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A Scintillator-based Monitor for Real-Time, High-Resolution Imaging and Analysis of High-Intensity to Single-Particle Ion Beams

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Acknowledgement

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Office of Science *and* Office of Nuclear Physics

Phase-IIB: <u>Customer Centered Approach</u>

- **FRIB customer & NP market**: ***<u>No one-size-fits-all</u>*** 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.

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 Nuclear Physics device to **NIH Cancer Institute** for **FLASH Radiotherapy**

Program 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**)

Demonstrated Specs

- **~ 20-40 µm position resolution, same as gafchromic film!**
- 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)

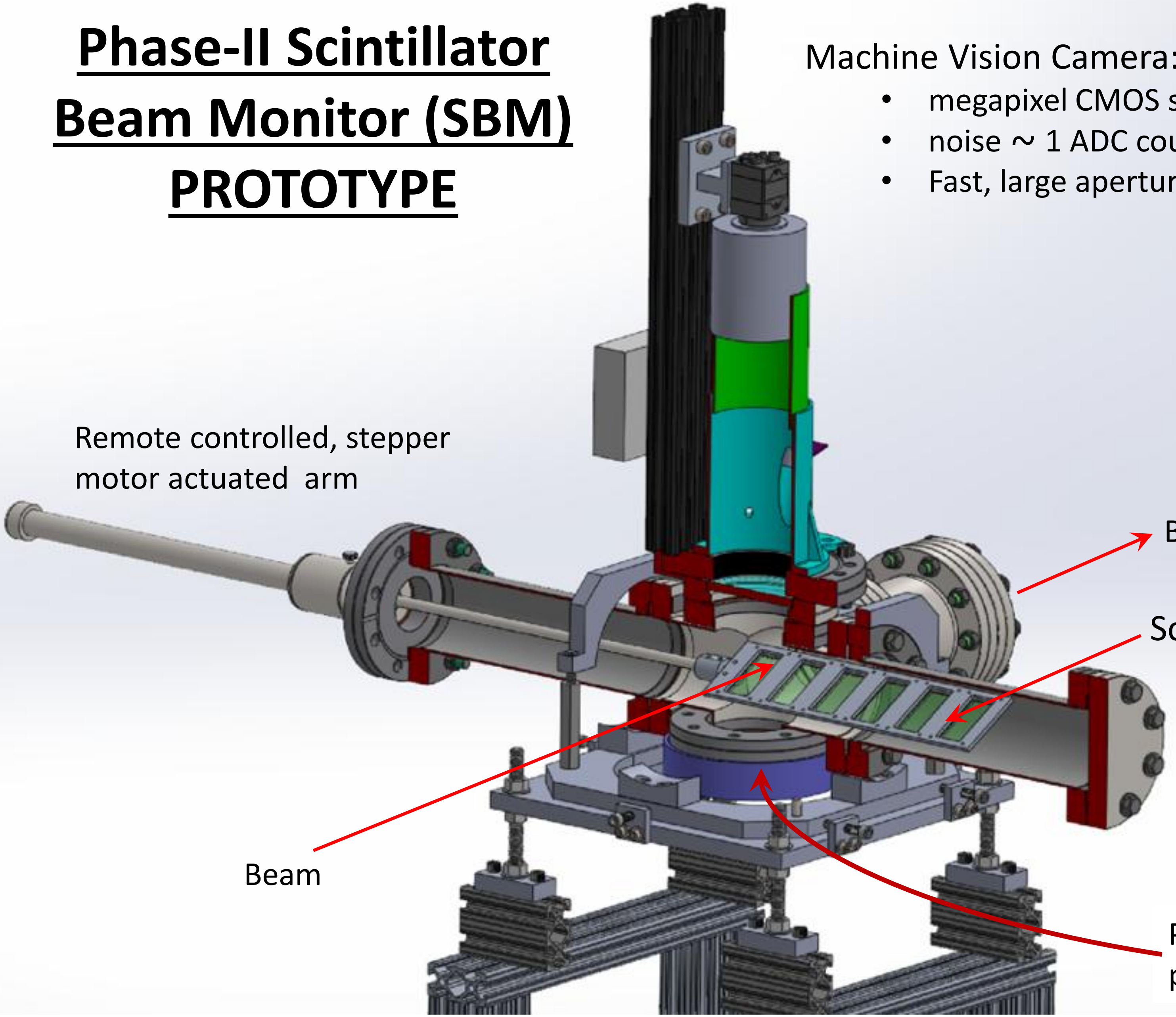
Type 2: **Polymer Material (PM)** – Semicrystalline

- ***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

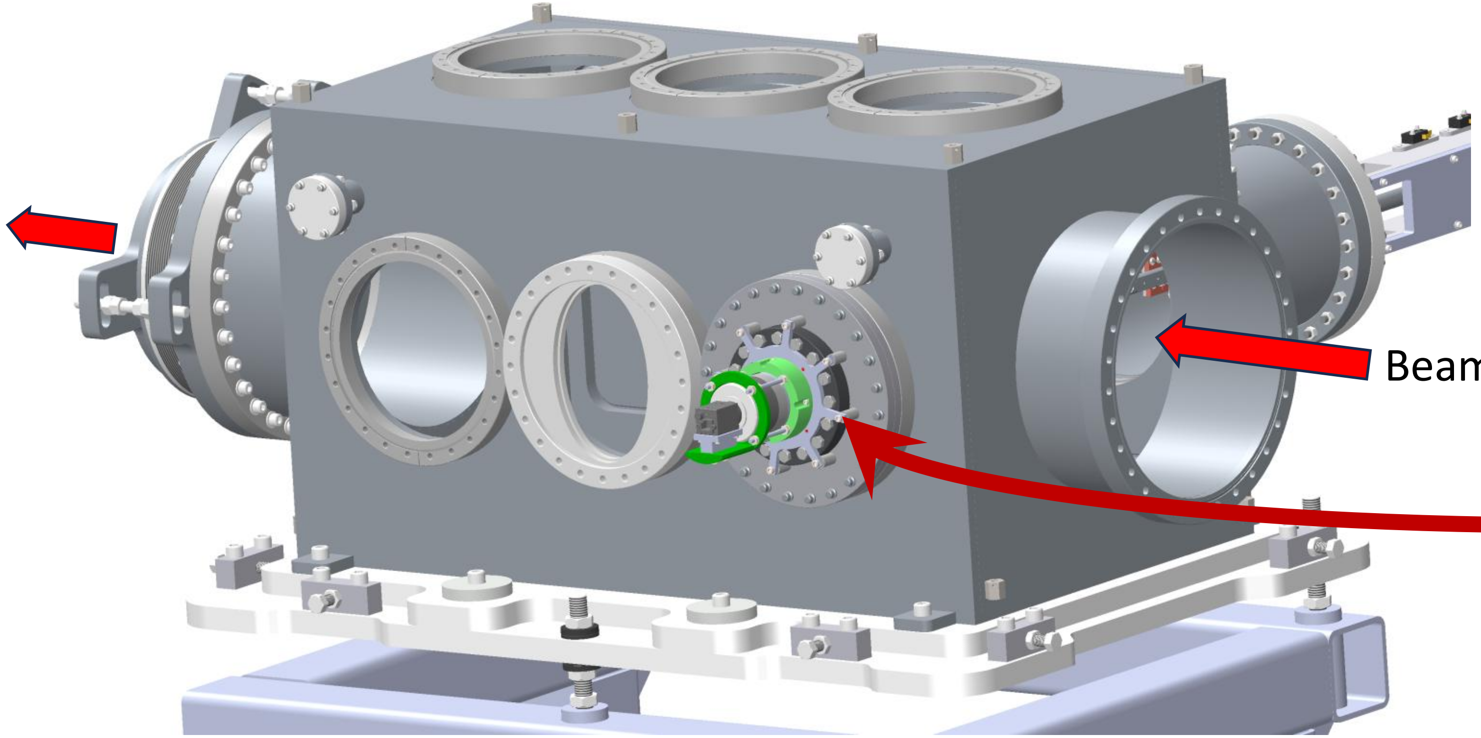
Beam

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

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

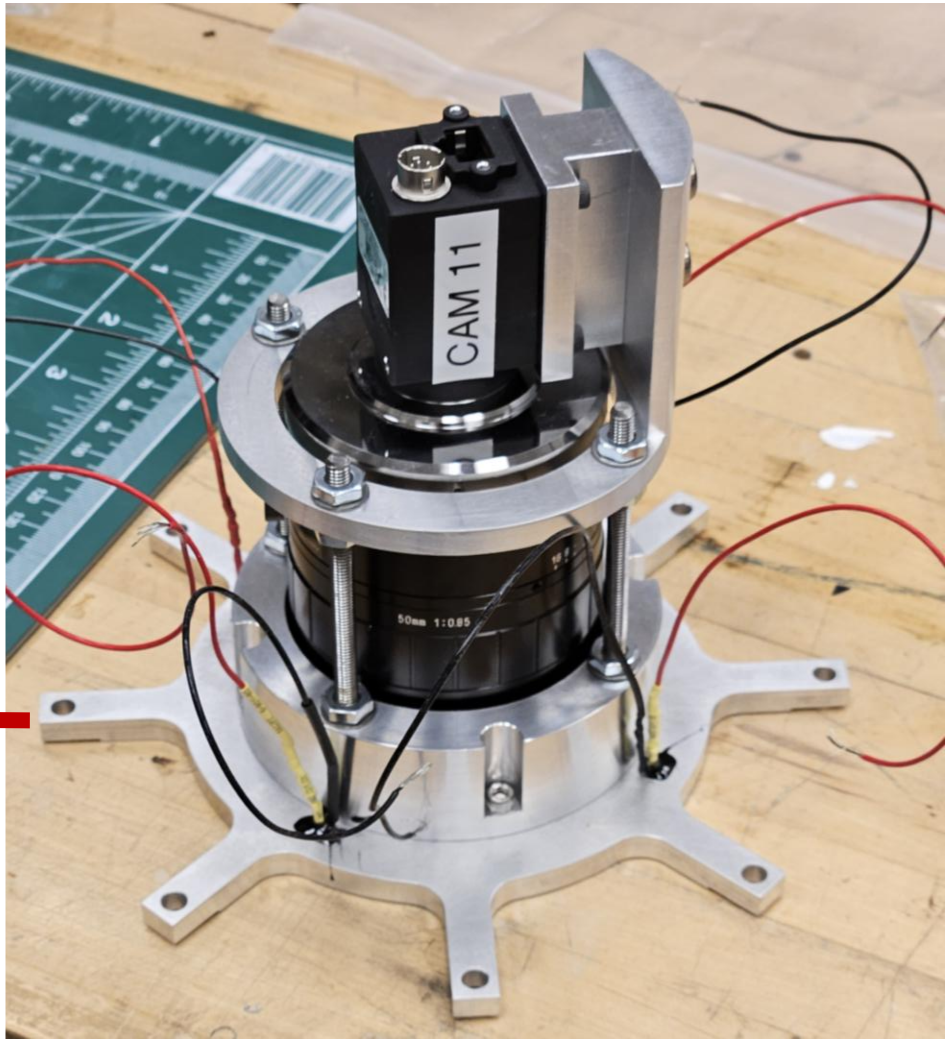
*SECAR = Separator for Capture Reactions

Mounting Scheme onto High Vac Instrument Box



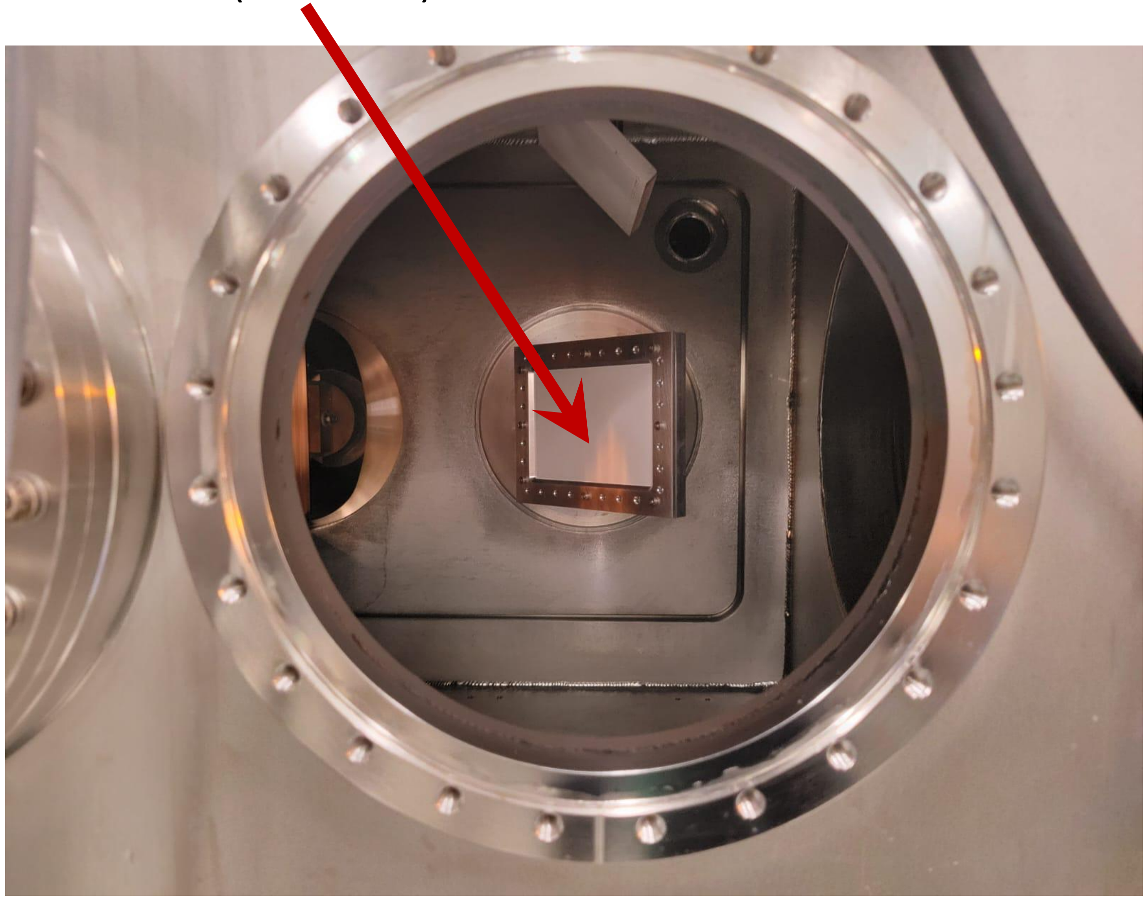
Beam

Camera Assembly

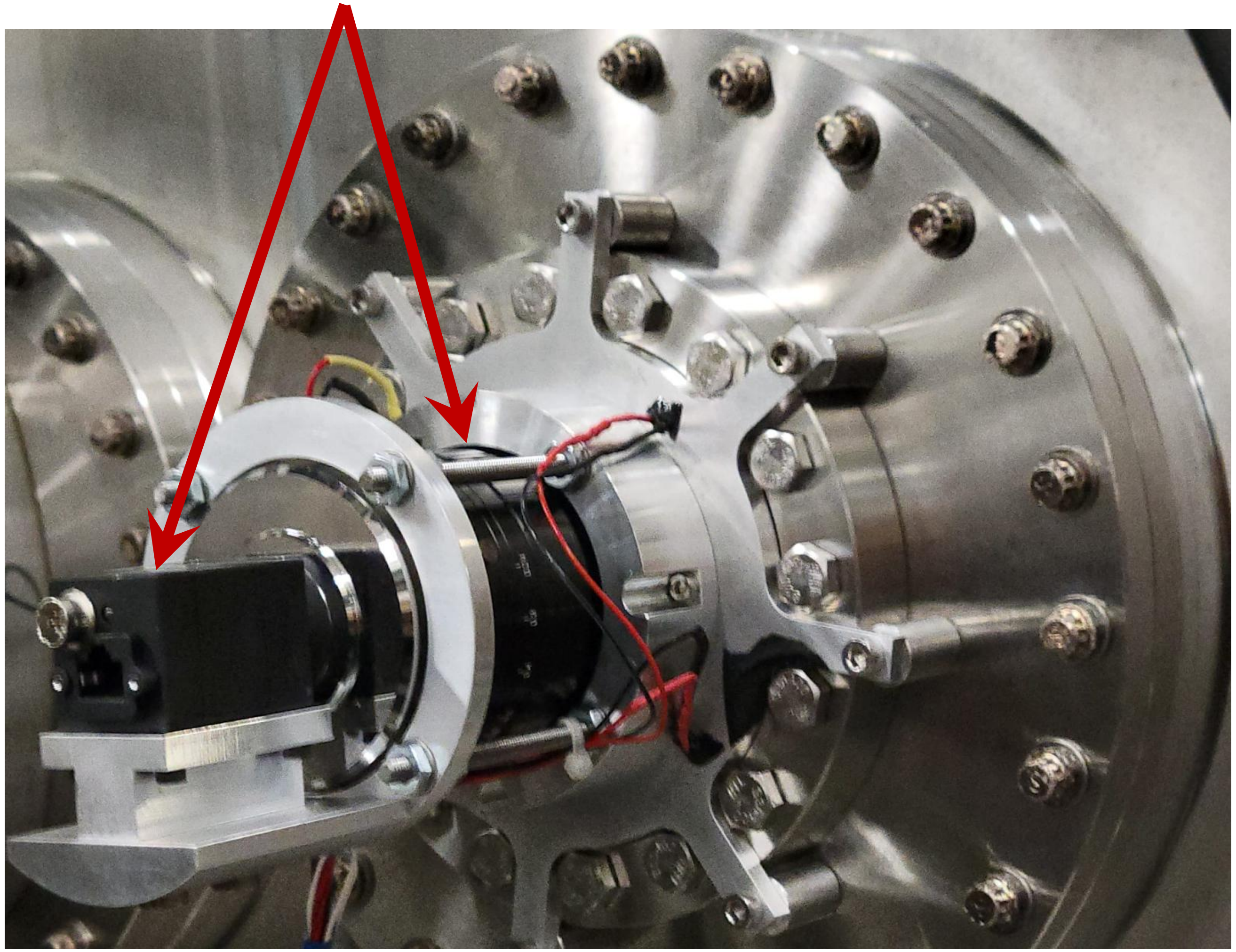


Installed ReA3-SECAR Beam Monitor PRODUCT

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

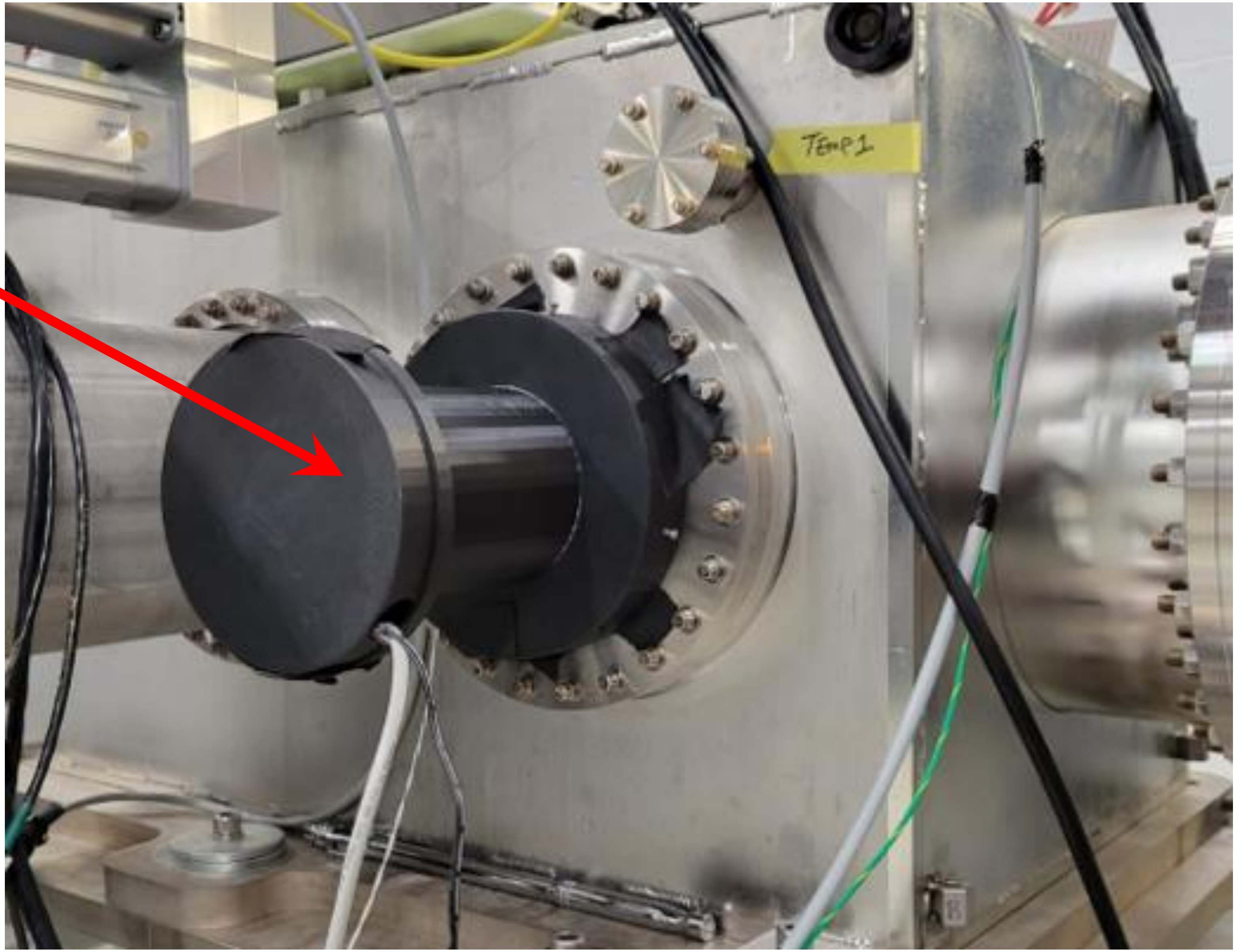


Camera Assembly mounted to Instrument Box



ReA3-SECAR SBM Camera-Lens Housing

3D-Printed
Camera-Lens
Light-Tight
Housing



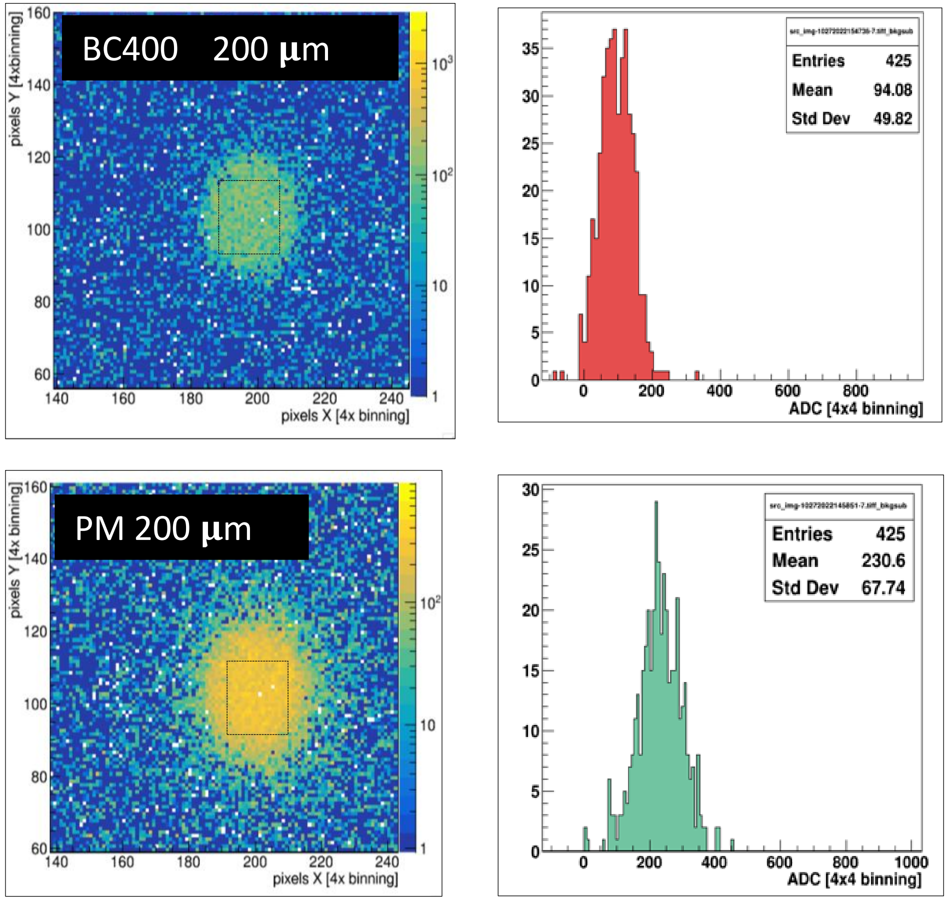
Test Beams (Phase-II and Phase-IIB)

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
UM Hospital (Radiation Oncology)	e^-	6 -16

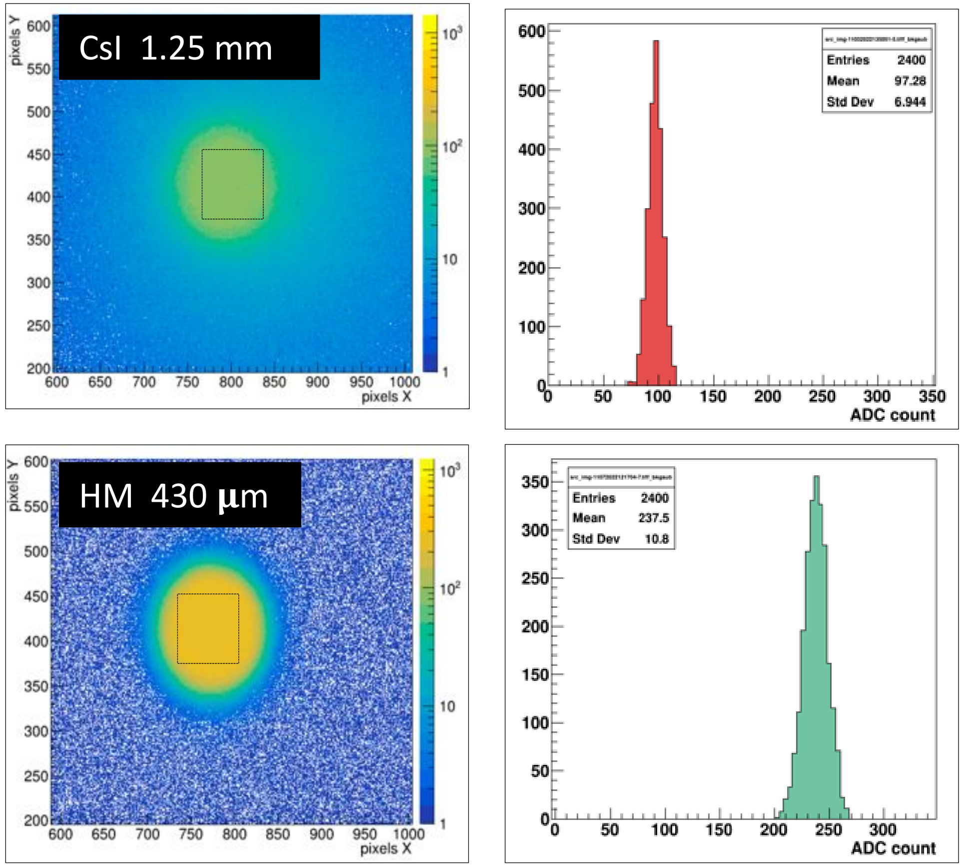
Scintillator Efficiency Comparisons to Benchmarks

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

PM type

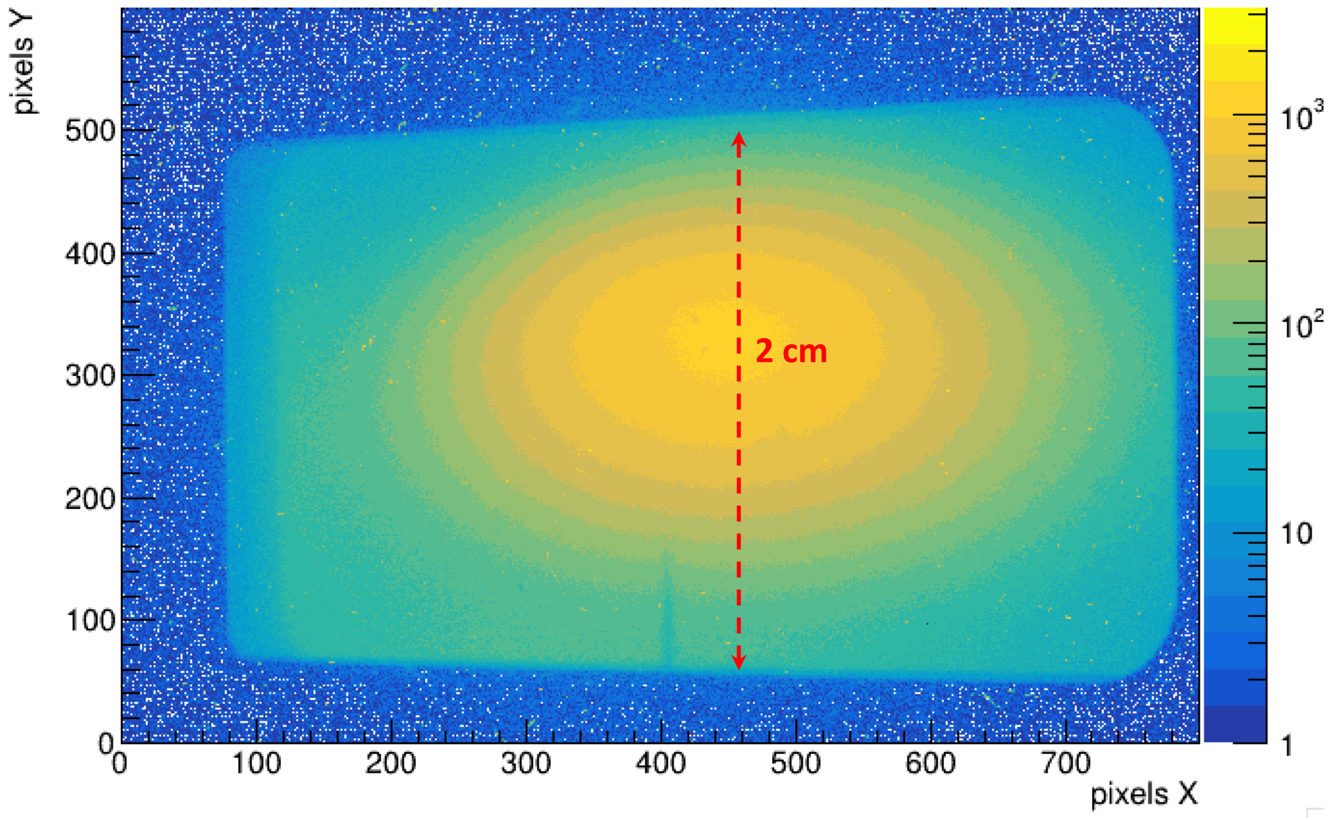


HM type

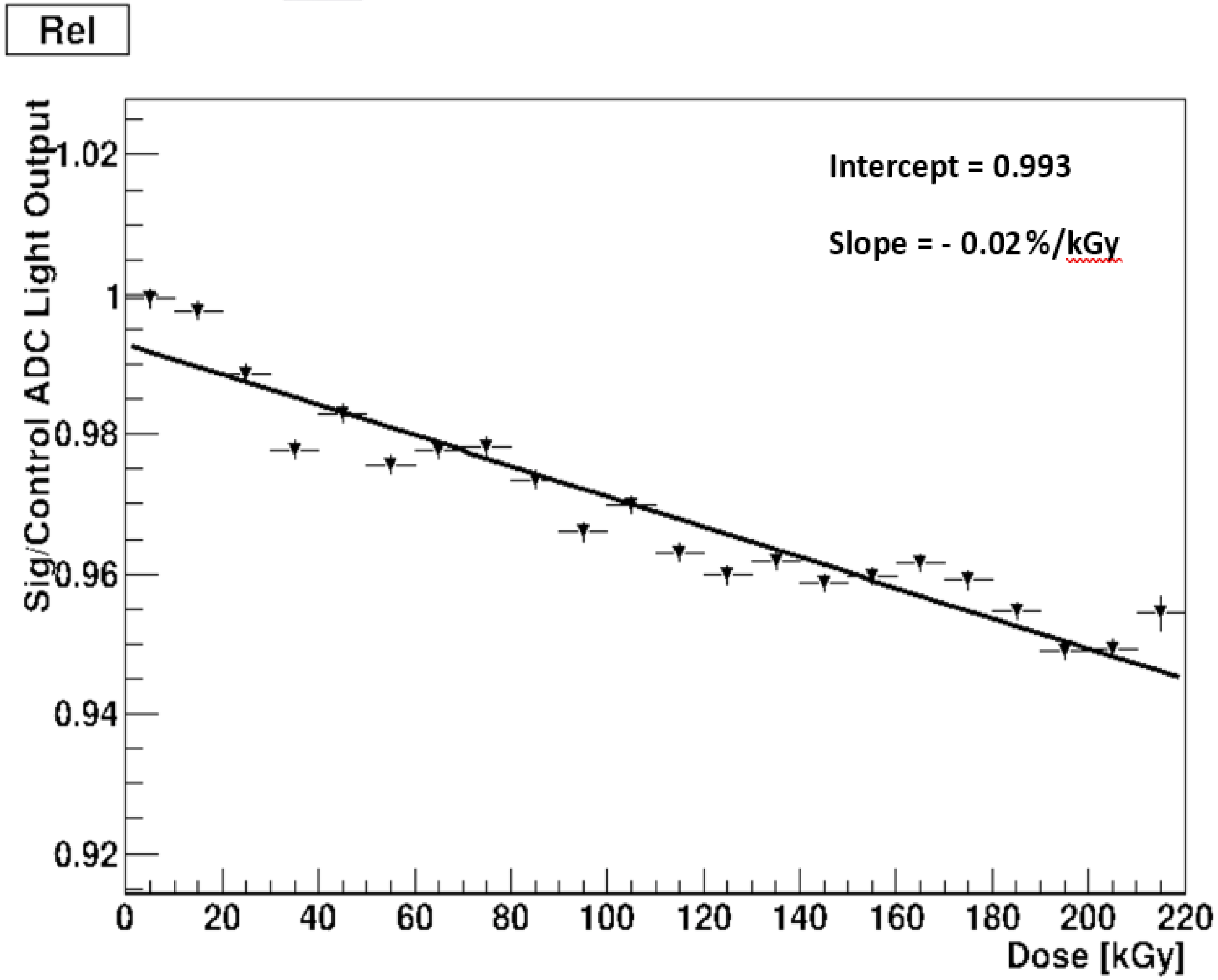


Beam Image on HM at NDRL (camera coordinates)

- **Single 2 ns duration pulse** (1.9 Gy) at a peak current of **1 A**
- 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

<u>DAQ Functionality</u> (Phase-II)

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

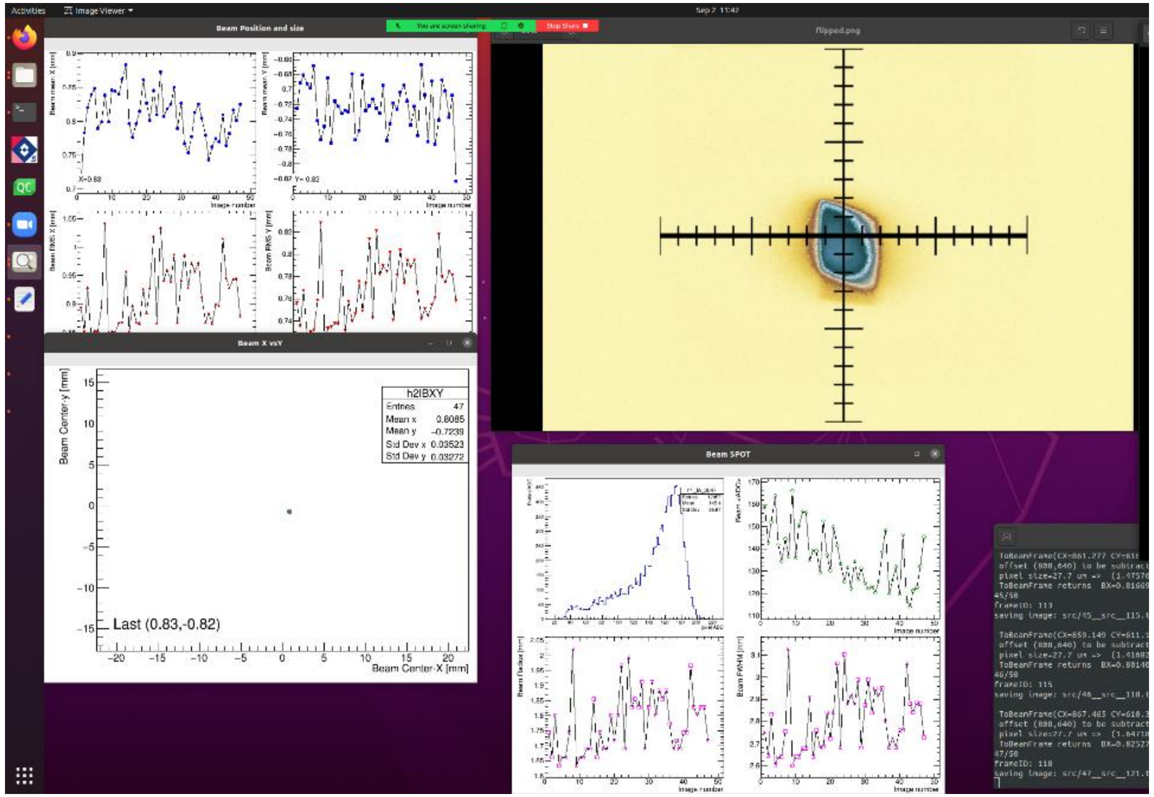
2. **<u>Image processing in real-time:</u>**
   - background subtraction
   - faulty pixel removal
   - affine (perspective) matrix transformations and rotations for display in beam coordinate system

3. **<u>Image analysis in real-time:</u>**
   - beam finding
   - beam profiling (centroids, RMS widths)
   - peak amplitude

4. **<u>Display</u>**
   - 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

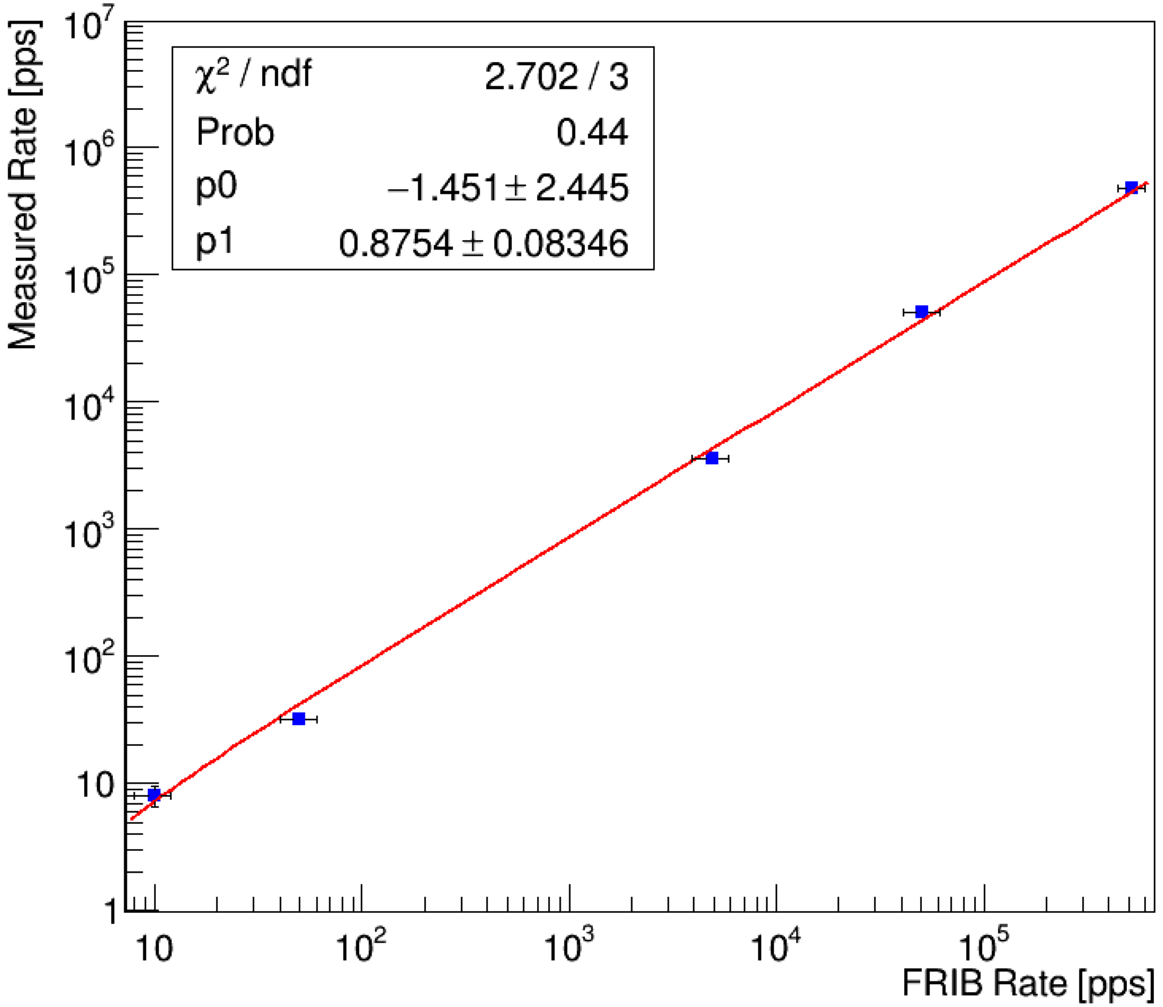


Shown above:

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

$^{86}Kr^{+26}$ Beam Current in HM Scintillator

(Measured Rate vs. FRIB "Given" Rate)



Result 1:

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

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

Result 2:

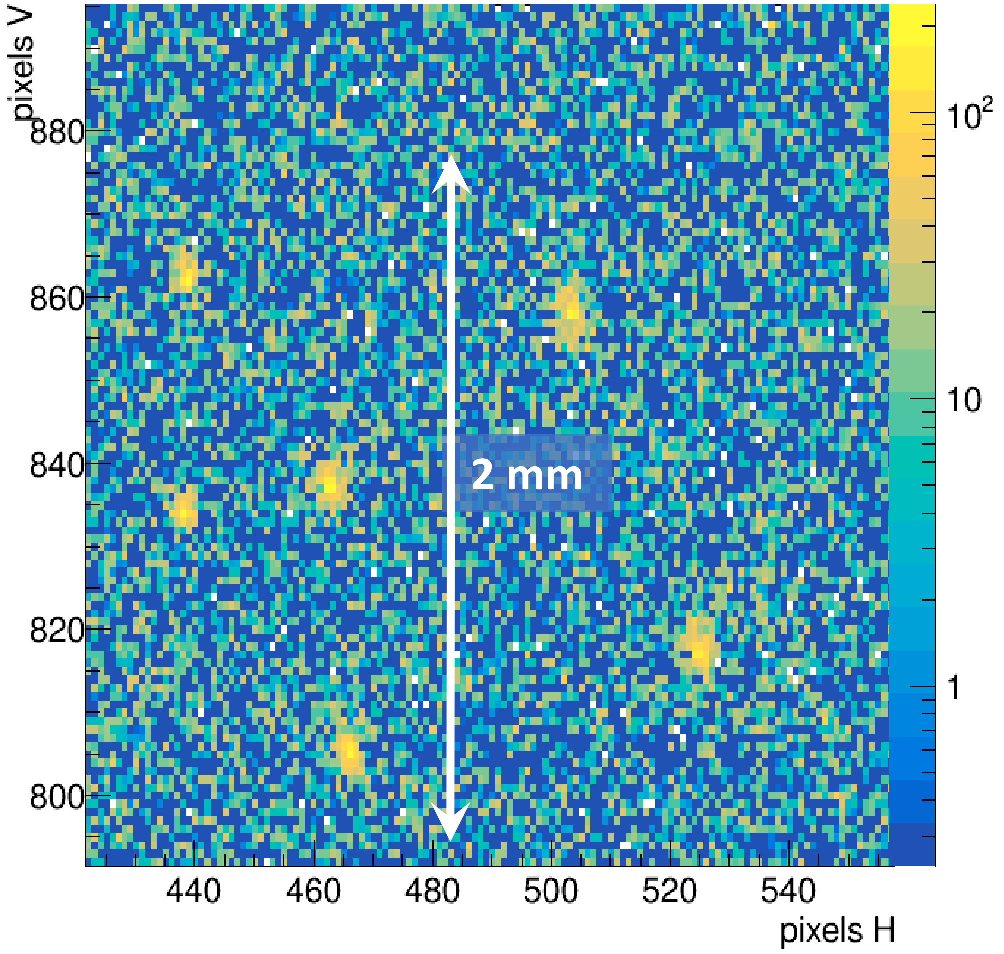
SBM measurement is *linear over more than* 5 orders-of-magnitude (the full range has not been determined)

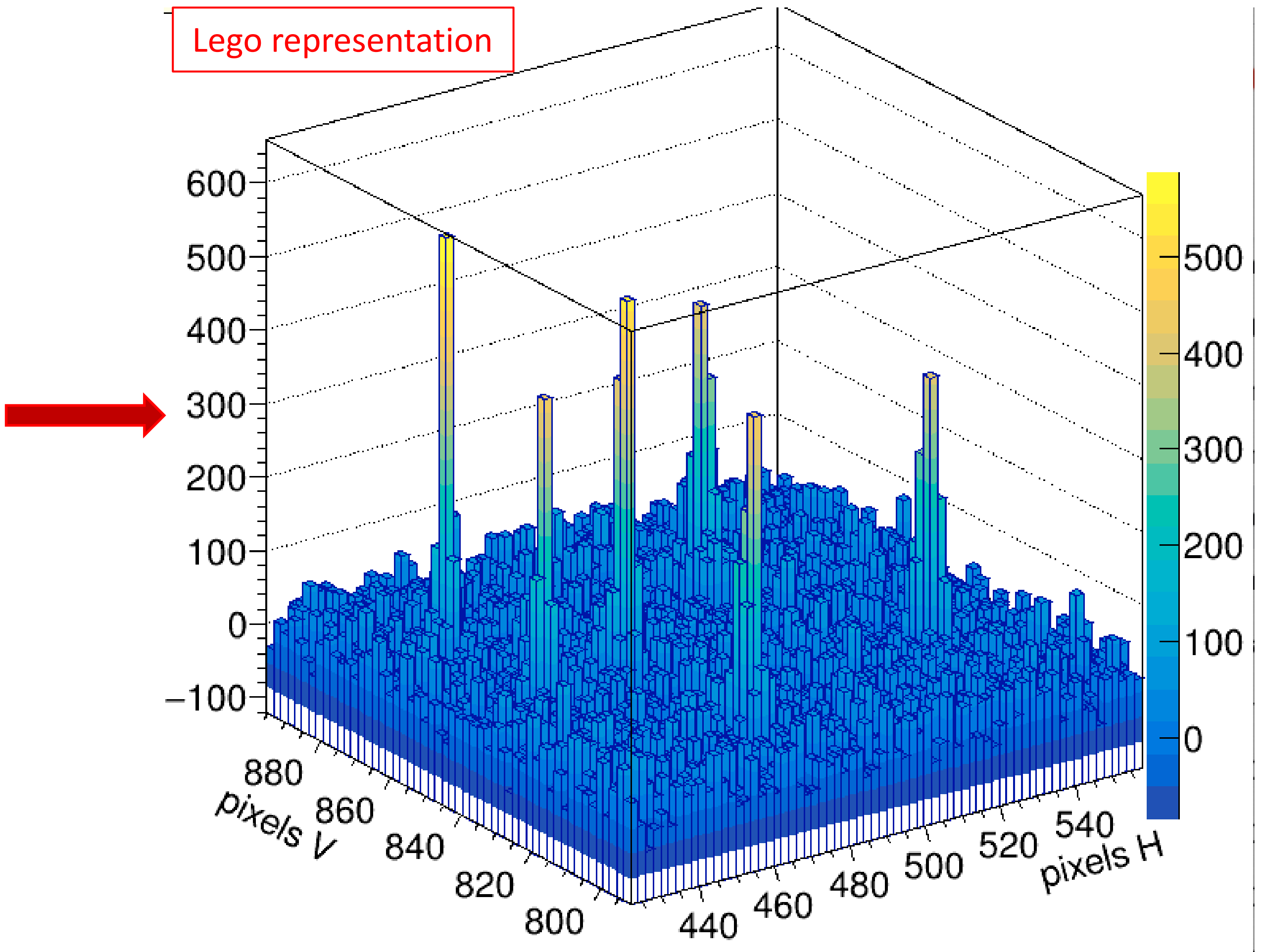
“Single Particle” hits/images

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

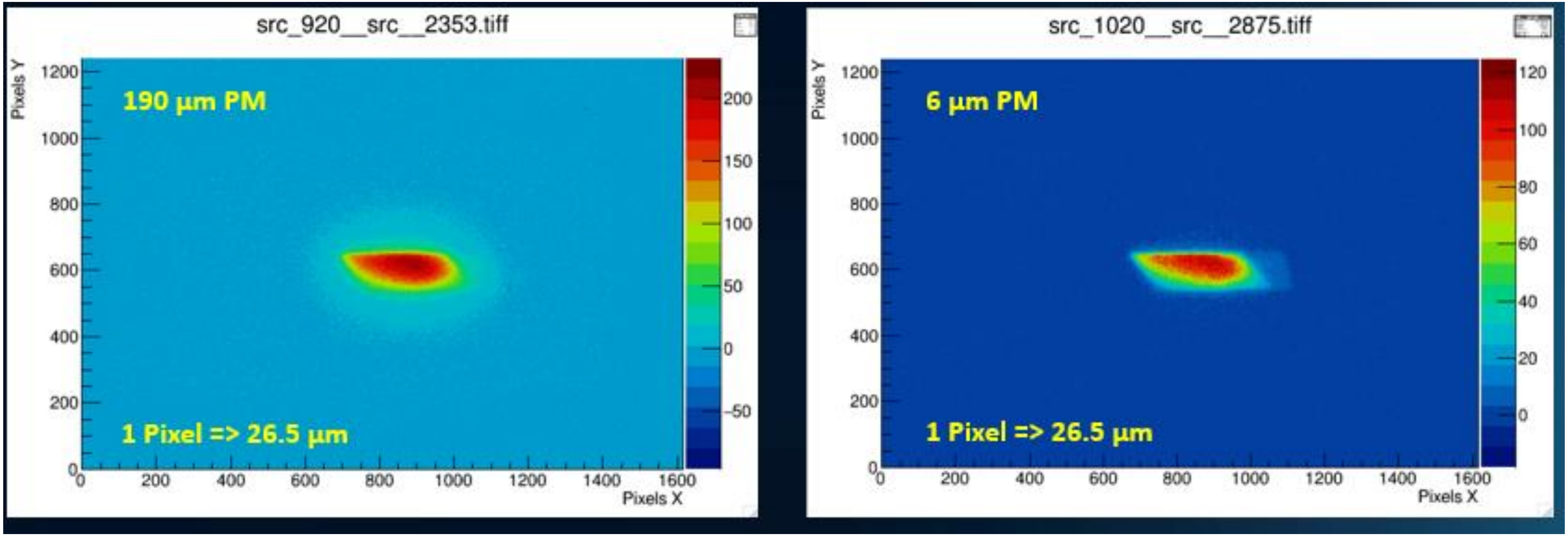
Beam current ramped down to < 10 Hz

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





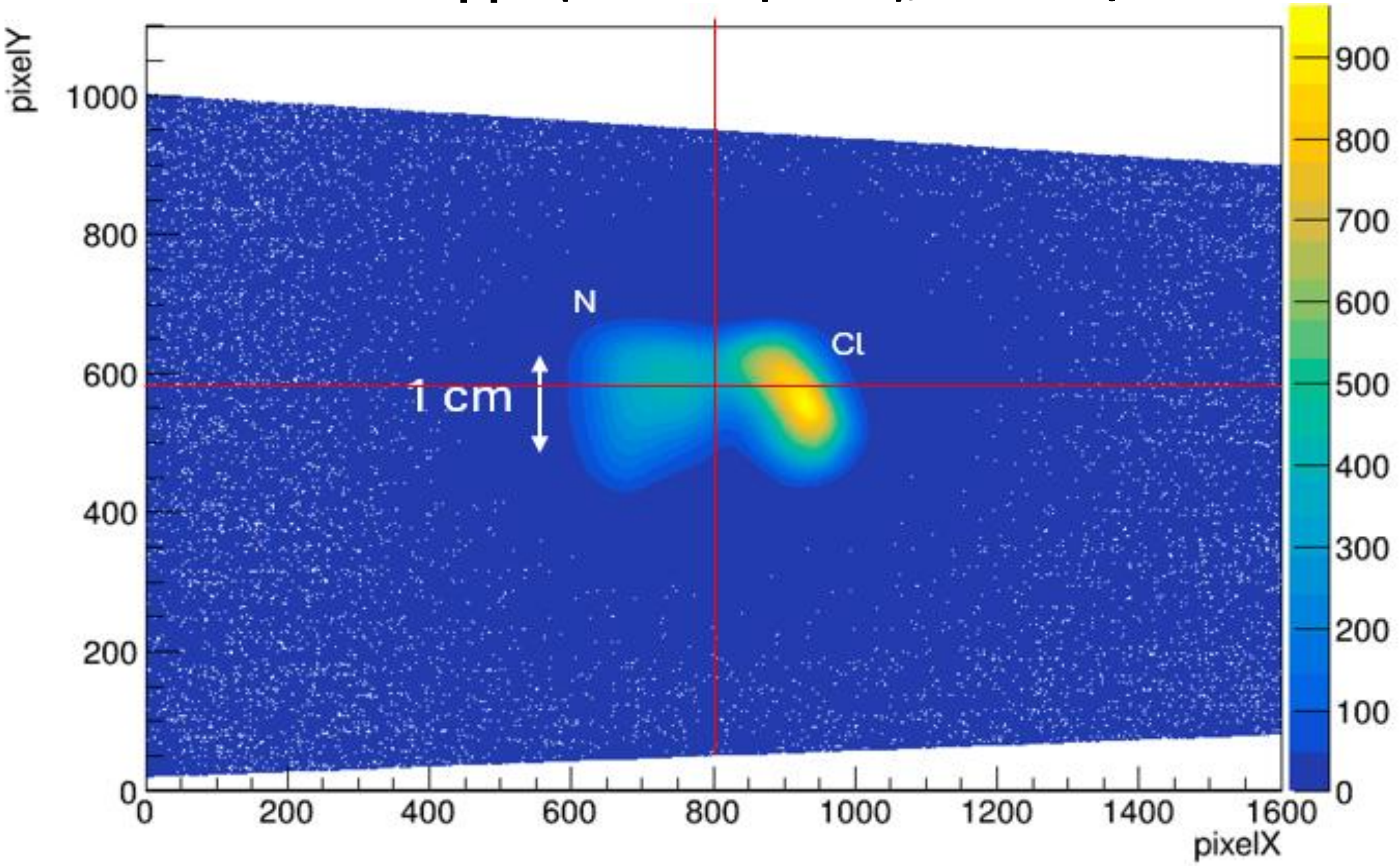
Phase-II Beamline Images of $^{86}Kr^{+26}$



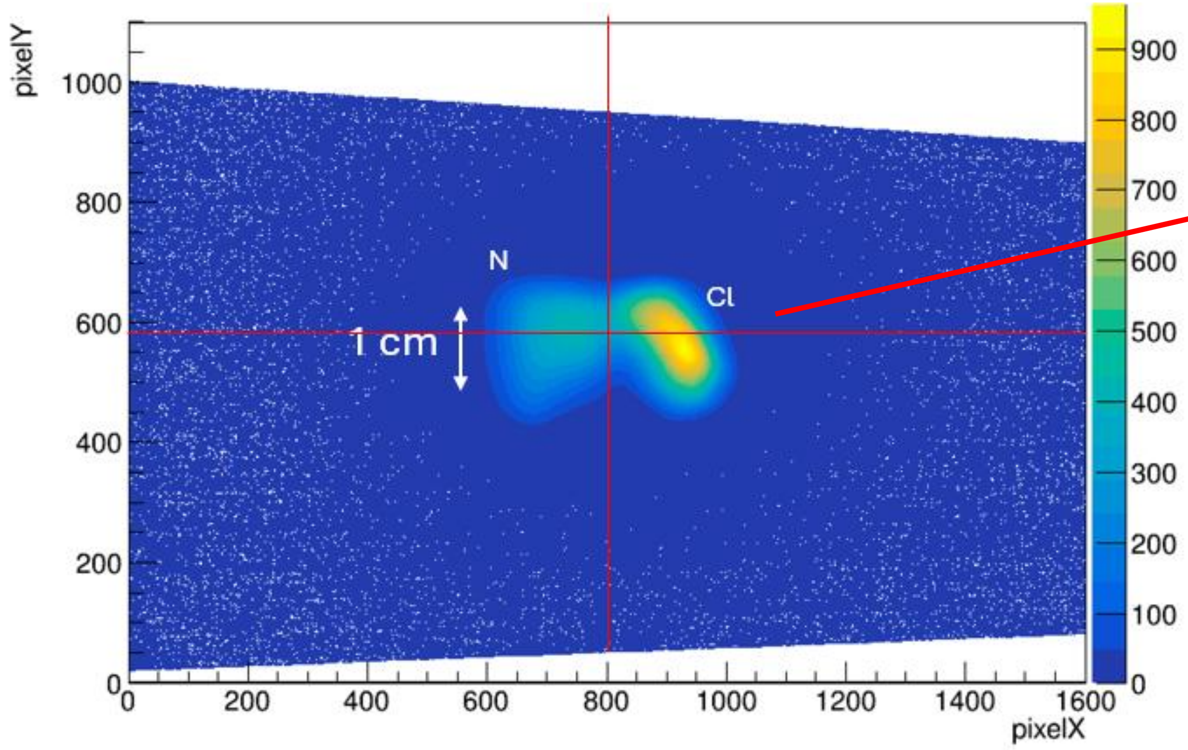
Above beamline images captured in real-time of same 2.75 MeV/u beam of $^{86}Kr^{+26}$ (**Z=36**) particles irradiating two different thickness 2x2 cm **PM** scintillators at a rate of **5.2 x 10^5 pps**. Image on Left was with **190 µm** thick **PM;** image on Right was with **6 µm** thick **PM** that **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.

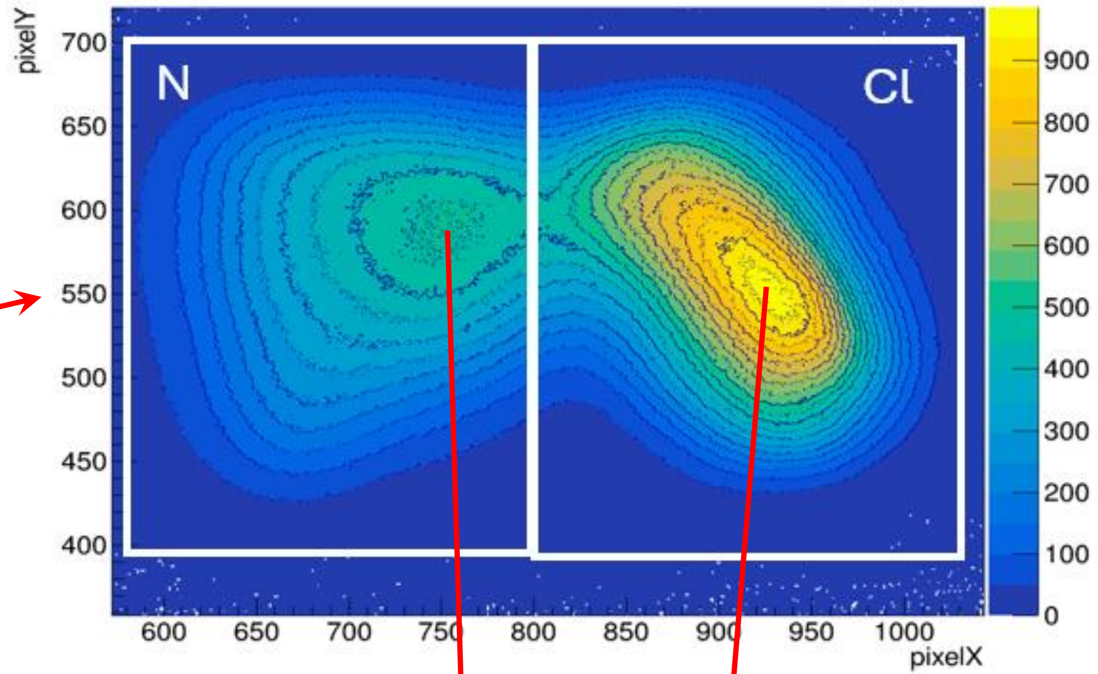
Phase-IIB Mixed Beam of $^{14}N^{+6}$ and $^{35}Cl^{+15}$

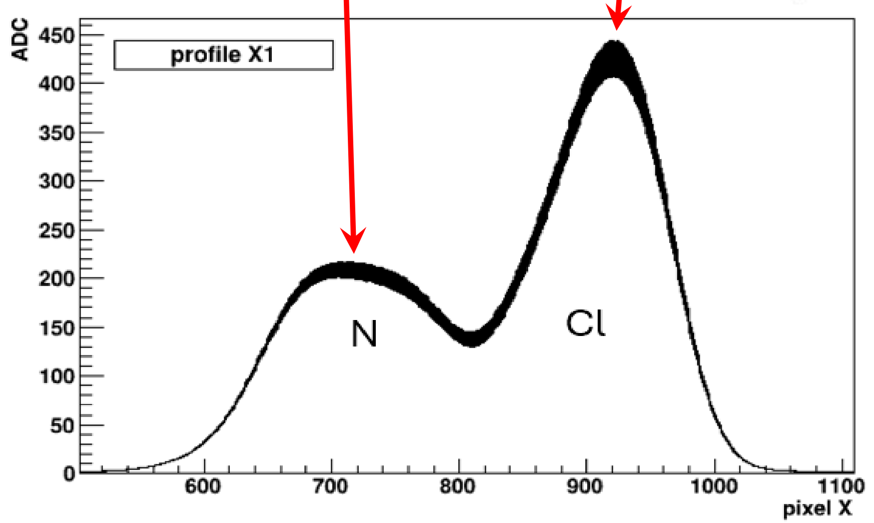
1.35 x 10^6 pps (0.1 sec exposure), 4.5 MeV/u



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

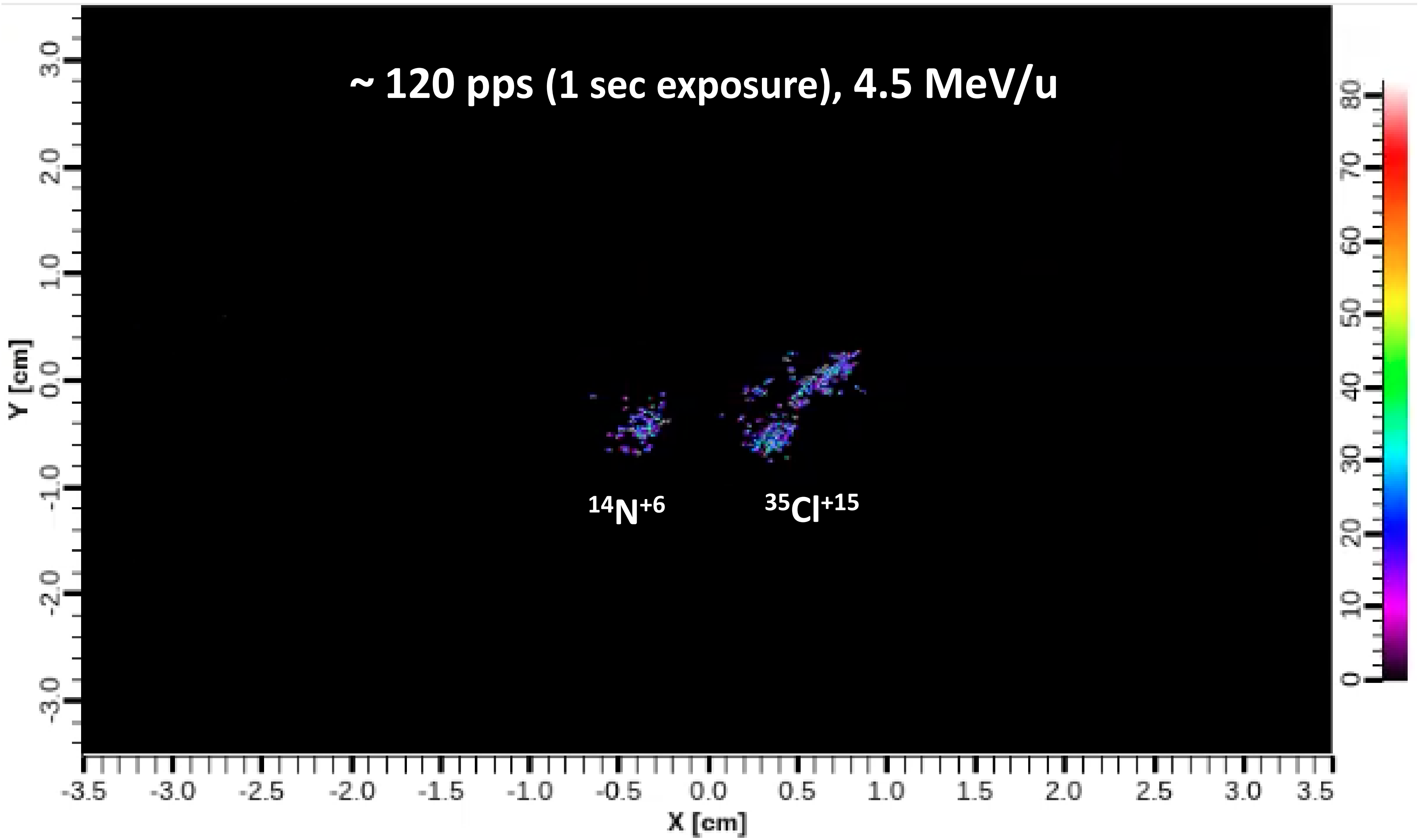




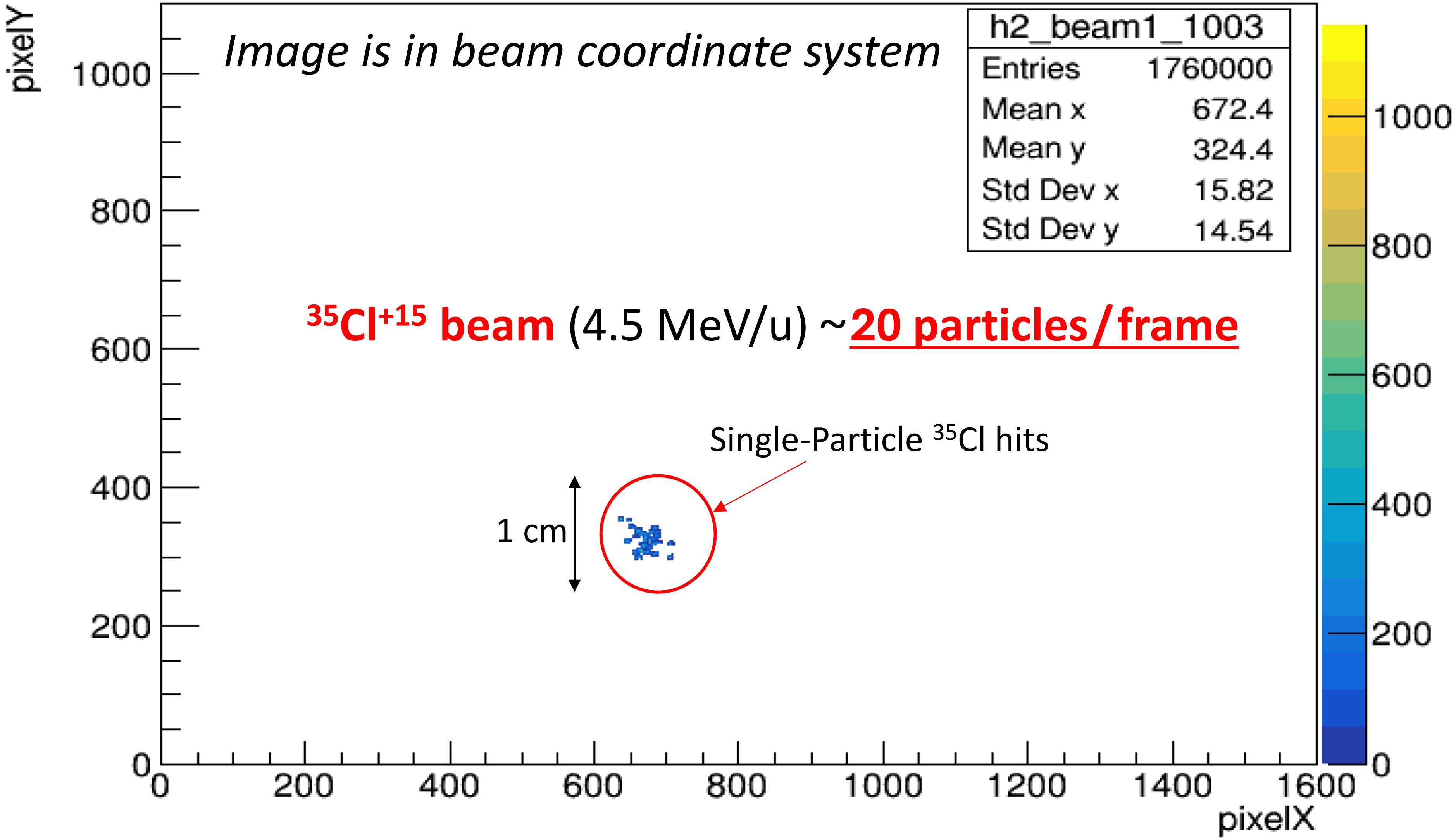


Shown above is image of **1.35 x 10⁵ particles/frame** of mixed ^{14}N (**Z=7**) and ^{35}Cl (**Z=17**) beam. Bottom Right is *average of all ADC* counts along Y axis as a function of X axis beam position.

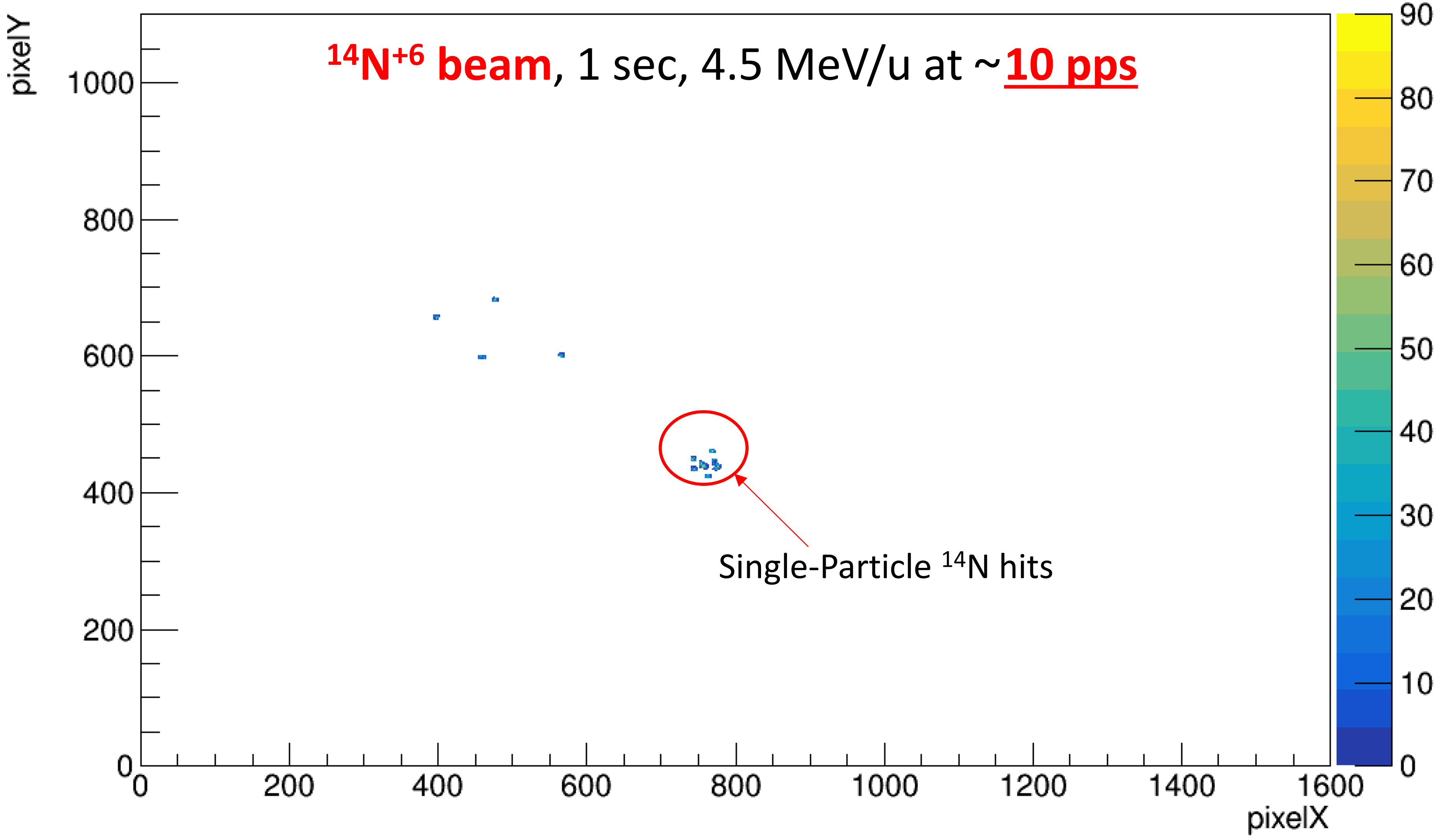
Ultra-Low Intensity Mixed Beam of $^{14}N^{+6}$ and $^{35}Cl^{+15}$



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



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



Summary

1) SBM provides **real-time, precise 2D beam tuning, profiling & imaging** with **spatial resolution ~ 20-40 µm**

2) **High sensitivity & dynamic range**: **single-particles** to ~ **10^7 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.