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ORIGINAL PAPER

ADJUSTING SAFIIRA BEAM LINE FOR THE CHARACTERIZATION OF A TRACKER GAS DETECTOR

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ABSTRACT

This work presents the structural and instrumental modifications carried out on the Ion beam system for irradiation and applications (SAFIIRA) beamline at the Pelletron accelerator of the Universidade de São Paulo to enable the in-beam characterization of a gas tracker prototype developed for the Nuclear Matrix Elements for Neutrinoless Double Beta Decay (NUMEN) Project. The beamline was adapted to operate with high-purity isobutane at low pressures (10–30 mbar), requiring the implementation of a dedicated gas handling system, the installation of a thin silicon nitride (Si_3N_4) entrance window, a motorized target tower, and a chamber extension. The detector was tested with ^{16}O, ^{12}C, and ^{7}Li ion beams under various tilt angles and beam rates. The system exhibited high stability during operation, with no signs of discharge or vacuum failure, confirming the suitability of the modified SAFIIRA setup for gas detector characterization under realistic experimental conditions.

KEYWORDS: Low-Pressure Detector Operation, Beamline Modification, Pelletron Accelerator.

AJUSTE DA LINHA DE FEIXE SAFIIRA PARA A CARACTERIZAÇÃO DE UM DETECTOR GASOSO DE RASTREAMENTO

RESUMO

Este trabalho apresenta as modificações estruturais e instrumentais realizadas na linha de feixe Sistema de Feixes Iônicos para Irradiações e Aplicações (SAFIIRA) do acelerador Pelletron da Universidade de São Paulo para viabilizar a caracterização em feixe de um protótipo de detector gasoso do Projeto de Elementos da Matriz Nuclear para Decaimento Beta Duplo sem Neutrinos (NUMEN). A linha de feixe foi adaptada para operar com isobutano de alta pureza em baixas pressões (10–30 mbar), exigindo a implementação de um sistema dedicado de manuseio de gás, a instalação de uma fina janela de entrada de nitreto de silício (Si_3N_4), uma torre de alvos motorizada e a extensão da câmara. O detector foi testado com feixes de íons de ^{16}O, ^{12}C e ^{7}Li sob diversos ângulos de inclinação e taxas de feixe. O sistema apresentou alta estabilidade durante a operação, sem sinais de descarga ou falha de vácuo, confirmando a adequação da configuração modificada da SAFIIRA para a caracterização de detectores gasosos em condições experimentais realistas.

PALAVRAS-CHAVE: Operação de Detector de Baixa Pressão, Modificação da Linha de Feixe, Acelerador Pelletron.

INTRODUCTION

The Ion beam system for irradiation and applications (SAFIIRA) beamline of the 8UD Pelletron accelerator at the Universidade de São Paulo is a multipurpose irradiation facility originally designed for studies involving radiation effects on electronic devices and materials. One of its key features is the ability to control the flux and spatial distribution of incident ions over several orders of magnitude, enabling irradiation conditions ranging from ~10 to ~10^{10} particles $s^{-1} \cdot cm^{-2}$. These capabilities make SAFIIRA a suitable environment not only for applied irradiation studies but also for detector development and characterization, provided that specific operational conditions—such as gas handling, vacuum integrity, and beam shaping—are appropriately adapted.

Such adaptations became necessary in the context of the Nuclear Matrix Elements for Neutrinoless Double Beta Decay (NUMEN) Project, which aims to extract information on nuclear matrix elements relevant to neutrinoless double beta decay ($0\nu\beta\beta$) through the study of heavy-ion double charge exchange reactions[1-4]. NUMEN experiments are carried out using the MAGNEX magnetic spectrometer at the Istituto Nazionale Fisica Nucleare-Laboratori Nazionali del Sud (INFN-LNS) in Catania, Italy. As part of the forthcoming upgrades to the MAGNEX focal-plane detector system, a new low-pressure gas tracker based on multiple thick gas electron multipliers (M-THGEM) is under development to measure ion trajectories and momenta with high-angular and position resolution[5–7]. Before installation in MAGNEX, the prototype must undergo in-beam characterization under controlled conditions that reproduce the ion energies, rate of incident particles, angular ranges, and gas pressures expected in NUMEN experiments.

To meet these requirements, the SAFIIRA beamline was selected as a test platform, but several structural and instrumental modifications were necessary to operate the tracker under low-pressure isobutane while maintaining the upstream ultra-high vacuum.

This work provides a detailed description of the modifications implemented on the SAFIIRA irradiation chamber—including the installation of a thin silicon nitride entrance window, a chamber extension, a motorized target tower, and a dedicated gas handling system—, specifically designed to enable the in-beam characterization of the NUMEN tracker prototype.

EXPERIMENTAL SETUP

The prototype

A new gas tracker for the focal plane detector of the MAGNEX spectrometer, based on M-THGEM, is under development at INFN-LNS (Fig. 1). The gas tracker must meet strict requirements regarding tracking capability: an angular resolution smaller than 0.5° and position resolution of 0.5 mm. Additionally, it must handle high rates of medium to heavy ions, about 30 kHz.

The structure of the gas tracker is composed of three main stages:

- A drift region, that is the active volume of the detector, crossed by the reaction ejectiles of interest;
- An electron multiplication stage, based on M-THGEM;
- A segmented read-out electrode.

The vertical position and angles of the track are determined by measuring the drift time of the electrons, while the horizontal position and angles are from the charge distribution measured by the segmented anode. From this information, the full ion track, including the impact point and angle of incidence at the focal plane, can be reconstructed.

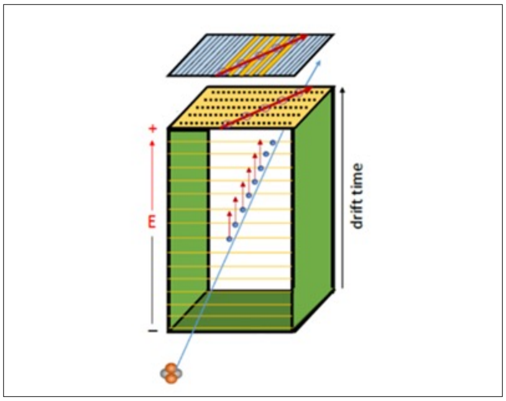

Figure 1: Scheme of the working principle of the Nuclear Matrix Elements for Neutrinoless Double Beta Decay (NUMEN) gas tracker prototype. Source: Elaborated by the authors.

SAFIIRA beamline

The aim of the test at the 8UD Pelletron Tandem facility was to characterize the gas tracker prototype by measuring:

- The position and angular resolution;
- The dependence of performance on the tracker tilt angle relative to the incident ion beam;
- The response of the tracker under varying beam rates.

The experimental setup is shown in Fig. 2. The accelerated beam crosses a thin silicon nitride window (thickness of 1 μm) located at the entrance pipe of the 45-cm diameter irradiation chamber installed at the Pelletron facility. The chamber was filled with high-purity (99.95%) isobutane gas (iC_4H_{10}), with pressures ranging from 10 to 30 mbar during the measurements.

Inside the chamber, the tracker prototype was mounted with a variable tilt angle (θ_{tilt}), adjustable between 0 and 70°, relative to the beam direction. A silicon carbide (SiC) telescope detector was employed to stop the beam and provide timing signals for drift velocity measurements. These SiC detectors are part of the particle identification wall developed for the NUMEN experiment at the MAGNEX focal plane.

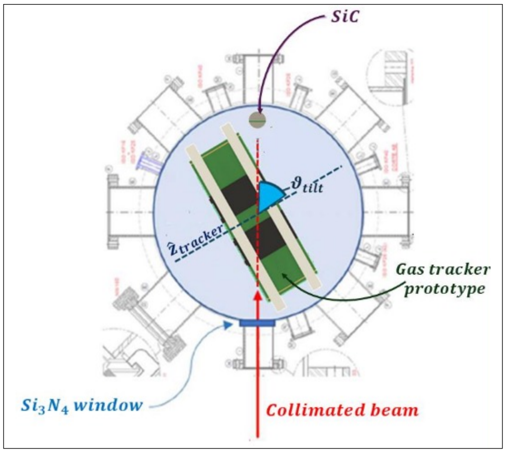

Figure 2: Schematic representation of the experiment setup at the 0° Pelletron beam line chamber.

Source: Elaborated by the authors.

Three ion beams were used: ^{12}C at ~45 MeV, ^{7}Li at ~28 MeV, and ^{16}O at ~64 MeV. These beam energies were selected to replicate the typical conditions encountered in NUMEN experiments, particularly regarding the energy loss of ions in the gas volume[1–3].

To achieve a low-emittance beam profile, the SAFIIRA beamline combines beam focusing/defocusing via a quadrupole doublet with successive multiple scattering in thin gold foils, followed by spatial filtering through Ta collimators (Fig. 3)[8]. This arrangement enables significant reduction of beam divergence and intensity, resulting in a final spot diameter of 0.3 mm and divergence of 0.2° full width at half maximum at the chamber entrance.

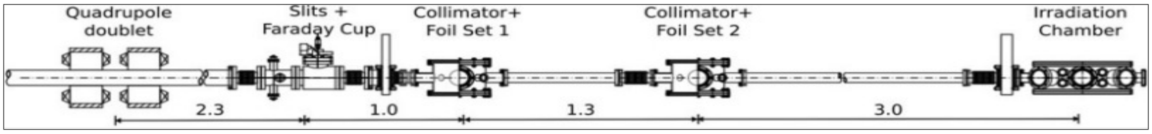

Figure 3: Schematic drawing of the Ion beam system for irradiation and applications (SAFIIRA) beamline layout showing quadrupoles, scattering foils, faraday cup, and vacuum chambers. The dimensions are in meters.

Source: Elaborated by the authors.

Modifications to the beamline

To accommodate the detector prototype, some modifications were made to the main chamber of the SAFIIRA beamline (Fig. 4). An extension was installed at the top of the chamber to house the detector. To preserve the internal pressure in the region in which the detector was positioned, a silicon nitride window was added. A target tower was introduced on the upper lid of the beamline to mount the collimator and Faraday cup, and a dedicated gas system was implemented to control the pressure and ensure a stable gas flow in the chamber.

The following sections provide a detailed description of each of these modifications.

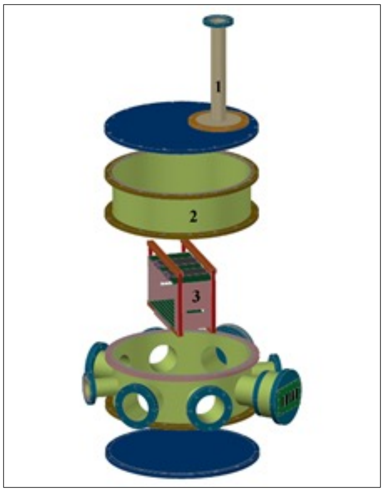

Figure 4: Schematic drawing of the Ion beam system for irradiation and applications (SAFIIRA) irradiation chamber with: (1) target tower; (2) extension; (3) tracker prototype.

Source: Elaborated by the authors.

Chamber extension

To allow the prototype to fit inside the irradiation chamber, an extension was installed on the top flange. This extension was designed to increase the internal height of the chamber—originally 18 cm—by an additional 15 cm. As a result, the total internal volume increased from 0.24 to 0.53 m3. The entire chamber, including the extension, is made of stainless steel.

The modification was necessary to accommodate the dimensions of the tracker prototype, which measures approximately 30 cm in length, 10.8 cm in width, and 15 cm in height[4].

Target tower

A motorized target tower was designed and installed on the upper flange of the SAFIIRA irradiation chamber to allow remote-controlled positioning of beam-interacting elements during the in-beam tests of the tracker detector prototype. This vertical system enables insertion and retraction of a Faraday cup and a fixed collimator along the beam axis without breaking vacuum or opening the chamber, simplifying alignment procedures and beam diagnostics during operation (Fig. 5).

The system is composed of:

- A stepper motor mounted externally to the chamber lid, responsible for actuating a vertical threaded shaft;
- A nylon guide block inside the chamber, coupled to the shaft via two holes: one threaded (engaging the shaft), and one smooth (acting as a linear bearing);
- A vertical rail that mechanically supports the target components and guides their translation inside the chamber;
- A Faraday cup for beam current integration and a collimator (Ø1-mm opening) for beam shaping and spatial filtering.

The vertical motion is controlled by a custom LabVIEW-based interface, allowing the operator to:

- Select which element (Faraday cup, collimator, or empty beam path) is positioned along the axis;
- Control insertion and retraction with millimetric resolution;
- Monitor system status remotely from the control room.

To ensure precise beam alignment, the upper flange is equipped with a micrometer-based tilt adjustment system, which allows fine tuning of the horizontal orientation of the internal rail. This is essential to compensate for any chamber tilt or mechanical imperfections, ensuring that the beam crosses the collimator and enters the detector volume accurately.

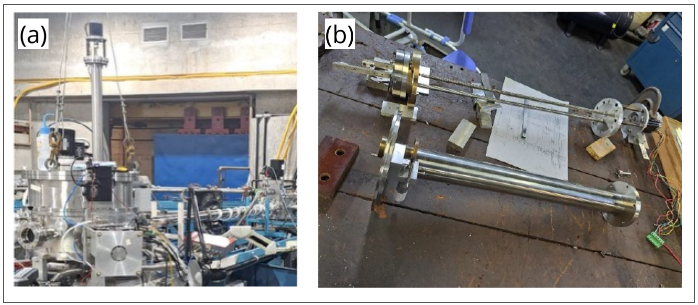

Figure 5: Target tower developed for the irradiation chamber. (a) Target tower installed on the beamline irradiation chamber; (b) disassembled target tower showing both external and internal components. Source: Elaborated by the authors.

Silicon nitride window

To separate the low-pressure gas volume inside the irradiation chamber from the high-vacuum section of the beamline, a thin silicon nitride (Si_3N_4) window was installed at the beam entrance. This component is essential for maintaining vacuum integrity in the upstream line while allowing ion beams to enter the detector volume with minimal energy degradation and angular straggling.

The window is composed of a 1-μm thick silicon nitride membrane mounted on a frame and sealed to withstand the pressure difference between the two regions—typically up to 30 mbar on the gas side and 10^{-6} Torr in the beamline. Its mechanical robustness, chemical stability, and excellent transmission properties for heavy ions make Si3N4 a suitable material for such applications.

Given the substantial pressure differential between the two regions, a custom four-part mechanical adapter was developed to ensure both leak-tightness and mechanical stability of the window assembly.

All components were fabricated in nylon, chosen for its low outgassing and vacuum compatibility, except for the outer fastening tool, which was machined in inox to provide sufficient mechanical rigidity for external fixation.

Adapter assembly

The window mounting system is composed of four interlocking parts (Fig. 6):

- Upper support ring: this component secures the window frame to the overall assembly. It is designed with a lip that exerts axial pressure onto the frame, locking it against the lower section;
- Window frame: holds the 1-μm thick silicon nitride membrane. Fabricated in nylon, this frame centers and supports the window while distributing mechanical stress evenly across the surface;
- Lower support ring: this part interfaces with the upstream vacuum pipe and contains a machined groove for accommodating a standard O-ring seal between parts 2 and 3, ensuring vacuum integrity;
- Base adapter: affixed to the irradiation chamber flange, this part receives and holds the lower support ring (3), completing the sealing structure.

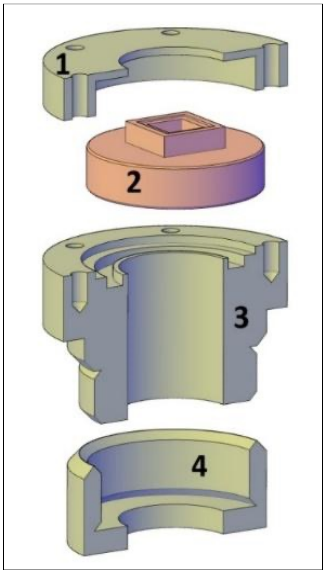

Figure 6: Schematic drawing of the window mounting system: (1) upper support ring, (2) window frame, (3) lower support ring, and (4) base adapter. Source: Elaborated by the authors.

The connection between components 3 and 4 is mechanical and secured by the outer fastening tool mentioned above. This external metallic piece engages with tabs on part 3, allowing the entire assembly to be compressed and locked in position with a simple quarter-turn motion. This mechanism allows easy removal for maintenance or replacement, while providing robust axial compression for the O-ring seal.

This assembly method requires no complex procedures: the sealing is achieved purely through mechanical compression, and the tool allows easy removal or replacement of the window when needed. The resulting interface provides sufficient robustness to withstand the pressure differential between the low-pressure gas region and the upstream high-vacuum beamline. Leak testing was conducted prior to beam operation to verify the integrity of the interface.

To evaluate the impact of the window on beam properties, simulations were performed using the Stopping and Range of Ions in Matter (SRIM) software[9]. For 45 MeV ^{12}C ions, the results indicated low energy loss (~0.2 MeV) and small angular straggling, confirming that the beam remained well-collimated after passing through the window (Fig. 7). These conditions are compatible with the experimental requirements for tracking resolution and ion identification.

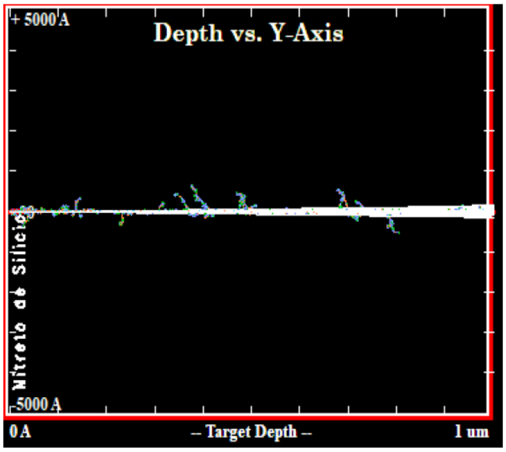

Figure 7: Stopping and Range of Ions in Matter (SRIM) simulation showing the trajectories of 45 MeV 12C ions crossing the Si3N4 window. White lines represent ion paths, while colored lines indicate recoiled atoms.

Source: Elaborated by the authors.

Gas system

The operation of the gas tracker prototype required a controlled low-pressure environment filled with high-purity isobutane (C_4H_{10}, 99.95%). To meet this requirement, a dedicated gas handling and vacuum system was implemented in the SAFIIRA beamline, allowing operation within the pressure range of 10 to 30 mbar while maintaining compatibility with upstream ultra-high vacuum conditions.

The system was designed to enable progressive evacuation, controlled gas injection, pressure stabilization, and safe isolation from the beamline (Fig. 8). Vacuum generation was carried out through a two-stage pumping system: a mechanical pump was responsible for roughing down the chamber pressure, while a turbomolecular pump—connected downstream of the beamline—ensured the maintenance of high-vacuum conditions near the silicon nitride window interface. Proper sequencing of pump operation was strictly followed to prevent backflow and to protect the turbo pump; the turbomolecular unit was started only after the mechanical pump reached operational conditions.

Gas injection into the chamber was manually regulated using a combination of needle and ball valves arranged in a modular distribution panel. Needle valves were used for fine tuning of the isobutane flow rate, while ball valves allowed rapid isolation or venting of individual sections. The system also included two pneumatically actuated gate valves positioned along the beamline path. These valves enabled physical decoupling of the gas-filled scattering chamber from the upstream vacuum line during filling and purge cycles, preserving the integrity of the beamline vacuum even when the chamber was at relatively elevated pressure.

Pressure monitoring was achieved using both strain gauge sensors and a differential Baratron capacitance manometer. The Baratron, installed near the gas inlet, provided measurements in the 1–100-mbar range, with stability better than ± 1 mbar during beam operation. Additionally, the pressure at various points in the beamline was monitored by Pirani sensors installed along the vacuum path. These readings were continuously logged and visualized through a custom-built LabVIEW interface, which also allowed real-time supervision.

The vacuum system was operated from an external control panel equipped with visual indicators for valve positions, pump status, and sensor outputs. Prior to each experimental run, the system was flushed with nitrogen to eliminate atmospheric contaminants, and all connections were helium leak-tested to ensure the absence of leaks.

The overall setup proved highly effective during all irradiation campaigns. Pressure conditions remained stable even under high-beam current exposure, with no signs of pressure oscillations or contamination-induced discharge events. This reliable performance validated the system's design and confirmed its suitability for extended tracker operation, especially in environments requiring clean transitions between vacuum and low-pressure gas volumes.

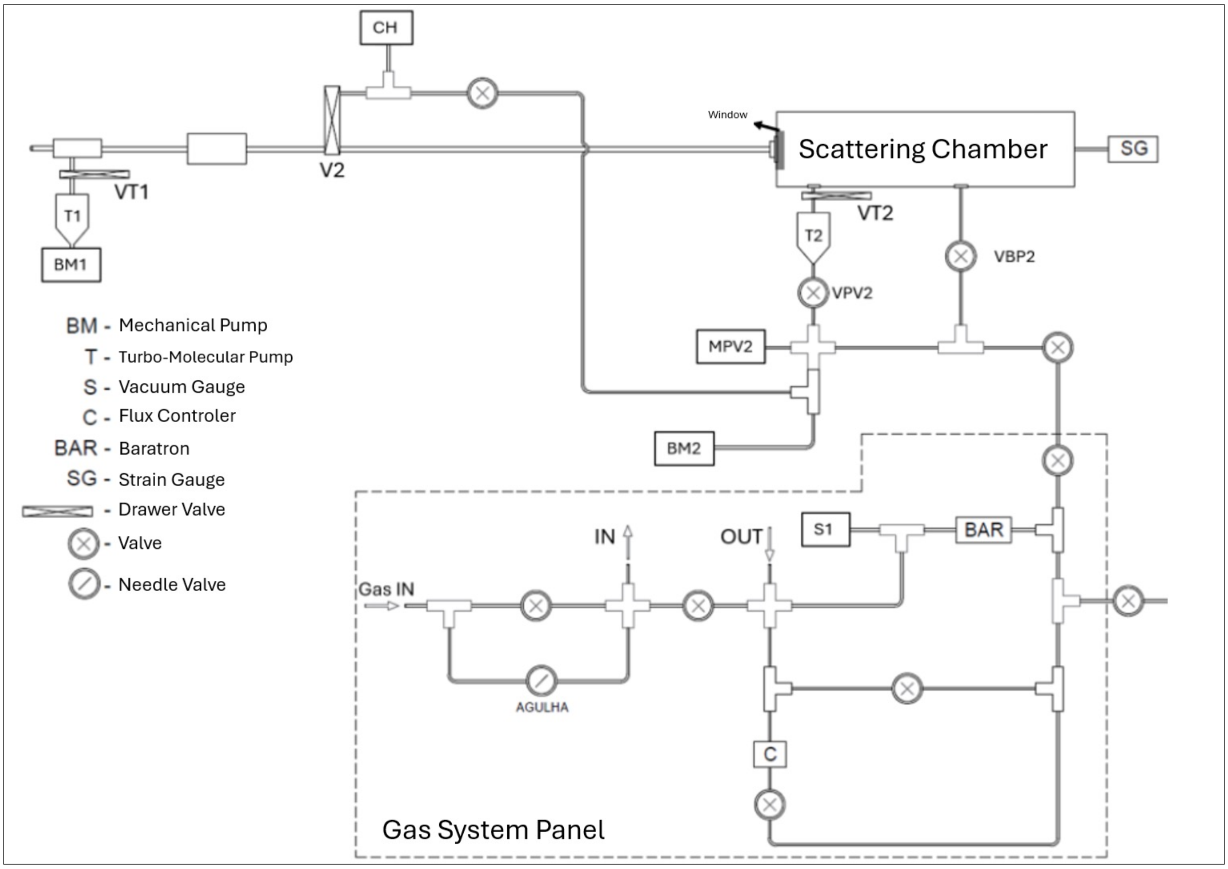

Figure 8: Schematic diagram of the gas system at the Ion beam system for irradiation and applications (SAFIIRA) beamline. The setup includes the gas inlet and outlet lines, pressure control and gauges.

Source: Elaborated by the authors.

RESULTS

The characterization campaign of the gas tracker prototype at the SAFIIRA beamline demonstrated the operational stability of both the detector and the newly implemented infrastructure. The tracker operated successfully in an environment filled with high-purity isobutane (iC_4H_{10}, 99.95%) at controlled pressures ranging from 10 to 30 mbar, with tests performed using ^{16}O, ^{12}C, and ^{7}Li ion beams at 45 and 28 MeV, respectively.

A critical parameter for the operation of the detector was the stability of the gas pressure inside the chamber, especially under continuous beam irradiation. Due to the sealing provided by the 1-μm silicon nitride (Si_3N_4) window, it was possible to maintain a stable low-pressure environment without compromising the upstream ultra-high vacuum. Figure 9 shows the average internal pressure measured during a typical run, illustrating the high degree of stability (± 1 mbar) even under varying beam currents. This behavior validated both the sealing efficiency of the Si3N4 window and the functionality of the gas control system.

A brief pressure step visible during the ^{7}Li measurement corresponds to a controlled refilling procedure. At that stage, a slight pressure decrease—faster than expected from the nominal leak rate—was identified during monitoring. This behavior was later attributed to a temporary reduction in the sealing efficiency of the Si3N4 window mounting. After adjusting the mechanical interface, the system returned to the expected stability, and no additional substantial pressure deviations were observed in the subsequent ^{12}C and ^{16}O runs.

The detector was tested at various tilt angles (θ_{tilt}) ranging from 40 to 70° with respect to the beam axis to evaluate the effect of track inclination on charge collection. Signal quality remained stable throughout the angular scan, with no evidence of gaining degradation or signal suppression due to beam rate or orientation.

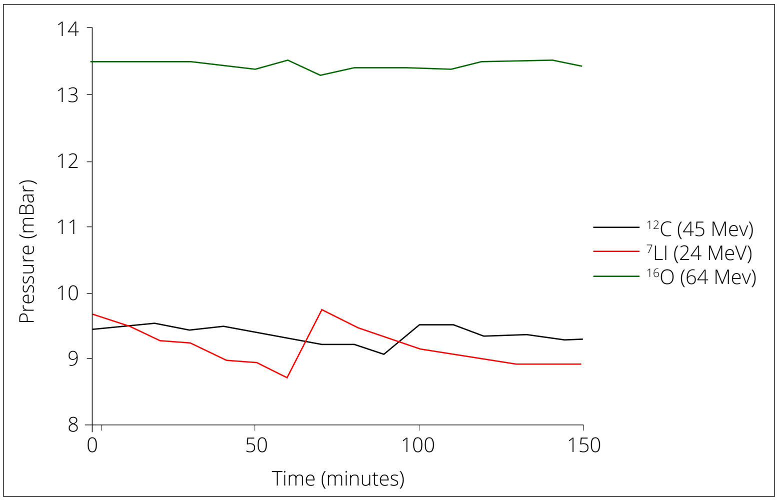

Figure 9: Average pressure in the main chamber during one hour of operation with ^{12}C and ^{7}Li ion beams.

Source: Elaborated by the authors.

Coincidence measurements with a downstream SiC telescope allowed the acquisition of timing signals, essential for determining the electron drift velocity inside the gas. These measurements, combined with the segmented readout of the anode, allowed the identification of well-defined ion tracks within the detector volume. Figure 10 presents a schematic illustration of ion trajectories crossing the drift region, showing the projection of the charge collected on the anode.

The prototype showed excellent robustness under beam intensities up to 105 particles s^{-1}·cm^{-2}. No sparking events or substantial pressure drops were observed during operation, confirming the mechanical and electrical stability of the M-THGEM structure.

These results provide solid evidence of the detector's compatibility with high-intensity heavy ion beams and confirm the suitability of the SAFIIRA-modified chamber for future in-beam characterization campaigns.

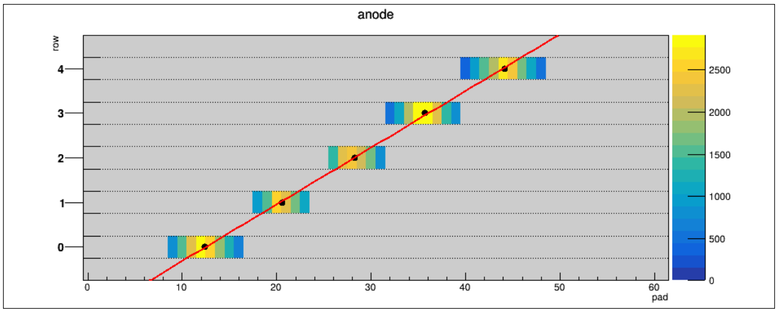

Figure 10: Typical track projection on the anode measured by the tracker of a ^{12}C beam at 45 MeV.

Source: Elaborated by the authors.

CONCLUSION

A series of structural and instrumental modifications were successfully implemented in the SAFIIRA beamline of the Pelletron accelerator at Physics Institute of the Universidade de São Paulo to enable the in-beam characterization of a gas tracker prototype developed for the NUMEN Project. Key upgrades included the installation of a chamber extension, a silicon nitride entrance window, a motorized target tower, and a dedicated gas handling and vacuum system. These adaptations transformed the SAFIIRA irradiation chamber into a suitable environment for operating low-pressure gas detectors without compromising the high-vacuum conditions upstream in the beamline.

The integration of a 1-µm Si_3N_4 window proved effective in separating the detector volume from the vacuum line, maintaining differential pressures of up to 30 mbar with excellent leak tightness. The gas system provided precise control and stability of isobutane pressure during operation, as verified through continuous monitoring via a LabVIEW-based interface. The pressure remained stable even under sustained beam exposure, confirming the system's robustness.

In-beam tests with ^{16}O, ^{12}C, and ^{7}Li ion beams demonstrated the prototype's ability to operate under realistic NUMEN-like conditions. Signals were successfully collected over a range of detector tilt angles, with optimal performance observed at approximately 60°. The prototype exhibited no signs of sparking, discharge, or pressure-induced instabilities, even under high-beam rates.

The successful integration of the modified SAFIIRA beamline and the gas tracker prototype demonstrates the system's mechanical reliability and operational stability under realistic experimental conditions. These results establish a robust framework for future NUMEN detector characterizations and highlight the potential of the setup for broader applications involving in-beam tests of low-pressure gas detectors.

CONFLICT OF INTEREST

Nothing to declare.

AUTHOR CONTRIBUTIONS

Conceptualization: Schervenin JV, Medina NH, Aguiar VÂP, Added N, Oliveira JRB, Guazzelli MA, Cavallaro M, Cappuzzello F, Spatafora A, Torresi D, Agodi C, Carbone D, Sgouros O and Soukeras V. **Formal Analysis:** Schervenin JV, Medina NH, Aguiar VÂP, Added N, Oliveira JRB, Guazzelli MA, Cavallaro M, Cappuzzello F, Spatafora A, Torresi D, Agodi C, Carbone D, Sgouros O and Soukeras V. **Investigation:** Schervenin JV, Medina NH, Aguiar VÂP, Added N, Oliveira JRB, Guazzelli MA, Cavallaro M, Cappuzzello F, Spatafora A, Torresi D, Agodi C, Carbone D, Sgouros O and Soukeras V. **Resources:** Schervenin JV, Medina NH, Aguiar VÂP, Added N, Oliveira JRB, Guazzelli MA, Cavallaro M, Cappuzzello F, Spatafora A, Torresi D, Agodi C, Carbone D, Sgouros O and Soukeras V. **Supervision:** Schervenin JV, Medina NH, Aguiar VÂP, Added N, Oliveira JRB, Guazzelli MA, Cavallaro M, Cappuzzello F, Spatafora A, Torresi D, Agodi C, Carbone D, Sgouros O and Soukeras V. **Validation:** Schervenin JV, Medina NH, Aguiar VÂP, Added N, Oliveira JRB, Guazzelli MA, Cavallaro M, Cappuzzello F, Spatafora A, Torresi D, Agodi C, Carbone D, Sgouros O and Soukeras V. **Data curation:** Schervenin JV, Medina NH, Aguiar VÂP, Added N, Oliveira JRB, Guazzelli MA, Cavallaro M, Cappuzzello F, Spatafora A, Torresi D, Agodi C, Carbone D, Sgouros O and Soukeras V. **Writing – first draft:** Schervenin JV, Medina NH, Aguiar VÂP, Added N, Oliveira JRB, Guazzelli MA, Cavallaro M, Cappuzzello F, Spatafora A, Torresi D, Agodi C, Carbone D, Sgouros O and Soukeras V. **Writing – review and editing:** Schervenin JV, Medina NH, Aguiar VÂP, Added N, Oliveira JRB, Guazzelli MA, Cavallaro M, Cappuzzello F, Spatafora A, Torresi D, Agodi C, Carbone D, Sgouros O and Soukeras V. **Final approval:** Medina NH.

AVAILABILITY OF DATA AND MATERIALS

All datasets generated or analyzed during the current study are included in the study.

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DECLARATION OF USE OF INTELLIGENCE ARTIFICIAL TOOLS

The authors declare the manuscript was reviewed with the assistance of artificial intelligence tools to improve grammar, clarity, and overall coherence.

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