A Real-Time, Large-Area Transparent FLASH Beam Monitor and Dosimeter

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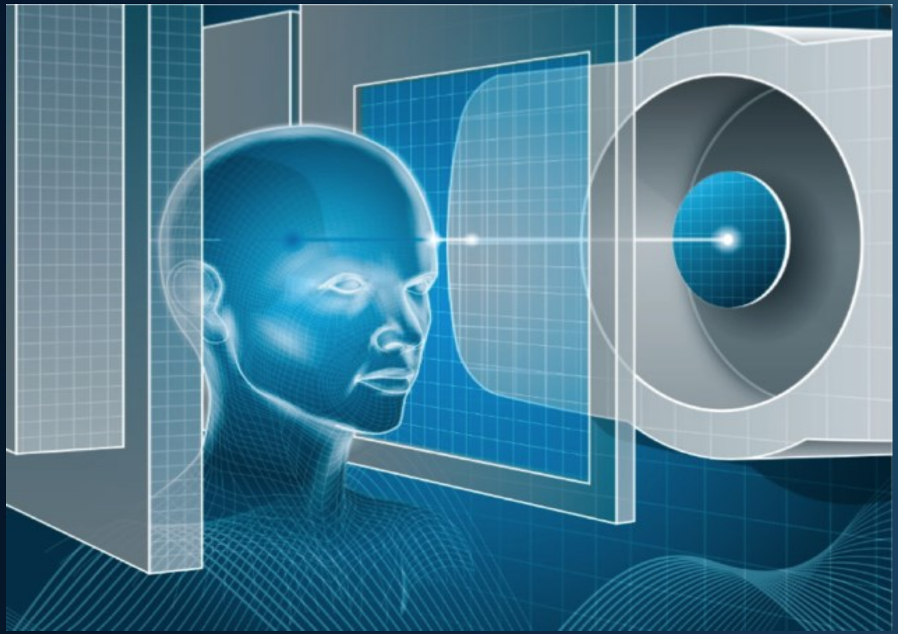
Safety Problem: Monitoring FLASH Delivery

- To be clinically approved by the 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 to 0.5 sec** total delivery time.

- Conventional beam monitors are not capable of large-area 2D imaging with sampling and analysis in real-time at FLASH rates (**~ 50 µs**).

- **SOLUTION:** Beam monitor that continuously images & analyzes FLASH-RT beam every **50 µs** (20,000 fps) as the patient is irradiated.

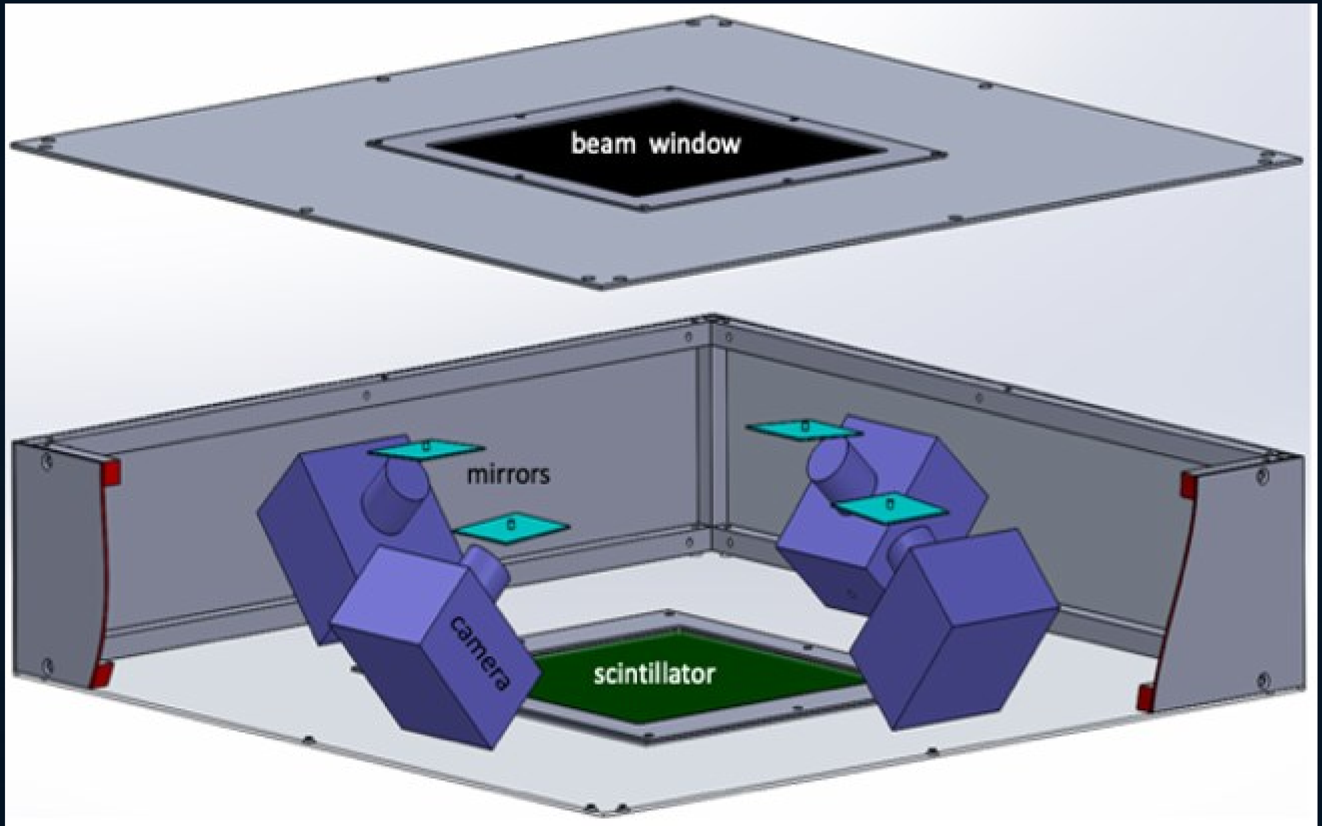


FLASH-RT Monitor Performance Objectives

✓= achieved

- Fast, real-time response to produce beam interlock, IEC compliant (in progress)
  - **Deliver < 10% of total dose in case of fault**
  - Scanning ***proton*** beams: process at 20 kfps → **50 μs**, analysis in **< 1 μs** ✓
  - Pulsed ***electron*** beams: data acquisition/process rate 100-1000 Hz → **1 ms** (in progress)
- Spatial resolution: **<** 100 μm on centroids ✓
- Dynamic range: beam center to tails span 2 orders-of-magnitude ✓
- Low mass & thin profile: < 0.7 mm WE and profile/depth of ~ 11 cm ✓
- Large area: 15 cm x 15 cm ✓ to 30 cm x 30 cm (in progress)
- Real-Time Dosimetry (within ~ 50 μs for protons): < 4% ✓
- Radiation resistance: 1 year of clinical usage (5d/wk) ≤ 1% signal loss ✓

Large-Area FLASH Beam Scintillator Monitor



FBSM Conceptual Design

- Large 30 cm x 30 cm sensitive area
- Quadrant system with 4 cameras
- Thin 11 cm profile using folded optics
- Ultrafast machine-vision cameras
- Triggered or quasi-free-running modes
- FPGA data processing & analysis
- Low mass profile < 700 μm WE

Large-Area Proprietary Scintillators

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

- Thin < 700 μm 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 – no internal reflections
- Non-hygroscopic
- Transmissive
- High light emittance for their respective type

Test Beam Results from Prototypes

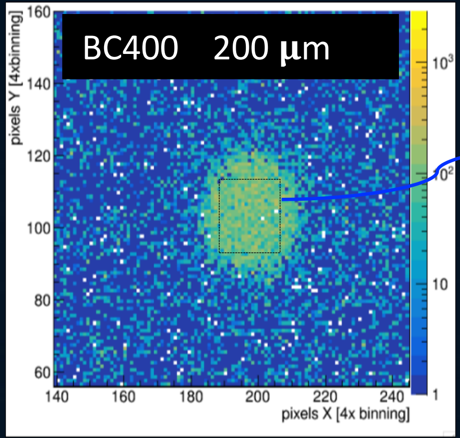
FLASH Dose Rates

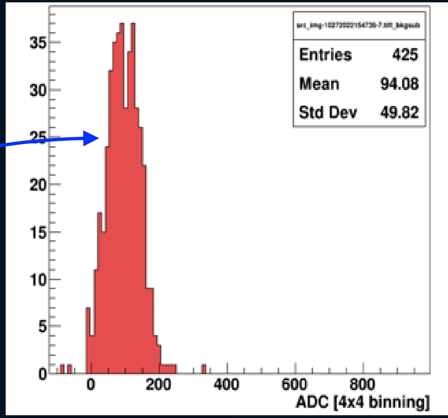
Notre Dame Radiation Lab ……………...	e^-	8 MeV,	0.2-235 Gy/s
U. Michigan Ion Beam Laboratory ……	p+	5 MeV,	> 300 Gy/s
Facility for Rare Isotope Beams ……...	Kr^{+26}	2.75 MeV/u,	> 50 Gy/s

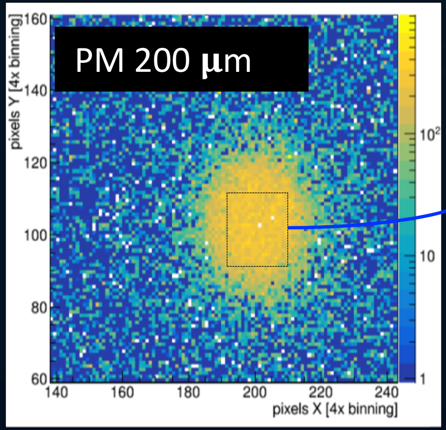
Scintillator Efficiency Comparisons to Benchmarks

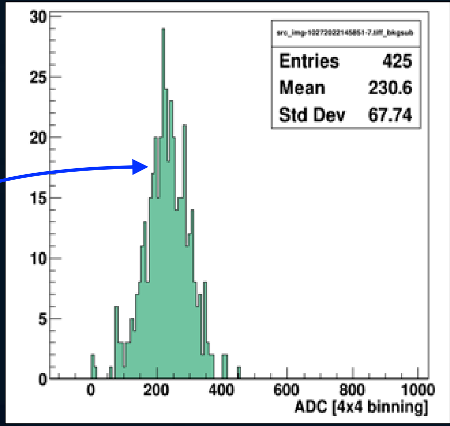
3 mm collimated electron beam (β^- source ^{90}Sr)

PM type

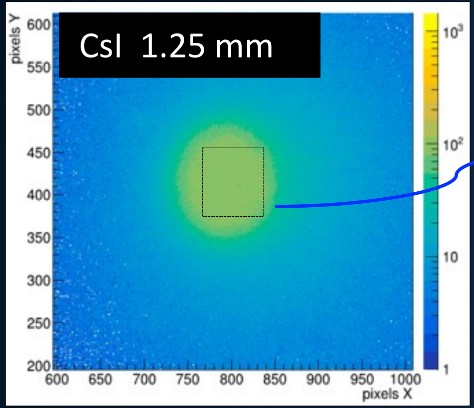


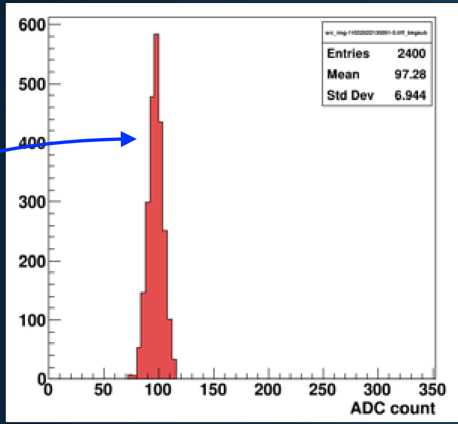


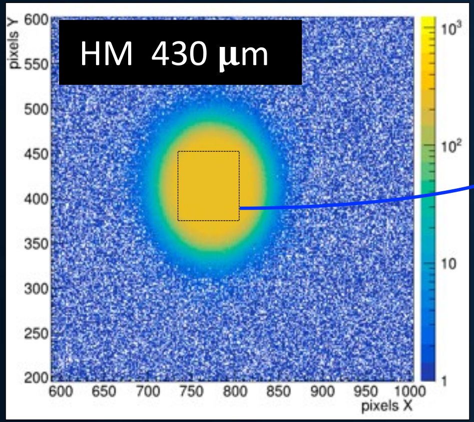


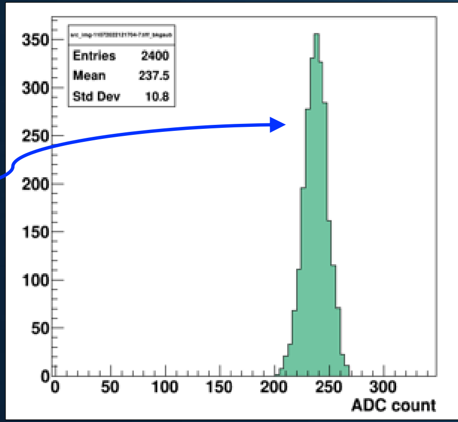


HM type



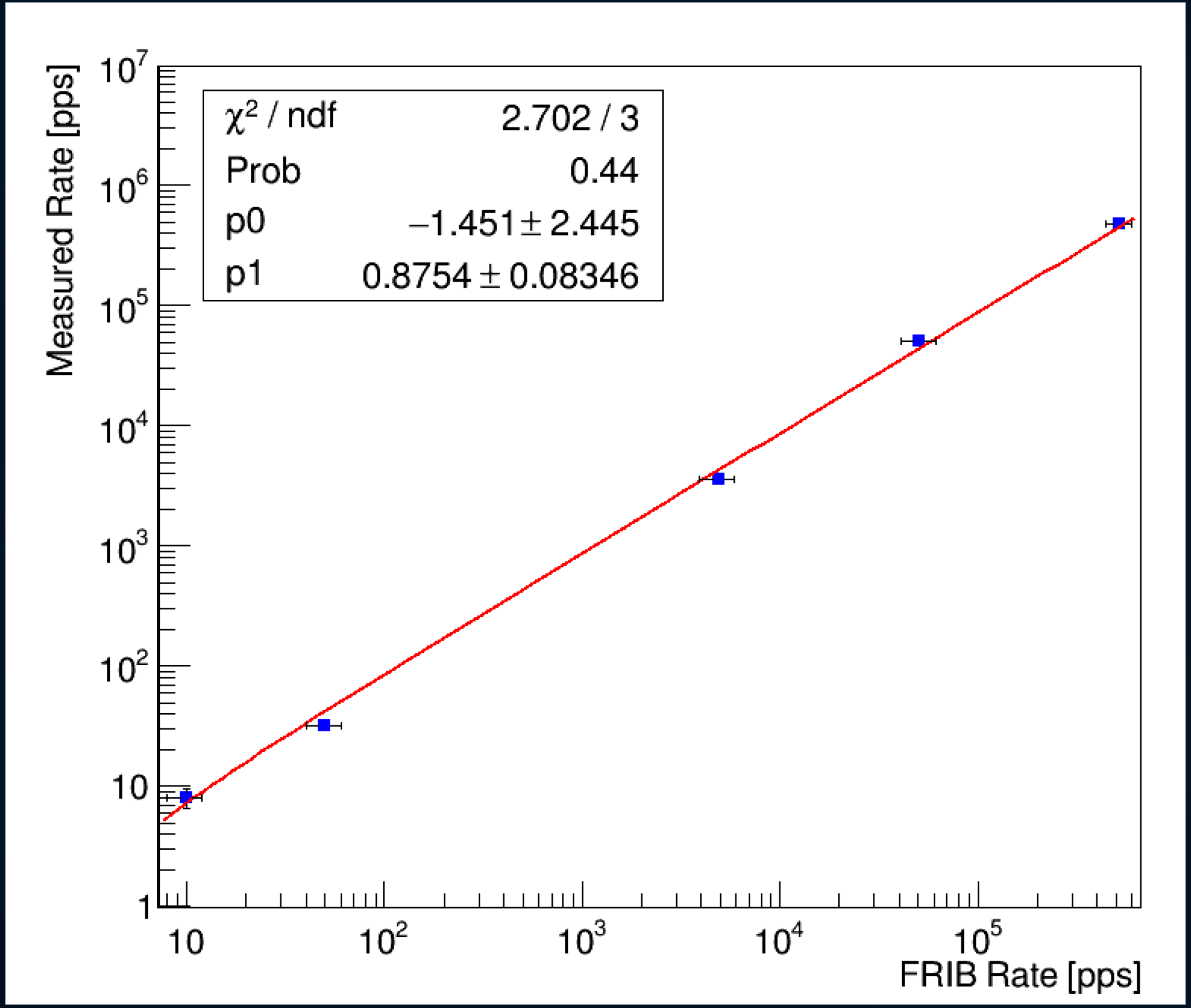






Beam Current in HM Scintillator

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



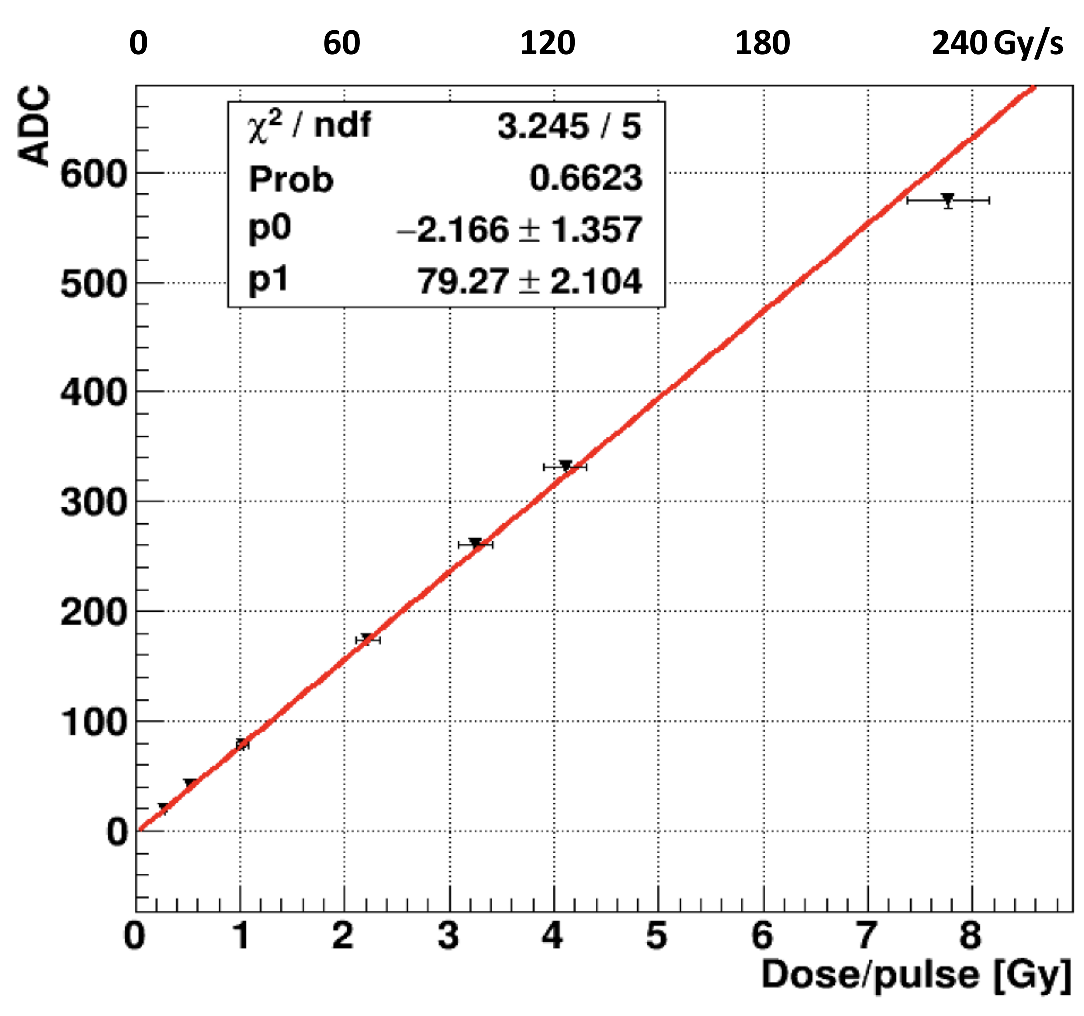
➔ Result 1: Beam monitor measures currents over range covered by *4 different FRIB devices*

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

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

Dose Response in HM Scintillator

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



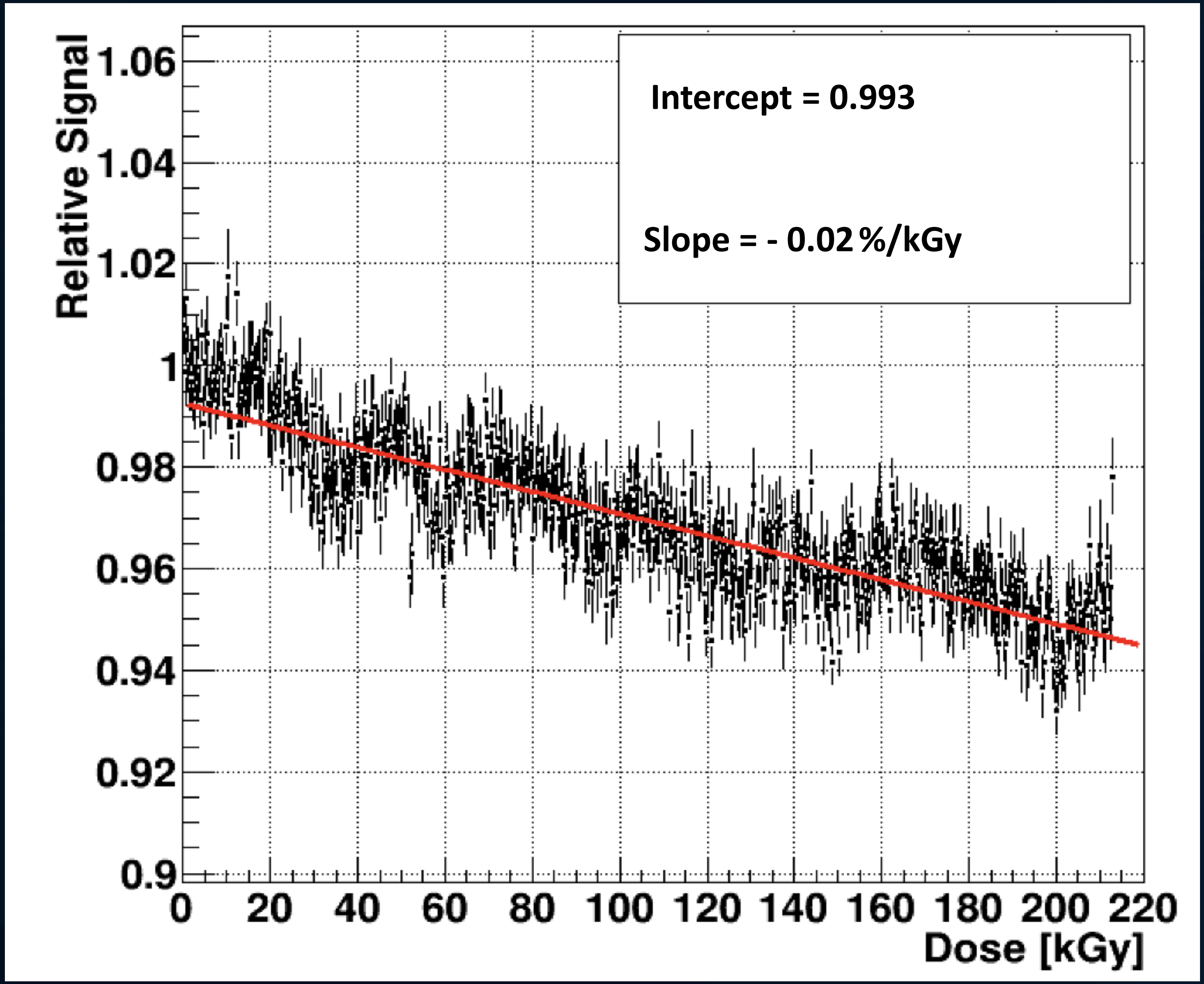
Each data point = average of 100 pulses.

Pulse width in all cases = 2 ns.

At 30 Hz, average dose rate ranges from **6 to 234 Gy/s**, which is well beyond 40 Gy/s for FLASH.

Linear response from Conventional-RT dose rate, to FLASH-RT high dose rate.

Radiation Hardness of HM Scintillator



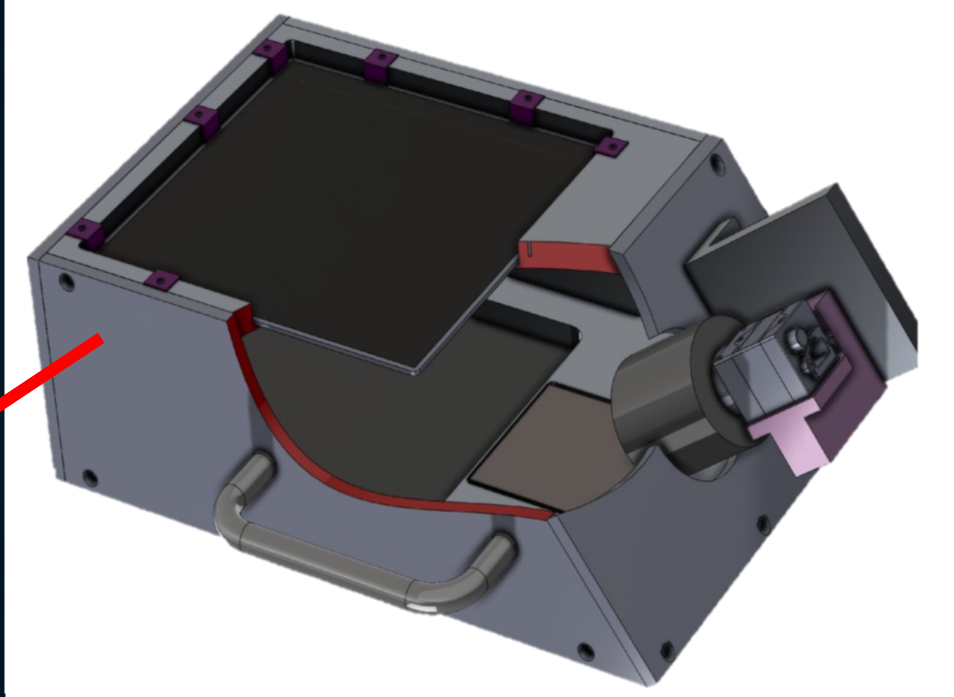
Low signal loss of 0.02%/kGy measured over 212 kGy.

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

Signal loss is correctable with internal UV calibration system.

Beam Tests at U. Michigan Radiation Oncology

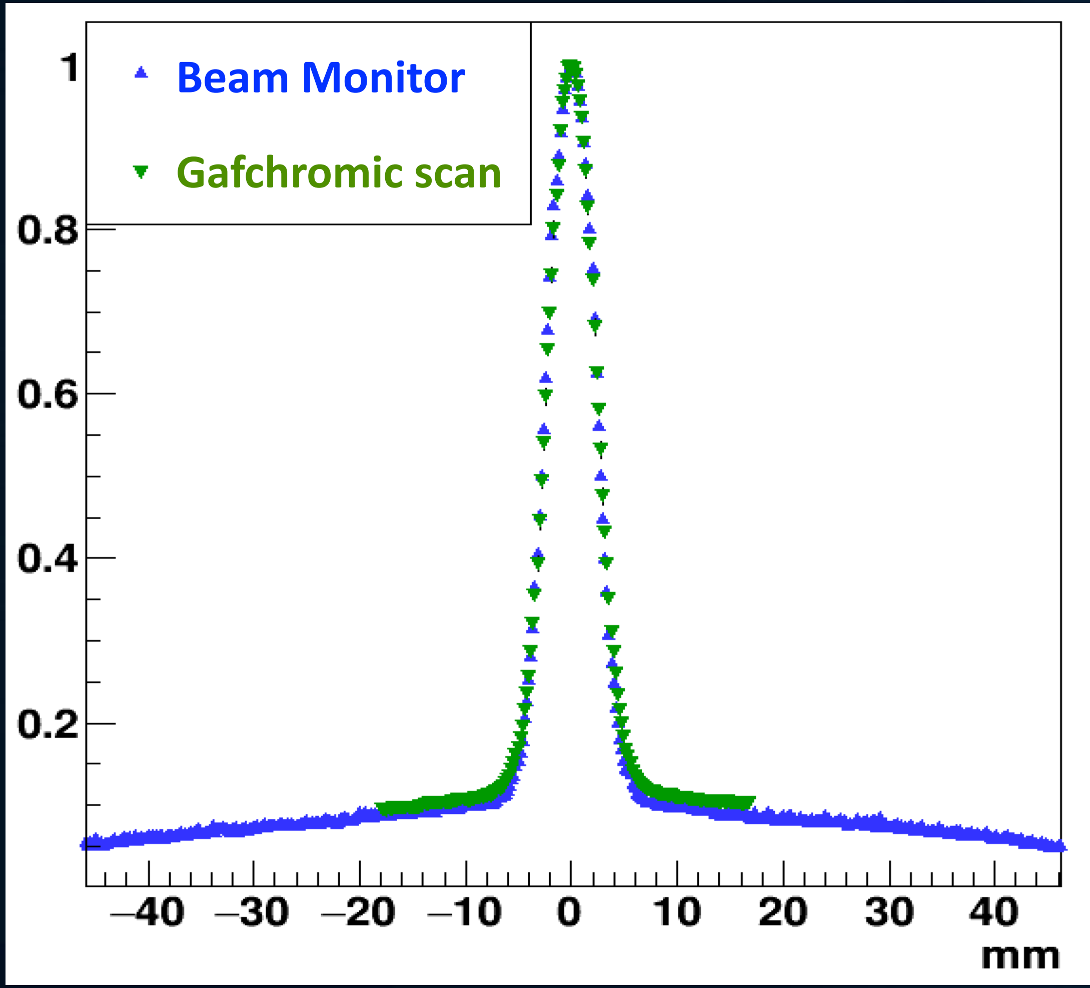
Varian linac: electron energy 6-16 MeV
Conventional dose rate = 1 – 10 Gy/min



Protoype FLASH monitor
single camera, 15 cm x 15 cm

Beam Shape & Spatial Resolution

HM Scintillator vs Gafchromic Film



Beam monitor resolution is equal to Gafchromic film resolution (≲ 25 μm).

2D beam profiles are nearly identical.

Beam monitor primary advantage is real-time analysis

Conclusions

✓ = *achieved*

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

- **2D Imaging** with large area 15 cm x 15 cm ✓ 30 x 30 cm in development
- **High sensitivity & dynamic range**: single-particles to high FLASH level for RT ✓
- **Linear response** for FLASH dose rates ✓
- **Spatial resolution** comparable with Gafchromic film: < 25 um ✓
- **Excellent radiation hardness** ✓
  - PM scintillator radiation damage: none observed to 9 kGy ✓
  - HM scintillator radiation damage: overall -0.02 %/kGy, tested to 212 kGy ✓
- **Real-time FLASH data processing** ✓
  - 20 kHz for protons with < 1 μs required for data analysis ✓
  - 1 kHz electrons (in progress)

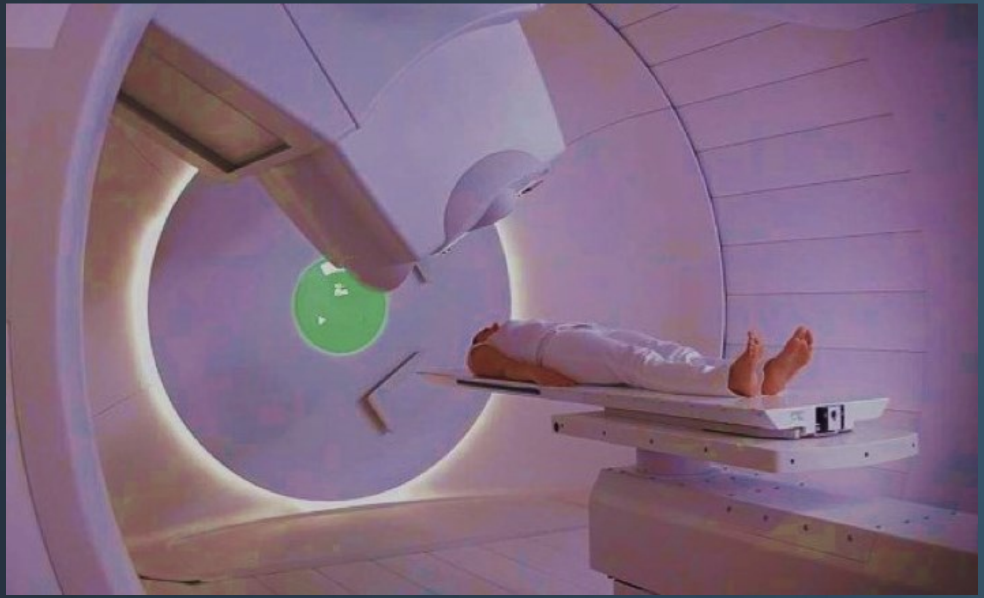
Backup

FBSM Competitive Advantages

The FBSM is a patented, enabling technology for FLASH-RT

- Two New High Efficiency Scintillators
  - PM-scintillator (polymer) ultra-thin rolls
  - HM-scintillator (hybrid) highest efficiency

- Innovative UFT Patented Configurations
  - Ultra-fast beam analysis ~ **50 µs** *(continuous)*
  - Real-time dosimetry, beam position & shape
  - High spatial resolution (~ 25 µm)
  - Water-equivalent thickness <700 µm
  - Internal calibration
  - Multiple cameras & folded optics
  - Detector area: up to ~ 30 cm x 30 cm



Applications

- **FLASH-RT** (electrons, protons, ions, x-rays, neutrons)
- Electron – FLASH – IORT (Intraoperative radiation therapy)
- Advanced EBRT including heavy-ions (alphas, carbon-ions, etc.)
- Beamline Monitoring (medical & scientific applications – e.g., FRIB, ANL-ATLAS)
- Boron Neutron Capture Therapy (BNCT)
- Spatially Fractionated EBRT (Grid, Lattice, Minibeam, Microbeam)

Validation & Collaborations

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

Transmission in 6 µm PM Scintillator

$^{86}Kr^{+26}$ ion (2.75 MeV/u) beam current measured with scintillator in/out of beam