Integrated Design, Simulation, and Fabrication of a PIG Ion Source Accelerator for Functional Materials Research

Manjeet Mor* and Puneet Jain

Department of Physics, Indian Institute of Technology Roorkee, Roorkee-247667, Uttarakhand, India

*manjeet@ph.iitr.ac.in

Abstract ID #155

Abstract

We present the design and development of a compact ion accelerator based on a Penning Ion Generator (PIG) ion source for controlled irradiation of thin films. Simulation-driven optimization using IBSimu and COMSOL guided the fabrication of key subsystems, including the ion source, electrostatic quadrupole triplet, and Wien velocity filter. The system delivers ions up to 50 keV with µA-level currents under high-vacuum conditions, offering a versatile, cost-effective platform for nanoscale materials engineering.

Introduction

- Ion irradiation is a powerful tool for tailoring the structural and electronic properties of thin films used in advanced functional applications.
- Conventional accelerators are large and costly, limiting accessibility for laboratory-scale research.
- To overcome these challenges, a compact ion accelerator system based on a Penning Ion Generator (PIG) ion source has been developed.
- The objective is to design, simulate, and fabricate a cost-effective platform that ensures stable ion beam extraction, precise focusing, and mass-to-charge separation, enabling versatile applications in nanoscale materials engineering.

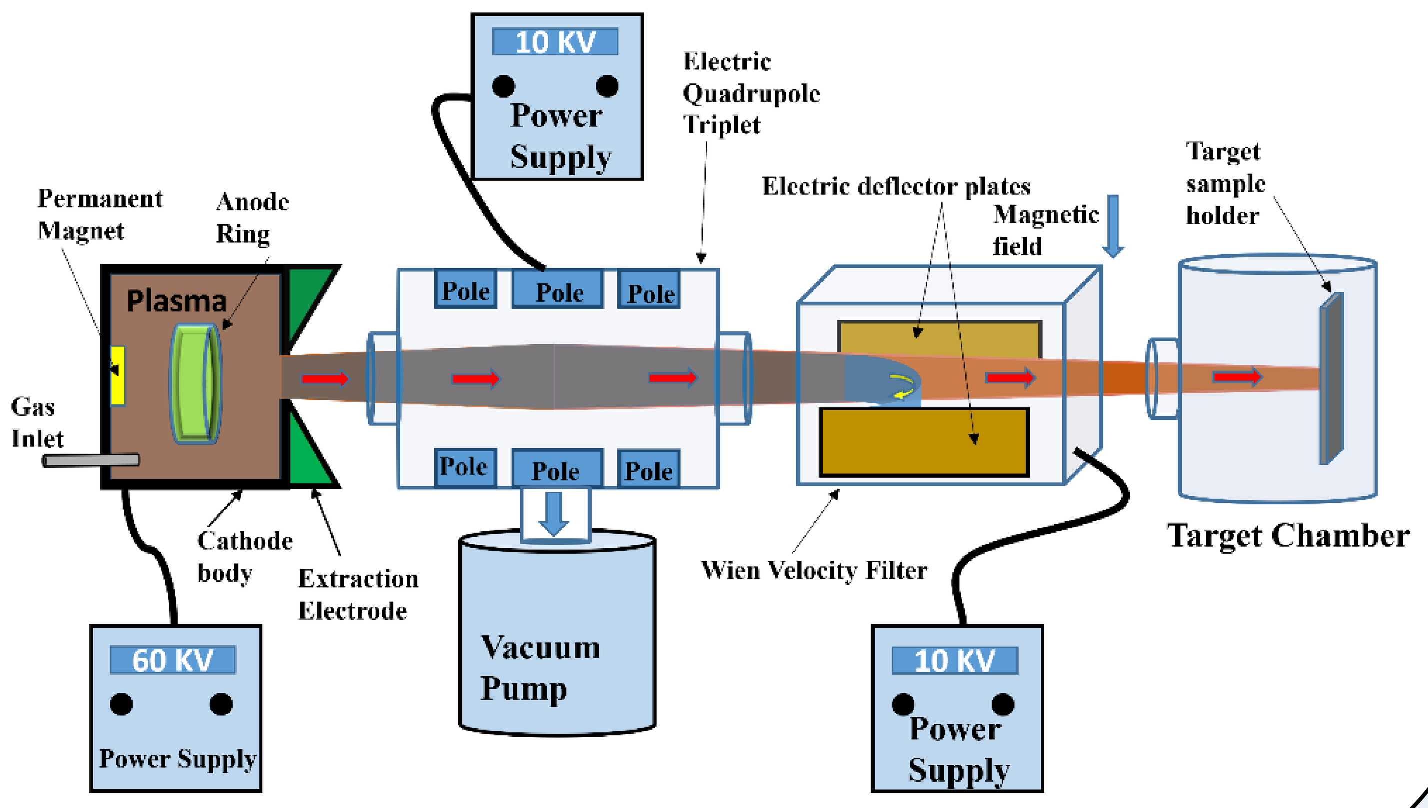

Fig. 1. Design schematic of the in-house tabletop ion accelerator

Design & Methodology

The accelerator was conceived as a compact, modular system integrating four key subsystems:

- Penning Ion Generator (PIG) for stable ion production,
- Electrostatic Quadrupole Triplet (EQT) for precise beam focusing,
- Wien Velocity Filter (WVF) for mass-to-charge separation, and
- High-vacuum target chamber for irradiation studies.

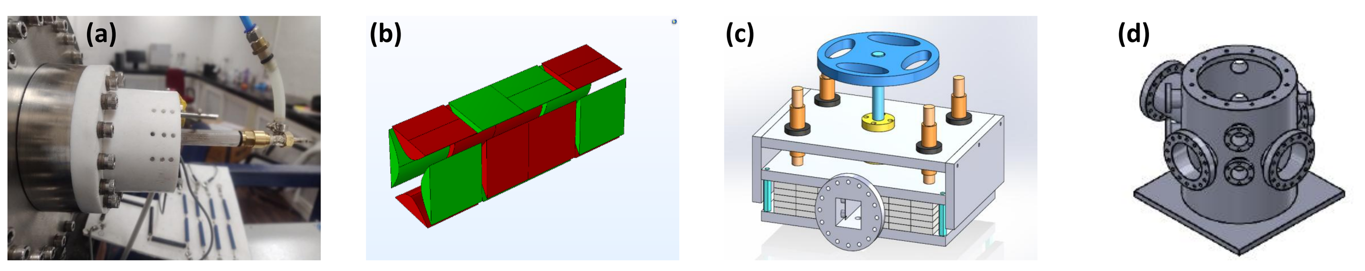

Fig. 2. Major components of the tabletop ion accelerator: (a) Penning Ion Source for beam generation, (b) Electrostatic Quadrupole Triplet for focusing, (c) Wien Velocity Filter for ion separation, and (d) Target Chamber for irradiation studies

A simulation-guided approach ensured optimal performance:

- IBSimu optimized the plasma extraction region, enhancing ion yield and reducing beam divergence.
- COMSOL Multiphysics modeled electric and magnetic fields, enabling precise tuning of ion trajectories through the EQT and WVF.

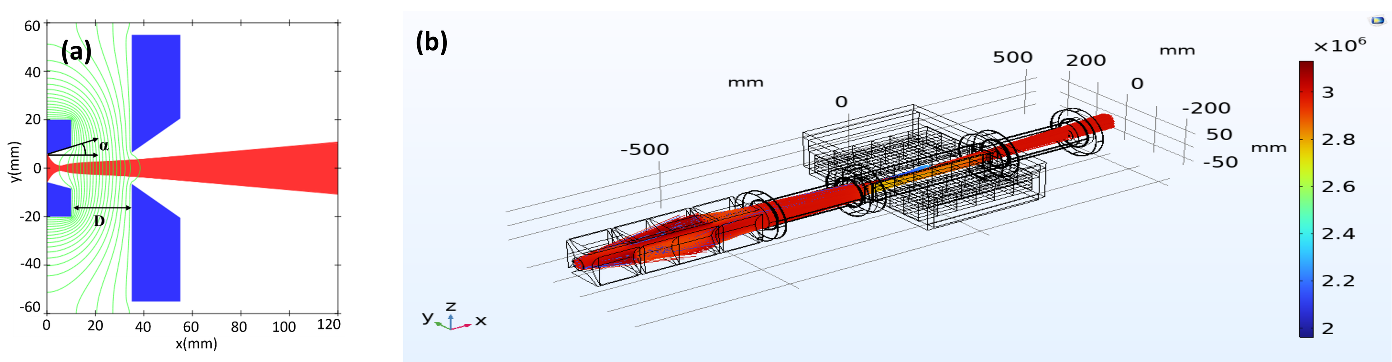

Fig. 3. (a) Ion extraction simulation using IBSimu, and (b) beam transport through EQT and WVF modeled in COMSOL Multiphysics.

Following optimization, all subsystems were fabricated in-house using stainless steel chambers, Teflon insulators, Neodymium magnets, and high-voltage supplies. The components were integrated into a compact tabletop assembly, with mu-metal shielding added to suppress fringe fields and maintain beam quality.

Acknowledgment

This work is financially supported by IIT ROORKEE, MoE, INDIA

Results & Discussion

- Beam extraction improves: Decreasing angle (α) increases extracted ion current.
- Transport optimization: Ion beam current decreases with distance (D) as beam focusing decreases.
- Beam quality preserved: Mu-metal shielding suppresses fringe fields, minimizing transport losses.

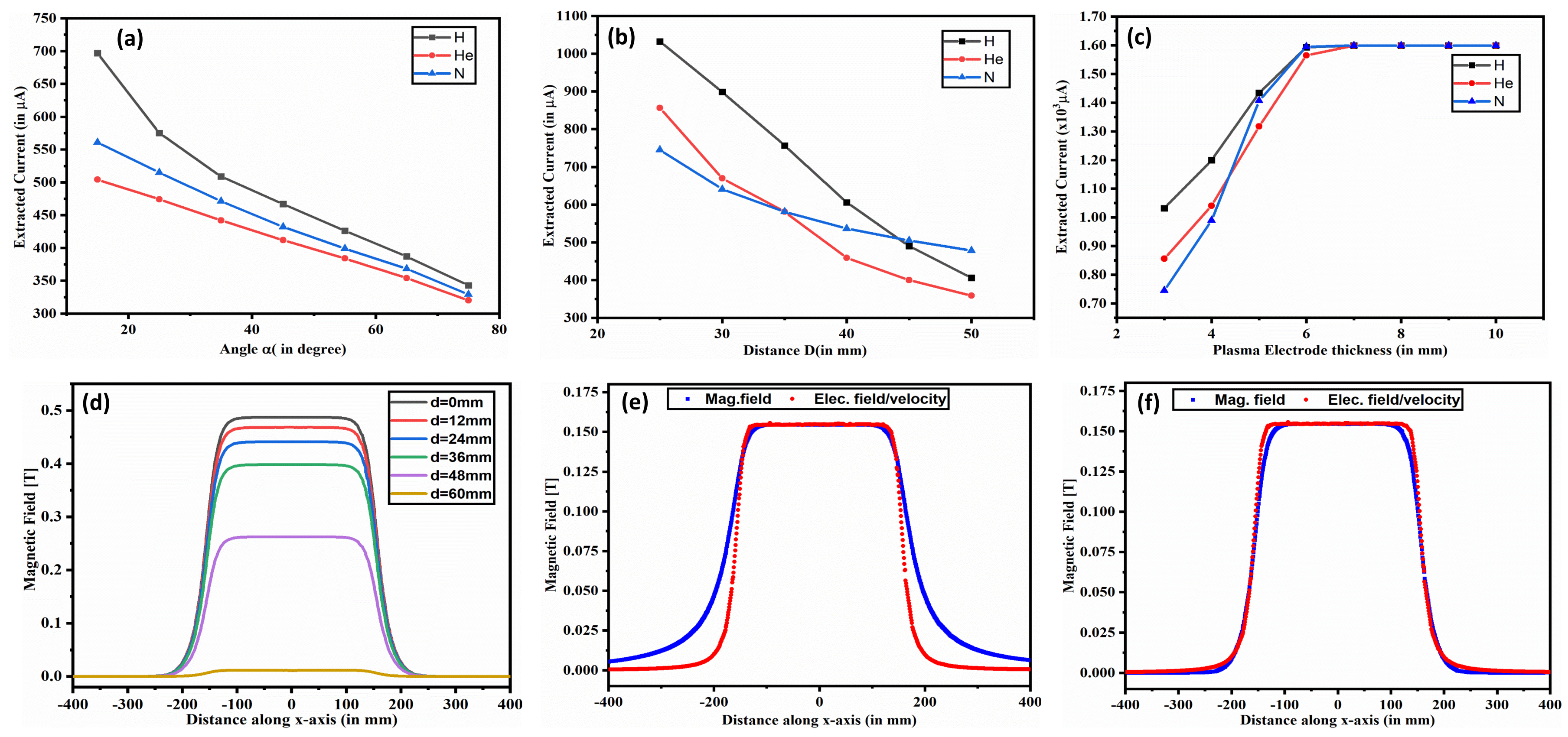

Fig. 4. Simulation studies: (a) ion beam current vs. angle α, (b) ion beam current vs. distance, (c) ion beam current vs. plasma electrode thickness using IBSimu; COMSOL results for WVF showing (d) magnetic field variation with shunt plate movement, (e) electric and magnetic field profiles without mu-metal shielding, and (f) profiles with mu-metal shielding.

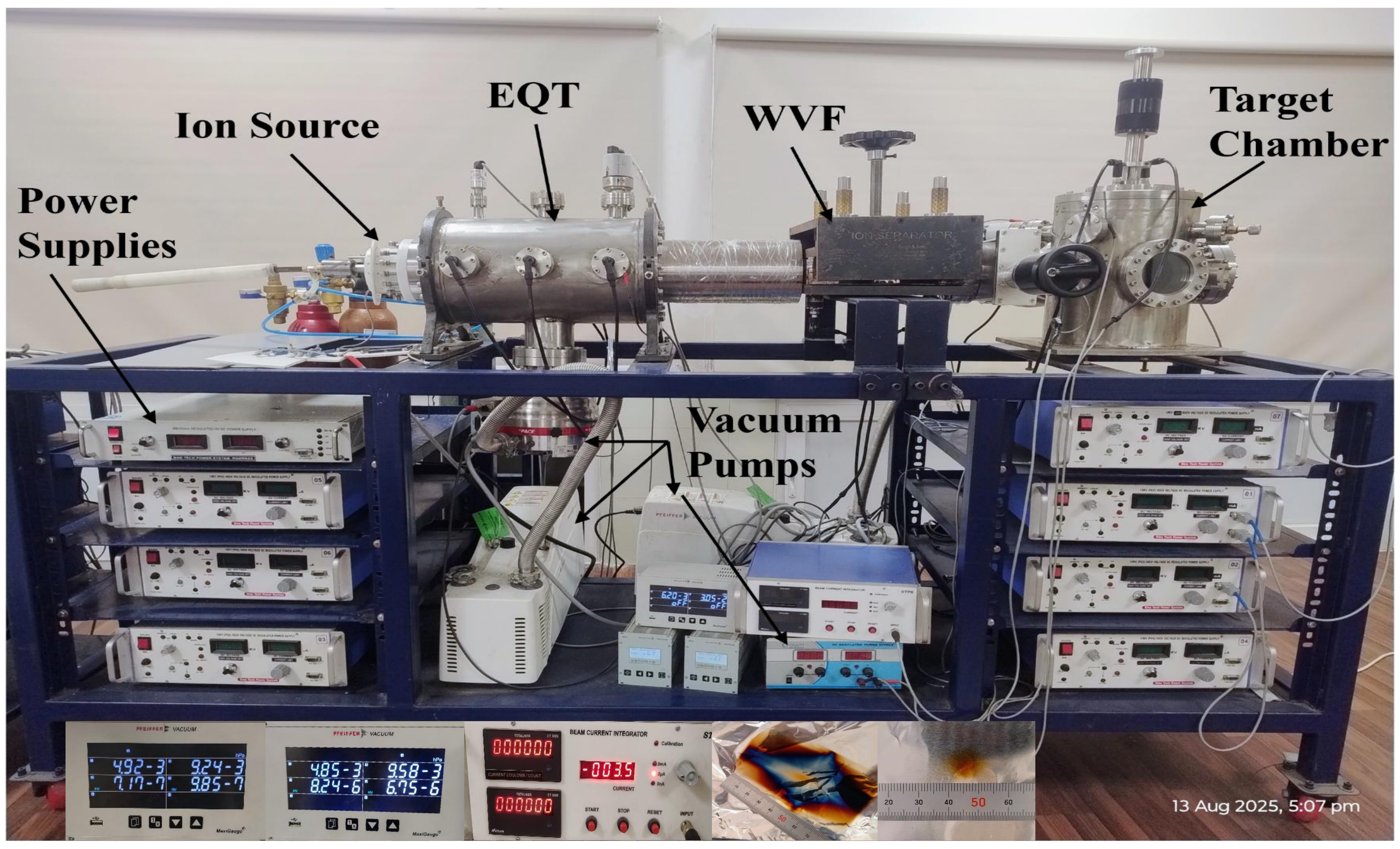

Fig. 5. Installed ion accelerator system showing assembly, vacuum performance, beam current, and beam spot on aluminum foil.

- Energy range: 5 – 50 keV.
- Ion species supported: H_2, N_2, O_2, He etc..
- Beam current: From 1 nA to 3 µA.
- Beam size of less than 1 cm ensures controlled irradiation.
- Operating vacuum: better than ~10^{-5} mbar, ensuring high beam purity.
- Transport stability: Achieved efficient focusing and separation with EQT & WVF.
- Demonstrated a compact, reliable platform for thin-film irradiation experiments.

Conclusions

A compact, cost-effective ion accelerator based on a PIG ion source was successfully designed, simulated, and fabricated entirely in-house. Simulation-driven optimization ensured efficient beam extraction, transport, and delivery. The system demonstrates stable operation over a wide energy range and supports multiple ion species, enabling flexible irradiation studies. This platform provides a practical laboratory-scale tool for nanoscale defect engineering and materials research.

References

1. Huang et al., Recent Progress in Ion Beam Technology in Nanostructured Energy, ACS Nano, 2024.
2. Zhou et al., Emerging 2D Metal Oxides: Synthesis and Integration, Adv. Mater., 2023.
3. Jung et al., Oxygen Content Manipulation on Metal Oxide Surfaces, ACS Nano, 2023.
4. Zhang H., Ion Sources, Springer, 1999.
5. Kalvas et al., Three-Dimensional Simulation Software for Particle Optics, Rev. Sci. Instrum., 2010.
6. Rovey et al., Simple Penning Ion Source for Research, Rev. Sci. Instrum., 2007.