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# DEVELOPMENT OF A MULTI-CAMERA SYSTEM FOR TOMOGRAPHY IN BEAM DIAGNOSTICS

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*Abstract*

Embedded visual systems in industry led to advancements of single board computers and single board cameras. Due to the lower power consumption and high flexibility of these miniature devices, a multi-camera system can be developed more effectively. A prototype of a beam-induced residual gas fluorescence monitor (BIF) has been developed and successfully tested at the Institute of Applied Physics (IAP) of the Goethe University Frankfurt. This BIF is based on a single-board camera inserted into the vacuum. The previous promising results led to the development of a multi-camera system with 10 cameras. One of the advantages of such a system is the miniature design, allowing this detector to be integrated within the vacuum and in regions that are difficult to access. The overall goal is to study the beam with tomography algorithms at a low energy beam transport section. We hope to reconstruct an arbitrary beam profile intensity distribution without assuming a Gaussian beam.

## INTRODUCTION

Beam-induced fluorescence (BIF) monitors are standard detectors at accelerator facilities [1]. For ultrahigh vacuum beam diagnostics, scientific cameras are commonly used in combination with MCP photon amplifiers to determine the beam position and profile. New BIF monitors have been successfully tested at the low-energy beamline of the Frankfurt Neutron Source at the Stern Gerlach Center [2,3]. These developments lead to new ways to study the beam. One idea is to view the beam from multiple angles. This allows the use of tomography algorithms to reconstruct the intensity distribution of the transverse beam profile. Beam tomography has previously been studied using a camera and a rotating vacuum chamber to rotate the camera and obtain any number of views. Another approach is to view the beam through viewing windows.

Our goal is to maximize the number of viewing angles and develop a fast tomographic detector with a minimal form factor to be as flexible as possible. Our approach is to use non-scientific single-board cameras with single-board computers and to put as many cameras as possible in the vacuum. Figure 1 shows a photo of the cameras mounted on the holder. It is designed to fit into a vacuum vessel with a diameter of 200 mm and a length of 300 mm.

The detector is built for low energy beam transport sections in high vacuum regions of about $10^{-7}$ mbar. To increase the emitted light, it is possible to introduce a buffer gas during image acquisition. We tested the cameras at a residual argon gas pressure down to $1 \times 10^{-4}$ mbar. There were several challenges to overcome in developing such a detector. One challenge was to get all cameras in parallel into full operation and retrieve all data. Another challenge was to align each of the cameras so that their center of field of view matched. The following sections present our approaches to solving these challenges.

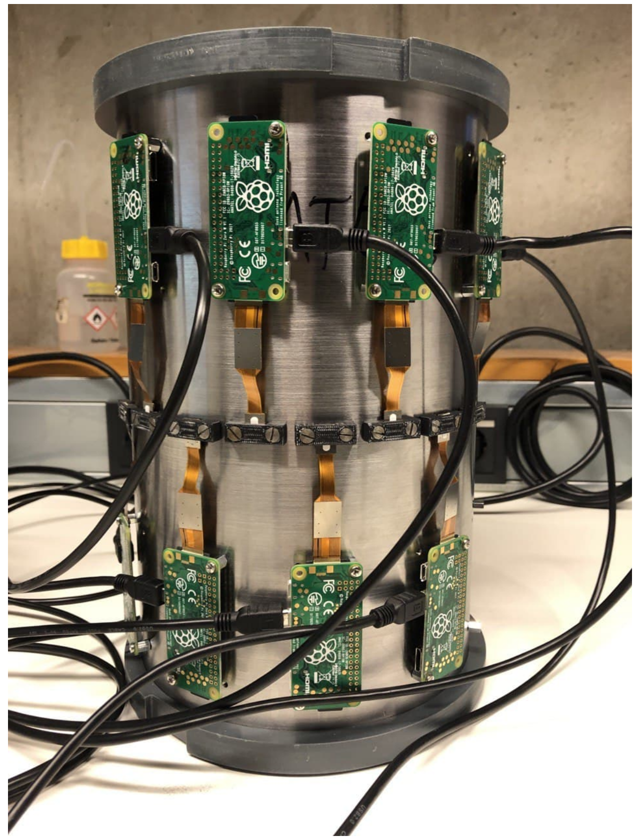

Figure 1: The picture shows a photo of the tomography detector with the Raspberry Pi Zero and its camera modules attached to a stainless steel pipe.

## HARDWARE SET UP

### *Raspberry Pi Zero and its Camera*

The cameras you see in Fig. 1 are single-board cameras with so-called raspberry pi zero single-board computers. The Raspberry Pi Zero is the Raspberry Pi with the smallest dimensions among the Raspberry Pi computer models. The Raspberry Pi and especially its camera are gaining more and more attention not only in the Maker scene, but also in the scientific community [4]. Due to its compact dimensions and low power consumption of about 15 mW, they are predestined for projects like drones, robots or any mobile

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devices. The camera consists of a 5 MP high resolution Omnivision OV5647 CMOS image sensor. The sensor size is 3.76 mm × 2.74 mm and has a pixel size of 1.4 m × 1.4 m. It has a focal length (3.6 mm) with a single aperture (F2.9). The sensor sensitivity can be varied between ISO values from 100 to 800, and it is possible to vary the analogue gain of the ADC for the blue and red color pixels, i.e. to change the white balance manually. The camera has been tested in high vacuum up to $1 \times 10^{-7}$ mbar and in strong magnetic field (up to 0.6 T) [5].

### *Powering the Cameras*

To supply the cameras with 5 V and at least 300 mA, we used a USB hub. This is also integrated into the vacuum. Its power management unit was suitable to supply all ten Raspberry Pis. With this solution, only one power and ground vacuum feedthrough pin was required. Figure 2 shows a wiring diagram of the cabling.

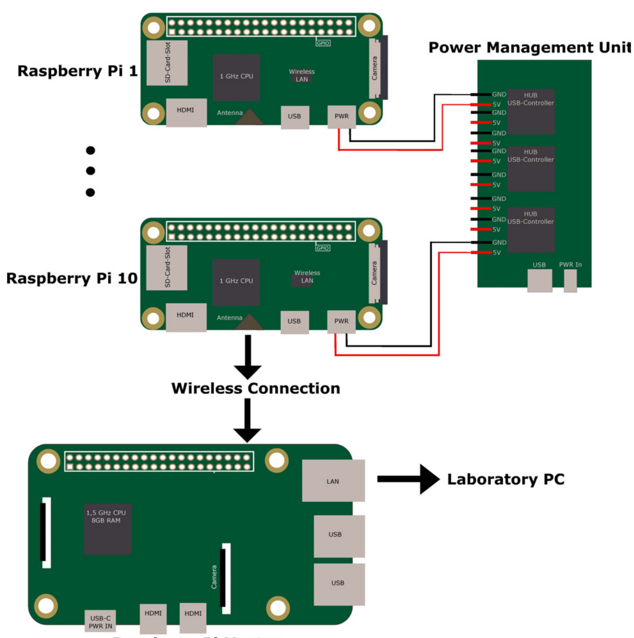


Figure 2: Ten Raspberry Pi Zeros are connected to the power supply unit of the USB hub in the vacuum.

### *Retrieving the Data and Controlling the Cameras*

We used a wireless connection to control the cameras. A master Raspberry Pi with an external WIFI antenna was installed as an access point. All ten cameras connect wirelessly to the access point. The master sends the command to capture the image and the slaves send the image back to the master. At this point, initial image processing can be performed before all images are sent to the main laboratory computer for further processing and application of tomographic reconstruction algorithms. The main computer is not located inside the vacuum, only the external antenna. Therefore, only two pins for the power supply and five pins for the USB connection were needed to control the tomography detector.

## CALIBRATION

### *Scaling*

The first step was to align the cameras to the center of the beam path and determine the focal point for sharp images. The cameras are equipped with a board lens or officially with an $M12 \times 0.5$ mm lens. A ruler with 0.5 mm steps was used for initial adjustment and a 0.1 mm thread was used for fine adjustment. The camera sensors were attached to the mount with two screws. Perfect alignment was not possible. It was decided to align the cameras as best as possible by hand and then match the images by software.

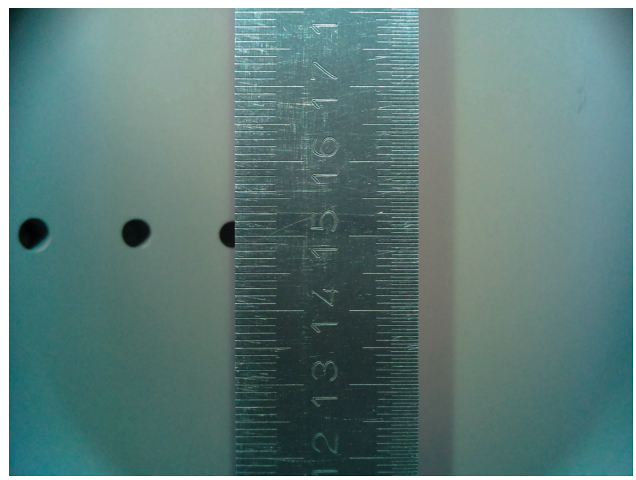

Figure 3: This ruler, which was placed in the center of the beam path at a distance of 0.5 mm, was used for scaling.

For the (mm/px) scaling, a ruler was placed in the center of the beam path (Fig. 3). The scaling of the cameras is approximately 0.03 mm/px or 31 px/mm. There is an individual scaling lookup table for each camera. A calibration wire was used to determine the beam path center (Fig. 4). Two wire holders were attached to the end flanges of the detector. The wire holders were aligned with a matching ring to the flanges. The position relative to the beam path center or line of side was determined using the Taylor-Hobson telescope at the end of the beam line.

### *Multi-Camera Image Matching*

As already mentioned, the cameras are only aligned with two screws. In addition, all camera lenses have an offset. The fields of view of the individual cameras must match each other. For this purpose, the image of the first camera was selected as a reference and all other camera images were matched to it. A stick with a black and white pattern was placed in the center (Fig. 5). Using this pattern, one can select a set of three points in each image and match these sets of points to the reference camera by affine image transformation.

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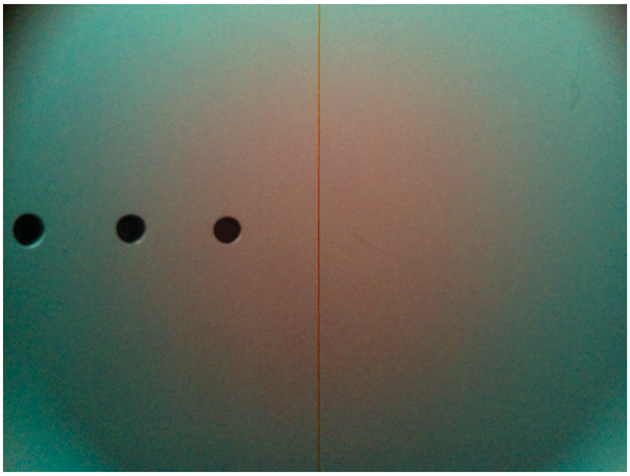

Figure 4: The calibration wire with a diameter of 0.25 mm has a gold layer that is reflective. A white thread was not reflective enough to distinguish it against the background.

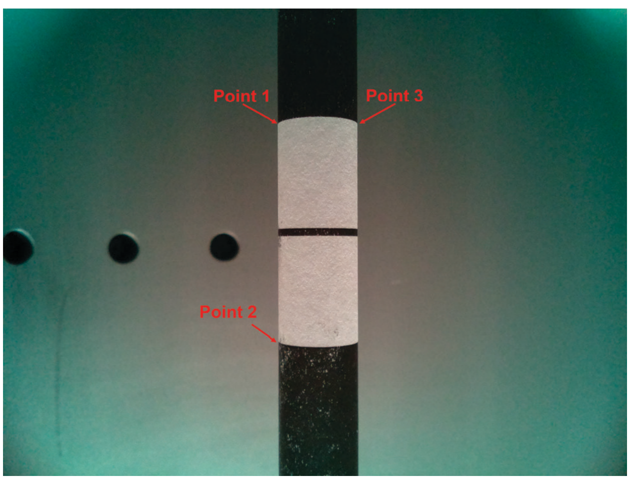


Figure 5: A 10 mm diameter rod with a pattern on it was held in the center of the detector. Three points were determined that matched the images from each camera.

## TOMOGRAPHIC RECONSTRUCTION

### *Image Pre-processing*

To evaluate the calibration and test the tomographic reconstruction algorithm, the images must be pre-processed. After affine transformation, each image was normalized and converted to grayscale. A Canny edge detection algorithm was used to highlight the contour of the calibration bar. Finally, the image was converted to black and white. These conversions are the best prerequisite for optimal reconstruction and detection of alignment errors. The result of the pre-processing is shown in Fig. 6.

### *Tomographic Algorithm*

The development of tomographic reconstruction algorithms, especially in accelerator facilities, is a current scientific topic [6]. Time and resource efficient software has been developed in different laboratories. Here we use the python-based software toolbox Tomopy [7]. Most of the commonly used tomographic reconstruction algorithms such as Algebraic Reconstruction Tomography (ART) or Filtered Back Projection (FBP) are implemented here. Unlike the usual detectors with an X-ray source rotating over the object and creating as many profiles as necessary, here we have limited viewing angles. The ART algorithm was developed for iterative reconstruction of objects examined at a particular viewing angle [8]. In contrast, the filtered back projection is better suited for unlimited viewing angles. For this reason, the ART algorithm was used to evaluate detector calibration for an initial test.

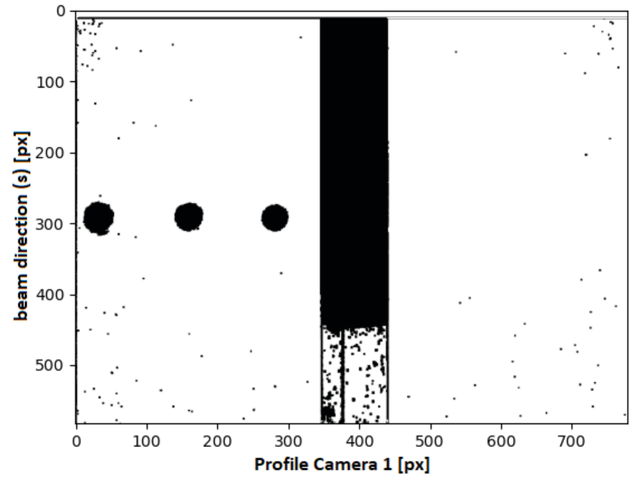


Figure 6: Result after pre-processing the image in Fig. 5.

Figure 7 shows one reconstructed slice of the calibration rod.

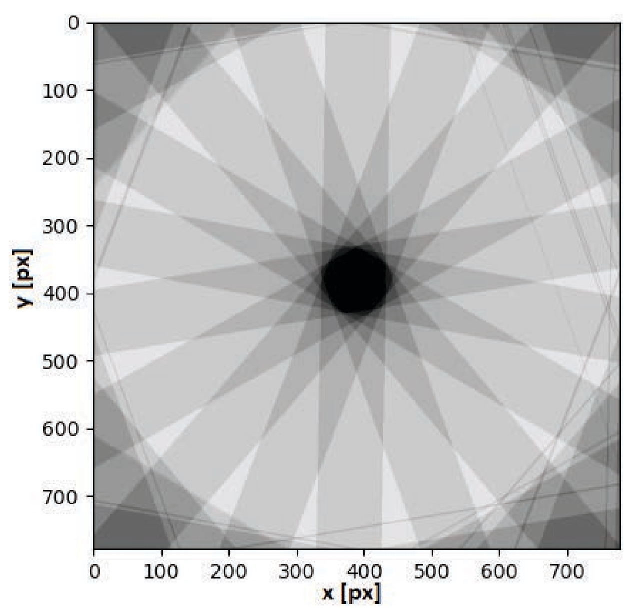


Figure 7: One slice of the tomographic reconstruction of the calibration rod.

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Tomopy Software Toolbox has also integrated an effective image post-processing algorithm. The result of post-processing is shown in Fig. 8.

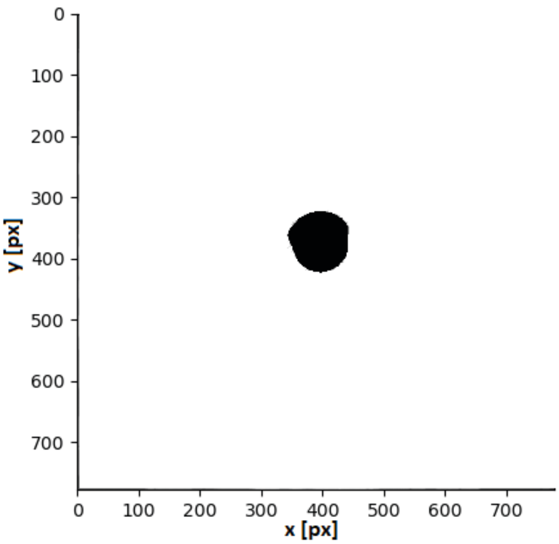


Figure 8: After image post-processing of the reconstruction.

Fig. 8 shows a asymmetrically shaped reconstruction of the calibration rod. There could be two reasons for this. One is a misalignment of the cameras, the other could be a problem in the pre- and post-processing. To investigate the misalignment of the cameras, the calibration wire from Fig. 4 was used. Figure 9 shows the tomographic reconstruction of the calibration wire of 0.25 mm thickness. One can see the misalignment, which could not be corrected yet.

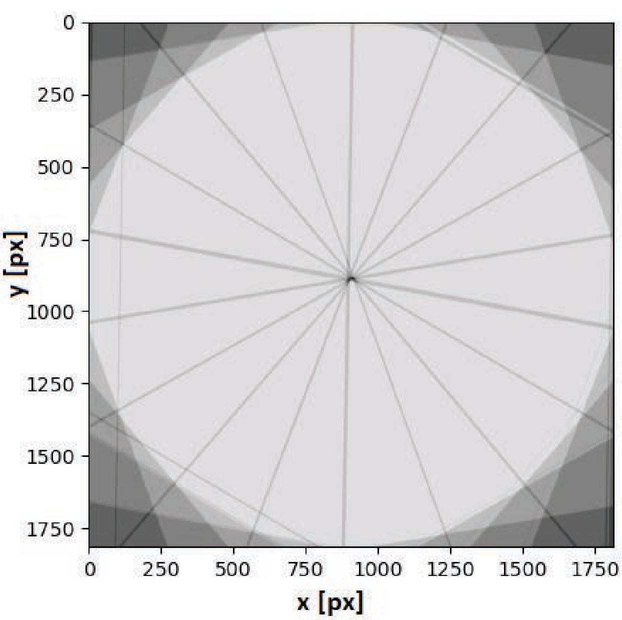


Figure 9: Tomographic reconstruction of the calibration wire from Fig. 4.

## CONCLUSION

In this paper, a tomographic BIF detector for ion beam investigations is presented. This BIF is based on ten single-board cameras on a tube concentrically aligned to the beam axis and hold by the outer vacuum pipe. Several challenges had to be overcome. Data communication was provided by an edge device serving as a WiFi access point and master control unit. Camera calibration for real-world scaling was performed using a ruler placed in the center of the detector. The detector was aligned to the center of the beam path using a calibration wire and a Taylor-Hopson telescope. The problem of matching the fields of view of the cameras has not yet been perfectly solved. Reconstruction by the tomographic algorithms showed misalignment that could not yet be corrected. Further investigations will be performed using the python-based Tomopy software toolbox. The toolbox contains image pre- and post-processing that can be integrated. It also implements other reconstruction algorithms that may be better suited for this purpose. The tomography detector is installed in the beamline at IAP and will be tested with a 25 mA, 30 keV proton beam in the near future.

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