



## Full Length Article

## Spatial resolution studies with the BabyIAXO Micromegas prototype

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## ARTICLE INFO

## Keywords:

MPGD

Micromegas

BabyIAXO

IAXO

Spatial resolution

## ABSTRACT

The spatial resolution of the Micromegas prototype developed for the BabyIAXO experiment was evaluated using a low-energy X-ray beam at the SOLEIL synchrotron facility. BabyIAXO, currently under construction, aims to search for hypothetical solar axions. A key component of the experiment is a low-background X-ray detector with high efficiency in the 1–10 keV energy range and stringent background rejection capabilities. Achieving a spatial resolution on the order of, or better than, 1 mm is critical for accurately reconstructing signal shapes and positions, and for effectively discriminating between signal and background events. Therefore, a precise characterization of the detector's spatial resolution is essential to validate its suitability for the experiment.

This study involved scanning the IAXO-D1 Micromegas detector under various beam energies, positions, and drift field configurations to evaluate their influence on spatial resolution. A resolution of approximately 100  $\mu\text{m}$  at 6 keV was achieved, confirming the strong potential of this technology for application in the final BabyIAXO setup.

## 1. Introduction

BabyIAXO [1,2] is a fourth-generation helioscope designed to search for hypothetical solar axions, conceived as a first step towards the International AXion Observatory (IAXO). Axions are hypothetical particles predicted by the Peccei–Quinn mechanism, originally proposed to solve the long-standing strong CP problem in the Standard Model (SM) of particle physics. Beyond this, axions are compelling candidates for cold dark matter (DM) and could potentially explain several astrophysical anomalies [3,4].

A helioscope consists of three main components: a powerful superconducting magnet to induce axion-photon conversion, X-ray optics to focus the resulting photons, and low-background X-ray detectors to image the signal. The detector must combine high efficiency in the 1–10 keV energy range with excellent background rejection capabilities down to a level of  $10^{-7}$  counts  $\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$ .

This paper presents a detailed study of the spatial resolution of the Micromegas [5] detector developed for the BabyIAXO experiment. Microbulk Micromegas technology [6] is especially well suited for such low-background applications, as demonstrated by its performance

in the CAST experiment [7–11] and in recent developments towards fulfilling BabyIAXO requirements [12]. Fabricated from radiopure materials such as copper and Kapton, these detectors combine low intrinsic background with high-energy resolution, achieved through a precisely defined amplification gap determined by the Kapton thickness. In addition, the implementation of a 2D readout anode enhances spatial resolution, further contributing to effective background rejection.

In the BabyIAXO detector, the expected signal is confined to a small region of the detection plane, typically a few millimeters in size [1]. This spatial confinement allows for powerful background rejection via fiducial cuts but also imposes constraints on the spatial resolution. To accurately reconstruct the signal's shape and position and to effectively distinguish it from background events, a spatial resolution on the order of, or better than, 1 mm is essential. This makes the precise characterization of the detector's spatial resolution a crucial step in validating its performance for the experiment. Moreover, in the event of a positive detection, high spatial resolution could contribute to solar studies, particularly by enabling the determination of the solar temperature and Debye screening scale in different layers of the Sun's interior [13].

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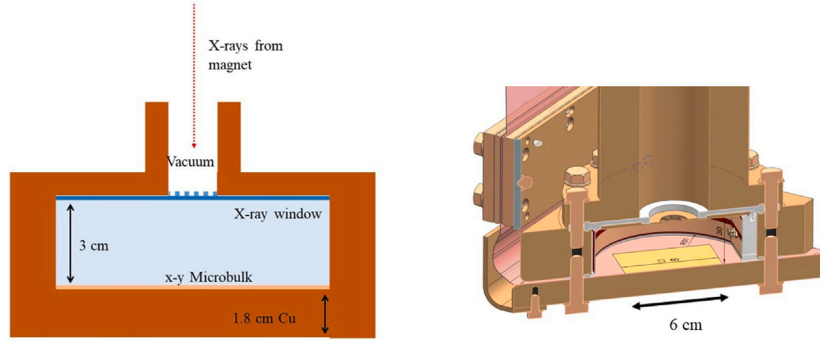


Fig. 1. Left: Sketch of the design of the Micromegas detector. Not to scale. Right: Cross-section of the IAXO-D1 prototype.

In this work, we present for the first time a dedicated study of the spatial resolution achieved with the 2D readout anode, within the framework of the BabyIAXO detector design.

## 2. The IAXO-D1 detector

To achieve the target sensitivities of IAXO and BabyIAXO, it is essential to optimize detector efficiency in the energy range below 10 keV, while maintaining ultra-low background levels. This goal requires a combination of low-background techniques, including extensive shielding, radiopurity screening of detector components, and advanced event discrimination strategies based on detailed topological information of background events.

The baseline detection technology for BabyIAXO consists of small Time Projection Chambers (TPCs) equipped with two-dimensional Micromegas readouts fabricated using the Microbulk technique [6]. These detectors have undergone significant low-background development in recent years, particularly within the CAST experiment [12] by identifying background sources, refining analysis methods and improving the shielding. These developments are comprehensively documented in the BabyIAXO Conceptual Design Report [1].

### 2.1. Detector description

The BabyIAXO Micromegas detector design is based on the last generation of CAST Micromegas detectors [11,14]. The simplified design of the detector is shown in Fig. 1 (left) consisting of a small copper gas chamber with a 2D Micromegas readout plane coupled to the BabyIAXO beam line via an X-ray transparent window.

The detector, named IAXO-D1, is a small TPC with 3 cm conversion volume filled with Argon in addition to a small quantity of quencher (5 % Isobutane) at atmospheric pressure. An alternative gas mixture of 500 mbar of Xe (50 %Xe - 48 %Ne - 2 %Isobutane) is also being considered.

The X-rays coming from the magnet enter the conversion volume via a gas-tight window made of 4  $\mu\text{m}$  aluminized mylar foil. This foil is also the cathode of the TPC, and it is supported by a metallic strong-back. The thin windows are designed to withstand the pressure difference between the gas-filled detector and the vacuum line while efficiently transmitting low-energy X-rays (1–10 keV).

The detector chamber is made of 18 mm thick radiopure copper (Cu-ETP) walls. A view of the design is shown in the right of Fig. 1. All the gaskets are made of radiopure PTFE. A Kapton field shaper has also been installed, to increase the uniformity of the drift field and reduce border effects. The field shaper is externally covered by a 1.5 mm thick PTFE coating to block 99% of the copper fluorescence from the body of the detector. The Microbulk-type [6] readout plane consists of a X-Y strip pattern of 120 strips per axis at a pitch of 500  $\mu\text{m}$  covering a surface of  $6 \times 6 \text{ cm}^2$ . In Fig. 2 the routing of the readout plane is shown as well as a picture of the Microbulk Micromegas detector on its support frame. In the zoom, a microscope view of the Microbulk mesh is shown where the pattern of the 40  $\mu\text{m}$  diameter holes is visible.

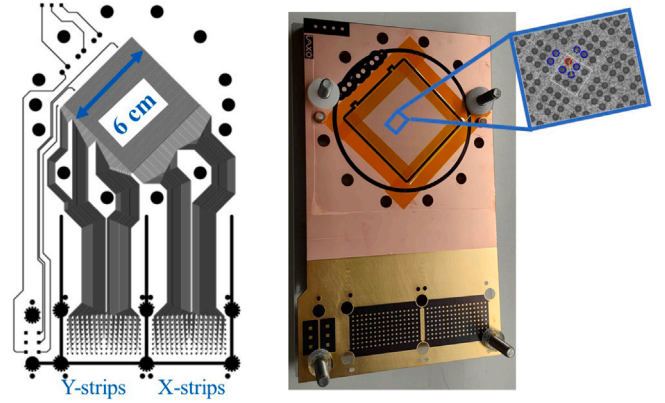


Fig. 2. Left: Readout plane routing of the  $6 \times 6 \text{ cm}^2$  active area showing the X and Y strips. Right: Picture of the readout plane on its support. The zoom shows a microscope view of the Microbulk mesh.

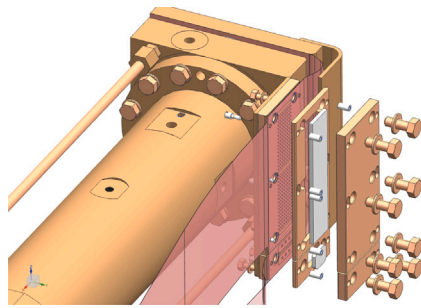
### 2.2. Front end electronics and acquisition system

The detector is connected to the front-end electronics via a custom-designed, solder-less interface known as the “face-to-face connector” [15]. This system avoids traditional soldering by mechanically compressing a flat Kapton cable with copper pads matching the readout plane pads—between two screwed copper pieces. An illustration of this connector is shown in Fig. 3. For the present test, we employed the AGET electronics [16], interfaced through a FEMINOS card [16], which acts as a bridge between the analog front-end and the digital data acquisition (DAQ) system by digitizing and aggregating signals from the AGET ASIC. The face-to-face connector is integrated into a 45 cm-long flat Kapton cable, enabling a direct and reliable connection between the detector and the AGET front-end card. The capacitance of the detector strips, including the contribution from the flat Kapton cable, was measured to be approximately 20 pF.

### 2.3. Implementation for BabyIAXO: lead shielding and cosmic veto

In its final implementation within the BabyIAXO experiment, the detector will be enclosed by a passive shield consisting of a 20 cm lead wall designed to suppress external radiation. Surrounding this shielding, an active muon veto system will provide nearly  $4\pi$  coverage with a targeted efficiency of 99%. This system will use 5 cm-thick plastic scintillators, each approximately 20 cm wide and 1 m long, arranged in a customized geometry.

Recent results from prototype tests and simulations [12] suggest that cosmic-ray-induced neutrons – generated by nuclear interactions of cosmic rays with the atmosphere – may represent a significant background source. These neutrons can interact directly with the detector gas, producing nuclear recoils that mimic the signature of X-rays [17].



**Fig. 3.** Face-to-face connector mechanism for the connection of the readout strips to the front-end electronics.

To further mitigate this background, a neutron tagger is under development. One proposed design consists of three layers of plastic scintillator panels interleaved with cadmium sheets. Monte Carlo simulations indicate that primary neutrons can interact within this setup, producing secondary neutrons that become thermalized in the plastic scintillators. If these thermal neutrons are subsequently captured by the cadmium sheets, characteristic gamma rays are emitted and can be detected by the surrounding scintillators, thereby tagging the neutron interactions.

For the purposes of this test, neither the lead shielding nor the cosmic veto system were included, as they are not pertinent for spatial resolution studies.

### 3. Experimental setup

The detector was installed in the Metrology beamline [18,19] at the SOLEIL synchrotron facility (Saint-Aubin, France), which produces an X-ray beam from 6 keV to 28 keV with small divergence and high flux. The beam is shaped using focusing mirrors and collimating slits, while a monochromator is used to tune the energy.

The setup, shown in Fig. 4, consists of collimator slits aligned with the beam exit and two movable platforms. On the platform closest to the beam exit, the IAXO-D1 detector was mounted and a diode to use for reference was placed alongside it. On the second platform, a Basler camera [20] was installed to monitor shape and size of the X-ray beam.

Throughout the test, the detector operated with a gas mixture of Argon and 5% Isobutane in an open-loop configuration and maintained a constant flow rate of 5 L/h. The mesh voltage was set to 360 V, a value chosen to ensure optimal Micromegas performance in terms of both gain ( $\sim 10^4$ ) and energy resolution ( $\sim 18\%$  at 6 keV). The field shaper was intentionally left disconnected, as its connection was found to introduce significant noise into the data acquisition system.

Upon installation of the detector on the beamline, elevated noise levels were recorded in comparison to those observed under controlled laboratory conditions (see Fig. 5). This required the use of an energy threshold of around 120 ADC counts over the baseline, notably higher than the 40 ADC counts that is typically applied. Furthermore, the high particle flux environment, in combination with the self-triggered readout system, required that only data from hit channels be recorded, as opposed to the full set of readout channels. This setup differs significantly from the expected conditions in BabyIAXO, where typical event rates are below 1 Hz. These constraints introduced additional limitations in the evaluation of gas diffusion and spatial resolution, which are reflected in the reported measurement uncertainties.

The detector was tested at different drift field values (from 50 V/cm to 400 V/cm) and under different beam energies (from 5 keV to 10 keV). The beam sizes were adjusted to several values between  $90 \times 90 \mu\text{m}^2$  to  $1.3 \times 1.3 \text{ mm}^2$ . The smallest beam size was chosen for the spatial resolution study in the center of the detector. For the position scan of the spatial resolution, different beam sizes were tested. A summary of the measurements performed is given in Table 1.

**Table 1**

Summary table of the measurements taken during the test. Four beam sizes were measured  $90 \times 90$ ,  $200 \times 200$ ,  $900 \times 900$  and  $1300 \times 1300 \mu\text{m}^2$ . The X-ray energies were varied across five values: 5, 6, 7, 8.5, and 10 keV.

Energy scan	
Position	Center
Beam size	$90 \times 90 \mu\text{m}^2$ to $1.3 \times 1.3 \text{ mm}^2$
Energy	5 keV to 10 keV
Drift field	100 V/cm
Drift field scan	
Position	Center
Beam size	$90 \times 90 \mu\text{m}^2$
Energy	5 keV to 10 keV
Drift field	50 V/cm to 400 V/cm
Position scan	
Position X	-7 to 9 mm
Position Y	-7 to 7 mm
Beam size	$90 \times 90 \mu\text{m}^2$ to $1.3 \times 1.3 \text{ mm}^2$
Energy	6 keV
Drift field	100 V/cm

### 4. Data processing and analysis

The data acquired with the Microbulk Micromegas detector are processed and analyzed using the REST-for-Physics software framework [21]. This software processes the signals from each strip extracting the spectra and the 3-dimensional information of the charge deposition.

The data are processed in three sequential steps using the REST-for-Physics framework. In the initial stage, raw signal analysis, noise events are identified and removed, and individual signal pulses are isolated. In the subsequent detector hits analysis, signals from the electronic channels are translated into energy deposits (“hits”) and assigned physical coordinates (X, Y) within the readout geometry. The extent of the energy deposit along the Z-axis is inferred from the charge collection time, using a drift velocity calculated with the Garfield++ simulation package [22]. In the final stage, cluster reconstruction, the identified energy deposits are connected into three-dimensional cluster. This is achieved through a series of algorithms designed to determine the shortest paths interlinking hits within an event, thereby providing additional topological information. This data processing workflow yields a broad set of observables – per-event quantities extracted from the recorded signals – which are subsequently used to define selection criteria for background rejection and signal discrimination.

For the purpose of this analysis, the only cuts applied for the event selection were:

- Minimum hit requirement: Events were required to have at least one hit in both the X and Y coordinates. This standard pre-selection step is used so that the event can be assigned a readout position and to eliminate possible non-physical or spurious events.
- Single-cluster selection: Only events reconstructing a single cluster were retained. X-rays photoabsorption is a point-like event that results in a single-track signature. By applying this cut, approximately 96 % of the total calibration events are selected.

The spatial resolution is estimated from the mean position of the events. Since the size of the beam chosen is sufficiently small and the X-rays are point-like events in the IAXO-D1 detector, the resolution can be estimated as the standard deviation ( $\sigma$ ) of the mean position observable from a Gaussian fit of the histogram as shown in Figs. 6 and 7. Alternative fit models were also explored, including a step function convoluted with a Gaussian—to account for the square shape of the beam. However, no significant differences were observed in

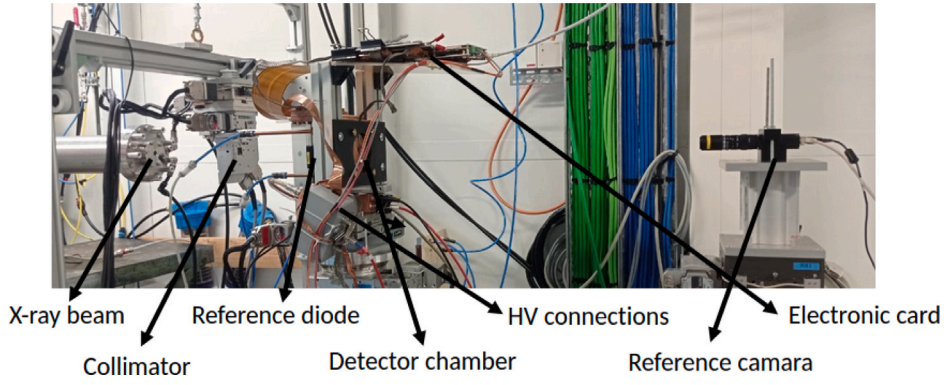
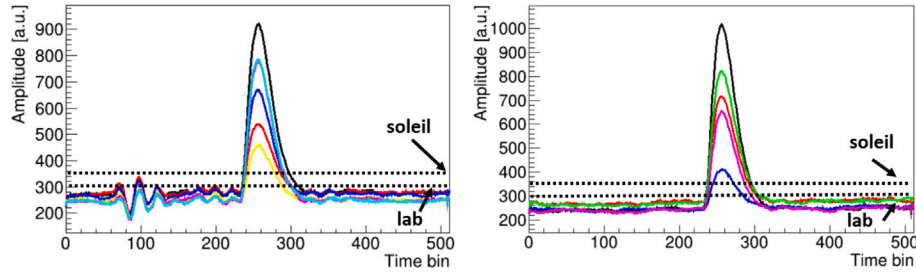
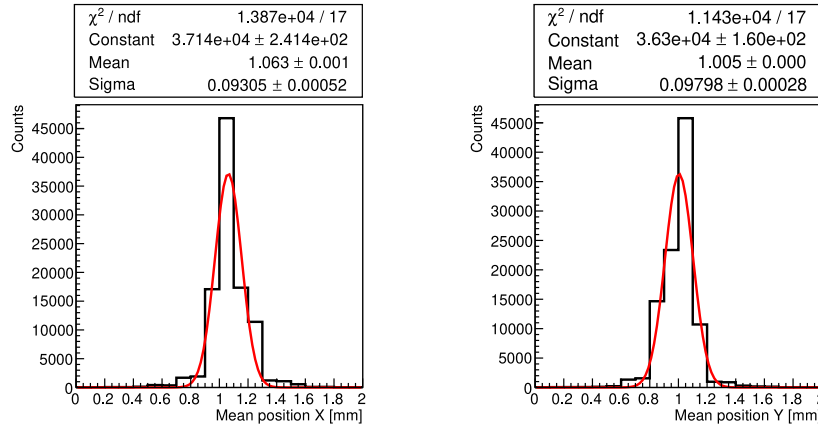


Fig. 4. Display of the setup at SOLEIL.

Fig. 5. Example of two events with the corresponding raw signals recorded by the detector for a calibration with  $^{55}\text{Fe}$ . The threshold at SOLEIL and laboratory conditions are represented.Fig. 6. Histogram of the observable of the mean position in X(Y) and its Gaussian fit for the case of 6 keV, a beam size of  $90 \times 90 \mu\text{m}^2$ , and a 100 V/cm drift in the detector chamber.

the extracted resolution, suggesting that the detector resolution is of the order of the beam size. Since the beam width is comparable to the intrinsic detector resolution, the measured spatial distributions correspond to the convolution of the beam profile with the detector response. The extracted widths should therefore be interpreted as upper limits of the intrinsic spatial resolution.

## 5. Simulations

The study has been complemented with extensive radiation transport simulations using Geant4 [23]. REST-for-Physics has been used as the software framework to interface with Geant4, and for processing the resulting data [21]. The model used includes the detector chamber and the Micromegas readout. The libraries from REST-for-physics allow to change from the Geant4 energy deposits to the ones that would be produced by the physical setup mimicking the raw signals. To achieve

a faithful simulation of the data, relevant physical processes such as electron drift and diffusion within the gas, along with realistic noise conditions and energy thresholds observed during data acquisition, are incorporated. These simulated signals are then subjected to the same reconstruction and analysis pipeline as the experimental data, enabling a direct and meaningful comparison between the two.

For the simulation setup, events are generated just above the Mylar entrance window, with an initial direction perpendicular to the readout plane. The spatial distribution of the beam is modeled as a square profile, consistent with the size and shape of the beam measured by the reference camera.

For the purpose of this study, the simulations were carried out under two distinct operating conditions: the high noise and elevated threshold environment characteristics of the SOLEIL beamline, and the more favorable noise and threshold conditions typically encountered during laboratory operation of the detector. For these two scenarios, the



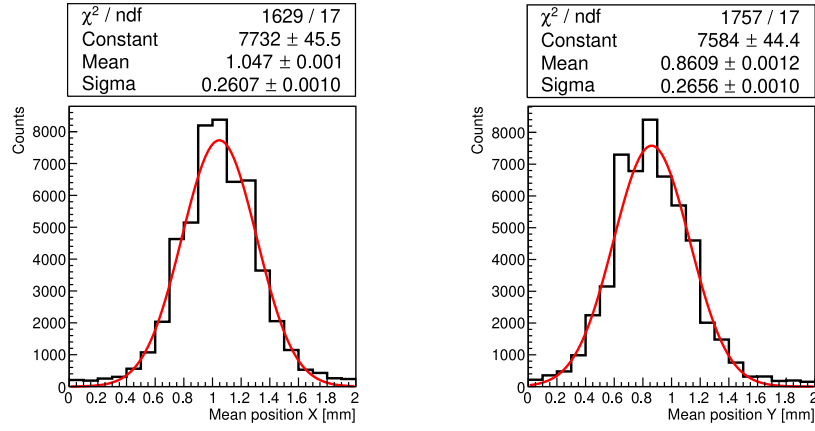


Fig. 7. Histogram of the observable of the mean position in X(Y) and its Gaussian fit for the case of 10 keV, a beam size of  $90 \times 90 \mu\text{m}^2$ , and a 100 V/cm drift in the detector chamber.

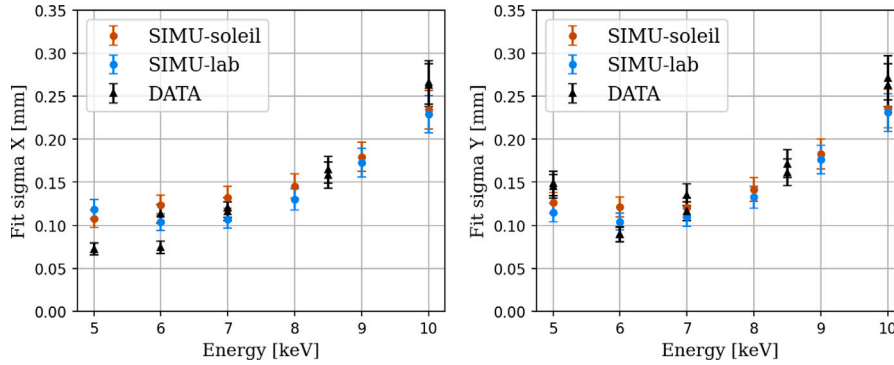


Fig. 8. Resolution X(Y) vs energy at 100V/cm. The error bars are  $\times 30$  the statistical error of the sigma estimation from the Gaussian fit.

energy thresholds were set to the values mentioned in Section 3, and the noise was added as a Gaussian oscillation from the ideal signal with the sigma measured from the baseline during the test at the beamline and in the laboratory.

## 6. Results

This section presents the main results of the spatial resolution study conducted at the SOLEIL synchrotron using the IAXO-D1 detector setup described in Section 3. The resolution is estimated from the mean position observable, as discussed in Section 4. Simulated data were produced as described in Section 5, for each data point a sample of  $10^5$  events were generated.

### 6.1. Resolution as a function of energy

To assess the spatial resolution of the IAXO-D1 detector, its response to different beam energies was measured, as shown in Fig. 8. The detector was operated at nominal voltage settings: mesh voltage of 360 V and a drift field of 100 V/cm. The X-ray beam size was fixed at  $90 \times 90 \mu\text{m}^2$ , the smallest one explored, to ensure that the estimate of the resolution, as the standard deviation of the mean position, serves as a good approximation of the detector's resolution.

Fig. 8 shows that the experimental results are in good agreement with the simulated data under both SOLEIL and laboratory conditions. The differences between these two simulated scenarios are visible, supporting the hypothesis that laboratory conditions would result in an improvement of the measurement of the spatial resolution. The resolution exhibits symmetric behavior in the X and Y directions, with a minimum slightly under  $100 \mu\text{m}$  at 6 keV and higher values for increasing energies reaching  $\sim 260 \mu\text{m}$  at 10 keV. This degradation observed at

higher energies is associated with longer photoelectron tracks produced in the gas mixture, leading to increased charge spread, reducing the precision in position reconstruction [24]. The observation of the track size influence on the sigma indicates that the intrinsic resolution of the detector is at least as good as the lowest value measured.

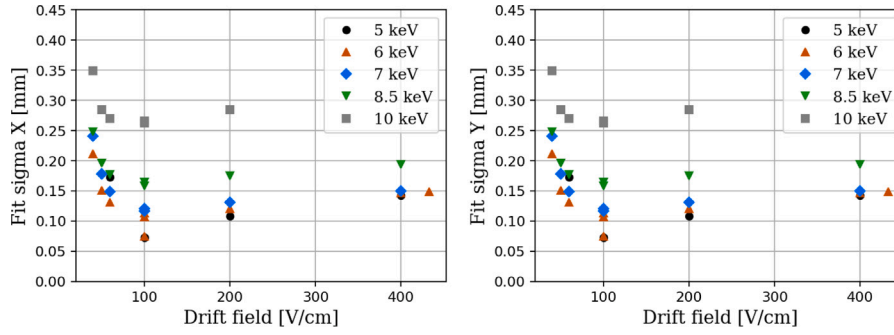
### 6.2. Resolution as a function of drift field

The IAXO-D1 detector response was also studied for several values of the electric field in its drift region by setting the voltage of the cathode. The spatial resolution as a function of the drift field was measured for various X-ray energies and is summarized in Fig. 9. The behavior is consistent for all the energies tested: the resolution reaches a minimum value around 100 V/cm, degrades rapidly at lower drift fields, and increases gradually for higher intensities of the drift. For all the cases shown, the spatial resolution at lower energies is better.

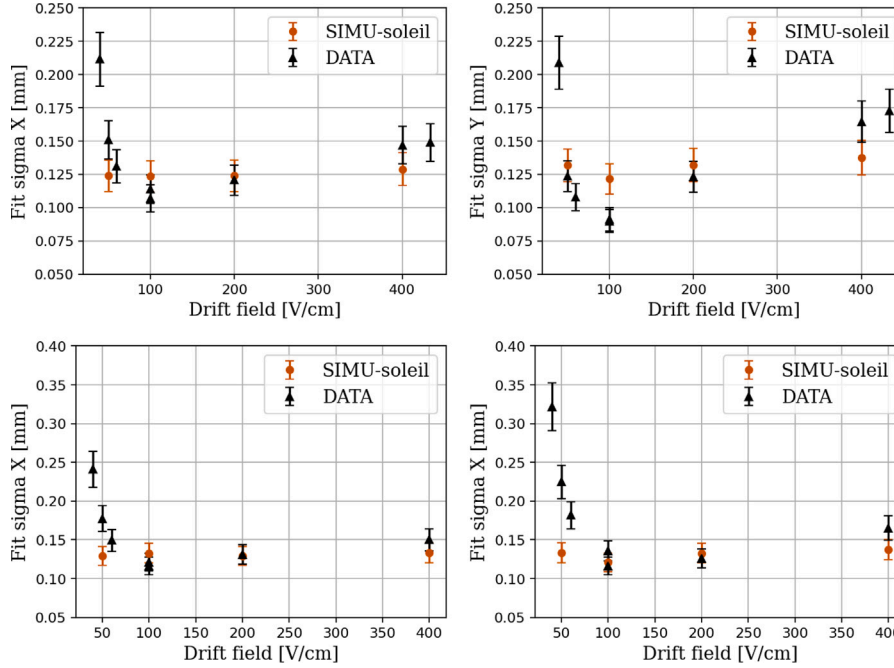
The dependence of spatial resolution on the drift field was also compared with simulated data. As representative examples, the cases of 6 keV and 7 keV are shown in Fig. 10. The experimental data follow the expected behavior for drifts above 100 V/cm, although, for lower drift fields, there is a noticeable discrepancy. This mismatch can be explained by the presence of impurities in the gas, such as  $\text{O}_2$  or  $\text{H}_2\text{O}$ , which became more relevant at low drift field, reducing the electron collection efficiency, an effect not implemented in our simulation. The gradual deterioration of the resolution at higher drifts is attributed to the increase in transverse diffusion.

### 6.3. Resolution as a function of beam detector position

To conclude with the study of the spatial resolution, various positions of the IAXO-D1 readout plane were measured by moving the



**Fig. 9.** Resolution X(Y) vs drift field, for different energies. The error bars are not represented on the plots in order to facilitate the visualization of all the values shown. The uncertainty of the fit sigmas is the order of 2-5%.

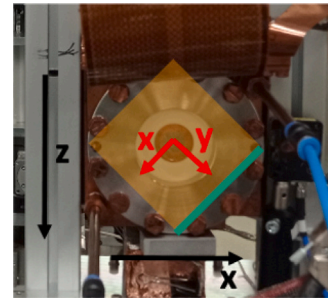


**Fig. 10.** Resolution X(Y) vs drift field at 6 keV (upper plots) and 7 keV (lower plots), and its comparison with the simulated data. The error bars are  $\times 30$  the statistical error of the sigma estimation from the Gaussian fit.

detector platform along its X and Z axis. The results presented correspond to a beam of  $90 \times 90 \mu\text{m}^2$  and 6 keV, and a drift field of 100 V/cm. The displacement is illustrated in Fig. 11 where the coordinates of the platform and readout are depicted. To facilitate the interpretation of the spatial resolution, the results will be presented as a function of the mean position in that same axis. Before proceeding to the discussion, it is important to recall that the field shapers were not operational during the tests conducted at SOLEIL.

The measured spatial resolution as a function of the position is shown in Fig. 12. Along the X axis, the resolution exhibits a minimum of about  $100 \mu\text{m}$  at the center of the detector, as expected due to the symmetry of the electric field. However, this is not the case for the Y axis, where the same minimum is observed at approximately  $Y \sim 2 \text{ mm}$ . This asymmetry is attributed to the drift field caused by the high-voltage connections located on one side of the readout, perpendicular to the Y axis (as illustrated in Fig. 11). These field distortions were not investigated further in the scope of this study.

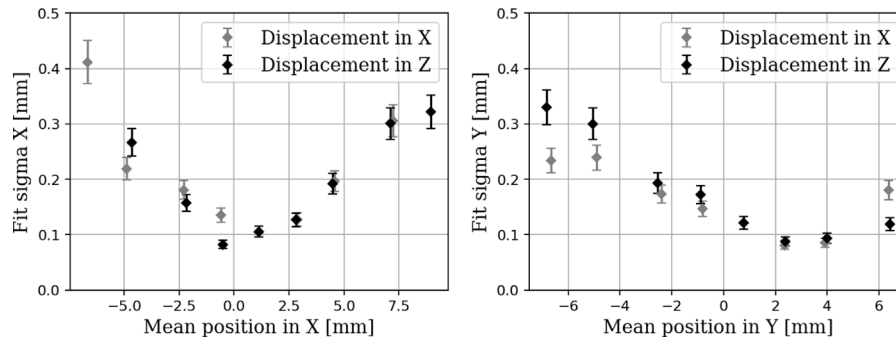
In Fig. 12 is shown that, when placing the beam just a few millimeters away from the center, a noticeable degradation in resolution by a factor 3–4 is observed. This emphasizes the importance of the field shaper rings, even within the fiducial radius smaller than 1 cm from the center. Although the effect on the position is significant, the spatial resolution is well below the needed constrain of 1 mm.



**Fig. 11.** Front view of the detector in the beam line. Red: the coordinates of the readout. Black: coordinates of the platform. Green: position of the HV connections inside the detector chamber.

## 7. Conclusions and perspectives

The use of SOLEIL's X-ray beam allowed a detailed characterization of the IAXO-D1 two-dimensional Micromegas detector. At the detector center, the spatial resolution measured was  $100\text{--}300 \mu\text{m}$ , in the range between 5 keV and 10 keV, when operating at a drift field of at least



**Fig. 12.** ResolutionX(Y) vs the position along the axis. The error bars are  $\times 30$  the statistical error of the sigma estimation from the Gaussian fit. Gray: values obtained when the detector was being moved in X. Black: values obtained when the detector was being moved in Z.

100 V/cm. The results are in good agreement with the dedicated simulations performed. These values represent conservative estimates, as discussed throughout the article, the beam size is comparable to the measured resolution. Therefore, the extracted values include contributions from both the intrinsic detector resolution and the finite beam width. Inhomogeneities in the fiducial region of 1 cm radius from the center have been observed to cause a degradation of the spatial resolution, while its worst value was still well below the 1 mm constraint on BabyIAXO experiment. Small effect on the spatial resolution due to higher noise conditions were also verified with simulation. This study experimentally demonstrates that the Micromegas technology fulfills and exceeds the required BabyIAXO performance specifications.

The measured spatial resolution positions the 2D-Microbulk Micromegas technology as a strong candidate for neutron imaging [25–28], where high spatial precision and minimal material thickness are critical requirements.

#### CRediT authorship contribution statement

**A. Quintana:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J. Castel:** Visualization, Methodology, Conceptualization. **S. Cebrián:** Writing – review & editing, Supervision, Methodology, Conceptualization. **T. Dafni:** Writing – review & editing, Supervision, Methodology, Conceptualization. **D. Díez-Ibáñez:** Methodology, Conceptualization. **E. Ferrer-Ribas:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **A. Ezquerro:** Methodology, Conceptualization. **J. Galán:** Software, Methodology, Conceptualization. **J.A. García:** Methodology, Conceptualization. **A. Giganon:** Resources, Investigation, Data curation, Conceptualization. **C. Goblin:** Resources, Investigation, Data curation, Conceptualization. **N. Goyal:** Methodology, Investigation, Data curation. **F.J. Iguaz:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **I.G. Irastorza:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **C. Loiseau:** Resources, Investigation, Conceptualization. **G. Luzón:** Writing – review & editing, Methodology, Conceptualization. **C. Margalejo:** Software, Methodology, Conceptualization. **H. Mirallas:** Methodology, Conceptualization. **L. Obis:** Software, Methodology, Conceptualization. **T. Papaevangelou:** Writing – review & editing, Validation, Supervision, Methodology, Data curation, Conceptualization. **O. Pérez:** Methodology, Conceptualization. **J. Porrón:** Methodology, Conceptualization. **M.J. Puyuelo:** Software, Methodology, Conceptualization.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Acknowledgments

The authors acknowledge support from the Agence Nationale de la Recherche (France) ANR-19-CE31-0024, from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (ERC-2017-AdG IAXO+, grant agreement No. 788781), from the Agencia Estatal de Investigación (AEI), Spain under the grant agreement PID2022-137268NB-C51 funded by MCIN/AEI/10.13039/501100011033/FEDER, as well as funds from “European Union NextGenerationEU/PRTR” (Planes complementarios, Programa de Astrofísica y Física de Altas Energías). The authors acknowledge SOLEIL for provision of synchrotron radiation facilities (proposal number 20221337) and we would like to thank Pascal Mercere and Paulo Da Silva for assistance in using METROLOGIE beamline.

#### Data availability

Data will be made available on request.

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