DESIGN AND TEST OF C-BAND LINAC PROTOTYPES FOR ELECTRON FLASH RADIOTHERAPY

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Abstract

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FLASH Therapy [1], a novel cancer treatment technique, aims to control the tumor-grown sparing the healthy tissue from radiation damage, increasing the therapeutic index. Translating FLASH therapy into clinical practice, especially for treating deep-seated tumors, necessitates achieving Very High Electron Energy (VHEE) levels within the 50-150 MeV range [2]. In the framework of the SAFEST project [3-7], Sapienza University, in collaboration with INFN, is actively developing a compact C-band linac demonstrator at the energy of 24 MeV (loaded) with a 100 mA peak current. This paper provides insights into the design strategy and electromagnetic characteristics, focusing on prototype testing and tuning conducted at the Sapienza Accelerator Laboratory. The progress of this innovative linac represents a step toward realizing an advanced FLASH VHEE source in cancer treatment.

INTRODUCTION

FLASH radiotherapy (RT) has attracted significant attention within the cancer research community due to its potential to effectively treat tumors while minimizing damage to surrounding healthy tissues. Preclinical studies have shown that delivering electron radiation in extremely short bursts (less than 100 ms) at ultra-high instantaneous dose rates (exceeding 10^6 Gy/s) can significantly reduce toxicity in healthy tissues while maintaining therapeutic efficacy against cancer.

The first experiment involving FLASH-RT was conducted by V. Favaudon and his team at Institut Curie in 2014 [1]. Since then, various in-vivo and in-vitro radiobiological studies have reported substantial sparing of normal tissues, nevertheless, more research is necessary to fully comprehend the advantages and limitations of FLASH-RT and to identify the best clinical applications. Currently, only a limited number of dedicated electron linacs are employed for experimental research, with ongoing studies and technological advancements aimed at developing more compact and cost-effective linacs for high-energy electrons. The ultimate goal is to

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adapt these linacs for the treatment of deep-seated tumors using Very High Energy Electron FLASH radiotherapy.

At La Sapienza University of Rome, in collaboration with the Italian Institute for Nuclear Research (INFN), we are developing a high gradient C-Band (5.712 GHz) FLASH linac demonstrator [8] with the aim of testing all key components necessary for a VHEE Linac (Fig. 1). The first stage of the demonstrator consists of a compact Standing Wave (SW) bi-periodic structure operating in $\pi/2$ mode followed by a high-gradient traveling wave (TW) structure, with a phase advance of $\frac{2}{3}\pi$, intended to accelerate the electron beam up to 24 MeV (loaded with 100 mA pulse current), the maximum energy being limited by radio-protection constraints in the University laboratory.

In this paper, we present the status of the design and construction of the prototype which has to deliver ultra-high dose rate (UHDR) pulses typical of the FLASH regime [9], as reported in Table 1.

Table 1: Most Used Parameters for	for FLASH Irradiation
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Symbol	Description	Value
PRF	Pulse repetition frequency	> 100 Hz
t_p	Electron pulse width	0.1-4.0 μs
t_i	Total irradiation time	< 100 ms
$\overline{\dot{D}}$	Time-averaged dose rate	> 100 Gy/s
$\dot{D_p}$	Dose-rate in a single pulse	> 10 ⁶ Gy/s
$\dot{D_p}$	Dose in a single pulse	> 1 Gy

The facility will offer an adaptable platform for conducting radiobiology experiments using both in-vitro and in-vivo samples, and it will support the development and testing of innovative devices for precise measurements and monitoring of electron beam parameters in FLASH conditions.

FACILITY PARAMETERS AND LAYOUT

The proposed basic system (Fig. 1) is composed of a standing wave injector and a traveling wave accelerating structure. A continuous electron beam of about 220 mA is generated by a DC gun with a pulse length of 1 μ s. The accelerating structures are powered by a 5 MW klystron with an RF pulse length of 5 μ s. The klystron output feeds a pulse

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Figure 1: Layout of VHEE FLASH linac demonstrator.

compressor to obtain a pulse length of 1.67 μ s and 24.4 MW peak power available; then a power splitter distributes the power asymmetrically downstream of the pulse compressor. The standing wave structure receives 30% of the maximum available power, while 70% is directed to the traveling wave structure.

The standing wave structure captures and accelerates a 1 μ s pulse current of 100 mA, up to the energy of about 10 MeV, which is brought to the energy of 24 MeV by the traveling wave section. The main parameters of the whole system are reported in Table 2.

Table 2:	Linac	Parameters	at Sapienza	University
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Parameters	Value
Frequency	5.712 GHz
Klystron Power	5 MW
RF pulse width	5 µs
Repetition frequency	< 200 Hz
Peak power after compression	24.4 MW
Total linac length	150 cm
Nominal beam energy (loaded)	24 MeV
Pulse current	100 mA
Pulse current duration	1 µs

PULSE COMPRESSOR

A preliminary RF design of a spherical pulse compressor (Fig. 2) has been developed for the VHEE as part of the FRIDA project by INFN [10]. It consists of two subsystems: a special 3 dB coupler (or circular polarizer) and a spherical storage cavity. These components were first designed separately and then assembled together, using the CST MW Studio ®2022 [11] simulation software. For the spherical cavity, two degenerated TE₁₁₄ have been chosen as operating modes because of their high unloaded quality factor, Q_0 = 134 × 10³. The main specifications of the spherical cavity pulse compressor are summarized in Table 3.



Figure 2: Spherical cavity pulse compressor showing the TE114 electric field.

Table 3: Main Specification	s of the Pulse Compressor
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Parameter	Design Value
Resonant frequency [GHz]	5.712
Operating mode	TE_{114}
Unloaded Quality Factor Q_0	134000
Coupling coefficient β_{sled}	3
RF input pulse length [µs]	5

STANDING WAVE STRUCTURE

The standing-wave, bi-periodic structure is composed of 27 accelerating cells alternated with coupling cells, where the electric field is null (Fig. 3).



Figure 3: Electric field in the Standing Wave injector.

The first three accelerating cells form the bunching section, where a higher peak electric field improves the beam capture [12]. The standing wave field configuration offers the advantage of maintaining a stable and well-focused particle beam without requiring additional focusing magnets, such as solenoids. To maximize the shunt impedance (R_{shunt}) we adopted a nose-cone geometry that concentrates a very high electric field on the axis, enhancing the beam acceleration along the structure. The power from the splitter flows through a waveguide at the center of the structure designed with a coupling coefficient (β_c =1.58) accounting for the beam loading effects. The main parameters of the SW structure are detailed in Table 4.

A 5-cells copper prototype of the SW structure was constructed in collaboration with SIT Sordina IORT Technology Spa and characterized at the Accelerator Laboratory of Sapienza University of Rome [13]. The bead-pull technique was employed to investigate the on-axis accelerating electric field of the prototype. The tuning procedure provided a nearly uniform electric field distribution across the accelerating cells and, as expected, no field was detected in the coupling cells.

Table 4: Standing Wave Parameters

Parameters	Value
Structure length	69 cm
Shunt Impedance R _{shunt}	116 MΩ/m
Quality factor Q_0	10178
Mode of operation	Bi-periodic $\pi/2$
N of accelerating cells	27
Coupling cells length	3 mm
Iris radius	3 mm
Filling time	0.220 µs
Beam capture	45%
Beam output energy	10 MeV

TRAVELING WAVE STRUCTURE

Further, we designed the C-band traveling wave (TW) accelerating structure, Fig. 4, to operate in the TM_{01} -like mode with a phase advance per cell of $\frac{2}{3}\pi$. Preliminary studies were focused to achieve a high shunt impedance with a reasonable iris radius which was varied within the range from 3 to 7 mm in the Constant Impedance (CI) configuration, keeping the frequency precisely at 5.712 GHz. Due to maximum energy constraints of 24 MeV, a 43 cm long structure with an iris radius of 5 mm was selected, with a group velocity of 0.01*c* and a filling time of 0.143 µs.



Figure 4: Electric field in the Traveling Wave structure.

Using CST Studio SUITE, we obtained the main RF parameters, a quality factor $Q_0 = 10630$, and the shunt impedance per unit length $R_{shunt} = 107 \text{ M}\Omega/\text{m}$, as reported in Table 5. Prototypes of the TW structure were constructed "in-house", in collaboration with INFN, and tested at Sapienza RF laboratory.

BEAM DYNAMICS SIMULATION

Extended beam dynamics simulations were conducted to analyze the behavior of the electron beam from the gun to the Linac exit using the ASTRA code [14] codes. The electron beam is generated at the cathode at a nominal energy of 12 keV.

Our study first focused on the acceleration and transport of a single bunch of 18 pC, through the linac using a field pattern ensuring the 24 MeV final energy. The primary objective was to evaluate the transport efficiency from the cathode to the end of the accelerator, particularly concerning

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Table :	5:	Travelin	g Wave	Parameters

Parameters	Value
Structure length	43 cm
Shunt Impedance R _{shunt}	107 MΩ/m
Quality factor Q_0 (cell)	10630
Туре	Constant Impedance
Operation mode	$\frac{2}{3}\pi$
Iris radius	5 mm
Filling Time	0.143 µs
Group velocity	0.01c
Final beam energy	24 MeV

beam capture through the SW cavity. According to ASTRA simulations, the beam capture efficiency is approximately 45%. Therefore, to achieve nominal beam current of 100 mA at the accelerator's exit, an emission of roughly 220 mA is required at the cathode.

At the final energy of 24 MeV, the bunch transverse size is around 1.2 mm (rms), and the bunch length is approximately 23 ps (rms).

CONCLUSIONS

The proposal of a C-band linac demonstrator at the Sapienza Accelerator Laboratory for FLASH radiotherapy represents significant advancements in the development of efficient and precise compact acceleration systems in view of VHEE-RT applications.

The design and optimization of the RF power system, of standing wave and traveling wave structures have been performed, as well as start-to-end beam dynamics simulations. A total electron beam current of 100 mA at an energy of 24 MeV can be transported through the system allowing UHDR pulses for in-vitro and in-vivo radiobiology experiments.

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