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

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Ion irradiation has emerged as a vital tool for engineering the structural and electronic properties of materials, particularly thin films used in advanced functional applications. Its precision and tunability make it highly effective for defect modulation at the nanoscale, driving innovations in materials research. In this work, we present the design, simulation, and fabrication of a compact ion accelerator system, centred around a Penning Ion Generator (PIG) ion source, developed entirely in-house to enable controlled and localized ion irradiation. The accelerator delivers ions up to 50 keV and comprises four components: a Penning Ion Source for stable production, an Electrostatic Quadrupole Triplet (EQT) for focusing, a Wien Velocity Filter (WVF) for mass-to-charge separation, and a high-vacuum Target Chamber for uniform delivery. The design and optimization of each subsystem were guided by computational simulations. The plasma extraction region was optimized using IBSimu to enhance ion yield and minimize divergence. COMSOL Multiphysics simulated the electric and magnetic fields in the EQT and WVF, enabling ion trajectory tuning and efficient transport. Following the simulation, each subsystem was fabricated and assembled in-house, resulting in a compact, efficient, and cost-effective platform for laboratory-scale irradiation. The accelerator supports H_2, N_2, O_2, and He gases and delivers beam currents up to 1 μA. High-voltage supplies drive the EQT and WVF, with Neodymium magnets generating the WVF magnetic field. A mu-metal shield minimizes fringe fields and maintains beam quality. The final beam spot (~1.5 cm × 1.0 cm) ensures localized irradiation. The system operates under high vacuum (~10^{-6} mbar) to maintain purity.
In summary, the developed PIG ion source-based accelerator offers a versatile, cost-effective platform for ion irradiation research, with high flexibility and control for nanoscale materials engineering.

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