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SAFEST PROJECT, A COMPACT C-BAND RF LINAC FOR VHEE FLASH RADIOTHERAPY

L. Giuliano*[1], M. Carillo[1], E. Chiadroni[2], D. De Arcangelis, A. De Gregorio[1], L. Ficcadenti[1], D. Francescone[1], G. Franciosini[1], M. Magi[1], M. Migliorati[1], A. Mostacci[1], V. Patera[1], F. Perondi, M. Petrarca[1], R. Remetti, A. Sarti[1], L. Palumbo[1]
Sapienza University of Rome, Italy
D. Alesini, F. Cardelli, R. Di Raddo, L. Faillace, G. Franzini, A. Gallo, L. Piersanti, B. Spataro, A. Vannozzi
INFN - LNF, Frascati, Italy
G. Cuttone, G. Torrisi, INFN - LNS, Catania, Italy
G.M. Bisogni[3] University of Pisa, Italy
[1]also INFN-Roma, Italy
[2]also INFN-LNF, Frascati, Italy
[3]also INFN-Pisa, Italy

Abstract

FLASH therapy, an innovative cancer treatment, minimizes radiation damage to healthy tissue while maintaining the same efficacy in tumor cure as conventional radiotherapy. Successful integration of FLASH therapy into clinical practice, specifically for treating deep-seated tumors with electrons, relies on achieving Very High Electron Energy (VHEE) within the 50-150 MeV range. In collaboration with INFN, Sapienza University actively develops a compact C-band high-gradient VHEE FLASH linac called SAFEST. This paper presents the general layout and key characteristics of the machine, as well as the prototypes developed at Sapienza University of Rome. This endeavor is a significant step towards the clinical implementation of FLASH VHEE radiotherapy.

INTRODUCTION

FLASH radiotherapy (RT) has emerged as a promising avenue in cancer treatment, demonstrating the potential to effectively target tumors while minimizing damage to surrounding healthy tissues. This approach involves delivering electron radiation in extremely short durations (< 100 ms) with ultra-high instantaneous dose rates (> 10^6 Gy/s).

The pioneering work in the field of FLASH-RT was conducted at Institut Curie in 2014 by V. Favaudon and his team [1], sparking widespread interest and subsequent research efforts. Significant efforts have indeed been dedicated to the development of linacs for FLASH irradiation, showcasing promising advancements in particle acceleration technology [2–7]. However, the translation of these advancements into clinical practice necessitates achieving high energies suitable for effective cancer treatment. At La Sapienza University of Rome, in collaboration with INFN, significant strides are being made in the development of a Very High Energy Electron (VHEE) FLASH linac [8]. This paper presents the design, fabrication, and evaluation of C-band SW and TW cavity prototypes intended for integration into the VHEE FLASH linac.

* lucia.giuliano@uniroma1.it

FACILITY PARAMETERS AND LAYOUT

The proposed basic modular system consists of one standing wave injector and two traveling wave high-gradient accelerating structures operating at a frequency of 5.712 GHz in the C-band technology. This design achieves a good compromise between a high accelerating gradient and sufficiently large iris radius to ensure efficient particle transmission even at high currents. The layout of the system is depicted in Fig. 1.

The first component is a standing wave (SW) injector, capable of accelerating the current emitted from a pulsed DC gun to an energy of 10 MeV. Subsequently, the beam is directed into two linear traveling wave (TW) structures, each 1 m in length, featuring high accelerating gradients. The system is designed to be fed by a single 50 MW Klystron, providing an effective available power of 45 MW through the use of asymmetric and symmetric splitters. With this configuration, the system achieves an energy of approximately 80 MeV.

Table 1: SAFEST Module Key Parameters

Description	Value
Frequency	5.712 GHz
Beam energy	80 - 100 MeV
Pulse repetition frequency	100 Hz
RF Pulse duration	1,25 - 2,5 µs
Nominal current	100 mA
In-pulse dose rate	> 10^6 Gy/s
Dose per pulse	»1 Gy
Average dose rate	> 100 Gy/s

To further increase the energy while sacrificing RF pulse duration a power pulse compressor has been considered [9].

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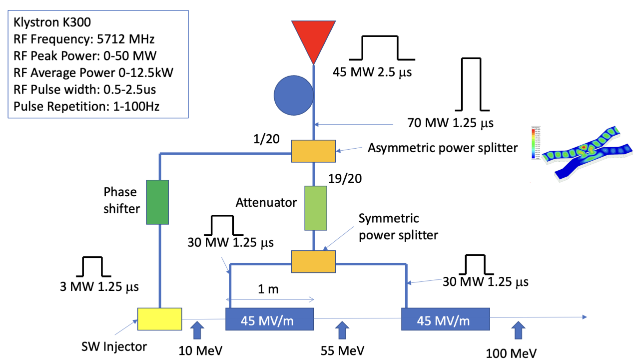

Figure 1: Layout of the proposed basic modular system comprising a standing wave injector and two traveling wave high-gradient accelerating structures.

RF STRUCTURES DESIGN

STANDING WAVE INJECTOR

The initial component of the VHEE FLASH machine comprises a standing-wave, bi-periodic structure consisting of alternating accelerating cells and coupling cells where the electric field is null. This design choice offers the advantage of maintaining a stable and well-focused particle beam without the need for additional focusing magnets like solenoids. A nose-cone structure was employed in these cavities to maximize the shunt impedance (R_{sh}), concentrating a very high electric field in the middle of the accelerating cells to facilitate efficient beam acceleration along the beam axis. Crucially, optimizing the waveguide-to-linac coupling coefficient (β_c) is essential to minimize reflected RF power during electron beam acceleration, with the determined optimal value of β_c being 1.5.

A full-scale copper prototype of the SW structure linac (see figure 2) was constructed in collaboration with SIT Sordina IORT Technology Spa and characterized at the Accelerator Laboratory of Sapienza University of Rome [10]. The purpose of this prototype was to determine the operating resonant frequency, evaluate the quality factor, and assess the electromagnetic field using the bead-pull method. Each cell of the prototype was equipped with a tuner, such as a screw, to compensate for fabrication errors and thermal distortions. The tuning procedure involved adjusting each cell to the specified resonant frequency of 5.712 GHz.

To investigate the on-axis accelerating electric field of the standing wave prototype, the bead-pull technique was employed, allowing for precise evaluation before and after tuning.

The results, as illustrated in Fig. 3, indicate a nearly uniform electric field distribution across the five accelerating cells. As anticipated, the $\frac{\pi}{2}$ mode exhibited a substantial electric field within the accelerating cells, while no field was detected in the coupling cells. The presence of double peaks in the electric field profile per cell can be attributed to the nose-cone geometry of the accelerating cells, which accentuates field values in the neighboring regions of the nose.

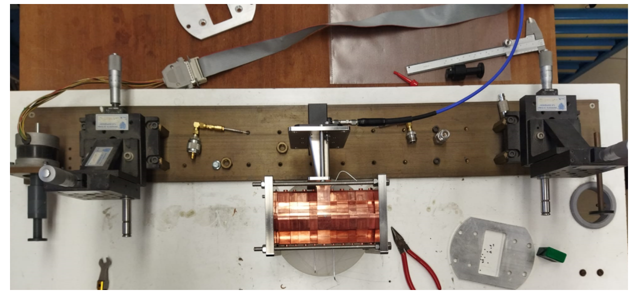

Figure 2: Standing wave prototype.

Table 2: C-band Standing Wave Parameters

Description	Value
Frequency	5.7123 GHz
Beam final energy	up to 10 MeV
Quality factor	11260
Shunt Impedance	112 MΩ /m
Waveguide-to-linac coupling β	1.5
Power Input	3 MW

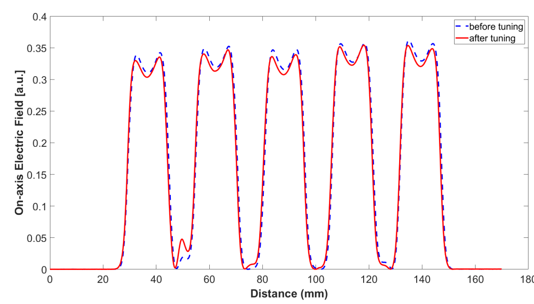

Figure 3: Electric field distribution across the five accelerating cells of the SW prototype.

TRAVELING WAVE STRUCTURE

The TW structure of the VHEE FLASH linac operates in the TM01-like mode, featuring a phase advance per cell of $\frac{2}{3}\pi$, chosen for optimal efficiency. The iris radius of the linac cells was carefully selected in the Constant Impedance (CI) configuration, set to 5 mm, to ensure uniformity in the electromagnetic fields and impedance matching.

Using CST Studio SUITE [11], comprehensive simulations of the entire TW structure were conducted to obtain crucial RF parameters such as the quality factor and the shunt impedance per unit length. Additionally, the design incorporated two couplers, one for input power and one for output power, each meticulously optimized to ensure uniform electric field distribution and maximal power transfer efficiency. Further, a detailed study was undertaken to optimize the geometrical parameters of the power splitter, ensuring perfect power division from the klystron into two parts.

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In collaboration with LNF-INFN Frascati, a full-scale prototype of the TW structure was fabricated (Fig. 4), comprising 13 accelerating cells, 11 regular cells, and 2 couplers. The input coupler featured a splitter for even power distribution.

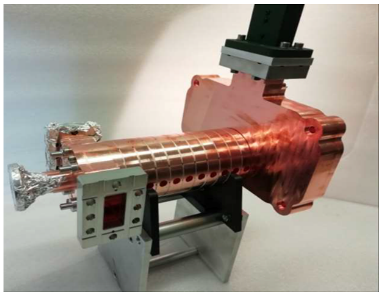

Figure 4: A prototype of the TW structure constructed and tested.

The tuning process for the TW structure followed a systematic approach, proceeding from the last cell to the first cell. This methodology was adopted to minimize reflections within each cell, optimizing performance. Throughout the tuning process, meticulous efforts were directed towards achieving resonance of the accelerating cells at the frequency of 5.712 GHz and a phase advance of $\frac{2}{3}\pi$.

A critical aspect of the tuning process was the characterization of the electric field distribution along the axis after tuning. This was vital for ensuring uniformity and efficiency in beam acceleration. Figures 5 and 6 present respectively the electric field profile on the axis post-tuning and the correct phase advance on the axis, demonstrating the successful optimization of the TW structure for efficient particle acceleration.

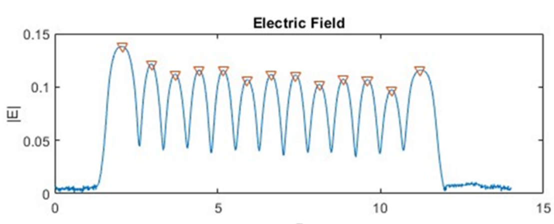

Figure 5: Electric field distribution along the axis post-tuning.

CONCLUSION

In conclusion, the design and tuning of the standing wave (SW) and traveling wave (TW) structures for the Very High Energy Electron (VHEE) FLASH linac represent significant advancements in the development of efficient and precise particle acceleration systems for FLASH radiotherapy applications. Moving forward, ongoing research and development efforts will focus on further optimization of RF parameters, beam dynamics, and integration of additional components to enhance the performance and clinical applicability of the VHEE FLASH linac.

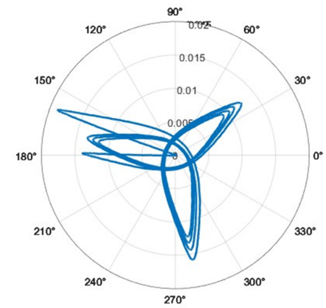

Figure 6: Electric field distribution in polar coordinates.

Table 3: Traveling Wave Parameters

Description	Value
Structure length	1 m
Type	Constant Impedance
Iris radius	5 mm
Gradient@30MW	45 MV/m
Filling Time	0.350 µs
Quality factor	10.000
Shunt impedance	100 MΩ/m

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