A High Performance Scintillator Ion Beam Monitor (SBM)*

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* The SBM is a patented invention by <u>Integrated Sensors, LLC.</u>

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System Overview

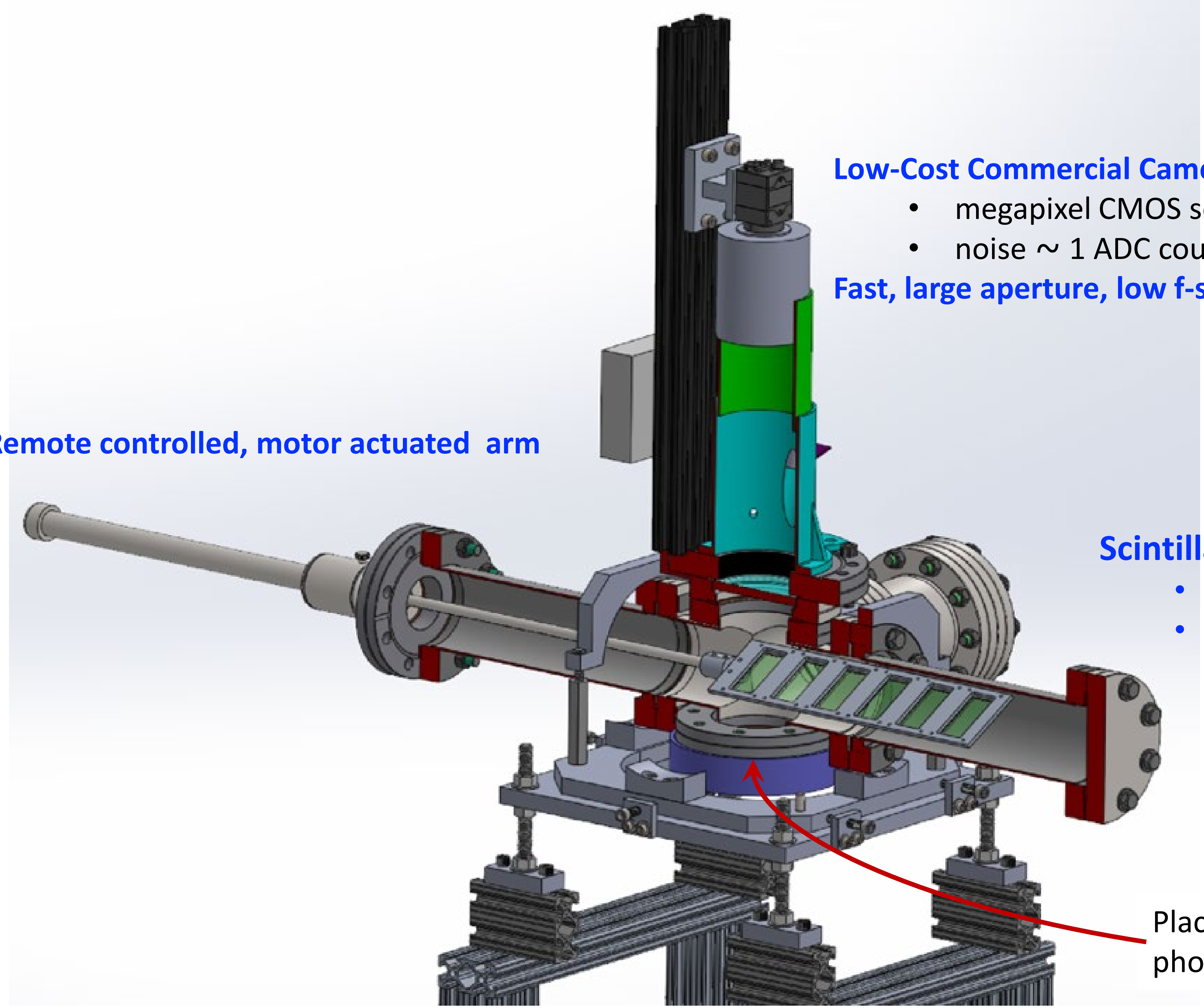
Motivation

I. **Precision beam analysis // display results in real-time** ← this presentation

II: related to high dose rate (FLASH) radiotherapy beam monitoring (PTCOG60-Miami, FRPT21-Vienna, FRPT22 Barcelona)

Main Features

- **Novel-use thin scintillators: very high sensitivity, clean imaging**
- **Scintillators are insertable/retractable without breaking vacuum using translation arm**
- **High resolution beam imaging : beam centroids, widths, amplitudes**
- **Thin, low low mass scintillators: higher energy beams are transmissive**
- **Wide dynamic range of ion currents: single ions (at low energy) to nA/cm^2**



Low-Cost Commercial Camera:

- megapixel CMOS sensor
- noise ~ 1 ADC count (2.4 pe)

Fast, large aperture, low f-stop lens

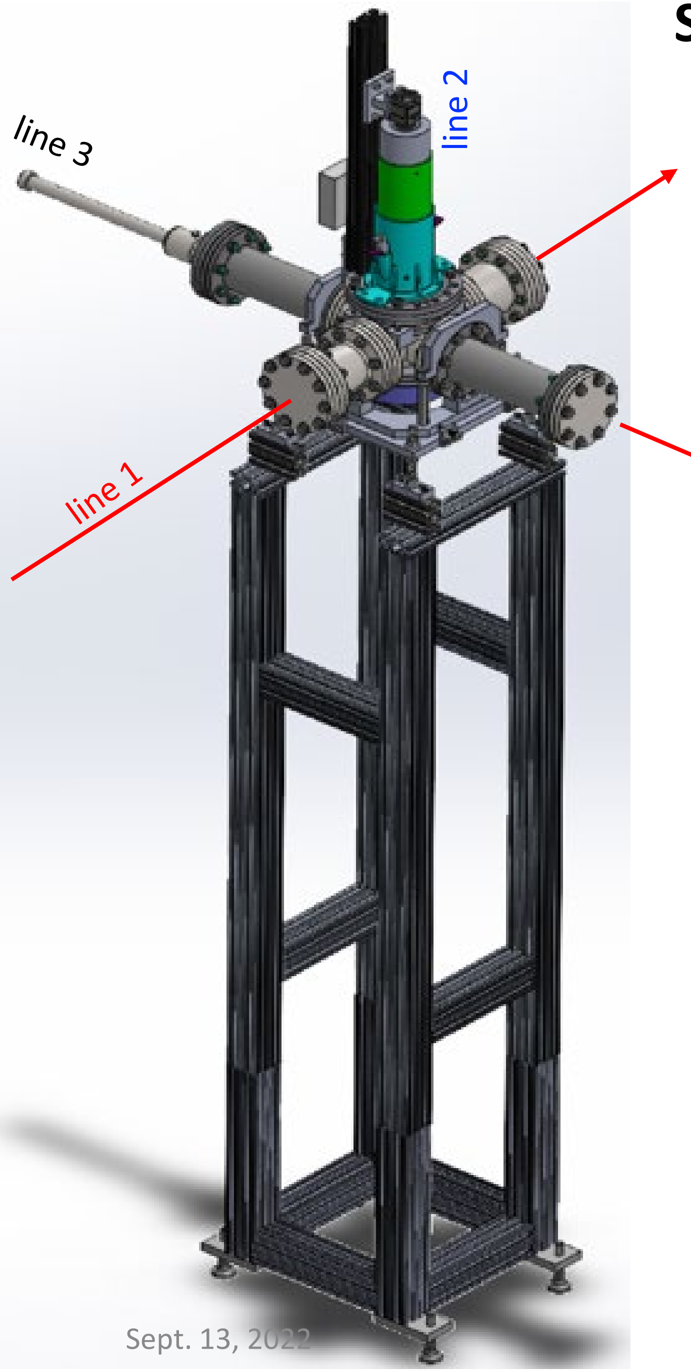
Remote controlled, motor actuated arm

Scintillator cassette

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

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

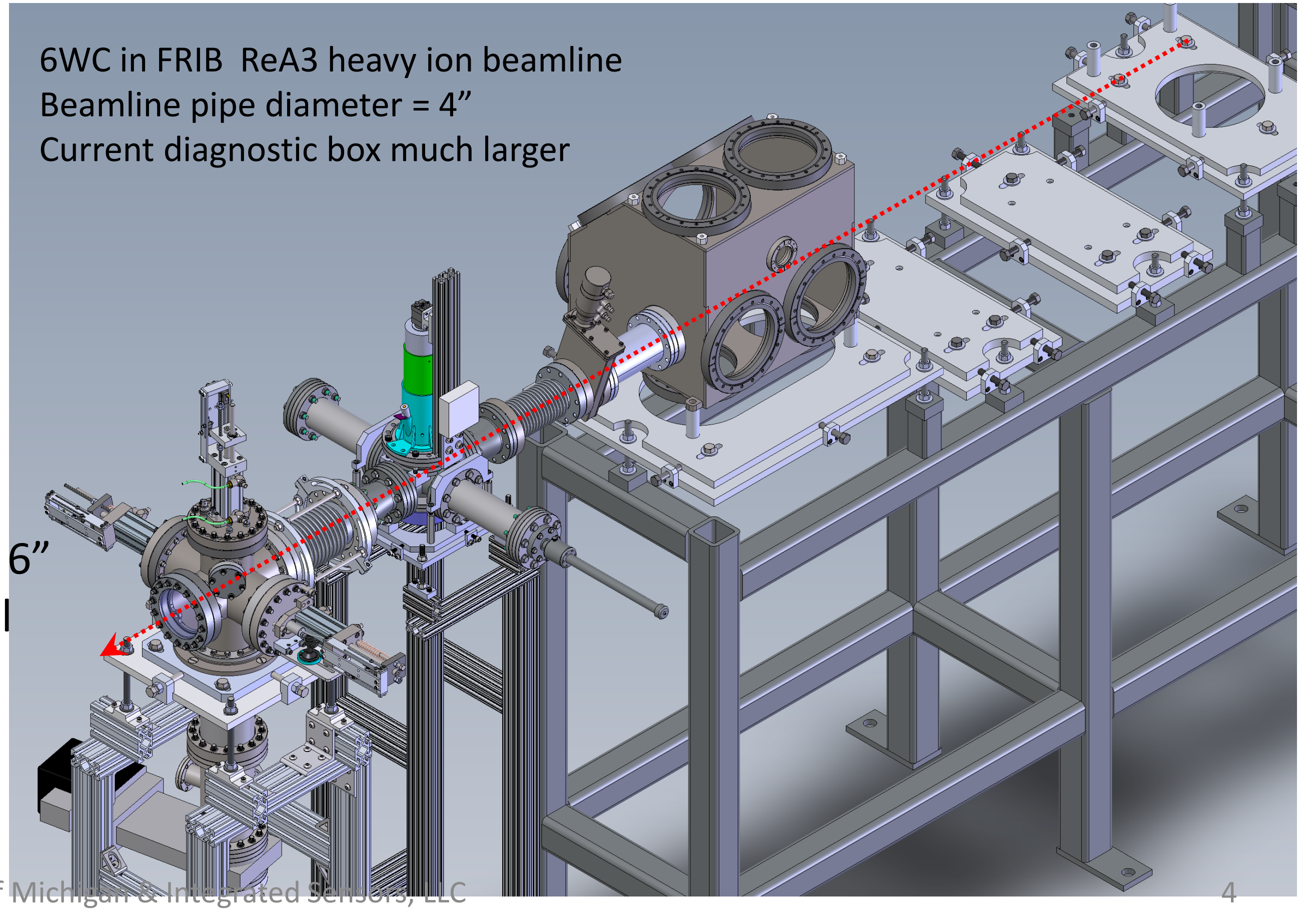
SBM configured as “Six-Way-Cross” (6WC) with 3 orthogonal lines



Line 1: beam path (vacuum) fore/aft

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

Line 3: scintillator ladder travel



Only about 6” longitudinal footprint

Scintillators - Two types of thin, non-hygroscopic and radiation resistant materials*

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 (& polystyrene) 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 & radiotherapy)

Type 2: Hybrid Material (HM): Inorganic polycrystalline ceramic hybrid

- active layer embedded in a polymer matrix. Support substrate and protective polymer layer
- available in large area sizes & thinner than single crystal CsI(Tl), (e.g. < 0.5 mm)
- high light emittance: generates significantly larger amplitude signals than CsI(Tl)
- no internal reflections

PM and HM are designed and widely used for other purposes

* Four patents issued to Integrated Sensors on PM & HM materials for beam monitoring applications.

DAQ - Display System

Image processing:

- **background subtraction**
- **faulty pixel removal**
- **perspective & rotation transformations**

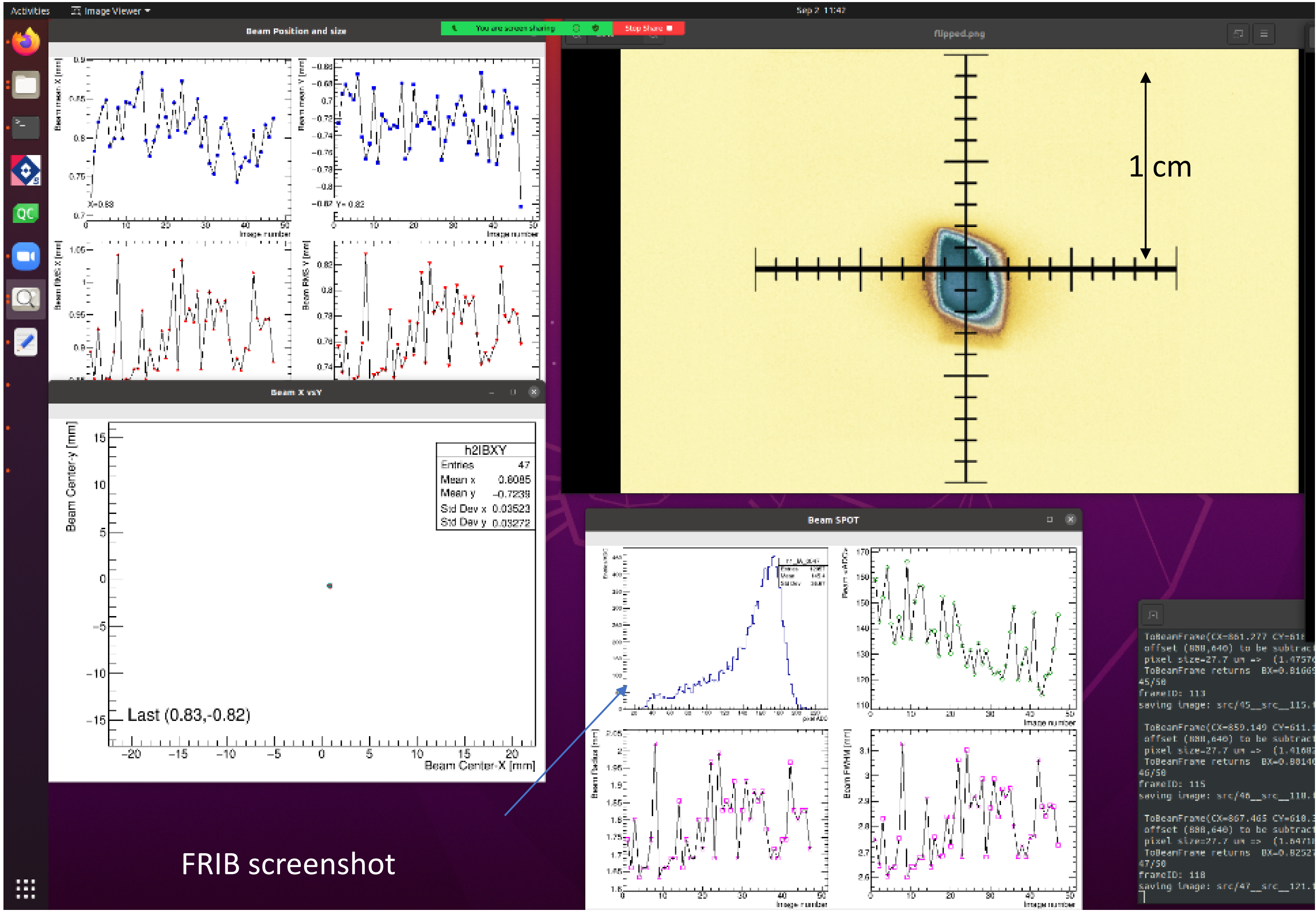
➔ **display in beam coords**

Analysis:

- beam finding
- beam profiling (centroids, widths)
- peak amplitude

Display

- False color image
- real-time analysis
- updating graphics

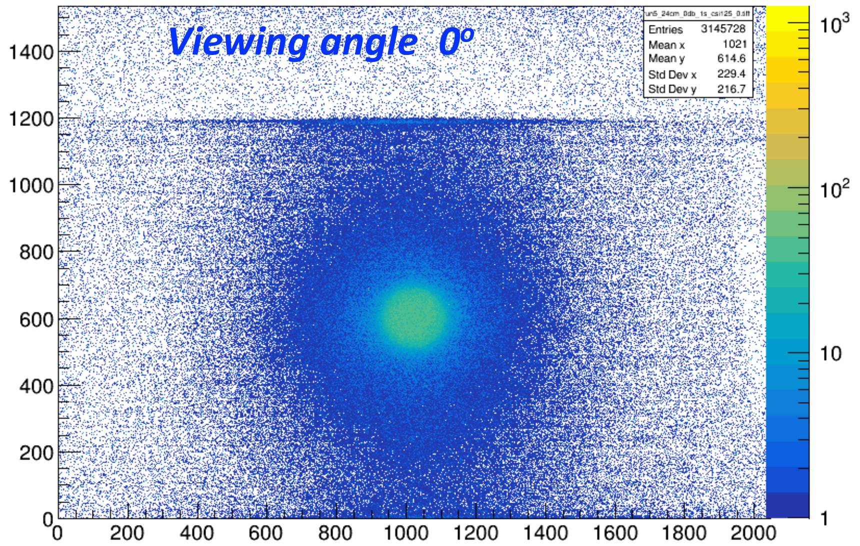


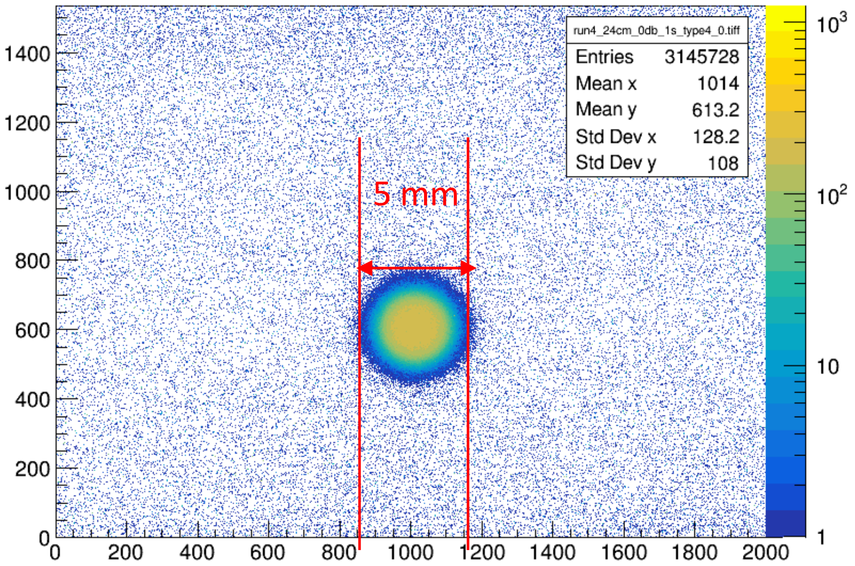
FRIB screenshot

Test Results

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

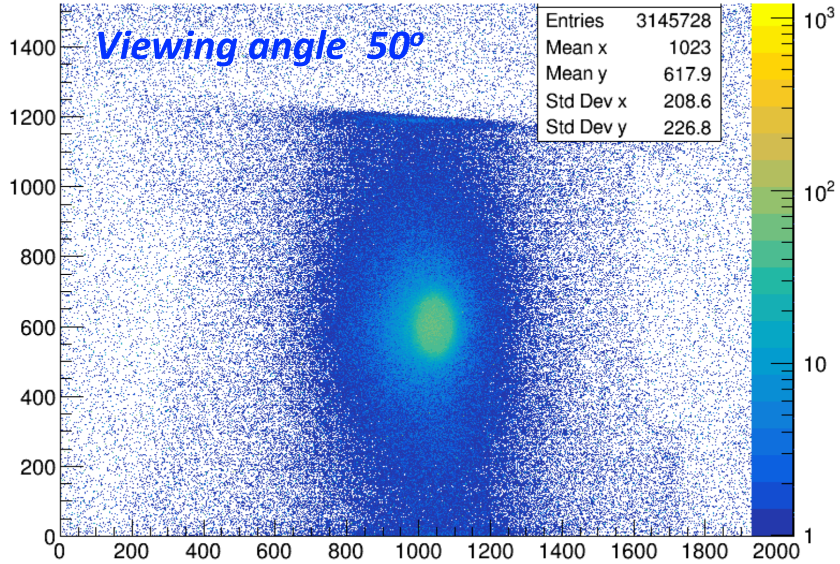
UM Benchtest of Scintillators: Compare HM to CsI(Tl) single crystal

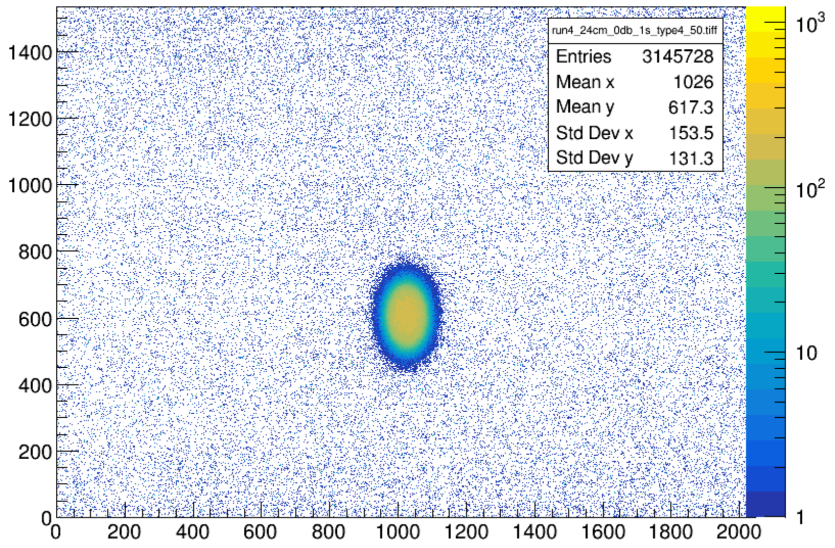




CsI unpolished, 1.25 mm

HM 435 μm





- **Result 1:**

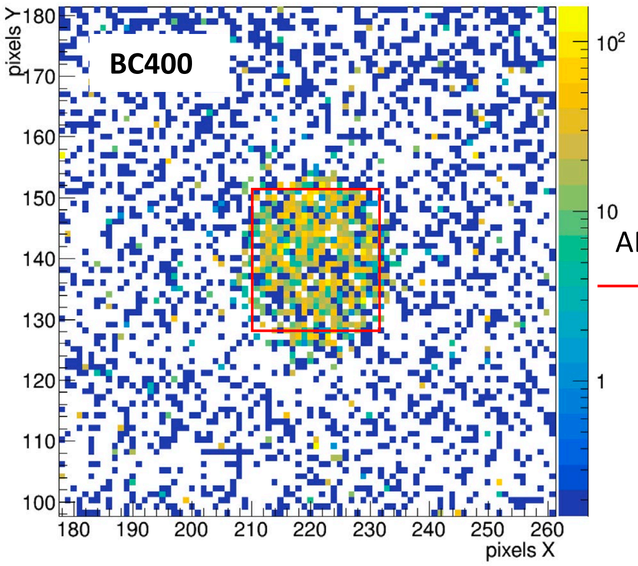
HM offers a clean beam image: free of reflections, blooming, distortion & sidewall emissions

- **Result 2**:

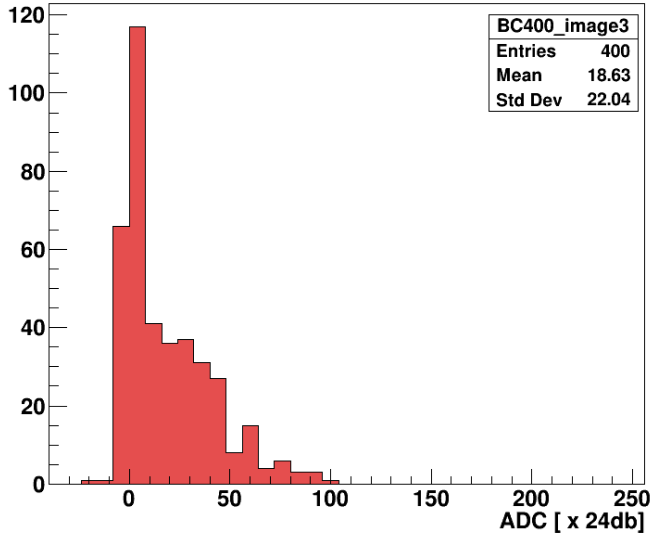
HM/CsI(Tl) relative signal strength normalized to material thickness:
(ADC/mm) at 0º 12x

UM Lab Test of Scintillators: Compare PM to BC400

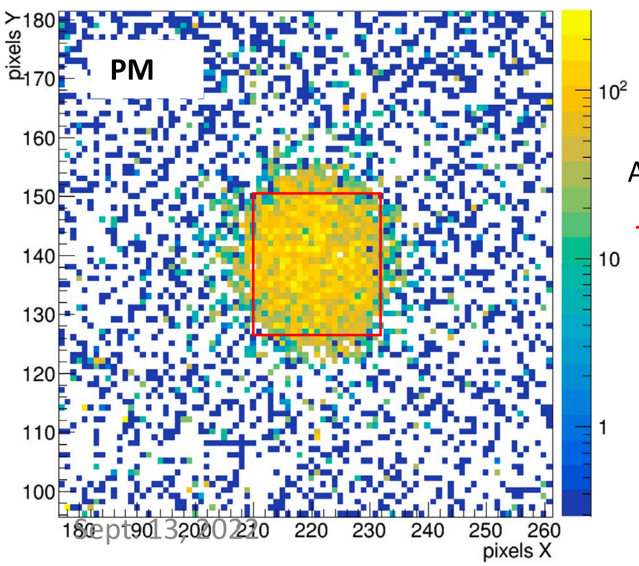
~200 μm thick + ^{90}Sr source + 1 s exposures + 24 dB pixel gain



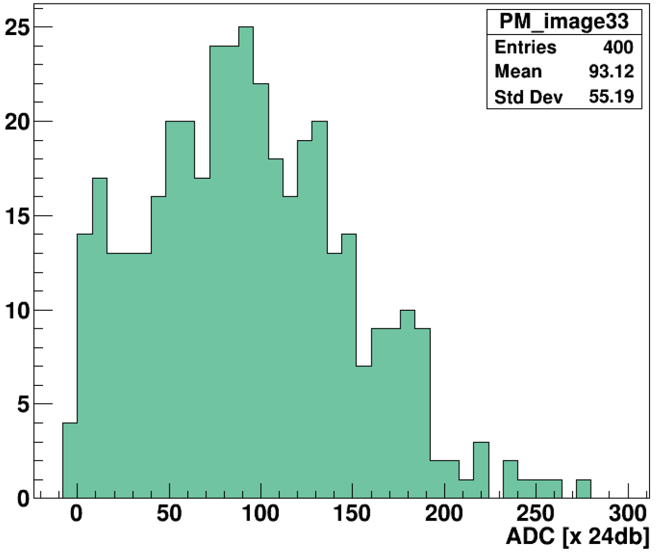
ADC of box



PM 24 db



ADC of box



Result:

BC400 (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 ~ 5x (93:19)

<u>Facility for Rare Isotope Beams (E. Lansing, Mich)</u> *(FRIB ReA3 beamline)*

Project objective: provide FRIB with advanced & fast beam monitoring.
effective cost of beam operations: $\gtrsim$ \$20K/hr → high premium for fast tuning technology

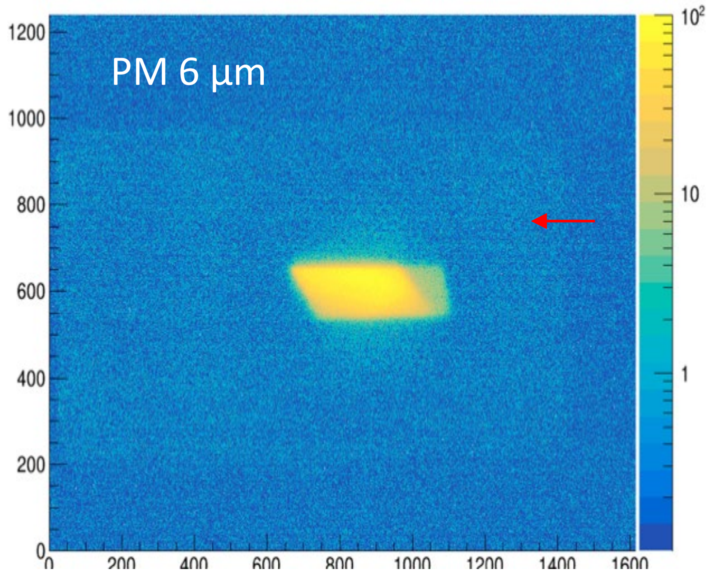
- Ion: $^{86}Kr^{+26}$ at 2.75 MeV/n (236 MeV/nucleus)
- Current: 5- 10 pps (single particles) up to 520,000 pps

Selected results:

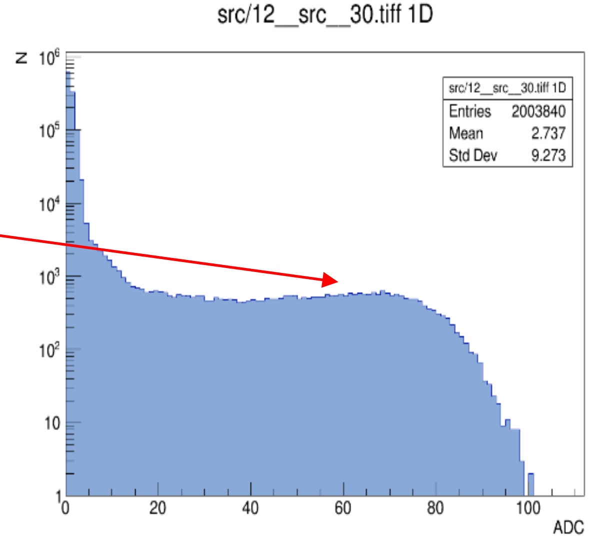
1. PM scintillators
   - Beam imaging
   - Signal amplitude vs thickness
   - Signal amplitude vs current
   - Transmission

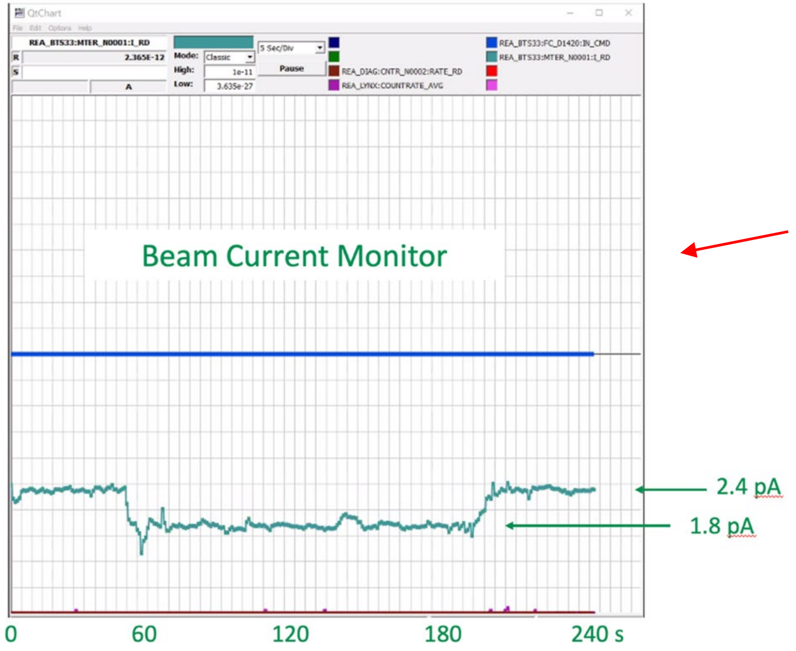
2. HM type scintillator:
   - Single particle detection
   - Response vs beam current
   - Beam tracking & profiling

Signal and Beam Imaging in PM: 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:

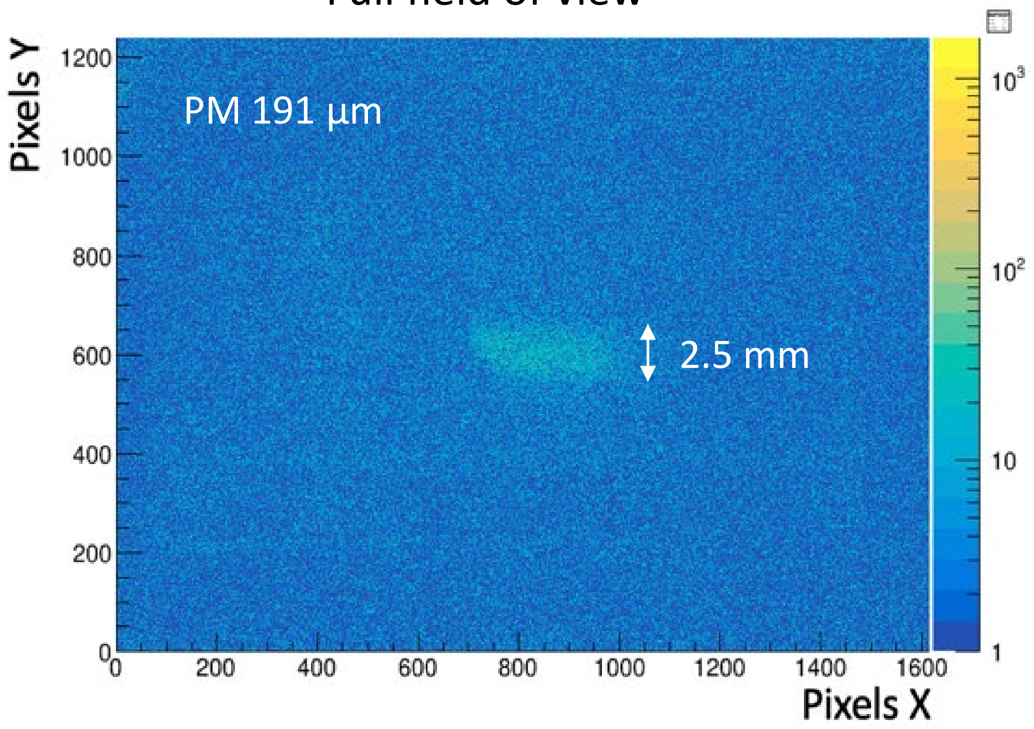
with 6 μm PM

→ 75% transmissive of ^{86}Kr 3 MeV/n

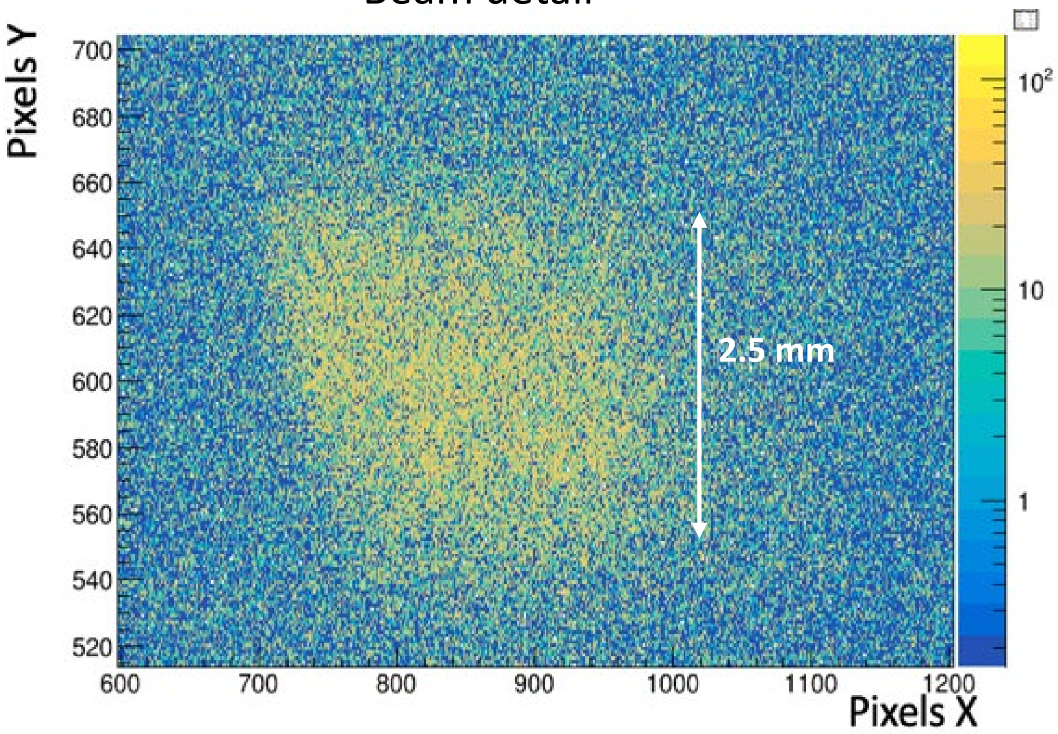
→ Energy loss = 42 MeV (from 236 MeV initial)

Signal and Beam Imaging in Thin PM Scintillator *--> reduce beam current 100X to 4.9 kHz*

Full field of view



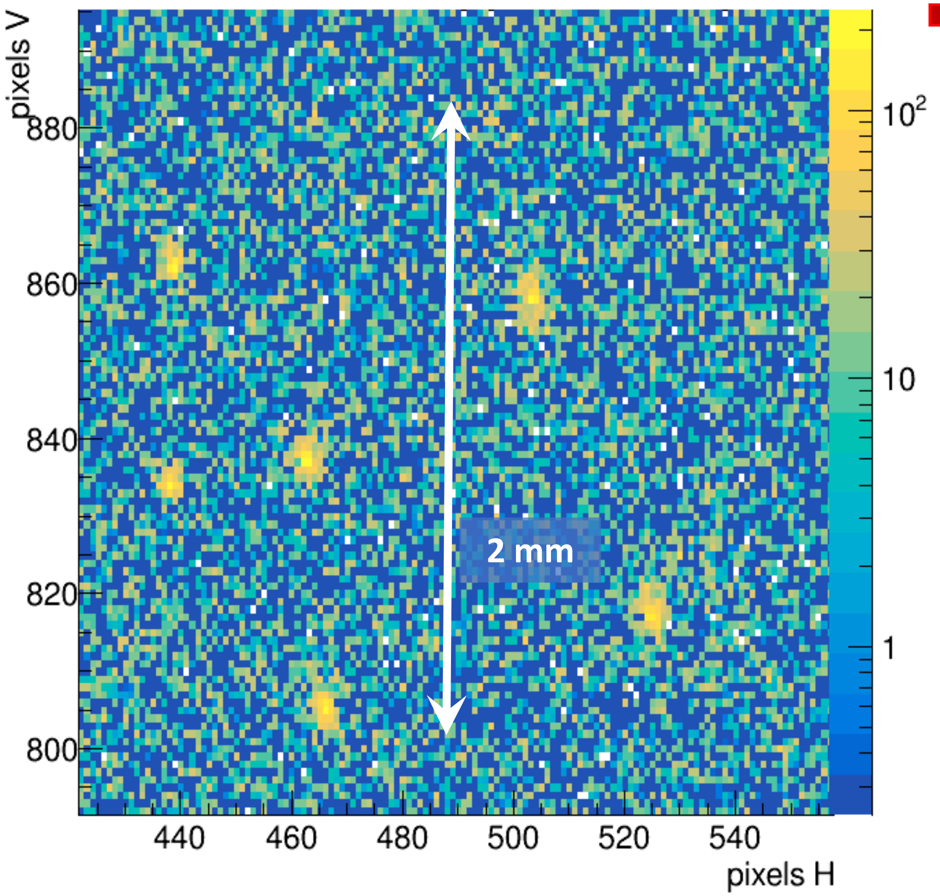
Beam detail

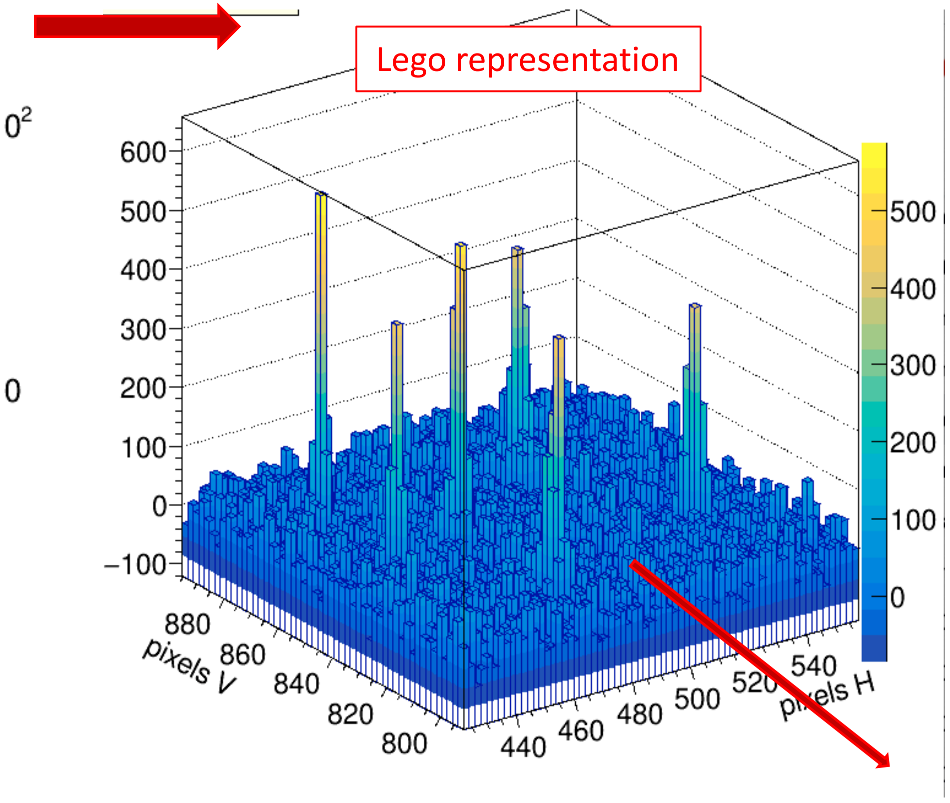


Result 1: Clean beam profile is imaged. ADC signals well above noise

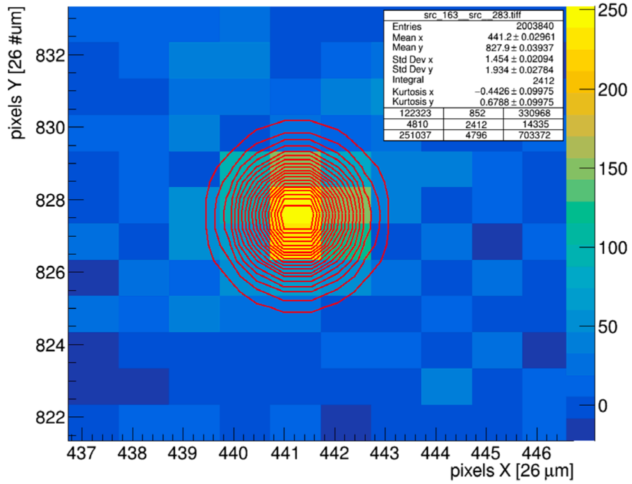
Result 2: Another ~5x reduction to ~1 kHz beam currents would be detectable

Signal and Beam Imaging in HM Scintillator: Beam set to 5 – 10 Hz



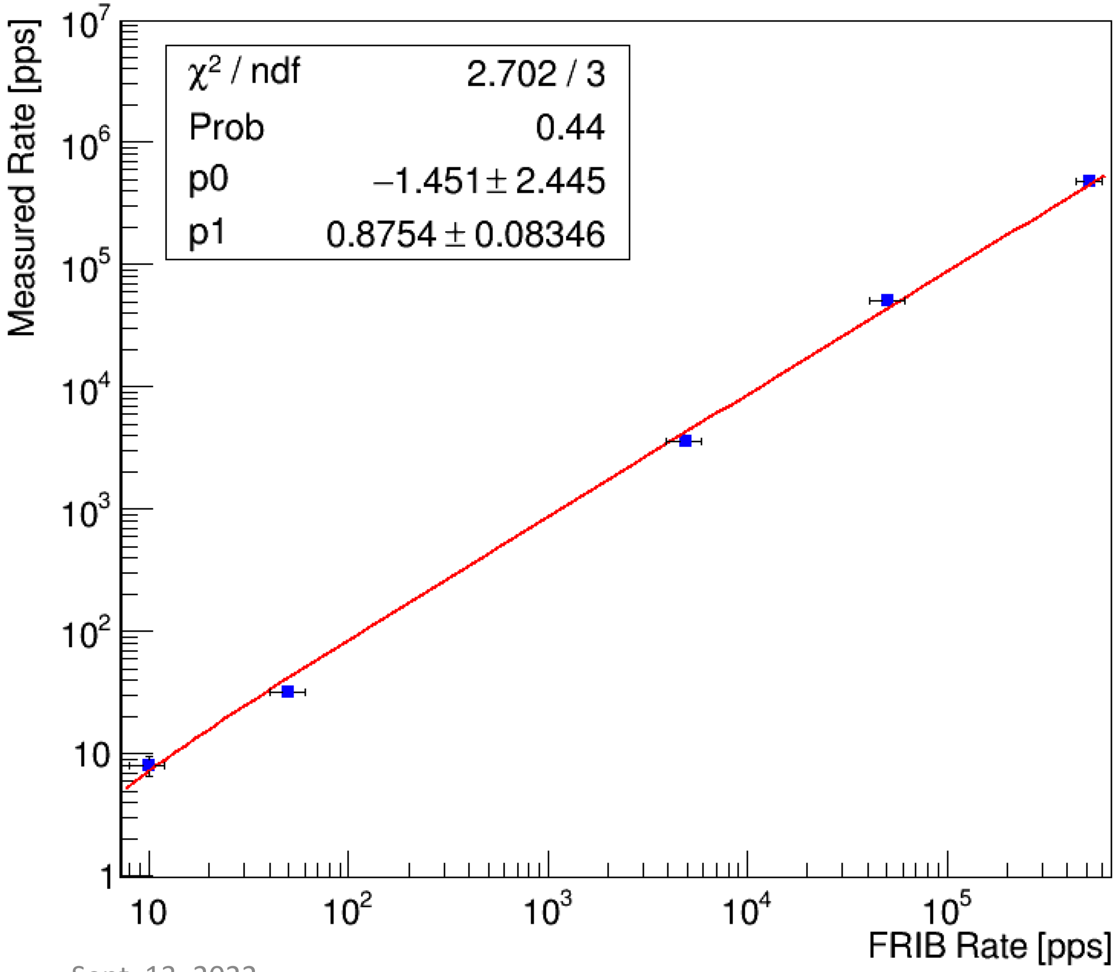


Single hit
centroid error < 2 um



Beam current in HM scintillator:

Meausured rate vs FRIB “given” rate



Result 1:

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

- Faraday Cup
- Calibrated beam attenuator
- MCP detector
- Silicon detector

Result 2:

SBM measurement is linear over 5 orders-of-magnitude

<u>**Beam finding, profile analysis & display in real-time**</u>

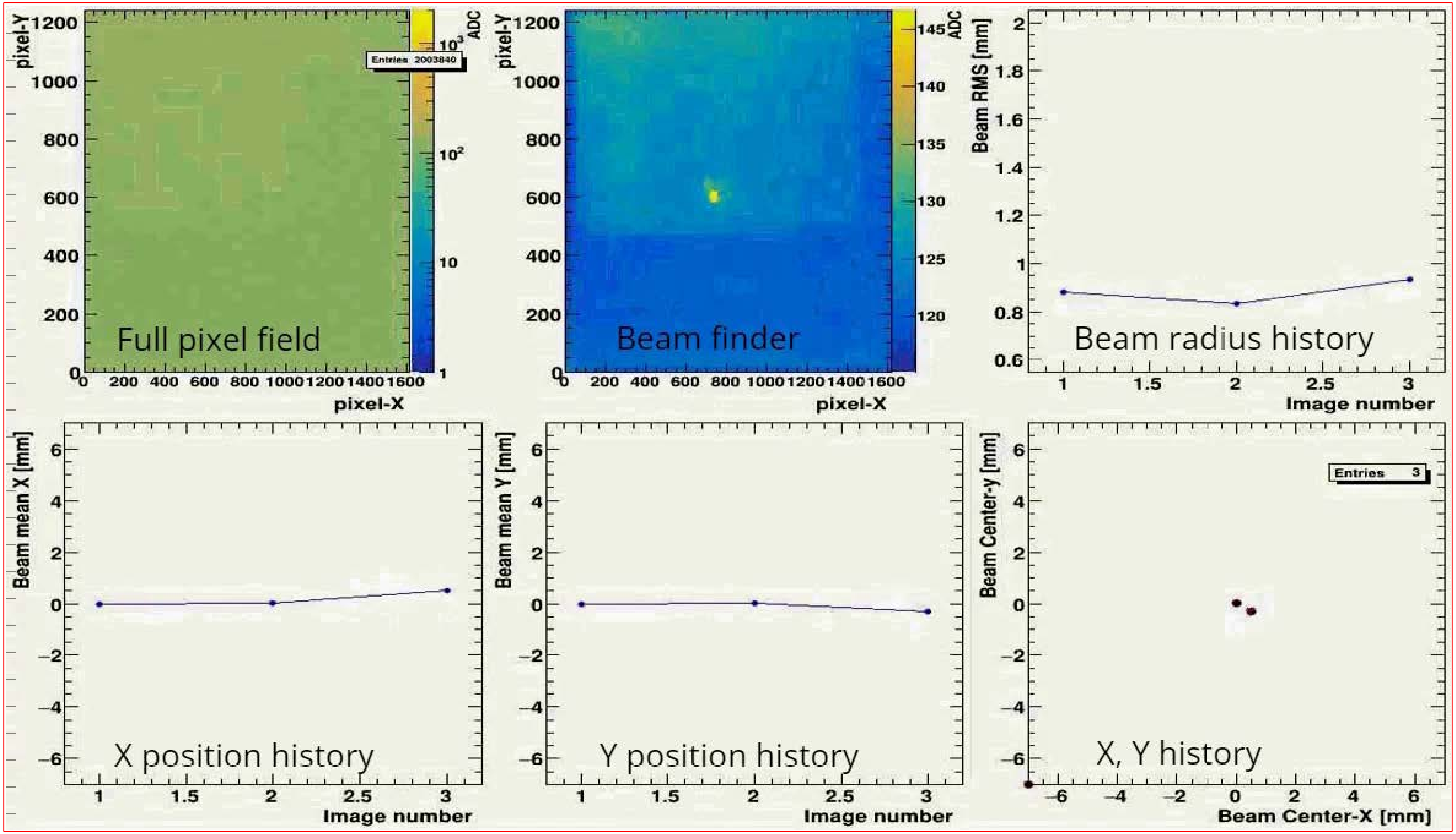
Conditions:

1) Beam current 50 pps – *very low rate.* ➔ *use HM scintillator*

2) *Beam width ~ 2 mm*

3) *Beam moved in square pattern by control room operations*

4) *1 s frames*



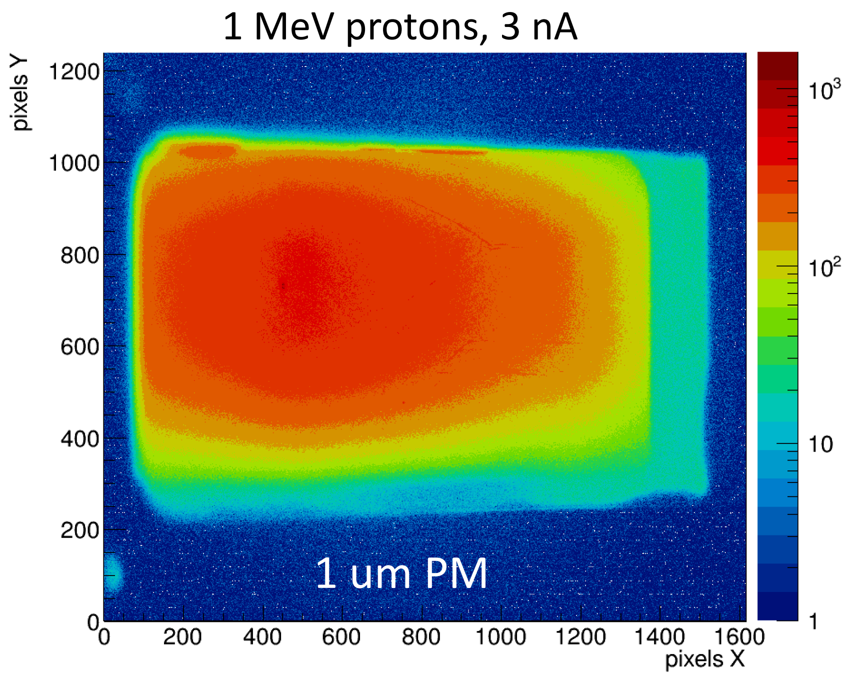
pixel-Y
1200
1000
800
600
400
200
0
200 400 600 800 1000 1200 1400 1600
pixel-X
ADC
Full pixel field
Beam finder
145
140
135
130
125
120
Beam RMS [mm]
Image number
Beam radius history
Beam mean X [mm]
X position history
Beam mean Y [mm]
Y position history
Beam Center-y [mm]
Beam Center-X [mm]
Entries 3
X, Y history

Conclusion

1) SBM provides a precise beam profiling in real-time ($\lesssim$ 1 Hz)

2) Data from:
   FRIB -- linear to *at least* **5 orders-of-magnitude** for $^{86}Kr^{+26}$
   MIBL -- 1-6 MeV protons ~10^{11} pps/cm^2 →
   NDRL -- 8 MeV pulsed **electron** beams to **4x10^{11} pps/cm^2**

==> response range: single particles to 10^{11} pps without breaking vacuum



3) PM: thin to ultra-thin materials produce clean imaging and accurate profiling

- Ultra-thin PM tested: from ~ 1- 200 um sample thickness

- **HM**: ***order-of-magnitude higher signal output*** compared to a much thicker CsI(Tl) standard

  → allows for very high sensitivity (single particles) at FRIB etc.