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Design and Test of C-band Linac Prototypes for Electron FLASH Radiotherapy

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Abstract. Flash Therapy is a revolution in cancer cure since it spares healthy tissue from the damage of ionization radiations without decreasing its effectiveness in tumor control. To allow the implementation of the FLASH therapy concept into actual clinical use and treat deep tumors, Very High Electron Energy (VHEE) should be achieved in a range of 50-150 MeV. In the framework of the VHEE project carried out at Sapienza University, in collaboration with INFN, we investigate the main issues in designing a compact C band (5.712 GHz) electron linacs for FLASH Radiotherapy. In this paper, we describe the design strategy, the electromagnetic properties, and the first prototypes of the RF structures to be tested at Sapienza University.

1. INTRODUCTION

FLASH radiotherapy (RT) has gained attention in the cancer research community due to its potential to cure tumors while sparing healthy tissues surrounding cancer. In preclinical studies, treatment with electron radiation delivered in a very short time (< 100 ms) with ultra-high instantaneous dose rate ($> 10^6$ Gy/s) has shown to significantly decrease the toxicity in healthy tissue while maintaining the same cure efficacy in cancer treatment.

The first experiment with FLASH-RT was conducted at Institut Curie in 2014 by V. Favaudon and his team [1], since then, numerous in-vivo and in-vitro radiobiological experiments have reported significant normal tissue sparing [2, 3, 4, 5]. However, further research is needed to understand the benefits and limitations of this methodology fully and to determine the best use cases for its application in clinical settings. Currently, only a few dedicated electrons linacs are employed for experimental research [6, 7, 8, 9, 10, 11, 12, 13], ongoing studies and technological advancements aim to make these linacs more compact and cost-effective for high-energy electrons. The ultimate goal is to use these linacs to treat deep tumors with FLASH radiotherapy in the future. A VHEE FLASH linac is under study at La Sapienza University of Rome (Italy) in collaboration with the Italian Institute for Nuclear Research (INFN). The initial section of the VHEE machine consists of a compact bi-periodic structure that operates at a frequency of 5.712 GHz and uses Standing Wave (SW) technology in $\pi/2$ mode. The second part of the VHEE machine is composed of a high gradient traveling wave (TW) structure, with a working frequency of 5.712 GHz and a phase advanced of $\frac{2}{3}\pi$ able to bring the energy of the electron beam up to about 130 MeV (Fig.1). In this paper, we present the design, the realization

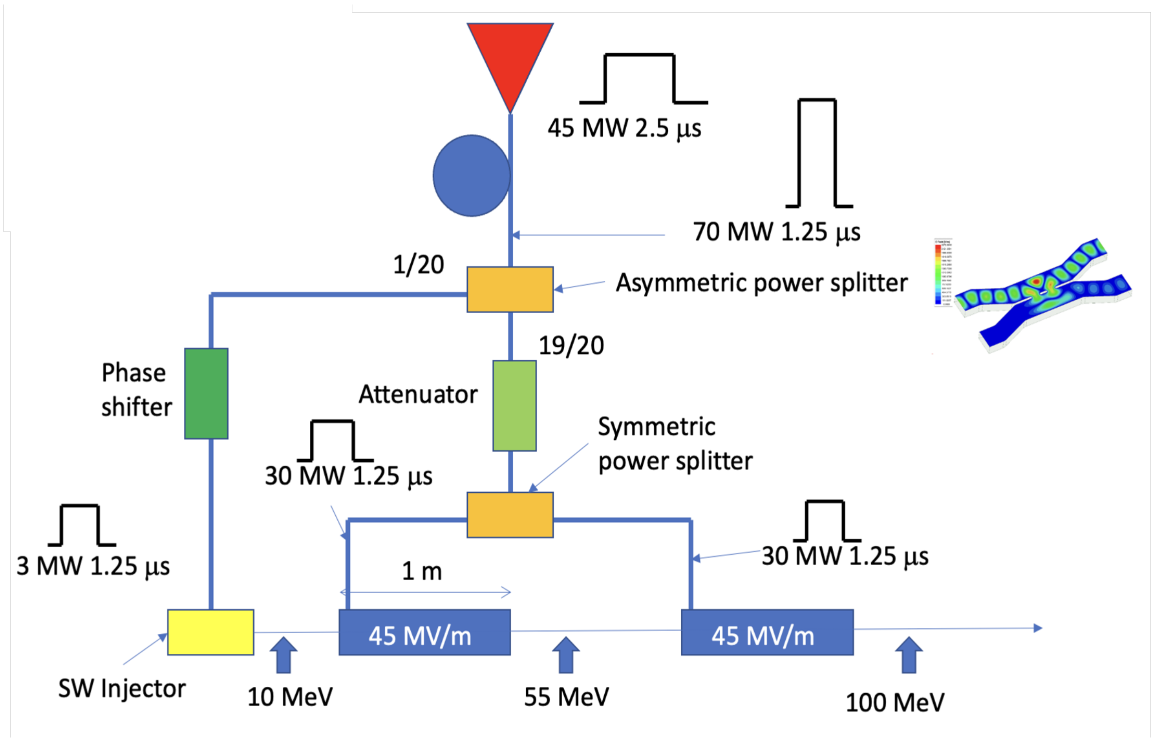

Figure 1. Layout of VHEE FLASH linac.

and the tests of C-band standing wave and traveling wave cavities prototypes that are currently under consideration for implementation in a VHEE FLASH machine. The primary objective of constructing these prototypes is to evaluate the quality and effectiveness of the brazing technique employed and to ensure the accurate execution of the in-house mechanical design.

2. Standing wave design

The first part of the VHEE machine is a standing-wave, bi-periodic structure; it consists of accelerating cells that are arranged in a repeating pattern, alternating with coupling cells in which the electric field is null. One of the advantages of using a standing wave design is that it can help to maintain a stable and well-focused beam of particles without the need for additional focusing devices, such as solenoids. The choice of frequency is crucial in designing a linac. A higher frequency of operation can lead to a higher breakdown limit, allowing for a higher accelerating gradient and a more efficient structure. Furthermore, increasing frequency leads to more compact and lighter structures, which is advantageous in medical applications where space and portability are important factors. In this regard, C-band, with an operating frequency of 5.712 GHz, has been found to be a good compromise that allows for a high accelerating gradient, high transmission efficiency, and a high beam peak current. For these cavities, a nose-cone structure was adopted to maximize the shunt impedance R_{sh} (Fig.2).

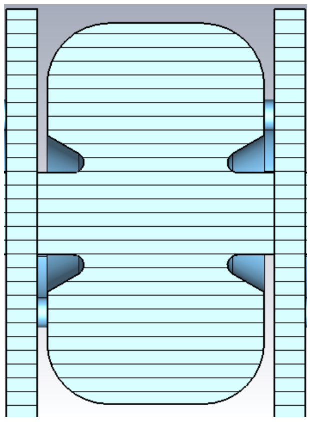

Figure 2. Nose-cone geometry design.

The nose cone allows the localization of a very high electric field in the middle of the accelerating cells, creating a very efficient acceleration of the beam propagating along the beam axis. To achieve efficient coupling between the power supply and the accelerating structure in our C-band linac design, we incorporated the waveguide into the central cell, also known as the coupler cell. By implementing central coupling, we effectively eliminate half of the resonant modes within the linac that would otherwise be excited. The optimization of the waveguide-to-linac coupling coefficient, denoted as β_c, is crucial to minimize the reflected RF power during electron beam acceleration. By considering the specific parameters of our RF linac setup, we have determined the optimal value of β_c be 1.3. The main RF parameters of the accelerating cells were determined and are presented in Table 1. The structure had a coupling coefficient of 1.3, a resonant frequency for the $\pi/2$ mode of 5.7115 GHz, and a total shunt impedance of 97.35 MΩ/m. By adjusting the number of cells, it is possible to achieve an energy until 12 MeV.

Table 1. Key Beam Output Parameters

Description	Value
Frequency	5.7115 GHz
Waveguide-to-Linac coupling coeff. β_c	1.3
R_{sh}	97.35 MΩ/m
Number of accelerating cells	32
Linac length	82 cm

Figure 3 shows the electric field distribution along the SW structure axis obtained using the CST STUDIO SUITE® code, with a concentration of the field in the region corresponding to the nose cone.

3. High Gradient TW structure design

The 3D design of the high gradient traveling wave structure and its electromagnetic study were conducted using CST STUDIO SUITE® (Fig.4).

A detailed report on this process has been published elsewhere [14]. The optimization process resulted in a single-cell design with an iris radius of 5 mm that strikes a good balance between

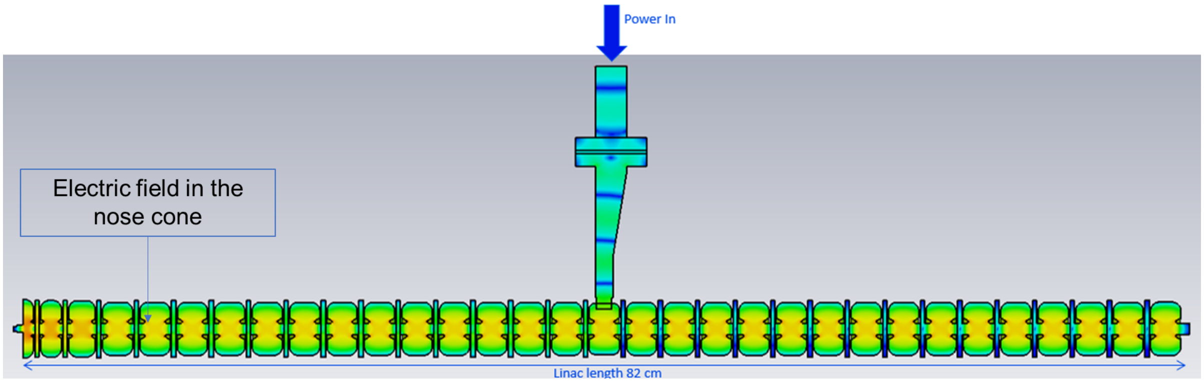

Figure 3. Electric field distribution along the axis obtained using the CST code, with a concentration of the field in the region corresponding to the nose cone.

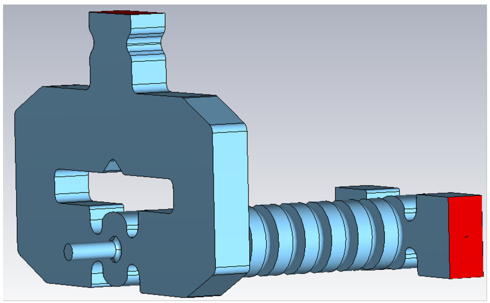

Figure 4. 3D design of the TW structure

high shunt impedance and avoiding discharge in the structure. After optimizing the single-cell design, we proceeded to design and optimize the couplers for the traveling wave structure. The structure includes two couplers, one for input power and one for output power. We designed and optimized each coupler independently to ensure the best possible performance in terms of electric field flatness and to maximize power transfer efficiency. Subsequently, we studied the power splitter to achieve appropriate values of its parameters for perfect power division from the klystron into two parts. After several iterations, the splitter was optimized, and the resulting 3D design is shown in Figure 5.

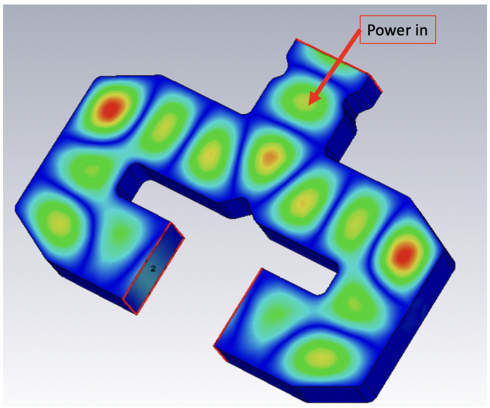

Figure 5. 3D design of the optimized power splitter

4. Tests of prototypes

Two copper prototypes of the linac, comprising five cells each, were constructed and characterized at the Accelerator Laboratory of Sapienza University of Rome. One prototype was specifically designed for the standing wave structure (Fig.6) [15]), while the other prototype was tailored for the traveling wave structure (Fig.7).

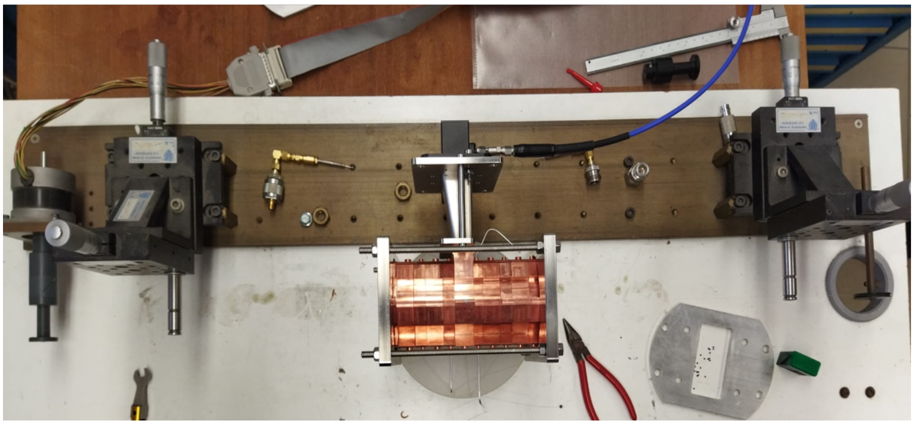

Figure 6. Standing wave prototype.

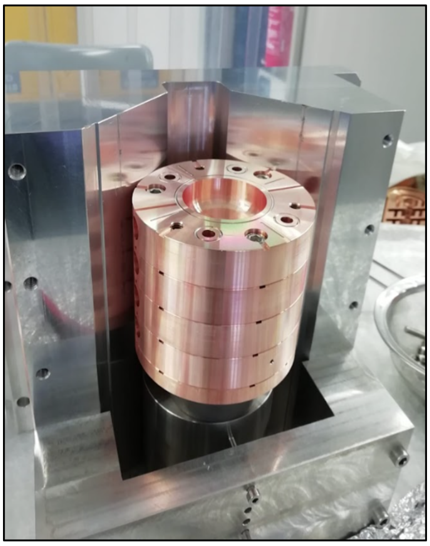

Figure 7. Traveling wave prototype.

The purpose of the prototypes was to determine the operating resonant frequency, evaluate the quality factor and assess the electromagnetic field using the bead-pull method. Low-power RF characterization was conducted using the Agilent N5230A network analyzer. Each cell of the prototypes was equipped with a tuner, such as a screw, to compensate for fabrication errors and thermal distortions. The tuning procedure began by adjusting each cell to the specified resonant frequency which is 5.712 GHz in this case.

For the standing wave structure, the screws were adjusted to minimize the reflection coefficient, suppress unwanted modes at the same frequency in the coupling cells, and obtain symmetric peaks in the S11 spectrum. Figure 8 shows the S11 spectrum after the tuning procedure and the central peak represents the $\pi/2$ mode of the resonant frequency that is equal to 5.7139 GHz for this structure.

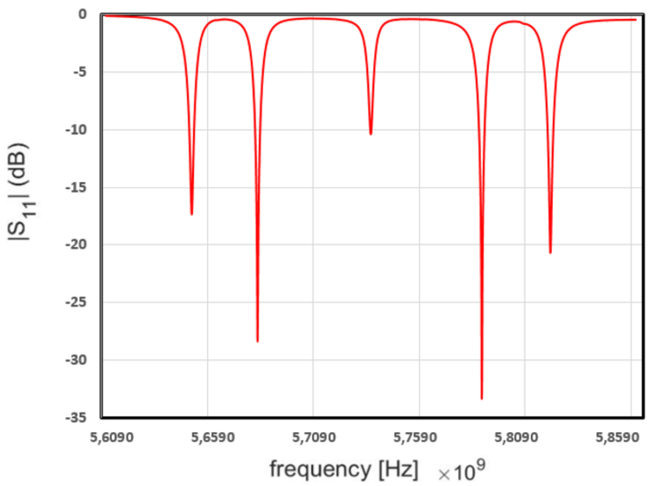

Figure 8. S11 spectrum of the standing wave structure.

To measure the electric field inside the prototypes before and after tuning, the bead-pull technique was used. A small antenna was introduced into the waveguides to excite the electromagnetic field inside the cavity without altering the field distribution. The measurement setup was controlled by a PC that managed the Agilent N5230A network analyzer and the control circuit for the stepper motor, both interfaced through Labview. In the bead-pull technique, a 1 mm diameter sphere was used as a perturbing object, attached to a horizontal fishing line aligned with the prototype's axis. The results of the test are reported in Fig. 9 for the standing wave structure which shows an almost equal flatness of the electric field in the cells. This indicates that the tuning procedure was successful in optimizing the resonant cavity and ensuring a uniform electric field distribution.

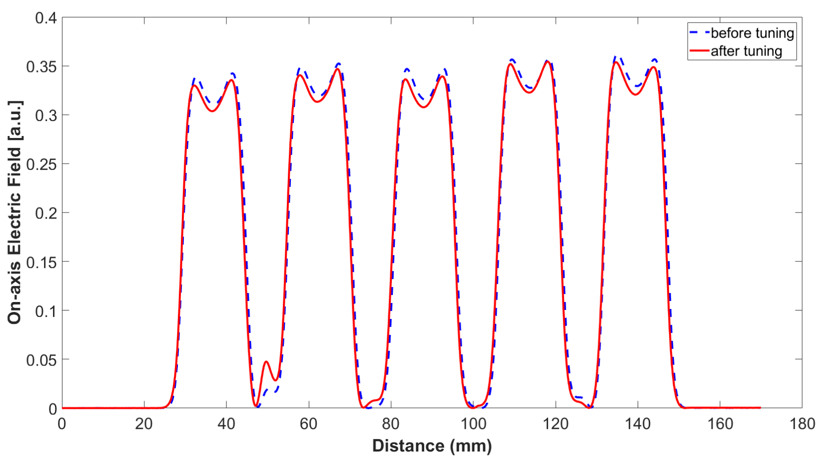

Figure 9. Electric field in the SW prototype cells before and after tuning.

Similar low-power RF tests were conducted on the traveling wave structure. In this instance, the tests were performed on a prototype consisting of five cells to assess the quality of production and in-house realization. Figure 10 presents a favorable comparison between the field simulated with CST STUDIO SUITE® and the field measured using the bead pull technique.

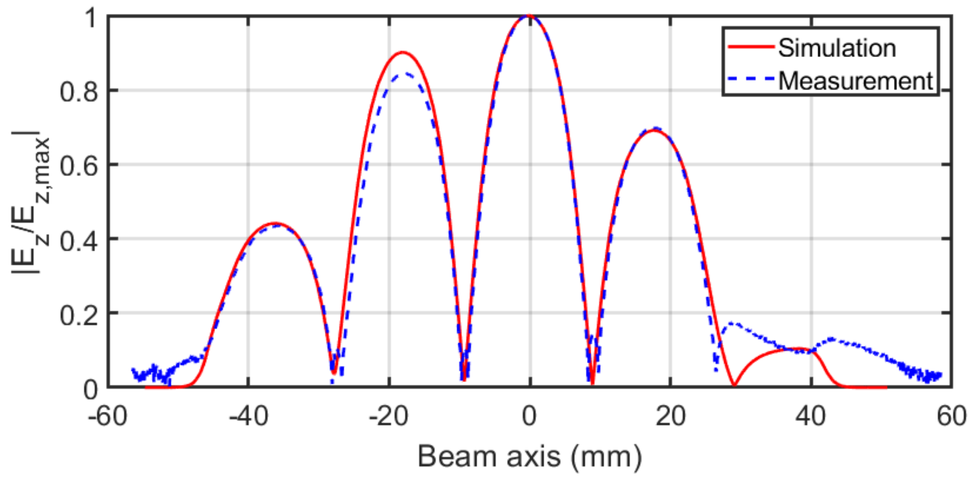

Figure 10. Comparison between the electric field measured and simulated with CST STUDIO SUITE®.

Furthermore, the measured Q-factor and the simulated Q-factor (Fig. 11)demonstrate excellent agreement, further validating the accuracy of the prototype.

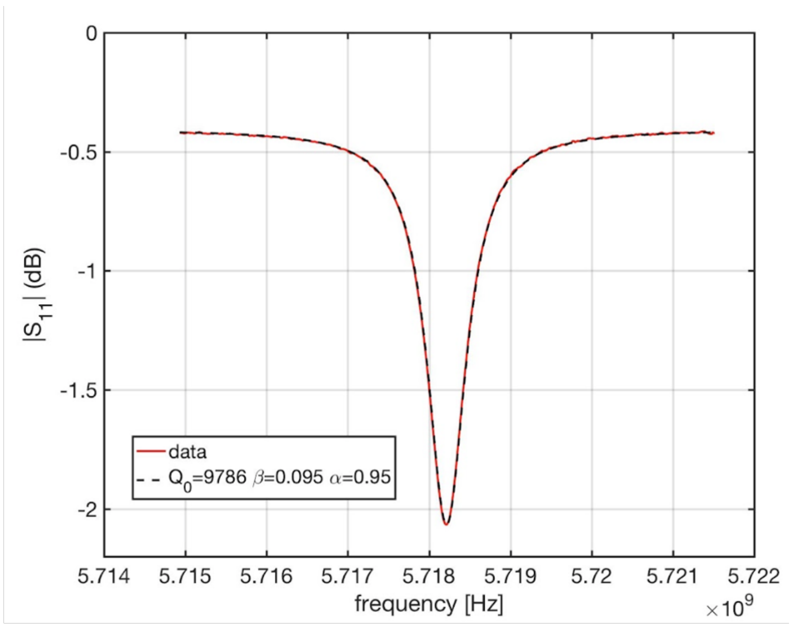

Figure 11. Measurements confirmed the accuracy of the simulation of the Quality factor (Q).

5. CONCLUSION

In conclusion, this paper has presented the successful study, design, and development of compact VHEE C-band prototypes for FLASH radiotherapy. The low-power RF tests of prototypes have supported the electromagnetic studies. The feasibility study of the prototype marks the initial phase in the realization of two new C-band sections, which are essential for the successful implementation of the final project. These results demonstrate a promising foundation for developing VHEE accelerators for FLASH radiotherapy in the future.

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