Mu3e experiment - filter farm and camera alignment system

By

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Overview

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Paul Scherrer Institute (PSI)

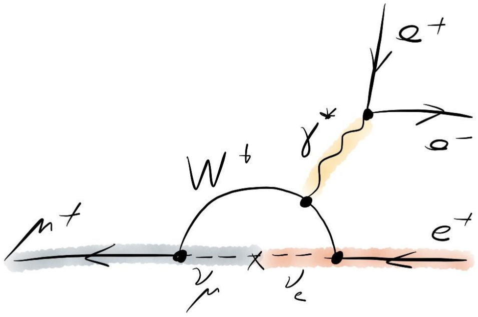
Fig. 1: Aerial view of the PSI premises.

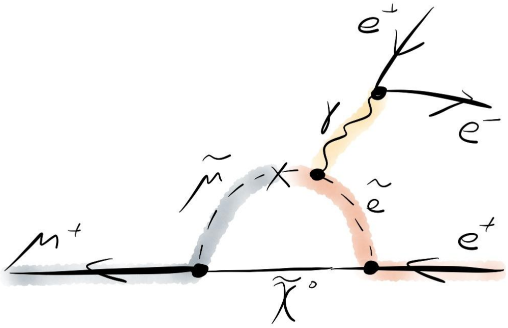
The Paul Scherrer Institute at Villigen, Switzerland.

- PSI has a very high intensity proton beam of 2.2 mA at 590 MeV/s.
- In the muon source, at the core are two carbon-ring targets that are struck by a beam of fast protons.
- During the collisions between protons and carbon nuclei initially pions are produced which decay into muons.
- The muons are guided with the aid of magnets to the Mu3e detector.

Source: PSI

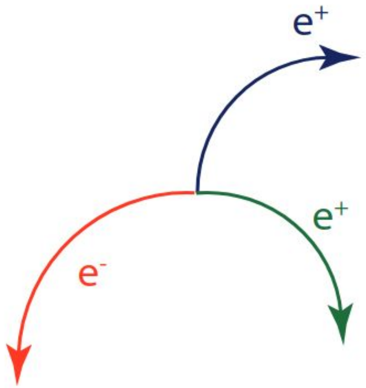
Mu3e Experiment



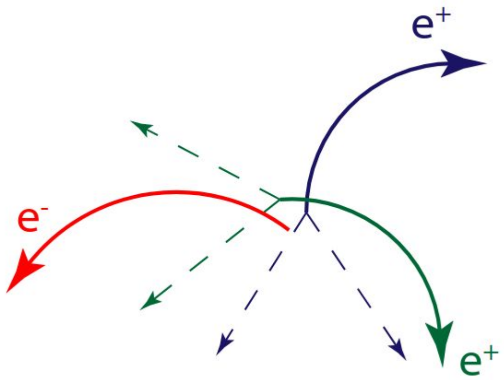


- The Mu3e experiment searches to observe or exclude the decay of a positive muon to two positrons and an electron.
- Such an observation would be a violation of the lepton flavour conservation and indicate for Physics Beyond the Standard Model of particle physics.
- In standard model, the lepton flavour violating decay is possible via neutrino mixing but suppressed to a branching ratio Br < 10^{-54}.
- SINDRUM achieved Br < 10^{-12} (1988) PSI.
- The Mu3e experiment will observe more than > 10^{16} muon decays in order to probe existence of new physics beyond the standard model in the Br > 10^{-16}.

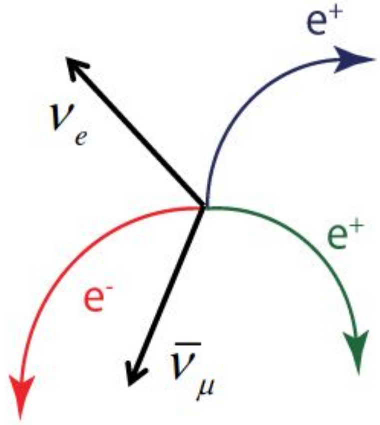
Signal and Background processes



Signal



Combinatorial Background



Internal photon conversion
(Br = 3.4×10^{-5})

Mu3e Detector

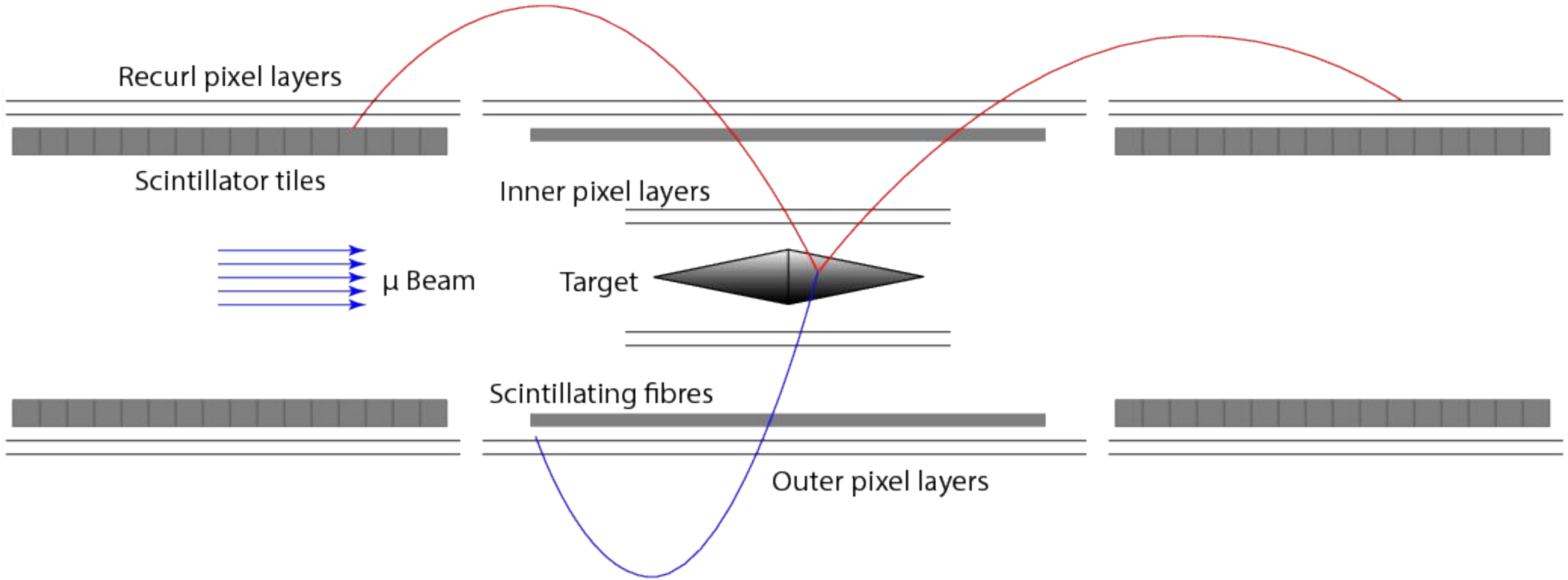
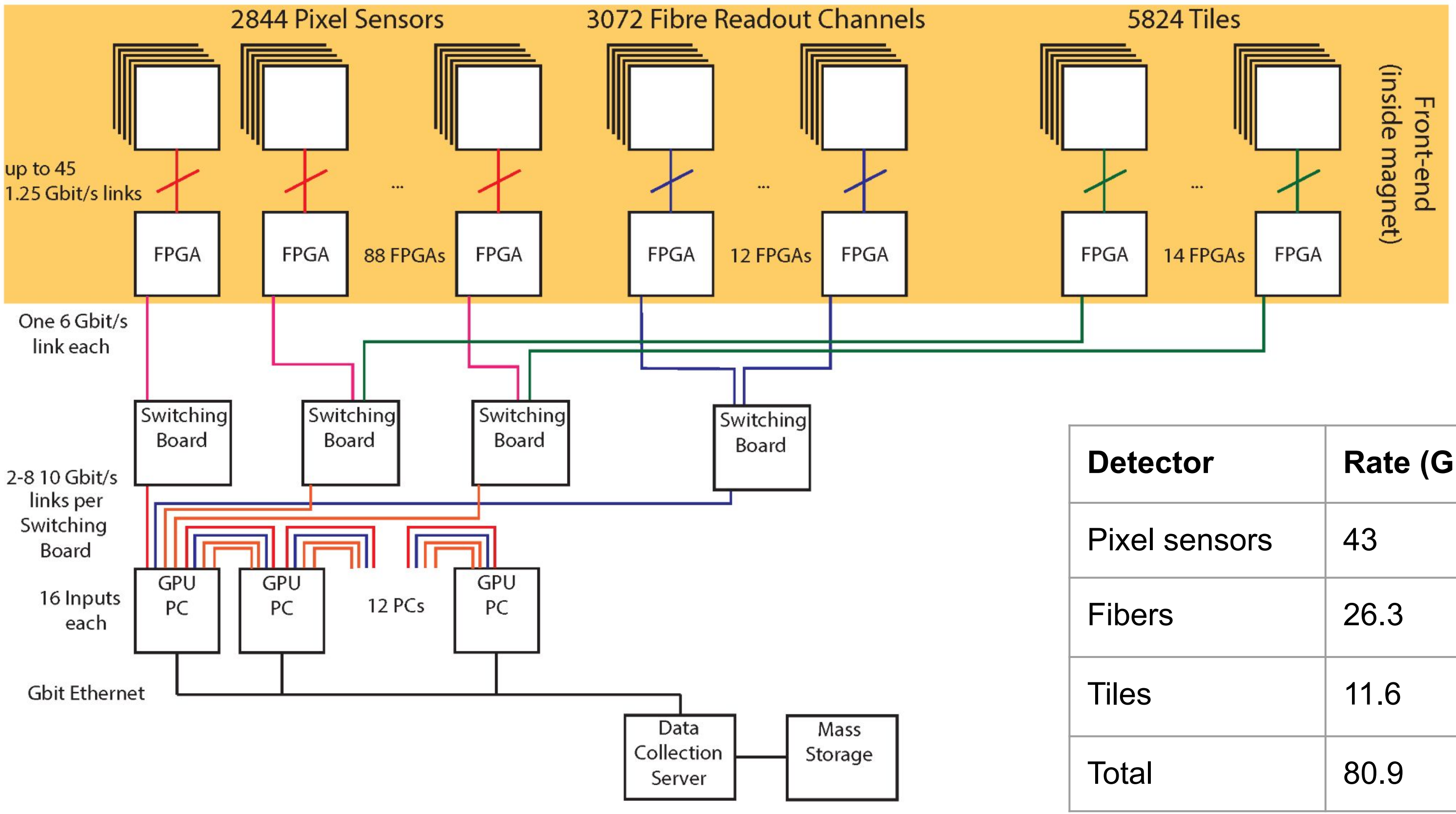


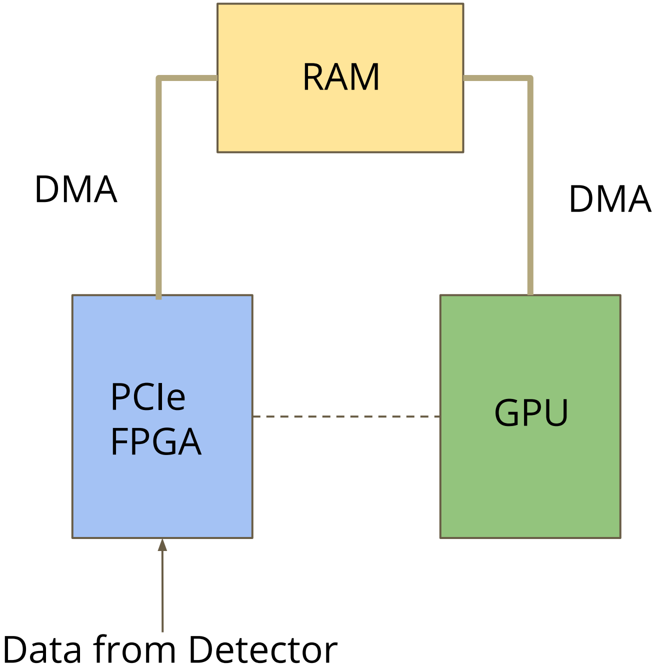
Fig. 2: Schematic diagram of Mu3e detector.

DAQ Readout System



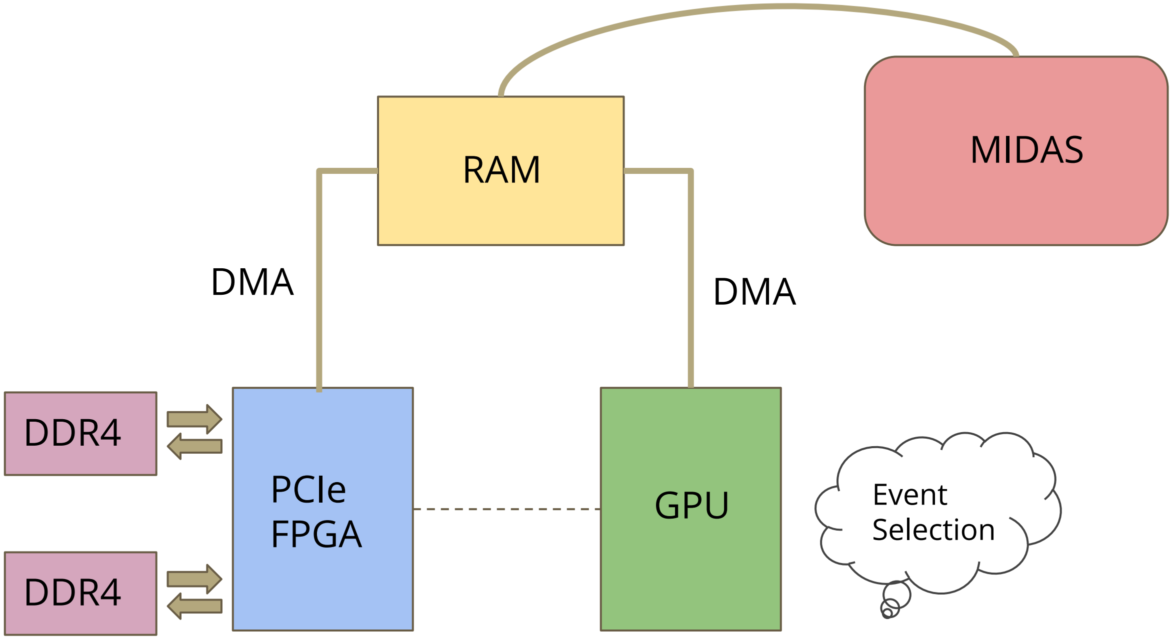
Detector	Rate (Gbit/s)
Pixel sensors	43
Fibers	26.3
Tiles	11.6
Total	80.9

Filter farm



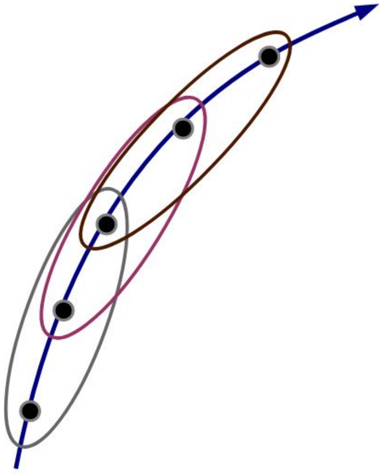
Data flow in DAQ PC	Rate (GB/s)
FPGA to RAM	1.67
RAM to GPU	4.35
GPU to RAM	5.73

Filter farm



Online Track Reconstruction

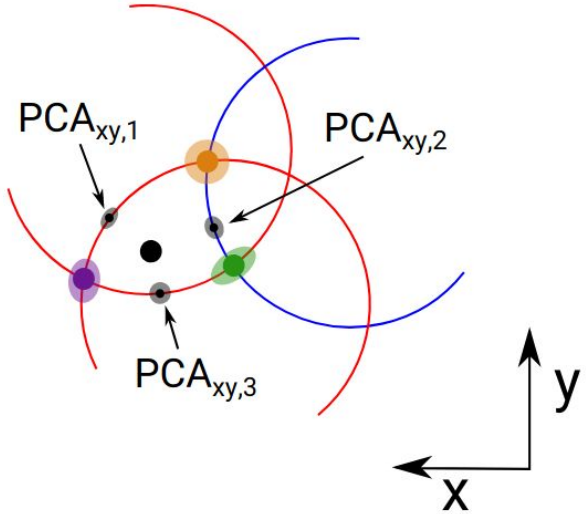
- Hits from the first 3 layers of the inner detector are selected based on a few simple geometrical selection criteria in the FPGA.
- Triplets of hits are fit with a fast Multiple Scattering fit.
- The triplet must pass the χ^2 selection and then it is extrapolated to the fourth layer, where the presence of an additional hit compatible with the triplet is required.



Source: Ref. 1

Vertex Reconstruction

- All combinations of two positrons and one electron are considered within each time slice of 50 ns.
- The weighted mean is calculated only if all three reconstructed tracks intersect and it is calculated for all combinations of three intersections from three tracks.
- The χ^2 for a vertex estimate is computed from the differences between the point of closest approach and the weighted mean both in the transverse plane and in the z-coordinate.



Source: Ref. 1

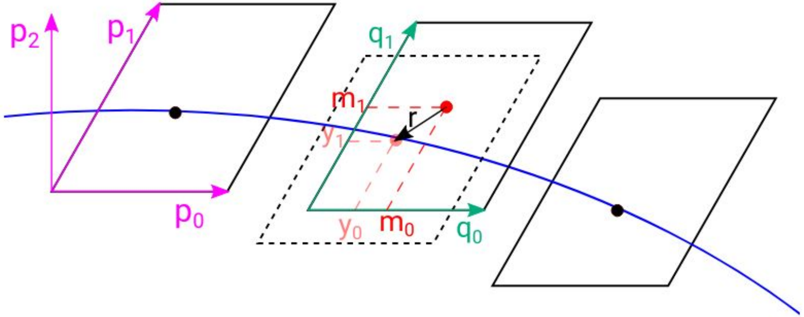
Track-based Alignment

- In order for the track reconstruction to work properly, the positions, orientations and surface deformations of all detector parts must be known to great precision.

- This fixed set of global parameters is used for the track fit depending only on a small set of parameters like the hit positions, the inclination angles or the curvature of the track.

- The obtained residuals will be biased as they depend on a wrong model, assuming fixed global parameters. This is fixed by including all global parameters into the track fits and fitting them all at the same time as the track parameters.

- Minimisation of this function is done by MILLEPEDE - II algorithm to obtain an optimal combination of track parameters and global parameters.



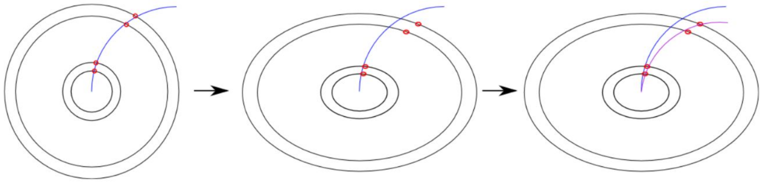
$$r_{ij} = m_{ij} - f(\boldsymbol{q}_j, \boldsymbol{p}).$$

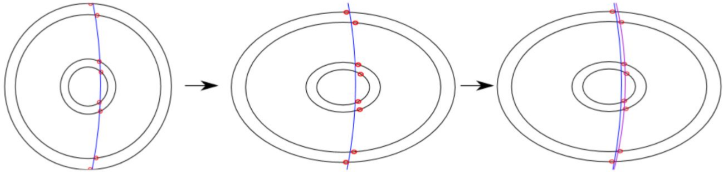
$$\chi^2(\boldsymbol{q}_j, \boldsymbol{p}) = \sum_j^{\text{tracks}} \sum_i^{\text{hits}} \left(\frac{r_{ij}}{\sigma_{ij}}\right)^2$$

Source: Ref. 4

Misalignments

- The misalignment in the position of the Mu3e detector system affects the precision of track reconstruction.
- Weak modes of the detector misalignment causes track-based alignment software to fit deformed tracks.
- Cosmic muons offer insight into detector deformation by connecting detector parts that would otherwise not be connected by the tracks coming from decay of muon beam.
- Precise position measurement of the detector segments using camera system would provide additional information regarding the detector geometry.





Source: Ref. 4

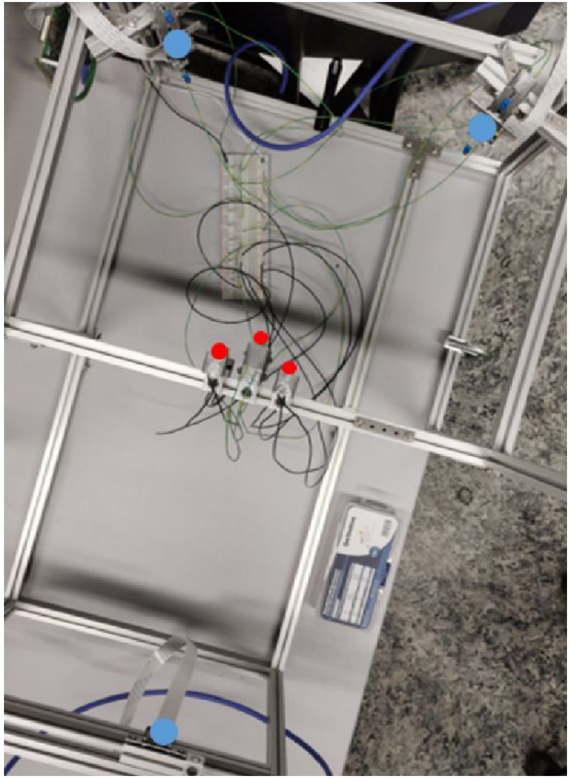
Camera Alignment System

- Using the magnification formula, the distance between the camera and the object is easily calculated with the size of the observed object and the focal length of the camera lens.

- The detector shape and position in space can be determined by placing camera modules with pairs of LED and LED pairs on the detector.

- The initial test setup for such a system was built with Raspberry Pi NoIR v2 cameras and Raspberry Pi 4 Model B.

- The resolution of the cameras is sufficient to achieve a precision of 80 µm (size of the individual MuPix pixel) at distances that are expected for Mu3e.



Source: Ref. 5

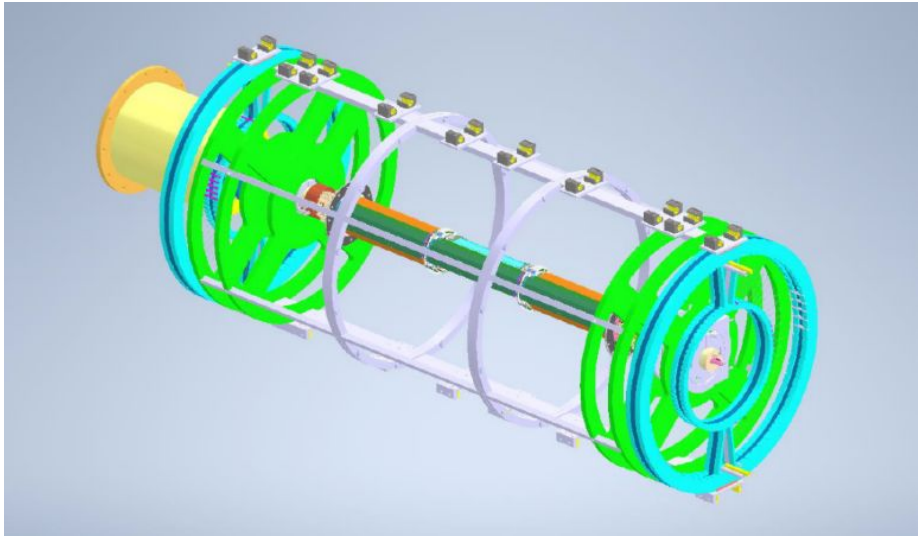
Challenges

- Need to figure out how many camera modules will be required for the final camera alignment system.

- Ethernet connection has to be replaced because of the magnetic properties of the connector (optical fibers as an alternative).

- Need to ensure that the IR LED will not disturb the sub-components inside the cage and the scintillators.

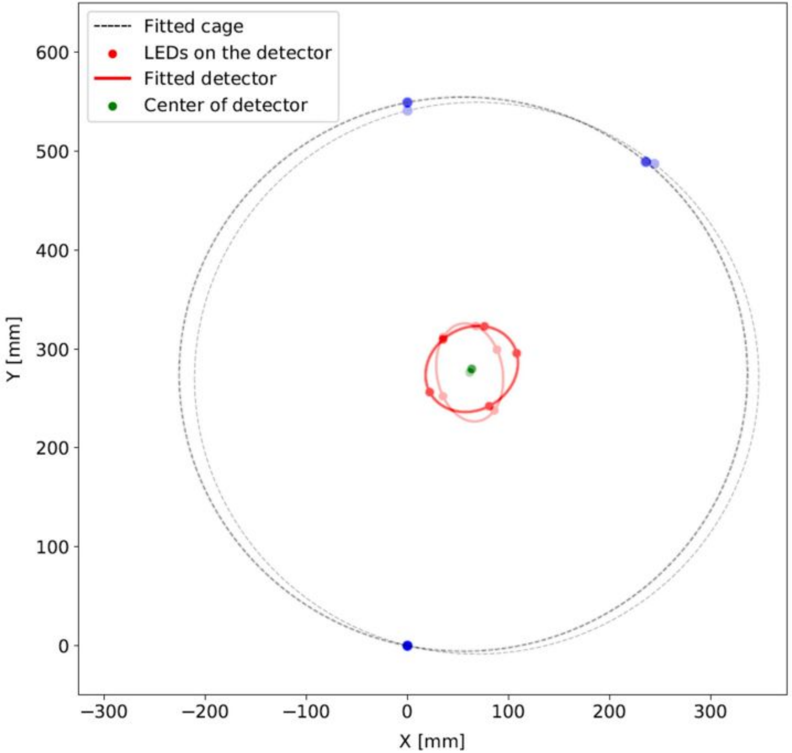
- The Raspberry Pi will be replaced by an FPGA dedicated to the purpose of the camera alignment system.



Source: Ref. 5

Updates made to the Setup

- With help of an adapter board, a single Raspberry Pi is now able to capture images from different camera modules to estimate the distances.
- The camera module and a pair of LEDs have been attached to individual PCBs.
- The program estimating the distance from the camera to the detector has been optimized to measure distances of objects not within the camera's plane.
- This needs to be tested with models similar to the Mu3e detector and check if the system can detect the misalignments.



Source: Ref. 5

Plans

- To implement the event selection (hit count) in filter farm during cosmic run in spring at PSI.
- Enable the precision measurements of the detector misalignment for the complete detector geometry with the camera alignment system.
- Work with algorithms used in the offline reconstruction of tracks and apply them in the filter farm for online reconstruction of tracks to obtain excellent momentum resolution.
- Utilize the camera alignment system measurements to calibrate the online reconstruction of tracks in filter farm.

PhD Requirements:

- I have applied to register and enroll as doctoral student at JGU.
- There is no requirement to complete course work for the PhD.
- Need to be teaching assistant for 3 semesters, 1 course in each semester.
- I will be the teaching assistant for the summer semester F-Praktikum course on Balmer series.

Training:

- I attended the International Workshop on Cosmic-Ray Muography 2021, Gent, Belgium online.

References

1. D. V. Bruch, *Pixel Sensor Evaluation and Online Event Selection for the Mu3e Experiment*, 2017.
2. M. Köppel, *Data Flow in the Mu3e Filter Farm*, 2019.
3. N. Berger, A. K. Perrevoort (Mu3e Collaboration), *Searching for New Physics with The Mu3e Experiment,* 2019.
4. U. Hartenstein, *Track Based Alignment for the Mu3e Pixel Detector,* 2019.
5. G. Stanic, *A Camera Alignment System for the Mu3e Experiment*, 2021.

Thank You