Dottorato in Fisica degli Acceleratori, XXIX ciclo

Optimization of hadron therapy proton beam using Monte Carlo code on GPU

Candidata: **Martina Senzacqua**
N° matricola: **1163436**

Supervisor: **Prof. Vincenzo Patera** Second Supervisor: **Prof. Angelo Schiavi**

Particle Therapy (PT)

Cancer treatment technique using accelerated beams of protons or positive ions to treat solid tumor volumes.

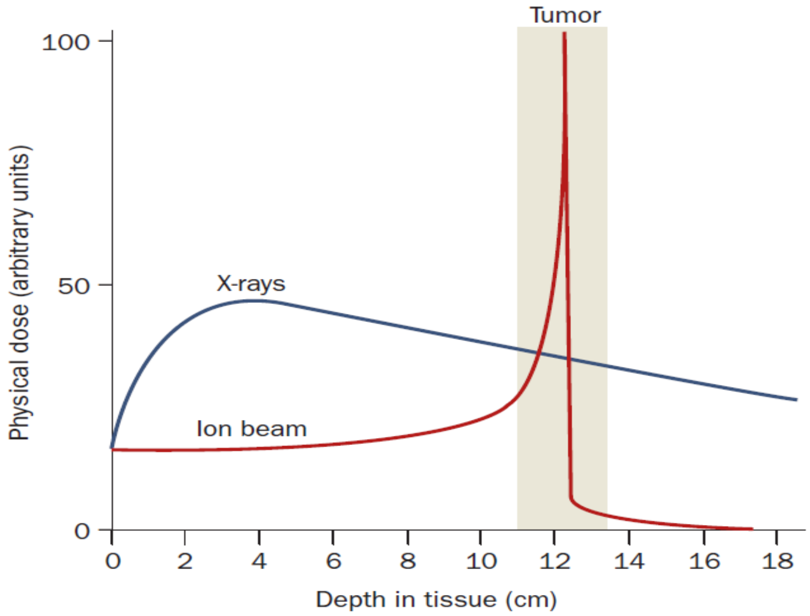
Dose $$D = \frac{\mathrm{d}\,E}{\mathrm{d}\,m}$$ Gy [J/Kg]

Particle Therapy (PT)

Cancer treatment technique using accelerated beams of protons or positive ions to treat solid tumor volumes.

Dose $$D = \frac{\mathrm{d}E}{\mathrm{d}m}$$ Gy [J/Kg]

X-rays radiotherapy vs particle therapy



Most of the energy released at the end of path

Sharp decrease in energy after the Bragg Peak

⇨

Better dose distribution to preserve critical organs and surrounding healthy tissues

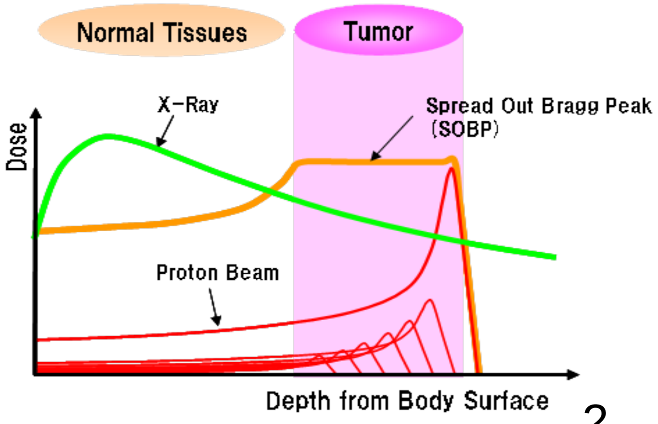
Cancer irradiation techniques goal:

Conformal dose distribution

concentrate all the dose to tumor and spare healthy tissues

- x-rays radiotherapy   Intensity Modulated Radiation Therapy (**IMRT**)
    - Different beam directions (**fields**)
    - Dynamic delivery (Different beams fluences, tissue compensator)

- Particle therapy   Spread Out Bragg Peak (**SOBP**)
    - Active tumor volume scanning
    - Superposition of beams with different energies



Cancer irradiation techniques goal:

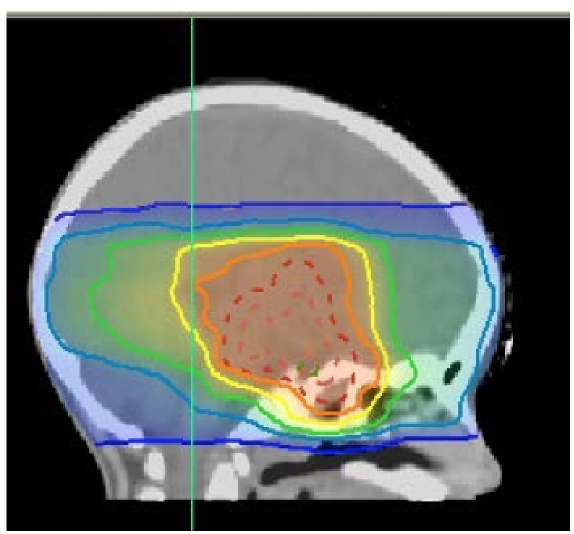
Conformal dose distribution

concentrate all the dose to tumor and spare healthy tissues

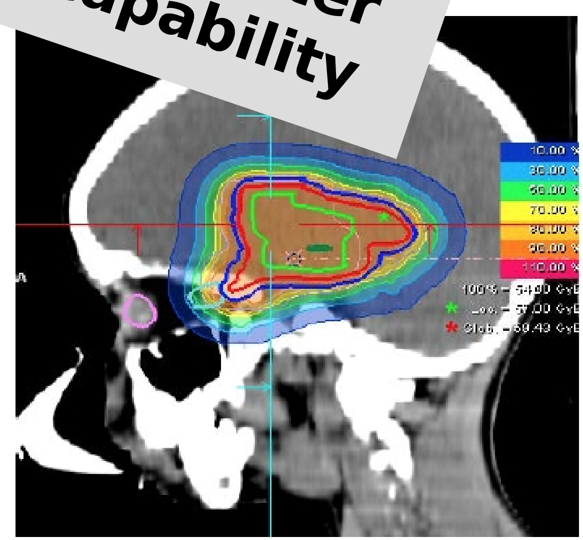
PT exhibits a better conformal capability

- x-rays radiotherapy Intens lated Radiation Therapy (**IMRT**)
  - Different beam directions (m
  - Dynamic d or)
- Particle thera
  - Active tur
  - Superpos

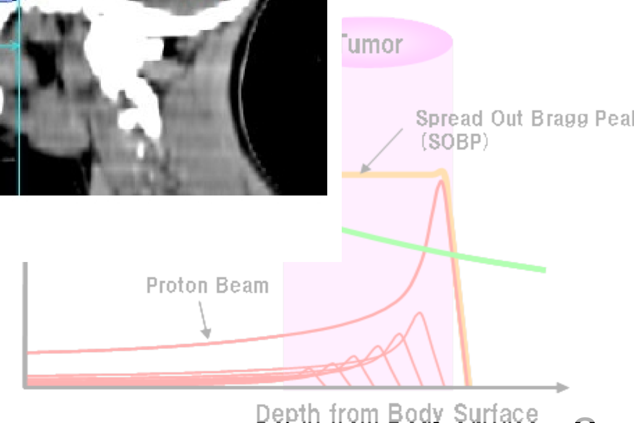
Photon-IMRT



Universitätsklinikum Dresden



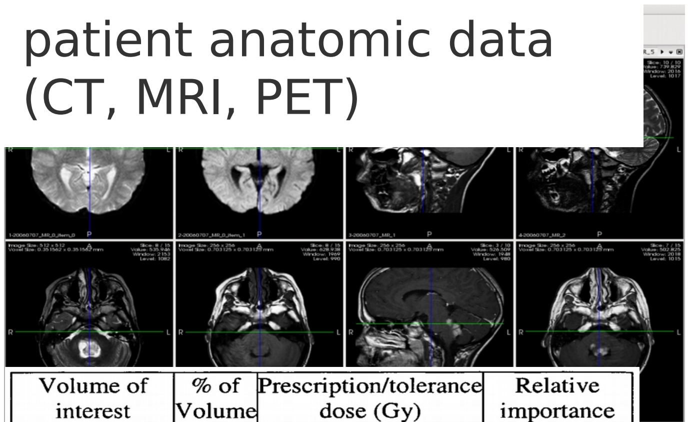
HIT, Heidelberg



The high **selectivity** in energy release asks for an high level of **accuracy** in the computation of beams to be delivered to the patient

Treatment Planning System (TPS)

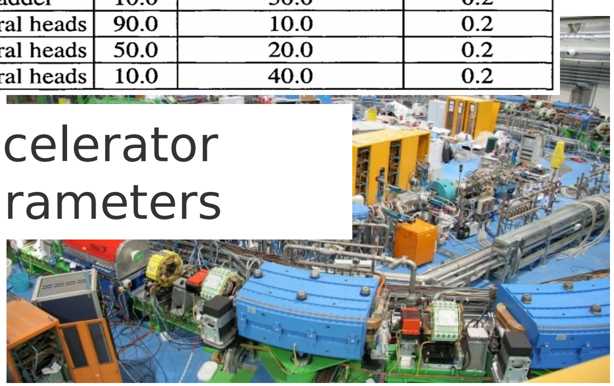
patient anatomic data
(CT, MRI, PET)



Volume of interest	% of Volume	Prescription/tolerance dose (Gy)	Relative importance
Prostate PTV	100	74.0	1.0
			1.0
			1.0
			0.5
			0.5
			0.5
[illegible]	[illegible]	[illegible]	0.2
Bladder	50.0	20.0	0.2
Bladder	10.0	30.0	0.2
Femoral heads	90.0	10.0	0.2
Femoral heads	50.0	20.0	0.2
Femoral heads	10.0	40.0	0.2

Radiotherapist
prescriptions

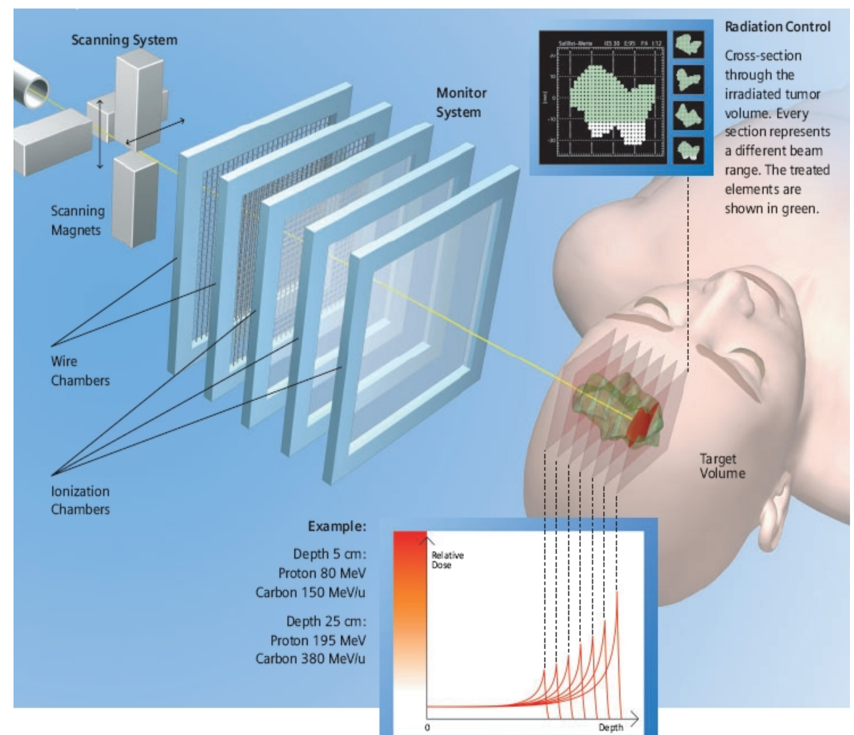
Accelerator
parameters



TPS

Treatment Plan (TP)
Accelerator control:

- Fluence Φi
- Energy Eki
- Direction θi



Nowadays one of the major issues related to the TPS in Particle therapy is the **large CPU time needed**.

Options:

- FULL-MC recalculation using standard codes ~ 72 h/core
- Commercial TPS using analytical pencil beam algorithm ~ 1 h/core

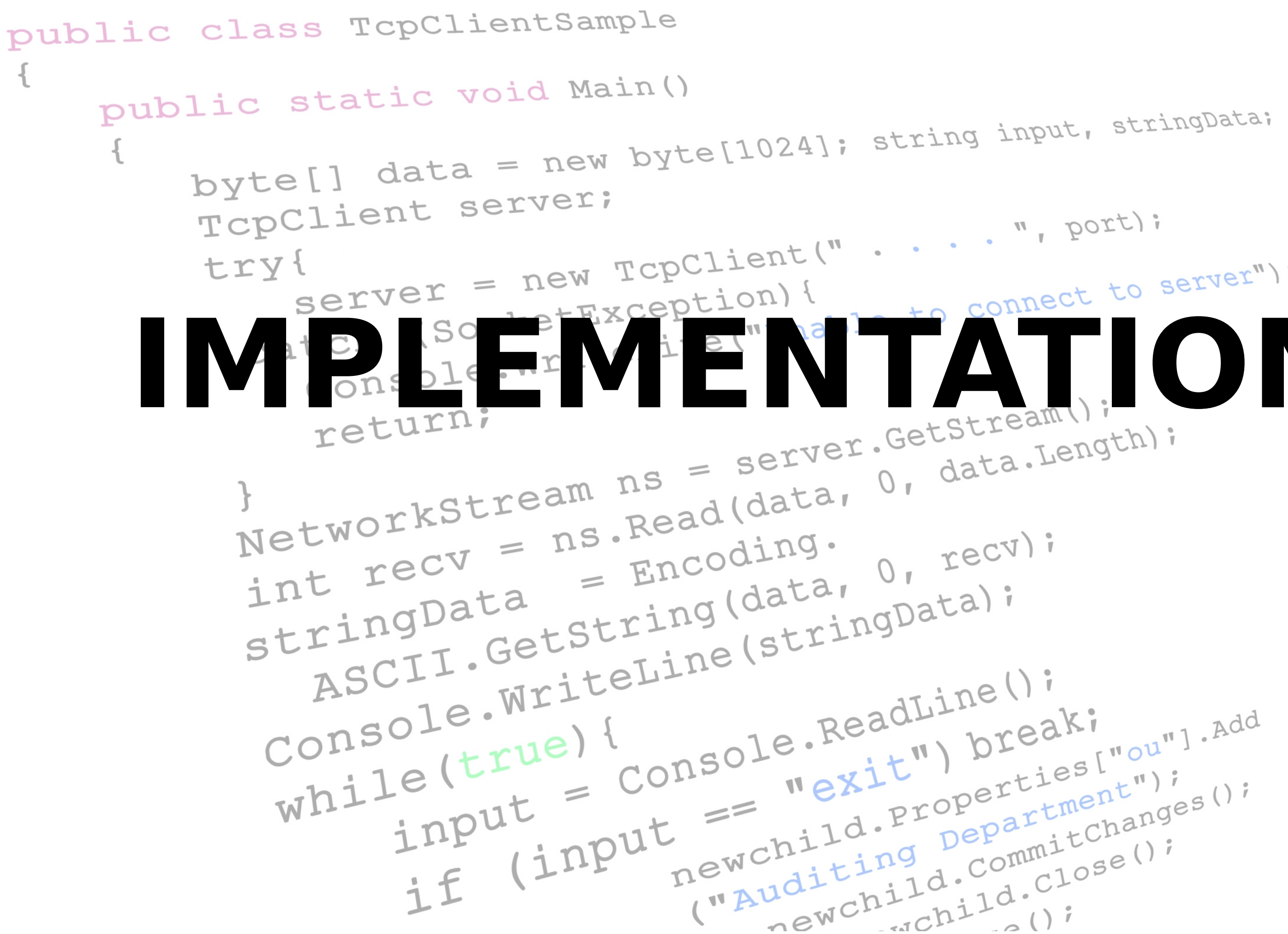
FRED is a fast MC able to perform a complete recalculation of **proton** TP in **less than 1 minute**

(**F**ast pa**R**ticle th**E**rapy **D**ose evaluator)

NVIDIA Graphic Process Units

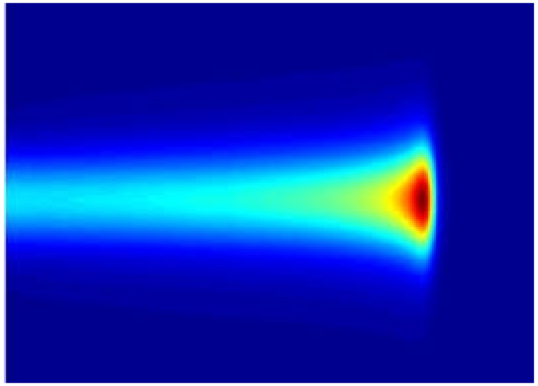
- Low budget
- Redundancy
- In-house maintenance

IMPLEMENTATION



Physics models in FRED

- Stopping Power
- Energy fluctuations
- Multiple Coulomb scattering (MCS)
- Nuclear Interactions



Stopping power and energy fluctuations

Stopping Power $\frac{dE}{dx}(x, N_e, v, E, \beta, \gamma, I)$ [1]

Mean energy loss per travelled distance

Energy fluctuations

Thick absorber

Gaussian distribution of energy loss

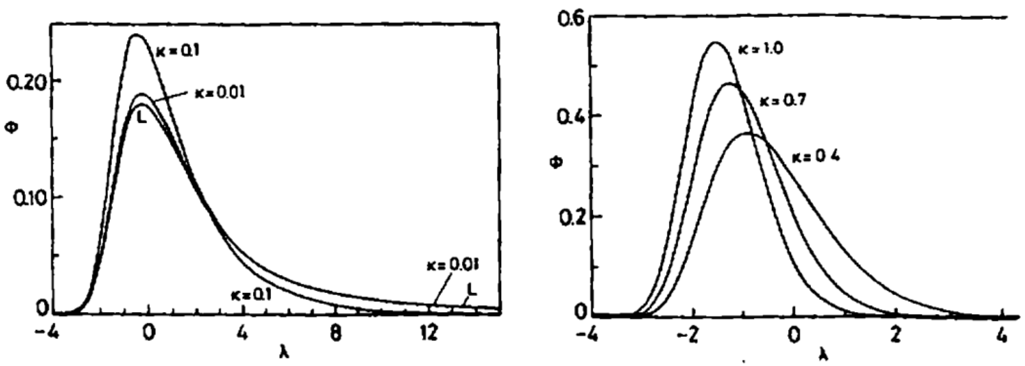
$$\Omega^2 = 0.0855\rho\delta z \frac{Te_{\max}}{\beta^2}\left(1 - \frac{1}{2}\beta^2\right) \mathrm{MeV}$$

[1] H. Bethe und J. Ashkin in "Experimental Nuclear Physics", ed. E. Segré, J. Wiley, New York, 1953, p. 253

Energy fluctuations

Thin absorber

Landau-Vavilov distribution of energy loss



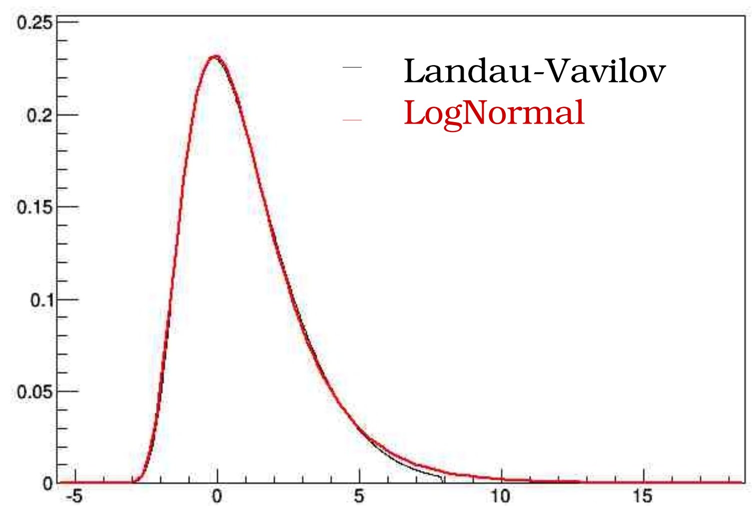
$$\phi(\lambda) = \frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} \exp(u + \ln(u) + \lambda u)du \quad c \geq 0$$

$$\lambda = \frac{\epsilon - \bar{\epsilon}}{\xi} - \gamma' - \beta^2 - \ln\frac{\xi}{E_{\max}}$$

Large time-consuming computation

Approximation with
logarithmic normal function

$$L_N(\lambda_v) = \frac{1}{(\lambda_v - \theta)\sqrt{2\pi}\sigma} \exp - \frac{(\ln(\frac{\lambda_v - \theta}{m}))}{2\sigma^2}$$



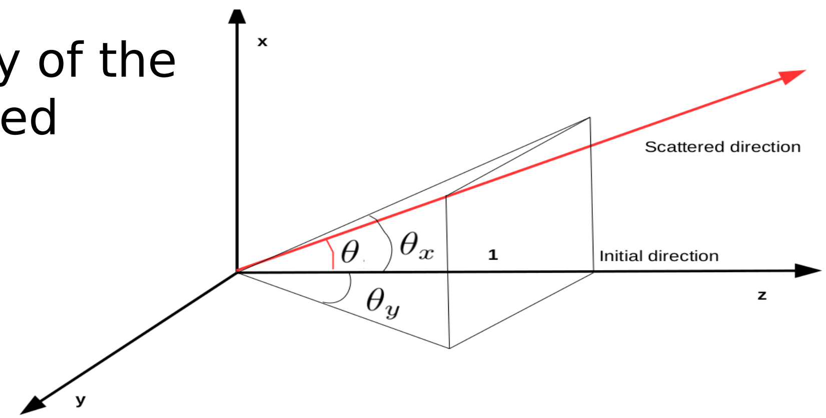
Fast sampling algorithm

Multiple Coulomb Scattering [1/3]

Distributions of **projected angles** θx and θy of the angle θ have been studied and modelized

Small angles approximation: sin(θ) ~ θ:

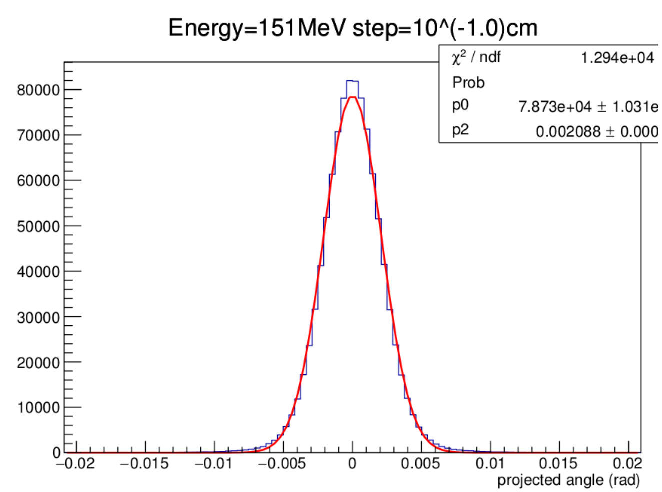
$$\theta = \sqrt{\theta_x^2 + \theta_y^2}$$

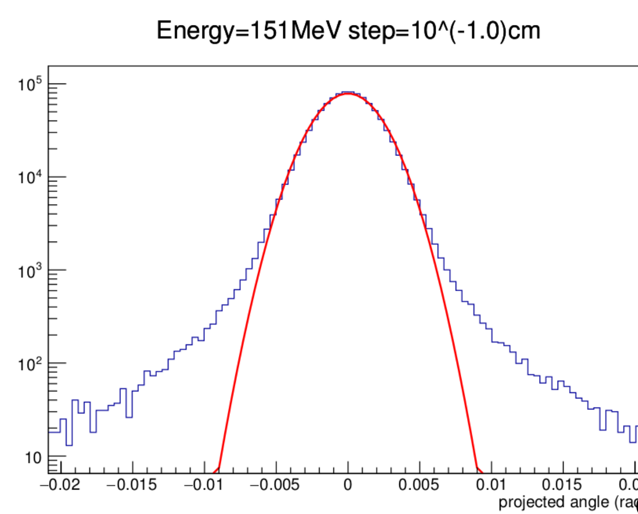


1) Single Gaussian model $f_G(\theta_{x,y}) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\theta_{x,y}}{\theta_0}\right)^2\right]$

<u>Highland formula:</u>

$$\theta_0 = \frac{14.1MeV}{pv} z \sqrt{\frac{L}{L_R}} \left[1 + \frac{1}{9}\log\left(\frac{L}{L_R}\right)\right] rad$$



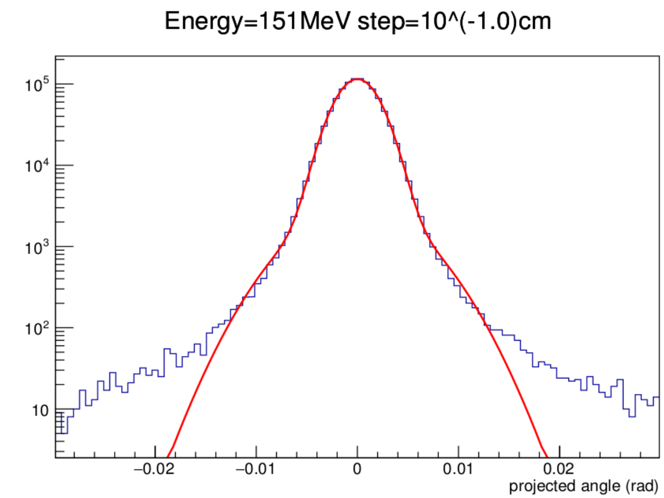


Multiple Coulomb Scattering [2/3]

2) Double Gaussian model

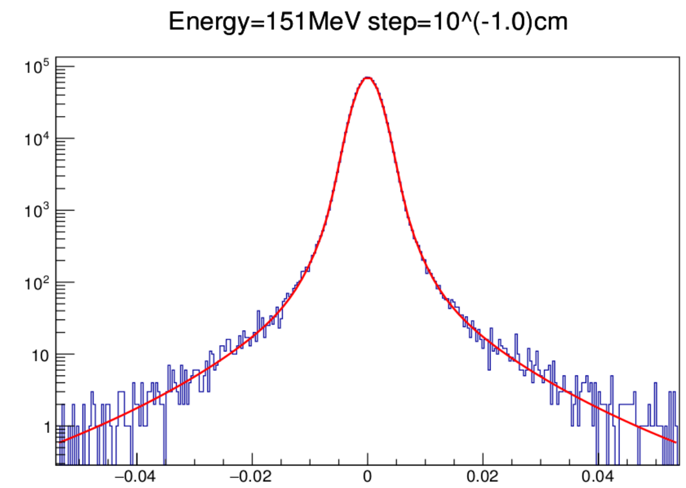
$$f_{2G}(\theta_{x,y}) = \frac{(1-w)}{\sqrt{2\pi}\sigma_1}\exp\left[-\frac{1}{2}\left(\frac{\theta_{x,y}}{\sigma_1}\right)^2\right] + \frac{w}{\sqrt{2\pi}\sigma_2}\exp\left[-\frac{1}{2}\left(\frac{\theta_{x,y}}{\sigma_2}\right)^2\right]$$

$$\text{with } \sigma_1 < \sigma_2 \text{ and } w \ll 1$$



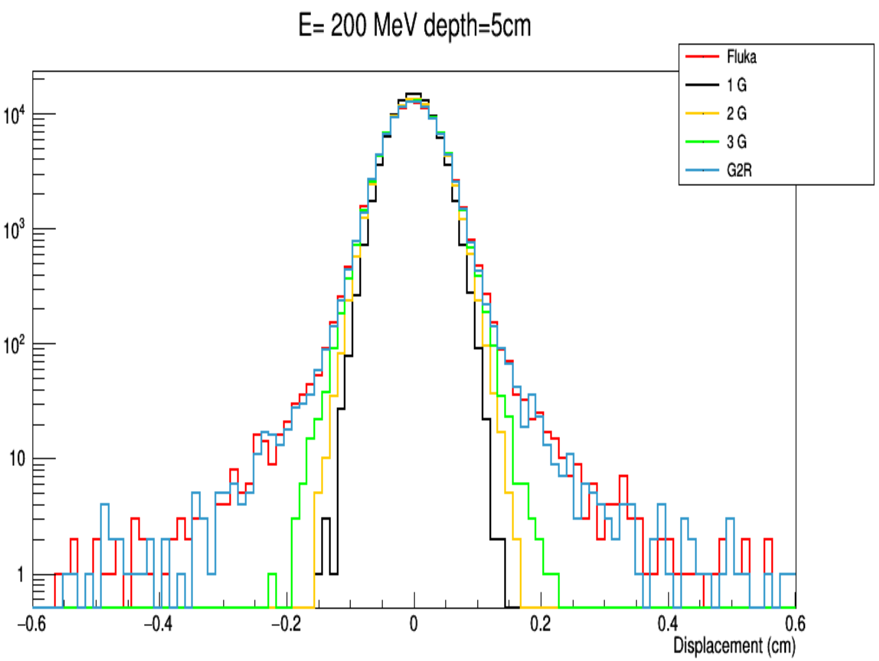
3) Gauss-Rutherford like model

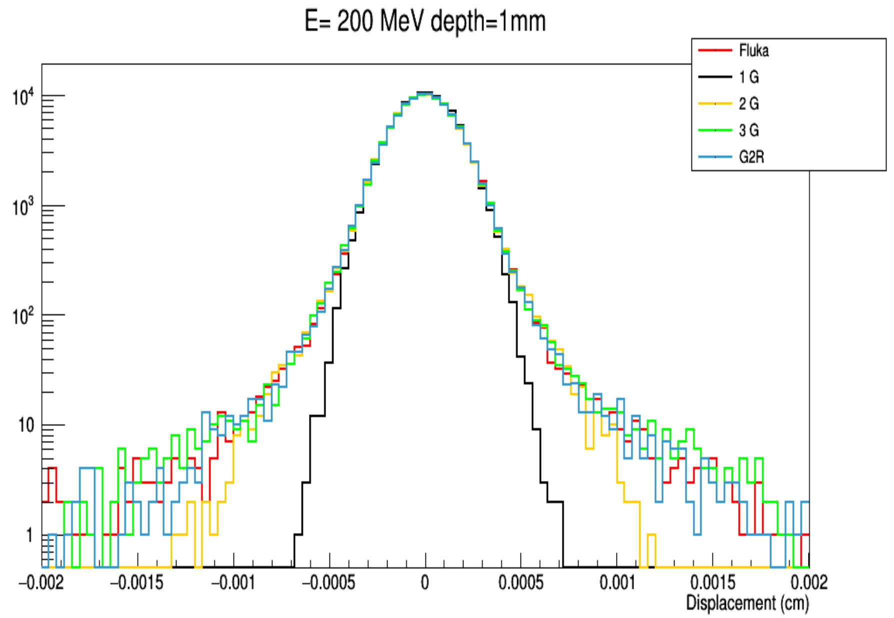
$$f_{GR}(\theta_{x,y}) = \frac{1-w}{\sqrt{2\pi}\sigma_1}\exp\left[-\frac{1}{2}\left(\frac{\theta}{\sigma_1}\right)^2\right] + w\frac{a}{(\theta_{x,y}^2+b)^c} \quad , \quad c \sim 2.0$$

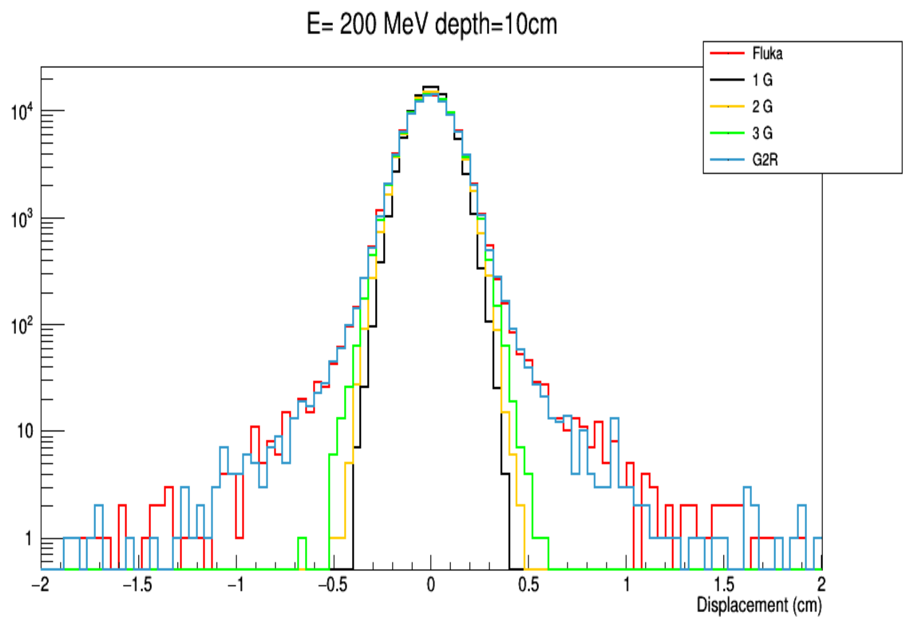


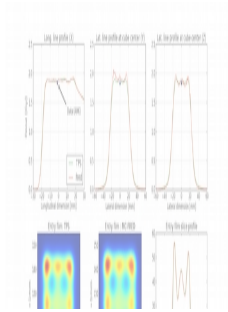
Multiple Coulomb Scattering [3/3]

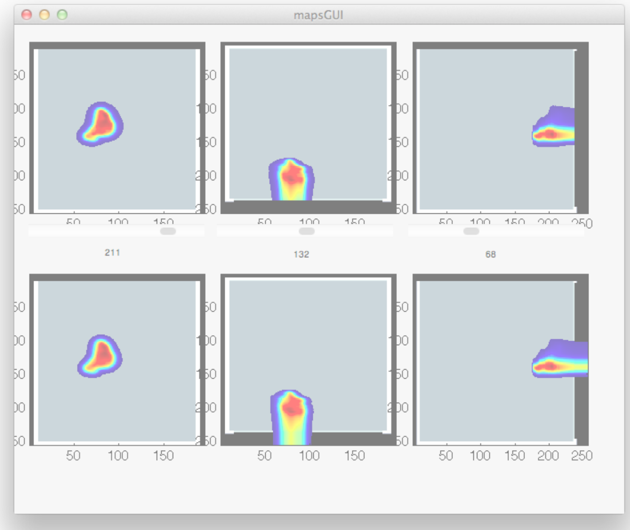
200 MeV water



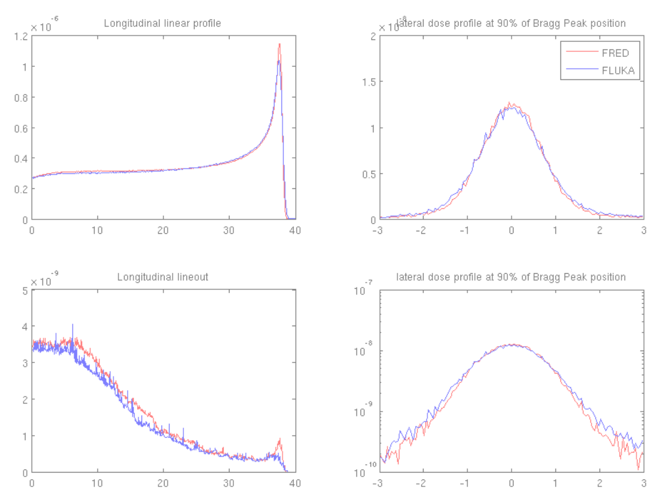


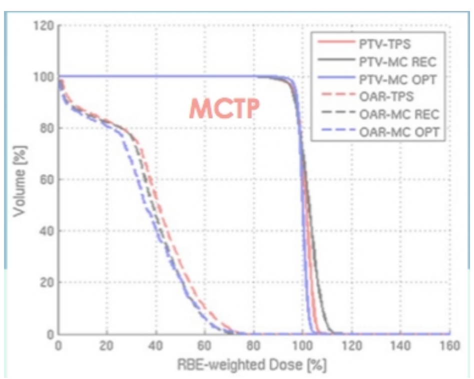


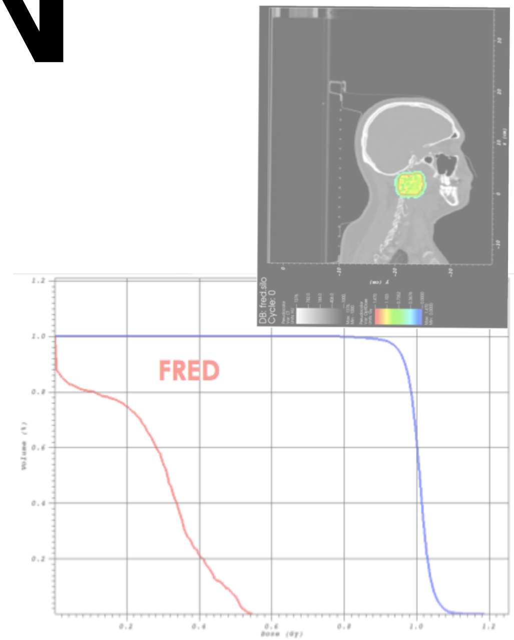



mapsGUI

VALIDATION

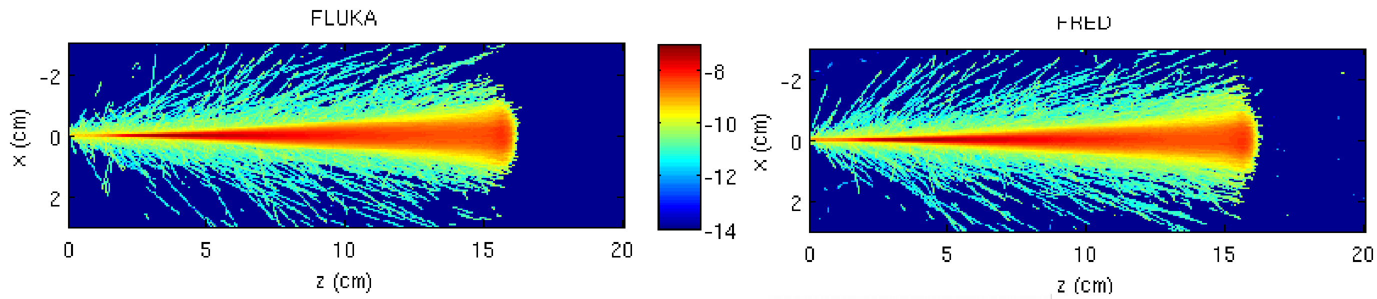

Longitudinal linear profile
lateral dose profile at 90% of Bragg Peak position
FRED
FLUKA
Longitudinal lineout
lateral dose profile at 90% of Bragg Peak position

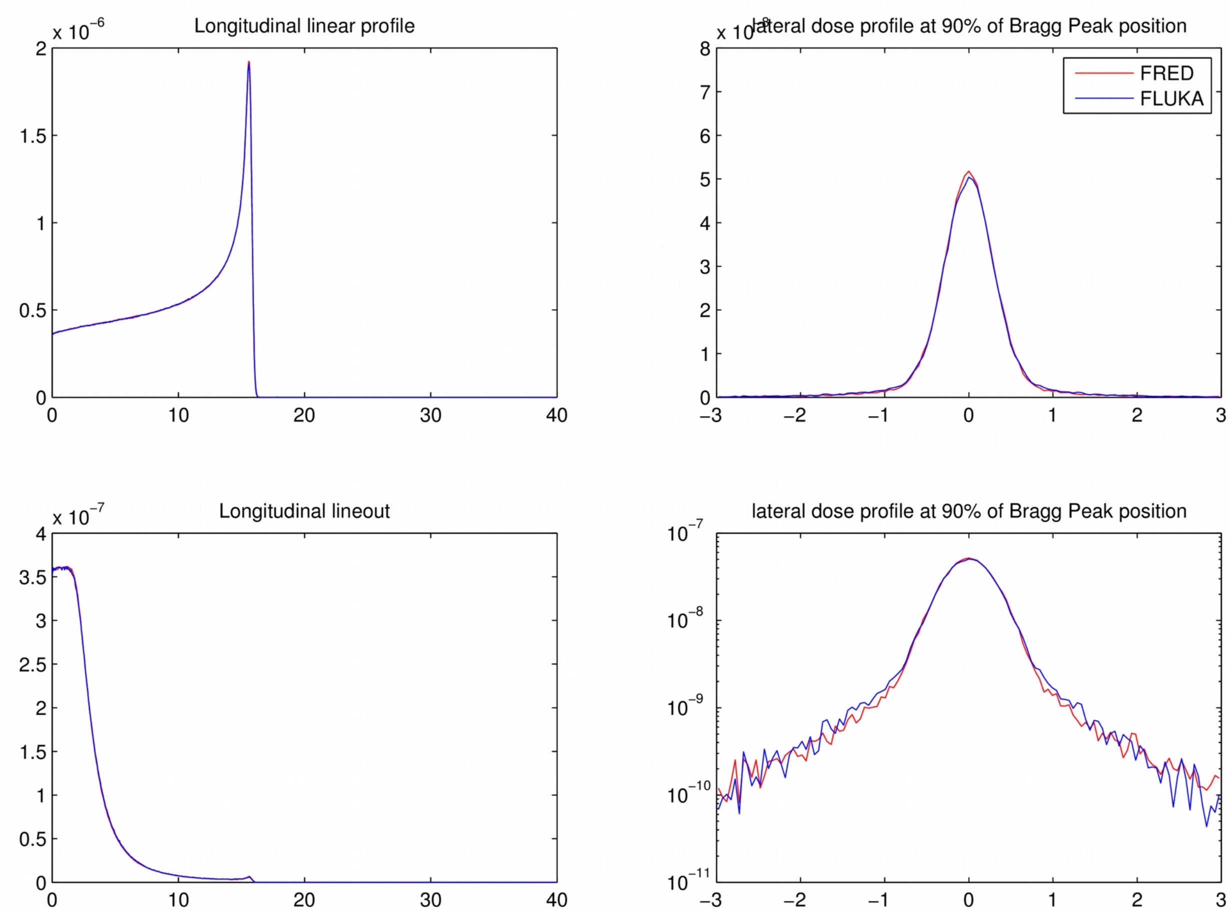

MCTP
PTV-TPS
PTV-MC REC
PTV-MC OPT
OAR-TPS
OAR-MC REC
OAR-MC OPT
Volume [%]
RBE-weighted Dose [%]


FRED

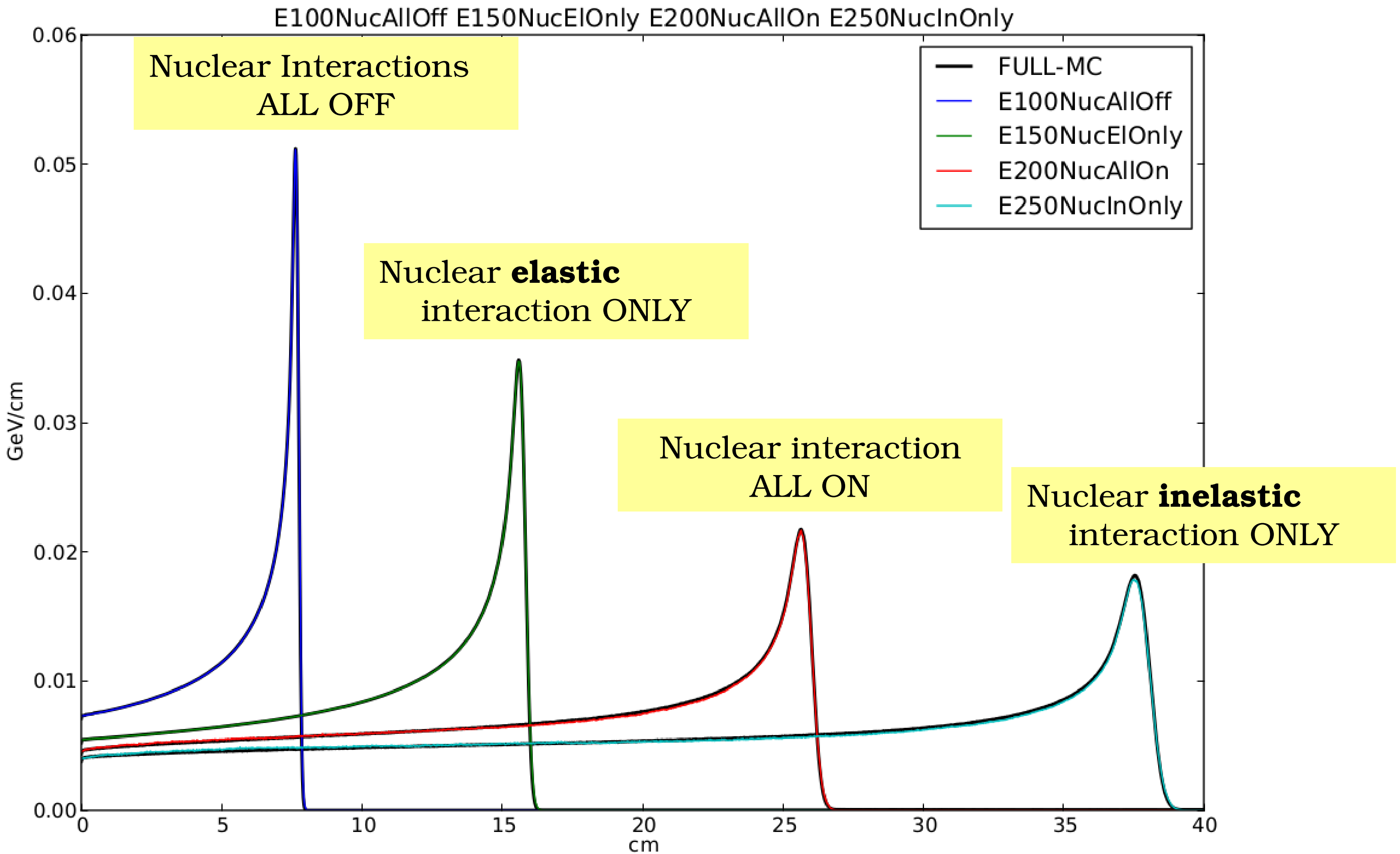
Results - Pencil beam

E_p = 150 MeV (range~15 cm)
FWHM = 0.0 cm
Material: water





Results – Bragg Peaks



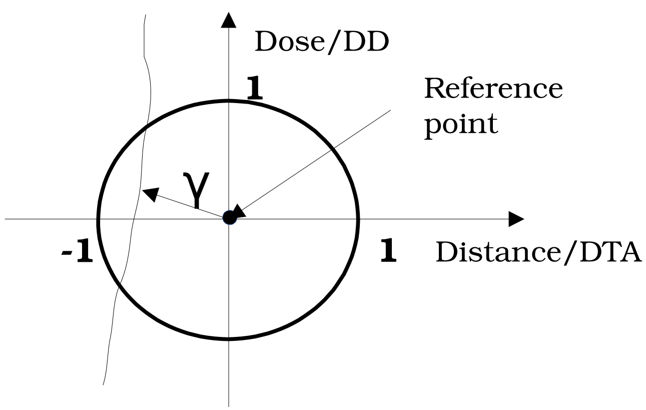
Γ-index pass rate

DTA = Distance to agreement $\quad *_r$ = reference dose map

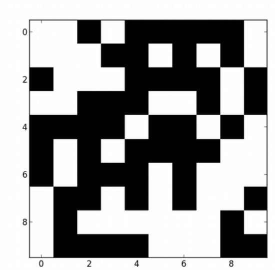
DD = Dose Difference $\quad *_e$ = evaluated dose map

$$\Gamma(\vec{r_e}, \vec{r_r}) = \sqrt{\frac{|\vec{r_e} - \vec{r_r}|^2}{\mathrm{DTA}^2} + \frac{[D_e(\vec{r_e}) - D_r(\vec{r_r})]^2}{\mathrm{DD}^2}}$$

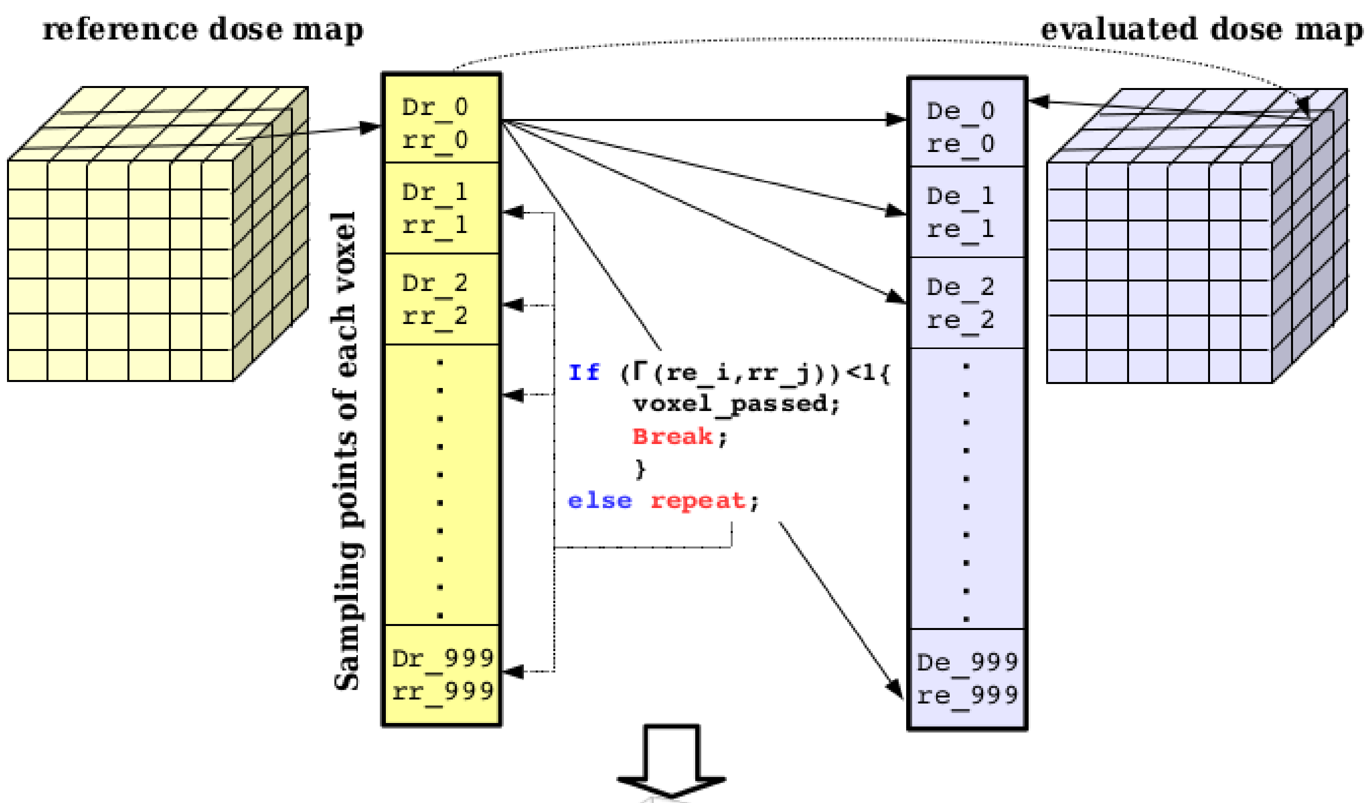
$$\gamma(\vec{r}_r) = \min\{\Gamma(\vec{r}_e, \vec{r}_r)\} \forall \{\vec{r}_e\}$$



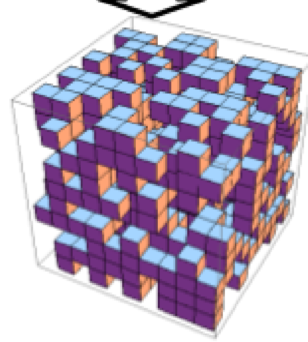
If γ<1, the reference point passes the γ-test, otherwise it fails.



Γ-index pass rate – the algorithm
(CUDA)



Boolean 3D matrix
Pass/failed tag



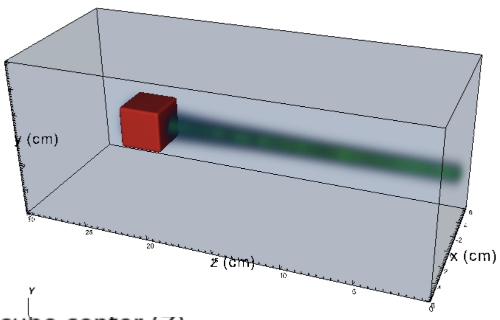
Results

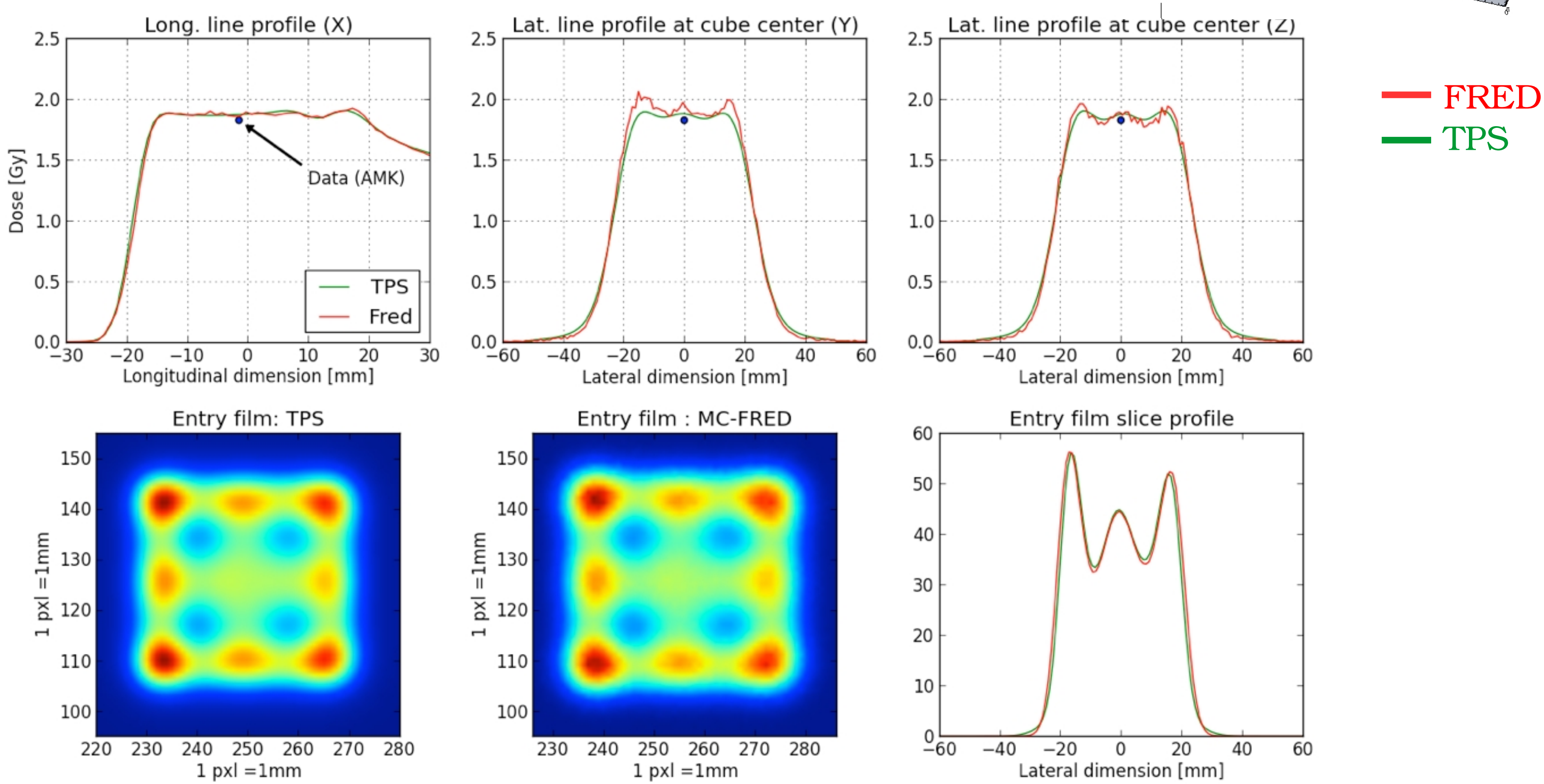
DTA	DD	% voxel passed
2 mm	2%	95 %

Results - Quality assurance cube [1/2]

fondazione CNAO
Centro Nazionale di Adroterapia Oncologica per il trattamento dei tumori

SOBP 3 cm cube @ 20 cm depth
20000 primary protons per PB



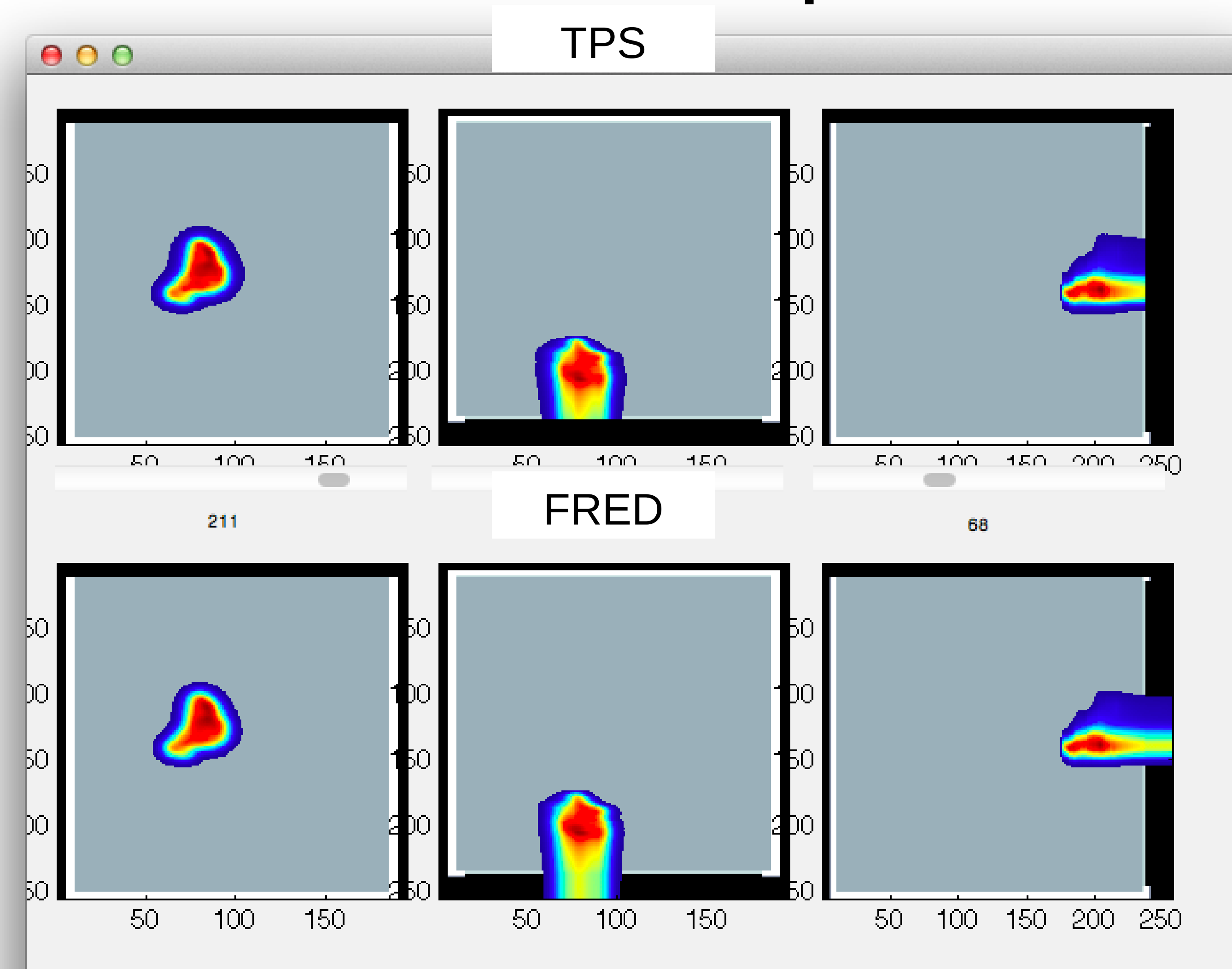


Results - Quality assurance cube [2/2]

DD: 2%
DTA: 2mm

CUBO	whole map	TPS (dose>0.1 Gy)	PTV (dose>1.5 Gy)
9 cm	99.58%	99.00%	97.76%
15 cm	99.91%	99.76%	99.94%
21 cm	99.97%	99.92%	99.92%
21 cm (3x3 cm)	99.77%	99.01%	100.00%
27 cm	99.30%	97.50%	94.95%

Results – Verification plan



DD	DTA	Γ-index pass rate
2 %	2 mm	99.6 %
1 %	1 mm	96.7 %

Conclusions

- Particle Therapy is an efficient cancer treatment techinque tanks to its conformal energy release
- Treatment Planning System goal: high accuracy of dose delivery to the patient and short computing time
- FRED: fast MC on GPU
- Very good agreement in pencil beam linear profiles with Full-MC data
- Excellent good dose maps agreement with TPS data and Full-MC simulations
- Computing time > 1000 times less than a full MC tool
- Application to CNAO validation protocol