High Spatial Resolution Detectors for Nuclear Physics Applications

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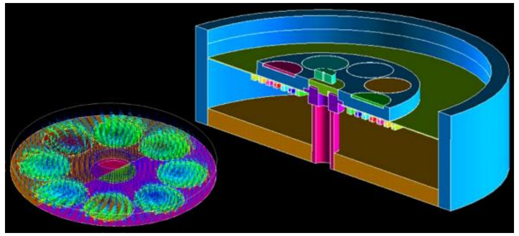
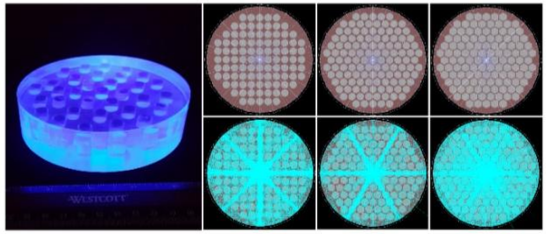
On CapeSym

- Founded 1992
- Employees: 12
- Science + Manufacturing:
  - Materials engineering and processing
  - Crystal growth
  - Materials Characterization
  - Radiation detectors and instruments
  - GEANT4 Scintillation modeling, Thermal modeling.
- Strong commercialization history from US government-supported initiatives:
  - DOE, DHS, DoD, NIH, NASA

CapeSym Commercial R&D Capabilities

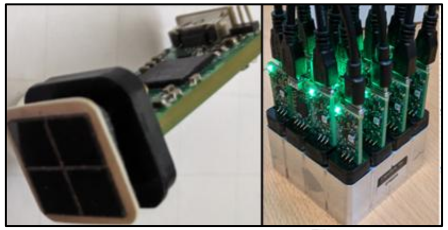
GEANT4 Scintillation Modelling



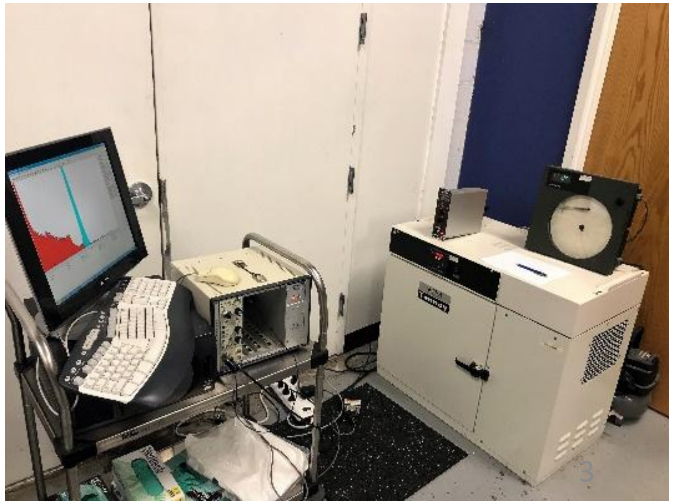


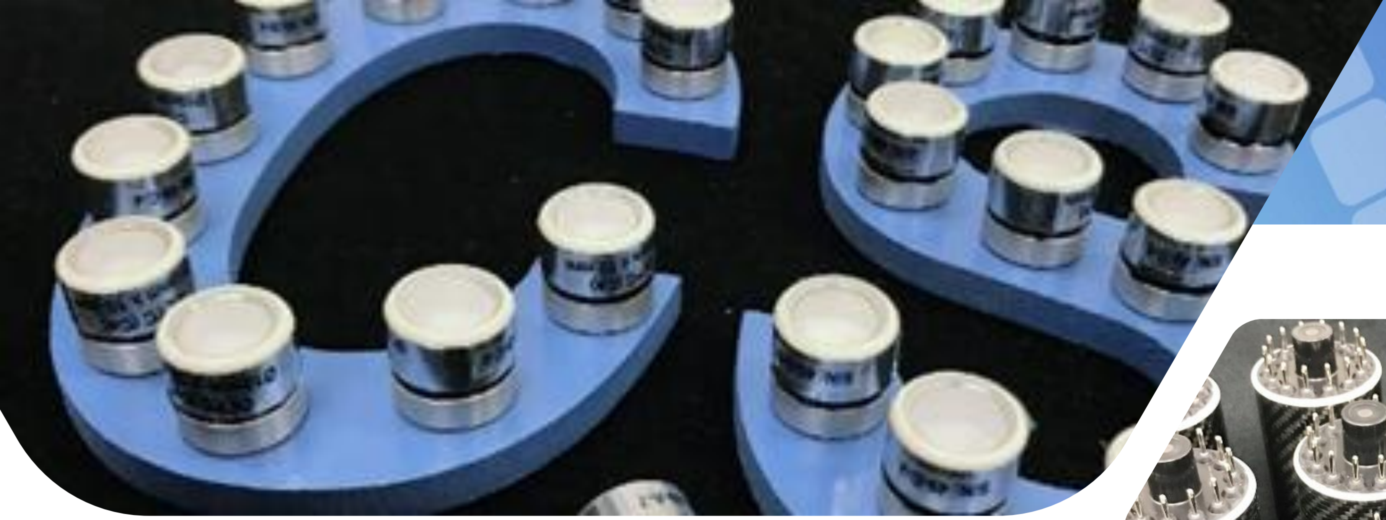
Scintillator Crystal Growth

Radiation Detection Electronics and Instruments Development



Radiation Detection Characterization



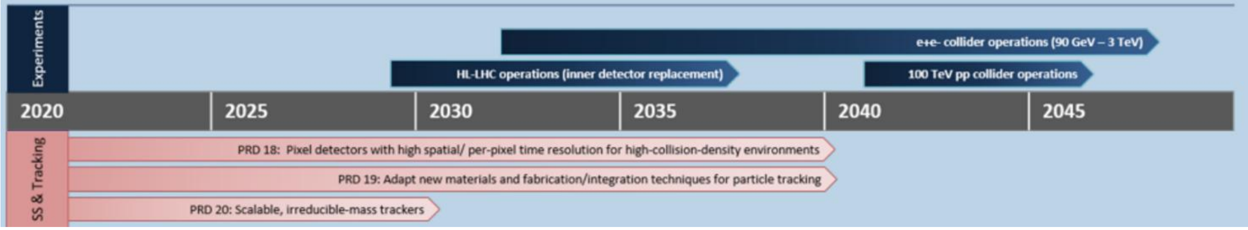


CapeSym Manufacturing Capabilities

- Today: ~1000 large size detectors/year
- All process stations + furnaces designed and built at CapeSym
  - Low cost
  - Can scale rapidly – 3 months
- Automated crystal growth, cutting and polishing
- Low moisture glove boxes, multiple gamma sources, DD neutron generator, environmental chamber, oxygen tester
- High-throughput encapsulation process
- Rugged encapsulation with PMTs and SiPM arrays
  - Meets ANSI environmental standards

NP Challenge

The next generation of nuclear physics instruments (e.g., Electron-Ion Collider) demands a new class of detectors.



The following are a few needs:

- Unprecedented Granularity: To resolve particle tracks in extremely dense environments.
- Ultrafast Timing: 4D tracking to disentangle simultaneous events.
- Extreme Radiation Hardness: To survive for years inside particle colliders.
- Low Mass & Scalability: To cover large areas without disrupting particle trajectories.

Current detector technologies are reaching their fundamental limits.

Program Overview & Core Objectives

Program Goal: The goal of this program is to develop high spatial resolution radiation-hard detectors with ultrafast timing for a wide range of nuclear physics applications

Key Performance Targets:

Spatial Resolution: Push towards the physical limits (tens of microns).

Timing Resolution: Achieve ultrafast timing for 4D particle tracking.

Radiation Hardness: Ensure long-term reliability in high-radiation environments like particle colliders.

High Efficiency & Light Yield: Maximize detection probability while maintaining excellent signal characteristics.

Technical Approach:
Develop scalable fabrication processes for large-area detectors.
Integrate advanced photodetectors (quantitative CMOS cameras, high-granularity SiPMs).
Validate performance through rigorous simulation and multi-particle beamline testing (protons, ions, neutrons).

Our Vision: Microcapillary Plate (MP) Detectors

Our approach is to leverage Microcapillary Plates filled with Organic Glass Scintillators (MP-OGS).

The Concept:

Use glass plates with microscopic channels (down to 5 μm) as a structural matrix.

Fill the channels with a high-performance Organic Glass Scintillator (OGS) material.

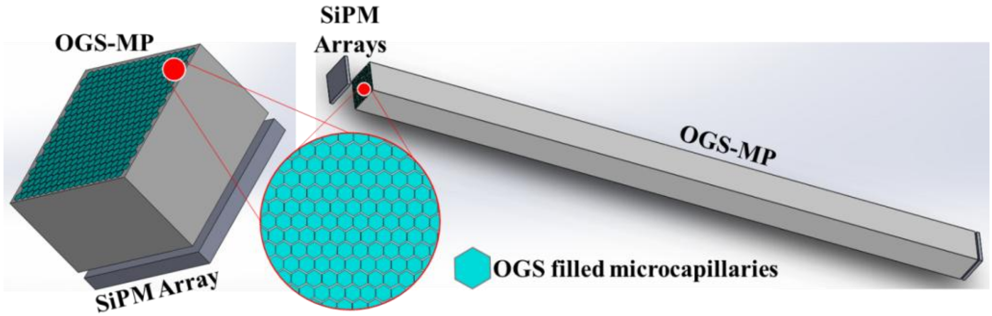
The glass walls confine the scintillation light, providing intrinsic high spatial resolution.

Target performance:

High Light Yield: 18,000 photons/MeV

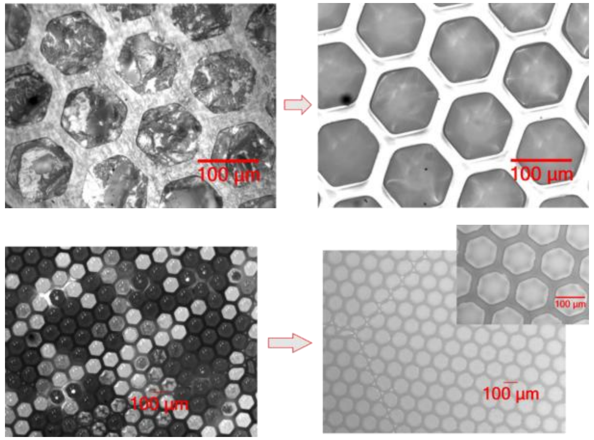
Ultrafast Decay: 1.7 ns

Excellent Particle Discrimination (PSD)

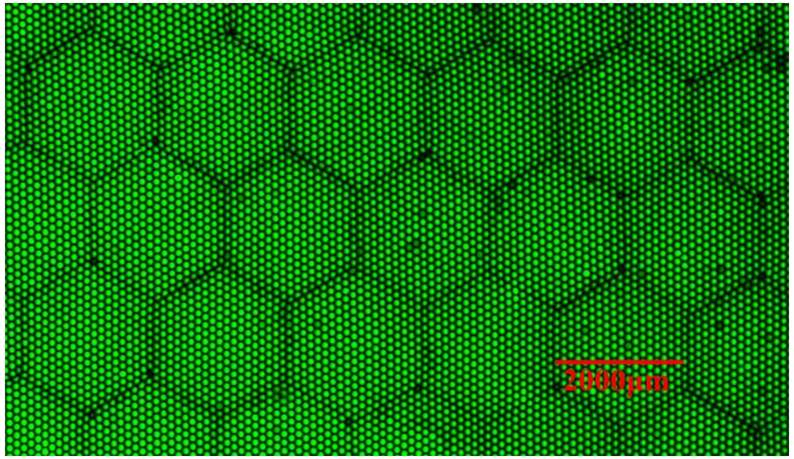


Phase I

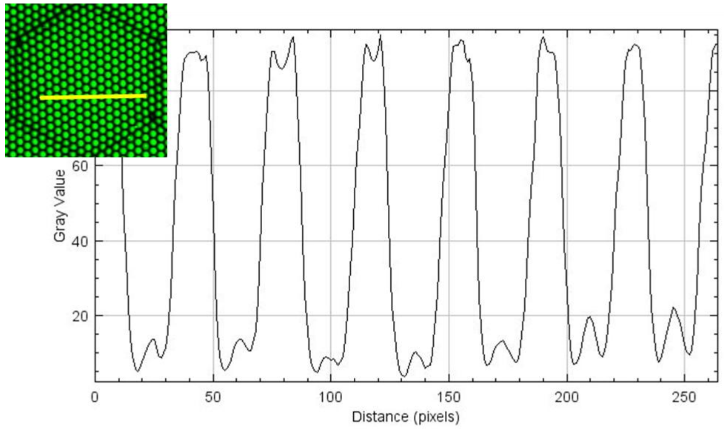
The MP-OGS concept was successfully validated in Phase I.



Process Optimization



High Granularity Fluorescence Characterization



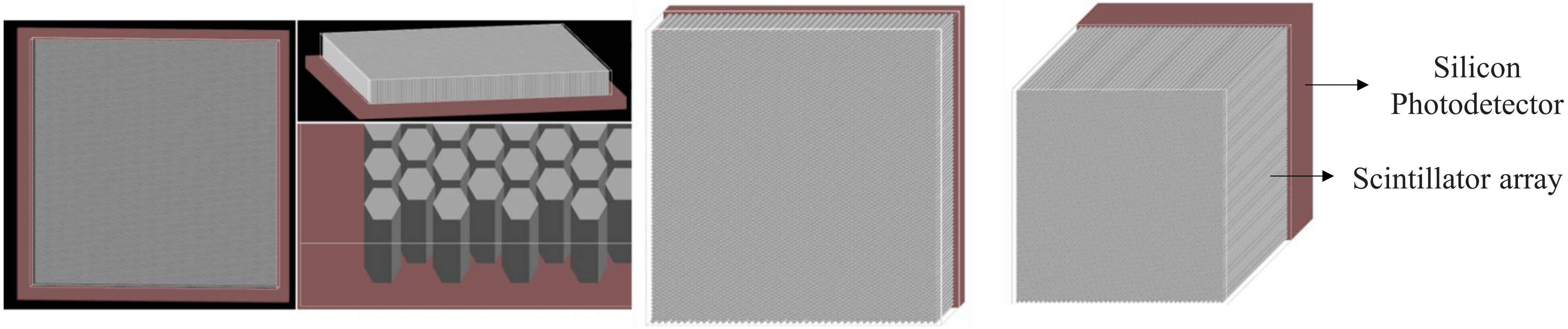
Good uniformity

- **Feasibility Demonstrated:** Fabricated uniform, crack-free detectors with 100µm and 20µm pores.
- **Excellent Light Confinement:** Lab tests with lasers and beta particles confirmed high spatial resolution.
- **Fast Timing & PSD:** Measured fast decay times (~2.5 ns) and a high PSD Figure of Merit (FoM) of 2.8, demonstrating key performance metrics.

Phase II Achievements: GEANT4 Validation

Design Validation Through GEANT4 Simulations

The expected performance of the proposed detector is fully supported by extensive GEANT4 simulations.



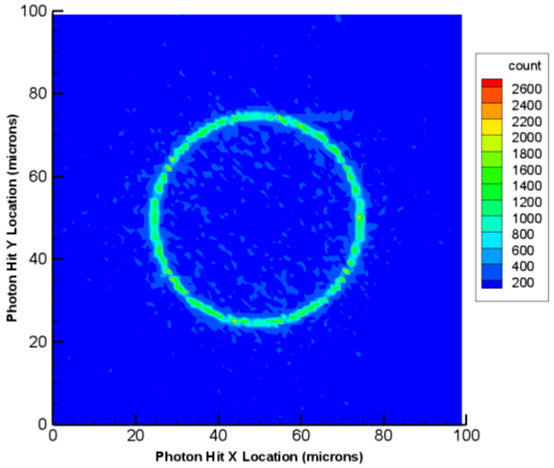
GEANT4 model geometry of the MP architecture with examples of different detector thicknesses and the detailed view of the hexagonal OGS columns arranged in a lower refractive index matrix.

Phase II Achievements: GEANT4 Validation

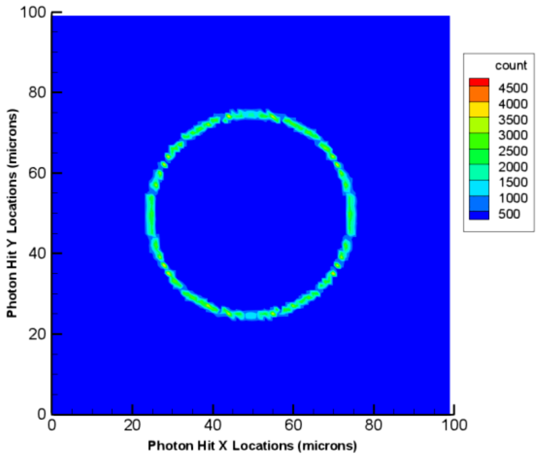
Validation Through GEANT4 Simulations

The expected performance of the proposed detector is fully supported by extensive GEANT4 simulations.

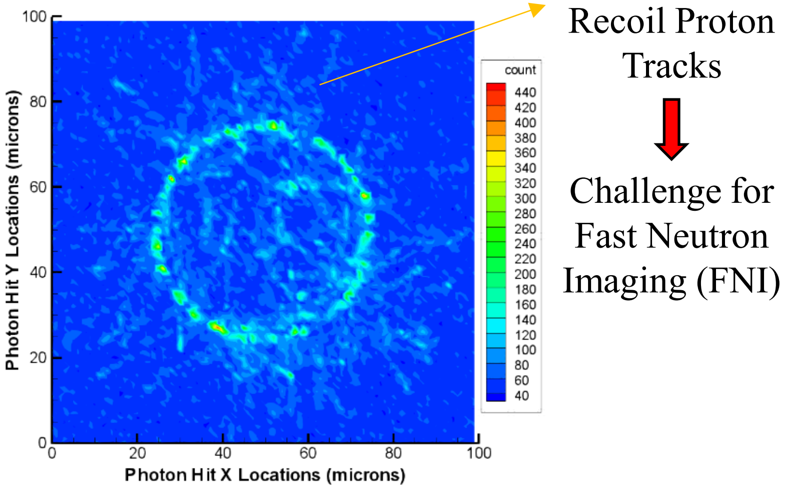
800 MeV Protons



12 GeV Electrons



2.5 MeV fast neutrons



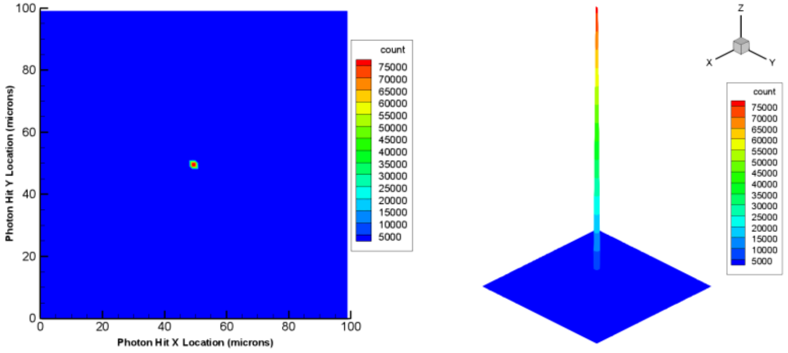
Imager hitmap from 10000 simulations of particles fired in a circular pattern, demonstrating high spatial resolutions

Phase II Achievements: GEANT4 Validation

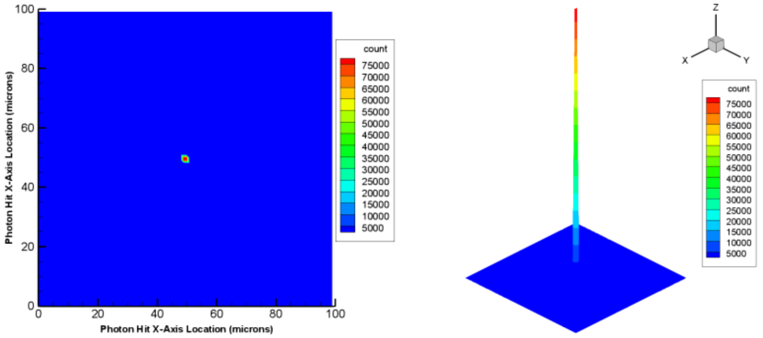
Validation Through GEANT4 Simulations

The expected performance of the proposed detector is fully supported by extensive GEANT4 simulations.

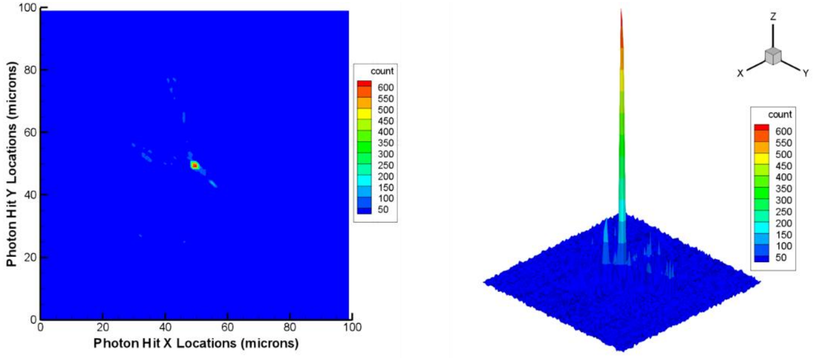
800 MeV Protons



12 GeV Electrons



2.5 MeV fast neutrons

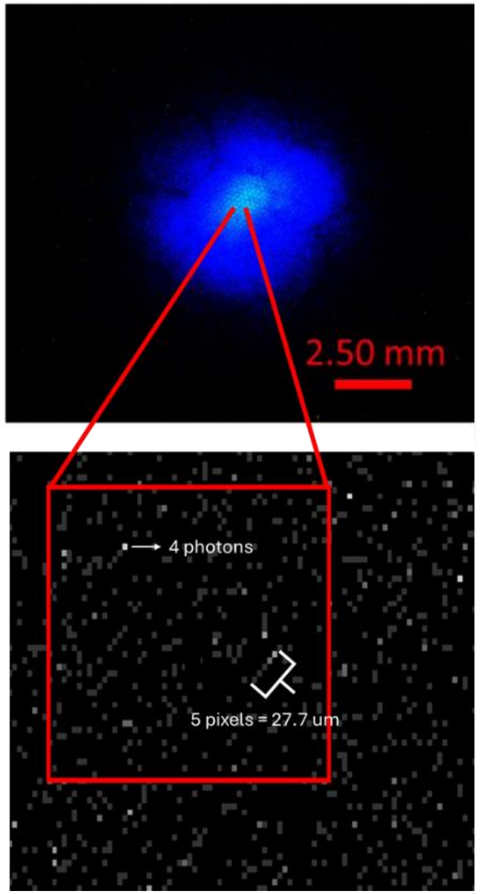


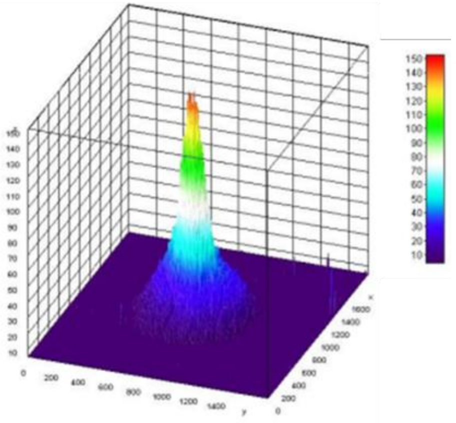
Imager hitmap from 10000 simulations of vertical passage of particles, demonstrating high spatial resolutions

Phase II Achievements: Charged Particle Tracking

Beta Particle Tracking

High spatial resolution beta particle tracking was demonstrated with a low activity Sr-90 source.





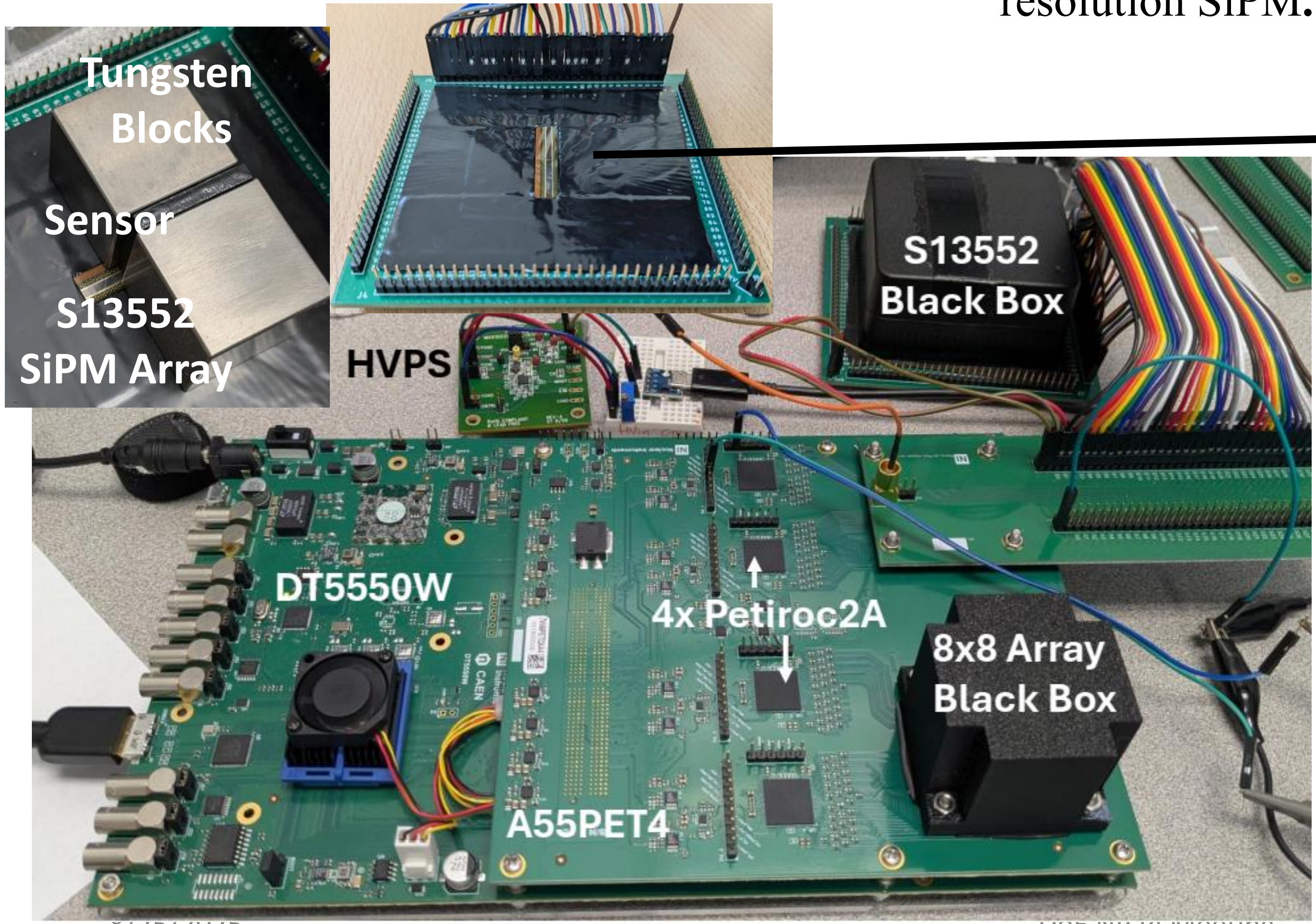
macroscopic scintillation event, while the top-right shows a 3D surface plot of its light intensity

Direct visualization of a single beta particle tracks using a single-photon-resolving camera

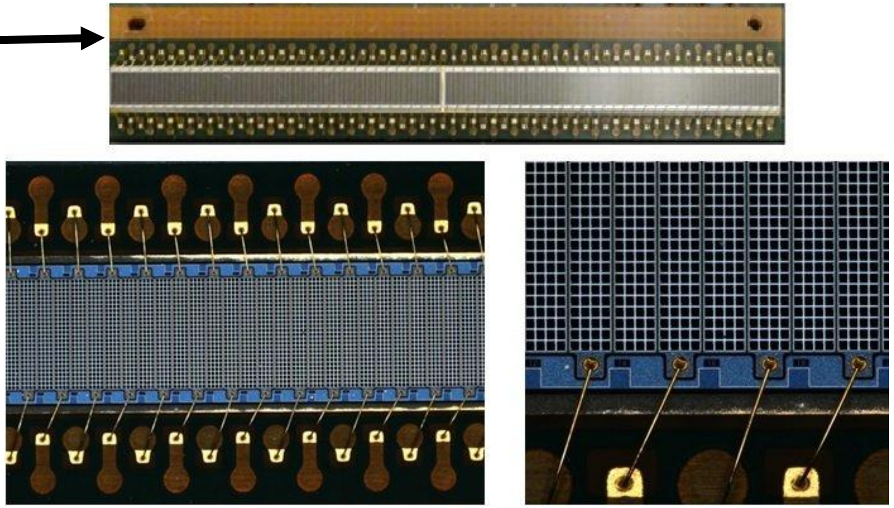
Phase II Achievements: Charged Particle Monitoring

Beta Particle Monitoring using High Spatial Resolution SiPMs

High spatial resolution beta particle monitoring was demonstrated with a low activity Sr-90 source and a high spatial resolution SiPM.



Hamamatsu S13552 SiPM Array



Test setup for readout of the 128-channel Hamamatsu S13552 using four 32-channel Petrioc2A readout chips

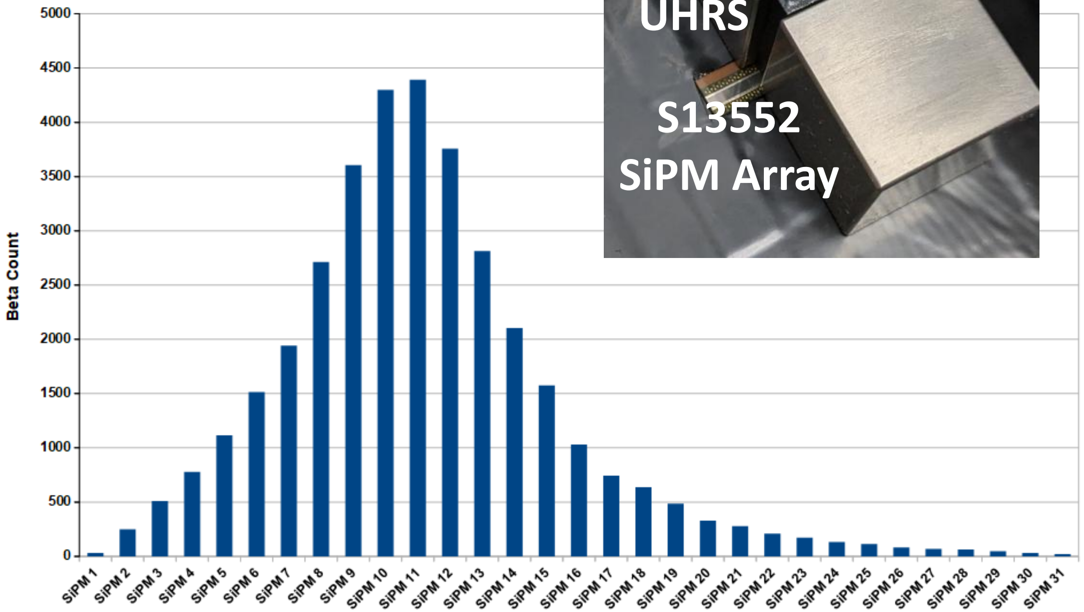
Phase II Achievements: Charged Particle Monitoring

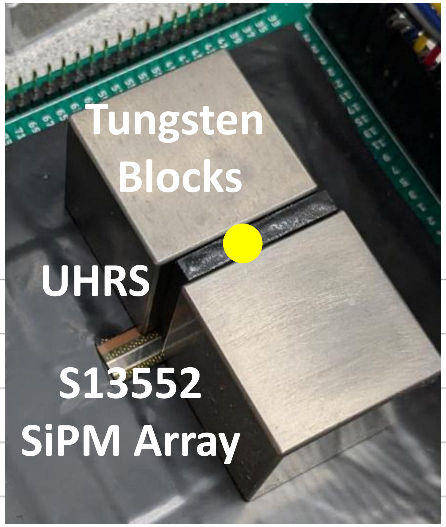
Beta Particle Monitoring using High Spatial Resolution SiPMs

High spatial resolution beta particle monitoring was demonstrated with a low activity Sr-90 source and a high spatial resolution SiPM.

Spatially resolved spectroscopic detection of a collimated beta source using the SiPM array readout system.
The plot shows how the beta count is distributed across 32 SiPM channels.

Peak Center (SiPM Channel #)	*11*
Peak Center (Position in mm)	2.53
Fitted Gaussian Width (σ, in channels)	3.05 ± 0.09
Fitted Gaussian Width (σ, in μm)	702 ± 21 μm
FWHM (channels)	7.18 ± 0.21
FWHM (in μm)	1650 ± 50
Total Integrated Counts	30,500



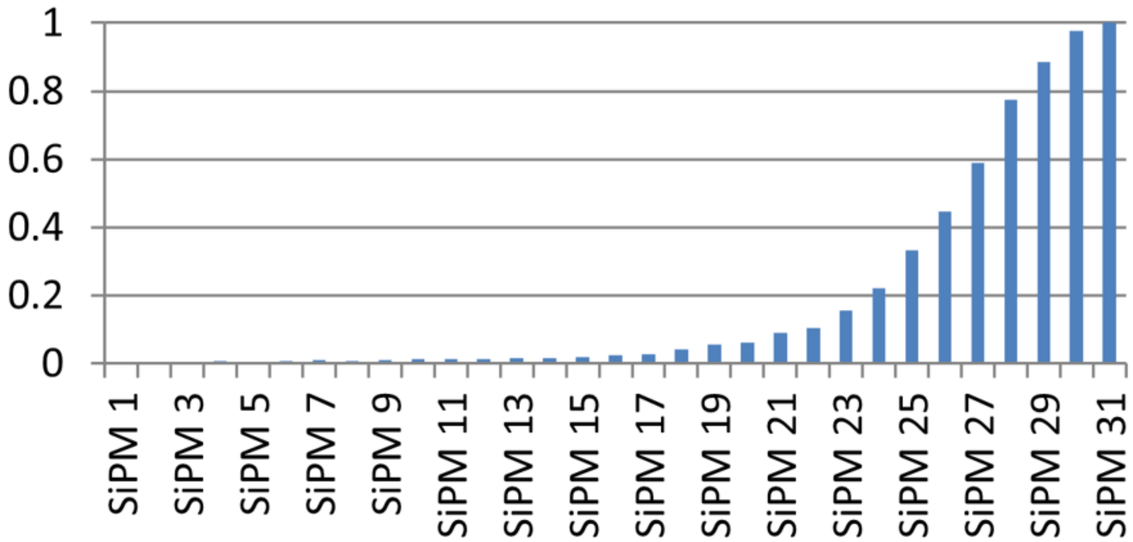


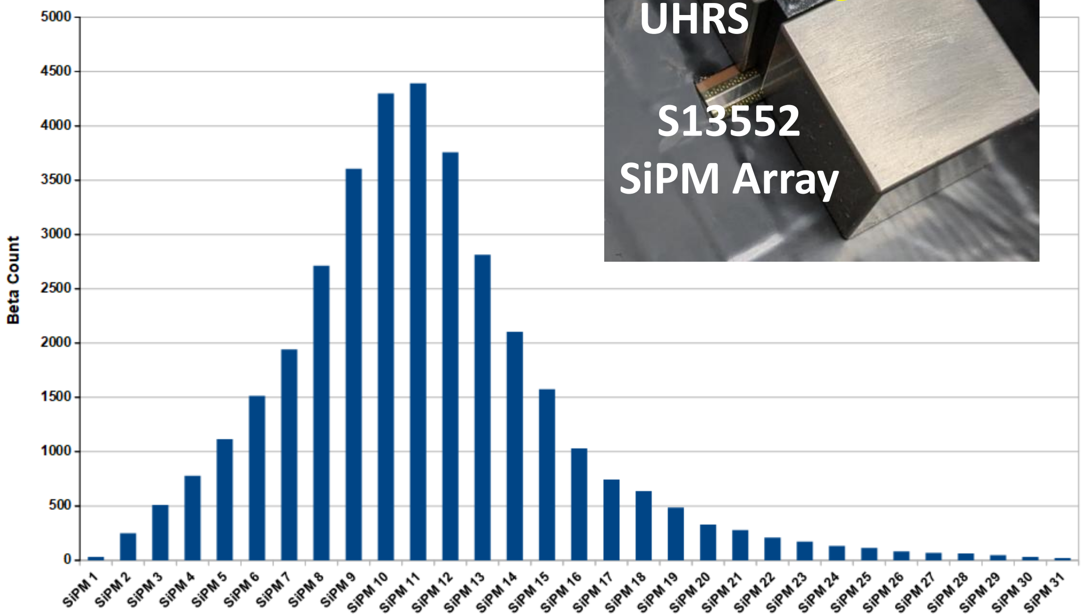
Phase II Achievements: Charged Particle Monitoring

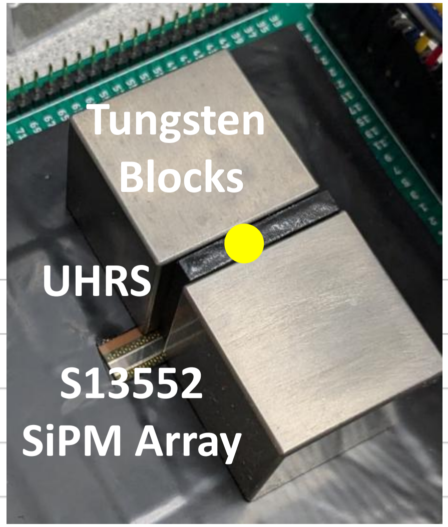
Beta Particle Monitoring using High Spatial Resolution SiPMs

High spatial resolution beta particle monitoring was demonstrated with a low activity Sr-90 source and a high spatial resolution SiPM.

The plots show how the beta count distribution changes across 32 SiPM channels when the source is moved.







Phase II Achievements: X-ray Imaging

High Spatial Resolution with X-rays

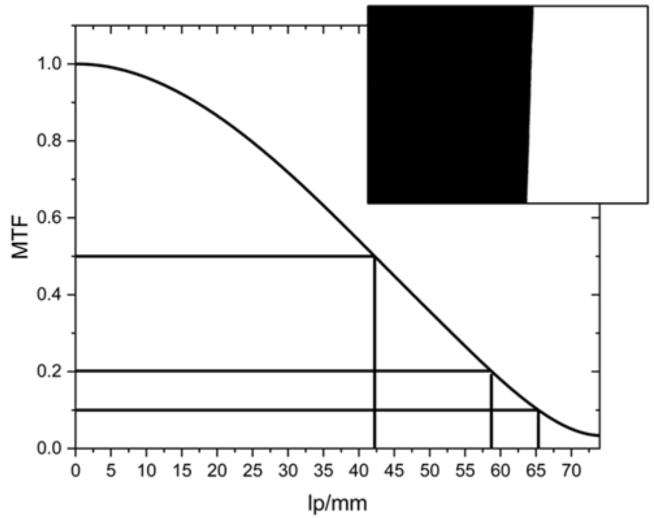
Our MP-based imaging system has achieved a spatial resolution that fundamentally **inverts the traditional design paradigm of high-resolution imaging.**

X-ray Imaging Result with a 25mm thick detector:

- With further decreasing the pore diameter (<5microns), we can achieve an MTF of 0.5 (50% contrast) at a spatial frequency of approximately 43 lp/mm, again with a 16 mm-thick sensor

Significance:

- The resolution is no longer limited by the scintillator. The scintillator can now outperform the photodetector.
- Conventional scintillator structures are not appropriate at these frequencies.



Phase II Achievements: Fast Neutron Imaging

Simultaneous High Spatial Resolution and High Efficiency with Fast Neutrons

FNI is one of the most challenging imaging modalities due to:

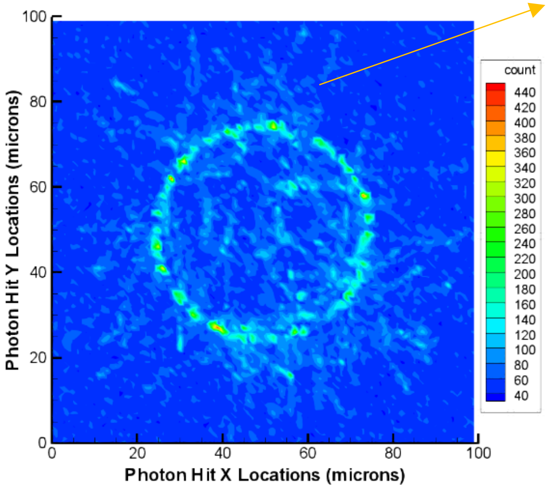
1. Low Interaction Probability: Neutrons pass through most materials easily.

2. Indirect Detection: Detection relies on neutron-proton scattering, which creates a "recoil proton."

3. Inherent Physical Blur: The recoil proton travels up to 100µm (for 2.5MeV), creating a non-point-like light source.

The historical challenge has been an inescapable trade-off: high efficiency (thick detector) meant poor resolution, and vice-versa.

2.5 MeV fast neutrons



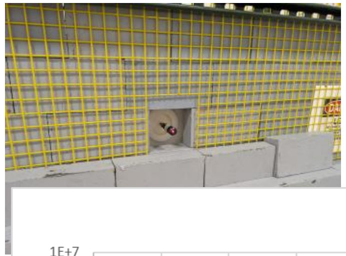
High Energy Recoil Proton Tracks

Challenge for Fast Neutron Imaging (FNI)

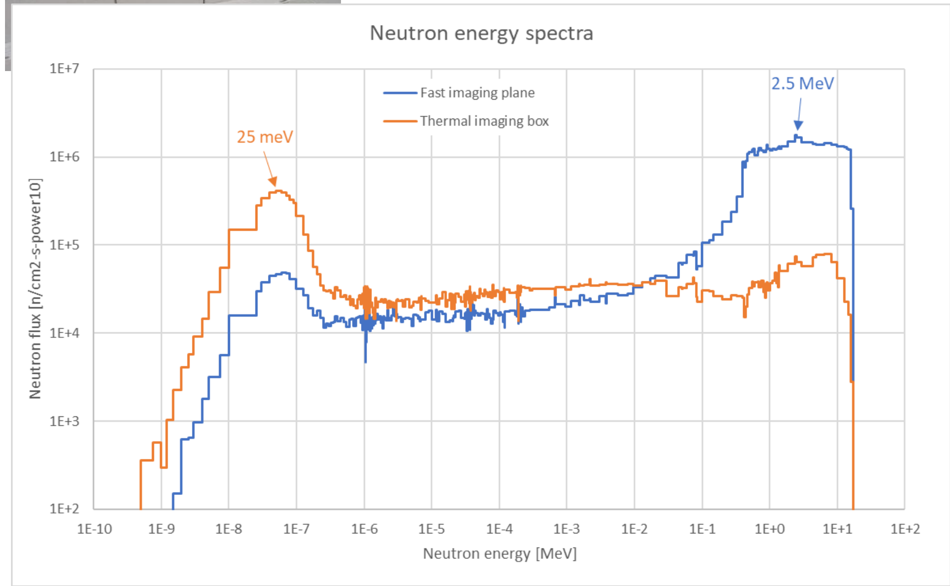
Phase II Achievements: Fast Neutron Imaging

Simultaneous High Spatial Resolution and High Efficiency with Fast Neutrons

FNI Set up at a third-party site



Neutron Source Spectra



CapeSym Detectors in Fast Neutron Beam

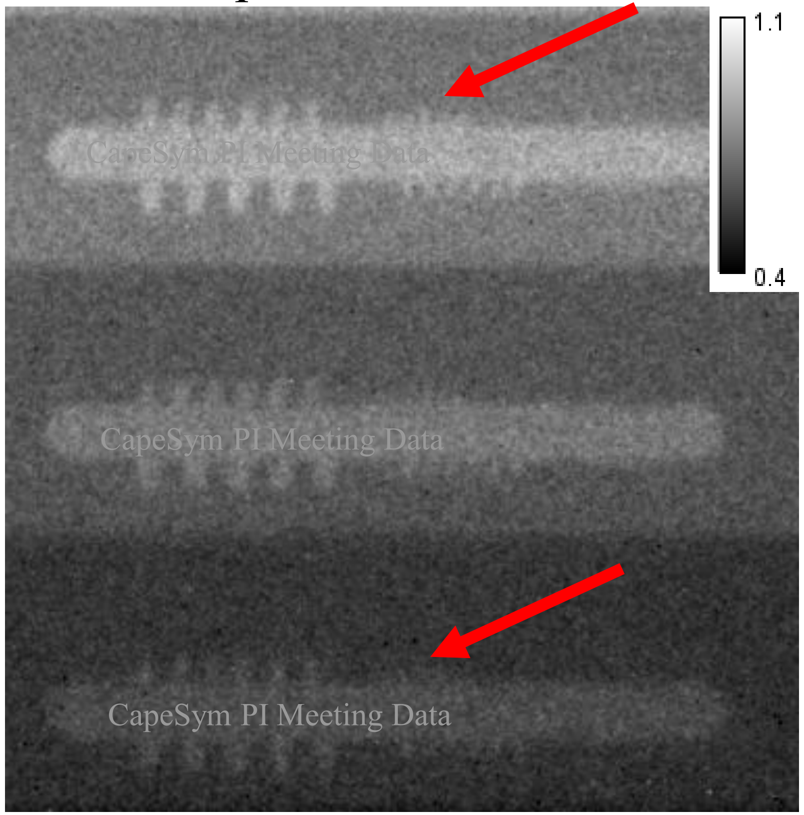
Resolution and Contrast Targets on CapeSym Detectors

Phase II Achievements: Fast Neutron Imaging

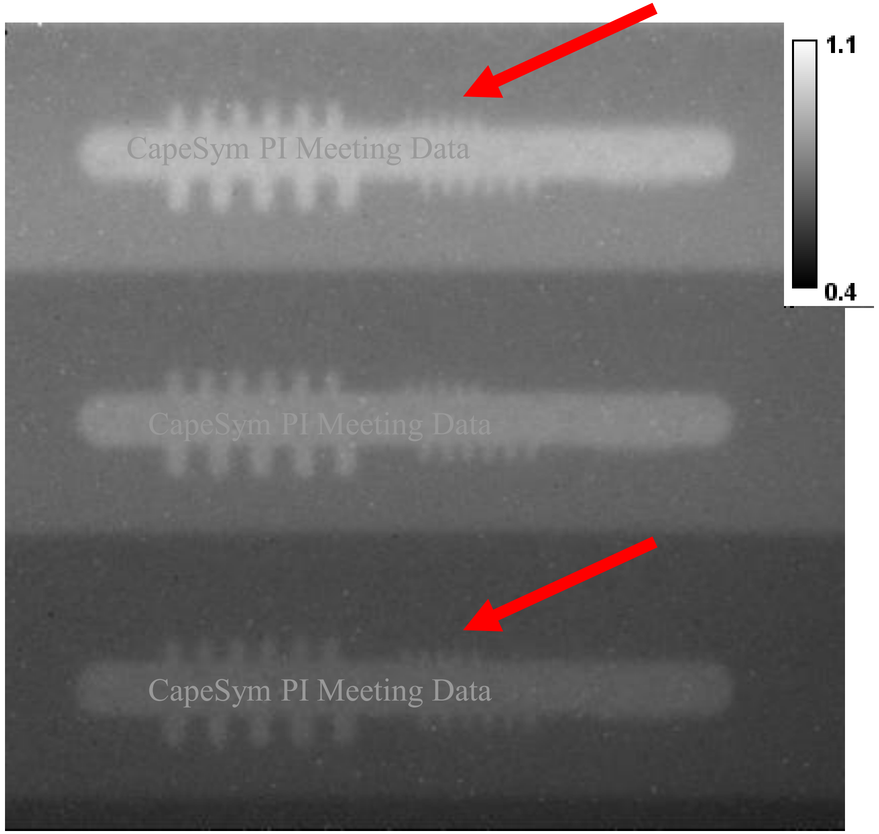
<u>Simultaneous High Spatial Resolution and High Efficiency with Fast Neutrons</u>

FNI Performance measured at a third-party site

Current State of the art for highest spatial resolution



CapeSym Phase II Scintillator

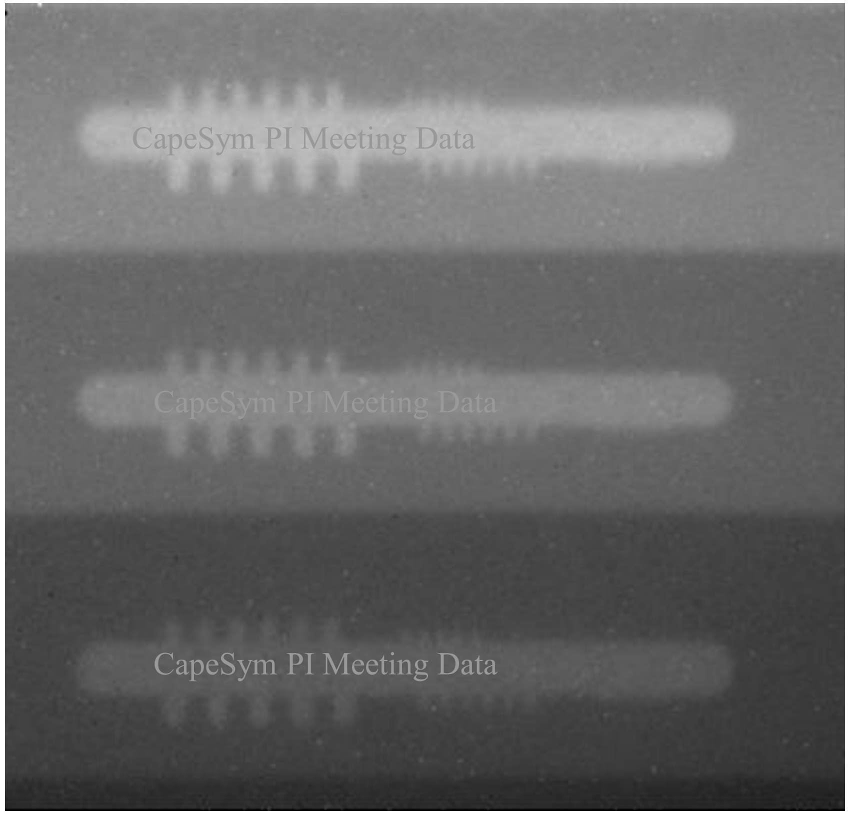


Phase II Achievements: Fast Neutron Imaging

<u>Simultaneous High Spatial Resolution and High Efficiency with Fast Neutrons</u>

Excellent FNI Performance

Phase II Scintillator



Scintillator Name	*Thickness (mm)*	*Light Yield (ADU/pix/min)*	*Spatial Resolution (MTF10% in mm)*
Plastic	0.5	3.7	0.843
Plastic	10	104.4	1.216
High-light yield Plastic	9.5	97.1	0.558
Current State-of-the-art 1	2.5	185.1	0.603
Current State-of-the-art 2	0.06	43.2	0.330
CapeSym Detector 1	25	281.7	0.473
CapeSym Detector 2	25	90.6	0.303
CapeSym Detector 3	25	586.0	0.722
CapeSym Detector 4	25	188.0	Not Measured

More Results in the NP Progress Report

Phase II Achievements: Fast Neutron Imaging

Simultaneous High Spatial Resolution and High Efficiency with Fast Neutrons

A **25mm thick** optimized detector achieved:

• Resolution (MTF10%): 303 μm

The highest resolution ever reported for a thick (>1mm) FNI scintillator based on our experiments and literature study.

• Detection Efficiency: ~44%

~up to 2 orders of magnitude higher than the high-resolution scintillators currently used.

• Light Yield: up to ~13.6x higher than the state-of-the-art under similar imaging conditions.

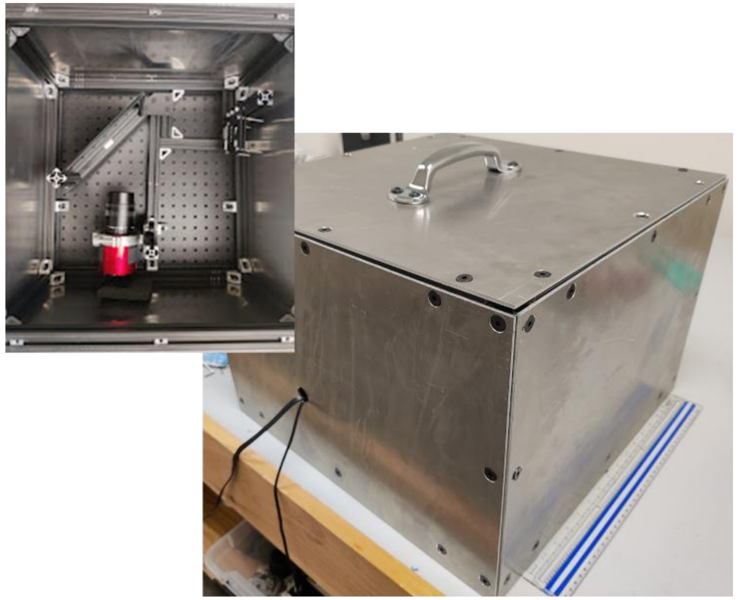
Our resolution is now limited by the fundamental physics of proton recoil, not by optical crosstalk.

Phase II Achievements: Camera Prototype

Camera Prototypes for Beamline Characterization

Compact Camera Prototype

Smaller Field of view, Higher Magnification



Large Area Camera Prototype

Larger Field of view, 1:1 Magnification

Phase II Project Status: Future Work

Future work in Phase II

The remaining work focuses on final validation and preparing for real-world deployment.

Task	Objective
Beamline Characterization	Execute beamline and tracking tests. Finalize schedule and setup with Fermilab (protons)—beam down currently. Plan subsequent tests with FRIB (ions).
Radiation Hardness	Quantify the performance of OGS sensors under high doses of gamma and neutron radiation.
OGS Optimization	Improve large area uniformity and explore higher Z-loading (with Sandia) to further boost light yield and stopping power.
Next-Gen SiPMs	Continue collaboration with Hamamatsu and FBK to integrate cutting-edge SiPMs with TSV technology as they become available.

Phase II Project Status: Acknowledgements

Acknowledgements

This work was made possible by the support of the DOE Office of Science **Nuclear Physics (NP) program** under award DE-SC0023561.

We extend our sincere thanks to our collaborators:

- **Sandia National Laboratories (Dr. Patick Feng and Dr. Annabelle Benin)**
- **Fermilab (Dr. Jim Freeman)**
- **University of Tennessee (Dr. Dr. Robert Grzywacz)**

Thank You for Your Attention!

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