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SAFEST: A COMPACT C-BAND LINEAR ACCELERATOR FOR VHEE-FLASH RADIOTHERAPY

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Abstract

FLASH Radiotherapy is a promising revolutionary new technique in cancer cure. Several pre-clinical studies have demonstrated that a treatment with electron radiation delivered with mean dose rates above $100 Gy/s$, an ultra-high instantaneous dose rate $> 10^6 Gy/s$ and total irradiation time $< 100 ms$, significantly decreases the toxicity in the healthy tissue while keeping the same efficacy in cancer treatment.

Although recent studies shed some light on the biological mechanisms and on the effects of FLASH electron beams on tissues and organs of small animals, more research investigation is necessary before the FLASH technique can be translated into clinical applications. Researchers also aim to explore the radio-therapeutic effects of high-dose beams delivered at Very High Electron Energy (VHEE), in the range of 50-250 MeV, suitable for treating deep-seated tumors. Since 2021 Sapienza University, in collaboration with INFN, developed a feasibility study of SAFEST, (SApienza Flash Electron Source for radioTherapy) [6], a compact C-band VHEE facility, at the energy of 60-130 MeV, able to deliver a high peak current of $100 mA$ and the very high dose rates required in the FLASH regime. In this paper, we present the project of the first module of SAFEST, partly funded through the PNRR Project, Heal-Italia.

INTRODUCTION

FLASH radiotherapy [1] is an innovative radiation therapy technique that delivers high doses of radiation in very short bursts, typically in less than a second, centrally to conventional radiation therapy, which delivers the same total radiation dose over a longer period of time. The main advantage of FLASH radiotherapy is that it appears to spare healthy tissues while effectively killing cancer cells. FLASH radiotherapy (RT) has witnessed significant advances in recent years, focusing on improving and developing new facilities [2–5, 7–10] and on radio-biology experiments addressed to unveil the mechanism underlying the FLASH effect. In this paper, we describe a module of the SAFEST project, a research facility based on a compact VHEE LINAC operating in C-band (5.712 GHz) [6]. The LINAC is designed to deliver a high current required for the FLASH regime when irradiating large fields, e.g., an area of $10 cm$ x$10 cm$, which is considered the utmost case. The facility would provide a uniquely flexible platform for conducting radiobiology experiments, using in-vitro and in-vivo samples for deep tumors. Additionally, it would facilitate the development and testing of innovative devices that can accurately measure and monitor electron beam features in FLASH conditions.

FACILITY PARAMETERS AND LAYOUT

Table 1: SAFEST Module Key Parameters

Description	Value
Frequency	5.7115 GHz
Beam energy	80 - 100 MeV
Pulse repetition frequency	100 Hz
RF Pulse duration	1,25 - 2,5 µs
Nominal current	100 mA
In-pulse dose rate	> 10^6 Gy/s
Dose per pulse	»1 Gy
Average dose rate	> 100 Gy/s

The proposed basic modular system comprises one standing wave injector and two traveling wave high-gradient accelerating structures operating at a frequency of 5.712 GHz in the C-band technology. It provides a compact design resulting in a good compromise between a high accelerating gradient and sufficient large irises radius to achieve good particle transmission efficiency even when a high current is required. The basic layout is shown in Figure 1, it consists of two parts. The first is a standing wave (SW) injector that can accelerate the current emitted from a pulsed DC gun at an energy of 10 MeV. After that, the beam is injected into

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two successive linear traveling wave (TW) structures, 1 m long, with a high accelerating gradient. We consider feeding the three structures with a single 50 MW Klystron, with an effective available power of 45 MW, using asymmetric and symmetric splitters. With a feeding power of 20 MW, each TW structure has an unloaded gradient of about 37 MV/m, which is reduced to 35 MV/m in the loaded case with a beam current of 100 mA. With this configuration, the system accelerates the beam at an energy of about 80 MeV.

To increase the energy, at the expense of a shorter RF pulse and consequently less charge per pulse, we envisage using a power pulse compressor [12]. Assuming a realistic compression factor of 1.6 which reduces the RF pulse length and increases available power at 70 MW, which allows powering the TW sections with 30 MW, and reaches a final energy of about 100 MeV.

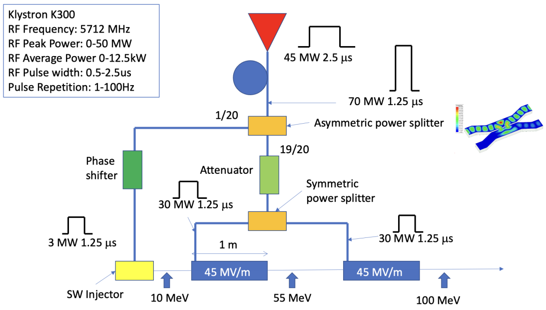

Figure 1: Basic layout with pulse compressor.

RF STRUCTURES DESIGN

Standing Wave Injector

The Injector is designed using a C-Band, standing-wave (SW), bi-periodic structure based on previous experience with FLASH Linacs [5]. The Linac operates in a $\pi/2$ - mode, alternating coupling cavities with no electric field and accelerating cavities where the electric field on the beam axis is maximum. The first part of the Linac presents a bunching section composed of three SW cavities with different lengths, which considers the initial non-relativistic speed of the electron beam $\beta \ll 1$. To maximize R_{sh} and, thus, the efficiency of the acceleration, a nose-cone structure was adopted. The main parameters of the $\pi/2$ -mode, bi-periodic SW section are listed in Tab.2 First prototype (Fig.2) has been developed and tested at Sapienza laboratory.

Table 2: C-band Standing Wave Parameters

Description	Value
Frequency	5.7123 GHz
Beam final energy	up to 10 MeV
Quality factor	11260
Shunt Impedance	115.94 MΩ /m
Waveguide-to-linac coupling β	1.3
Power Input	3 MW

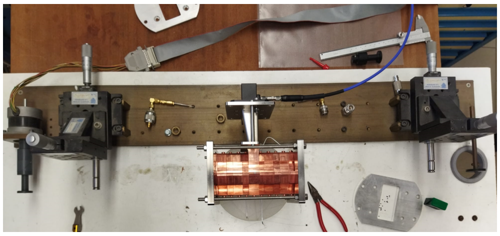

Figure 2: Standing Wave prototype.

Traveling Wave Structure

We designed the C-band high gradient TW accelerating structure operating in the TM01-like mode with a phase advance per cell of $\frac{2}{3}\pi$, which guarantees the best efficiency for this type of accelerating cavity. Preliminary studies aimed to optimize the accelerating gradient, the length of the accelerating structures, and the radius of the irises. The iris radius of the linac cells was studied in the range between 3 and 7 mm in the Constant Impedance (CI) configuration, keeping the frequency of mode TM01-like exactly at 5.712 GHz. In Fig. 3 we show the attainable average accelerating gradient versus the iris radius for two lengths of the structures (1.8 *m* and 1.0 *m*), assuming different feeding power scenarios. In Fig. 4, we show the filling time versus the iris radius for the two structure lengths.

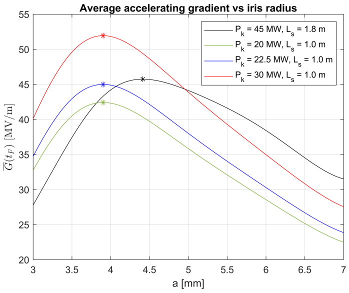

Figure 3: Average accelerating gradient vs. iris radius.

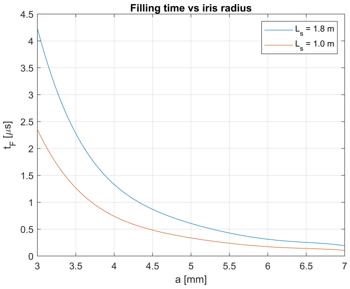

Figure 4: Filling time vs. iris radius.

We clearly see that the highest accelerating gradient would be obtained in the case of a structure 1 m long, with an iris of 3.8 cm fed with 30 MW power. However, as shown in Fig.4, with this iris radius, the filling time is 0.75 µm., too long compared to 1.25 µm, the length of the compressed RF pulse. Therefore, a structure 1.0 m long with an iris radius of 5 mm was chosen to provide an unloaded accelerating gradient of

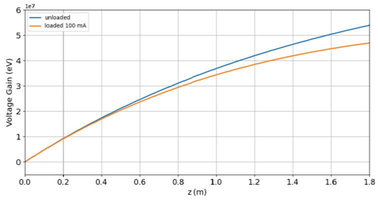

Figure 5: Voltage gain vs. length, unloaded and loaded @100 mA.

45 MeV/m and a filling time of 0.35 µs. Using CST Studio SUITE we simulated the whole structure obtaining the main RF parameters. The quality factor is around $Q = 10.000$, and the shunt impedance per unit length of the accelerating mode is in the order of R=100 $\mathrm{M}\Omega/m$. With these values of Q and R we obtained the Voltage gain vs structure length for the unloaded and 100 mA loaded cases.

Table 3: Traveling Wave Parameters

Description	Value
Structure length	1 m
Type	Constant Impedance
Iris radius	5 mm
Gradient@30MW	45 MV/m
Filling Time	0.350 µs
Quality factor	10.000
Shunt impedance	100 MΩ/m

A first prototype of the TW structure, constructed and tested at Sapienza University of Rome Laboratory, is shown in Fig.6

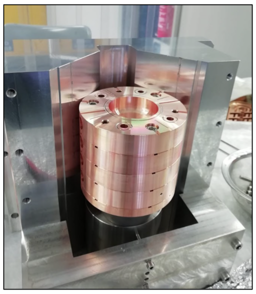

Figure 6: A first prototype of the TW structure constructed and tested.

RF DESIGN OF A SPHERICAL PULSE COMPRESSOR

A spherical pulse compressor has been designed for the VHEE in the framework of the FRIDA project of INFN [12]. It is made of two subsystems which are a special 3 dB couplers (or circular polarizer) and a spherical storage cavity. They were first designed separately by the simulation software CST MW Studio ®2022 and then assembled together to simulate the complete device. The main specifications of the spherical cavity pulse compressor are summarized in Table 4.

Table 4: Main Specifications of the Pulse Compressor

Parameter	Design Value
Resonant frequency [GHz]	5.712
Operating mode	TE_{114}
Unloaded Quality Factor Q_0	134000
Coupling coefficient β_c	8
RF input pulse length [µs]	2.5
RF compressed pulse length [µs]	> 0.5

The considered traveling-wave constant-impedance accelerating structure is 1.0 m long, has a shunt impedance per unit length 100 MΩ/m, a filling time $T_f = 350$ ns (group velocity of 1 % speed of light) and attenuation factor α=0.5 Neper. The output waveforms obtained with an RF pulse duration of 2.5 µs and a phase flip of 180° can be as short as 500 ns.

BEAM DINAMICS SIMULATIONS

Extended beam dynamics simulations have been performed to analyze the behavior of the electron beam from the gun up to the Linac exit. [14]. To this end, TSTEP [16] and ASTRA [15] codes were employed to simulate the beam dynamics. The electron beam is generated at the cathode, a triode with an emission region of approximately 6 mm in diameter, and operates at a nominal energy of 12 keV.

The beam dynamics study considers first the accelerator system without the pulse compressor, which utilizes a modular section with two TW structures operating at an unloaded gradient of approximately 35 MV/m and 100 mA beam current (Fig.5). The electromagnetic field maps of each TW structure were produced using the SUPERFISH code and were given as input to TSTEP for beam dynamics analysis. The design was verified to transport the beam optimally up to the nominal current of 100 mA at the exit. The high gradient due to the C-band induced an RF focusing, which confines the beam without the need for solenoids.

CONCLUSION

In this paper, we report on the status of the SAFEST project at La Sapienza University. The main RF components have been designed, and the first tests have been successfully performed.

ACKNOWLEGMENTS

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