# Ultrafast & Precise External Beam Monitor for FLASH and Other Advanced Radiation Therapy Modalities

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Collaborators

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# FLASH Radiotherapy (RT)

- FLASH-RT is ≥ ***1,000*** **times faster** with **<u>order-of-magnitude higher dose</u>** than conventional RT and delivered in **~ 0.1-0.5 sec**.

- The ultra-high dosing of FLASH-RT results in ***reduced toxicity*** thus providing a better tumor response and at ***reduced cost***.

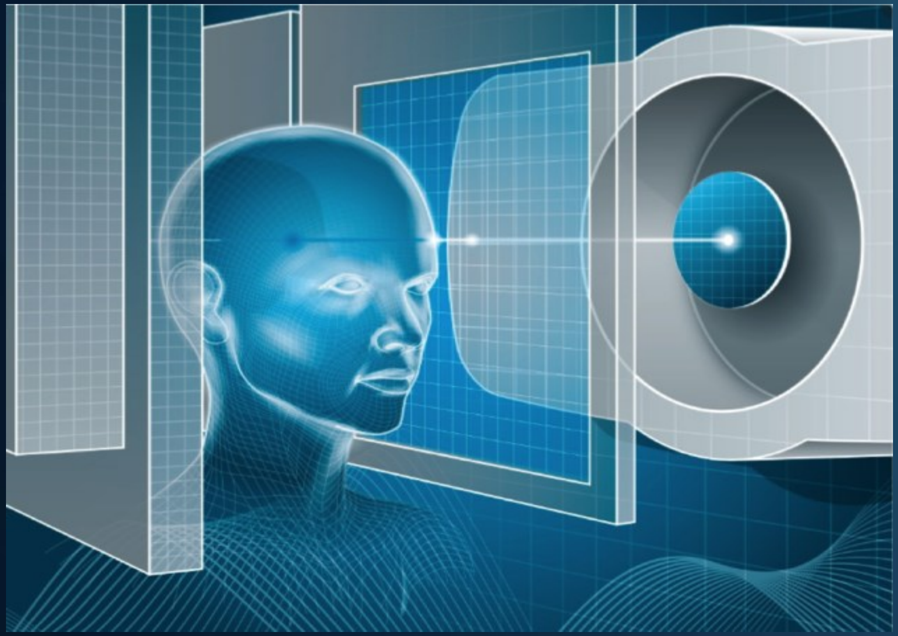
- Standard dosimetry methods are not fast enough and ***<u>do NOT work</u>*** at the radiation intensity/rates of FLASH-RT delivery

# **Safety** Problem: Monitoring FLASH Delivery

- Challenge: To be clinically approved (FDA/NIH/IRB) FLASH-RT must be monitored in real-time so the beam can be ***immediately*** terminated if a problem develops given the **~1000X higher dose rates** and **~ 0.1 sec** total delivery time.

- Conventional beam monitors are not capable of large-area 2D imaging with full analysis in real-time at FLASH rates.

- Our Solution: **F**LASH **B**eam **S**cintillator **M**onitor (FBSM) that continuously images & analyzes beam every **~50 μs** as the patient is irradiated.

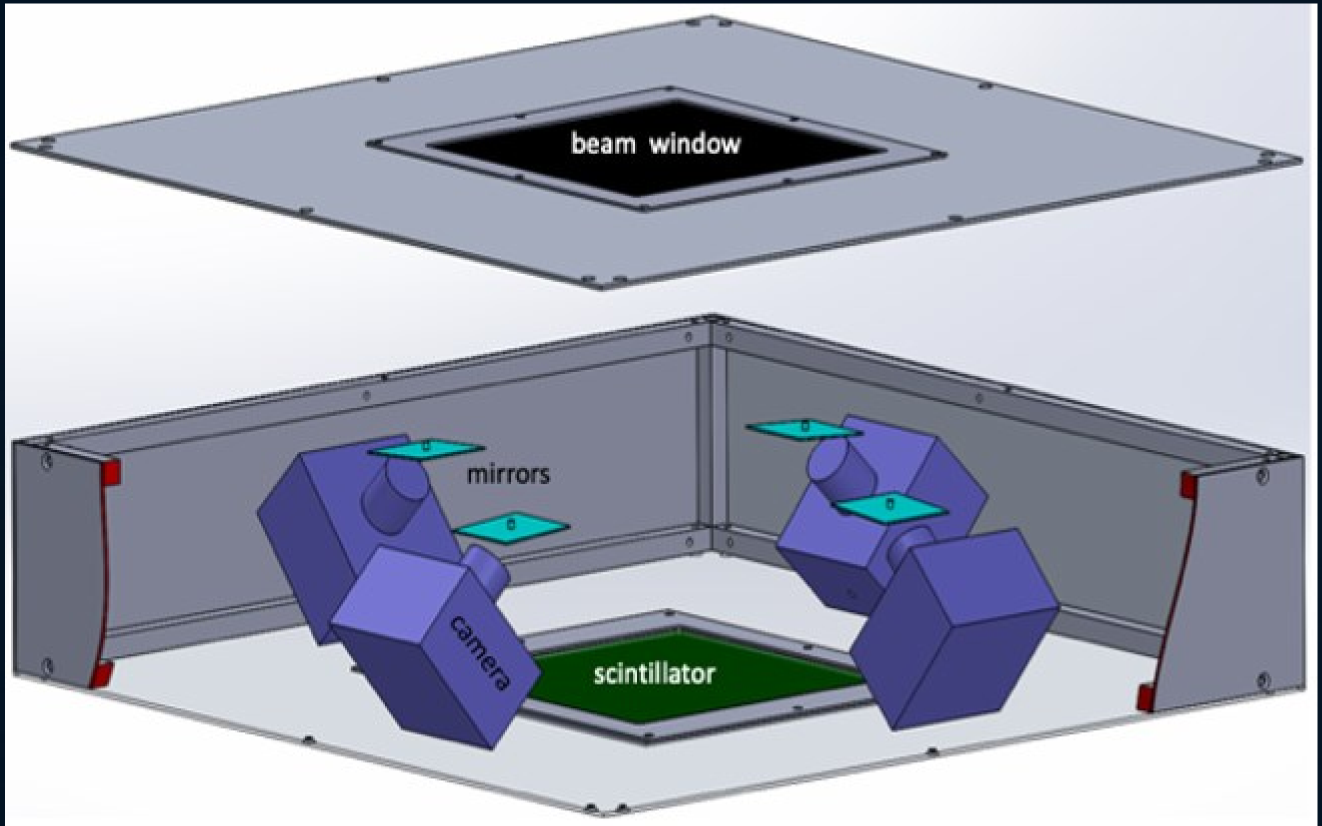


# Performance Objectives

✓= *achieved*

- Fast, real-time response to produce beam interlock, IEC compliant (in progress)
    - Deliver **< 10% of total dose** (or < 10% deviation from treatment plan) **in case of fault**
    - Scanning ***proton*** beams: process at **50 μs** → 20,000 fps, analysis in **~ 1 μs** ✓
    - Pulsed ***electron & VHEE*** beams: data acquisition/process rate ≤1000 Hz → **1 ms** (in progress)
- Spatial resolution: ~ 50 μm on centroids ✓
- Dynamic range: beam center to tails span 2 orders-of-magnitude ✓
- Low mass & thin profile: ~ 0.5 mm WE and profile/depth of ~ 10 cm ✓
- Large area: 15 cm x 15 cm ✓ to 15 cm x 23 cm (in progress)
- Real-Time Dosimetry: within ~ 50 μs for protons ✓
- Radiation resistance: > 1 year of clinical usage (5 d/wk; 50 wk/yr) < 1% signal loss/yr ✓

# Large-Area FLASH Beam Scintillator Monitor*




* 1st Generation **FBSM** Conceptual Design

- Large 30 cm x 30 cm sensitive area
- Quadrant system with 4 cameras
- Thin 11 cm profile with folded optics
- Ultrafast machine-vision cameras
- Triggered or quasi-free-running modes
- FPGA data processing & analysis
- Low mass profile ~ 0.5 mm WE

**NIH-NCI $1.9M "Direct-to-Phase-II" SBIR Award 2021-2024*

# Large-Area Proprietary Scintillators

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

- Thin < 400 µm WE

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

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

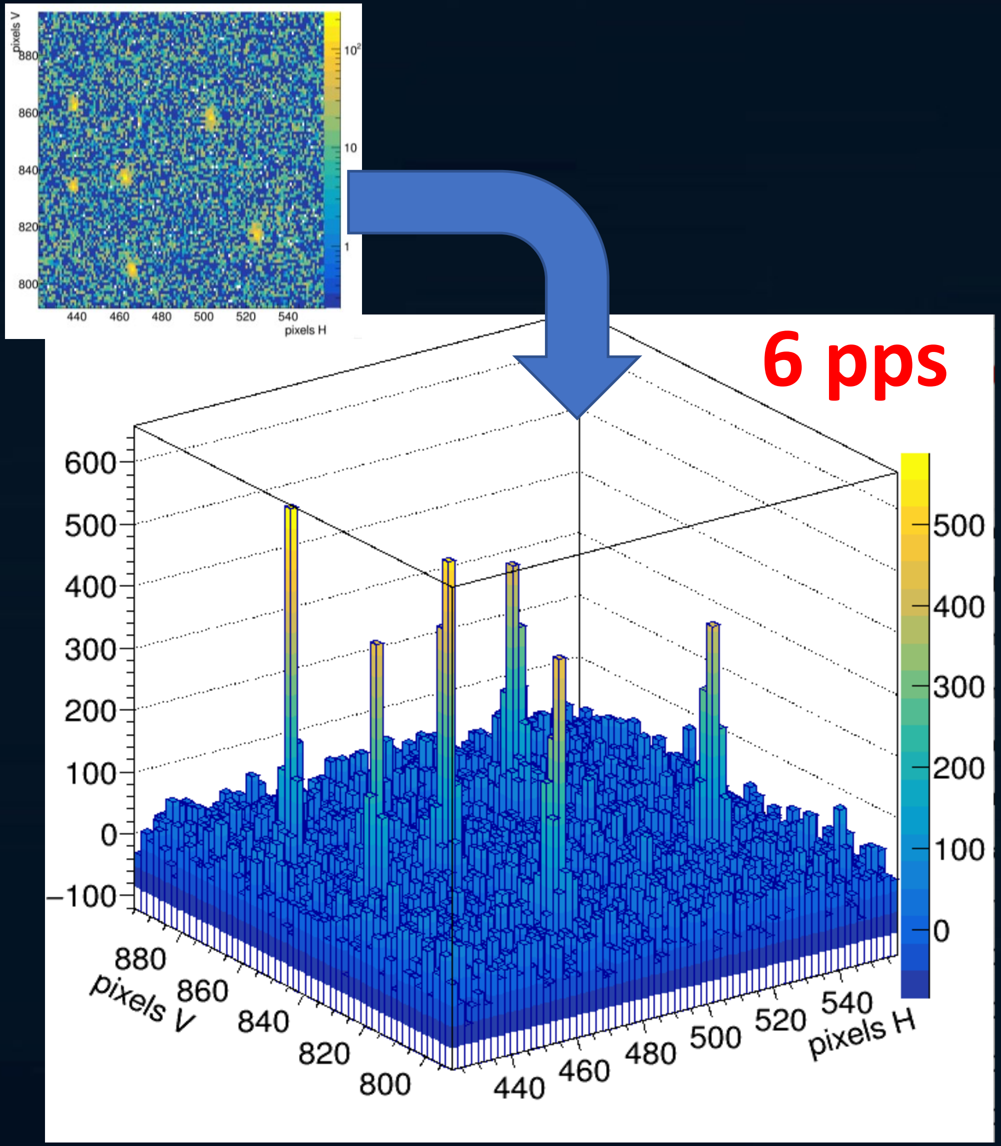
Both Types 1 & 2 have favorable properties:

- Radiation hard
- Sharp images – no internal reflections
- Non-hygroscopic
- Highly transmissive
- Extremely high light emittance for their respective type

# Test Beam Results for Prototypes *at **FLASH Dose Rates***

| | | | |
|---|---|---|---|
| Notre Dame Radiation Laboratory……. | $e^-$ | 8 MeV, | > 200 Gy/s |
| U. Michigan Ion Beam Laboratory …… | p+ | 5 MeV, | > 300 Gy/s |
| Facility for Rare Isotope Beams ……. | $^{86}Kr^{+26}$ | 2.75 MeV/u, | ~ 0 - 50 Gy/s |

# Single-Particle to FLASH Dose* with $^{86}Kr^{+26}$



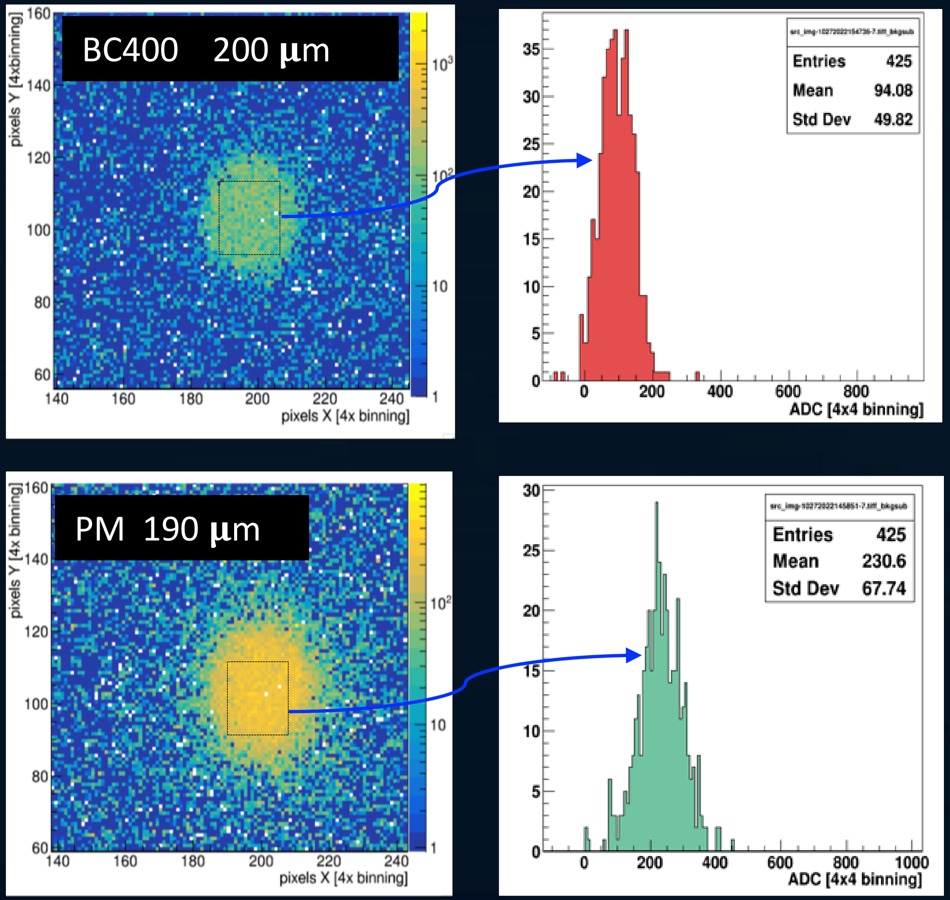


*Krypton is a mixture of six stable isotopes with <u>$^{86}$Kr being the heaviest</u> of its natural isotopes.

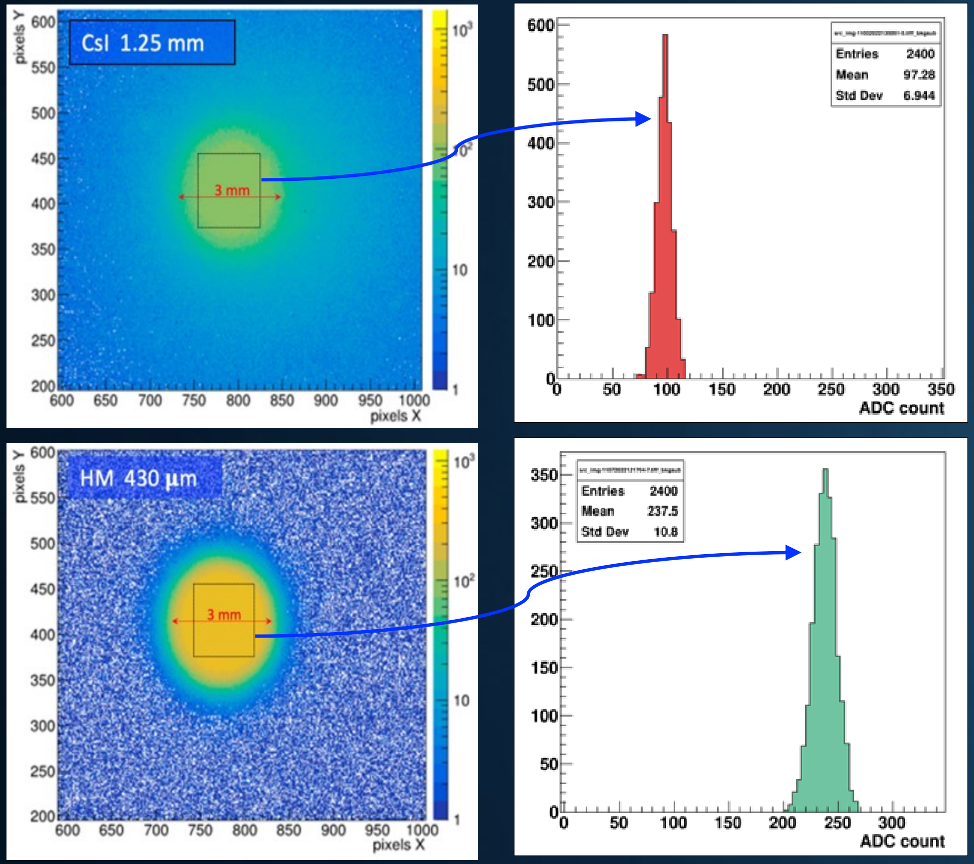
# Scintillator Efficiency Comparisons to Benchmarks

3 mm collimated electron beam ($\beta^{-}$ source $^{90}Sr$)

## PM type

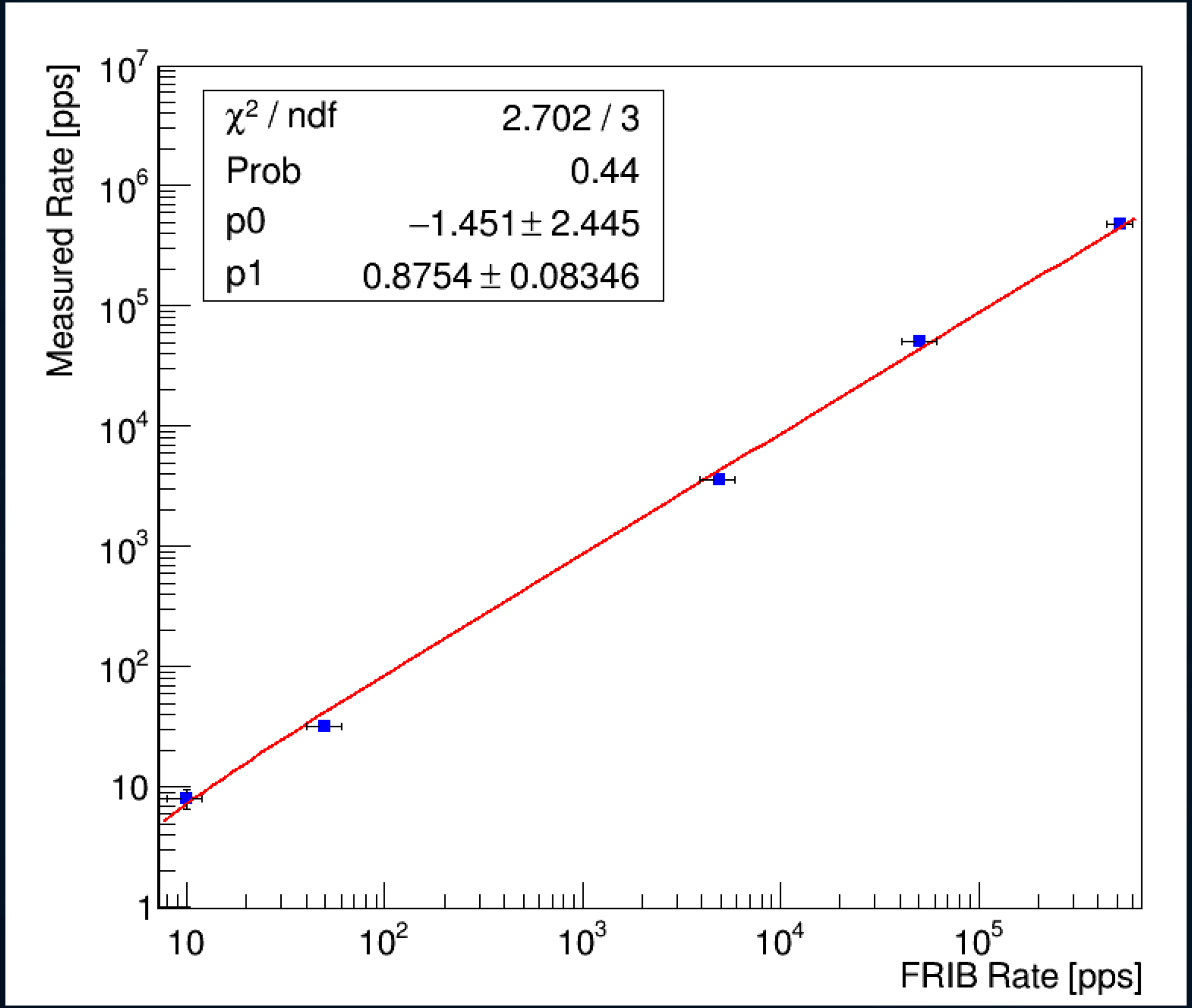



## HM type



# Beam Current in HM Scintillator

Kr$^{+26}$ Beam Monitor Rate vs FRIB Instruments Rate



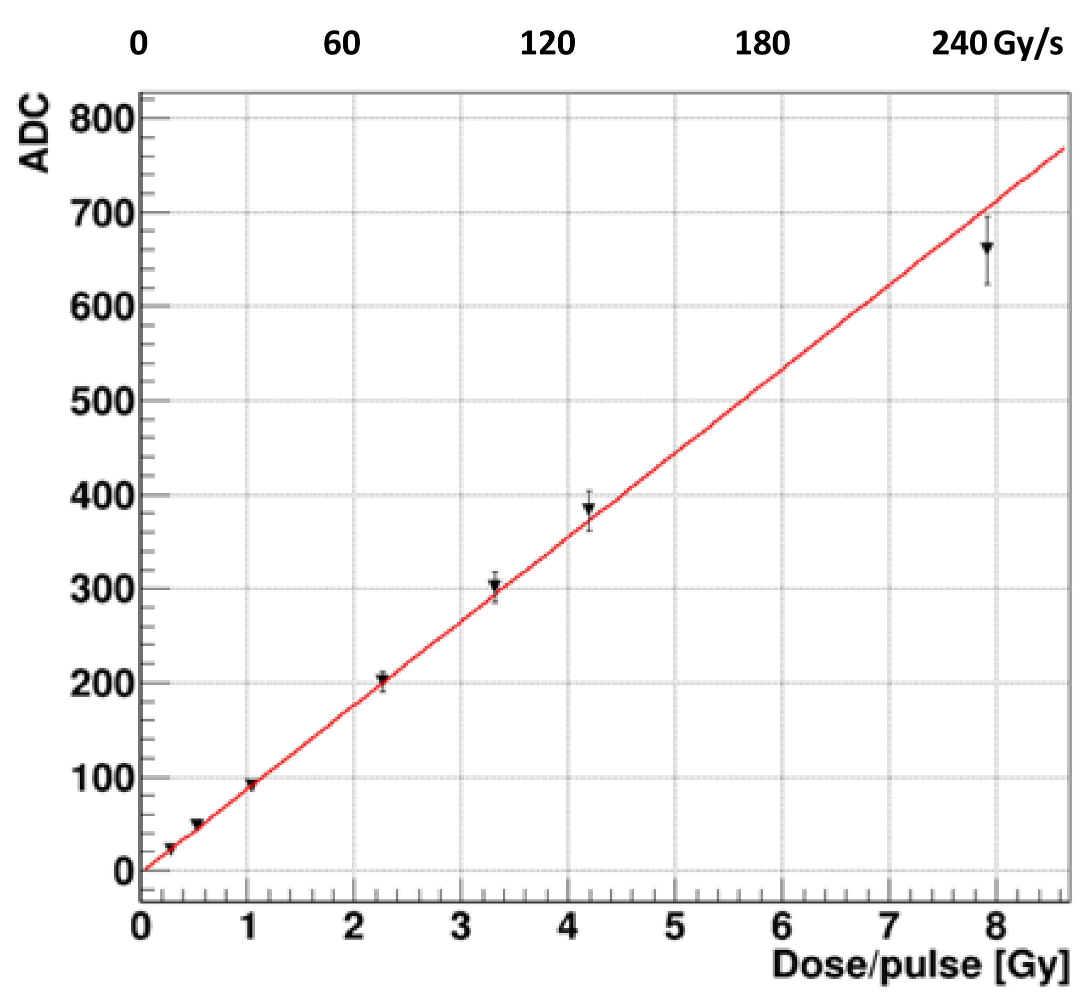

➔ Result 1: Beam monitor measures currents over range covered by *4 different FRIB devices*

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

➔ Result 2: **Linear up to *at least* 5 decades to FLASH dose rates**

# Dose Response in HM Scintillator

8 MeV Electron Beam at 30 Hz (Notre Dame Lab)



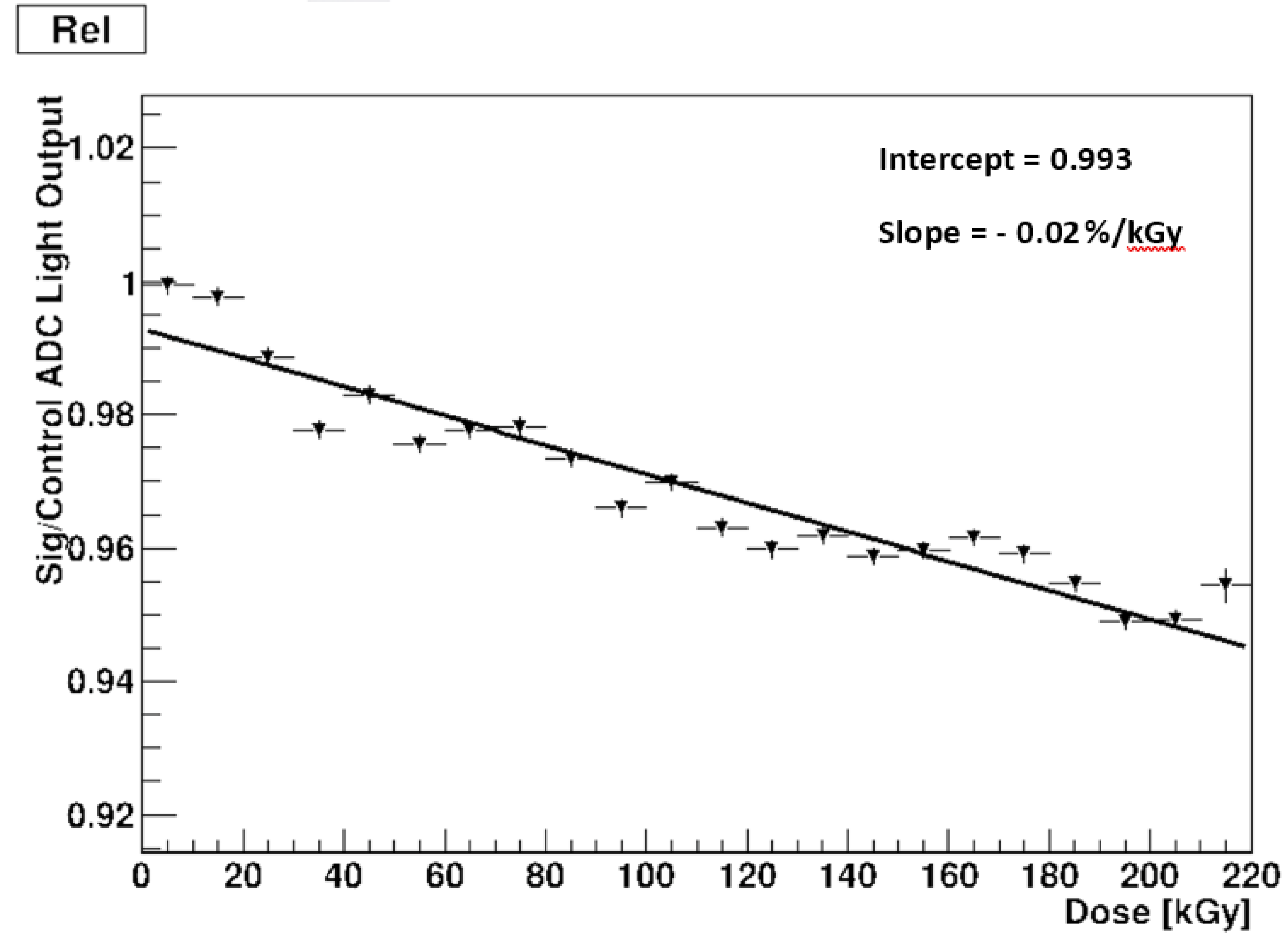

Each data point = average of 100 pulses.

Pulse width in all cases ~2 ns.

At 30 Hz, average dose rate ranges from **~6 to >200 Gy/s**, which is well beyond the required 40 Gy/s for FLASH.

Linear response to *high dose* FLASH rates.

# Radiation Hardness of HM Scintillator

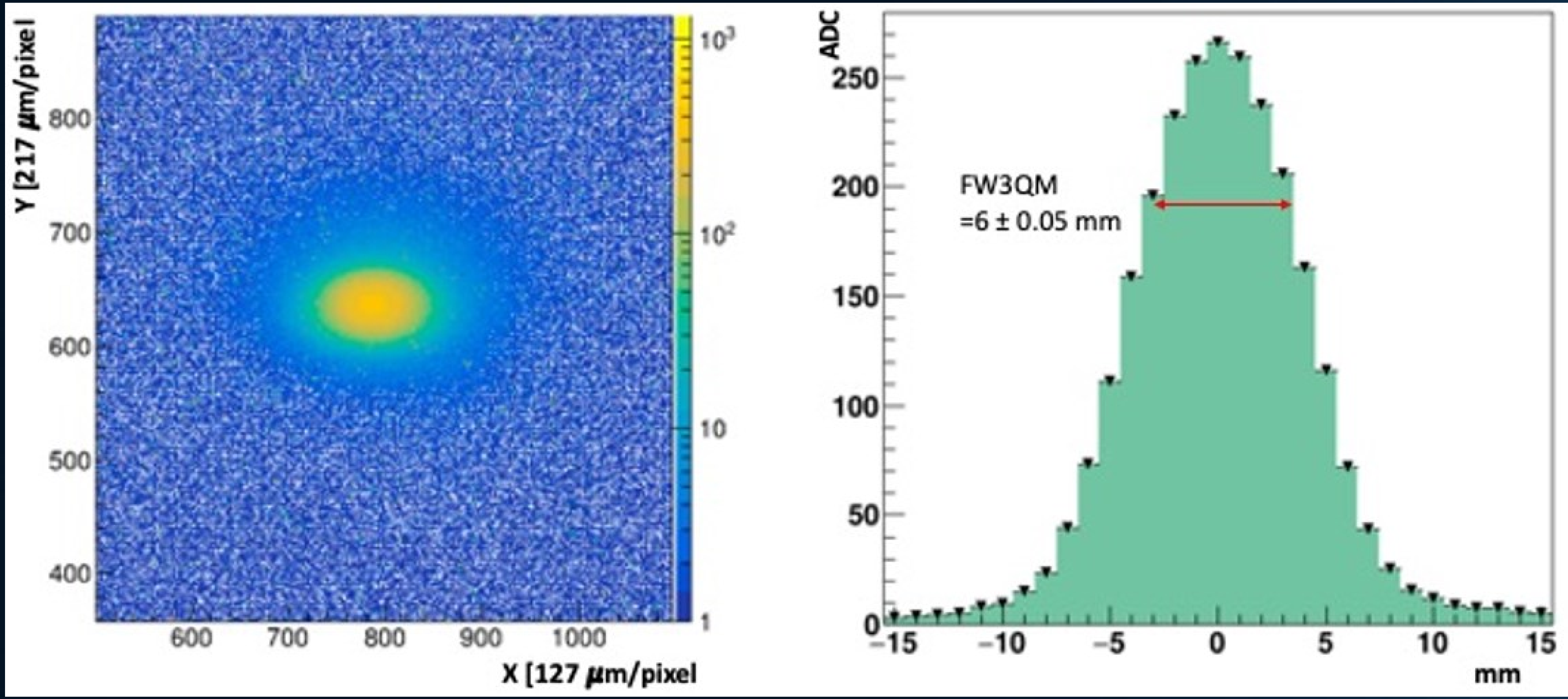



Low signal loss of ~0.02%/kGy measured over 216 kGy in 15 minutes (i.e., rate = 237 Gy/s).

> 1 yr of continuous FLASH patient use yields < 1 % signal loss (>$10^5$ acceleration factor).

Signal loss is correctable with periodic calibration system.

# HM Scintillator Image of 1 ns FLASH Pulse




Left – Single 1 ns pulse image of **3.3 nC** electron beam (8 MeV) hitting the HM scintillator.
Right – From pulse profile, dose per pulse = **7.9 Gy/pulse** (at 30 Hz) => **237 Gy/s**.

# Beam Monitor Energy Loss & Scattering*

***140 MeV*** *Proton Beam ➡ Energy Loss in Beam Monitor =* ***0.32 MeV***

***100 MeV*** *Electron Beam ➡ Energy Loss in Beam Monitor =* ***0.11 MeV***

***10 MeV*** *Photon Beam ➡ Energy Loss in Beam Monitor =* ***0.005 MeV***

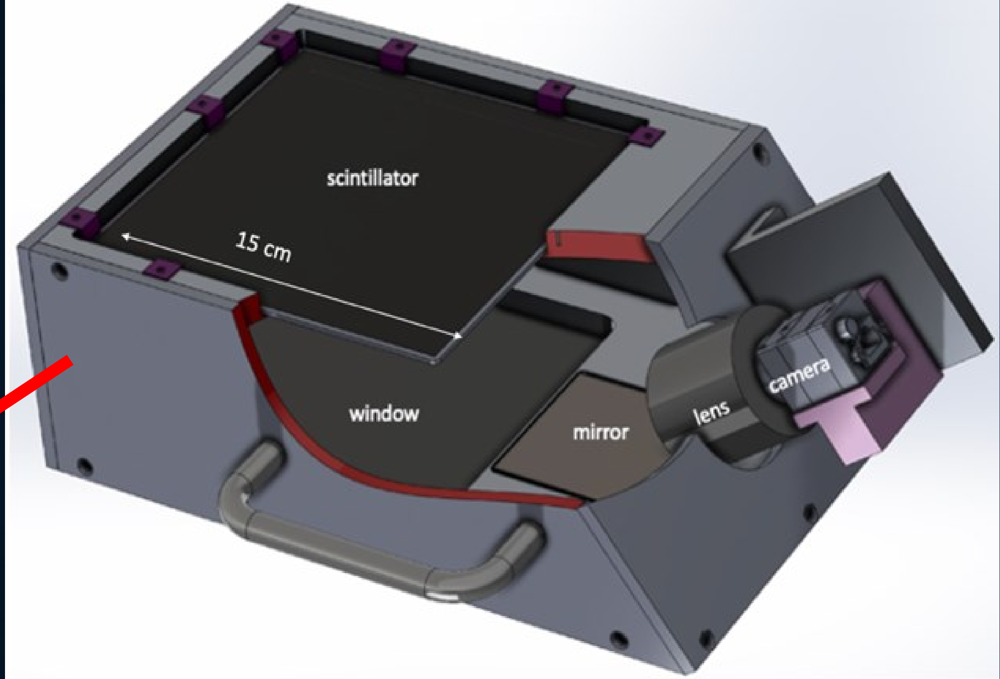
*Beam Spread (σ = 3.5 mm) 30 cm Downstream from Monitor**

**4.4%** for Protons, **20.7%** for Electrons, **~ 0.8%** for Photons

**Geant4-11.2 simulations excluding losses in air & assuming incident beam is non-divergent*

# Beam Tests at U. Michigan Radiation Oncology

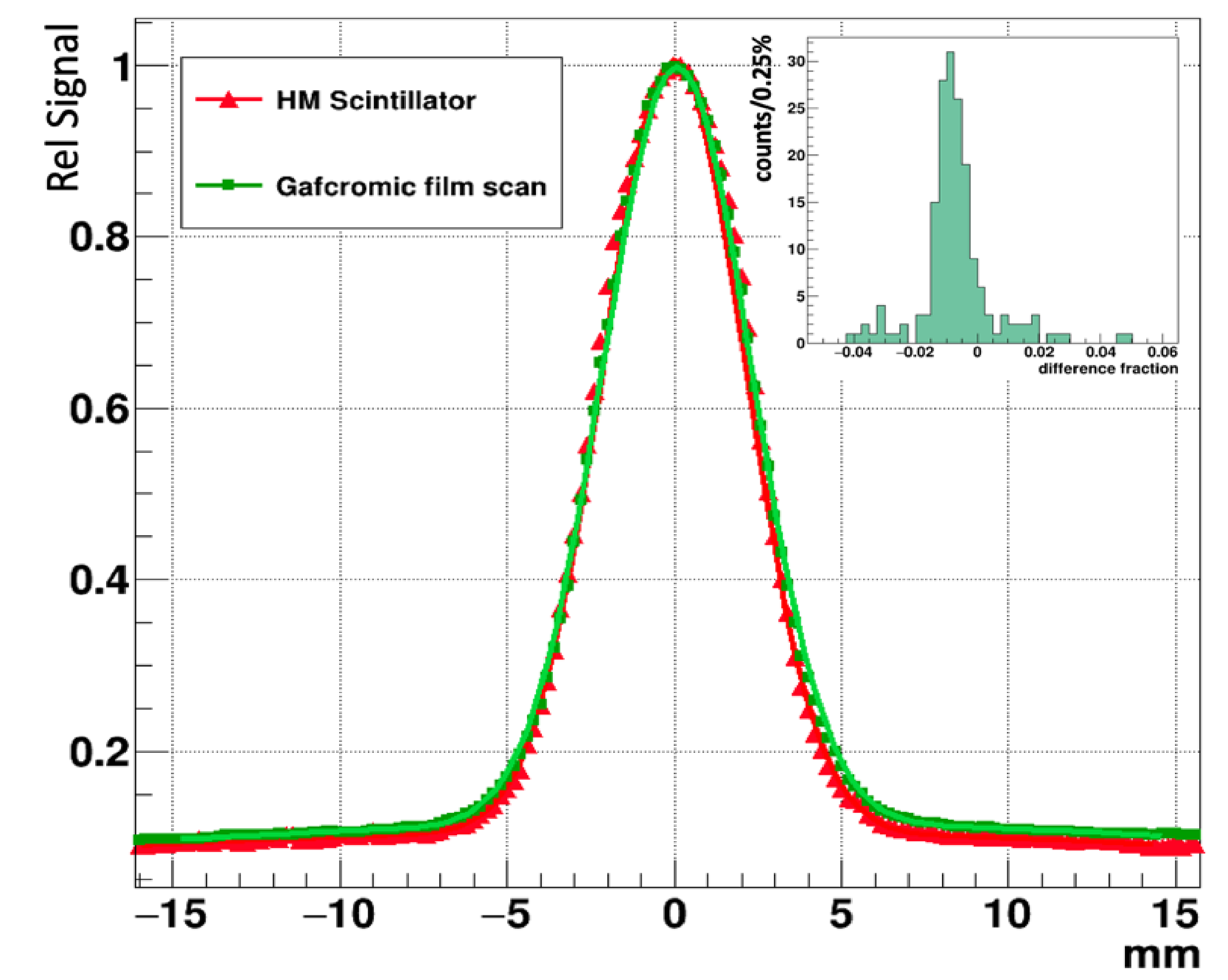

Varian linac: electron energy 6-16 MeV
Conventional dose rate = 1 – 10 Gy/min




*Protoype* FLASH Beam Scintillator Monitor (FBSM) single camera, 15 cm x 15 cm

# Beam Shape & Spatial Resolution

## HM Scintillator vs Gafchromic Film

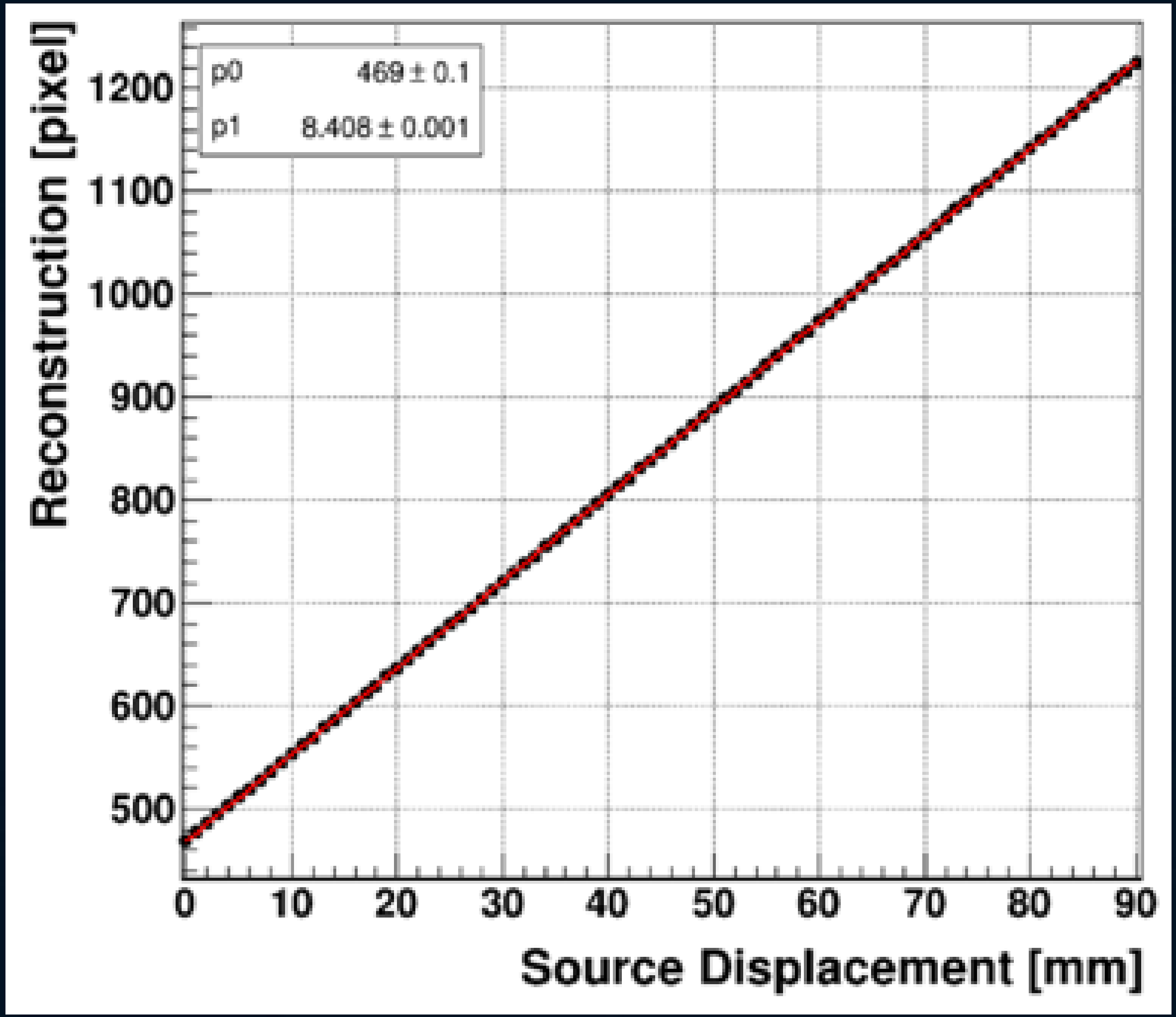


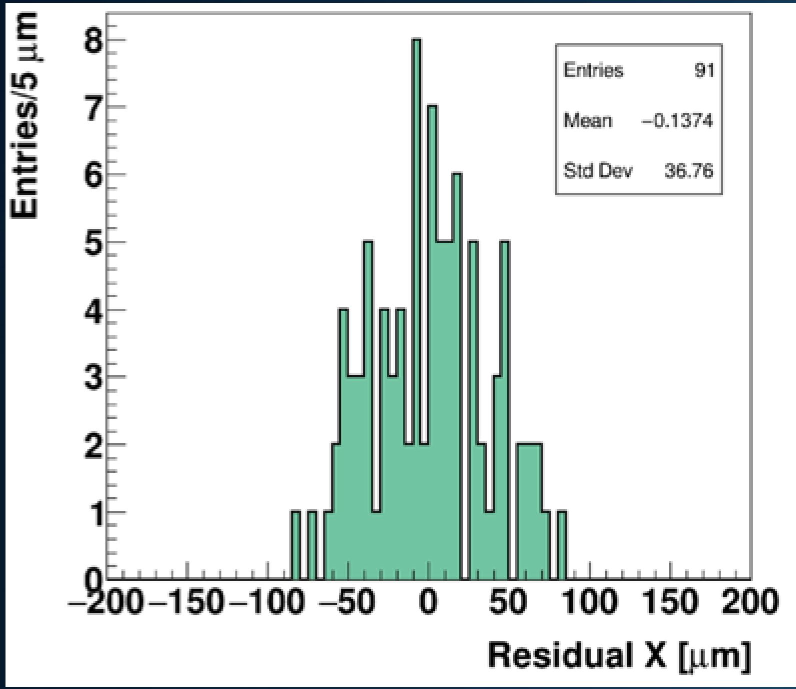

HM scintillator resolution is similar to Gafchromic film resolution (≲ 25 μm).

2D beam profiles are nearly identical.

Beam monitor primary advantage is real-time analysis

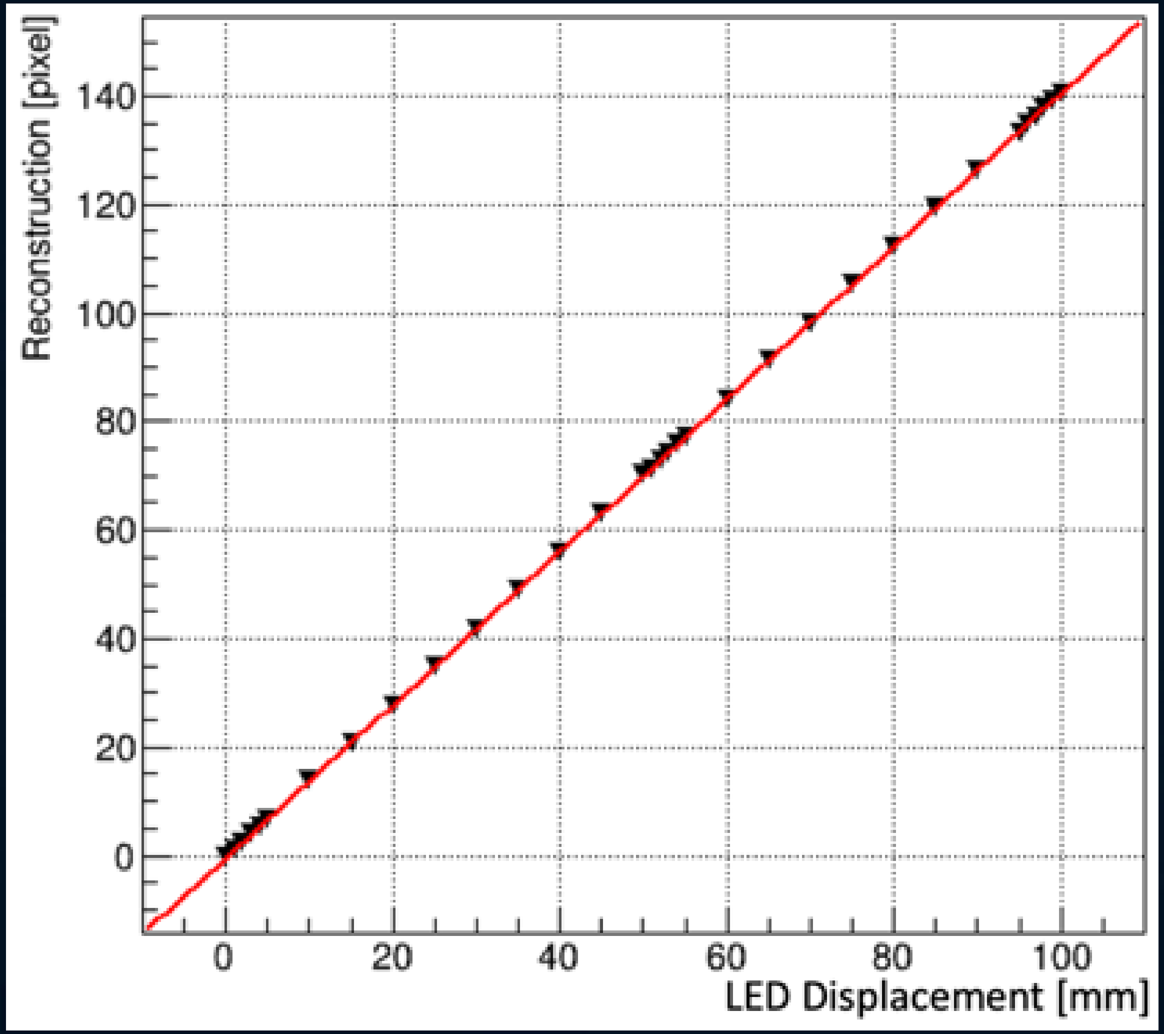
# FBSM Spatial Resolution at 200 fps

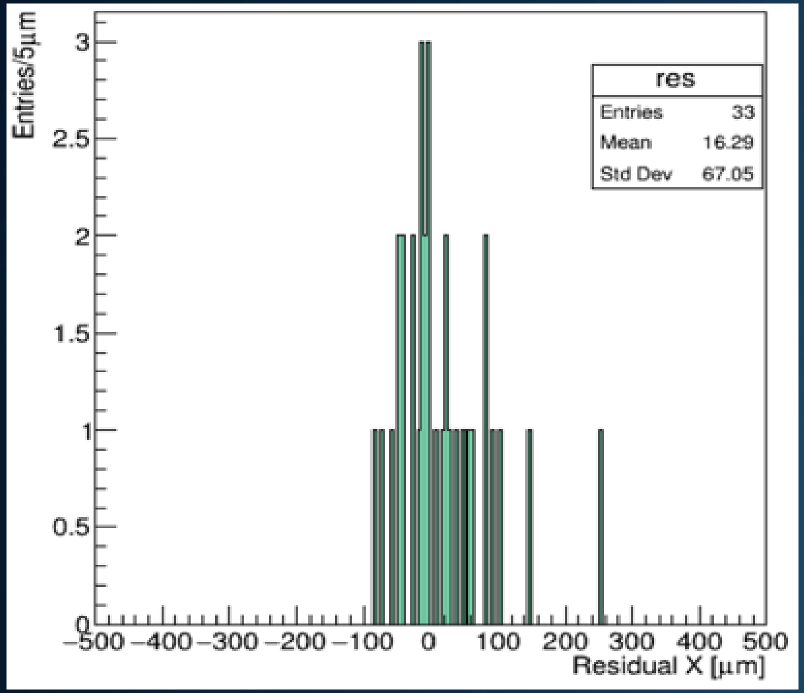



(Left) reconstructed beam centroids in pixel units plotted against precise location of a 3 mm beta source translated along the X coordinate of the FBSM. (Right) The residual distribution of the reconstructed positions yields spatial resolution of **37 µm** (RMS of fit residuals using Camera-E at **200 fps**).

# FBSM Spatial Resolution at 20,000 fps




(Left) reconstructed beam centroids in pixel units plotted against precise location of a 10 mm LED source translated along the X coordinate of the FBSM. (Right) The residual distribution of the reconstructed positions yields spatial resolution of **67 µm** (RMS of fit residuals using Camera-P at **20,000 fps**).

# Validation & Collaborations

***Radiotherapy*** *(NIH-NCI) and* ***Nuclear Physics*** *(DOE-NP)*

- Leading Academic & Government Institutions
  - University of Michigan
  - Loma Linda University
  - Stanford Cancer Institute
  - University of Texas / MD Anderson
  - Texas A&M
  - Notre Dame University
  - Florida State University
  - DOE Argonne National Laboratory
  - DOE Facility for Rare Isotope Beam

# Applications

- **FLASH-RT** (electrons, protons, ions, x-rays)
- **Electron – FLASH – IORT** (Intraoperative radiation therapy with MD Anderson)
- **Advanced EBRT** with *reduced range uncertainty* due to target motion
- Synchrotron based Proton and Carbon-ion EBRT
- Boron Neutron Capture Therapy (BNCT – EBRT)
- Beamline Monitoring (medical & scientific applications – e.g., FRIB, ANL-ATLAS)

# Technical Summary

*✓= achieved*

*We have **demonstrated** prototype monitors for FLASH-RT beams ✓*

- **2D Imaging** with large area 15 cm x 15 cm ✓   15 x 23 cm in development
- **High sensitivity & dynamic range**: single-particles to FLASH-RT dose rates ✓
- **Linear response:** up to highest FLASH dose rates ✓
- **Spatial resolution** ~ 50 µm, comparable with Gafchromic film ✓
- **Excellent radiation hardness** ✓
  - PM scintillator radiation damage: none observed to 9 kGy ✓
  - HM scintillator radiation damage: overall -0.02 %/kGy, tested to 216 kGy ✓
- **Real-time FLASH data processing** ✓
  - 20 kHz for protons with < 1 µs required for data analysis ✓
  - 1 kHz electrons (in progress)