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Original Paper

Perspectives in linear accelerator for FLASH VHEE: Study of a compact C-band system

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A R T I C L E I N F O

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A B S T R A C T

Purpose: In order to translate the FLASH effect in clinical use and to treat deep tumors, Very High Electron Energy irradiations could represent a valid technique. Here, we address the main issues in the design of a VHEE FLASH machine. We present preliminary results for a compact C-band system aiming to reach a high accelerating gradient and high current necessary to deliver a Ultra High Dose Rate with a beam pulse duration of 3 µs.

Methods: The proposed system is composed by low energy high current injector linac followed by a high acceleration gradient structure able to reach 60–160 MeV energy range. To obtain the maximum energy, an energy pulse compressor options is considered. CST code was used to define the specifications RF parameters of the linac. To optimize the accelerated current and therefore the delivered dose, beam dynamics simulations was performed using TSTEP and ASTRA codes.

Results: The VHEE parameters Linac suitable to satisfy FLASH criteria were simulated. Preliminary results allow to obtain a maximum energy of 160 MeV, with a peak current of 200 mA, which corresponds to a charge of 600 nC.

Conclusions: A promising preliminary design of VHEE linac for FLASH RT has been performed. Supplementary studies are on going to complete the characterization of the machine and to manufacture and test the RF prototypes.

1. Introduction

Nowadays Radiotherapy (RT) is the best ally for tumor treatment and more than 50% of cancer patients are treated with RT [1,2]. The benefits associated with RT are widely recognized, but in some cases still limited by the secondary effects in the healthy tissues. Several studies on non-conventional structures in time of the beams used in radiation therapy have been shown to protect healthy tissues from the damage of the ionization radiations while the efficiency in the tumor cure remains unchanged. This effect is called FLASH effect [3–5] and it is based on very high dose-rate irradiation (>10^6 Gy/s), short beam-on times (<100 ms) and large dose in the pulse (>10 Gy). These are experimental parameters established to give biological and potential clinical effects. If it is possible to irradiate the healthy tissues

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without side effects it is equally possible to increase the dose delivery, improving the curative effect and the therapeutic window.

In order to improve the accessibility of sources which can provide irradiation with ultrahigh dose-rates, different accelerator have been commissioned [6–9] and significant effort has been done to adapt existing clinical linacs for electron FLASH-RT experiments [10–12] A previous experience of medical linacs for FLASH therapy is related to the design of a compact S-band standing wave linear accelerator, the ElectronFLASH, dedicated to FLASH radiotherapy in collaboration with SIT company [13]. This machine works at 5 and 7 MeV in conventional (CONV) and FLASH modality. It was commissioned and installed at the Curie Institute in Orsay in August 2020. The paper which describes this initial low-energy project was published elsewhere [14]. A new paper on the dosimetric characterization of the ElectronFLASH was recently submitted for publication on Medical Physics. From this experience we started our investigations about the Very High Electron Energy prototype. Previous theoretical studies [15,16] have shown the potential of 150–250 MeV VHEE beams for radiotherapy.

In fact, nowadays, a certain number of linac-based test facilities are already available to perform VHEE studies. As an example, we mention the normal-conducting (NC) linac-based accelerator facilities such as the Next Linear Collider Test Accelerator (NLCTA) at SLAC National Accelerator Laboratory at SLAC [17] and the CERN Linear Electron Accelerator for Research (CLEAR) which is able to provide both high-energy (50–250 MeV) and high-charge beams [18]. Other facilities are the VELA-CLARA [19] at Daresbury Laboratory and PITZ at DESY and finally ELBE-HZDR [20] using the superconducting radiofrequency technology at Dresden. These facilities, also in collaboration with other laboratories, are working on new acceleration technologies in order to move towards the possibility of offering VHEE FLASH-RT investigation in the range of few hundreds MeV's (100-250 MeV). In particular, an S-band NC linac-based machine has been proposed by the multidisciplinary R&D facility PRAE [21] and the CLIC-RF group at CERN in collaboration with the CHUV of Lausanne are developing a linac VHEE RT facility for FLASH [22] in the range of 100 MeV. Moreover, by using X-band structures developed by the SLAC laboratory, a second generation of the PHASER (Pluri-directional High-energy Agile Scanning electronic Radiotherapy) for electrons with energy ranging from 80–150 MeV has also been proposed [23].

In this scenario, our proposed VHEE linac-based accelerating machine will employ optimized linacs based on our well-developed C-band technology for the foundation of a research laboratory dedicated to VHEE-FLASH investigation in the framework of a collaboration between Sapienza University of Rome and the Italian Institute for Nuclear Physics of Frascati (INFN-LNF). The choice of operation in C-Band, by using a compact and modular layout, is an optimal compromise for working with high-charge electron bunches, limited in X-Band due to the small cavity dimensions, and still for having more compact accelerating structures than the S-Band ones.

The scheme of the proposed VHEE linac System is shown in Fig. 1. Differently from the ElectronFLASH, it is based on the C-band technology, working at a frequency of 5.712 GHz, which allows a more compactness with respect to the S-band, and, at the same time, has still a sufficient large radial aperture in the irises of the cavities to give a good particle transmission efficiency even at large currents, as those necessary for the FLASH therapy.

The accelerator is divided into three main sections which can be realized in two successive phases (phase 1 and phase 2). In phase 1 we can distinguish, on the left, the first accelerating standing wave (SW) linac, called the injector, capable of accelerating a current exiting from a pulsed DC gun up to 200 mA at an energy of 10 MeV. This injector linac is essentially based on the experience gained with above mentioned ElectronFLASH, also operating in SW mode. The electron beam is then matched by means of quadrupoles (matching optics) and injected into a compact linear traveling wave (TW) accelerating structure characterized by a high accelerating gradient (above 40 MeV/m) able to bring the energy of the electron beam up to at least 60 MeV in phase 1, and up to 130 MeV in phase 2 by means of a total of four 90 cm long accelerating structures, each one followed by quadrupoles for matching conditions. We forsee the use of magnetic solenoids around the accelerating structures to guarantee the necessary focusing to the beam.

Conventional feeding schemes provide the RF power. A first C-band klystron of 5 MW, upstream of a circulator necessary to prevent reflected waves from the accelerating structure and, as consequence, damages to the klystron itself, is used for the injector. A second 50 MW klystron, foreseen for phase 1, feeds the first two accelerating structures. The power is split and fed into the two 0.9 m long linacs by means of a waveguide network. Another 50 MW C-band klystron provides power to the other two linacs.

In the case of employing RF pulse compressors [24], which are devices for RF power amplification, it is possible to obtain a 100 MeV beam in 3 m for Phase 1, and 160 MeV in less than 4 m without using the fourth structure, as discussed later in this section. The machine layout with the use of RF pulse compressors is given in Fig. 2.

The choice of the TW sections instead of the standing wave ones for the realization of high gradient linacs, has been made to avoid the circulator for the high RF power required in the accelerating structures. Additionally, a previous experience in the design of the ELI accelerating TW structures [25] is very useful and it served as a guide in the design of these structures. Finally, since at the entrance of the High Gradient linac the bunch has a speed close to that of light, in a TW accelerating structure the phase between the bunch and the accelerating field remains unchanged during the acceleration process (in the sense that bunch and accelerating field travel together inside the structure since the bunch cannot increase its speed any further). Consequently, by injecting the bunch with the correct phase with respect to that of the accelerating field, it will travel inside the structure always on the crest of the accelerating field: this guarantees an optimal accelerating process, even over long distance.

2. Materials and methods

2.1. RF design optimization

The accelerator design is performed by using CST 3D code [26]. The electrons are emitted from the cathode, pre-accelerated in a DC gun at energies of about 15 keV and injected into the "bunching section" shown in Fig. 3. At this stage, the electron beam is still non relativistic with a speed below the speed of light ($\beta < 1$). Therefore, the first part of the injector is composed of three SW cavities aimed at generating the bunches (bunching section), gathering particles continuously emitted by the gun. The bunching section is optimized to reduce the amount of particles lost at the entrance of the linac (see Fig. 4, showing the on-axis profile of the accelerating electric field). 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. In the bunching section, the profile of the electric field peaks was tailored in order to get the best beam capture. After the bunching section, the beam continues its acceleration in the accelerating sections designed for $\beta \simeq 1$ and the particles reach the required energy after 22 accelerating cells.

The C-band high gradient is a Traveling Wave (TW) accelerating structure and operates in the TM01-like mode with a phase advance per cell of $2/3\ \pi$. One single RF structure increases the beam energy up to about 35 MeV in a space of about 90 cm, thus respecting the available space constraints. The phase advance per cell of $2/3\ \pi$ guarantees the best efficiency for this type of accelerating structures. With the help of CST Studio Suite, we performed the electromagnetic characterization and the design of the single cell constituting the TW structure. Following preliminary results of beam dynamics, the cell has been simulated with values of the iris radius "a" in the range of 3÷7 mm, ensuring that for each "a" the frequency of the monopolar accelerating mode

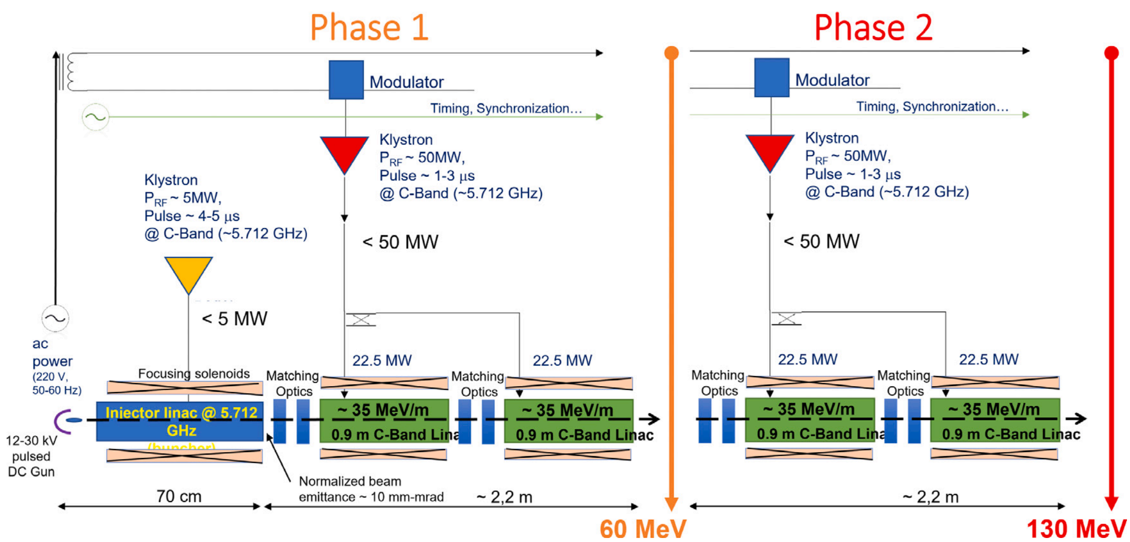

Fig. 1. Layout of the VHEE Linear Accelerator System for VHEE FLASH radiotherapy with one injector and four TW high-gradient accelerating structures. The maximum expected beam energy is about 130 MeV.

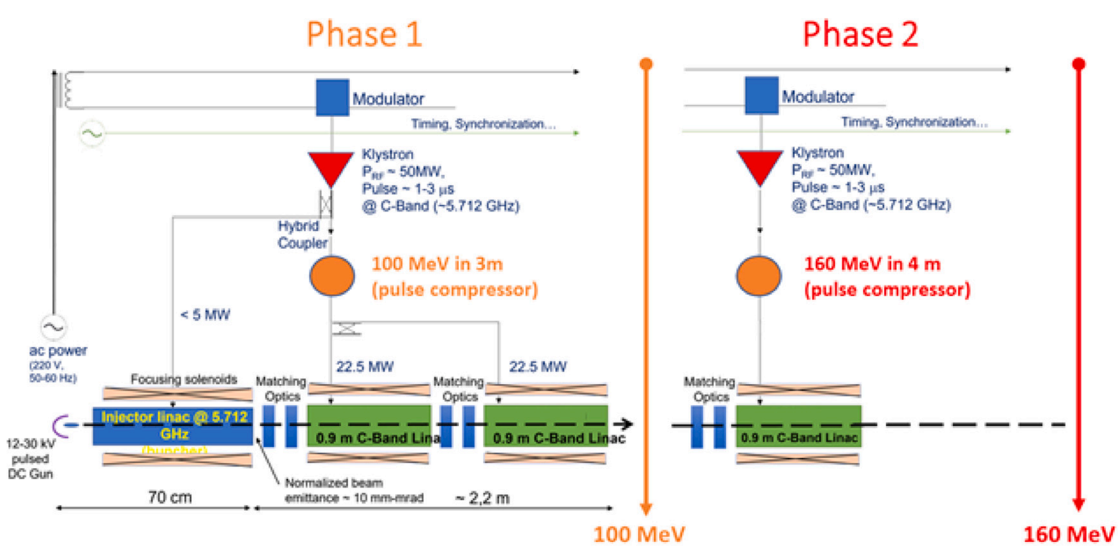

Fig. 2. Layout of the VHEE Linear Accelerator System for VHEE FLASH radiotherapy with one injector and three TW high-gradient accelerating structures. Two pulse compressors are used in this layout. The maximum expected beam energy is about 160 MeV.

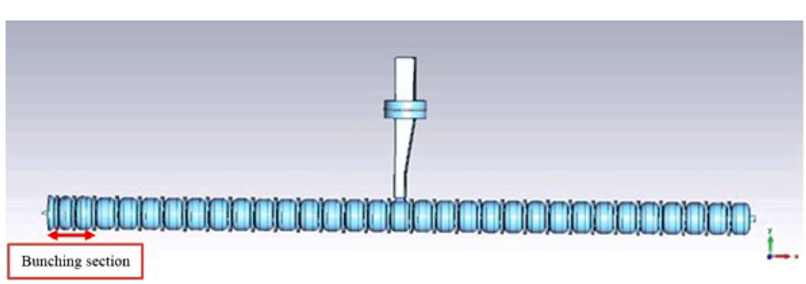

Fig. 3. 12 MeV injector linac in C-band. The output pulsed beam current is 200 mA.

TM01-like supported by the cell is exactly at 5.712 GHz. The cell and its geometric parameters are shown in Fig. 5.

The main RF parameters obtained for the single cell at different iris radii are shown in Fig. 6. The analysis was performed considering an iris radius variation in the range a between 3 and 7 mm. On the top left of the figure the quality factor Q (blue line) of the accelerating mode and the normalized Poynting vector Sc_{max}/E_{acc^2} (orange line) are shown, while on the top right we can find the shunt impedance R and the normalized group velocity v_g/c.

After the optimization of the single cell, a prototype of the whole structure was carried out as shown in Fig. 7 Using CST Studio SUITE in frequency domain solver, we obtained the accelerating electric field profile along the axis (Fig. 8).

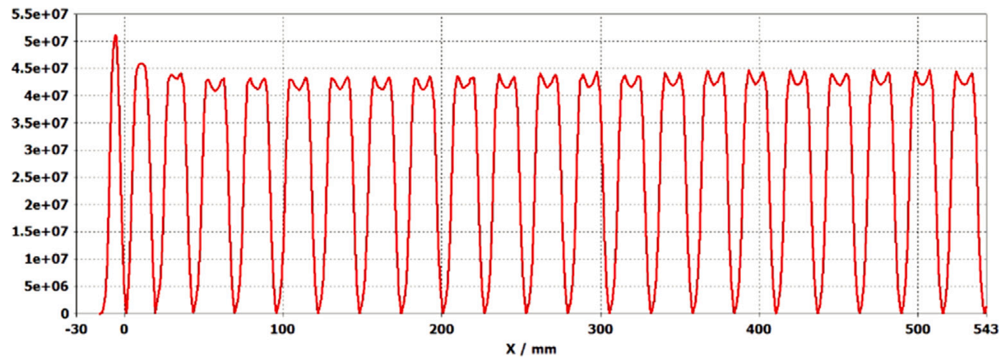

Fig. 4. Electric field on the injector axis simulated with CST studio SUITE code in eigenmode modality.

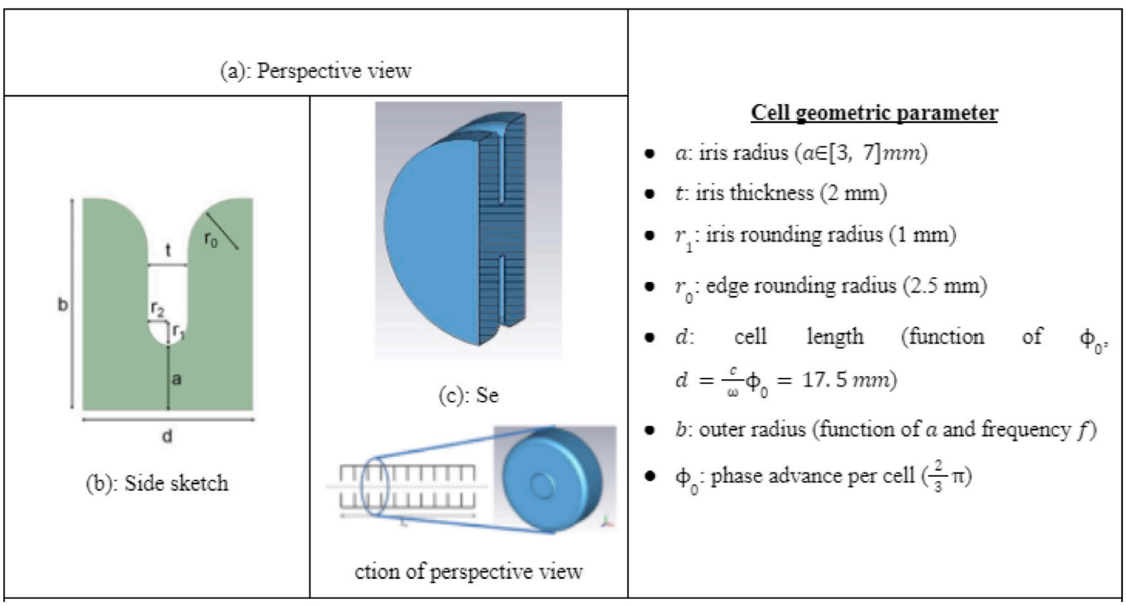

Fig. 5. Cell and its geometric parameters. (a): Perspective view of the single cell CST model; (b): Side sketch of the single cell with main dimensions; (c): Section of perspective view of the single cell CST model.

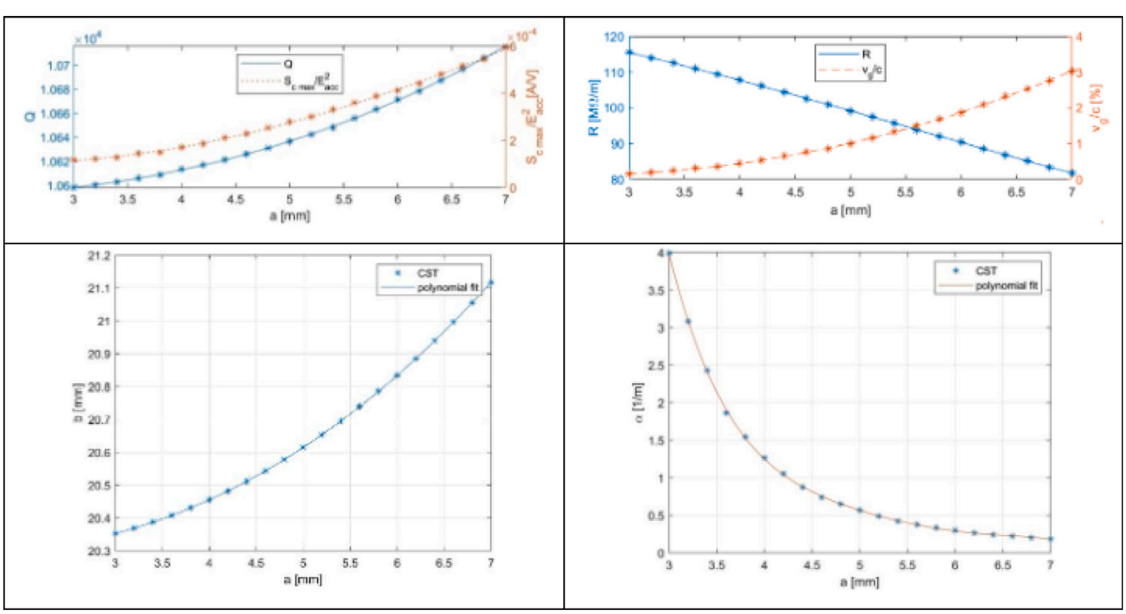

Fig. 6. Main parameters of single cell as function of the iris radius. R: shunt impedance per unit length, Q: quality factor, v_g/c: normalized group velocity, Sc_{max}/E_{acc^2}: normalized Poynting vector, b: outer radius, α: attenuation per unit length.

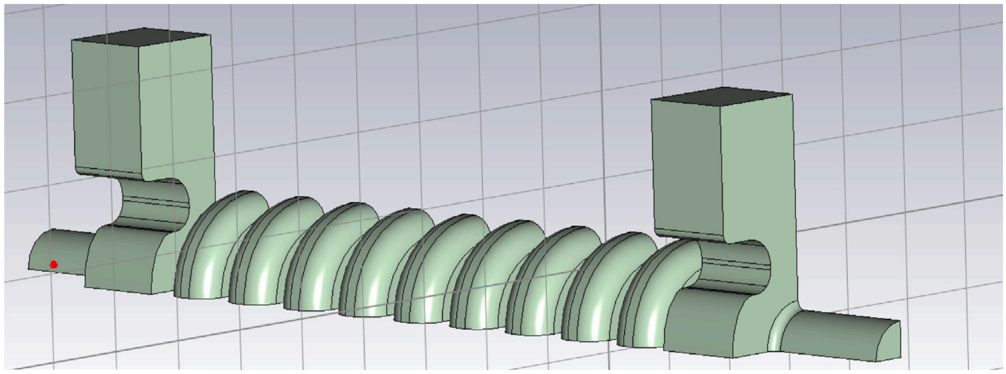

Fig. 7. RF design of the VHEE high gradient Linear Accelerator prototype for VHEE FLASH radiotherapy.

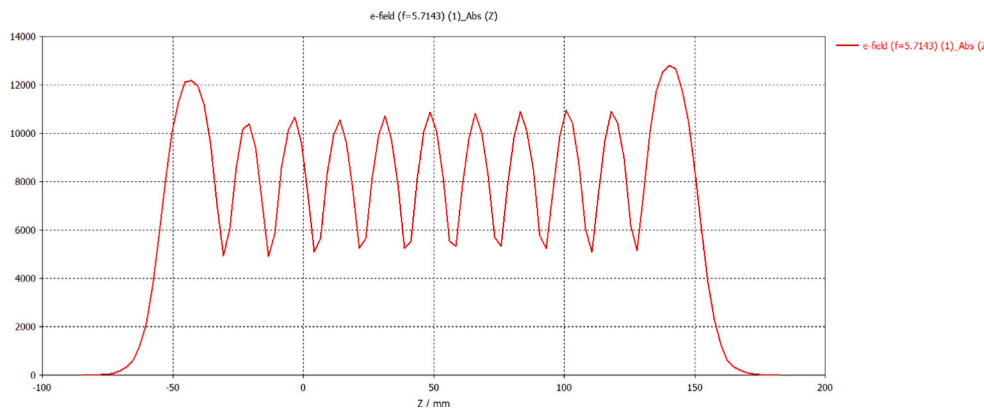

Fig. 8. On axis electric field of the high gradient prototype for VHEE FLASH radiotherapy.

2.2. Beam dynamics: electron beam transport

After the RF beam layout was agreed upon, we performed the beam dynamics simulations with the TSTEP [27] and ASTRA [28] codes. In Fig. 9, the electron beam energy gain from the cathode, located at z = 0 m, is shown. The cathode is a triode electron gun with spherical emission area with a diameter of about 6 mm. The nominal operation energy is around 12 keV but adjustable up to 30 keV, in order to increase the beam capture inside the first injector linac. The cathode electron beam current is 600 mA. The bunching section of the injector linac, discussed above, is optimized in order to maximize the beam charge capture which results to be around 45%, corresponding to 225 mA. Some percentage of this current will be lost in the transport through the following accelerating structures and is evaluated for radioprotection simulations. In the VHEE layout, the injector is followed by four TW linacs operating at about 35 MV/m loaded gradient at 200 mA beam current, which is the maximum current of our proposed project. Each TW linac is composed of 50 cells and the main RF parameters are discussed previously in this chapter. The electromagnetic field maps of each TW structure are generated with the SUPERFISH code and imported into TSTEP for beam dynamics simulations. The accelerating gradient is 35 MV/m and all linacs are phased with the electron beam in on-crest operation. A sketch of the linacs layout and the beam energy gain are shown in Fig. 9. The maximum energy is around 145 MeV in this case and above the predicted value of 130 MeV, discussed in the introduction of this section. Simulations with output energy up to 160 MeV have been carried out and used for the dosimetry simulations discussed later in the paper. This modular layout confirmed the possibility of optimal transport of the beam up to desired maximum current of 200 mA at exit. The total linac length is within 5 m.

In Fig. 10, the RMS beam envelope is shown. The high-gradient linacs induce beam RF focusing in order to confine the beam without the use of solenoids. The final linac exit is located at about 500 cm. The beam transverse RMS size is about 0.8 mm.

The beam phase-space plots at the linac exit are given in Fig. 11. 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.

The effect of higher-order modes (HOM'ss) has been preliminarily performed by using a dedicated fast code which was developed in-house and called MILES [29]. We simulated the case of maximum RF pulse current of 200 mA with a bunch length = 2 μs and total RF pulse charge = 400 nC. The entire train of bunches is injected 50 μm off-axis. It was also assumed no-detuning (worst-case scenario) of all HOM's at the same resonant frequencies. As a result, the displacement from the linac axis is contained and negligible, that is all bunches, subjected to deflection, remain close to the nominal trajectory within 20% of the entrance value.

Full 3D simulations of the electron beam dynamics inside the accelerating structures are in-progress in order to estimate the effect from higher-order components in the RF fields. Nevertheless, the current design already follows a well-established symmetrization procedure [30, 31], as for the accelerating structure design, in order to minimize higher field components, especially in the asymmetry regions, such as the RF power couplers, which we apply to any structure fabricated nowadays for high-energy physics applications.

2.3. Dosimetry simulations with FLUKA

Monte Carlo simulations were performed, using the FLUKA software [32], in order to obtain dose distributions and absolute dose values and so to have an estimation of the necessary beam current. The simulated setup is made of a cubic water phantom of dimensions

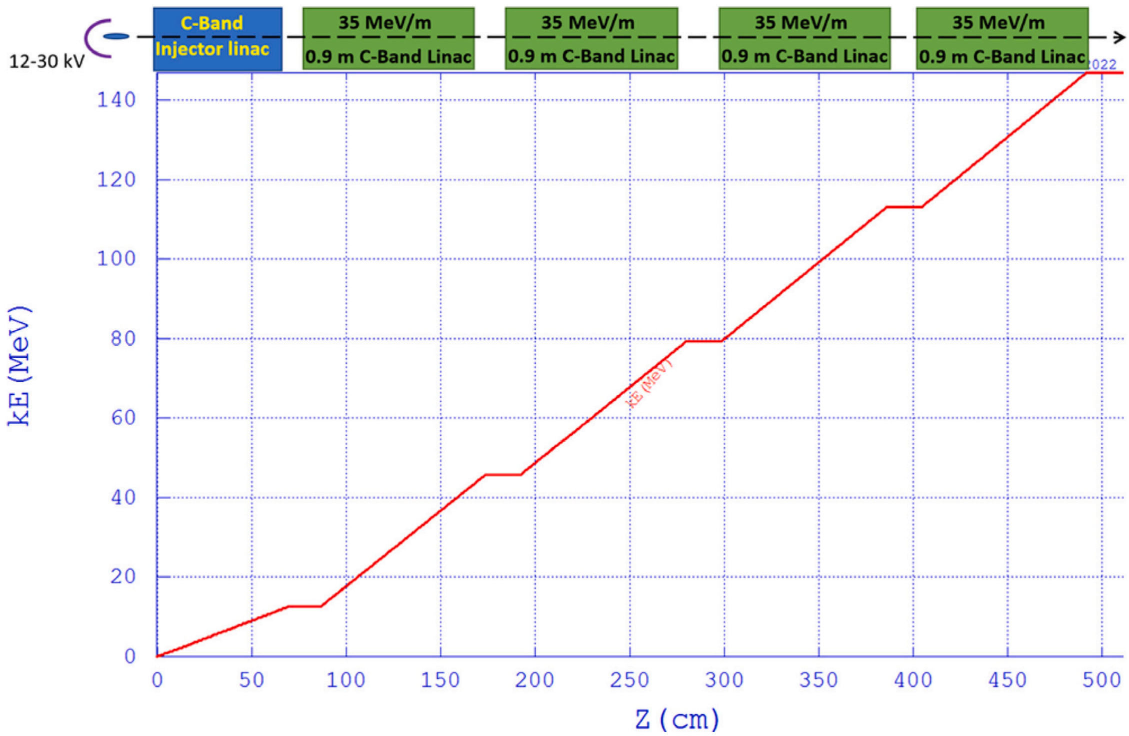

Fig. 9. Beam energy gain. The 12 MeV electron beam, from the injector, in launched into four 90 cm long TW linacs with an accelerating loaded gradient of 35 MV/m. The beam current at the exit is 200 mA.

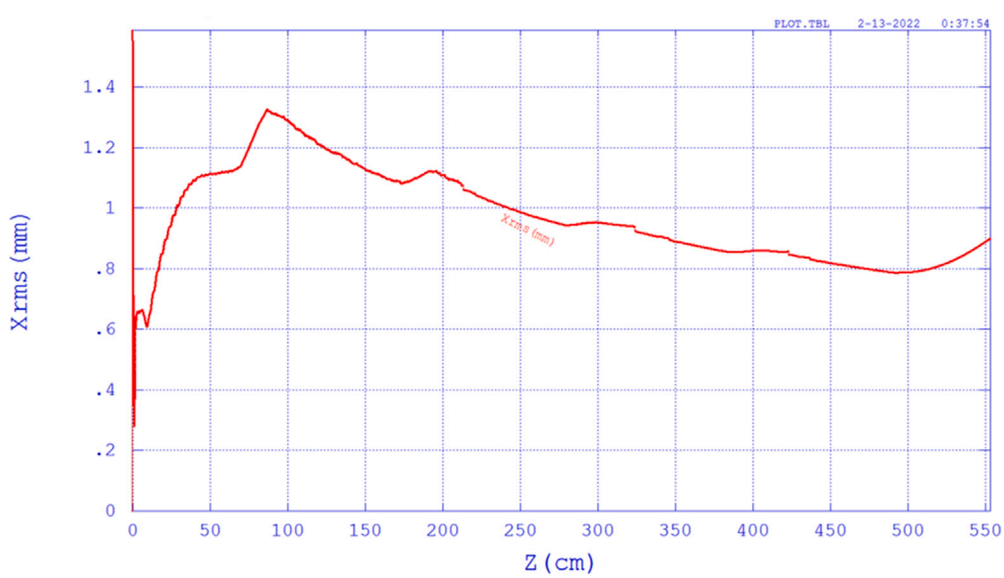

Fig. 10. RMS Electron beam envelope from the cathode up to the last linac exit at 500 cm.

$50 \times 50 \times 50$ cm^3 which is irradiated by an electron beam, traveling along the z axis in vacuum, generated at a chosen distance of 50 cm from the surface of the phantom. The beam has a gaussian profile with a FWHM = 1 cm and a negligible mean angular spread. The simulation has been performed using 10^7 primaries electron in order to reduce the statistical MC fluctuation. The kinetic energy cutoffs for transport and production were set to EMFCUT = 50 KeV for electrons EMFCUT = 10 KeV for photons. An energy spectrum, evaluated with the TSTEP code and shown in Fig. 12, has been used as an input for the simulation: in this way, particles with an energy below these thresholds are not transported and their energies is locally deposited.

2.4. MC simulation for radio-protection studies

Preliminary Radio-Protection studies have been performed simulating the accelerator structure (and the related materials) using the FLUKA code [32].

To evaluate the impact of the dispersed flow of the VHEE high gradient linear accelerator prototype (see Fig. 13), the interactions between the electrons exiting from the beam pipe and the copper structure have been analyzed. For the secondary particles produced (electrons, Bremsstrahlung photons and photo-reactions neutrons) the fluences have been studied in order to have an estimate of the radiation

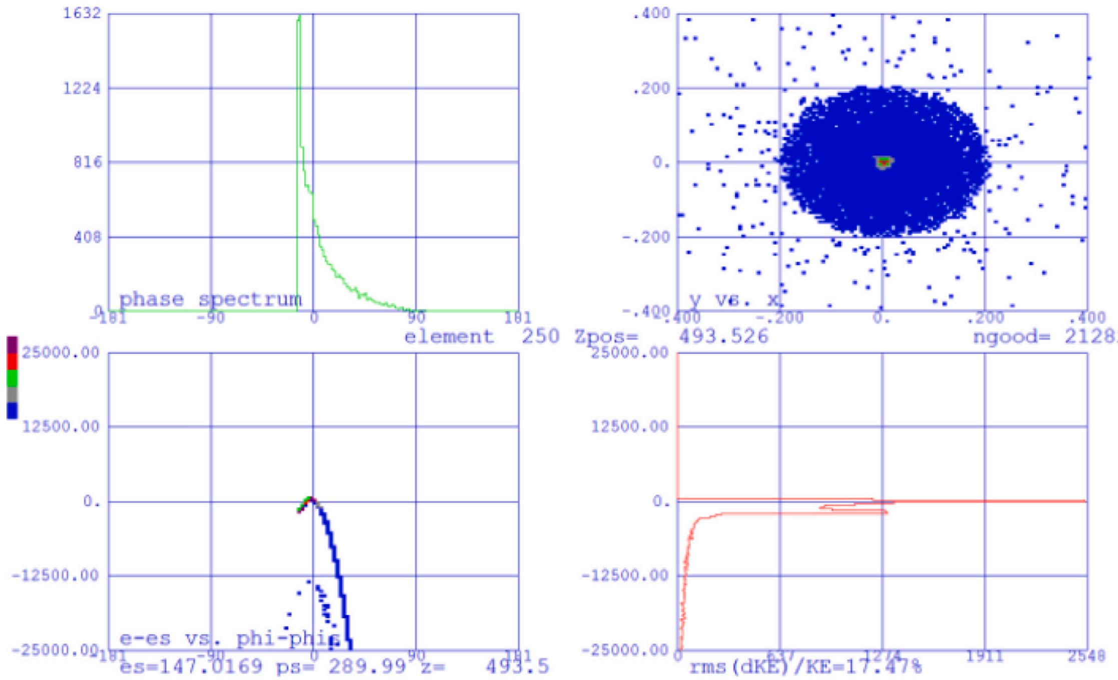

Fig. 11. TSTEP output electron beam parameters. In clockwise order: longitudinal phase distribution in degrees; transverse beam spot size in cm; beam energy spectrum in MeV; beam longitudinal phase-space (energy vs. RF phase).

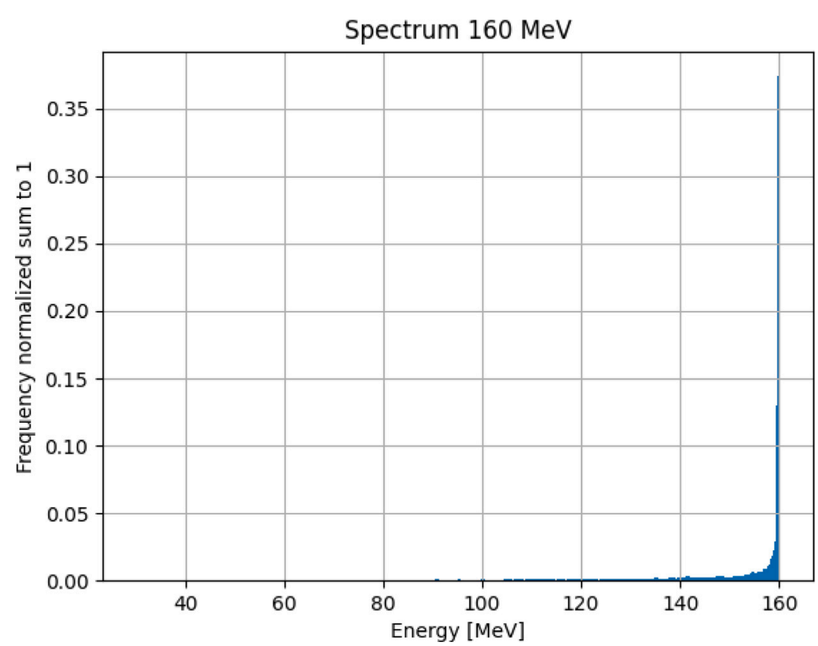

Fig. 12. 160 MeV VHEE spectrum evaluated with TSTEP code.

loss in the surrounding environment and so to design efficient radiation shields. The obtained results, as given in Fig. 14, show that the fraction of primary electrons that exit from the beam pipe and hit the cylinder walls is $\sim 1\%$ of the total, producing: $0,06\%$ of electrons, $0,34\%$ of photons and $9,06\cdot 10^{-5}\%$ of neutrons. The dose released from this secondary radiation field have been evaluated (in air) in the region all around the cylindrical structure of the linac: a value of $2,866 \cdot 10^{-6}$ GeV/g per primary has been obtained. These observations drive the design of the radioprotection shields that have to be build all around the prototype.

The principle that guides optimization of radiation protection is often described by the acronym "ALARA, — as low as reasonably achievable". In ensuring a proper optimization of radiation protection, it is most important to set up a proper relationship between dose limits and radiation protection goals. In setting up this relationship, four principal regions of potential exposure should be considered:

- areas routinely occupied by workers directly involved with accelerator operation;
- areas such as laboratories and offices routinely occupied by workers not directly involved with accelerator operation;
- areas infrequently occupied;
- areas accessible to members of the general public.

The design of new facilities should be optimized to limit dose to occupationally exposed individuals to a fraction of the annual dose

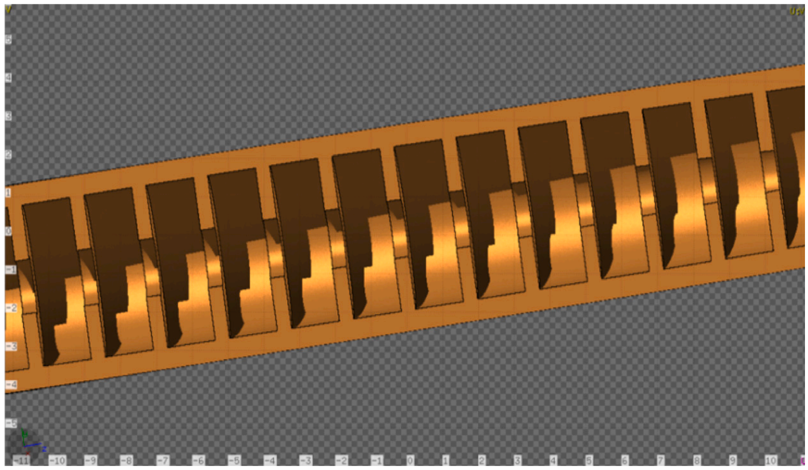

Fig. 13. Layout of the copper RF cavity of the VHEE high gradient linear accelerator prototype performed with FLUKA.

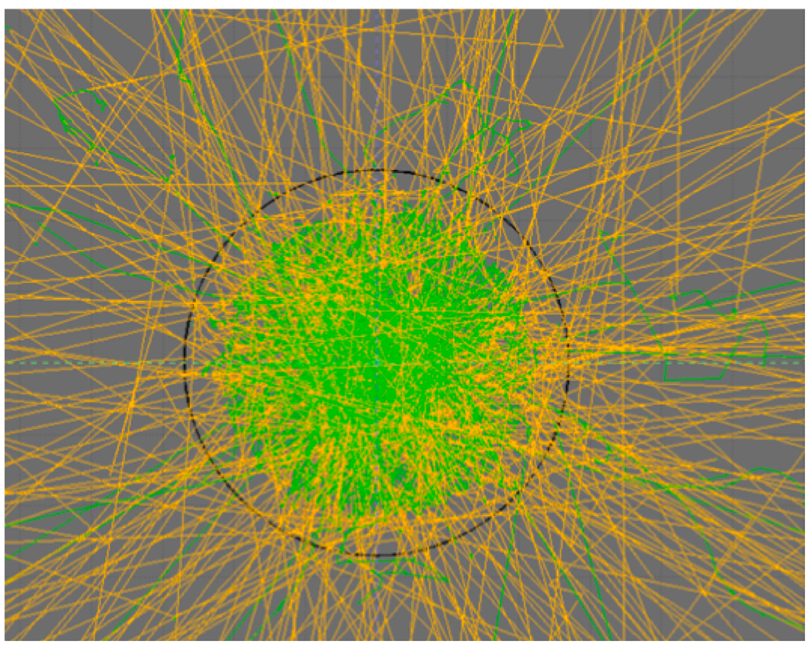

Fig. 14. FLUKA simulation of the interactions between the primary electrons exiting from the beam pipe and the copper of the structure. The produced secondary particles are: Bremsstrahlung photons (in yellow), secondary electrons (in green) and photo-reaction neutrons (in blue).

limit (20 mSv/a of effective dose for exposed workers). As members of the public are involved, the dose outside the facility should be kept under a reference value that typically coincides with the level of no radiological relevance (comprised between 10–300 $\mu Sv/a$). The Shielding design goal (P) is defined by the dose equivalent H calculated on the basis of the annual dose limit. When designing the facility, P is correlated with other parameters, such as Workload (W), Occupancy factor (T), and Use factor (U). The final thickness is obtained is calculated by $dx_{barrier} = TVL_1 + (n-1)TVL_1$. The first ($TVL_1$) and equilibrium ($TVL_e$) tenth-value layers are related to a specific material and account for the spectral changes in the radiation as it penetrates the barrier. Calculations must be repeated for the primary beam emerging from the accelerator, and the secondary beam due to leakage radiation during electrons acceleration and to diffusion of the primary beam from the target. Further, every zone of the facility will be characterized by its own Shielding design goal, Occupancy factor and Use factor; i.e., barrier design shall be repeated for each wall separating different areas. The bunker hosting the accelerator will be realized in concrete (2.35 g/cm^3), layout will be characterized by a maze having the aim to reduce the radiological load at the door and due attention will be devoted to barrier penetrations by electricity and hydraulic ducts. Due to the experimental nature of this project, the major effort will be due to calculation of TVL_1 and TVL_e. Calculations will be carried out by means of radiation transport codes by trying different design hypotheses.

3. Results

The expected dose per primary electron has been evaluated in the water phantom. In order to score the energy deposition, the phantom has been divided into 500 × 500 × 500 voxels of size $1 \times 1 \times 1$ mm^3 in $x \times y \times$ z direction. A two dimensional projection of the calculated dose map as a function of space coordinates is shown in Fig. 15. To reduce the statistical MC fluctuation the simulation has been performed using 10^7 primaries electron. The simulated curves of the relative dosimetry, i.e. Percentage Depth Dose (PDD) along the beam axis and dose profiles at depth of 20.9 ± 0.1 cm (R_{100}), 36.5 ± 0.1 cm (R_{80}) and 48.4 ± 0.1 cm (R_{50}) are reported in Figs. 16 and 17.

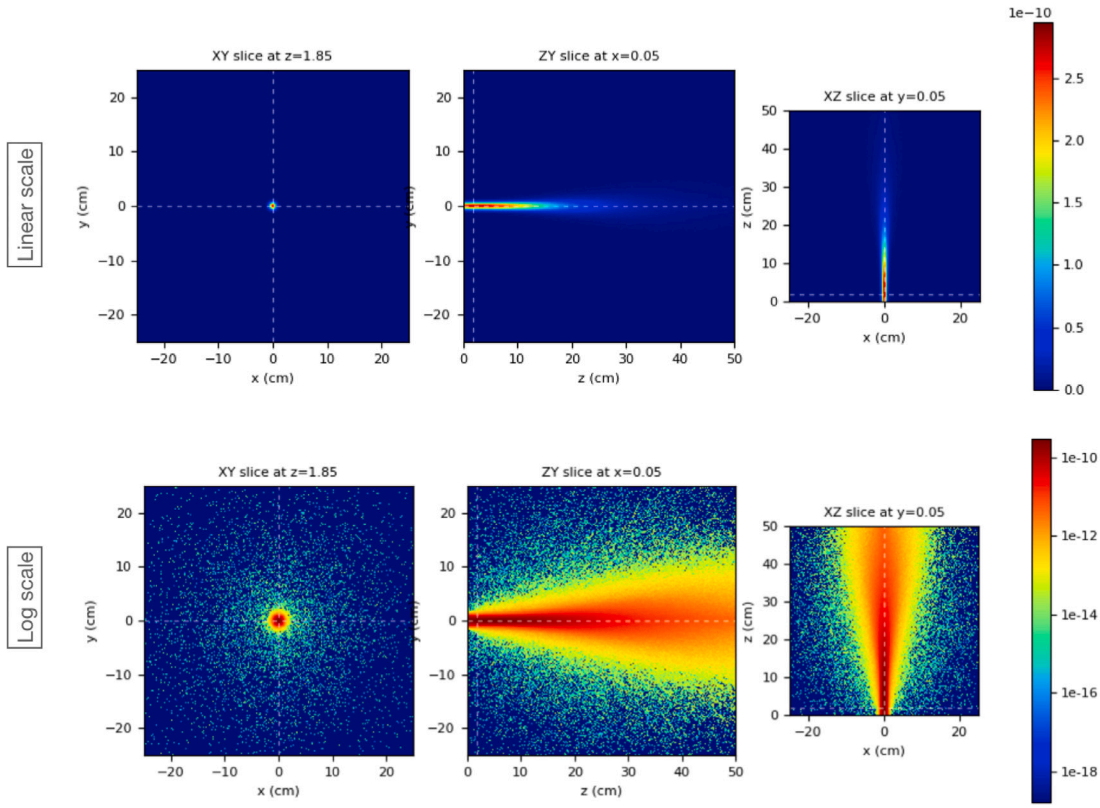

Fig. 15. 2D dose distributions on the XY slice at z = 1.85 cm (left), YZ slice at x = 0.05 cm (center) and on the ZX slice at y = 0.05 cm (right) per primary electron inside the water phantom for an electrons beam having 160 MeV nominal energy. The *z* linear scale represents the dose released in Gy/primary units.

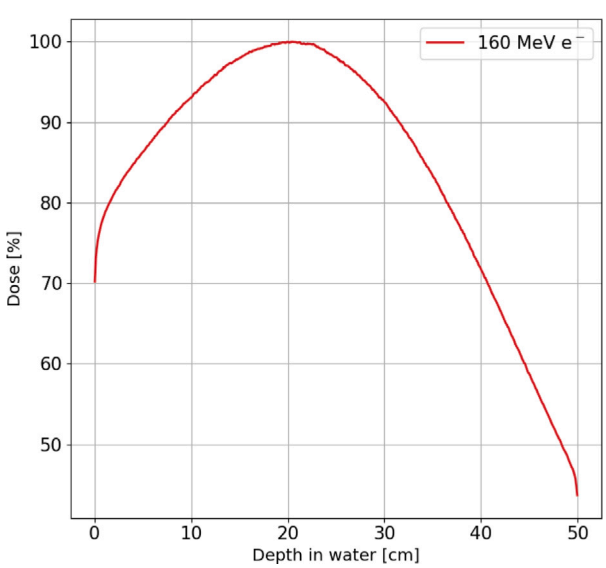

Fig. 16. Absorbed dose integrated over the longitudinal axis, i.e. the beam direction, in a water phantom for a 160 MeV electrons beam, with a Gaussian profile (FWHM = 1 cm) simulated with FLUKA. The dose has been evaluated using a 50 × 50 × 50 cm^3 scoring grid with a voxel size of 1 × 1 × 1 mm^3 and by simulating 10^7 primary electron in order to reduce the statistical MC fluctuation.

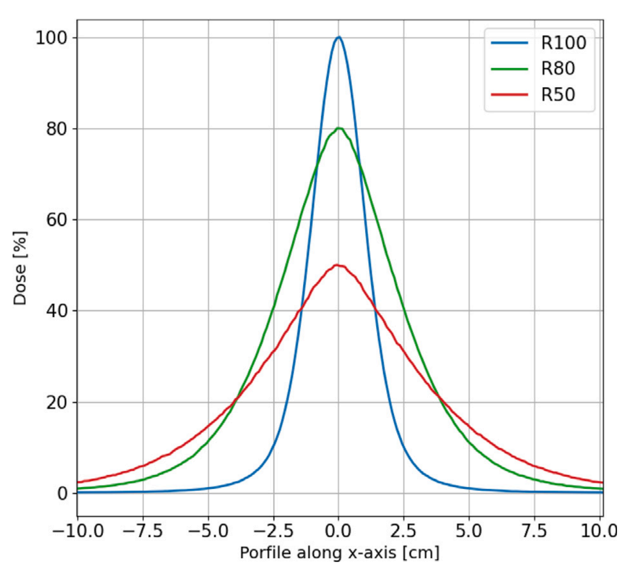

Fig. 17. Absorbed dose integrated over the transverse plane in a water phantom for a 160 MeV electrons beam, with a Gaussian profile (FWHM = 1 cm) simulated with FLUKA. The dose has been evaluated using a 50 × 50 × 50 cm^3 scoring grid with a voxel size of 1 × 1 × 1 mm^3. The transverse profiles have been evaluated at the peak value (R100), z = 21 cm, at the 80% (R80) and % 50 (R50) of the peak value, respectively at z = 37 cm and z = 49 cm.

From the FLUKA simulation we have evaluated the dose deposit at the build-up value of the longitudinal profile reported in Fig. 16. A dose value of 5.861 ± 0.003× 10^{-11} Gy/electron has been obtained. According to the VHEE high gradient linear accelerator, the value has been scaled up to an equivalent charge of $Q = 600$ nC (maximum charge per pulse), obtaining a dose per pulse of 219 Gy.

4. Proposed infrastructure layout

Our proposed project for a VHEE linac-based machine is intended for a VHEE-LINAC FLASH-RT Research Laboratory to be installed at Sapienza University for dosimetry, radiobiology and pre-clinics FLASH

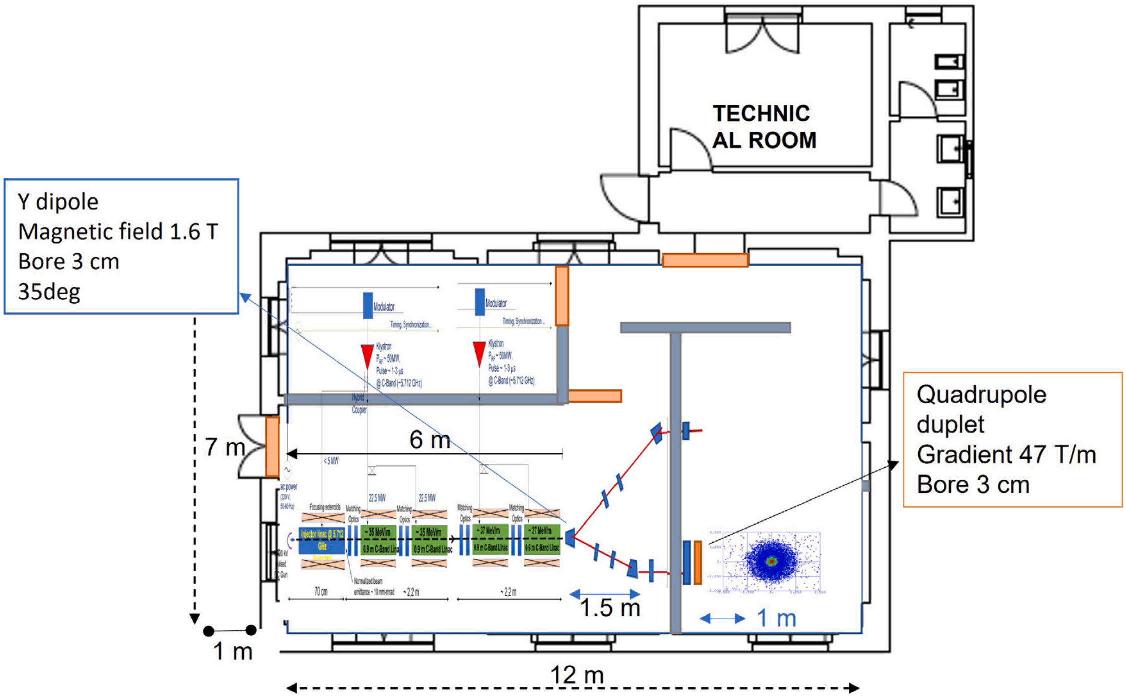

Fig. 18. Proposed infrastructure layout at Sapienza University.

experiments. In Fig. 18, the proposed layout of the infrastructure that will host the laboratory is shown. The laboratory for hosting the VHEE machine occupies a 7 m × 12 m footprint, excluding technical/control rooms.

All main subsystems are being investigated: the RF system (accelerating sections, RF power and RF Network); magnets and power supplies; beam diagnostics and electronics; radiation safety and beam dump; auxiliary plants; control system; vacuum and engineering.

5. Conclusions

In this paper, the design of the VHEE FLASH linac-based machine has been reported. The accelerator is able to deliver high-dose in single pulse or pulses sequences at ultrahigh dose-rate suitable to investigate the FLASH effect. We have developed the RF design and the beam dynamics characterization of the VHEE system optimized to operate in electron modality with two nominal output beam energies: 60 and 130 MeV (with possible upgrade up to 160 MeV by using RF pulse compressors) with a pulsed current beyond 200 mA. In order to produce variable output field sizes a dual magnetic quadrupole scheme was investigated and optimized. Studies are on going to complete the characterization of the machine and to manufacture and test the RF prototypes.

The VHEE linac-based machine is intended for a VHEE-LINAC FLASH-RT Research Laboratory to be installed at Sapienza University for dosimetry, radiobiology and pre-clinical FLASH experiments. A description of the beam characterization and benchmark with Monte Carlo simulations of the VHEE linac at 160 MeV is provided, resulting in delivered in-pulse dose-rates $\gg 10^6$ Gy/s and a dose per pulse up to 200 Gy at the build up.

The machine is suitable for the investigation of the FLASH fundamental mechanisms in pre-clinical and radiobiological experiments paving the way to the clinical transfer of the technique.

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