Ultra-Fast, Transmissive, Real-Time Beam Monitor for FLASH-RT & Patient QA

Tracking Beam Position, Movement, Intensity Profile/Shape, Fluence/External Dosimetry & Angular Divergence in Real-Time, both Upstream & Downstream from Nozzle/Collimator

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Ultra-Fast Transmissive (UFT™) Beam Monitors*

New reaction-component (RC) material* *tested* with ***proton*** beams and simulated for ***photon*** and ***electron*** beams in RC layers as thin to 3.0 μm. Results show ***order-of-magnitude*** advantages over ionization chambers for 2D beam position (< 10 μm resolution capability), **full beam shape** and readout time (~ 0.1 ms). Real-time, high-resolution images captured at 10 μs for proton beams moving 80 mm / ms. Monitor radiation damage testing downstream from nozzle or multileaf collimator has demonstrated RC material capability for **FLASH** therapy. *Ultra*-thin layers can last > 1 year in a typical EBRT treatment room radiation environment. Simulations for heavy-ions show similar advantages, as do UFT™ monitors for MIPs and "exotic" heavy-ion particle beams at U.S. Dept. of Energy accelerators.

* *Integrated Sensors (I-S) UFT™ technology patents pending*

Targeted Applications: EBRT & NP
(*external beam radiotherapy & nuclear physics)*

Particles: **Protons*, electrons, heavy-ions*, neutrons**

- **Downstream – Beam exiting nozzle in air**
- **Upstream – Beam in *vacuum* beamline***

Photons: **Beam exiting multileaf collimator**

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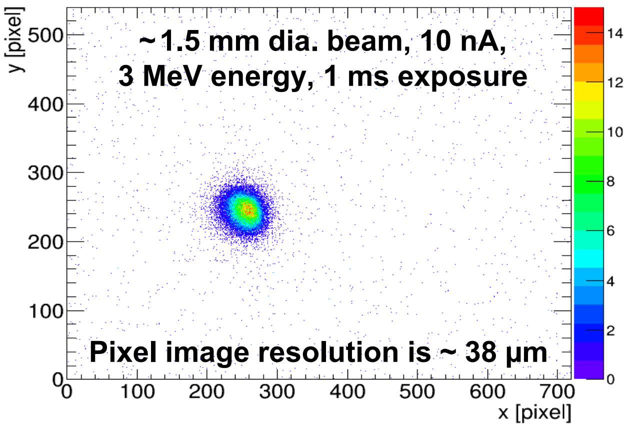
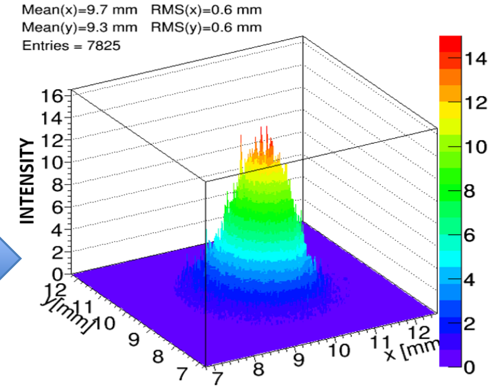
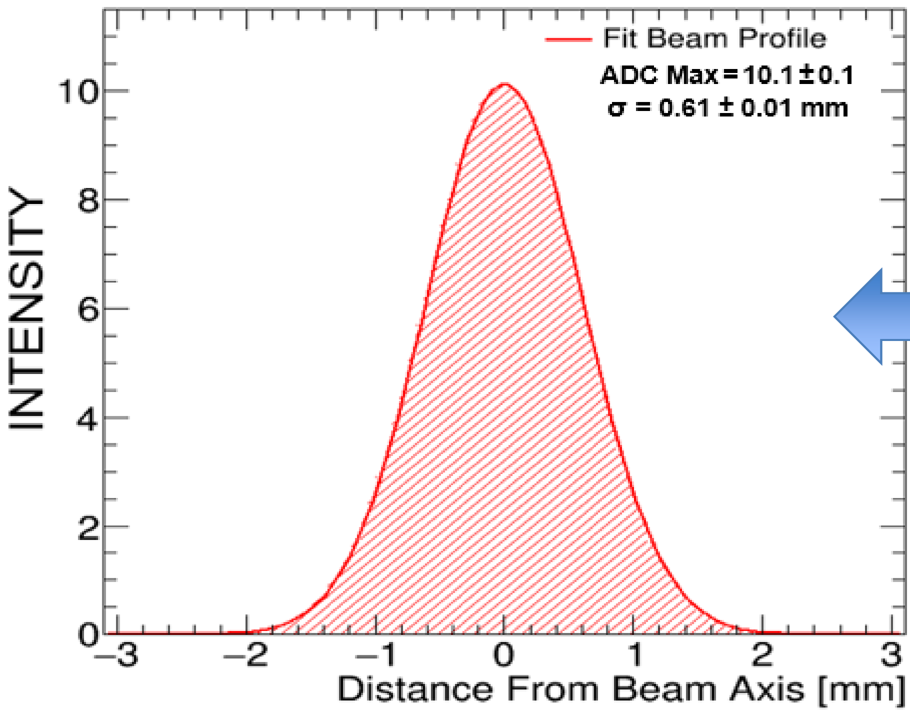
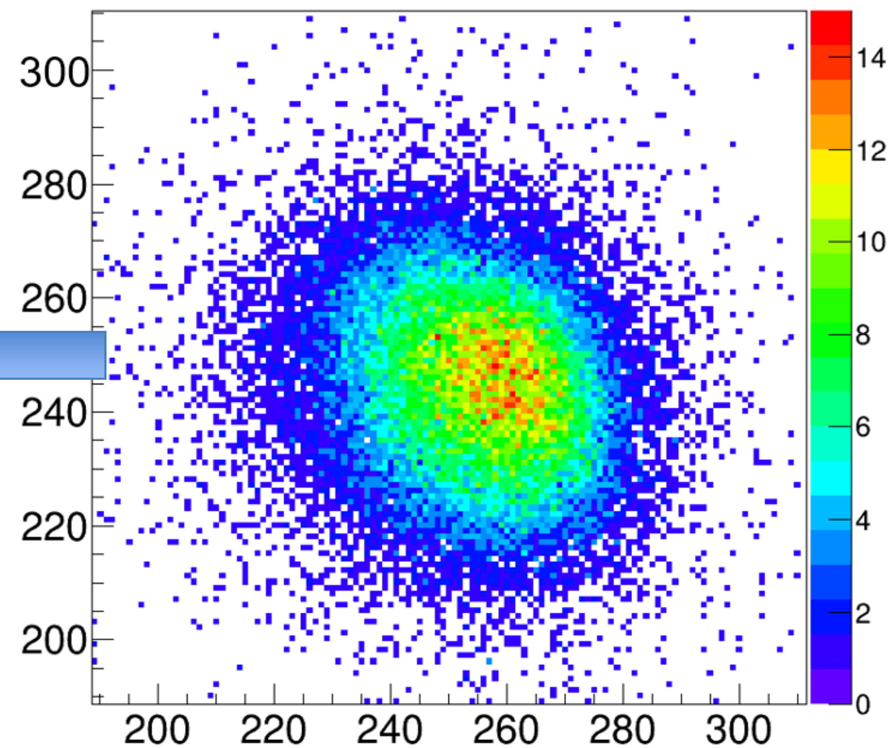
Example of Proton Beam Image & Analysis





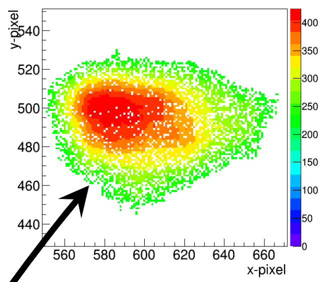
<u>Top Left</u> – Image field-of-view is 21 mm x 27 mm. <u>Bottom Right</u> is zoom image of Top Left. <u>Bottom Left</u> is Gaussian fit with measured average σ = 0.61 mm, and 99.7% of beam within 3σ, and only 0.3% of beam beyond 1.83 mm radius.

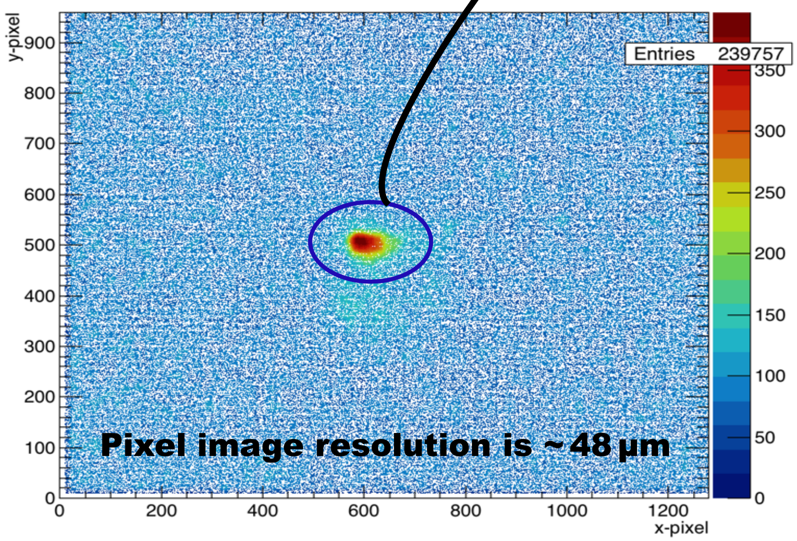




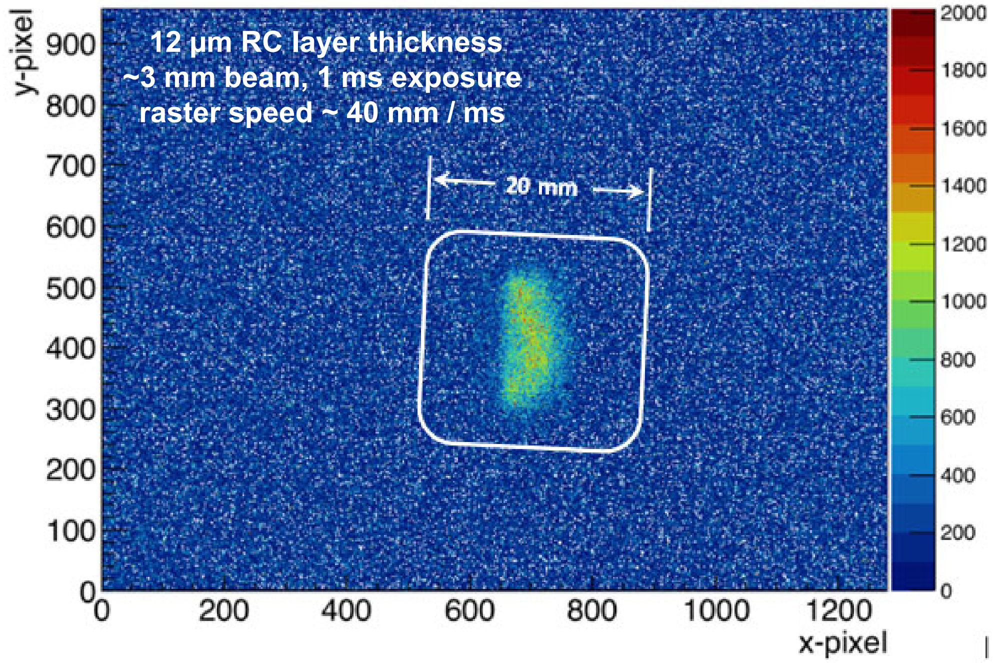
Ultra-Fast & Ultra-Thin Layer Beam Images

10 μs signal integration
raster speed 80 mm/ms
~3.6 mm beam diameter





Color-coded image of signal integrated over 10 μs, of 5.4 MeV proton beam moving at 80 mm/ms with beam current of 10 nA, irradiating an RC layer having a thickness of 0.19 mm.



Color-coded image captured in 1 ms of 5.4 MeV proton beam moving at raster line speed of ~40 mm/ms, although beam slows down at end of each raster line segment when reversing direction. Zig zag pattern for each line has ~50% overlap with previous line. Proton beam current was 10 nA with beam diameter of ~3 mm. Average beam path length traveled before changing direction is ~8-10 mm.

UFT™ Beam Monitor Radiation Hardness*

Summary of Proton Beam Test Results for Thin RC Layer

***(Rad-hardness for *PHOTONS* should be at least equal to that for *PROTONS*)**

Dose Rate (kGy/s)	Current Density (nA/cm^2)	Beam Current (nA)	Beam Energy (MeV)	Dose (kGy)	Radiation Damage Observations
0.11	1.35	5.4	5.4	33	Sample 9: Small to minimal rad-damage at this dose
0.20	2.4	9.6	5.4	59*	Sample 20: Minimal level of rad-damage at this dose
3.3	40	10.0	5.4	390	Sample 16: Upper limit of possibly manageable rad-damage
9.2	50	1	3.0	490	Sample 13: Rate of rad-damage is too high, but is still linear
92	500	10	3.0	6,100	Sample 13: At this rate, slow RC layer material ablation
460	2,500	50	3.0	15,000	Sample 13: At this rate, fast RC layer material ablation

Conventional proton therapy dose rate is ~ 0.03 Gy/s, versus flash therapy rate of >40 Gy/s (i.e., 0.04 kGy/s)

**5 minute exposure yielded 59 kGy dose and is equivalent to treating 30,000 patients at dose of 2 Gy per patient*

Performance Estimates for *Charged Particles*

- **Beam 2D Position Resolution (< 10 μm capability)***
- **Full Beam Shape / Intensity Profile including Tail***
- **Beam Fluence / External Dosimetry***
- **Automated Internal Self-Calibration (≤ 1 minute)***
- **Readout & Real-Time Analysis (~ 0.1 ms)**
- **Timing Resolution for Protons < 1 ns**
- **TOF Resolution for Heavy Ions (estimated) ~ 50 ps**
- **RC Response is Linear up to ~ 10 kGy/s**
- **RC Rad Damage – Not a Problem for FLASH therapy**

****Accuracy should be ~ 1-2%***

Charged Particles Performance Continued

- **Beam images captured in ultra-thin RC layers from 3 μm to 12 μm, at 1 ms, with rastered proton beam moving at 40 mm / ms.**
- **Beam images captured in 10 μs, in RC thickness of 0.19 mm, for a rastered proton beam moving at 80 mm / ms.**
- **Same image quality and signal response expected for ~ 230 MeV protons, as demonstrated at 3.0 MeV and 5.4 MeV, for monitor systems designed for EBRT and FLASH-RT applications.**
- **Proton lateral spread due to UFT™ monitor at 70 cm downstream from nozzle calculated (i.e. Geant4 simulation) to be 0.024 mm at 70 MeV, and 0.003 mm at 210 MeV.**
- **Proton beam energy loss through UFT™ monitor calculated to be $<$ 0.30 MeV at 70 MeV, and $<$ 0.14 MeV at 210 MeV.**

PHOTON Beam Performance Estimates:
(UFT^{TM} Beam Monitor compared to IBA Dolphin)

- **Geant4 simulation using 6 MV, 10 x 10 cm^2 photon beam phase-space file from IAEA database (www-nds.iaea.org/phsp/photon1/)**

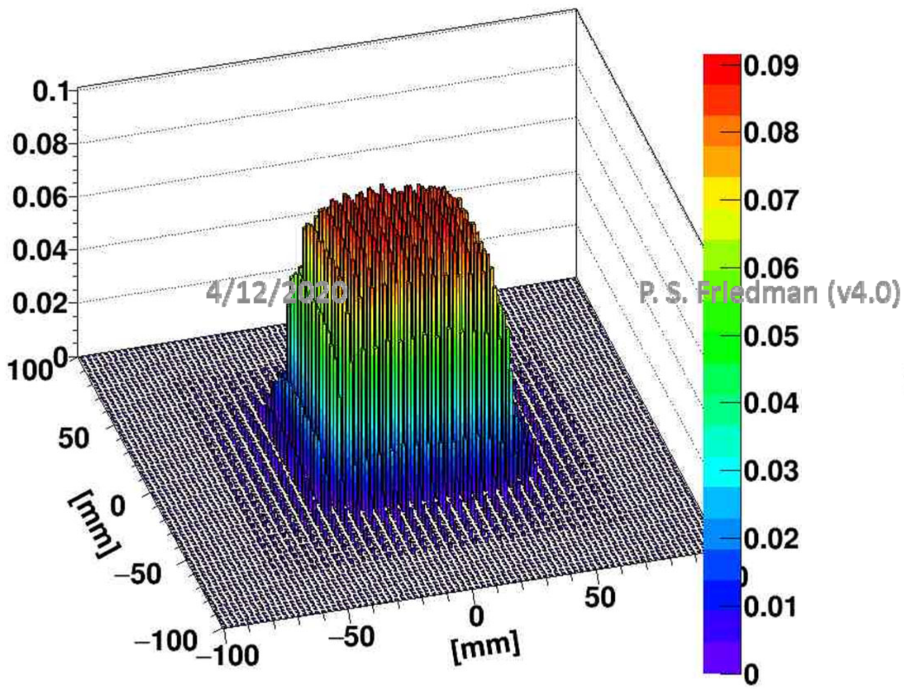
- **Beam Shape & Tail imaging with minimal shape distortion and better then 0.1 mm resolution, as compared to ~ 2 mm for the IBA Dolphin monitor.**

- **Readout Time / Real-Time Analysis ~ 0.1 ms (depending on platform), compared to ≥ 20 ms for the IBA Dolphin monitor.**

- **Beam hardening characterized by skin dose increase due to monitor materials in the beam path is about 2-3%, compared to ~ 15% for the IBA Dolphin monitor.**

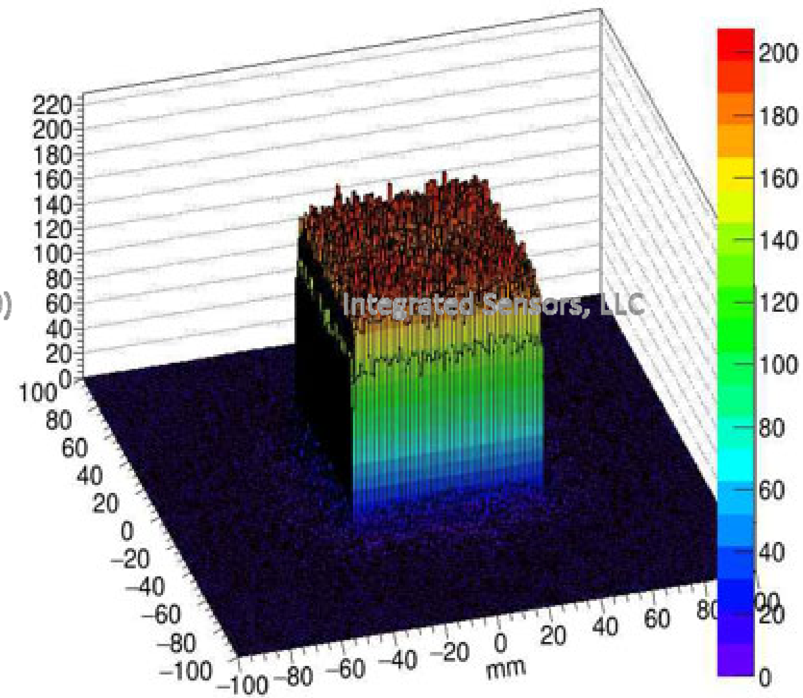
Image Quality Comparison with IBA Dolphin

Dolphin: Accuracy of the beam profile monitoring is defined by the ion chamber pitch (5mm), accuracy of charge measurements, and beam scattering (see halo/tail surrounding the base of beam profile below).



Simulated distribution of total charge (in pC per chamber) deposited in the Dolphin ion chambers by the collimated (i.e., 10 cm x 10 cm at isocenter) 6 MV *photon beam* of 2 x 10^9 photons.

UFT™ Monitor: Beam image has much less beam shape distortion, order of magnitude better spatial accuracy and greatly superior sensitivity than IBA Dolphin.



Simulated spatial signal/intensity distribution from UFT™ monitor under same collimated (i.e., 10 x 10 cm at isocenter) 6 MV *photon beam* of 2 x 10^9 photons (~2 ms exposure at dose rate of 300 cGy/min).