RF DESIGN OF A NOVEL S-BAND BACKWARD TRAVELLING WAVE LINAC FOR PROTON THERAPY

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Abstract

Proton therapy is a rapidly developing technique for tumour treatment, thanks to the physical and dosimetric advantages of charged particles in the dose distribution. Here the RF design of a novel high gradient accelerating structure for proton linacs is presented. The design discussed hereafter represents an unicum thanks to the accelerating mode chosen, a 2.9985 GHz backward travelling wave mode with 5π/6 phase advance, and to the RF design approach. The prototype has been designed to reach an accelerating gradient of 50 MV/m, which is more than twice that obtained before [1]. This would allow a shorter linac potentially reducing cost. The complete 3D RF design of the full structure for beta equal to 0.38 is presented.

INTRODUCTION

A collaboration between the TERA Foundation and CLIC has been established to study a novel linear accelerator for proton therapy. The main goal of the collaboration is to transfer the knowledge acquired by the CLIC group, mostly in terms of RF design, high-gradient limitations and linac optimization, to a medical linac. As a result, a low-β structure with an expected accelerating gradient of 50 MV/m has been designed, double that of the gradient reached in equivalent linacs. This design result (high-power tests have not been made yet) is based on a novel RF design approach, which will be discussed in detail in this paper. The KT – Knowledge Transfer – group of CERN has funded the construction of a first prototype of the structure, which will be produced and tested at high power at the beginning of 2015.

This accelerating structure is part of the TULIP project, a single room facility for proton therapy with the unique feature of having a linac mounted on a rotating gantry [2]. In this perspective, the high gradient structure hereafter presented remarkably improves the compactness and lightness of the rotating mechanism, with benefits in terms of cost and reliability.

REGULAR CELL DESIGN

The electromagnetic coupling between cells has been accomplished magnetically by means of magnetic *coupling holes* at the periphery of the cells. N*ose cones* are added to enhance the electric field near the axis and thus the transit time factor for the low beta structure. The regular cell geometry is shown in Fig. 1.

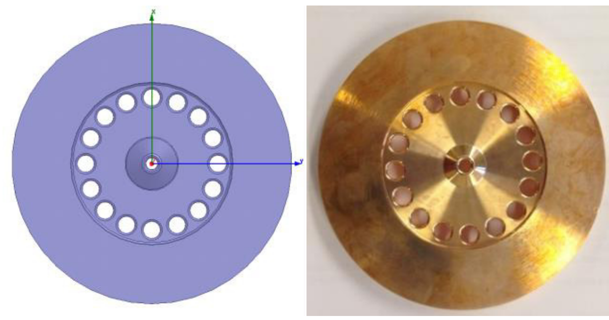

Figure 1: Regular cell design; 3D model (left) and copper piece (right) used in the creep test.

A local field quantity which predicts the high gradient performance of an accelerating structure is the modified Poynting vector S_c, defined in [3]. It has a limiting value of about 4MW/mm^2 at a pulse length of 200 ns and for a breakdown rate (BDR) of 10^{-6} bpp/m (BDs per pulse per meter). This limit is used in the design of the linac (which is approximately 6 m long) in order to have less than one BD per treatment session. By re-scaling these data to the pulse length typical of medical linacs, i.e. 2.5 μs flat-top, a limit quantity of S_c/E_a^2 – where E_a is the average accelerating gradient – lower than $7\cdot10^{-4}$ A/V has been found.

The goal of the regular cell design has been to minimize the value of S_c and at the same time the amount of RF power for a given accelerating field, i.e. the quantity:

$$\mu \equiv \frac{P_w}{E_a^2}\cdot\frac{S_c}{E_a^2} = \frac{v_g}{\omega}\cdot\frac{S_c/E_a^2}{R'/Q}, \qquad (1)$$

where ω is the angular RF frequency, R′ is the effective shunt impedance per unit length and Q is the quality factor of the cell. Eq. (1) equally weights the dissipated power and the modified Poynting vector; thus, minimizing μ one obtains for a given power the highest accelerating gradient with a low BD risk.

The optimum is found when Eq. (1) is minimized simultaneously on the nose, where the electric field is maximum, and on the coupling slot, where the magnetic field is maximum, as shown in Fig. 2.

A parametric study has been performed varying the cell gap, cone angle and phase advance per cell. The thickness of the iris has been carefully studied as well. The thinner the iris, the higher the shunt impedance is, but also the lower the mechanical resistance of the structure and the

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possibility of evacuating the heat from the nose to the outer walls of the structure which are water cooled.

Particular effort has been dedicated to the sensitivity analysis and the study of the tuning methodology. The tolerances specified in the mechanical drawings would, from simulations, give no more than ±5 MHz of frequency shift per cell. This possible error will be adjusted by means of 4 dimple tuners. The tuning capability obtained from simulations and mechanical tests on copper cells is higher than 6 MHz per cell, well beyond the tuning needs also in the worst case scenario.

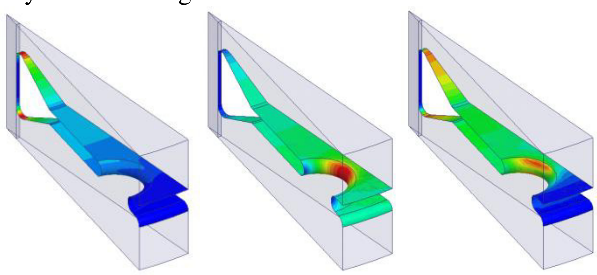

Figure 2: Electric (left), magnetic (centre) and modified Poynting vector (right) field distribution in a regular cell section (1/32 azimuthal symmetry).

TAPERING OF THE STRUCTURE

In a travelling wave linac, the RF power is injected into the structure and propagates along it at the *group velocity* v_g. It is absorbed both by the conductor walls and by the beam, resulting in an attenuation of the field amplitude. At the end of the structure the power is coupled to a load or a re-circulating circuit.

A low group velocity leads to a high accelerating gradient but at the same time to a rapid decay of the power. The group velocity can be adjusted by means of cell-to-cell coupling in the disk-loaded accelerating structure. In particular, the bigger the coupling, the higher the group velocity is. A *constant-gradient* structure has been chosen in the present design with the group velocity ranging between 0.4% and 0.2% of *c* as a compromise between acceptable filling time and efficient acceleration of the beam (Fig. 3).

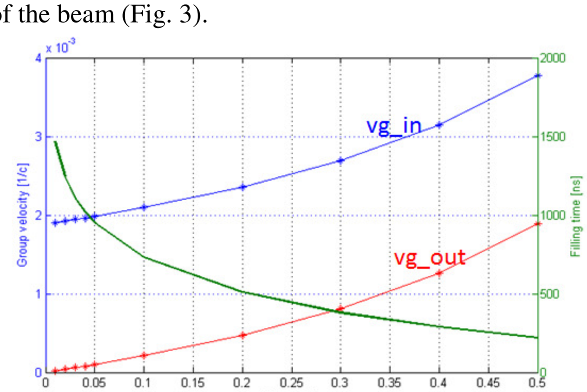

Figure 3: Input and output cells group velocity and filling time of the structure as a function of the ratio between output and input powers.

The tapering has been accomplished by varying linearly the coupling holes radii; the cell diameter and the radial distance of the coupling holes have been varied to adjust the resonant frequency. All the other geometrical parameters have been kept constant throughout the structure.

COUPLERS DESIGN

The input and output power couplers (or end-cells) represent a very delicate part of the design process. The presence of a slot to allow the RF power to penetrate into the structure enhances the electromagnetic field distribution and modifies the accelerating parameters of the coupling cell. The goal of the couplers design is to minimize the power reflections while perturbing as little as possible the field distribution and the accelerating performance of the end-cells.

The power coupling is made magnetically via a single slot, the area of which together with the coupling cell diameter is chosen for matching. The coupling holes radius in the input cell has been reduced in the coupling holes closer to the coupling slot, to compensate for the enhancement of the S_c due to the local increase of the power flow. The remaining coupling holes have been resized to maintain the design group velocity in the cells (Fig. 4 left), and as a result the end-cells provide the same acceleration as the regular cells (Fig. 4 right).

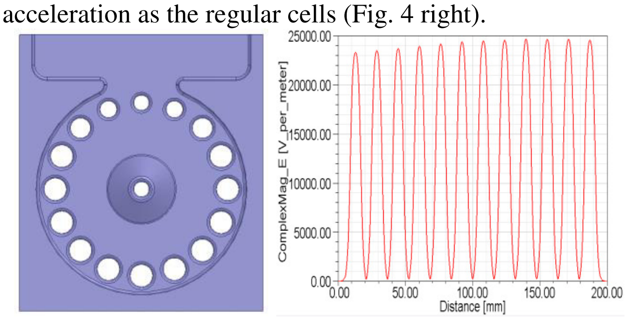

Figure 4: Input coupling cell (left) and electric field profile in the structure (right) for 1 W input power. It can be noticed the asymmetry in the coupling holes radii.

Eventually, an even distribution of the modified Poynting vector on all the accelerating structure noses and coupling holes has been reached, as shown in Fig. 5, and the limit of S_c/E_a^2 lower than $7\cdot10^{-4}$ A/V has been widely respected.

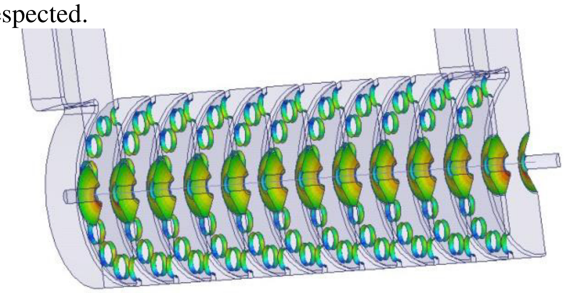

Figure 5: Modified Poynting vector normalized to the average accelerating gradient squared distribution on the structure noses and coupling holes. Red colour corresponds to $3\cdot10^{-4}$ A/V.

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Figure 6 shows (top) the frequency distribution of the resonating peak and (bottom) the phase advance per cell, which is equal to 150° at the chosen operating frequency. A reflection lower than 50 dB was reached at the resonant frequency of 2.9985 GHz.

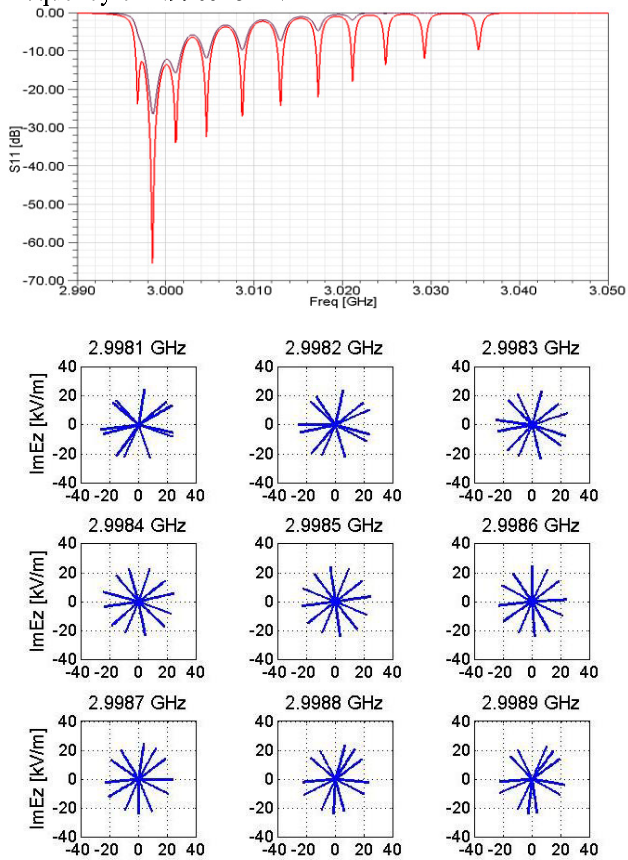

Figure 6: Input (red) and output (brown) couplers matching (top) and phase advance per cell (bottom) versus frequency.

ACCELERATING STRUCTURE PARAMETERS

The most important parameters of the backward TW accelerating structure (bwTW) are summarized in the first column of Table 1. The second column refers to a SW CCL (Coupled Cavity Linac) structure which has been previously designed for the TULIP project [4]. That structure has been optimized to maximize the shunt impedance, which is larger also thanks to the greater phase advance, but cannot withstand the same maximum gradients of the bwTW structure.

Table 1: Main parameters of the accelerating structures

Parameter	bwTW	CCL
RF phase advance per accelerating cell [rad]	5π/6	π
Wall thickness [mm]	2	3
Gap [mm]	7	5.1
Nose cone angle [deg]	65	25
Number of cells	12	10
Structure length including end-cells [mm]	189.9 (active)	189.9 (active)
Average accelerating gradient [MV/m]	50	31
Q factor (first/last cell)	6997/7463	8290
R'/Q (first/last cell)	7425/7369	8410
Normalized shunt impedance (first/last cell) [MΩ/m]	52.0/ 55.0	69.7
Filling time (w/o re-circulator) [ns]	900 (224)	1050
Peak input power (w/o re-circulator) [MW]	9.3 (20.6)	2.6
Max S_c/E_a^2 [A/V]	3.1e-4	7.8e-4
Max E_a (for BDR of 10^{-6} bpp/m) [MV/m]	74.9	47.1
Maximum surface electric field [MV/m]	219	159

SUMMARY AND FUTURE STEPS

A novel high gradient S-band accelerating structure for a proton therapy linac has been designed in collaboration between TERA and CLIC. The unique feature of such design is the capability of reaching an accelerating gradient never reached so far in equivalent structures.

In June 2014 the tender for the mechanical pieces has been launched. The final assembly of the prototype will start in autumn 2014, with the final goal of testing the structure at high power in 2015.

ACKNOWLEDGMENT

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