High Performance Scintillator and Beam Monitoring System

August 18, 2021
DOE-NP SBIR/STTR Exchange Meeting

P. S. Friedman
Integrated Sensors, LLC, Ottawa Hills, Ohio (419-536-3212)
www.isensors.net

Program Collaborators:

D. S. Levin, N. Ristow, C. Ferretti
University of Michigan, Department of Physics, Ann Arbor, MI
and
T. N. Ginter, M. Cortesi
Michigan State University / Facility for Rare Isotope Beams (FRIB), E. Lansing, MI

Two New Scintillator Materials[1]

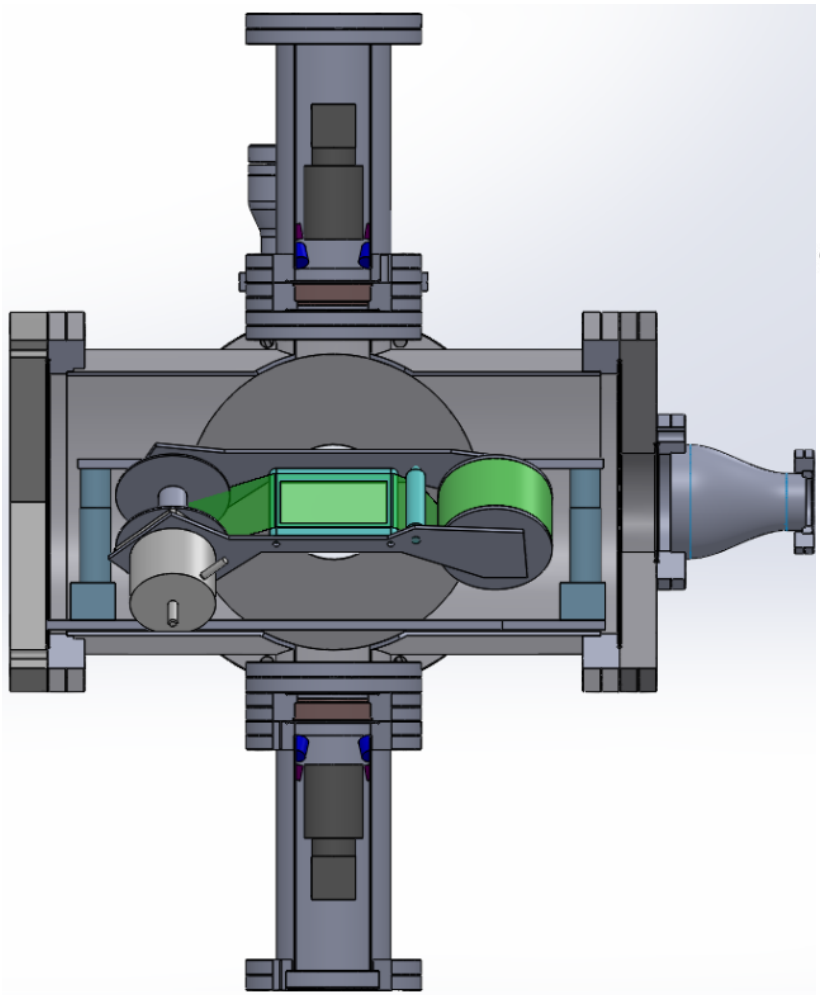
<u>Polymer</u> Material (PM)[1] – this <u>*semicrystalline*</u> polymer was developed several decades ago as a high performance, thin film substrate for automotive, electrical and aerospace applications. It was subsequently discovered to be an <u>*intrinsic*</u> scintillator with superior physical properties and higher light-yield than plastic scintillators based on host polymers PVT (polyvinyltoluene) and PS (polystyrene). Because PM is semicrystalline, it has a "hazy" appearance and is not capable of total internal reflection, thus resulting in: (1) a higher percentage of photons escaping from the film surface, (2) reduced back surface reflection, and (3) more accurate dosimetry.[1] The new PM-scintillator is highly radiation damage resistant and has proved to be significantly superior to conventional plastic scintillators such as BC-400.

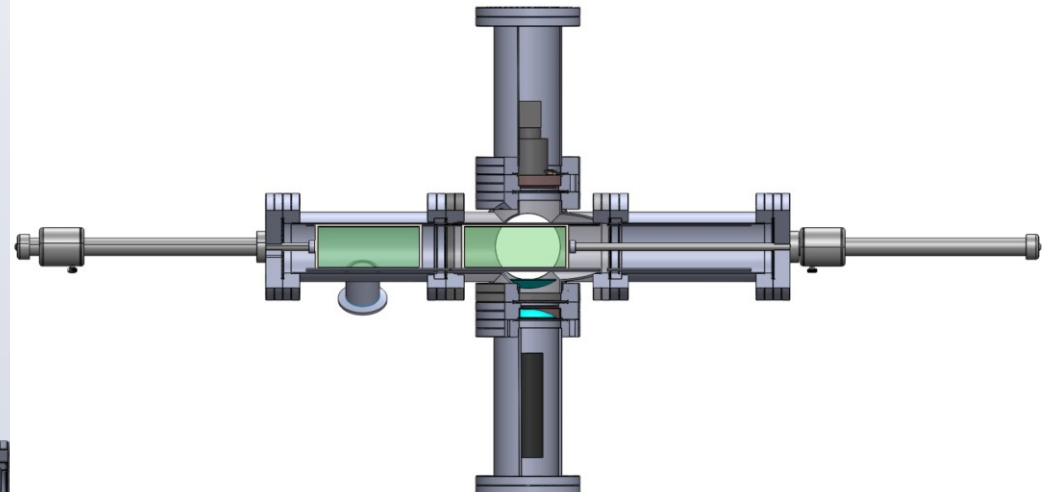
<u>Hybrid</u> Material (HM)[1] – the new HM scintillator is a "hybrid" <u>*inorganic-polymer*</u> material that is non-hydroscopic, appears to be more radiation damage resistant than CsI, is available in both thin and large area sizes, and delivers stronger signals than our CsI crystal scintillator. Being much thinner than single crystal CsI, and polycrystalline in nature, it is visually opaque and therefore not capable of total internal reflection, thus resulting in: (1) a higher percentage of photons escaping the film surface, (2) essentially eliminates back surface reflection, and (3) more accurate dosimetry.[1]

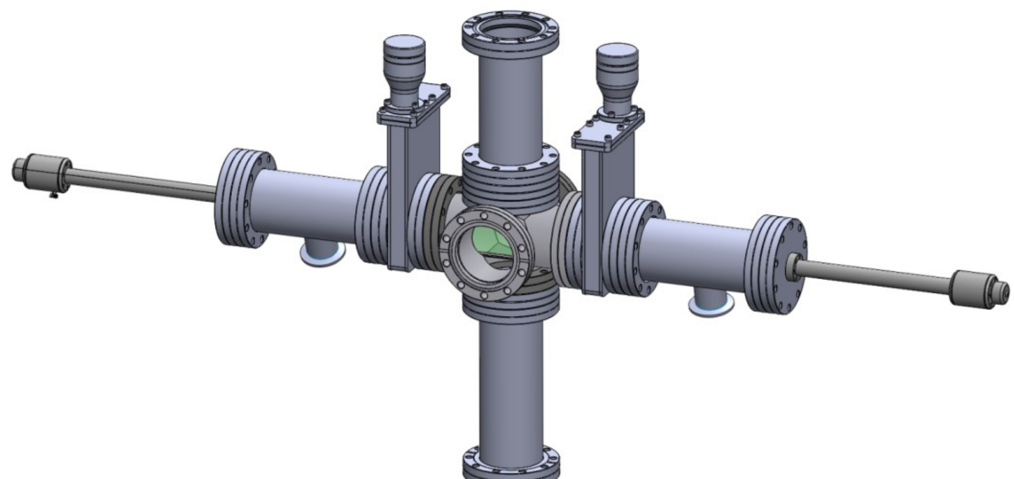
[1]Integrated Sensors has several <u>***patents pending***</u> on these two new scintillator materials for beam monitoring applications ranging from ***nuclear physics*** *to* ***radiation oncology***.

Beam Monitor Configurations

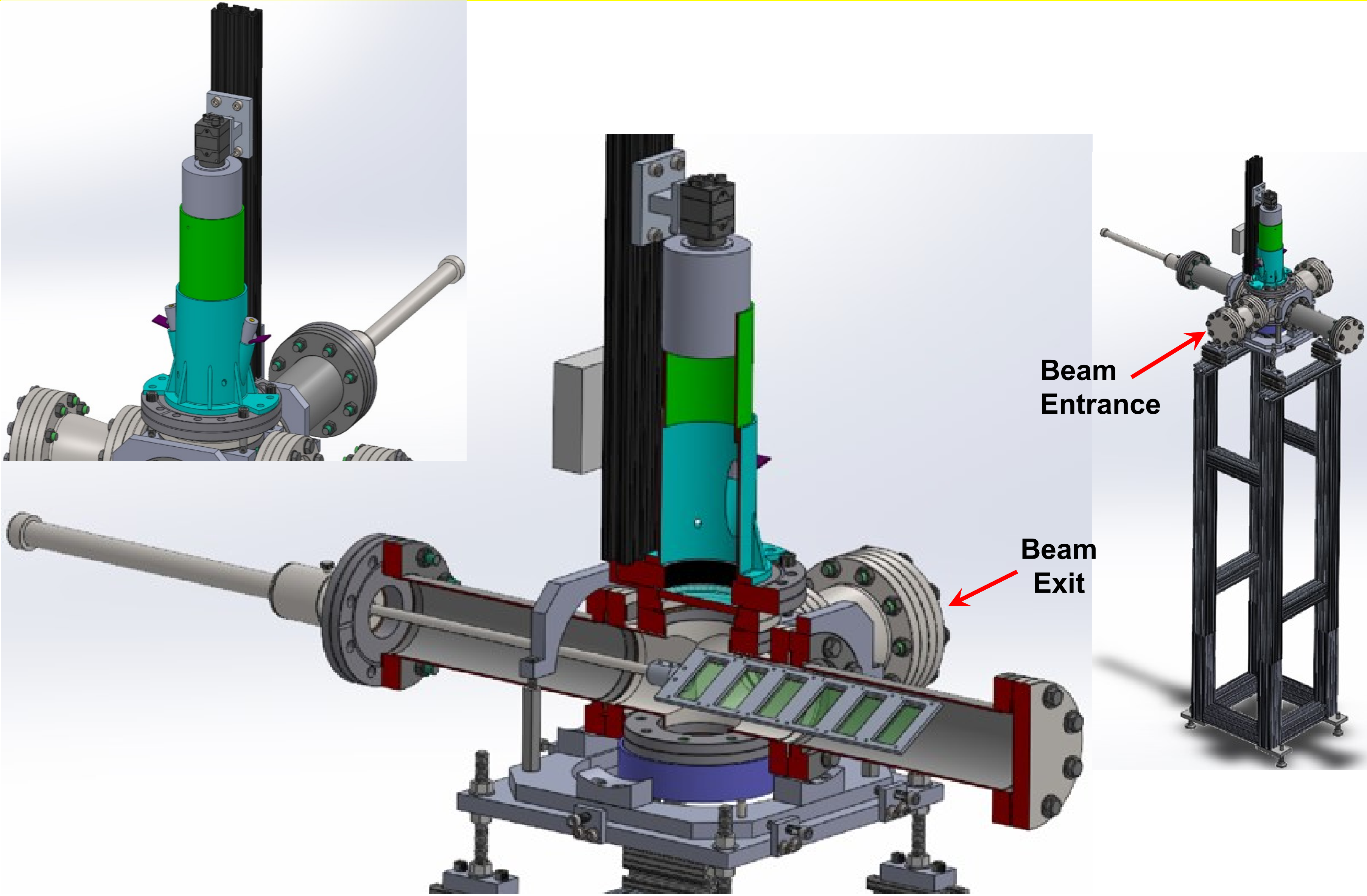
Many vacuum beamline configurations – 3 different examples shown







FRIB-ReA3 Beam Monitor



ReA3 Beam Monitor Test Setup

Fig. 1a - Top View of ReA3 test beam setup with I-S beam monitor in front of FRIB Mobile Diagnostics Stand

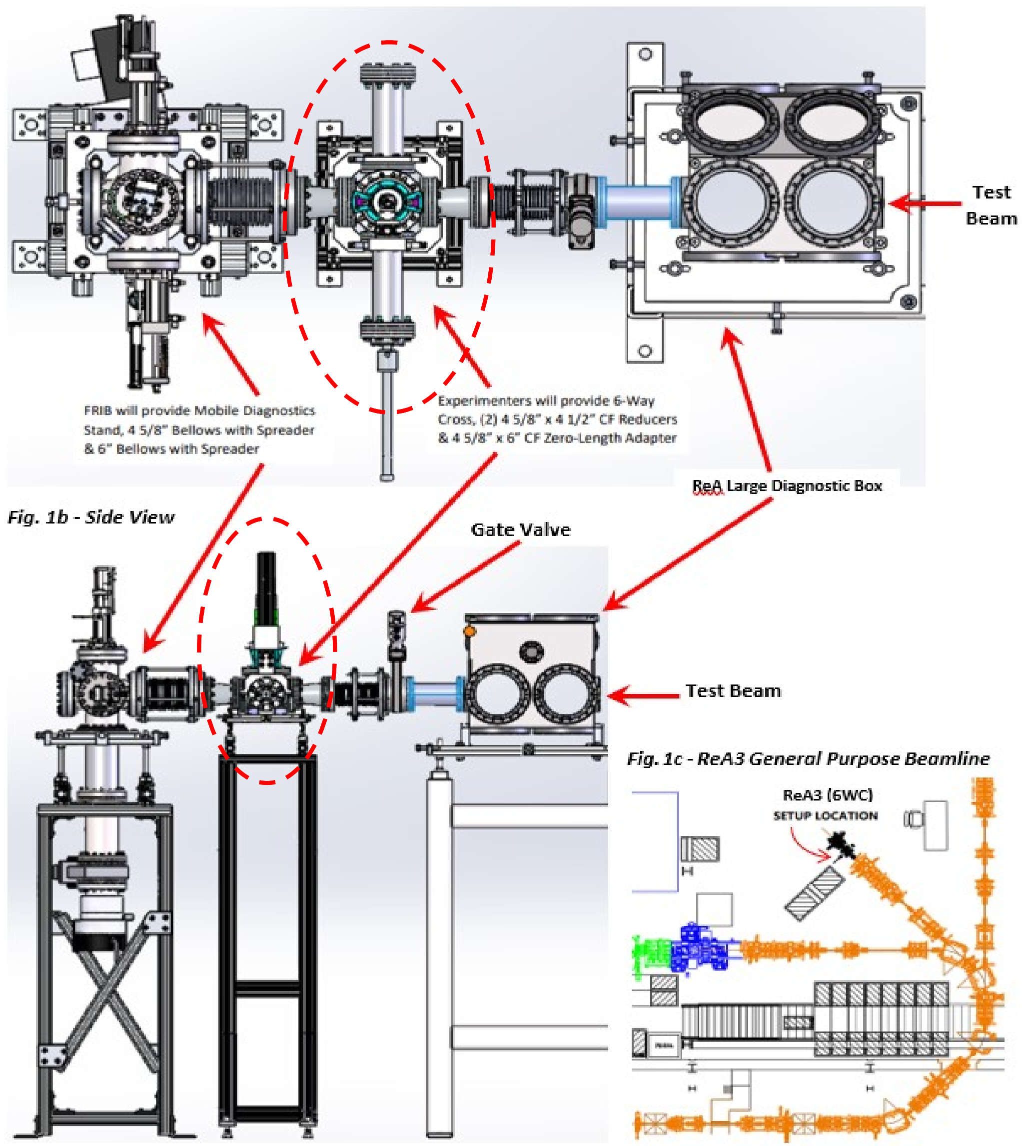


Fig. 1b - Side View

Fig. 1c - ReA3 General Purpose Beamline

Camera for 1st ReA3 Beam Test (9/1/2021)

- **Selected machine vision camera ($600) yields twice the ADC signal with same noise as dozen other cameras tested, including those at twice the price. Explanation due to combination of: (1) larger pixel size, (2) higher pixel Q.E., (3) better pixel-to-pixel noise uniformity, and (4) improved photon angular acceptance at smallest f-number.**

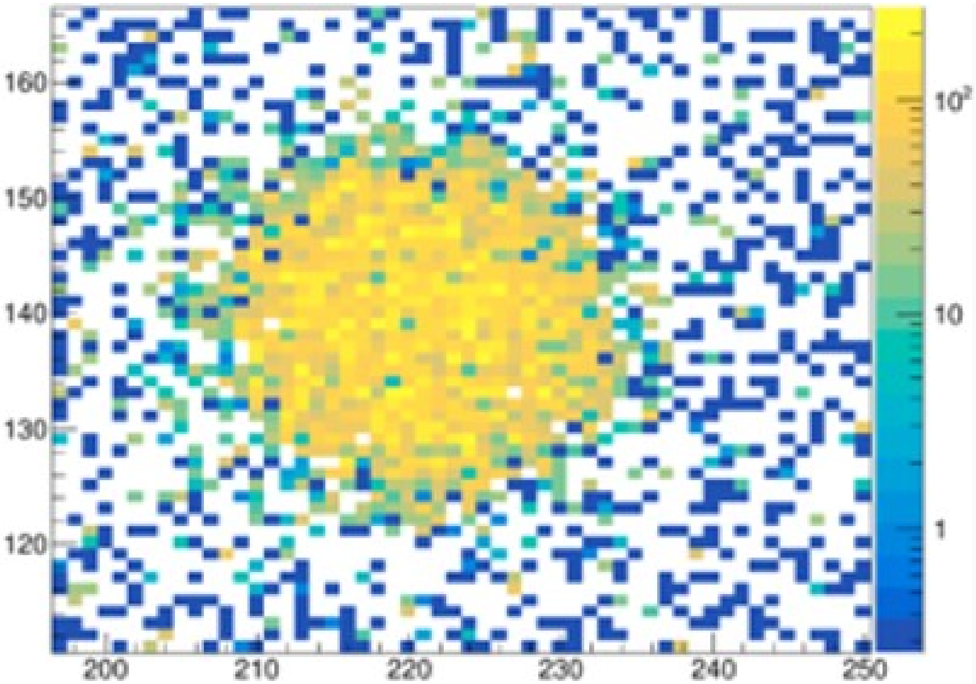
- **Selected lens costs more than camera, has ultrafast f/0.9 aperture.**

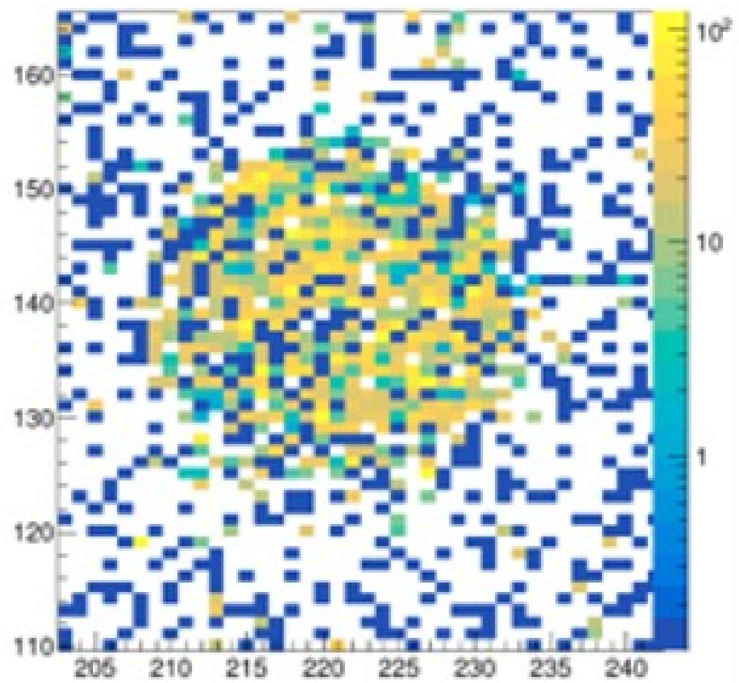
- **High probability of single-particle imaging with above $600 camera for *heavy-ions* (we've demonstrated single-particle imaging of alphas from smoke detector using a more expensive camera).**

- **Real-time correction for camera CMOS-sensor noisy pixels, image defocusing from depth-of-field distortions, background subtraction, image lens and perspective / tilt distortion *(note that we have not observed signal non-linearity or saturation)*.**

PM-Scintillator vs. BC-400

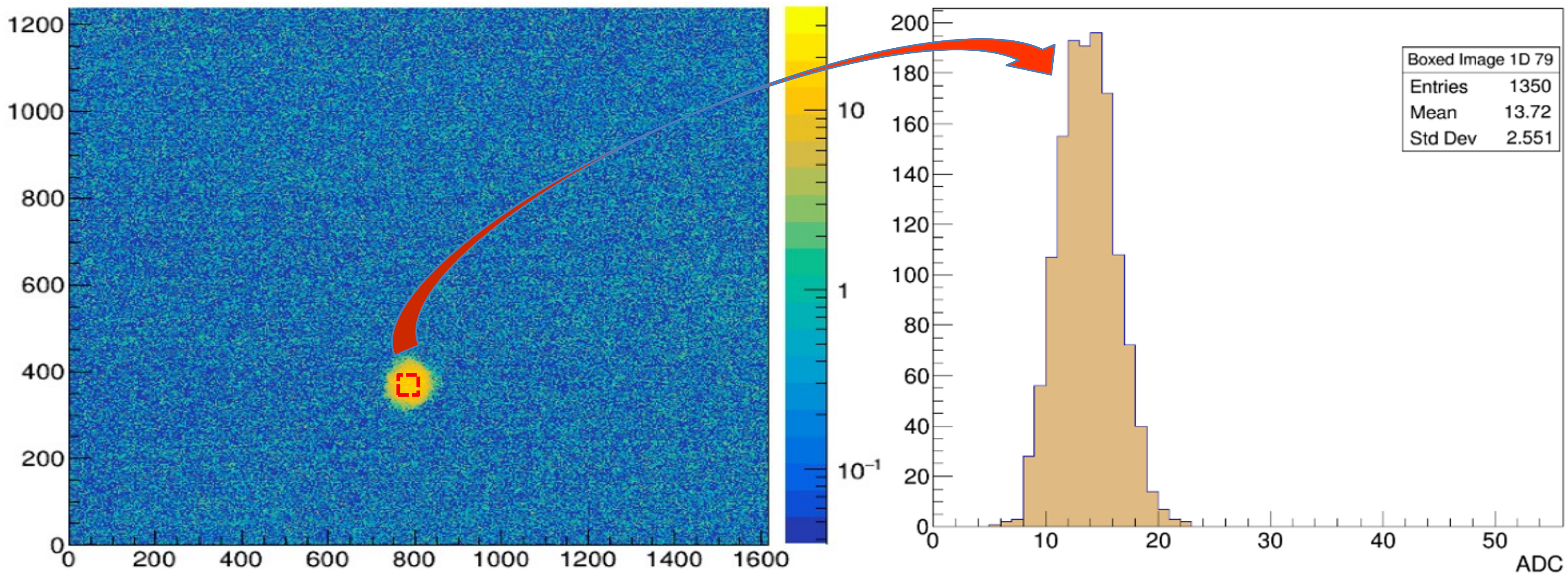
PM-scintillator ADC values ~ 250 counts vs. BC-400 ADC values <100 counts.





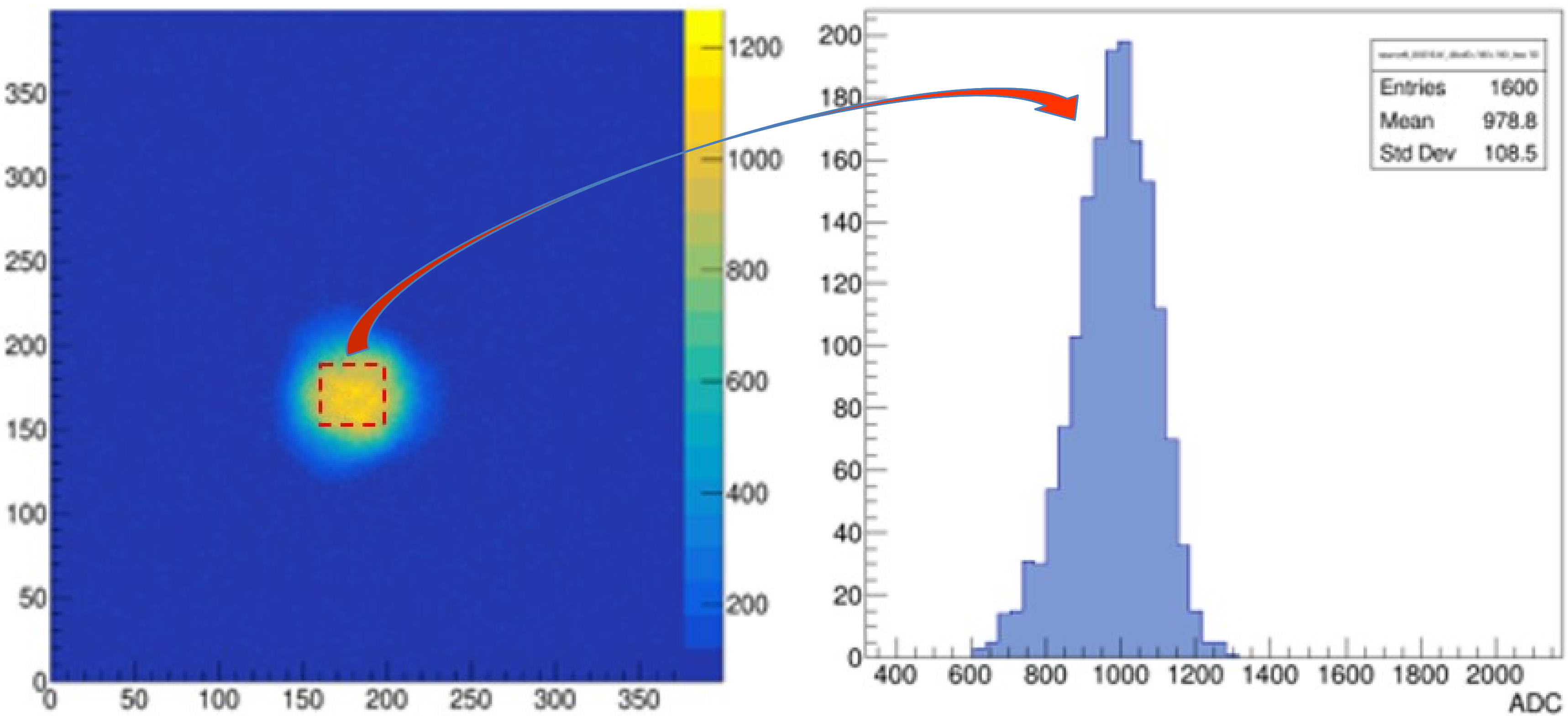
Same ^{90}Sr beta source (2 MHz/cm^2, ~3 mm diameter beam), $600 camera (1 sec), lens and setup for both scintillators. Energy loss per beta particle ~ 0.05 MeV.

Alpha "Beam" Image of ^{241}Am Source
(CMOS sensor, $600 camera)



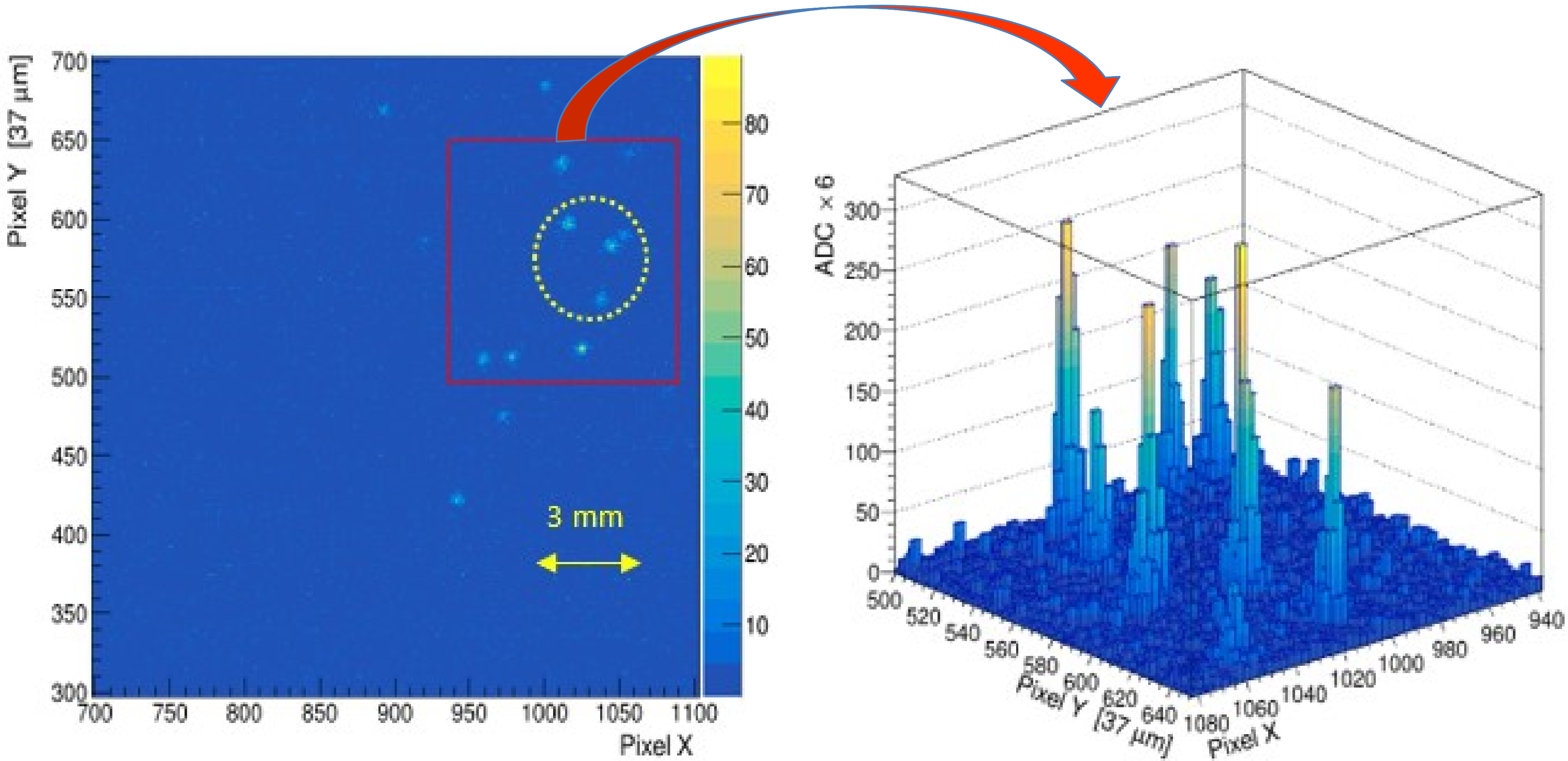
(*Left*) Beam Monitor setup with *full* field-of-view of HM-scintillator (21 x 38 mm) and 1 MeV/u smoke detector alpha source (particle rate is 7 kHz). (*Right*) ADC histogram of image signal distribution for a 40x40 pixel square fiducial box over central beam area with 1 sec exposure.

Alpha "Beam" Image of ^{241}Am Source
(*scientific*-CMOS sensor camera)



(*Left*) Beam Monitor setup with *zoomed-in* field-of-view image of HM-scintillator and 1 MeV/u smoke detector alpha source. (*Right*) ADC histogram of image signal distribution for a 40x40 pixel square fiducial box over central beam area with 1 sec exposure.

Single-Particle Alpha Images (^{241}Am)
(*scientific*-CMOS sensor camera)



HM-scintillator background subtracted image of 1 MeV/u alpha source with 2 ms exposure (i.e. 10-20 alpha particles). In left image, 14 individual hits are clearly visible with ADC counts of 40-50. Lego plot (rebinned) on right is of red box area. Strong alpha signal yields single-particle position resolution of ~ 5 µm.

Radiation Damage Test* for PM-Scintillator

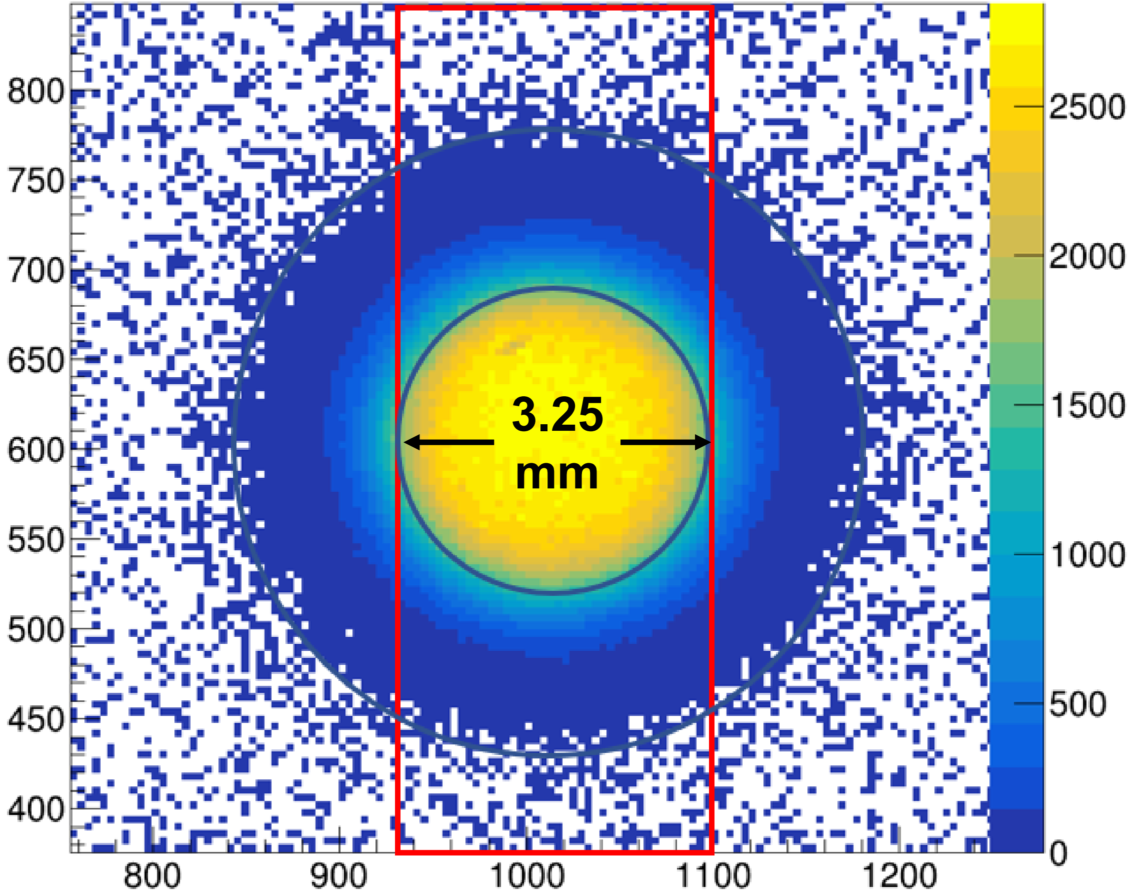
Summary of MIBL Proton Beam Accelerated Test Results for 191 μm thick Scintillator

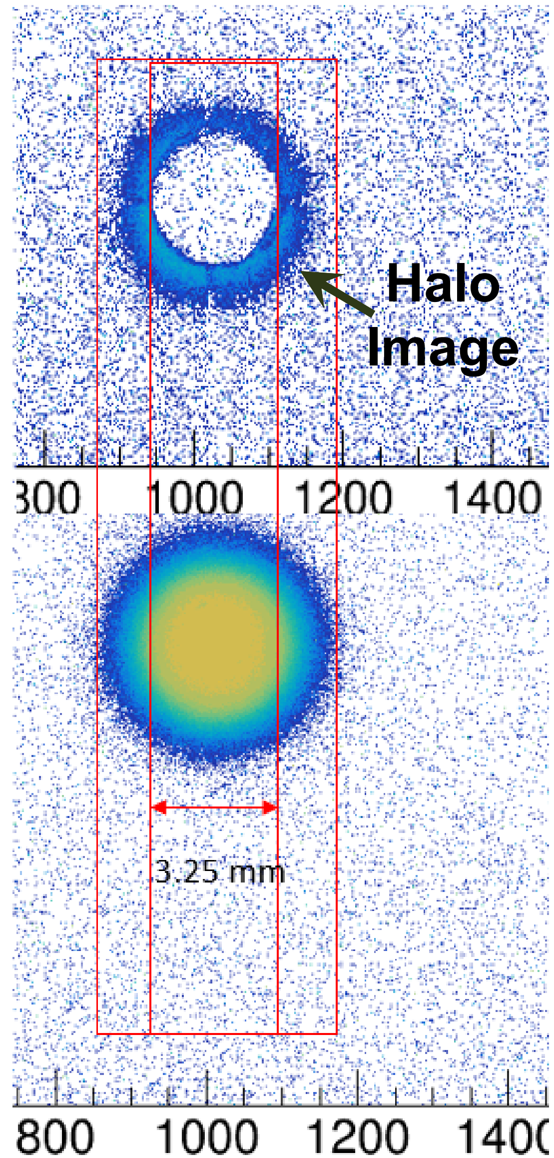
Dose Rate (kGy/s)	Beam Energy (MeV)	Total Dose (kGy)	Scintillator Rad-Damage Observations
0.11	5.4	33	No discoloration. Minimal rad-damage, **50% recovery in 4 hours**
0.20*	5.4	59	No discoloration. **Minimal rad-damage, largely reversible***
3.3*	5.4	390	**Manageable rad-damage**. Very slight darkening that eventually disappeared*
9.2	3.0	490	Unacceptable rad-damage. No ablation but rapid fluorescence decrease
92	3.0	6,100	Slow surface ablation and immediate fluorescence decrease
460	3.0	15,000	*Immediate fast* surface ablation, burning hole through 60-70% of scintillator
**Rates of 200 & 3,300 Gy/s with minimal rad-damage are well above that required for FLASH-RT*			

Delivered *continuous* dose of 59,000–390,000 Gy, at 200–3,300 Gy/sec (i.e. high-end of FLASH-RT) within 2-5 minutes in a single spot, with minimal to manageable scintillator degradation. Note that *59,000 Gy is equivalent to the full course of treatment for ~1,000 patients*.

Test at the Univ. of Michigan Ion Beam Laboratory (MIBL) was conducted to evaluate the PM-scintillator for both FRIB and FLASH-RT (radiotherapy).

Beta "Halo" Image from ^{90}Sr Source

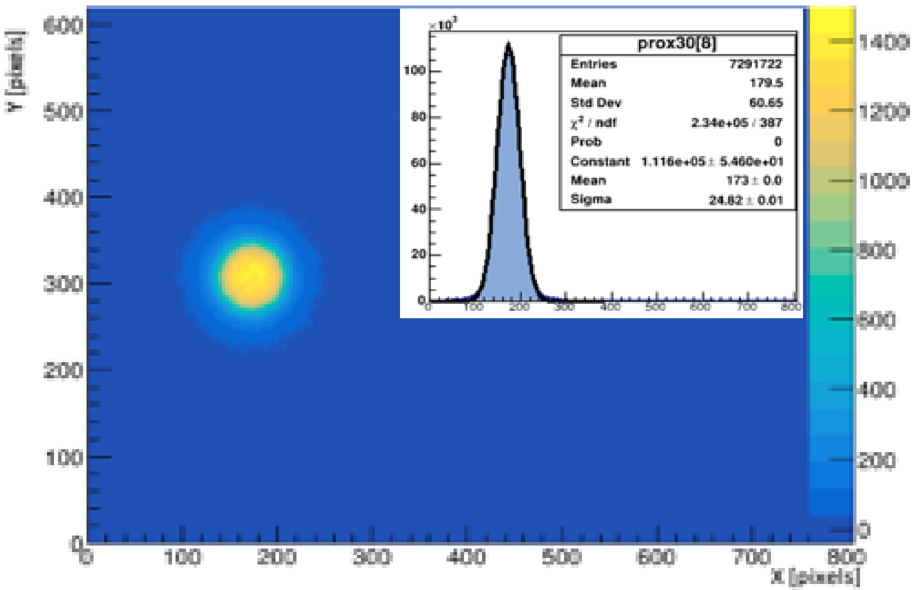


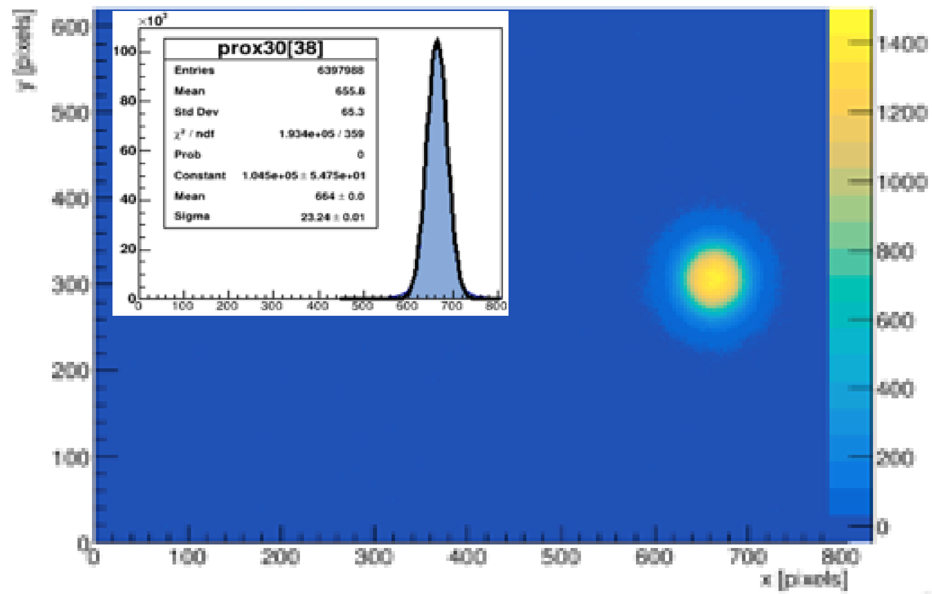


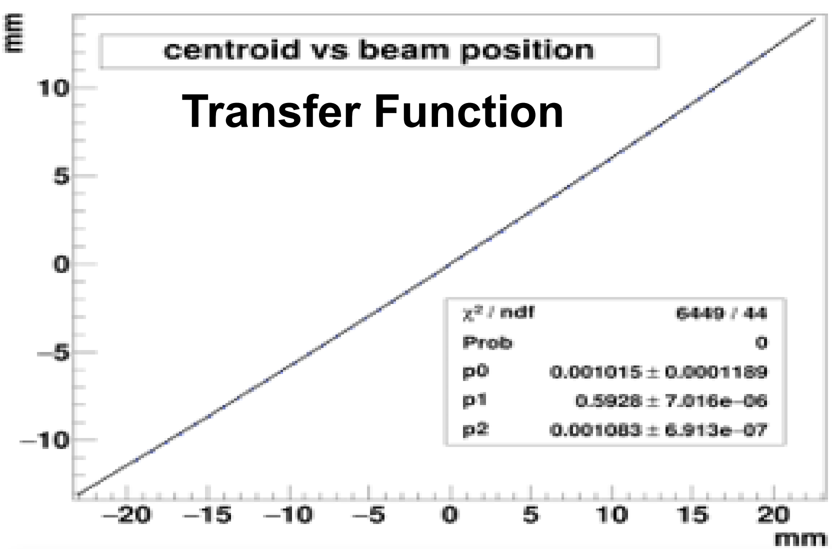
^{90}Sr beta source confined to a 3.13" diameter Al–collimator pressed against HM scintillator with 3.25 mm hole. Halo image is generated at the collimator edge by corner clipper betas.

Beam Centroid Position Resolution

(Transfer function of measured centroid to actual beam position)







Correction for magnification differences and defocusing at the scintillator edges due to the shallow f/0.9 lens depth-of-field. Defocusing is asymmetric and shifts by a small margin the centroids of the beam spots. The centroid position resolution and systematic shifts from defocusing were measured by translating a HM scintillator and alpha source assembly in precise increments of 1.000 mm across the field-of-view using an XY stepper motor drive.

Data Acquisition, Analysis & Software

- **Built-in rapid internal calibration capability for camera & scintillator via *UV-LEDs* & *photodiodes* to monitor *system stability / rad damage*.**

- **Corrections made via an experimentally determined *transfer function* for *defocusing* caused by shallow depth-of-field, *perspective distortion*, and *magnification differences* due to *tilted* scintillator plane with respect to the camera.**

- **Linux platform compatible DAQ system with proprietary software for beam monitor operation with *streaming data analysis updated at 1 Hz* and continuously displayed remotely and locally on high resolution, large area monitors, including:**
  - **Camera configuration and operation**
  - **Background processing & subtraction**
  - **Image processing including angle correction (at ~ 2 Hz)**
  - **Beam finding & position location**
  - **Beam data analysis – e.g., beam profile / shape / ion current**
  - **Single particle analysis**

Real-Time Beamline Monitoring

- **Camera image exposure time can vary from ~17 μs to 10 sec.**
- **Beam monitor for ReA3 beamline tuning has been set to update streaming images at 1 Hz with each image having a 1 sec exposure.**
- **1st ReA3 beam monitor test is planned for Sept. 1, 2021 with a ^{86}Kr beam to demonstrate real-time image analysis for beam rates that will vary over the range from ~10^1 to 10^6 pps (i.e. particles/sec).**
- **Beam monitor will first demonstrate its *beam tuning efficacy* at the *highest* beam rate of ~10^6 pps, and then evaluate 5 different PM and HM scintillators (thicknesses from 6 to 190 μm) plus a 1.25 mm thick CsI(Tl) reference, at each particle rate, working down from ~ 10^6 to 10^1 pps, the latter would be single-particle imaging.**
- **Beamline monitor has *internal calibration* capability and will update the data analysis at 1 Hz. It should provide faster, more precise and more accurate real-time 2D analysis of: beam profile, X-Y centroid position, particle flux, with standard statistical analysis.**

SUMMARY / Demonstrated Performance

- **Beam 2D centroid resolution is ~ 2 μm to 5 μm**
- **Absolute maximum beam positioning error is ~ 200 μm**
- **Full Beam Shape / Intensity Profile including Tail and Halo imaged**
- **Beam Fluence / Ion Current measurement capability**
- **Rapid Camera and Scintillator Calibration capability (≤ 1 minute)**
- **Continuous Beam Monitoring updated at 1 Hz (analysis in 0.5 sec)**
- **Single-Particle imaging demonstrated for 5 MeV alphas**
- **Beam images captured in 3 μm thick PM scintillator of 5 MeV protons**
- **PM scintillator response is linear up to ~ 5 – 10 kGy/s**
- **Radiation damage for camera and PM & HM scintillators should *not* be a significant problem in ReA and Fast Beam environments**

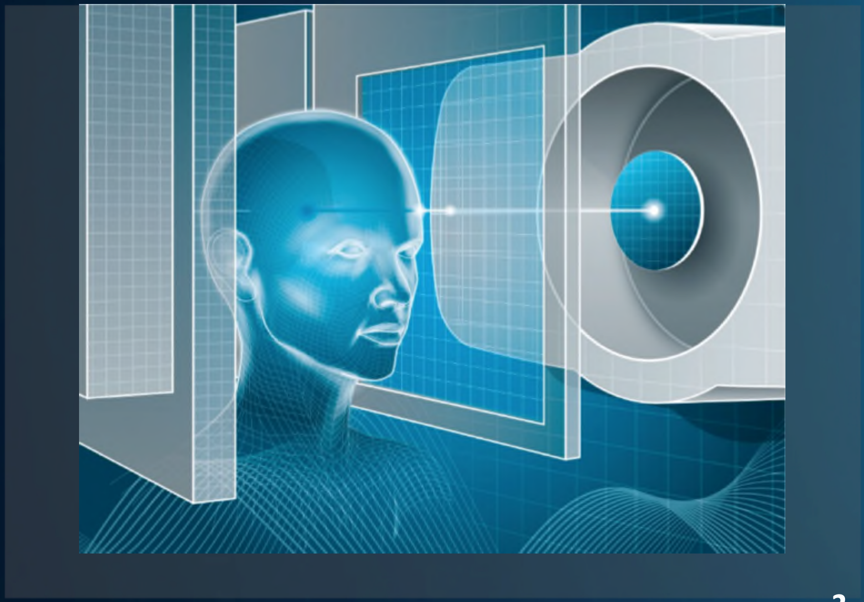
Medical Application

The “FLASH” Effect

- Radiation-induced normal tissue toxicities can be *reduced* without affecting tumor control by *ultra-fast* delivery of radiation at dose rates *orders-of-magnitude* greater than used in conventional EBRT clinical practice.

- This allows much higher radiation dose treatments, and increases the therapeutic index over conventional radiation delivery.

- **This is known as the FLASH effect.**



Major Problem – Monitoring FLASH Delivery

- FLASH is ~ ***1,000* times faster** with order-of-magnitude higher dose (e.g., ≥ 40 Gy) than conventionally-fractionated RT (~ 2 Gy)

- FLASH dose is typically delivered in **< 0.5 sec**. For *proton*-FLASH the corresponding beam luminosity is ~ **10^{11} to 10^{12}** protons / cm^2 s

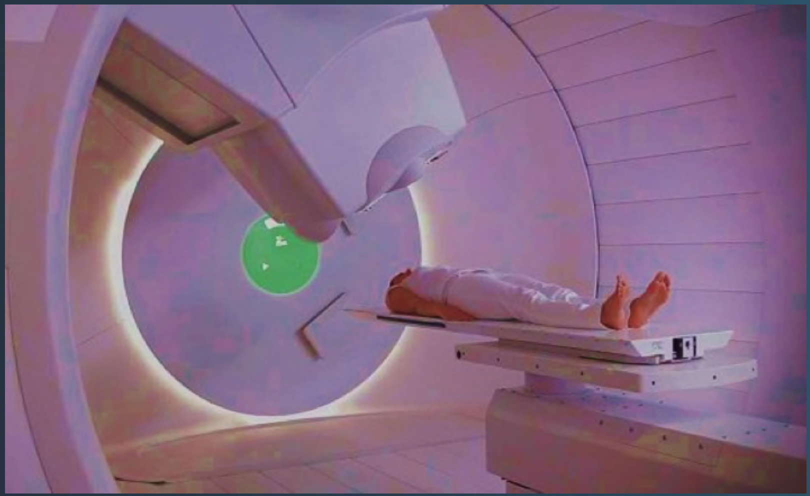
- Standard dosimetry methods are not fast enough and ***do not work*** at the radiation intensity of FLASH delivery

I-S Competitive Advantages

UFT beam monitor is a patented enabling technology for FLASH-RT

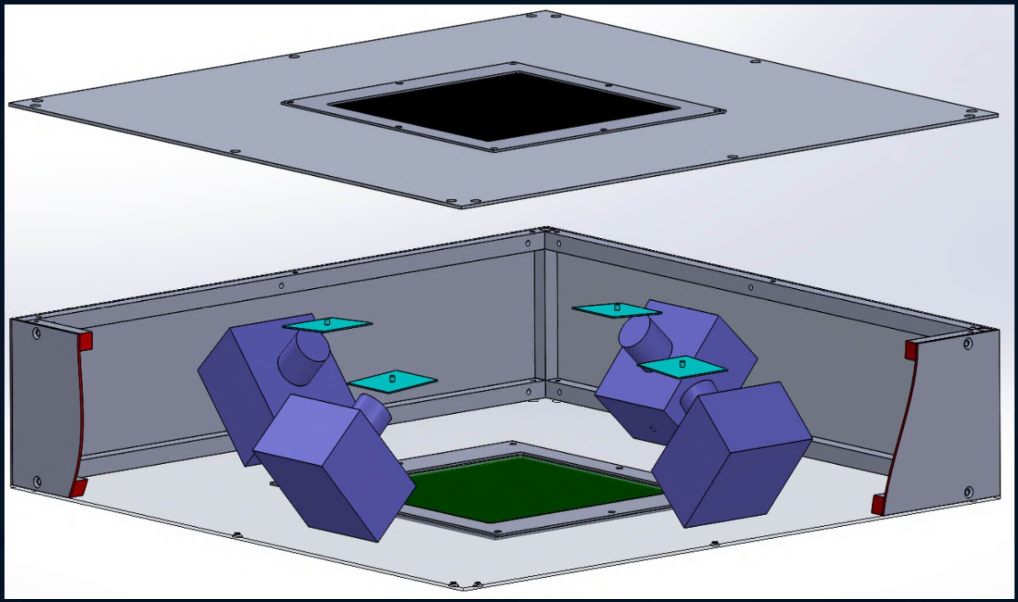
- Two New Patented High Efficiency Scintillators
  - PM-scintillator (polymer) ultra-thin rolls
  - HM-scintillator (hybrid) highest efficiency

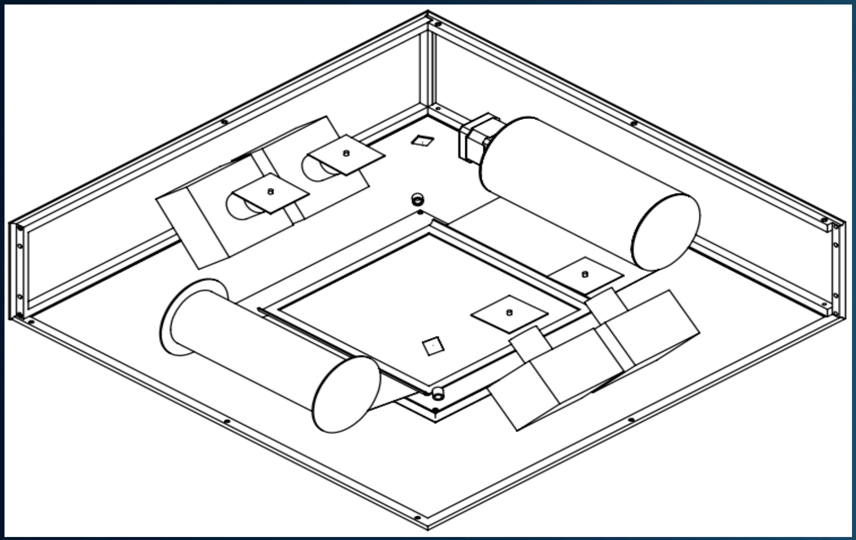
- Innovative UFT Patented Configurations
  - Ultra-fast beam analysis ~ **100 µs**
  - Real-time dosimetry, beam position & shape
  - High spatial resolution (~ 10 – 100 µm)
  - Water-equivalent thickness about ≤ 0.5 mm
  - Internal calibration
  - Multiple cameras & folded optics
  - Detector area: 26 cm x 30 cm (1st prototype)

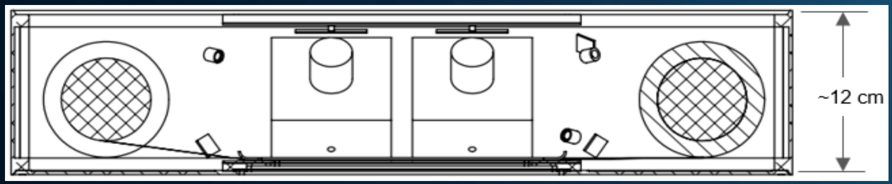


Many UFT Beam Monitor Configurations

Two examples with replaceable large-area (~ 26 x 30 cm) PM or HM scintillators







Real-time beam analysis & dosimetry with UV-LEDs and UV-photodiodes for internal calibration