Masters Dissertation

Study Field:
Medical and Mineral Imaging Technology

Topic of Study:
Developing On-Line High Performance PET Based Sorting

Student Name: Prince Nqobizitha Ncube
Qualification registered for: MEng In Mechanical Engineering
Date of first registration: 09 February 2026

Student Number: 221135808
Supervisor: Prof Simon H Connell
Co-Supervisor: Mr Tim Brooks

15 Oct 2026

- Diamond is made up of carbon-12
- Mined rocks are irradiated.
- The irradiation causes some formation of radioactive carbon-11 from carbon-12 [1]
- Carbon-11 produces positrons, which produce light when in contact with matter
- The PET detectors then reconstruct 3D maps of that light to locate the diamond

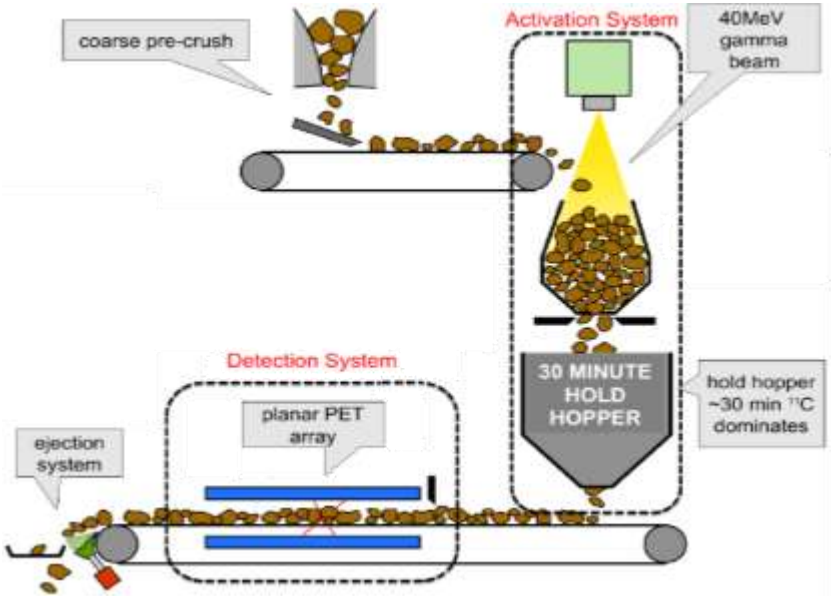
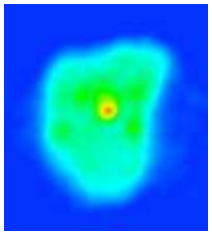


Figure: MinPET process



Irradiated Kimberlite rock



Reconstruction



Diamond recovery

- Specifications summarised in the “**MinPET Unit**”
- Unit of measurement to define the ability of MinPET to detect a diamond.

- Activity (Activated diamond or Na-22 in the lab)
- Detector Efficiency
- Throughput

For constant throughput:

- Inneficient detector
- very high activity.
- Government regulation,
- Worker dose radiation exposure

- Efficient detector
- Low activity.
- Can operate in more environments.
- Easier cormercialisation

Problem Statement

Mechanical Loading

- Detectors were designed for orientation in Figure 2
- Predominantly operated in orientation in Figure 1
- In some experiments:
- - Aluminium case not properly secured
- - Some screws unsecured.
- This allowed users to test different components without constant disassembly
- This possibly led to the breakage of multiple solder joints on a PMT module

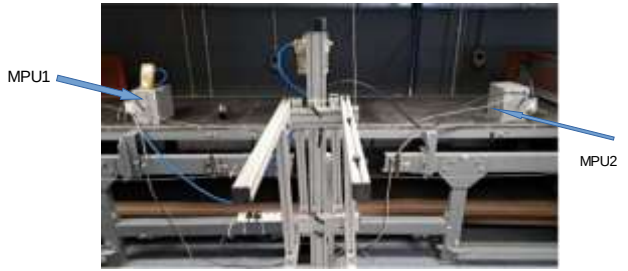


Figure 1: Horizontal Orientation

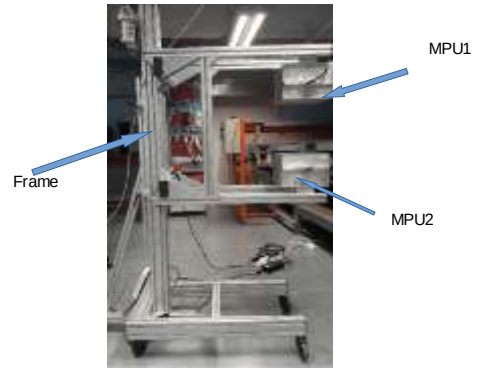


Figure 2: Vertical (mounted) Orientation

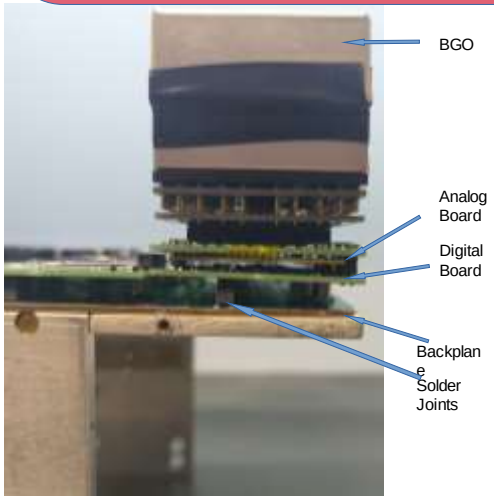


Figure 4: One PMT modules

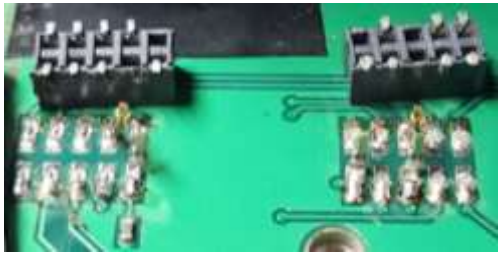


Figure 3: Broken Solder joints

UNIVERSITY OF JOHANNESBURG

Problem Statement

Optical Coupling

- Expected detector energy resolution:(9 – 14%)
- Actual energy resolution : 22.5%
- Therefore, low detector efficiency
- The French optics company Saint Gobain consulted
- Recommended changing from grease to silicon optical

AI

- Currently, the region with the most significant intersecting lines of light are said to be diamond-containing.
- This does not take into account, phenomena such as voids, absorption and scattering of the light by the rocks
- High error rate, low detector efficiency
- An AI was trianed in a PhD thesis to replace this simple decision threshold to improve efficiency

PMT Module Recovery

- These detectors are worth millions of Rands
- 5/16 of the PMT modules on MPU1 are non-performing
- In Lean Management, this is waste through an idle, non-performing asset

Source Activity

- The Na-22 positron source is now very weak.
- Releases so few positrons that 1hr experiments take 12 hrs
- Detectors are therefore exposed to more wear



Figure 7: Na-22 Positron Source

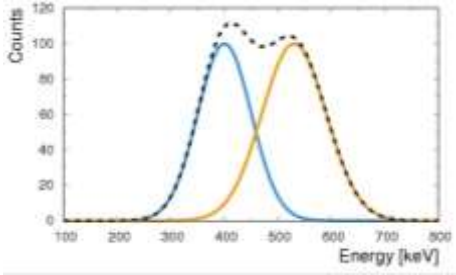


Figure 5: Poor resolution: Two peaks blending into each other

PMT	0	2	7	15	3
Voltage	✓	✓	✗	✗	✓
Read out	✗	✗	✗	✗	Partial

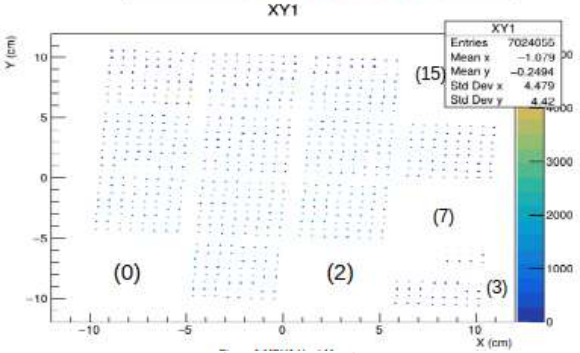


Figure 6: State of MPU1

UNIVERSITY OF JOHANNESBURG

Aim: **To effectively contribute to the development of commercially viable, high throughput diamond sorting**

- Objectives
- Install sillicon coupling and compare perfomance to previous coupling
- Use Finite Element Analysis to study different loading conditions and advise on loading minimisation
- Implement the AI and compare performance with the decision threshold
- Order new Na-22 positron sources

- **Significance of the study**: The MARK II generation is currently to only platform to experimentally test theoretical improvements in the technology and demonstrate the viabiility of the technology. Thus, the optimsation of this detector is a significant contribution

UNIVERSITY OF JOHANNESBURG

Literature Survey Results

Solder Joint Mechanical Loading:

- Majority of studies investigate solder fatigue instead of simply mechanical loading.
- Most use models such like: Anand + Syed (creep-dominated) & Coffin–Manson model (cyclic plastic strain dominated).
- However, some studies establish FEA as a viable analysis method [2]
- Especially when strictly studying mechanical loading

PMT Module Recovery

- Excessive voltage can break down the dielectric insulation in capacitors
- Short-circuit or open-circuiting diodes
- MOSFET Insulation can break down, especially with insufficient spacing in resistors [3]

Optical Coupling

- Lawrence Livermore Natioratory Lab study states: halving resolution from 8% to 4% gives 70% increase in extractable spectrum information. Best metric to improve detection [5].
- There is a lot of recent academic interest in Silicon optical coupling
- However, most studies state that it is preferrable for mechanical stability, as opposed to improved energy resolution

Source Activity

- Na-22 half life is 950.7 days[4]
- New sources must more active than the minimum required activity to account for this reduction of positrons overtime.

UNIVERSITY OF JOHANNESBURG

Methodology

Mechanical Loading

- Apply fixtures on the screws
- Apply the weight of the PMT module at the centre of mass.
- Apply the force due to the aluminium case on top surface of the module
- Compare the mechanical properties such as stress
- Create a hierarchy of acceptable loading and fixing

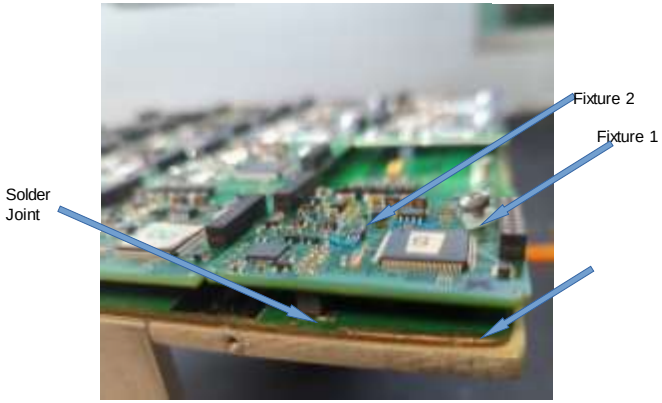


Figure 8: Digital Board

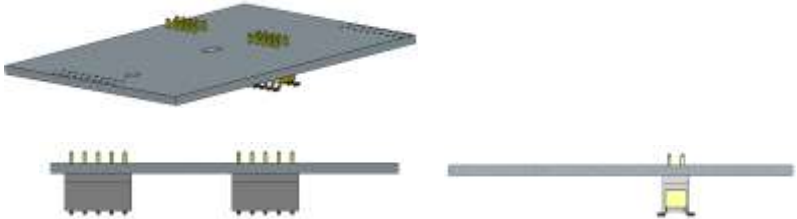
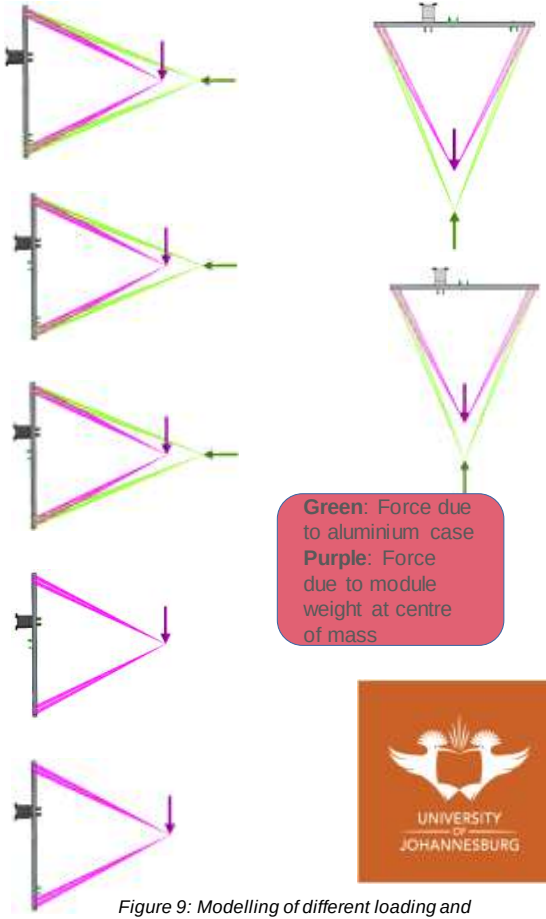


Figure 10: Digital Board Simplified model

Unmounted **Mounted**



Green: Force due to aluminium case
Purple: Force due to module weight at centre of mass

Figure 9: Modelling of different loading and fixtures

UNIVERSITY OF JOHANNESBURG

Methodology

Optical Coupling

- Remove the tape around the coupling
- Seperate the BGO from rest of module
- Clean both contact surfaces using alcohol
- Install the sillicon pads and obtain the resolution



Figure: Tape on PMT module



Figure: Old Grease Coupling



Figure: New Silicon Coupling

AI

- Split the processing program into a sender and receiver
- Place receivers on different machines for faster imaging computation
- Write up inference scripts for the C++ code to call the AI (python)
- Compare the performance of the AI vs the decision threshold

PMT Module Recovery

- Move the analog board of a faulty PMT module to another module and test
- Do the same for the digital boards
- Do the same for the PMTs themselves
- Isolate source of underperfomance based on the introduction of underperformance to a PMT module known to be working

UNIVERSITY OF JOHANNESBURG

Resourcing Plan

Na-22 Source

- UJ Research Funding allocated to the MinPET research group
- Purchasing from iThemba Labs

iThemba LABS
Laboratory for Accelerator Based Sciences

FEA

- Workstation 1 (64GB RAM) : Runs out of RAM at mesh element sizes < 0.2mm
- Workstation 2 (96GB RAM) : Runs sims of mesh element size < 0.1mm. 3 minute to solve on Workstation 2

PMT Module Recovery

- Microscope
- Soldering Machine
- Purchased replacement components (capacitors, diodes)

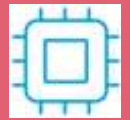
AI

Sufficient computing for inference

Workstation 3 &4 specs:



RAM: 251GB



Storage
1 TB



2xRTX A5000
Total GPU Memory
48 GB



Storage
4 TB

UNIVERSITY OF JOHANNESBURG

Current Results

Mechanical Loading

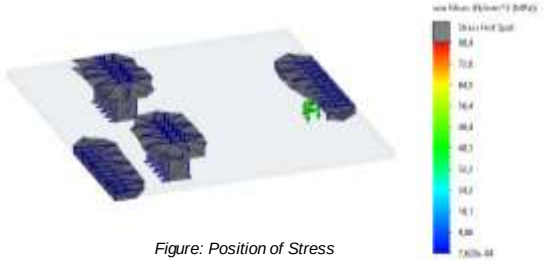
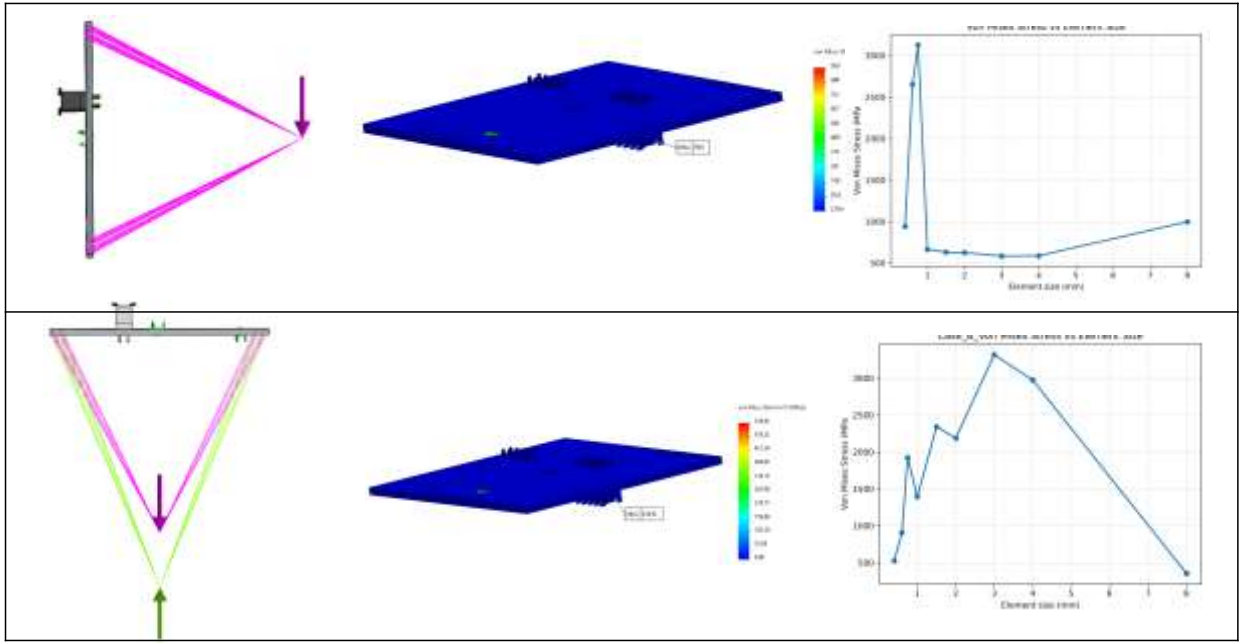


Figure: Position of Stress Hotspots

Excessive Presence of Stress Hotspots

Re-evaluate application of loading



Current Results

PMT Module Recovery

- The source of readout under-performance was localised to the backplane.
- The source of under-voltage was localised to the capacitors on the digital boards.
- Re-soldered solder joints & replaced capacitors

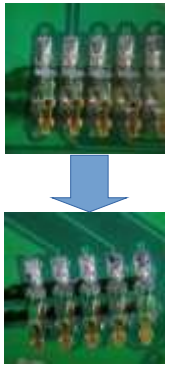
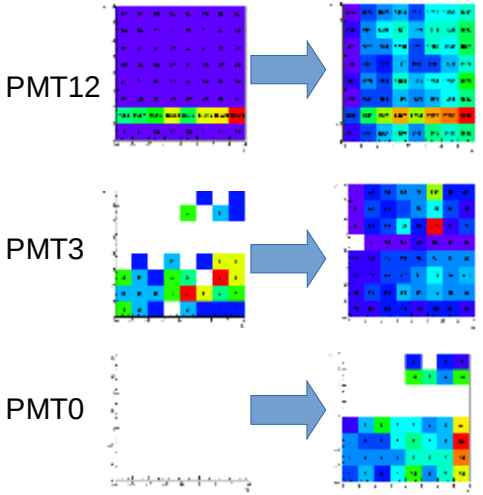


Figure: Re-soldered connector pins



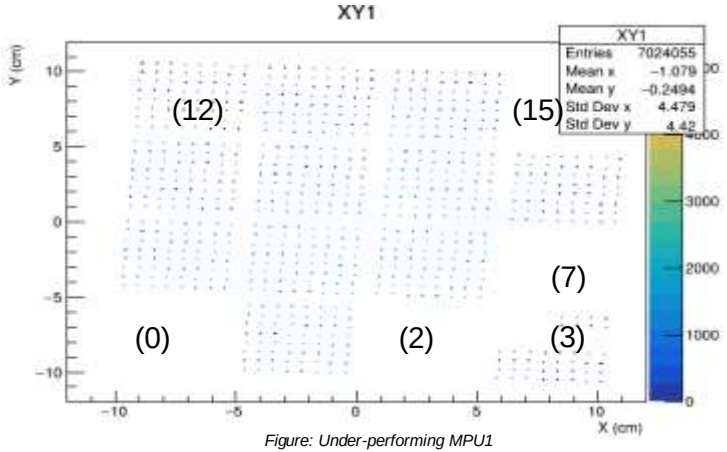


Figure: Under-performing MPU1 PMT modules

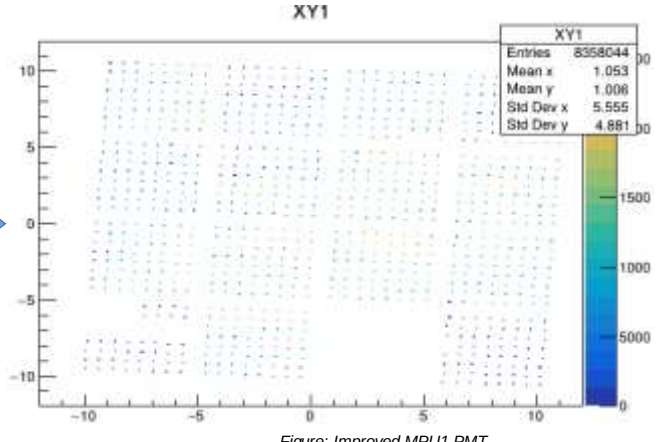
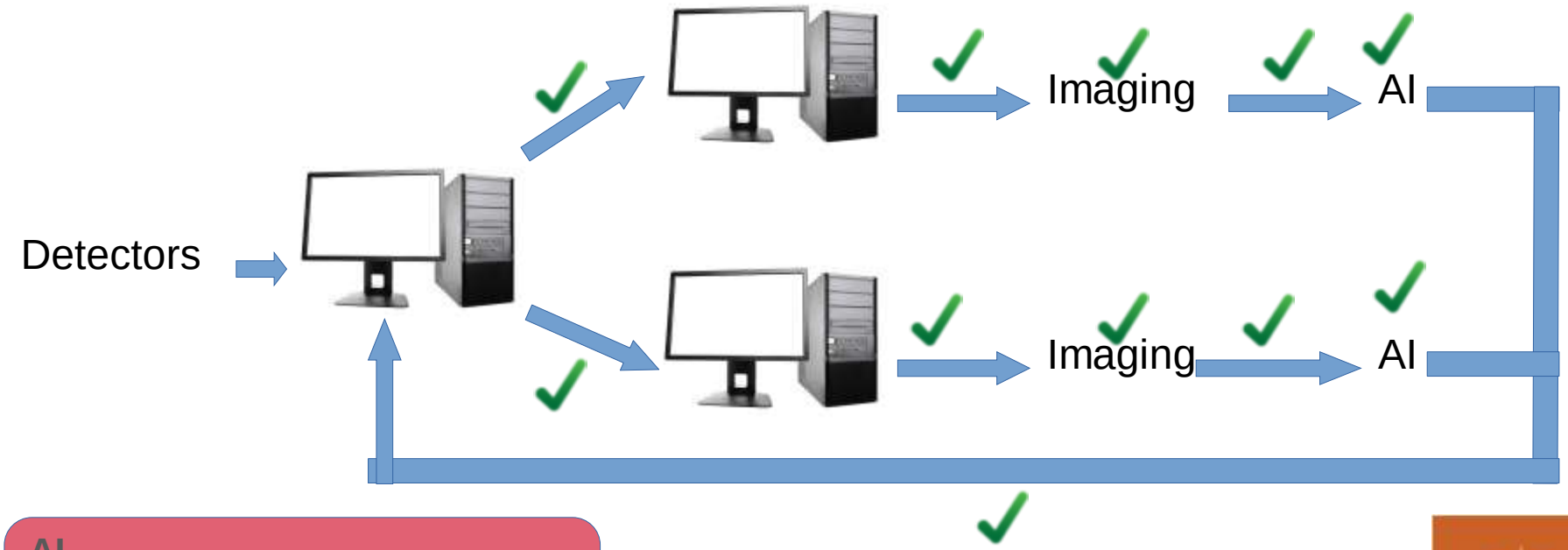


Figure: Improved MPU1 PMT modules

UNIVERSITY OF JOHANNESBURG

Current Progress



AI

- 600+ lines of C++ code written
- Processing successfully occuring on seperate workstations

UNIVERSITY OF JOHANNESBURG

Current Progress

Mechanical Loading

- Simulated 2/7 loading+ fixtures pairs
- Simulations show non-convergence
- Therefore, the simulations are currently invalid

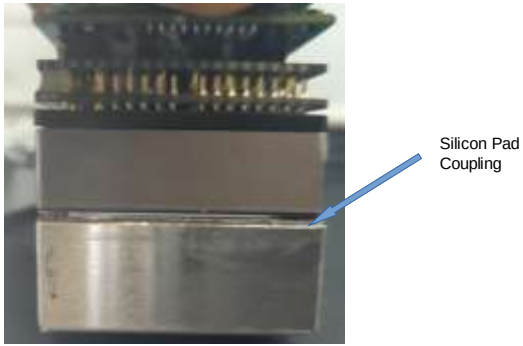


Figure: PMT module with new coupling

Optical Coupling

- Completed replacement of optical coupling on all PMT Modules on both MPUs
- Completed Analysis of Resolution

PMT Module Recovery

- Some PMT modules recovered

Na-22 Source

- Prepared requirements for one of the sources
- Submitted the requirements to iThemba Labs and requested a quotation
- iThemba Labs preparing quotation

UNIVERSITY OF JOHANNESBURG

Current Results

- **Optical Coupling**
- The energy resolution with the silicon coupling : 29.3%
- This is worse than the original 22.5% that was obtained with the grease coupling

Conclusion

- A conclusion cannot be made on the results of the FEA due to the instability of the simulation
- The optical coupling must be either reverted to the previous coupling or a better coupling must be found
- Most of the underperforming were successfully recovered. Recovery must continue.
- The AI inference and split workstation processing was successfully implemented. AI benchmarking must still be conducted.
- This thesis work improves the detector efficiency. This will allow reaching the MinPET unit with reduced activity than currently required

UNIVERSITY OF JOHANNESBURG

References

[1] M. Cook, "*Remote Detection of Light Elements Using Positron Emission Tomography*," PhD thesis, University of Johannesburg, 2014.

[2] Munshi M. Basit, David Burdick, Heshmat Aglan, "Analysis of the viscoplastic behavior of Pb-free solder using lap shear joints" Microelectronics Reliability, 2021

[3] Cook, M. Tchonang, E. Chinaka, M. Bhamjee, F. Bornman, and S. Connell, "*Overview of the Mineral-PET Run-of-Mine Diamond Bearing Rock Sorter*," in The Proceedings of SAIP2016, 2016, pp. 479–484.

[4] Iliyasu, U., Bature, M., Umar, M., Abubakar, U. and Shehu, A., 2024. Photon attenuation properties of samarium-doped zinc bismuth silicate glass: A study using Cs-137, Co-60, and Na-22 Radiation Sources. Caliphate Journal of Science and Technology, 6(3), pp.281-288.

[5] Riwar, R.P., 2020. Charge quantization and detector resolution. arXiv preprint arXiv:2012.13012.

UNIVERSITY OF JOHANNESBURG