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BEAM DYNAMICS OPTIMIZATION OF A MODULAR AND VERSATILE LINEAR ACCELERATOR-BASED SYSTEM EXPLOITING C-BAND TECHNOLOGY FOR VHEE FLASH APPLICATIONS

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Abstract

In the framework of a collaboration between Sapienza University of Rome, the Italian Institute for Nuclear Research (INFN) and the Curie Institute, the proposal of a new facility dedicated to the Very High Electron Energy (VHEE) FLASH irradiation is in progress. The aim is to exploit the promising VHEE regime for the translation of electron FLASH radiotherapy into clinical practice in order to treat deep tumors. For the translation to clinical practice, the electron energy should be varied in the 60-160 MeV range. The needed electron peak current is the order of 200 mA, that is 200 nC per 1 us pulse. The irradiation system also requires compactness for the installation inside a hospital or treatment facility. In order to satisfy both requirements, i.e. high energy and compact system, we propose a radio-frequency (RF) linear accelerator-based electron-beam source working in C-band at 5.712 GHz. In particular, we present the beam dynamics of the optimized high-gradient C-band linear accelerating system for the transport of high beam current beams for FLASH applications.

INTRODUCTION

Today, radiotherapy (RT) is the most effective tool for treating tumors, and more than 50% of cancer patients receive RT [1, 2]. Although the advantages of RT are widely acknowledged, they are occasionally still constrained by the side effects on healthy tissues. Studies on unconventional structures in the path of radiation therapy beams have demonstrated that they can shield healthy tissues from the harm caused by ionizing radiation while maintaining the same level of tumor-curing efficacy. This phenomenon, known as the FLASH effect [3-5], is characterized by very high dose-rate irradiation (>10^6 Gy/s), rapid beam-on periods (100 ms), and high dose in the pulse (>10 Gy).

The foundation of a research lab devoted to VHEE-FLASH investigation will be built using our proposed VHEE linac-based accelerating machine at Sapienza University and that is called SAFEST [6], which will make use of optimized linacs based on our highly developed C-band technology. This collaboration will be between Sapienza University of Rome and the Italian Institute for Nuclear Physics of Frascati (INFN-LNF). A more ideal compromise for working with high-charge electron bunches, which are constrained in X-Band due to the small cavity dimensions, while yet having more compact accelerating structures than in S-Band, is to operate in C-Band using a compact and modular configuration.

C-BAND VHEE LINAC SYSTEM

The scheme of the proposed VHEE linac system is shown in Fig. 1. It is based on C-band technology and operates at a frequency of 5.712 GHz, allowing for greater compactness than S-band while maintaining enough radial aperture in the cavities to provide good particle transmission efficiency even at high currents, like those required for FLASH therapy. The accelerator comprises three primary portions that can be implemented in two phases (phases 1 and 2). In phase 1, the first accelerating standing wave (SW) linac, the injector, accelerates a pulsed DC gun's current up to 200 mA at an energy of 10 MeV. After that, the electron beam is matched using quadrupoles (matching optics) and injected into a compact linear traveling wave (TW) accelerating structure with a high accelerating gradient (above 40 MeV/m) capable of bringing the energy of the electron beam up to at least 60 MeV in phase 1 and up to 130 MeV in phase 2, using a total of four 90 cm long accelerating structures, each of which is followed by quadrupoles for matching conditions.

In the case of employing RF pulse compressors 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.

The main parameters of the proposed VHEE linac system are listed in Table 1.

In this paper, we discuss the RF and beam dynamics results for one optimized configuration. In [6], new options are reported and discussed in order to optimize the system configuration with the use of RF pulse compressors.

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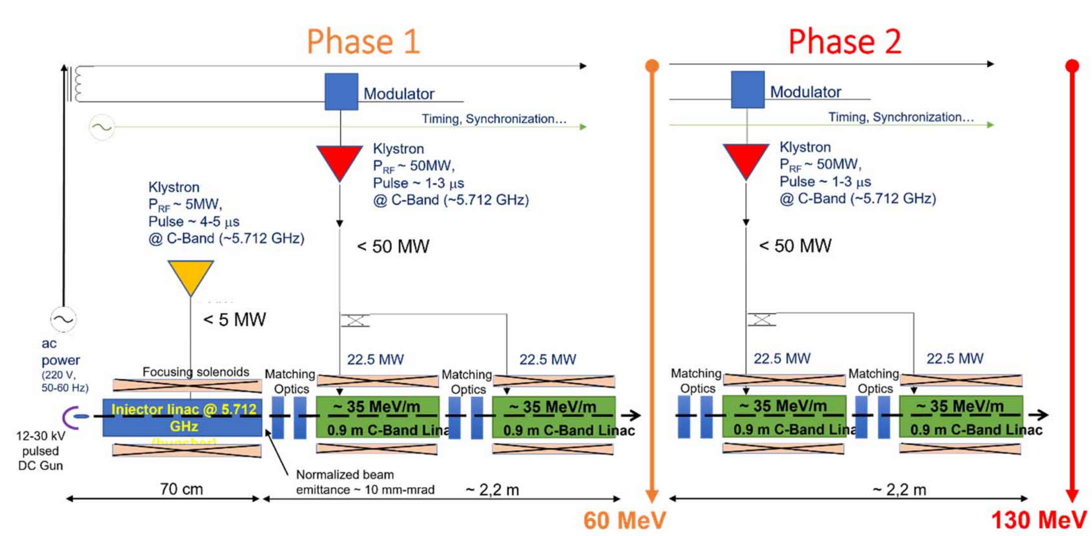

Figure 1: Beam energy gain Beam energy gain. The 12 MeV electron beam, from the injector, in launched into four 90 cm long TW linacs with an accelerating loaded gradient of 35 MV/m. The beam current at the exit is 200 mA.

RF DESIGN

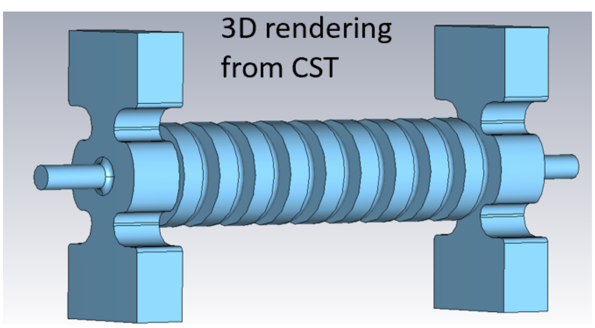

Figure 2: RF design with CST of the VHEE high gradient C-band linear accelerator prototype for VHEE FLASH radiotherapy.

The RF design of the VHEE high gradient C-band linear accelerator was carried out with the CST code. The 3D rendering is shown in Fig. 2. After an optimization process for the choice of the main accelerating linac in terms of efficiency, we decided upon a TW structure with a 90 cm length [7, 8]. We exploit the dual-feed input and output RF power couplers in order to cancel dipole field components. Moreover, a racetrack geometry for the cancellation of the quadrupole field components was used. The average iris aperture radius is a = 5 mm. The corresponding reflection coefficient is S_{11} = -35 dB at 5.712 GHz.

Table 1: Main VHEE Linac Parameters

Parameter	Value
Beam Energy	60 - 160 MeV
RF frequency	5.712 GHz
Pulse repetition frequency	> 100 Hz
Pulse width	1 - 3 µs
Pulse Charge	200 - 600 nC
Pulse Current	200 mA
In-Pulse Dose-Rate	>> 10^7 Gy/s

BEAM DYNAMICS OPTIMIZATION

The TSTEP and ASTRA numerical codes were used to run the beam dynamics simulations. We display the electron beam energy gain from the cathode, which is situated at z = 0 m, in Fig. 3. A triode electron cannon with an approximately 6 mm-diameter spherical emission region serves as the cathode. Although it can be adjusted up to 30 keV (to improve beam capture inside the first injector linac in the future), the nominal operating energy is around 12 keV. The cathode electron beam current is set at 600 mA. The bunching part of the injector linac, which was previously addressed, is adjusted to maximize beam charge capture, which is calculated to be roughly 45%, or 225 mA.

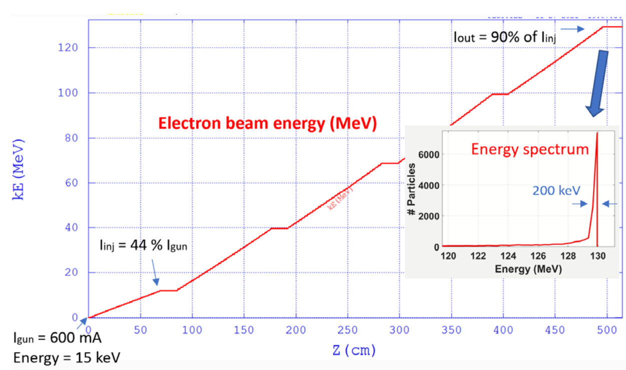

Figure 3: Beam energy gain Beam energy gain.

For radioprotection simulations, it is determined how much of this current will be lost during transport through the ensuing accelerating structures. The highest current of our suggested project, four TW linacs operating at about 35 MV/m loaded gradient at 200 mA beam current, are placed after the injector in the VHEE arrangement. 50 accelerating cells make up each TW linac, and this chapter has already covered the key RF parameters. For the

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purpose of simulating beam dynamics, the electromagnetic field maps of each TW structure are produced using the SUPERFISH code and given as input to TSTEP.

All of the linacs are phased with the electron beam operating in on-crest mode, and the accelerating gradient is 35 MV/m. Figure 3 illustrates the arrangement of the linacs and the beam energy gain. This modular design verified that the beam could be transported optimally up to the desired maximum current of 200 mA at exit. The total length of the linac is 5 m. The RMS beam envelope is displayed in Fig. 4.

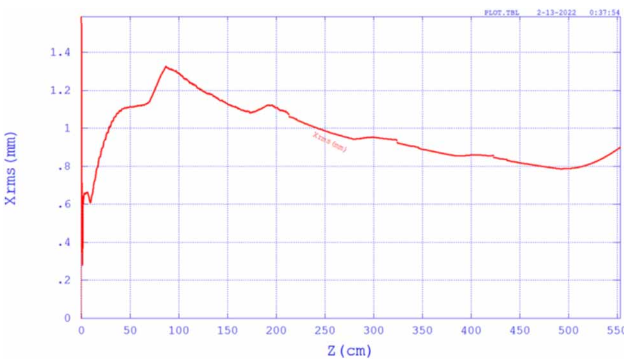

Figure 4: RMS Electron beam envelope from the cathode up to the last linac exit at 500 cm.

Thanks to the induced RF focusing of the high-gradient C-band linacs, the beam is confined without employing solenoids up to the linac exit at about 500 cm. The transverse RMS size of the beam is about 0.8 mm. Each bunch length is about 20 ps FWHM which is typical for DC cathode emissions. The FWHM value for the energy spread is 0.2%. The overall transverse distribution is concentrated in an area with a diameter of roughly 4 mm, and the beam spot has an FWHM value of 1.8 mm. The normalized transverse beam emittance is in the order of 10 mm-mrad.

BEAM BREAK-UP ANALYSIS

Preliminary beam break-up (BBU) analysis, i.e. the effects of higher-order modes (HOM's), has been preliminarily performed by using a dedicated fast code which was developed inhouse and called *MILES* [9]. We considered a maximum pulse current of 200 mA and an RF pulse length of 2 µs. The total RF pulse charge is 400 nC. The number of bunches is 11424 with a charge per bunch equal to 35 pC. The entire train of bunches is injected 50 μm off-axis. We considered the worst-case scenario, i.e. a constant iris radius a = 3 mm and all the cell HOMs at same RF frequencies (no-detuning).

It results that the displacement from the linac axis is contained and negligible, as shown in Fig. 5. The bunches subjected to deflection remain close to the nominal trajectory within 20%.

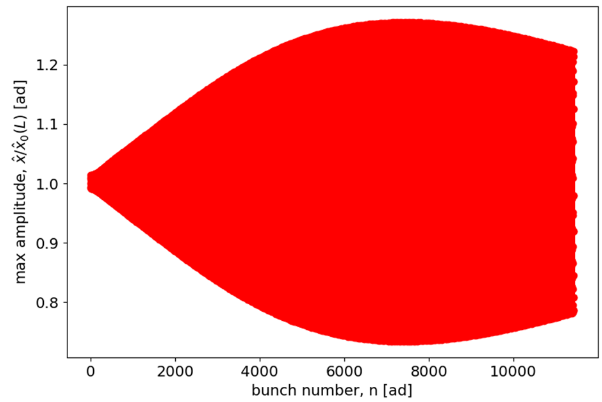

Figure 5: Transverse displacement of each bunch at linac exit.

CONCLUSIONS

The suggested linac system for a VHEE laboratory to be built at Sapienza University, termed SAFEST, in collaboration with INFN, consists of high acceleration gradient structures in C-band that can attain an energy range of 60 to 160 MeV. This high-energy end can be achieved by using energy pulse compressors with a total linac system within 4 m length. The injector section is a low energy (12 MeV), high current (200 mA per RF pulse) linac. Our initial RF and beam dynamics simulations show promising results.

The RF parameters of the linac were discussed and used as reference in both RF and beam dynamics simulations. The beam dynamics simulations were carried out with the aid of the TSTEP and ASTRA programs in order to optimize the accelerated pulse beam current.

Additional research is being done to finish the machine's characterization. We have recently realized two prototypes of the VHEE C-band linacs. The prototypes made out oc copper were brazed in a high-temperature furnace at INFN-Frascati. One of the prototypes was mechanically characterized to verify the brazing conditions. The other one was low RF power tested at the RF lab at Sapienza University. The fabrication of the final version of the linacs including the symmetrized power couplers is in-progress.

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