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

*Scintillator-based **Beam Monitor** (**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

- **~ 20-40 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

<u>Scintillators</u> – *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

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

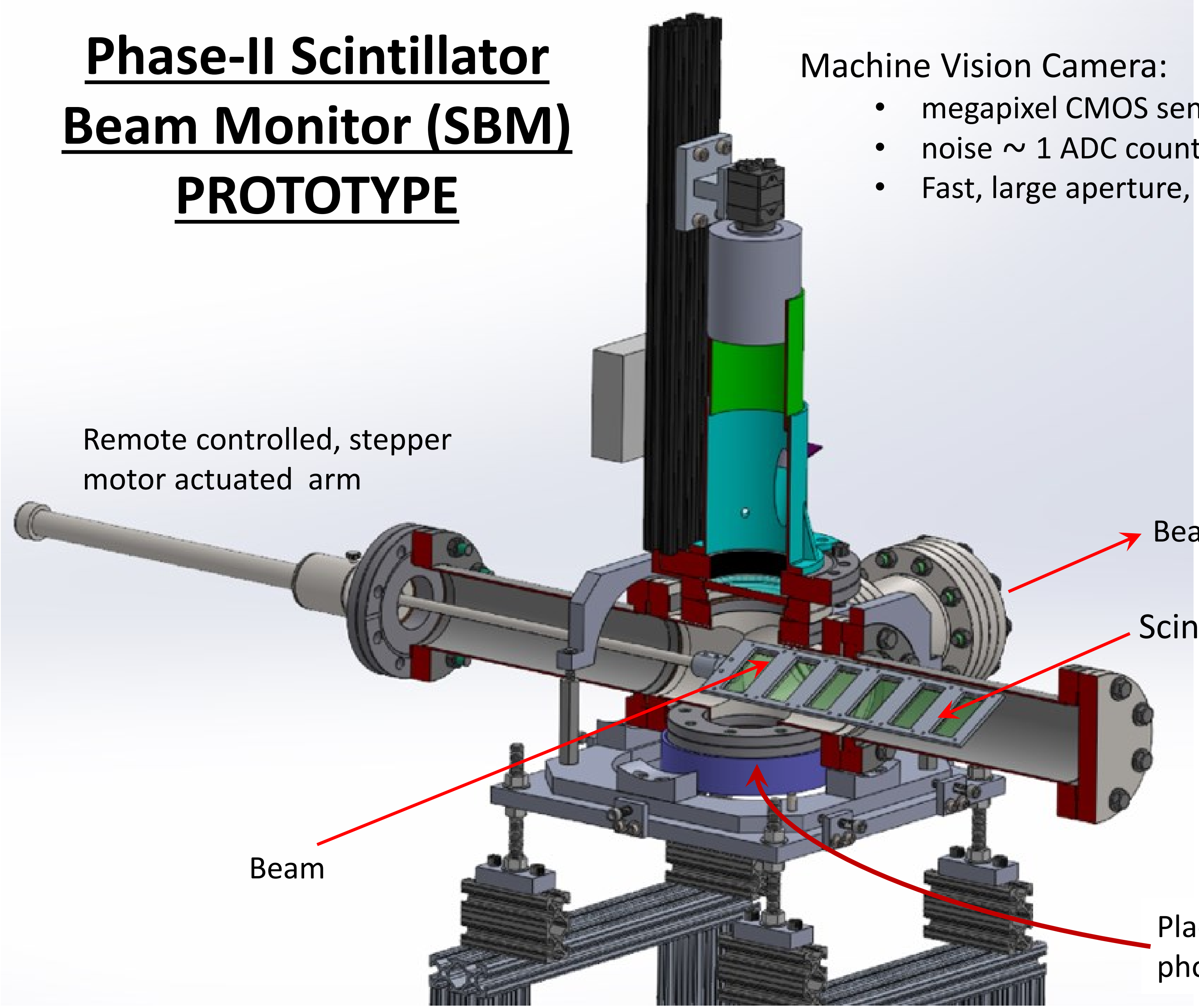
Both Types 1 & 2 have favorable properties:

- 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



Scintillator ladder

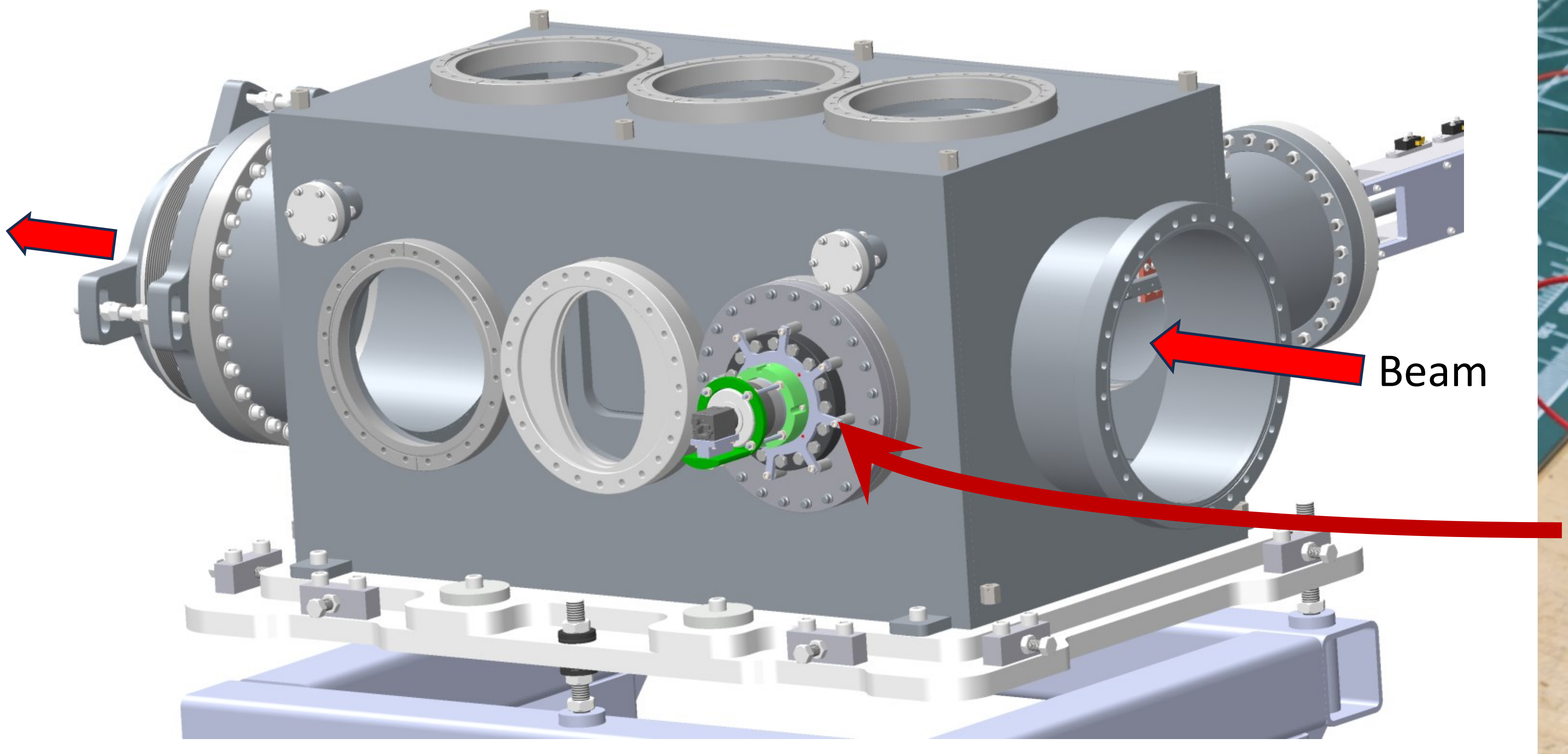
- Holds six 2x4 cm^2 scintillators
- moved in & out of beam by translation arm

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

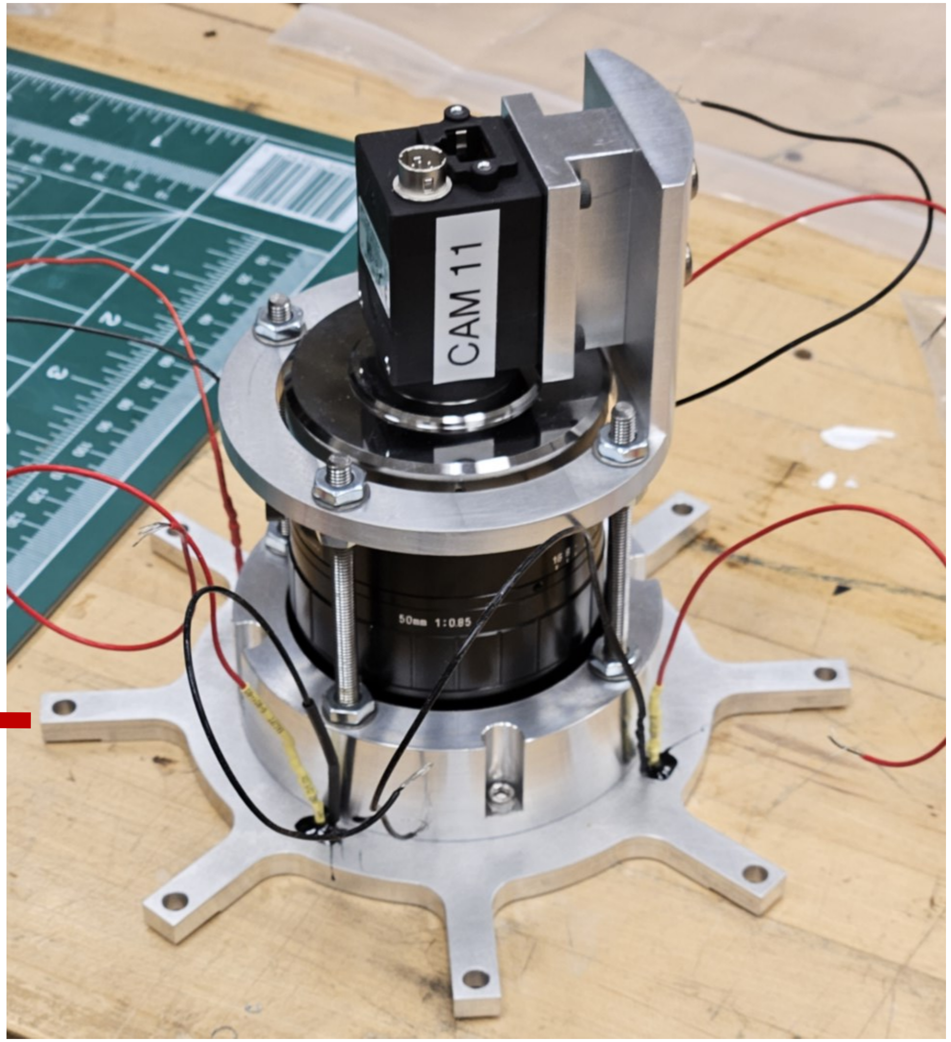
ReA3-SECAR* Scintillator Beam Monitor (Phase-IIB)

*SECAR = Separator for Capture Reactions

Mounting Scheme onto High Vac Instrument Box

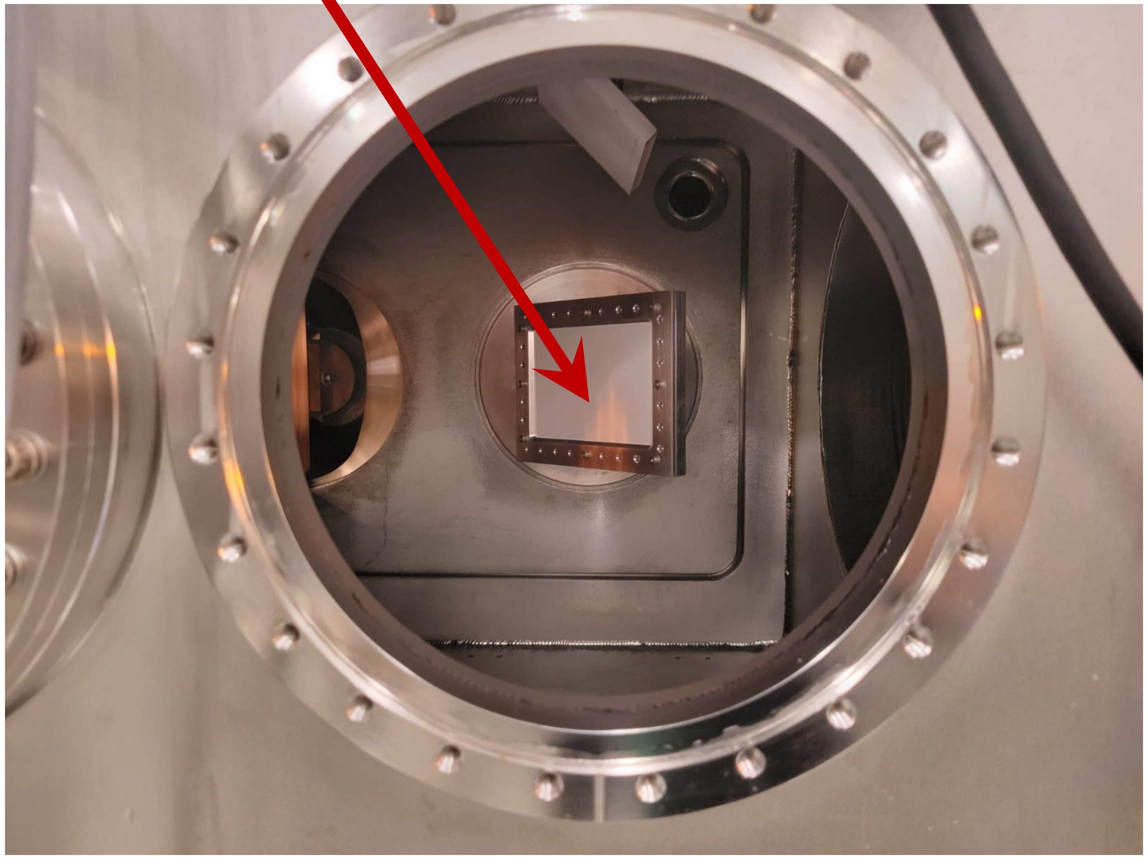


Camera Assembly

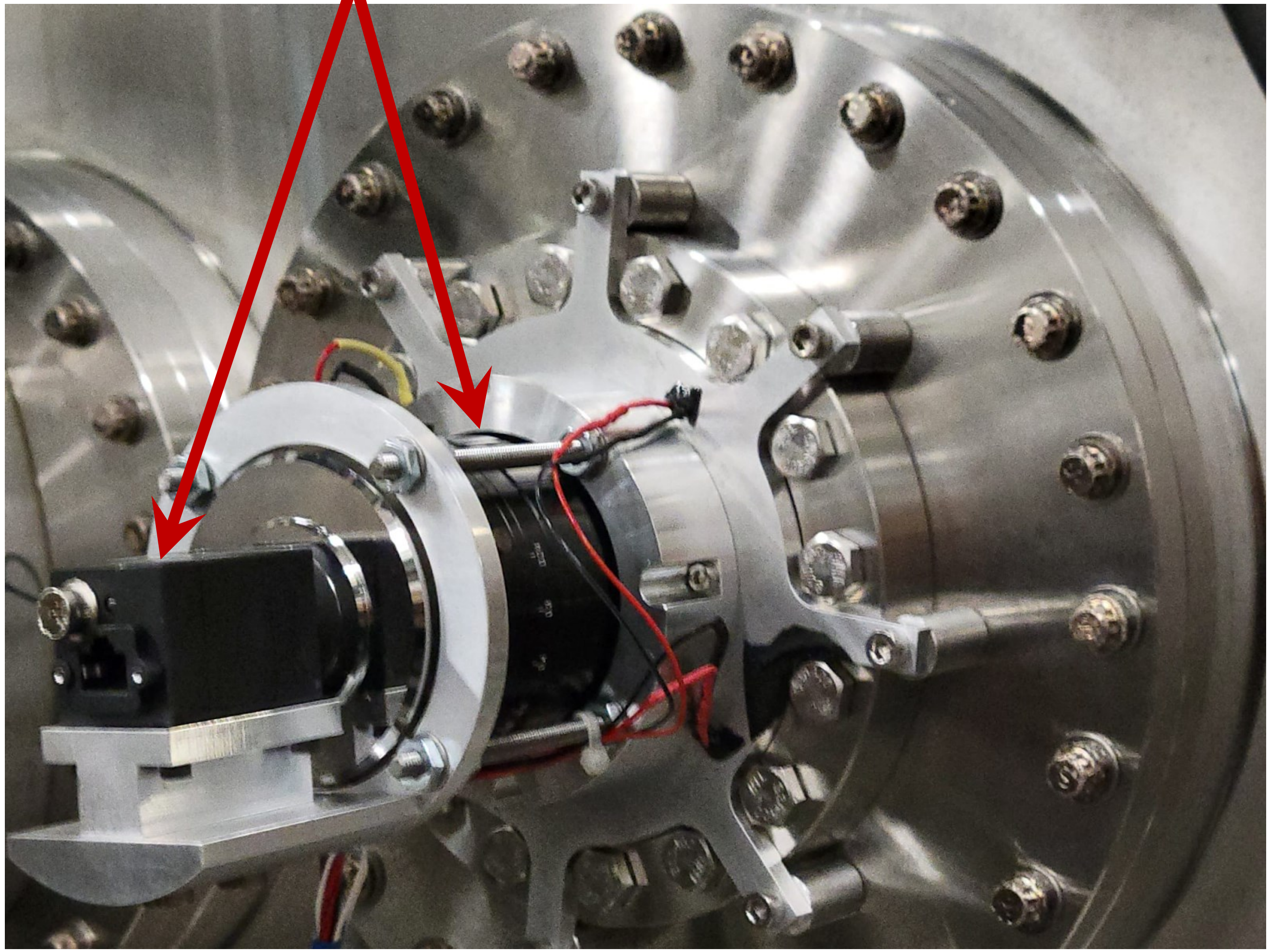


Installed ReA3-SECAR Beam Monitor PRODUCT

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

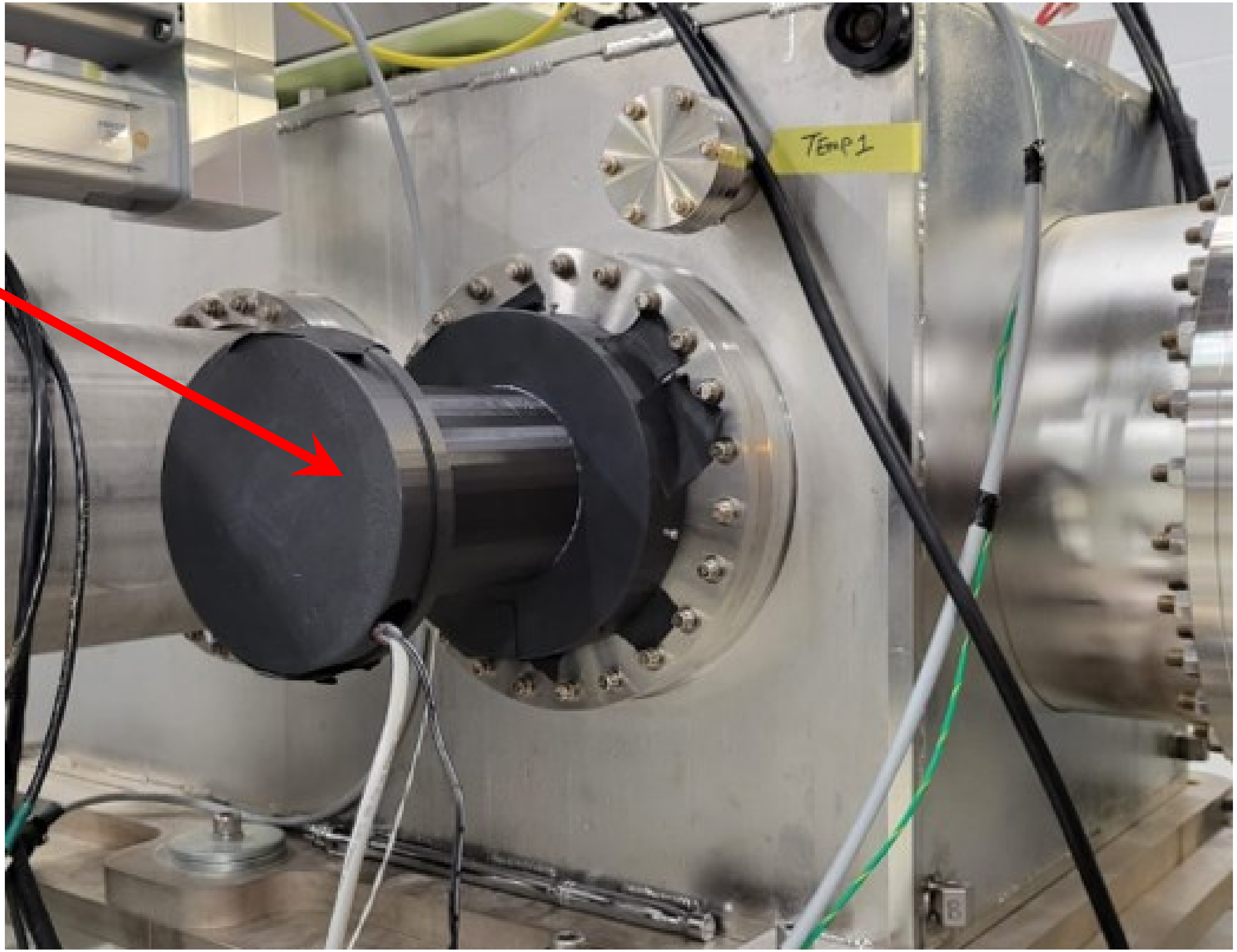


Camera Assembly mounted to Instrument Box



ReA3-SECAR SBM Camera-Lens Housing

3D-Printed
Camera-Lens
Light-Tight
Housing



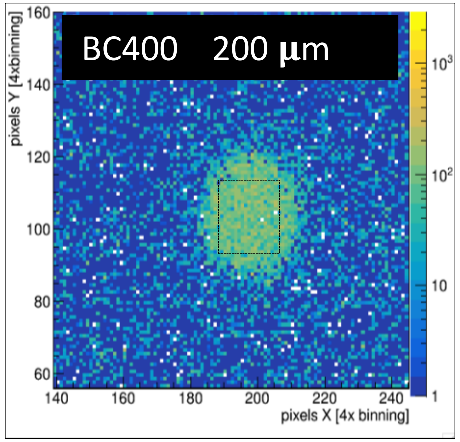
<u>Test Beams</u> (Phase-II and Phase-IIB)

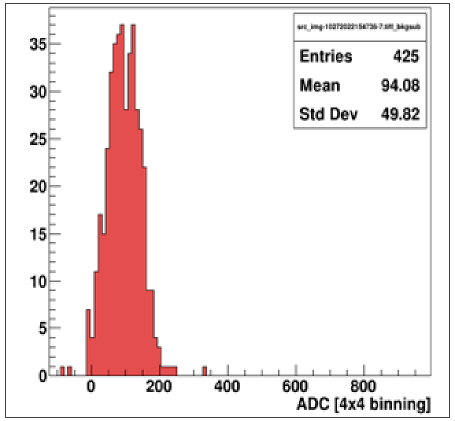
Location	*Source*	*Energy [MeV/u]*
UM Physics Lab	β (^{90}Sr) & α (^{241}Am)	~1
Michigan Ion Beam Laboratory (MIBL)	p	1 - 6
Facility for Rare Isotope Beams (FRIB)	**$^{86}Kr^{+26}$**	**2.75**
(FRIB SECAR Installation 7/11/2024)	**$^{35}Cl^{+15}$ & $^{14}N^{+6}$**	**4.5**
Notre Dame Radiation Laboratory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

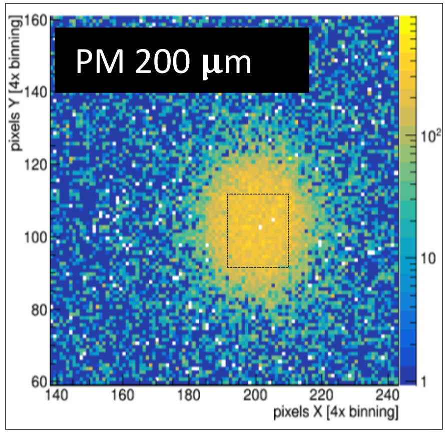
Scintillator Efficiency Comparisons to Benchmarks

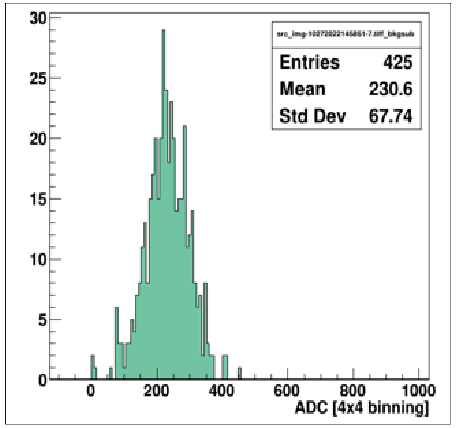
3 mm collimated electron beam (β^- source ^{90}Sr)

PM type

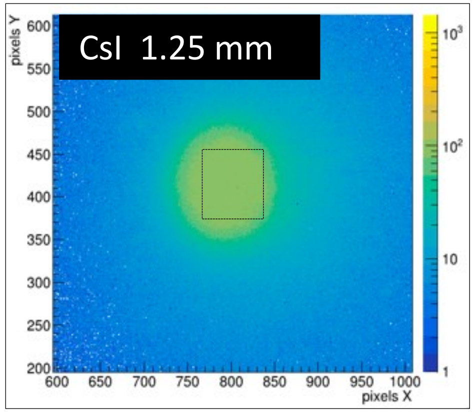


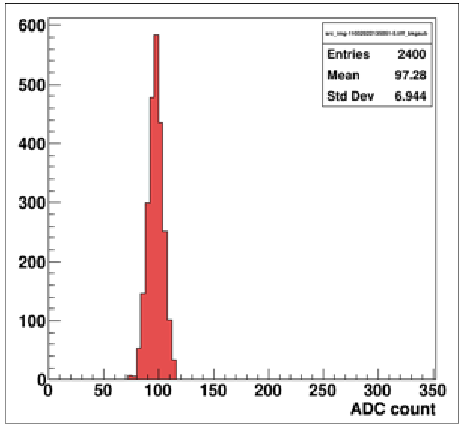


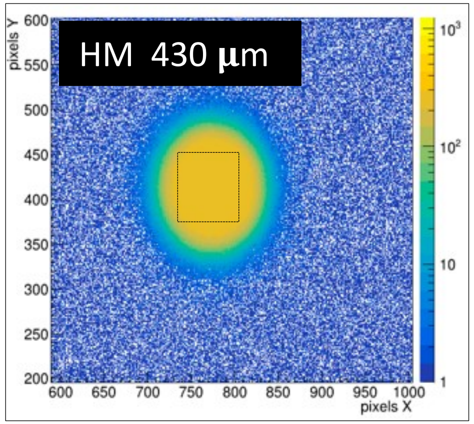


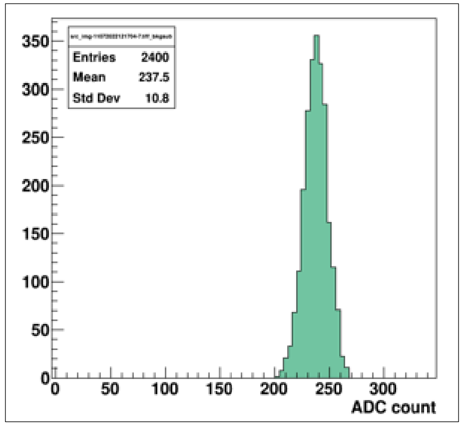


HM type



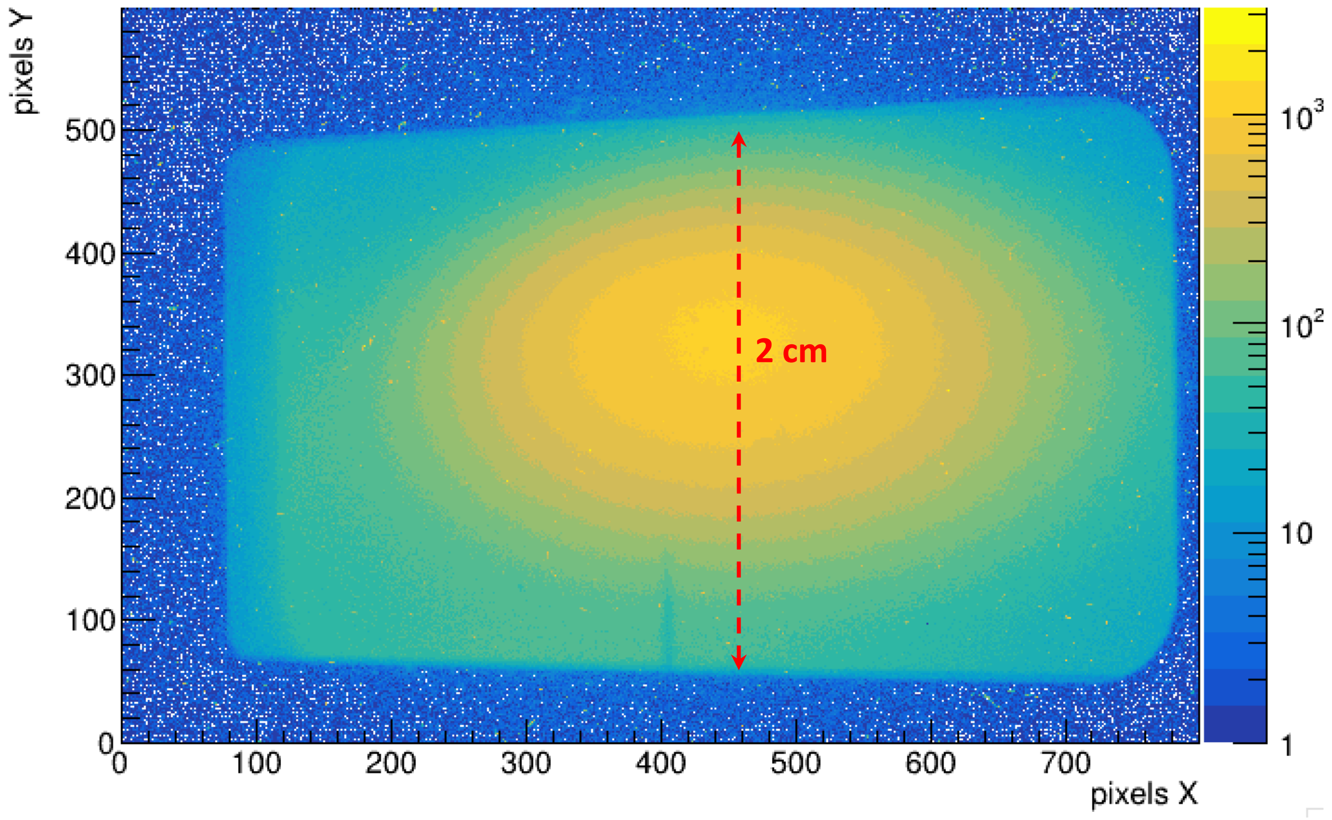




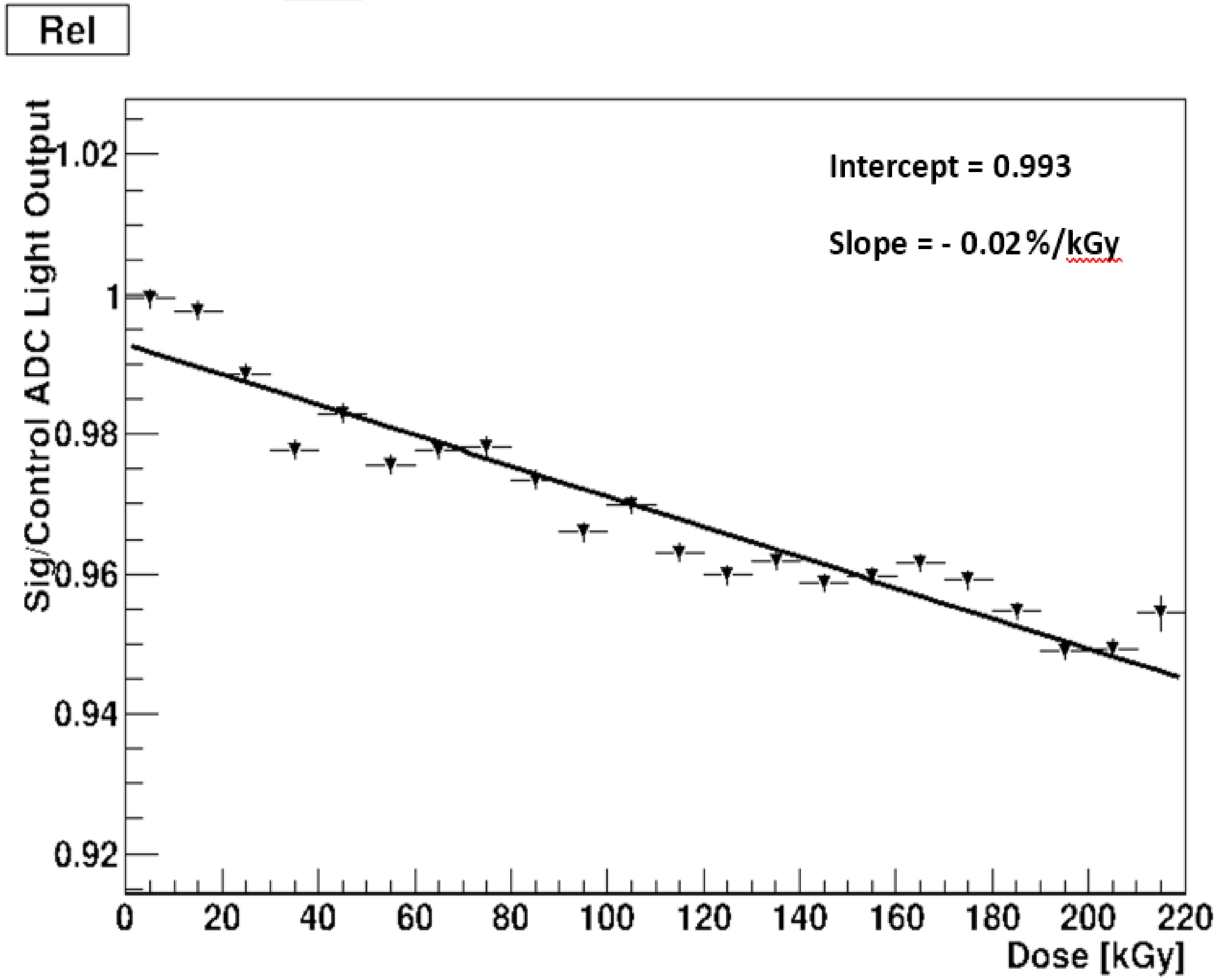


Beam Image on HM at NDRL (camera coordinates)

- **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



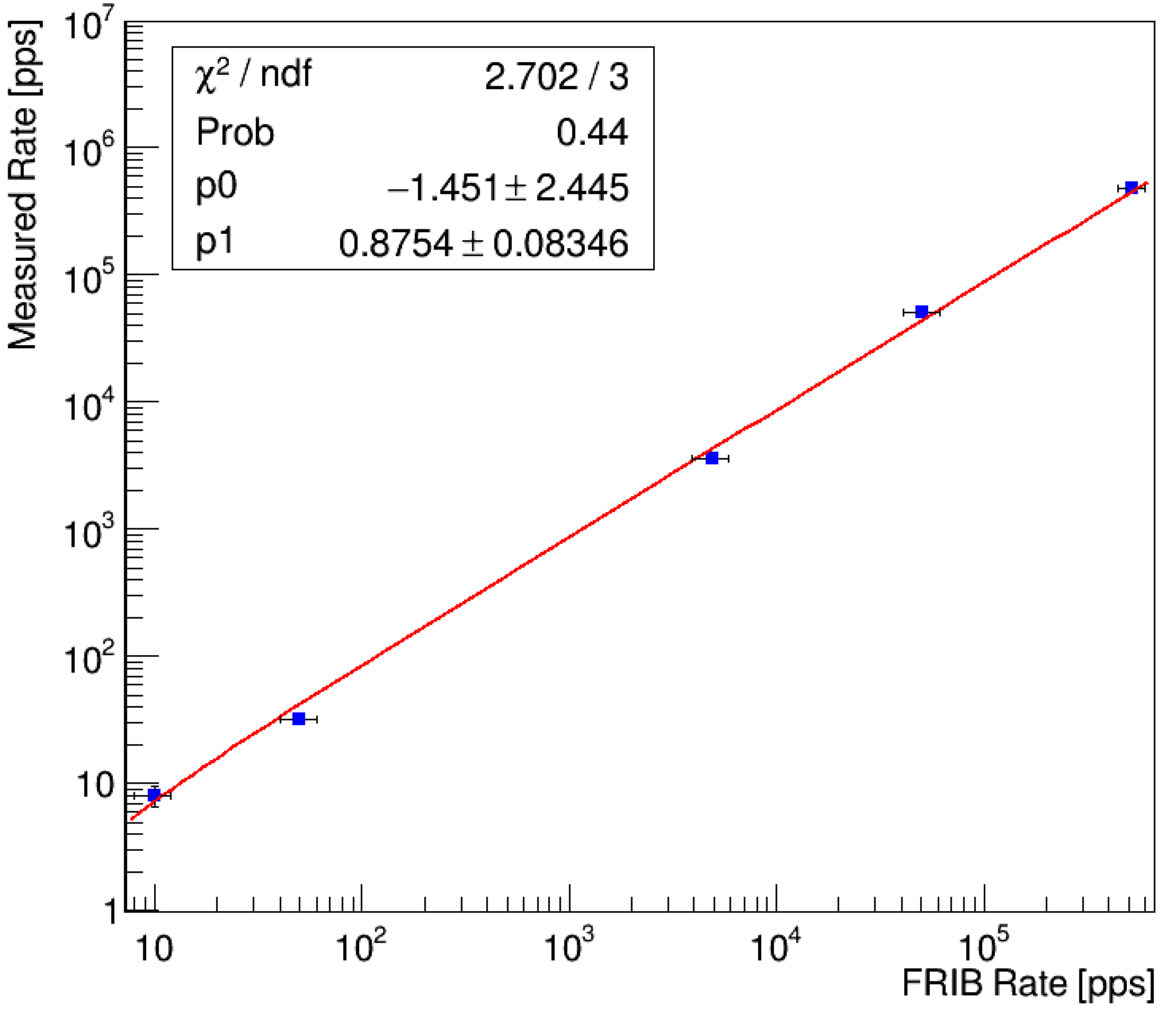
For proton-FLASH-RT @ 10 Gy/patient, 20 patients/day, 5 days/week, the dose is 1 kGy/wk or **50 kGy/yr**.

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.

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

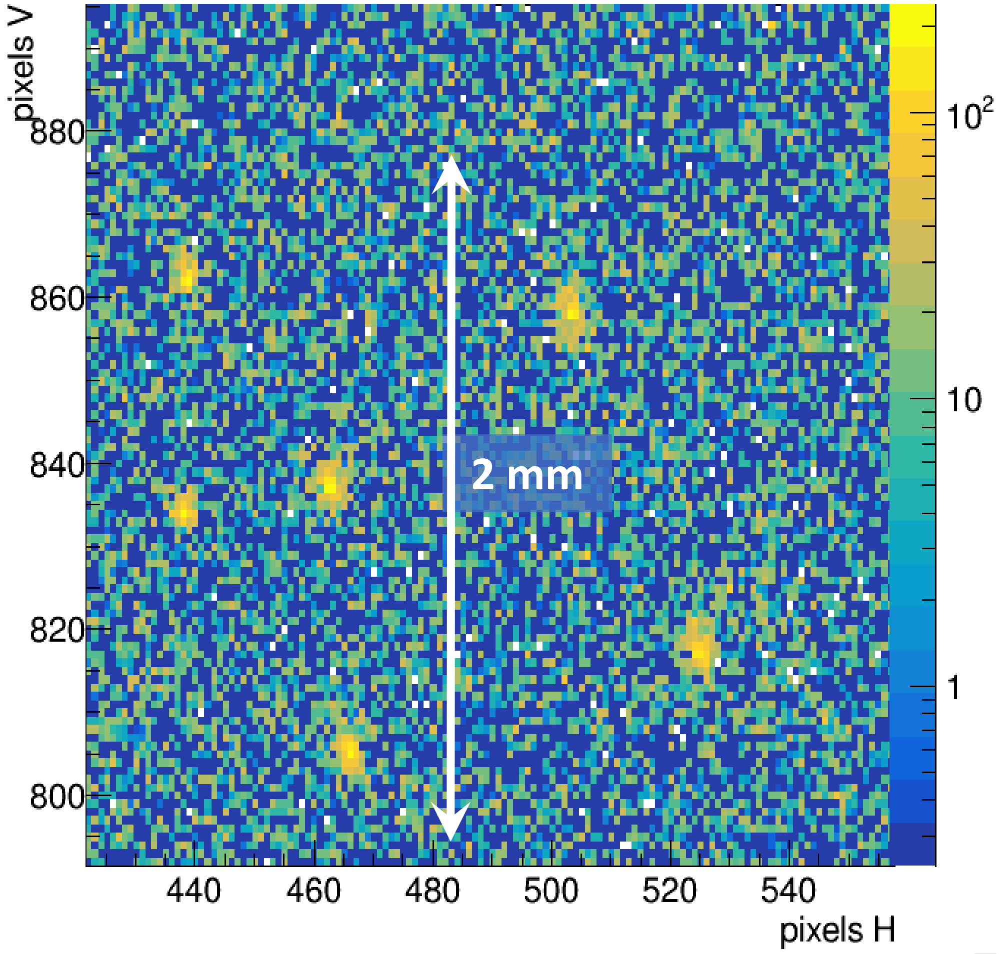
SBM measurement is *linear over more than* 5 orders-of-magnitude (the full range has not been determined)

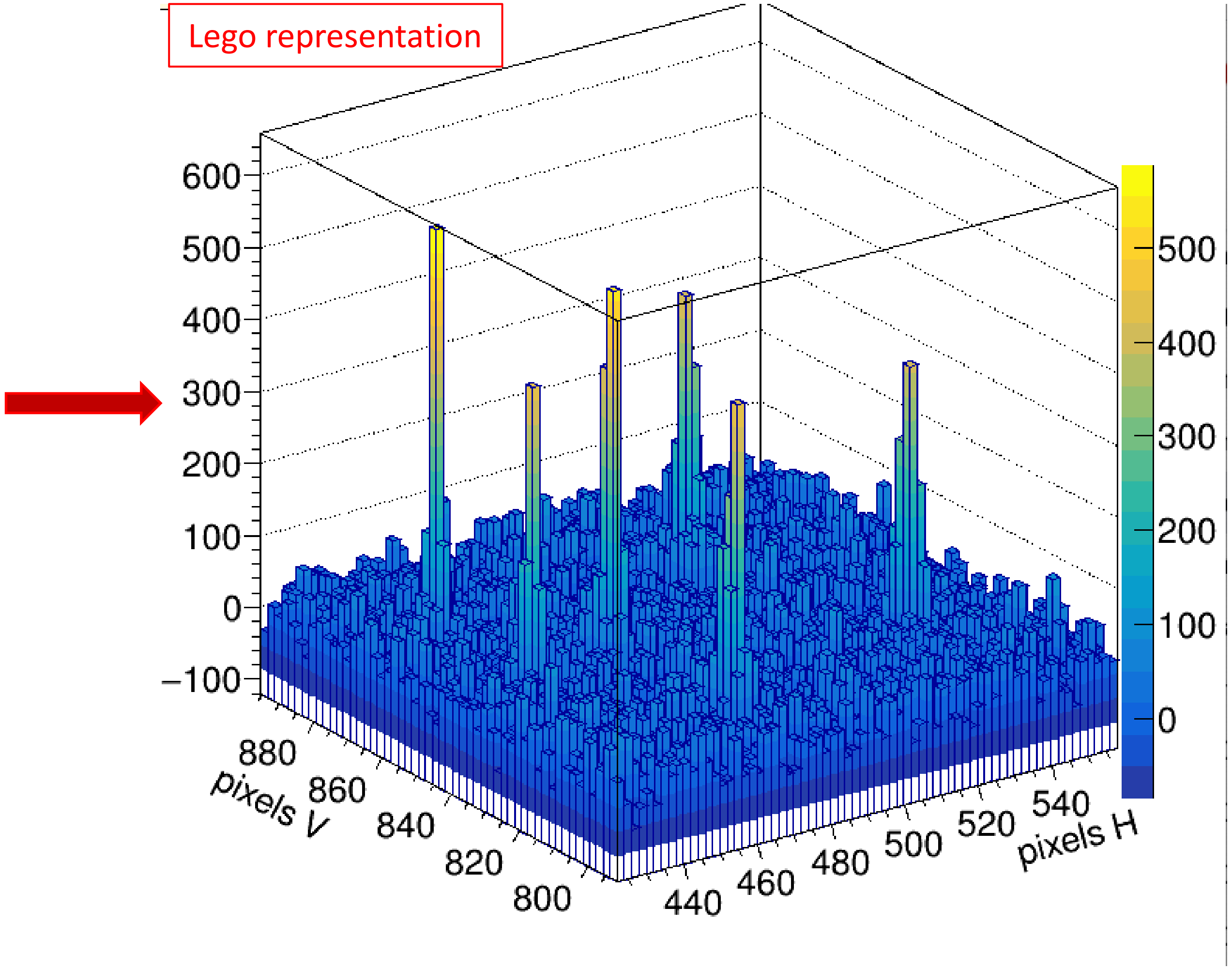
“Single Particle” hits/images

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

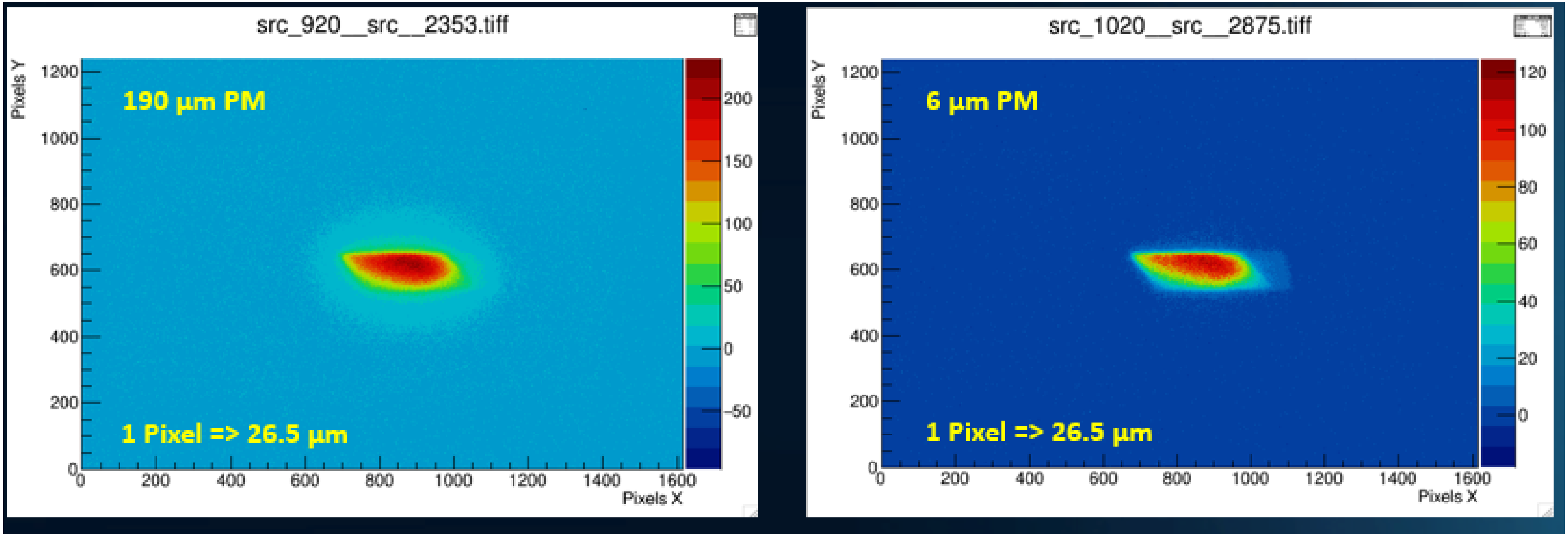
Beam current ramped down to < 10 Hz

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





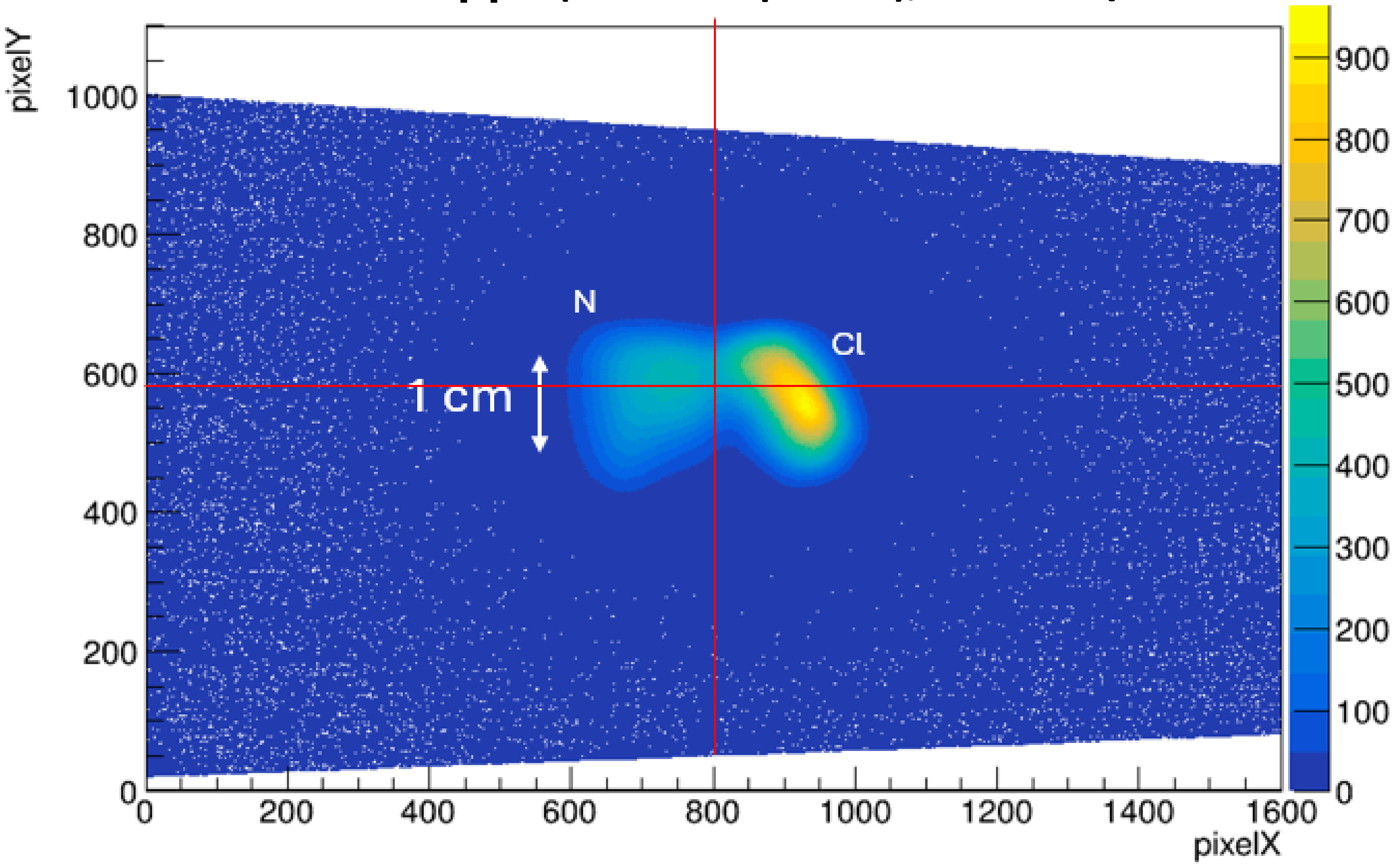
Phase-II Beamline Images of $^{86}Kr^{+26}$



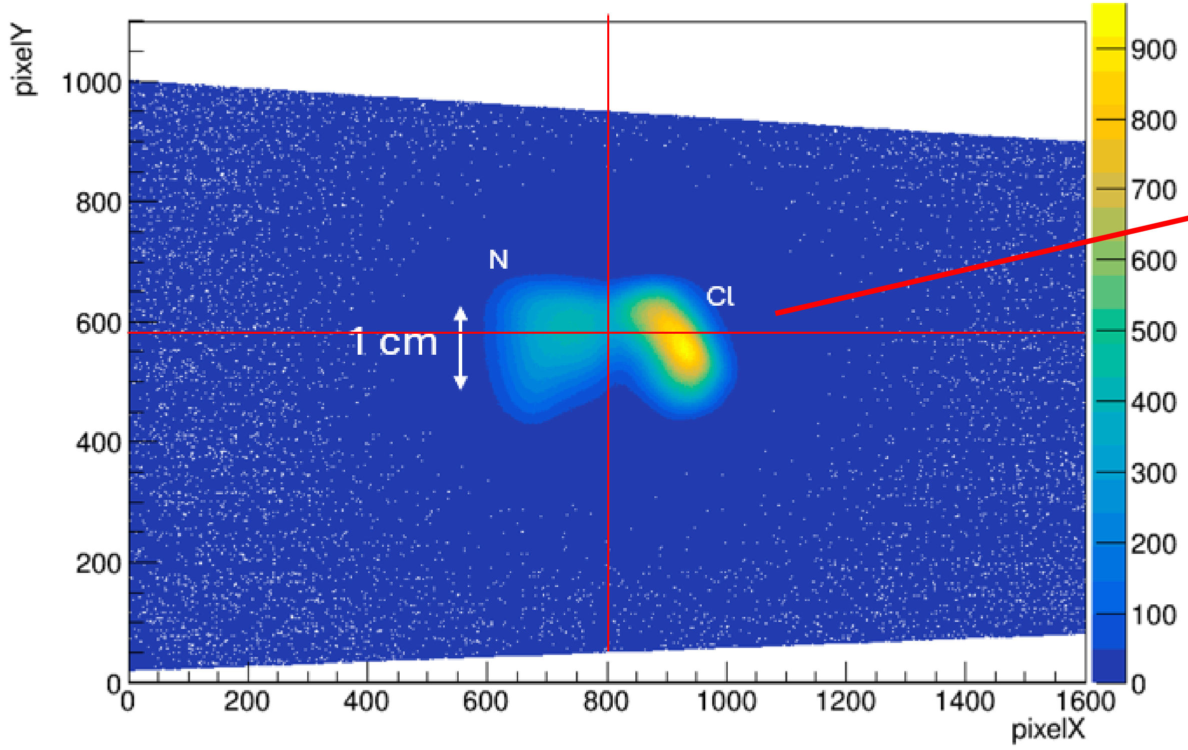
Above beamline images captured in real-time of same 2.75 MeV/u beam of $^{86}Kr^{+26}$ particles irradiating two different thickness 2x2 cm **PM** scintillators at a rate of **5.2 x 10^{5} pps**. Image on Left was with **190 μm** thick **PM;** image on Right was with **6 μm** thick **PM** that **transmits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

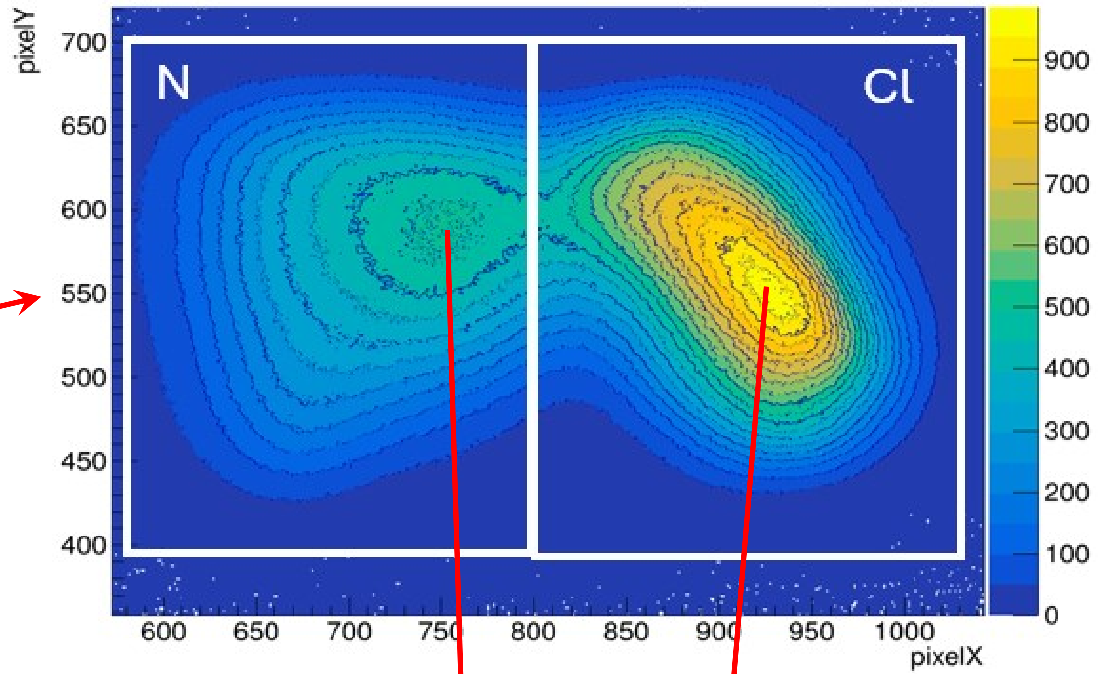
Phase-IIB Mixed Beam of $^{14}N^{+6}$ and $^{35}Cl^{+15}$

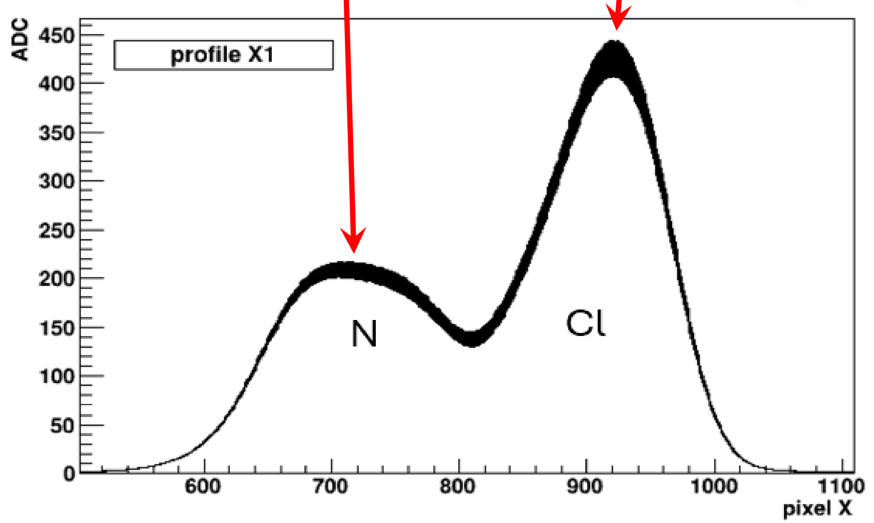
1.35 x 10^6 pps **(0.1 sec exposure), 4.5 MeV/u**



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

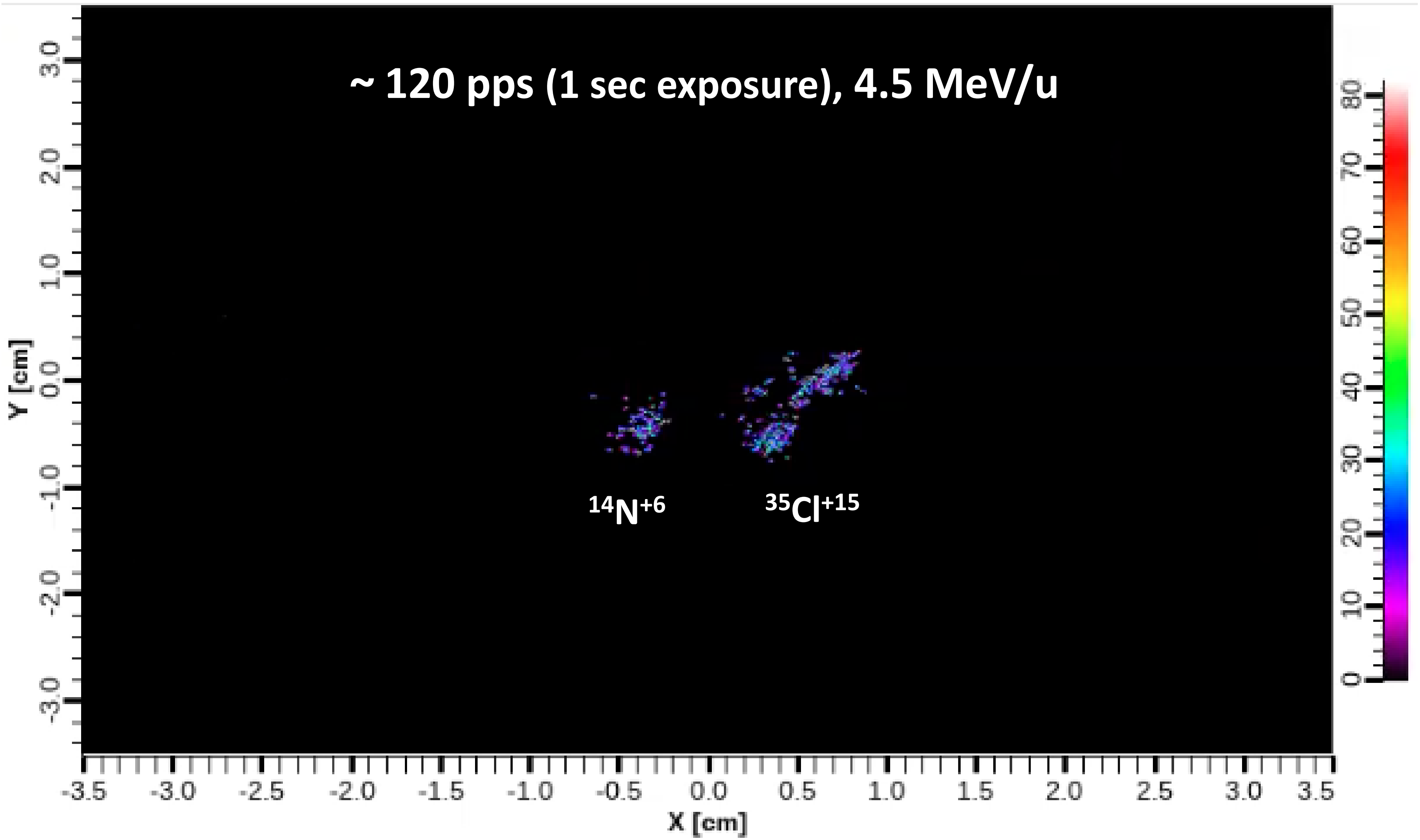




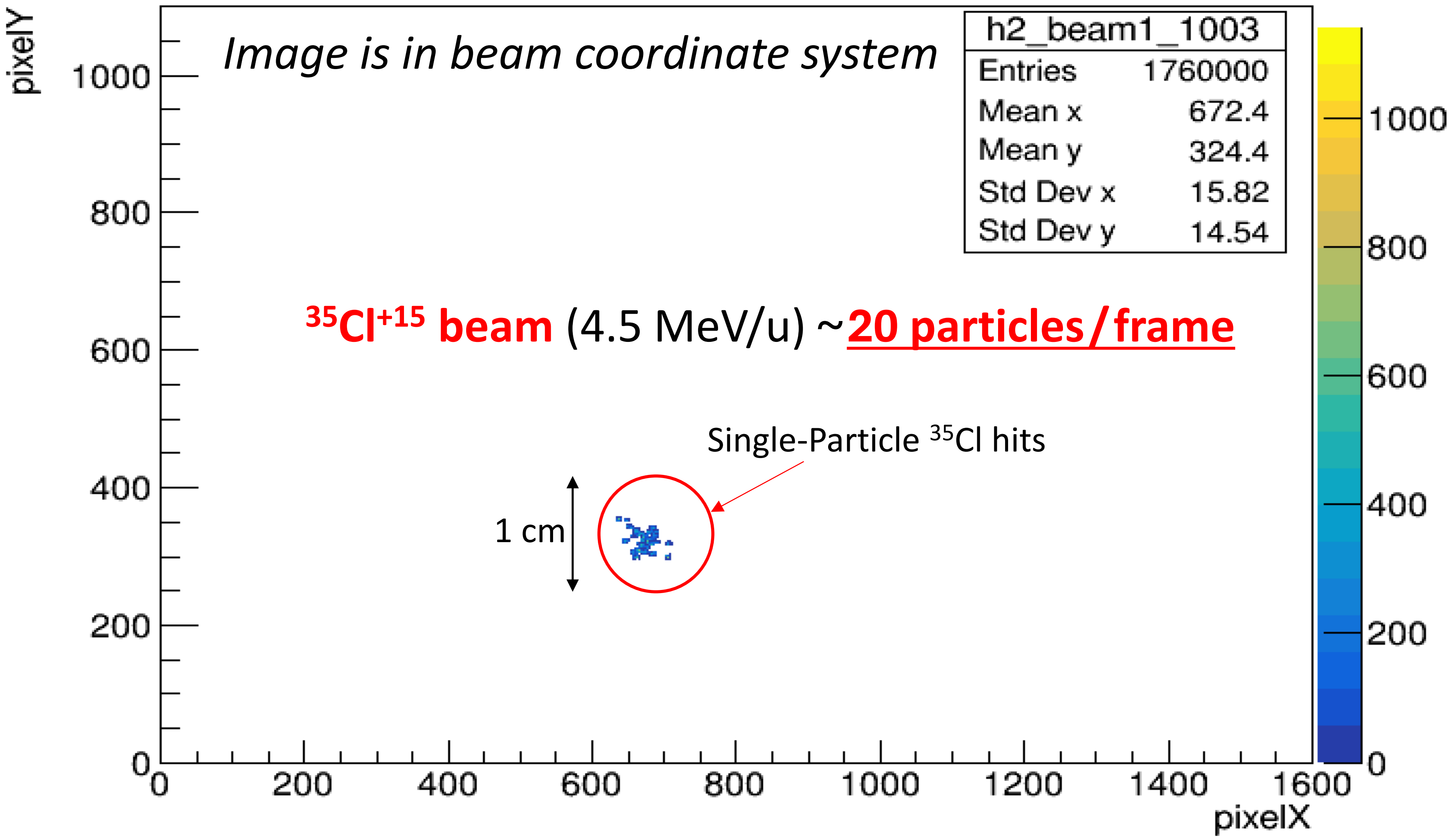


Shown above is image of **<u>1.35 x 10^5 particles/frame</u>** of mixed ^{14}N and ^{35}Cl beam. Bottom Left is the *average of all ADC* counts along the Y axis as a function of the X axis beam position.

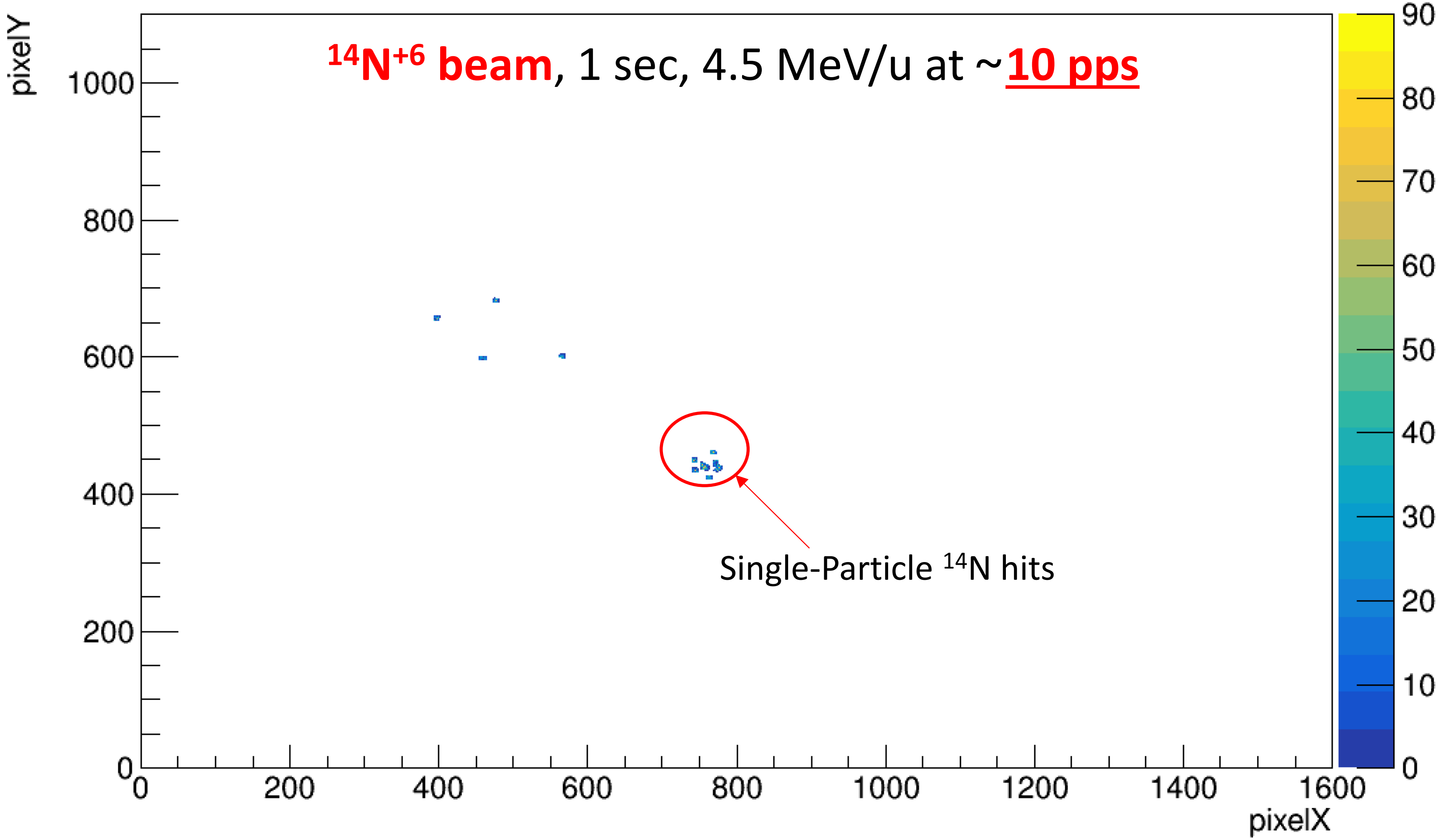
Ultra-Low Intensity Mixed Beam of $^{14}N^{+6}$ and $^{35}Cl^{+15}$



“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*