Proposal of a VHEE Linac for FLASH radiotherapy

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Abstract. Translation of electron FLASH radiotherapy in clinical practice requires the use of high energy accelerators to treat deep tumours and Very High Electron Energy (VHEE) could represent a valid technique to achieve this goal. In this scenario, a VHEE FLASH linac is under study at the University La Sapienza of Rome (Italy) in collaboration with the Italian Institute for Nuclear Research (INFN) and the Institut Curie (France). Here we present the preliminary results of a compact C-band system aiming to reach an high accelerating gradient and an high pulse current necessary to deliver high dose per pulse and ultra-high dose rate required for FLASH effect. We propose a system composed of a low energy high current injector linac followed by a modular section of high accelerating gradient structures. CST code is used to define the required LINAC's RF parameters and beam dynamics simulations are performed using TSTEP and ASTRA.

1. Introduction

In 2014 Favaudon et al. [1] discovered a new effect, called FLASH, that can change the scenario of the radiotherapy. Several pre-clinical studies demonstrated that a high dose per pulse (1-10 Gy) with ultra high dose-rate ($> 10^6$ Gy/s) and a total irradiation time < 100 ms, decreases dramatically the toxicity in the healthy tissue while keeping the same efficacy in cancer cure [2]. The technology of the accelerators actually used in the radiotherapy does not allow to explore this novel approaches in terms of dose and dose-rate, therefore a new low energy LINAC (7 MeV) [3,4] has been developed by our team in collaboration with S.I.T. - Sordina IORT Technologies S.p.A. [5] and has been installed at Institut Curie (Orsay-France) in August 2020, in order to investigate the FLASH effect.

A strong interest has also grown on high energy machines (60-150 MeV) able to treat deep tumours. Recent studies [6–8] have investigated the potential of the VHEE for clinical applications, showing that 60–150 MeV beams could become an alternative modality in radiotherapy.

The proposed VHEE source is based on a C-band LINAC, working at the frequency of 5.712 GHz, which allows more compactness compared to the traditional S-band cavities. The irises of the cavities have been designed with a radius such to get a high accelerating gradient and at the same time ensure a good transmission efficiency of electrons, necessary to transport the high peak current required for the high dose and dose rate in the FLASH irradiation.

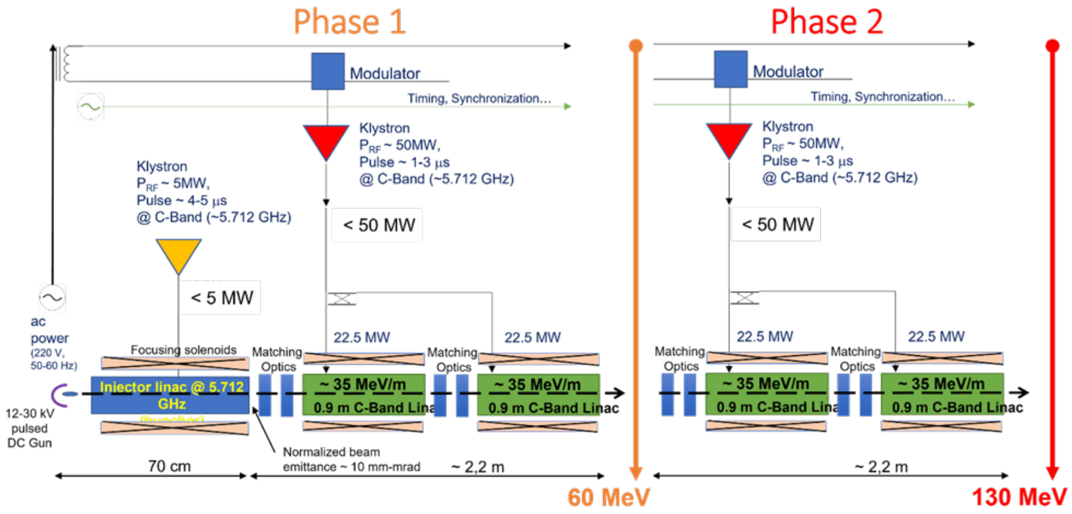

Figure 1. Layout of the VHEE Linear Accelerator for VHEE FLASH radiotherapy with the injector and four TW high-gradient accelerating structures.The maximum expected beam energy is about 130 MeV.

The whole system is thought to be realize in two successive phases (phase 1 and phase 2) as show in figure 1. In phase 1, we use an injector (standing wave LINAC) and two traveling wave accelerating structures 90 cm long. The injector accelerates, at an energy of 10 MeV, a current of 200 mA generated by a pulsed DC gun. The RF design of the C-band injector is essentially based on the experience gained with above mentioned S band low energy LINAC, scaling properly the whole geometry. The electron beam is injected into a compact traveling wave (TW) C-band structure characterized by a high accelerating gradient ($\sim$ 40 MeV/m without the beam) able to bring the energy of the electron beam up to about 60 MeV. In phase 2, with two addition accelerating structures the system can reach an energy up to 130 MeV. The injector is powered by a C-band klystron of 5 MW, upstream of a circulator necessary to prevent reflected waves from the accelerating structure that can damage the klystron itself. A 50 MW klystron, foreseen for phase 1, feeds the first two accelerating structures. The power is split such to feed two LINACs by means of a waveguide network. A second 50 MW C-band klystron provides power to the other two LINACs for the phase 2.

2. RF design optimization

The RF accelerator design is performed by using CST 3D code [9] with eigen and frequency domain solver. The electrons are emitted from a triode electron gun with spherical emission area (see figure 2) with a diameter of about 6 mm. The nominal operation energy is around 12 keV adjustable up to 30 keV. The first cavity of the injector is composed of a half cell with an input plate required to adapt the electric field from the gun to the linac (figure 3). The first linac is a Standing Wave (SW) bi-periodic structure, working in $\pi/2$mode with a frequency of operation of 5.712 GHz. The first part of the linac is composed of three SW cavities called

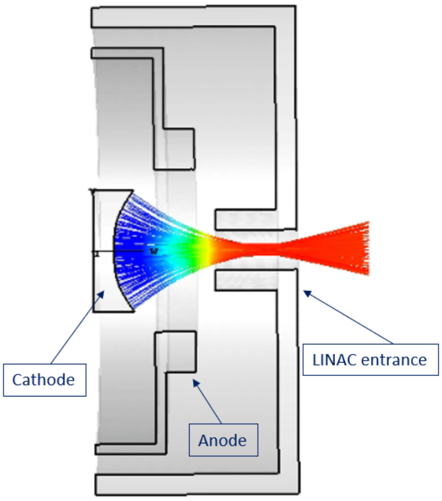

Figure 2. Transverse view of the DC gun. The electrons are emitted from the cathode, pre-accelerated in the gun at energies of about 15 keV and injected into the linac.

bunching section, aimed to generate the bunches and maximize the beam charge capture which results to be around 45%, corresponding to 225 mA.

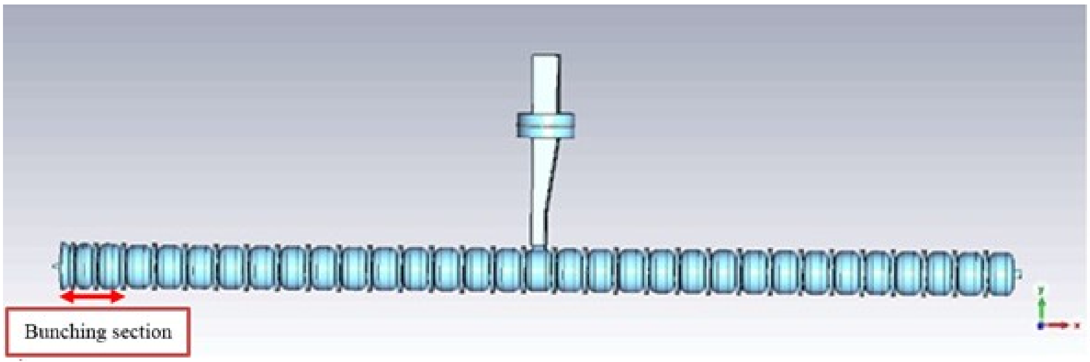

Figure 3. 12 MeV injector linac in C-band with bunching section. The output pulsed beam current is 200 mA.

After the bunching section, the accelerating cells are designed for $\beta \simeq 1$ and the particles reach the required energy after 22 cells.

The high gradient section is a travelling wave (TW) structure operating at 5.712 GHz with a phase advance per cell of $2/3\ \pi$ that guarantees the best efficiency for this type of accelerating structure. A previous experience with the ELI accelerating TW structures was useful to guide in the design of these structures [10–12]. Following preliminary results of beam dynamics, the single cell has been simulated with values of the iris radius "a" of 5 mm and a thickness "t" of 3 mm. Eventually, we performed an optimization of the elliptical shape of the irises, obtaining the best value at $r_1/r_2 = 1.55$. The cell and its geometric parameters are shown in figure 4.

After the single cell's optimization, the final TW structure with same cells was designed integrating the couplers (figure 5). The design procedure is based on an analysis of the phase of the reflection coefficient S11 (figure 6) for different lengths of the short-circuited structure [13].

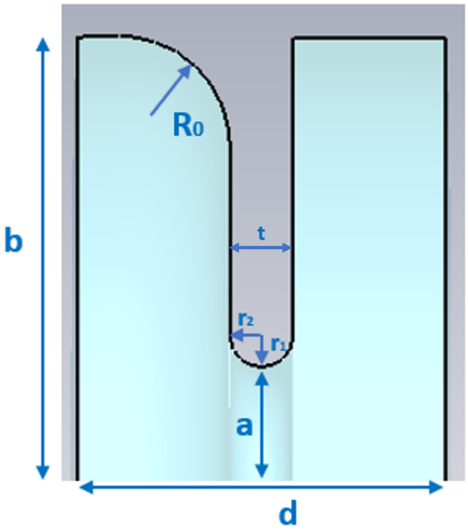

Figure 4. Cell and its geometric parameters: a = 5 mm; b = 20.908 mm; t = 3 mm; d = 17.45 mm; R0 = 5.25 mm; $r_1/r_2 = 1.55$

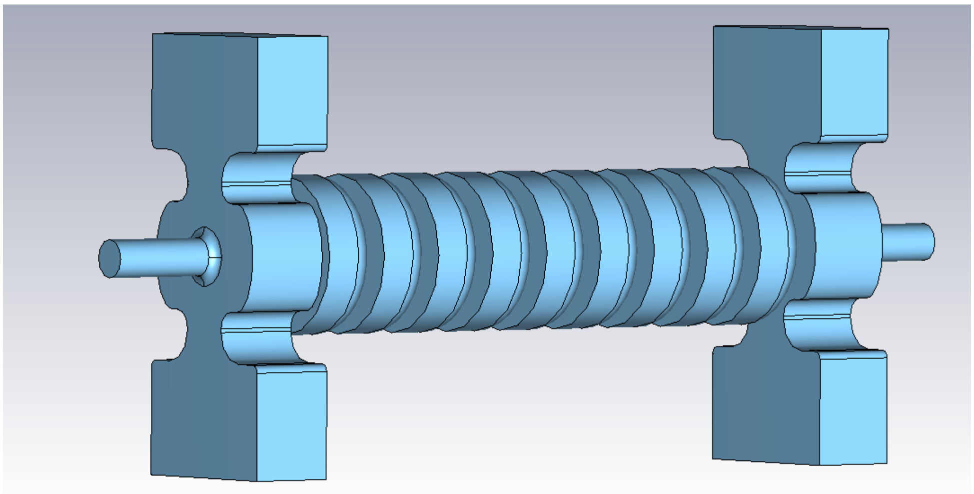

Figure 5. VHEE high gradient Linear Accelerator prototype for VHEE FLASH radiotherapy.

3. Beam dynamics studies

After finishing the layout system, we performed the beam dynamics simulations with the TSTEP [14] and ASTRA [15] codes. In figure 7, it is shown the beam energy gain at full RF power and on-crest operation for each linac. In this case, the maximum achievable energy is about 80 MeV in Phase 1 and 150 MeV in Phase 2, which are well above the minimum required energies for the two phases which are 60 MeV and 130 MeV, respectively. As a result, our proposed system has a very large range of flexibility in the output energy, by easily varying the delivered RF power and phase to each accelerating section. The plot starts from the cathode, located at z = 0 m up to the TW linacs operating at 35 MV/m loaded gradient with 200 mA beam current. In addition, beam dynamics simulations show that no focusing solenoids are required around the accelerating structures. Nevertheless, in our proposed layout, we introduce possible solenoids to distribute along the beamline if necessary, especially from a radiosafety

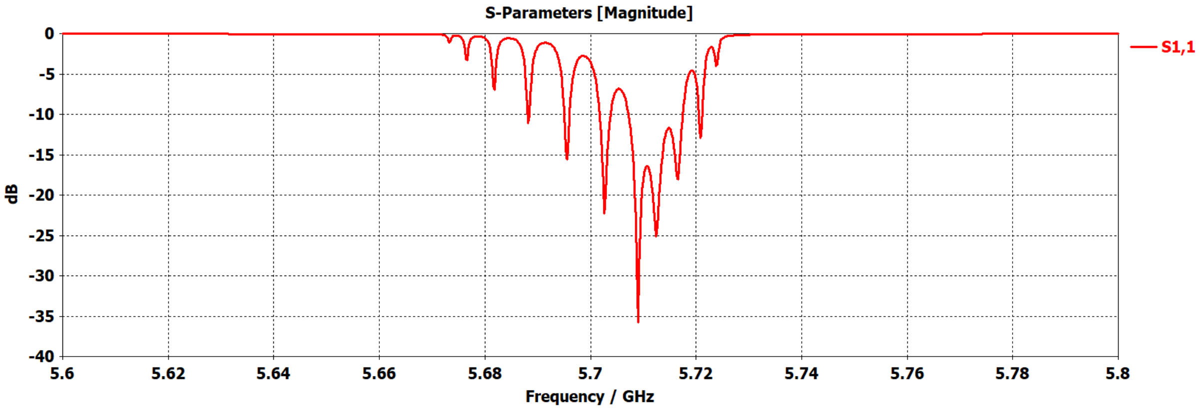

Figure 6. S11 of the TW high gradient structure calculated using CST Studio SUITE code.

point of view.

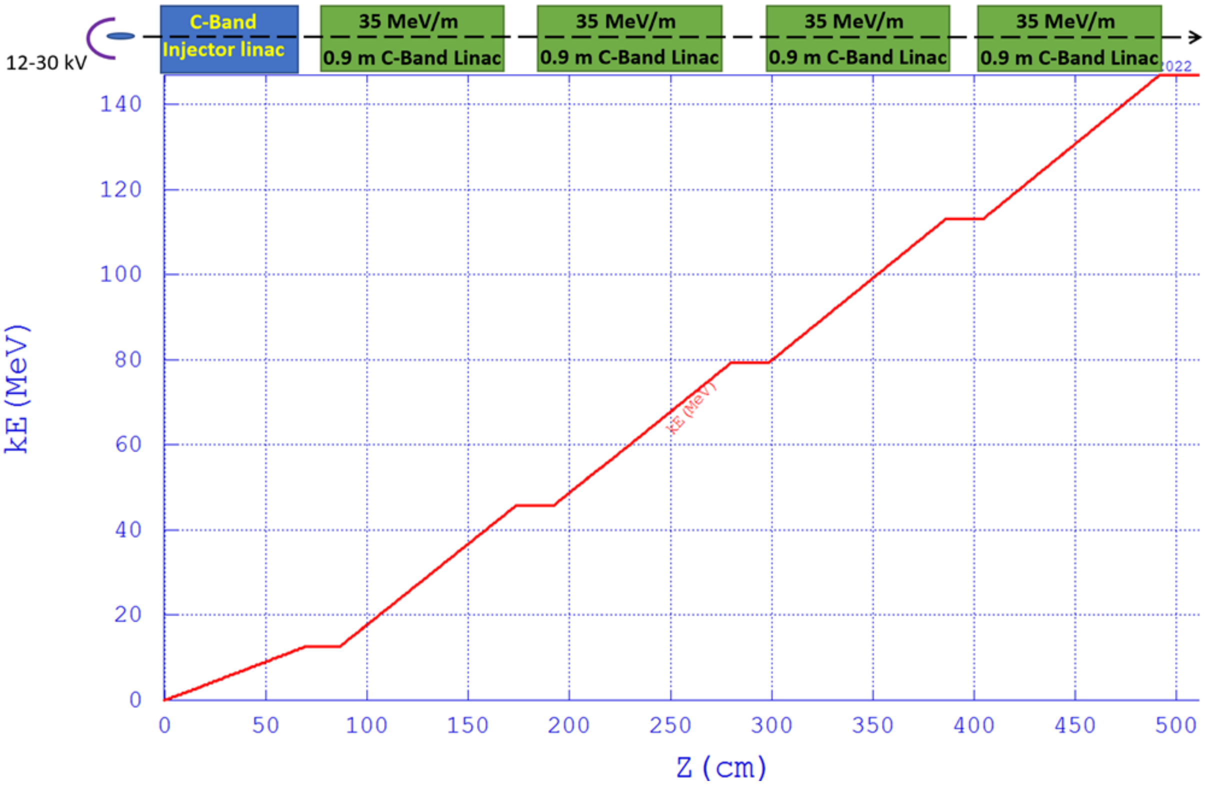

Figure 7. Beam energy gain. The 10 MeV electron beam, from the injector to the last 90 cm long TW linacs with an accelerating loaded gradient of 35 MV/m. The beam current at the exit is 200 mA.

The beam phase-space plots at the linac exit are given in figure 8. The bunch length is around 20 ps FWHM. The energy spread FWHM value is <0.2%. The beam spot shows a FWHM value of 1.8 mm with the total transverse distribution concentrated in about a 4 mm diameter. The normalized transverse beam emittance is in the order of 10 mm-mrad.

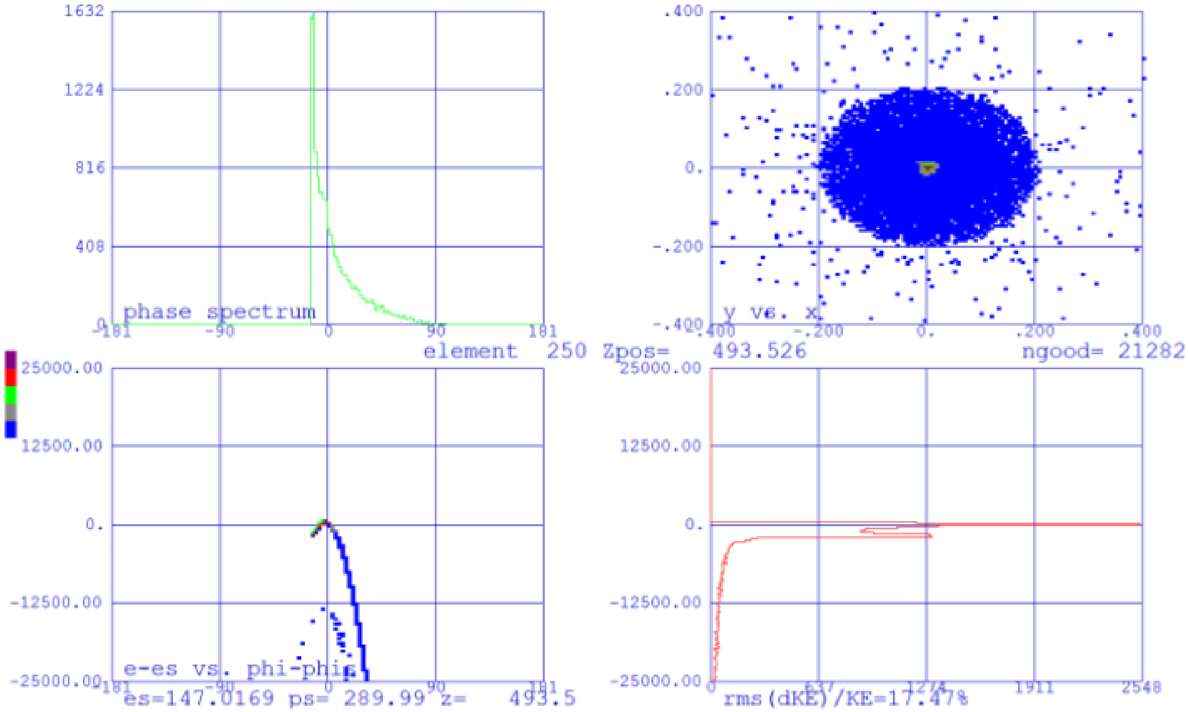

Figure 8. TSTEP output electron beam parameters. In clockwise order: longitudinal phase distribution in degrees; transverse beam spot size in cm; beam energy spectrum in MeV; beam longitudinal phase-space (energy vs. RF phase)

4. Conclusion

In this paper, the design of the VHEE FLASH linac-based machine for a VHEE FLASH-RT Research Laboratory proposed at Sapienza University has been reported. The accelerator is able to deliver high-dose in single pulse thanks to the high current per pulse (>200 mA), suitable to investigate the FLASH fundamental mechanisms in pre-clinical and radio-biological experiments opening the way to the clinical transfer of the technique. Different strategies for the transverse beam spot size magnification are under study, in order to irradiate large surface as required in the clinical practise. We have developed the RF design and the beam dynamics characterization of the VHEE system optimized to operate with two nominal output electron beam energies: 60 and 130 MeV. Studies are on going to complete the characterization of the machine and to manufacture and test the RF prototypes.

Acknowledgments

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