Fast, Transmissive, Real-Time Detectors for Beam Monitoring & 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*** beams in RC layers as thin to 3.0 µm. Results show ***order-of-magnitude*** advantages over ionization chambers in terms of 2D beam position (~0.03 mm resolution capability), full beam shape and readout time (≤0.1 to 1 ms). Real-time, high-resolution images captured at 10 µs for proton beams moving at 80 mm / ms. Radiation damage testing for monitors downstream from the nozzle or multileaf collimator has demonstrated RC material capability for FLASH therapy. *Ultra*-thin and 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 (minimum ionizing particles) 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 radiation therapy & nuclear physics)*

Particle **Beams: Protons*, heavy-ions*, electrons, neutrons**

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

Photon **Beams: Beam exiting multileaf collimator**

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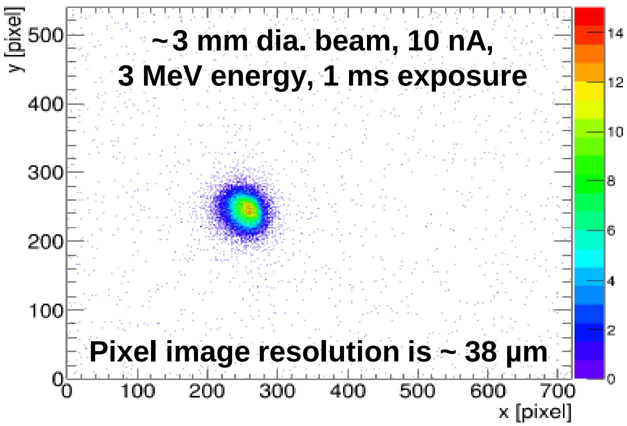
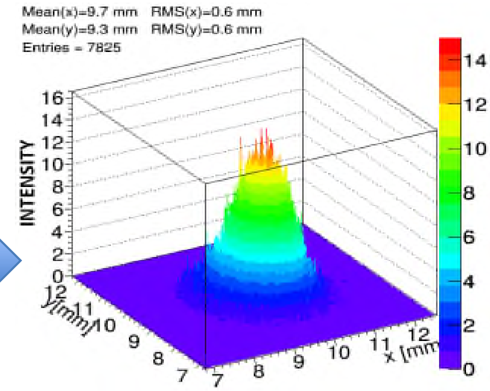
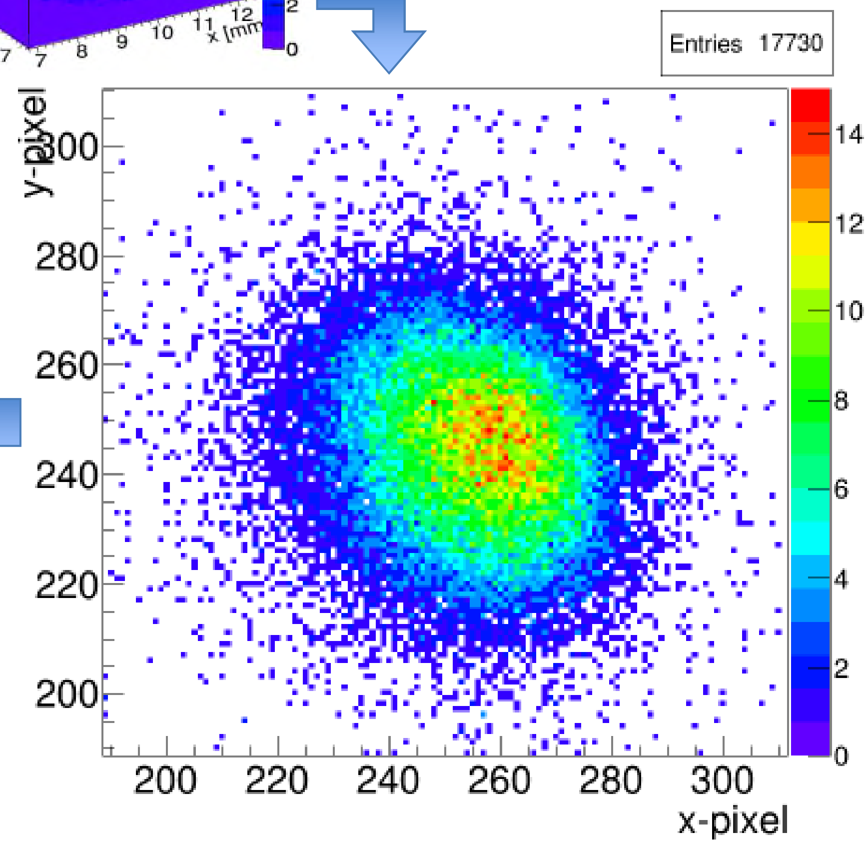
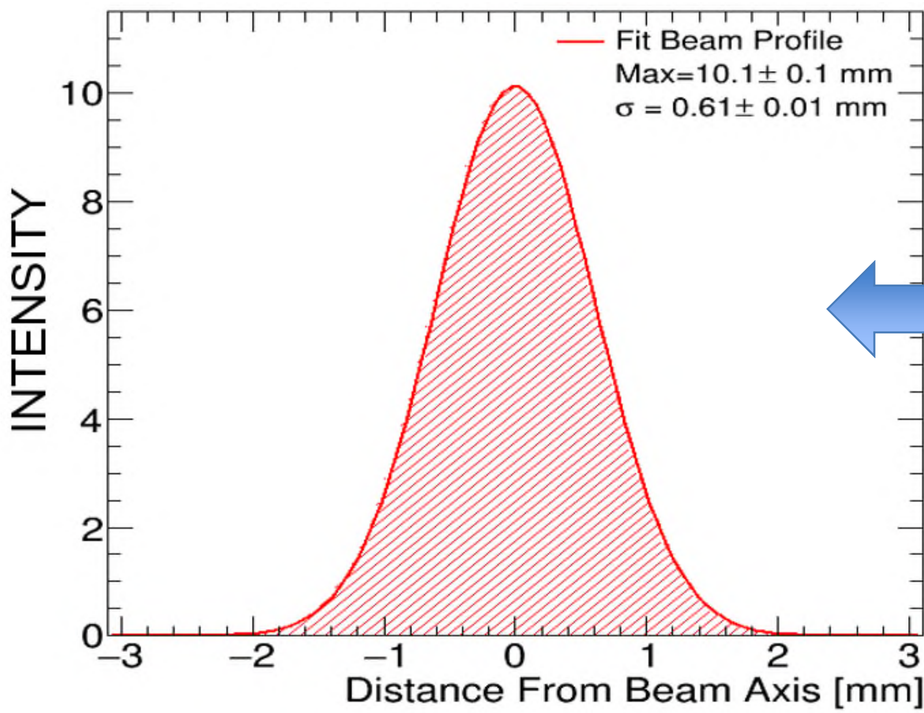
Example of Proton Beam Image & Analysis



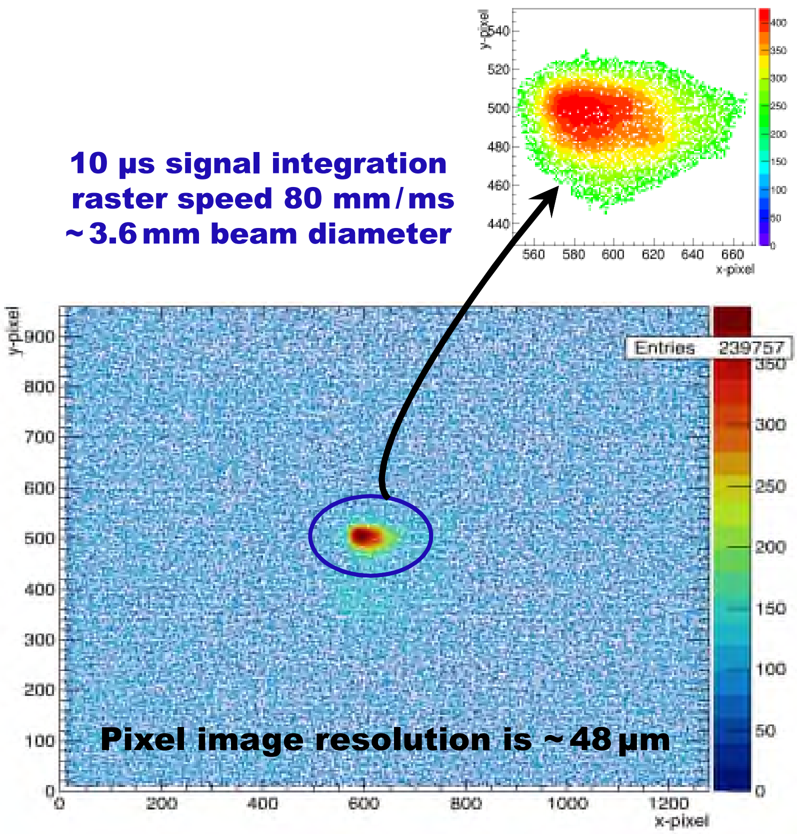


<u>Top Left</u> – Image field-of-view is 21 mm x 27 mm. <u>Bottom Right</u> is zoom image of Top Left. <u>Bottom Left</u> is Gaussian fit with measured average σ = 0.61 mm, and 99.7% of beam within 3σ, and only 0.3% of beam beyond 1.83 mm radius.

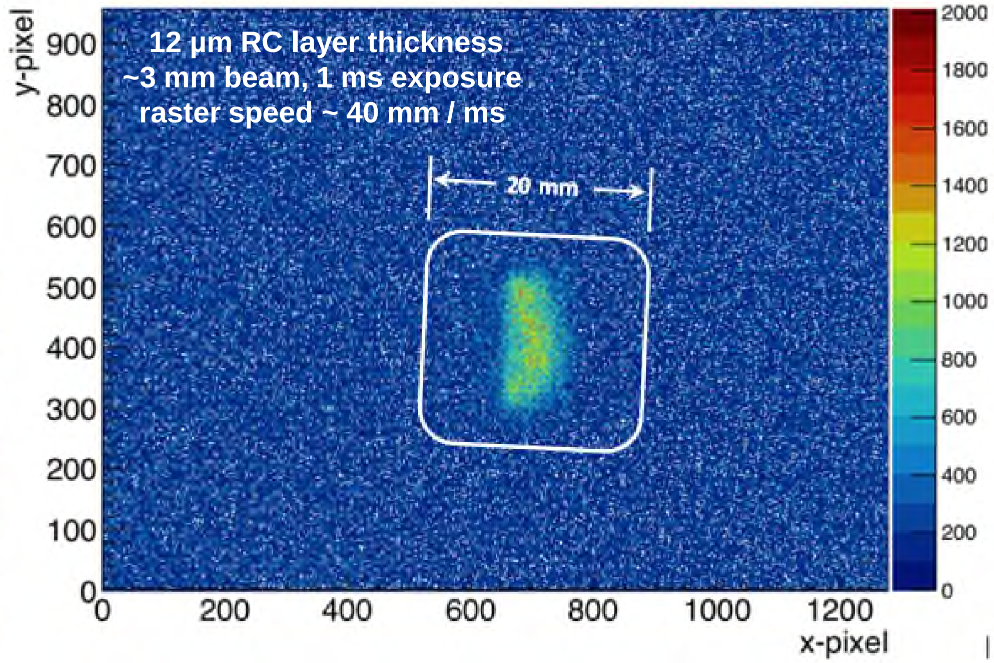




Ultra-Fast & Ultra-Thin Layer Beam Images



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: Acceptable 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 <u>linear</u>
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 <u>flash therapy rate</u> of ~ 40 Gy/s (i.e., <u>0.04 kGy/s</u>)

****5 minute exposure yielded <u>59 kGy</u> 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 (~ 0.03 mm capability)***
- **Full Beam Shape / Intensity Profile including Tail***
- **Beam Fluence / External Dosimetry***
- **Automated Internal Self-Calibration (≲ 1 minute)***
- **Readout & Real-Time Analysis (≲ 0.1 to 1 ms)**
- **Timing Resolution for Protons < 1 ns**
- **TOF Resolution for Heavy Ions (estimated) ≲ 100 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 applications.**
- **Proton lateral spread due to UFT^{TM} 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^{TM} monitor calculated to be < 0.30 MeV at 70 MeV, and < 0.14 MeV at 210 MeV.**

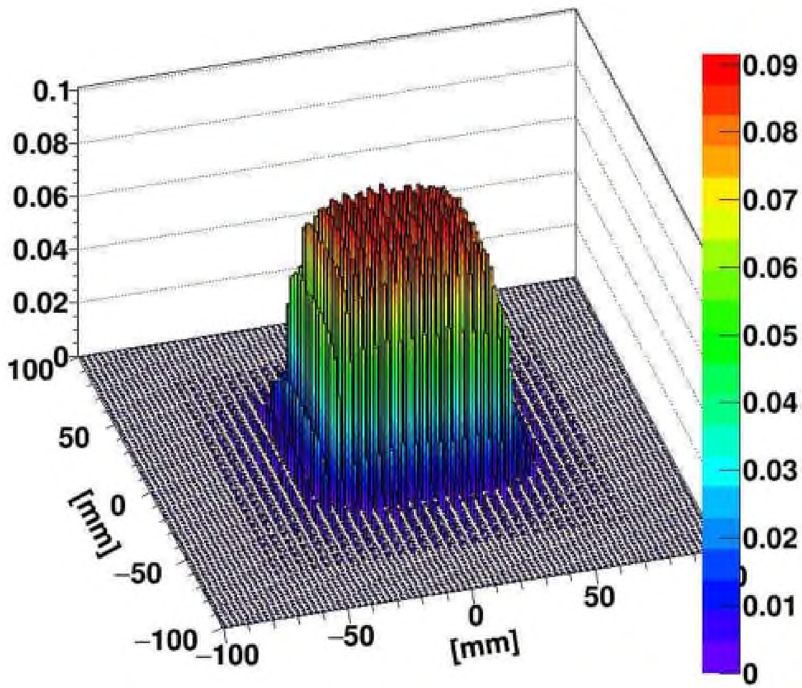
PHOTON Beam Performance Estimates: (UFT™ Beam Monitor compared to IBA Dolphin)

- **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 0.2 mm resolution, as compared to ~ 2 mm for the IBA Dolphin monitor.**
- **Readout Time / Real-Time Analysis ≤ 0.1 to 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.**

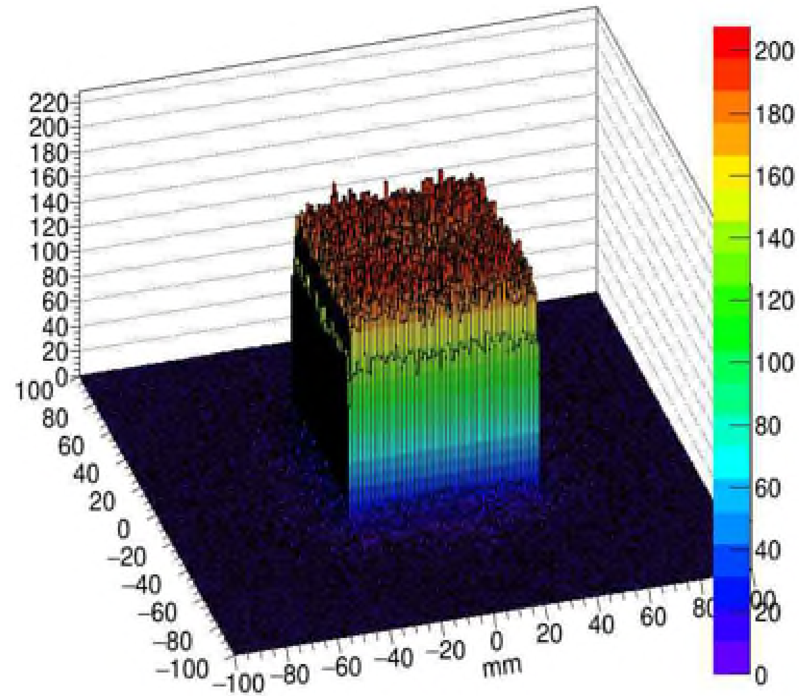
Image Quality Comparison with IBA Dolphin

<u>Dolphin</u>: 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).

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



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.



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