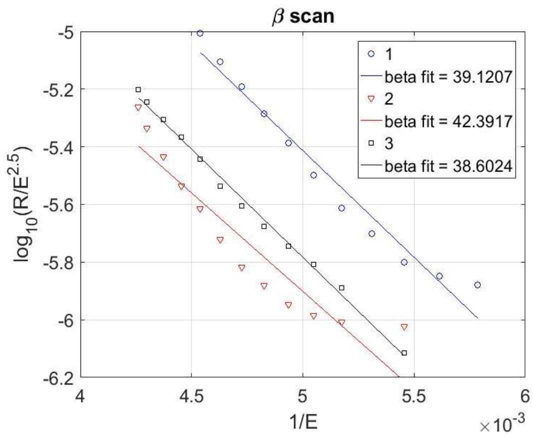

Figure 7: Linear fit of the Fowler-Nordheim formula.

BDR evaluation

The performance of the accelerating structures is assessed by the BDR. This parameter changes over time as structure conditions and has a strong dependence on the accelerating gradient and the pulse length. The reduction of the BDR measured for a certain field level indicates the conditioning status of the cavity. The BDR decay was measured for a peak power corresponding to 60 MV/m close to the limiting value. Fig. 8 shows the measurement during which the BDR dropped to $4\text{x}10^{-6}$ bpp. In this way, we can estimate the asymptotic value of the BDR in a conditioned structure.

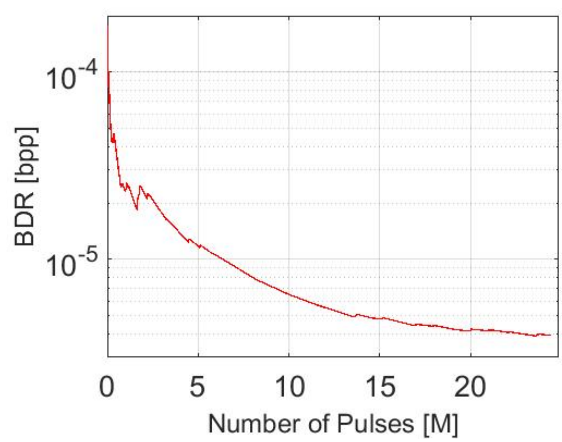

Figure 8: BDR with respect to the accumulated number of pulses during conditioning with constant power. Accelerating gradient is around 60 MV/m.

CONCLUSION

A unique high-gradient, low-beta structure is being tested in the Sbox at CERN. This structure is reaching an accelerating gradient never achieved so far in low beta RF structures. Accelerating gradient is currently above 60 MV/m at 1.2 μs pulse length with BDR about $2.5\text{x}10^{-5}$ bpp/m. The testing of the structure continues with a longer pulse width.

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