STATUS OF THE SAFEST PROJECT: THE SAPIENZA LINAC PROTOTYPE FOR VHEE FLASH RADIOTHERAPY

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Abstract

FLASH radiotherapy has shown the potential to preserve tumor control while significantly reducing normal-tissue toxicity. In this context, Sapienza University of Rome and INFN are developing a compact C-band linear accelerator prototype within the SAFEST project toward future VHEE-FLASH applications. The accelerator is designed to deliver 24 MeV loaded electron beams with doses up to 4 Gy per pulse over a 10 × 10 cm^2 field at 200 Hz repetition rate. Extensive electromagnetic, vacuum, and beam-dynamics studies have been carried out to optimize the machine performance for FLASH irradiation. The installation phase is currently underway. The facility will support forthcoming in vitro and in vivo experiments using both pencil-beam and wide-beam irradiation configurations.

INTRODUCTION

FLASH radiotherapy [1] is attracting growing interest as an innovative cancer-treatment modality due to its capability to reduce normal-tissue toxicity while maintaining tumor control. Recent experimental studies have highlighted the potential of ultra-high dose-rate irradiation to improve the therapeutic index with respect to conventional radiotherapy techniques.

For the treatment of deep-seated tumors, the use of Very High-Energy Electrons (VHEE) [2], typically in the 50–150 MeV range, is considered particularly promising because of their favorable penetration capability and reduced lateral scattering. Within this framework, and as part of the SAFEST project [3] aimed at the realization of a compact 100 MeV accelerator for FLASH applications, developing a compact C-band LINAC prototype is being developed at Sapienza University of Rome. The machine is designed to produce 24 MeV loaded electron beams delivering doses up to 4 Gy per pulse at a repetition rate up to 200 Hz.

THE SAFEST 100-MEV VHEE LINAC

The SAFEST accelerator is designed to combine high-gradient acceleration and reduced footprint, enabling installation in a hospital environment while maintaining the beam characteristics required for ultra-high dose-rate irradiation. The machine is conceived to deliver electron beams suitable for future VHEE-FLASH treatments of deep-seated tumors. Table 1 summarizes the target irradiation parameters of the facility. As a first step toward the realization of the complete 100-MeV machine, a 24-MeV prototype is currently under construction at Sapienza University. The prototype will validate the main accelerator technologies required for FLASH delivery, including high-power RF generation and distribution, beam acceleration, dosimetric stability, and irradiation modalities for biological experiments.

The 100-MeV SAFEST accelerator operates at the C-band frequency of 5.712 GHz and is powered by a 20-MW RF source operating at 100 Hz repetition rate. To achieve compactness and high accelerating gradients, the LINAC layout employs a thermionic-gun-based injector followed by traveling-wave accelerating structures. The main LINAC parameters are reported in Table 2. Figure 1 shows the conceptual RF layout of the accelerator. The RF power generated by the 20 MW klystron is first compressed through a pulse compressor and subsequently distributed by a power splitter to feed the accelerating structures. The accelerating system consists of a standing-wave injector section integrating the thermionic gun, followed by two traveling-wave accelerating sections optimized for high-gradient operation.

Beam-dynamics simulations have been performed to optimize the transport and acceleration of the electron beam along the full LINAC. Particular attention has been devoted to transverse beam confinement and energy gain optimization under high-current operating conditions. Figure 2 reports the simulated evolution of the transverse beam size along the accelerator together with the corresponding beam energy increase from injection up to 100 MeV.

Table 1: Target FLASH Dose Parameters for the SAFEST Accelerator

Dose Parameters	Value
Irradiation time	< 100 ms
Pulse duration	1 μs
Time-averaged dose rate	> 100 Gy/s
Dose rate in pulse	> 10^6 Gy/s
Single pulse dose	> 1 Gy

Table 2: LINAC parameters of the SAFEST accelerator

LINAC Parameters	Value
Frequency	5.712 GHz
RF power	20 MW
LINAC length	~ 3 m
Pulse current	100 mA
Repetition rate	100 Hz

24-MEV PROTOTYPE INSTALLATION

As an intermediate step toward the realization of the complete 100 MeV SAFEST accelerator, a compact 24 MeV prototype [4] is currently under installation at Sapienza University of Rome. The prototype is intended to validate the main technological solutions required for future VHEE-FLASH operation, including RF generation and distribution, beam production, accelerator conditioning, and beam diagnostics.

The installation activities are currently focused on the first operational phase of the machine. In this configuration, the accelerator will operate using only the standing-wave (SW) injector section. This setup allows initial RF conditioning and beam commissioning at reduced energy. The present configuration includes the installation of the ScandiNova K100 modulator together with the 5 MW klystron and part of the beamline infrastructure.

Figure 3 shows the current installation status of the prototype facility, including the RF power system and the initial beam transport line. In Phase 1, operation will be carried out using the SW injector only, targeting a beam energy of approximately 14 MeV in unloaded conditions and about 10 MeV under beam-loaded operation. The RF system is based on a klystron capable of operation up to 200 Hz rep-

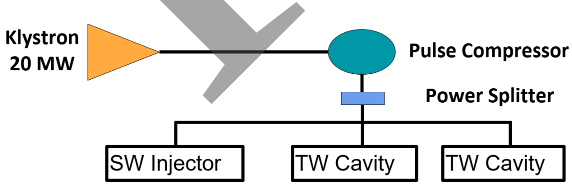

Figure 1: Conceptual RF power distribution scheme of the SAFEST 100-MeV LINAC. The RF power generated by the 20-MW klystron is compressed and distributed to the standing-wave injector section and to the two traveling-wave accelerating structures.

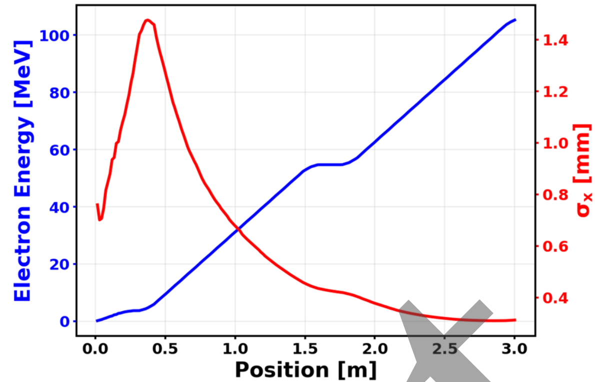

Figure 2: Simulated beam dynamics along the SAFEST accelerator. The figure shows the evolution of the transverse beam size along the LINAC together with the corresponding beam energy increase from injection up to 100 MeV.

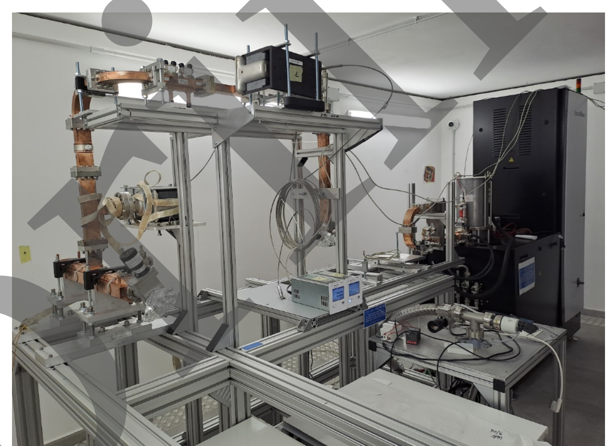

Figure 3: Current installation status (May 2026) of the SAFEST 24 MeV prototype at Sapienza University of Rome, including the ScandiNova K100 modulator, the 5 MW klystron, and part of the beamline infrastructure.

etition rate. In this phase, uncompressed RF pulses with a duration of up to 5 μs will be used. Depending on the pulse length and the captured beam current, the charge per pulse is expected to vary in the range from approximately 100 nC up to 2 μC. The thermionic electron gun (Heatwave Labs) is capable of delivering beam currents above 1 A, while a capture efficiency exceeding 30% is expected.

This phase will enable the first studies of injector performance, RF stability, vacuum behavior, and diagnostics response, and will form the basis for conditioning and commissioning activities planned for mid-2026. In Phase 2, the accelerator will be upgraded with the integration of a pulse compressor, RF power splitter, phase shifter, and a traveling-wave (TW) accelerating section. This configuration will allow operation at the full prototype energy of 24 MeV. The nominal prototype energy is limited to 24 MeV due to radioprotection constraints. However, the accelerator structure would be capable of reaching energies up to approximately 30 MeV over a total active length of about 1.5 m.

BEAM DELIVERY AND IRRADIATION CONFIGURATIONS

Initial irradiation tests will be performed using the SW injector operating at approximately 10 MeV under beam-loaded conditions. This energy range is suitable for first dosimetric studies and system commissioning.

Subsequently, operation at 24 MeV will enable deeper beam penetration and more flexible irradiation configurations, extending the experimental capabilities of the facility toward VHEE FLASH-relevant conditions.

Under current consideration is the possible integration of a converter to generate bremsstrahlung photons, allowing comparative studies between electron and photon irradiation regimes within the same experimental platform.

Two irradiation modes are foreseen for the SAFEST prototype [5]: a large-field (wide-beam) irradiation mode and a pencil-beam scanning configuration, conceptualized in Figs. 4 and 5. The wide-field mode is designed for uniform dose delivery over extended areas, while the pencil-beam scanning mode enables flexible dose painting through controlled beam steering.

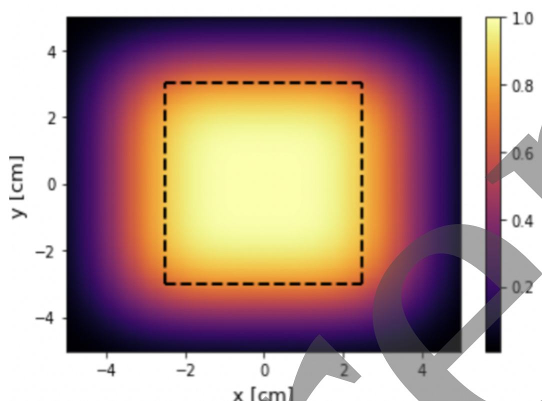

Figure 4: Schematic representation of wide-beam (large field) irradiation configuration, providing uniform dose delivery over a large area.

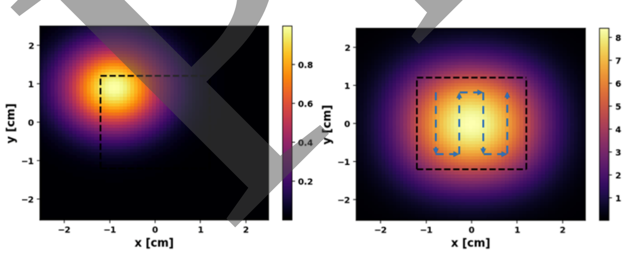

Figure 5: Pencil-beam scanning concept. (a) Single pencil beam spot; (b) reconstructed dose distribution obtained by scanning over a large field. The green arrow indicates the scanning trajectory.

CONCLUSIONS

The SAFEST project is developing a compact C-band VHEE linear accelerator for FLASH radiotherapy, targeting 100 MeV and a footprint compatible with clinical environments. A 24-MeV prototype is currently being installed at Sapienza University of Rome in collaboration with INFN. The prototype will validate key building blocks for ultra-high dose-rate operation, including high-power RF generation, thermionic-gun-based beam production, and flexible irradiation schemes.

Phase 1 will use the standing-wave injector, targeting 10–14 MeV and enabling initial commissioning and conditioning. Phase 2 will reach 24 MeV through the addition of a pulse compressor, RF distribution system, and a traveling-wave structure. The RF system is based on a 5 MW klystron operating up to 200 Hz, supporting uncompressed pulses up to 5 µs and charge per pulse from 100 nC to 2 µC depending on beam capture. A Heatwave thermionic gun is expected to deliver currents above 1 A with $\gtrsim$30% capture efficiency. First irradiation tests will be performed at 10 MeV, while full-energy operation will enable deeper penetration and VHEE FLASH-relevant studies.

Beyond the SAFEST 100 MeV demonstrator, the system will serve as a flexible test platform for beam dynamics, RF technology, and FLASH irradiation studies, supporting development of compact VHEE accelerators for medical applications.

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