Phase-IIB

High Performance Scintillator and Beam Monitoring System (SBM)

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Phase-IIB: Transition Towards Commercialization

- Description of SBM Technical Innovation for NP

- Description of NP Implementation/Commercialization Strategy:

  New ***Translational Approach*** in Phase-IIB to facilitate SBM design from a ***standalone Six-Way-Cross*** (6WC) commercial product, to a ***low cost***, flexible component, customizable ***platform integrated by the customer*** into ***existing*** NP beam monitoring diagnostic systems. Major advantages are *faster, more precise beamline tuning, eliminating new beamline real estate requirement need to switch to surrogate "pilot" beam for tuning.*

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

Phase-IIB: Translational Approach for NP

- NP customer market analysis: ***No one-size-fits-all*** product solution, especially for different energy ions and different beam pipe size beamlines.

- Power of SBM product customization placed in hands of customer.

- No new ***beamline real estate*** required for our SBM platform "retrofit".

- Customer installation eliminates our travel, installation & overhead charges.

- Customer's in-house labor/expertise provides maximum flexibility at lowest possible cost, especially for ***multiple*** SBM identical platform solutions.

Phase-IIB Program Overview

Goals

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

II: Critical components/software ***inserted by customer at low cost*** into existing NP beam monitoring diagnostic systems

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: ***ultra-fast*** **large aperture optics** for max light collection (i.e., **< F/1.0**)

Specs

- **~ 10 µm position resolution**
- Fast detection algorithms quickly find weak beams: ***< 1 sec for NP, and < 2 µs for proton-FLASH-RT (radiotherapy)***
- 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 **~ *10 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

Scintillators – *thin, non-hygroscopic & radiation damage resistant* [1]

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

- Thin < 700 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:

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

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

Translational Approach from NP to the NIH-NCI

- Based on positive results from NP Phase-I (02/2019) and Phase-II (04/2020), we submitted to NIH-NCI a ***"Direct-to-Phase-II"***, ***3-year, $1.9M*** proposal which was awarded starting 09/2021.

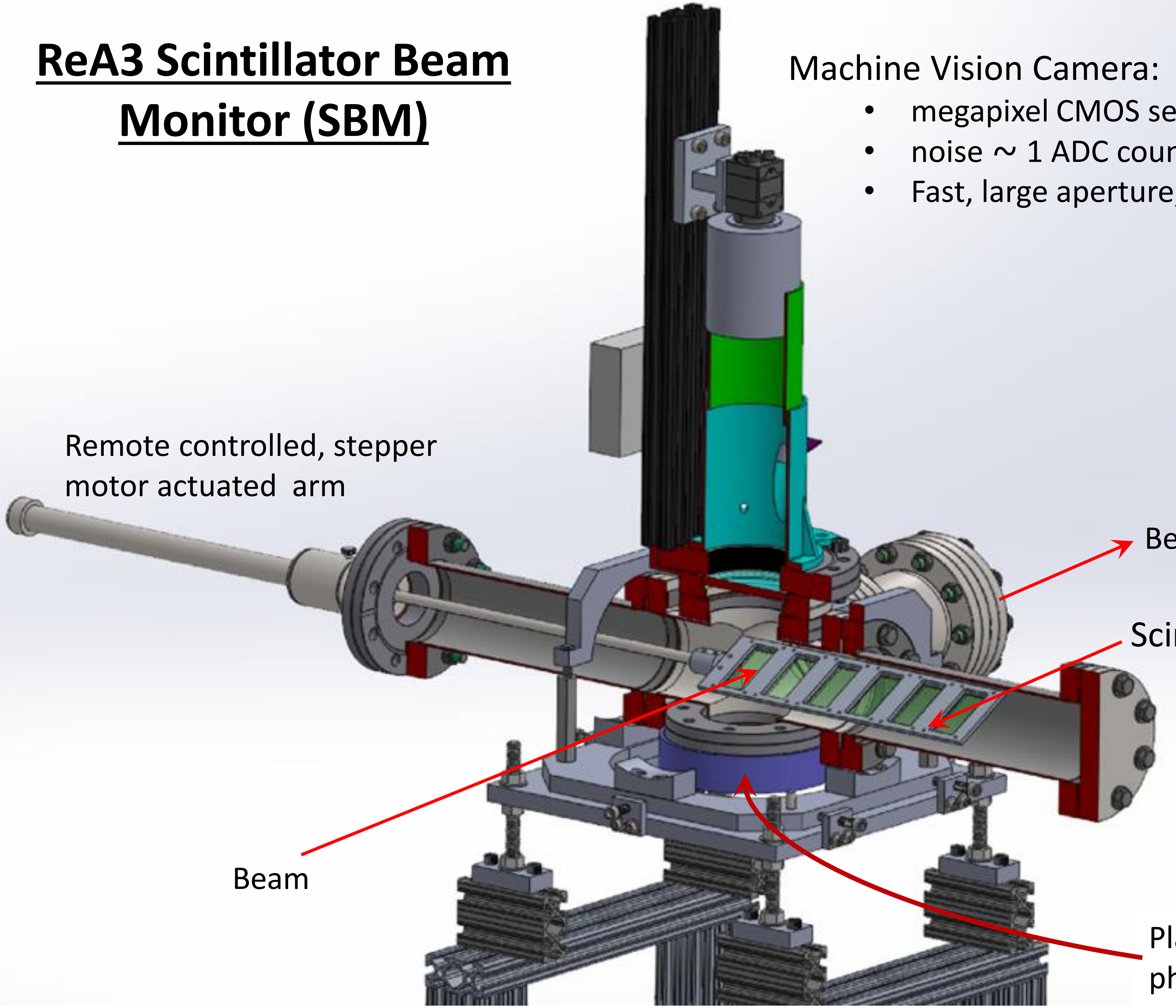
- NCI Award: ***"Utrafast and Precise External Beam Monitor for FLASH and Other Advanced Radiation Modalities"***.

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

- Scintillator radiation damage measured as signal loss / kGy dose = **0.02%/kGy**. For proton-FLASH-RT at 10 Gy/patient, 20 patients/day, 5 days/wk, or **1% signal loss/year.**

- Beam Monitor Analysis performed in **< 2 μs**, camera operates at **20,000 fps**.

ReA3 Scintillator Beam Monitor (SBM)



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

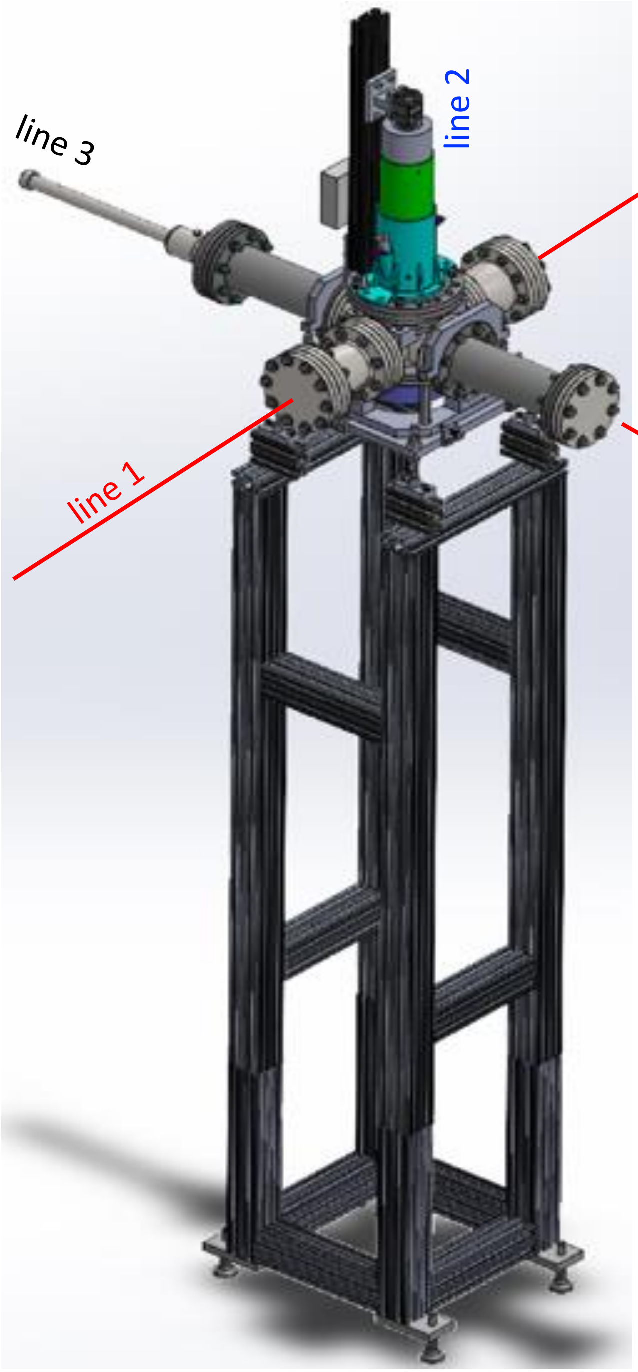
Beam exit

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

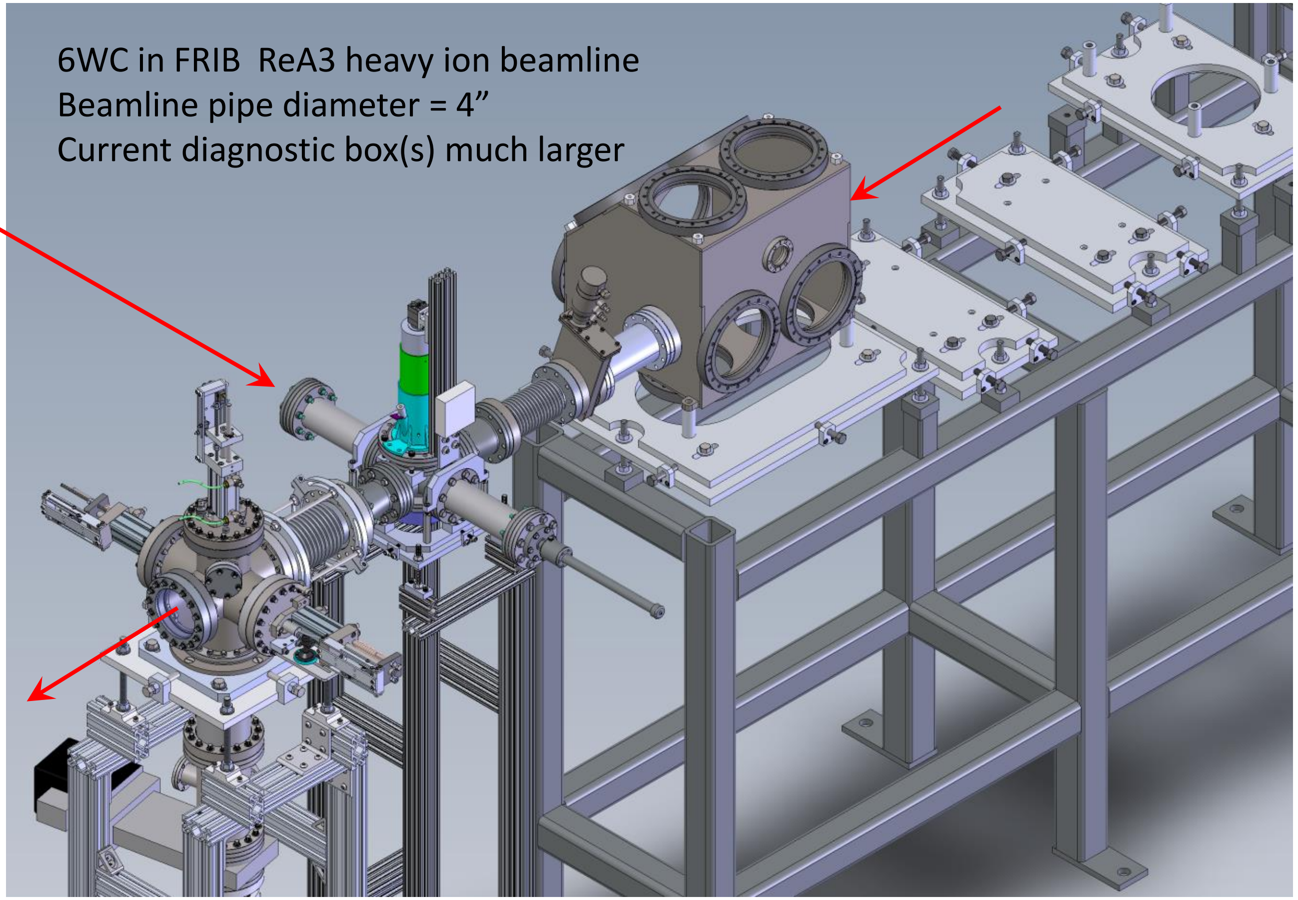
SBM Configured as “Six-Way-Cross” (6WC with 3 orthogonal lines)



Line 1: beam path (vacuum) fore/aft

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

Line 3: scintillator ladder travel



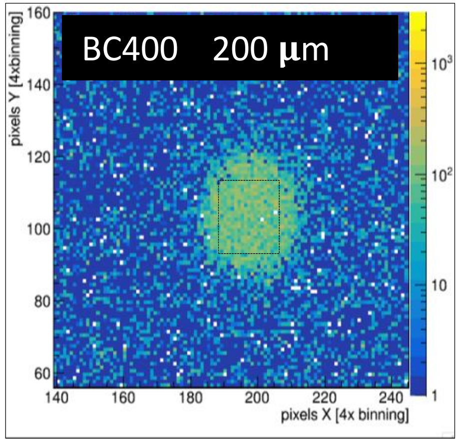
Test Beams

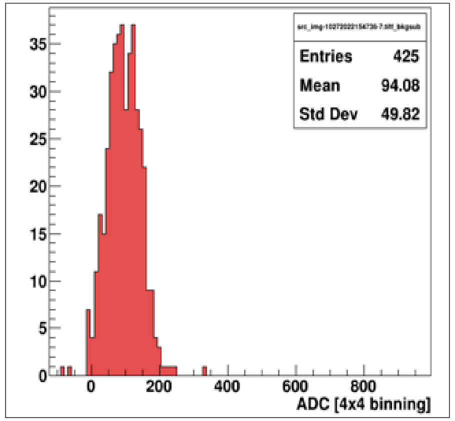
Location	*Source*	*Energy [MeV/n]*
UM Physics Lab	**β** (^{90}Sr) & **α** (^{241}Am)	~1
Michigan Ion Beam Laboratory (MIBL)	p	1 - 6
Facility for Rare Isotope Beams (FRIB)	$^{86}Kr^{+26}$	**2.75**
Notre Dame Radiation Laboratory (NDRL)	e^-	8

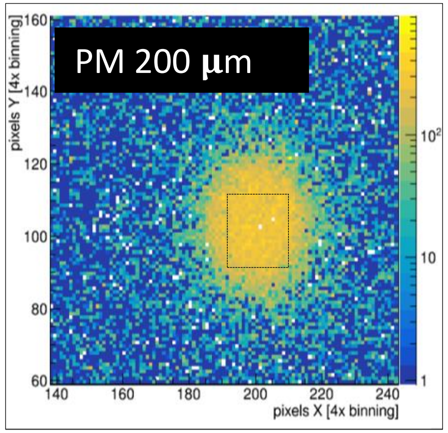
Scintillator Efficiency Comparisons to Benchmarks

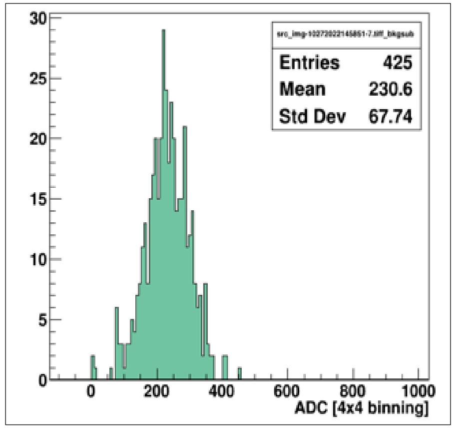
3 mm collimated electron beam (β^{-} source ^{90}Sr)

PM type

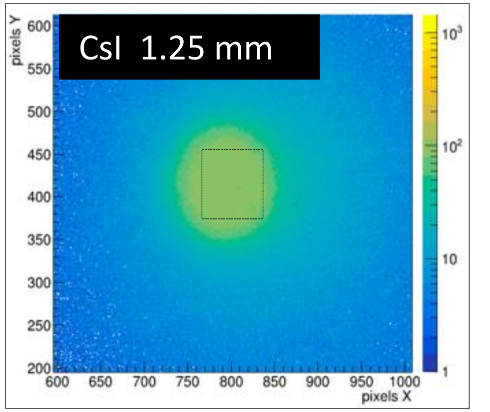


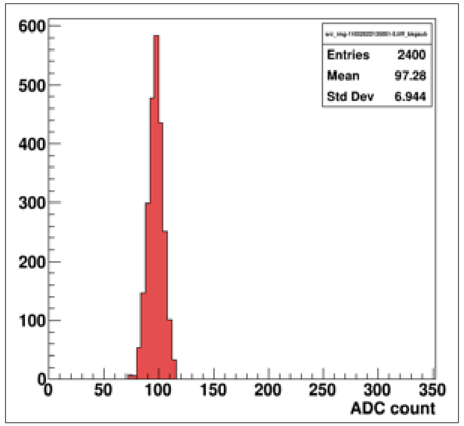


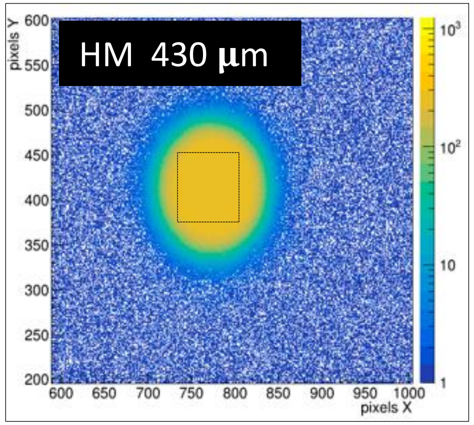


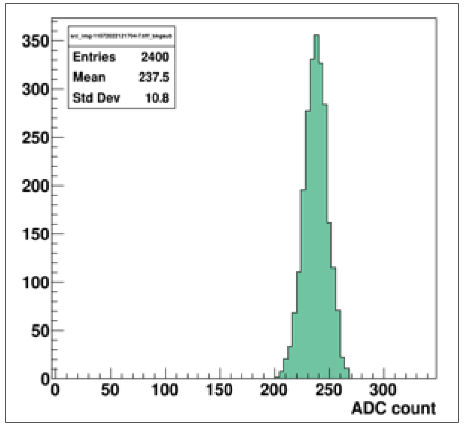


HM type

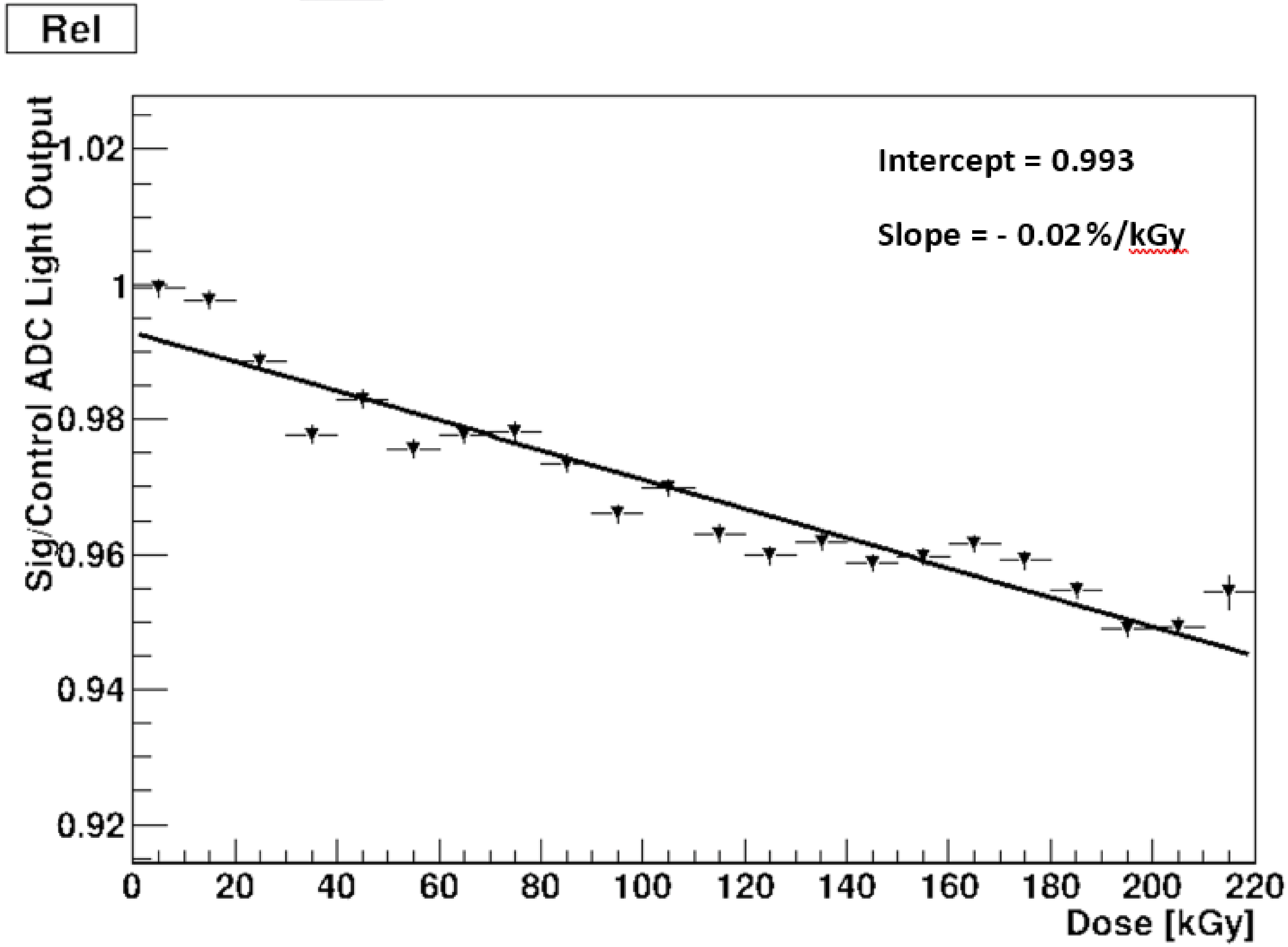








Radiation Hardness of HM Scintillator



Low signal loss of **0.02%/kGy** measured over 212 kGy.

> 1 yr of continuous clinical use
≤ 1 % signal loss

Signal loss is correctable with internal UV calibration system.

<u>Facility for Rare Isotope Beams</u> (FRIB *ReAccelerated 3 MeV Beamline*)

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

➔ ***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 for Beam Finding, Profile Analysis & Real-Time Display

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

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

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

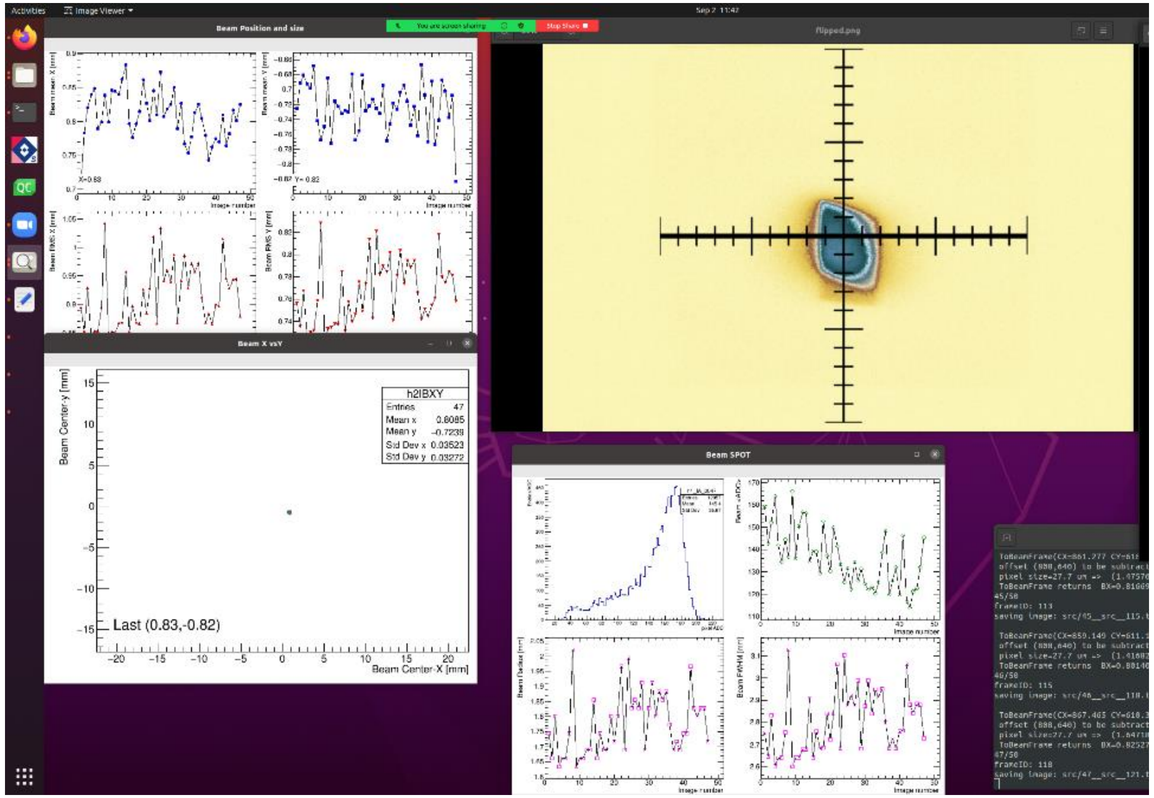
2. **Image processing in real-time:**
   - background subtraction
   - faulty pixel removal
   - affine (perspective) matrix transformations and rotations for display in beam coordinate system

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 in Control Room



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

Full pixel field

Beam finder

Beam radius history

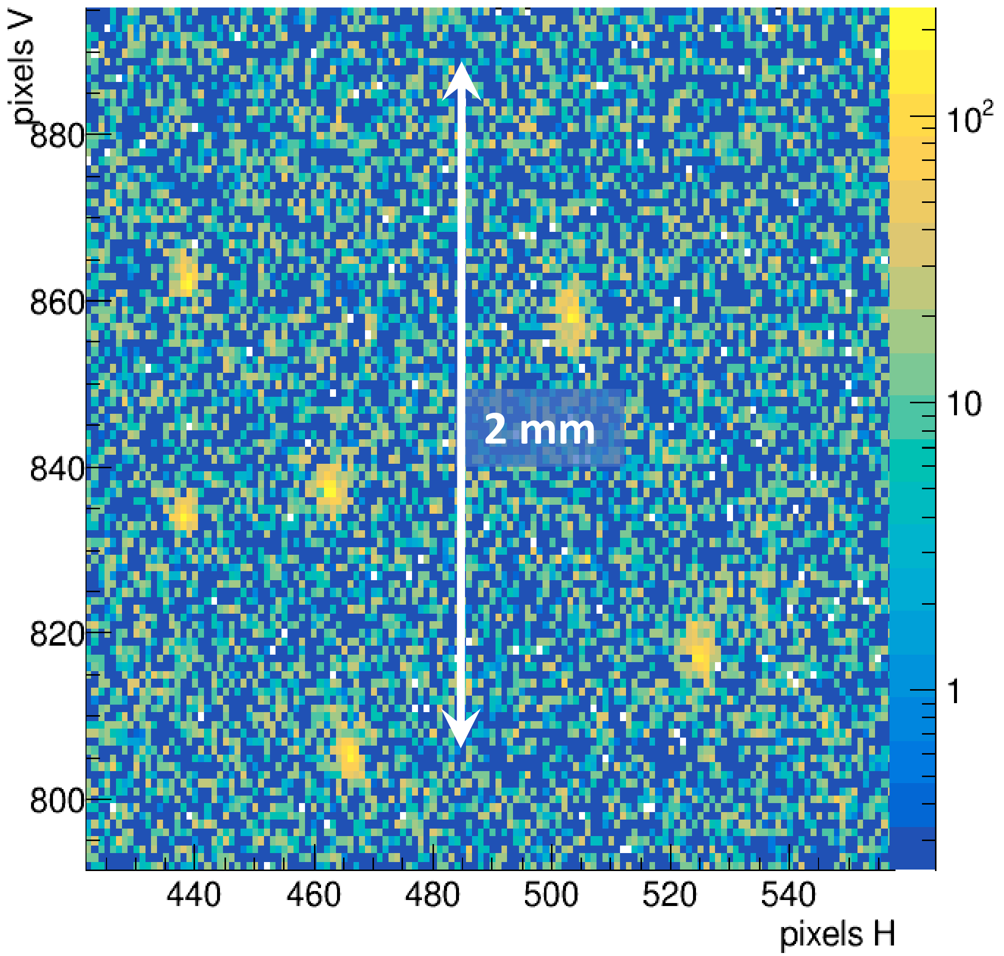
X position history

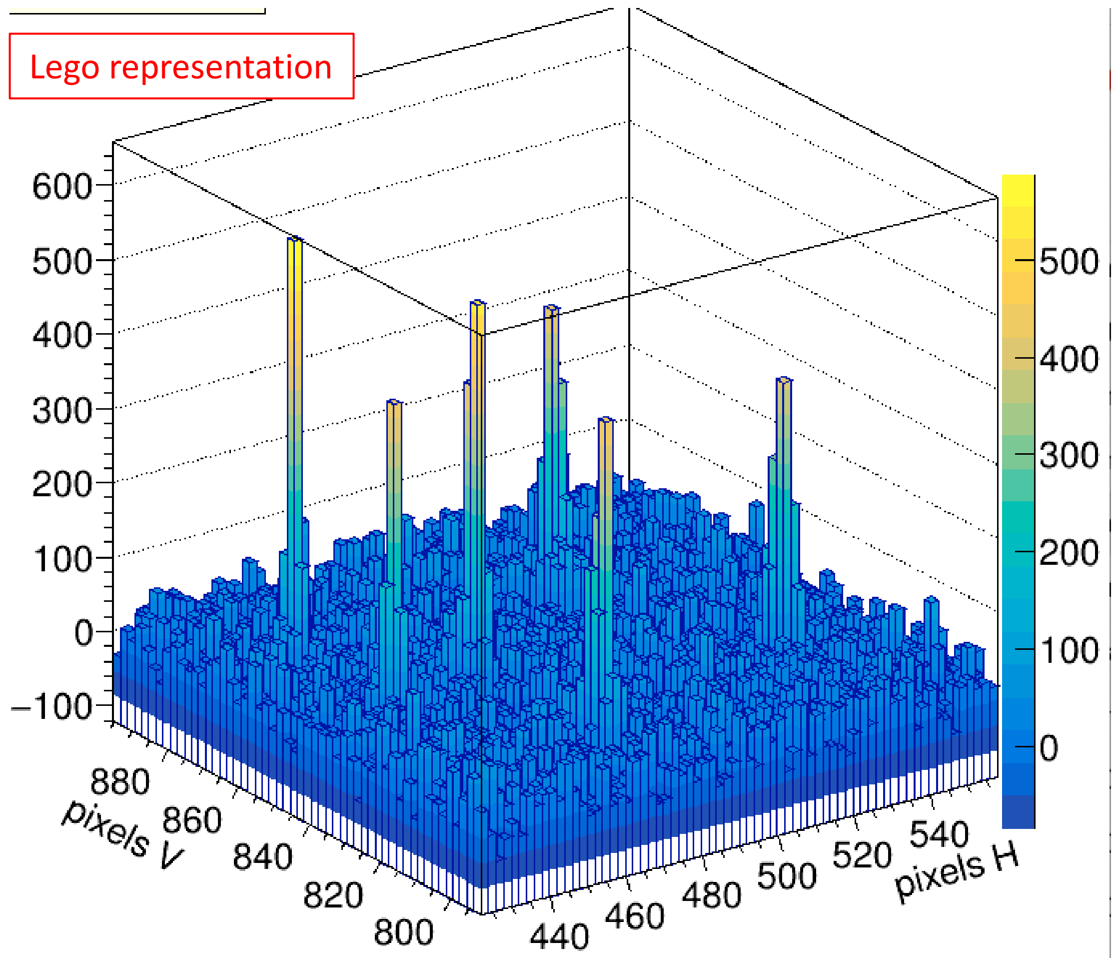
Y position history

X,Y history

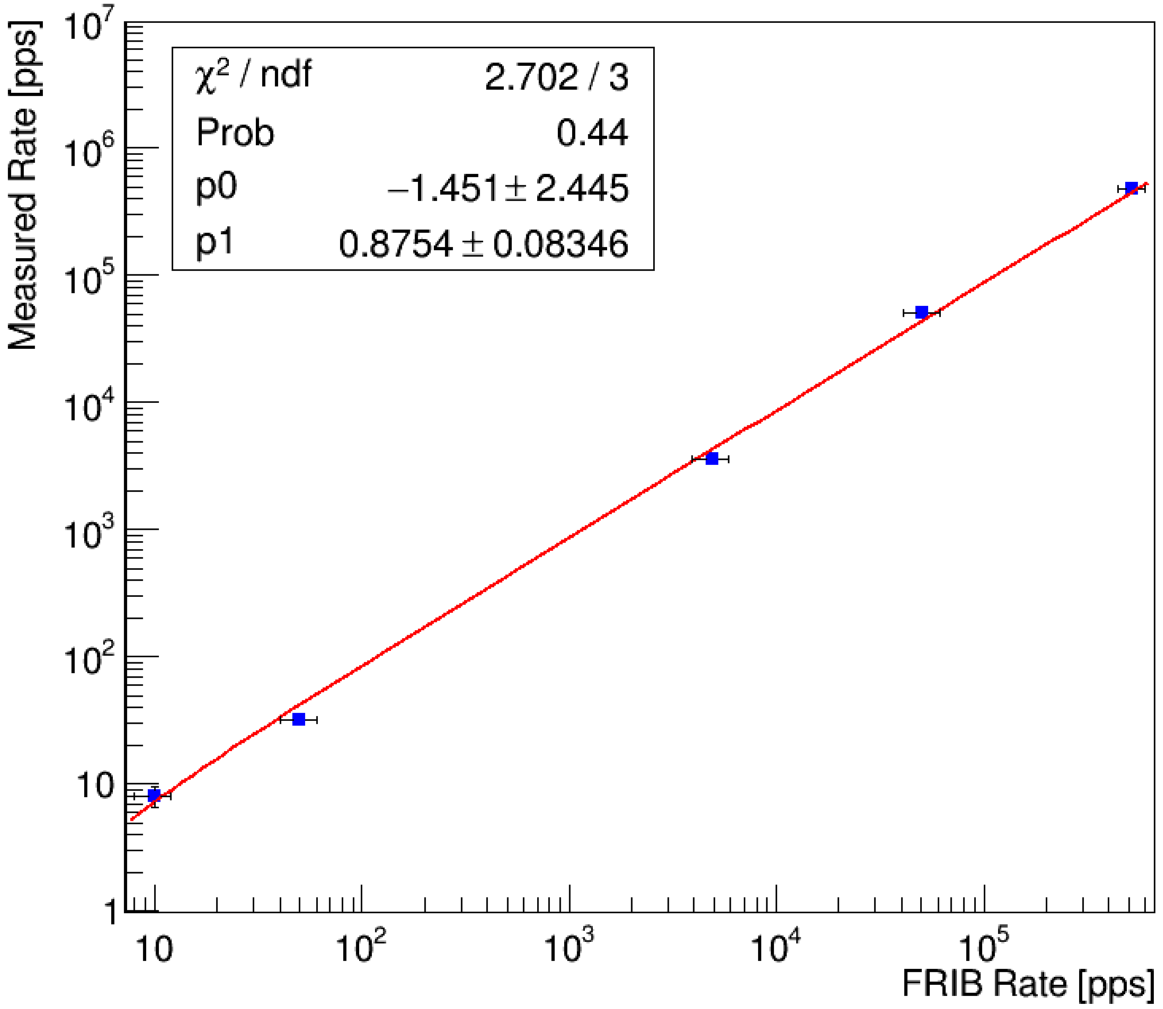
Signal & Beam Imaging in HM: *"Single Particle" hits/images*

Beam current ramped down to < 10 Hz
~ 5-6 Individual ^{86}Kr hits observed in 1 s frames





$^{86}Kr^{+26}$ Beam Current in HM Scintillator: Measured Rate vs. FRIB "Given" Rate



Result 1:

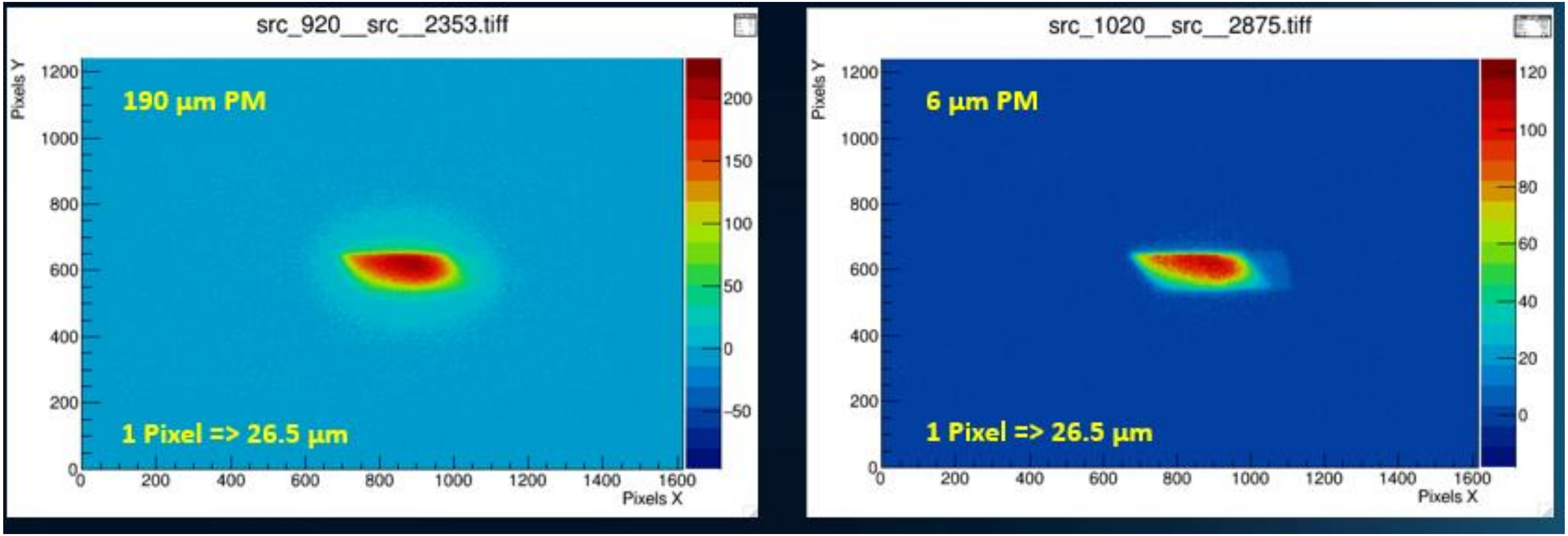
The <u>SBM can measure beam currents</u> that are now determined by 4 different FRIB devices:

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

Result 2:

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

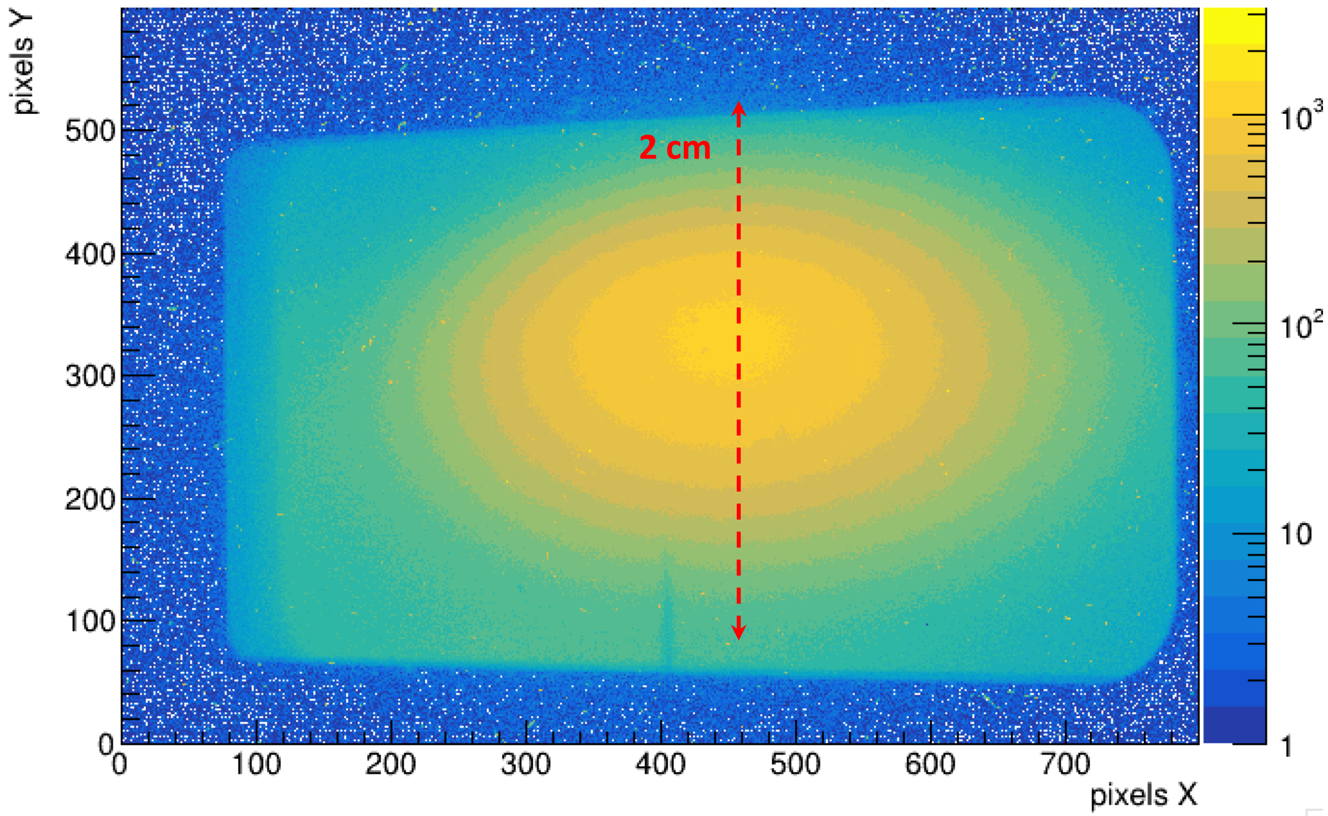
Beamline Images of $^{86}Kr^{+26}$



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.

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



U.S. Potential Customers for Phase-IIB Translational Platform

- FRIB – Potentially **3 dozen or more SBM** component systems (~ 20 in ReA)
- ANL-ATLAS – Potentially a **minimum of 12-15 SBM** component 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 **minimum of 3 SBM** systems

Commercial Applications

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

Conclusions

1) SBM provides **real-time, precise 2D beam tuning, profiling & imaging** with **spatial resolution ~ 10 μm**
2) **High sensitivity & dynamic range**: **single-particles** to ~ **10^{11} pps/cm^2** (~ 10 nA, depending on the particle)
3) **Linear Response to ≥ 5 orders-of-magnitude** for $^{86}Kr^{+26}$ (e.g., single-particles to ion-beam current of **$5x10^5$ pps**)
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) Larger potential commercial market for medical radiotherapy applications than for NP