FABRICATION AND TESTING OF A NOVEL S-BAND BACKWARD TRAVELLING WAVE ACCELERATING STRUCTURE FOR PROTON THERAPY LINACS

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Abstract

Compact and more affordable, facilities for proton therapy are now entering the market of commercial medical accelerators. At CERN, a joint collaboration between CLIC and TERA Foundation led to the design, fabrication and testing of a high gradient accelerating structure prototype, capable of halving the length of state-of-art light ion therapy linacs. This paper focuses on the mechanical design, fabrication and testing of a first prototype. CLIC standardized bead-pull measurement setup was used, leading to a quick and successful tuning of the prototype. The high power tests will soon start in order to prove that the structure can withstand a very high accelerating gradient while suffering no more than 10^{-6} breakdown per pulse per meter (bpp/m), resulting in less than one breakdown per treatment session.

INTRODUCTION

High gradient structures are limited mostly by breakdown (BD) phenomena. CLIC proposed [1] a new method to asses this limit, considering a Modified Poynting Vector (S_c) instead of the maximum Surface Electric Field. This theory was fully verified at high frequency (12 and 30 GHz) by CLIC with many experiments of structures designed for electron linacs. In this structure, the theory is applied to structures designed for particle velocities well below c. TERA Foundation addressed the issue at 3 GHz, hinting that such theory could still be valid at this lower frequency [2].

The test of this prototype, hereafter presented together with the mechanical design and fabrication, is thus of key importance in defining the upper limits in terms of accelerating gradient of S-Band cavities, and in verifying the S_c model in the 3 GHz and the low phase velocity regime.

MECHANICAL DESIGN

The mechanical design had to face a number of challenges, from the required micron-precision tolerances, to the slenderness of the inter-cell wall with respect to the mass of the ‘nose’. The latter presents a critical geometrical feature both for machining and for the bonding/brazing steps. Inter-cell wall thickness remarkably affects the accelerating efficiency of a cavity, so it has to be chosen the minimum possible. A series of high-temperature creep tests was thus carried out. More precisely, an experimental campaign was performed to define the minimum septum thickness that can withstand the creep-induced deformation during the hydrogen bonding heat cycle (with a maximum temperature of 1050 °C). A value of 2 mm was eventually chosen for the septum thickness. A machining test was also performed – with a prototype cell being produced in order to validate the following series.

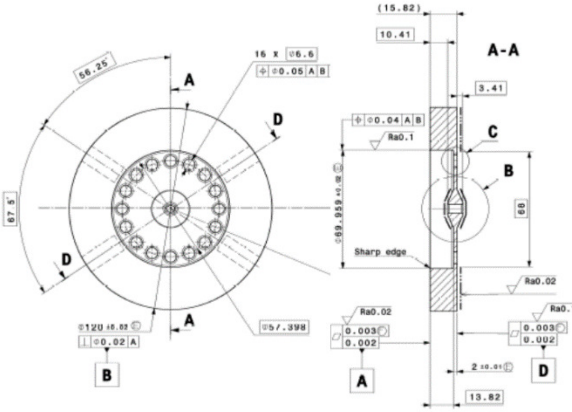

Figure 1: Mechanical drawing of one disk.

Tuning of the structure is made by four dimple tuners per RF cell (Fig.1 left). The number and size of the tuners was determined by an RF sensitivity and tuning analysis. The dimple tuners have a diameter of 10.5 mm, and wall thickness of 1.6 mm. This last parameter has to allow enough deformation of the cavity outer walls to produce a tuning effect, but without rupture. A series of numerical calculations and tests was also carried out on geometries with different diameter/wall thickness ratio, in order to find the best compromise between allowable tuning volume and safety in terms of possible rupture of the copper wall.

A weakly coupled thermo-structural analysis on the full structure was performed by importing the HFSS® electromagnetic field distribution to the thermal and structural packages of ANSYS® (Fig. 2).

The heat dissipation is limited by the peculiar RF design [3], which has 16 coupling holes in each RF cell outer region. As a result, the temperature distribution in the structure is mainly driven by this thermal resistance. Four cooling plates were designed. To prevent plastic deformation, a maximum thermal load of 0.75 kW is allowed, which corresponds to a duty cycle of about 0.075 10^{-3} at a maximum gradient 50 MV/m. Further developments could consider a thicker septum, at the price or reduced rf performance, in case a higher duty cycle is required.

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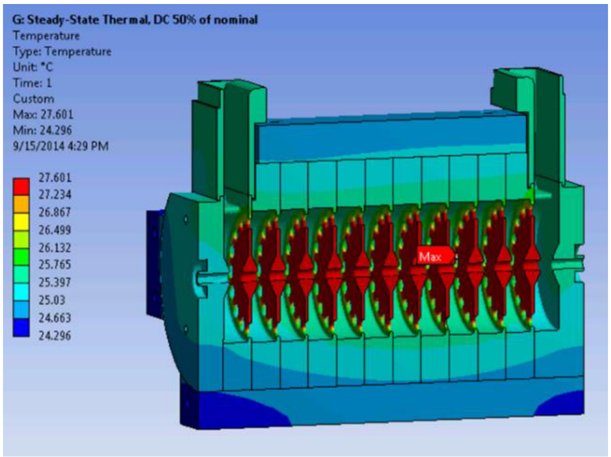

Figure 2: Temperature distribution in the structure in case of a load of 0.75 kW, and cooling water at 22 deg.

The full structure design is presented in Fig. 3. It is possible to notice the details of the cooling plates and pipes, dimple tuners and waveguides transition to standard WR284.

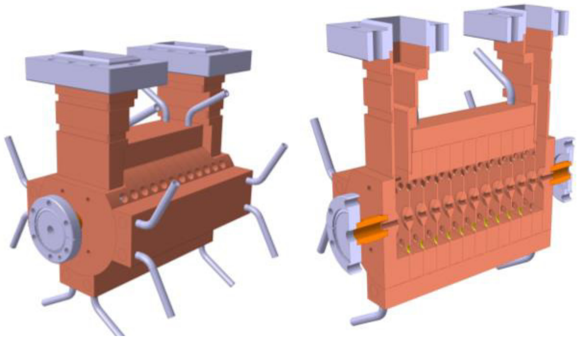

Figure 3: Mechanical design of the prototype.

FABRICATION

Once the ultra-precision machined disks arrived at CERN, they underwent visual and metrological inspection to check the presence of eventual surface defects and compliance with the nominal values indicated in the drawings (Fig. 4).

Figure 4: Regular and input cell of the prototype.

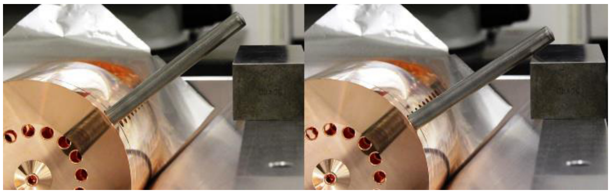

Figure 5: Disks alignment procedure.

A low power RF test was performed on the structure prior to bonding, in order to verify that the prototype was within the tuning range. The stack of disks was joined by diffusion bonding in a partial hydrogen atmosphere following the CLIC baseline fabrication procedure. The fabrication technique was chosen so that the high-gradient test results can be most easily compared to the structures tested in the CLIC high-gradient program. The axial alignment of the disks was ensured thanks to a precise V-shape support whereas azimuthal alignment was performed using the tuning holes as seen in Fig. 5.

After the structure was assembled by brazing the cooling blocks and vacuum tubes and input waveguides, it was returned to CERN for the final tuning. A summary of the tests performed on the prototype is shown in Fig. 6.

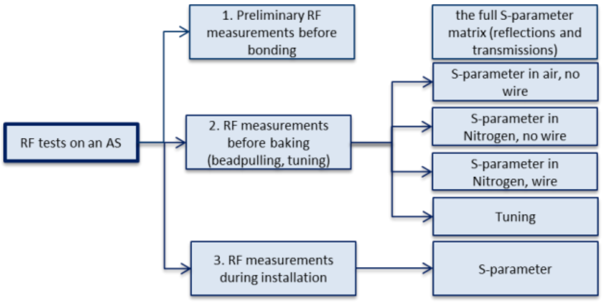

Figure 6: Scheme of the RF tests performed on the accelerating structure.

TUNING

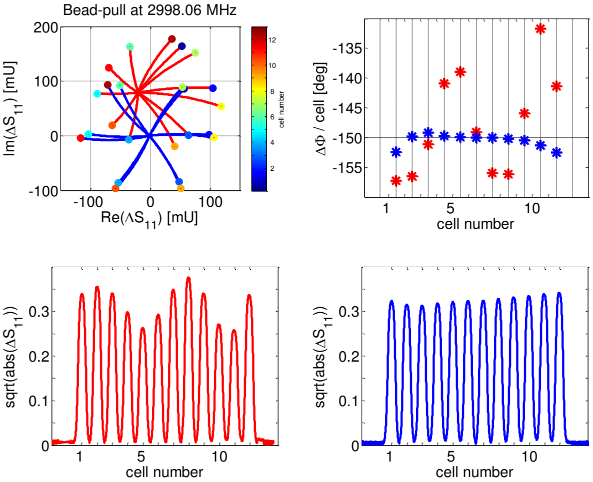

Figure 7: Electric field pattern along the structure for all 12 cells, before (in red) and after tuning (in blue). Top left: in the complex plane; top right: in phase advance per cell; bottom: in magnitude.

All 12 cells (10 regular and 2 coupling cells) of the structure were adjusted in frequency by pulling or pushing up to 4 tuning pins in each cell. The available tuning range per cell is about ±3 MHz. Bead-pull measurements were used to determine the electric field profile along the axis. The standing wave pattern was minimised and the desired phase advance of 150±1.5 ° for regular cells was adjusted for the operating frequency of 2.9985 GHz under vacuum at a temperature of 32 °. The frequency of the output coupling cell was increased by 2.2 MHz, the frequency of the 10 regular cells was increased between 0.1 and 0.8 MHz (average 0.3 MHz, std 0.2 MHz) while the frequency of the input coupling cell was decreased by 0.6 MHz. Fig. 7 shows the electric field pattern along the structure and Fig. 8 the measured S-Parameters after tuning.

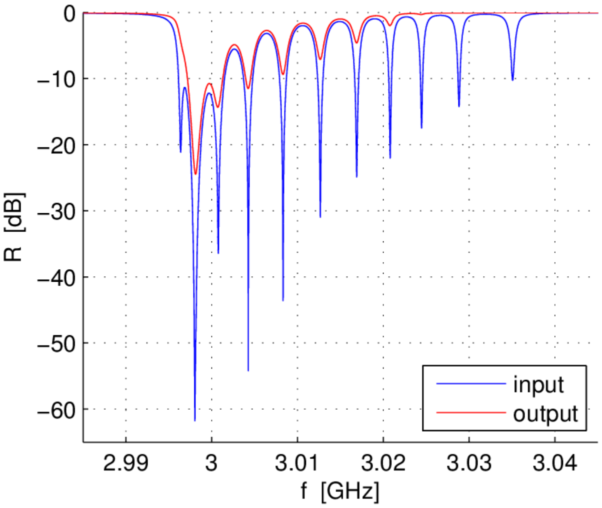

Figure 8: Input and output S-parameters of the tuned structure, measured at a temperature of 23°C in a dry nitrogen atmosphere.

HIGH POWER TEST SET-UP

A high power test of the prototype is under preparation using a bunker and infrastructure of the CLIC Test Facility (CTF3) to evaluate its breakdown performance. An S-band klystron unit is connected to the accelerating structure, located in the CTF2 bunker room, via WR284 waveguides (Fig. 9).

To ensure the ultra-high vacuum in the structure, below 10^{-8} mbar, an ion pump is installed next to the prototype through an RF pumping. In addition, a vacuum leak test of the prototype has been made in situ at the testing place.

The control and acquisition system are based on National Instrument electronics, a largely direct copy of the configuration of the Xbox-2 test stand [4]. The structure is equipped with a complete experimental set-up for breakdown diagnostics. Two Faraday cups are attached to both ends of the prototype for breakdown detection and dark current measurements. Incident, reflected and transmitted RF power is extracted by bi-directional couplers inserted before and after the structure. The amplitude and phase of these 3 GHz signals will be processed by down-mixing to 62.5 MHz and digitizing in 250 Msps ADCs. The analysis of these signals will allow the longitudinal localization of vacuum arcs in the structure [5].

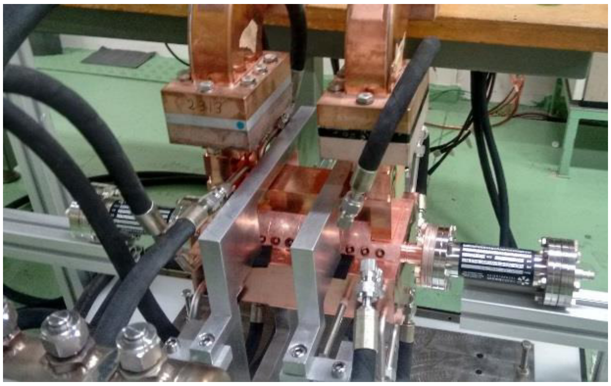

Figure 9: Picture of the prototype under test in CTF2.

SUMMARY AND FUTURE STEPS

A 3 GHz Backward Travelling Wave (BTW) accelerating structure with geometric beta of 0.38 was recently designed and built at CERN. The main goal of the project is to investigate the accelerating gradient limits of the S-band regime. In this paper, the mechanical design, fabrication and tuning of the prototype is discussed, together with the high power test set-up. The prototype is currently installed in CLIC CTF2. The start of high – gradient testing is imminent.

ACKNOWLEDGMENT

The authors are very grateful to the CERN KT group for having funded the accelerating structure prototype construction and supplied important test equipment.

REFERENCES

[1] A. Grudiev, S. Calatroni and W. Wuensch, “New Local Field Quantity Describing the High Gradient Limit of Accelerating Structures”, Phys. Rev. ST Accel. Beams 12 (2009) 102001.
[2] A. Degiovanni, “High Gradient Proton Linacs for Medical Applications”, EPFL PhD Thesis (2014).
[3] S. Benedetti *et al.*, “RF Design of a Novel S-Band Backward Travelling Wave Linac for Proton Therapy”, in Proceeding of LINAC Conference (2014).
[4] B.J. Woolley, “High Power X-band RF Test Stand Development and High Power Testing of the CLIC Crab Cavity”, Lancaster University PhD Thesis (2015).
[5] A. Degiovanni *et al.*, “Diagnostics and analysis techniques for high power X-band accelerating structures”, in Proceeding of LINAC Conference (2014).