Novel Dosimetry Systems for Radiation Oncology

Thomas Rockwell Mackie

- **Emeritus Professor, University of Wisconsin**
- **Co-Founder Leo Cancer Care, Madison WI**

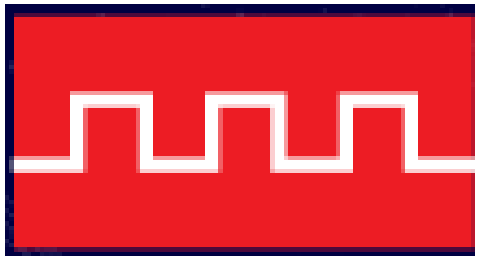


UW-Madison Memorial Union Terrace on Lake Mendota

Disclosure of Potential Conflicts of Interest



I am the Co-founder, Chief Innovation Officer and Chairman of the Board and have financial interest in Leo Cancer Care which is developing an upright radiotherapy system. Leo has partnerships with the following companies: Tecnologie Avanzate, Hitachi, Mevion, McLaren, RaySearch, Nelco, CQ, Neutron Therapeutics, Aviko, Theryq, Tibaray, and Cosylab.



COSYLAB

I am a Board Member and have financial renumeration by Cosylab which provides and maintains control software to science laboratories and particle therapy equipment manufacturers worldwide.

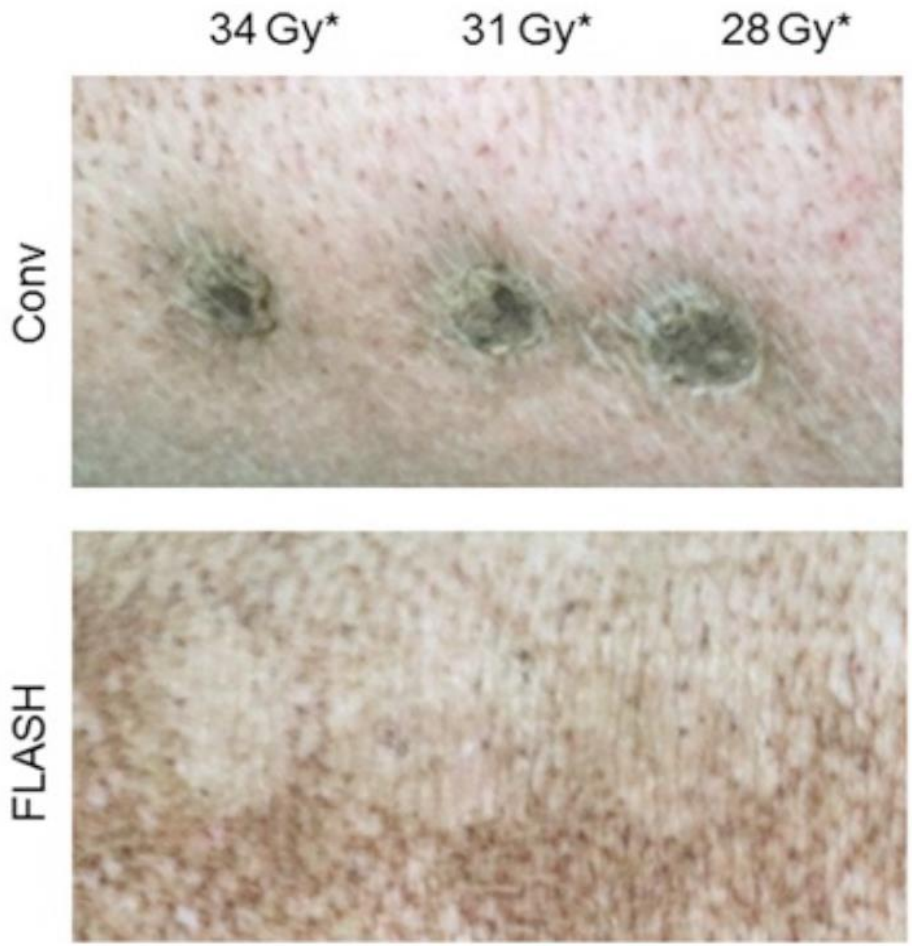
Issues That Need Addressing

- **Novel detectors for radiation oncology stem from the need for fast, image-guided, and dosimetric treatment verification to answer:**
  - **Is the patient set up in the right position?**
  - **Is the beam delivery accurate?**
  - **Given breathing and organ motion, is the tumor in the treatment field?**

- **Extremely high-dose, short delivery radiotherapy called FLASH challenges dosimetry systems:**
  - **Dose rates > 40 Gy/s and doses higher than 10 Gy per session:**
  - **Ionometry systems under-respond**
  - **Optical detection systems saturate**

FLASH Radiotherapy

- **Conventional radiotherapy > few Gy/min in multiple sessions of several minutes.**
- **FLASH mode must deliver greater than 10 Gy at an ultrahigh dose rate (> 40 Gy/sec).**
- **The FLASH effect delivers the same destructive effect on the tumor as conventional radiotherapy, while sparing normal tissue.**
- **Even if the FLASH effect turns out to be less promising, being able to deliver radiation faster solves positioning and motion issues.**
- **Need very high-speed detection systems.**



Thirty-six weeks postradiotherapy, macroscopic visualization showed severe fibronecrotic lesions in Conv-irradiated spots and the normal appearance of the skin in FLASH-irradiated spots.

Courtesy: Charlotte Robert, Gustave Roussy Cancer Campus, Paris

FLASH Radiotherapy Delivery Systems That Exist Today



IntraOp Mobitron
Low Energy
Electron Beam

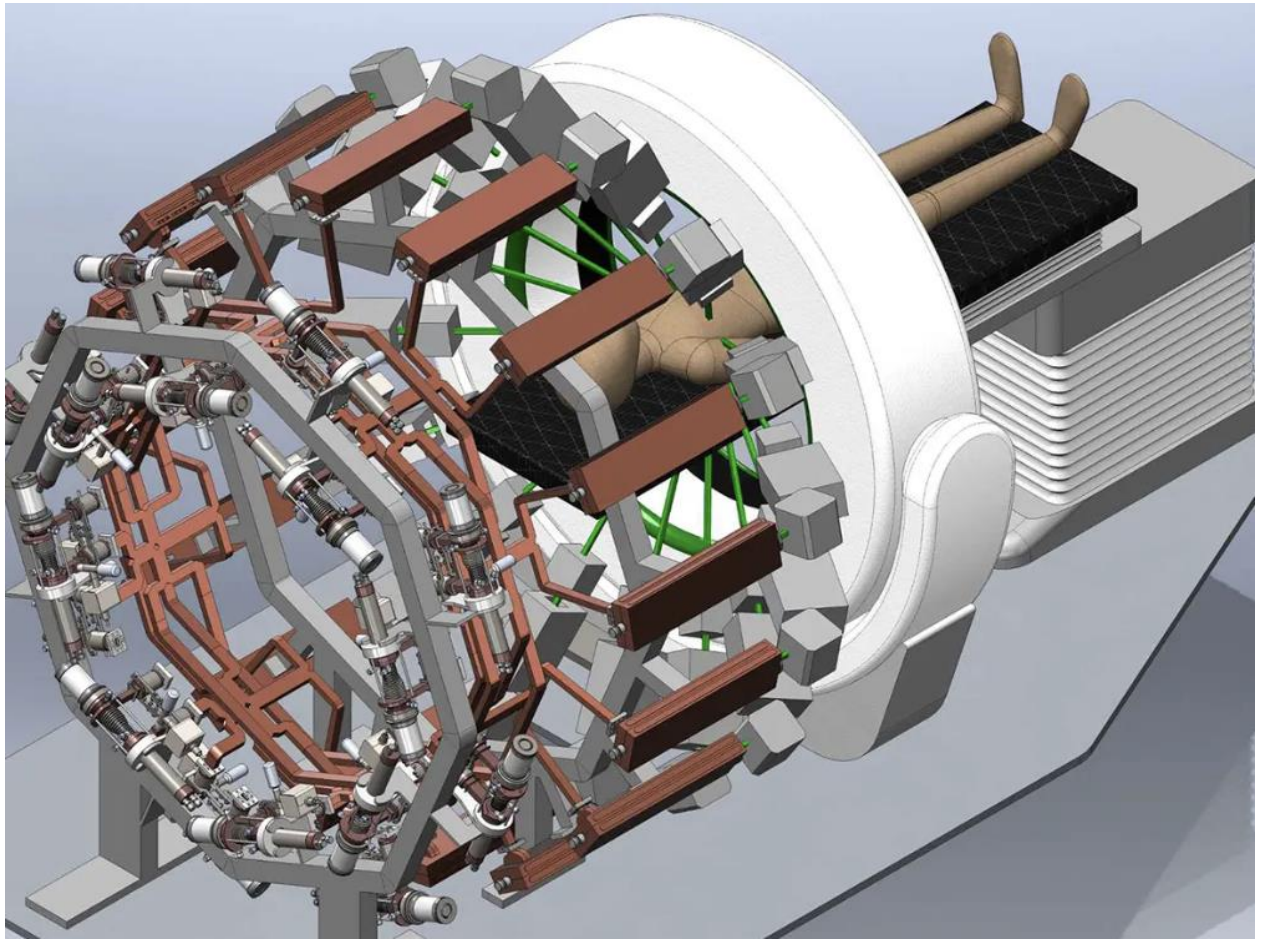


Theryq FLASHKNIFE
Low Energy
Electron Beam

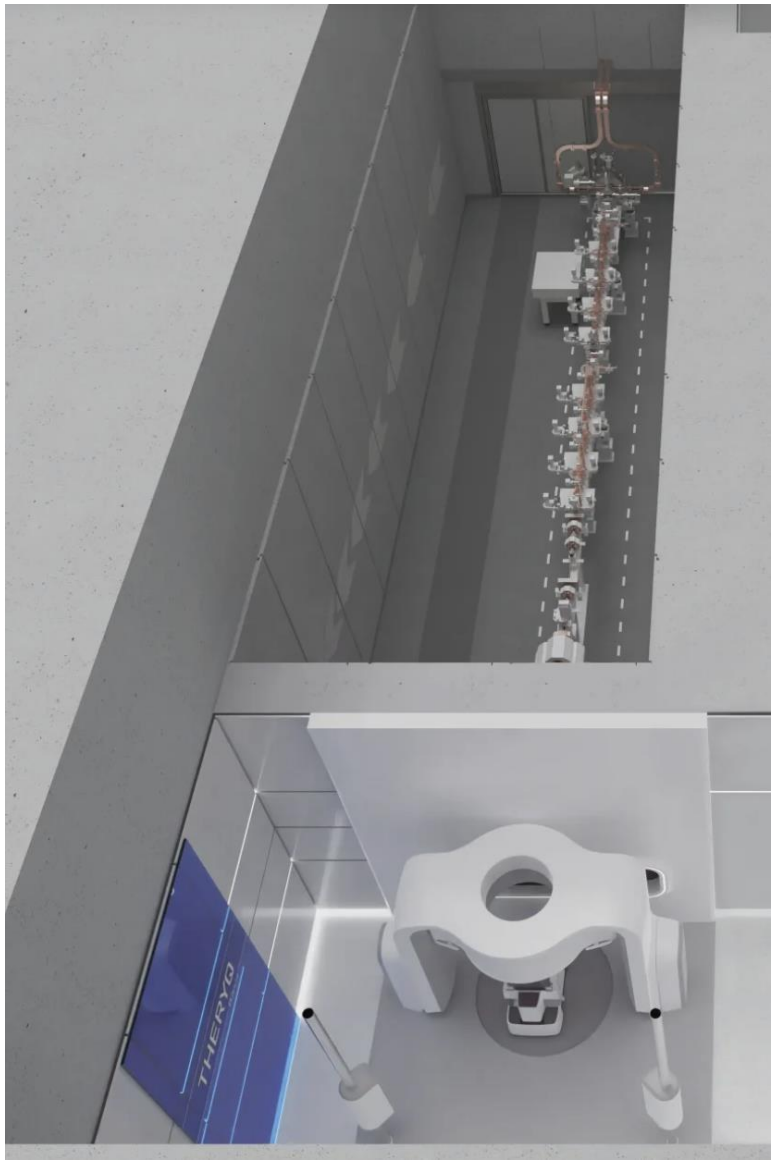


Proton Beams
Here Showing
IBA Proteus Plus

Future FLASH Delivery Systems

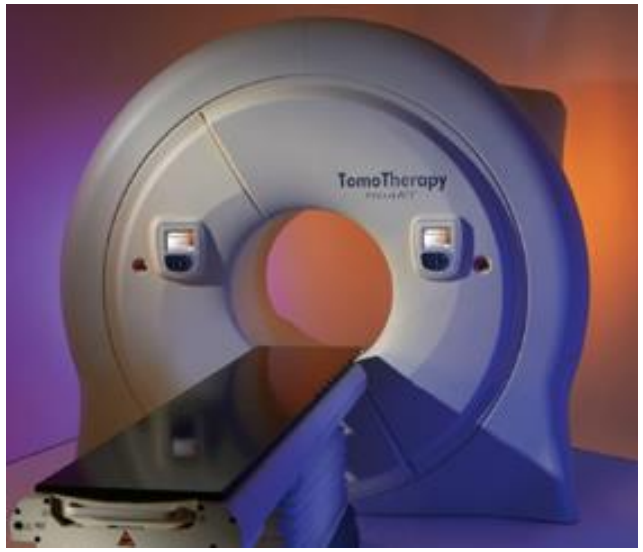


TibaRay Multi-Beam Photon System

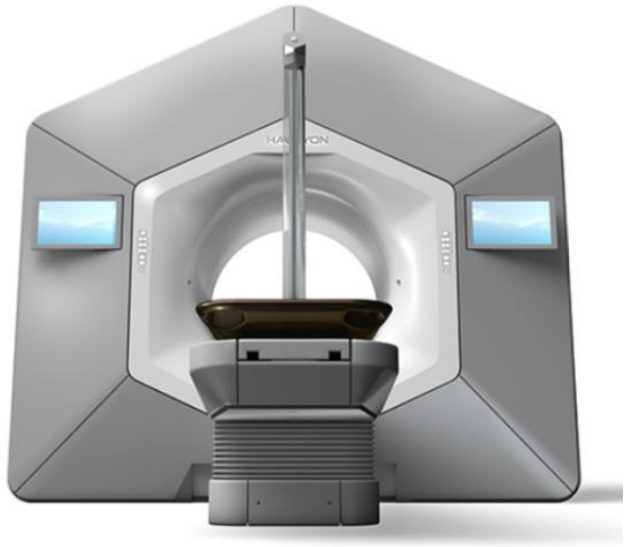


Theryq High Energy Electron Beam

Radiotherapy Equipment Designed for Image-Guidance



TomoTherapy HiArt (MVCT)



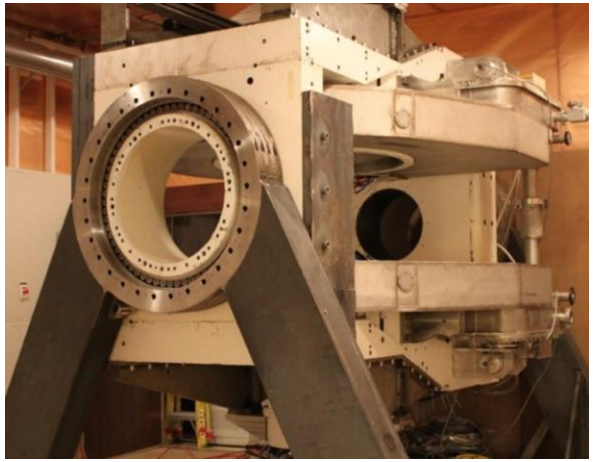
Varian Halcyon (CBCT)



Elekta Harmony (CBCT)



Elekta Unity (MRI)



MagnetTx Aurora-RT (MRI)



Reflexion SCINTIX (PET)

Cherenkov Light Detects Photon Beam's Entrance onto the Patient's Surface in Real-Time

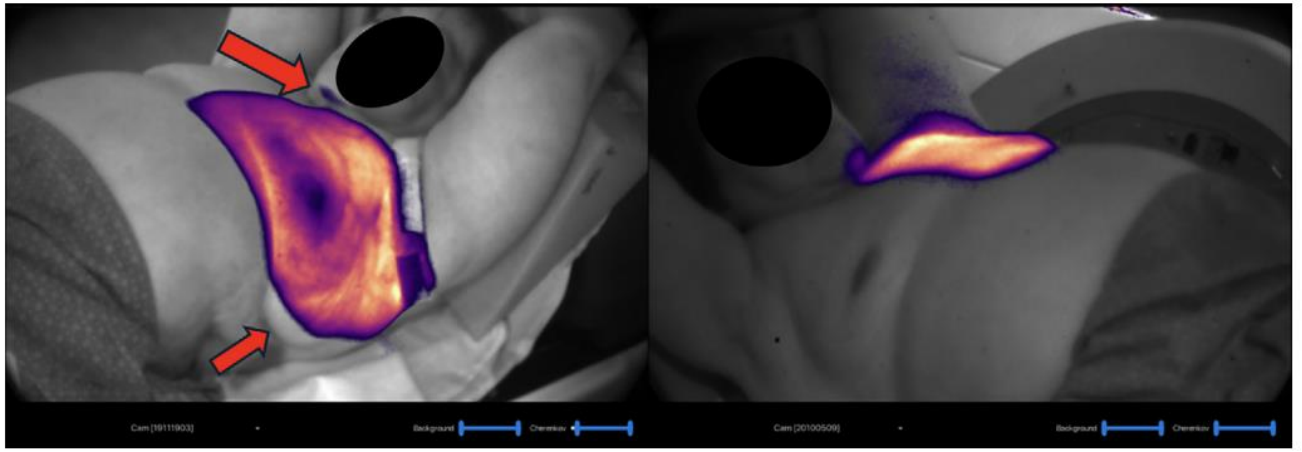


Figure 7 Cumulative Cherenkov image of left breast treatment. Images were captured on a Varian TrueBeam. Top arrow shows unwanted dose to the chin and bottom arrow shows underdosed region in the breast.

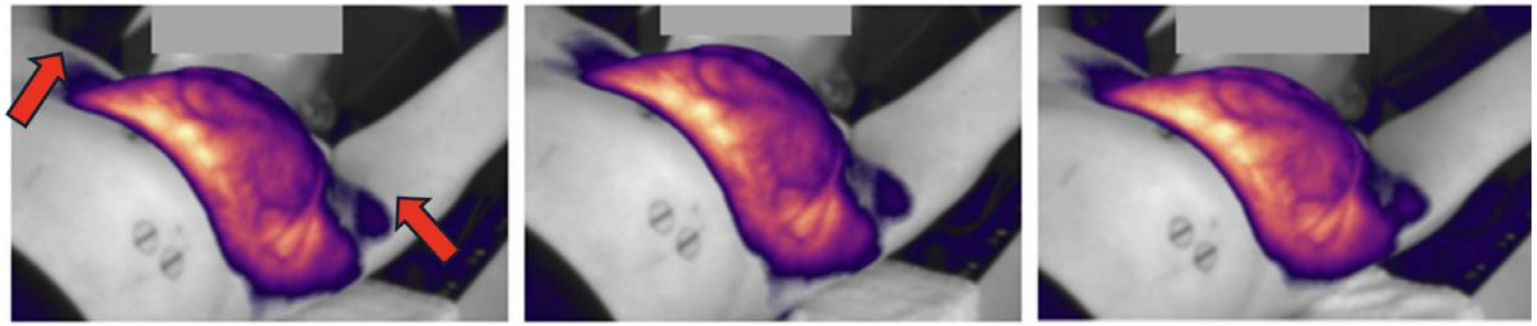


Figure 8 Cumulative Cherenkov image of deep inspiration breath-hold with volumetric modulated arc therapy treatment of the left breast. Images were captured on an Elekta Versa HD. Arrows show low intensity dose to the internal mammary lymph nodes and axilla.

Adi Robinson, * Michael Tallhamer, and Florian Stieler. A Review of Cherenkov Imaging for Real-Time Verification in Radiation Therapy Practical Radiation Oncology: March/April 2026 Volume 16, Issue 2E, 139-E154

Cherenkov Dosimetry for Beam QA

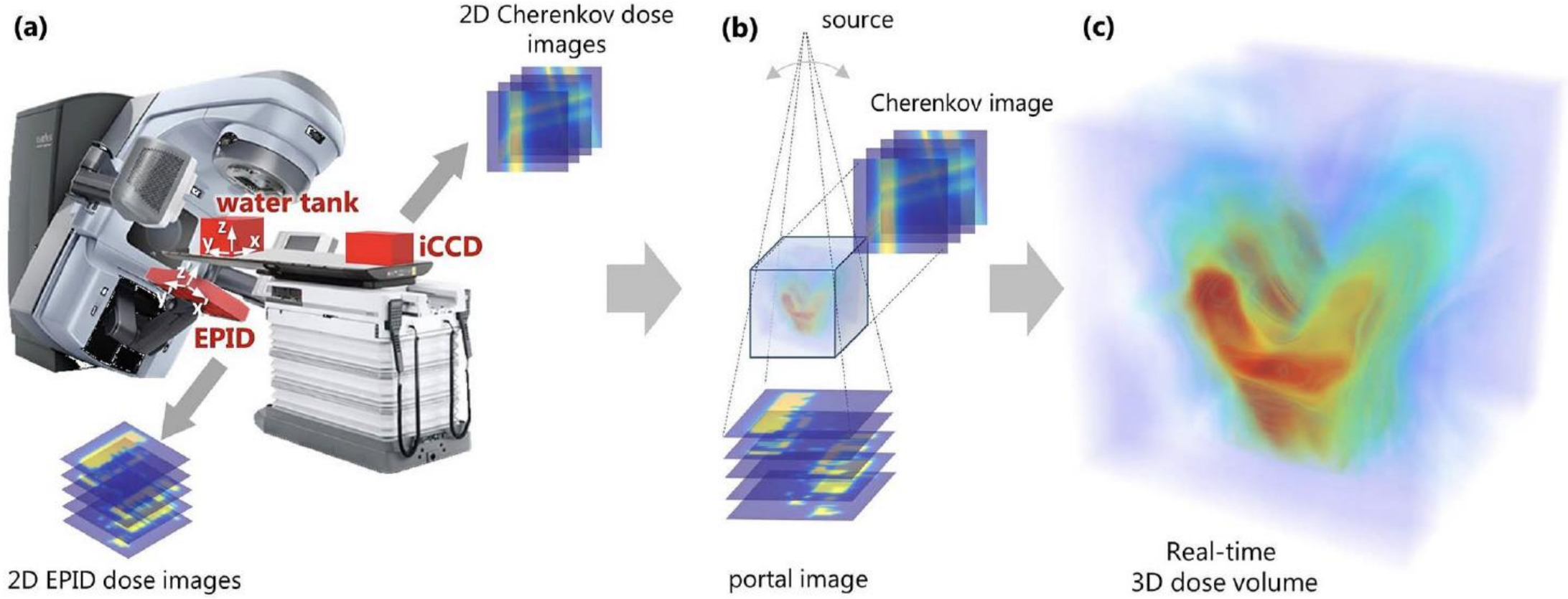


Fig. 1. a) Schematic experimental setup for the EPID-Cherenkov 3D dosimetry; b) illustration of the portal and Cherenkov imaging geometry; c) measured 3D cumulative dose map produced by a custom TG-119 C-Shape VMAT plan (6MV, 200 cGy) X-ray beam in a water phantom. The coordinate system of the water tank is (x,y,z). The coordinate system of the X-ray beam is (x', y', z'), where axis z' is coincident with the beam axis.

Bruza P, et al., Online Combination of EPID & Cherenkov Imaging for 3-D Dosimetry in a Liquid Phantom. IEEE Transactions On Medical Imaging, Vol. 36, No. 10, October 2017

Scintillation Dosimeters Can Detect 1-D, 2-D and 3-D Dose Distributions

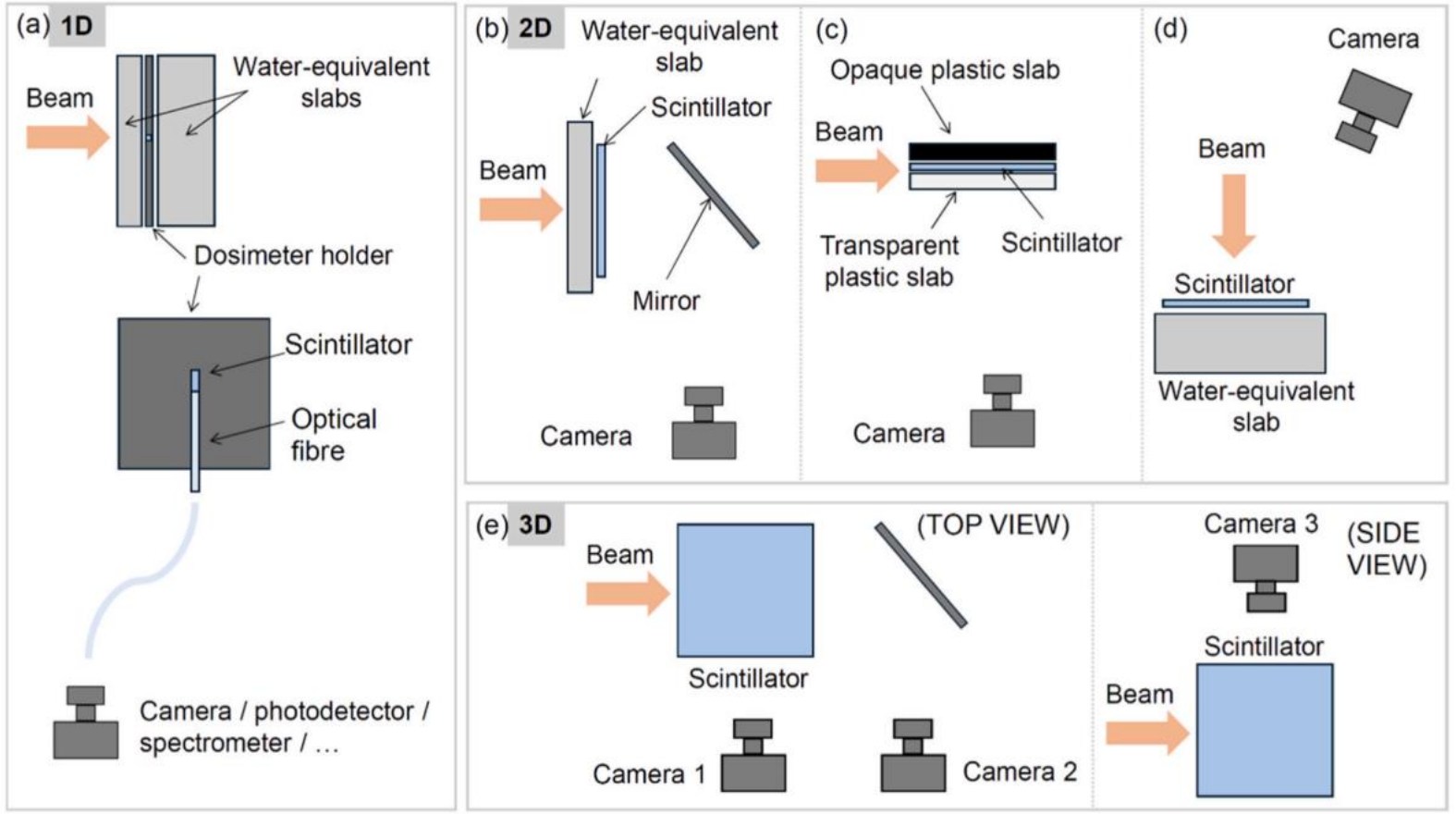


Fig. 2. Configurations for tests of point scintillation detectors (a), 2D detectors (b–d), and 3D detectors (e).

Esther Ciarrocchi Ivan Veronese. Scintillation dosimetry for FLASH radiotherapy. Radiation Measurements 193 (2026) 107625

Cherenkov Light Confounds Interpretation of Scintillation Signal

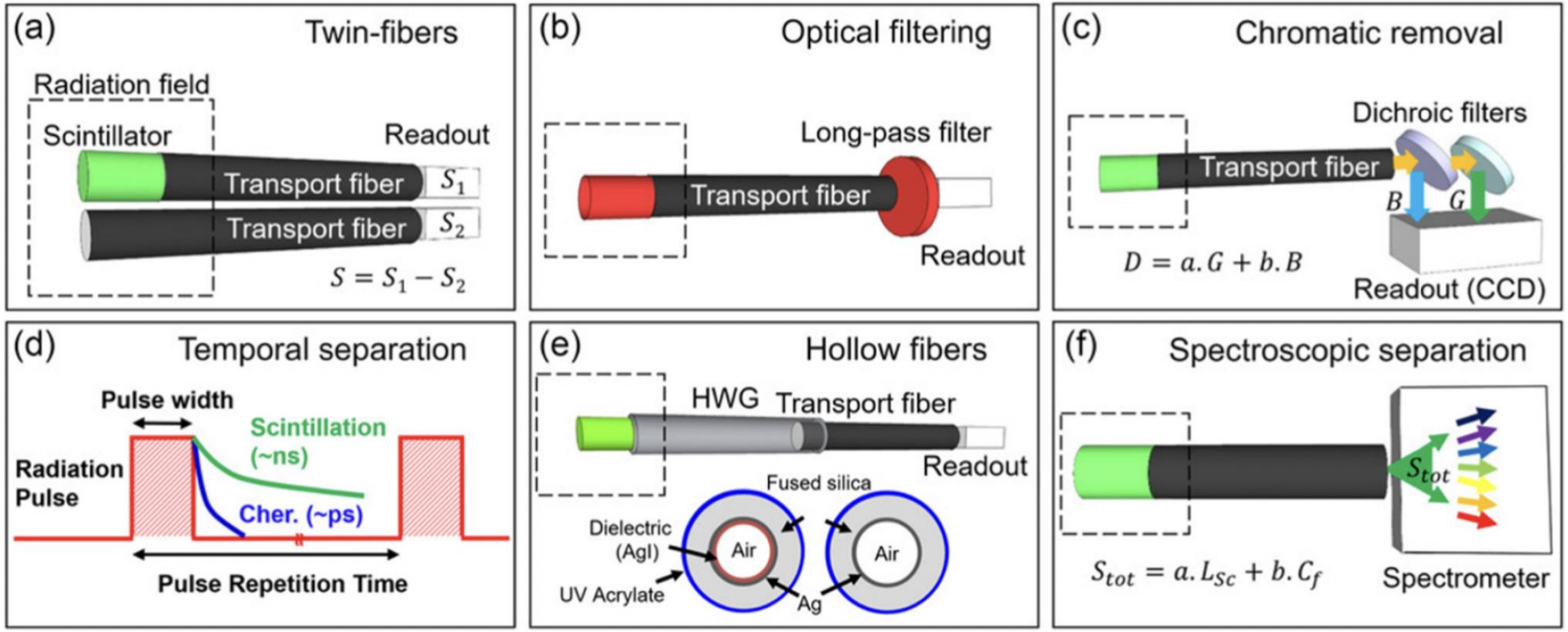
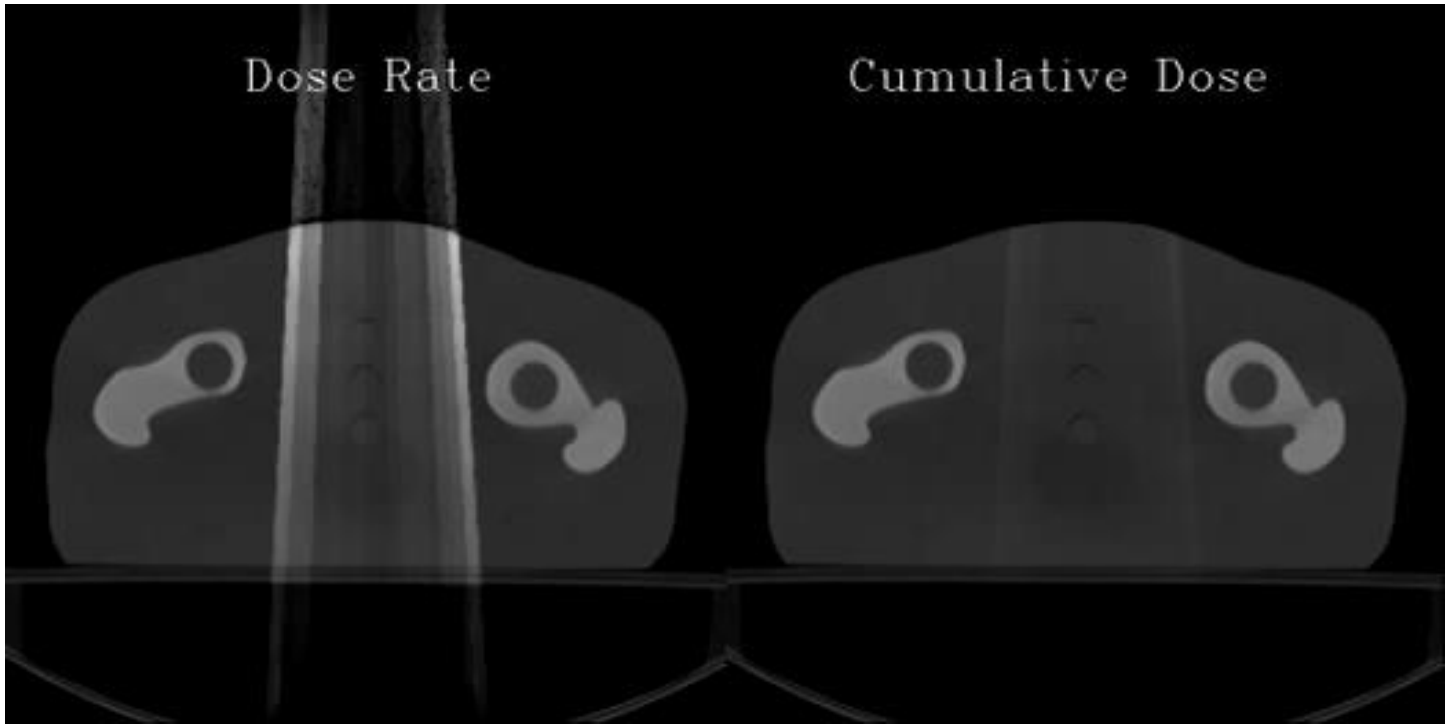


Fig. 3. Methods for Cerenkov contribution mitigation or correction: a) double-fibre method, b) optical filtering, c) chromatic removal, d) temporal separation, e) hollow fibres, f) spectroscopic separation (reproduced from Darafsheh et al. (2024), licensed under CC BY).

2-D or 3-D Scintillation Dosimetry



Treatment Plan of a Rotational Intensity Modulated Tomotherapy Beam

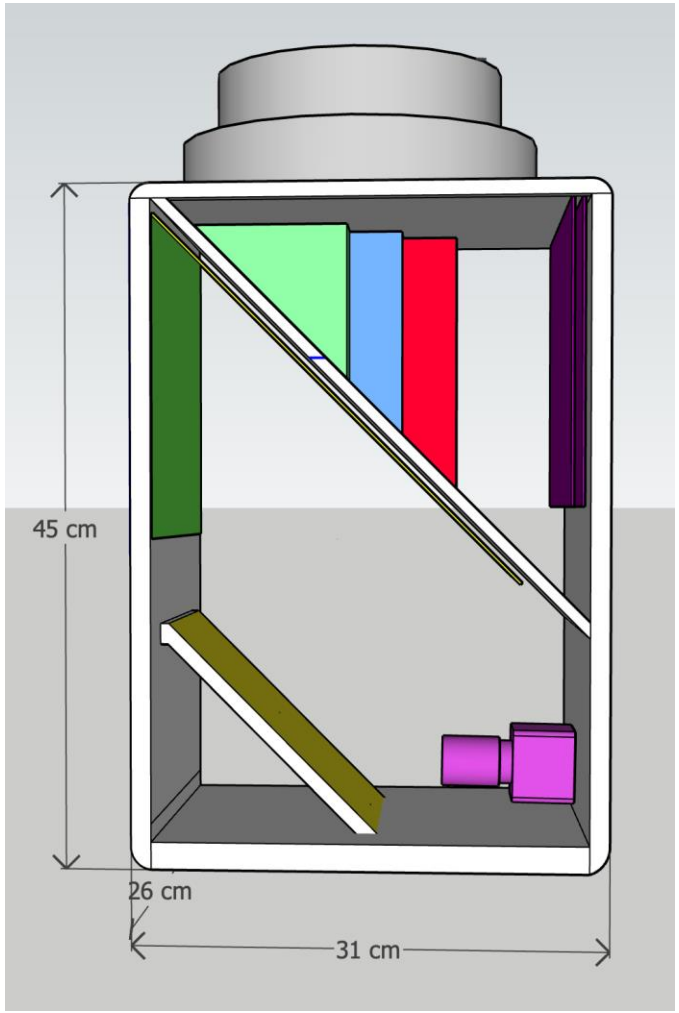


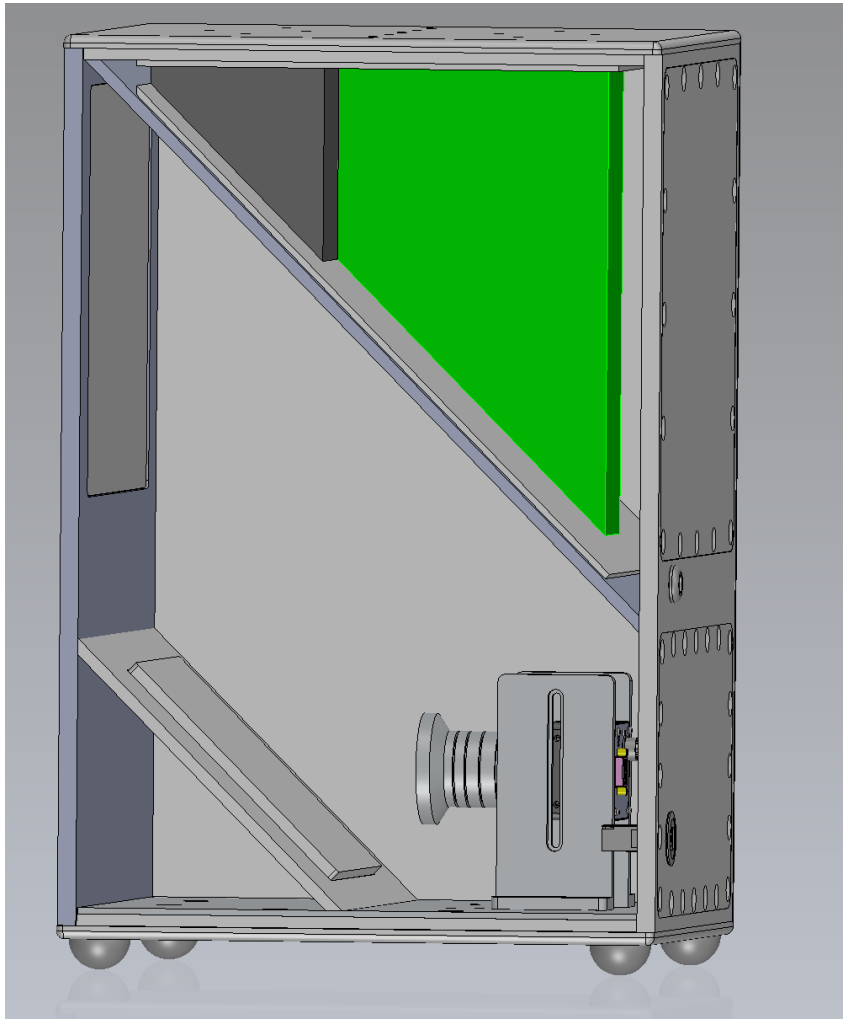


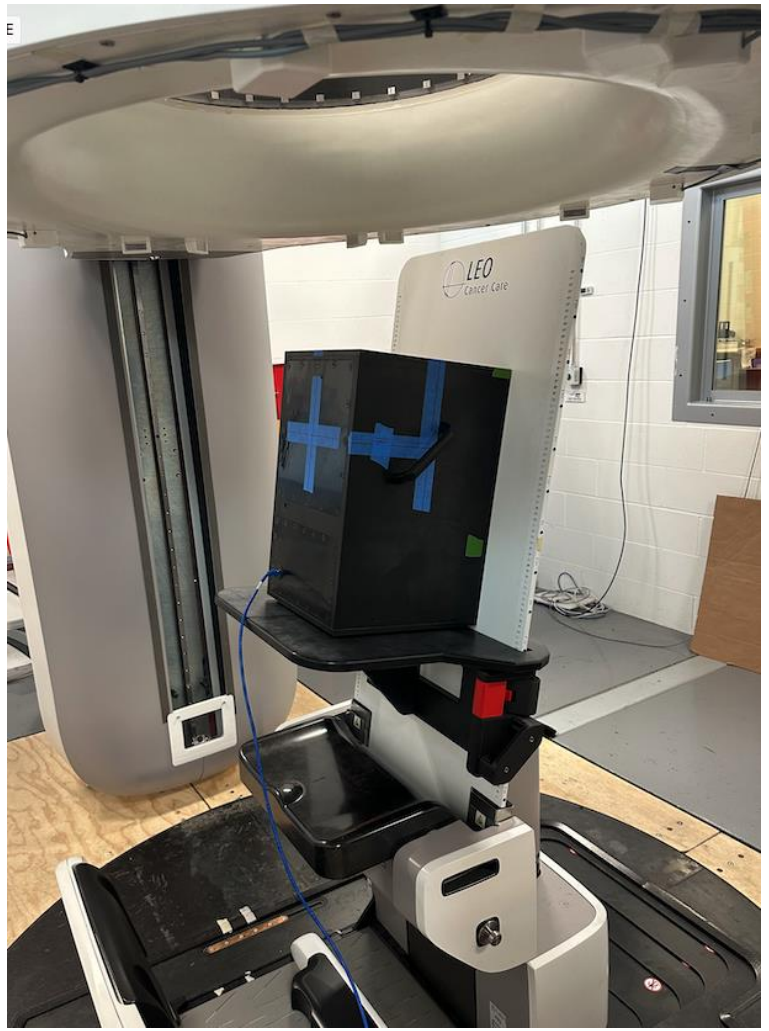
Delivering the Treatment to a Fishbowl Filled with Transparent Scintillation Fluid

Unique Multipurpose Scintillation QA System

Concept → **Designed + Manufactured** → **CT Scanned + Tested**

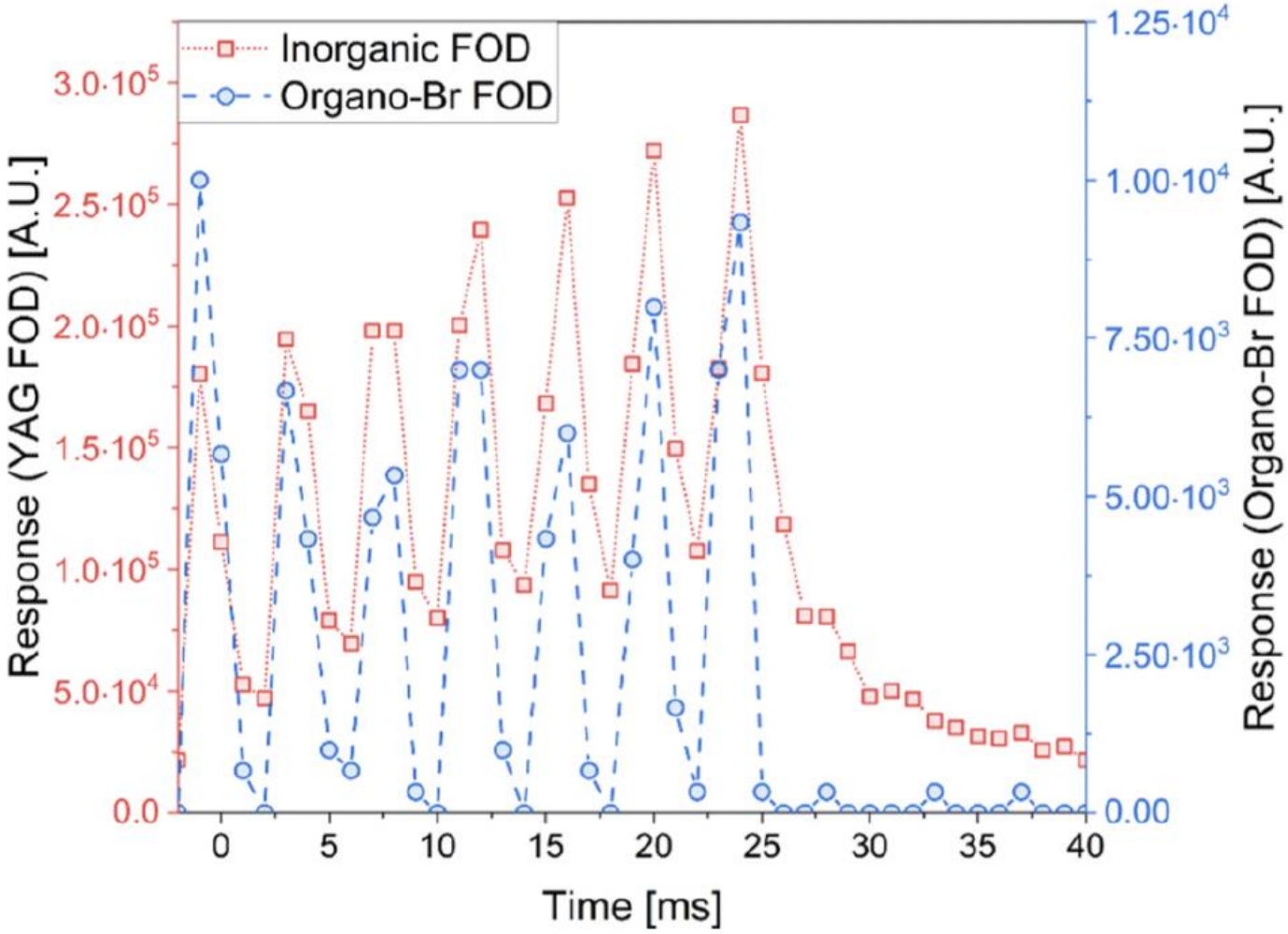






Courtesy: Solvis, Knoxville TN and Leo Cancer Care, Madison WI

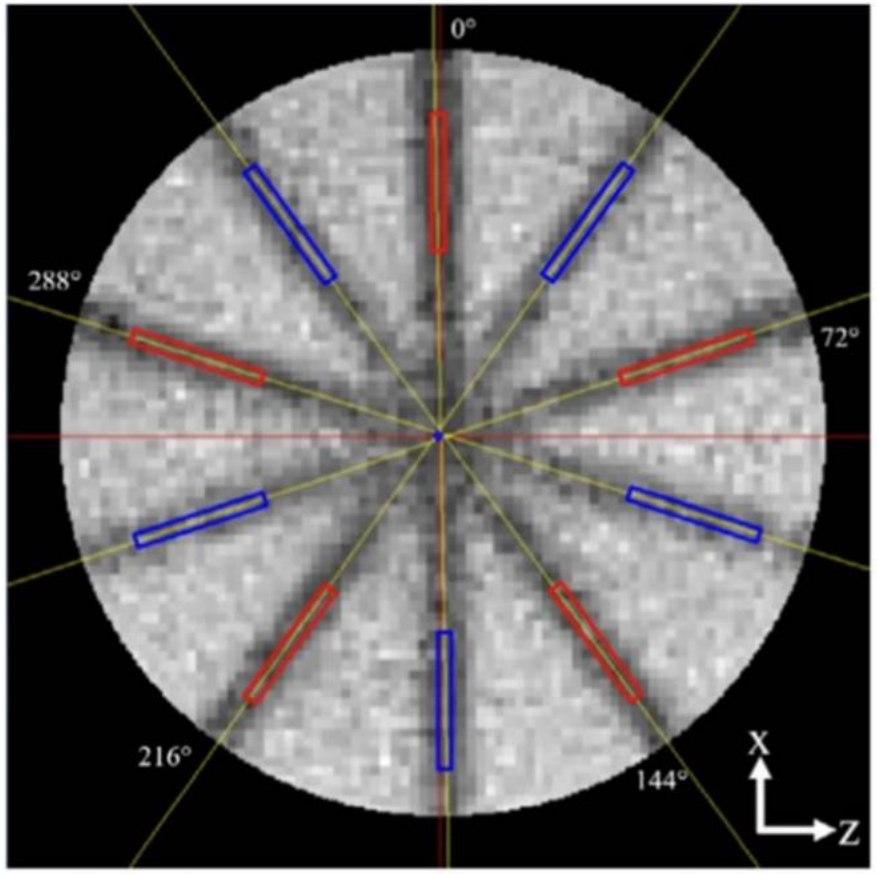
Scintillation Materials Have Wide Variations in Response Times



Esther Ciarrocchi Ivan Veronese. Scintillation dosimetry for FLASH radiotherapy. Radiation Measurements 193 (2026) 107625

MRI-Guided Systems Have Unique Challenges with Conventional Dosimetry

The Electron Return Effect: The magnetic field causing electrons to move in curved or circular paths rather than straight lines.
Altered Dose Distribution: Traditional reference dosimetry conditions can no longer be met using standard protocols.
Detector Response Perturbations: Standard ionization chambers and diodes change their response inside strong magnetic fields.
Lack of Electron Density Information (Synthetic CT): MRI does not map electron density directly like CT scans do.
Spatial Distortions: Geometric distortions inherent to MRI scanners can misalign the planned dose contours



Radiation Cross-linking Stiffens Polymer Gels Which Can Be Detected By MRI Scanners

Dorsch S, Mann P, Lang C, Häring P, Runz A and Karger C P 2018 Feasibility of polymer gel-based measurements of radiation isocenter accuracy in magnetic fields Phys. Med. Biol. 63 11NT02–1NT02

MRI-Readout of Gel Dosimetry

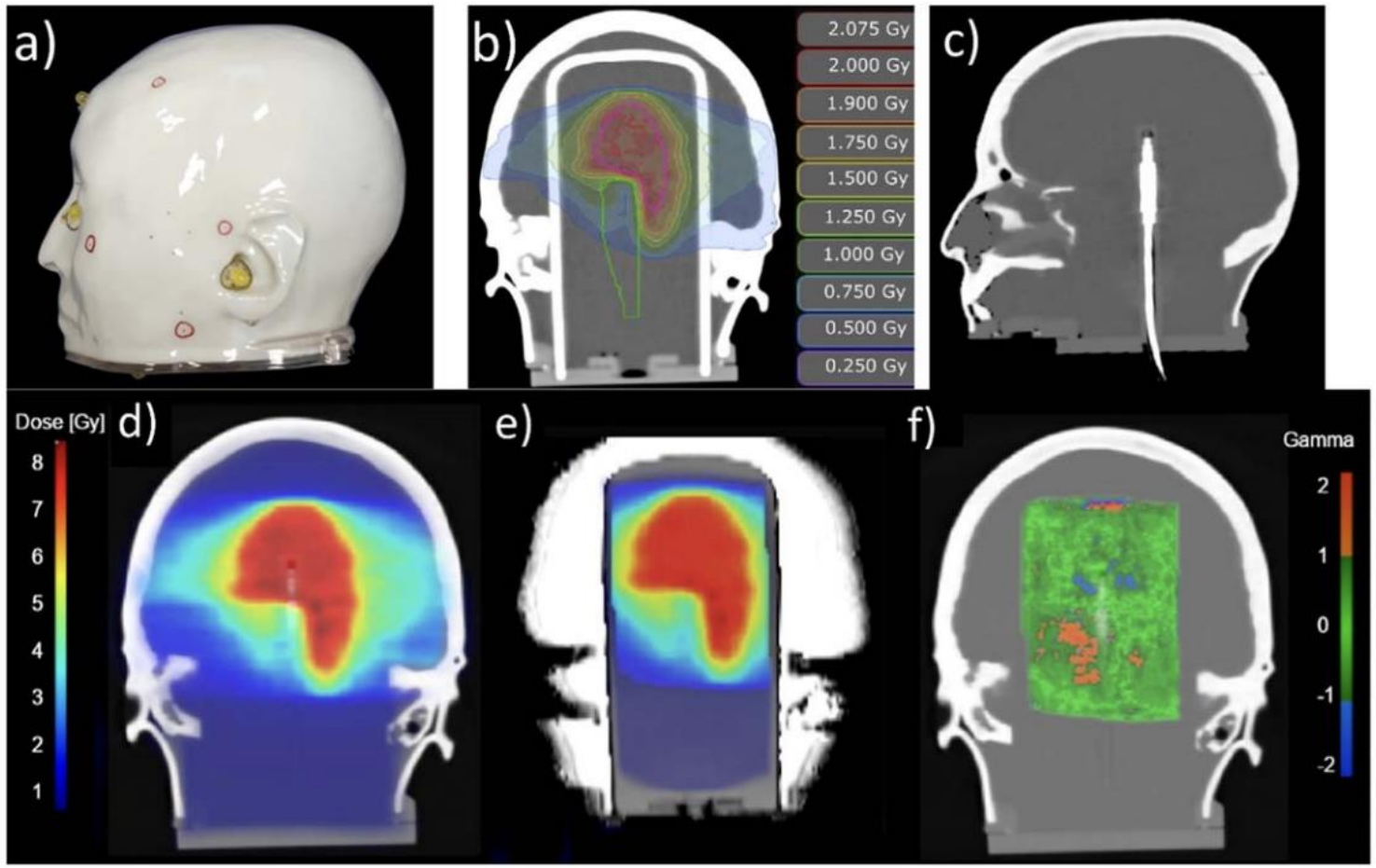
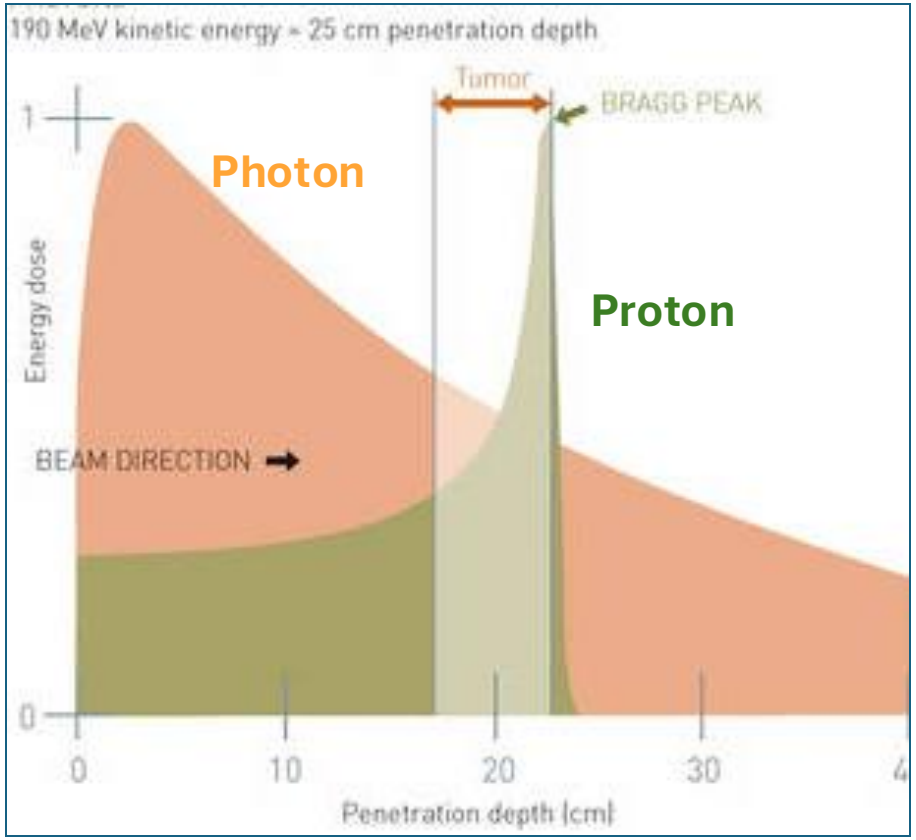


Figure 9. Anthropomorphic head phantom (a) equipped either with a PG container to measure the 3D dose distribution of a C-shaped PTV enclosing the brain stem as OAR (b), or with an ionization chamber for the dose response calibration of the PG (c). Comparison of planned (d) and PG measured (e) dose distributions results in a gamma map (f) with passing rates of 94.2% (3%/3 mm) and 83.0% (2%/2 mm). When the median R2-signal in the PG was instead normalized to the median planned dose (i.e. considering a relative dose measurement), the passing rates were 97.6% and 90.5%, respectively (reprinted from Nierer *et al* (2022) with permission of Elsevier under the CC BY-NC-ND License (http://creativecommons.org/licenses/by-nc-nd/4.0/)).

Radiation Cross-linking Stiffens Polymer Gels Which Can Be Detected By MRI Scanners

Nierer L, Kamp F, Reiner M, Corradini S, Rabe M, Dietrich O, Parodi K, Belka C, Kurz C and Landry G 2022 Evaluation of an anthropomorphic ion chamber and 3D gel dosimetry head phantom at a 0.35 T MR-linac using separate 1.5 T MR-scanners for gel readout Z. Med. Phys. 32 312–25

Particle Radiotherapy is Highly Dependent on Position of the Bragg Peak



CT Imaging and Conversion Inaccuracies

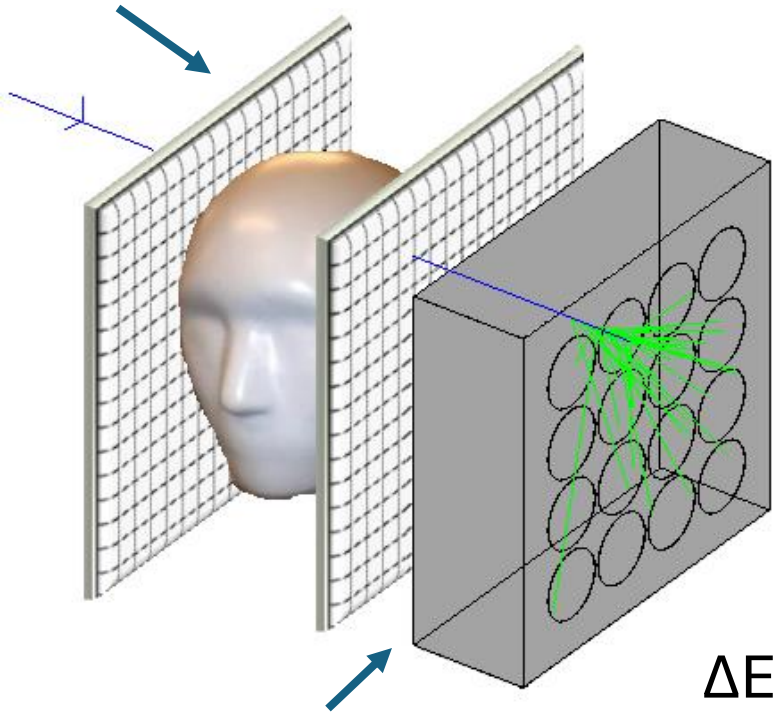
- **Stopping power:** The CT numbers (Hounsfield Units) must be mathematically converted into proton stopping powers.
- **Inherent errors:** This conversion process introduces a baseline range uncertainty of about 2% to 3.5%,

Anatomical Changes and Patient Movement

- **Internal organ motion:** Breathing, filling of the bladder or bowels, and digestive tract shifting change tissue thicknesses between daily fractions.
- **Weight loss or tumor shrinkage:** Changes in patient anatomy alter the path the proton beam travels.
- **Overshoot and undershoot:** These density shifts can cause the Bragg peak to stop short of the tumor (undershoot) or travel past it into healthy, sensitive tissue (overshoot).

Proton Radiography

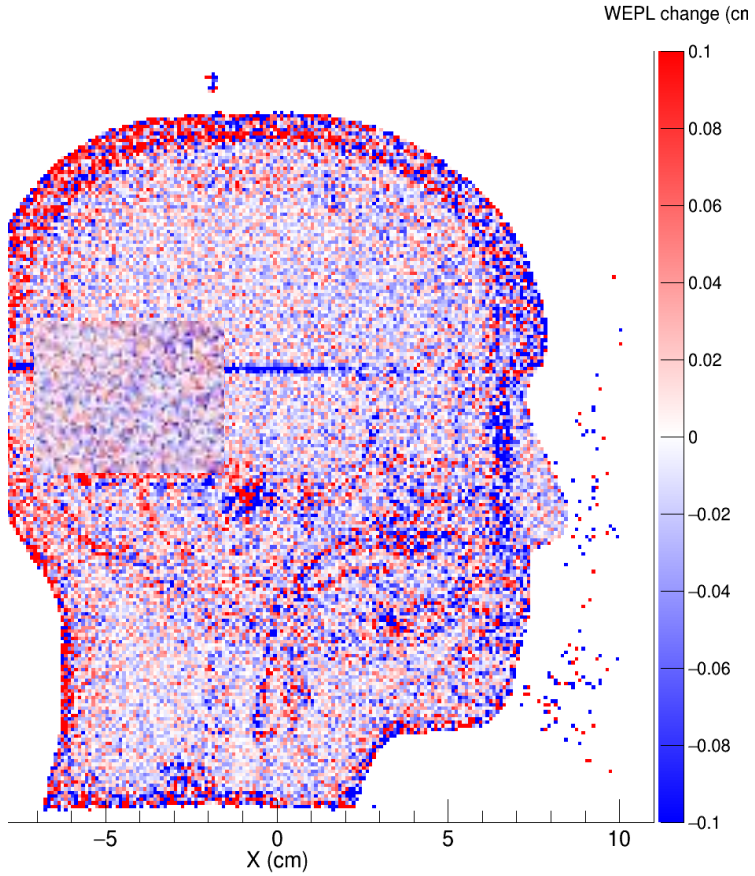
Front Position Detector



ΔE Detector

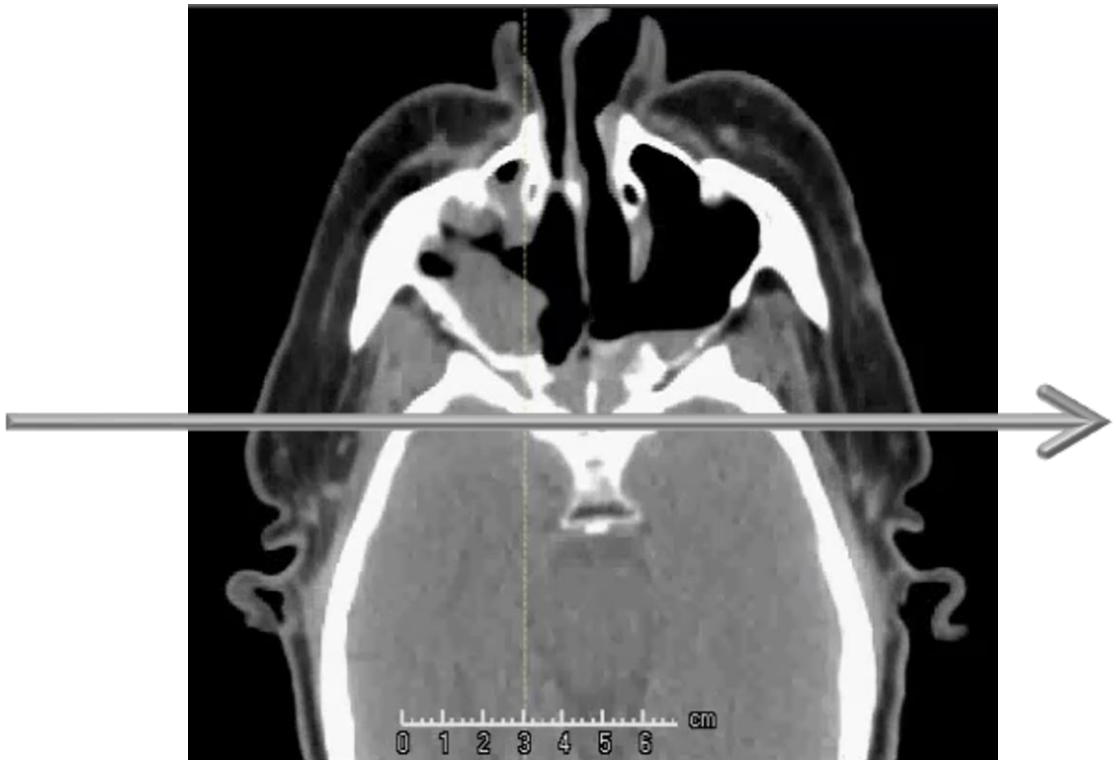
Distal Position Detector

Water Equivalent Range Difference Map



Courtesy: Fritz DeJongh, Proton VDA

Measure Water-Equivalent Thickness (WET) Through Patient

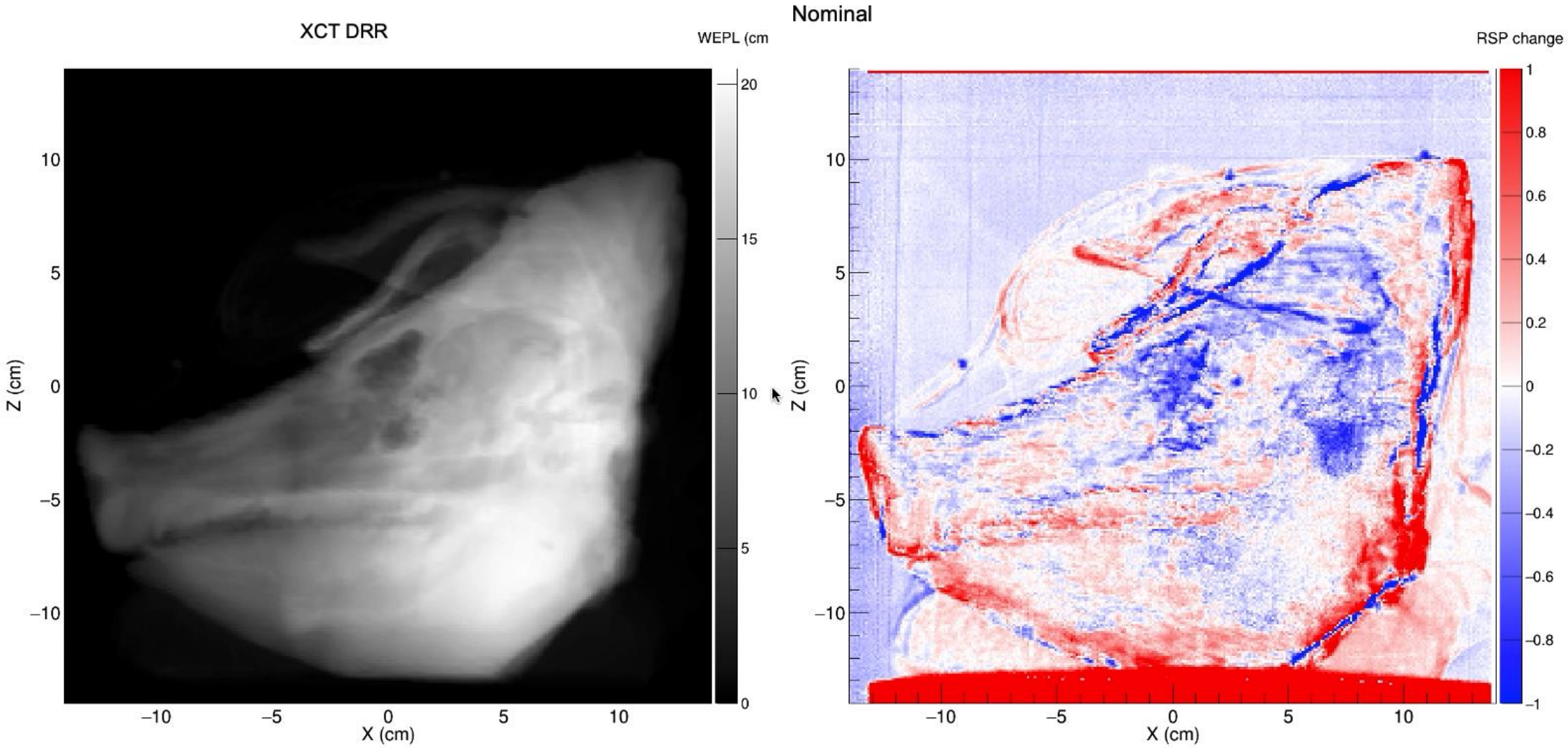




Also Calculate WET Through Patient Using X-Ray CT Hounsfield Units

Courtesy: Fritz DeJongh, Proton VDA

Alignment Sensitivity Analysis
~0.5 Degree Rotation along Beam Axis

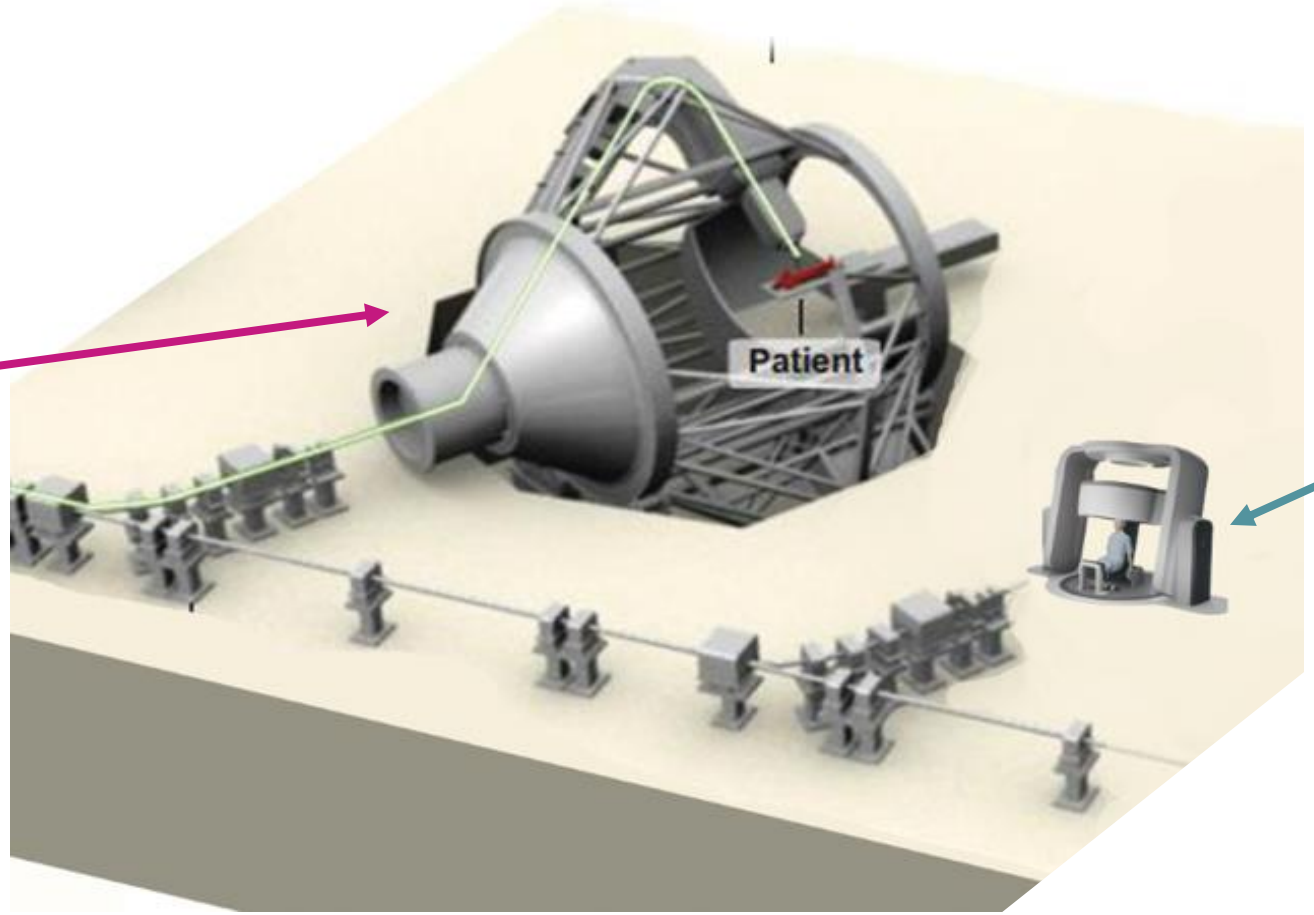


Courtesy: Fritz DeJongh, Proton VDA

Far Easier to Add Imaging Technology to a Stationary Beam

Keep Patient Still and Rotate Beam

- ❑ CBCT @ ISO
- ❑ X-rays @ ISO
- ❑ In-Room CT

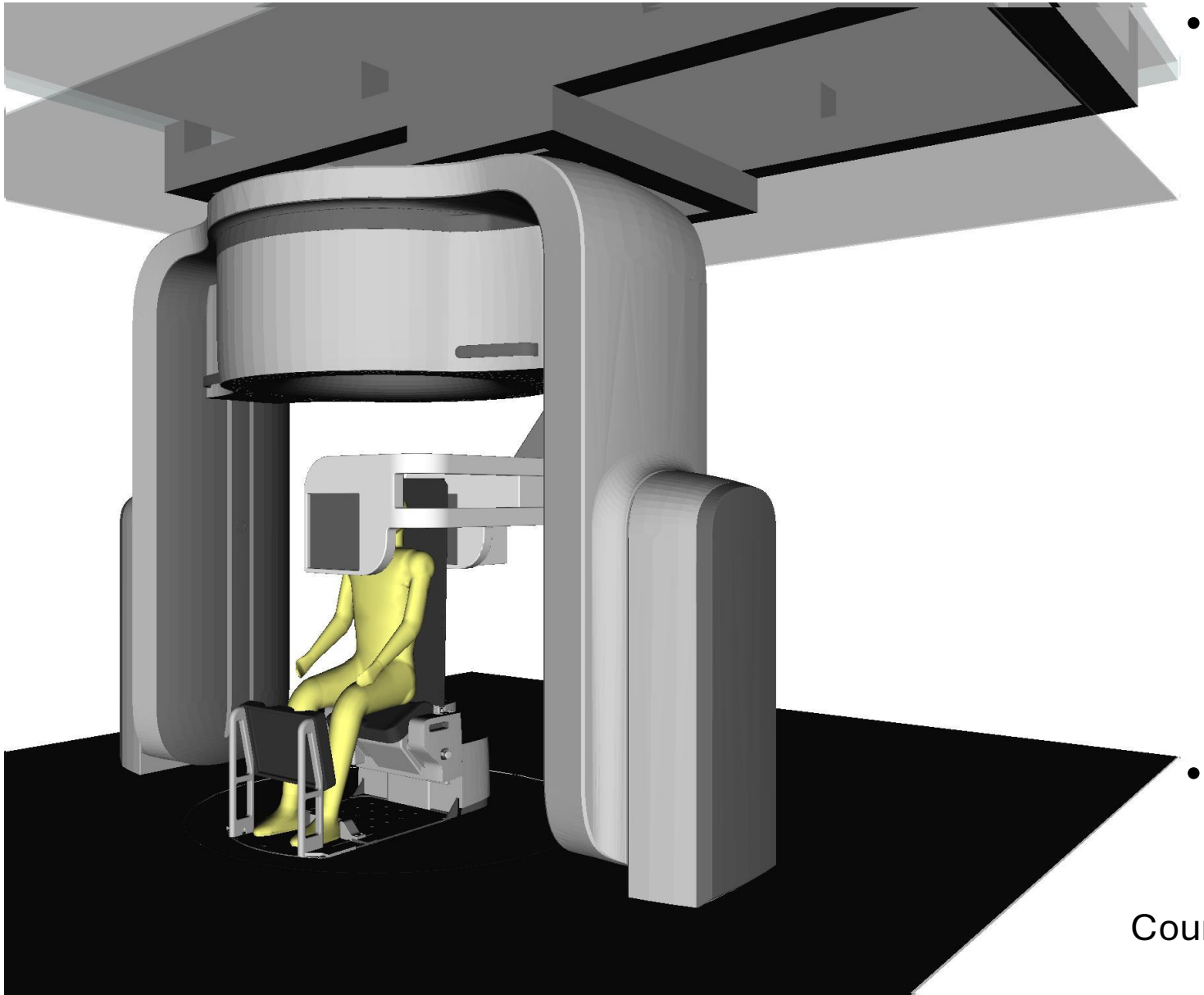


Keep Beam Still and Rotate Patient

- ❑ Fan-Beam CT
- ❑ Proton Radiography
- ❑ Prompt PET
- ❑ PET/CT
- ❑ CBCT
- ❑ Fluoro X-Rays
- ❑ Optical Guidance
- ❑ MR-Guidance

Courtesy: Leo Cancer Care, Madison WI

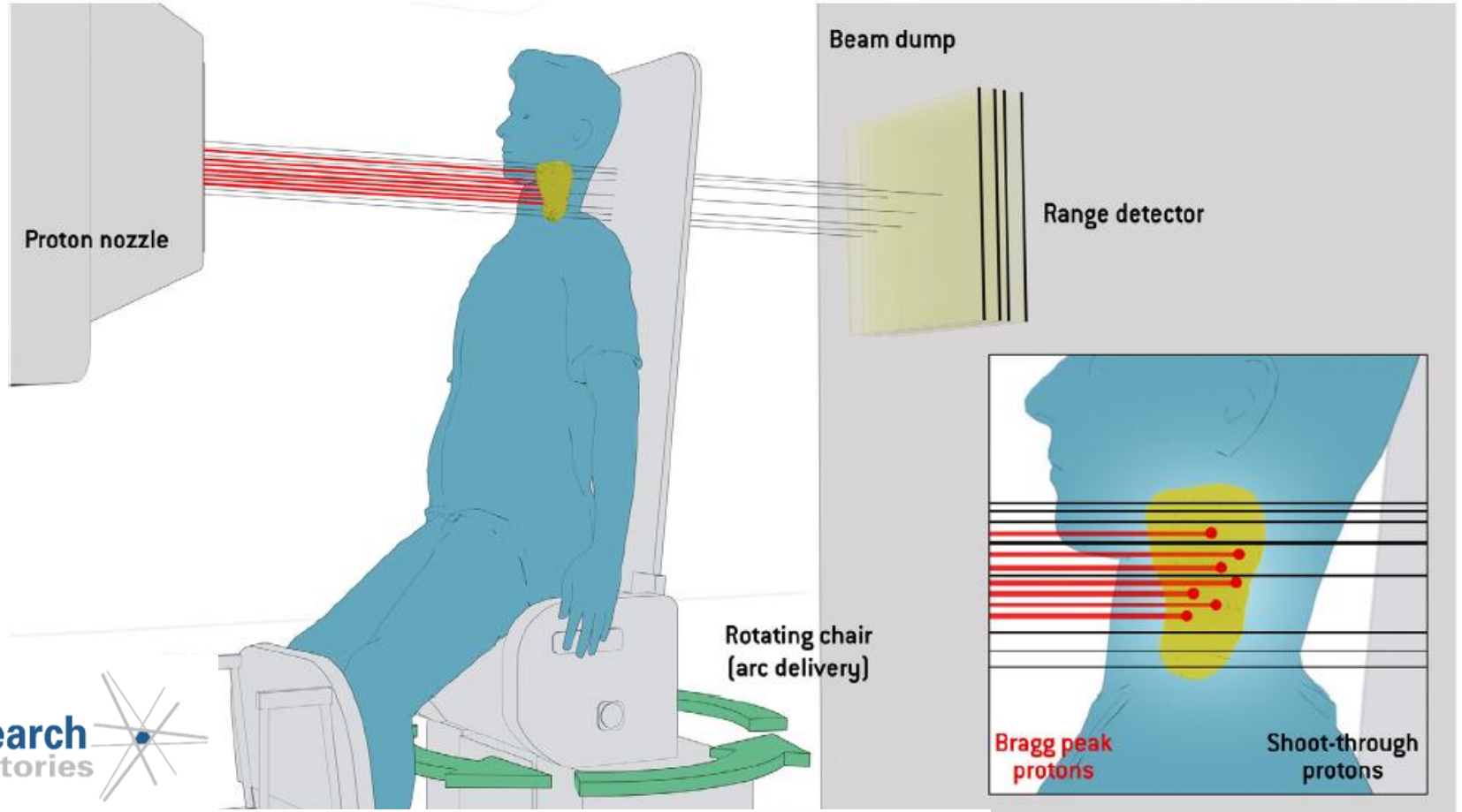
Far Easier to Add Imaging Technology to a Stationary Beam

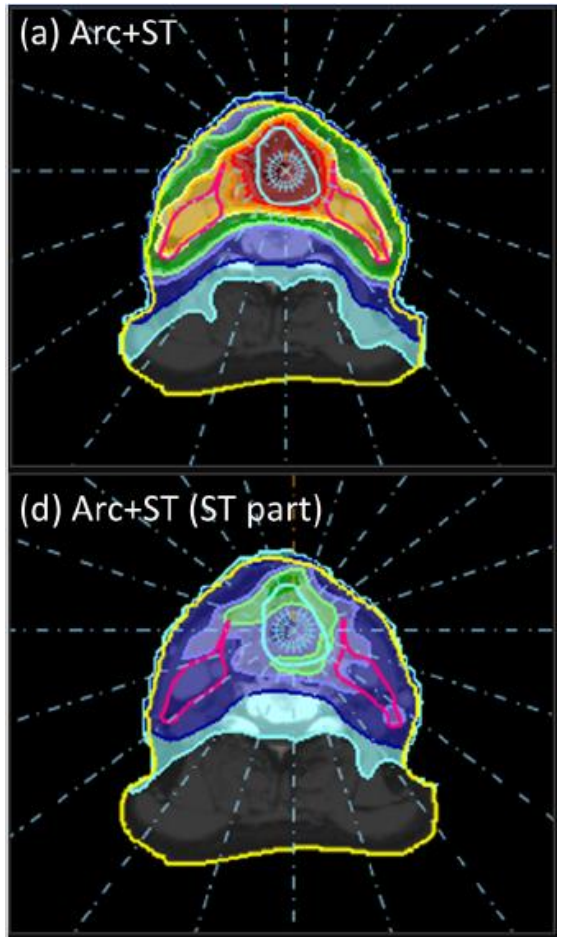


- Flexible platform for accepting imaging modalities:
  - Anatomical imaging:
    - Fan-beam CT (Setup)
    - Cone-beam CT (Real-Time)
  - Functional imaging:
    - MRI
    - PET
  - Other real-time motion detection:
    - Fluoroscopy
    - Optical Guidance
  - Dose verification (particle therapy).
- Stationary beams allow for easier independence of imaging systems.

Courtesy: Leo Cancer Care, Madison WI

Proton Rotational Therapy With Shoot-Through Protons





RaySearch Laboratories

DOI: 10.1002/mp.18051

RESEARCH ARTICLE

MEDICAL PHYSICS

Shoot-through layers in upright proton arcs unlock advantages in plan quality and range verification

Erik Engwall | Victor Mikhalev | Johan Sundström | Otte Marthin | Viktor Wase

- Improve plan quality
- Reduce delivery time
- Enabling range verification

Take Away Thoughts

- Novel detectors required fast, image-guided, and dosimetric radiotherapy treatment verification.
- FLASH is extremely high-dose and dose rate delivery.
- Cherenkov detection detects the entrance dose in photon and electron beam radiotherapy.
- Scintillation dosimeters capable of detecting dose with high spatial and temporal resolution.
- MRI systems in MR-guided radiotherapy systems can detect polymer cross-linking.
- Proton radiography uses particle transmission counting and residual energy to form an image.
- Shoot-through protons enable imaging, higher gradient dose distributions and real-time range verification.
- Radiotherapy is rapidly evolving and dosimetry systems need further development, commissioning and calibration for precision quality assurance.
- Easier to add image-guidance and dosimetry QA to stationary beam systems where the patient rotates instead of rotating the beam.