STATUS OF THE SAFEST PROJECT: THE SAPIENZA LINAC PROTOTYPE FOR VHEE FLASH RADIOTHERAPY

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Abstract

Delivered at Ultra-High Dose Rates (UHDR), in the so-called FLASH regime, electron irradiation has shown the remarkable ability to spare healthy tissues while preserving tumor control, opening new perspectives for next-generation cancer treatments. The advancement of high-gradient accelerating structures has enabled the development of compact and cost-effective linear accelerators suitable for clinical environments. Within this framework, we present the electromagnetic design and testing results of the C-band RF prototypes for a 24 MeV Linac being installed at Sapienza University. The linac is composed of a standing-wave and a traveling-wave section. The standing-wave structure has been designed, manufactured, and tuned in collaboration with SIT Company, while the traveling-wave structure has been entirely developed in-house, including full fabrication and tuning, in collaboration with INFN. These prototypes represent a key step toward the realization of an advanced FLASH VHEE source for future clinical applications.

INTRODUCTION

FLASH radiotherapy (FLASH-RT) has recently emerged as one of the most promising innovations in radiation oncology due to its potential to enhance the therapeutic ratio by preserving healthy tissues while maintaining tumor control. Preclinical studies have shown that the delivery of electron beams within extremely short irradiation times ($< 100ms$) and at ultra-high dose rates ($> 10^6$ Gy/s instantaneous dose rate) can significantly reduce radiation-induced toxicity in normal tissues without compromising antitumor efficacy.

The first evidence of the so-called "FLASH effect" was reported in 2014 by Favaudon et al. at Institut Curie [1]. Nevertheless, several aspects of the underlying mechanisms, technological implementation, and clinical applicability remain under active investigation, motivating the development of dedicated accelerator facilities capable of delivering stable and reproducible FLASH beams.

In this context, La Sapienza University of Rome, in collaboration with INFN, is developing a demonstrator of a Very High Energy Electron (VHEE) FLASH linear accelerator aimed at producing electron beams up to 24 MeV for both in vivo and in vitro irradiation studies [2]. The accelerator layout is based on a hybrid C-band architecture operating at 5.712 GHz. The injector section consists of a compact bi-periodic Standing Wave (SW) structure working in $\pi/2$ mode, while the downstream accelerating sections are based on high-gradient Traveling Wave (TW) cavities with a phase advance of $2/3\pi$ per cell. This configuration is designed to provide high accelerating gradients and efficient beam acceleration toward energies suitable for future VHEE FLASH applications (Fig. 1).

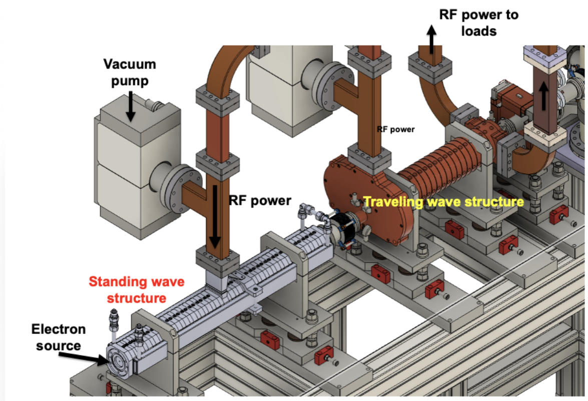

Figure 1: CAD models of the C-band accelerating structures developed for the VHEE FLASH linac demonstrator: Standing Wave (SW) bi-periodic cavity operating in $\pi/2$ mode at 5.712 GHz; (b) Traveling Wave (TW) high-gradient structure with $2/3\pi$ phase advance per cell.

This paper presents the electromagnetic design, fabrication, and experimental validation of the C-band SW and TW

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accelerating cavity prototypes, currently being installed in the 24 MeV VHEE FLASH linac demonstrator.

THE STANDING WAVE STRUCTURE

The first accelerating section of the VHEE FLASH linac is based on a compact bi-periodic Standing Wave (SW) [3] structure operating in the $\pi/2$ mode. The cavity is composed of alternating accelerating and coupling cells, where the electromagnetic field vanishes in the coupling sections. The adoption of a standing-wave configuration provides improved beam stability and transverse confinement, reducing the need for additional focusing elements such as solenoids in the low-energy section of the accelerator.

To maximize the shunt impedance (R_{sh}), the accelerating cells were designed with a nose-cone geometry. This configuration enhances the electric field concentration along the beam axis, thereby improving the accelerating efficiency while maintaining compact cavity dimensions. Particular attention was devoted to the optimization of the waveguide-to-cavity coupling coefficient (β_c), in order to minimize the reflected RF power during beam loading conditions. Numerical optimization and RF measurements identified an optimal coupling coefficient close to 1.3.

The electromagnetic characterization of the SW prototype was carried out using the bead-pull technique, allowing a precise reconstruction of the longitudinal electric field distribution before and after the tuning procedure. The measured field profile, shown in Fig. 2, demonstrates a nearly flat accelerating field over the five accelerating cells. As expected for the ($\pi/2$) operating mode, the electric field is concentrated inside the accelerating cells while remaining negligible in the coupling cells. Moreover, the double-peak structure observed within each accelerating cell is consistent with electromagnetic simulations and originates from the nose-cone geometry, which locally enhances the electric field near the cone edges.

The main RF and beam-dynamics parameters of the SW accelerating structure are summarized in Table 1. The cavity operates in biperiodic $\pi/2$ mode and consists of 27 cells. Simulations predict a shunt impedance of 103 $M\Omega/m$ and an unloaded quality factor of approximately 10178, indicating good RF efficiency. The optimized coupling coefficient is equal to 1.3, while the estimated beam capture efficiency reaches about 36%. The structure exhibits a filling time of 0.220 μs and is capable of sustaining an average accelerating gradient of 17 MV/m, with a peak surface electric field of approximately 50 MV/m. Under nominal operating conditions, the expected beam output energy is around 10 MeV.

TRAVELLING WAVE STRUCTURE

The second accelerating section of the VHEE FLASH linac is based on a high-gradient Traveling Wave (TW) [4] structure operating in the TM_{01}-like mode with a phase advance per cell of ($2/3\pi$). This operating mode was selected as an optimal compromise between shunt impedance,

Table 1: Main RF and Beam Parameters of the C-Band SW Accelerating Structure

Standing Wave parameter	**Value**
Mode of operation	Bi-periodic ; $\pi/2$
Number of cells	27
Shunt impedance	103 M/m
Quality factor	10178
Coupling coefficient	1.3
Beam capture	36%
Filling time	0.220 μs
Average gradient	17 MV/m
Peak electric field	50 MV/m
Beam output energy	10 MeV

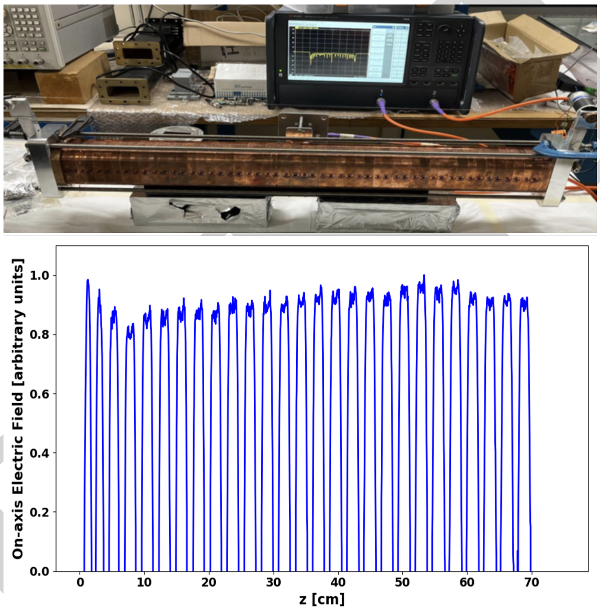

Figure 2: Standing wave structure and its electric field on the axis after brazing.

accelerating efficiency, and RF stability for C-band high-gradient applications. The structure was designed in a Constant Impedance (CI) configuration with an iris radius of 5 mm, ensuring stable propagation of the electromagnetic wave along the accelerating section.

Electromagnetic simulations of the complete structure were performed using CST Studio Suite in order to evaluate the main RF parameters, including the quality factor and the shunt impedance per unit length. The TW structure includes two dedicated couplers, one for RF input and one for RF output, both carefully optimized to guarantee efficient power transfer and a uniform longitudinal electric field distribution. In addition, a dedicated RF power splitter was designed to equally divide the klystron power into two branches while minimizing reflections and preserving phase balance. The structure was realized in collaboration with LNF-INFN Frascati and will be installed in the VHEE FLASH linac demonstrator.

The TW structure is composed of 23 accelerating cells, including 21 regular cells and two coupler cells. The input coupler integrates the RF splitter, through which the incident power is equally distributed. The tuning procedure is performed progressively from the last cell toward the first one, a strategy adopted to reduce local reflections during the adjustment process. The tuning activities are currently ongoing and are focused on achieving resonance at the operating frequency of (5.712 GHz) together with the required phase advance of $2/3\pi$ per cell. The measured on-axis electric field distribution after the preliminary tuning phase is reported in Fig. 3.

The main RF parameters of the TW accelerating structure are summarized in Table 2. The cavity operates in the $2/3\pi$ mode, adopts a Constant Impedance configuration, and exhibits a simulated shunt impedance of 107 $M\Omega/m$, indicating high RF efficiency. The unloaded quality factor is approximately 10127, while the filling time is estimated to be 0.143 μs. The group velocity of the traveling wave corresponds to approximately 0.01c, consistent with the compact high-gradient design.

Table 2: Main RF Parameters of the C-Band TW Accelerating Structure

Parameter	Value
Structure type	Constant Impedance
Shunt impedance	107 M/m
Quality factor	10127
Filling time	0.143 μs
Group velocity	0.01c
Mode of operation	$2/3\pi$

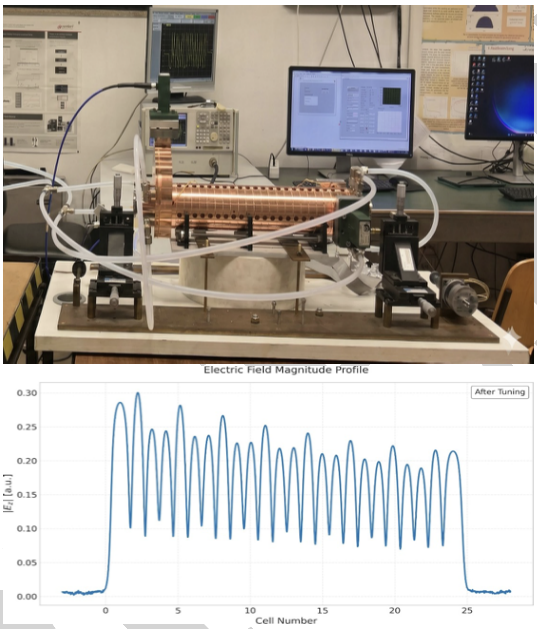

Figure 3: Traveling wave structure and its electric field on the axis after brazing (Tuning ongoing).

CONCLUSIONS

In this work, we presented the design, fabrication, RF characterization, and tuning activities of the C-band SW and TW accelerating structures developed for the VHEE FLASH linac demonstrator under construction at La Sapienza University of Rome in collaboration with INFN. The accelerator is intended to provide electron beams up to 24 MeV for future in vivo and in vitro FLASH radiotherapy studies.

The SW section, operating in bi-periodic $\pi/2$ mode at 5.712 GHz, demonstrated good RF performance in terms of field uniformity, shunt impedance, and coupling optimization. Bead-pull measurements confirmed the expected longitudinal electric field distribution and validated the effectiveness of the tuning procedure. The adopted nose-cone geometry allowed enhancement of the accelerating field while maintaining high RF efficiency. The structure has been installed in the linac in Sapienza University. The TW accelerating section, based on a Constant Impedance configuration with $2/3\pi$ phase advance per cell, was designed to provide high-gradient operation suitable for compact VHEE applications. Electromagnetic simulations and preliminary RF measurements confirmed the expected RF parameters and the effectiveness of the coupler and splitter design. The tuning activities are currently ongoing in order to achieve the target operating frequency and phase advance with optimized field flatness and minimized reflections.

Future activities will focus on the completion of the RF conditioning phase, beam commissioning of the accelerator, and experimental validation of FLASH irradiation capabilities for radiobiological investigations.

ACKNOWLEDGEMENTS

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