IL NUOVO CIMENTO **47 C** (2024) 321
DOI 10.1393/ncc/i2024-24321-7

Communications: SIF Congress 2023

Design and test of C-band prototypes linac for FLASH radiotherapy

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received 12 April 2024

Summary. — FLASH Radiotherapy (RT) represents an innovative technique in cancer treatment, delivering high radiation doses in microsecond pulses. In collaboration with INFN, Sapienza University of Rome is actively engaged in developing innovative C-band structures for Very High Electron Energy (VHEE) linac to achieve the FLASH regime and to treat deep tumors. The RF electromagnetic design of the accelerating structures was carried out using CST Studio Suite. Following the design phase, we proceeded with the mechanical design and fabrication of copper prototypes. To assess their performance, low-power RF tests were conducted at Sapienza University of Rome and the field measurements within the cavity were obtained using the bead-pull technique.These prototypes serve as crucial milestones towards the final structure of the VHEE Linac.

1. – Introduction

FLASH radiotherapy (RT) has garnered significant attention within the cancer research community due to its potential to effectively treat tumors while minimizing damage to surrounding healthy tissues. Preclinical studies have demonstrated that delivering electron radiation in extremely short durations ($<100\,\mathrm{ms}$) with ultra-high instantaneous dose rates ($> 10^6\,\mathrm{Gy/s}$) can notably reduce toxicity in healthy tissue while maintaining efficacy in cancer treatment.

The pioneering experiment in FLASH-RT was conducted at Institut Curie in 2014 by Favaudon and his team [1]. Since then, numerous *in vivo* and *in vitro* radiobiological experiments have consistently shown substantial sparing of normal tissues [2,3]. However, further research is essential to comprehensively understand the benefits and limitations of this approach and identify optimal clinical applications.

At La Sapienza University of Rome, in collaboration with INFN, a Very High Energy Electron (VHEE) FLASH linac is under investigation. The initial section of the VHEE

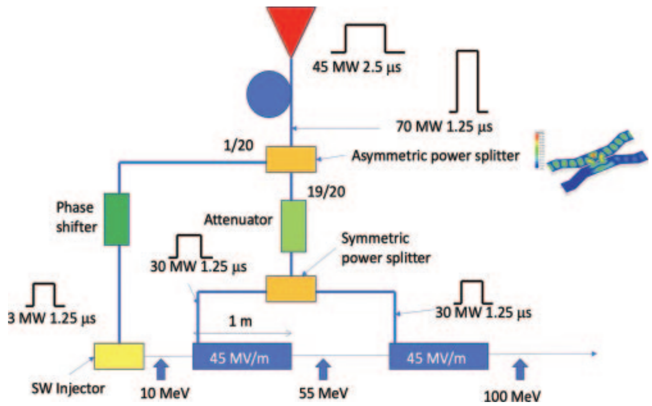

Fig. 1. – Layout of VHEE FLASH linac.

machine features a compact bi-periodic structure operating at a frequency of 5.712 GHz, utilizing Standing Wave (SW) technology in $\pi/2$ mode. The subsequent sections comprise high-gradient traveling wave (TW) structures, operating at the same frequency, with a phase advancement of $2/3\pi$, capable of elevating the electron beam's energy to approximately 100 MeV. Figure 1 shows the layout of the VHEE FLASH linac.

In this paper, we present the design, realization, and testing of C-band SW and TW cavity prototypes currently being considered for integration into a VHEE FLASH machine.

2. – Standing wave section

The initial component of the VHEE FLASH machine comprises a standing-wave, bi-periodic structure. This structure consists of alternating accelerating cells and coupling cells, where the electric field is null. Employing a standing wave design offers the advantage of maintaining a stable and well-focused particle beam without necessitating additional focusing devices like solenoids. For these cavities, a nose-cone structure was employed to maximize the shunt impedance (R_{sh}). The nose cone concentrates a very high electric field in the middle of the accelerating cells, facilitating efficient beam acceleration along the beam axis. Optimizing the waveguide-to-linac coupling coefficient, denoted as β_c, is crucial to minimize reflected RF power during electron beam acceleration, we determined the optimal value of β_c to be 1.3.

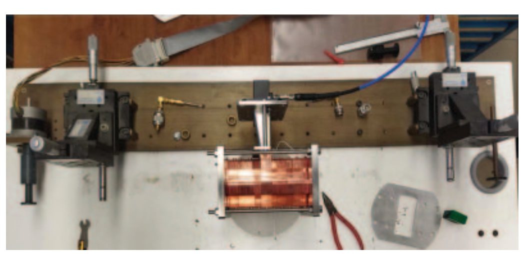

Fig. 2. – Standing wave prototype.

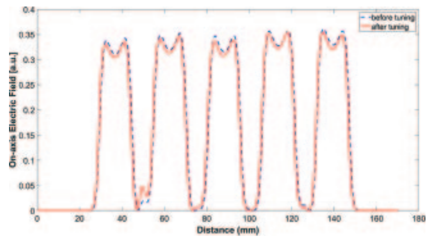

Fig. 3. – On-axis electric field from low-power RF tests before tuning (in blue) and after tuning process (in red).

A full-scale copper prototype of the SW structure linac was constructed in collaboration with SIT Sordina IORT Technology Spa [4], and characterized at the Accelerator Laboratory of Sapienza University of Rome. 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 (depicted in fig. 2) 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 of 5.712 GHz.

To investigate the Standing wave prototype on-axis accelerating electric field, the bead-pull technique was employed, allowing for precise evaluation before and after tuning. The results illustrated in fig. 3 indicate a nearly uniform electric field distribution across the five accelerating cells. As anticipated, the $\pi/2$ 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, as predicted by prior simulations, can be attributed to the nose-cone geometry of the accelerating cells, which accentuates field values in the neighboring regions of the nose.

3. – Travelling wave structure

The TW structure operates in the TM01-like mode, featuring a phase advance per cell of $\frac{2}{3}\pi$, ensuring optimal efficiency for this cavity type. The iris radius of the linac cells was chosen in the Constant Impedance (CI) configuration, equal to 5 mm of radius. Using CST Studio SUITE, we simulated the entire structure, obtaining key RF parameters as the quality factor, and the shunt impedance per unit length. This structure

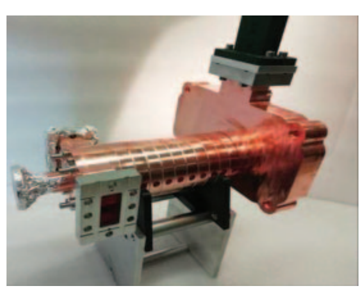

Fig. 4. – Traveling wave prototype.

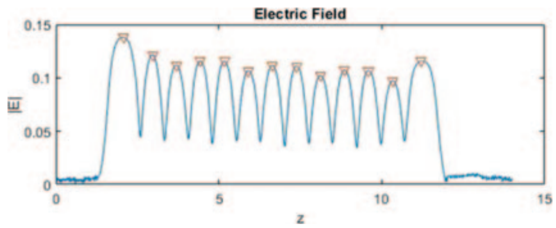

Fig. 5. – Electric field on the TW axis after the tuning process.

included two couplers: one for input power and one for output power. Each coupler was optimized to ensure uniform electric field distribution and maximize power transfer efficiency. Following this, the power splitter underwent a study to determine suitable geometrical parameter values for achieving perfect power division from the klystron into two parts. Also in this case we produced a full-scale prototype in collaboration with LNF-INFN Frascati.

The TW prototype is a constant impedance structure. It is composed of 13 accelerating cells, 11 regular cells, and 2 couplers. The input coupler is equipped with a splitter in which the power is fed and divided by two. In traveling wave tuning, we proceed with the tuning process from the last cell to the first cell. This approach is adopted to minimize reflections within the single cell. During the tuning process, efforts were directed toward achieving resonance of the accelerating cells at the frequency of 5.712 GHz and a phase advance of $\frac{2}{3}\pi$. The electric field on the axis, after tuning, is shown in fig. 5.

4. – Conclusions

In conclusion, this paper has showcased the accomplished study, design, and construction of C-band prototypes tailored for FLASH radiotherapy applications. The comprehensive electromagnetic study supported by low-power RF tests has underpinned the development process. The feasibility assessment of the prototype represents an initial milestone toward the realization of two new C-band sections critical for the successful execution of the FLASH VHEE linac project.

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