High Performance Scintillator & Beam Monitoring System (SBM)*

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* The SBM is a patented invention by **Integrated Sensors, LLC**

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System Overview / Description

Motivation

I. Provide **advanced, precise ion profiling beam analysis** with ***results continuously displayed in real-time***

II: Serve as a model for a related radiotherapy beam monitoring technology

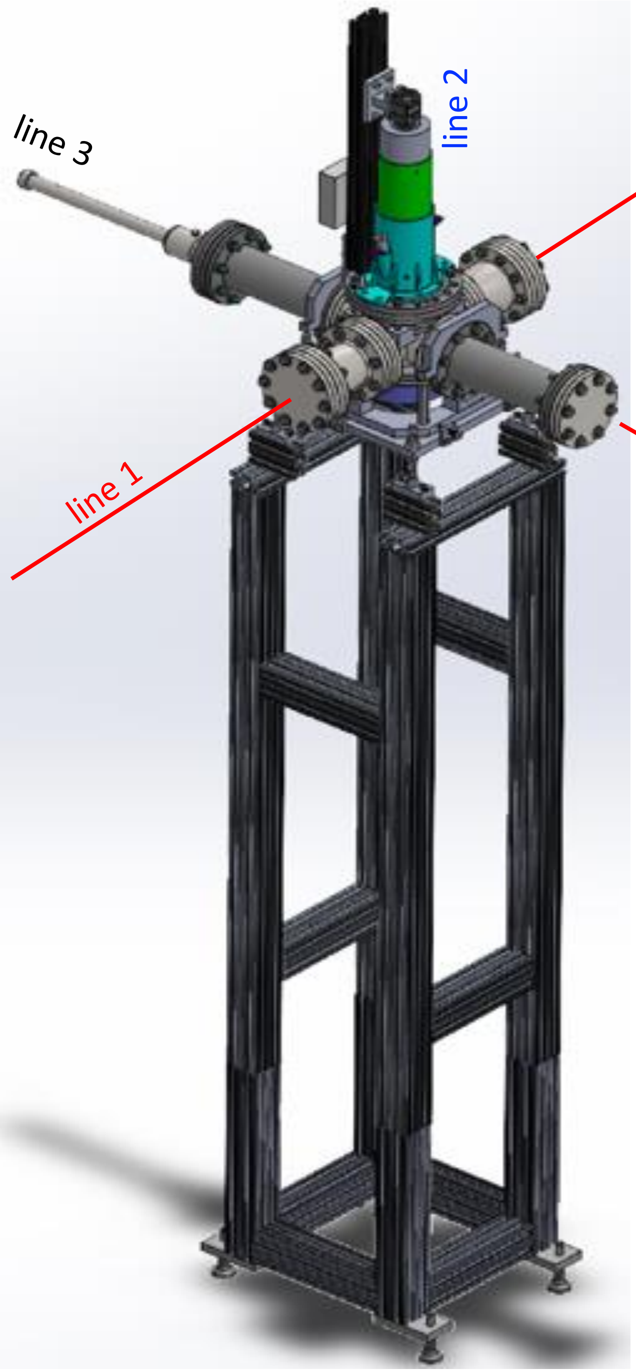
Features

- **Novel-use thin scintillators**: very high sensitivity, clean imaging, very low mass
- Scintillators are insertable/retractable without breaking vacuum using a stepper-motor translation arm
- Imaging detector: low noise, high resolution, high dynamic range camera
- Lens system: *fast* large aperture optics for max light collection

Specs

- **~ 10 μm position resolution**
- Fast detection algorithms quickly find weak beams
- Updating false-color display in beam coordinate system
- Analysis (location, RMS widths, amplitudes) *updating continuously* in real-time display at **~ 1 Hz**
- Wide dynamic range in beam current/pps over ~ ***11 orders-of-magnitude***, starting with ***single ions*** (at low energy)
- Higher energy beams are transmissive
- Linear to ***at least 5*** orders-of-magnitude in beam current

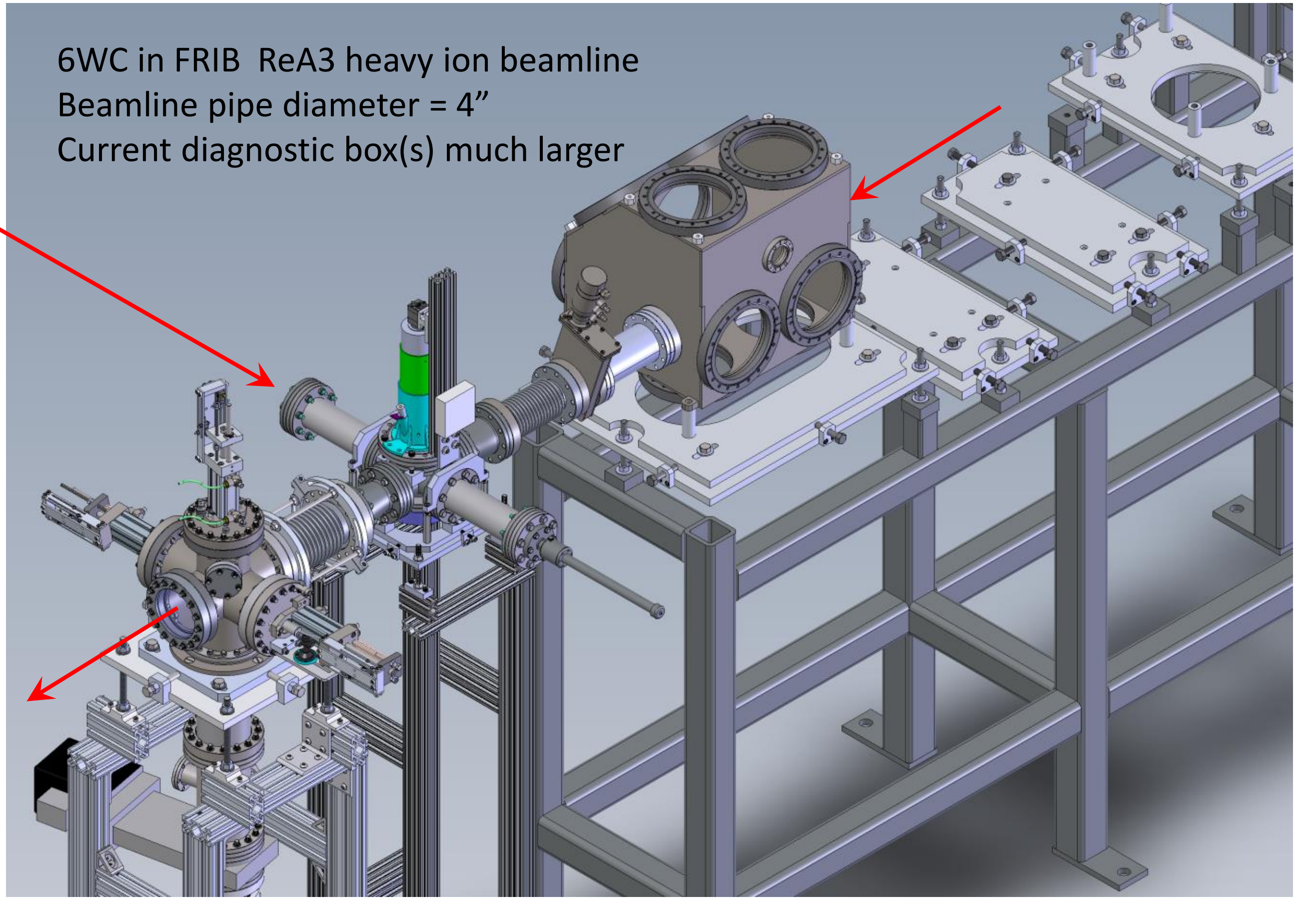
SBM Configured as "Six-Way-Cross" (6WC with 3 orthogonal lines)



Line 1: beam path (vacuum) fore/aft

Line 2: optical: light paths to camera top + alignment targets bottom

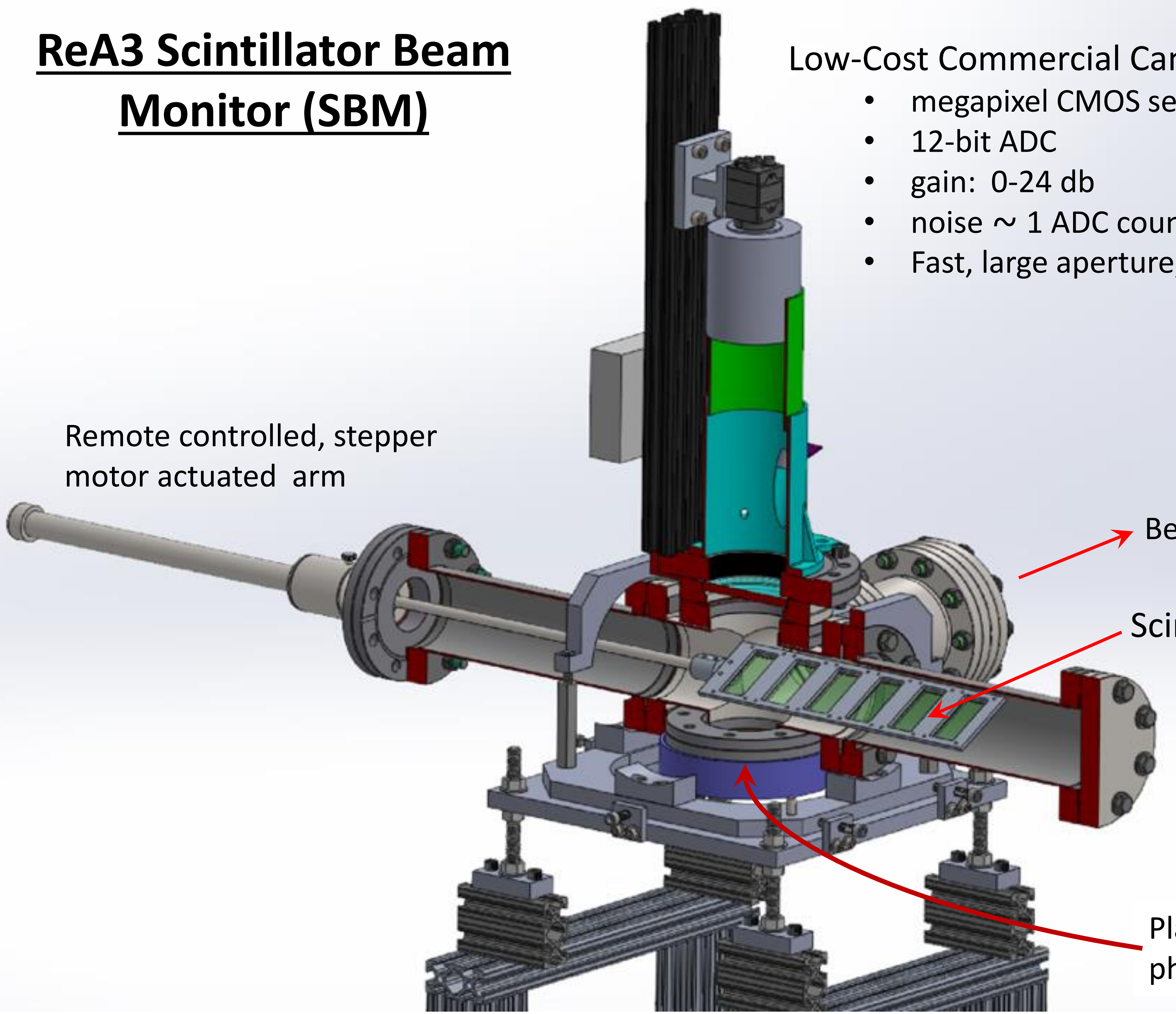
Line 3: scintillator ladder travel



ReA3 Scintillator Beam Monitor (SBM)

Low-Cost Commercial Camera:

- megapixel CMOS sensor
- 12-bit ADC
- gain: 0-24 db
- noise ~ 1 ADC count (2.4 pe)
- Fast, large aperture, low f-stop lens



Remote controlled, stepper motor actuated arm

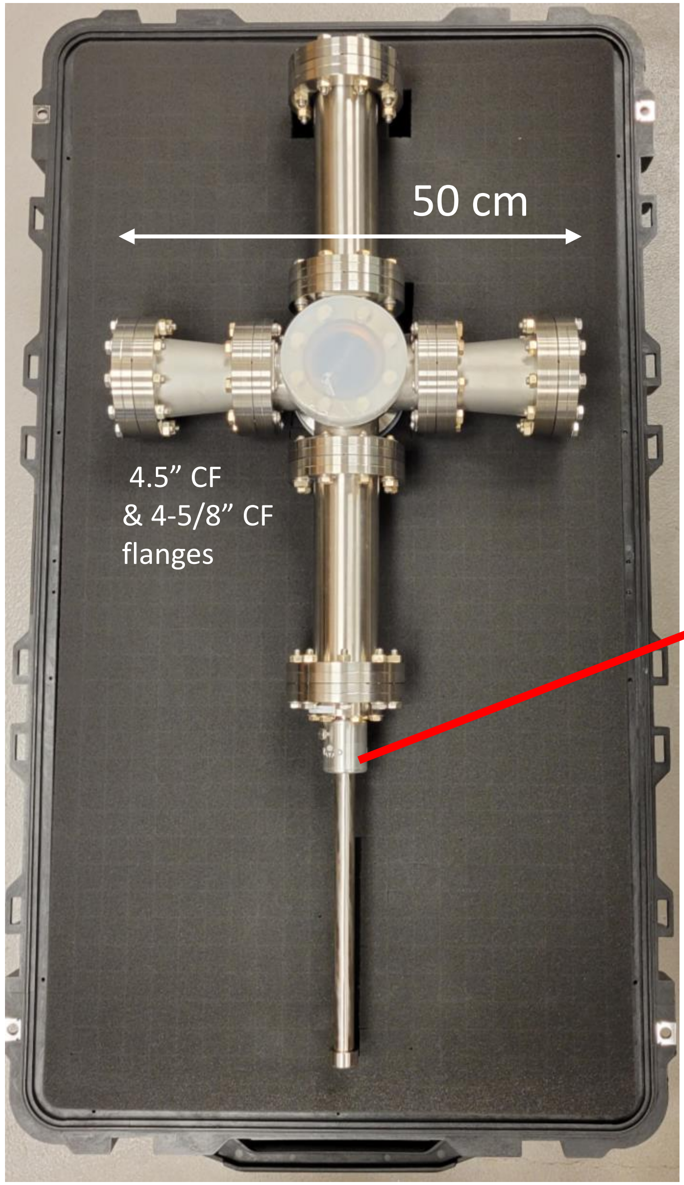
Beam exit

Scintillator ladder

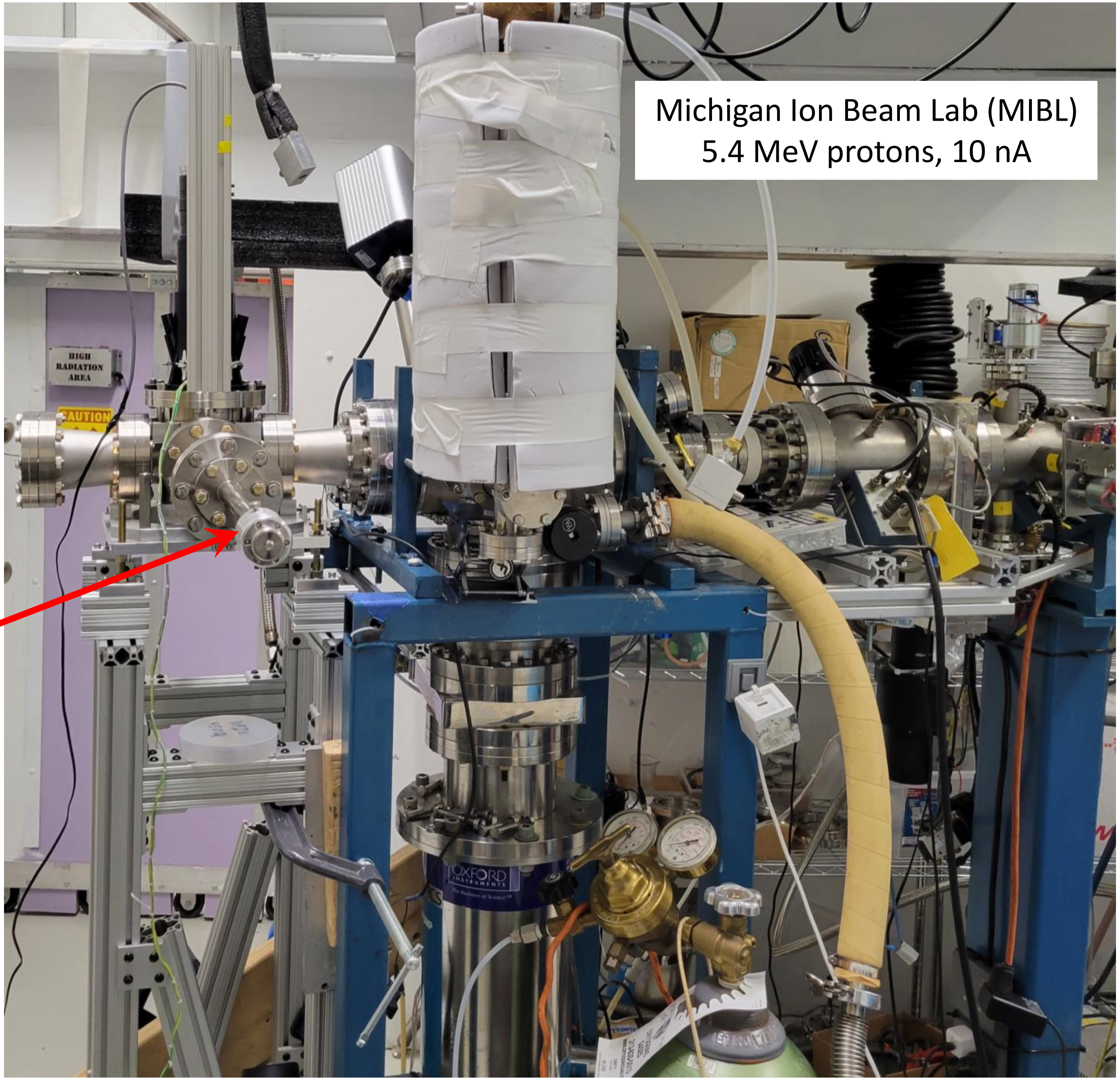
- Holds six 2x4 cm^2 scintillators
- moved in & out of beam by translation arm

Placeholder for alignment target or 2^{nd} photodetector: e.g., fast PMT for TOF

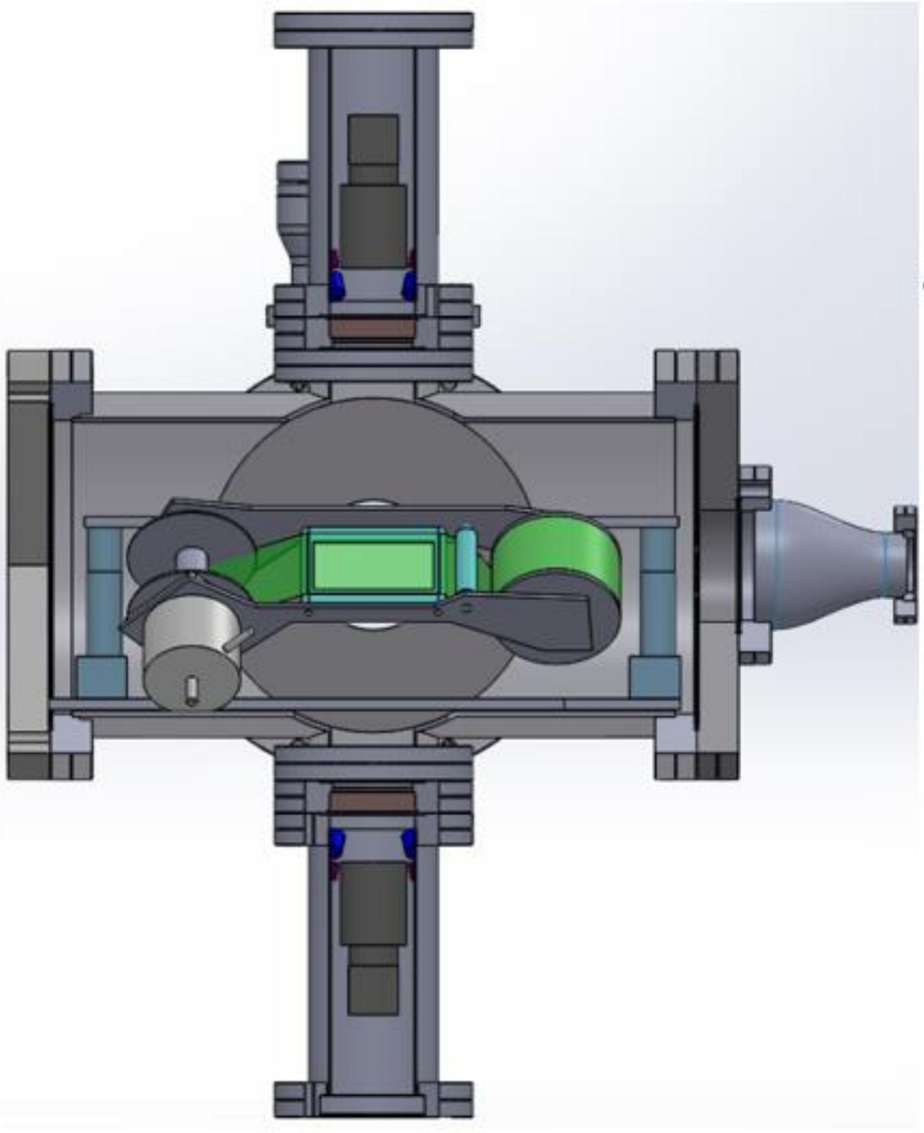
System Fits in Large Suitcase

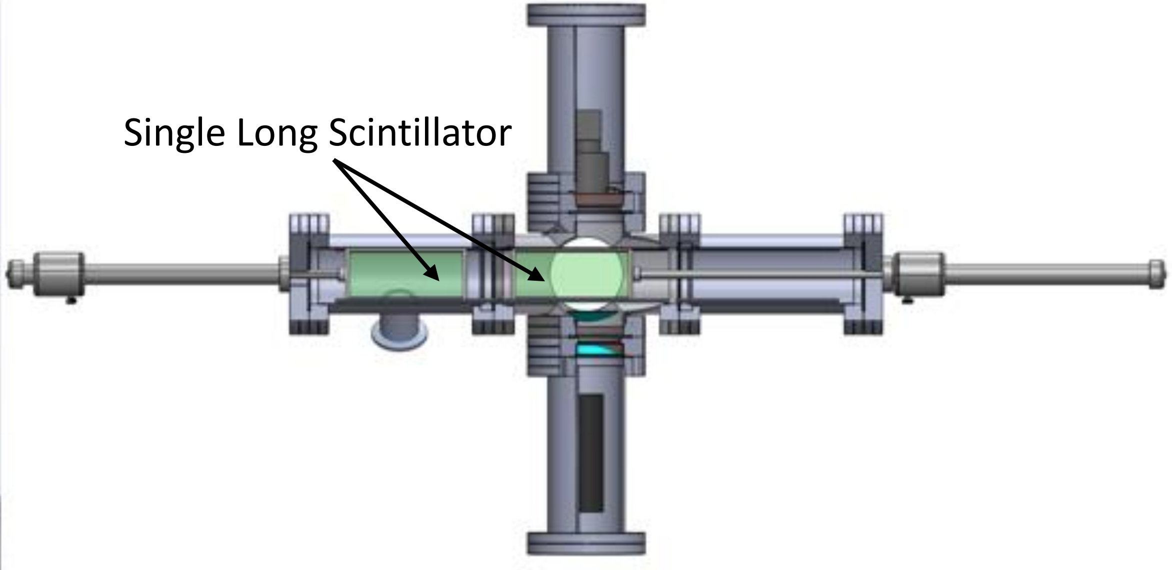


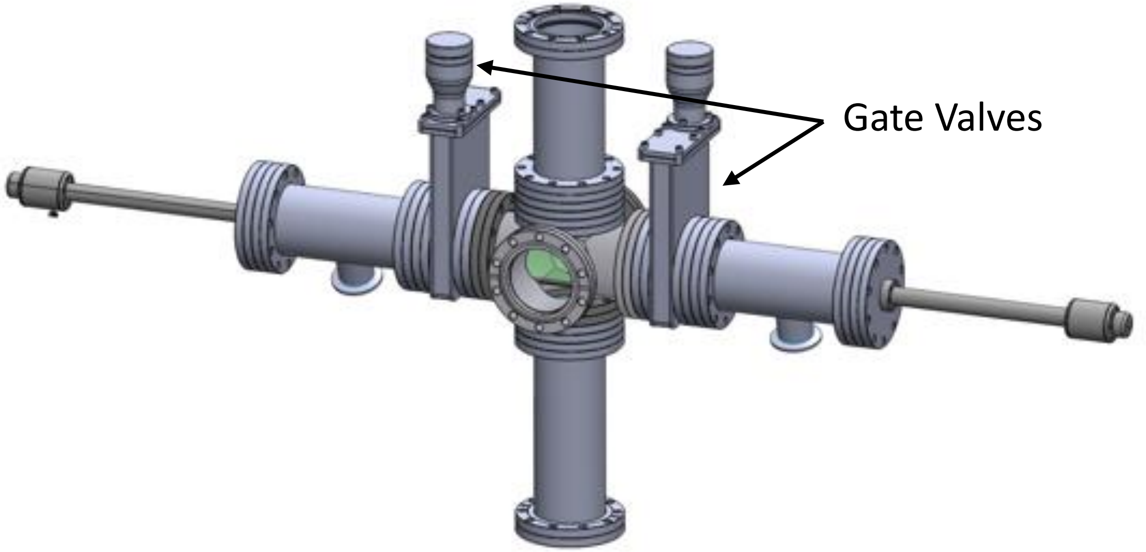
106 cm



***Many* 6WC Beam Monitor Configurations** – **3 of many other SBM designs shown below**







Scintillators - Two types of ***thin, non-hygroscopic & radiation damage resistant, novel materials***[1]

Type 1: Polymer Material (PM): ***a semicrystalline, organic plastic polymer:***

- superior physical properties: tough, thin to ultra-thin, can cover large areas
- high light emittance
- observed large amplitude signals compared to polyvinyltoluene (PVT) & polystyrene (PS) based plastic scintillators
- semicrystalline ➔ hazy appearance, **no internal reflections**, more light escapes the surfaces.
- available in variety of thickness. We tested 1 μm to 200 μm.
- thin films attractive for transmissive beam applications (e.g., continuous beam monitoring for NP & radiotherapy)
- fast decay (< 30 ns)

Type 2: Hybrid Material (HM): ***a polycrystalline inorganic-polymer hybrid:***

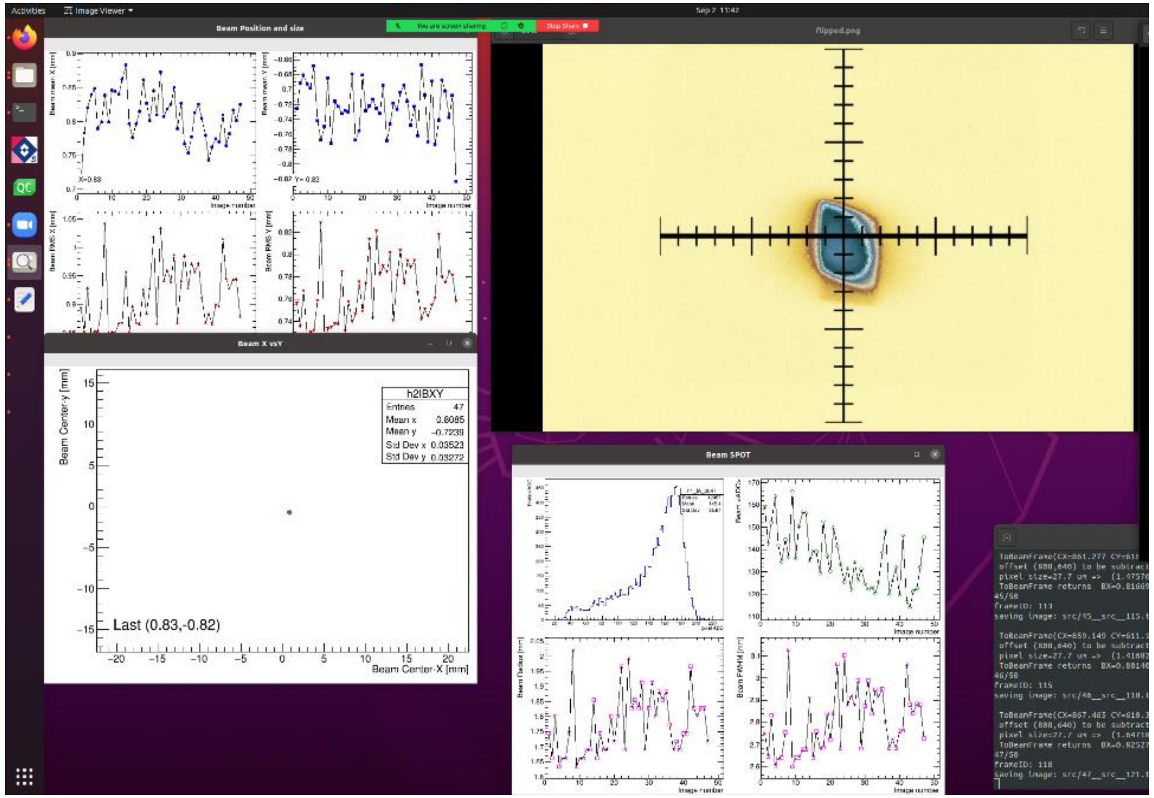
- HM scintillator layer is a matrix deposited on a support substrate
- available in large area sizes & thinner than single crystal CsI(Tl), e.g., < 0.5 mm
- very high light emittance – generates ***order-of-magnitude*** larger amplitude signals than CsI(Tl)
- **no internal reflection**
- decay time is ~ 3 μs

[1]*Integrated Sensors, LLC has **4 issued patents** on these two new scintillator materials for beam monitoring applications.*

DAQ System Functionality (beta version)

1. Loads text file of configuration parameters:
   - pixel field range and spatial offsets
   - frame exposure time
   - acquisition mode (triggered or asynchronous)
   - pixel binning
   - ADC digitization and gain factor
2. Image processing in real-time:
   - background subtraction
   - faulty pixel removal
   - affine (perspective) matrix transformations and rotations for display in beam coordinate system
3. Image analysis in real-time:
   - beam finding
   - beam profiling (centroids, RMS widths)
   - peak amplitude
4. Display
   - color-coded beam image
   - real-time analysis results in updating graphics
   - updates at 1 Hz
5. Data transfer to storage media for offline analysis

Screen capture of display



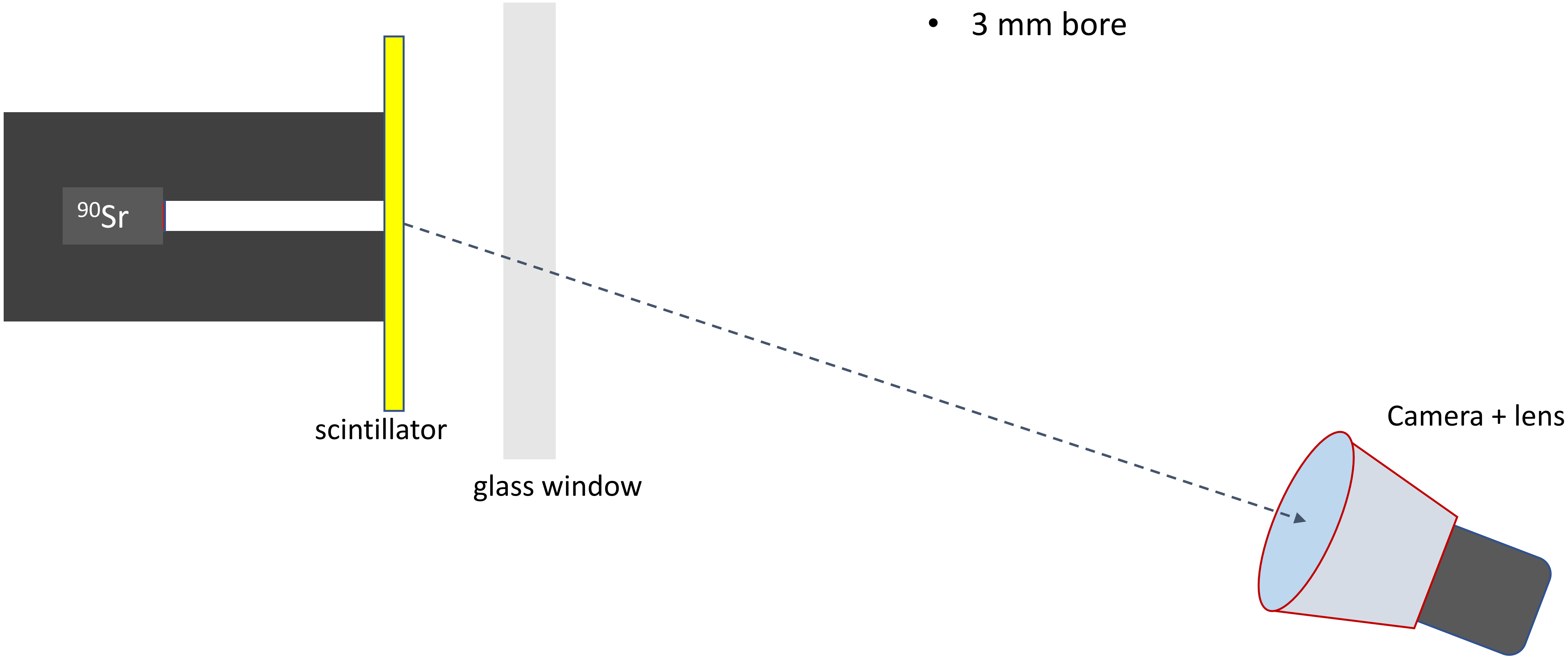
Shown above:
- beam false color
- 2D position history
- beam FWHM and radius
- 1D updating X,Y centroids
- peak ADC and RMS

Test Results

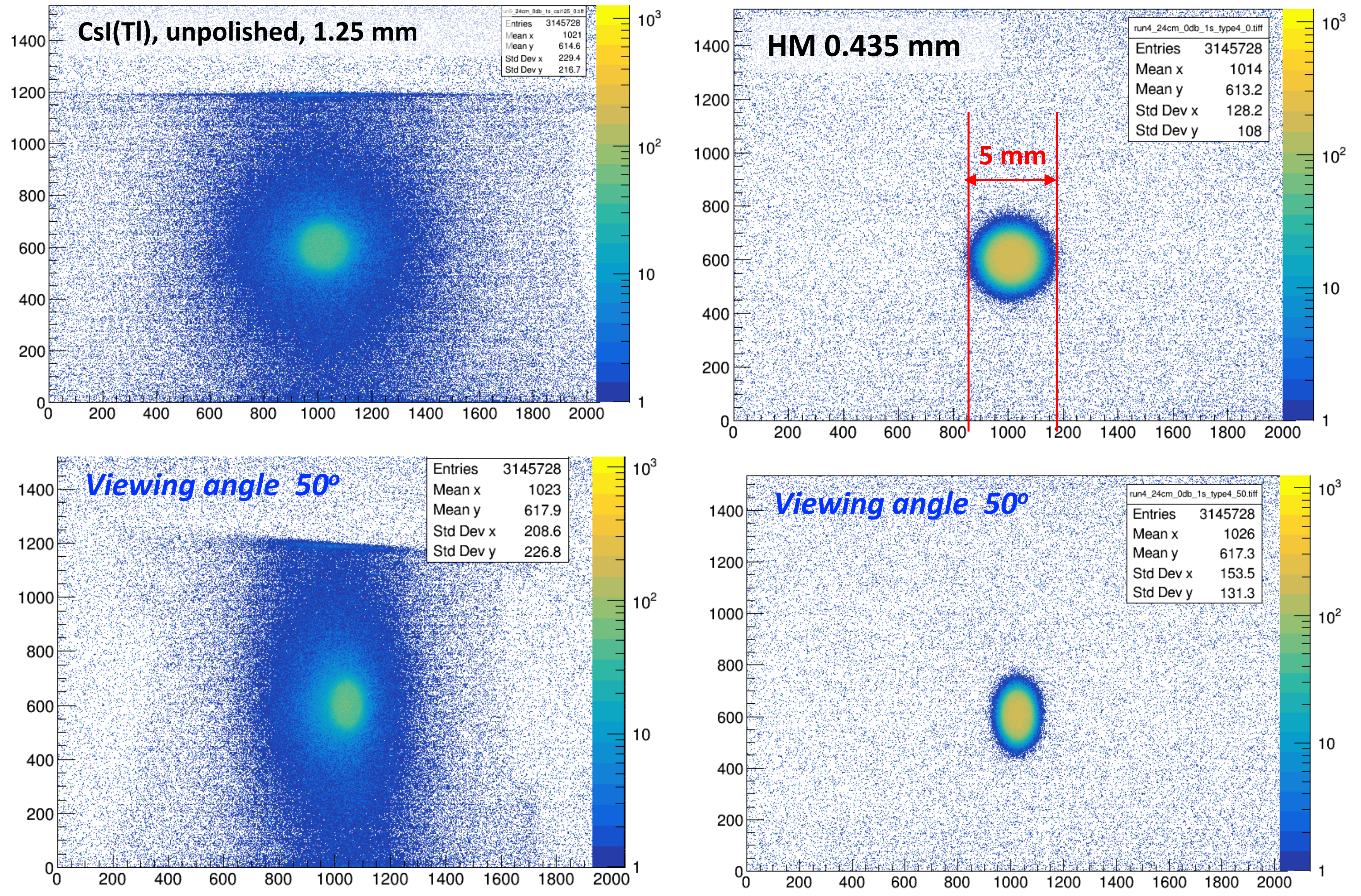
Location	*Source*	*Energy [MeV/n]*
UM Physics Lab	β (^{90}Sr)	~1
Michigan Ion Beam Laboratory (MIBL)	p	1 - 6
Facility for Rare Isotope Beams (FRIB)	$^{86}Kr^{+26}$	2.75
Notre Dame Radiation Laboratory (NDRL)	e^-	8

UM Lab Test of Scintillators Part 1: Compare HM to CsI(Tl) single crystal

- 1 s exposure
- unity gain
- ^{90}Sr source (2.4 mCi)
- 3 mm bore



UM Lab Test of Scintillators Part 1: Compare HM to CsI(Tl) single crystal

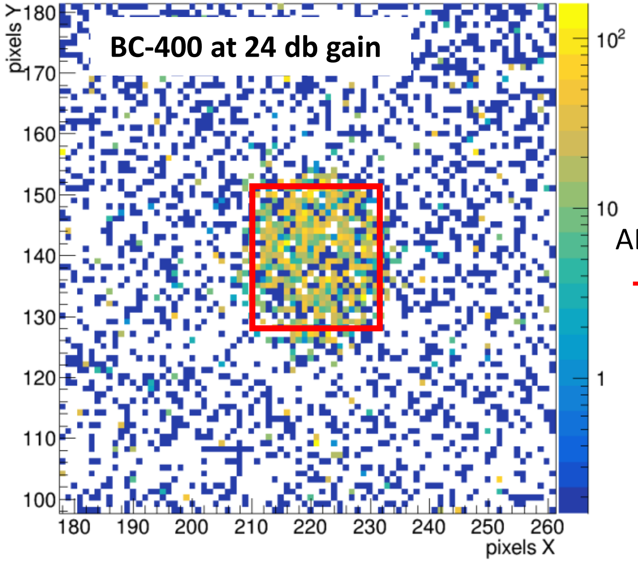


Result 1: HM offers a ***clean beam image, free of reflections, blooming, distortion & sidewall emissions*** (two types of HM: differentiated by dopants).

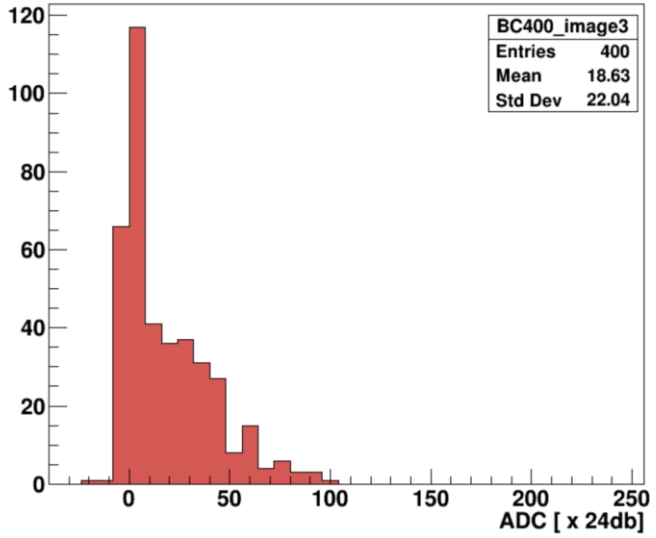
Result 2: HM/CsI(Tl) relative signal strength normalized to material thickness: (ADC/mm) at 0° is **<u>12.2 for HM-1</u>**.

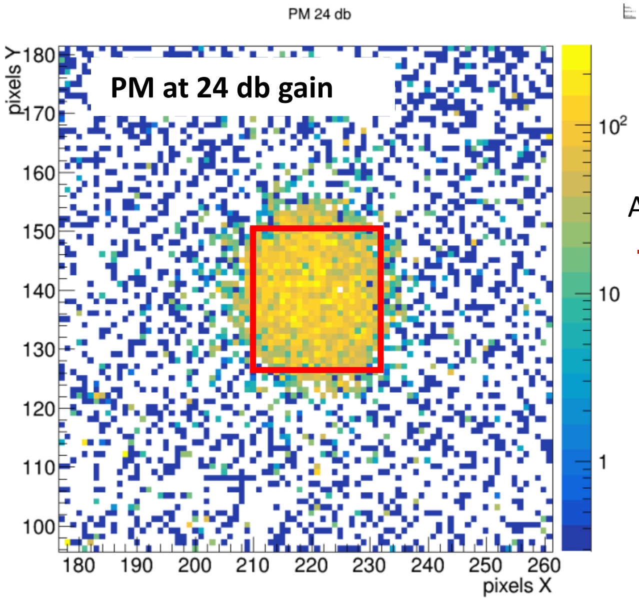
UM Lab Test of Scintillators Part 2:   PM vs BC-400

~200 µm thick + ^{90}Sr ***beta*** source (~3 mm FWHM) + 1 s exposures + 24 dB pixel gain

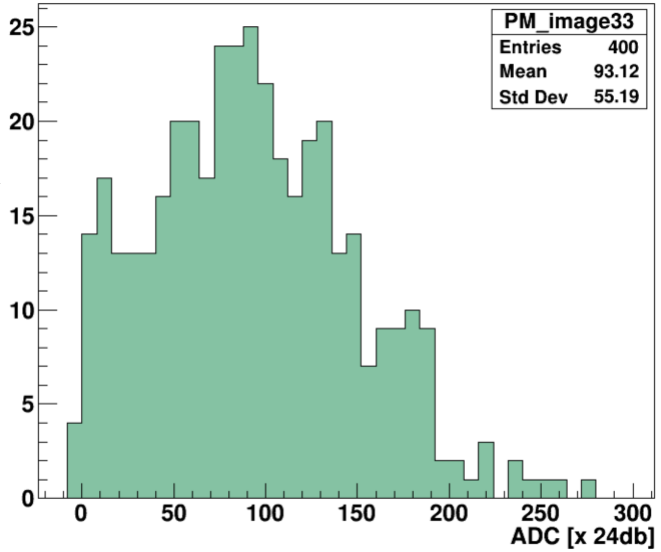


ADC of box





ADC of box



Result at 24 db gain

BC-400 (PVT based):
image more sparse hit distribution,
weak signal.

PM:
Clean image with well delineated source,
robust signal above background.

Mean Ratio of PM/BC-400 is ~5X
(i.e., 93:19)

Facility for Rare Isotope Beams (E. Lansing, MI) (*ReAccelerated 3 MeV Beamline*)

Project objective: provide FRIB with advanced & fast beam monitoring.
Estimated beam time cost ~$20K/hr ➔ *high premium for fast tuning*

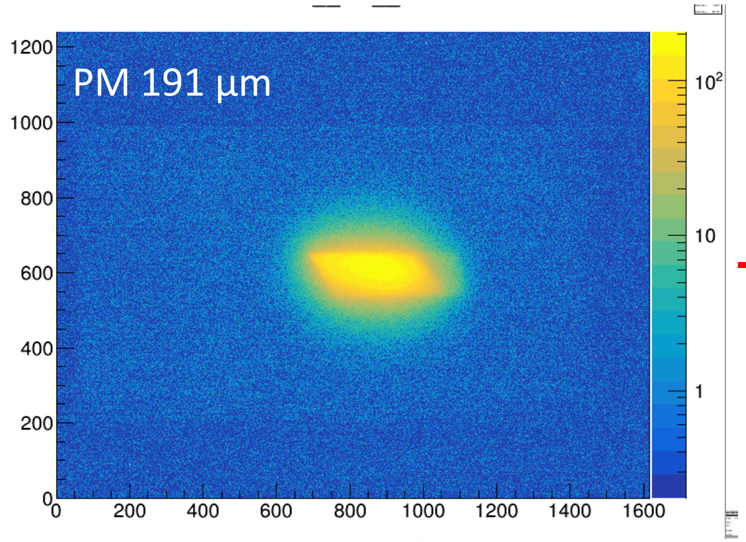
- Ion: $^{86}Kr^{+26}$ at 2.75 MeV/n
- **Currents 520,000 pps to < 10 pps**
- Beam shaped by collimating plates, quadrupoles

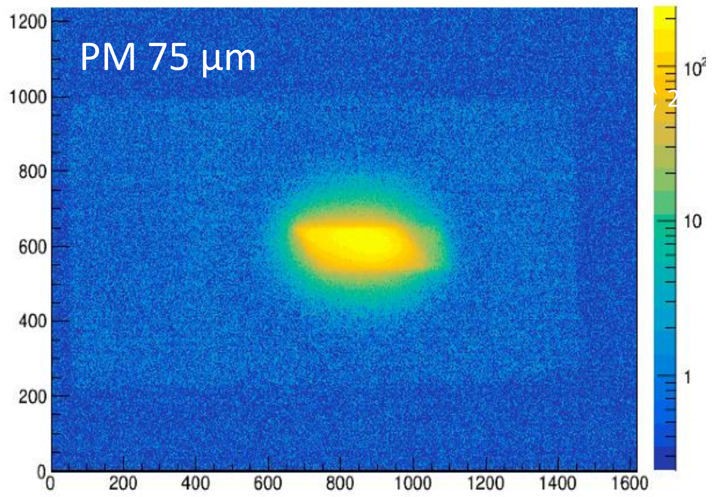
Selected results:

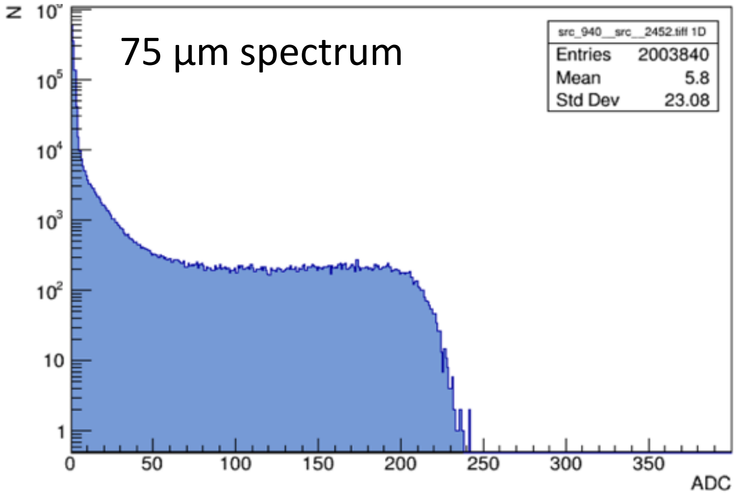
1. PM scintillators
   - Beam profile and signal amplitude vs thickness, current
   - Beam transmission
2. HM type scintillator:
   - Single particle detection
   - Response vs beam current
   - Beam tracking & profiling

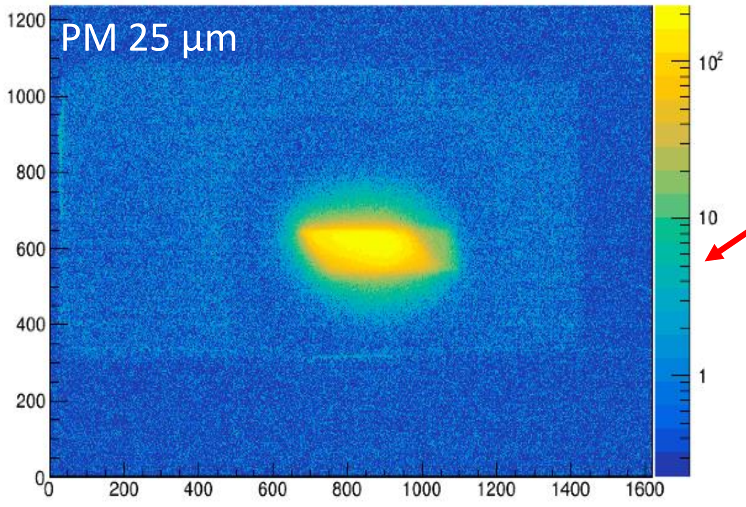
Signal & Beam Imaging in PM: (Beam current = 520,000 pps)

Similar profiles for 191 to 75 μm thickness; particle penetration depth ~38 μm

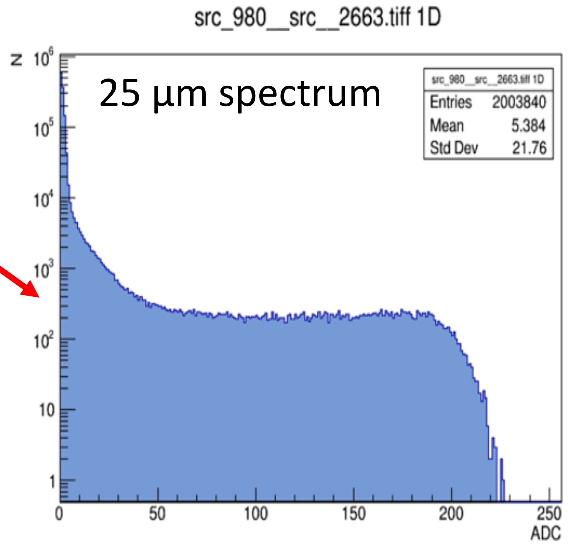




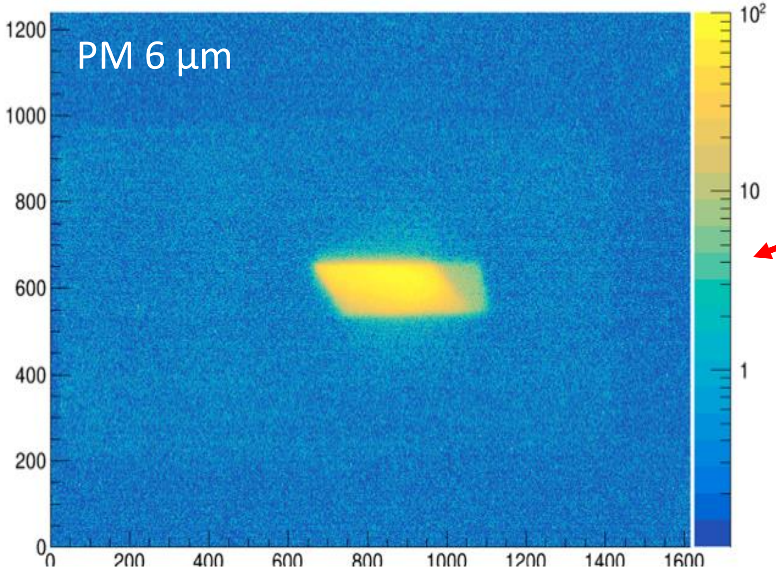




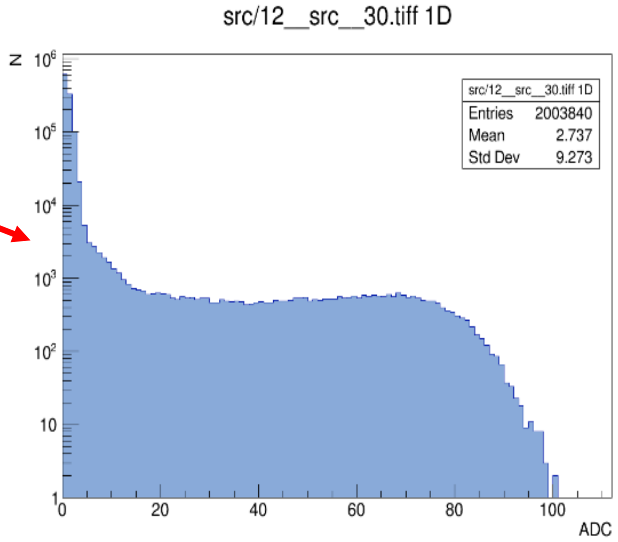
25 μm profile has modest reduction in ADC signal – both max & mean



<u>Signal & Beam Imaging in PM</u>: *"Beam Transmission"* (Beam current = 520,000 pps)

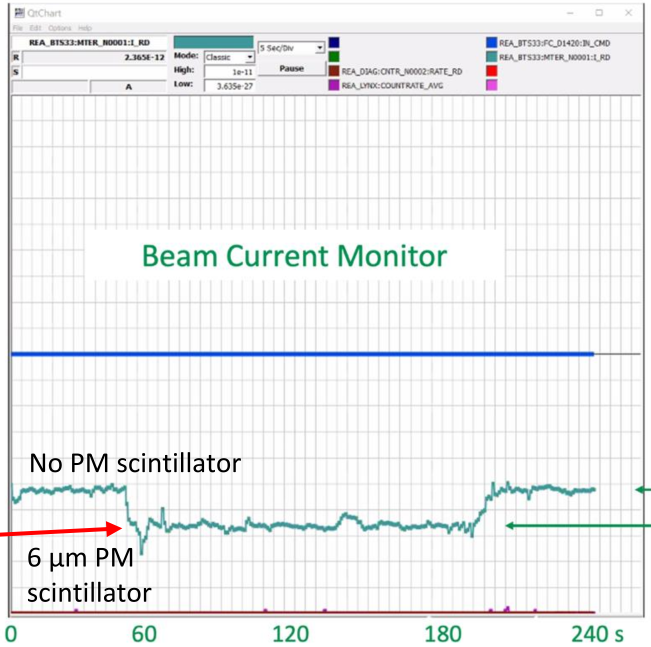


6 µm PM still shows clean beam profile with ~43% of the 75 µm PM ADC_{max} signal



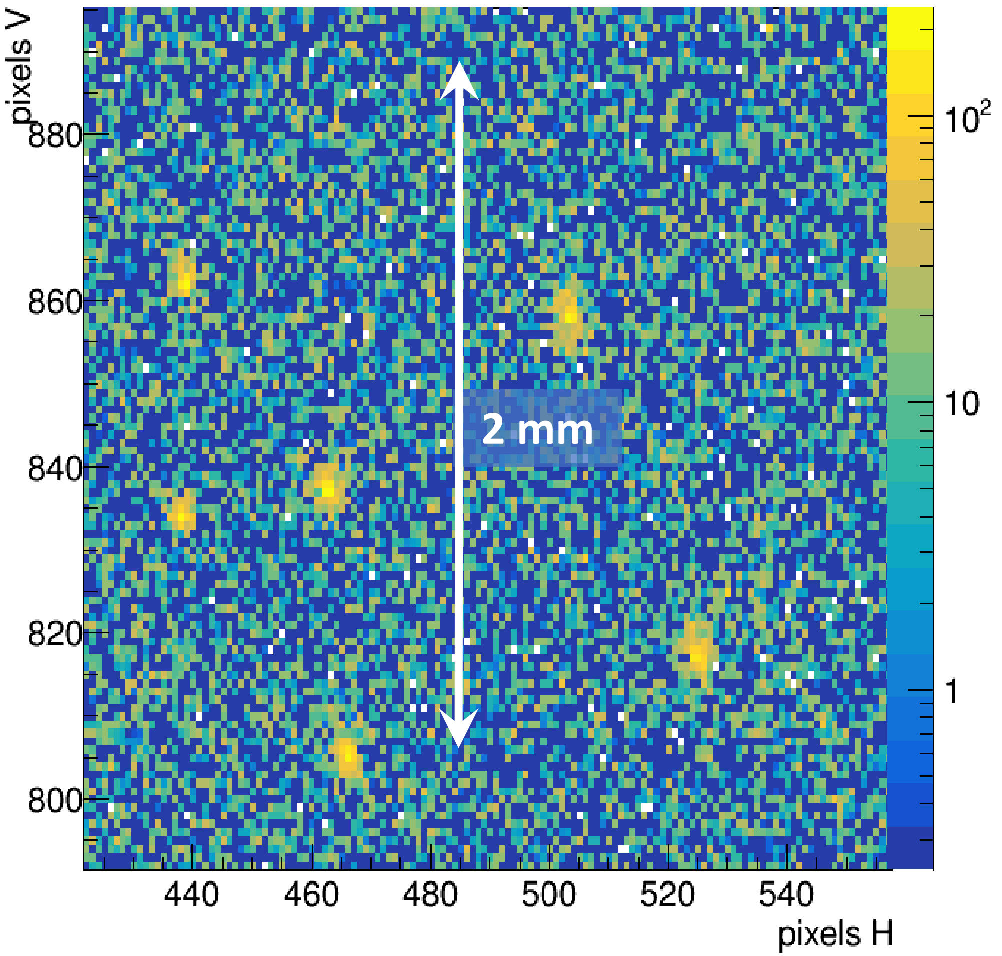
Beam current measured with Faraday Cup behind scintillator:

<u>**6 µm PM --> 75% transmission**</u>
of 2.75 MeV/n $^{86}Kr^{+26}$ beam

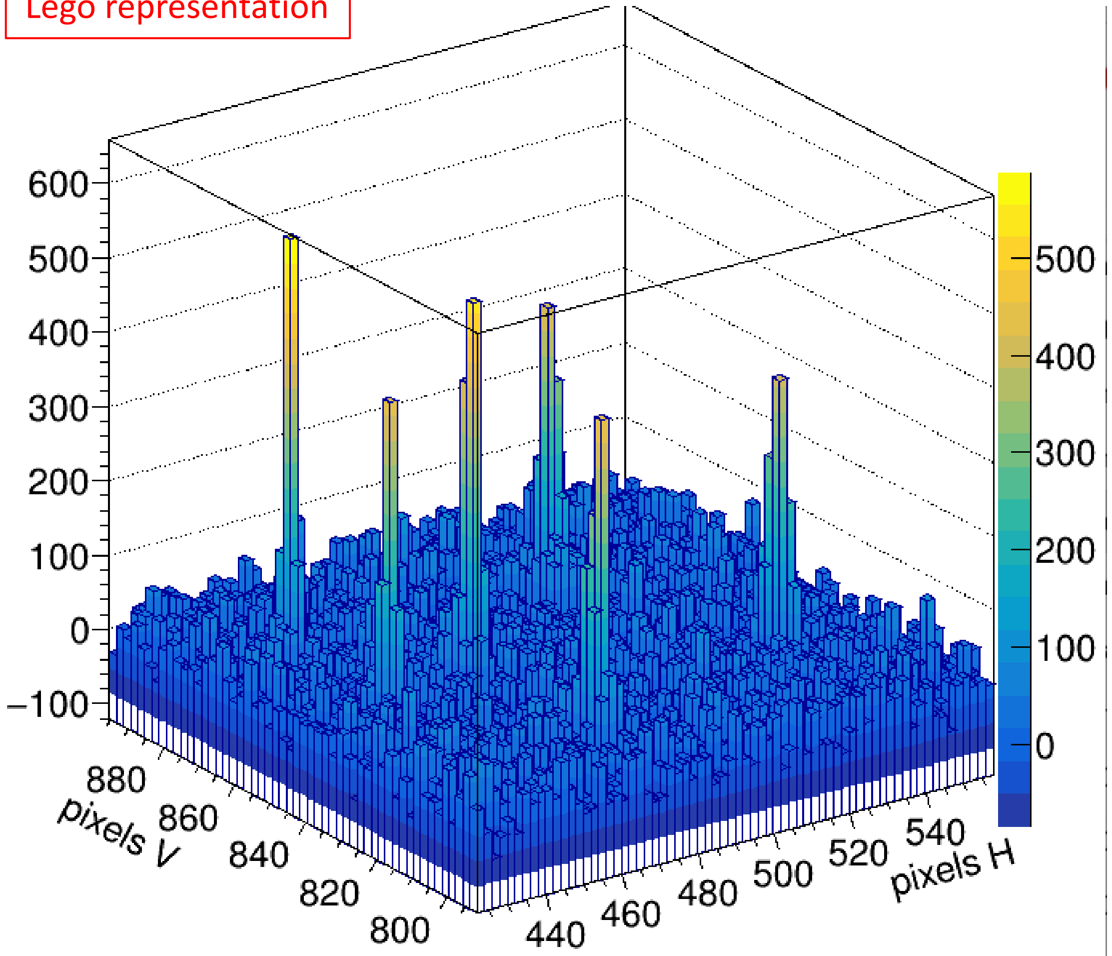


Signal & Beam Imaging in HM: *"Single Particle" hits/images*

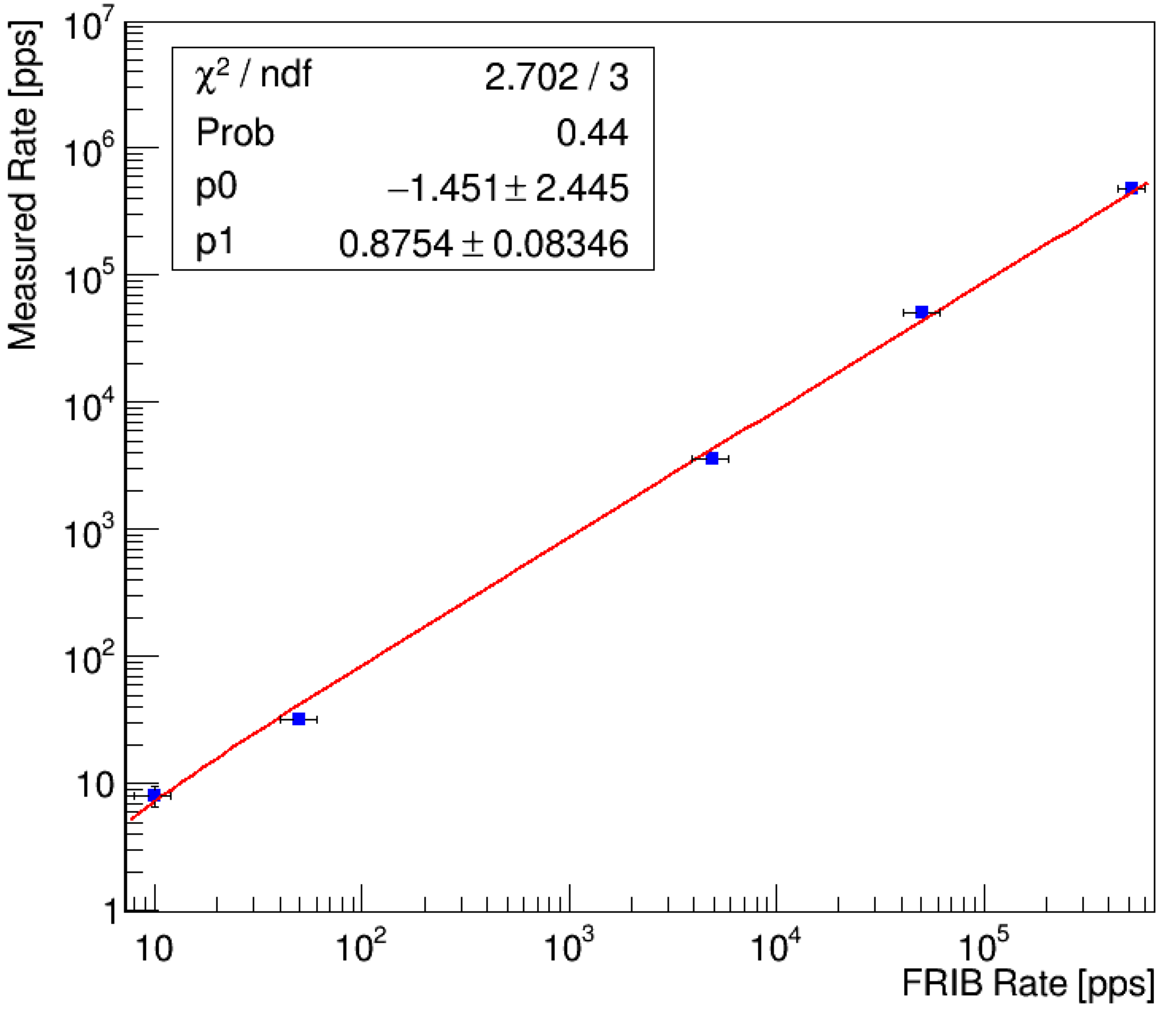
Beam current ramped down to ≤ 10 Hz
Individual ^{86}Kr hits observed in 1 s frames



Lego representation



Beam Current in HM Scintillator: Measured Rate vs. FRIB "Given" Rate



Result 1:

The <u>SBM can measure beam currents</u> that are now determined by 4 different FRIB devices:

- Faraday Cup
- MCP detector
- Silicon detector
- Calibrated Beam Attenuator

Result 2:

SBM measurement is <u>*linear over more than* 5 orders-of-magnitude</u> (the full range has not been determined)

Beam Finding, Profile Analysis & Real-Time Display

Conditions:

1) **Beam current 50 pps** – *very low rate.*
2) *Beam width – few mm*
3) *Beam moved by operator in square pattern in the beam pipe*
4) *HM type scintillator*
5) *1 s frames*

Full pixel field

Beam finder

Beam radius history

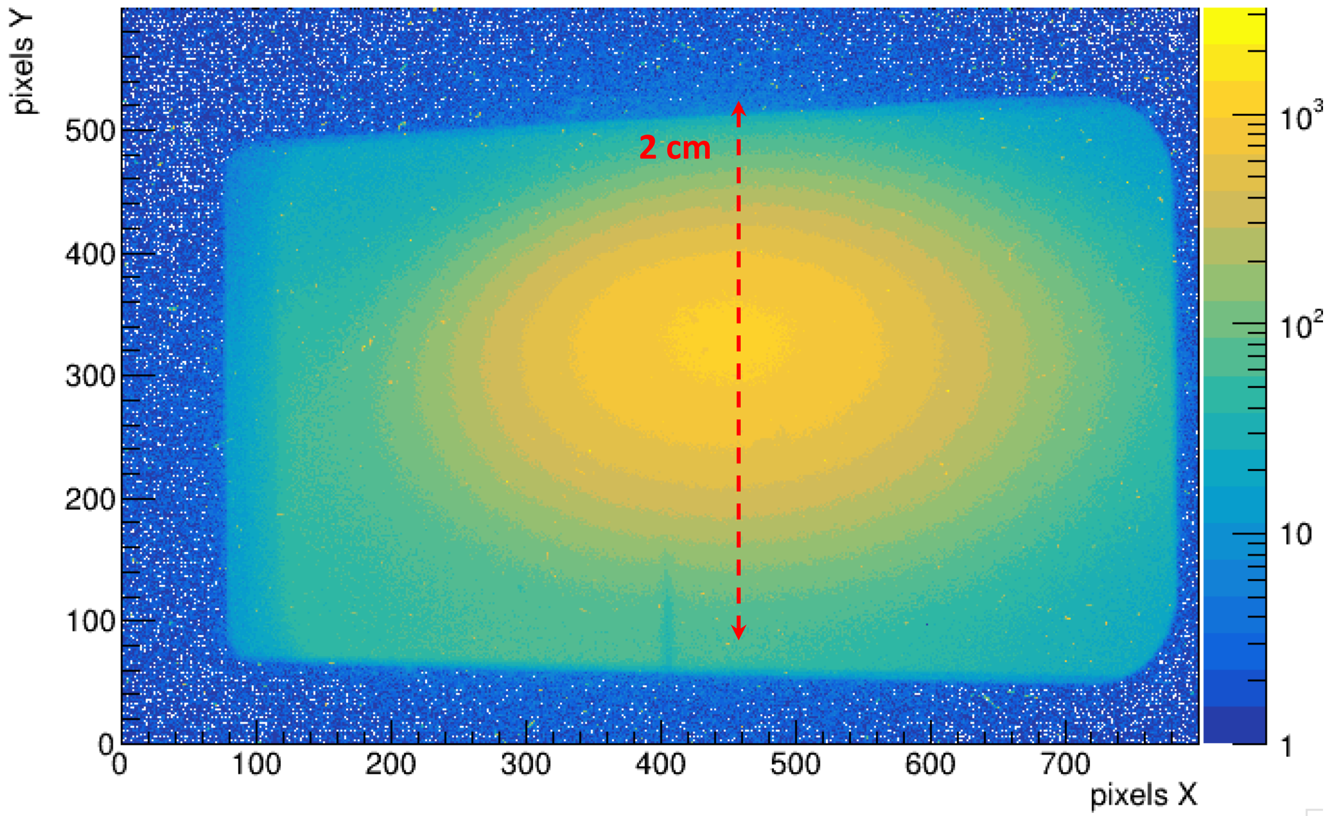
X position history

Y position history

X,Y history

Beam Image on HM at NDRL (camera coordinates)

- **Single 2 ns** duration pulse (1.9 Gy) at a peak current of **1 amp**
- Peak dose rate = **950 MGy/s**
- 8 MeV electrons



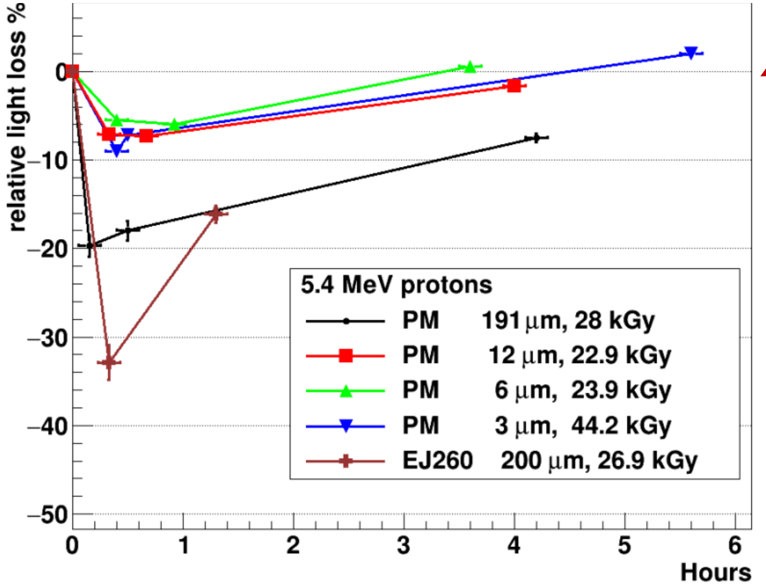
PM Radiation Exposure in Vacuum at Very High Dose Rates

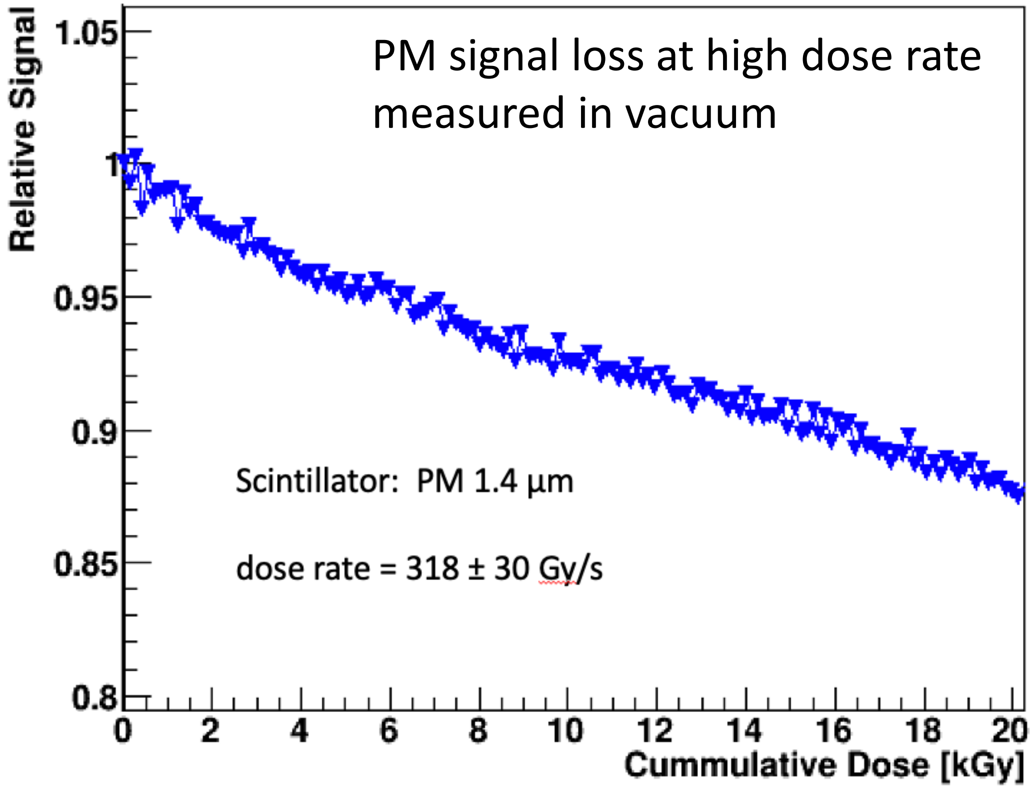
➔ ***No degradation*** was observed in PM type for FLASH doses in **air** for ~ **9 kGy** total dose, at rate of **10 Gy/s**

➔ However, in **vacuum** for much higher dose rates of **~300 Gy/s**
➔ (i.e., ~30 times higher dose) some degradation was measured. Specifically, the average signal change/drop was **-0.6 ± 0.1 %/kGy** averaged over a 20 kGy cumulative dose.

- This degradation largely recovers over several hours in air

PM signal loss/recovery measured in air





Conclusions / Summary

1) SBM provides precise beam profile & imaging with **spatial resolution < 10 µm**
2) Real-time analysis allows for **rapid (i.e., real-time) beam tuning**
3) Beam detection at very low rates starting at **single-particles**
4) Data from FRIB: **linear to *more than* 5 orders-of-magnitude** for $^{86}Kr^{+26}$ (e.g., single-particles to ion-beam current of **$5x10^5$ pps**)
   Data from MIBL: imaging of 10 nA **proton** beams to **$5x10^{10}$ pps/cm^2** (not shown here)
   Data from NDRL: imaging of 8 MeV pulsed **electron** beams to **$4x10^{11}$ pps/cm^2**
5) Novel applications of two specialized thin scintillator materials
   - **PM: *thin to ultra-thin* materials produce clean imaging and accurate profiling**
   - PM in **air** at rates of O(10) Gy/s → ***no degradation*** over first 9 kGy
   - PM in **vacuum** at 100-300 Gy/s → about ***0.6% signal loss/kGy*** over first 20 kGy
   - Ultra-thin PM tested: from ~ 1- 200 um sample thickness
   - **HM** in **air** at rates of O(10) Gy/s → ***no degradation*** over first 15 kGy
   - **HM**: ***order-of-magnitude higher signal output*** than much thicker CsI(Tl) standard
     → allows for ***new unprecedented sensitivity at FRIB***

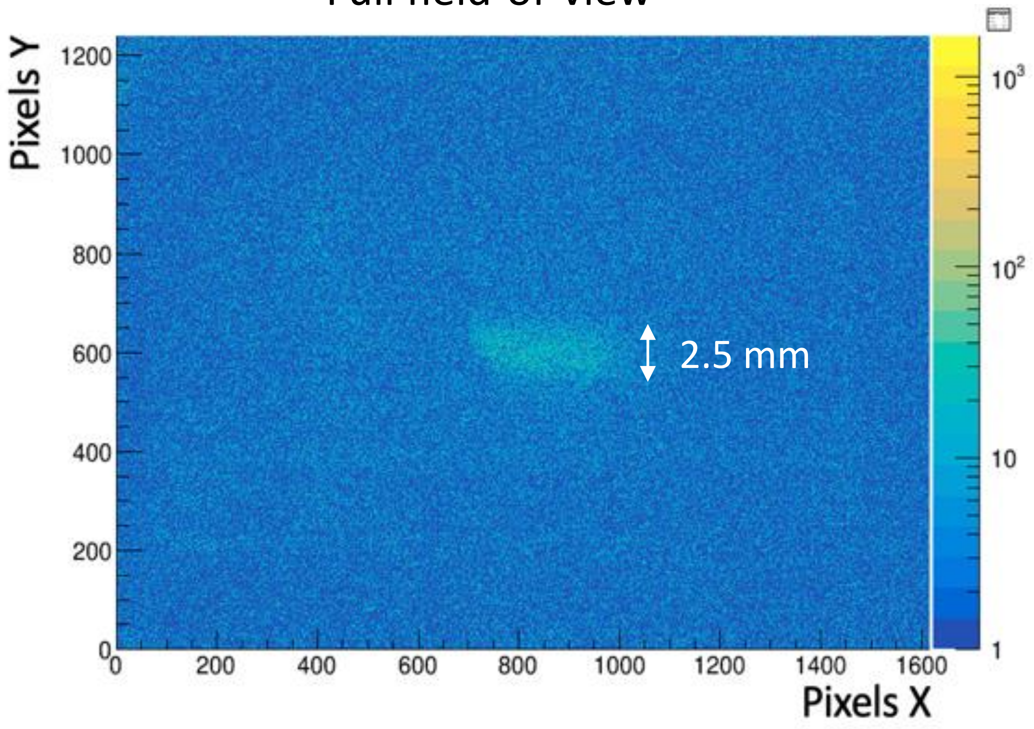
   " …[we] tested them yesterday with Fe at 1000 MeV/n. HM gave about 50% output compared to the [thick fluorescing] screen. It is remarkable for such a thin scintillator! I have tried this before with other scintillators and was not able to see any light from them." …BNL/NASA Space Radiation Lab

6) 6WC design operates in high vacuum (or in air)
7) Scintillators can be remotely inserted in beam or changed without breaking vacuum.

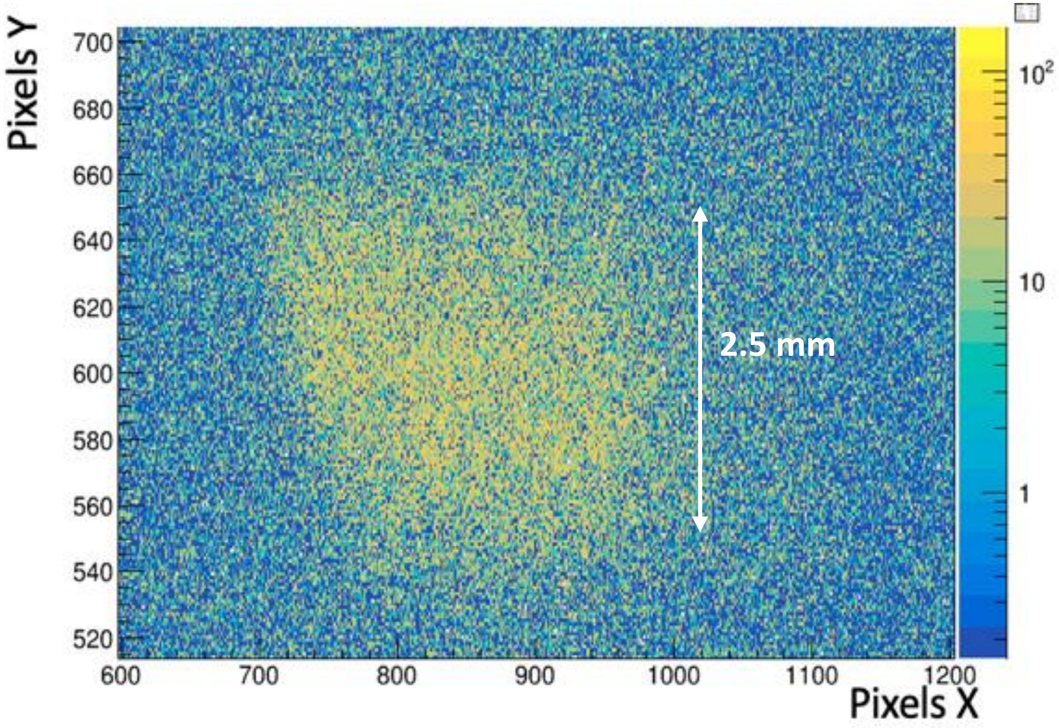
Back Up

Signal & Beam Imaging in PM: (Reduced beam current 100X to 4.9 kHz)

Full field-of-view



Beam detail

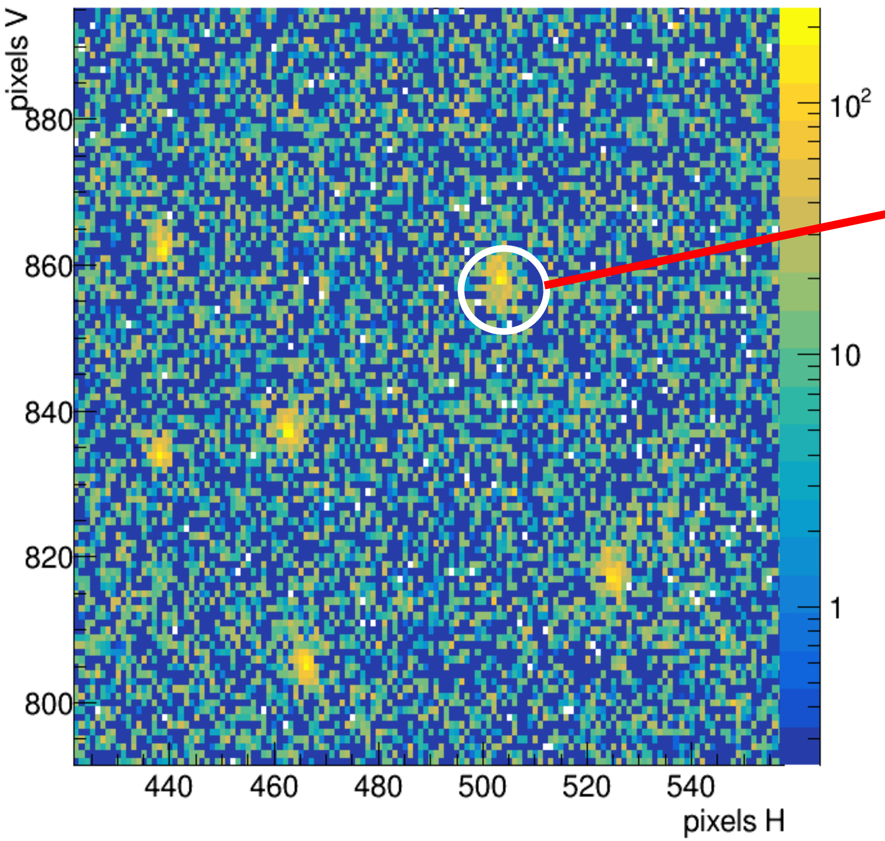


Result 1: Clean beam profile is imaged. ADC signals well above noise

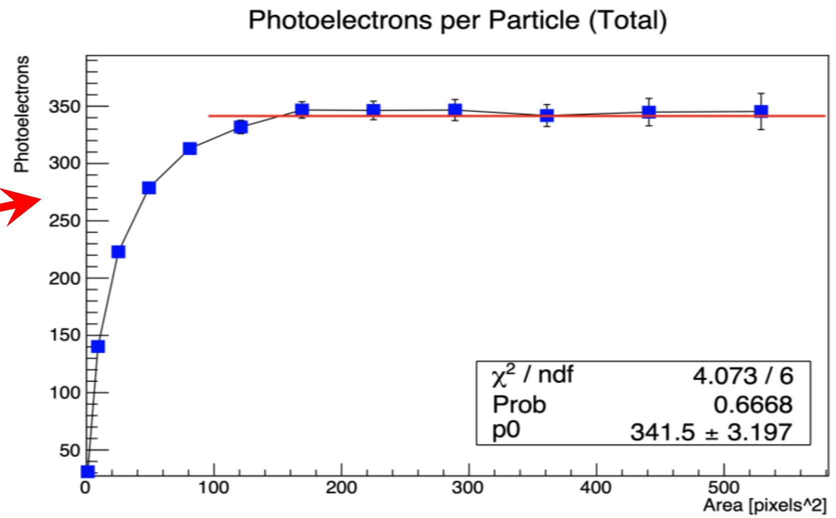
Result 2: Another ~5x reduction is possible ==> 1 kHz beam currents detectable

Beam Current: Simple Measurement in HM Scintillator

1. Integrate single particle hits to extract signal/particle.



Particle light yield vs area of hit pixels



2. Plateau value = single particle total light yield.
   (set by the range of the point spread function & light spread in scintillator).

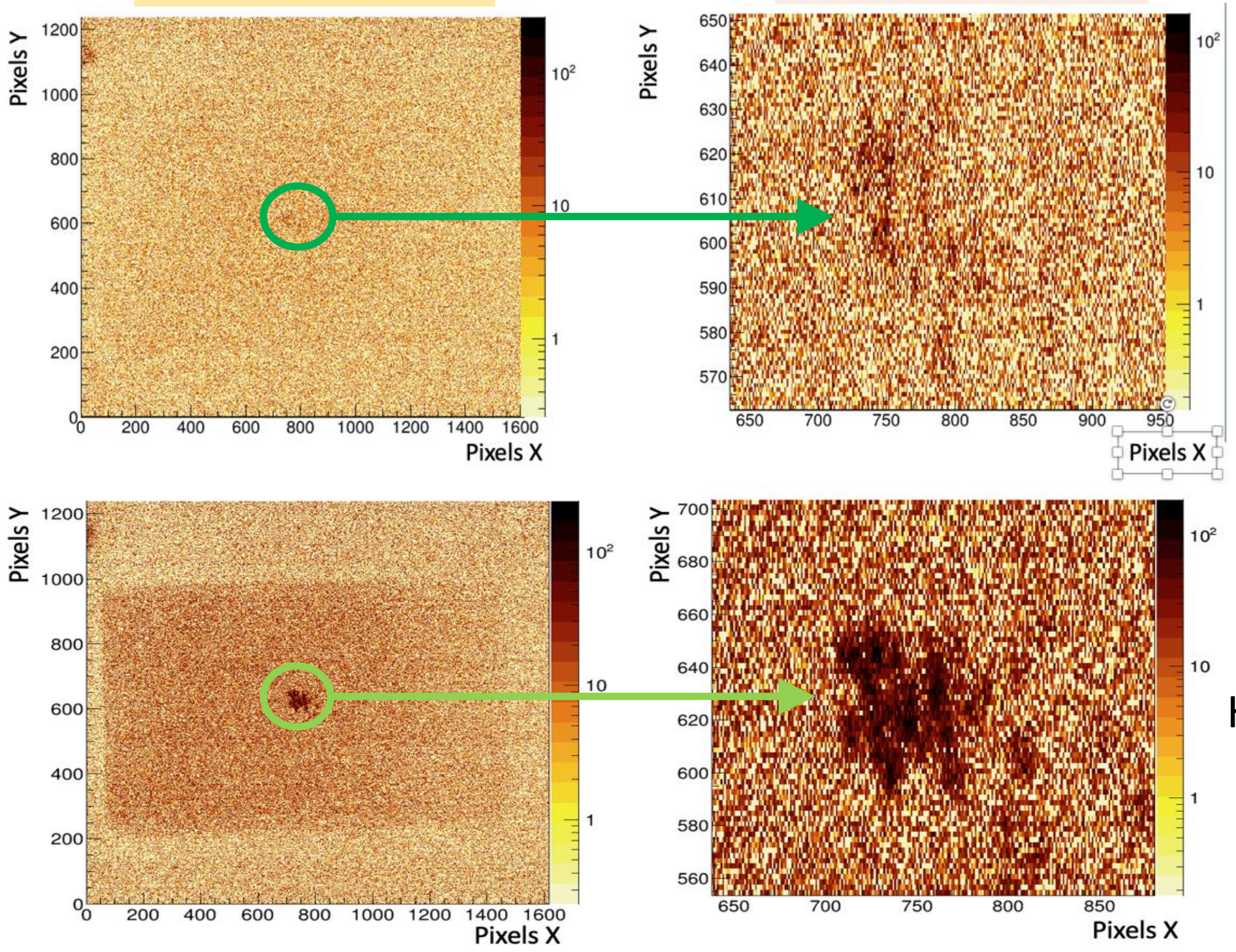
3. This normalization gives the beam particle current.

==> Result is number of particles/s

Comparison of HM to CsI(Tl) at Very Low Beam Current = 50 pps

Full Field-of-View

Zoomed-In Image



CsI(Tl)

HM

β^- Source using ^{90}Sr in lab

Camera gain = 24 db

Exposure = 1 s

Result:

HM beam image is:

- Easily visualized
- Qualitatively superior to CsI(Tl)
- Order-of-magnitude stronger signal

<u>Selected Results from Notre Dame Radiation Laboratory</u> (NDRL)

- Evaluated SBM beam imaging using intense beam of 8 MeV electrons

- Excellent signal quality at FLASH radiotherapy (RT) dose/pulse magnitude

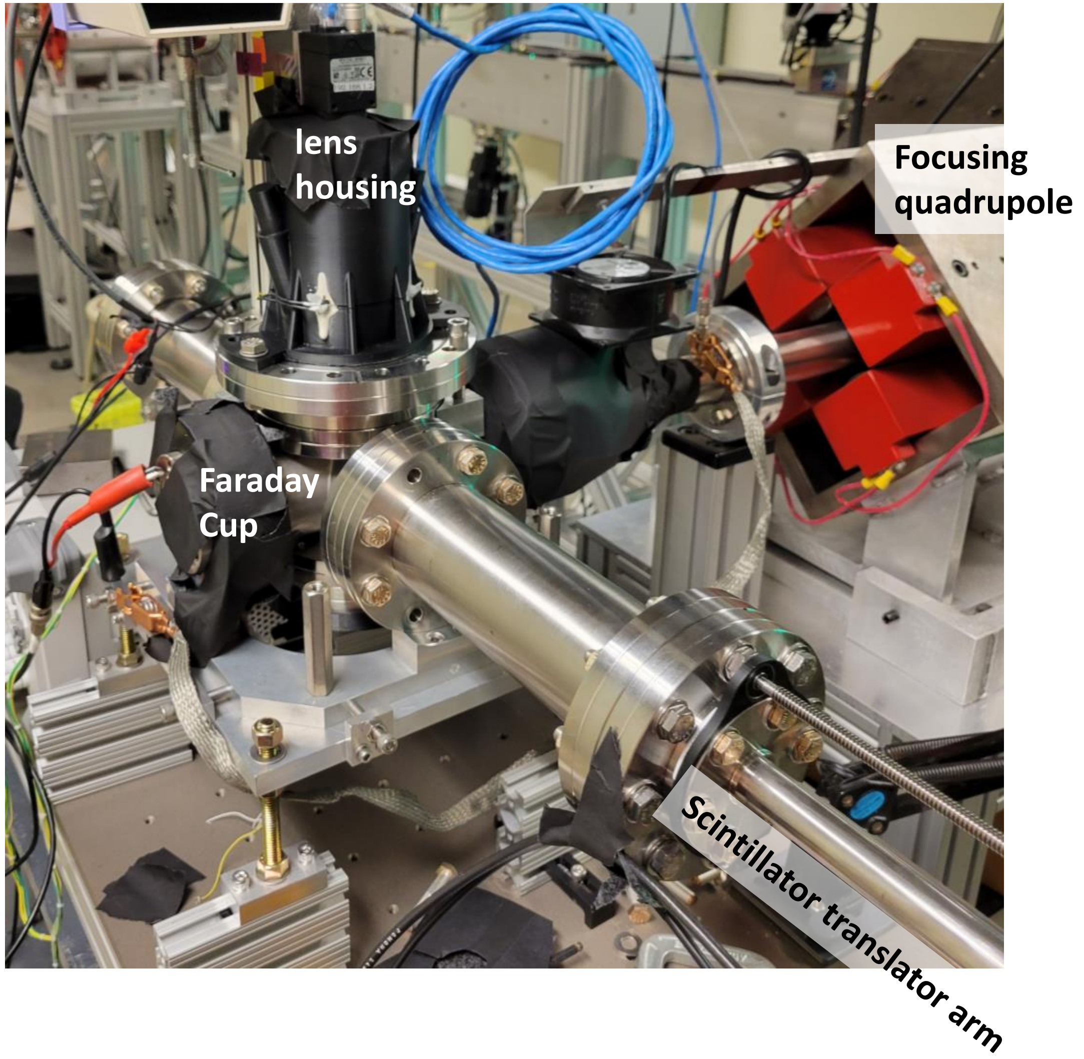
  i.e., we operated at ~<u>**1 amp/pulse**</u> (i.e., 1.9 Gy/pulse), which is ~ twice the minimum for FLASH-RT assuming at least 21 pulses delivered in 1 s pulse. <u>**Pulse duration was 2 ns**</u>.

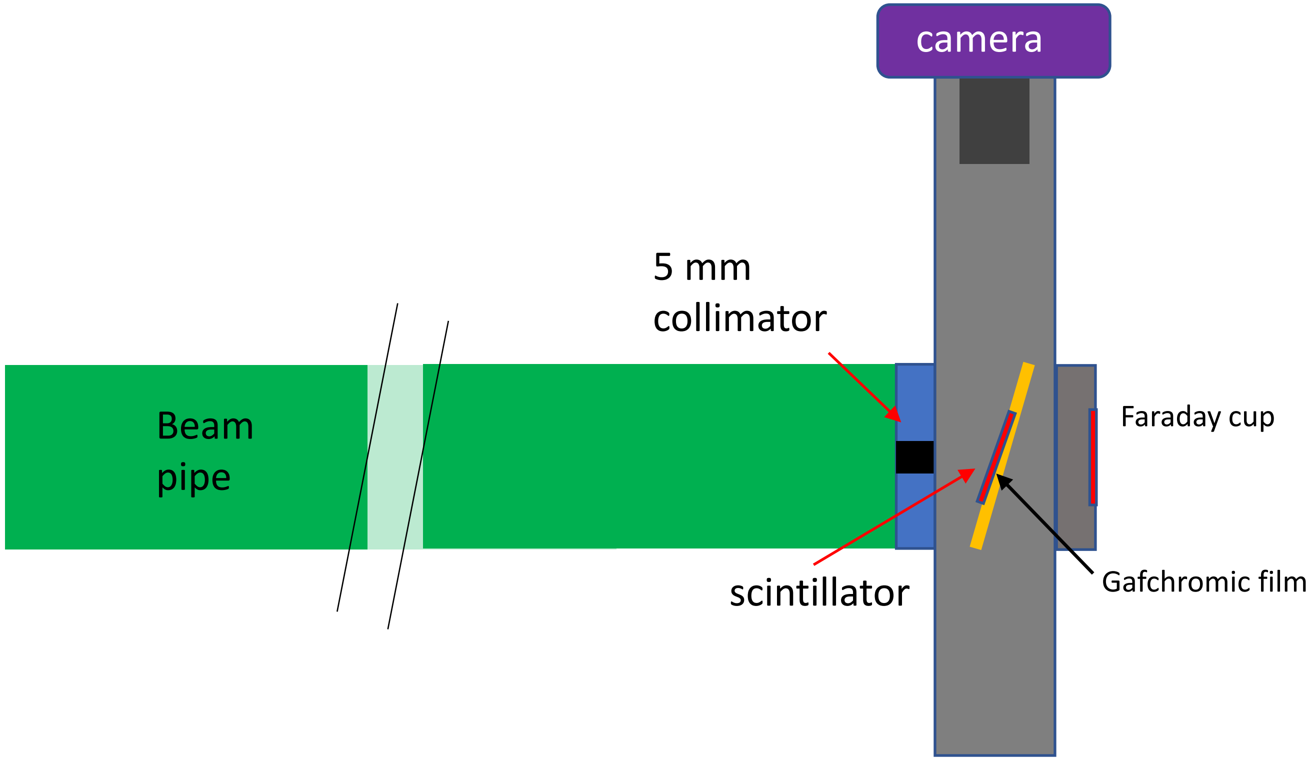
- Response ***linearity with beam current demonstrated for PM and HM scintillators***

- Evaluated radiation tolerance of PM and HM at FLASH-RT exposures

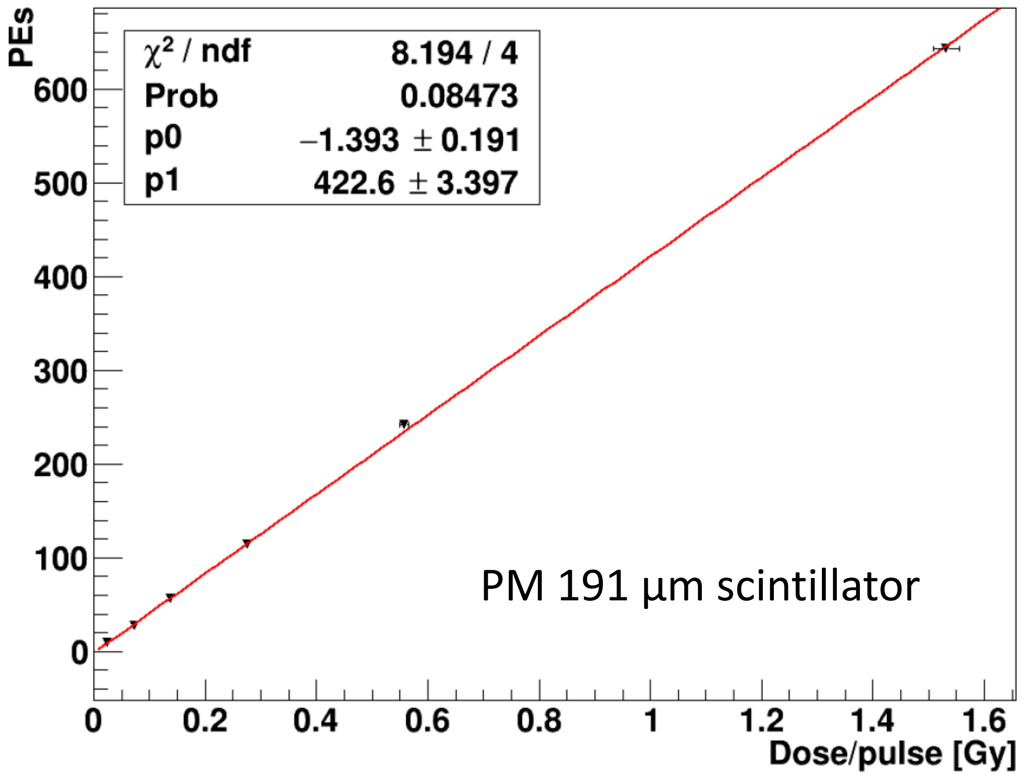
- Absolute calibrations were obtained using Gafchromic film standards

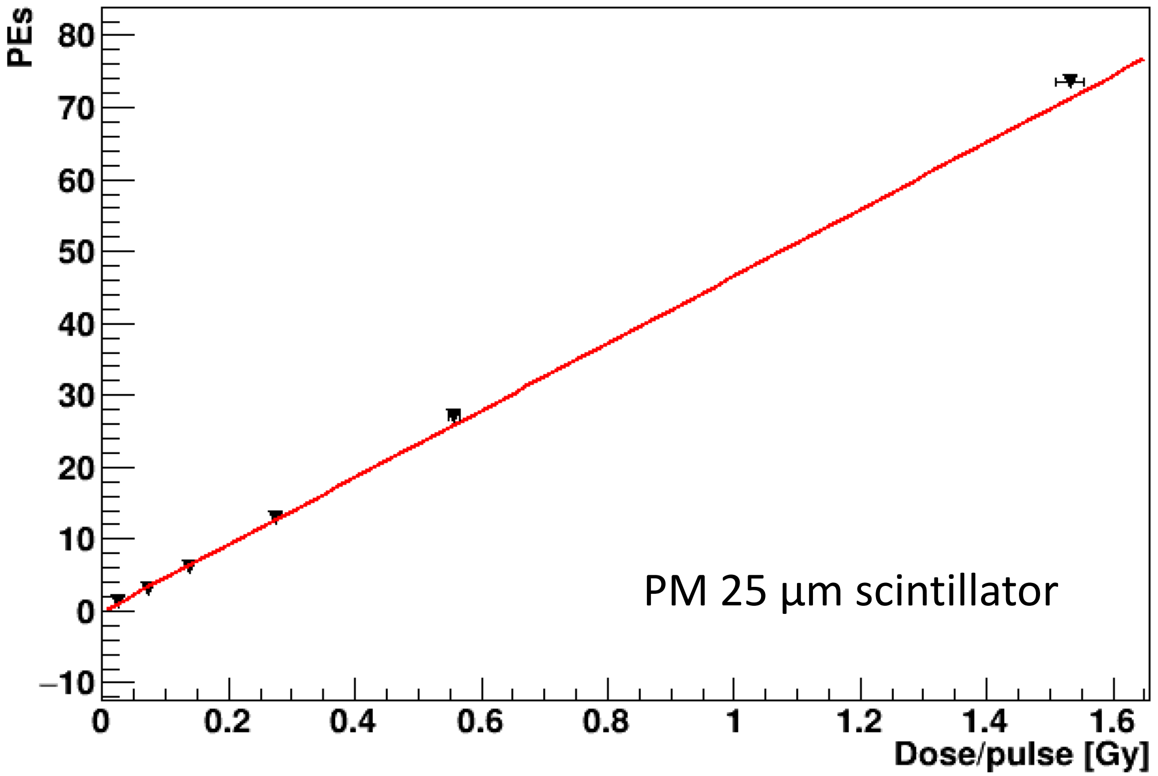
I. Set up at NDRL





Signal Strength vs. Beam Current (8 MeV electrons, NDRL data)

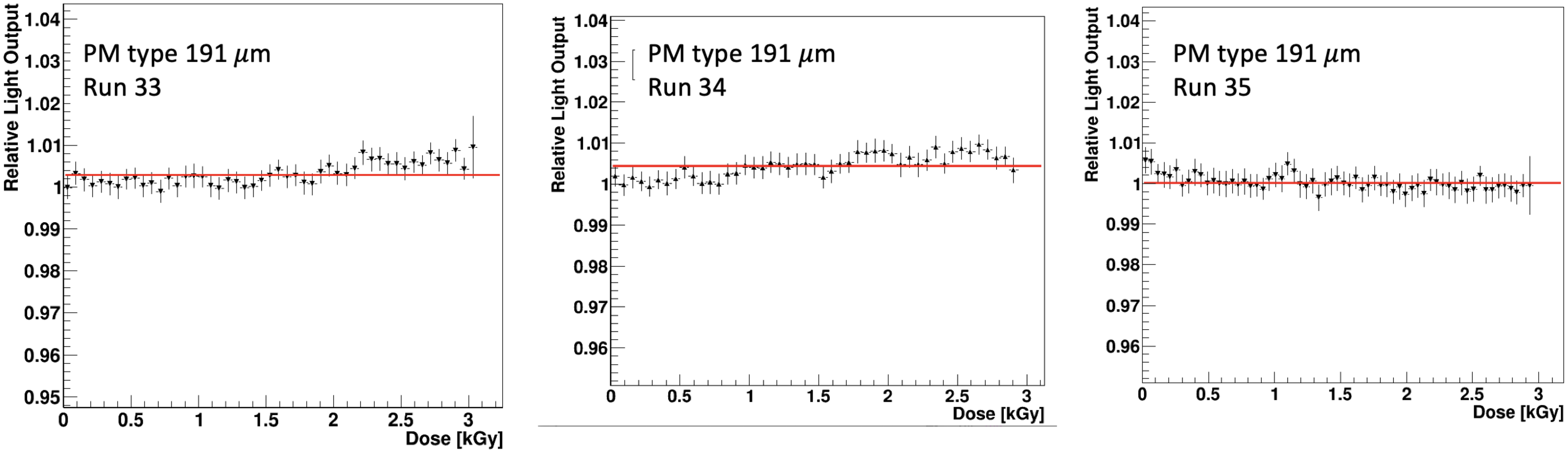




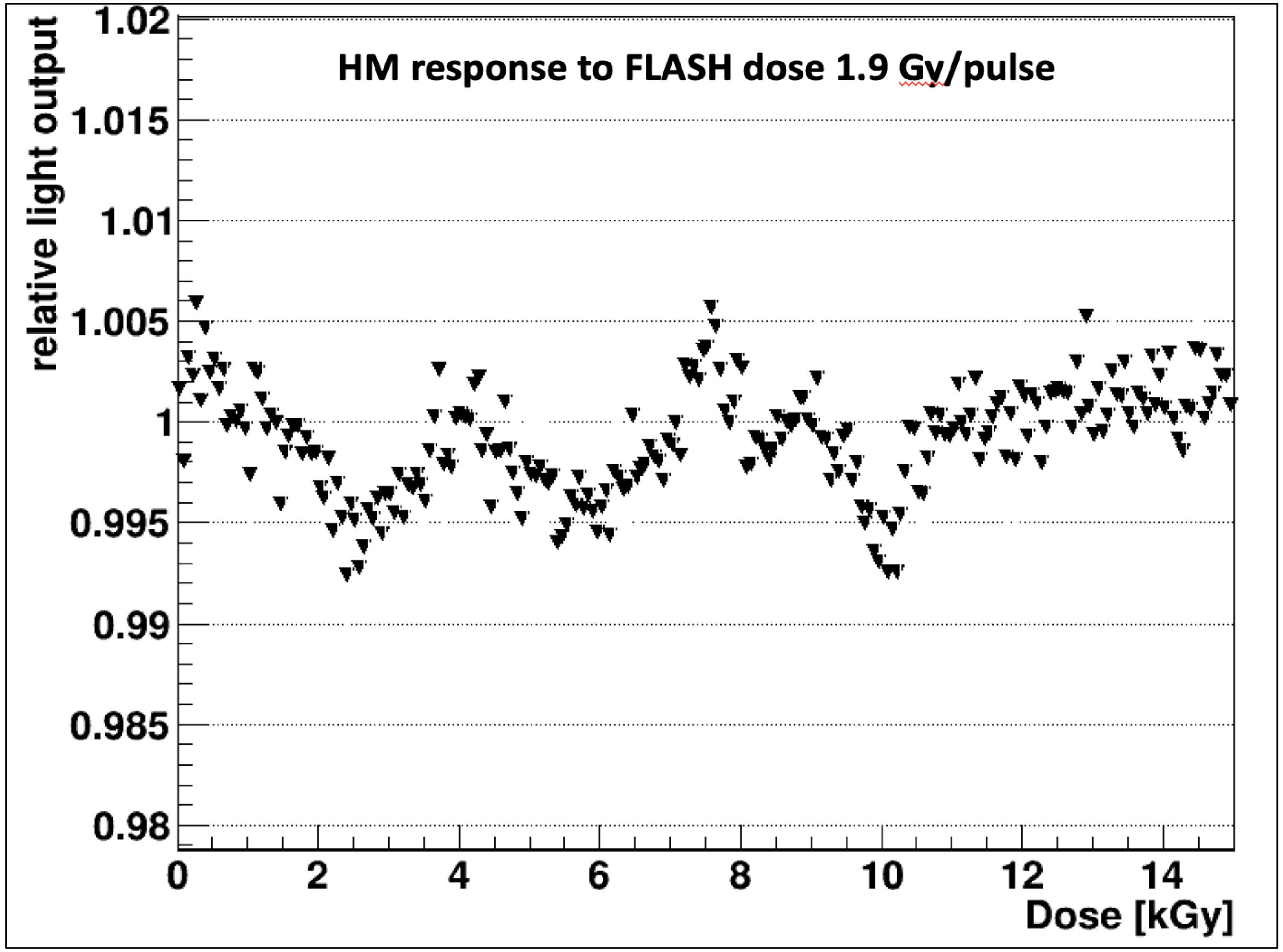
Radiation Degradation Experiment for PM (in air), 191 μm thickness

Three runs total dose = **9 kGy** total dose (in air)

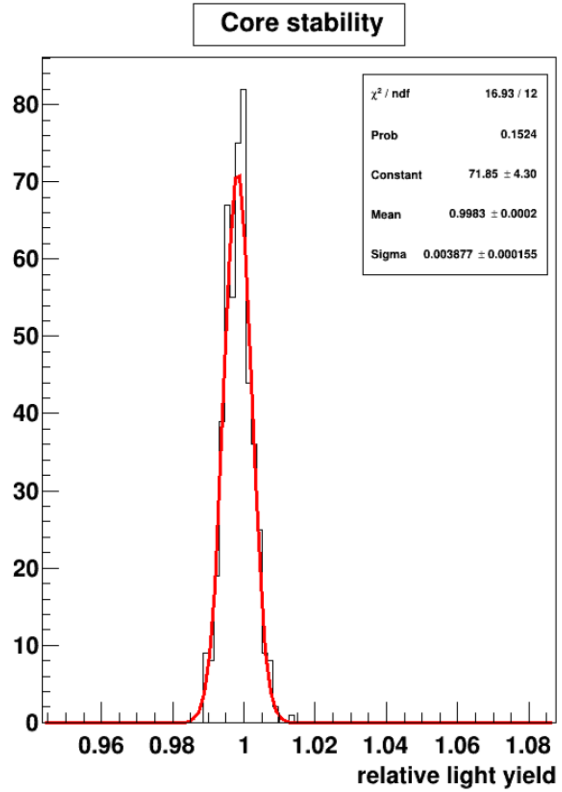
No observed degradation

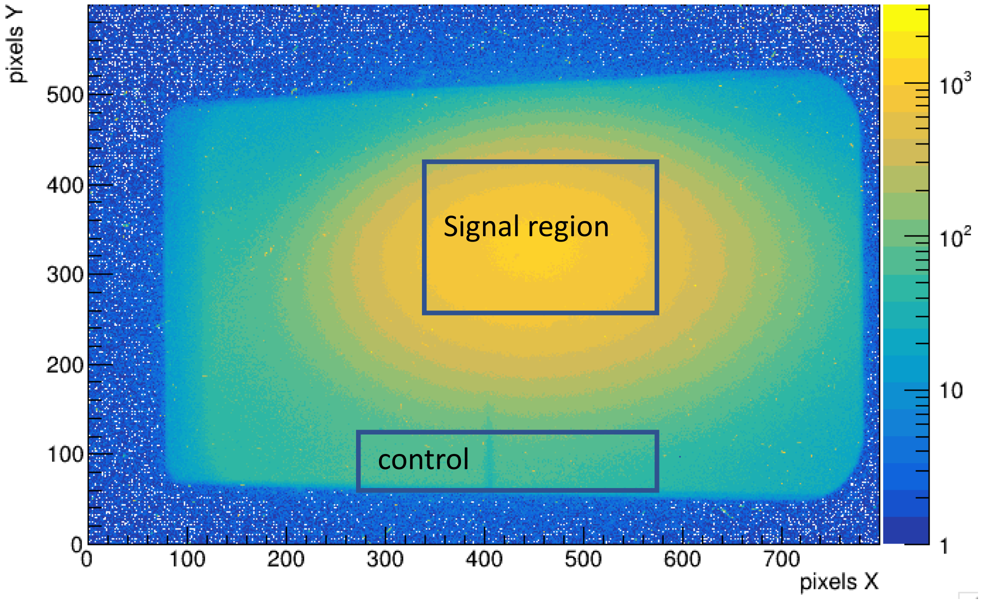


Radiation Degradation Experiment for HM (in air)



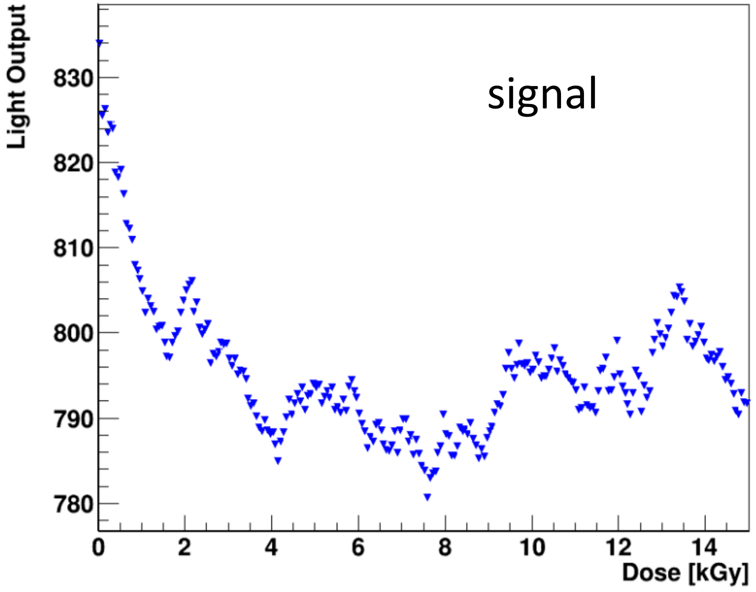
- Stable: RMS variation ~ +/- 0.4%
- ***No observed degradation*** ***trend over 15 kGy***
- Degradation limit < 0.03% /kGy (in air)

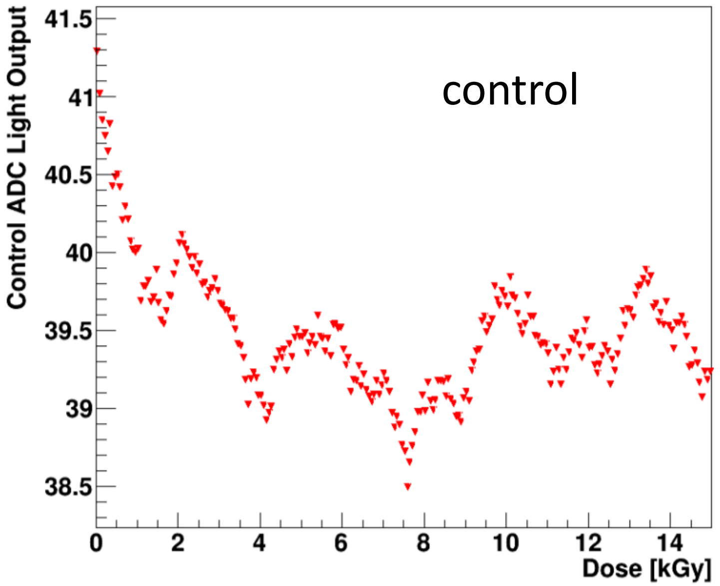




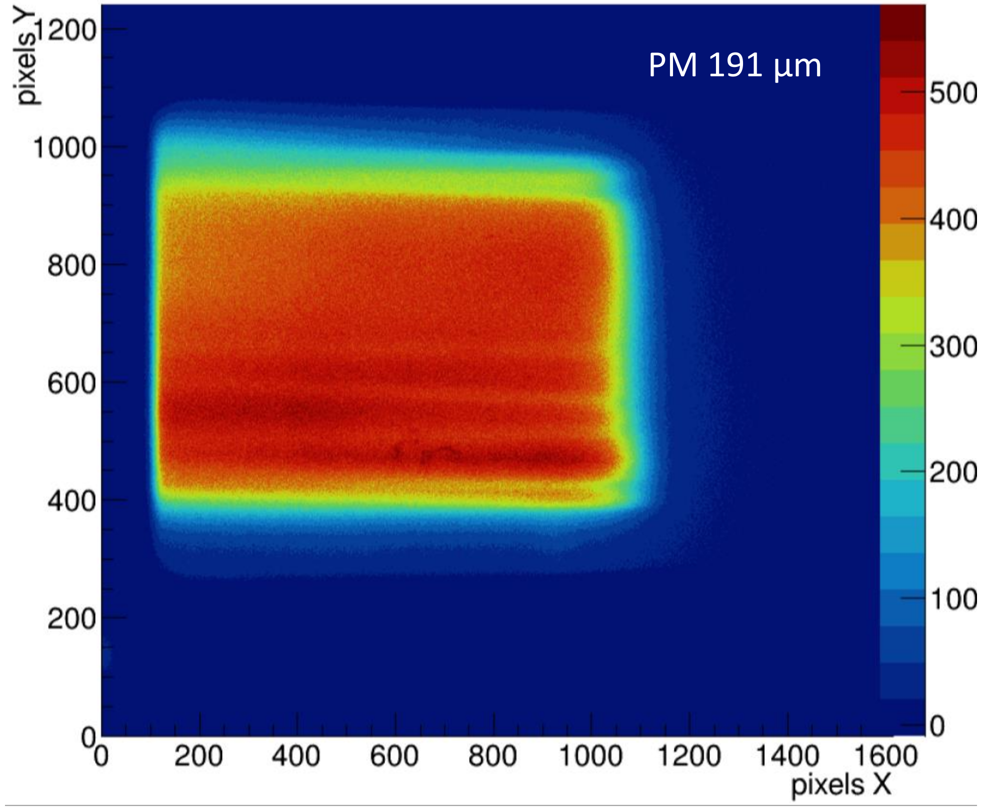
Radiation Degradation Experiment for HM

- Run duration = 30 min
- 1.9 Gy/pulse at 5 Hz
- Average dose rate (1 s) = 9 Gy/s
- 15 kGy total dose
- Metric = signal ratio high dose region/control region

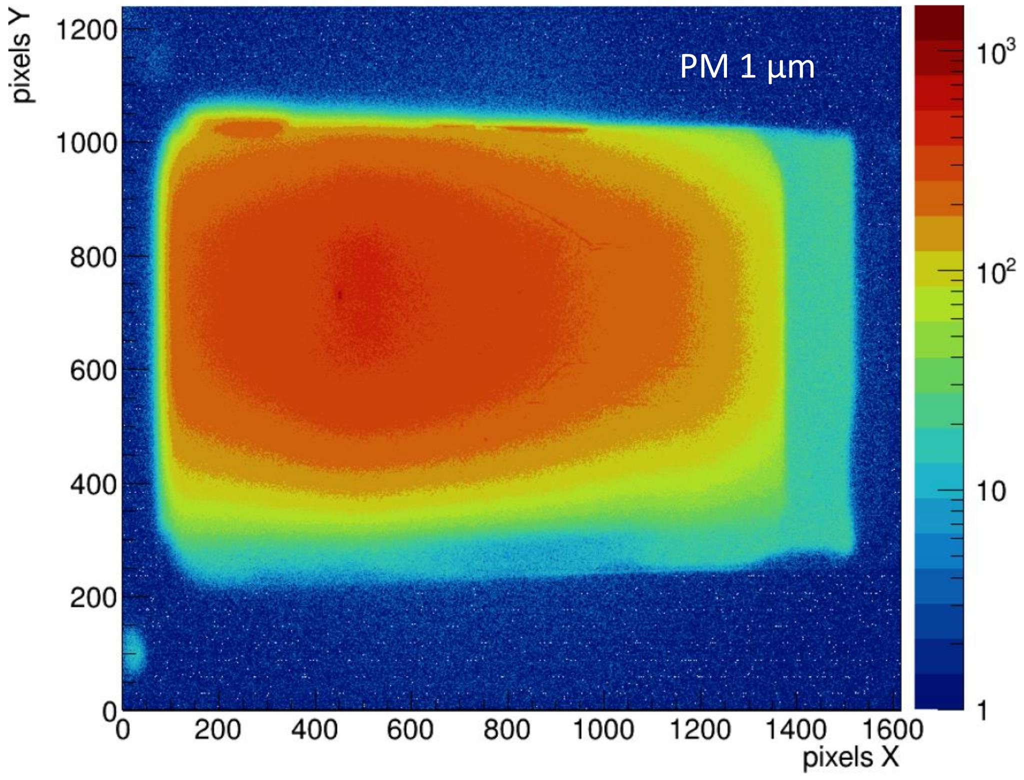




High Current Beam on PM Scintillator (Michigan Ion Beam Lab)



pencil beam at 2 kHz sweep rate
exposure = 10 ms
5.4 MeV protons (E_{loss} = 2.1 MeV)
10 nA



exposure = 1 s
1 MeV protons (E_{loss} = 0.046 MeV)
3 nA