STUDY AND TEST OF A TRIODE GUN FOR THE FLASH ELECTRON LINAC AT SAPIENZA

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Abstract

A 24 MeV prototype LINAC is under development at Sapienza University of Rome for FLASH radiobiological studies. The injector is a 12 keV triode thermionic electron gun from HeatWave Labs, providing grid-controlled current modulation for high current, low perveance, and short-pulse operation. To optimize its integration with the 24 MeV C-band hybrid standing- and travelling-wave structure, extensive particle tracking simulations of the electron gun were performed using CST Particle Studio. Parametric scans of the anode voltage and grid potential were used to evaluate beam current, perveance, and emittance, identifying operating points that balance beam stability and charge for FLASH applications. As the modern dispenser cathode requires stringent vacuum conditions below 1×10^{-6} mbar, the LINAC was also modeled in Molflow+ to predict pressure profiles under realistic gas-load scenarios. Simulations revealed a potential vacuum limitation near the gun, leading to the design and implementation of an additional pumping port for better evacuation of gas molecules. These results are benchmarked with initial experimental tests performed on an electron gun test bench at Sordina IORT Technologies. The combined simulation and experimental validation provide key design requirements for compact FLASH LINAC injectors.

INTRODUCTION

FLASH radiotherapy requires the delivery of ultra-high dose rates in microsecond-scale pulses, imposing stringent constraints on the electron injector in terms of peak current, beam stability, and temporal control [1]. In the framework of the SAFEST project, a 24 MeV prototype C-band hybrid standing- and travelling-wave LINAC is under development at Sapienza University of Rome for FLASH radiobiological studies [2-4].

The design of the injector presents several critical challenges. From a beam dynamics perspective, achieving high current while maintaining low emittance and stable transport requires accurate modelling of the emission process in thermionic triode electron guns. Parametric studies are particularly important during the initial commissioning phase of the LINAC, therefore requiring detailed particle tracking simulations.

In addition, vacuum conditions play a crucial role in the performance of modern dispenser cathodes, which require pressures below 10^{-6} mbar for proper activation and homogeneous emission. Due to limited vacuum conductance, cathode degassing at elevated temperature leads to gas accumulation near the gun region resulting in degraded emission performance and non-uniform cathode activation, thus limiting the achievable operating voltage and beam current [5].

Another key aspect is the control and operation of the electron gun. The dispenser cathode is activated by gradually increasing the heater voltage until stable electron emission is achieved [6]. This requires an automatic control logic which gradually increases the heater voltage in discrete steps while respecting the permissible vacuum limits. FLASH applications also require precise timing and reproducibility of beam for irradiation time of less than 100 ms, motivating the development of a dedicated control scheme capable of single-shot operation by generating a finite burst of pulses within a 100 ms irradiation window. This involves synchronization between the modulator trigger and grid pulses, with appropriate timing logic to ensure stable beam extraction [7].

This work addresses these challenges through a combined numerical and experimental approach. A detailed 3D model of a thermionic triode electron gun is simulated in CST Particle Studio to study emission and beam dynamics. Vacuum performance is analyzed using Molflow+ to identify and mitigate pressure limitations. Experimental measurements are performed to validate the model, and a dedicated control system is implemented to enable reliable activation of cathode and single-shot operation. The results provide key insights for the design of compact FLASH LINAC injectors.

DESIGN OF ELECTRON GUN

The injector is based on a 12 keV pierce-convergent type thermionic triode electron gun (HeatWave Labs), enabling grid-controlled emission as shown in (Fig. 1). The gun consists of a dispenser cathode, control grid, focusing electrode and anode, allowing precise modulation of the emitted current. A realistic control grid structure was implemented in the simulations using a honeycomb geometry with 0.5 mm apertures and 0.25 mm thickness, corresponding to an estimated beam blockage of 10–15%.

The gun is designed for short-pulse operation in the microsecond range, supporting high peak current and low perveance conditions. The integration of this gun into a LINAC for FLASH applications requires careful matching of beam parameters at injection.

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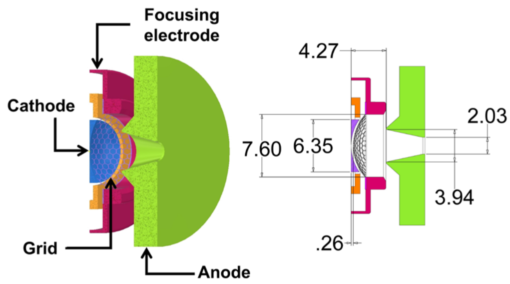

Figure 1: Geometry of triode electron gun (all dimensions are in mm) used in simulations and experimental setup.

PARTICLE TRACKING SIMULATIONS

Beam dynamics simulations were performed using CST Particle Studio with a full 3D model of the electron gun, including space-charge effects. In the simulations, the anode was biased at accelerating potential ($V_a = 5\ to\ 12\ kV$), the focusing electrode and grid were biased at the grid potential ($V_g = -100\ to\ 100\ V$), and the cathode was placed at ground potential. An electron generation model based on space charge emission was defined on the cathode surface with approximately 15,000 emission points. A transverse particle monitor was defined at the exit of the anode to evaluate beam parameters. The simulations were performed with 4.0 million mesh cells and were executed with solver accuracy of −30 dB. The simulations demonstrate smooth acceleration and efficient transport of 1.4 A current at 12 kV through the anode aperture, with no beam interception on the anode surface as shown in (Fig. 2A).

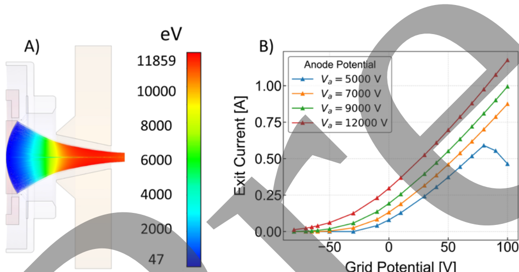

Figure 2: Particle tracking simulations. (A) Beam envelope inside the electron gun. (B) Extracted beam current as a function of grid voltage (V_g).

Parametric scans of the anode voltage (V_a) and grid voltage (V_g) were carried out to evaluate the extracted beam current, as shown in (Fig. 2B). The results show a strong dependence of the beam current on the grid voltage, enabling effective modulation of the emitted beam.

The simulations predict an emitted beam current of approximately 1.4 A, with a perveance of 1.08 µPerv at anode potential of 12 kV and grid potential of 100 V. The beam spot diameter at the anode exit is around 0.7 mm. The transverse phase space at the exit of the anode exhibits a converging beam profile with a positive Twiss parameter $\alpha_y = 2.59$ as shown in (Fig. 3A). The energy distribution of the emitted electrons spans from approximately 11.37 keV to 11.9 keV, with a most probable energy of 11.37 keV and an energy spread of 53.32 eV as shown in (Fig. 3B).

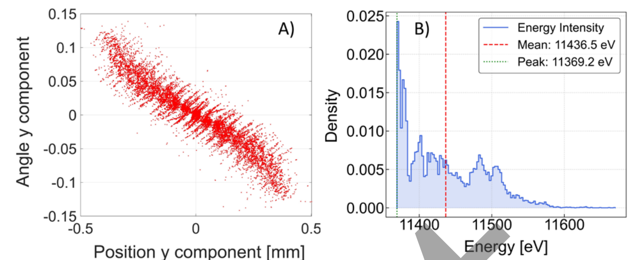

Figure 3: Post processing of CST results. (A) Vertical phase space at anode exit showing beam quality at extraction. (B) Particle energy distribution at anode exit indicating beam energy spread.

These results represent ideal emission conditions at the gun exit and serve as reference parameters for subsequent experimental evaluation and commissioning. A summary of the simulated parameters of the electron gun is provided in Table 1.

Table 1: Summary of Simulated Parameters

Parameters	Value	Unit
Beam energy	12	keV
Beam current	1.4	A
Spot size	<1.0	mm
Perveance	1.08	µPerv
$\epsilon_{rms,x}$ /$\epsilon_{rms,y}$	3.05/ 2.90	mm·mrad
Energy spread	53.32	eV

VACUUM ANALYSIS

The vacuum performance of the injector was analyzed using Molflow+ in the presence of gas load generated during activation of cathode, considering the stringent requirement of the dispenser cathode (<10^{-6} mbar) for activation. Simulations revealed a localized pressure increase near the electron gun without pumping port ($S_2 = 0$) on gun side, caused by limited conductance and gas accumulation as shown in (Fig. 4).

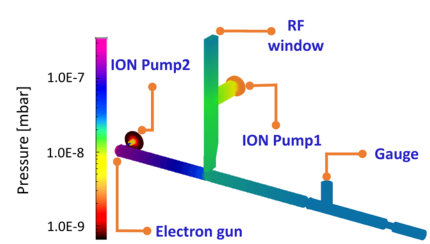

Figure 4: Simulated pressure distribution along the injector showing localized pressure increase near the electron gun.

Figure 5 shows longitudinal pressure profile along LINAC, the pressure increased up to the critical limit of $1 \times 10^{-6}\ mbar$ without pumping port on gun side. To mitigate this effect, an additional pumping port was introduced near the gun region and tube diameter was optimized. The pressure was significantly reduced after implementation of the additional pumping port. Optimization of the diameter of pumping port to 6 mm resulted in approximately one order of magnitude reduction in local pressure, improving operating conditions for stable cathode activation and beam extraction.

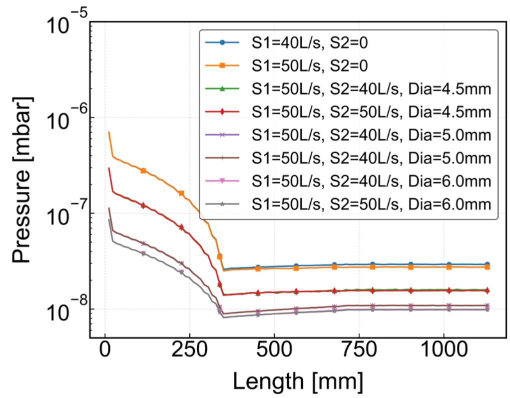

Figure 5: Longitudinal pressure profile before and after implementation of an additional pumping port.

EXPERIMENTAL VALIDATION

Experimental tests were performed at Sordina IORT Technologies to validate the emission characteristics of the electron gun.

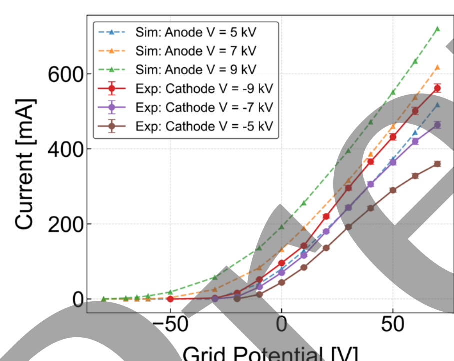

Figure 6: Measured emission current vs grid voltage showing non-ideal behavior due to incomplete cathode activation.

The setup included an ultra-high vacuum chamber with gun assembly mounted inside it. The heater voltage, grid voltage and high voltage were provided by Teledyne ETM electronic gun driver through high voltage feedthroughs. The beam extracted from anode was collected on a circular copper disk connected with external feedthrough, where voltage drop across resistor was measured using oscilloscope.

A comparison between simulation and experimental results is shown in (Fig. 6). The extracted beam current increases with increasing grid potential and the observed trend is consistent with simulation predictions. The deviation of measured current is attributed to insufficient vacuum conditions and incomplete cathode activation. The operation was also limited to −9 kV due to high outgassing from the cathode causing electrical discharges during high voltage operation.

Despite these non-ideal conditions, the experimental trends show good agreement with the simulation results, confirming the validity of the numerical model.

CONTROL & OPERATION

A dedicated control scheme was developed using the Teledyne ETM gun driver to enable automatic cathode conditioning and reliable electron gun operation based on pressure-monitor feedback. The implemented control logic gradually ramps the heater voltage to its nominal operating value, and the ramping state is determined based on low, threshold, and high vacuum limits as illustrated in (Fig. 7).

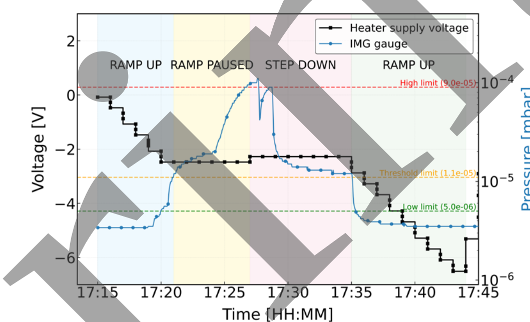

Figure 7: Cathode activation process showing operational logic during cathode conditioning.

A dedicated timing logic was implemented to enable single-shot operation of the electron gun, in which only a finite burst containing a predefined number of pulses is injected during the irradiation cycle. A continuous 100 Hz trigger from the modulator is gated to produce a low-repetition trigger at 0.1 Hz, which initiates burst generation. After completion of the 100 ms burst sequence, the signal generator output is disabled to prevent further beam extraction.

This approach allows precise synchronization and reproducible pulse generation, meeting the requirements for FLASH operation.

CONCLUSION

A comprehensive study of a thermionic triode electron gun for a 24 MeV prototype FLASH LINAC has been presented. Beam dynamics simulations identified optimal operating conditions, while vacuum analysis highlighted and resolved critical limitations near the gun region. Experimental measurements validated the simulation trends, and a dedicated control system enabled reliable overall gun operation and single-shot irradiation for FLASH studies. The developed numerical model and operational studies provide important design guidelines for future compact FLASH LINAC injectors and their integration into full accelerator systems.

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