OPTIMIZED DESIGN OF A C-BAND 100 MeV ELECTRON LINAC FOR FLASH RADIOTHERAPY

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Abstract

Electron LINACs are key tools for radiotherapy. Conventional low energy ones can treat only superficial tumors. Achieving Very High Energy Electrons (VHEE, >100 MeV) enables treatment of deep-seated tumors. Furthermore, electrons are well-suited for delivering Ultra-High Dose Rates (UHDR) required for FLASH therapy, which improves healthy-tissue sparing. Combining VHEE and FLASH in a hospital environment represents an important step forward for Radiotherapy. In the context of the SAFEST project at Sapienza, this work presents a compact and cost-effective accelerator layout capable of delivering hundreds of nC at 100 MeV within tens of pulses over 1 ms of irradiation. The design emphasizes efficient RF power usage through high-efficiency C-band structures and a pulse compressor. Beam dynamics simulations and low-power RF tests validate the approach. A strong focus is placed on flattening the compressor signal, which must remain stable over 1 µs to accommodate electrons from a triode thermionic gun, a compact and economical source for this accelerator. The resulting 3 m LINAC, powered by a single 20 MW klystron, shows strong potential for future hospital based FLASH VHEE treatments.

INTRODUCTION

Medical accelerators must be compact, cost-effective, and simple for hospital integration. VHEE (E > 100 MeV) and UHDR operation can improve the treatment of deep-seated tumors and enhance tissue sparing [1,2] through the FLASH effect. Radio Frequency (RF) accelerators currently represent the most reliable technology for this purpose [3,4]. Standard S-band structures lead to excessive footprints for a clinical accelerator with E > 100 MeV, while X-band systems require strict tolerances and expensive components. The C-band (5.712 GHz, $E_{acc} \approx 50\,\mathrm{MV\,m^{-1}}$) offers an optimal compromise between efficiency and cost-effectiveness [5]. At present, no cost-effective and compact VHEE accelerators are available in clinical environments. It is therefore crucial to investigate the feasibility of developing such accelerator, ensuring a step forward in research for cancer treatment.

A 24 MeV FLASH LINAC [6], currently under construction at Sapienza University, will serve as a testbed for this technology. This work presents the design of a VHEE and UHDR accelerator tailored for deep-seated tumors as a future extension of the Sapienza LINAC, using a genetic algorithm for working point optimization, ASTRA for beam transport, and FLUKA for dose mapping.

100 MeV COMPACT ACCELERATOR LAYOUT

A commercial 14 kV thermionic triode gun [7] generates the beam, delivering a continuous 100 mA with a 35 % capture efficiency when installed directly onto the first structure. The selected model can emit up to 1.5 A, ensuring reliable operation at 100 mA within the LINAC.

After electrostatic acceleration, the continuous electron beam is captured, bunched, and accelerated to 4 MeV in a 22 cm standing-wave (SW) C-band injector [8], derived from the SAFEST prototype [6]. Two subsequent constant-gradient traveling-wave (TW) structures (1.2 m total length) operate at $40\,\mathrm{MV\,m^{-1}}$ to reach 100 MeV. The TW cells are derived from the 24 MeV prototype.

A 20 MW klystron (5 µs pulse, 200 Hz repetition rate), combined with a BOC-type pulse compressor, feeds the accelerating structures. The compressor design is based on the system implemented in the Sapienza prototype [9]. To deliver sufficient dose, the beam duration must be on the order of 1 µs. High-intensity beams (100 mA) of this duration induce strong beam loading [10], requiring dedicated RF pulse shaping. It reduces the accelerating field along the bunch train, requiring increasing RF compensation for later bunches, which in turn increases energy spread and reduces average energy. More details can be found at [10]. Additionally, the pulse compressor response is not flat in the amplified region, further complicating the optimization. The required klystron modulation is therefore obtained via a multi-variable genetic algorithm. Table 1 and Fig. 1 summarize the main parameters.

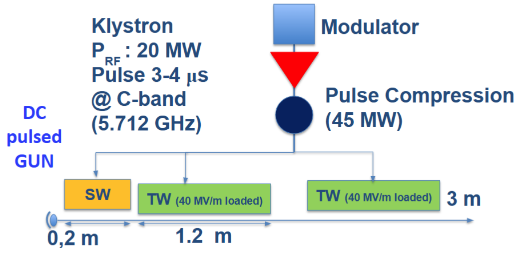

Figure 1: Accelerator layout scheme.

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Table 1: Detailed Accelerator Parameters and Operating Conditions

Parameter	Value
General Layout	
RF Frequency	5.712 GHz (C-band)
Total LINAC Length	3 m
Structure Configuration	SW Injector + 2 TW (CG) Sections
Final Beam Energy	100 MeV
Electron Source	
Gun Type	Thermionic Triode
Extraction Voltage	14 kV
Maximum Current	1.5 A
Operating Current	100 mA
Capture Efficiency	35 %
RF Power System	
Klystron Peak Power	20 MW
RF Pulse Length	5 µs
Repetition Rate	200 Hz
Pulse Compressor Type	BOC
Coupling Factor (β)	3
Quality Factor (Q_0)	10^5
Accelerating Structures	
Injector Type	Standing Wave (SW)
Injector Length	22 cm
TW Total Length	1.2 m
Average Gradient	40 MV m^{-1}
Shunt Impedance	100 MΩ m^{-1}
Initial Group Velocity	$1.75 \times 10^{-2}c$
Final Group Velocity	$0.4 \times 10^{-2}c$
Iris Radius (in/out)	6 mm / 3.5 mm
Beam Parameters	
Max Beam Pulse Duration	1 µs
Max Bunch Train Length	5712 bunches
Max Beam Current	100 mA
Max Charge per Pulse	100 nC

WORKING POINT

A pulse compressor is essential to reach the target energy by concentrating RF power during the beam pulse. Achieving an amplified flat-top profile to compensate beam loading requires modulation of both the klystron phase and amplitude.

The RF pulse is parameterized into discrete time, amplitude, and phase variables over a 5 µs window. The beam injection timing (T_{on}) and duration (T_b) are optimized simultaneously to match the compressor response. The RF envelope is constructed via piecewise linear interpolation, subject to a thermal constraint equal to the energy of an unmodulated flat-top pulse.

An NSGA-II algorithm [11] is used to optimize the system by simulating the full RF chain, from the klystron to the accelerating structures, and evaluating the energy gain for each bunch. The objectives are average energy, energy spread, and total charge. The result is a Pareto front of optimal non-dominated solutions. Figure 2 shows the selected configuration, including energy evolution and RF modulation.

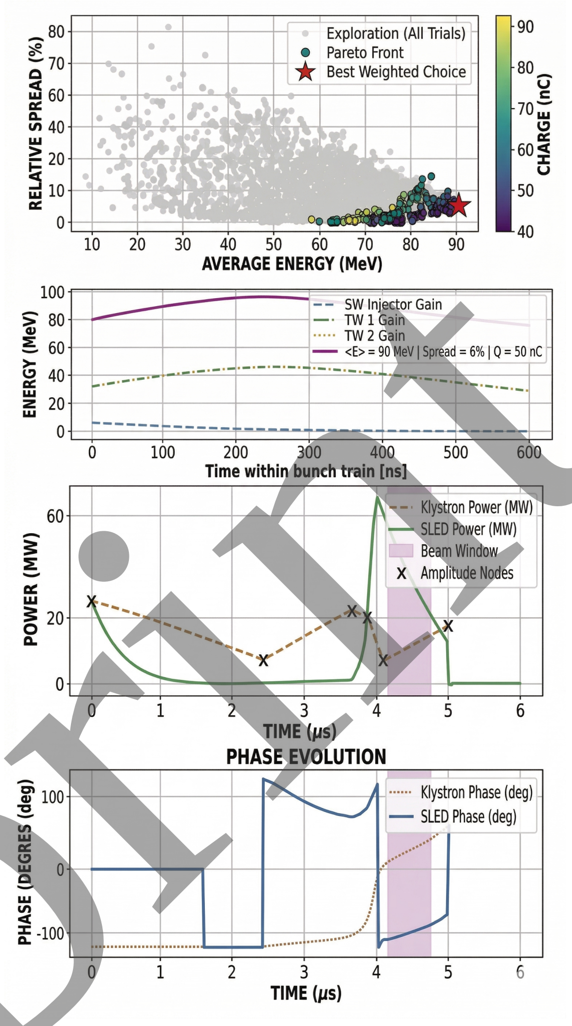

Figure 2: Pareto front metrics (top), bunch train energy (middle-top), klystron RF envelope and compressor response (middle-bottom), and phase response (bottom).

Beam transport is validated using ASTRA [12]. A uniformly sampled bunch train is simulated, confirming stable transport along the accelerator. The transverse beam size remains well confined, with negligible transverse momentum.

Due to continuous emission within the RF bucket, a low-energy tail is transported, increasing the energy spread to 12.2 MeV (Fig. 3). However, this does not significantly affect the penetration depth in a water phantom, preserving the capability to treat deep-seated tumors, as can be seen in the following section (Fig. 4).

Beam Delivery and Dose Distribution

A robust delivery system must adapt the narrow LINAC beam (< 5 mm) to clinically relevant target volumes. Two strategies are evaluated: Wide Field (WF) and Pencil Beam Scanning (PBS), using FLUKA Monte Carlo simulations [13].

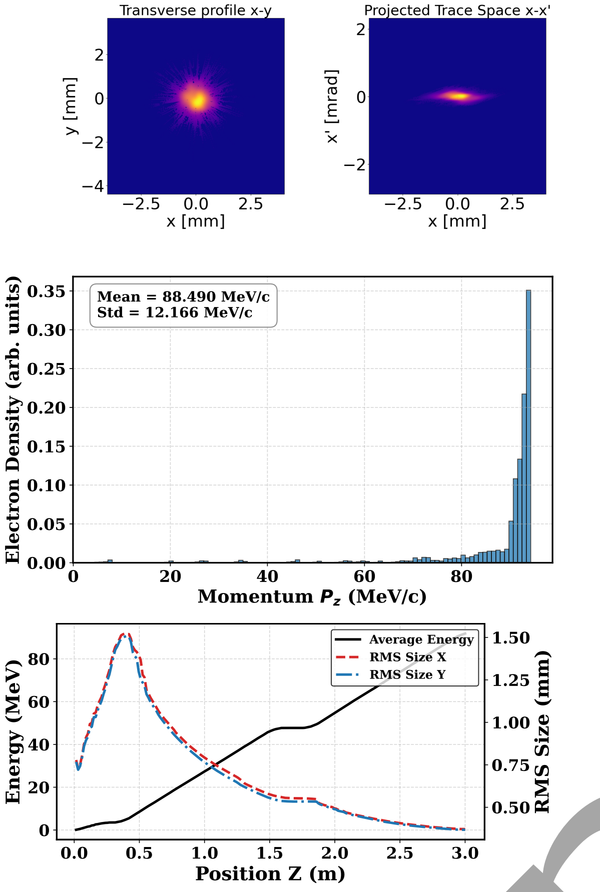

Figure 3: Exiting beam characteristics: transverse plane/trace space (top), momentum distribution (middle), and energy gain/transverse rms size (bottom).

Wide Field Irradiation The WF configuration uniformly irradiates a large area (5×5 cm^2) within a single RF pulse using a 500 µm Polyether ether ketone (PEEK) scattering foil [14]. PEEK minimizes radiation-induced activation. Its radiation length (X_0 = 31.5 cm) results in only 1.6×10^{-3} of primary electron energy converting to photons, making Bremsstrahlung contributions negligible. This yields an instantaneous dose rate of 3.6×10^6 Gy/s, delivering UHDR up to 15 cm deep (Fig. 4b). The 600 ns (Fig. 2) optimized pulse achieves 6 MGy/s (UHDR regime).

Pencil Beam Scanning (PBS) PBS enhances spatial dose conformity by irradiating target portions across multiple pulses. A thinner 100 µm PEEK scatterer creates a ~ 1 cm FWHM spot size (Fig. 4c), steered dynamically by two 0.15 T ferromagnetic dipoles over a 30 cm path. 20 pulses are scanned in 100 ms (200 Hz of rep. rate). While the time-averaged dose rate is lower, the instantaneous dose rate remains high (5×10^6 Gy/s), preserving UHDR biological advantages per pulse (Fig. 4d).

LOW POWER TEST

A Libera Low Level RF (LLRF) system is used to modulate the RF pulse prior to amplification, ensuring also pulse stability. To validate the predictive capability of the algorithm about the evolution of the RF pulse, its drive out signal is sent to a test cavity, modeled in the same algorithm which give theoretical prediction for the pulse compressor pulse modulation. In such a way we are mimicking pulse compressor behavior. This test validates the ability of the system to reproduce the optimized RF modulation, although it does not include beam loading or high-power effects. The measured results (Fig. 5) show good agreement with the theoretical time evolution.

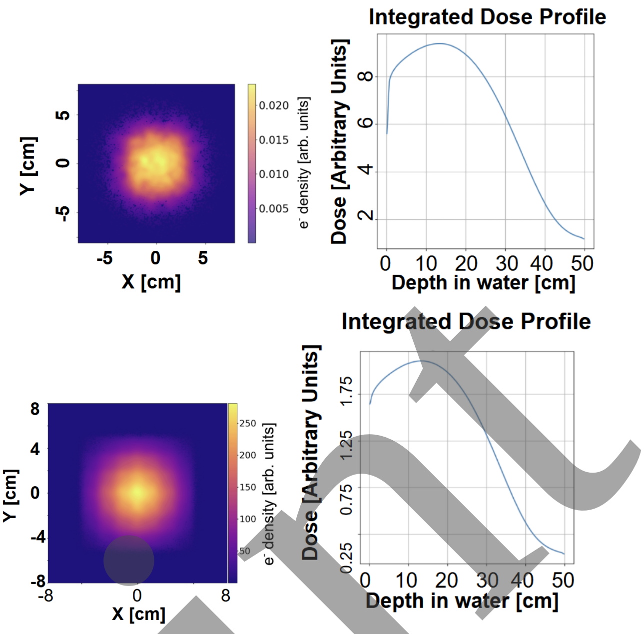

Figure 4: Delivery comparisons. Top (WF): Spatial distribution, Dose profile. Bottom (PBS): Spatial distribution, Pencil beam dose.

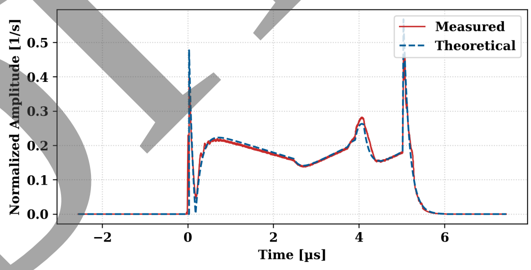

Figure 5: Low power test measurements vs. theoretical results.

CONCLUSION

This work demonstrates a compact 3 m VHEE source capable of delivering UHDR beams for FLASH applications, powered by a single 20 MW klystron. NSGA-II optimization enables flexible RF modulation, validated through beam dynamics and FLUKA simulations, achieving penetration depths of approximately 15 cm. These results support the development of compact electron sources for advanced clinical radiotherapy.

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