

## Power and beam dynamics optimization of a compact LINAC for FLASH radiotherapy with prospects for VHEE

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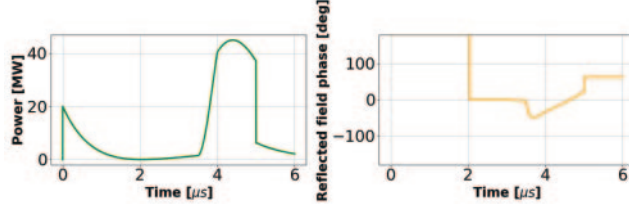
**Summary.** — Radiotherapy represents a cornerstone of cancer treatment, playing a central role in tumor control and volume reduction. Recently, the delivery of Ultra-High Dose Rates (UHDR) has emerged as a promising method to enhance healthy tissue sparing via the FLASH effect (FAVAUDON V. *et al.*, *Sci. Transl. Med.*, **6** (2014) 245ra93), while maintaining tumor toxicity. When combined with Very High Energy Electrons (VHEE), this modality allows for the effective targeting of deep-seated tumours (SARTI A. *et al.*, *Front. Oncol.*, **11** (2021) 777852; BAZALOVA-CARTER M. *et al.*, *Med. Phys.*, **42** (2015) 2615). This work, conducted within the framework of the SAFEST project at Sapienza University (GIULIANO L. *et al.*, *Front. Oncol.*, **15** (2025) 1516576; FAILLACE L. *et al.*, *Phys. Med.*, **104** (2022) 149), investigates the design of a compact electron LINAC suitable for a hospital environment. We present a comprehensive optimization of the RF power system and beam dynamics for a C-band accelerator capable of reaching 100 MeV in a 4 m footprint. The accelerator exploits a 20 MW klystron coupled with a pulse compressor, and achieves the high peak currents required for UHDR thanks to a thermionic triode gun. Furthermore, two beam delivery strategies —passive scattering and pencil beam scanning— are analyzed to validate the clinical feasibility of this technology.

### 1. – Accelerator layout and working point

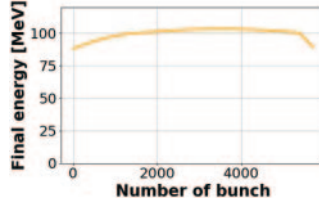
Medical electron accelerators must seek compactness, cost-effectiveness, and simplicity to allow implementation in hospitals. These requirements are often mutually conflicting. Radio Frequency (RF) accelerators are currently the most stable and reliable [1, 2]. The first step is to determine the RF working frequency (band), affecting efficiency, accelerating gradient and so LINAC length. If the final goal is reaching 100 MeV in hospital environment, S-band (3 GHz,  $E_{acc} \sim 20$  MV/m) structures are too long, while X-band (10 GHz  $E_{acc} \sim 100$  MV/m) demands expensive tolerances and extortionate components.

This work presents the design principles of a Very High Energy Electron (VHEE) and Ultra-High Dose Rate (UHDR) accelerator, specifically tailored to exploit the FLASH effect for the treatment of deep-seated tumours.

To balance the need for compactness and cost, C-band RF structures were chosen (5.712 GHz, Max  $E_{acc} \sim 50$  MV/m). The designed structures are efficient enough to reach 30 MV/m of accelerating gradient exploiting a 20 MW klystron with 5  $\mu$ s pulse



(a) Pulse compressor (SLED type) output power and phase.



(b) Final energy vs. bunch index.

Fig. 1. – RF power feeding the structures (a) and resulting  $1 \mu\text{s}$  electron final energy (b).

duration, 160Hz of repetition frequency, and a pulse compressor (SLED type) [3]. This last device can distribute the RF power within the pulse, increasing it up to about 40 MW over  $1 \mu\text{s}$  within the  $5 \mu\text{s}$  RF pulse duration as delivered by the klystron. During the amplified power phase, it is possible to inject a  $1 \mu\text{s}$  electron beam. The accelerating structures design is based on the ones realised for the SAFEST project prototype at 24 MeV [4].

The electron beam is generated by a thermionic triode gun [5], providing 100 mA of beam current in the LINAC. The beam is initially captured and accelerated to 10 MeV by a 70 cm long standing-wave C-band injector. Downstream, three constant-gradient traveling-wave C-band structures (cited above), each 1 m long and operating at an accelerating gradient of 30 MV/m, complete the acceleration. All four structures are powered by RF pulses with peak power compressed by the SLED as shown in fig. 1.

The temporal structure of the  $1 \mu\text{s}$  pulse will be a train of 5712 bunches, corresponding to the ratio between beam duration and C-band period. The resulting final energy for each bunch, obtained by theoretical computations, is depicted in the plot in fig. 1(b). Note that beam loading modulation is taken into account. More details on energy gain computations can be found in [2, 6].

These preliminary results state that, in principle, a 4 m C-band accelerator powered by a 20 MW klystron can reach 100 MeV of electron energy if the pulse compressor is properly exploited (table I).

It is worth mentioning that we are considering the highest possible current and at the maximum designed duration. These aspects maximize the beam loading modulation [2, 6] requiring careful optimization of the SLED output power shape. The final result is an increase in the average energy together with an increased energy spread. However, the dose deposition still reaches depth of roughly 15 cm, the typical value of VHEE, as shown in the third section. If a future application does not require 100 nC per pulse, the user can either decrease current or beam duration. In this way beam loading modulation can be more easily compensated, reducing inter-bunch energy spread.

It is necessary at this point to check if the beam is successfully transported to the end through beam dynamics simulations and to implement the simplest scheme possible for beam delivery.

TABLE I. – *Accelerator working point and main beam parameters.*

| Parameter                         | Value                                 |
|-----------------------------------|---------------------------------------|
| RF frequency                      | 5.712 GHz (C-Band)                    |
| Structure type                    | Standing Wave (Inj.) + Traveling Wave |
| Total length                      | 4 m                                   |
| RF peak power                     | 20 MW                                 |
| RF pulse duration                 | 5 $\mu$ s                             |
| Repetition rate                   | 160 Hz                                |
| <i>Target beam specifications</i> |                                       |
| Average final energy              | 100 MeV                               |
| Max. beam pulse duration          | 1 $\mu$ s                             |
| Max. beam current                 | 100 mA                                |
| Max. charge per pulse             | 100 nC                                |
| Dose rate regime                  | UHDR (FLASH)                          |

## 2. – Accelerator beam dynamics simulations

The previous section established the accelerator working point, optimizing RF power manipulation and beam injection. Furthermore, we assume the maximum achievable current —100 mA— associated with 100 nC per pulse, implying that this represents a conservative worst-case beam quality. The optimization estimated the beam loading modulation and the expected bunch energy, shown in fig. 1(b). It is now possible to build beam dynamics simulations based on these data using ASTRA (A Space Charge Tracking Algorithm) [7].

Knowing the input power in the 1  $\mu$ s beam time interval, it is possible to establish the cavities' electric field amplitude seen by each bunch, the key parameter for the ASTRA single-bunch simulation. The curve in fig. 1(b) was sampled by choosing 100 bunches uniformly and for each a beam dynamics simulation was run. In this way, we can achieve a complete description of the behavior of each bunch.

The axis parallel to the ideal trajectory is  $z$ , while  $x$  and  $y$  represent the horizontal and vertical components, respectively.

Each simulation starts at the electron source: a thermionic triode gun, capable of generating the high-intensity beams required for UHDR delivery. The device consists primarily of a spherical cathode that releases electrons via thermionic emission. Following emission, an electrostatic field focuses and accelerates the electrons, consisting of a 14 kV of gun voltage. To ensure compactness, cost-effectiveness, and operational stability, a commercial off-the-shelf thermionic gun was selected. The critical beam parameters—specifically the waist position and size, along with the cathode dimensions— are determined by the manufacturer's specifications.

Based on these specifications, an electron distribution with convergent characteristics was initialized in ASTRA. This approach allows for the accurate simulation of the capture process within the standing-wave injector. Table II presents the initial conditions for a single bunch. Its charge was calculated after obtaining a transmission efficiency of 37 % in preliminary simulations, ensuring an average current of 100 mA throughout the accelerator. The resulting emitted current is smaller than the triode gun specifications ( $I_{Max} \sim 1.5$  A). It must be noted that the transmission parameter is not uniform for each bunch. This parameter is strictly dependent on the peak electric field in the SW injector.

TABLE II. – *Initial electron beam parameters at the cathode.*

| Parameter                                    | Symbol              | Value                    | Unit            |
|----------------------------------------------|---------------------|--------------------------|-----------------|
| <i>General Parameters</i>                    |                     |                          |                 |
| Simulated bunches                            | $N_b$               | 100                      | –               |
| Simulated particles per bunch                | $N_p$               | 3000                     | –               |
| Real bunch per pulse                         | $N_{Bpulse}$        | 5712                     | –               |
| Bunch charge                                 | $Q_b$               | $-4.7400 \times 10^{-2}$ | nC              |
| <i>Transverse Phase Space</i>                |                     |                          |                 |
| RMS H/V Size                                 | $\sigma_{x,y}$      | 1.500                    | mm              |
| Geom. proj. Emit. $(x, y)$                   | $\varepsilon_{x,y}$ | 7.339                    | $\pi$ mrad · mm |
| <i>Longitudinal Phase Space &amp; Energy</i> |                     |                          |                 |
| Cathode curvature radius                     | $R$                 | 5.89                     | mm              |
| Emission time                                | $\sigma_t$          | 0.175                    | ns              |
| Mean kinetic energy                          | $E_{kin}$           | $1.4001 \times 10^{-2}$  | MeV             |
| Energy spread                                | $dE$                | $2.8867 \times 10^{-2}$  | keV             |

Following capture, the electrons rapidly attain relativistic velocities within the initial stages of the injector. This acceleration effectively “freezes” the transverse phase space distribution and imprints a bunched structure onto the originally continuous emission from the cathode [8].

Figure 2 illustrates the average beam evolution for the sampled bunches, specifically highlighting the figures of merit regarding transverse confinement and energy gain.

Regarding the motion in the  $xy$  plane, the transverse field component in the cavities shows a significant focusing force. The output  $\sigma_x$  and  $\sigma_y$  are around 0.685 mm.

The electric field  $z$  component not only allows the average energy to reach 100 MeV, but also makes the  $XZ$  and  $YZ$  divergence negligible, as can be seen in fig. 2. Finally, the energy spread suffers from the presence of different expected energies for each bunch, reaching 15 MeV RMS at the accelerator exit, considering all the simulated electrons.

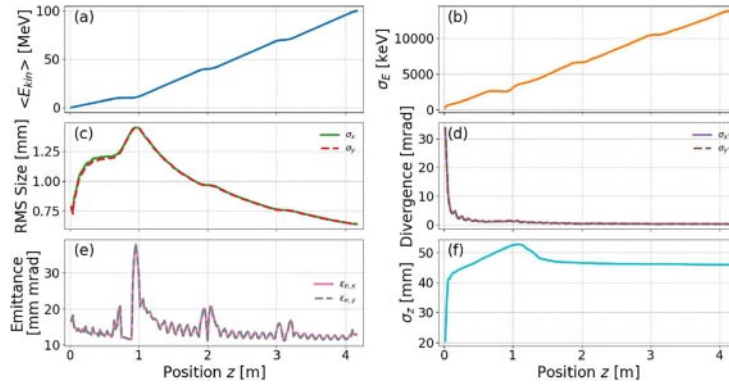
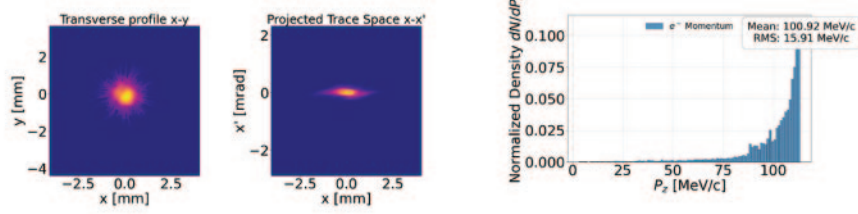


Fig. 2. – Average evolution of the main beam parameters for the sampled bunches: (a) mean kinetic energy, (b) kinetic energy spread, (c) transverse beam sizes, (d) transverse divergences, (e) RMS emittances, (f) bunch length.



(a) Transverse space at exit ( $Z = 4.3$  m). (b) Momentum distribution (15% spread).

Fig. 3. – Output beam characteristics: transverse distribution (a) and longitudinal momentum (b).

Despite this, it will be shown that this beam can irradiate deep-seated tumours, reaching 15 cm of depth in a water phantom with its maximum deposition.

At this point, it is necessary to check in more detail the status of the electron beam exiting the accelerator. Figures 3(a) and (b) show the spot size, transverse trace space and momentum ( $p_z$ ) distribution respectively.

For the transverse behaviour, the beam is compact around the nominal trajectory with negligible divergence. This allows for effective beam manipulation after the accelerator for beam delivery schemes.

The longitudinal behaviour confirms the achievement of the 100 MeV average energy, although the energy spread shows a long tail towards low energy values, as expected from the spread evolution through the accelerator. The main cause is the inter bunch energy spread in fig. 1.

Thanks to the simulations, the beam transport has been proven. In the next section are shown the performances of two possible beam delivery schemes and the related dose distribution.

### 3. – Beam delivery and dose distribution

The previous section demonstrated the feasibility of reaching 100 MeV using RF cavities powered by a 20 MW klystron, with an electron beam generated by a thermionic triode.

Here, two beam delivery schemes are presented, supported by Monte Carlo (FLUKA) simulations of the dose deposition. For both schemes, the primary objective is to enlarge the beam to match the transverse dimensions of typical tumours. Both active (pencil beam scanning) and passive (multiple scattering) beam enlargement methods are evaluated, highlighting their critical differences regarding the temporal structure and dose conformity.

**3.1. Wide field irradiation.** – The electron beam exits the accelerator with a size smaller than the iris radius (5 mm). Consequently, it is crucial to expand the beam profile for irradiation of clinical samples. To achieve rapid irradiation and trigger the FLASH effect via UHDR, the required charge can be allocated within a single 1  $\mu$ s RF pulse.

In this modality, the single electron pulse is enlarged using a passive multiple scatterer. Following the introduction of beam divergence, a drift space is required to allow the beam to expand. Polyether ether ketone (PEEK) was selected for scattering simulations [9].

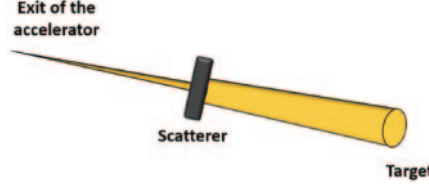


Fig. 4. – Beam enlargement scheme utilizing a passive multiple scatterer.

Beam-PEEK interactions were simulated with a custom Monte-Carlo in order to optimise computational time, while the drift space was implemented in ASTRA. This scheme is illustrated in fig. 4. A key advantage of PEEK is its low radiation-induced activation, which is critical for radiation protection.

Scatterer thickness is a critical parameter. An excessively thick material leads to significant intensity loss, while a thickness that is too low results in insufficient divergence, necessitating an impractically long drift space.

By using a  $500\ \mu\text{m}$  PEEK scatterer, it is possible to achieve a quasi-uniform surface  $5 \times 5\ \text{cm}^2$  for sample irradiation (fig. 5(a)) with a 1 m long drift space. Regarding photon emission due to Bremsstrahlung, we rely on Bethe-Heitler equation for computing the emitted energy. Computing the radiation length for PEEK, we find  $X_0 = 31.5\ \text{cm}$ , and considering the thickness of  $500\ \mu\text{m}$ , only the  $1.6 \times 10^{-3}$  of the electron energy is converted into photons. Giving a photon beam of very low intensity compared with the electron beam. Further more, the absorption coefficient of water for photons can be approximated at 40 cm, not affecting electron peak dose distribution. Thus, photon contribution to dose distribution is neglected.

Dose deposition simulations within a water phantom were carried out for this scheme. The integrated dose profile is presented in fig. 5(b). As predicted for Very High Energy Electrons (VHEE), the simulated beam deposits the majority of the dose at a depth of 13 cm. Scaling the simulation primaries to the actual transported charge (100 nC max), the beam delivers a maximum dose of 4 Gy/pulse. Given the duration of the pulse  $1\ \mu\text{s}$ , this accelerator achieves an instantaneous dose rate of  $4 \times 10^6\ \text{Gy/s}$ , well within the UHDR regime required to trigger the FLASH effect, potentially improving the preservation of healthy tissue.

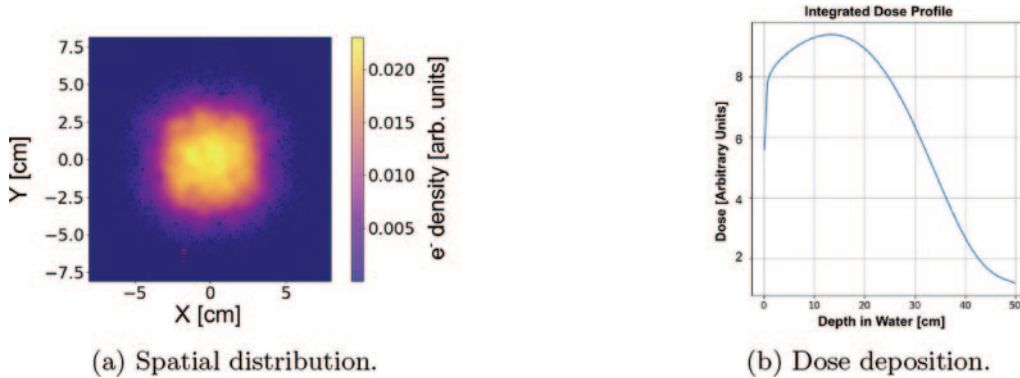


Fig. 5. – Wide field results: (a) electron  $XY$  distribution after 1 m drift and (b) dose deposition profile.

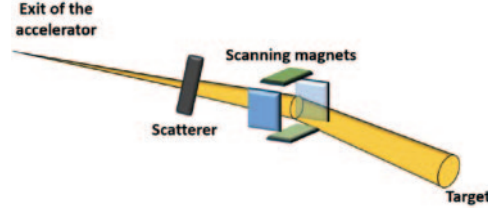


Fig. 6. – Beam delivery scheme for the pencil beam scanning.

**3.2. Pencil Beam Scanning (PBS).** – Alternatively, the sample area can be irradiated using Pencil Beam Scanning (PBS) mode (fig. 6). This method employs several pulses, each targeting a specific portion of the sample. The centroid of each pulse is controlled via two dipolar fields that vary from pulse to pulse, simulated in ASTRA. A thinner PEEK scatterer is still needed since a FWHM of approximately 1 cm must be achieved. This scheme significantly improves dose conformity. In addition, such a strategy adds dispersion to the beam. It results in a moderate broadening of the pencil beam spot along the magnetic field direction. Despite this, the single beam spot divergence is dominated by the interaction with the PEEK scatterer.

Furthermore, less charge is required per pulse since each targets a smaller area, thereby reducing the impact of beam loading modulation (RF power absorption by the beam). However, the necessity of multiple pulses requires a repetition frequency in the range of hundreds of Hz, typical of commercial klystrons. Although the instantaneous dose rate remains comparable to the wide-field scheme,  $0.6 \times 10^6$  Gy/s, the time-averaged dose rate is approximately three orders of magnitude lower, scaling with the beam duty cycle.

To achieve the coverage shown in fig. 7(b), a 100  $\mu\text{m}$  PEEK scatterer was used in combination with two ferromagnetic dipoles. The maximum field required for full deflection is 0.15 T for a 30 cm dipole. The integrated dose distribution (fig. 7) confirms that the 100 MeV beam maintains sufficient energy to treat deep-seated tumours up to 15 cm depth. In table III is shown a comparison among these two schemes.

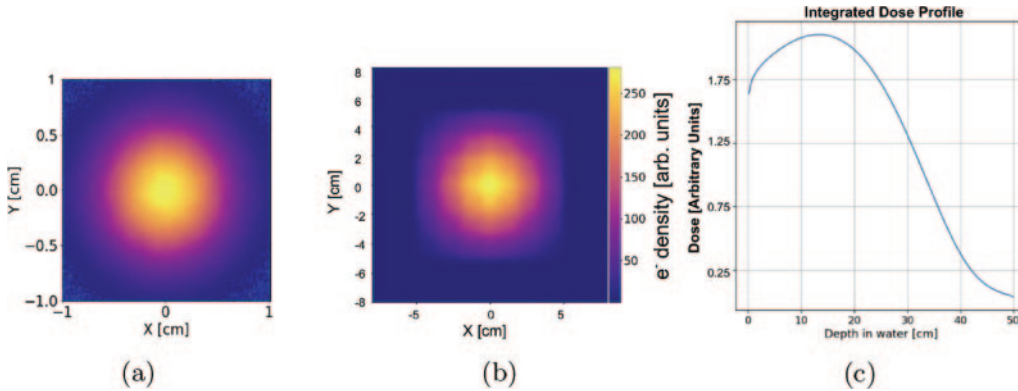


Fig. 7. – Pencil Beam: transverse distribution for a single pencil beam (a), magnetic scanning coverage (b), dose deposition for pencil beam scanning irradiation (c).

TABLE III. – *Summary of beam delivery parameters for Wide Field and PBS schemes.*

| Feature            | Wide Field                        | PBS                                    |
|--------------------|-----------------------------------|----------------------------------------|
| Enlargement method | Passive (PEEK 500 $\mu\text{m}$ ) | Hybrid (PEEK 100 $\mu\text{m}$ + Mag.) |
| Drift space        | 1 m                               | 1 m                                    |
| Spatial conformity | Moderate                          | High                                   |
| Max magnetic field | –                                 | 0.15 T                                 |
| Irrad. time        | $\sim 1 \mu\text{s}$              | $\sim 100 \text{ ms}$                  |
| Inst. dose rate    | $4 \times 10^6 \text{ Gy/s}$      | $0.6 \times 10^6 \text{ Gy/s}$         |

#### 4. – Conclusions and future perspectives

The combination of VHEE and UHDR radiation represents a breakthrough in radiotherapy, allowing the treatment of deep-seated tumours while using the FLASH effect to save healthy tissue. The presented design demonstrates that a 100 MeV beam can be delivered within a compact footprint by optimising the RF power requirements to 20 MW.

Future work will involve experimental validation using the SAFEST project prototype to assess the practical feasibility of this LINAC layout in a clinical environment.

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