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Development and Preliminary Testing of a Low-Cost Electron Source Using Gas Discharge Techniques: A Case Study from Afghanistan

Mohammad Bilal Hilal[1]✉, **Arash Gharibi** [2] **Musa Khan Khpalwak**[3], **Noor Mohammad Azizi** [4]

[1]Kabul University, Physics and Electronics Department, Physics Faculty, Kabul, Afghanistan
[2]Kabul University, Physics Faculty, Kabul, Afghanistan
[3]Mirwais Khan Nika University-Zabul, Physics Department, Education Faculty, Zabul, Afghanistan
[4]Kabul University, Atomic and Nuclear Physics Department, Physics Faculty, Kabul, Afghanistan
✉ku.ed.afg911@gmail.com (corresponding author)

ABSTRACT

Electron sources constitute an important part of linear accelerators (LINACs) as they determine the initial characteristics, stability, and quality of the generated electron beam. However, conventional electron guns generally require complex vacuum systems, expensive components, and complex maintenance, limiting their availability in countries with limited resources. Therefore, developing a simple and low-cost electron source is an important step towards the expansion of the accelerator technology and supporting experimental research in such environments. This study was designed to develop, fabricate, and test a low-cost electron source using gas discharge techniques and locally available materials in Afghanistan. A combined theoretical and experimental approach was taken in the study of the basic processes of electron emission, electrostatic acceleration, and gas ionization. The prototype consisted of a cathode-anode assembly mounted in a low-pressure argon-filled glass discharge tube powered by a variable high-voltage supply. System performance was characterized by glow discharge formation, electron transport, and magnetic beam deflection under different conditions. The developed prototype successfully generated a stable glow discharge and showed evidence of electron emission, acceleration, and controlled charged-particle motion under fore-vacuum conditions. The estimated construction cost was about 2450 AFN which shows that the system can be developed with limited finances for laboratory scale applications. Although the lack of sophisticated diagnostic instruments prevented quantitative beam characterization, the prototype demonstrated the basic operating principles of an electron source. These findings provide a practical basis for future development of low-cost accelerator hardware and radiation technology research in Afghanistan and other resource-limited settings.

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INTRODUCTION

Particle accelerators generate controlled beams of charged particles with energies ranging from kiloelectronvolts to several teraelectronvolts, and are now essential to modern science, engineering and clinical medicine (Valković, 2022). In particular, electron beams dominate

the global installations because of their fundamental importance in high intensity radiography, industrial radiation processing (e.g. medical sterilization, food preservation), and as a main tool for cancer treatment (Valković, 2022; Adil et al., 2024; Zimek, 1998). The electron source, or injector, is the fundamental component of such systems that defines the initial quality, stability and brightness of the generated beam (Adil et al., 2024; Zheng et al., 2023). Traditional electron guns are based on thermionic emission of metallic filaments. These well-developed technologies have major drawbacks in operation such as limited lifetimes due to cathode poisoning and the need for sophisticated ultra-high vacuum environments to prevent element degradation (Valković, 2022; Kutsaev, 2021; Gondol & Tajmar, 2023). To solve these problems, research has been conducted on plasma-cathode electron (PCE) guns, which use advanced gas discharge techniques like pseudospark or arc discharges to generate high-current beams without fragile filaments (Pal et al., 2012; Shen et al., 2022; Taploo et al., 2023). Gas discharge electron sources generate electrons by ionization of a low-pressure gas by an applied electric field. The plasma produced in this way serves as an electron-emitting cathode, so that heated filaments are no longer necessary and electrons can be extracted stably under fore-vacuum conditions. This operating principle offers a simple and robust alternative to conventional thermionic electron guns especially for applications where reduced system complexity and lower maintenance costs are desired (Oks & Schanin, 1999). A major advantage of these sources is their efficient work at high pressures in the fore-vacuum range of 1-100 Pa, which simplifies the vacuum infrastructure and reduces mechanical complexity (Kazakov et al., 2013; Burdovitsin et al., 2022). This shift to cold cathode technology is crucial for developing nations, where the high acquisition and maintenance costs of commercial units often hinder adoption (IAEA, 2025; Valković, 2022). In these settings, low-energy electron beams (LE-EB) are preferred because they offer lower unit costs, reduced maintenance requirements, and a modest physical footprint (Zimek, 1998; (IAEA, 2025).

In Afghanistan, linear accelerator technology research has been mainly computational, such as Monte Carlo simulations for dose distribution and target optimization (Ibrahimi et al., 2026), while experimental development of accelerator hardware, especially electron sources, is still limited. This study attempts to fill this gap by developing and testing a low-cost electron source. However, there is an urgent need to establish domestic particle-beam infrastructure to support medical and scientific advancement, and the country faces a notable scarcity of physical hardware components. So, there is still a big gap between theoretical modeling and the development of physical hardware. This study aims to address this hardware gap by designing, developing and testing a low-cost electron source specifically designed for the Afghan environment using gas discharge techniques. Ultimately the aim is to provide a sustainable, locally adaptable and cost-effective foundation for the future of radiation technology in Afghanistan. The specific objectives of the study were to find out the following:

1. To develop a low-cost electron source based on gas discharge techniques.

2. To study the electron emission properties of the developed source.
3. To determine the stability of the electron source in operation under laboratory conditions.
4. To estimate the construction cost and assess the feasibility of using locally available materials.

METHODS AND MATERIALS

Research Design

In this study, a simple electron source was designed, constructed and tested for potential application in a linear accelerator (LINAC) using an experimental design based on well-established theoretical principles of electron emission and gas discharge. The approach was chosen because the purely theoretical and purely experimental studies cannot fully and reliably describe the behavior of vacuum electronic and charged particle systems.

The theoretical framework was based on the principles of electron thermionic emission Gondol and Tajmar (2023), electrostatic acceleration Humphries (1999), beam dynamics Kutsaev (2021), gas discharge physics Shen et al. (2022), and vacuum physics Chambers (2005). Basic electrostatic field relations and the Lorentz force principle Humphries (1999), were used as theoretical references for understanding electron emission, acceleration and beam behavior.

The experimental methodology was based on a theory driven experimental model where theoretical predictions were used to guide the design and experimental observations were used to validate system performance. No numerical simulation tools were used. All evaluations were performed by direct physical construction and laboratory observation. The research was carried out in sequential steps including theoretical analysis and parameter estimation, conceptual and physical design of the electron source, building the system with the available laboratory resources, experimental testing in controlled conditions and final evaluation with comparison to theoretical expectations.

Sampling

This study did not involve human subjects or biological samples. The experimental unit was one laboratory-built electron source prototype. The electron source was designed, built and tested in laboratory-controlled conditions. The same prototype was used for repeated experimental measurements of electron emission, glow discharge formation and beam behavior under various operating conditions.

Data Collection Tools

The electron source was built from basic laboratory components that are locally available due to the limited access to advanced accelerator infrastructure. The key elements included a thermionic cathode (tungsten or metal filament) for electron emission, a positively biased anode, a DC high-voltage power supply to create the potential difference between the cathode and the anode, a glass vacuum enclosure to maintain low pressure, insulating mounts to prevent electrical breakdown, and simple measuring instruments (voltmeters and

current indicators) to monitor electrical parameters. Advanced diagnostic tools such as Faraday cups, beam profile monitors and ultra-high vacuum systems were not available due to resource limitations.

Table 1. *Materials and Equipment Used in the Experimental Setup*

No.	Material / Equipment	Specification	Quantity	Use
1	Glass discharge tube	Handmade glass tube	1	Vacuum chamber for gas discharge
2	Argon gas	Argon, low pressure	1	Filling gas for glow discharge
3	Electrode — Cathode	Metallic electrode	1	Electron emission
4	Electrode — Anode	Metallic electrode	1	Electron collection
5	Variable AC Power Supply (PHYWE Variac)	0–250 V, 6 A	1	Adjustable voltage source
6	Electrical wires	Copper wire, insulated	Several	Electrical connections
7	Alligator clips	Electrical connection clips	4	Secure laboratory connections
8	Adhesive	Sealing adhesive for glass	As required	Sealing the discharge tube as required
9	Glass vacuum bulbs	Experimental trial bulbs	Several	Experimental trials
10	Laboratory support stand	Metal stand with holders	2	Fixing the tube and components
11	Measuring devices	Voltmeter and ammeter (built-in)	1 set	Monitoring voltage and current

Data Collection and Experimental Procedure

The electron source was designed as a thermionic electron gun system with a cathode-anode configuration in a vacuum environment. When heated, the cathode releases electrons which are collected by the anode via an electric field.

The electron kinetic energy is governed by $E_k=eV$, where E_k represents the kinetic energy of the electron and V is the applied voltage (Humphries, 1999). The electric field between electrodes is given by $E=V/d$, where d is the cathode–anode distance (Zhu & Ang, 2011). The electrode spacing was optimized to balance electron acceleration efficiency and the risk of electrical breakdown (Tarasenko et al., 2008).

The cathode was mounted and aligned directly opposite to the anode for symmetric electron emission and to reduce the beam divergence. The anode was designed for electron transmission and control beam geometry. All components were mounted in a closed glass vacuum glass. Sufficient vacuum levels were maintained to allow observable electron

transport and gas ionization effects although ultra-high vacuum conditions were not reached. A DC high-voltage power supply was connected across the electrodes, and a gradual increase in applied voltage was used to initiate the electron emission and ionization within the glass. The indirect confirmation of the beam formation was the presence of a glow discharge inside the vacuum tube, which indicated that the residual gas molecules were ionized due to their interaction with the accelerated electrons. The applied voltage was observed using the power supply display and a voltmeter and correlated with changes in the discharge intensity and beam stability. Direct beam current measurements were not possible due to lack of advanced diagnostic tools, but qualitative assessment was done based on glow intensity, stability of emission, and response to voltage changes. Beam deflection was also observed with a simple magnetic field, confirming the motion of charged particles. The complete experimental setup (Source of Schematic image: Author's illustration) is shown in Figure 1.

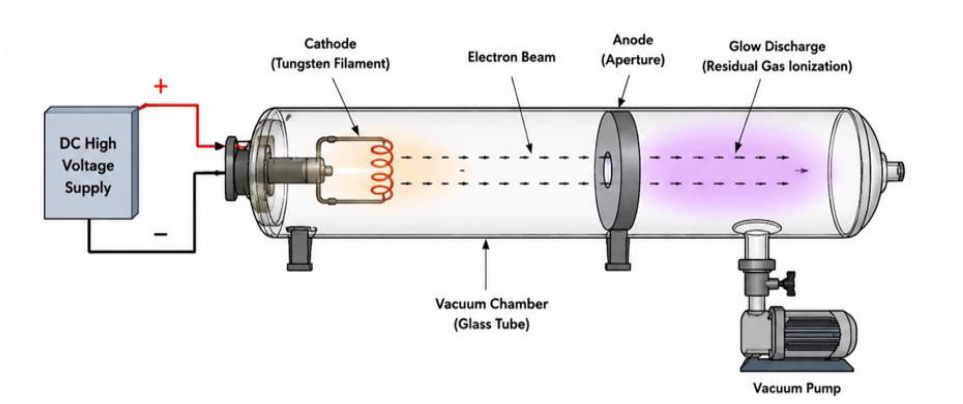


Figure 1. *Experimental Setup Schematic image is Illustrated).*

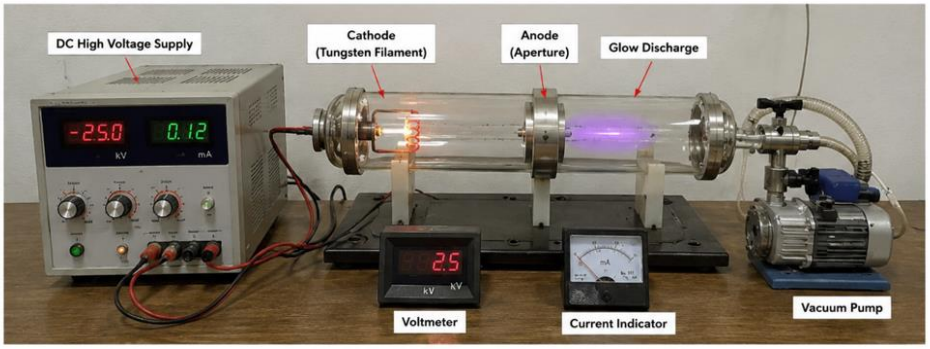
Table 2. *Experimental Operating Conditions*

No.	Parameter	Value	Unit
1	Working Gas	Argon	—
2	Gas Pressure	Low pressure (estimated)	≈ 0.5–1 Torr
3	Distance Between Cathode and Anode	3	cm
4	Input Voltage	0–250	V
5	Initial Voltage for Glow Discharge	160	V
6	Stable Voltage	250	V
7	Type of Power Supply	Variable AC (PHYWE Variac)	—
8	Vacuum Condition	Evacuated Glass Tube	—
9	Type of Discharge	Glow Discharge	—

No.	Parameter	Value	Unit
10	Material of Tube	Glass	—
11	Material of Electrodes	Metallic Electrodes	—
12	Environment of Experiment	Laboratory	—

FINDINGS

In this work a low-cost electron source system was designed and experimentally realized as a first prototype, based on the fundamental principles of vacuum electronics and charged particle physics. The main goal of the system is to produce a controllable electron stream that could be used as an injector for future linear accelerator (LINAC) applications. The system is made up of several key parts that work together to produce electron emission and acceleration. These include a thermionic cathode (heated filament), an anode electrode, a vacuum chamber made of a glass tube, a DC high-voltage power supply and a basic observational and measurement set-up. Each part serves a particular function in producing, accelerating, and precisely directing electrons in the system. The overall configuration is modularly designed so that each component works independently and contributes to the behavior of the entire system. The modular structure also allows for easier modification and improvement of individual components without a need to redesign the entire system. The



schematic configuration of the developed electron source (Source of Schematic image: Author's illustration) is presented in Figure 2.

Figure 2. *Schematic diagram of the electron source system showing cathode, anode, and vacuum chamber arrangement.*

Limitations

The methodology had some limitations such as the lack of ultra-high vacuum conditions, limited voltage stability, lack of precision diagnostic instruments, incomplete control over the uniformity of the cathode temperature, material constraints and lack of computational simulation tools. The system had these and other shortcomings. But it did manage to demonstrate the fundamental principles of electron emission, acceleration and gas ionization.

Electron Emission and Acceleration Mechanism

The process of electron generation in this system is based on thermionic emission, where thermal energy provides electrons with sufficient energy to overcome the potential barrier known as the work function and escape into the vacuum (McCarthy et al., 2014). Once these particles are liberated, the electric field created by the potential difference between the cathode and anode accelerates them, a process which is essentially the transfer of kinetic energy to the particles. The kinetic energy acquired by the beam is directly related to the applied voltage; for instance, an electron volt (eV) is defined as the energy gained by an electron passing through a potential difference of one volt. Therefore, by modulating the applied electrical potential (voltage), the overall energy of the electron beam can be precisely controlled (Humphries, 1999).

The experimental observations confirm that the higher the applied voltage, the stronger the electron acceleration and the interaction with residual gas molecules inside the glass chamber, which finally contributes to gas ionization and visible discharge formation.

Electric Field Configuration and Control

The process of electron acceleration is fundamentally governed by the electrostatic field established between the cathode and the anode (Humphries, 1999). The intensity of this electric field is determined by the magnitude of the applied voltage and the physical separation between the electrodes, a relationship mathematically defined as $E=V/d$ (where E is the electric field, V is the voltage, and d is the distance (Zhu & Ang, 2011). Based on this principle, regulating the inter-electrode gap is a critical factor in managing field strength and the resulting energy distribution of the electron beam (Tarasenko et al., 2008).

The experimental results indicate that the electric field strength increases with the decrease of electrode distance, which results in the enhancement of electron acceleration. But the distances are too short and the risk of breakdown and uncontrolled discharge inside the system is high. Conversely, wider electrode spacing reduces the field strength and thus weakens the electron acceleration and ionization efficiency. Thus, the system performance depends heavily on an optimized balance between the electrode spacing and applied voltage, which directly influences the formation and stability of the beam.

Influence of Vacuum Conditions

The establishment of a high-quality vacuum environment is a fundamental requirement for the stability and transport of an electron beam (Chambers, 2005). According to the principles of vacuum physics, a sufficiently rarefied space is necessary to allow the free passage of particles; otherwise, electrons frequently undergo collisions with residual gas molecules (Shen et al., 2022). These interactions directly lead to beam scattering and the loss of kinetic energy, which significantly reduces the directionality and focus of the beam as electrons are diverted from their intended trajectory (Chambers, 2005; Shen et al., 2022).

The experimental observations reveal three different regimes of behavior depending on the pressure conditions. At relatively high pressure, the electron motion is strongly scattered and no clear beam formation is observed. Electrons collide with gas molecules and excite and ionize them. At intermediate levels of vacuum, you get a glow discharge that is visible inside the glass. At lower pressure conditions electron transport becomes more directional and stable, but the formation of complete beam still remains limited due to non-ideal vacuum conditions. These results indicate that partial vacuum conditions are sufficient to observe fundamental gas discharge phenomena and electron-gas interactions even without ultra-high vacuum systems. Before ignition, the vacuum tube remained dark, as shown in Figure 3. Source of image: Author experiment setup)

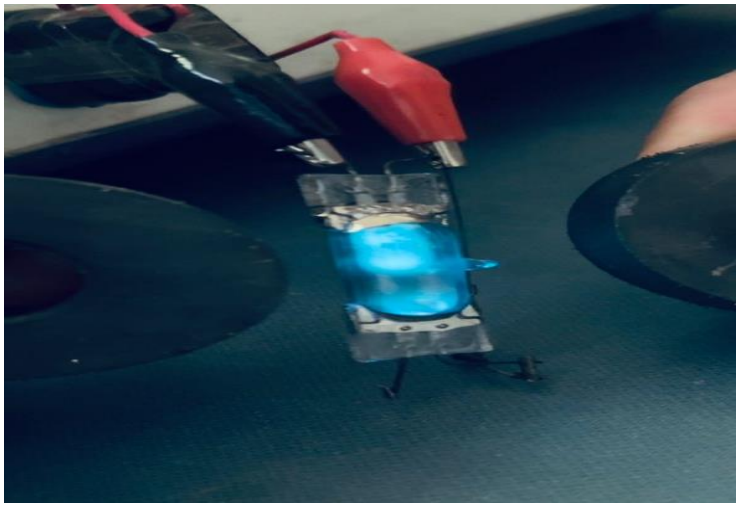


Figure 3. *Vacuum tube before glowing*

High Voltage Behavior and Gas Discharge Formation

The application of a high-voltage DC source is a fundamental prerequisite for both the electrostatic acceleration of particles and the initiation of gas ionization processes. (Humphries, 1999); (Shen et al., 2022).

The dependence of the discharge behavior on the magnitude of the applied voltage is clearly shown in the experimental results. At low voltage levels, no visible discharge can be observed inside the glass, indicating that the electron energy is not enough for ionization. As the voltage is slowly increased, first ionization events occur due to the collision of electrons with residual gas atoms. At higher voltage levels, a glow discharge is established which is

stable and continuous. There is visible light emission inside the vacuum tube. This transition illustrates the fundamental process of gas discharge, in which the higher energy of electrons results in excitation and ionization of the gas molecules and the emission of photons during the de-excitation processes. A stable glow discharge formed inside the vacuum tube, as illustrated in Figure 4.

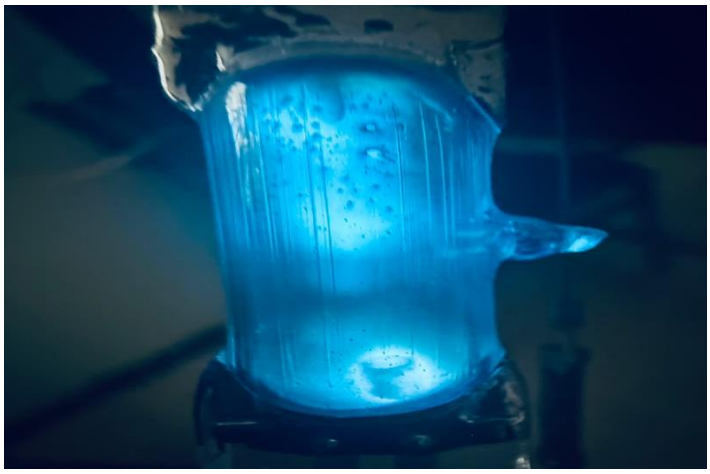


Figure 4. *Glow discharge formation inside the vacuum tube. (Image is taken from Author experiment setup)*

Observation of Electron Beam Behavior

Qualitative observations were successfully recorded despite the absence of advanced diagnostic equipment such as beams profilers or current density meters. The presence of electron–gas interactions and energy transfer processes is shown by a visible luminous path inside the glass tube. Also, the existence of an anode made possible a partial directionality of electron motion, pointing to the formation of a rudimentary electron beam. The magnetic field also provided an additional qualitative check by visibly deflecting the electron trajectory. These observations collectively confirm that in principle the system is able to generate and manipulate electron motion in a qualitative sense, even with simplified experimental conditions. Electron beam deflection under an external magnetic field is shown in Figure 5.

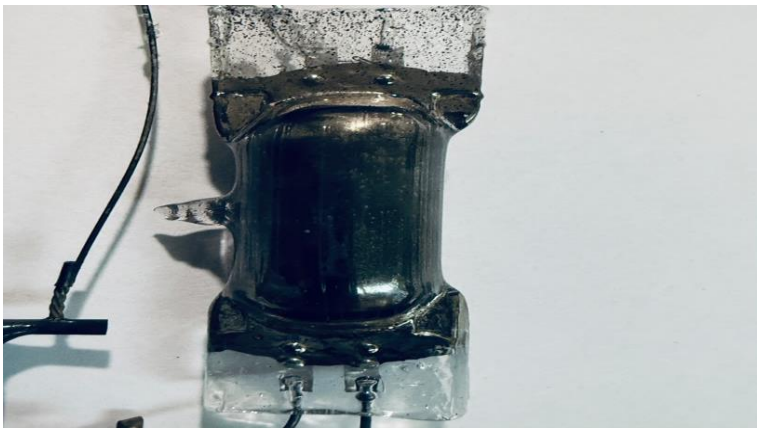


Figure 5. *Electron beam deflection by magnetic field*

Electron beam deflection under with and without magnetic field is shown in Figures 6,7 below:



Figure 6. *Electron beam deflection with magnetic field*



Figure 7. *Electron beam deflection without magnetic field*

System Stability and Performance Behavior

The accuracy of the accelerating potential and the preservation of structural durability within the source form the fundamental guarantees of the operational stability and reliability of an electron beam system (Gondol & Tajmar, 2023). Fluctuations in the applied voltage are particularly detrimental to the spatial uniformity of the discharge, as exceeding specific current thresholds can trigger instabilities such as the formation of cathode spots or transitions into unstable arc modes (Kazakov et al., 2013). Concurrently, thermal imbalances within the cathode lead to mechanical deformation of the filament and electrodes, a process that exponentially alters emission rates and results in an enlarged beam spot and degraded focusing precision (IAEA, 2025) Finally, the maintenance of a high-quality, stable vacuum is essential to preventing cathode oxidation, as prolonged exposure to residual gases can contaminate the surface and permanently alter the work function and its resulting emitting characteristics (Schaber et al., 2023).

The system was limited but demonstrated stable glow discharge characteristics under reasonably controlled operating conditions. This indicates that the fundamental electron source functionality can be achieved with a simplified setup.

Gas Discharge Mechanism Observations

The experimental setup clearly demonstrated the main processes of the gas discharge: electron impact ionization, atomic excitation and visible light emission. These processes take place when the fast electrons interact with the gas molecules in the vacuum glass, transferring energy and causing excitation or ionization. Excited atoms then de-excite, giving

off photons which we see as a visible glow in the interior of the glass. This shows that the system reproduces the basic plasma-like behavior well under the controlled low-pressure conditions.

Experimental Limitations

During the course of the experiment a few limitations were experienced. The main limitation was the lack of precise vacuum measurement instrumentation, which limited the accurate characterization of pressure conditions inside the chamber. Also, due to the lack of sensitive diagnostic equipment, the electron beam could not be measured in direct current mode. Moreover, advanced beam characterization parameters such as emittance, beam profile and energy distribution could not be determined. Control of the gas pressure was similarly approximate rather than precise. However, the system has successfully demonstrated the basic principles of electron emission, acceleration and gas discharge behavior in a simplified experimental environment. In summary, this work shows that a simple electron source can be made from cheap materials, which still shows important physical phenomena such as thermionic emission, acceleration by an electric field, interaction with electron gas, and formation of glow discharge. Although the system is preliminary and lacks advanced diagnostic precision, it provides clear experimental evidence of electron generation and basic gas discharge physics under low-resource conditions.

Estimated Construction Cost

The estimated construction cost of the experimental electron source was about 2,450 AFN. This includes the glass discharge tube, argon gas, electrodes, electrical wires and clips, adhesive materials and other laboratory consumables. Major laboratory equipment such as high voltage power supply and vacuum pump was available in the laboratory and was not included in the cost of construction.

Table 3. *Estimated Construction Cost of the Experimental Electron Source*

No.	Component	Unit	Estimated Cost (AFN)
1	Glass discharge tube	1	350
2	Vacuum glass bulbs (used in experiments)	3	450
3	Argon gas filling	1	300
4	Cathode	1	100
5	Anode	1	100
6	Wires and clips, electrical	1 set	250
7	Adhesive and sealing materials (Glue)	1	600
8	Miscellaneous laboratory materials	—	300
	Total Estimated Cost		**2,450 AFN**

DISCUSSION

Experimental results of this study show the successful implementation of a functional prototype of an electron source specifically designed for high-resource efficiency. One of the major findings of this work is the ability to produce a stable glow discharge and preliminary electron emission at a construction cost of only 2,450 AFN, effectively overcoming the technological barriers in developing nations where the high acquisition costs of commercial particle accelerators often hinder scientific and medical advancement. In contrast to high-energy facilities where multi-stage vacuum systems are needed to reach pressures of 10-5 Torr or lower, the prototype operated efficiently in the fore-vacuum range (1–100 Pa). This operational stability aligns with the findings of Oks and Schanin (1999), who noted that plasma-based electron guns are inherently more reliable and have longer lifespans because they can operate at pressures achievable by simple mechanical pumps. Furthermore, these observations of stable glow discharge in this pressure range mirror the experimental results of Kazakov et al. (2013), who successfully utilized arc-discharge techniques to form pulsed electron beams in the 4–15 Pa range.

In terms of emission mechanisms, while many modern plasma cathode sources aim for a "filament-less" or cold cathode design to eliminate the risk of cathode poisoning Oks & Schanin (1999); Pal et al. (2012), the study employed a thermionic tungsten filament to assist in gas ionization. This hybrid approach ensured reliable electron generation despite the absence of the high-precision pulse-triggering units typically found in advanced pseudospark sources. The findings confirm that electron kinetic energy is governed by the relation Ek=eV, adhering to the fundamental principles of electrostatic acceleration as established by (Humphries, 1999). Qualitative assessments showed that increasing the negative voltage enhanced discharge intensity and electron emission stability, a trend consistent with the observations of Shen et al. (2022), who reported that higher applied voltages significantly enhance electron emission current while weakening electron scattering.

A critical technical aspect of this design was the optimization of the cathode–anode distance d. We found that reducing this gap increased the electric field strength E=V/d, thereby improving acceleration efficiency, but excessively small distances led to uncontrollable arcing and electrical breakdown. This phenomenon is well-supported by (Tarasenko et al., 2008), who experimentally demonstrated that the inter-electrode gap is a primary factor influencing beam current amplitude and that an "optimum value" must be chosen based on voltage and gas pressure to prevent discharge contraction. Finally, this study represents a vital transition in the Afghan scientific context; while previous local research, such as the Monte Carlo investigations by Ibrahimi et al. (2026), focused on theoretical dose distributions, this prototype provides a tangible proof-of-concept for the domestic development of physical hardware components for future linear accelerators in Afghanistan. Overall, the results suggest that the developed electron source has achieved the main goal of this study. The prototype was able to produce a stable glow discharge and

preliminary electron emission using low cost and locally available materials. This answers the research question by demonstrating the construction and building of a simple and inexpensive electron source, potentially for use in a LINAC, particularly in resource-constrained environments

CONCLUSION

The study successfully demonstrated the design, construction and preliminary experimental evaluation of a low-cost electron source based on gas discharge techniques using locally available materials in Afghanistan. The prototype developed produced stable glow discharge under low pressure conditions, providing qualitative evidence of electron emission, acceleration and electron-gas interactions. Although there were no sophisticated tools for beam diagnostics, the measured discharge characteristics and magnetic deflection demonstrated the presence and controlled motion of charged particles, showing the basic operating principles of an electron source. The experimental results demonstrate a strong dependence of the system performance on the applied voltage, cathode-anode distance and vacuum conditions, which is in good agreement with the basic principles of electron acceleration and gas discharge physics. The prototype has performed well in fore-vacuum conditions, without the need of high vacuum infrastructure, demonstrating the practicality of gas-discharge based electron sources for low-resource environments. Also, the estimated construction cost of approximately 2,450 AFN suggests that a working experimental electron source can be built with limited financial resources, making it suitable for educational laboratories and early accelerator research in developing countries. The limitations are the absence of accurate vacuum measurement and direct beam current diagnostics and sophisticated beam characterization systems. However, the prototype is a practical proof of concept for local development of electron-source technology. The study is therefore an important first step towards the development of indigenous accelerator hardware research in Afghanistan and helps to close the gap between theoretical accelerator studies and experimental implementation. In the future work, precision vacuum instrumentation, regulated gas-pressure control, high voltage DC power supplies, and advanced diagnostic devices such as Faraday cups and beam profile monitors can be included, which will allow quantitative characterization of beam properties. Further optimization of the electron optics and numerical simulations should be also included in order to improve the beam quality and to develop a complete injector system for the future low-energy linear accelerator (LINAC) applications.

Authors Contribution

- Mohammad Bilal Hilal: Developed the research idea, designed the study and supervised the whole research process.
- Arash Gharibi: Contributed to the experimental design, participated in experimental work, and assisted in the collection and analysis of data.
- Musa Khan Khpalwak: Theoretical analysis, drafting and revision coordination of the manuscript.

- Noor Mohammad Azizi: Assisted in the experimental setup, experimental testing and interpretation of the results.
- All authors have read, revised and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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Conflict of Interest Statement

The authors confirm that there are no conflicts of interest related to this review.

Data Availability Statement

Data related to this study are available from the corresponding author upon request.

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