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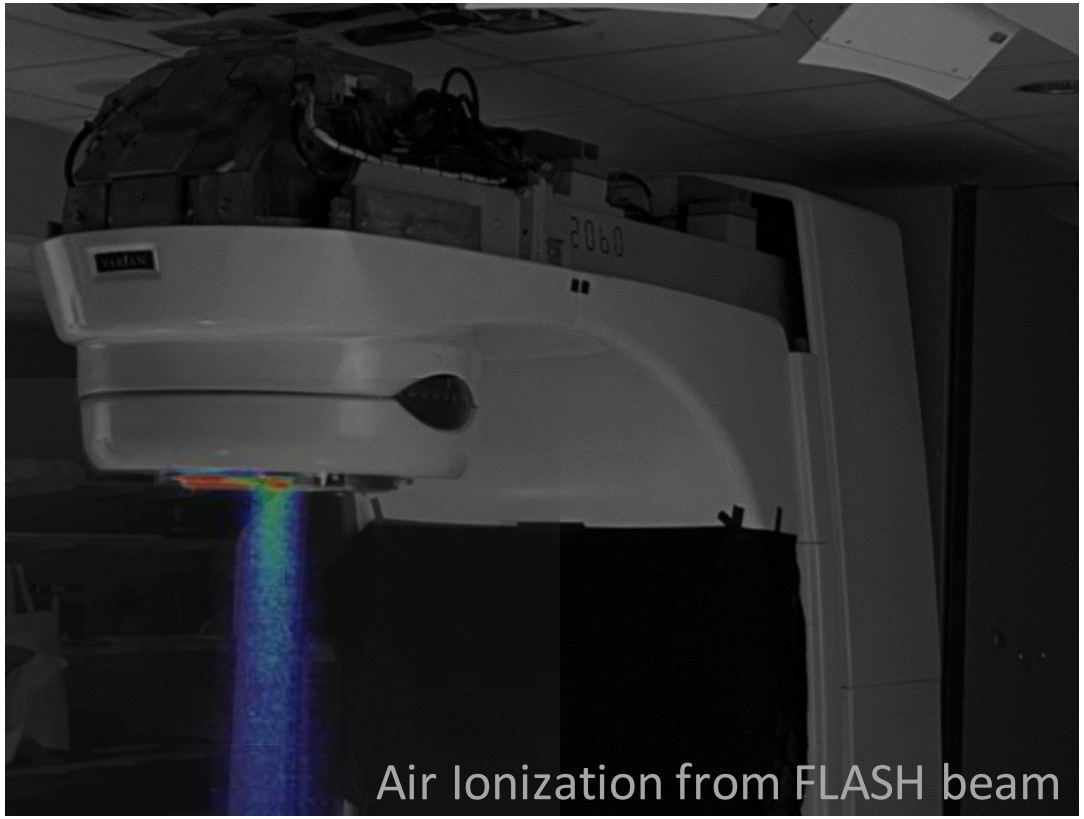
Electron FLASH in Clinical Setting: LINAC Conversion, Commissioning and Treatment Planning



Mahbubur Rahman[1*], M. Ramish Ashraf[1], David J. Gladstone[1,2,3], Petr Bruza[1], Lesley A. Jarvis[2,3], Philip E. Schaner[2,3], Xu Cao[1], Brian W. Pogue[1,3,4], P. Jack Hoopes[1,2,3,4], Rongxiao Zhang[1,2,3*]

[1] Thayer School of Engineering

[2] Department of Medicine, Radiation Oncology, Geisel School of Medicine

[3] Dartmouth-Hitchcock Medical Center

[4] Department of Surgery, Geisel School of Medicine

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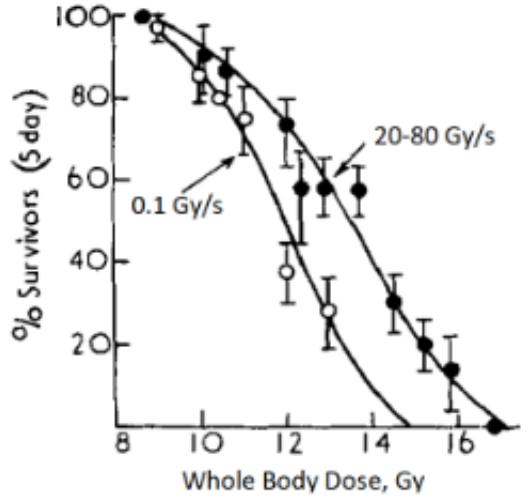
Motivation: FLASH RT Reduces Normal Tissue Toxicity

Mice after Whole Body Irradiation

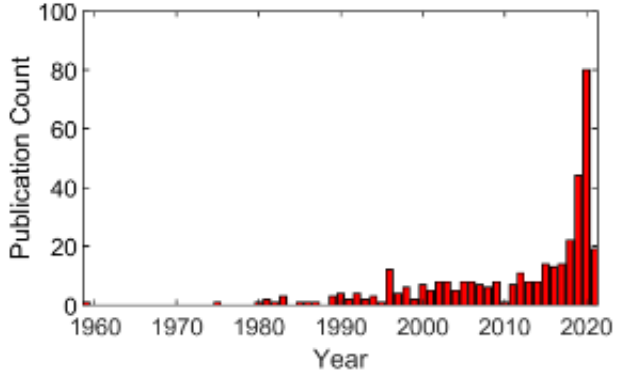


Hornsey S, Bewley DK. *IJRBRSPCM*. 1971.

Human Cutaneous Lymphoma

Bourhis J et al. *Radioth. Oncol.* 2019.

Favaudon V. et al. *Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumor tissue in mice*. **Science Trans. Med.** 2014.



Feline Nasal Carcinoma

Vozenin M-C et al. *Clin. Cancer Res.* 2019.

Prior LINAC Conversion for UHDR Delivery

High dose-per-pulse electron beam dosimetry: Commissioning of the Oriatron eRT6 prototype linear accelerator for preclinical use

Problem: There is a lack of availability to UHDR delivery systems with a FLASH-enabled treatment planning system (TPS) with minimally modified clinical settings

Experimental Platform for Ultra-high Dose Rate FLASH Irradiation of Small Animals Using a Clinical Linear Accelerator

Emil Schüler, PhD * Stefania Trovati, PhD * Gregory King, PhD *

Purpose: Develop a widely accessible and adoptable method of FLASH radiotherapy incorporating treatment planning.

Modifying a clinical linear accelerator for delivery of ultra high dose rate irradiation

Michael Lempart [a], Börje Blad [a], Gabriel Adrian [b], Sven Bäck [a,c], Tommy Knöös [a,c], Crister Ceberg [c], Kristoffer Petersson [a,*]

[a] Radiation Physics, Department of Hematology, Oncology and Radiation Physics, Skåne University Hospital; [b] Division of Oncology and Pathology, Clinical Sciences, Lund, Skåne University Hospital; and [c] Department of Medical Radiation Physics, Clinical Sciences, Lund, Lund University, Sweden

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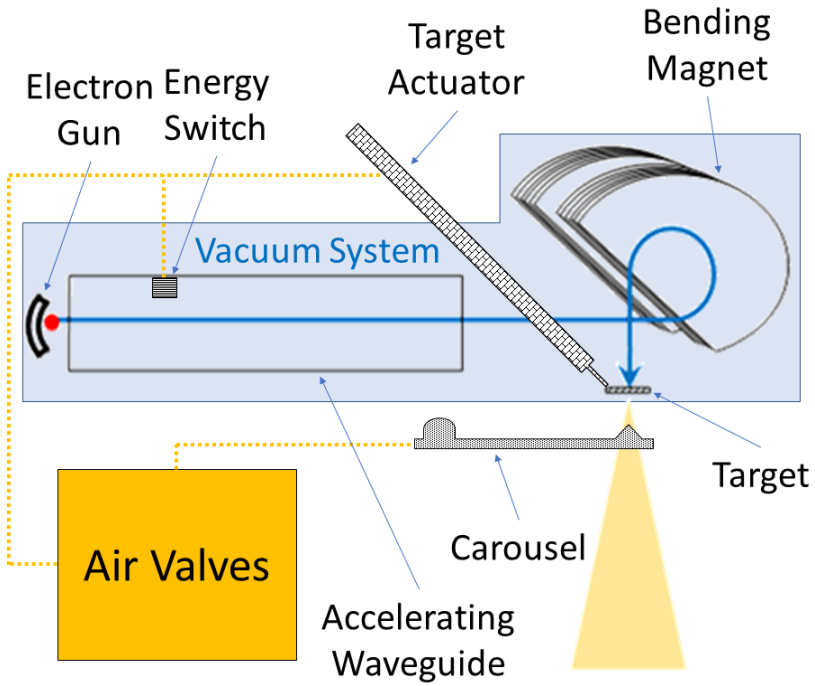
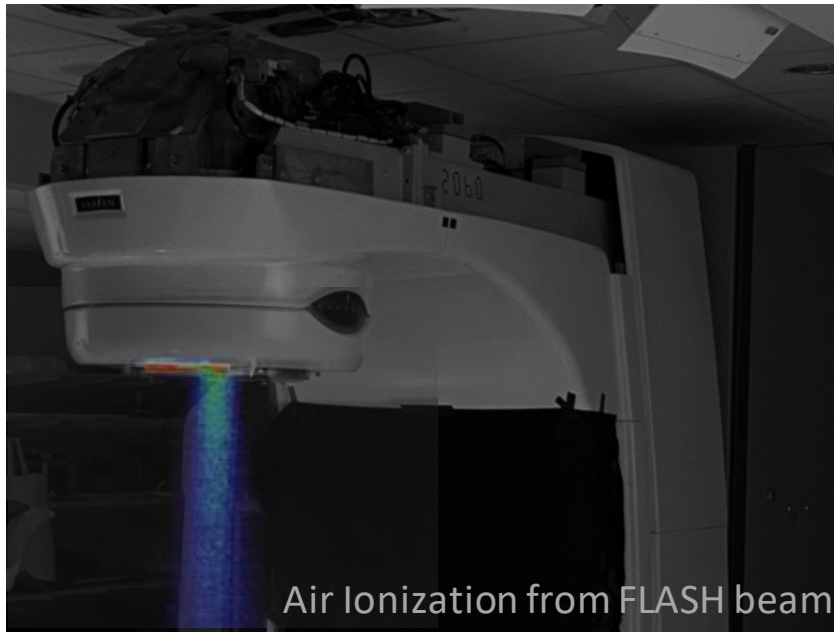
LINAC Conversion and Delivery Method

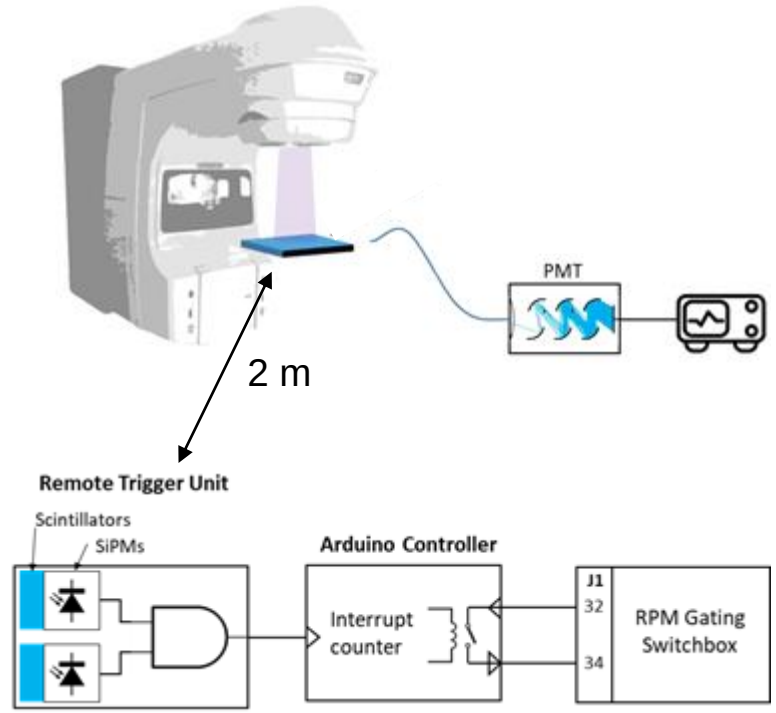




>290 Gy/s at Isocenter

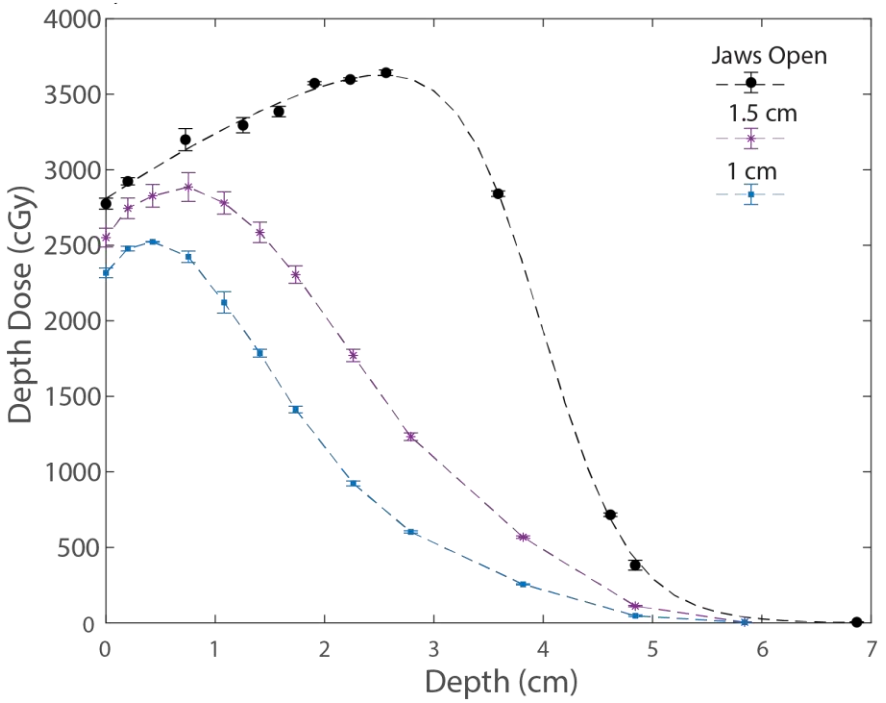
	Total dose, Gy	Mean dose rate, Gy/s	Dose per pulse, Gy
Jaws open	28.2 ± 0.5	290 ± 5	0.81 ± 0.01
1.5 cm circular	25.5 ± 0.5	262 ± 5	0.72 ± 0.01
1 cm circular	23.2 ± 0.5	238 ± 5	0.66 ± 0.01

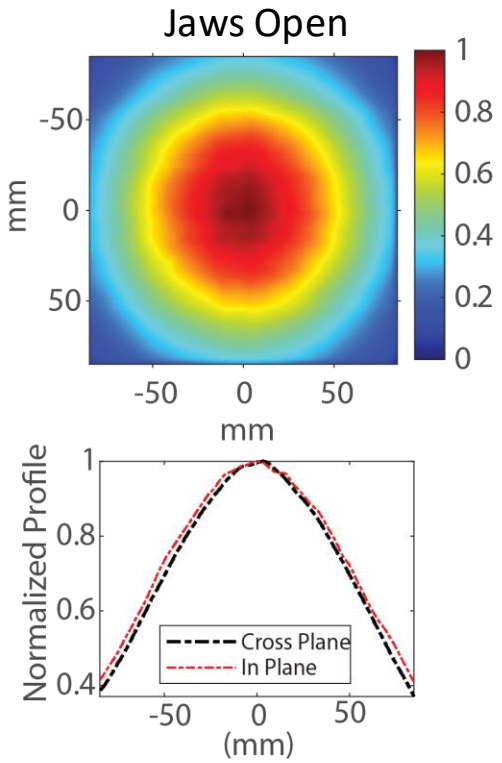
Pulse Controller

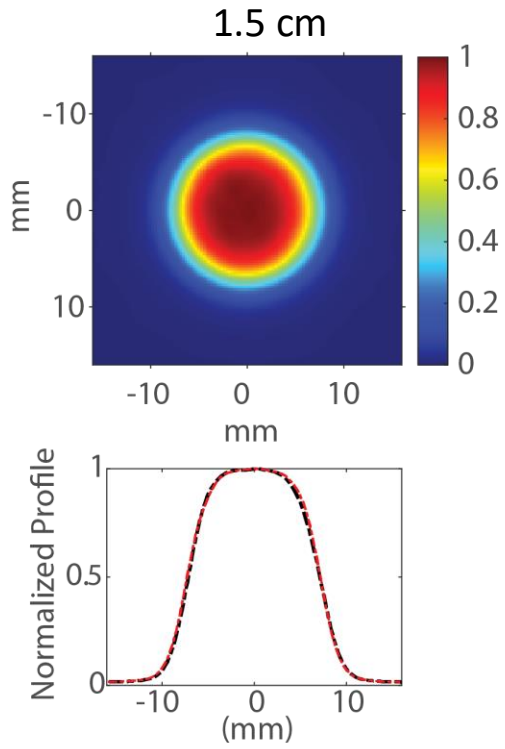


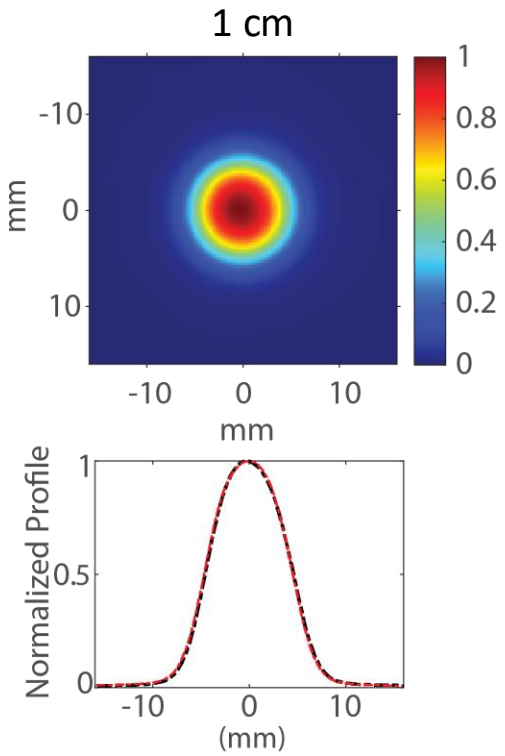
Rahman M* et al. *IJROBP*. 2021

Spatial Beam Characterization







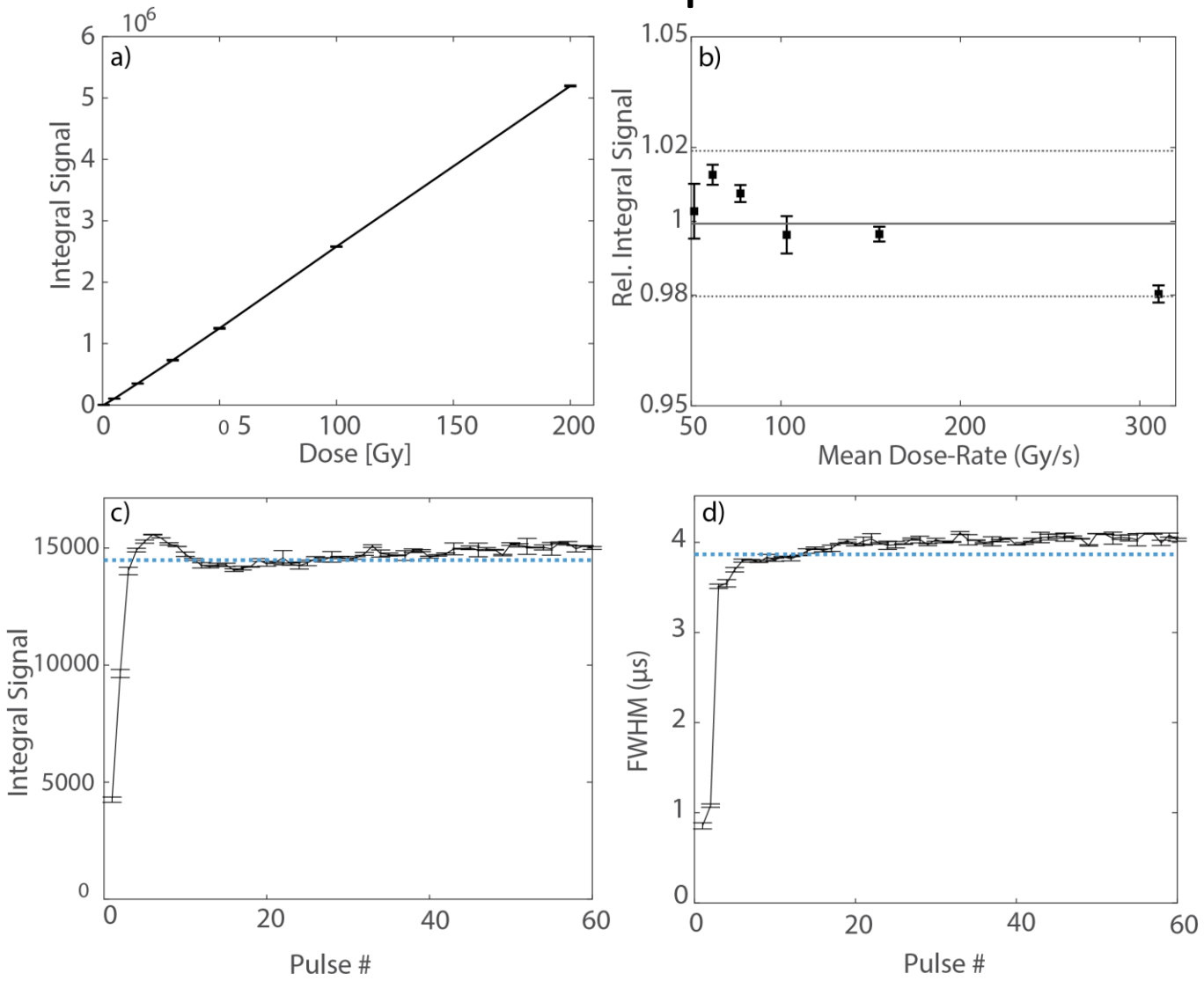


Beam Characteristics

	D_{max}	R_{50}	R_p	FWHM	Radial Symmetry
Jaws Open	2.6 cm	4.0 cm	4.9 cm	14.1 cm	2.4%
1.5 cm	0.8 cm	2.5 cm	3.9 cm	1.4 cm	0.5%
1 cm	0.5 cm	1.6 cm	3.0 cm	0.9 cm	0.2%

Rahman M* et al. *IJROBP*. 2021

Beam Stabilizes after 4-5 pulses Delivered



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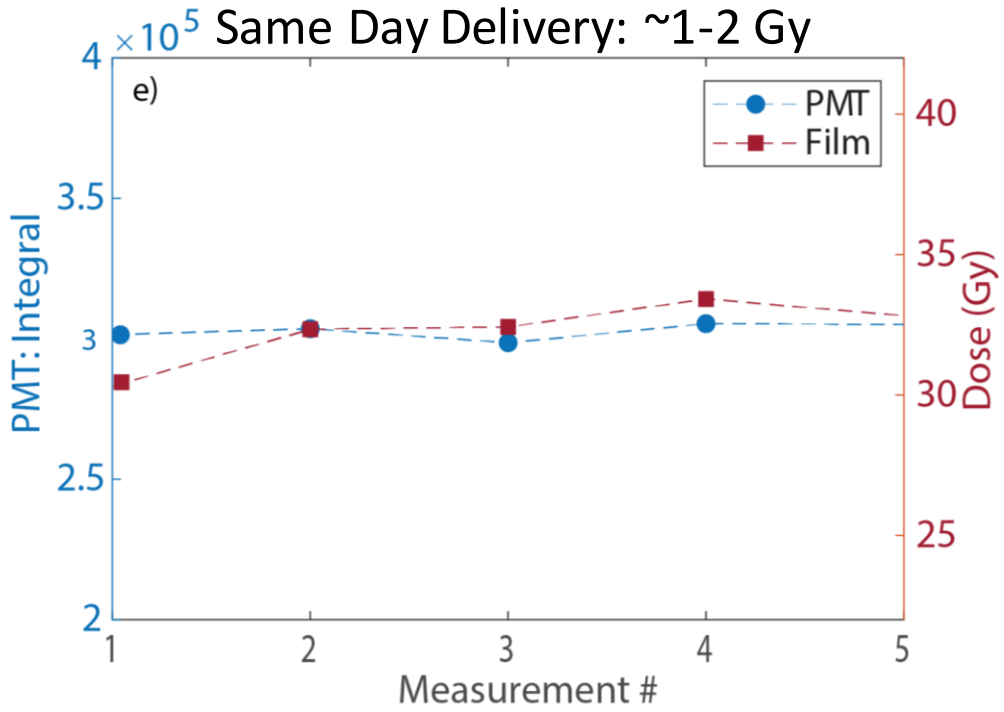
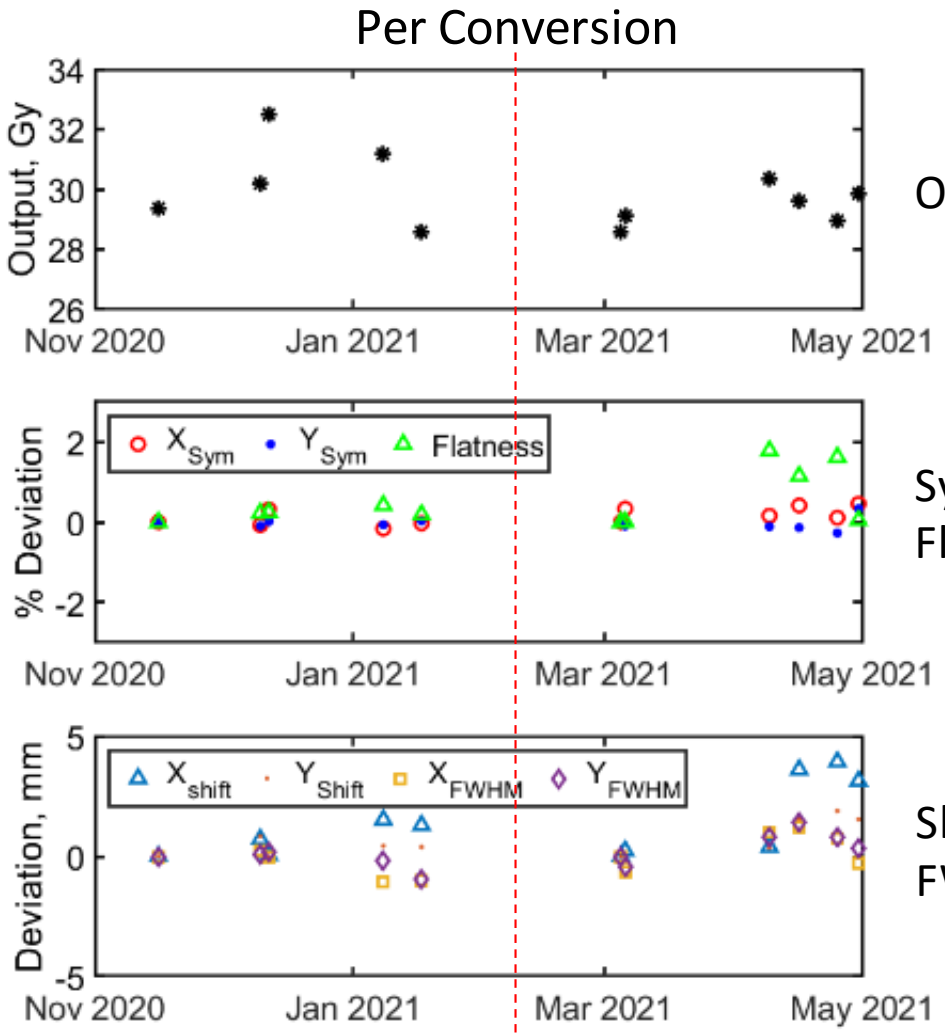
Beam Stability





Output: ~1-2 Gy

Symmetry: 1%
Flatness: 2%

Shift: 2 mm*
FWHM: 2 mm

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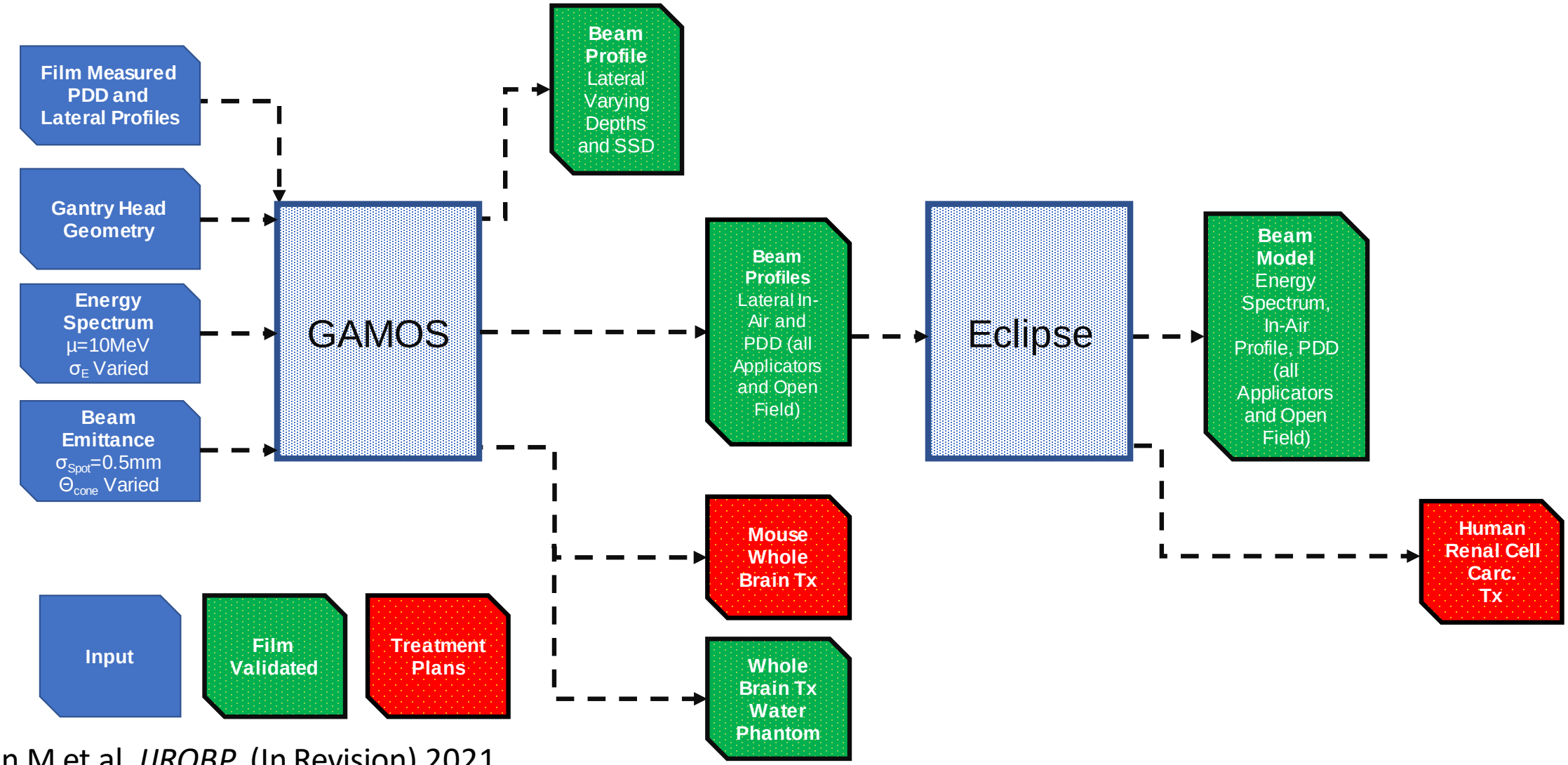
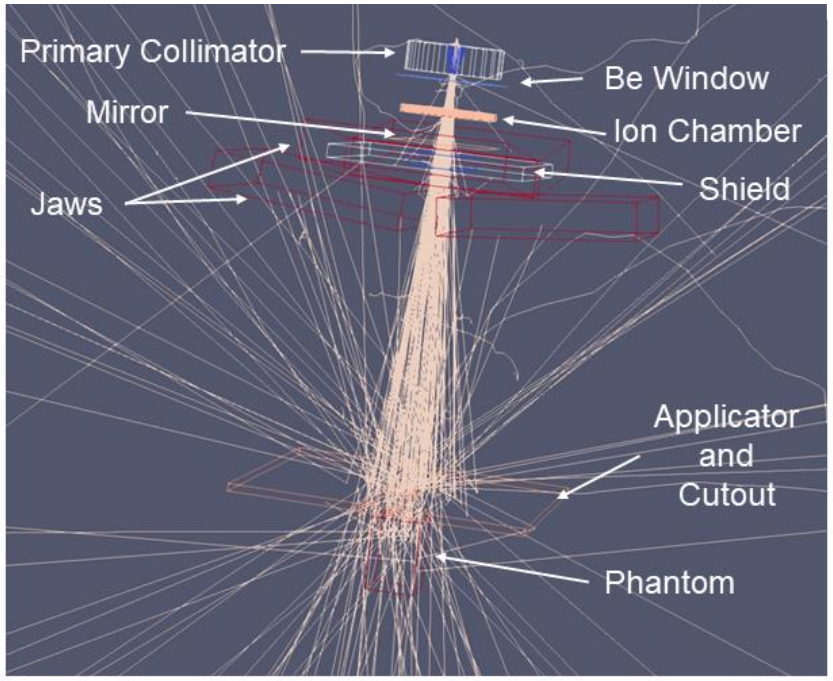
Electron FLASH Clinical Treatment Planning

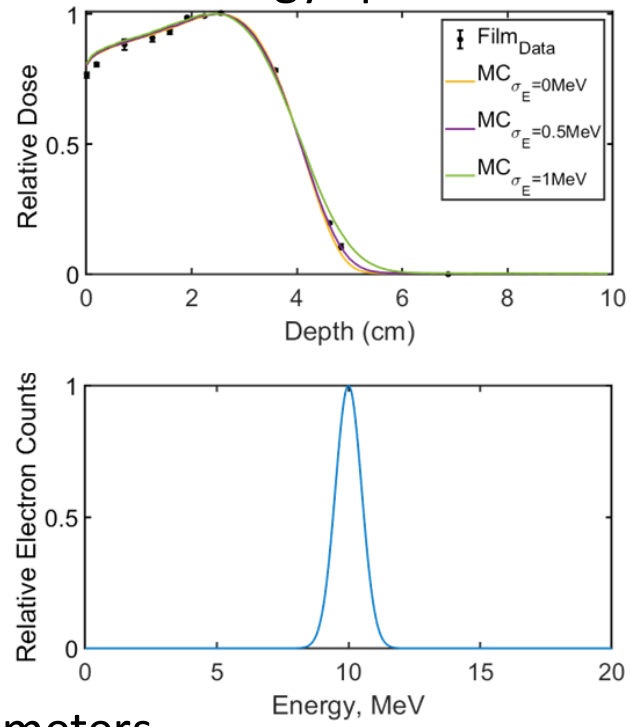


Rahman M et al. *IJROBP*. (In Revision) 2021.

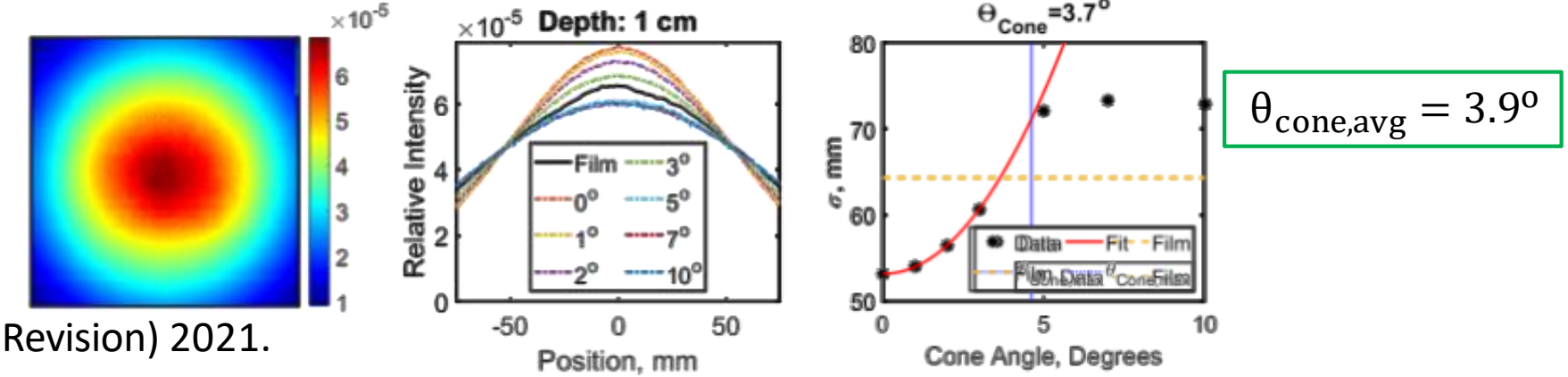
Creating the Beam Model



Energy Spectrum



Emittance Parameters



$\theta_{cone,avg} = 3.9^{o}$

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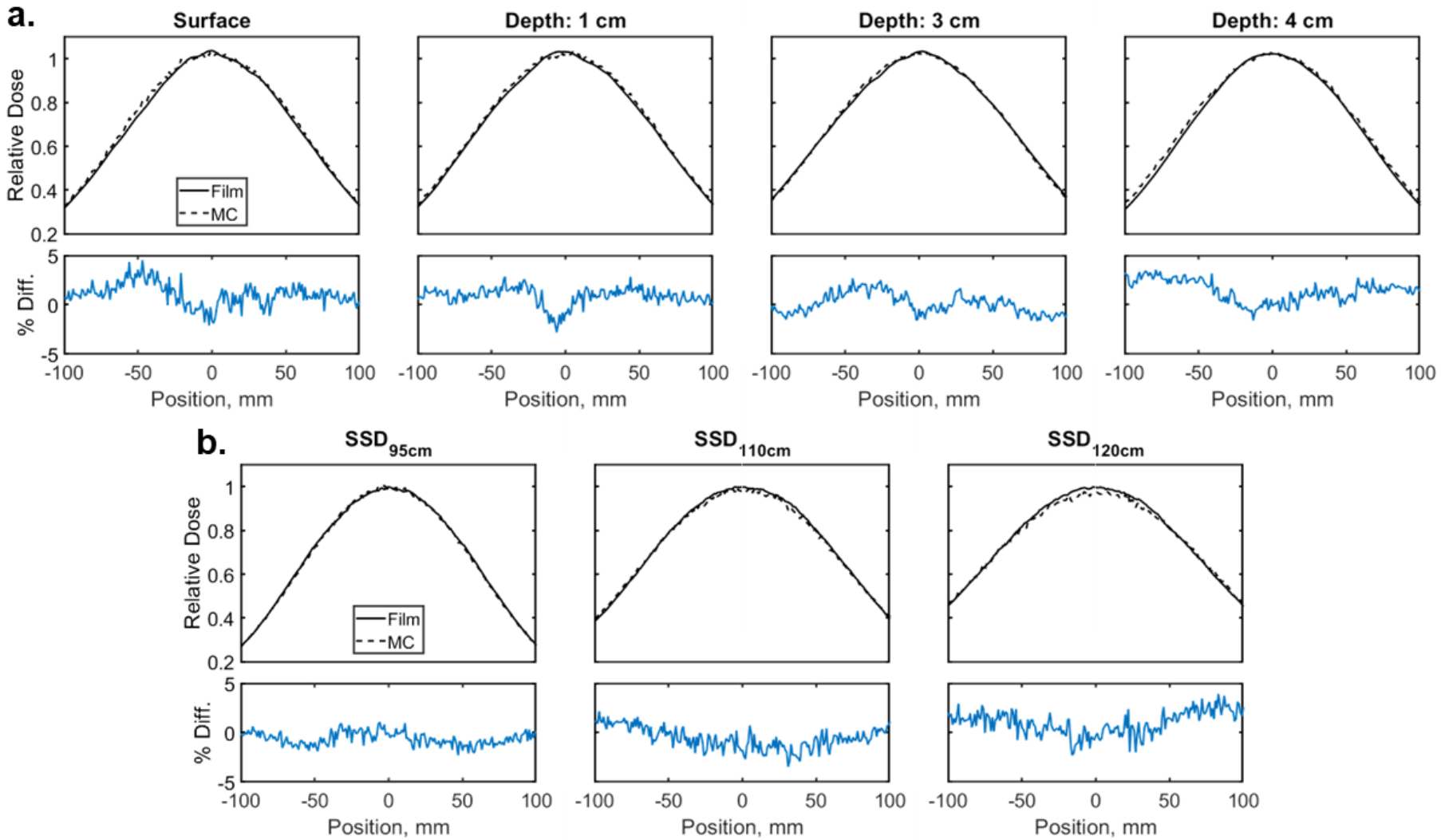
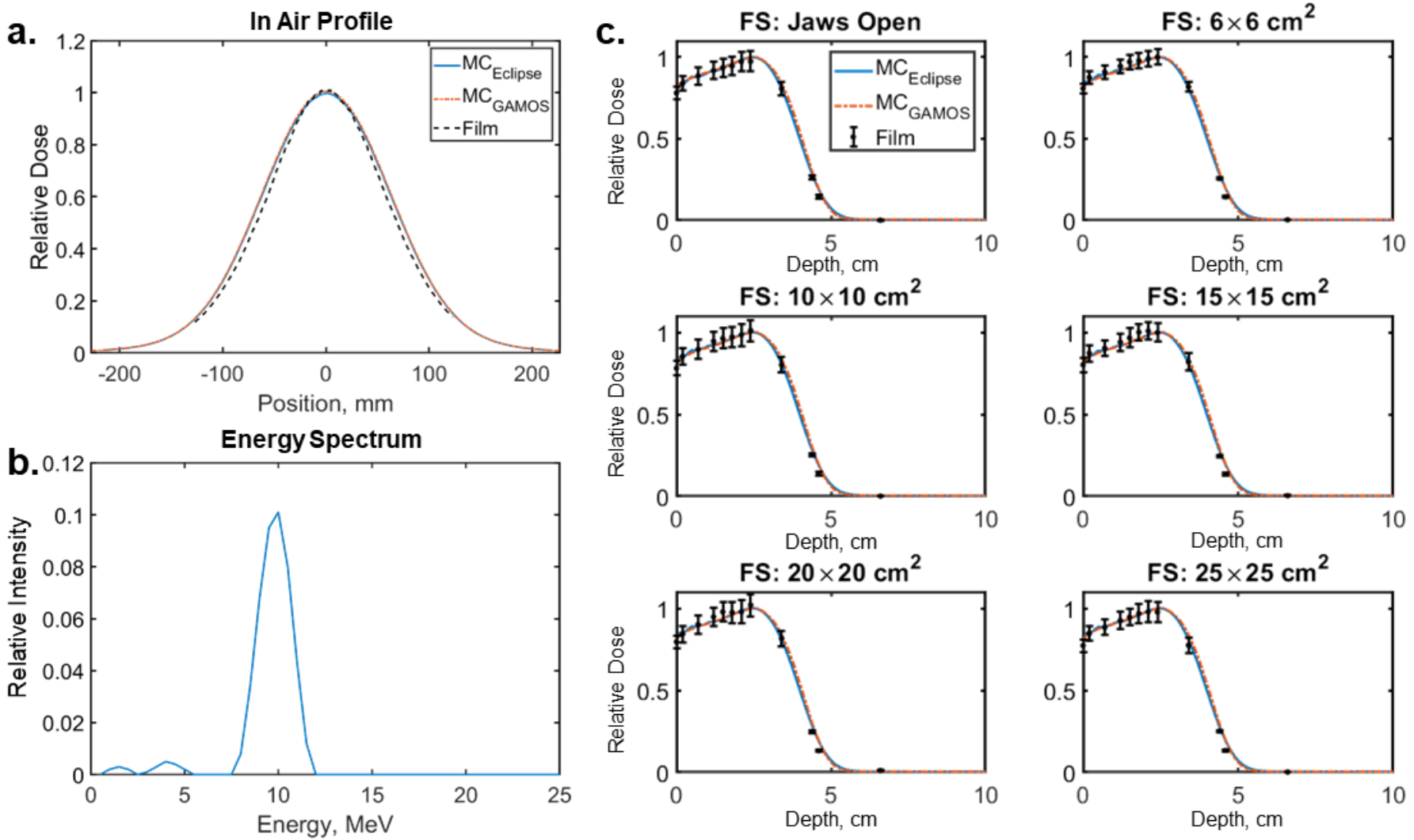
Verification of Lateral Beam Profiles within 1.5%



Rahman M et al. *IJROBP*. (In Revision) 2021.

Implementation Into Eclipse Treatment Planning Software



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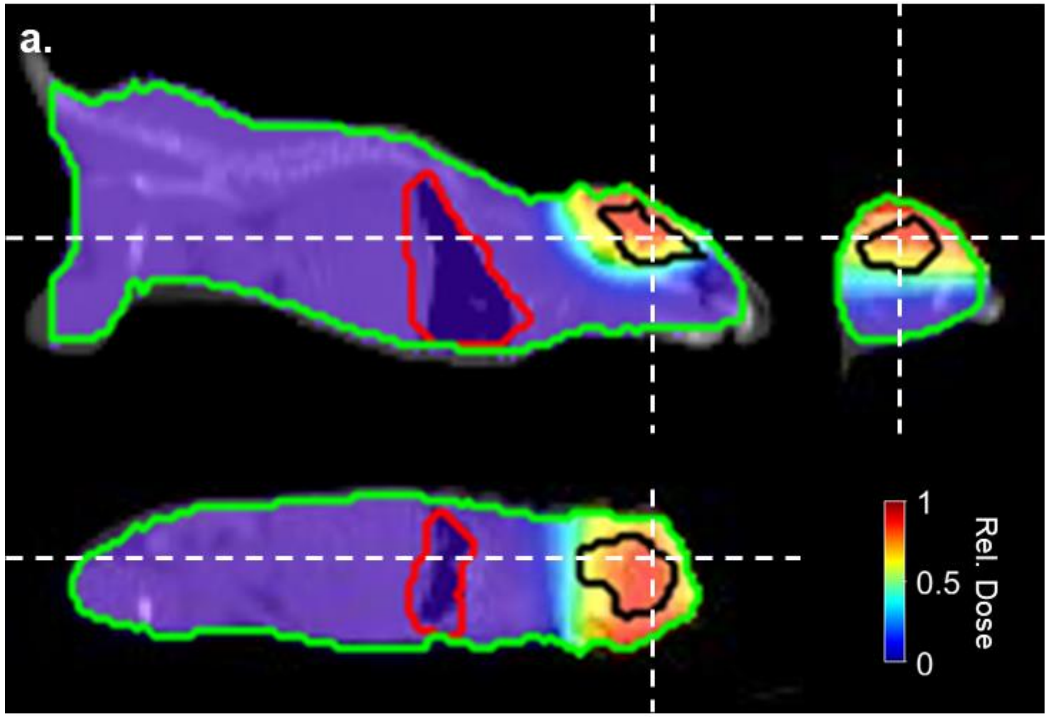
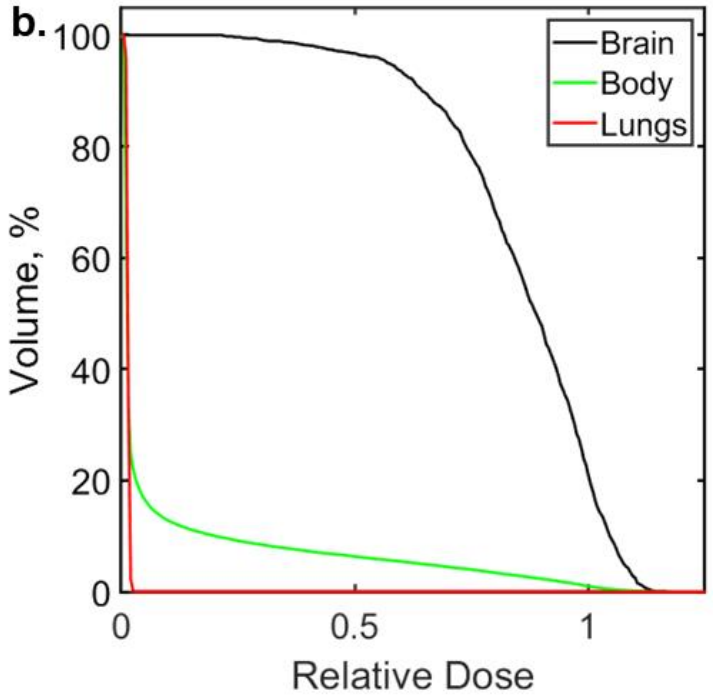
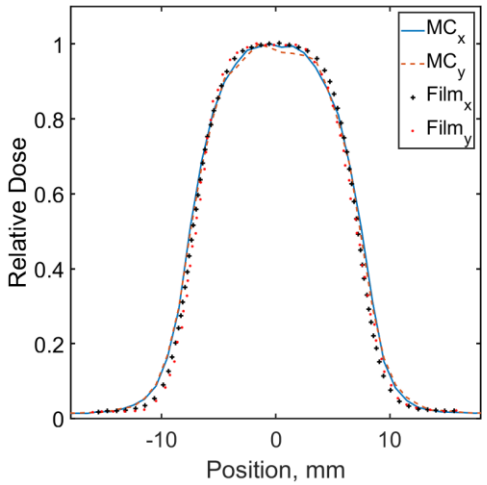
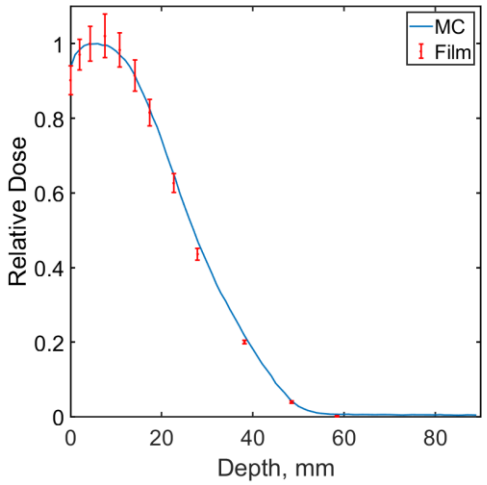
GAMOS Forward Dose Calculation: Whole Mouse Brain



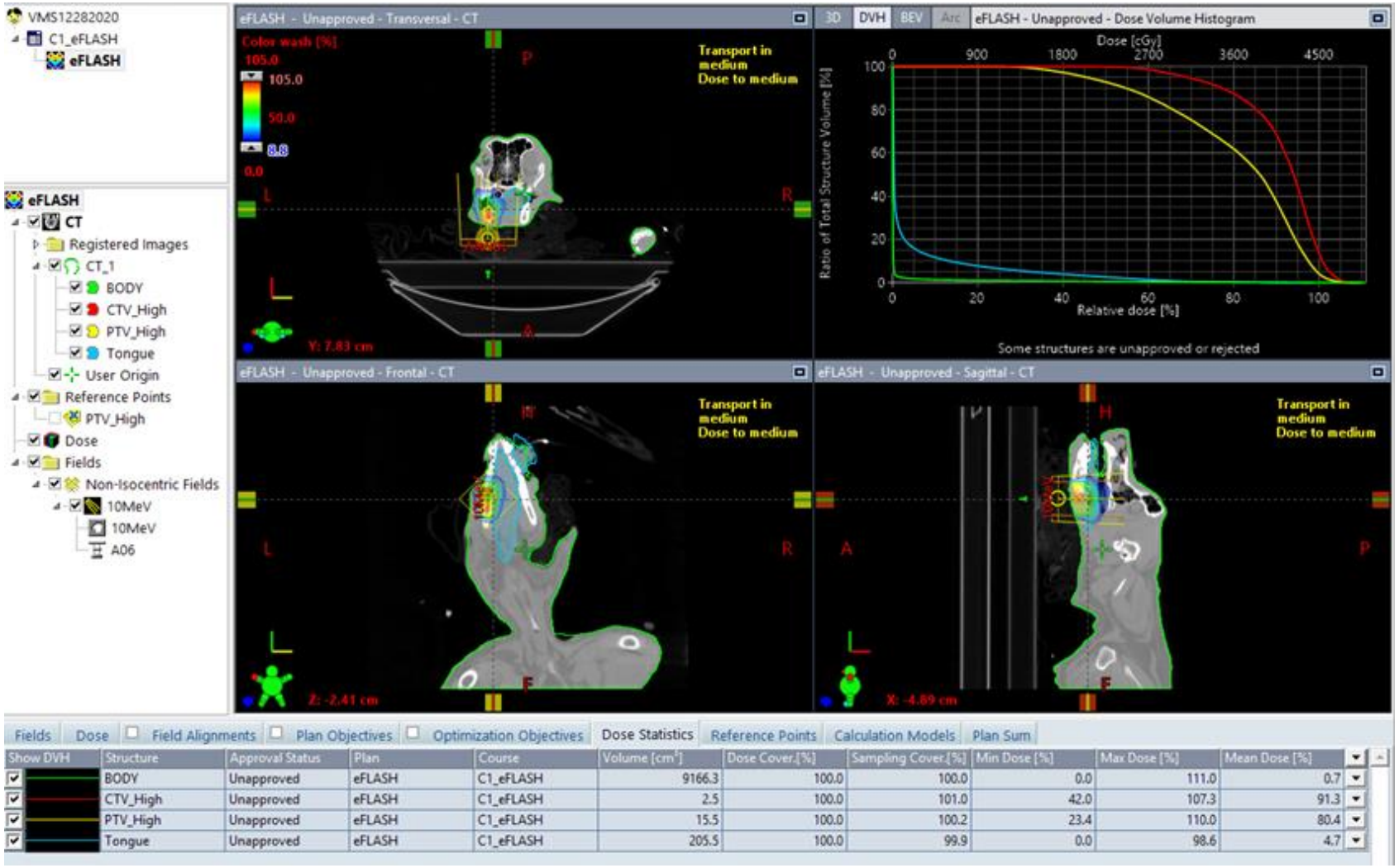






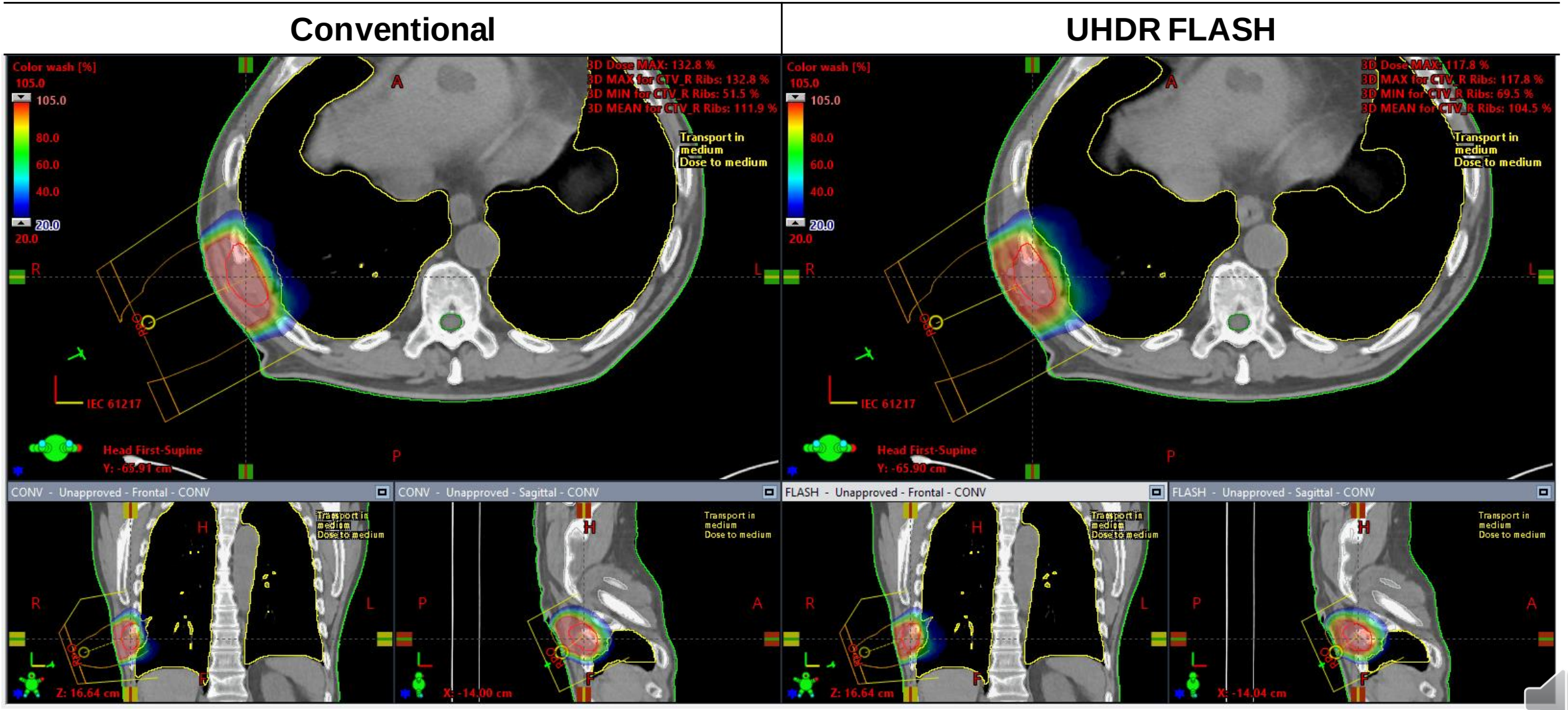
Rahman M et al. *IJROBP*. (In Revision) 2021.

Eclipse TPS: Canine Oral Melanoma



Rahman M et al. *IJROBP*. (In Revision) 2021.

Eclipse TPS: Human Patient with Rib Metastasis



Rahman M et al. *IJROBP*. (In Revision) 2021.

Open Source on GitHub

https://github.com/mr3536/eFLASHBeamModeltoTPS

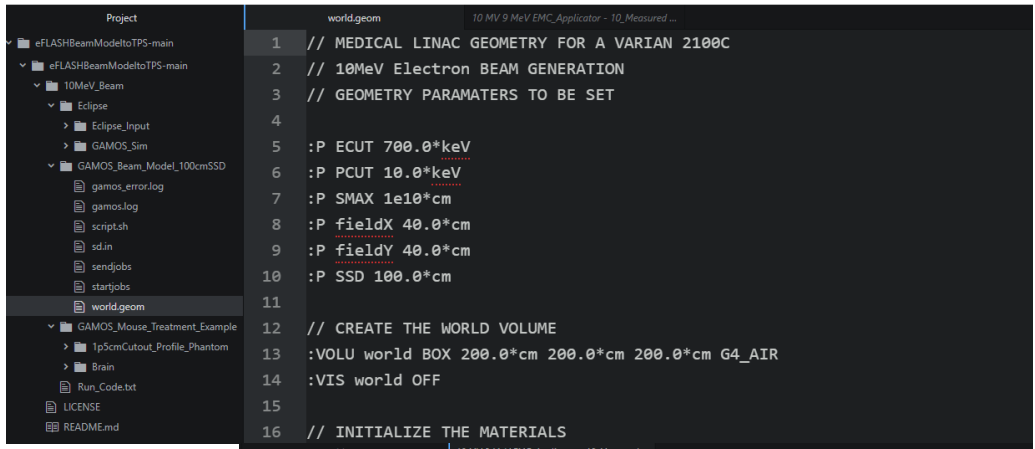
mr3536 Update README.md — `ff9c074` on Feb 25 — 12 commits

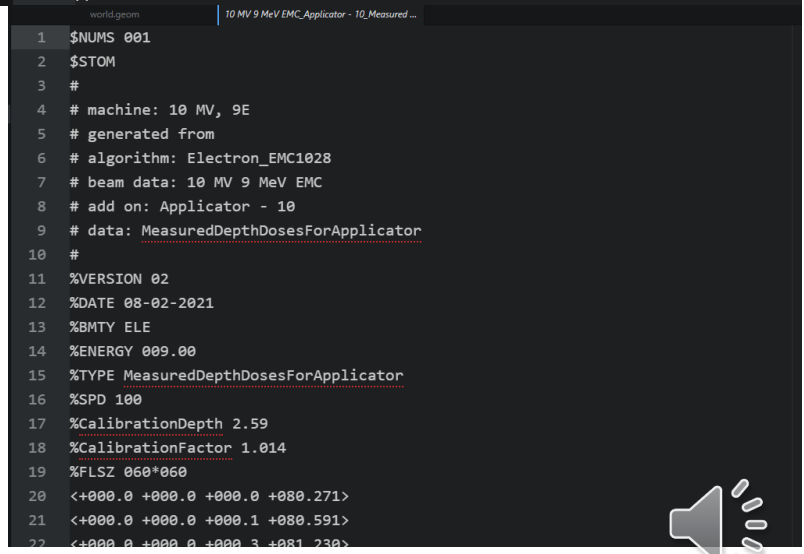
10MeV_Beam	Add files via upload	4 months ago
LICENSE	Initial commit	4 months ago
README.md	Update README.md	3 months ago

README.md

eFLASH Beam Model to TPS

Here is a configured beam model in a treatment planning software (Eclipse, Varian) of an electron ultra-high dose rate (>40GY/s) FLASH irradiator from a modified linear accelerator (Varian CLINAC 2100 C/D) utilizing clinical accessories and geometry. The modifications are described in doi:10.1016/j.ijrobp.2021.01.011. The GAMOS produced and confirmed model is included in the file "GAMOS_Beam_Model_100cmSSD". The GAMOS MC simulations for a mouse brain treatment and delivery in a water phantom for validation are included in "GAMOS_Mouse_Treatment_Example". "Run_Code.txt" provides the few lines of code input to terminal to run the simulation with the brain treatment as an example. The GAMOS simulation to produce Eclipse and the Eclipse input files for the beam model are included in the file "Eclipse".





Flexibility in Machine Promotes High Throughput in Studies

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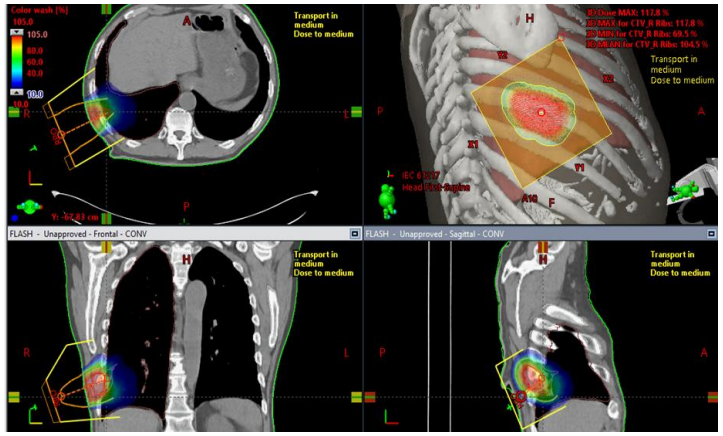
Treatment Planning



Rahman, IJROBP (in Revision)

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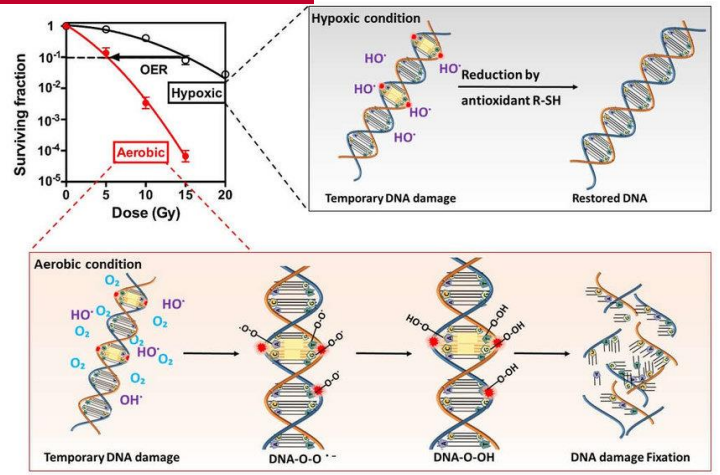
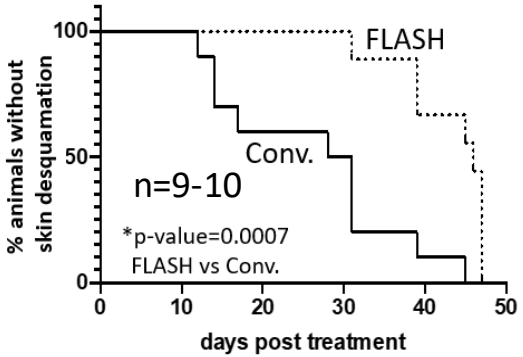
FLASH Oximetry



Cao et al, IJROBP (2021)

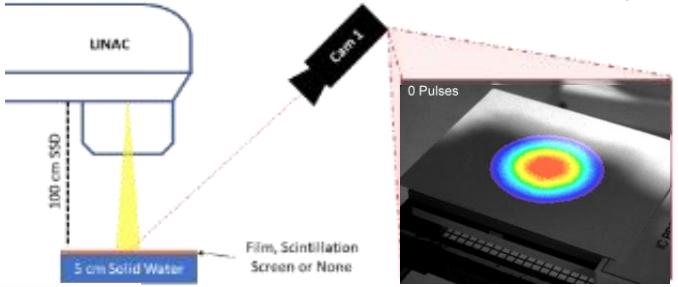
Animal Studies

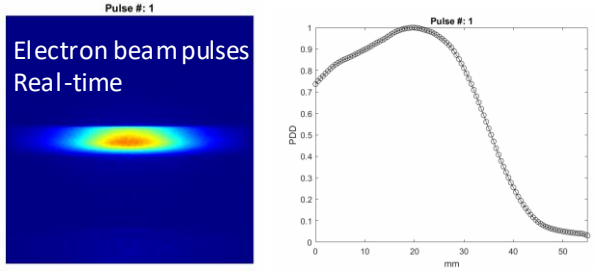
Delay in skin desquamation



Duval et al, (Submitted)

Radioluminescence Dosimetry





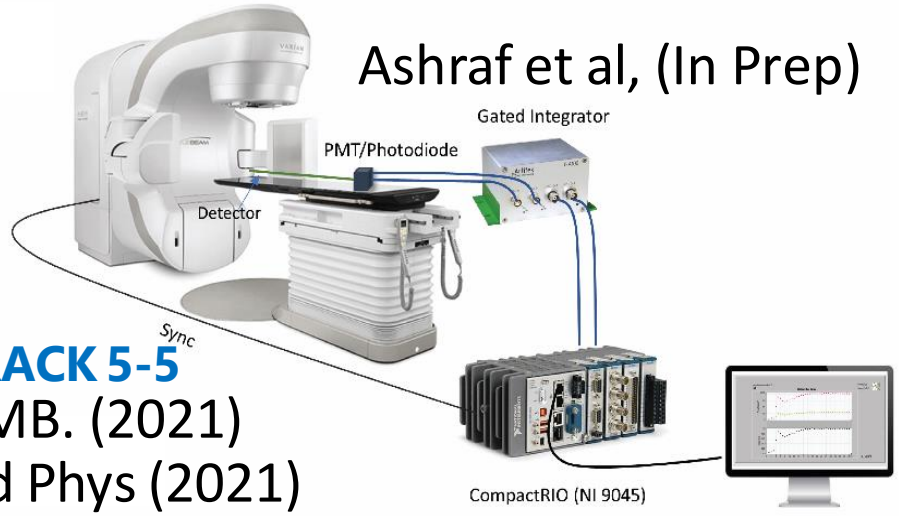
TU-EF-TRACK 4-7

TU-F-TRACK 5-5

Rahman et al, PMB. (2021)

Ashraf et al, Med Phys (2021)

Real Time Dose Feedback

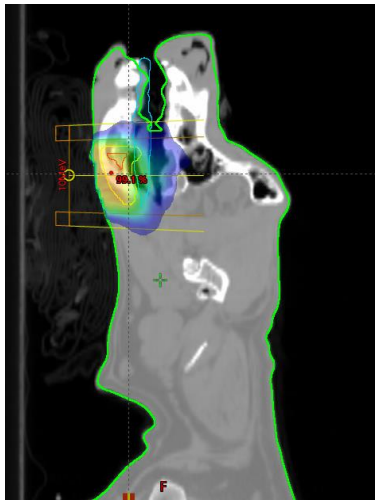


Ashraf et al, (In Prep)

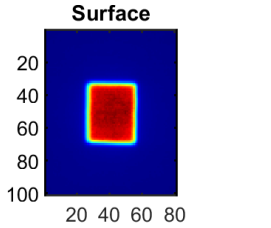
Minimal Changes to the Clinical Workflow

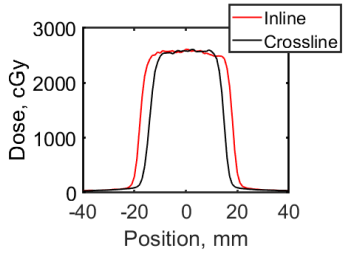
Patient Assessment → Simulation → Treatment Planning → QA & Treatment Delivery → Follow-Up

https://ctmedicalscanners.com/ge-lightspeed-rt-16-ct-scanner/



Clinical TPS

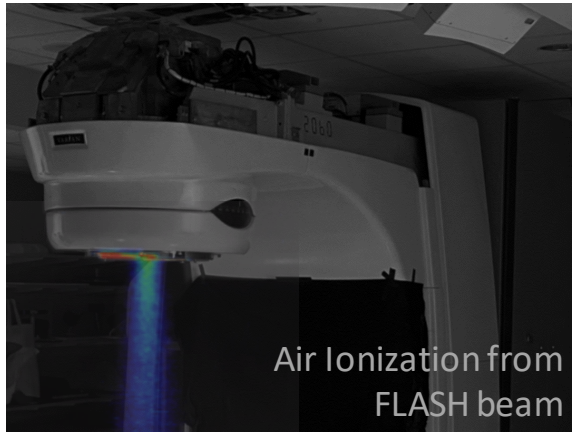


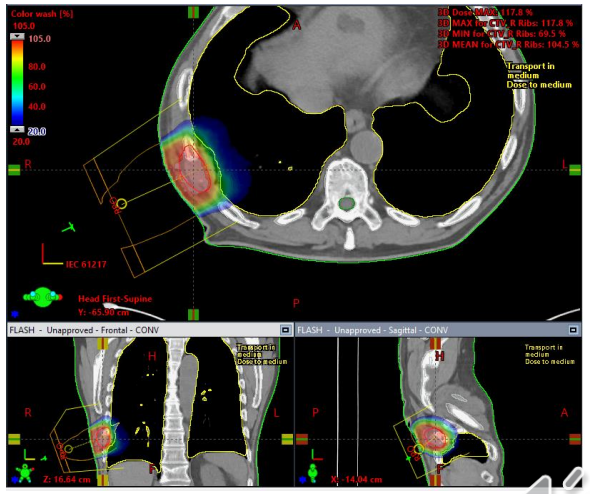


Utilizes all clinical accessories and geometry

Conclusion

- eFLASH-RT was feasible in **minimally modified radiation oncology clinical settings**
  - **~300 Gy/s at the isocenter**
  - Beam is **stable per delivery and per conversion**
  - The **first treatment planning system of a modified LINAC** for eFLASH-RT
  - Flexibility in machine allows for **high throughput in studies**
- A ramp-up period (first 4-5 pulses) was observed
- Future Work
  - **Dose rate implementation** into the treatment planning process
  - **Validations in animal studies** prior to considering clinical translation.
- **Open Source:** https://github.com/mr3536/eFLASHBeamModeltoTPS
- Publication
  - Rahman M* et al. Electron FLASH Delivery at Treatment Room Isocenter for Efficient Reversible Conversion of a Clinical LINAC. *IJROBP*. 2021.
  - Rahman M et al. Treatment Planning System for Electron FLASH Radiotherapy: Open-source for Clinical Implementation. Under Revision at *IJROBP*. (available on arXiv)


Air Ionization from FLASH beam



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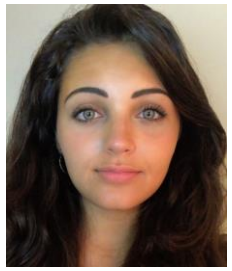
Muhammad R. Ashraf


Daniel Alexander


Rachael Hachadorian


Savannah Decker

DARTMOUTH

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

CENTER FOR IMAGING MEDICINE AT DARTMOUTH

Dartmouth-Hitchcock NORRIS COTTON CANCER CENTER

DOSEOPTICS Visualize radiation therapy

Commercial support

NIH National Institute of Biomedical Imaging and Bioengineering

NIH grants: R01 EB024498 and P30 CA023108.