Perspectives of GPU computing in Science

September 26 -28, 2016 - Sapienza Università di Roma

A fast - Monte Carlo toolkit on GPU for treatment plan dose recalculation in proton therapy

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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]

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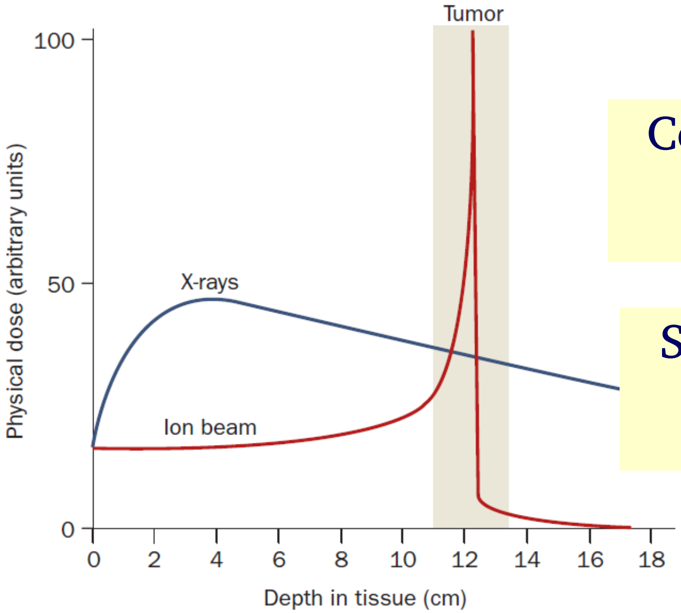
Radiotherapy vs particle therapy



Concentrated energy release at the end of path

Sharp decrease in energy after the Bragg Peak

Better dose distribution to preserve critical organs and surrounding healthy tissues

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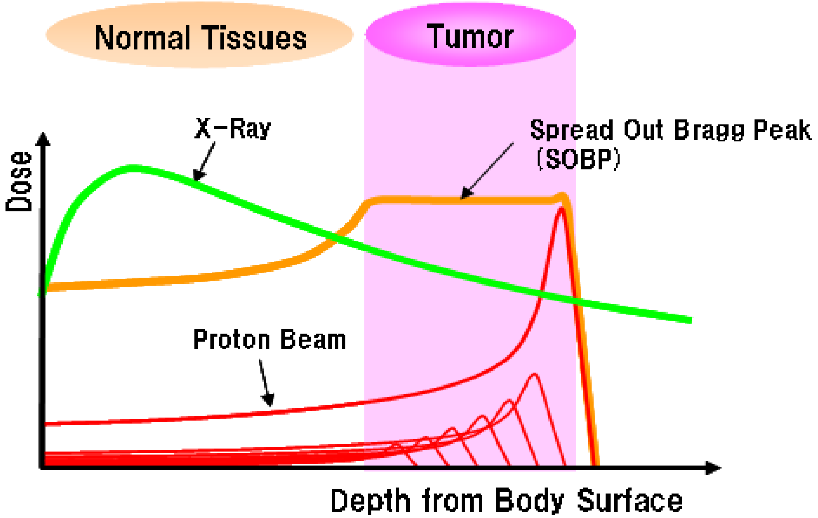
Cancer irradiation techniques goal:

Conformal dose distribution

concentrate all the dose to tumor and spare healthy tissues

- Standard 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



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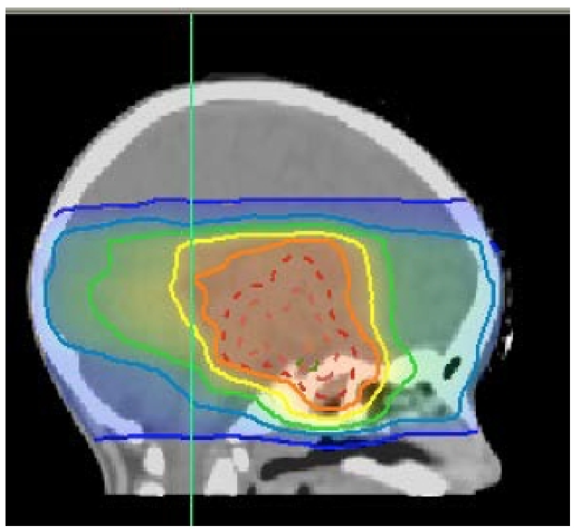
  - Active tu...
  - Superim...

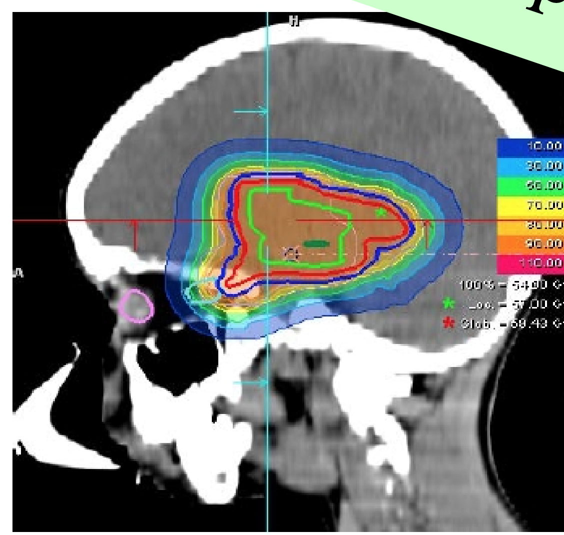
PT exhibits a better conformal capability

Photon-IMRT

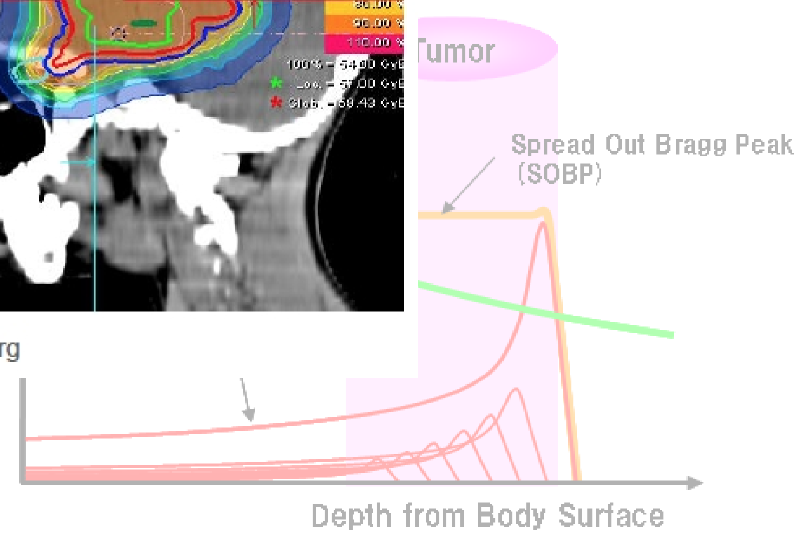


Universitätsklinikum Dresden

Protons



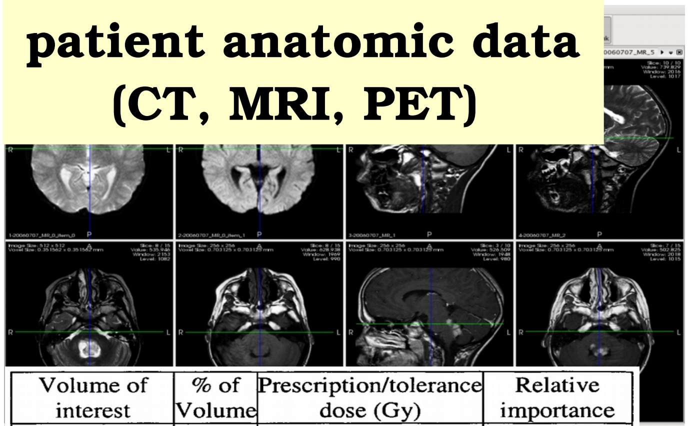
HIT, Heidelberg



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

Treatment Planning System (TPS)

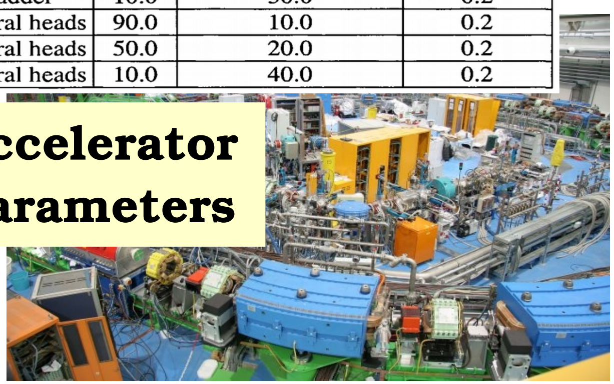
patient anatomic data (CT, MRI, PET)



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
Bladder	90.0	10.0	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

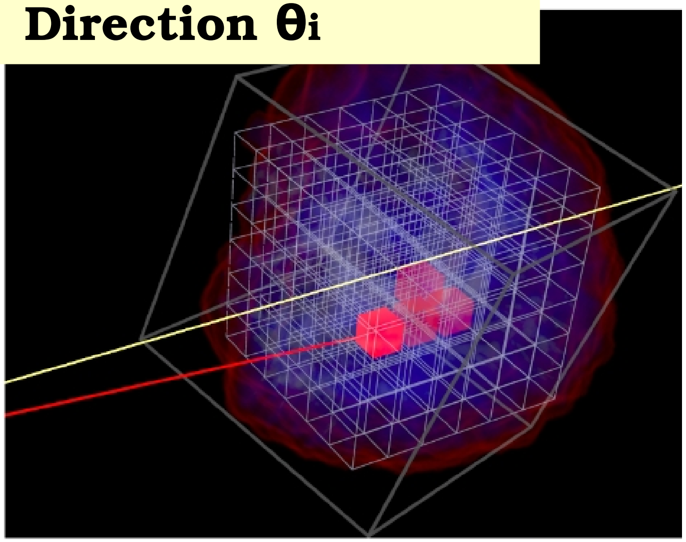
Accelerator parameters



T P S

Treatment Plan (TP)
For each beam:

- **Fluence Φ_i**
- **Energy E_i**
- **Direction θ_i**



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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**

How?!?

NVIDIA Graphic Process Units

- Low budget
- Redundancy
- In-house maintenance

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

- Both **carbons ions** and **protons** beam
- One of the 10 worldwide centers using carbon ions beams to treat tumor
- First patient treated in 2014
- ~ 900 patients treated


Pavia, PV

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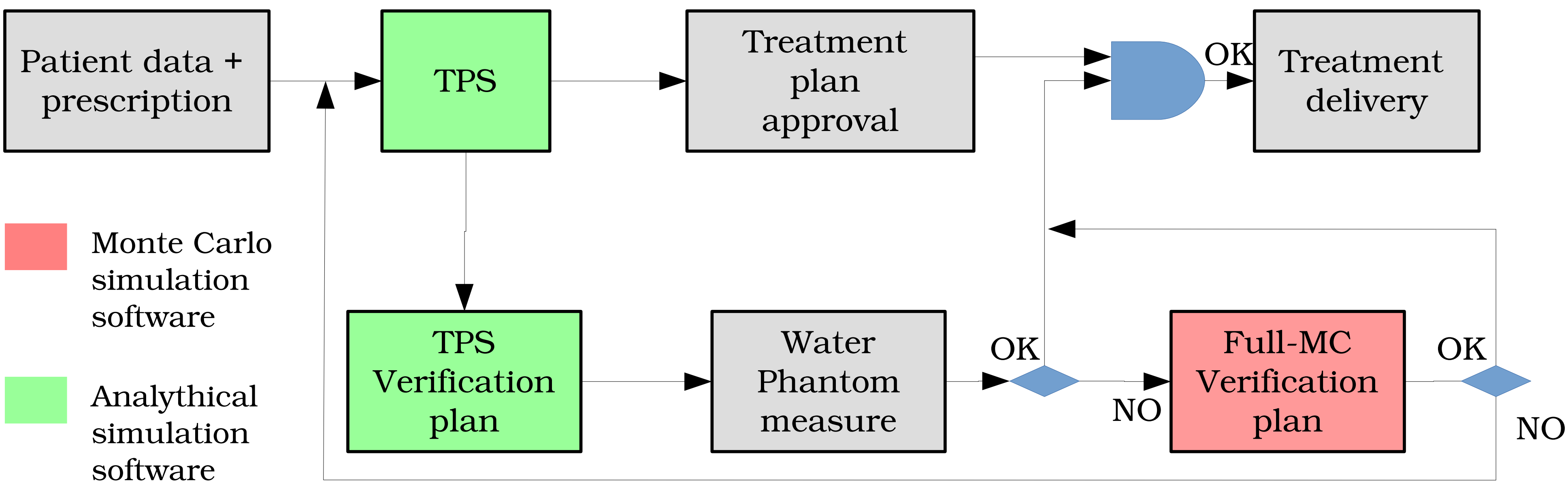
CNAO clinical protocol



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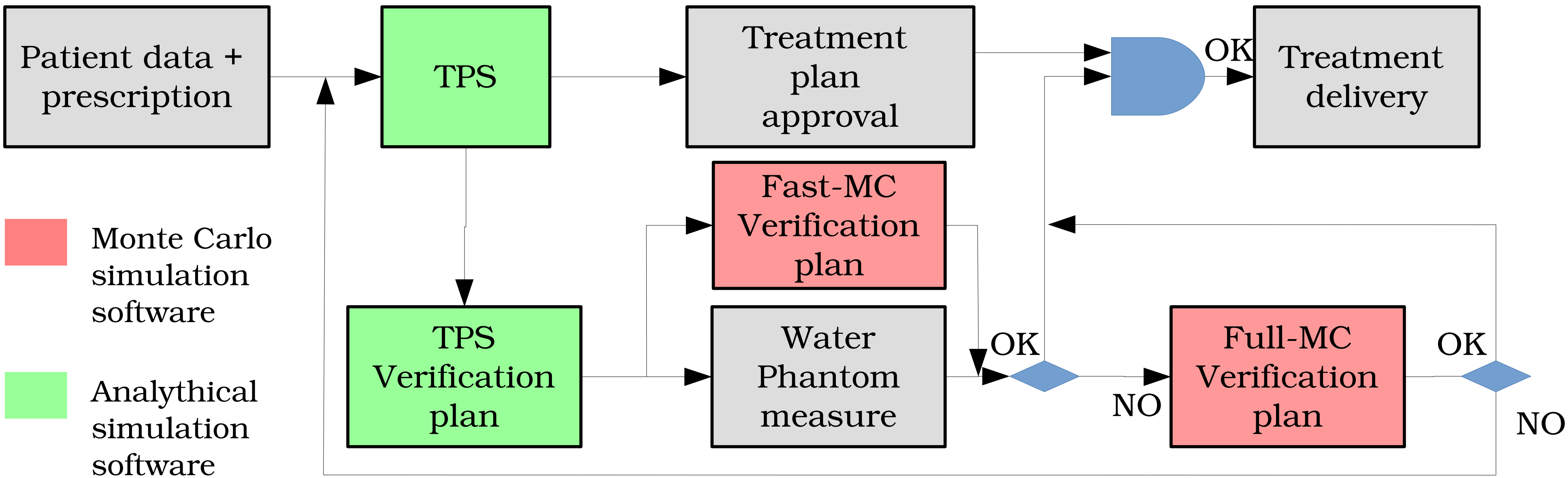
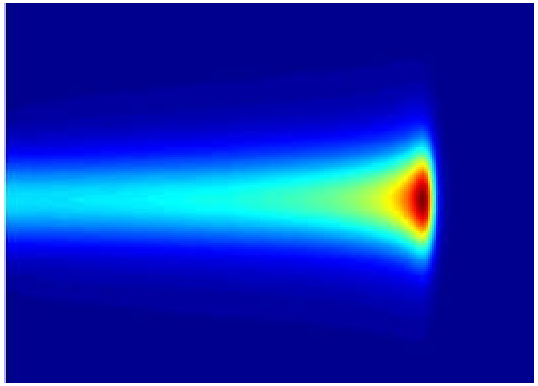


Physics models

Physics models implemented in the code are:



- **Stopping Power**
- **Energy Fluctuations**
- Multiple Coulombs Scattering **(MCS)**
- **Nuclear interactions** (elastic and inelastic)

Stopping power and energy fluctuations

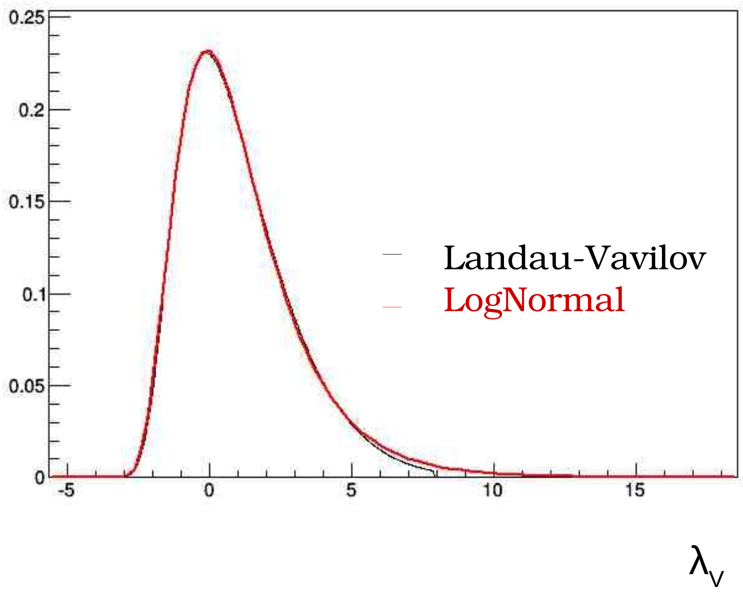
Bethe formula[1] $\frac{dE}{dx}(x, N_e, v, E, \beta, \gamma, I)$

Mean energy loss per travelled distance

Thick absorber — **Gaussian** distribution of energy loss

Thin absorber — **Landau-Vavilov** distribution of energy loss

Approximation with **logarithmic normal** function



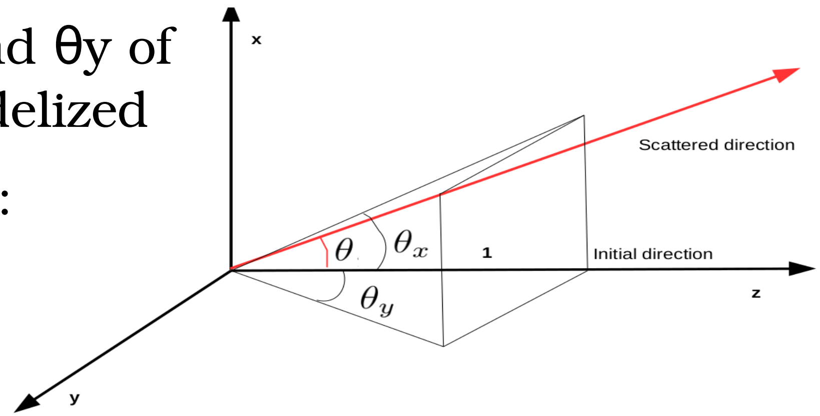
[1] *H. Bethe und J. Ashkin in "Experimental Nuclear Physics", ed. E. Segré, J. Wiley, New York, 1953, p. 253*

Multiple coulomb scattering

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

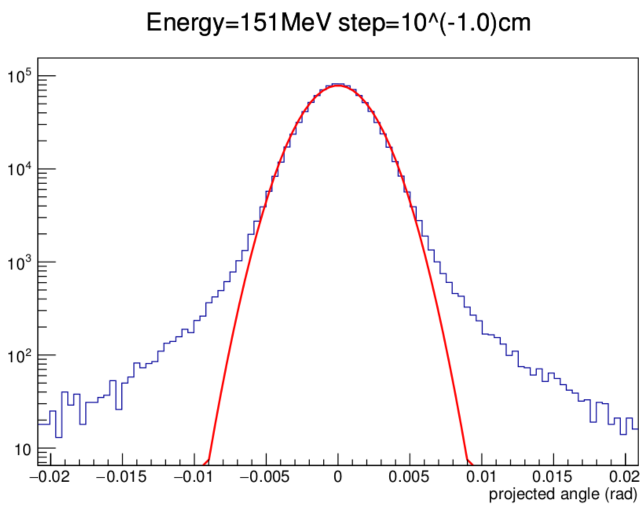
Small angles approximation: sin(θ) ~ θ:

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



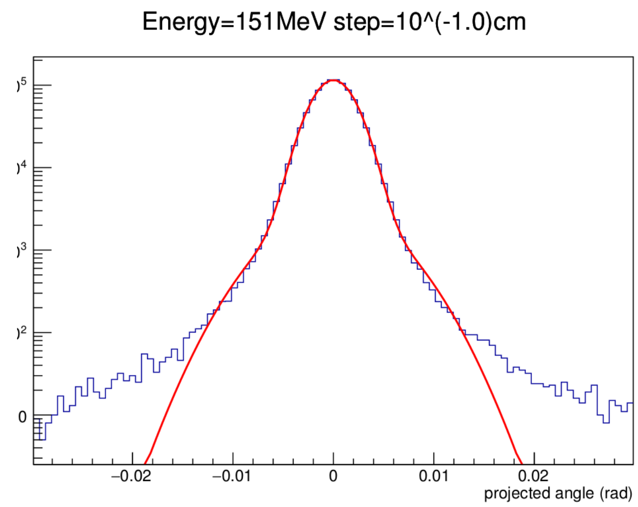
Three different models implemented:

Single Gaussian



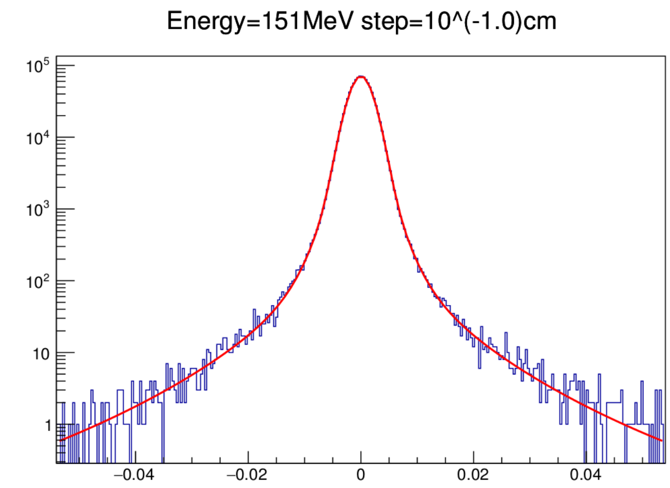
Double Gaussian

(used in clinical analythic TPS)



Gauss- Rutherford like

$$f_{GR}(\theta_{x,y}) = (1-w)G(\theta_{x,y},\sigma) + w\frac{a}{(\theta_{x,y}^2 + b)^c}$$

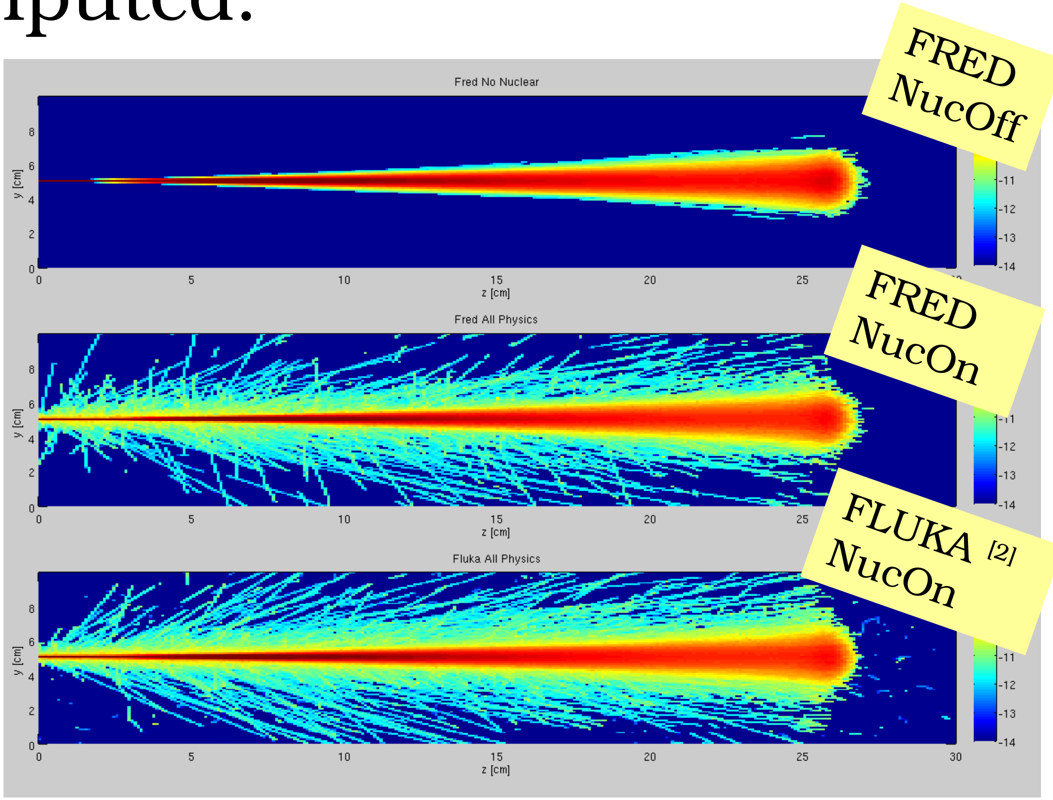


Nuclear interaction

Nuclear cross sections from ICRU report of 2003

Secondary fragments computed:

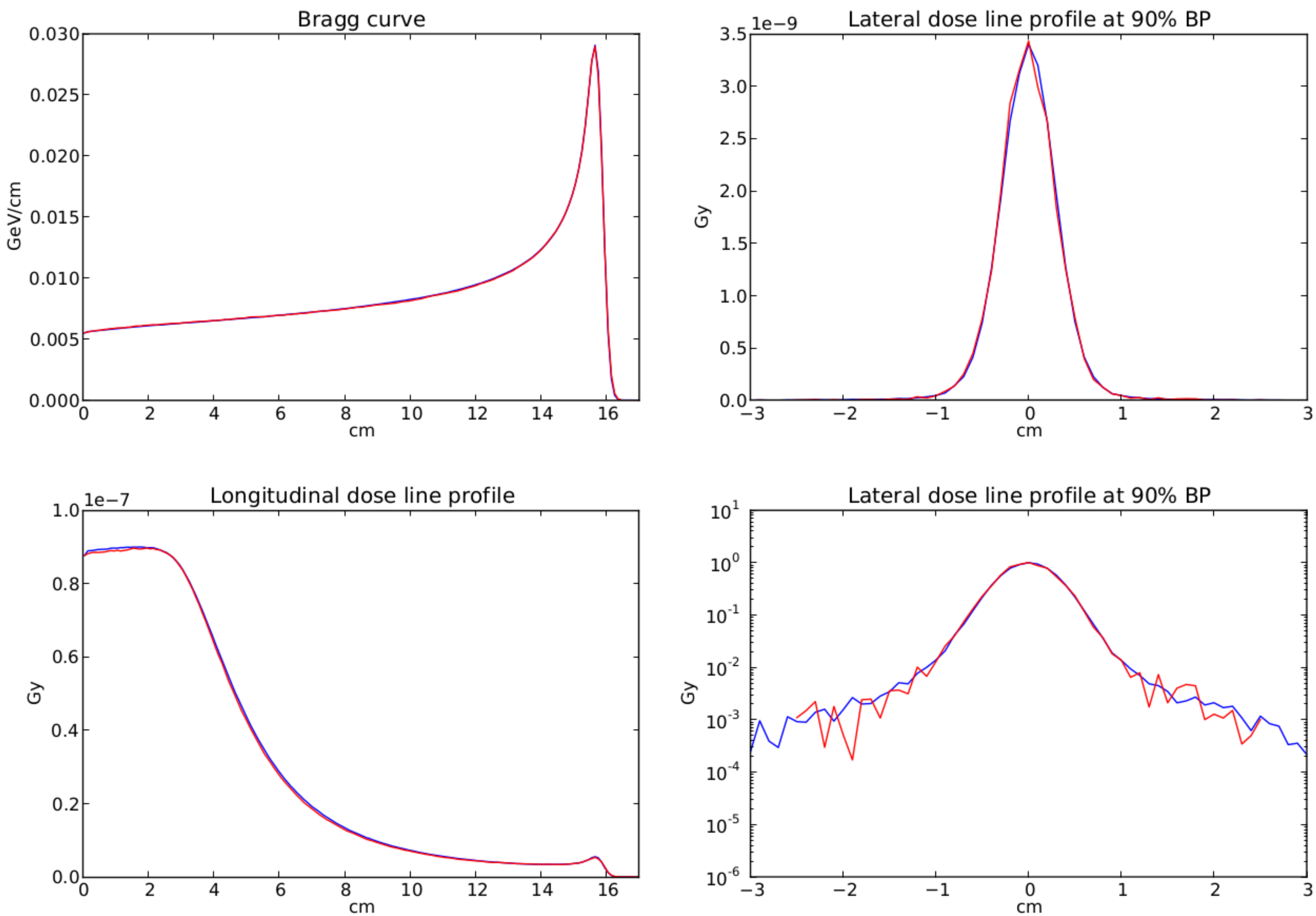
- ✔ **Protons**, tracked
- ✔ **Deuterons**, tracked
- ✗ **Neutrons**, neglected
- • **Heavier ions**, locally deposited



[2] http://www.fluka.org/fluka.php

Single PB dose profiles

150 MeV protons in water (FWHM=0.0)

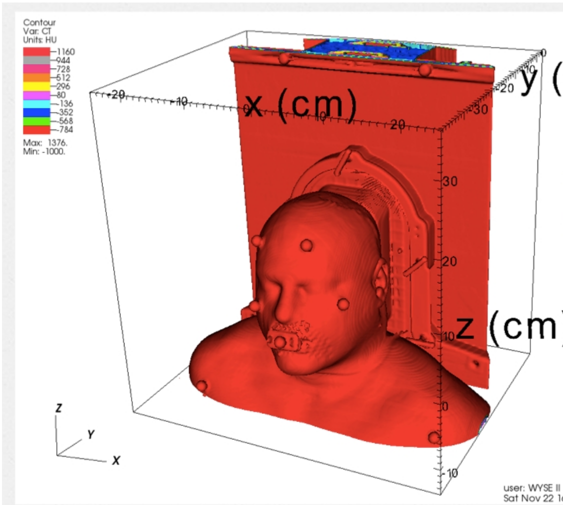


Full Monte Carlo (FLUKA)

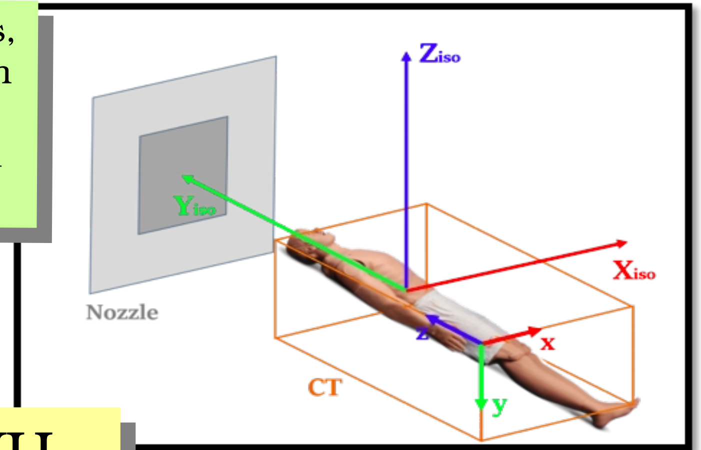
Fast Monte Carlo (FRED)

Clinical case: Glioblastoma

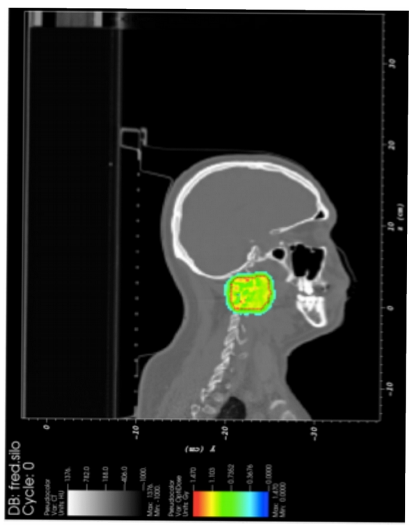
HU conversion in voxel density ρ and elemental composition from
"The Calibration of CT of CT Hounsfield units for radiotherapy treatment planning",
Schneider*, Pedroni, Lomax, 1996 Phys. Med. Biol. 41 111*

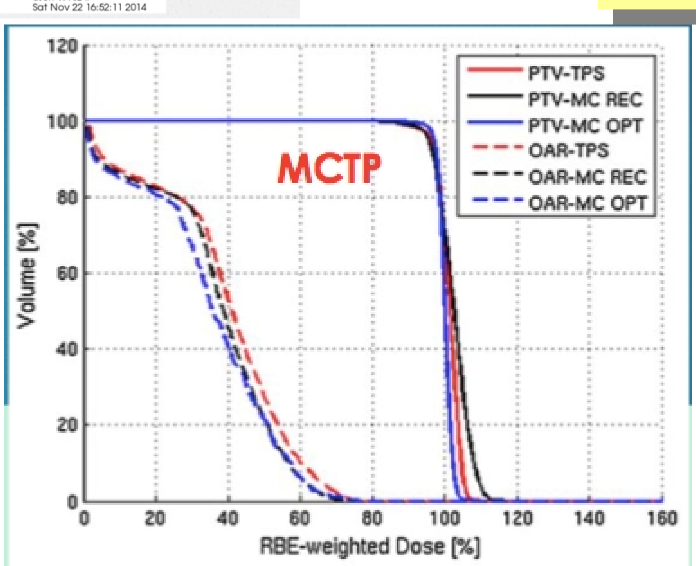


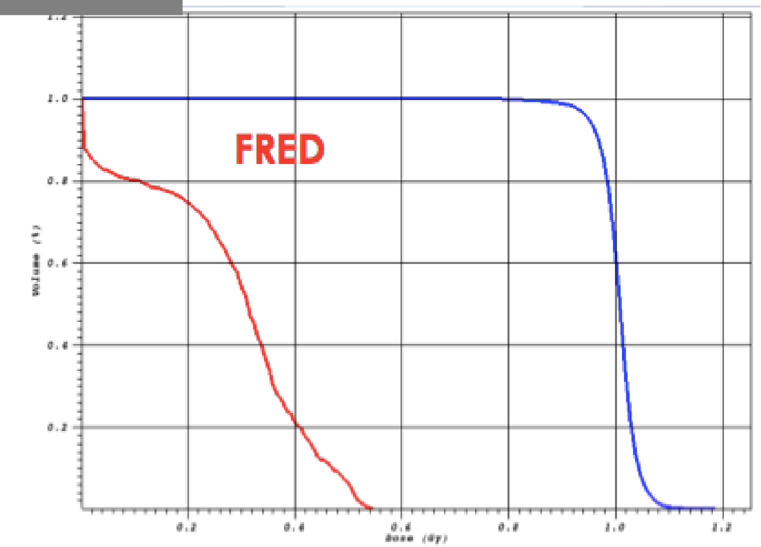
6400 pencil beams,
5000 primary each
Dose scoring
volume resolution
2 x 2 x 2 mm



DVH







Hardware and performance

DUTY CYCLE

Under sustained raytracing workload, in order to keep temperature of all GPU cads below 70°, we obtain:

AIR-COOLED 2X NVIDIA GTX TITAN 30% duty cycle

WATER-COOLED 4X NVIDIA GTX 980 100% duty cycle

		THREADS	primary/s	µs/primary
CPU	FLUKA	1	0.75 K	1340
	FRED	1	15K	68
	FRED	16	48K	21
	FRED	32	80K	12.5
GPU	FRED	1 GPU*	800K	1.35
	FRED	2 GPU**	3500K	0.3
	FRED	4 GPU***	20000K	0.05

*LAPTOP: MacBookPro(AMD Radeon R9 M370X)

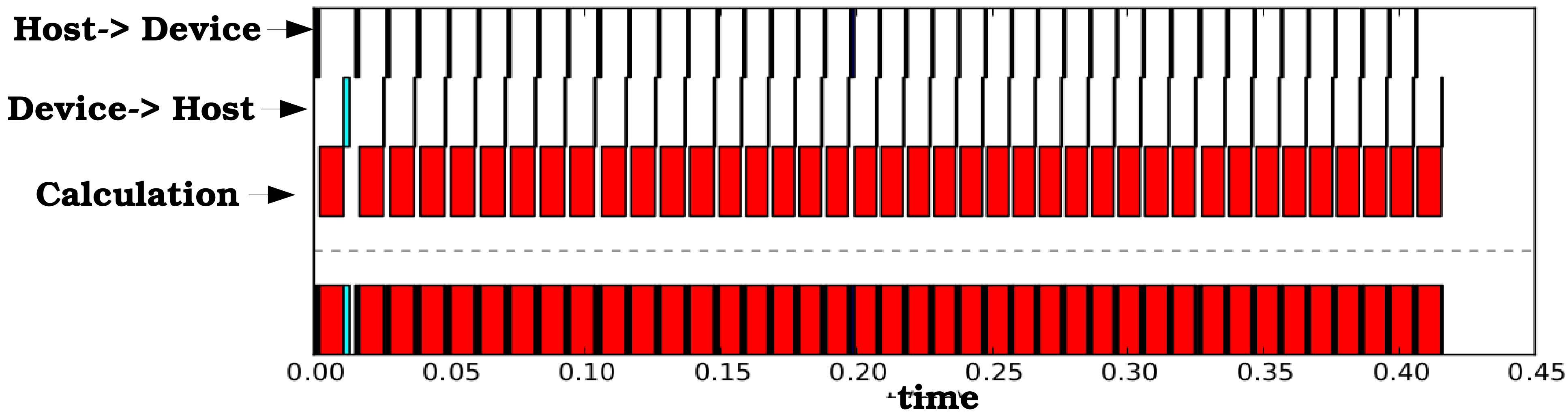
** DESKTOP: Mac Pro (AMD FirePro D300)

***LINUX WorkStation with 4 NVIDIA GTX 980 GPUs

Synchronous/asynchronous execution

WATER-COOLED 4X NVIDIA GTX 980

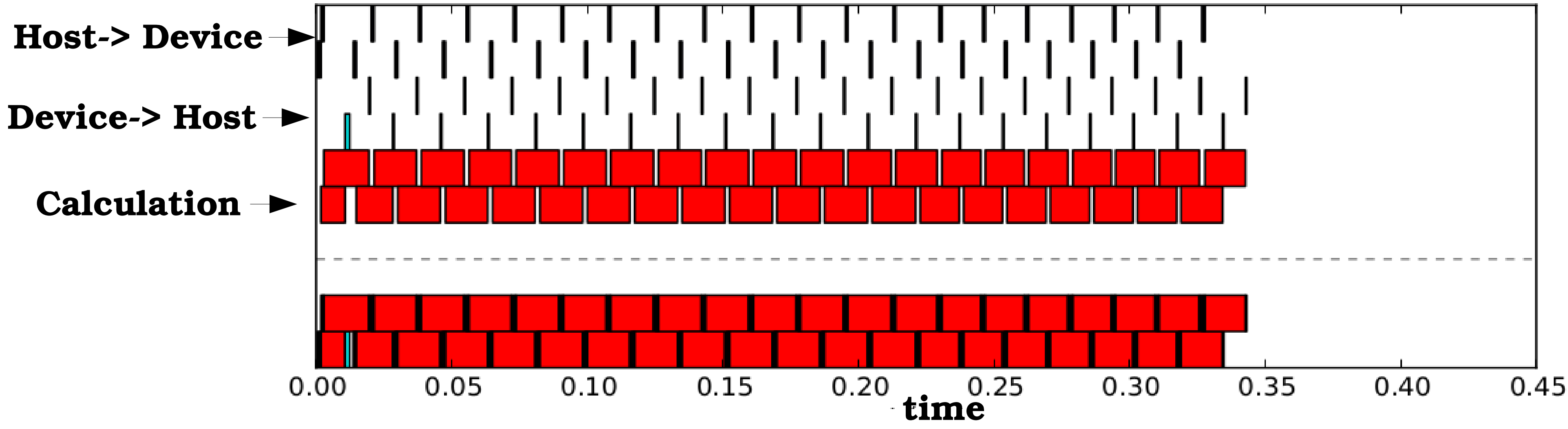
1 DEVICE
1 QUEUE



Synchronous/asynchronous execution

WATER-COOLED 4X NVIDIA GTX 980

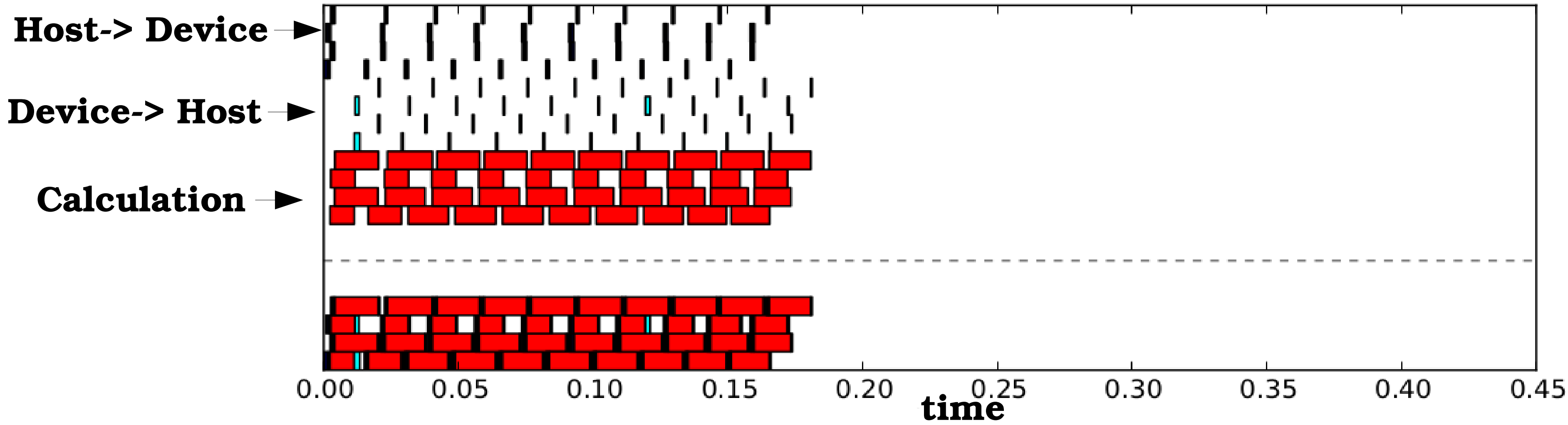
1 DEVICE
2 QUEUES



Synchronous/asynchronous execution

WATER-COOLED 4X NVIDIA GTX 980

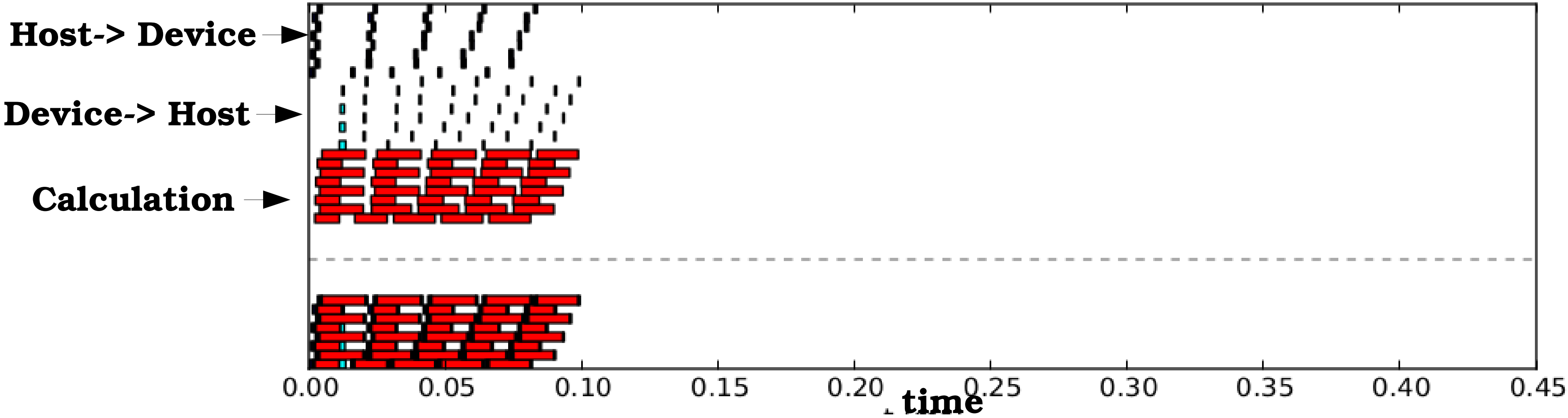
2 DEVICES
2 QUEUES



Synchronous/asynchronous execution

WATER-COOLED 4X NVIDIA GTX 980

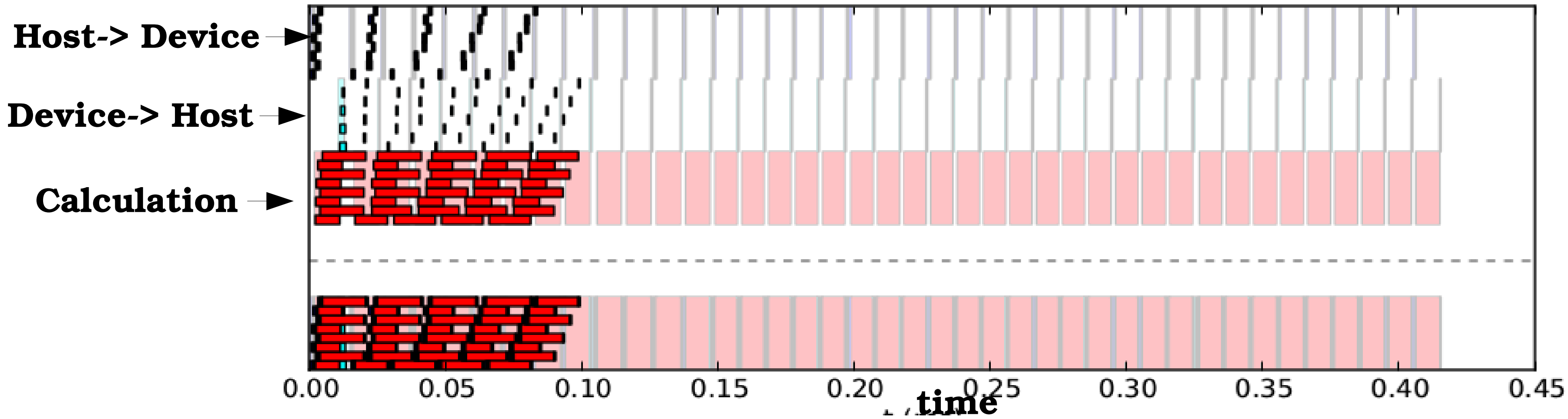
4 DEVICES
2 QUEUES



Synchronous/asynchronous execution

WATER-COOLED 4X NVIDIA GTX 980

4 DEVICES
2 QUEUES



Conclusions and future developments

- Good dose maps agreement with TPS data and Full-MC simulations

- Time computing expense > 1000 times less than a full MC tool

Conclusions and future developments

- Good dose maps agreement with TPS data and Full-MC simulations
- Time computing expence ~ 1000 times less than a full MC tool

- Clinical validation of fast-recalculation tool
- Applications to clinical routine
- Extensions to include other ions (Carbon, Helium)
- Improvement of radiobiological models (RBE)
- Dose monitoring using secondary particles

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Thank you for your attention!

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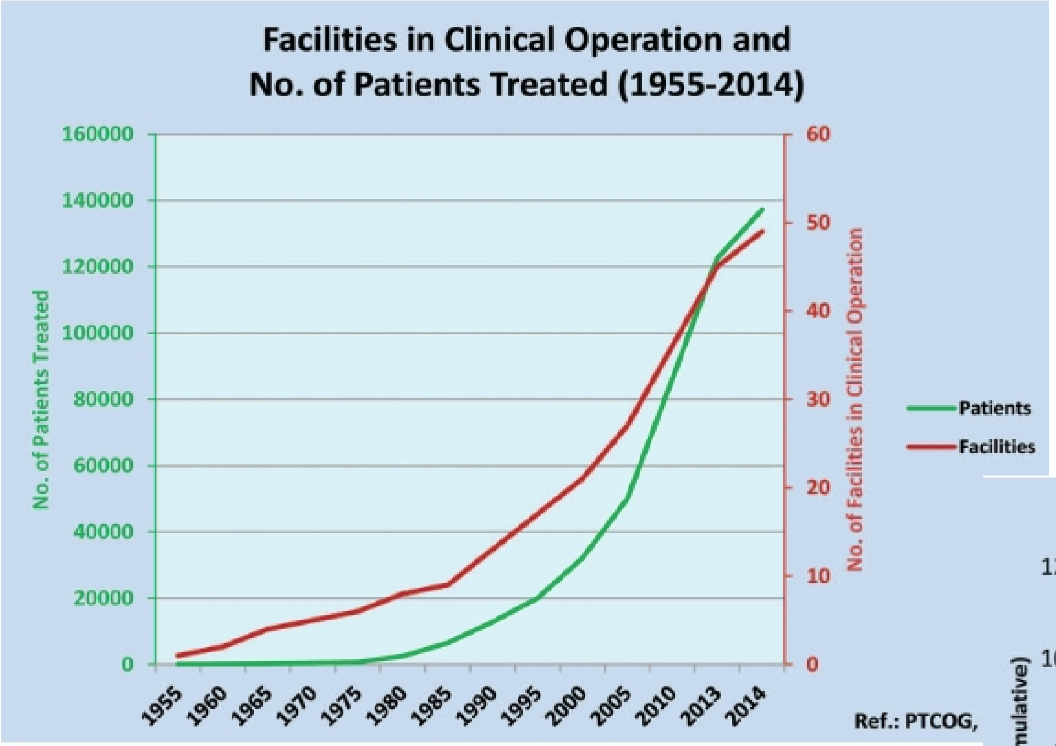
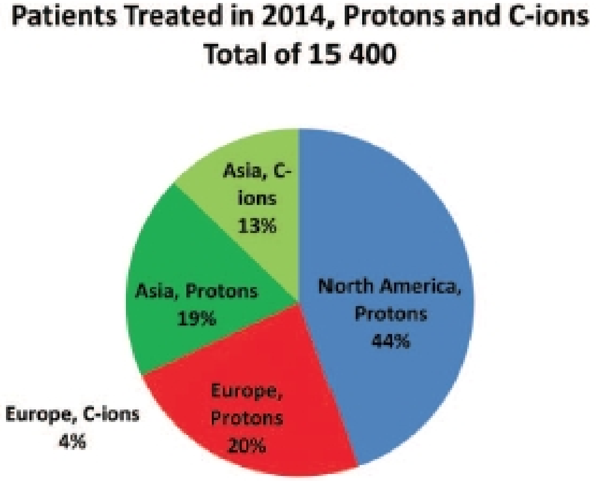
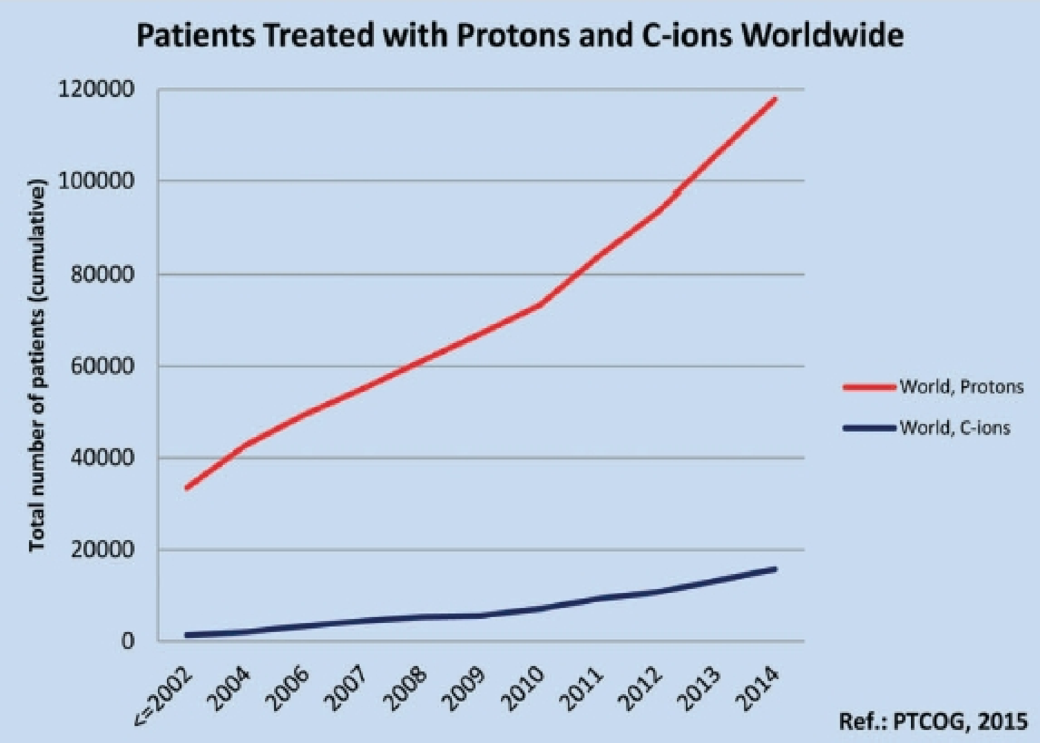
Patient statistic

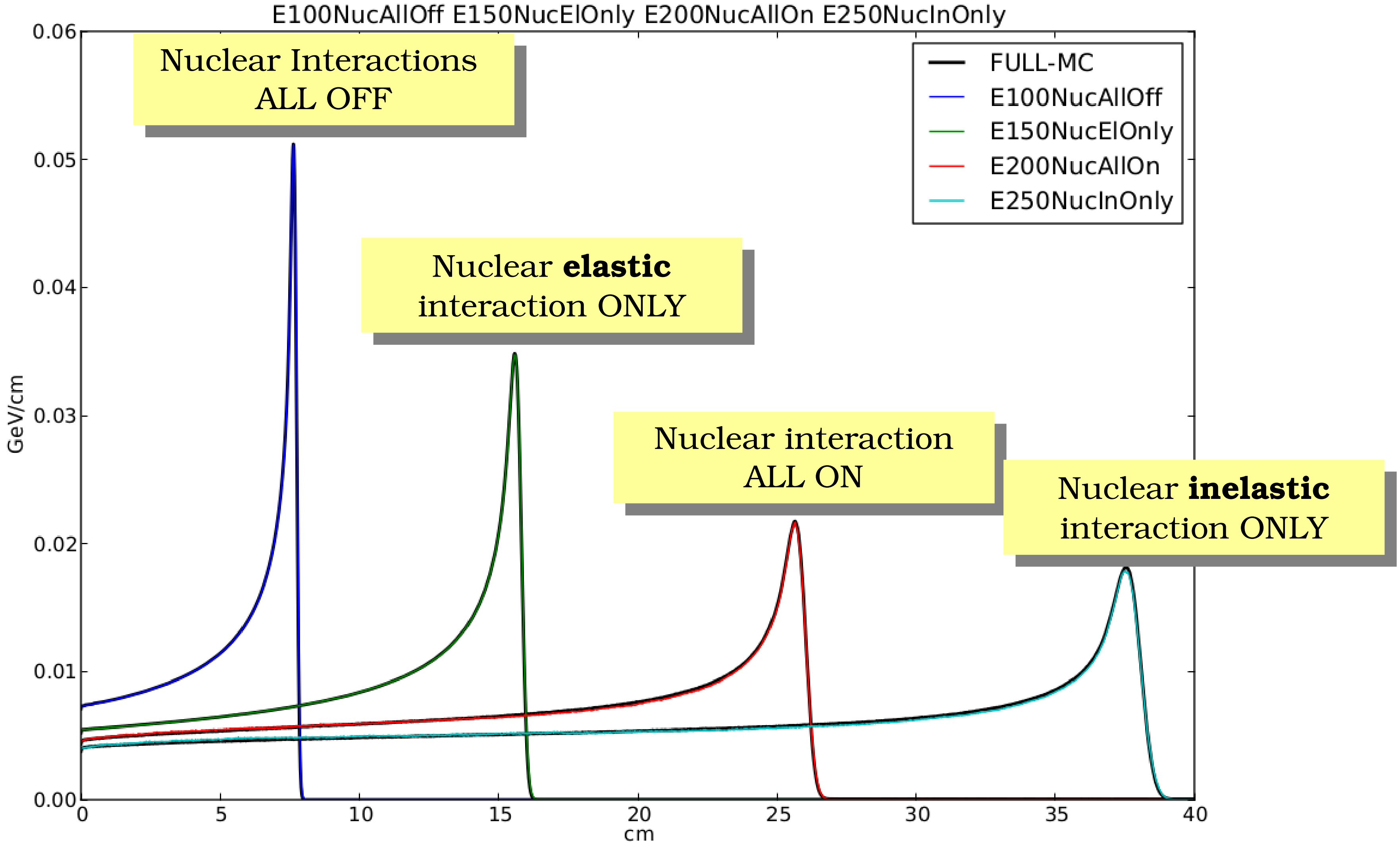


www.ptcog.ch





Bragg Peaks

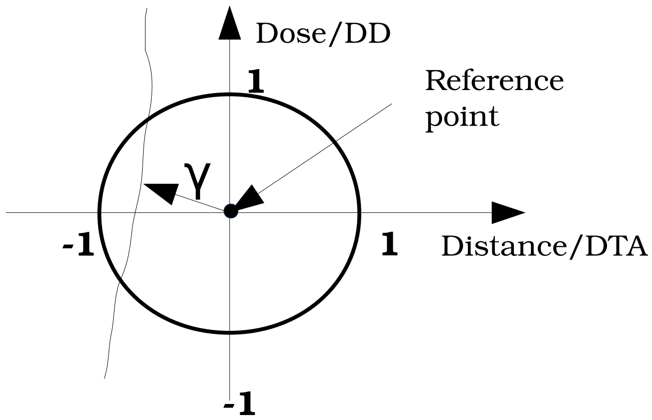

E100NucAllOff E150NucElOnly E200NucAllOn E250NucInOnly
GeV/cm
cm
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0
5
10
15
20
25
30
35
40
FULL-MC
E100NucAllOff
E150NucElOnly
E200NucAllOn
E250NucInOnly
Nuclear Interactions ALL OFF
Nuclear **elastic** interaction ONLY
Nuclear interaction ALL ON
Nuclear **inelastic** interaction ONLY

Gamma Index pass rate[3]

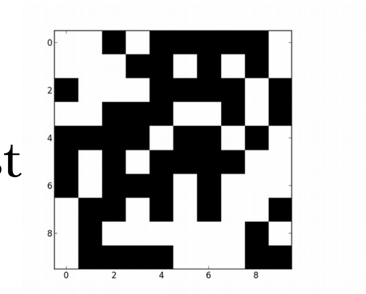
DTA = Distance to agreement $*_r$ = reference dose map
DD = Dose Difference $*_e$ = evaluated dose map

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

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

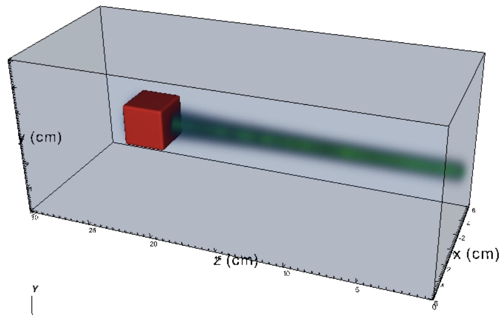


If γ<1, the reference point passes the γ-test otherwise it fails.



[3]Daniel A. Low, William B. Harms, Sasa Mutic, and James A. Purdy, ***"A technique for the quantitative evaluation of dose distributions"***, Medical Physics, Vol. 25, No. 5, May 1998

Quality assurance cube



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