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Proposal of a compact VHEE-linac for FLASH radiotherapy

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Summary. — The present study regards the design of a Very High Electron Energy (VHEE) machine for use in radiotherapy to treat deep tumors in a FLASH regime. The proposed system includes a low energy, high current injector linac followed by high acceleration gradient structures capable of reaching 60–130 MeV energy range. We used the CST code to define the linac's RF parameters and the codes TSTEP and ASTRA in beam dynamics simulations to optimize the accelerated current and the delivered dose. Preliminary results show a compact VHEE-linac system reaching a peak current of 200 mA, equivalent to 600 nC per pulse. The realization of the prototype for vacuum and brazing tests is ongoing to evaluate the strength and integrity of the joints and connections in the linac and to perform the low-power RF tests. The outcome of these tests helps to make any necessary design adjustments or improvements before developing the final structure.

1. – Description

FLASH radiotherapy is a non-conventional method of radiation therapy that aims to protect healthy tissues from the damage of ionization radiations while maintaining the efficiency in the tumor cure. It is characterized by high dose rates (>100 Gy/s), short beam-on times (<100 ms), and large doses in each pulse (>1 Gy) of irradiation. This approach was first proposed in 1966 [1] but then abandoned until its rediscovery in 2014, with the first successful treatment conducted at the Curie Institut by Favaudon and his team [2]. This experiment was conducted on mice using both conventional RT and FLASH-RT. Both treatments delivered the same spread-out dose of 17 Gy, but the dose rate in FLASH-RT (60 Gy/s) was much higher than in conventional RT (0.03 Gy/s). The results showed that FLASH-RT was as effective as conventional RT in suppressing tumor growth but without causing damaging side effects in healthy tissues. The FLASH effect has been confirmed also in large mammals, such as pigs and cats, through skin irradiation experiments using both conventional RT and FLASH-RT [3]. Despite the considerable interest of the scientific community in this new technique, only a few machines worldwide can deliver FLASH radiation, and most of them are limited to low-energy electrons (5–12 MeV). However, with ongoing research and developments, more FLASH machines will likely become available in the future, enabling researchers to investigate the potential benefits of FLASH radiotherapy and its potential application in clinical settings. Our previous experience with medical linacs for FLASH therapy was related to the design of a compact S-band (2998 GHz) standing-wave linear accelerator, the ElectronFLASH (EF) operating at 5 and 7 MeV in conventional and FLASH modalities [4-6]. The EF is currently utilized in several research centers for FLASH radiotherapy, including the Institut Curie, the Department of Radiotherapy in Antwerp, Belgium, and the Unit of Health Physics at the Hospital of Pisa. To effectively translate the FLASH effect into clinical use and treat deep tumors, high-energy electron machines are required. Very High-Energy Electrons (VHEE) are able to penetrate the patient's body and reach deep-seated tumors. At Sapienza University of Rome, we proposed a VHEE-linac to contribute to the ongoing efforts of FLASH-RT investigations in the 100–250 MeV range. The VHEE-linac is being developed through a collaboration between the Sapienza University of Rome and the Italian Institute for Nuclear Physics (INFN). This collaboration brings together the expertise and resources of these two institutions to design and test the linac machine. In this paper we describe the design of a compact C-band (5.712 GHz) linac for VHEE FLASH irradiation. In particular, the paper describes the RF design, beam dynamics studies in the linac, and the ongoing work to manufacture RF prototypes. The linac has to deliver ultra-high dose rates (UHDR) in single pulses or a sequence of pulses suitable for investigating the FLASH effect. The design focuses on creating an efficient and compact machine that can be easily installed in existing hospital bunkers and used for research and clinical purposes. C-band technology allows for a more compact layout than other technology options, such as S-band, which has longer accelerator structures. On the other hand, the X-band option may not be the best choice, even though it is more compact than the C-band because it has a smaller iris size which limits the beam current passing through the small aperture. Conversely, C-band linacs have larger iris sizes, allowing for higher currents and doses, making them more suitable for this application. Therefore, compared to other technology options, the C-band choice is an excellent compromise to get a high gradient and high current.

2. – Linac layout and RF study

The accelerator scheme reported in fig. 1, comprises three main parts. In the first stage, the injector is a standing-wave (SW) structure that accelerates electrons provided by a DC gun from 12–30 KeV to 10 MeV. The injector is powered by a 5 MW klystron. In the second stage, the electron beam is injected into a traveling wave (TW) structure characterized by a high unloaded accelerating gradient (above 40 MV/m) to bring the beam's energy up to at least 60 MeV. A 50 MW klystron feeds the two accelerating TW structures of this stage. The third stage, identical to stage two, allows the beam to reach the energy of 130 MeV.

The 3D design of the accelerator is performed using CST code [7], and optimization techniques are used to ensure the best performance while fulfilling space constraints. The SW linac starts with three cells having different length, guaranteeing the synchronous acceleration of the non-relativistic particles emitted by the gun. The electromagnetic coupling between cells is obtained using holes located off-axis, as shown in fig. 2.

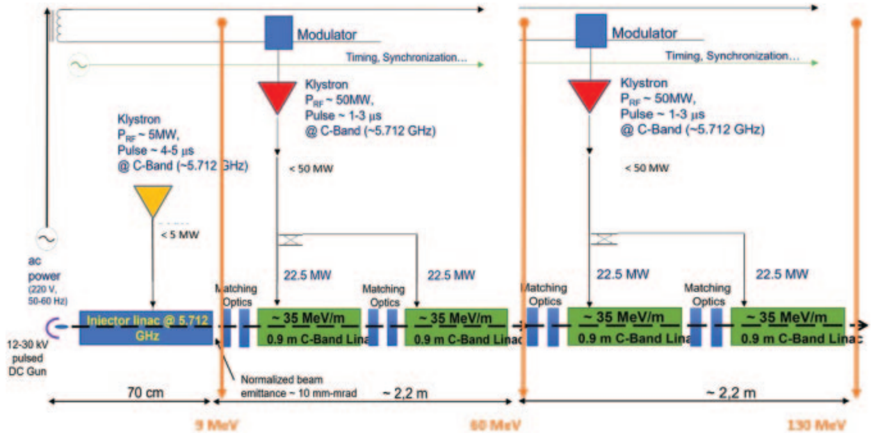

Fig. 1. – Layout of the Linear Accelerator System for VHEE FLASH radiotherapy with one injector and four TW high-gradient accelerating structures. The maximum expected beam energy is about 130 MeV.

Indeed, by adjusting the length of the coupling slots, the electric field (fig. 3) peaks profile is tailored to optimize the acceleration of low-velocity particles, resulting in more effective beam capture. After the bunching section, the beam is accelerated, and the particles reach the required energy of 10 MeV after 22 cells. For the accelerating cells, we chose a nose cone geometry (fig. 4) to increase the electric field on the beam axis, which can improve the beam acceleration and acceleration gradient. The nose cone shape helps to focus the electric field onto the beam axis, leading to a more efficient energy transfer to the beam. Additionally, this design can also help to reduce the amount of RF power loss in the structure, furtherly improving the overall efficiency of the linac. The CST code has been used to investigate the electromagnetic properties of the structures, such as the quality factor (Q) and shunt impedance (R_{shunt}), and optimize the geometrical parameters of the cells, such as the diameter (2D) to reach the correct resonance frequency of 5.712 GHz and a good field flatness. The quality factor (Q) is correlated with the ratio between the energy stored in the cell and the power dissipated at the walls. A high shunt impedance value (R_{shunt}) is obtained by minimizing losses and maximizing the energy

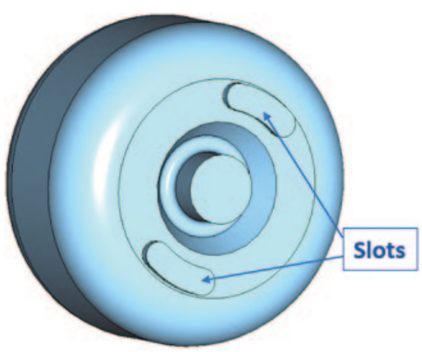

Fig. 2. – Off-axis slots for the electromagnetic coupling.

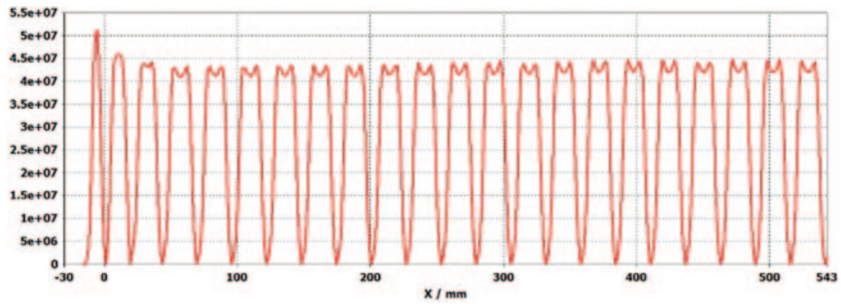

Fig. 3. – The electric field on the beam axis in the injector.

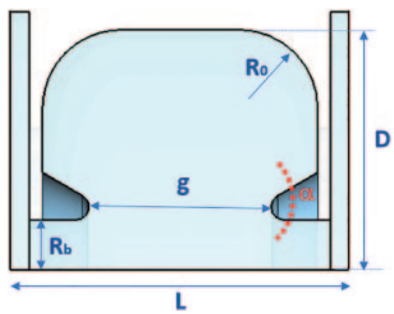

Fig. 4. – Nose cone geometry of the acceleration cells.

transfer to the particle beam. This can be achieved by adjusting the geometry of the nose gap (g) and the iris radius (R_b) on the axis. The 3D draw of the entire injector is shown in fig. 5.

The injector is followed by four C-band (5.712 GHz) high gradient structures that are Traveling Waves (TW) and operate in the TM01-like mode with a phase advance per cell of $2/3\pi$. The phase advance per cell of $2/3\pi$ guarantees the best efficiency for this type of accelerating structure. One single RF structure, with a length of 90 cm, increases the beam energy to about 35 MeV. The main RF parameters are obtained for the single cell at different iris radii using CST Studio Suite as reported in fig. 6. This optimization aims to find the best compromise between high shunt impedance, high gradient, avoiding discharge in the structure; the optimal iris radius is 5 mm.

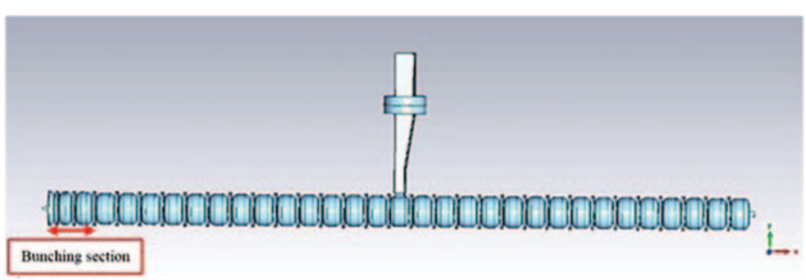

Fig. 5. – 12 MeV injector linac in C-band.

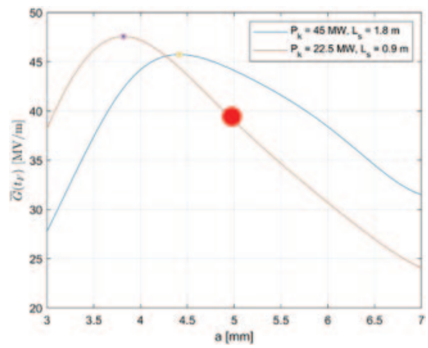

Fig. 6. – Average accelerating gradient *vs.* the irises radius.

Figure 7 reports the 3D traveling wave structure simulated with CST.

3. – Beam dynamics study

The beam dynamics study allows the simulation of the entire accelerator system, including the injector, bunching section, and high-gradient TW linacs, to evaluate the accelerator's performance. These simulations provide information on the beam properties, such as the emittance, energy spread, and current at each accelerator stage, which is essential for the overall performance and efficiency. We use the CST code to generate electromagnetic field maps imported into TSTEP [8] for beam dynamics simulations. The accelerating beam-loaded gradient obtained is 35 MV/m, and all linac sections are phased with the electron beam in on-crest operation. In this case, the maximum achievable particle energy is around 145 MeV (fig. 8), which is higher than the predicted value of 130 MeV, discussed before. The modular layout confirmed the possibility of optimal beam transport up to the maximum current of 200 mA at the exit.

Figure 9 gives the beam phase-space plots at the LINAC exit. The RMS beam envelope at the exit has a transverse size of 0.8 mm, the bunch length is around 20 ps FWHM, the energy spread FWHM value is $< 0.2\%$, and the beam spot shows a FWHM value of 1.8 mm with the total transverse distribution concentrated in about 4 mm. The normalized transverse beam emittance is in the order of 10 mm mrad.

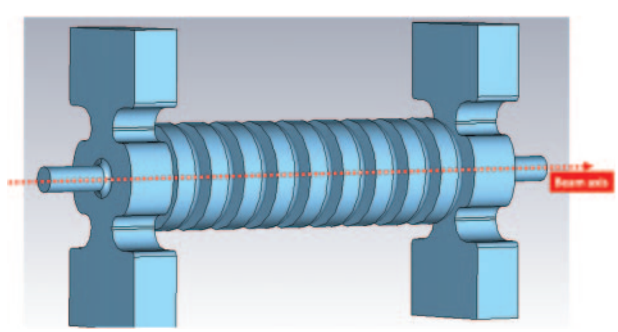

Fig. 7. – 3D design of the TW structure.

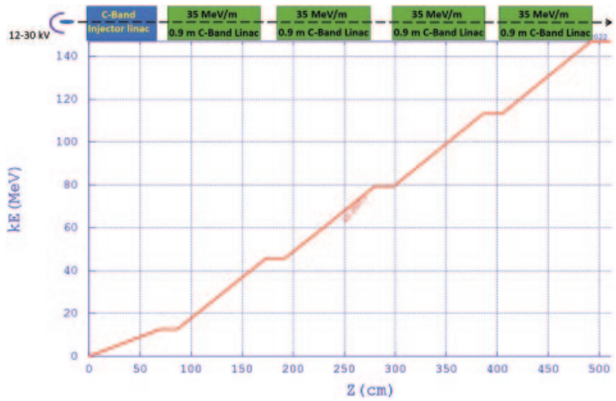

Fig. 8. – Beam energy gain. 12 MeV from the injector into four 90 cm long TW linacs with an accelerating loaded gradient of 35 MV/m. The beam current at the exit is 200 mA.

4. – Conclusion

The proposed VHEE-linac system is a compact, high-gradient accelerator based on C-band technology intended to be used for dosimetry, radiobiology, and pre-clinical FLASH experiments. The accelerator is divided into three main sections and can be realized in two phases. It combines the standing-wave and traveling-wave structures to achieve high accelerating gradients. Simulations have been performed using CST and TSTEP codes to optimize the design and beam dynamics. The final design includes a cathode electron gun, a bunching section, and four traveling-wave structures, with a maximum beam energy of 145 MeV and a maximum current of 200 mA. The VHEE FLASH linac-based machine is a high-dose, ultrahigh-dose-rate accelerator that can deliver single pulses or pulse sequences. The device is suitable for investigating the fundamental FLASH mechanisms in pre-clinical and radiobiological experiments and for the clinical transfer of the technique.

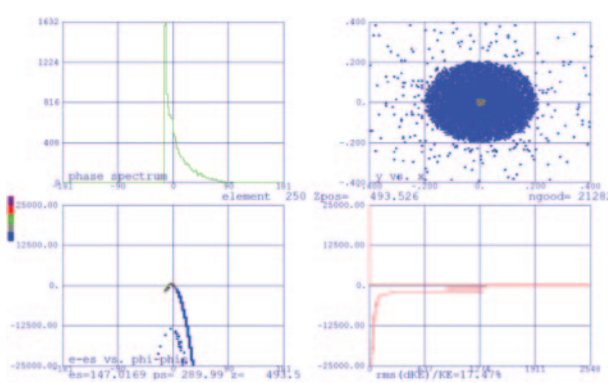

Fig. 9. – Phase-space plots at the exit of the fourth high-gradient structure.

REFERENCES

[1] Hornsey S. and Alper T., *Nature*, **5032** (1966) 212.
[2] Favaudon V., Caplier L., Monceau V., Pouzoulet F., Sayarath M., Fouillade C., Poupon M.-F., Brito I., Hupé, P., Bourhis J. *et al.*, *Sci. Transl. Med.*, **6** (2014) 245ra93.
[3] Vozenin M.-C., Fornel P. D., Petersson K., Favaudon V., Jaccard M., Germond J.-F., Petit B., Burki M., Ferrand G., Patin D. *et al.*, *Clin. Cancer. Res.*, **25** (2018) 35.
[4] Faillace L., Barone S., Battistoni G. *et al.*, *Phys. Rev. Accel. Beams*, **24** (2021) 050102.
[5] Martino F. D., Barca P., Barone S. *et al.*, *Front. Phys.*, **8** (2020) 481.
[6] Giuliano L., Franciosini G., Palumbo L. *et al.*, *Appl. Sci.*, **13** (2023) 631.
[7] CST, https://www.3ds.com/products-services/simulia/products/cst-studio-suite/.
[8] TSTEP Software, https://tstep.lmytechnology.com/TSTEP.html.