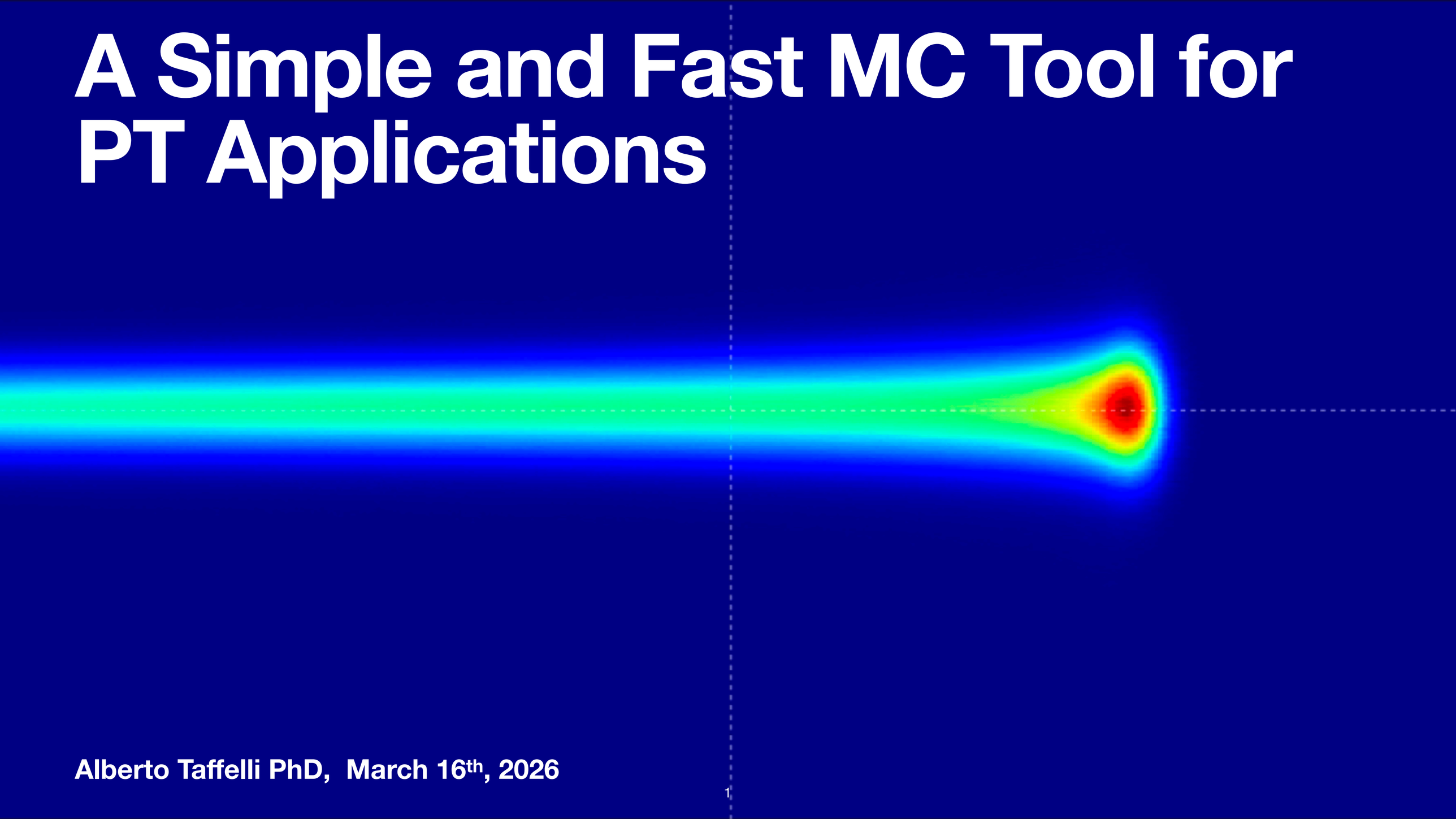
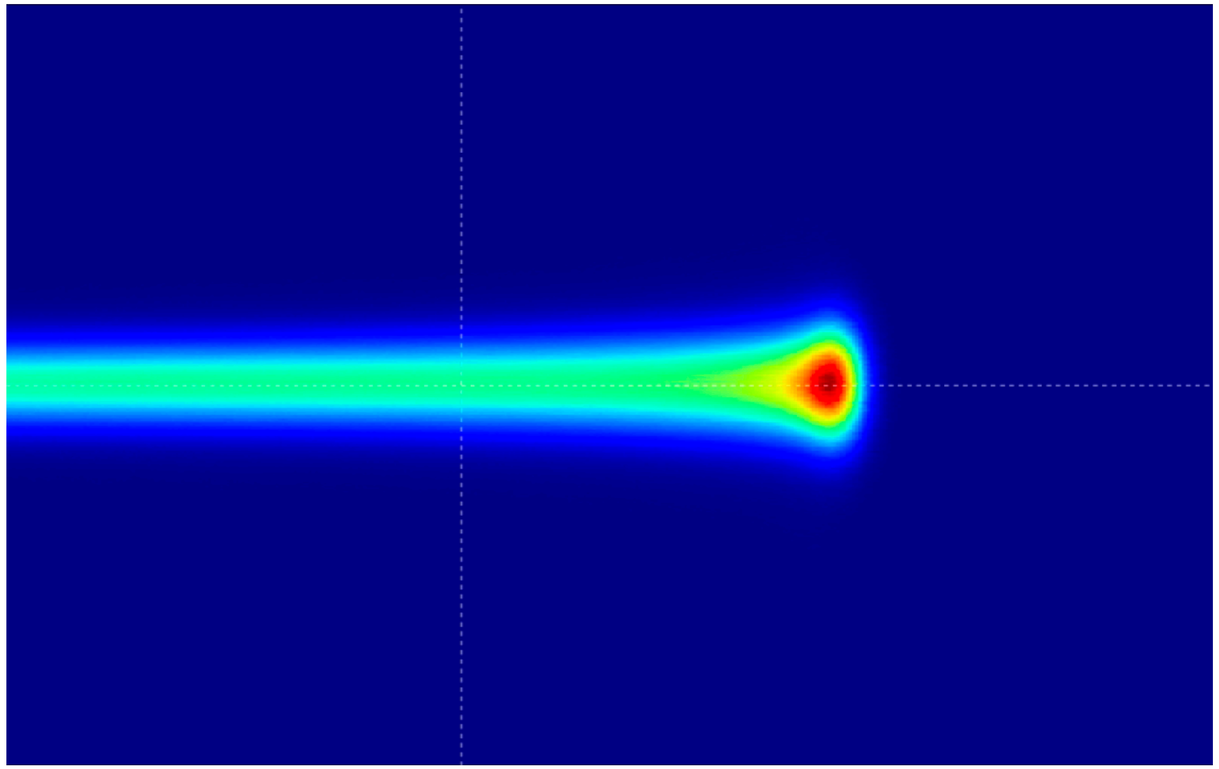
A Simple and Fast MC Tool for PT Applications



Alberto Taffelli PhD, March 16th, 2026

A Simple and Fast MC Tool for PT Applications



Alberto Taffelli PhD, March 16th, 2026

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BiMeR
Bio–Medical Radiation physics lab

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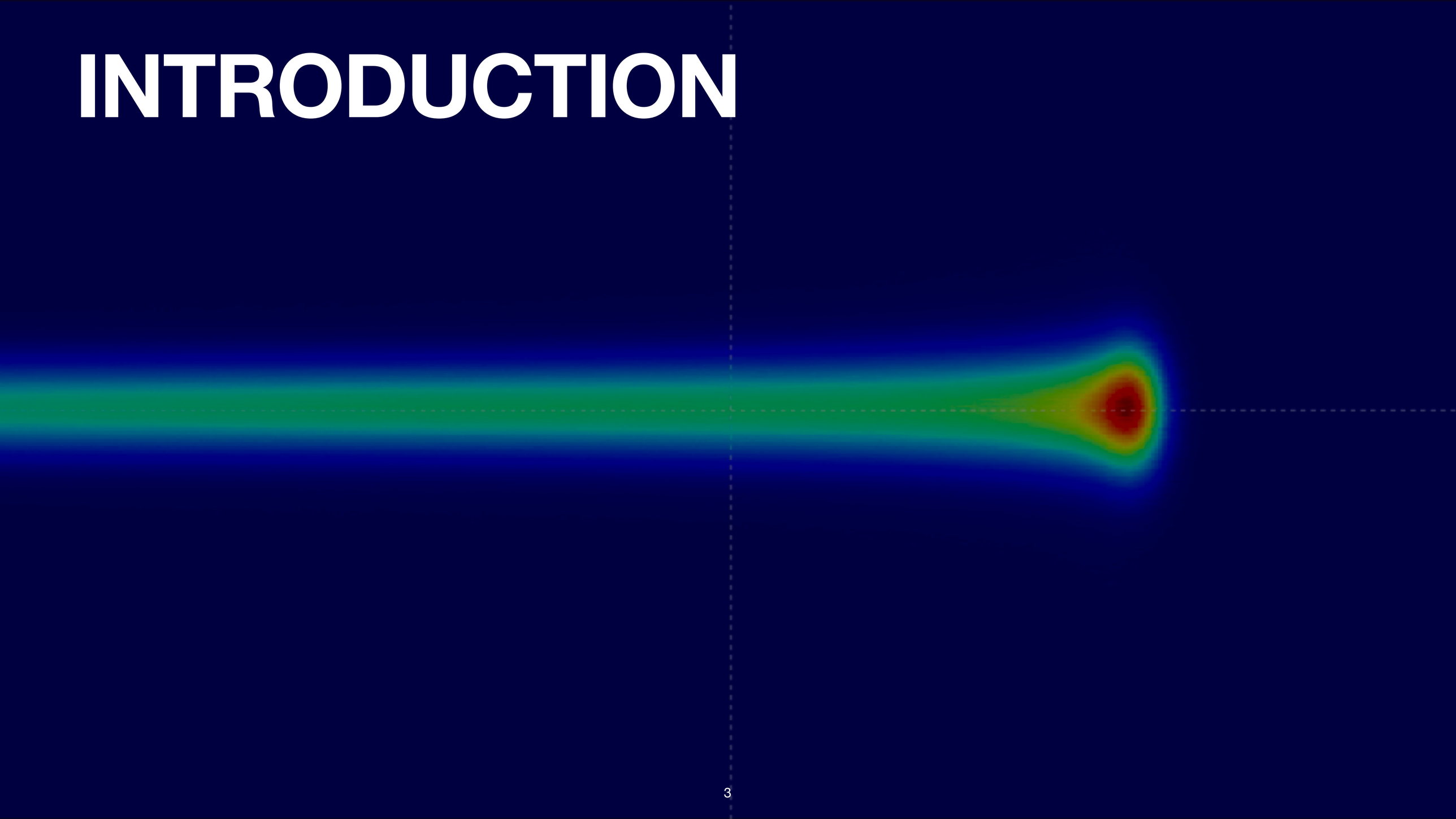
Provincia Autonoma di Trento

UNIVERSITÀ DI TRENTO

FORM3D
Fast Optimization of Range Modulators 3D

INTRODUCTION

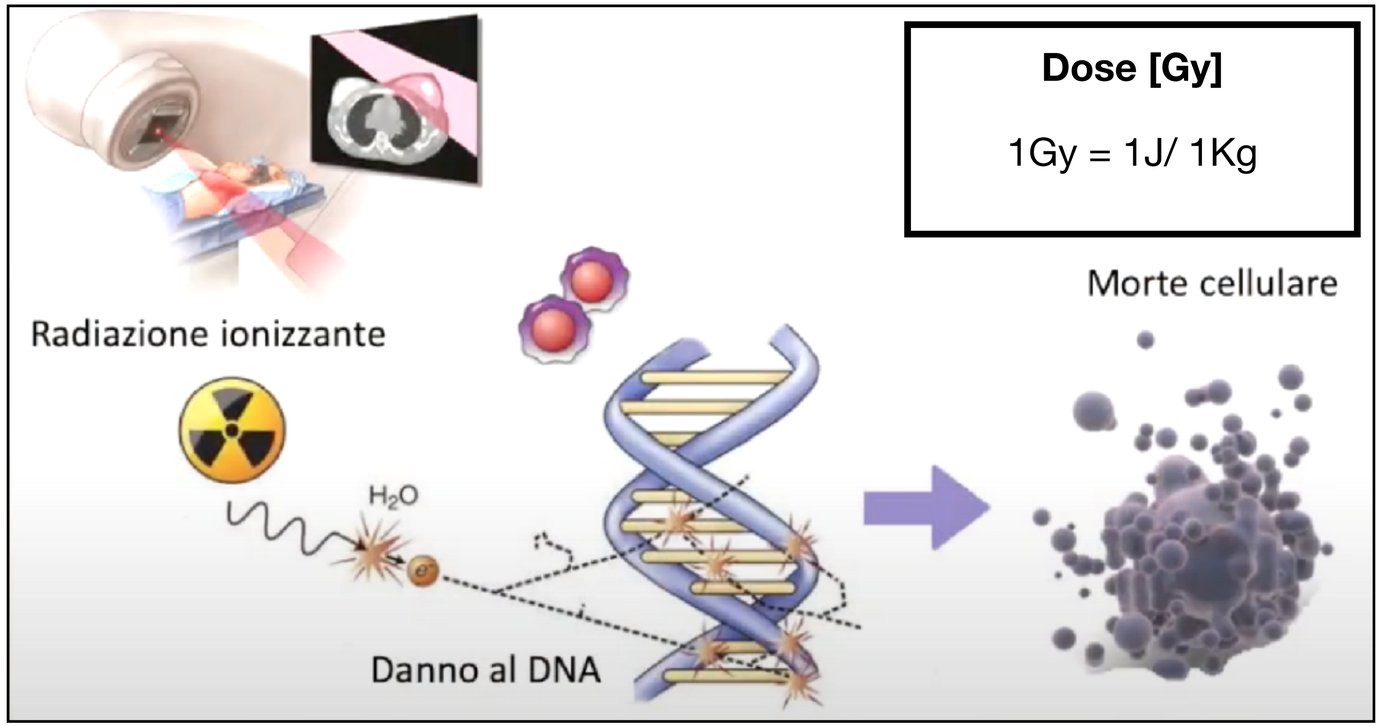


Radiotherapy

“In 2022, there were an estimated 20 million new cancer diagnoses, with approximately 10 million new patients needing radiotherapy … In 2050, GLOBOCAN 2022 data indicated 33.1 million new cancer diagnoses, with 16.5 million new patients needing radiotherapy…”

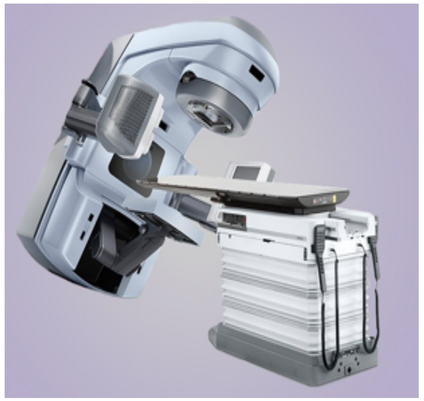
Zhu et al. 2024, Lancet

Working principle

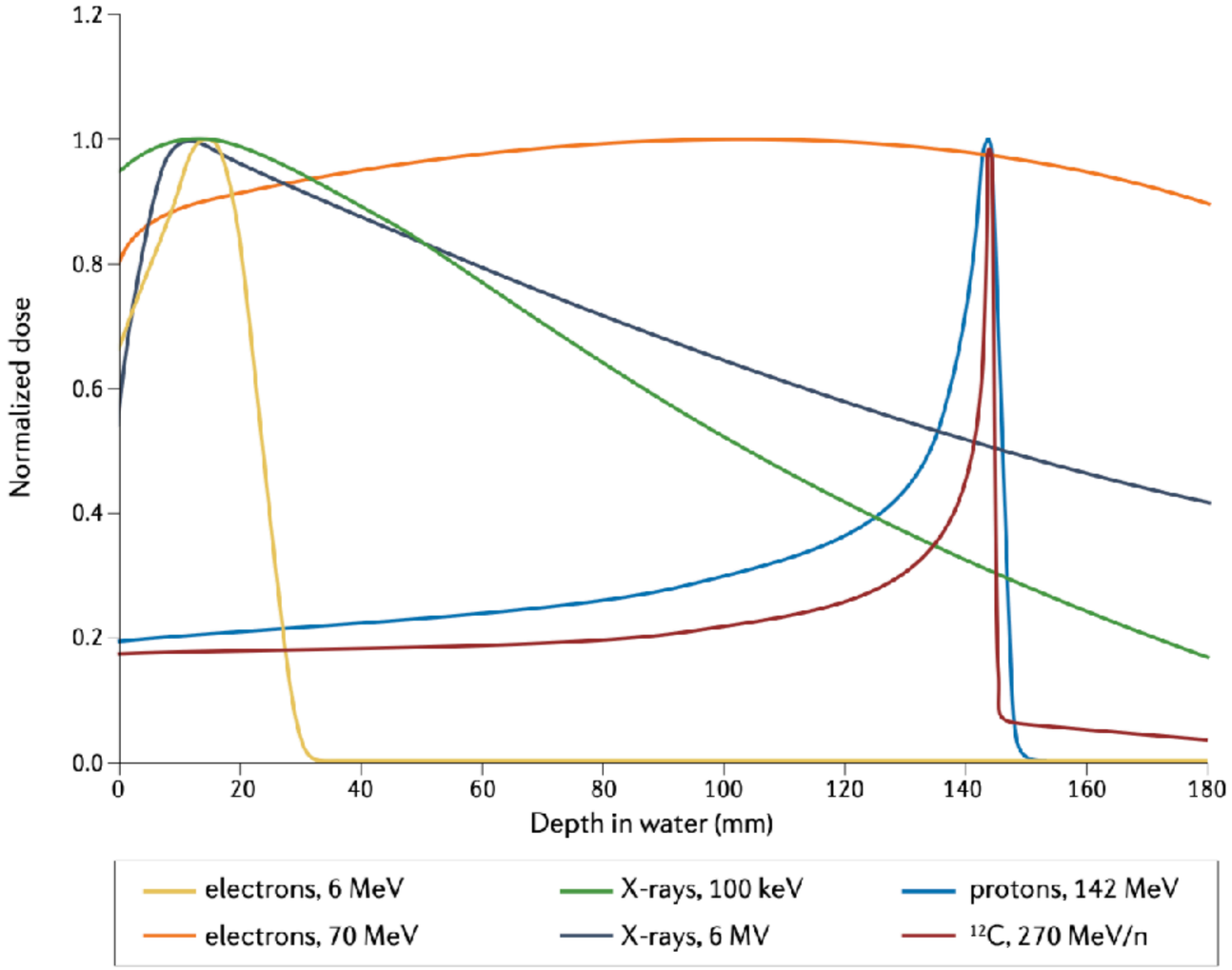


Ionizing radiations in RT

X-rays



Protons



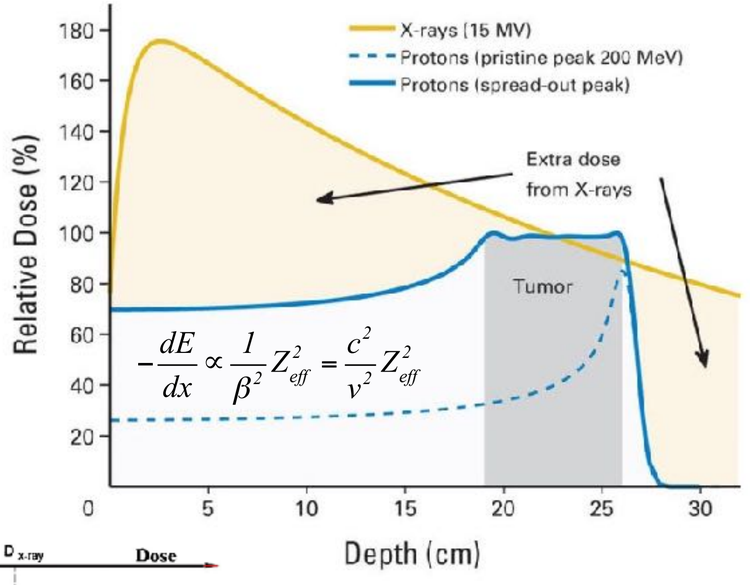
Vozenin, 2022

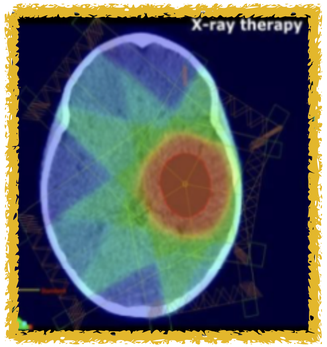
Electrons

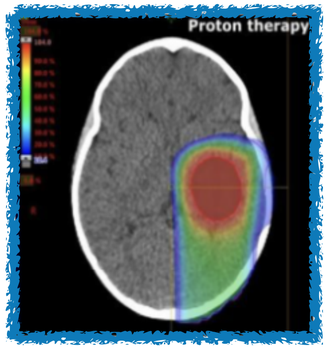
Heavy ions

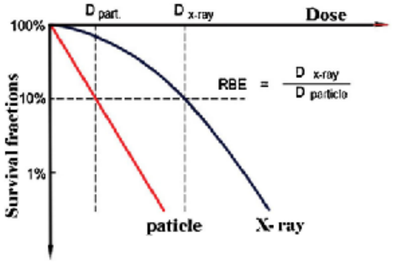
Proton therapy

- Protons can deliver dose precisely in deep seated tumours thanks to their peaked dose distribution in depth (Bragg peak), thus **sparing normal tissues**
- Combining different energies it is possible to cover the tumour extension (SOPB)
- (Slightly) enhanced biological effectiveness RBE 1.1
- The standard approach is the **intensity modulated proton therapy** (IMPT). Active Pencil beam scanning (PBS) systems make use of **different energy layers** to optimize the dose uniformity in the target and spare the normal tissues

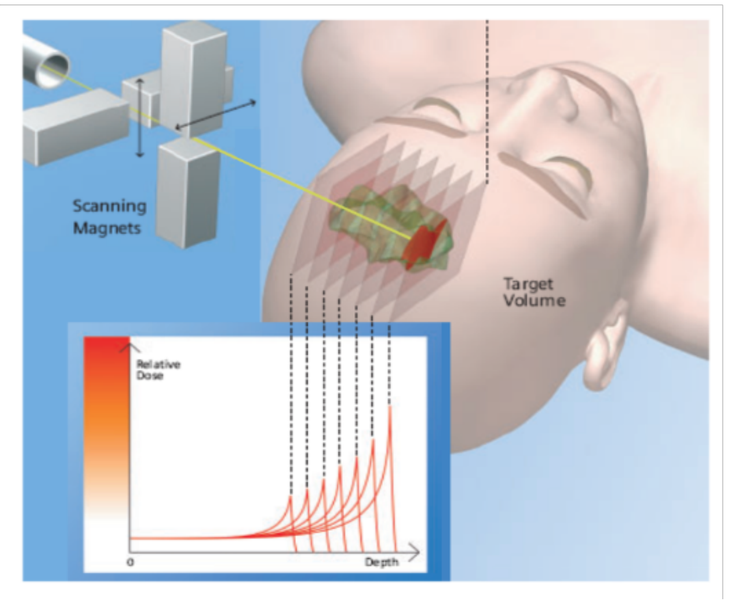






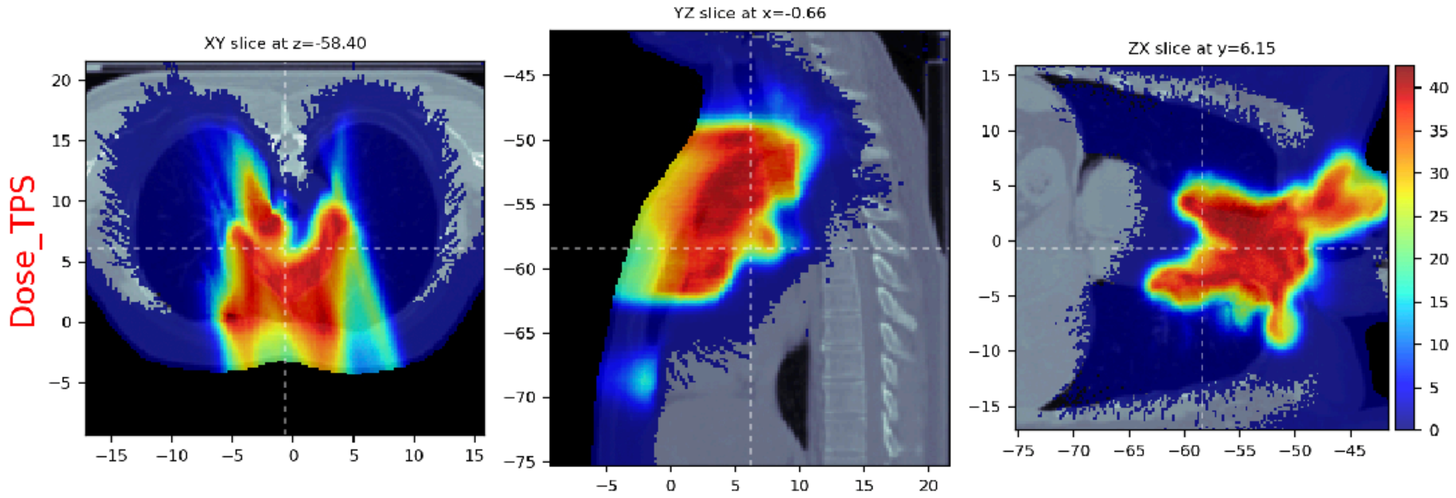


Desouky 2015



Dose engines

- An algorithm within the Treatment Planning System (TPS)
- Allows to calculate the dose distribution of the pencil beams inside a medium (patient's body)



Analytic pb

- Fast
- Based on analytical functions describing the pb
- Accurate for homogeneous media
- Still present in some commercial solutions

Monte Carlo

- Models the primary interaction at every step
- Very accurate also for heterogeneous media
- Generally slow
  - **Fast MC**
  - **GPU-accelerated**

Deep Learning

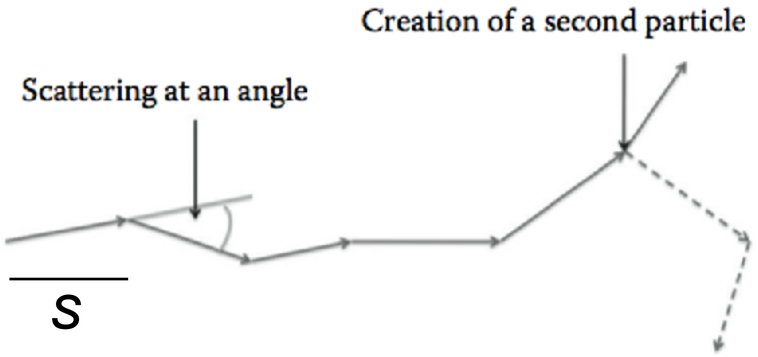
- Emerging method
- Based on AI
- Very Fast
- Requires a huge amount of data
- Accuracy depends on the level of training

Monte Carlo

In pills

MC codes are used to simulate particle transport on a step-by-step basis.

- Particle transport is based on **cross sections** (i.e., interaction probabilities) per unit distance
- MC algorithms thus sample from **stochastic distributions** and the mathematical basis is governed by the central limit theorem.
- **Random numbers** are sampled from a probability density function. At each step *s* of the particle through the geometry, the probability density function is representing the probability of physics interactions and their outcome.



Why Monte Carlo (MC)?

- To save time for experiments
- To investigate configurations difficult to realise with experiments
- Because the patient cannot be used for experiments

Monte Carlo

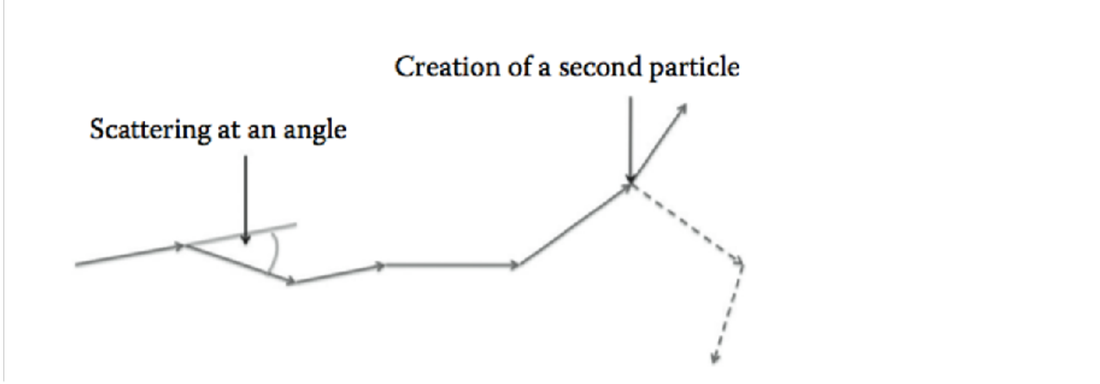
In pills

- **Particle history:** is defined as the knowledge of the trajectory of one particle including potential secondary particles.
- Simulation of particle histories begins by sampling a number of events from a starting source distribution. Then, the passage of particles through a well-defined geometry is simulated. This is known as **tracking**
- **Many particles** need to be simulated in order to achieve a given accuracy. The uncertainty of MC is proportional to 1/ sqrt(*N*).
- **Materials** are characterized by their **physical properties**, such as: elemental composition, electron density, mass density, or mean excitation energy.

Material: Water

"Liquid water"
type: compound (single pure substance)
empirical formula: H2O
mean Z: 3.33333 mean A: 6.0051 => <Z/A> = 0.555084
mass density: 1 g/cm^3
mean ionization potential: 75 eV
radiation length: 36.08 g/cm^2

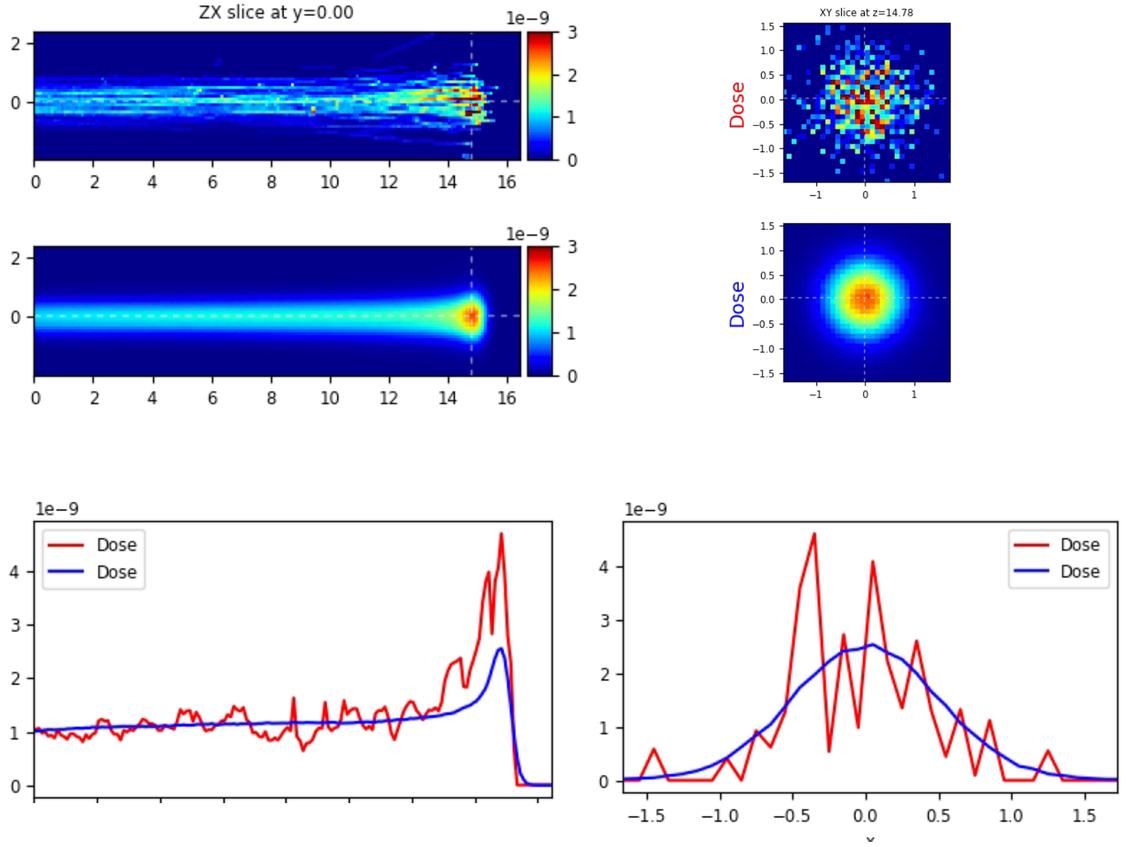
Element	Z	A	m	x	w	rho
			g/mol			g/cm^3
H	1	1	1.00794	0.666667	0.111898	0.111898
O	8	16	15.9994	0.333333	0.888102	0.888102



Proton beam in water

Nprim 1e3

Nprim 1e6



Monte Carlo codes for radiotherapy

Commercial TPS

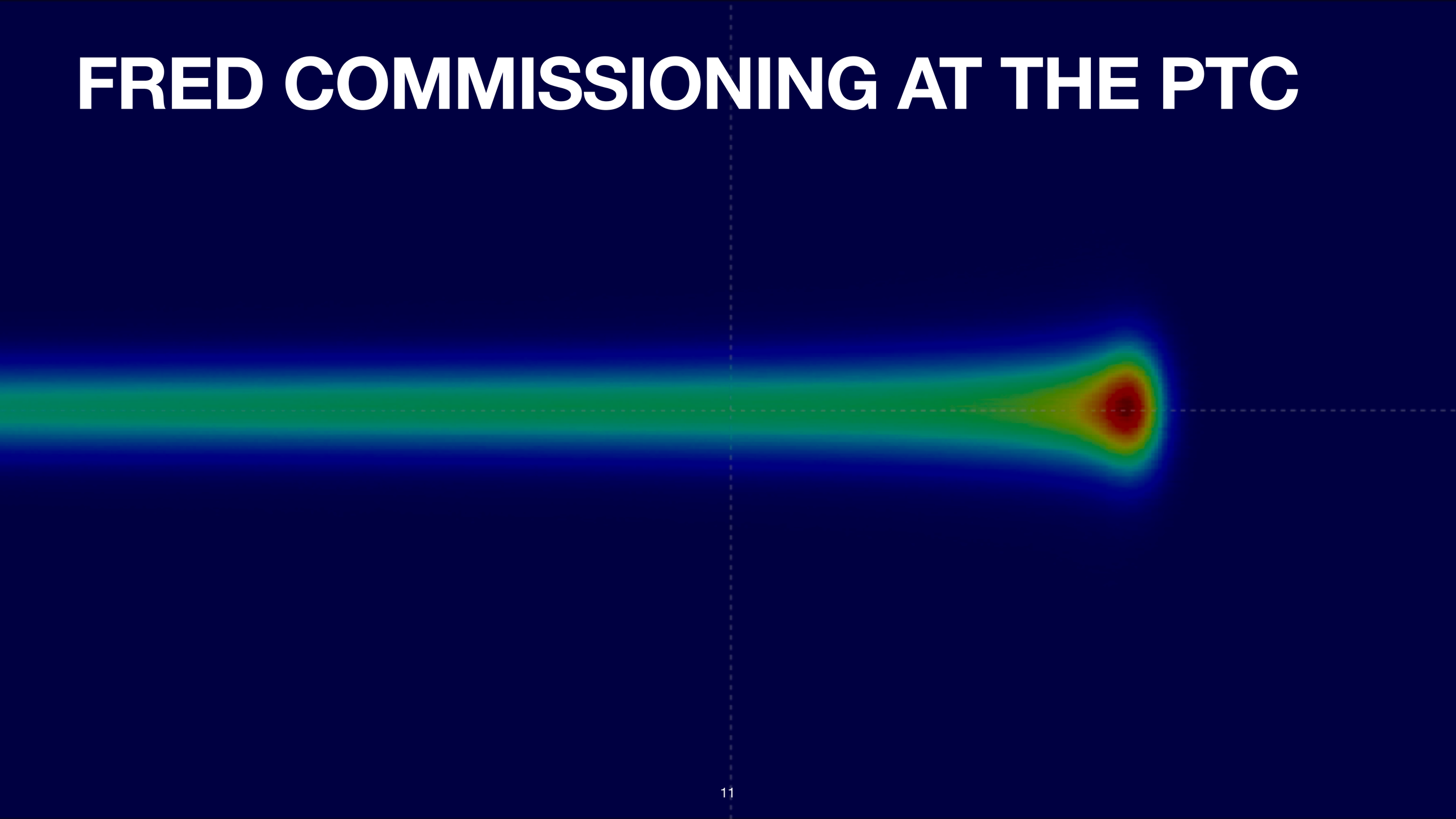
- Closed environments
- They have their own MC codes
  - e.g. VMC++, McVee, MCNP

Research

Much more flexibility:

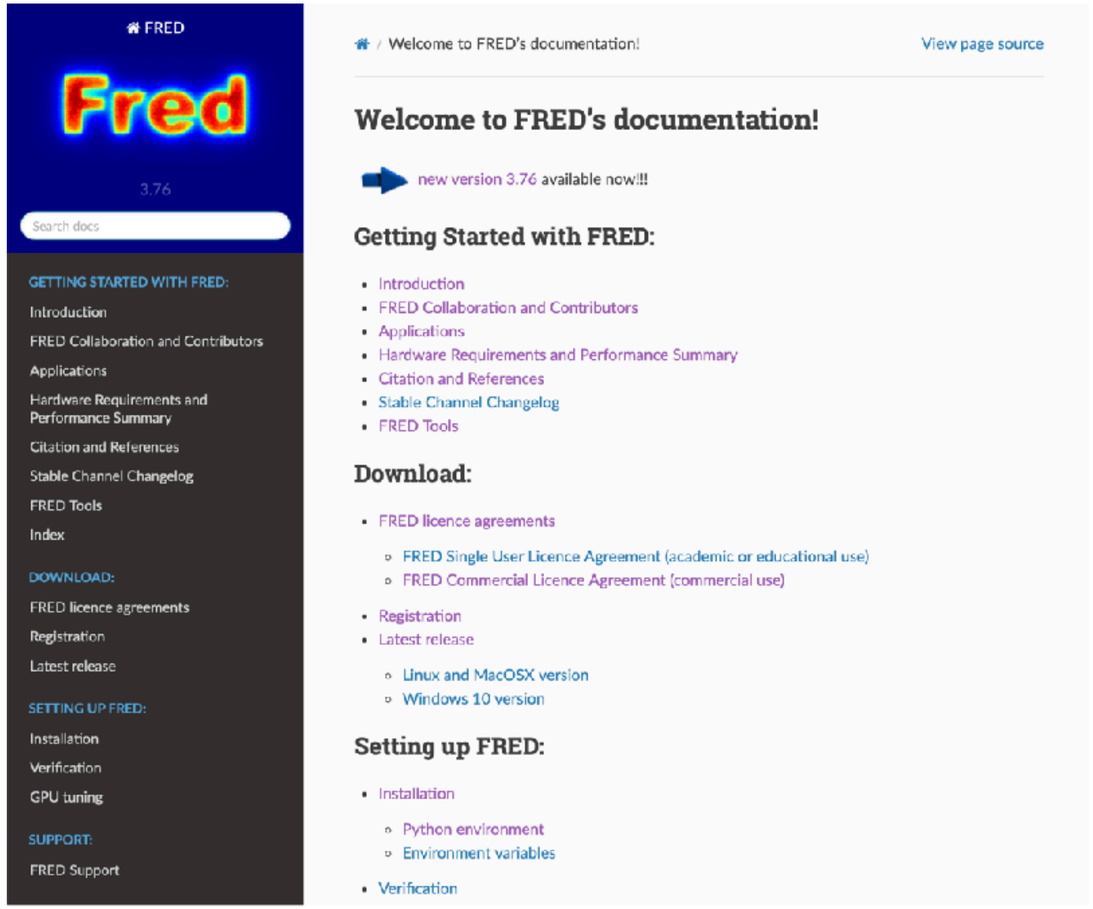
- TOPAS/GEANT4
- FLUKA
- PHITS
- FROG
- FRED

FRED COMMISSIONING AT THE PTC

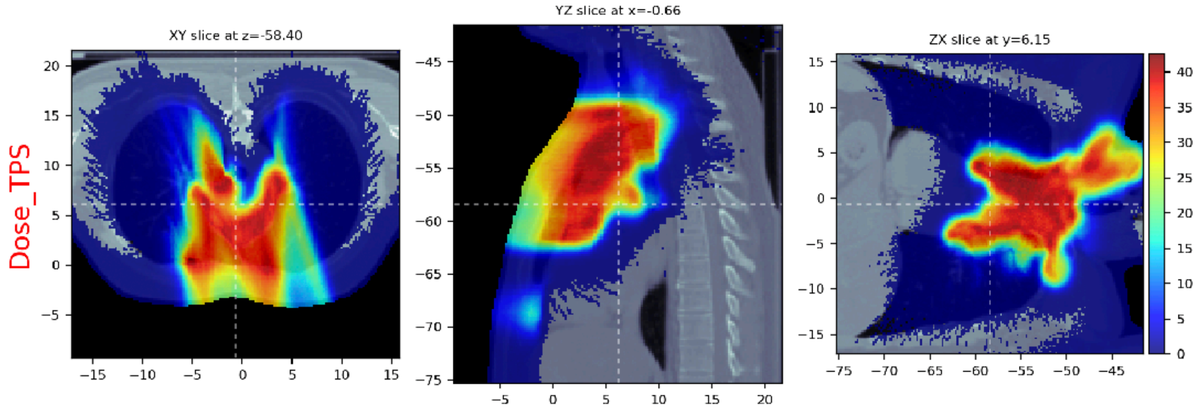


FRED

https://www.fred-mc.org

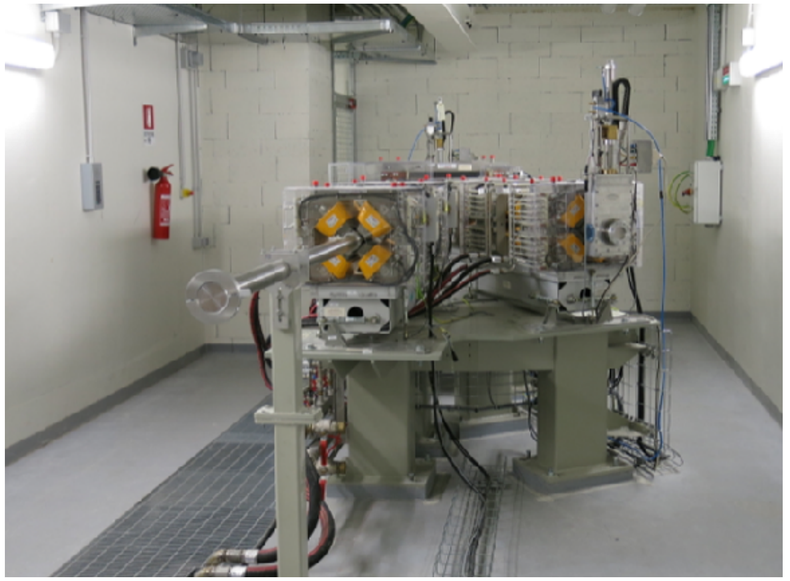


Fred	Hardware	primary/s	Patient plan recalculation*
FLUKA/GEANT4	single CPU card	750	16 days
FRED	single CPU card	15000	19 hours
FRED	single GPU card	10 mln	2.3 min
FRED	cluster of 144 GPU cards	300 mln	3 s



- Fast GPU-based MC simulation tool
- Free to download
- Already used in several centers (Krackow)

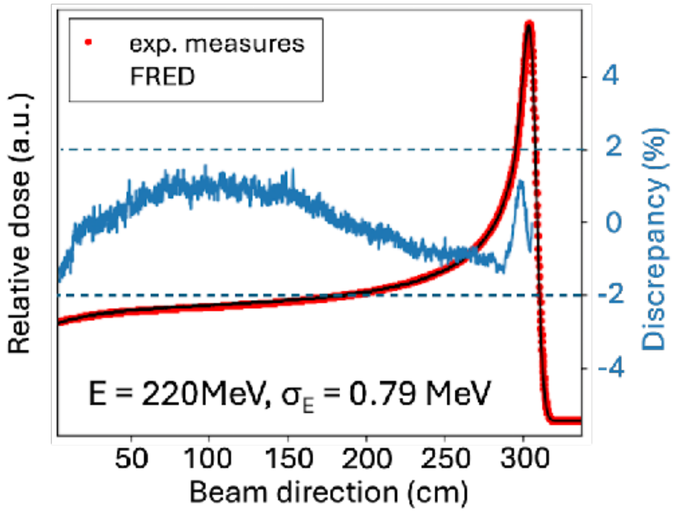
Proton Therapy Center



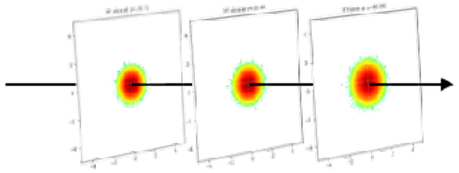
Commissioning of FRED at the Trento PTC:

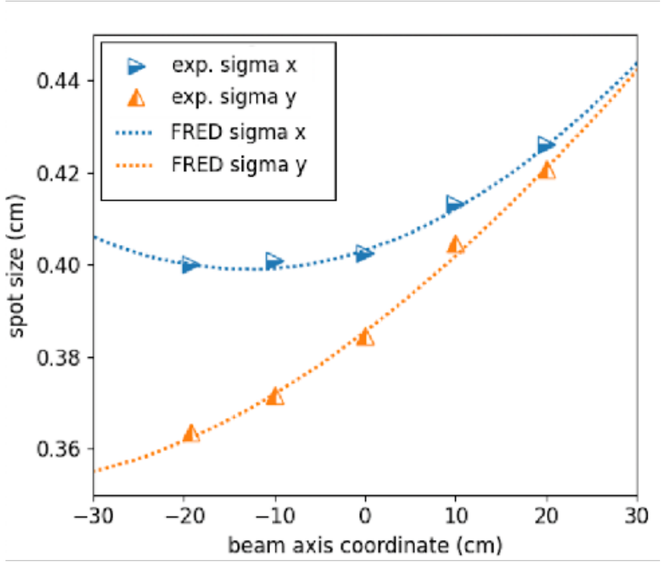
Implementation of a beam model in FRED that reproduces the experimental measurements:

IDD curves in water



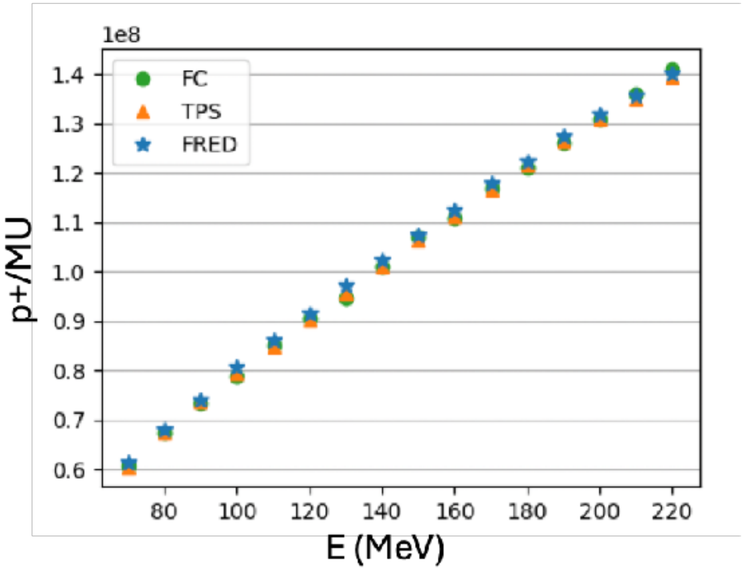
Beam envelope





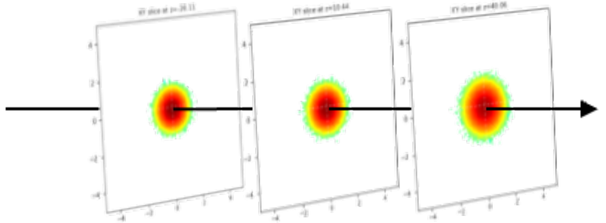
Absolute dose

p+ per MU



Commissioning of FRED at the Trento PTC:

FRED beam model of the Trento PTC gantry:

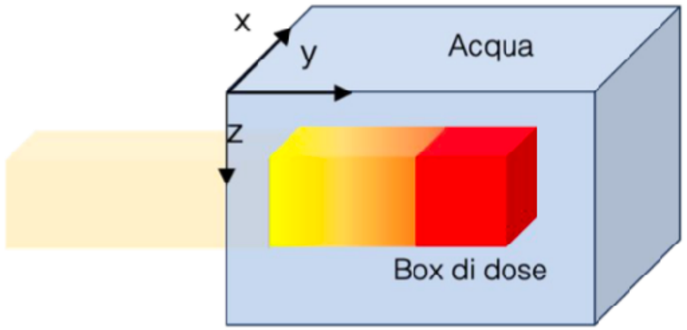


BeamModelTrento.txt — Edited

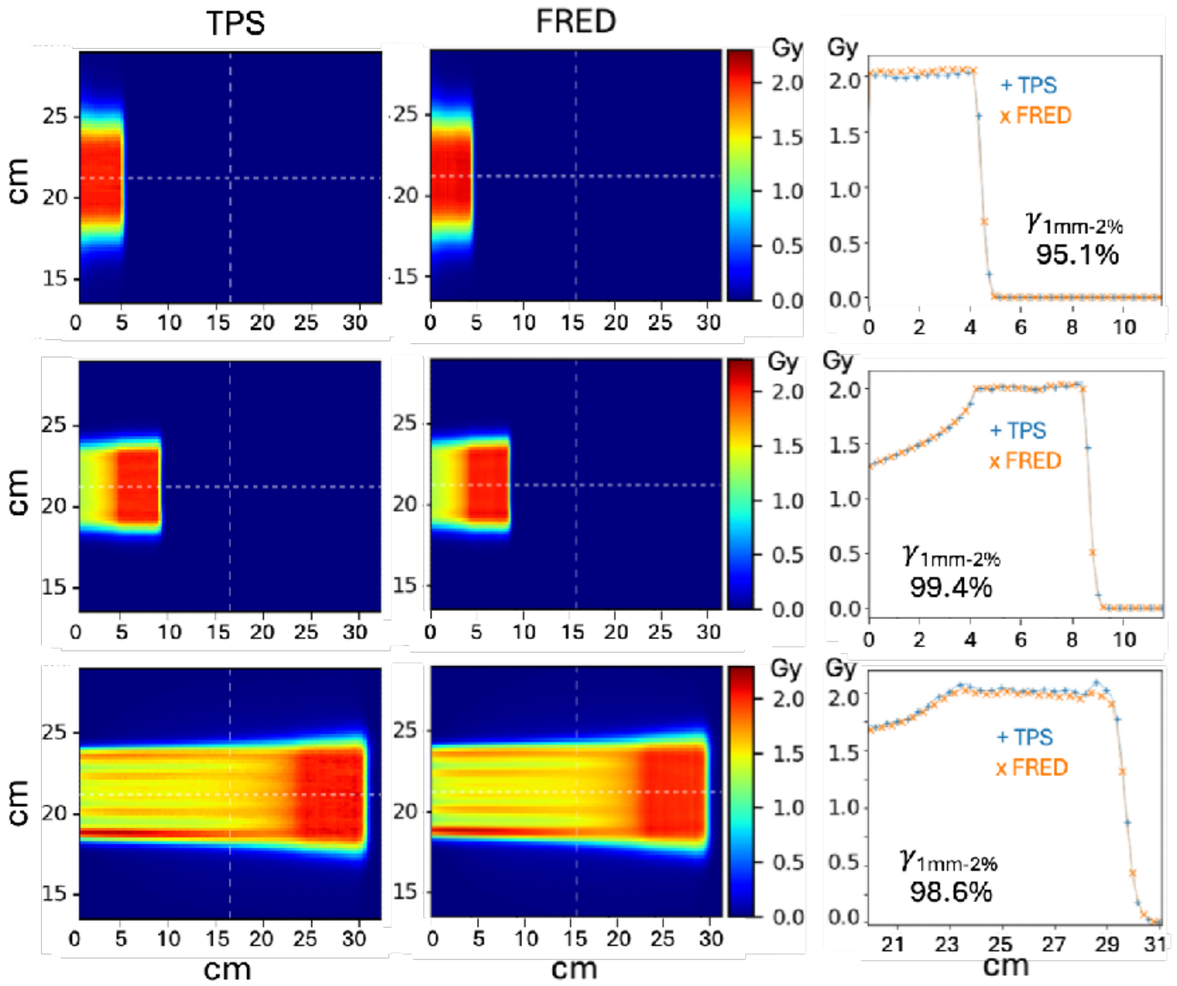
Energy	E_FRED	Estdv	scalingFactor	a	b	c
70	70	0.537	61763796	0.45942997	0.00507897173	0.0000466983828
80	79.5	0.601	68057733	0.379112328	0.00401386678	0.0000439473706
90	89.5	0.665	74516367	0.3119864565	0.002741264225	0.000031538124
100	100	0.725	80889750	0.251406487	0.00215583417	0.0000321582368
110	110	0.738	86143765	0.215123026	0.0019394009245	0.00002360597665
120	120	0.798	91770089	0.198061716	0.001930697131	0.00003234590525
130	130	0.866	96945631	0.1682579565	0.001058369548	0.00002173380445
140	140	0.914	102407639	0.155987675	0.000845052968	0.0000170596508
150	150	0.971	107486207	0.1384399995	0.000851585233	0.0000172967244
160	160	1.026	112368148	0.1237049995	0.0006565873705	0.00001452123535
170	170	1.080	117656017	0.1120199995	0.000578855607	0.00001048901939
180	180	1.132	122499841	0.09584710505	0.000576236009	0.000010670525415
190	190	1.180	127195521	0.0887478485	0.000525056504	0.0000123867057
200	200	1.028	131652819	0.08538307215	0.0005117450605	0.000009917546775
210	210.2	0.953	135451081	0.07801664675	0.000464558035	0.000008006540575
220	220	0.814	139696134	0.06997294125	0.0004193365505	0.00000737237942
226	226	0.754	142696134	0.06997294125	0.0004193365505	0.00000737237942

Commissioning of FRED at the Trento PTC:

Reproduction of Boxes of dose in water

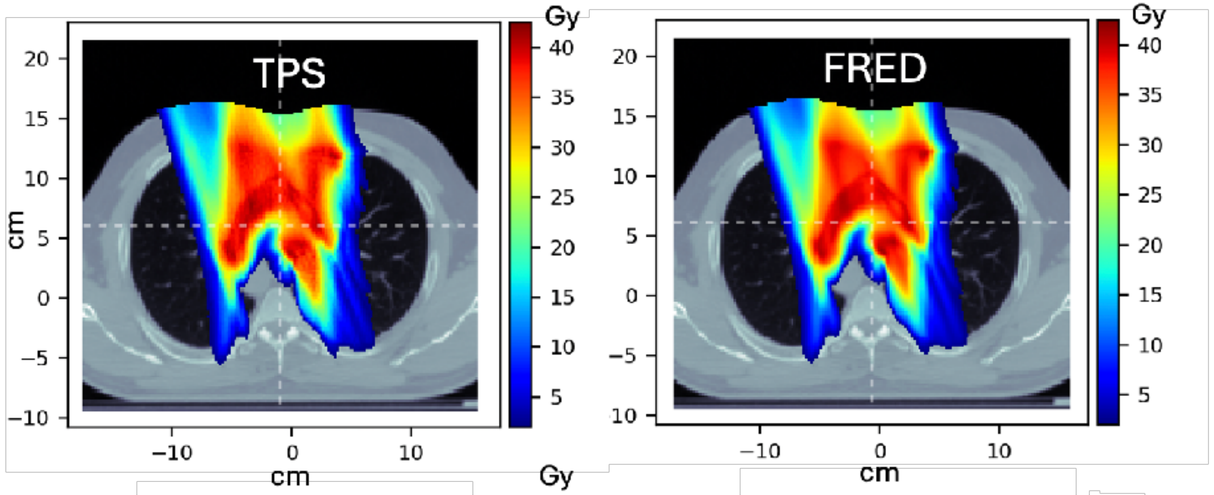


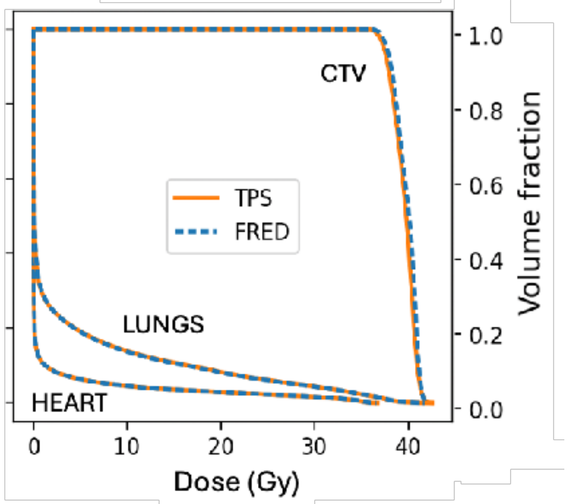
Esempio di piano di trattamento



Commissioning of FRED at the Trento PTC:

Validation of the model against a series of clinical cases





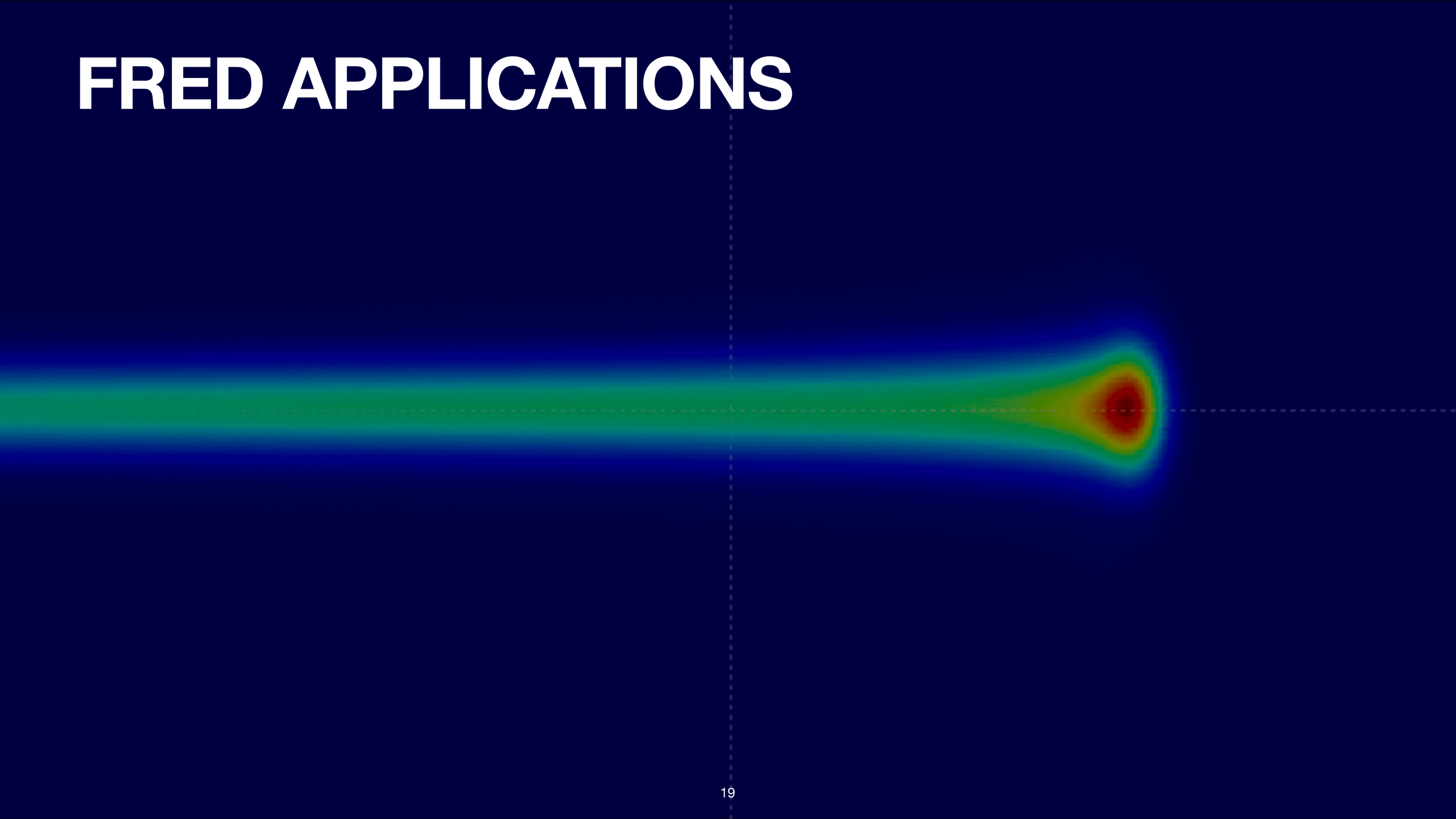
Patient pool:	γ pass rate 3%,3mm:
Lymphoma	99.9 %
Brain tumor	100%
Lung	99.8%
Paranasal sinunes	100%
CSI	98.5%
SRS	100%
Extremity	99.8%

“Taffelli et al. submitted, Physica Medica”

Now we have a Tool

What can we do with it?

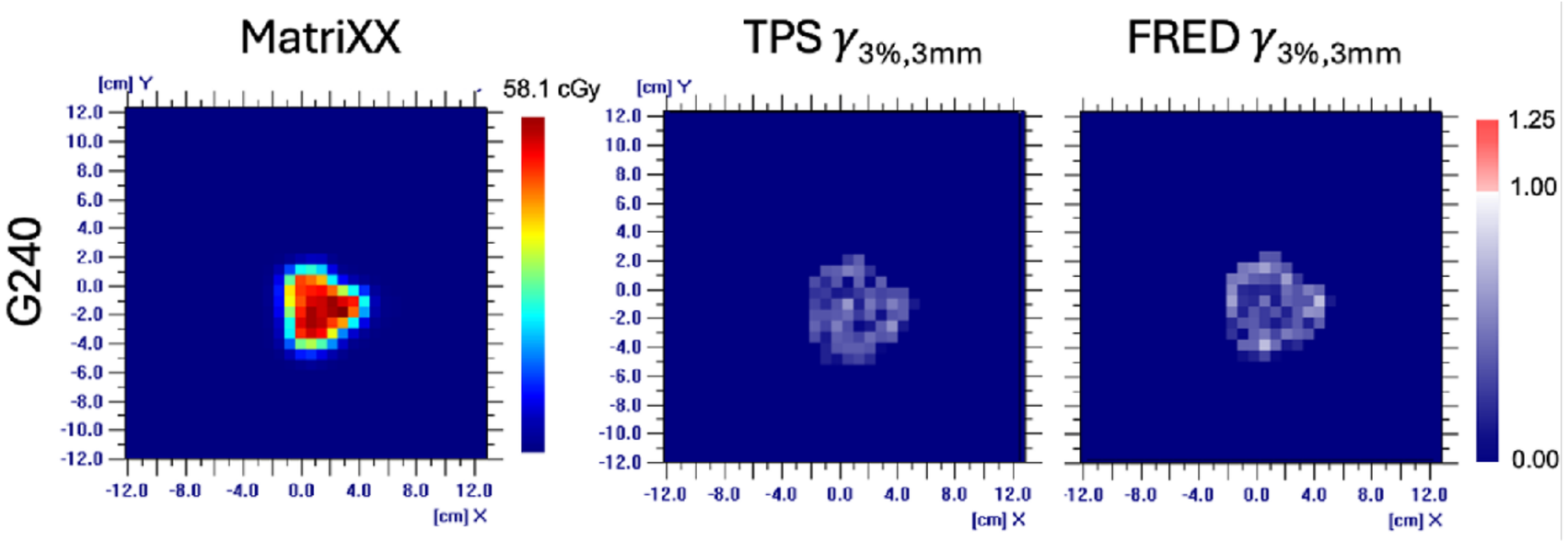
FRED APPLICATIONS



Applications: Patient-Specific Quality Assurance

- Quality assurance of the patient plan
- Procedure needed before irradiation
- Requires time and resources

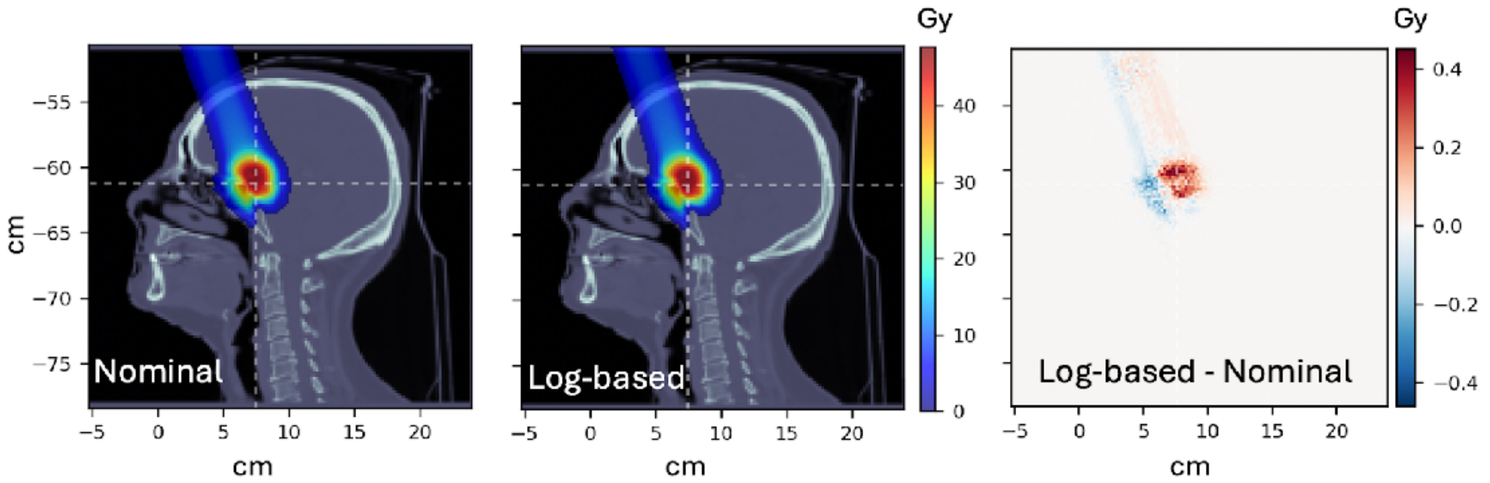
With an independent MC could be possible in seconds



Applications: Assessment of delivered plans

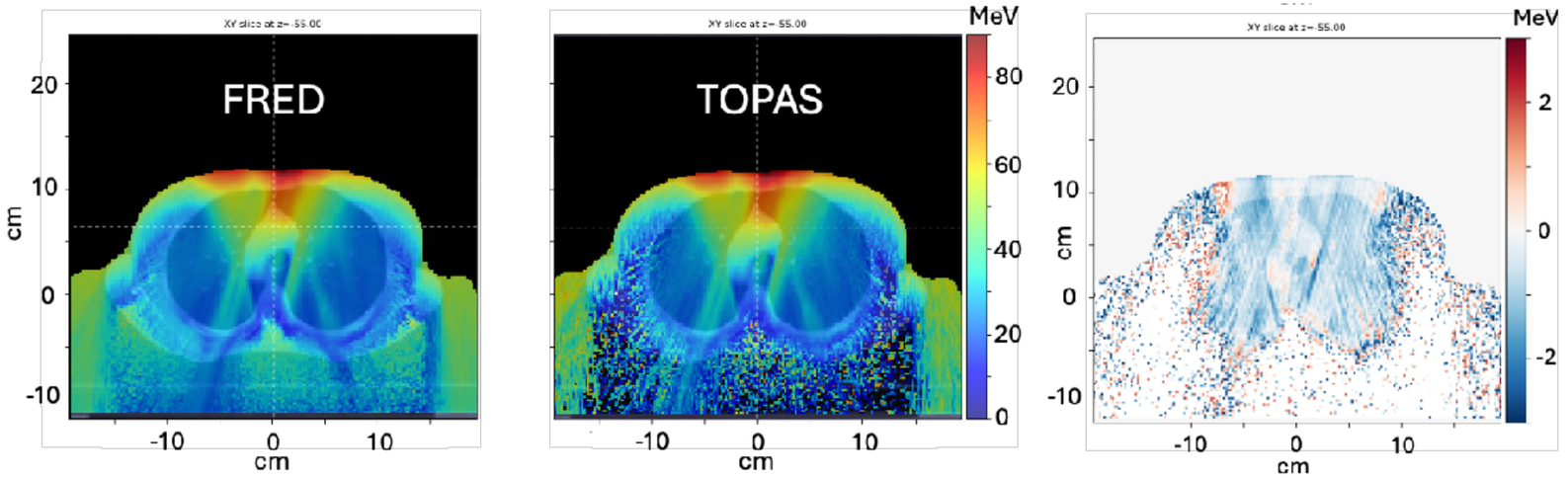
From the log-based irradiation files (information on the delivered plan), we can:

- Simulate the **delivered plan**
- Acquire information on the time-dose delivery structure
- Study possible correlation between **dose rate maps** and potential clinical outcomes

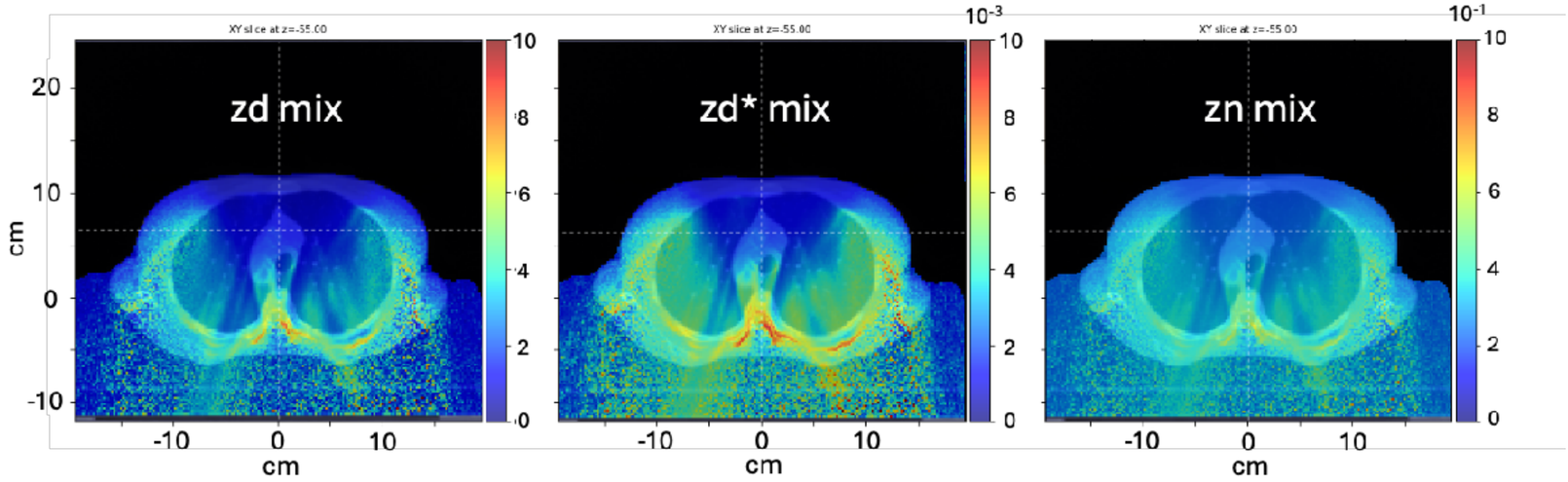


Applications: Assessment of radiobiological features

- With FRED we can also score fluence spectra of protons at the voxel level



- Assess important microdosimetric quantities for further radiobiological evaluations



Applications: UHDR irradiation and FLASH proton therapy

What's FLASH? ⚡

- An effect that occurs when irradiating at ultra-high dose rates (**UHDR > 40Gy/s**)
- Conventional irradiation is 0.01 Gy/s
- There is a **protective effect on normal tissues**, while maintaining the same efficacy against tumours
- The mechanism is still **unclear**

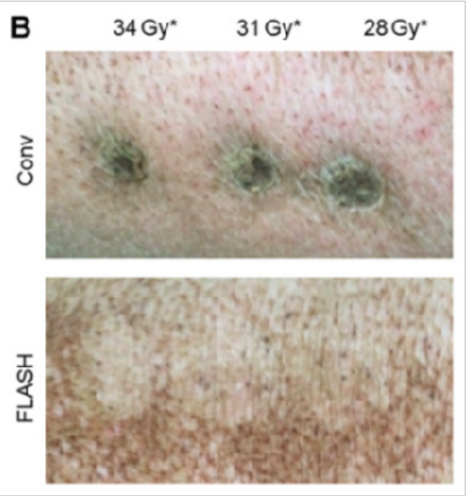
  Hypoteses:

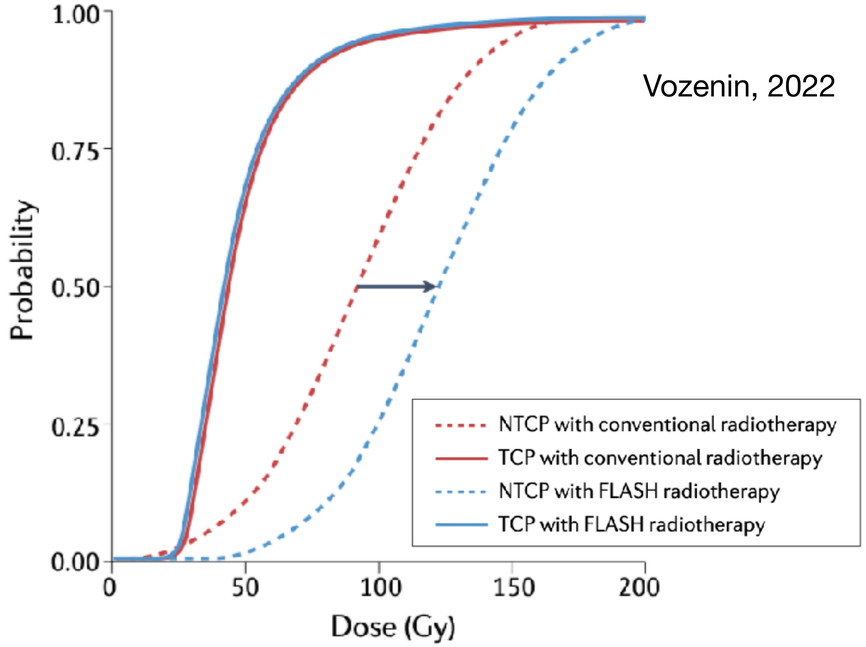
  - ◆Transient hypoxia
  - ◆ Radical recombination
  - ◆ Inter-track effects
  - ◆ Immune system

- In RT = increase the **therapeutic window**

Favaudon 2014
Sci Transl Med;
Vozenin 2019 Clin
Cancer Res

6 MeV e- beam



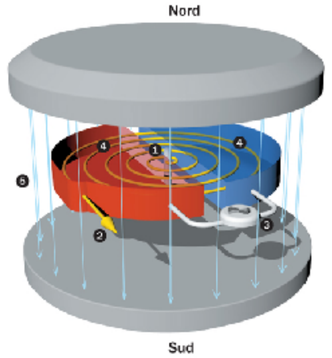


Vozenin, 2022

Applications: UHDR irradiation and FLASH proton therapy

Proton delivery systems:

The proton beam is accelerated by a cyclotron up to energies of 230 MeV



Dose rate: $\dot{D} = \frac{i_p}{A}\frac{S}{\rho}\ \frac{\mathrm{Gy}}{\mathrm{s}}$

i_p= beam current in nA
A= transversal area in cm²
S/ρ= Mass Stopping Power in MeV*cm²/g

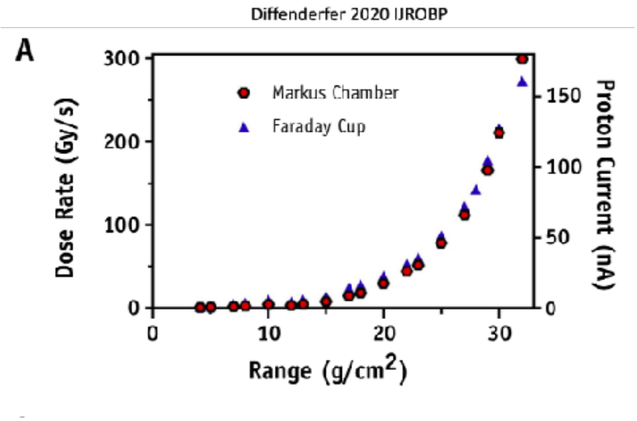
With values representative for current practice, e.g. i_p=2nA, A=25 cm² and S/ρ=5 MeV*cm²/g

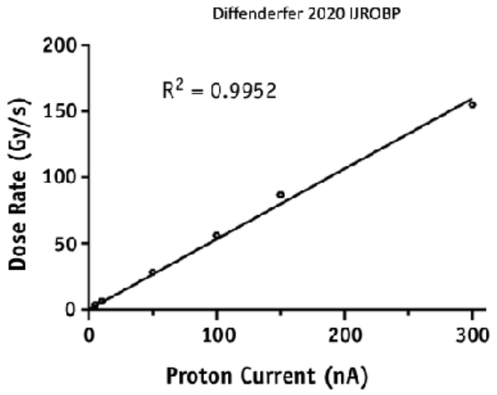
Dose rate = 0.4 Gy/s

increasing the I_p up to 200nA?

Dose rate > 40 Gy/s

Perfect for studies in the experimental room, but..





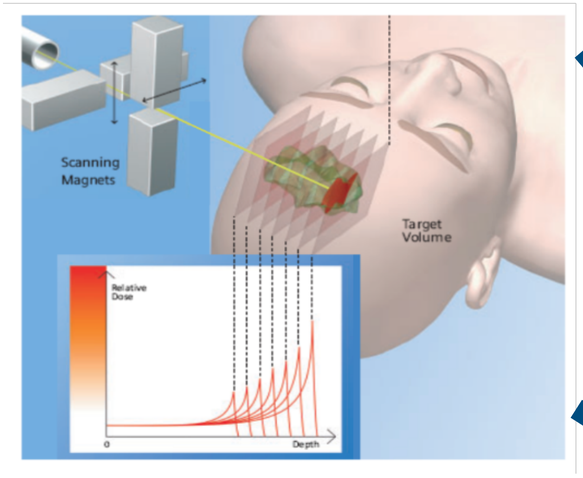
Applications: UHDR irradiation and FLASH proton therapy

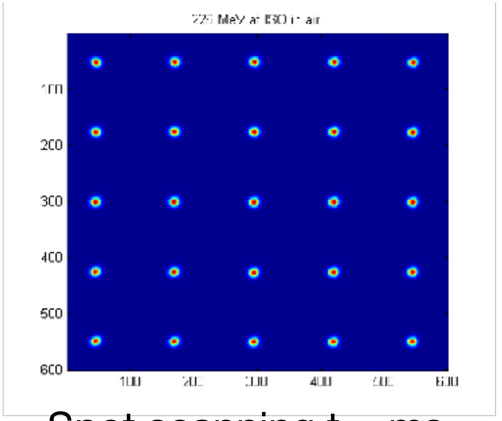
Proton delivery systems:

The proton beam is actively scanned to deliver dose to the target

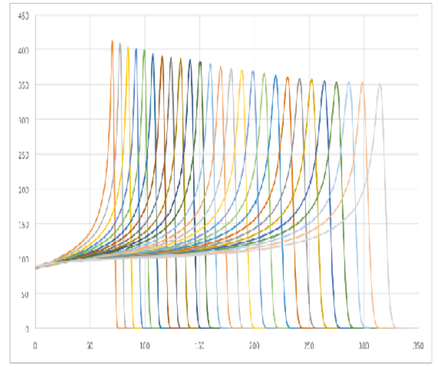
$$\dot{D}(x,y,z) = D(x,y,z)/T$$

$$T = \sum_n \left[T_0(x_n, y_n) \frac{MU_n}{MU_{n0}} \frac{I_o}{I_n} + T_{slew} \right] + \sum_m T_{energy\ switch,\ m}$$





Spot scanning t ~ ms

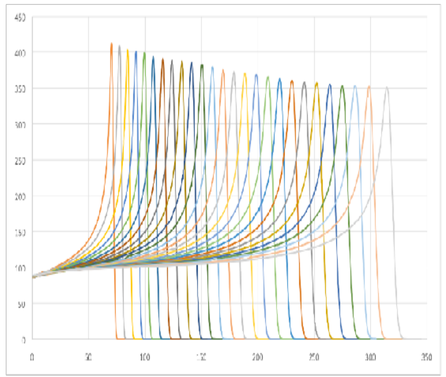


Energy switching t ~ 0.5-2s

FLASH is incompatible with what we are doing in proton therapy

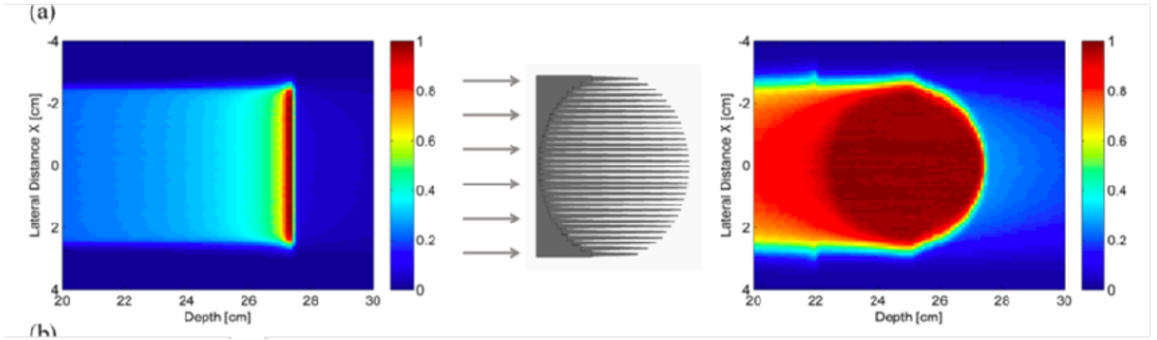
Applications: UHDR irradiation and FLASH proton therapy

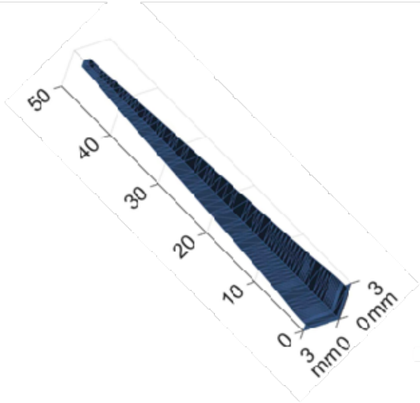
Active scanning

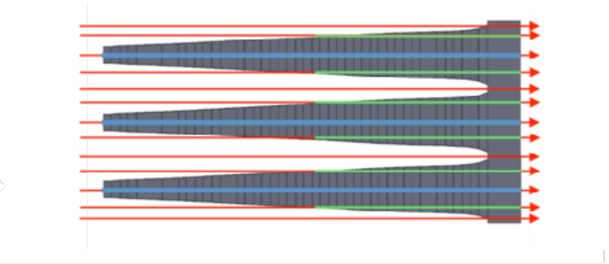


Energy switching t ~ 0.5-2s

Passive scanning with 3D Range Modulators



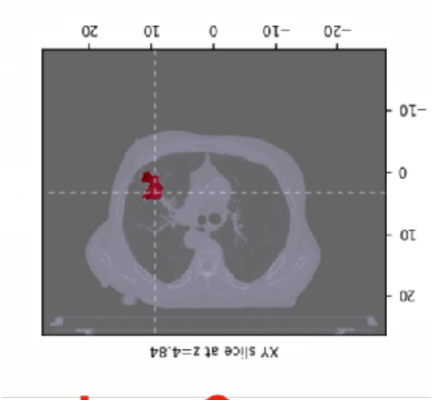




- 3D printed objects
- Attenuate the protons passively
- No switching, only maximum energy

Applications: UHDR irradiation and FLASH proton therapy

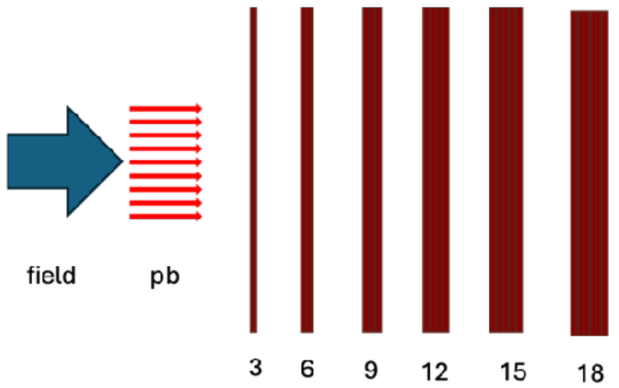
Use of FRED to model the 3DRM

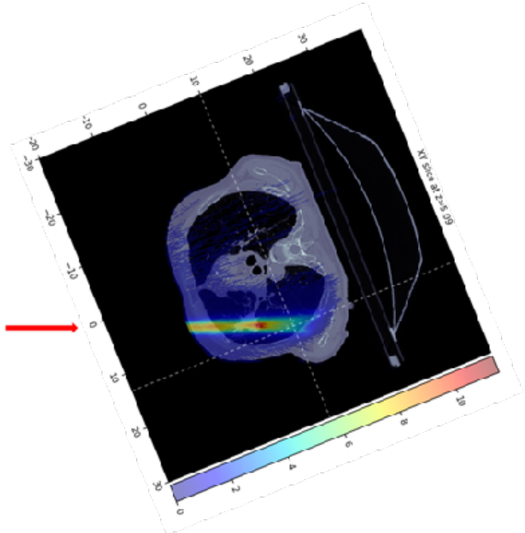


Case: **Lung Cancer**

- Creation of Look Up Tables (LUTs) of dose distributions with Fred
- Opposed to standard analytical methods

for each pb we simulate with FRED a dose map
for increasing thickness of the attenuator



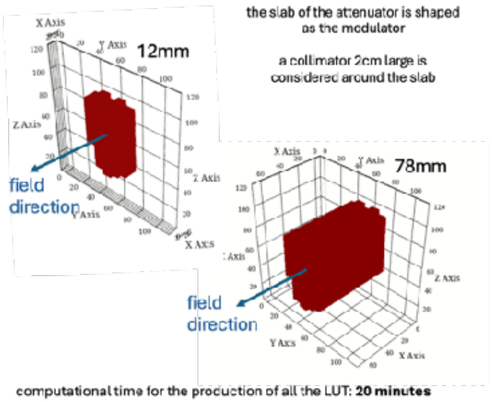


Dose map for #pb and #thickness

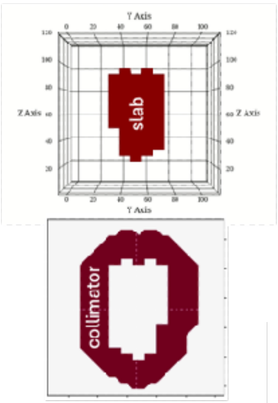
attenuator

the slab of the attenuator is shaped as the modulator

a collimator 2cm large is considered around the slab



computational time for the production of all the LUT: **20 minutes**

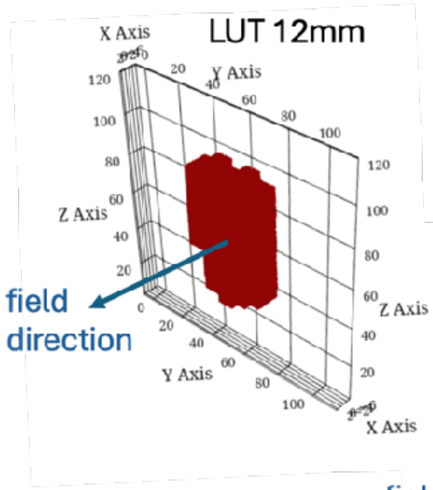


FORM3D

Fast Optimization of Range Modulators 3D

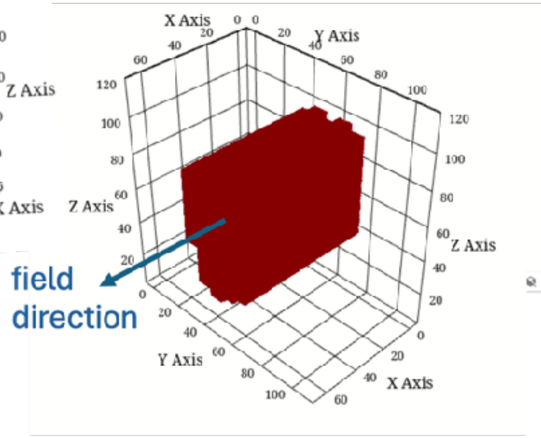
Applications: UHDR irradiation and FLASH proton therapy

Use of FRED to model the 3DRM

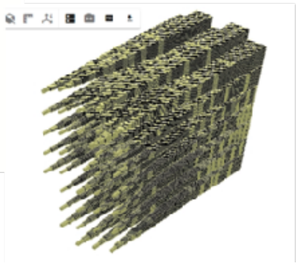


New LUTs

LUT 78mm

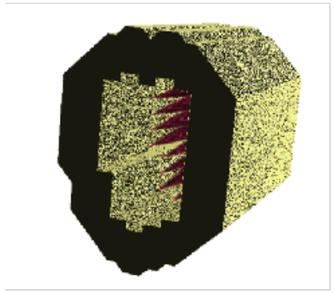


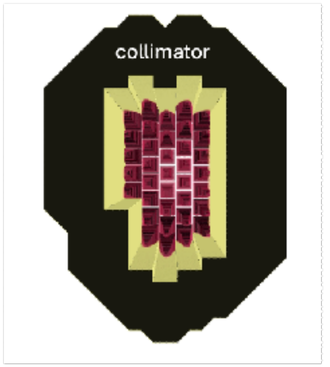
Optimized 3DRM shape

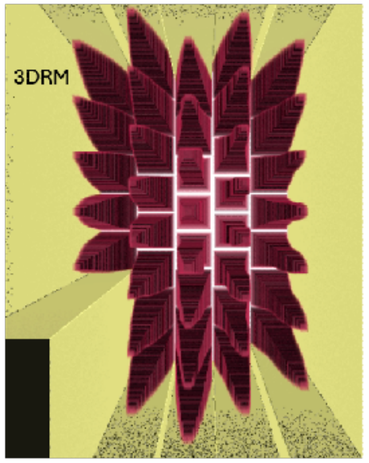


pb	mm	weight	pin length (res 0.1mm)
1	0.0	2.369	0.80 cm
1	3.0	2.318	0.79 cm
1	6.0	2.430	0.77 cm
1	9.0	2.390	0.75 cm
1	12.0	2.448	0.74 cm
1	15.0	2.560	0.72 cm
...	...	...	...
2	0.0	...	...
...	...	...	...

collimator + 3DRM







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Fast Optimization of Range Modulators 3D

Applications: UHDR irradiation and FLASH proton therapy

Comparison with the active case:

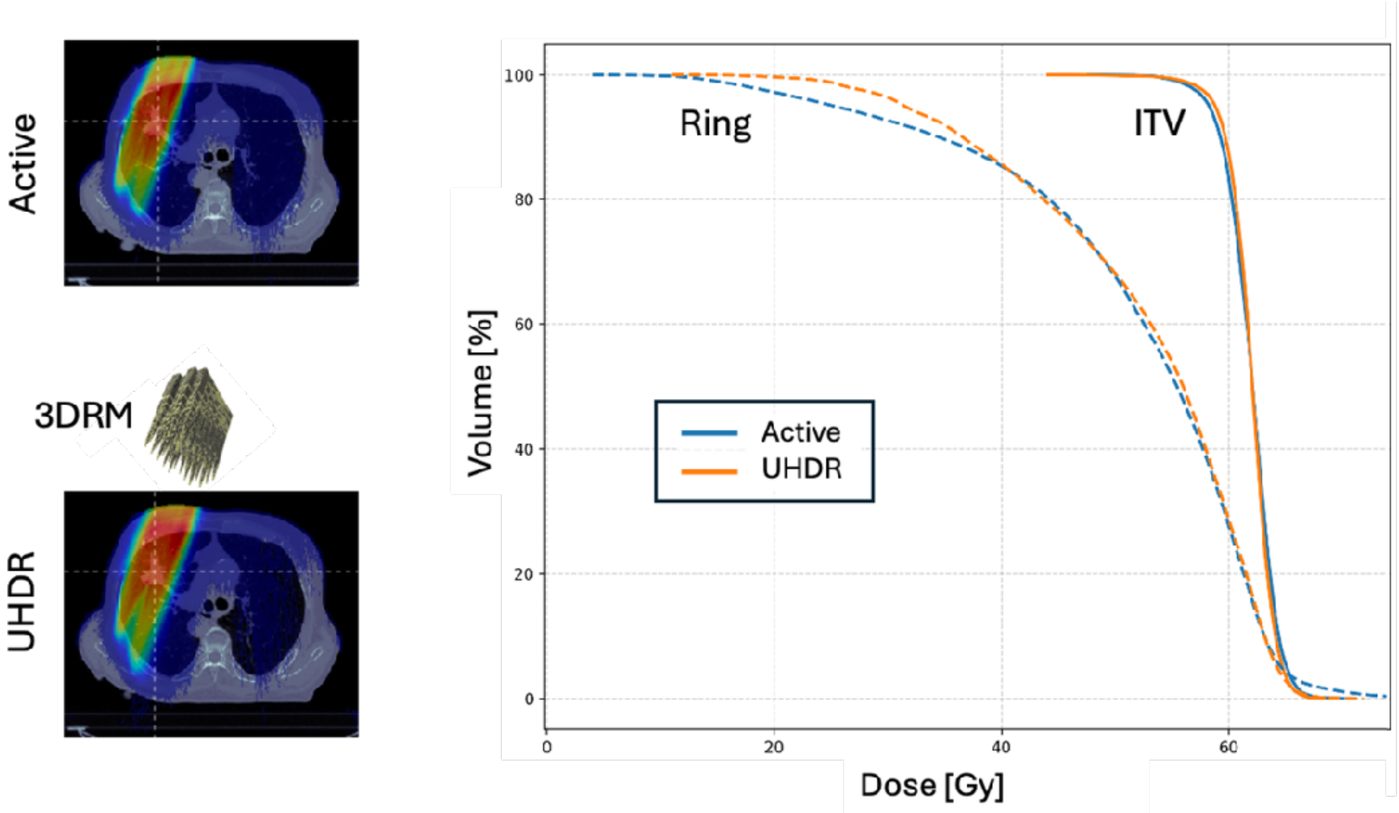

Fig.1: Dose distribution for the active plan and passive (UHDR) plan (left), and corresponding DVHs for the ITV and Ring structures (right).

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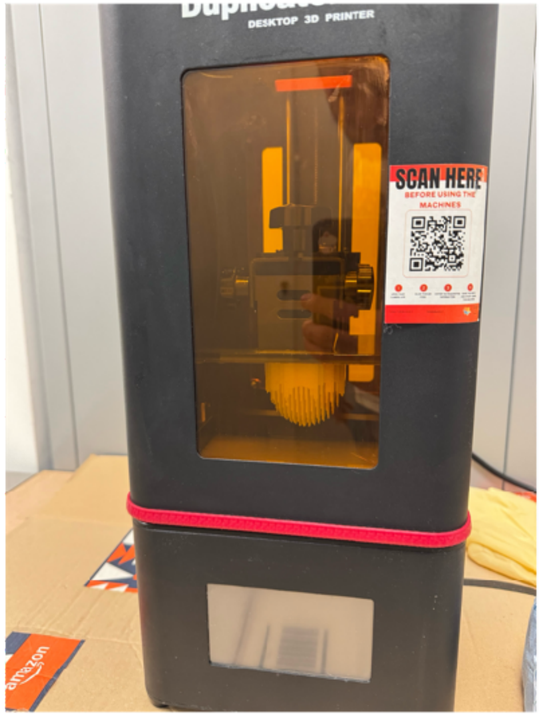
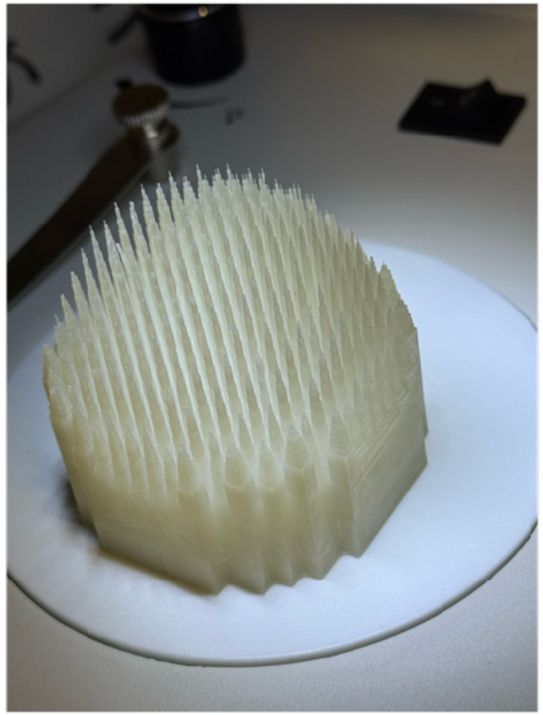
Fast Optimization of Range Modulators 3D

Applications: UHDR irradiation and FLASH proton therapy

Printing of the modulator:





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Fast Optimization of Range Modulators 3D

Incoming event on FLASH radiotherapy:

Submit your abstract before 31st of March!!!

https://4thflashworkshop.unitn.it/