ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB410

PRELIMINARY STUDIES OF A COMPACT VHEE LINEAR ACCELERATOR SYSTEM FOR FLASH RADIOTHERAPY

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Abstract

The FLASH Radiotherapy is a revolutionary new technique in the cancer cure: it spares healthy tissue from the damage of the ionizing radiation maintaining the tumor control as efficient as in the conventional radiotherapy. To allow the implementation of the FLASH Therapy concept into actual clinical use, it is necessary to have an accelerator able to deliver high dose per pulse (>1-2 Gy) in very short time pulse duration (μs) and high dose rate (> 10^6 Gy/s). Today, low energy (up to 7 MeV) S-band LINACs are being used in radiobiology and pre-clinical applications. However, in order to treat deep tumors the energy of the electrons should achieve the range of 50-250 MeV [1,2]. In this paper we address the main issues in the design of a compact C band (5.712 GHz) Very High Electron Energy (VHEE) for FLASH Radiotherapy. We present preliminary studies of a C-band system done at La Sapienza and INFN, aiming to reach a high accelerating gradient and high current necessary to deliver a dose >1 Gy/pulse, within a beam pulse of μs.

INTRODUCTION

Nowadays conventional radiotherapy is the best ally for tumor treatment, it requires several weeks to deliver the necessary dose for the cancer cure and to preserve the healthy tissues from the damage of the ionization radiations. In 2014 Favaudon et al. [3] discovered a new effect, called FLASH, that can change the scenario of the radiotherapy. Several preclinical studies demonstrated that a high dose (> 10 Gy) in a limited number of 1-10 Gy pulses, ultra fast beam delivery and total irradiation time < 100 ms, decreases dramatically the toxicity in the healthy tissue while keeping the same efficacy in cancer treatment. In this scenario our group was involved in the design of an accelerator dedicated to the FLASH irradiation (S-band, 7 MeV, peak current 100 mA, RF pulse < 4 μs). The accelerator was built by the company SIT - Sordina IORT Technologies S.p.A. and is now in operation at Curie Institute in Orsay (France) [4,5]. Currently, a new design of a compact 12 MeV electron LINAC adopting a C-band accelerating structure is being developed in collaboration with SIT - Sordina IORT Technologies S.p.A. In order to treat deep tumors we are investigating also a VHEE system which would allow to treat patients with a high dose rate in very short time of irradiation in FLASH regime [6]. In the following, the preliminary study of a VHEE accelerator, based on a RF injector able to accelerate a current of 200 mA at 10 MeV, followed by a compact C-band RF structure with a high accelerating gradient (> 50 MeV/m), is presented. The case of a solution using a power pulse compressor is also discussed.

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FLASH PARAMETERS

The definition of FLASH regime requires the specification of different inter-dependent temporal parameters such as pulse repetition frequency (PRF), pulse-number n_p and width t_p, dose per pulse (D_p), in-peak dose-rate ($\dot{D}_p$), as well as the time-averaged dose rate ($\bar{\dot{D}}$) and the total irradiation time from the beginning of the first delivered pulse to the end of the last delivered pulse [7]. These FLASH parameters are illustrated in Fig.1 and their reference values are given in Table 1.

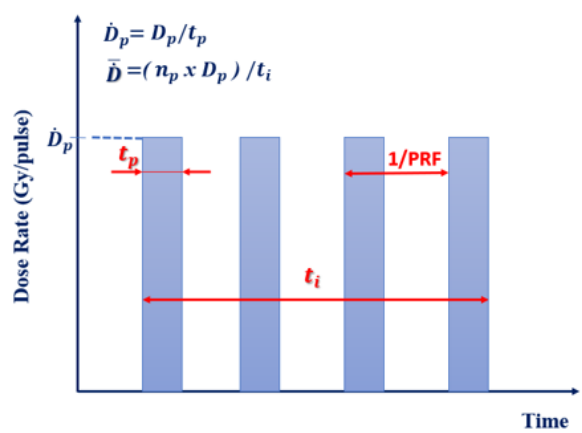

Figure 1: Scheme of an ideal pulsed beam temporal structure.

VHEE LINAC LAYOUT

The scheme of the VHEE System under study at Sapienza and INFN team is shown in Fig. 2. Typically, a linear accelerator comprises three main parts: electron beam injector, the

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Table 1: Reference FLASH Parameters

Symbol	Description	Value
PRF	Pulse repetition frequency	> 100 Hz
t_p	Pulse width	0.1-4.0 µs
t_i	Total irradiation time	< 100 ms
$\bar{D}$	Time-averaged dose rate	> 100 Gy/s
$\dot{D}_p$	Dose-rate in a single pulse	> 10^6 Gy/s
D_p	Dose in a single pulse	> 1 Gy

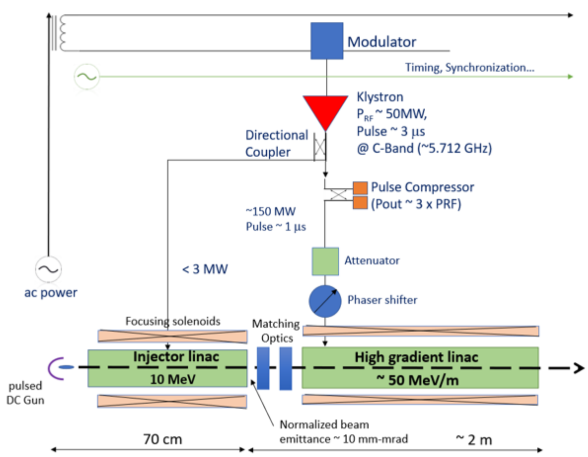

Figure 2: Layout of the C-band accelerator for VHEE FLASH radiotherapy.

accelerating structure and RF power distribution system. In the following sections we will describe the main accelerator components having parameters suitable to deliver FLASH beams.

Injector

The electron beam, provided by a pulsed DC gun, is captured and accelerated by a low energy LINAC. The injector structure is a standing wave, magnetically coupled, biperiodic and it operates at 5.712 GHz (C-band) in the $\pi/2$ mode (see Table 2). In this configuration the accelerating cells are alternated with non excited coupling cells on axis. The injector is designed to deliver an electron beam with a current up 200 mA and an energy of about 10 MeV.

Table 2: Injection Parameters Lists

Parameter	Value
Frequency of operation	5.712 GHz
Effective shunt impedance	110 MΩ/m
Quality factor	~ 10000
Pulse length	1.0-3.0 µs
LINAC length	~ 60 cm
Output Energy	10 MeV
Peak Beam Current	~ 200 mA
RF Input Power	< 3 MW

Several simulations of the electromagnetic field inside the structure were performed with the code CST [8] for the optimization of the main RF parameters, such as the operating frequency, the effective shunt impedance, the quality factor and the bandwidth.

In Fig. 3 we show the behavior of the on axis electric field obtained with CST. The field in the first bunching section is optimized to increase the beam capture.

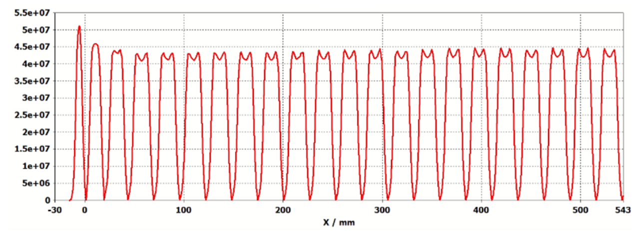

Figure 3: Injector's on-axis electric field.

The injector is matched to the high gradient accelerating structure which brings the electron energy up to 100 MeV. Both the injector and accelerating structure are fed by a C-band RF power source (klystron). The klystron power signals are timed and synchronized between the two acceleration parts. The electron beam is confined and guided by magnetic matching quadrupoles and solenoids.

High Gradient Structure

The realization of the proposed compact VHEE LINAC requires a high gradient accelerating structure (> 50 MeV/m). It is well known that the surface electric field inside the structure is the main limitation of the high gradient structure, as high fields increase the probability to have discharges at walls. In recent years, a high gradient C-band accelerating structures has been studied and developed at Sapienza University and LNF-INFN [9–11], and installed at the SPARC facility in Frascati Laboratory. A second C band prototype, with higher order modes dampers for multibunch operation, was successfully tested at the nominal gradient of 33 MeV/m [12–15]. More recently, C-band disk-loaded-type accelerating structures were developed and installed on the EUV-FEL beam line at SACLA, operating with an accelerating gradient of 41.4 MeV/m [16].

For the compact VHEE FLASH LINAC we are studying an optimized high gradient C-band (5.712 GHz) accelerating structure able to achieve > 50 MeV/m. It consists of a typical travelling wave (TW) LINAC operating in the TM_{01} mode with a field phase advance per cell of $2\pi/3$ with advance coupling [17]. A prototype will be tested at low power at the Radio Frequency Laboratory for Accelerators at La Sapienza University in order to measure and validate the RF parameters and the main electromagnetic features such as the electric field profile along the structure.

The total LINAC length is given by the length of the injector plus the high gradient structure, including the matching optics. The VHEE parameters LINAC suitable to satisfy the criteria for FLASH beam are described in Table 3. With a

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peak current of 200 mA and pulse duration of 3 µs the charge is 600 nC, corresponding to about 12 Gy in a single pulse with ∅10 cm of irradiation surface.

Table 3: VHEE FLASH LINAC Parameters

Marginarameter	Value
Frequency of operation	5.712 GHz
Output Energy	> 60 MeV
Output Beam Current	200 mA
Pulse width	3.0 µs
PRF	100 Hz
Klystron RF Power	50 MW
Effective shunt impedance	> 110 MΩ/m
Quality factor	~ 10000
High gradient structure length	~ 180 cm
Total LINAC length	~ 300 cm

Preliminary results for Shunt impedance and group velocity for the single cell of the high gradient LINAC are shown in Fig. 4 for various iris radii.

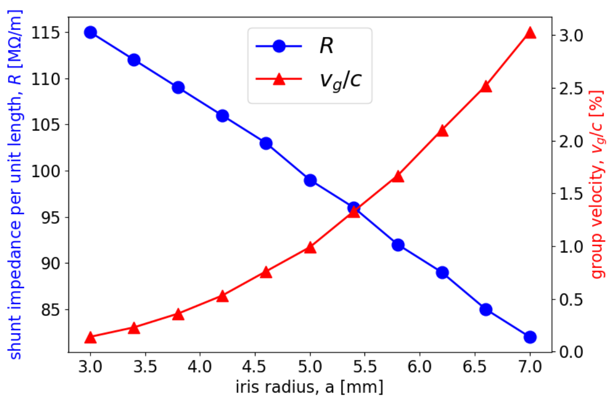

Figure 4: Preliminary results for Shunt impedance and group velocity for single TW cell.

RF Power and Pulse Compressor Option

In order to reach the design range of energy, the whole LINAC has to be powered by a klystron providing 50 MW in an RF pulse of 3.0 µs, with a repetition frequency rate of 100 Hz [18]. Part of the power, ~ 3 MW , is used for the injector, the remaining power feeds the high gradient structure which would accelerate a total charge of 600 nC at a maximun energy of 60 MeV assuming the modality option without pulse compressor. In order to reach a higher energy, the system is equipped with a pulse compressor (SLED type from SLAC or BOC from PSI), which compresses the RF pulse to 1.0 µs such to multiply the available power by a factor 3. The corresponding pulse charge of 200 nC is accelerated at a maximum energy of 100 MeV. In the Table 4 we report the principal parameters obtained with the pulse compressor. The design of a dedicated pulse compressor is under development at INFN-LNS and INFN-LNF. The full 3D-wave electromagnetic simulations are being performed to find the optimal waveguide-to-cavity coupling and to simulate the main RF pulse compressor parameters. The design of RF mode converters from the input waveguide mode to the RF Pulse Compressor cavity mode will benefit from the experience at INFN in the design of high-power mode launcher with reduced undesired modes [19, 20]. Moreover, the experience gained by INFN in manufacturing and testing high power components for LINAC will be used to obtain lower risk of RF breakdown such as reducing RF field around the edges, avoiding a large number of brazed parts, using if possible special joint-free open structures [21].

Table 4: VHEE FLASH LINAC Parameters With Pulse Compressor

Parameter	Value
Frequency of operation	5.712 GHz
Output Energy	100 MeV
Output Beam Current	200 mA
Pulse width	1.0 µs
PRF	100 Hz
RF Power	~ 150 MW

The output energy at 100 MeV takes into account the beam loading effect due to the high beam current that we have estimated to be roughly -13 MeV/100 mA. The achievable dose parameters with pulse power compressor on/off are reported in Table 5.

Table 5: Dose Parameters for VHEE FLASH LINAC

Parameter	Value
Beam energy	100 – 60 MeV
Pulse width	1.0 – 3.0 µs
Pulse charges	200 – 600 nC
D_p	4 – 12 Gy in ∅10 cm
$\dot{D}$	> 100 Gy/s
$\dot{D}_p$	> 10^6 Gy/s

CONCLUSION

A compact C-band LINAC for VHEE FLASH irradiation is under study at Sapienza University of Rome and INFN. The system is composed by an injector with high current (> 200 mA) and low energy (10 MeV) followed by high gradient structure able to reach an energy up to 100 MeV. Several studies for the RF components are being developed with the aim of testing the prototypes.

ACKNOWLEDGEMENTS

This work is supported by La Sapienza University, research grant “grandi progetti di ricerca 2020”

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