3D Display of Events on the Current OSCURA Testing Setup and Redesign of the OSCURA Testing Setup Copper Box

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Abstract

This study focuses on two primary objectives: the redesign of the OSCURA's testing setup copper box and the development of a new 3D display algorithm for events. The redesigned copper box facilitates a vertical orientation, accommodating up to 21 Multi-Chip Modules (MCMs) to optimize beam usage. Concurrently, a novel 3D display algorithm is introduced, enabling the visualization of particle events captured by the 160 CCDs within the OSCURA testing setup. This visualization maintains spatial accuracy equivalent to that of the CCDs. Central to this research is the implementation of a sophisticated 3D image analysis algorithm. This algorithm marks a crucial initial step towards the creation of 3D particle tracking identification and analysis algorithms, aimed at mitigating background events. The successful implementation of this algorithm establishes a strong foundation for the development of advanced 3D image analysis tools, fostering innovative avenues for reducing noise and enhancing accuracy. The outcomes of this research hold profound implications for the study of dark matter interactions and fundamental particles within accelerator facilities. By providing an innovative framework, this work sets the stage for more comprehensive and nuanced investigations in this domain. Moreover, the results signify an initial stride towards refining 3D imaging analysis techniques, indicative of the potential for future breakthroughs.

1 Introduction

The OSCURA experiment [Aguilar-Arevalo et al., 2022] aims to construct a 10 kg setup using ultra-low readout noise silicon Charged-Coupled Devices (skipper-CCDs) to investigate electron recoils from sub-GeV dark matter. The OSCURA experiment required the creation of a testing setup to study and test the equipment and electronics [Chierchie et al., 2023], and its also planned to search for mCPs (Millicharged Particles) produced in the NuMI beam line [Perez et al., 2023]. The OSCURA testing setup will be vertically placed. OSCURA won't face problems when it comes to the background radiation such as cosmic rays instead, but instead a early science was to be acomplish with partial load of CCDs at shallow-depth facilities. To accomplish this early science, this study focused on two primary objectives: improving the spatial accuracy of particle event detection within the OSCURA testing device and developing an advanced 3D image analysis algorithm for effective three-dimensional visualization of particle events.

2 Objective and Goals

To achieve the goals mentioned in section 1, an effort was taken to optimize the OSCURA testing setup. The copper box of the current OSCURA setup was redesigned, enabling a vertical orientation that can accommodate up to 21 Multi-Chip Modules (MCMs). This redesign maximizes beam usage, thereby enhancing the sensitivity and efficiency of the setup for detecting millicharged particles (mCPs). Additionally, a new algorithm was developed for visualizing particle events, seamlessly integrating it into the OSCURA testing setup. This was done by implementing 3D image analysis techniques and the "skipper2root" tool to process captured images from the CCDs.

3 Spatial Study of the CCDs on the OSCURA Testing Setup

In order to reconstruct any 3D representation of a model using measuring tools, the accurate spatial orientation and location of those measuring tools are important. The current OSCURA testing setup (shown in Figure 1) was designed to hold up to 16 MCMs (Multi-Chip Modules), which are ceramic plates containing 16 skipper-CCDs (Charge-Coupled Devices) as illustrated in Figure 2.

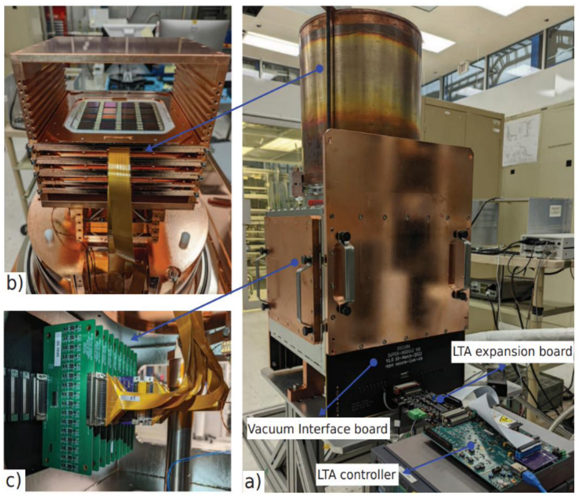

Figure 1: The current OSCURA testing setup along with its components. [Chierchie et al., 2023]

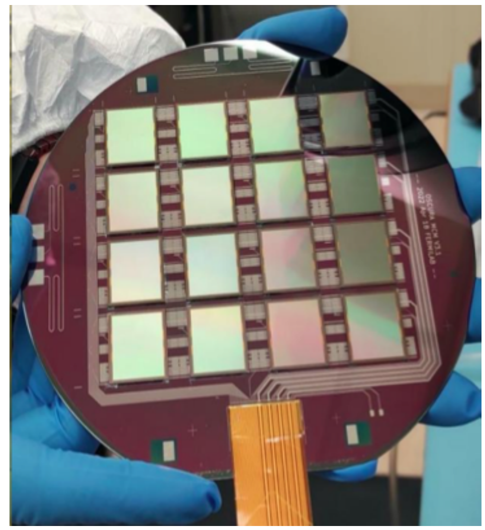

Figure 2: Single MCM module with 16 CCDs. [Chierchie et al., 2023]

During data collection, only 10 MCMs were used, and they were arranged in a no symmetric way and differently from how they are shown in the CAD (Computer-Aided Design) of the OSCURA testing setup (Figure 3). Initially, the arrangement of the MCMs was not important since it was used for testing OSCURA's new electronics. However, for future event analysis and applications, such as particle tracking, developing a tool for 3D event visualization as well as modifying the mechanics of the box are necessary.

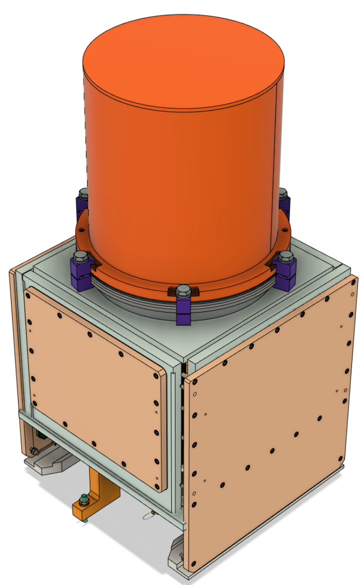

Figure 3: CAD model of the OSCURA testing setup.

Depending on how the MCMs were arranged, each MCM could be placed with a front or back offset with respect to a defined origin of the OSCURA testing device, resulting in different x and y coordinates, not just a different z coordinate as shown in Figure 4.

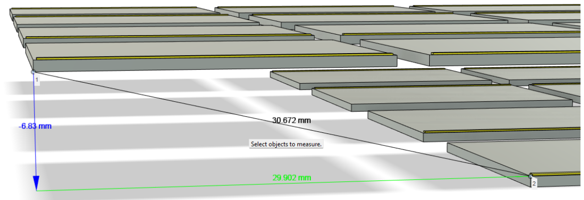

Figure 4: Offset of the front and back MCM orientation. A front (back) offset means that the MCM has an offset of 0 (29.9) mm with respect to the origin.

After studying the offset in the real OSCURA testing setup, the CAD, originally containing 16 MCMs, was modified to account for the offset of the 10 installed MCMs. This new CAD of the CCDs on the OSCURA testing setup was designed using Fusion 360, as illustrated in Figure 5.

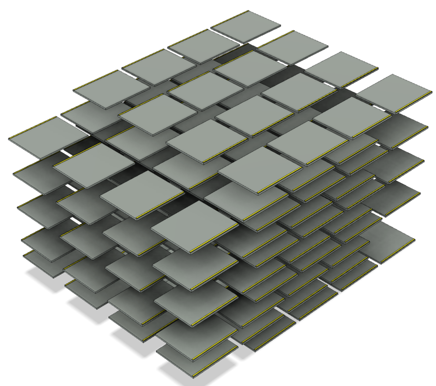

Figure 5: Arranged MCMs according to the real OSCURA testing setup.

With the 3D model of the CCDs accurately placed in the OSCURA testing setup, an Excel sheet was created to document all the reference points, the origin of the model, and specifications regarding whether the MCM had front or back coordinates. Each CCD has only two different sets of x and y coordinates corresponding to front or back, with the z coordinate changing due to the varying height of each MCM with respect to the origin, as depicted in Figure 6.

4 3D Plotting of Data From the OSCURA Testing Setup

4.1 CERN ROOT Program Trees and Branches

CERN ROOT is a software framework setup [Brun et al., 2019] developed at CERN with the objective of data analysis for high-energy physics experiments. With its tools, CERN ROOT efficiently manages, analyzes, and visualizes the large data sets obtained from particle physics experiments, including data from the current OSCURA testing setup. The data contains thousands of pixel information from 160 CCDs, and CERN ROOT is specifically designed to handle such large data sets.

The data was obtained from previous data collections specifically the data shown in Figure 7 this data is in a format called fits and therefore it had to be processed using ”skipper2root”, a tool developed by members of the SENSEI collaboration [Barak et al., 2023], to obtain a root file containing trees with multiple branches. Trees are data structures used for storing and organizing large data sets, while branches are elements within trees that hold specific data items. The important branches in this case

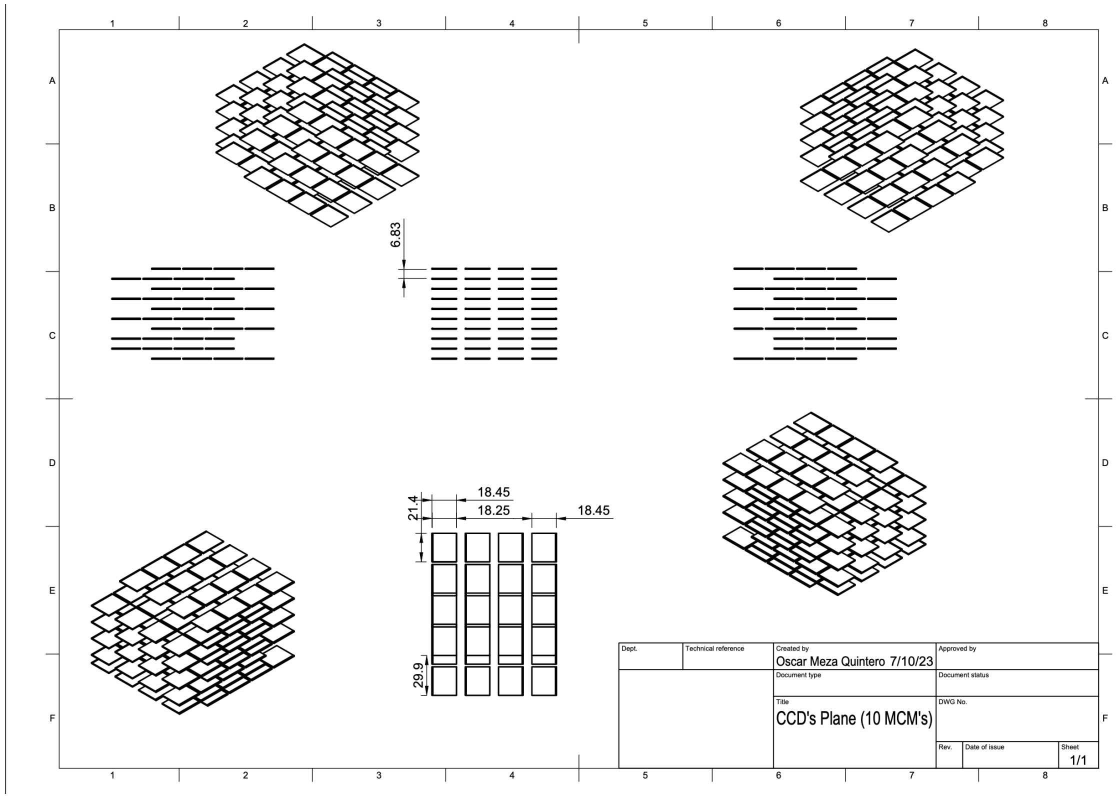

Figure 6: Drawing of the corrected MCM location (x, y and z view units in mm)

are the y, x, pix, and Ohdu branches, which provide information about the location of the pixels on the CCD and the CCD number on the testing setup.

Once the tree with all the information about the pixels of the CCDs was created, a new tree was needed to contain all the coordinates of the CCDs. A code was developed to create a vector with the coordinates of the front and back offsets. Then, a loop was implemented to go through each MCM and assign the right coordinates with respect to the origin. The result was a root file and a text file with the x, y, and z positions of the 160 CCDs, along with the Ohdu number and the MCM to which each CCD was located. A 3D plot of the spatial location of the CCDs was also generated (Figure 8).

4.2 Development of the 3D Display Algorithm

Once the new tree with the CCD coordinates was created, an algorithm was implemented to extract pixel information from 10 different MCMs, each with their respective trees. The goal was to process the information from these trees and plot it in a 3D space. The algorithm needed to effectively associate each file containing a tree with the corresponding MCM on the new tree. String concatenation was utilized to achieve this by identifying and matching the file names to their respective MCMs.

However, another challenge was encountered, which involved accurately placing each pixel in the 3D space along with its pixel value and the origin of the CCD. To address this issue, a data looping technique combined with conditional data processing and histogram filling was employed. This approach ensured that the pixel information was processed accurately and efficiently. As a result of the algorithm's computations, 3D images were generated, as shown in Figure 9.

The implemented algorithm successfully processed the pixel information from the 10 different MCMs with their respective trees, assigned the files to their corresponding MCMs, and accurately plotted the data in a 3D space. The resulting images provided valuable visualizations of the pixel distribution and CCD origin in the space.

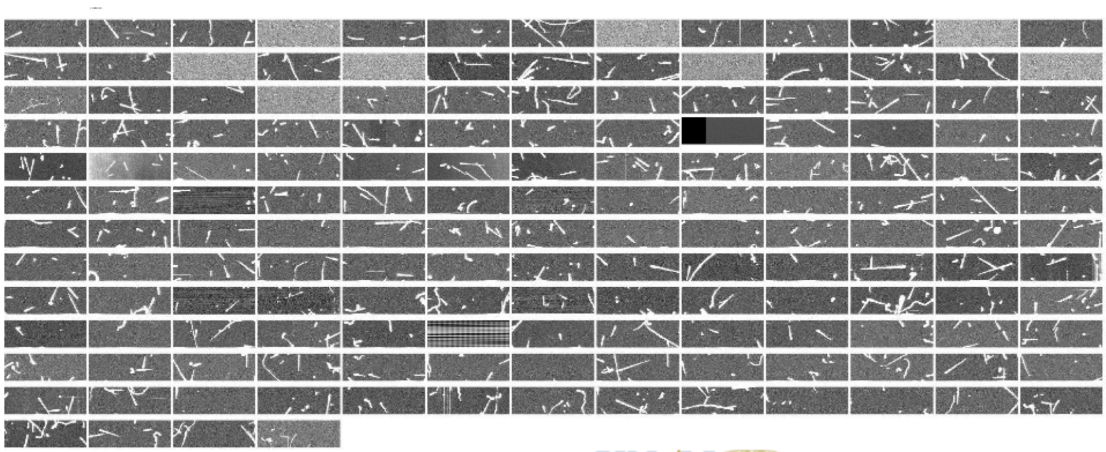

Figure 7: An image showing sub-images with cosmic rays interactions of all the 160 sensors of the array. [Chierchie et al., 2023]

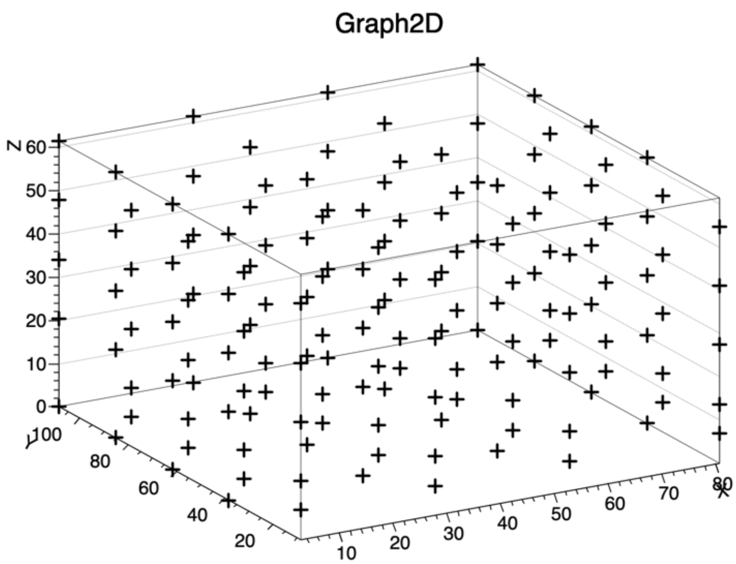

Figure 8: 160 CCDs origin location on a 3D canvas coded with CERN root.

4.3 Optimization of Parameters

When graphing the 3D plot, the graph would be saturated with thousands of pixels, and it would take a long time to compute. Therefore, a threshold had to be implemented to find the most optimal parameters when filling the graph. The threshold was calculated by choosing a point where the pixel values significantly deviate from the background or noise levels. This threshold came to be of 3.75 eV according to the conversion of 327.403 ADU/e. This threshold was applied to the algorithm, reducing significantly the saturation of pixels and the computing time.

Another parameter that had to be optimized was the number of bins when graphing. This number would reduce the resolution of the graph, where the lower the number, the less resolution the graph will have, and the more bins, the greater the resolution and better visualization of the events on the CCDs. However, increasing the number of bins also increases the computing time. An optimal number of bins had to be implemented to obtain the best image possible while still being computable which resulted to be about 1200 bins in the x and y directions and 600 bins in the z direction.

After implementing these parameters, a new graph was created (Figure 10.) with more resolution, less

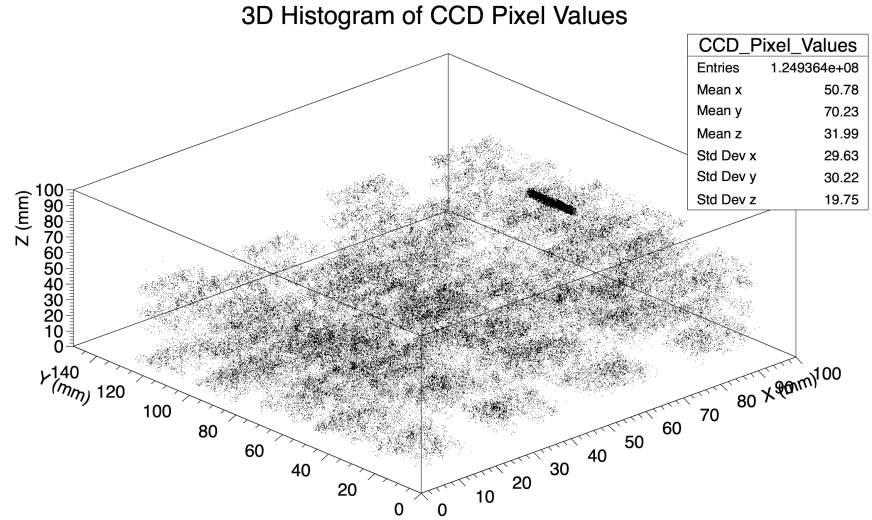

Figure 9: Saturated 3D plot with no parameters applied.

saturation, and showing only the important pixel values corresponding to muons, electrons, or x-rays.

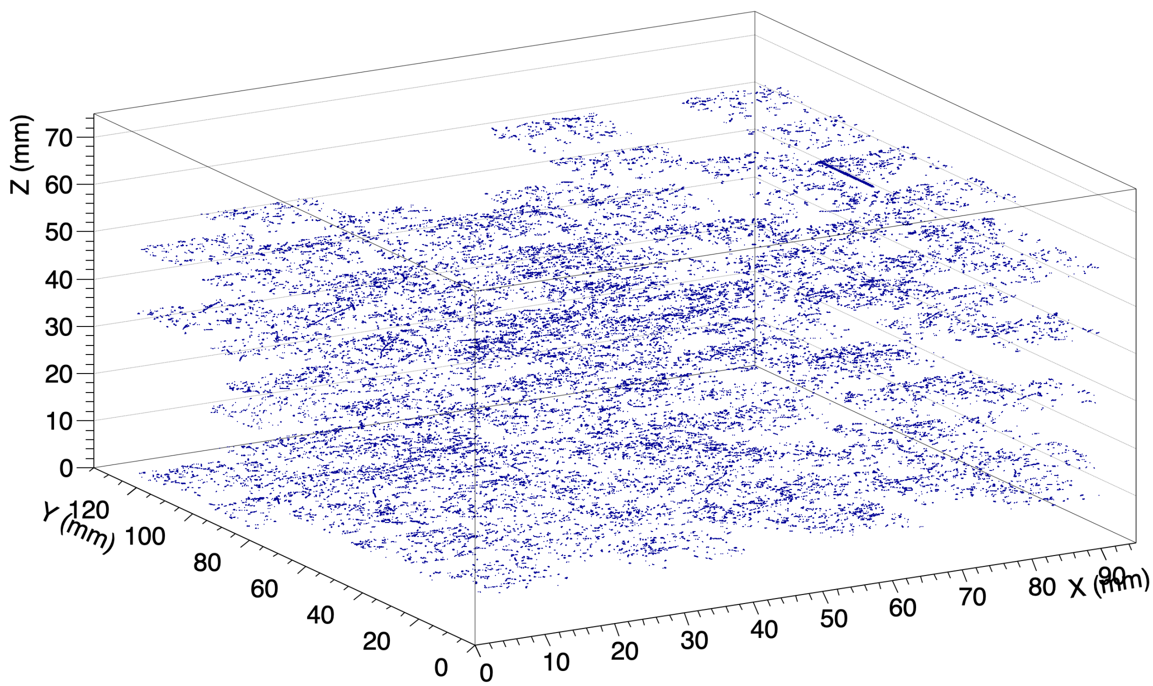

Figure 10: 3D plot of events with better resolution and with optimal visualization parameters applied.

To further study the events graphed in (Figure 10.) a constraint was needed where all of the events in a single MCM were plotted. By doing this its possible to determinate if the 3D graph is showing accurate data of each of the MCM in the space. The code was modified so only the 4th MCM shows with all of the events displayed, this since the 4th MCM was the one with remarkable events. To show this the MCM is projected in the xy plane from the z view as shown in Figure 11.

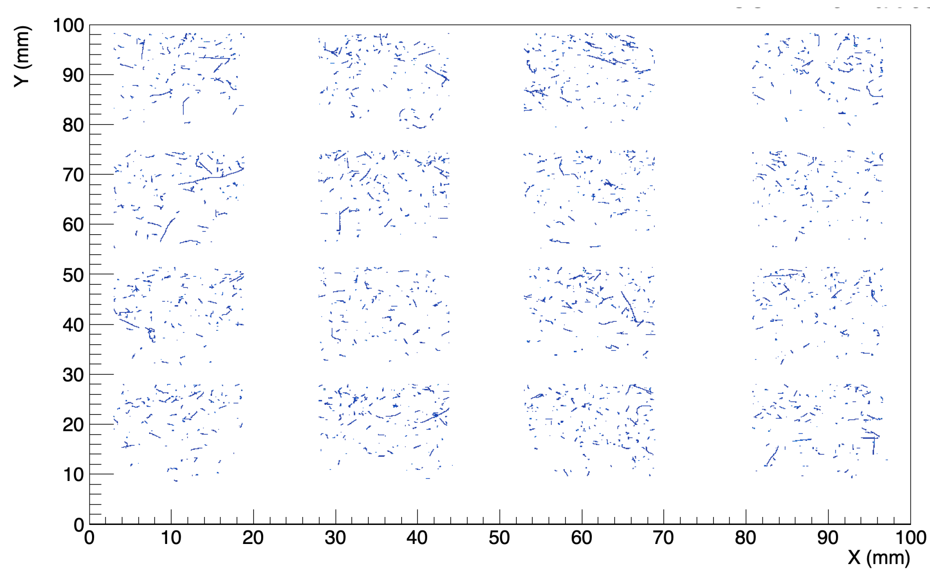

Figure 11: Plot of events in the xy projection with better resolution and with parameters applied.

5 Redesign of the OSCURA Testing Setup Copper Box

The OSCURA testing setup consists of a device capable of holding up to 16 MCMs facing upwards, arranged one on top of the other. The original design of this setup did not consider specific applications or implications related to the orientation and arrangements of the MCMs (Figure 13.).

Recently, there has been an interest in using the OSCURA testing setup device in a beam facility to further study millicharged particles [Perez et al., 2023]. To enable this, a new device with MCMs in a vertical orientation was required. Rather than redesigning the entire OSCURA testing setup, a solution was found by modifying only the copper box inside the device. The new copper box retains the necessary dimensions and allows for the vertical orientation of the MCMs, accommodating up to 21 MCMs, which is 5 more than the old setup (Figure 12.). This enhancement provides a broader window for studying millicharged particles in the beam without major changes to the existing setup.

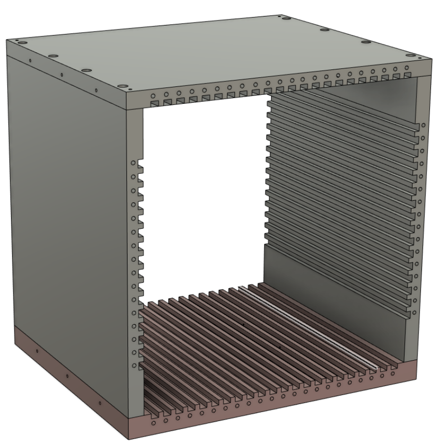

Figure 12: Redesigned copper box

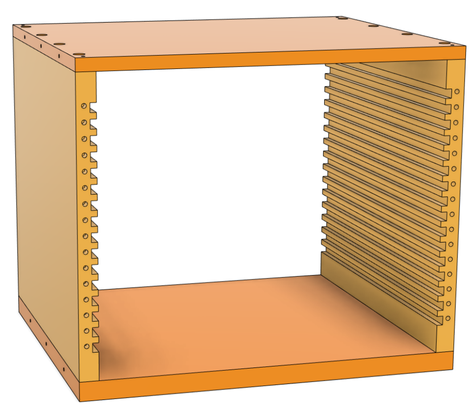

Figure 13: Original copper box

6 Future Implementations beyond OSCURA

In this study, significant advancements were achieved in the OSCURA testing setup, focusing on the detection and enabling a design that could be used for particle tracking in a beam. The redesigned copper box will allow for the vertical orientation of up to 21 MCMs, allowing to discard background events that are not aligned with the beam, particularly useful for mCPs search.

The implementation of the 3D display algorithm further enhanced the capabilities of the OSCURA setup. By accurately processing pixel information from the 160 skipper-CCDs, this algorithm enabled precise three-dimensional visualization of particle events. The association of each file containing a tree with the corresponding MCM on the new tree ensured spatial accuracy and effective data analysis.

Looking forward, these developments hold great promise for future implementations in the field of particle physics:

- **Tracker Development:** The redesigned copper box's flexibility and capacity to hold multiple sensor layers create opportunities for developing advanced trackers. These trackers, with their enhanced spatial accuracy and 3D visualization techniques, have the potential to significantly improve particle tracking in accelerator facilities. Such advancements will facilitate comprehensive studies of various fundamental particles and their interactions.
- **Advancements in 3D Image Analysis:** The 3D display of events represents an initial step towards the development of more sophisticated tools for analyzing 3D images. Future research may explore the integration of machine learning and artificial intelligence to further refine the algorithm and enhance particle tracking accuracy. These improvements could lead to the identification and characterization of specific particle interactions with higher precision and sensitivity.

7 Conclusion

In conclusion, the new copper box and the 3D image analysis algorithm show promise for improving particle physics research. There is still a lot of work to do, but these advancements constitute the first steps towards performing dark sector searches with skipper-CCD arrays at accelerator facilities, allowing us to perform tracking and to study, for example, millicharged particles. Hopefully, this research motivates the work in this area and helps as the first step to a more advanced engineered algorithm for particle tracking as well as for a better setup design.

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