Phase-IIB: High Performance **S**cintillator & **B**eam **M**onitoring System

*Scintillator-based **B**eam **M**onitor (**SBM**) for Real-Time Tuning, Imaging & Analysis from **Single-Particles** to High-Intensity Beams*

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Phase-IIB Program

Transition of Phase-II R&D to Commercialization

Phase-IIB: Customer Centered Approach

- **FRIB customer & NP market**: ***No one-size-fits-all*** product solution, especially for different energy ions, different ion energies, and different size beamlines.
- SBM platform "retrofit" approach requires no new ***beamline real estate***.
- Customer installation & in-place diagnostic boxes ***greatly reduces system cost***.
- Customer's in-house labor/expertise provides ***flexibility*** *and* ***customization*** at lowest possible cost, especially for ***multiple*** SBM identical platforms.

Phase-IIB: Implementation at FRIB

- Phase-II to Phase-IIB:

  Transition from ***standalone Six-Way-Cross*** **Prototype** in Phase-II with a **4 cm^2** (beam cross-section) scintillator, to a customizable **PRODUCT** ***platform*** in Phase-IIB with a **49 cm^2** (beam cross-section) scintillator **integrated** into ***existing*** NP beam monitoring diagnostic systems by I-S and customer. Major advantages: ***single particle imaging*** *(first time ever), faster, more precise beamline tuning, eliminating new beamline real estate requirement and having to switch to surrogate "pilot" beam for tuning.*

- Application of NP Phase-II to **NIH-NCI** for **FLASH Radiotherapy**

Phase-IIB Overview

Goals

I. **Advanced beam analysis in real-time over wide-range down to single-particles**

II: Critical components ***inserted*** into existing beam diagnostic systems by I-S or customer

Features

- **Novel-use thin scintillators**: very high sensitivity, clean imaging, low mass
- Optical system: ***ultra-fast*** **large aperture optics** for max light collection (i.e., **F/0.9**)

Specs

- **~ 20-30 µm position resolution**
- Fast detection finds weak beams within **~ 0.3 sec**; updated continuously at **1-3 Hz**
- Updating false-color display in beam coordinate system
- **Wide dynamic range: ~ *7 orders-of-magnitude***, and down to ***single-ions***
- Higher energy beams are **transmissive**
- Linear to ***at least 5* orders-of-magnitude** in beam current

Scintillators – ***thin, non-hygroscopic & radiation damage resistant***

Type 1: **Hybrid Material (HM)** – Inorganic polycrystalline ceramic hybrid

- ***Thin***, ~ 300-500 µm water-equivalent thickness (WE)

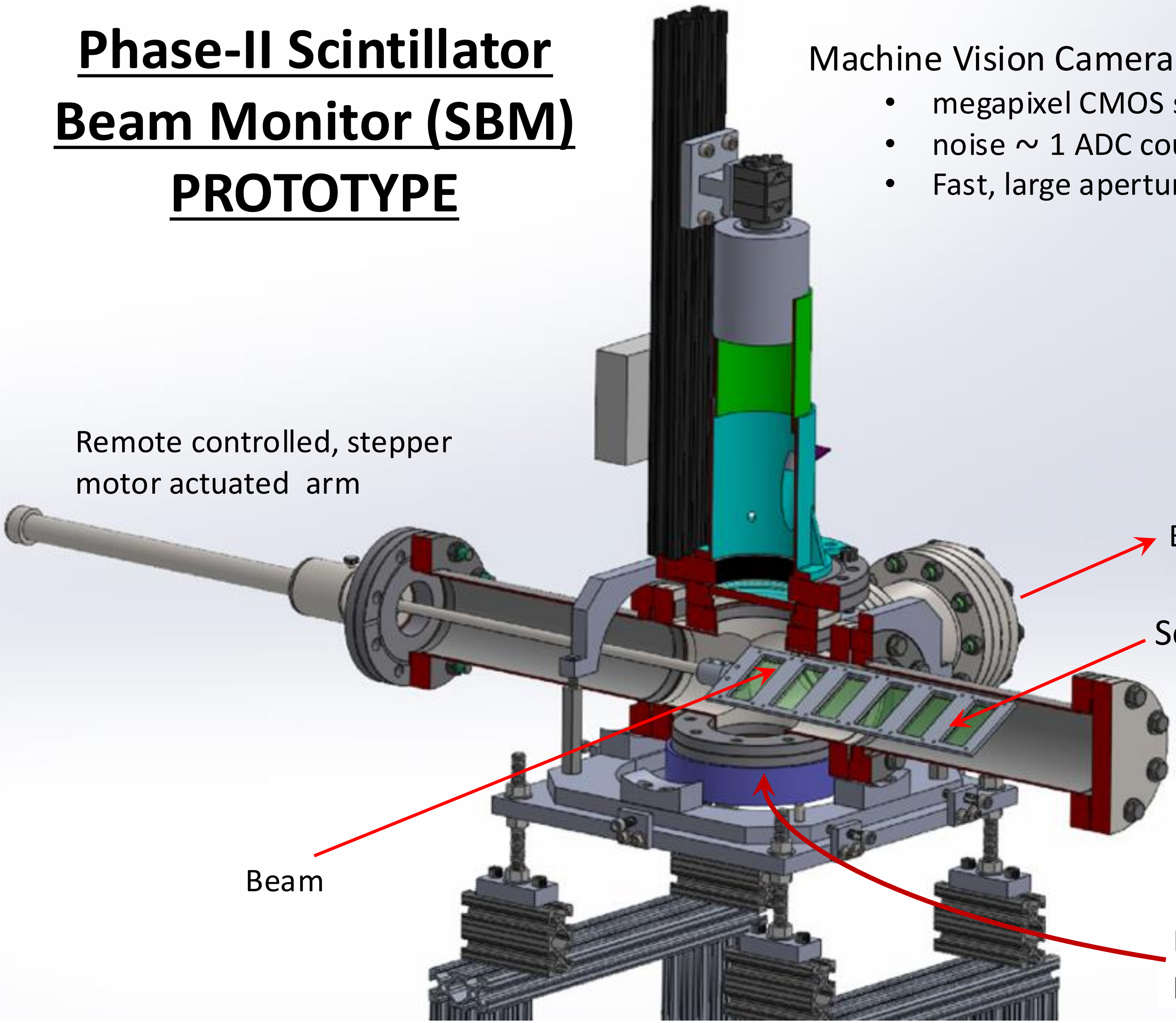
Type 2: **Polymer Material (PM)** – Semicrystalline

- ***Ultrathin*** to Thin: tested 2 µm WE to < 300 µm WE

Both Types 1 & 2 have favorable properties:

- Excellent radiation hardness
- Sharp images – essentially no internal reflections
- Non-hygroscopic
- Transmissive (depending on ion and beam energy)
- High light emittance for their respective type

Phase-II Scintillator Beam Monitor (SBM) PROTOTYPE



Machine Vision Camera:

- megapixel CMOS sensor
- 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

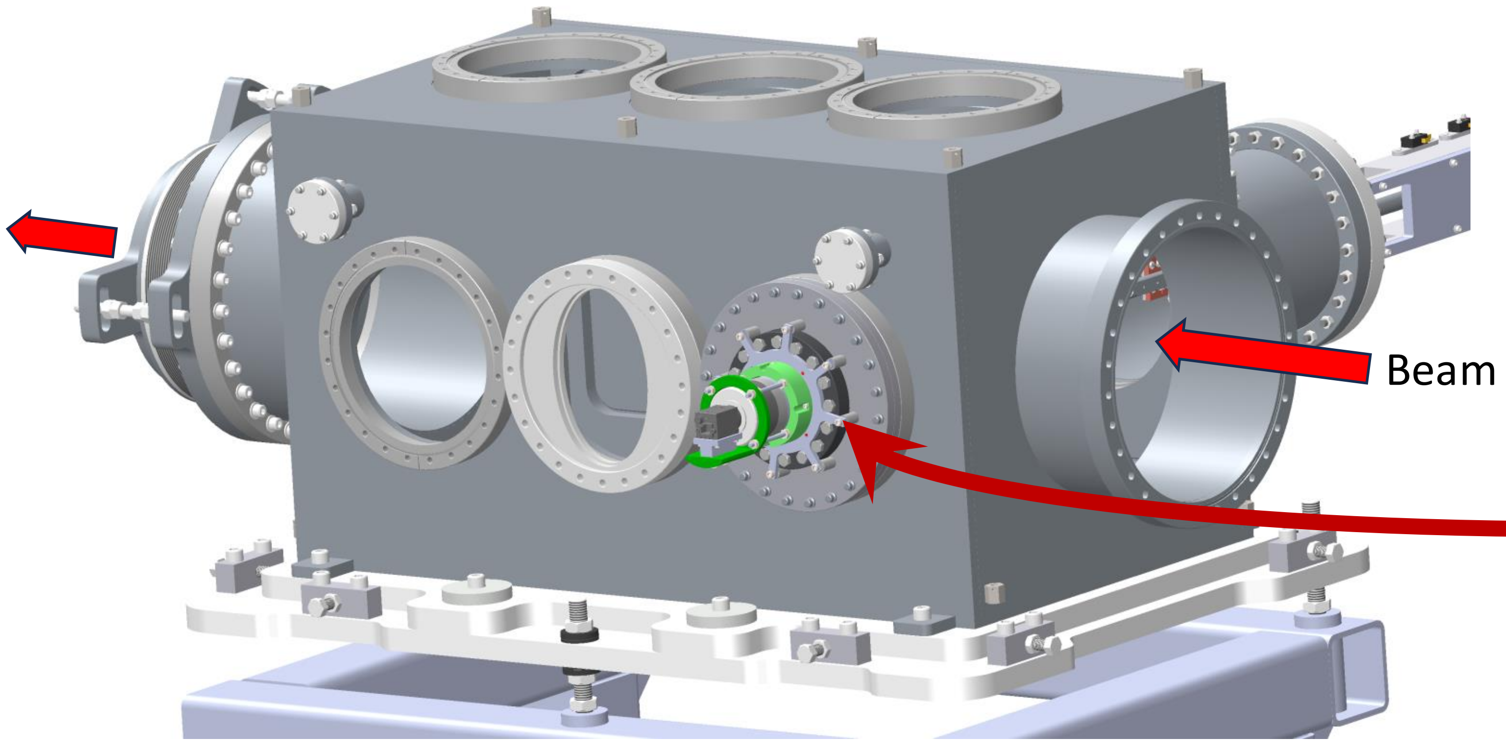
Beam

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

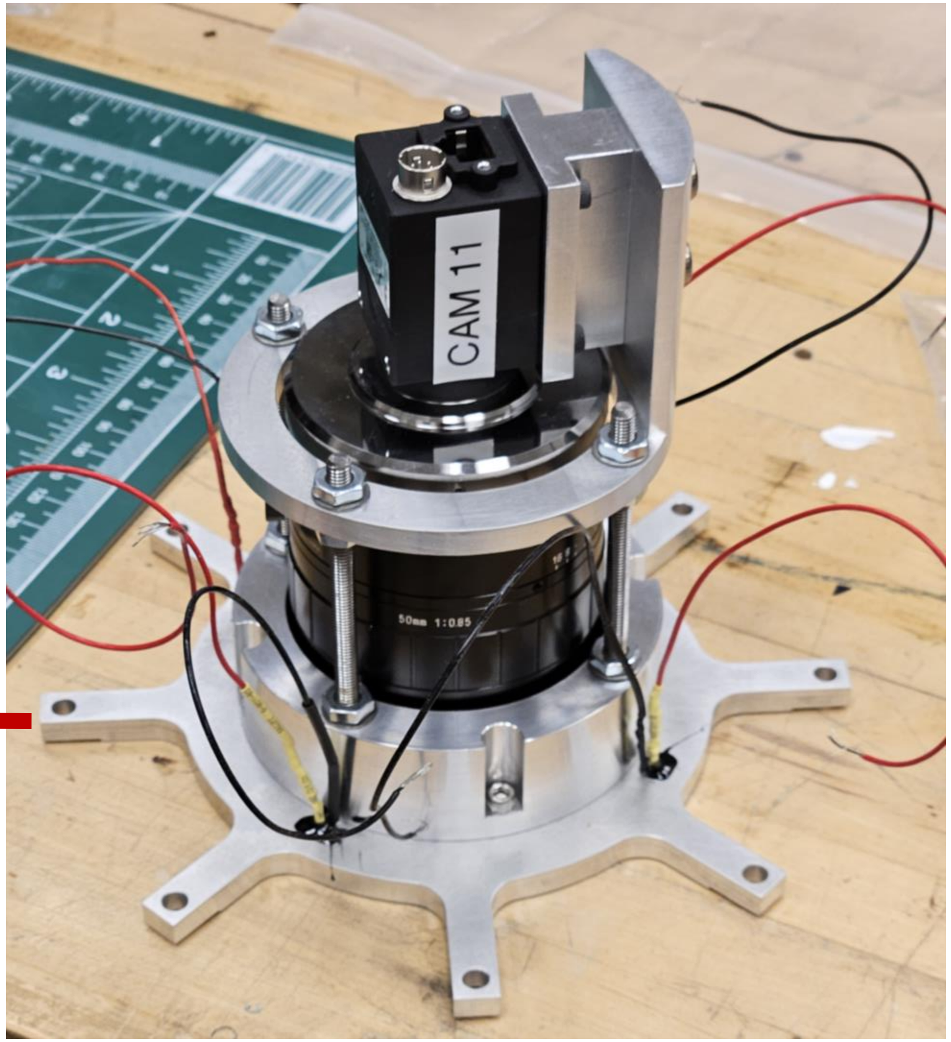
ReA3-SECAR* Scintillator Beam Monitor (Phase-IIB)

*SECAR = Separator for Capture Reactions

Mounting Scheme onto High Vac Instrument Box

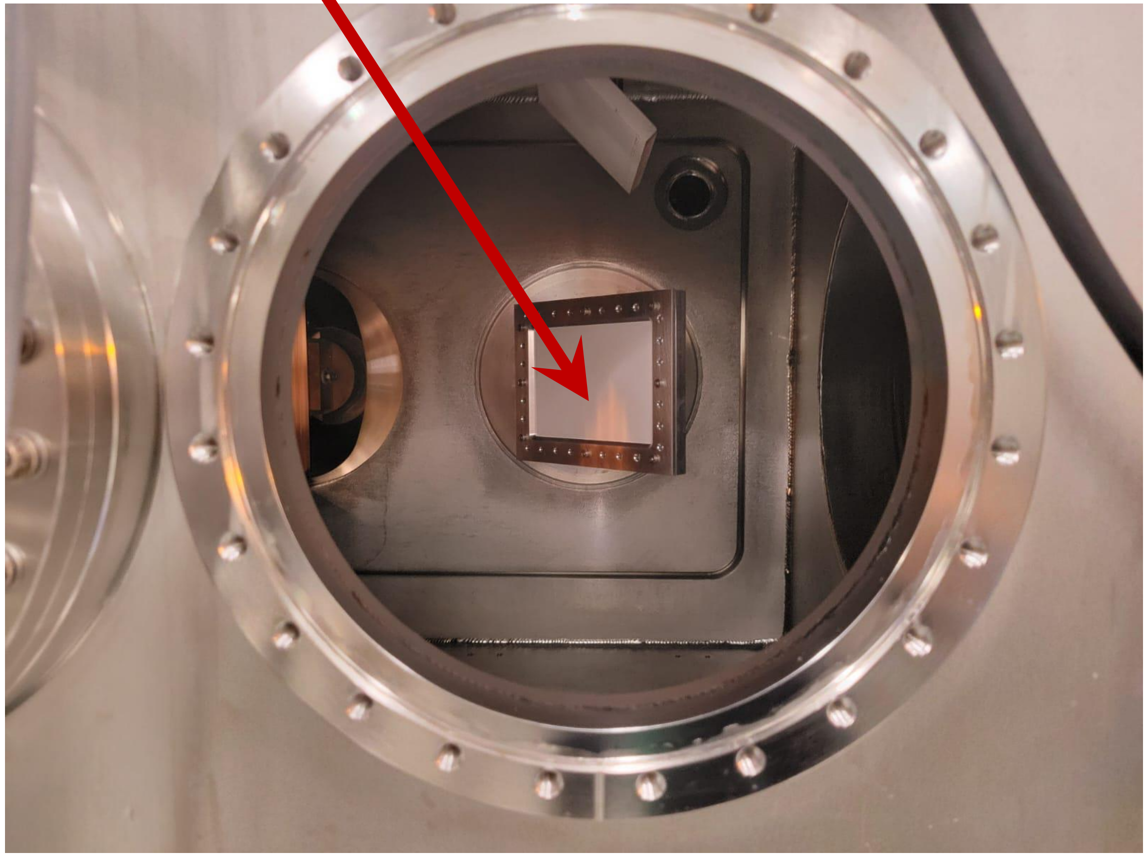


Camera Assembly

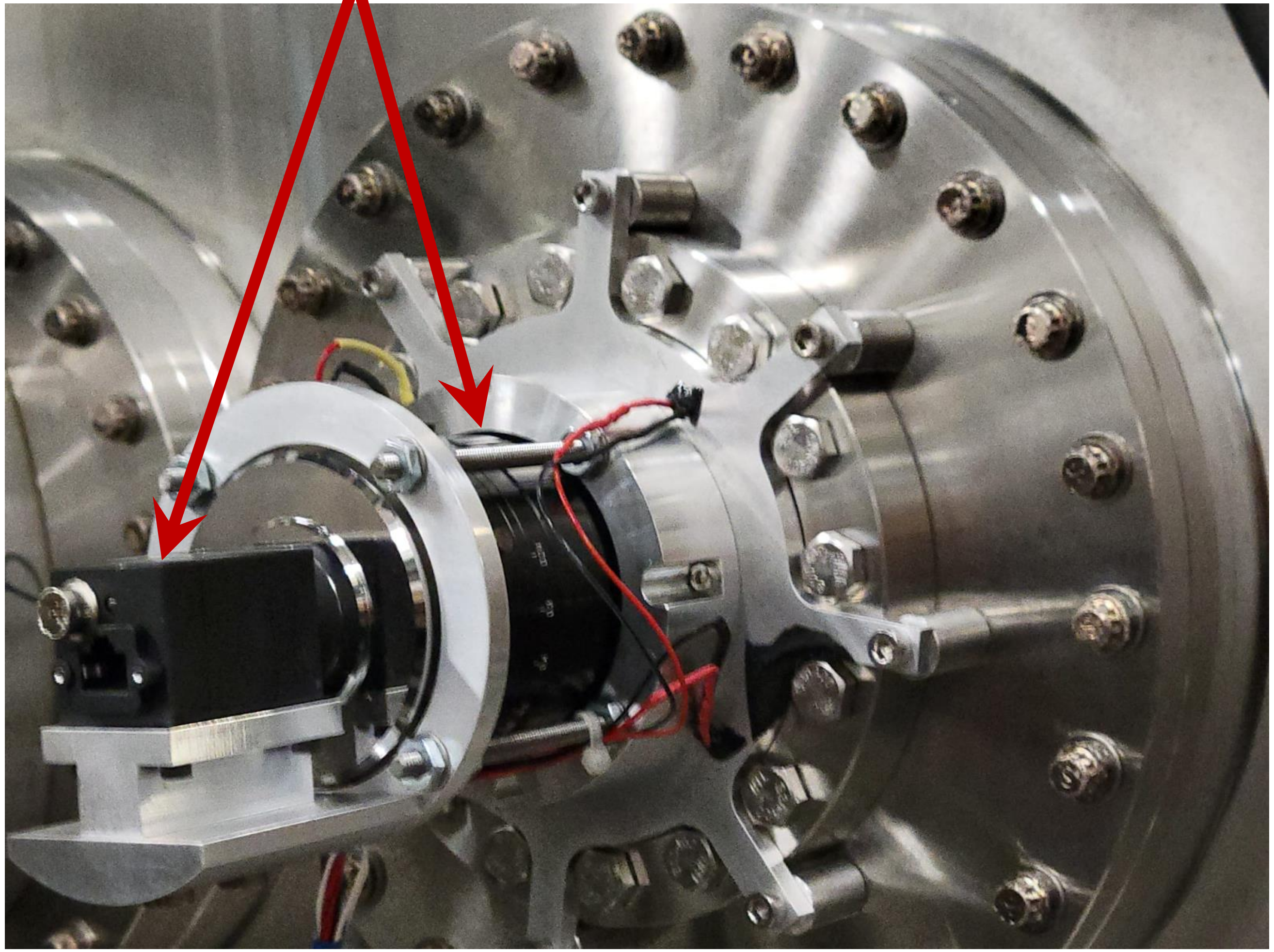


Installed ReA3-SECAR Beam Monitor PRODUCT

Scintillator (7 x 10 cm) installed at 45° inside Instrument Box

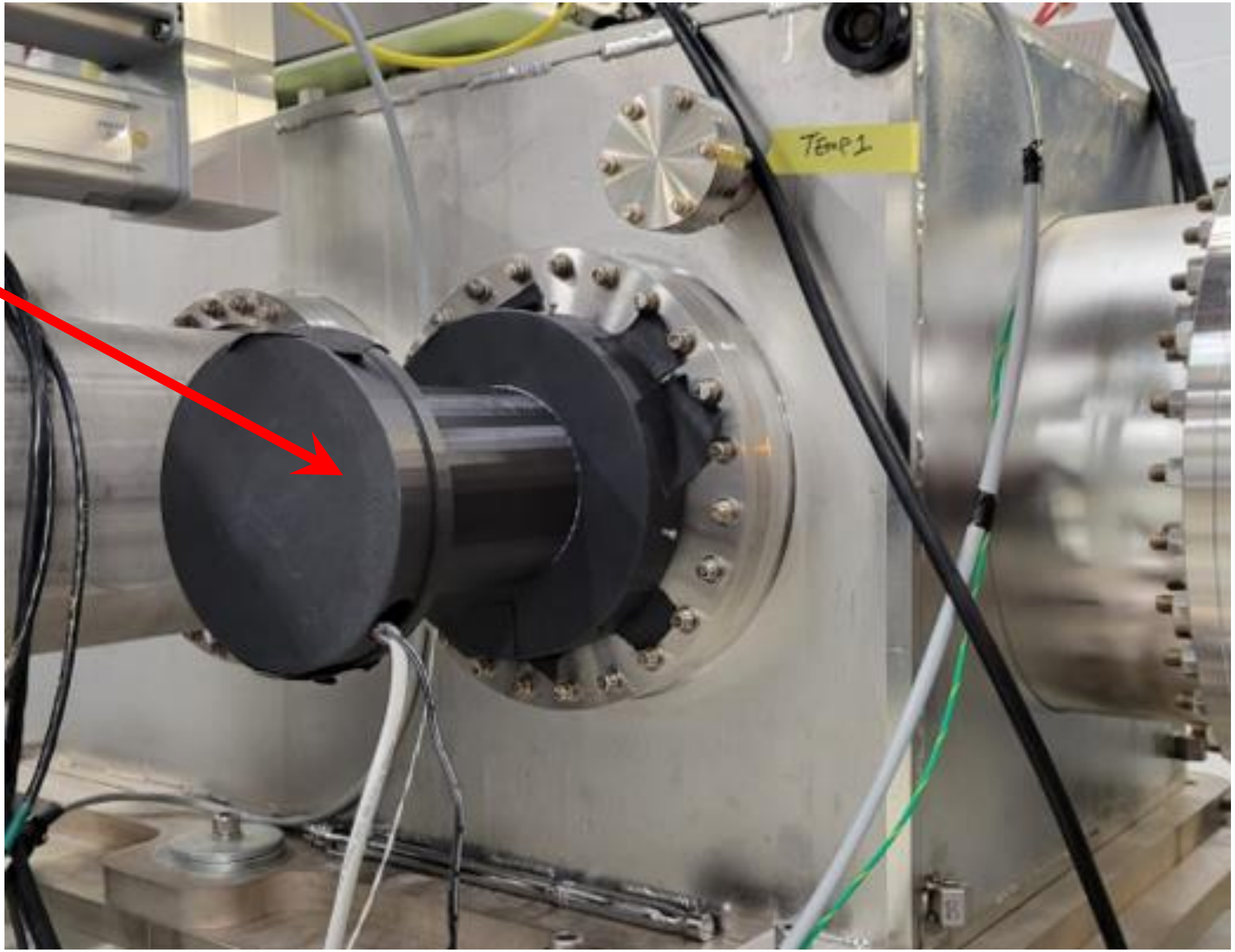


Camera Assembly mounted to Instrument Box



ReA3-SECAR SBM Camera-Lens Housing

3D-Printed
Camera-Lens
Light-Tight
Housing



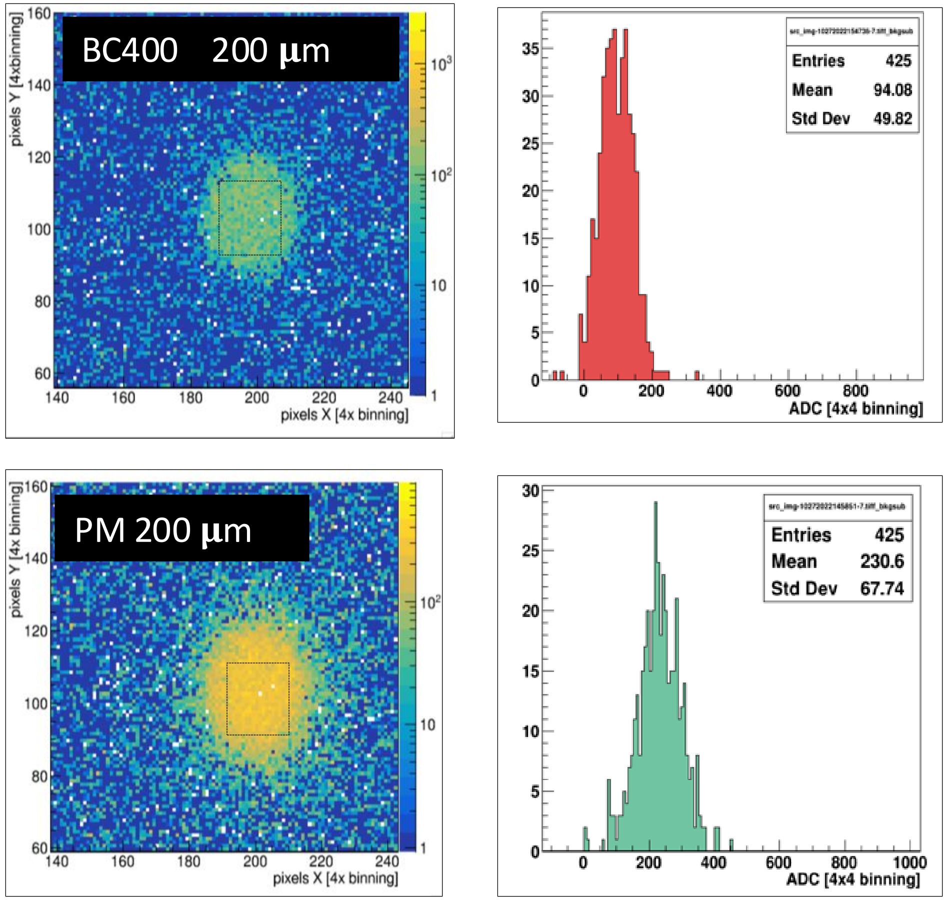
Test Beams (Phase-II and Phase-IIB)

Location	*Source*	*Energy [MeV/u]*
UM Physics Lab	**β** (^{90}Sr) & **α** (^{241}Am)	~1
Michigan Ion Beam Laboratory (MIBL)	p	1 - 6
Facility for Rare Isotope Beams (FRIB)	**$^{86}Kr^{+26}$**	**2.75**
(FRIB SECAR Installation 7/11/2024)	**$^{35}Cl^{+15}$ & $^{14}N^{+6}$**	**4.5**
Notre Dame Radiation Laboratory (NDRL)	e^-	8

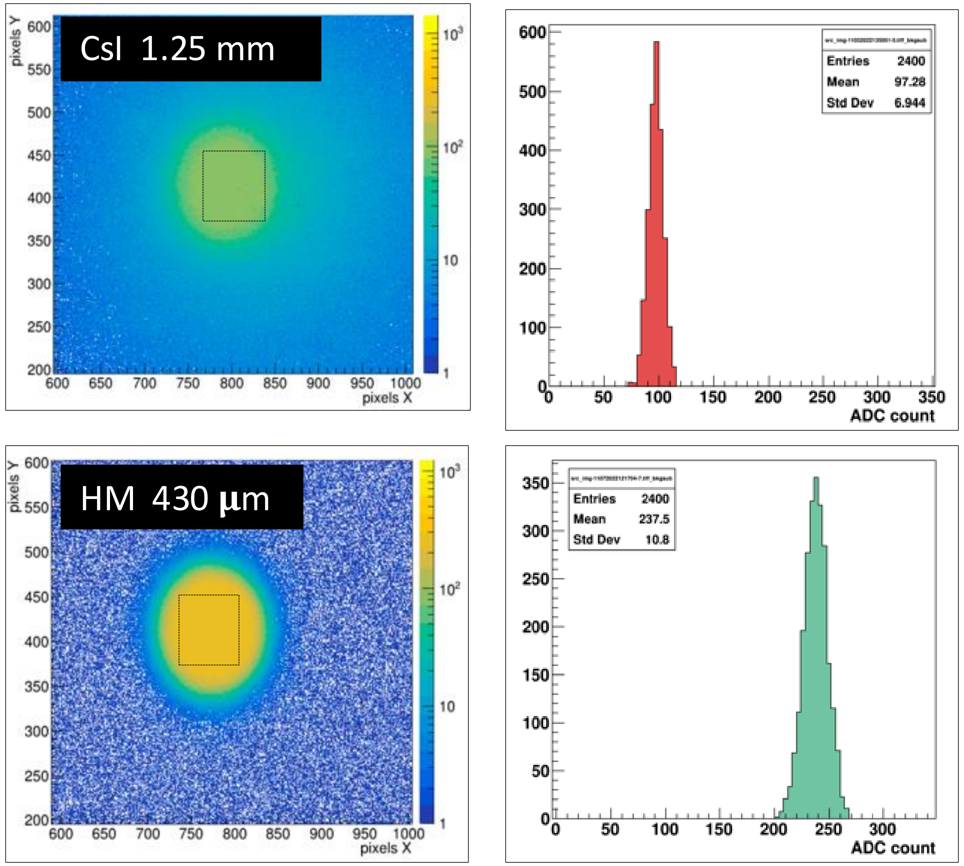
Scintillator Efficiency Comparisons to Benchmarks

3 mm collimated electron beam (β^- source ^{90}Sr)

PM type

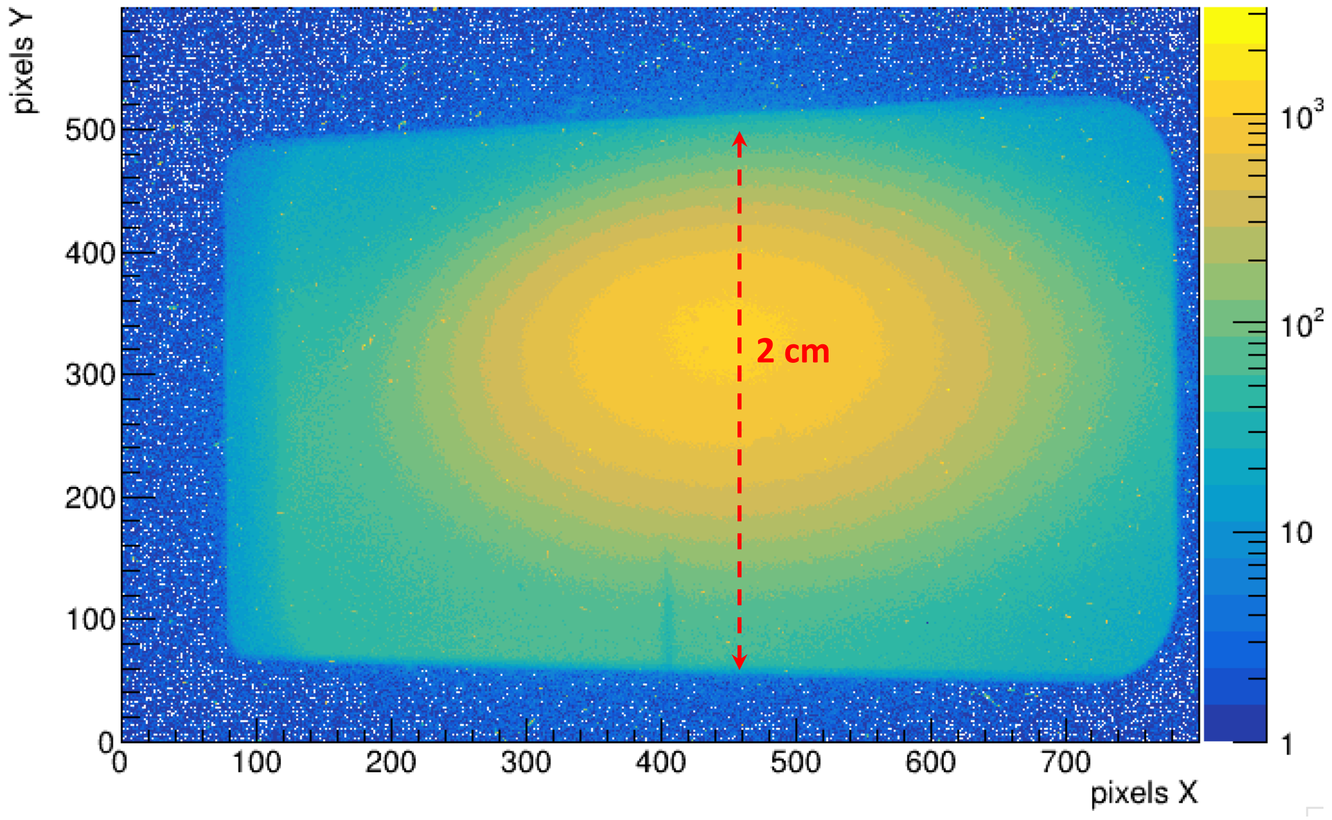


HM type

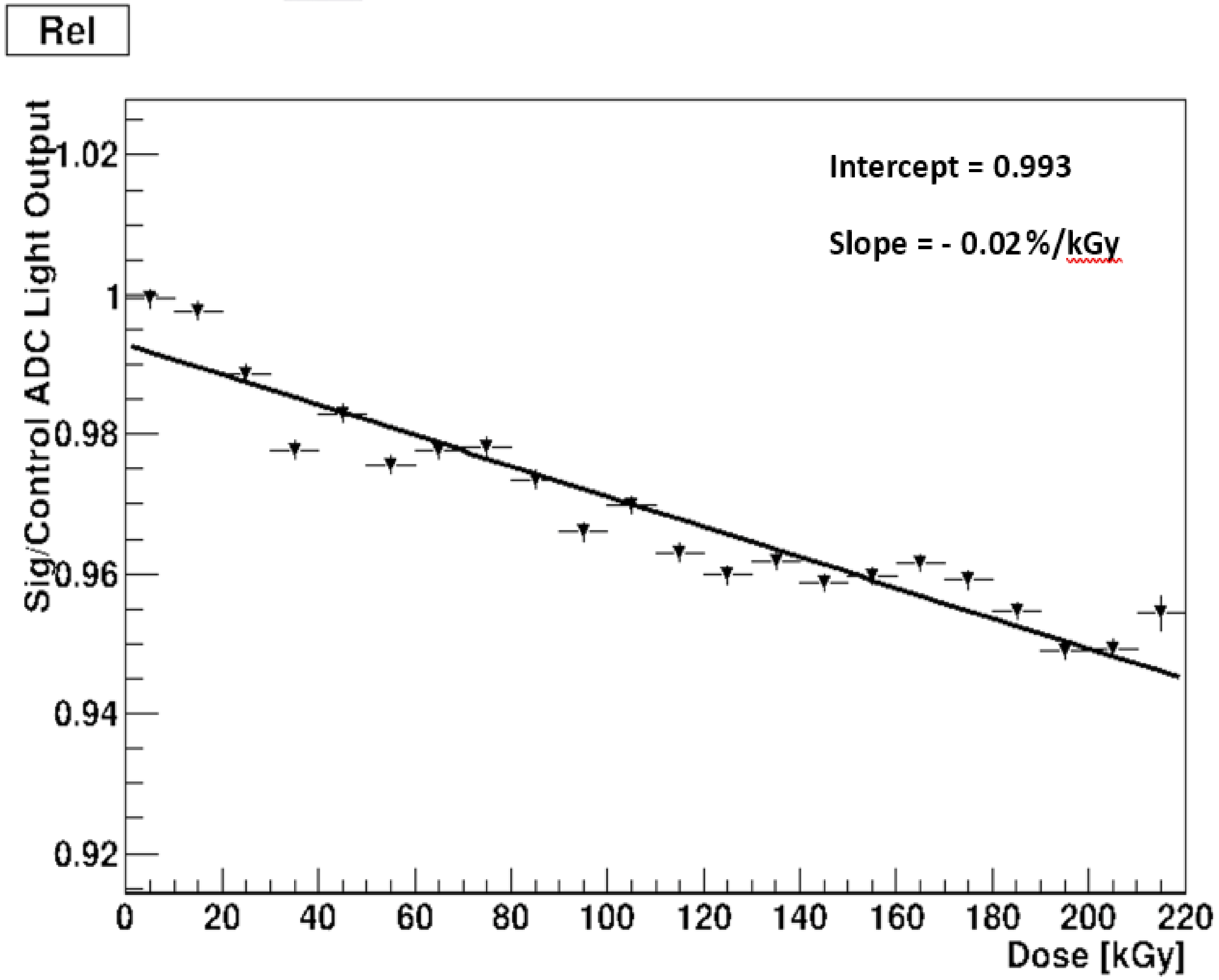


<u>Beam Image on HM at NDRL</u> (camera coordinates)

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



Radiation Hardness of HM Scintillator



For proton-FLASH-RT @ 10 Gy/patient, 20 patients/day, 5 days/week, the dose is 1 kGy/wk or **50 kGy/yr**.

Rad hardness measured over **212 kGy** or > 4 yrs, max. signal loss of ~ 4%, or **< 1% signal loss/yr**, i.e. **0.02%/kGy**.

Signal loss is reduced by spontaneous rad damage recovery & correctable with internal UV calibration system.

Full pixel field at 50 pps

Beam finder

Beam radius history

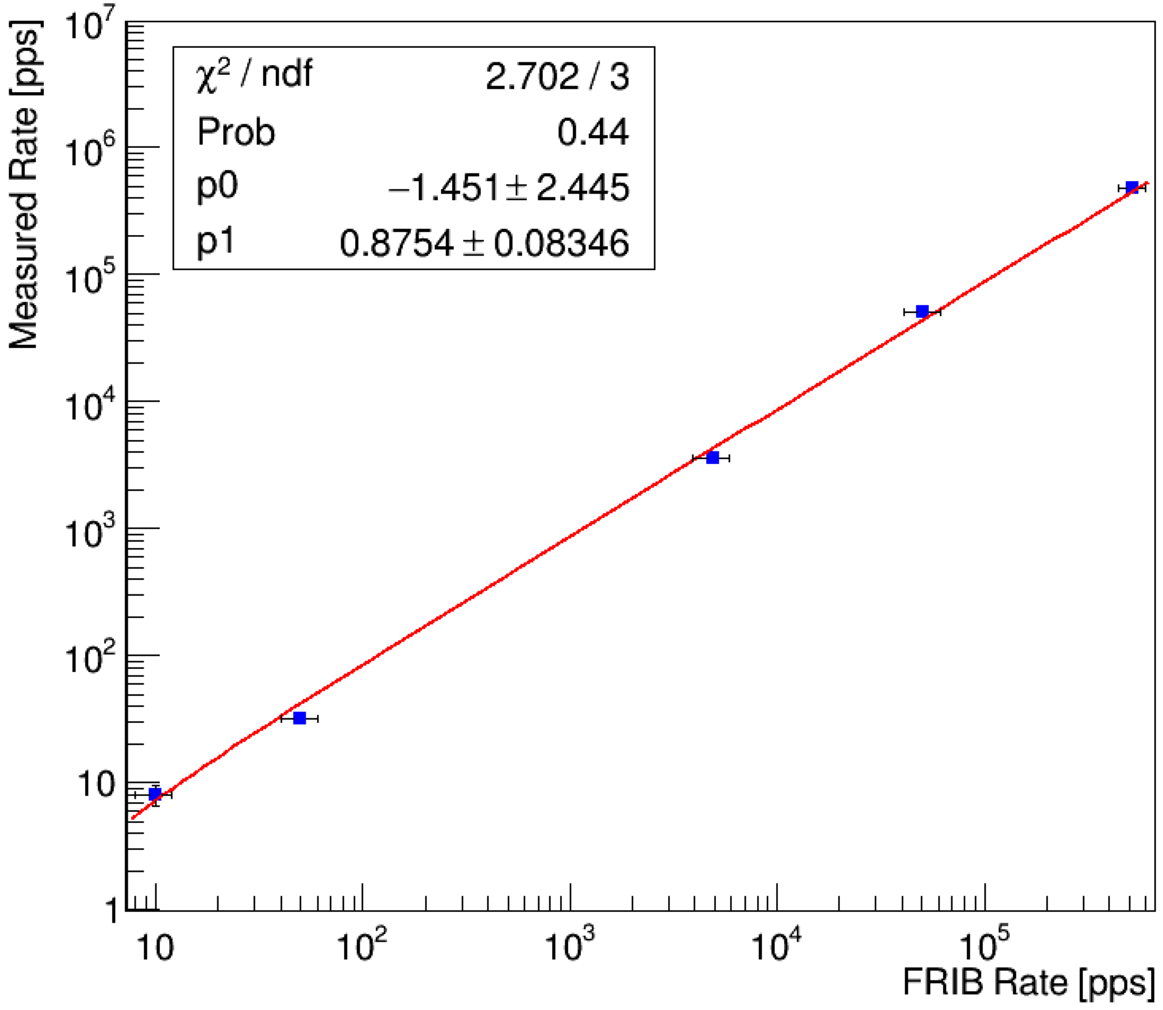
X position history

Y position history

X,Y history

$^{86}Kr^{+26}$ 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:

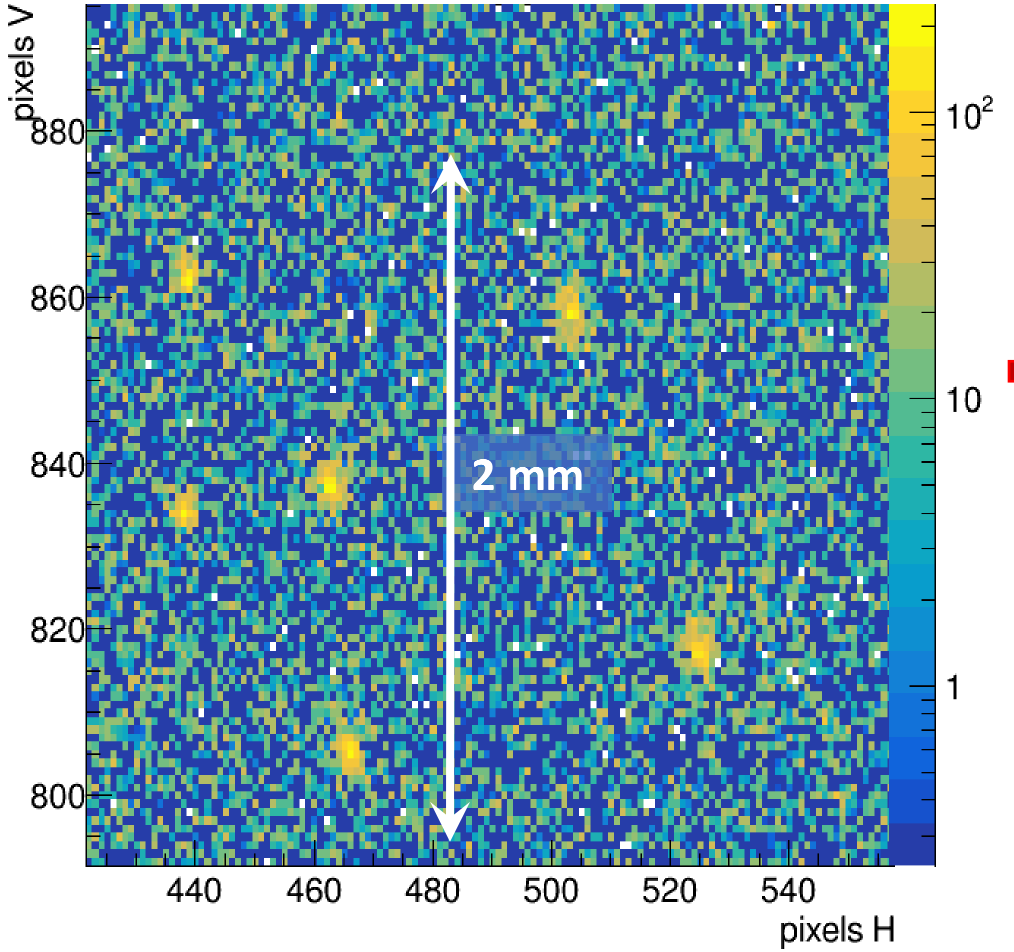
SBM measurement is <u>*linear over more than*</u> <u>5 orders-of-magnitude</u> (the full range has not been determined)

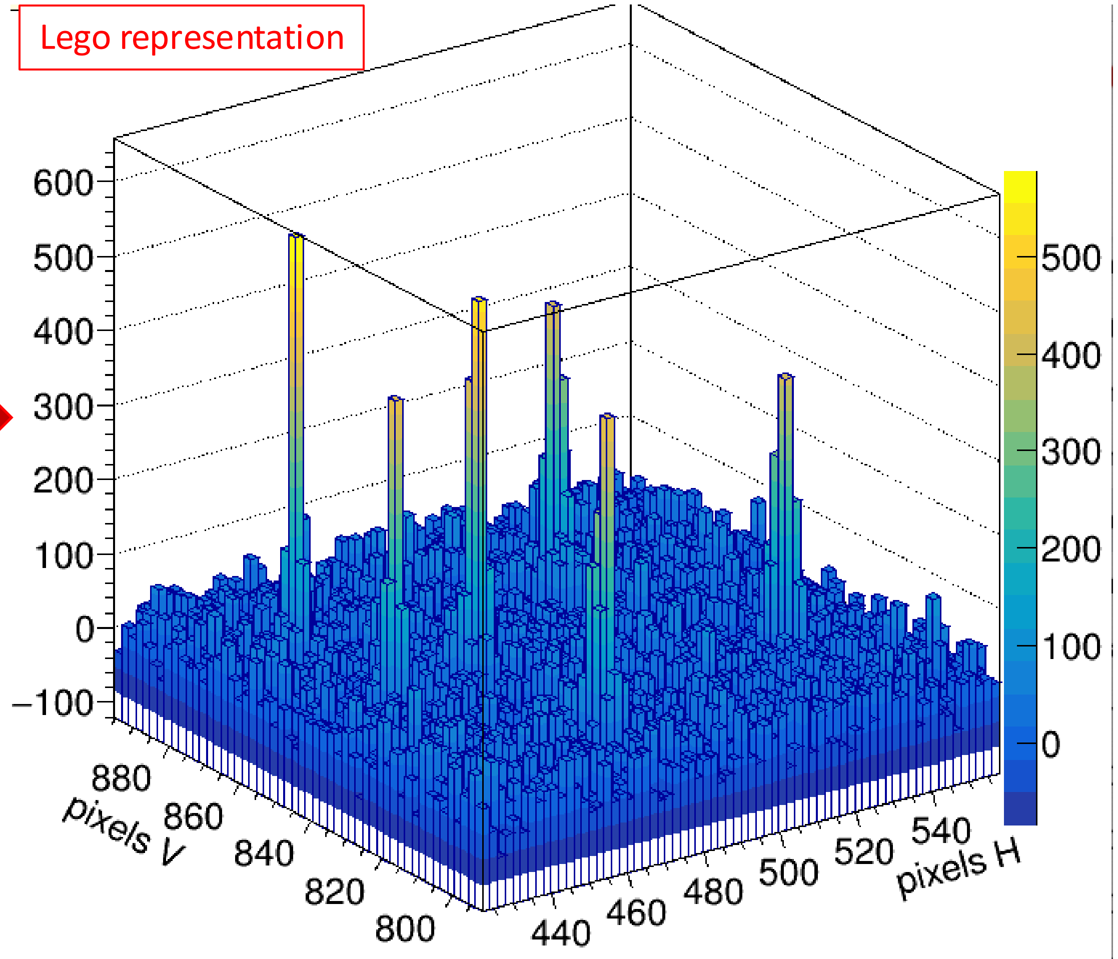
"Single Particle" hits/images

($^{86}Kr^{+26}$ Beam Imaging in HM Scintillator)

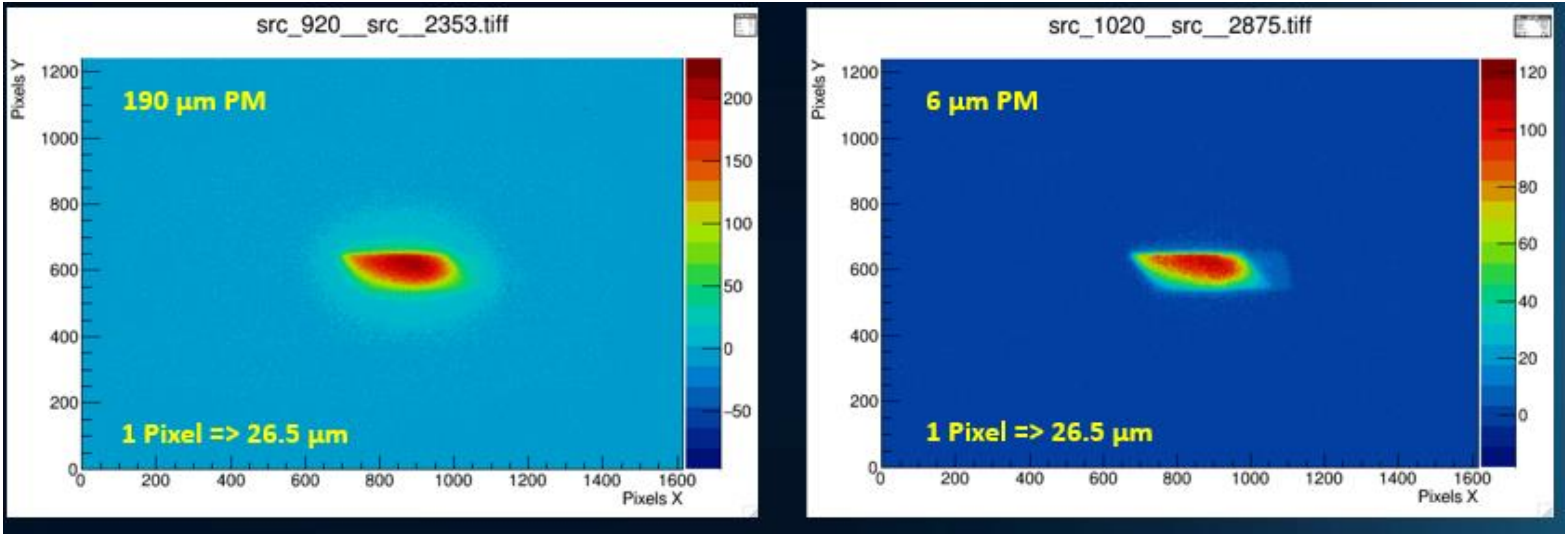
Beam current ramped down to < 10 Hz

~ 5-6 Individual ^{86}Kr hits observed in 1 s frames





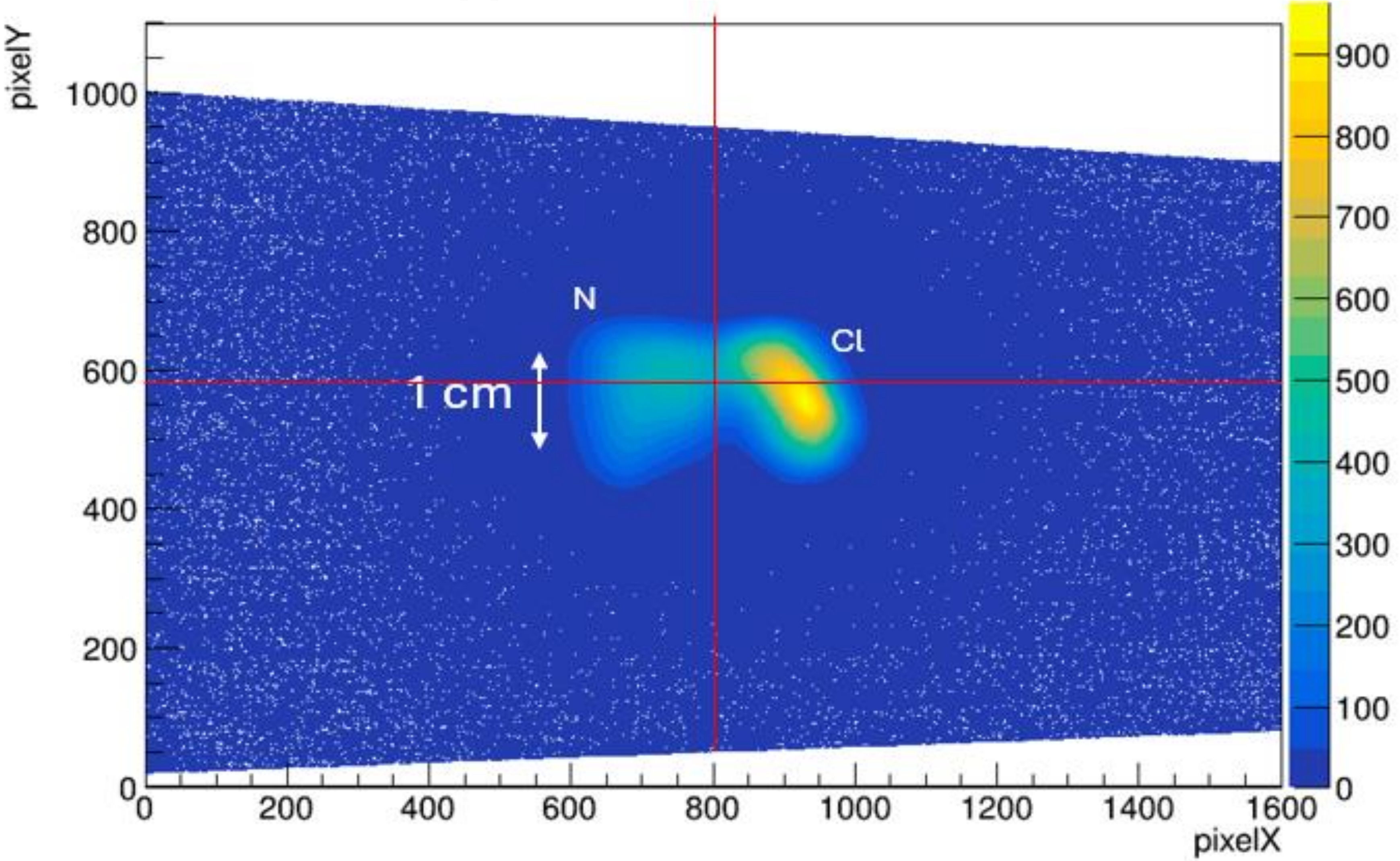
Phase-II Beamline Images of $^{86}Kr^{+26}$



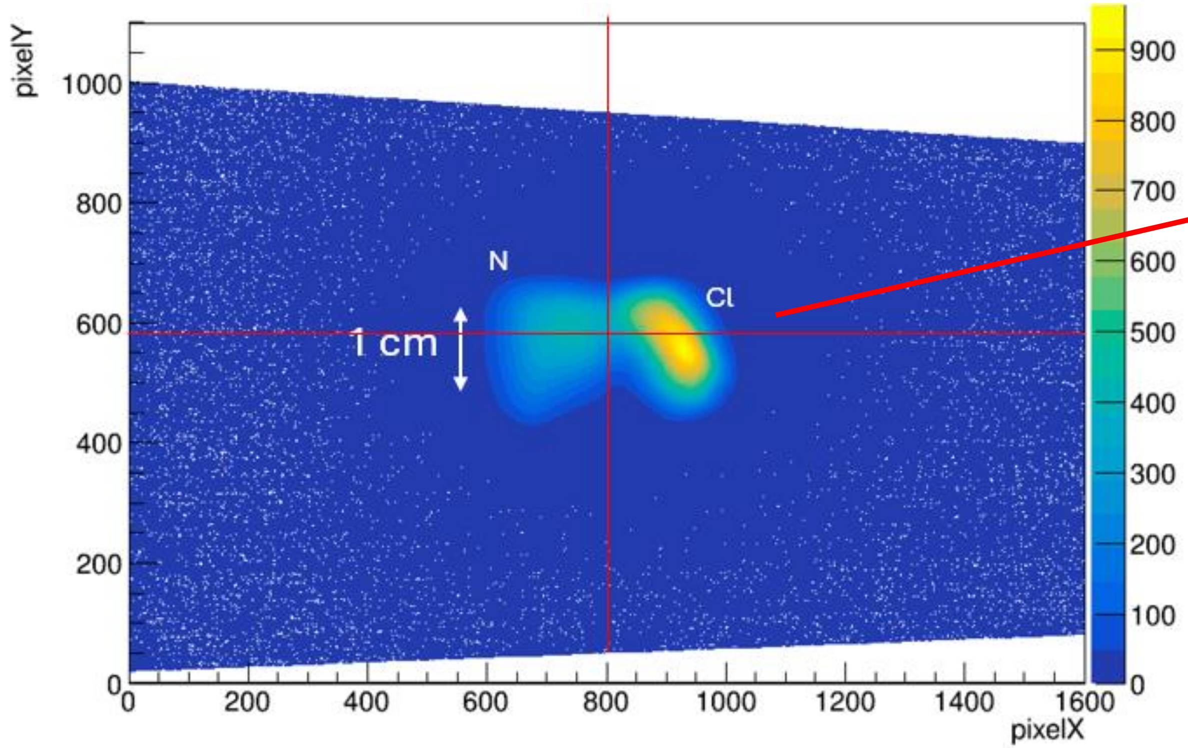
Above beamline images captured in real-time of same 2.75 MeV/u beam of $^{86}Kr^{+26}$ particles irradiating two different thickness 2x2 cm **PM** scintillators at a rate of **5.2 x 10^5 pps**. Image on Left was with **190 µm** thick **PM;** image on Right was with **6 µm** thick **PM** that **transmits 75% of the beam**. Z-bar intensity scale is different for the two images with max intensity of Left image twice that of Right image.

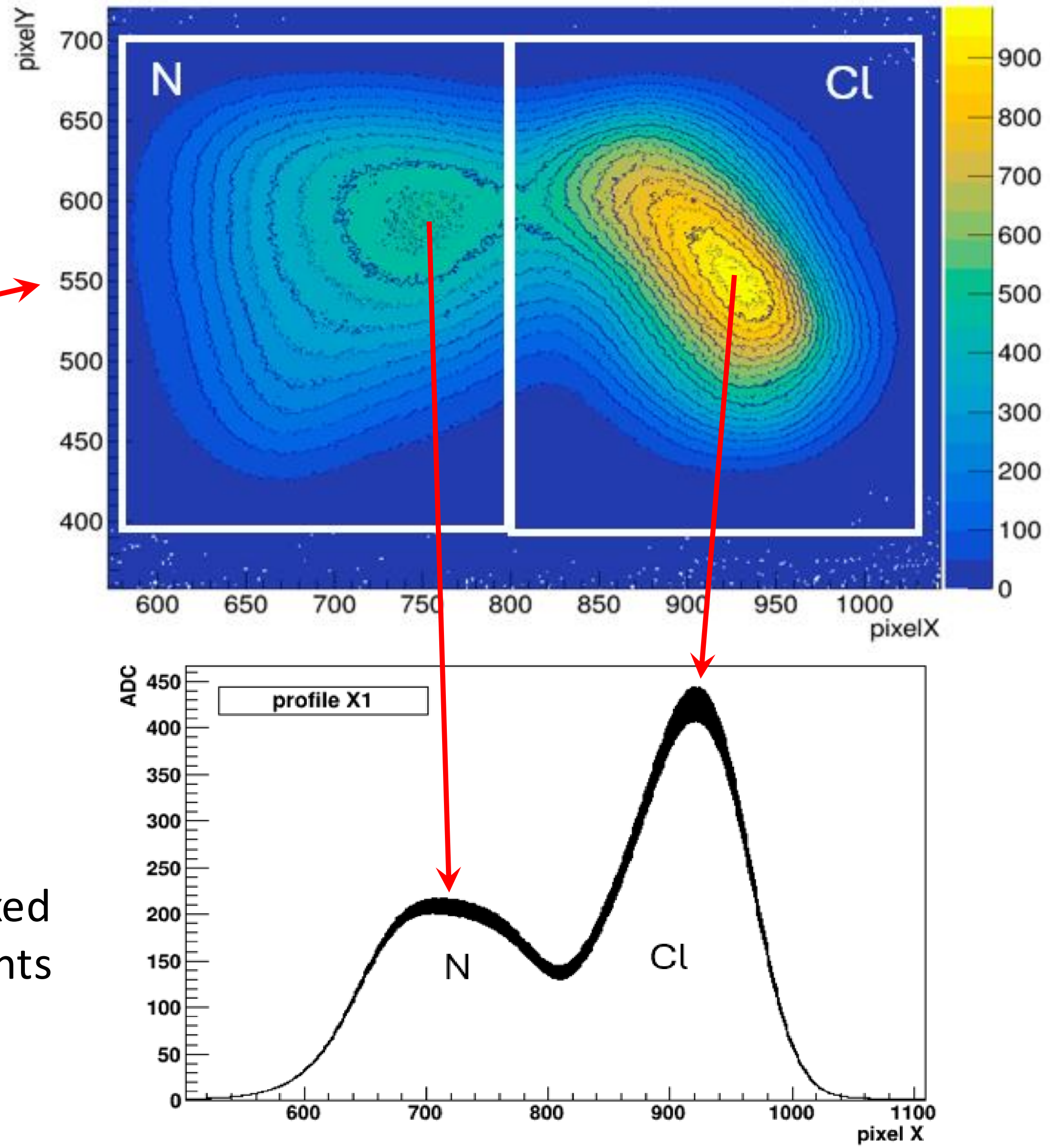
Phase-IIB Mixed Beam of $^{14}N^{+6}$ and $^{35}Cl^{+15}$

1.35 x 10^6 pps (0.1 sec exposure), 4.5 MeV/u



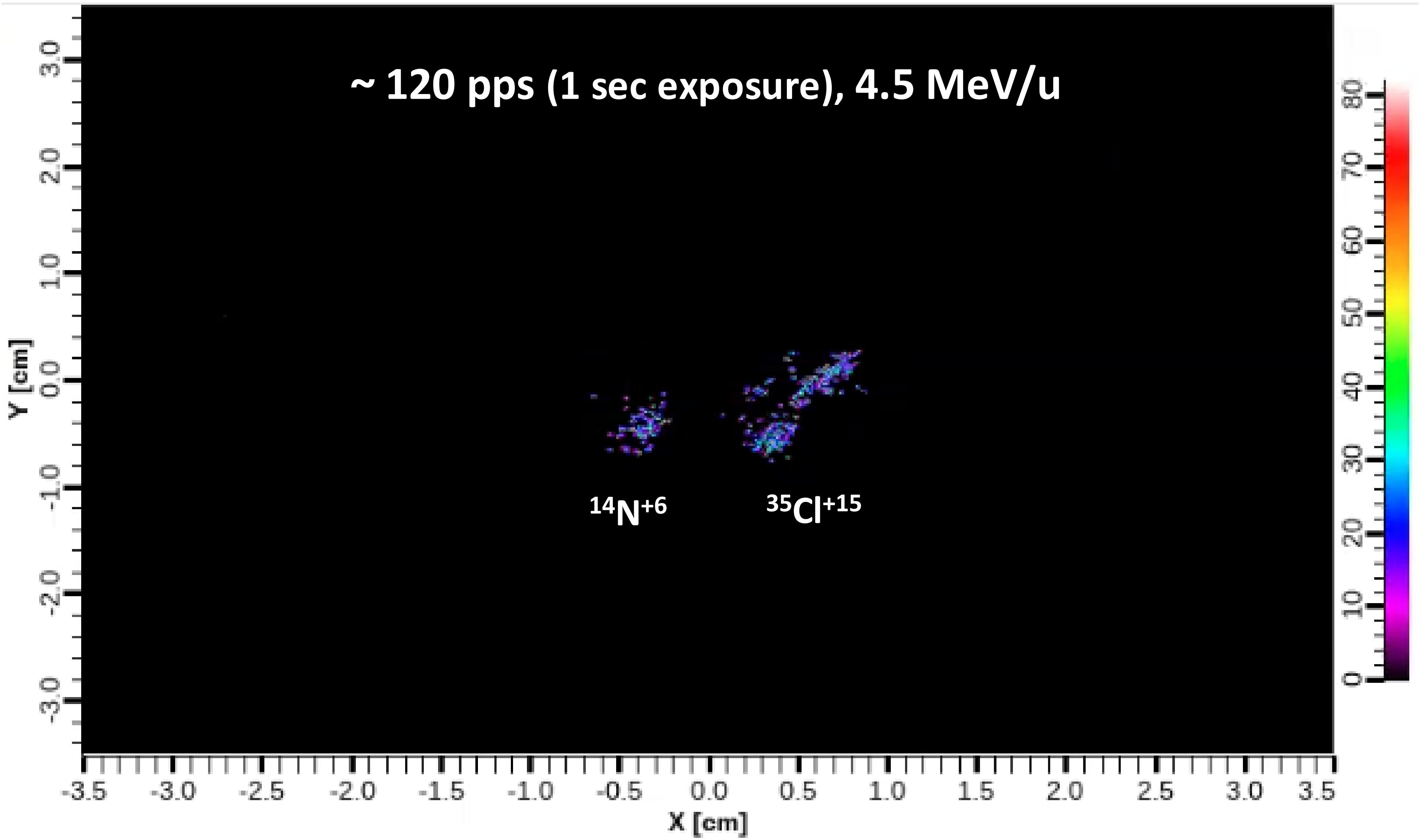
Mixed Beam Analysis of $^{14}N^{+6}$ and $^{35}Cl^{+15}$



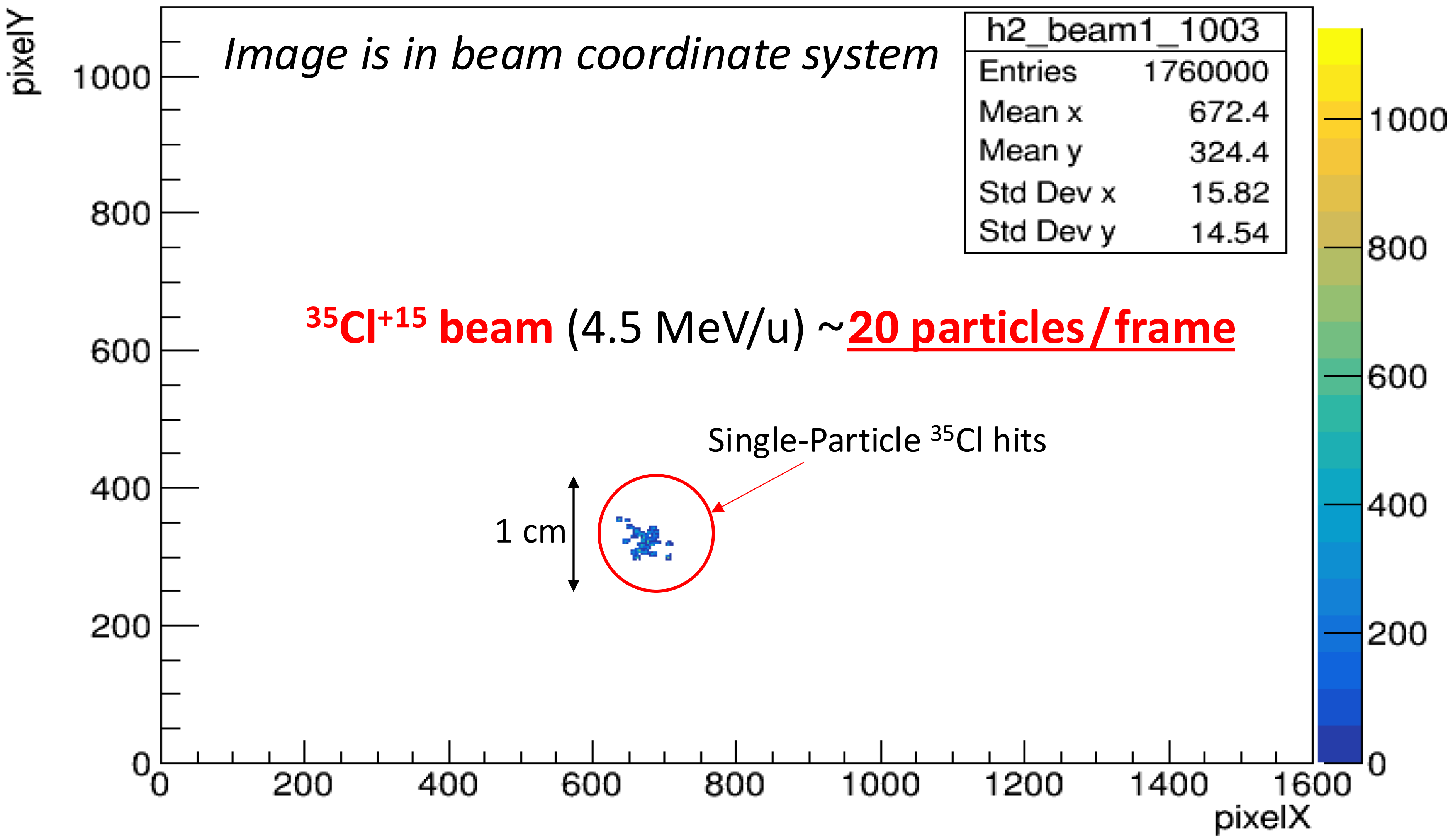


Shown above is image of **<u>1.35 x 10^5 particles/frame</u>** of mixed ^{14}N and ^{35}Cl beam. Bottom Left is the *average of all ADC* counts along the Y axis as a function of the X axis beam position.

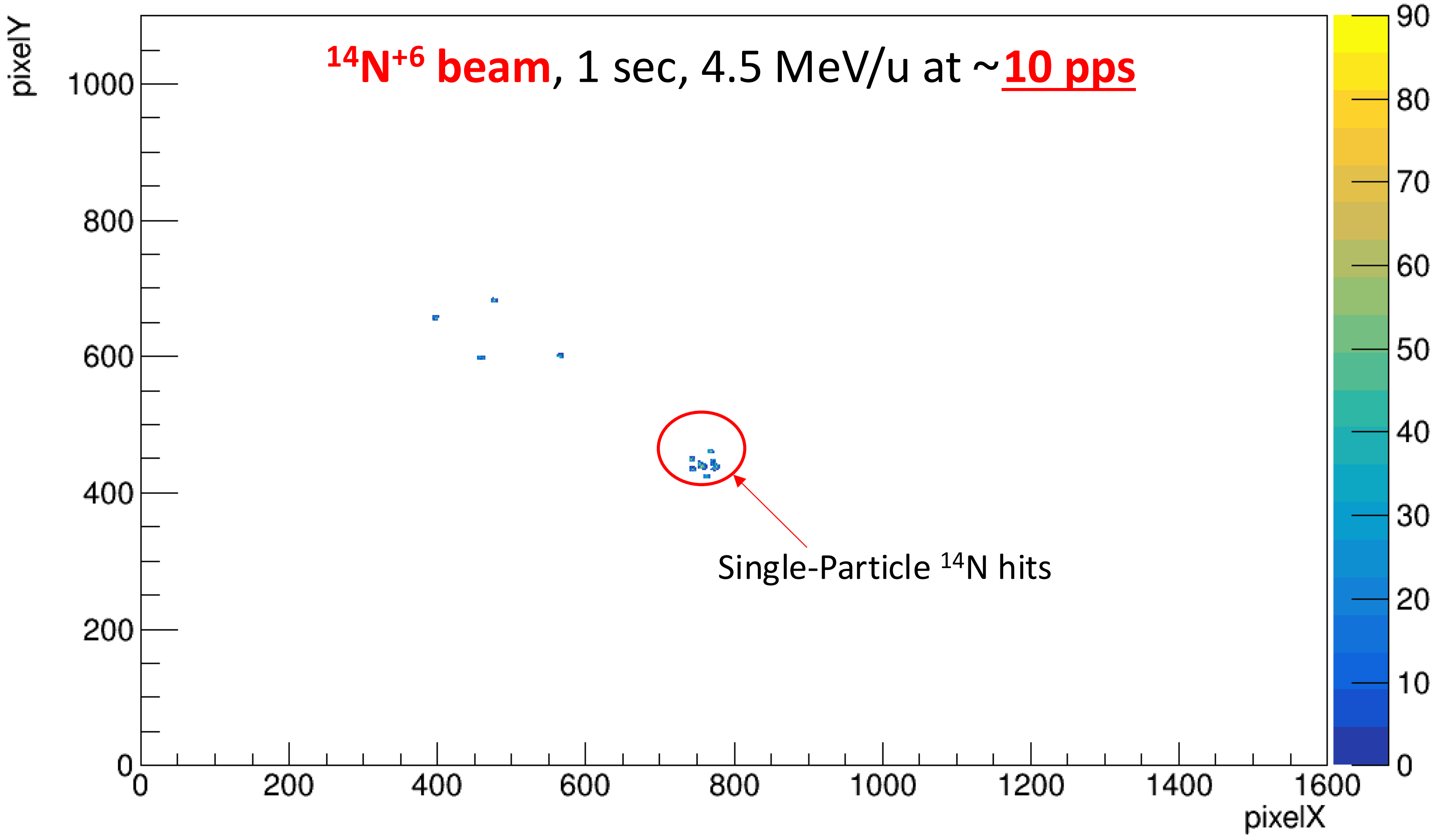
Ultra-Low Intensity Mixed Beam of $^{14}N^{+6}$ and $^{35}Cl^{+15}$



“Single Particle” Beamline Images of $^{35}Cl^{+15}$



“Single Particle” Beamline Images of $^{14}N^{+6}$



U.S. “Potential” Customers* for Phase-IIB SBM Platform

- FRIB – Potentially **several dozen SBM** systems
- ANL-ATLAS – Potentially a **dozen SBM** systems
- Texas A&M Cyclotron Institute – Potentially a **half-dozen SBM** systems
- Notre Dame Nuclear Science Laboratory – Potentially a **half-dozen SBM** systems
- Florida State Accelerator Laboratory – Potentially a **several SBM** systems
- Others …

**Organizations that wrote “Letters of Support” for our Phase-IIB proposal*

Transition from DOE-NP to NIH-NCI (National Cancer Institute)

- Based on the early positive NP Phase-II results, we submitted a ***"Direct-to-Phase-II"***, ***3-yr, $1.9M*** proposal to NIH-NCI for proton-FLASH-RT, which was awarded 09/2021.

- NCI Award: ***"Ultrafast and Precise External Beam Monitor for FLASH and Other Advanced Radiation Modalities"***.

- Same **Type 1 and Type 2 scintillators** from NP used for NCI, but for larger area beam monitors up to **30 x 30 cm²**.

- For proton-FLASH, total delivery time is typically ~ 0.1 sec. So for ***real-time analysis***, camera operates at **20,000 fps**, or **50 µs/image**. **Beam analysis in < 2 µs.**

Back Up

Phase-II Prototype FRIB Beamline Testing

Project Objective: provide DOE-NP facilities with advanced & fast beam monitoring.

➔ ***high premium for fast tuning***

- Ion: **$^{86}Kr^{+26}$ at 2.75 MeV/u**
- **Very Wide Dynamic Range: 520,000 pps to < 10 pps**

Selected Results for Beam Finding, Profile Analysis & Real-Time Display

Type 1 – HM type scintillator (selected for SECAR In Phase-IIB)

- **Single particle detection**
- Response vs beam current
- Beam tracking & profiling

Type 2 – PM scintillators

- Beam profile and signal amplitude vs thickness, current
- Beam transmission (75% for 6 μm thick scintillator film)

Phase-II DAQ Functionality

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

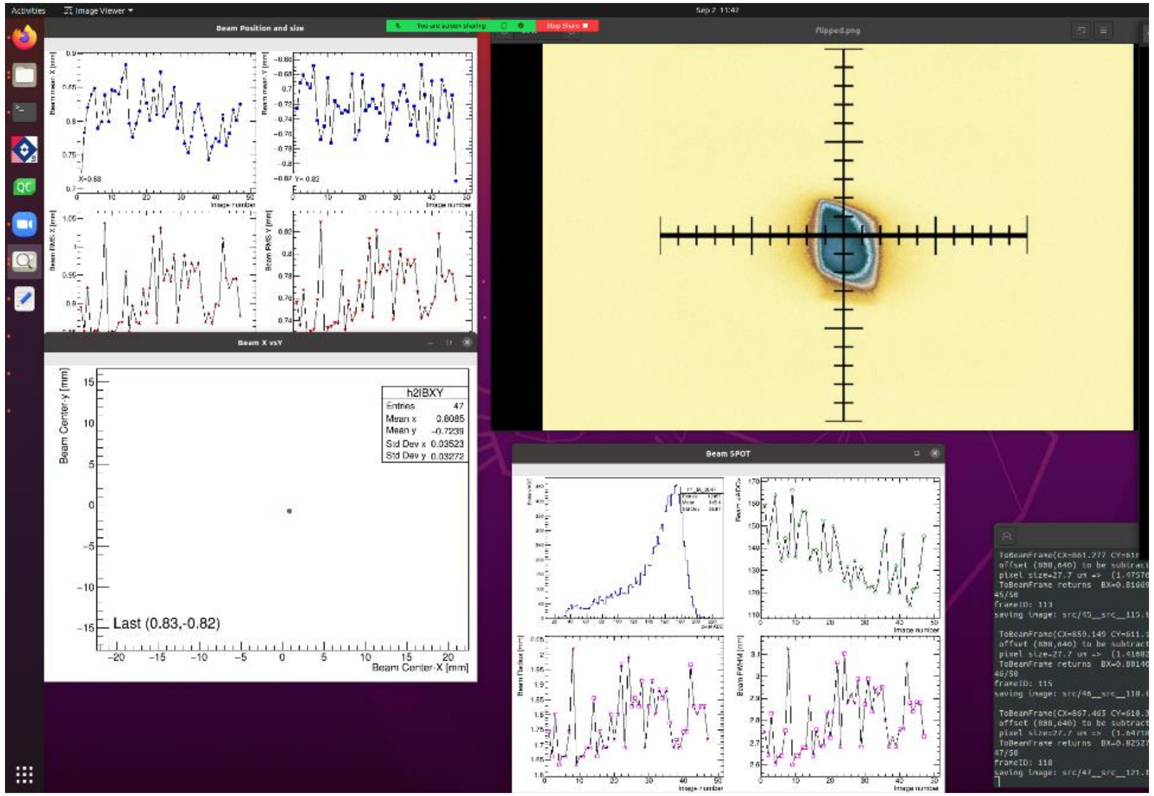
2. **Image processing in real-time:**
   - background subtraction
   - faulty pixel removal
   - affine (perspective) matrix transformations and rotations for display in beam coordinate system

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 in Control Room



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

Summary

1) SBM provides **real-time, precise 2D beam tuning, profiling & imaging** with **spatial resolution ~ 20-30 μm**
2) **High sensitivity & dynamic range**: **single-particles** to ~ **10^{11} pps/cm^2** (~ 10 nA, depending on particle/energy)
3) **Linear Response to > 5 orders-of-magnitude** for $^{86}Kr^{+26}$
4) Novel applications and **radiation hardness** for two specialized 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 "observable" degradation*** over first 9 kGy
   - Ultra-thin PM tested: from ~ **1- 200 μm** sample thickness
   - **HM**: ***order-of-magnitude higher signal output*** than much thicker CsI(Tl) standard
   - HM in air at rates of O(10) Gy/s → ***minimal degradation*** *of 0.02%/kGy*
5) SBM design operates in high vacuum (or in air)
6) SBM real-time analysis for NP is **< 1 sec**, but for proton-FLASH-RT is **< 2 μs** for camera operating at 20,000 fps
7) Scintillators can be remotely inserted in beam or changed without breaking vacuum.
8) Much larger potential commercial market for medical radiotherapy (RT) applications than for NP

Commercial Applications

- **Ion Beam Monitoring** – NP & EBRT (i.e., external beam radiation therapy)

EBRT Applications:

- **FLASH-RT** (electrons, protons, ions, X-rays)
- Electron – FLASH – IORT (intraoperative radiation therapy)
- Advanced EBRT including heavy-ions (helium, carbon ions, etc.)
- High-Resolution, Volumetric Patient Specific QA (FLASH & conventional EBRT)
- Boron Neutron Capture Therapy (BNCT)
- Spatially Fractionated EBRT (minibeam, grid, lattice, microbeam)