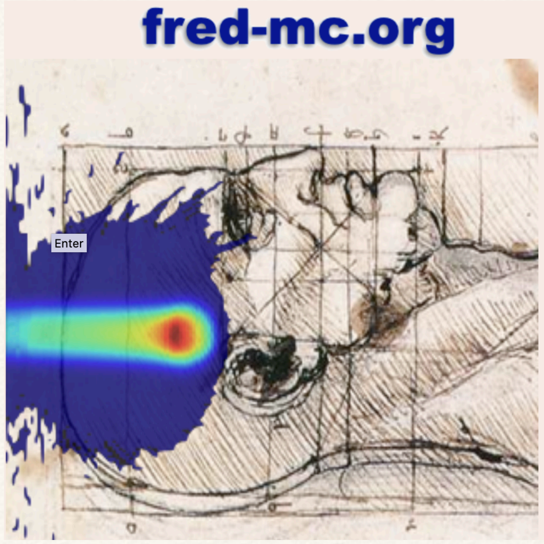


Development of tools for quality control on therapeutic carbon beams with a fast MC code (FRED)

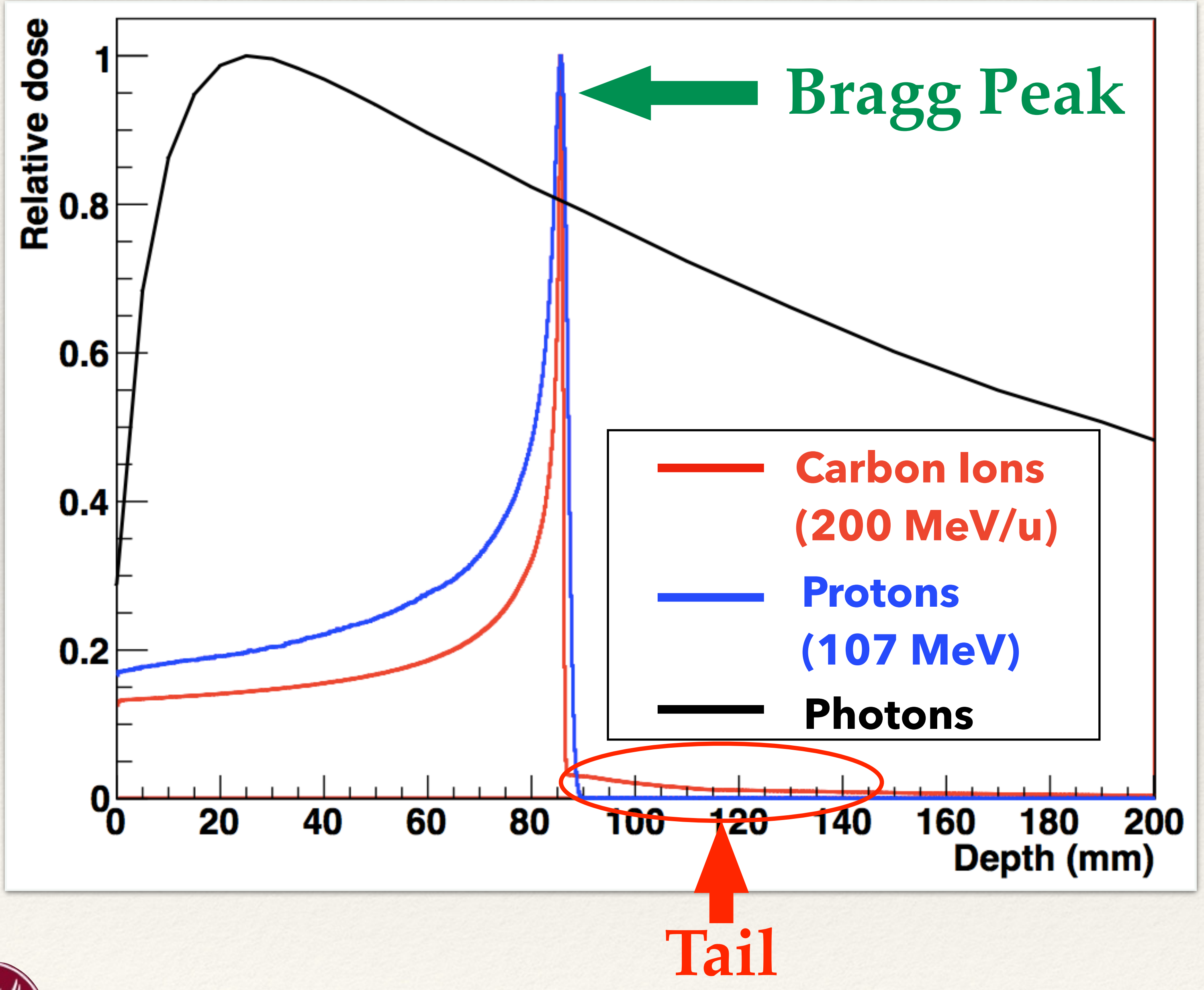
Candidate: **Micol De Simoni**

Supervisor: **Prof. Vincenzo Patera**
Co-Supervisor: **Prof. Angelo Schiavi**

PhD "Accelerator Physics", XXXIII cycle
" Sapienza", University of Rome

Particle Therapy (PT)

PT is a modern technique of non-invasive radiotherapy mainly devoted to the treatment of tumours untreatable with surgery or conventional radiotherapy.
It uses charged particle beams to release energy into the tumour volume causing the apoptosis of tumour cells.



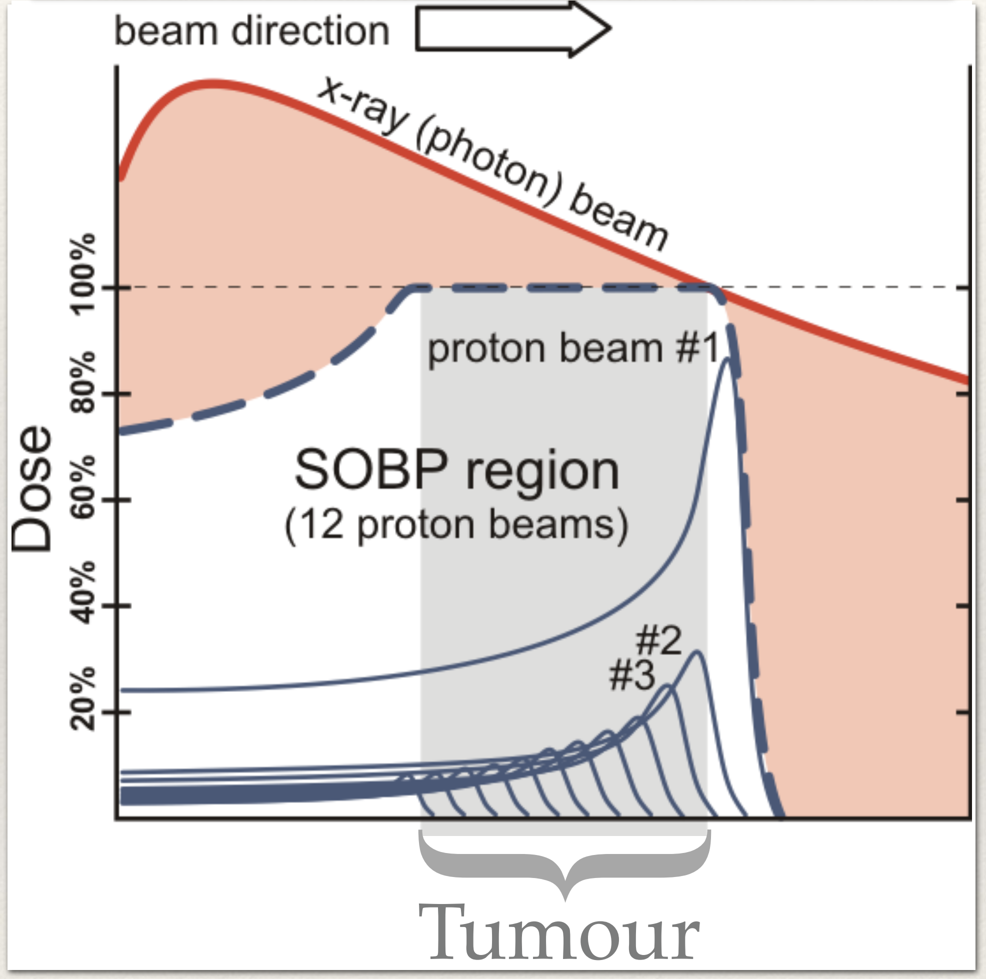
The **biological damage** is related to the **released energy**, **ionization density** and **type of projectile used**.

$$D = \frac{dE}{dm} \left[1Gy = 1\frac{J}{kg}\right]$$

Particle Therapy (PT)

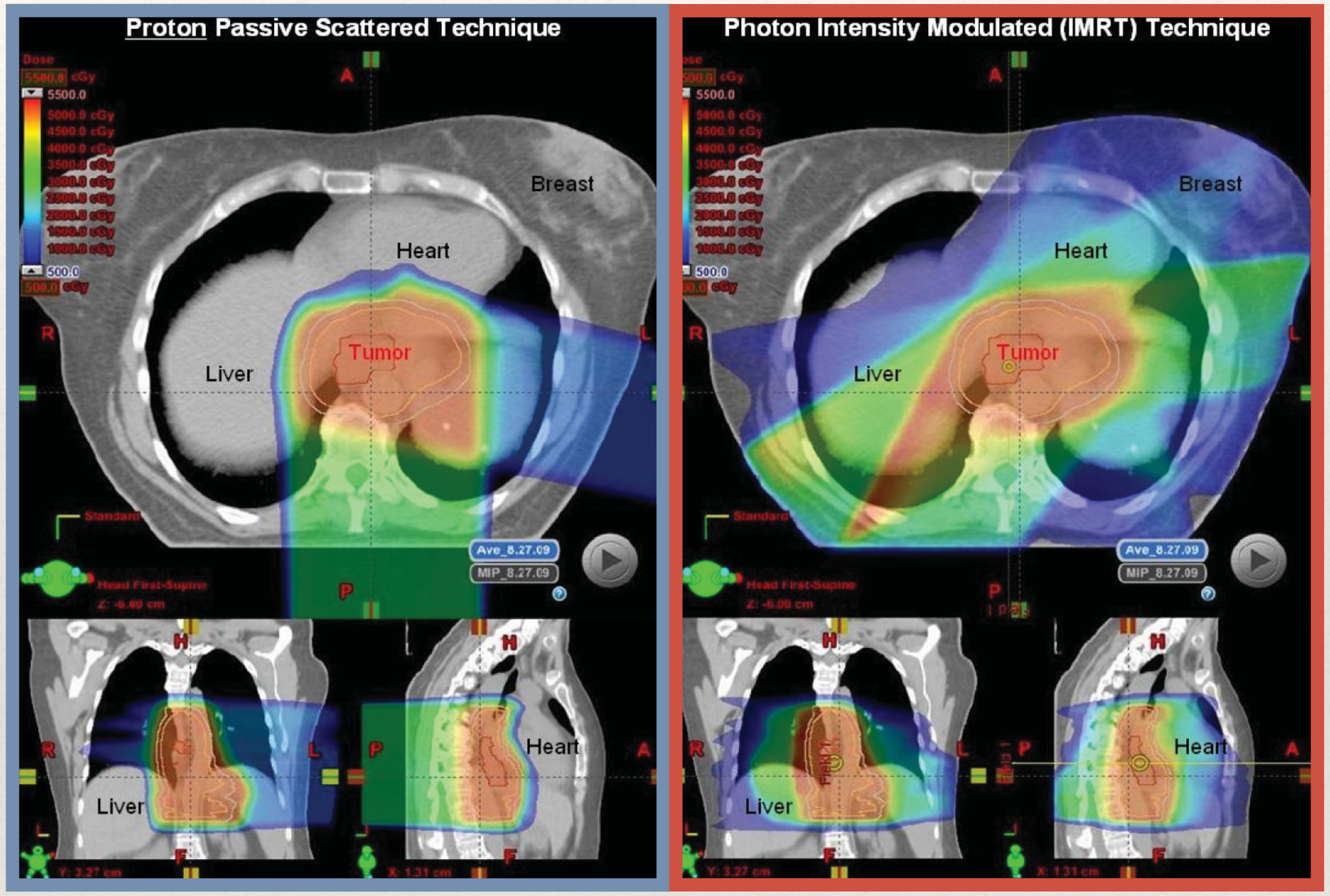
To cover the entire tumor volume, an overlap of beams at different energies is used obtaining a wider irradiation profile:

SOBP (Spread Out Bragg Peak)



proton treatment
(2 proton beams)

photon treatment
(5 photon beams)

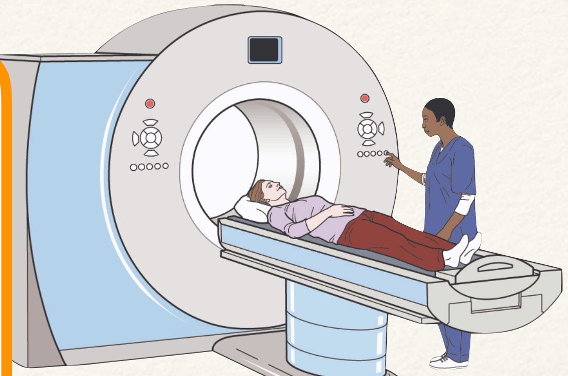


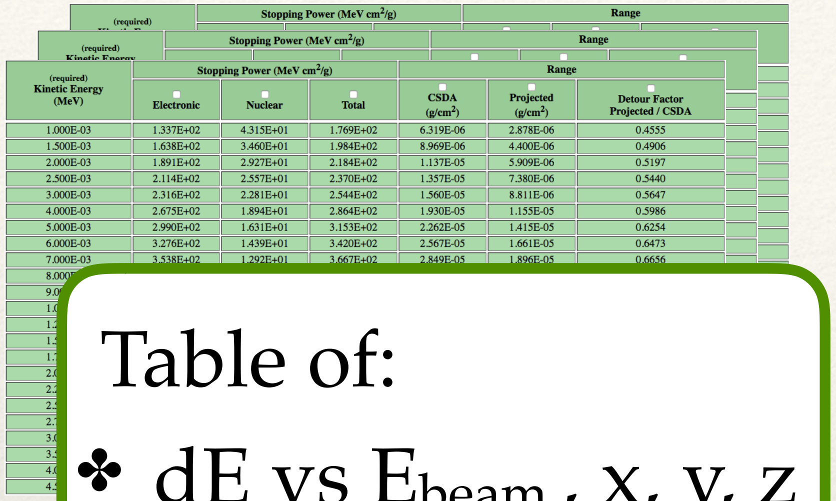
S. H. Lin, in Cancer, Volume 3 (2011), pp. 490-4101

Dose release control at the min level demands for an **accelerator control system of absolute precision and reliability** since benefit for the patient can only be achieved if the treatment is delivered exactly as planned.

Treatment Planning System

Patient anatomic data (CT, MRI, PET)





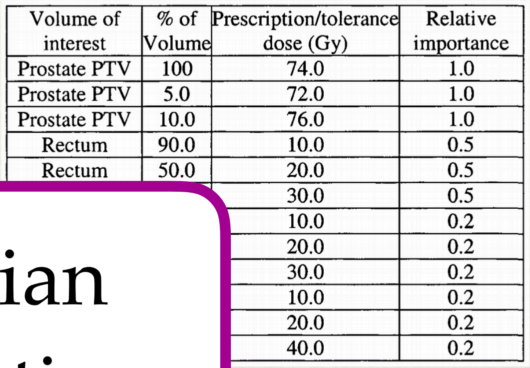
(required) Kinetic Energy (MeV)	Stopping Power (MeV cm²/g)			Range		
	☐ Electronic	☐ Nuclear	☐ Total	☐ CSDA (g/cm²)	☐ Projected (g/cm²)	☐ Detour Factor Projected / CSDA
1.000E-03	1.337E+02	4.315E+01	1.769E+02	6.319E-06	2.878E-06	0.4555
1.500E-03	1.638E+02	3.460E+01	1.984E+02	8.969E-06	4.400E-06	0.4906
2.000E-03	1.891E+02	2.927E+01	2.184E+02	1.137E-05	5.909E-06	0.5197
2.500E-03	2.114E+02	2.557E+01	2.370E+02	1.357E-05	7.380E-06	0.5440
3.000E-03	2.316E+02	2.281E+01	2.544E+02	1.560E-05	8.811E-06	0.5647
4.000E-03	2.675E+02	1.894E+01	2.864E+02	1.930E-05	1.155E-05	0.5986
5.000E-03	2.990E+02	1.631E+01	3.153E+02	2.262E-05	1.415E-05	0.6254
6.000E-03	3.276E+02	1.439E+01	3.420E+02	2.567E-05	1.661E-05	0.6473
7.000E-03	3.538E+02	1.292E+01	3.667E+02	2.849E-05	1.896E-05	0.6656

Table of:

- dE vs E_{beam} , x, y, z
- RBE vs E_{beam}, dE, x, y, z

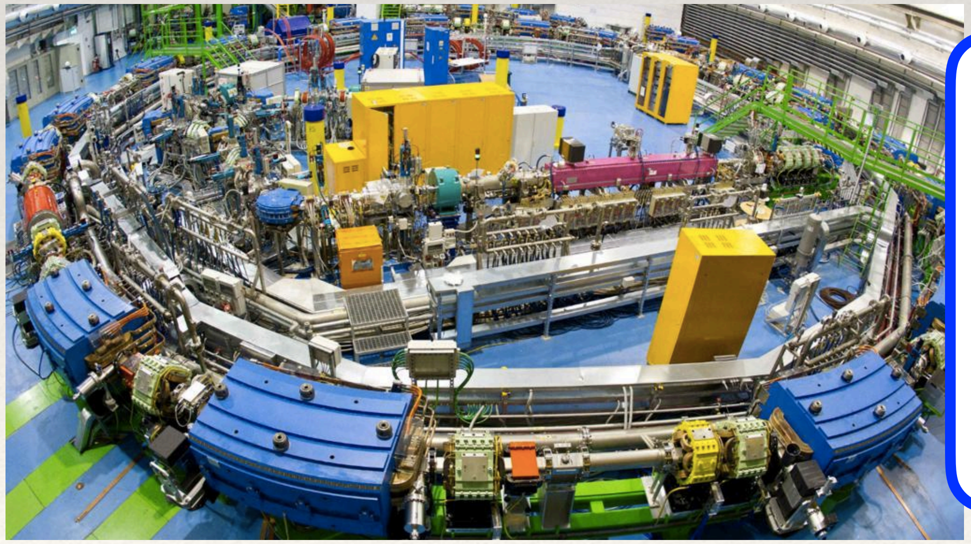
TPS

Physician Prescription



Volume of interest	% of Volume	Prescription/tolerance dose (Gy)	Relative importance
Prostate PTV	100	74.0	1.0
Prostate PTV	5.0	72.0	1.0
Prostate PTV	10.0	76.0	1.0
Rectum	90.0	10.0	0.5
Rectum	50.0	20.0	0.5
		30.0	0.5
		10.0	0.2
		20.0	0.2
		30.0	0.2
		10.0	0.2
		20.0	0.2
		40.0	0.2

Accelerators Parameters: Fluences for each beam spot



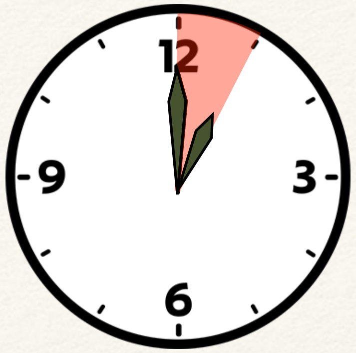
TPS is a sofisticate software tool which provides to the accelerator control system the position, intensity and direction of the beams in order to produce a patient-specific set of particle beams

Treatment Planning System

ANALYTIC TPS

- Fast (~ 1 h/core, minutes on GPU)
- Simplified beam-body interaction model using a 3D water equivalent representation of the patient morphology

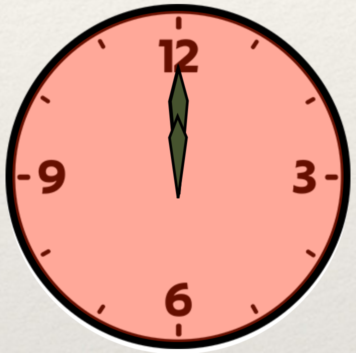
Routinely used in PT treatment



MC TPS (FLUKA and TOPAS/Geant4)

- Slow (~ days/core)
- Explicitly take into account the details in the interaction of particles with human tissues

Only used to check treatment plans for a restricted number of difficult cases



OCTOBER 2020

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	[illegible]	2	[illegible]	22	23	24
25	26	27	28	29	30	31

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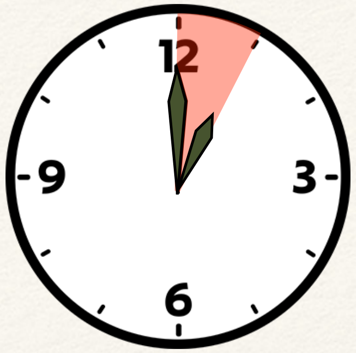

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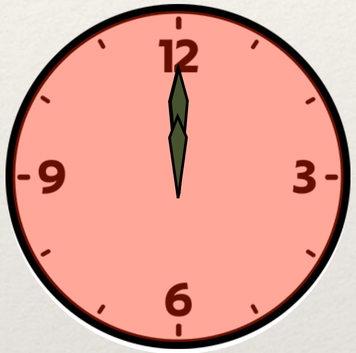

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18	~~19~~	~~20~~	~~21~~	22	23	24
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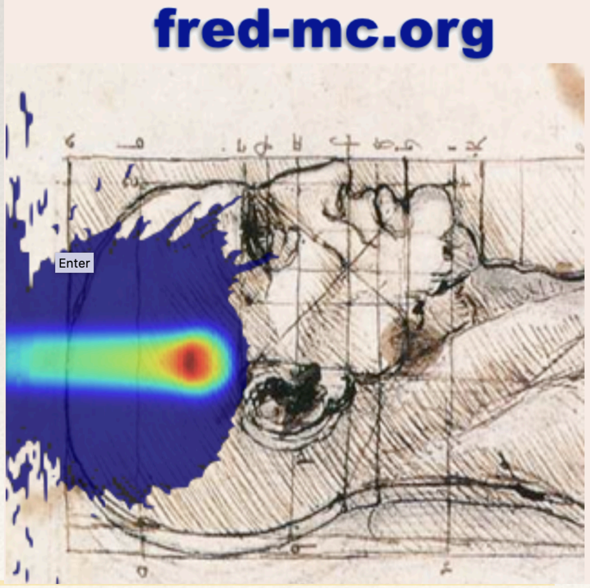
www.cr-printable-calendar.com

NEW!!

FAST MC: FRED

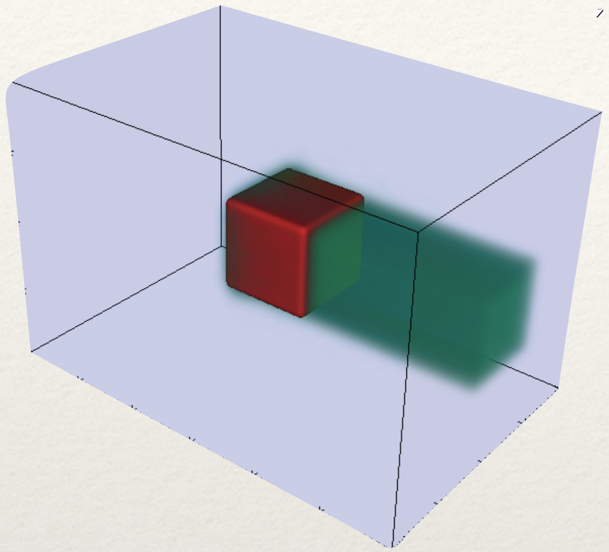
(Fast paRticle thErapy Dose evaluator)

- Fast (few minutes)
- Takes into account the details in the interaction of particles with human tissues that are needed for a TPS



FRED as tool for quality control

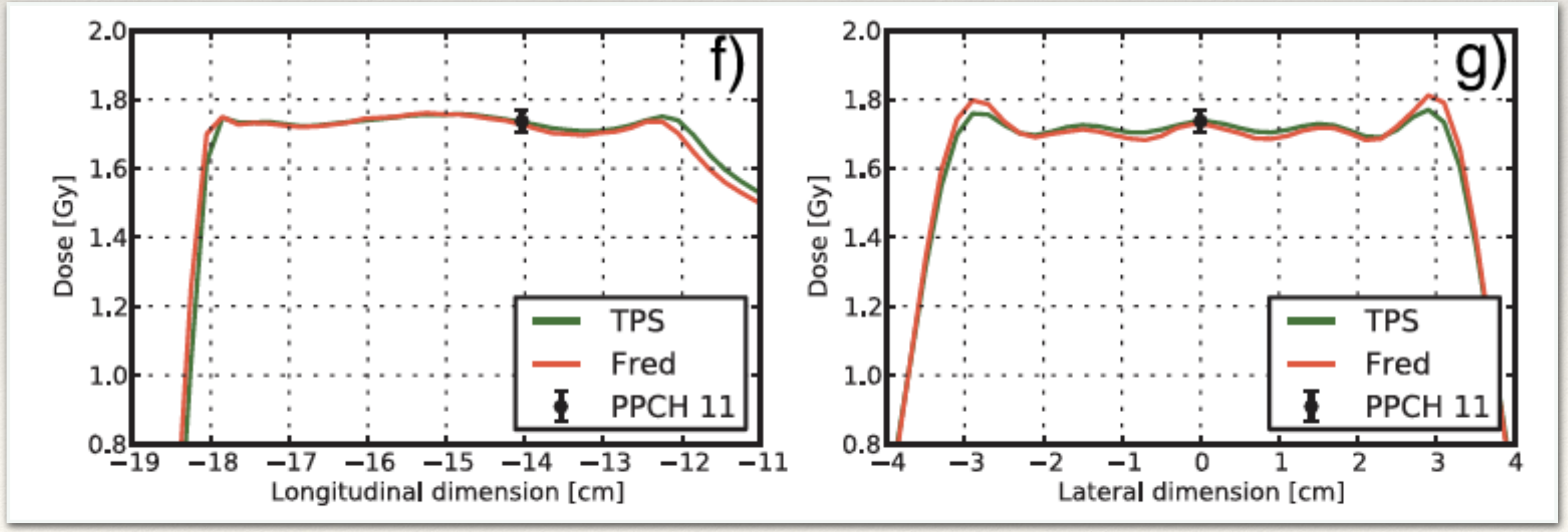
TPS are periodically tested to verify that the accelerators parameters have been calculated correctly for each patient.



The accelerator delivers the beams in a tank full of water following the TPS instructions and the dose is measured in different points of the target with ionization chambers.

FRED can be used to verify that the TPS is correct instead of delivering the beam with the accelerator.

Proton beam



Carbon Therapy

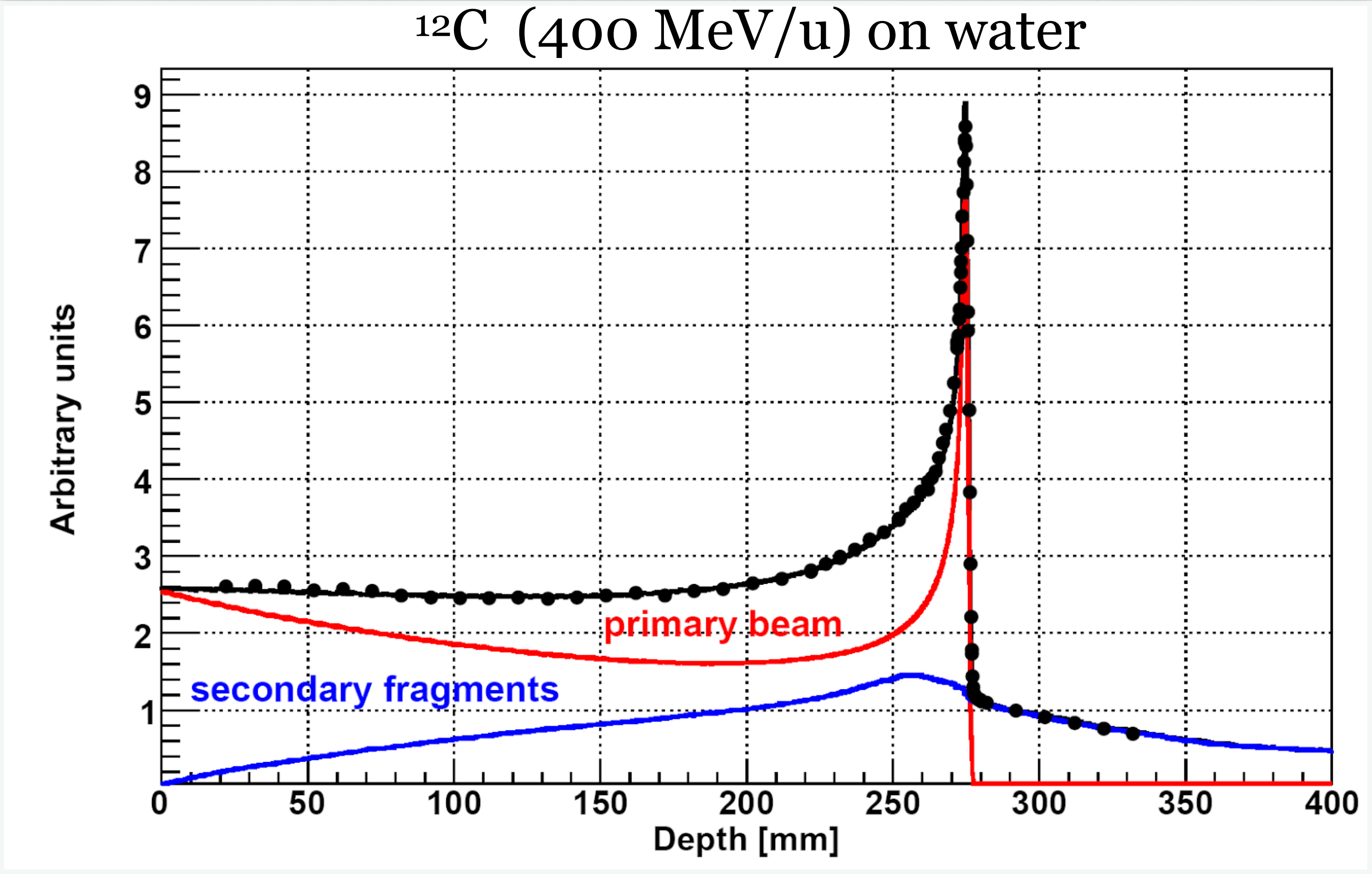
FRED is already used in proton therapy as a quality assurance tool in the clinical center of Maastricht and Krakow and as a research tool at several clinical and research centers in Europe (Krakow, Trento, Maastricht, Lyon and PSI)

Interest of CNAO and MedAustron for the use of FRED in Carbon Therapy

fondazione CNAO

MedAustron

Production of different fragments



^{12}C (400 MeV/u) on water

- Mitigation and attenuation of the primary beam
- Different biological effectiveness of the fragments wrt the beam
- Different fragment ranges

Double differential cross section needed: **lack of experimental data** at the energies of interest in medical physics

My PhD work

Beam

- **Ionization energy loss** (Bethe-Bloch, Gaussian approximation, Vavilov and Landau distributions)
- **Multiple Coulomb Scattering** (theory of Moliére adding a scaling factor following Fippel and Soukup approach)

Beam and Frag.

- **Nuclear Model** (phenomenologic approach based on Ganil measurement at 95 MeV/u**):**
  - **Coefficient of mass attenuation** to decide when ther is an elastic and non-elastic event. Base on data found in literature;
  - **Sampling of the fragments** and their **energy and angle distributions**. Base on Ganil measurement;

D_{bio} and RBE

- **Biological Dose and Relative Biological Effectiveness** (LEM I model)

Comparison with :

- full MC (FLUKA);
- experiments found in literature.

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Coefficient of Mass Attenuation

$$\frac{\mu}{\rho} = \sum_i \frac{N_A w_i \sigma_i}{A_i}$$

Elastic cross-section

Obtained from a fit on data and using the *Ranft* model;

ENDF/B-VII Incident-Proton Data

Non-elastic cross-section

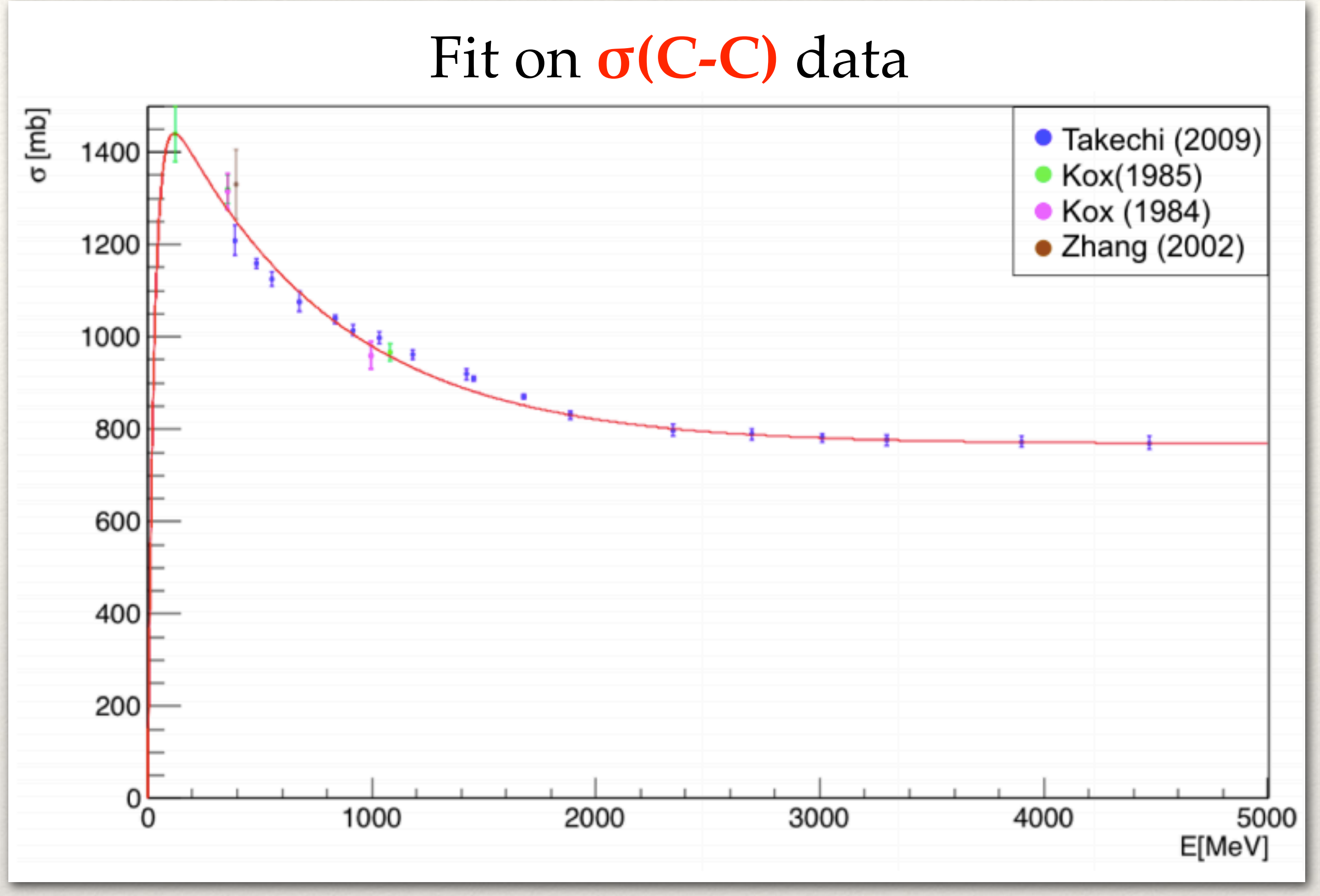
σ(C-C) and σ(C-H) obtained from a fit on data;

Zhang H. Y. et al. Nucl. Phys. 707 (2002)

Takechi M. et al. Phys. Rev. C 79.6 (2009)

Kox S. et al. Nucl. Phys. 420 (1984), Phys. Letters 159 (1985)

ICRU (International Commission on Radiation Units & Measurements)


Fit on σ(C-C) data

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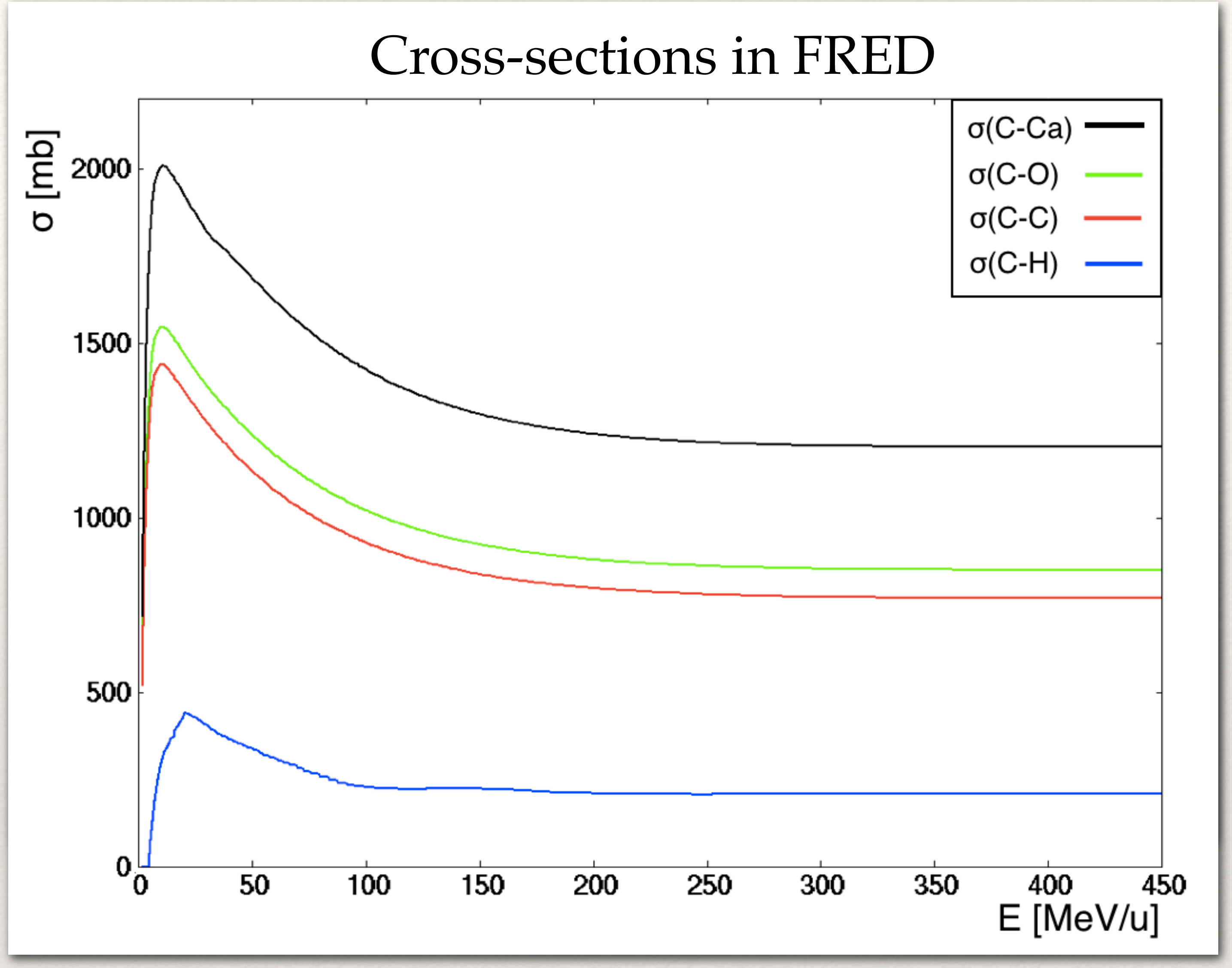


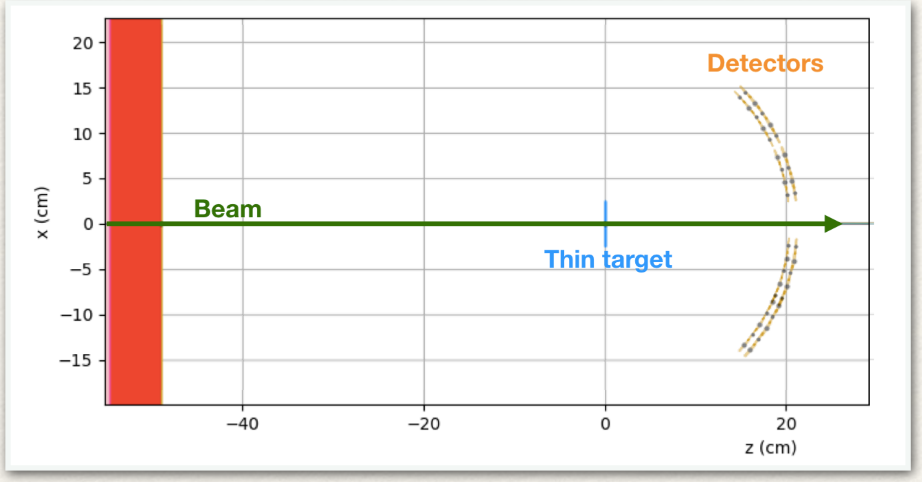
σ(C-Ca) and **σ(C-O)** obtained starting from **σ(C-C)** and scaled with the *Kox* formula.

$$K(N_p, N_t, E_{cm}) = \frac{\sigma_K(N_p, N_t, E_{cm})}{\sigma_K(^{12}C, ^{12}C, E_{cm})}$$

$$\sigma(N_p, N_t, E) = K(N_p, N_t, E)(1 - e^{\frac{E}{E_c}})(p_0 + p_1 E + e^{p_2 - p_3 E})$$

Genereting a fragmentation event

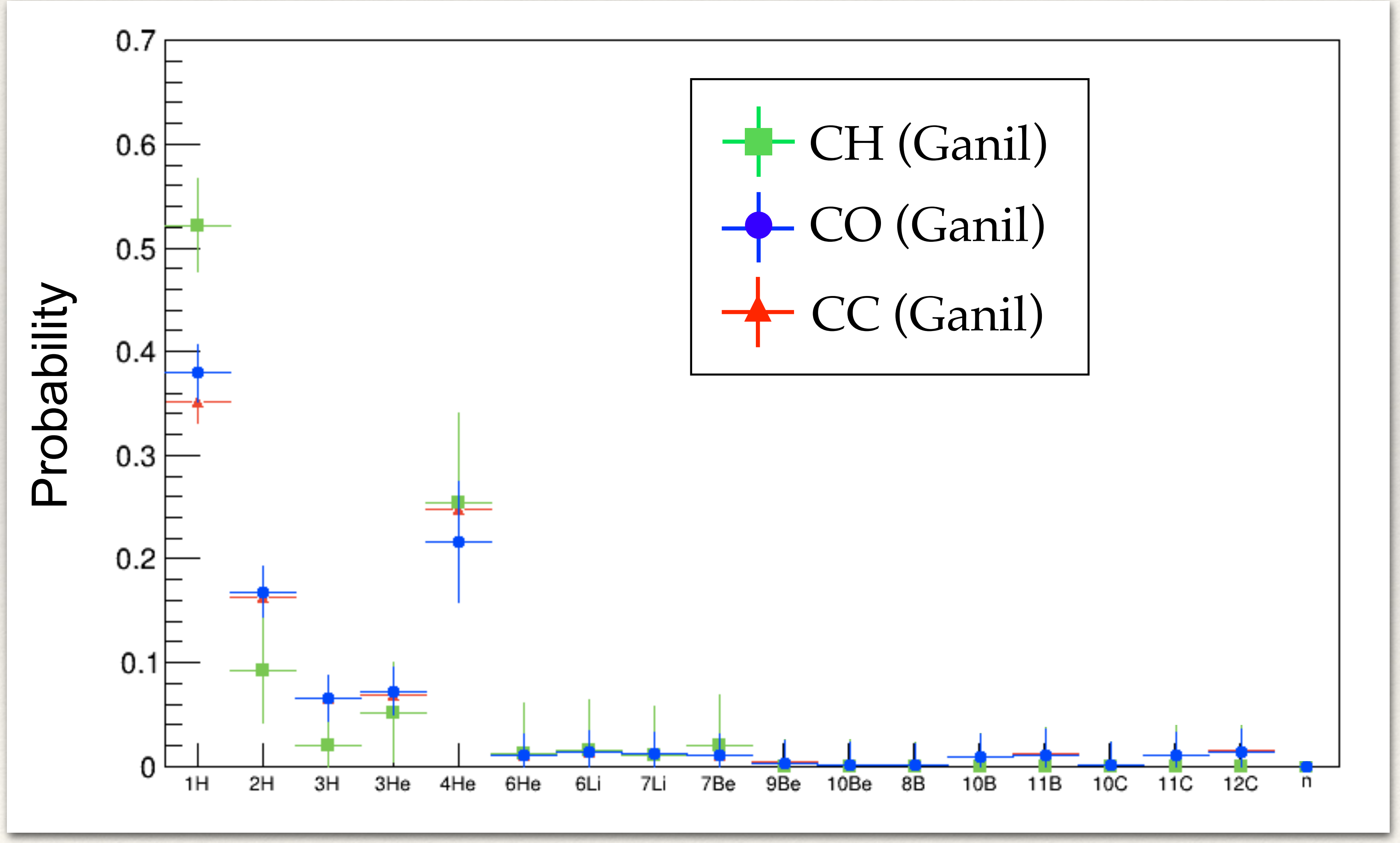
simulated with FRED

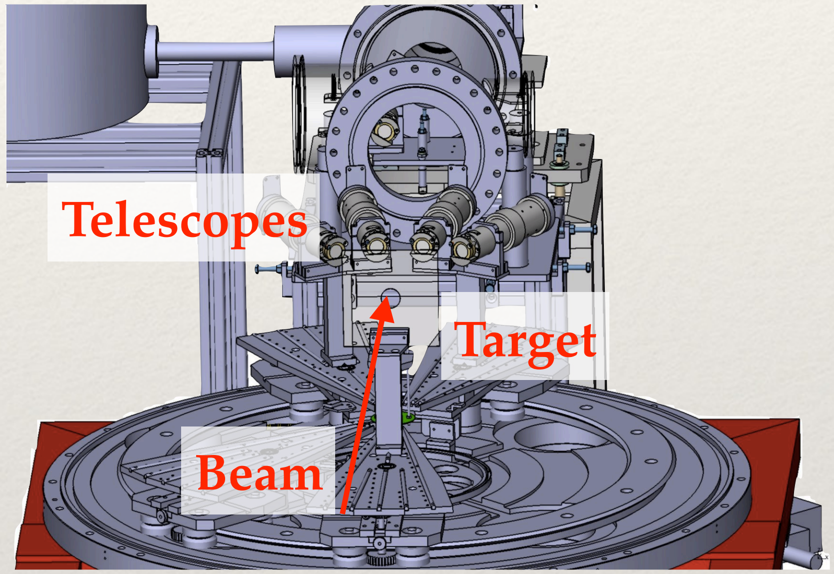


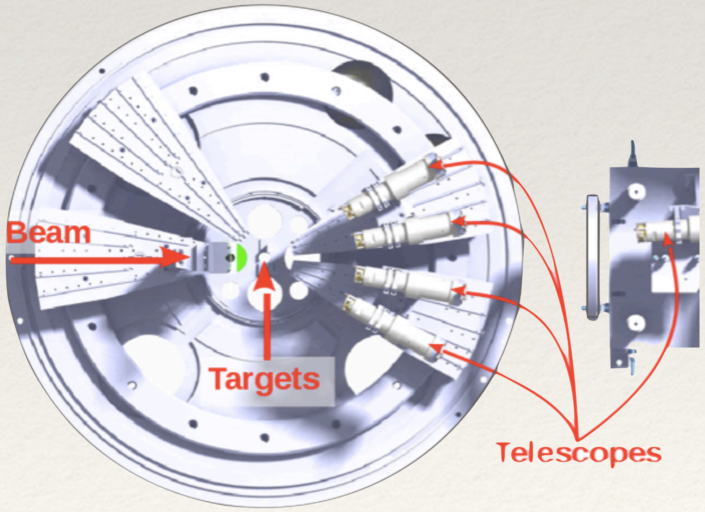
What do we have? **GANIL's probability of emission**

Fragmentation experiment of ^{12}C beam @95MeV/u on different thin targets (O, C, H, Al, Ti). The only experiment which provides double differential cross-section at the energy of interest of PT.

Dudouet. J. et al. Phys Rev C 88 (2013)







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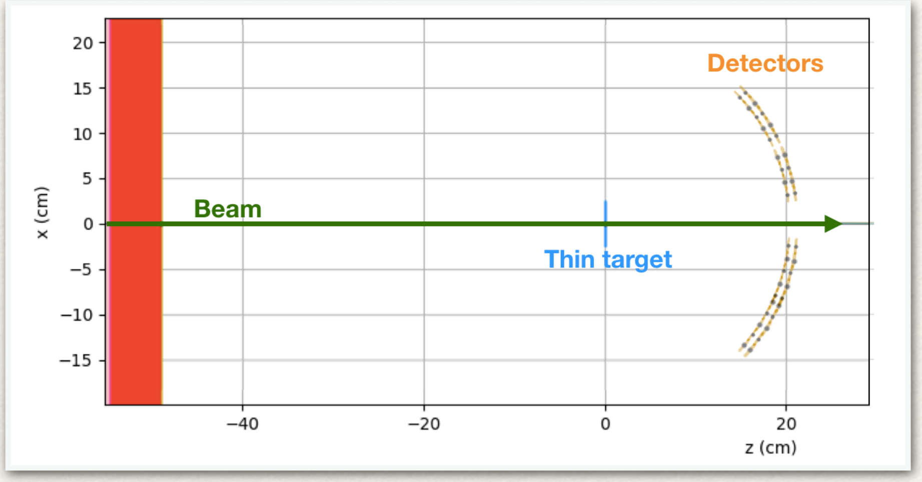
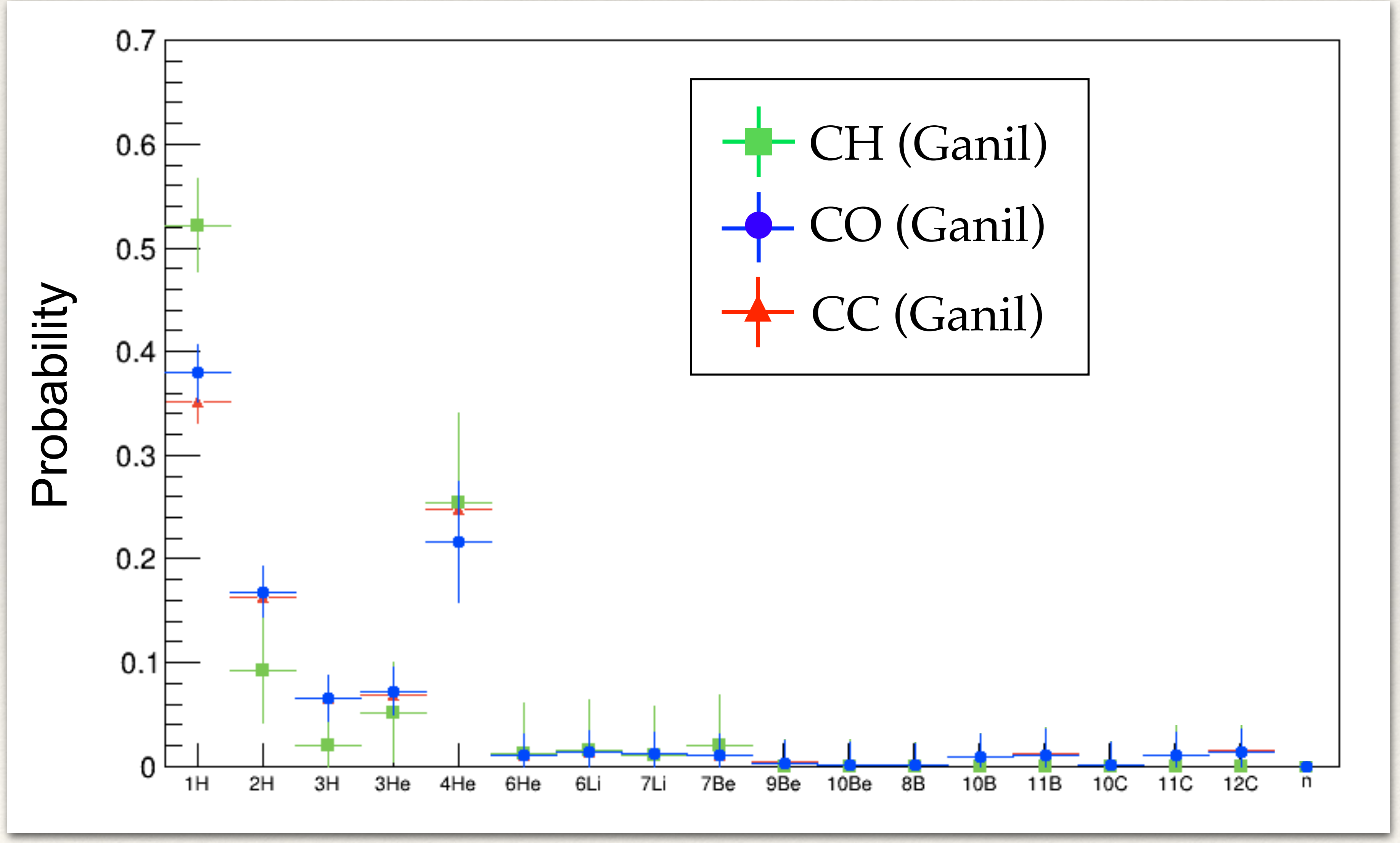


What do we have? **GANIL's probability of emission**

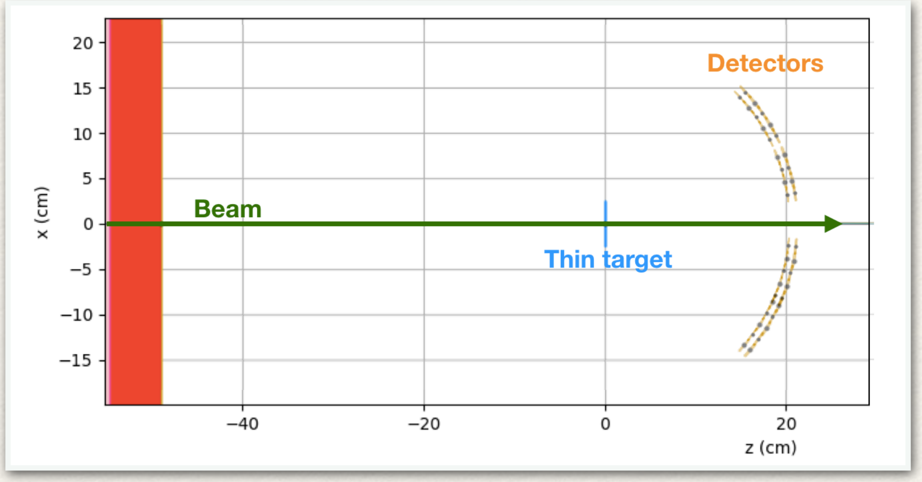
If the Ganil probabilities would be used directly for the fragments sampling the final fragments' distribution would be different from that one measured by Ganil due to the sampling procedure.



Mass and charge conservation

Beam and Frag.

Genereting a fragmentation event



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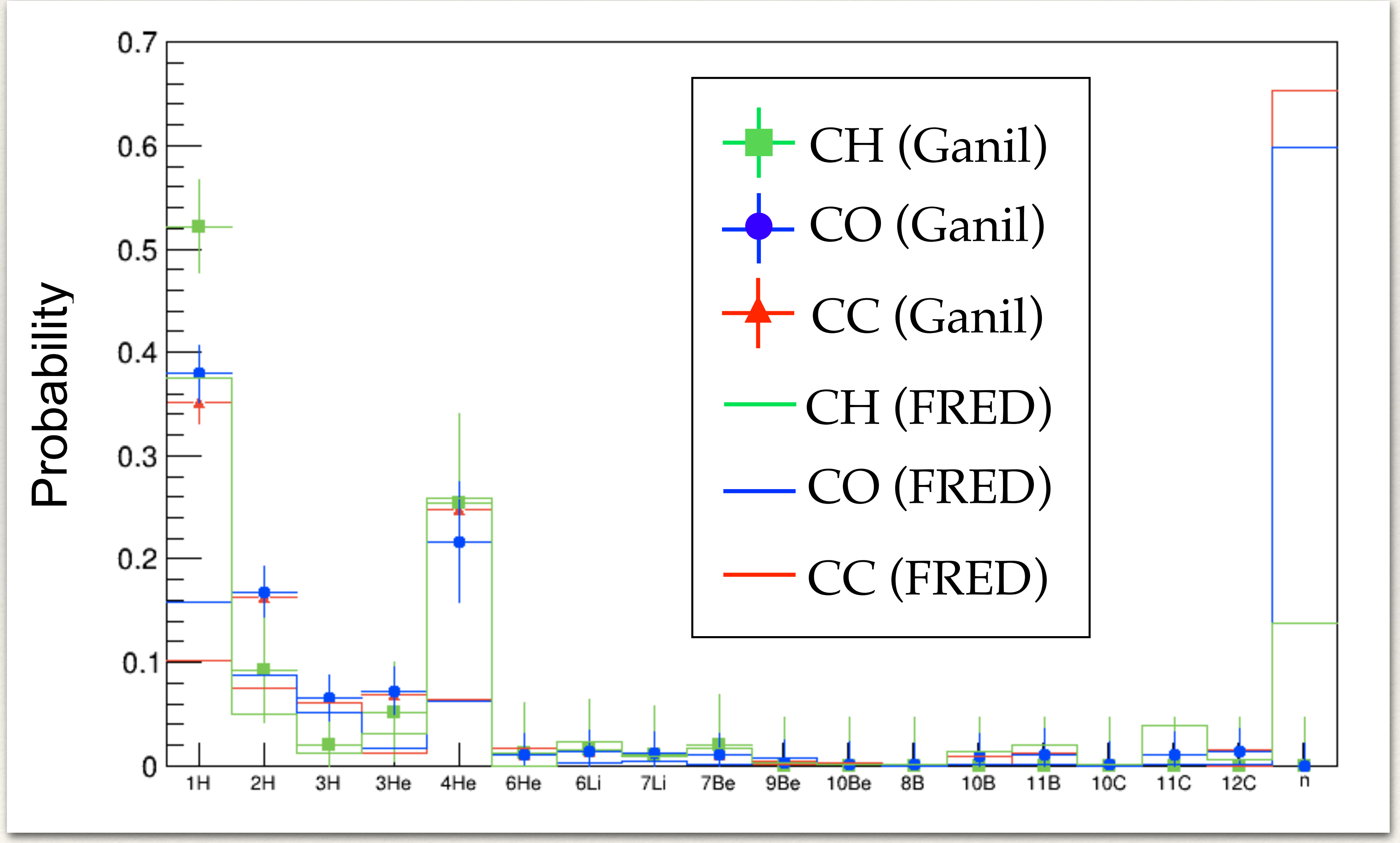


Mass and charge conservation

Use of an iterative formalism to have the same generating probability of the Ganil experiment:

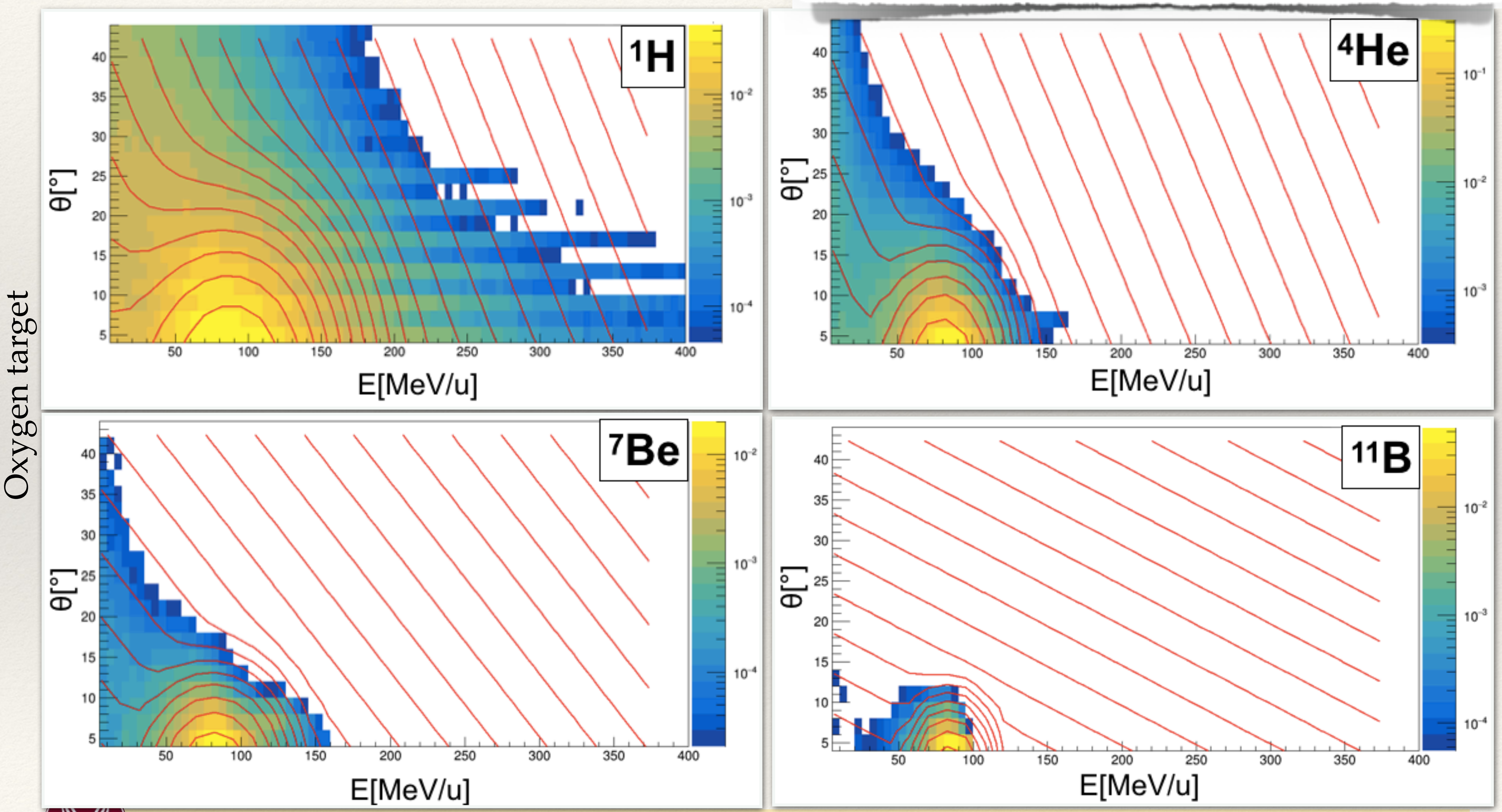
NEW probability of emission

Sampling of energy and angular distribution

Bidimensional fits on GANIL data show that the distribution is composed of:

- a **gaussian** function (projectile fragmentation) ;
- an **exponential** function (target fragmentation).

$$f(E,\theta) = A_1 e^{-(\alpha_E E + \alpha_\theta \theta)} + A_2 e^{-\left(\frac{(E-<E>)^2}{2\sigma_E} + \frac{(\theta-<\theta>)^2}{2\sigma_\theta}\right)}$$



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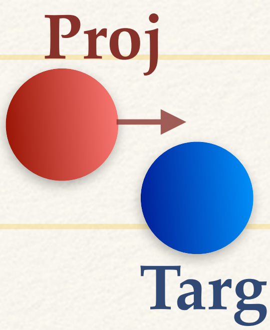
Energy and angular distribution of GANIL correspond at a 95 MeV/u beam.
Extrapolation of new energy and angle

$$E^i = E^i_{95\mathrm{MeV/u}} \frac{E_{proj}[\mathrm{MeV/u}]}{95}(1-k)$$

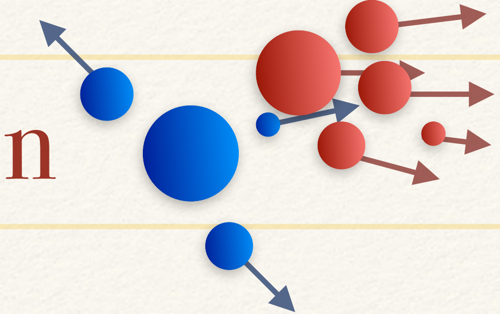
$$\theta^i = \theta^i_{95\mathrm{MeV/u}} \sqrt{\frac{95}{E_{proj}[\mathrm{MeV/u}]}}$$

energy conservation

Beam and Frag.



Fragmentation



Sampling of the target → *Using Kox's cross-section to build a cumulative distributions.*

$$P^i = \frac{n^i \sigma^i_K}{\sigma^{tot}}$$

$$\sigma^{tot} = \sum_{j=0}^{j=N} n^j \sigma^j_K$$

Sampling of the fragments → *The code reads probability tables built to have the same generating probability of the GANIL experiment*

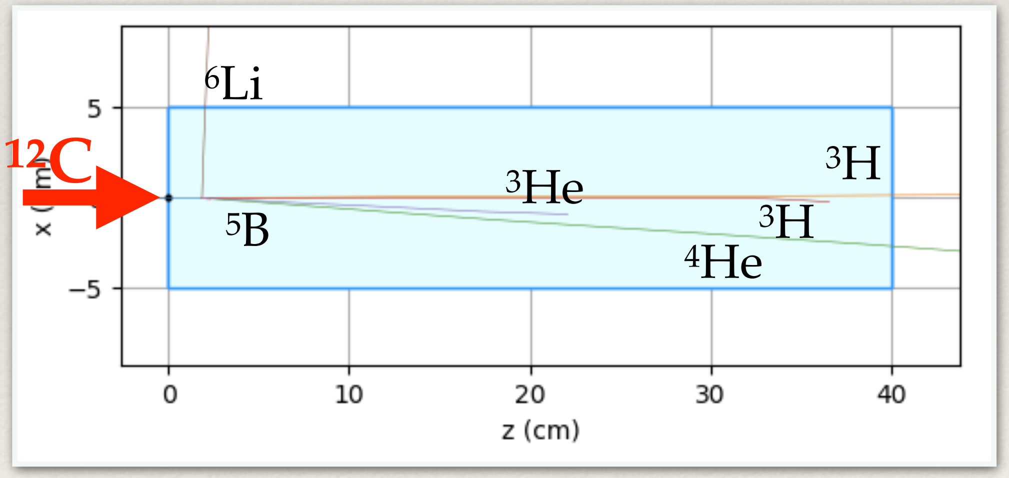
Fragments from the projectile

Mass and charge conservation? NO → Fragments from the projectile; YES ↓

Fragments from the target

Mass and charge conservation? NO → Fragments from the target; YES ↓

Sampling of energy and angle of new fragments → *Base on GANIL data (next slide)*

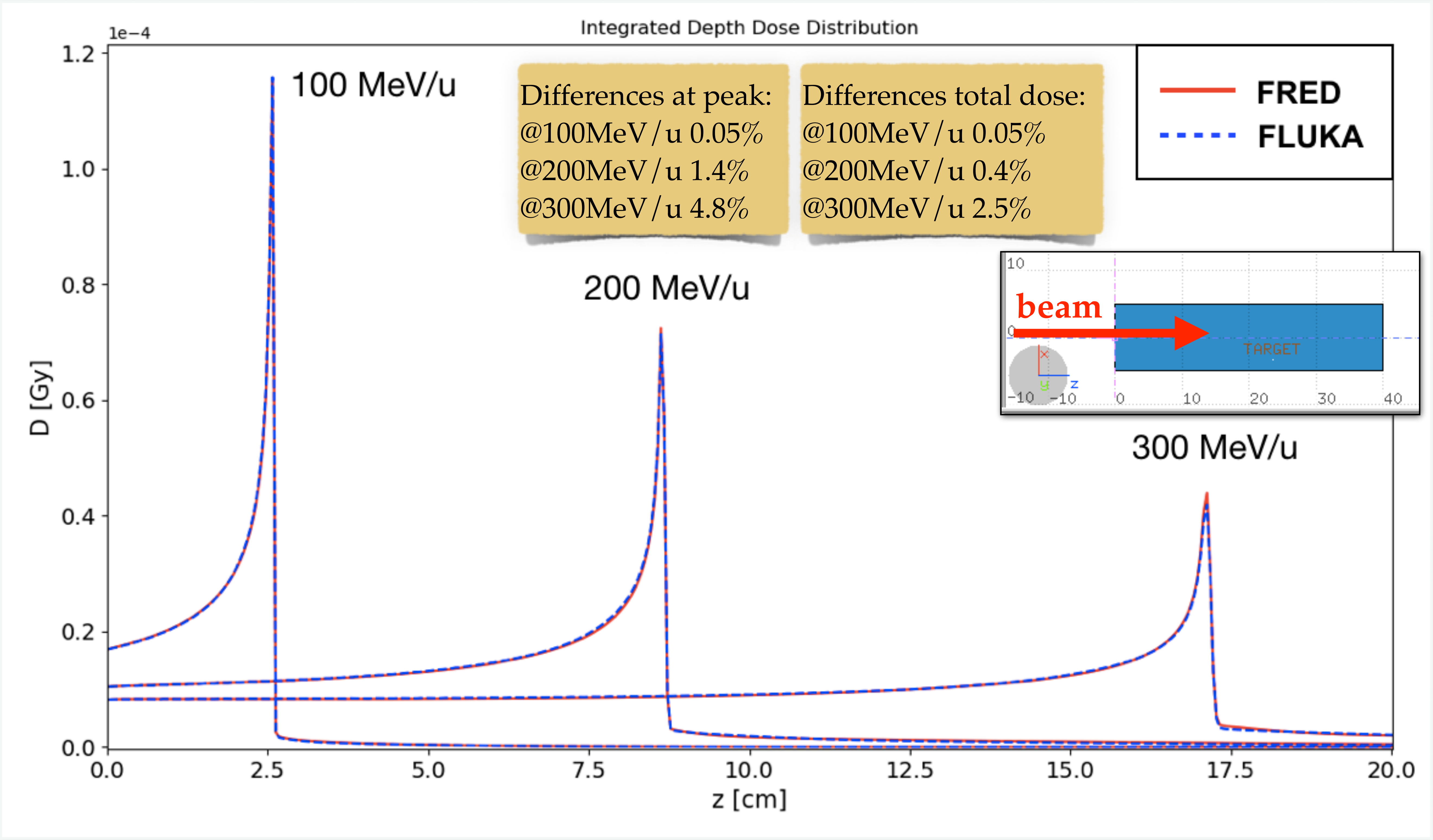


Extrapolation to different beam energy

Energy conservation? NO → Sampling of the fragments; YES →

Creating new particles and tracking them with FRED

Results: DDD of a single PB of ^{12}C in water

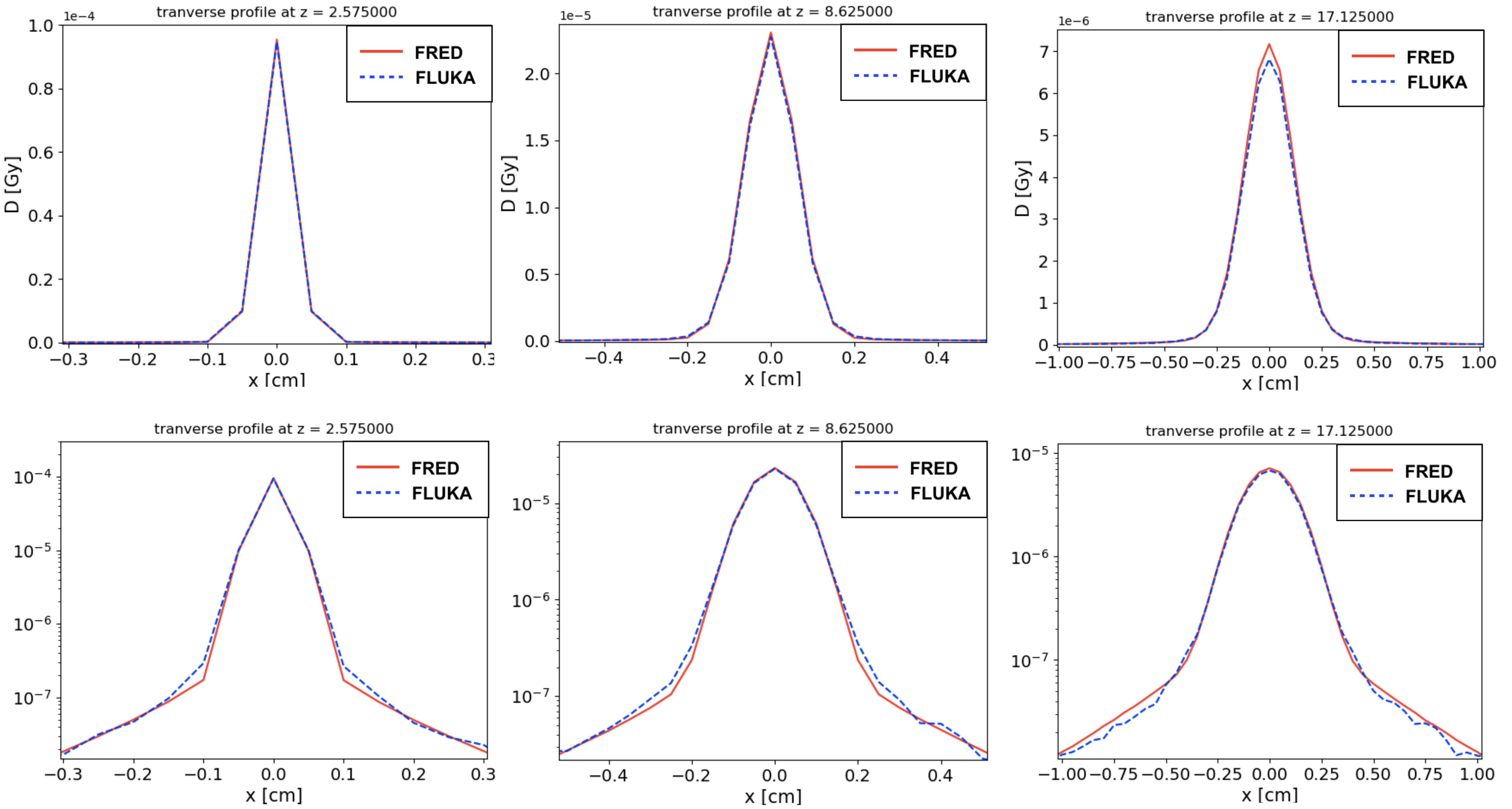


Differences at peak:
@100MeV/u 0.05%
@200MeV/u 1.4%
@300MeV/u 4.8%

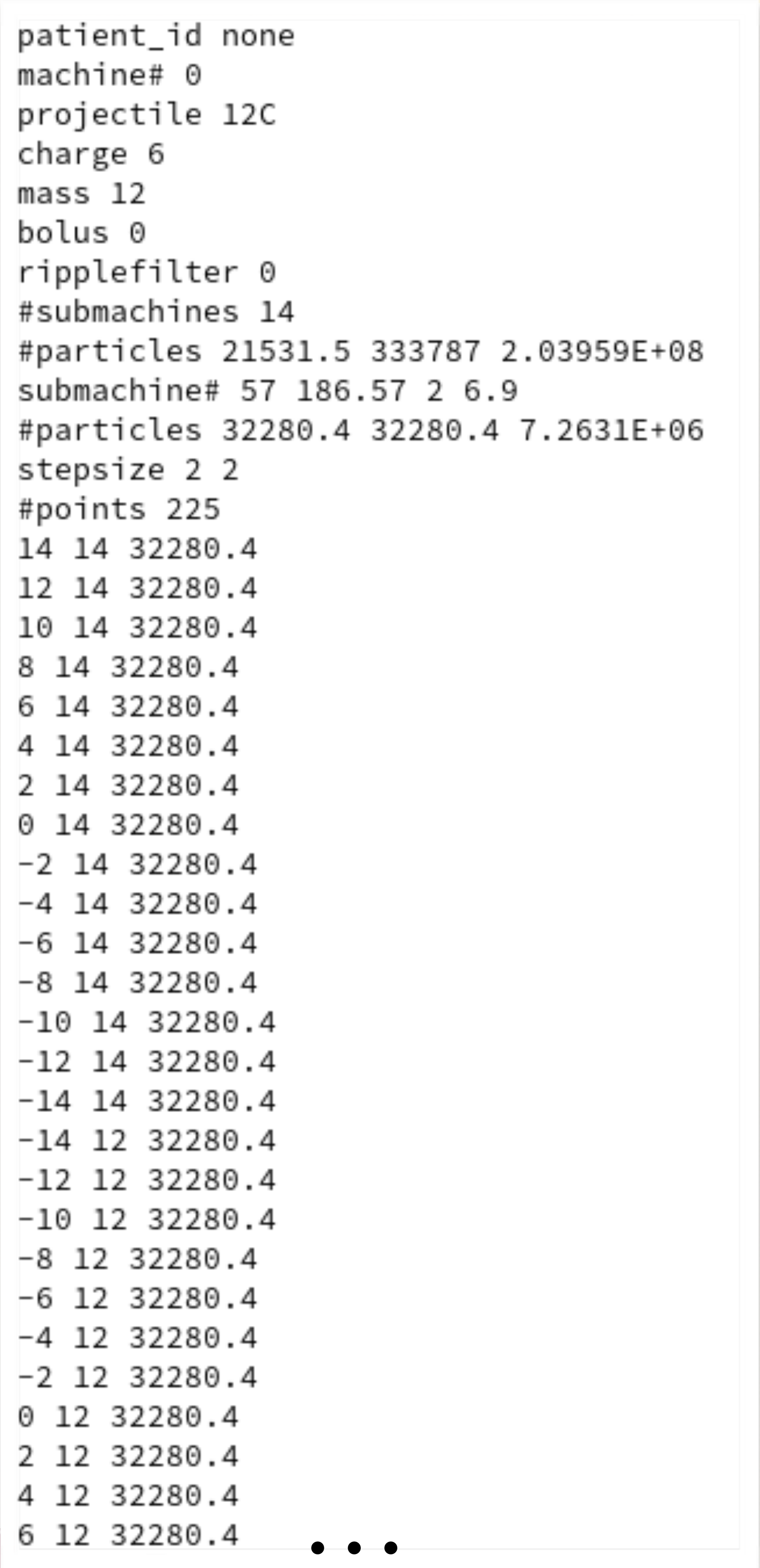
Differences total dose:
@100MeV/u 0.05%
@200MeV/u 0.4%
@300MeV/u 2.5%

Results: Lateral dose at peak of a single PB of ^{12}C in water

100 MeV/u **200 MeV/u** **300 MeV/u**



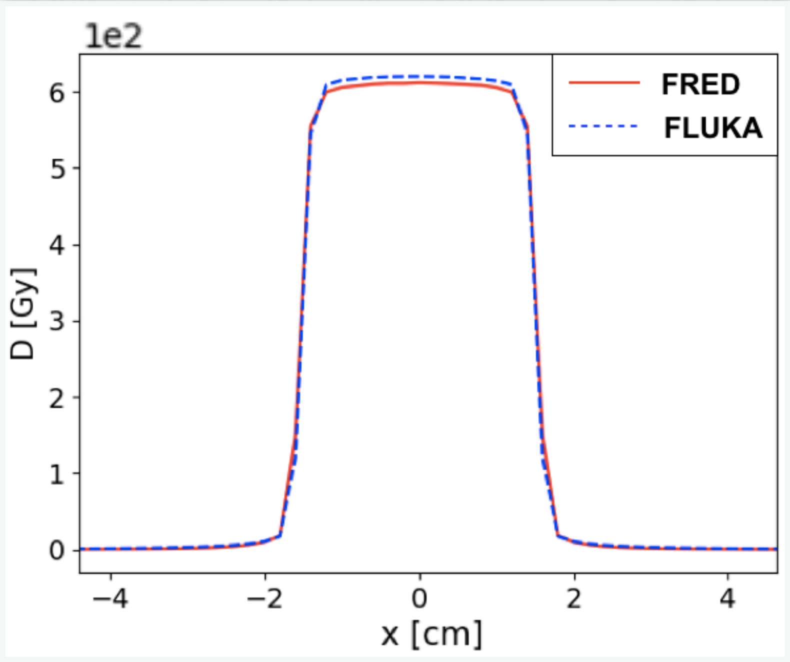
SOBP from raster file of CNAO

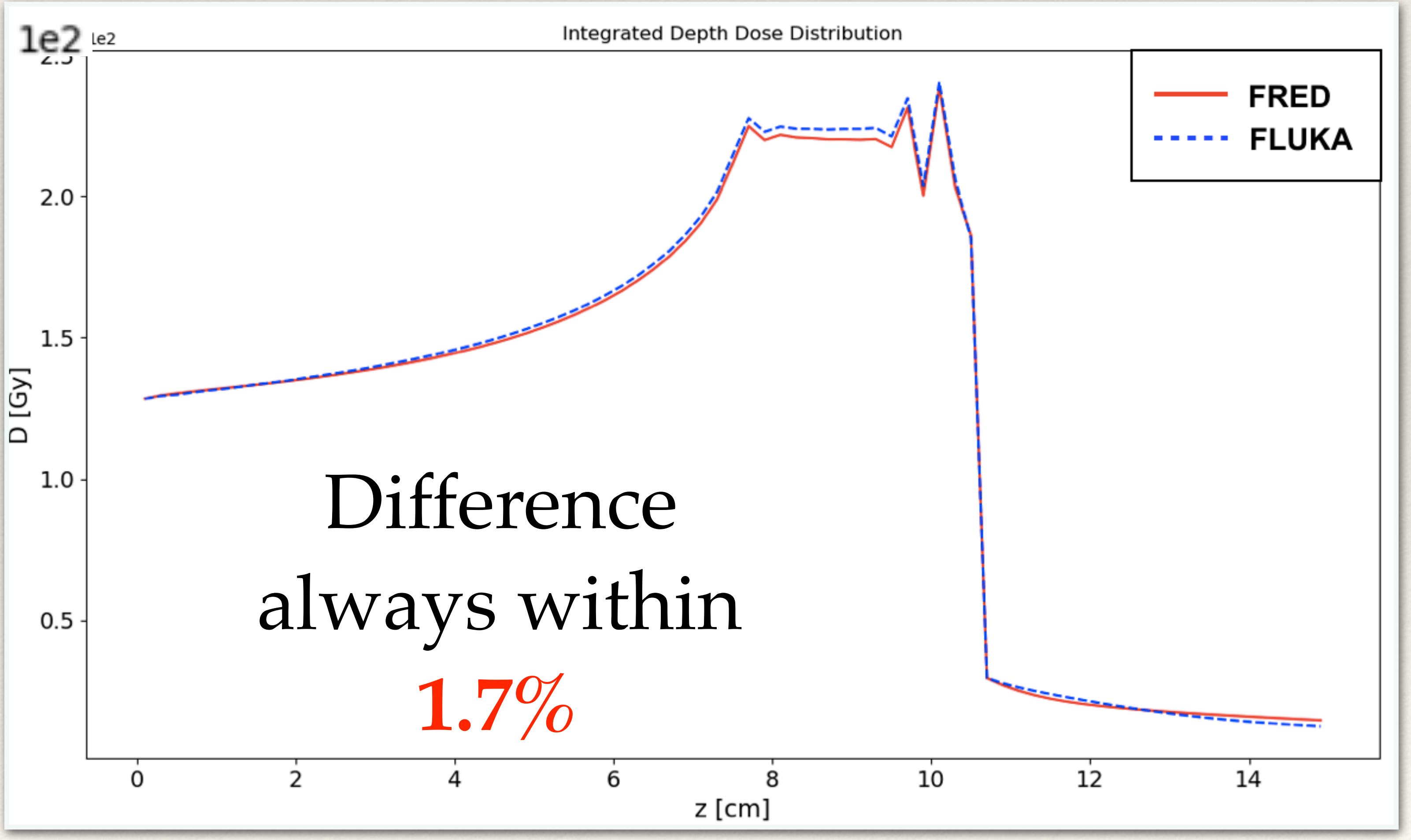


```
patient_id none
machine# 0
projectile 12C
charge 6
mass 12
bolus 0
ripplefilter 0
#submachines 14
#particles 21531.5 333787 2.03959E+08
submachine# 57 186.57 2 6.9
#particles 32280.4 32280.4 7.2631E+06
stepsize 2 2
#points 225
14 14 32280.4
12 14 32280.4
10 14 32280.4
8 14 32280.4
6 14 32280.4
4 14 32280.4
2 14 32280.4
0 14 32280.4
-2 14 32280.4
-4 14 32280.4
-6 14 32280.4
-8 14 32280.4
-10 14 32280.4
-12 14 32280.4
-14 14 32280.4
-14 12 32280.4
-12 12 32280.4
-10 12 32280.4
-8 12 32280.4
-6 12 32280.4
-4 12 32280.4
-2 12 32280.4
0 12 32280.4
2 12 32280.4
4 12 32280.4
6 12 32280.4
```

…

Combination of:
Beams at 14 different energies from 186.57 to 223.56 MeV/u,
for each energy
225 beams in different positions



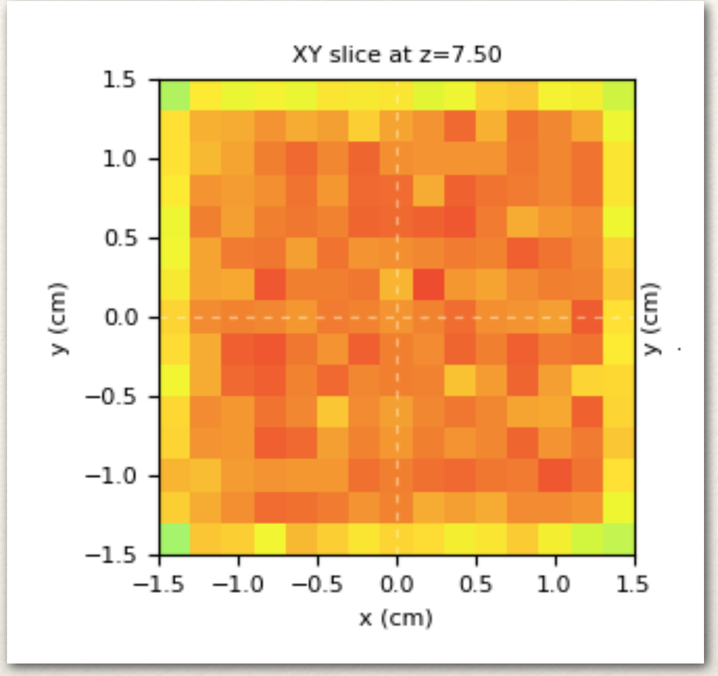


Difference always within **1.7%**

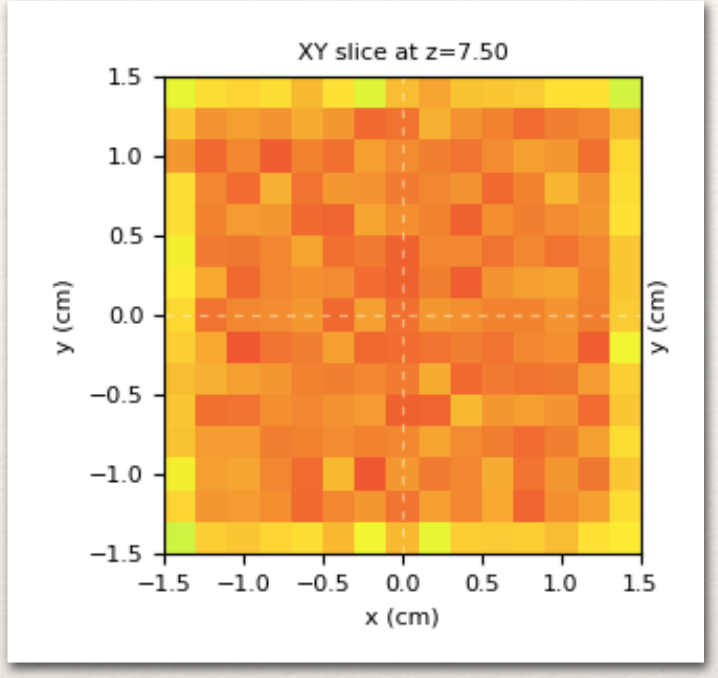
Gamma-index

γ-index 2mm/3%

Reference Map (FLUKA)



Evaluation Map (FRED)



Gamma-index

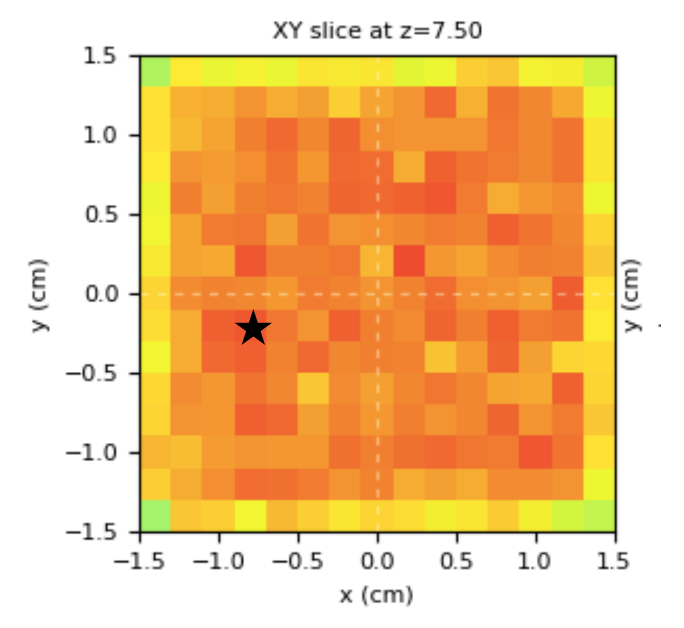
γ-index 2mm/3%

$$\Gamma(\vec{r_e},\vec{r_r}) = \sqrt{\frac{|\vec{r_e}-\vec{r_r}|^2}{\Delta d^2} + \frac{[D_e(\vec{r_e}) - D_r(\vec{r_r})]^2}{\Delta D^2}}$$

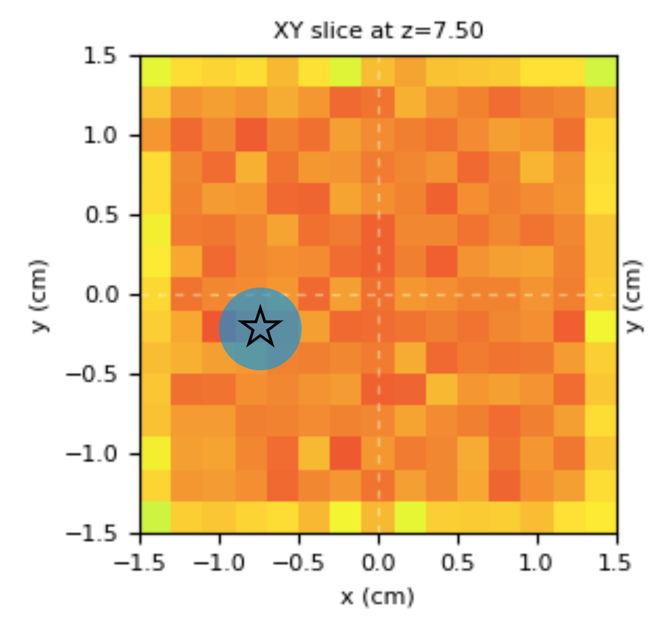
D= dose (D_r of the reference map, D_e of the evaluation map)

r = position of the evaluated point (r_r of the reference map, r_e of the evaluation map)

Reference Map (FLUKA)



Evaluation Map (FRED)



Gamma-index

γ-index 2mm/3%

$$\Gamma(\vec{r_e},\vec{r_r}) = \sqrt{\frac{|\vec{r_e}-\vec{r_r}|^2}{\Delta d^2} + \frac{[D_e(\vec{r_e}) - D_r(\vec{r_r})]^2}{\Delta D^2}}$$

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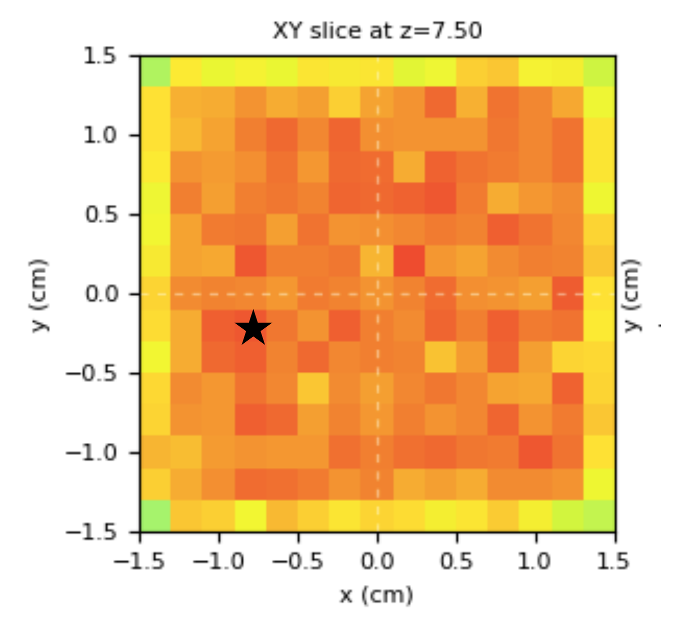
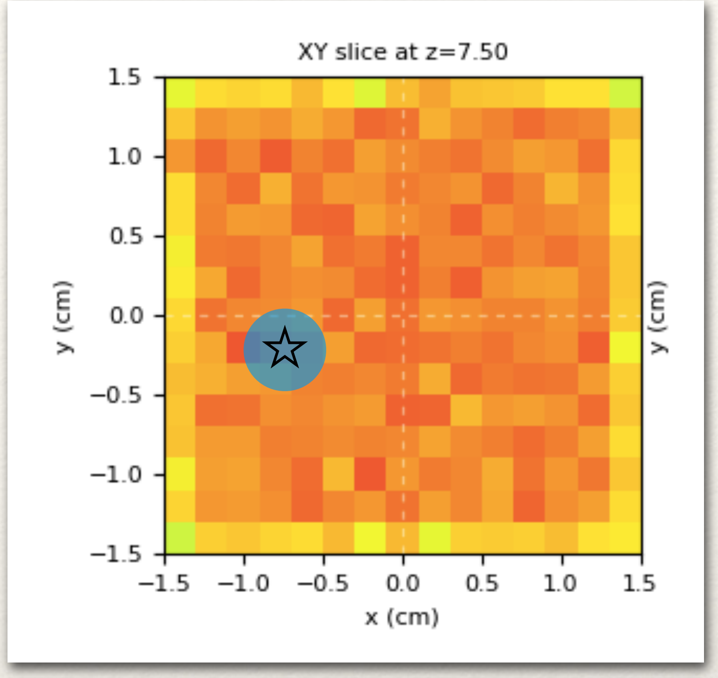
Reference Map (FLUKA)



Evaluation Map (FRED)

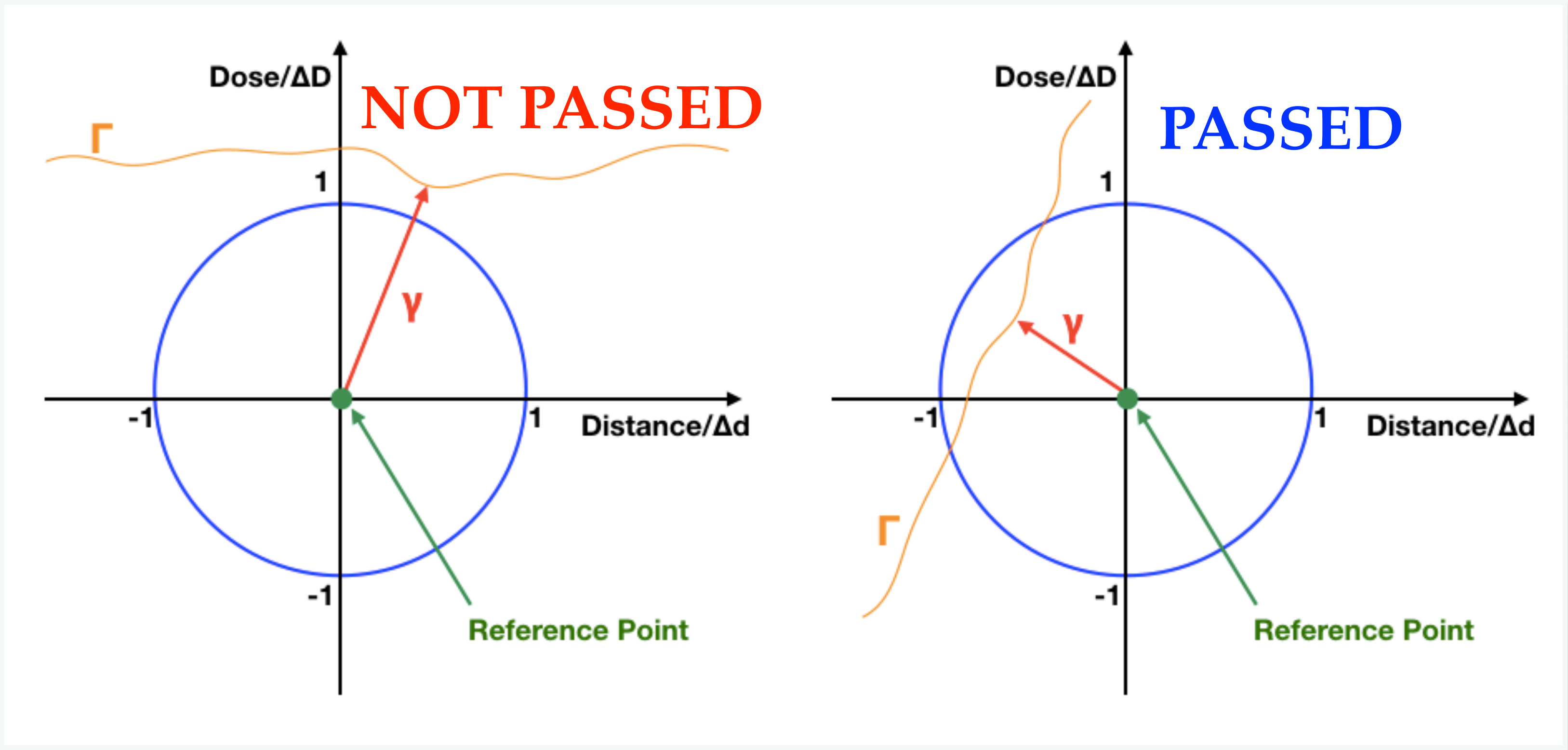


$$\gamma(\vec{r_r}) = \min\{\Gamma(\vec{r_e},\vec{r_r})\}\forall\{\vec{r_e}\}$$

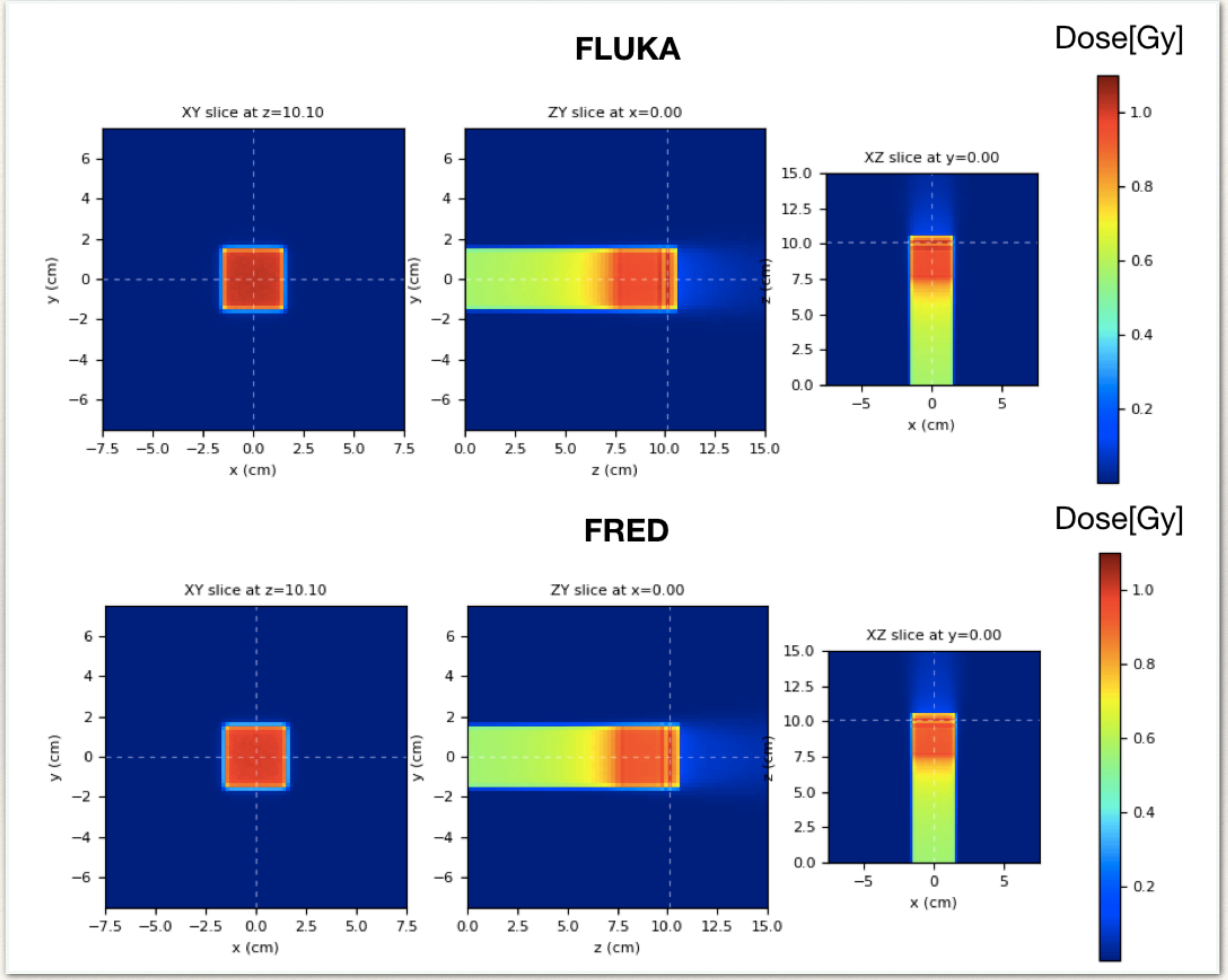
$\gamma \le 1$ = test passed

$\gamma > 1$ = test NOT passed

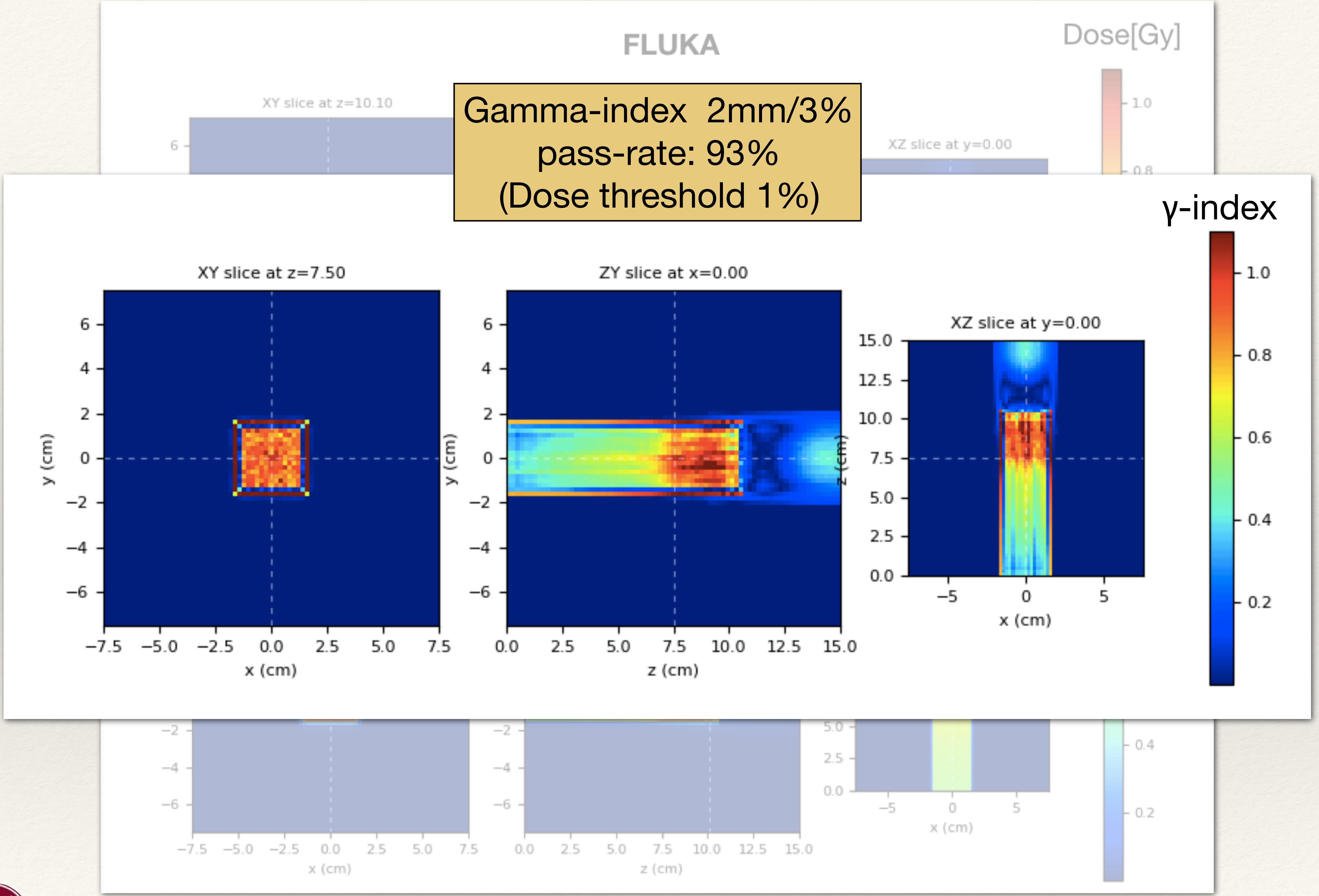
pass rate ≥ 92%
clinical acceptance



SOBP from raster file of CNAO



SOBP from raster file of CNAO

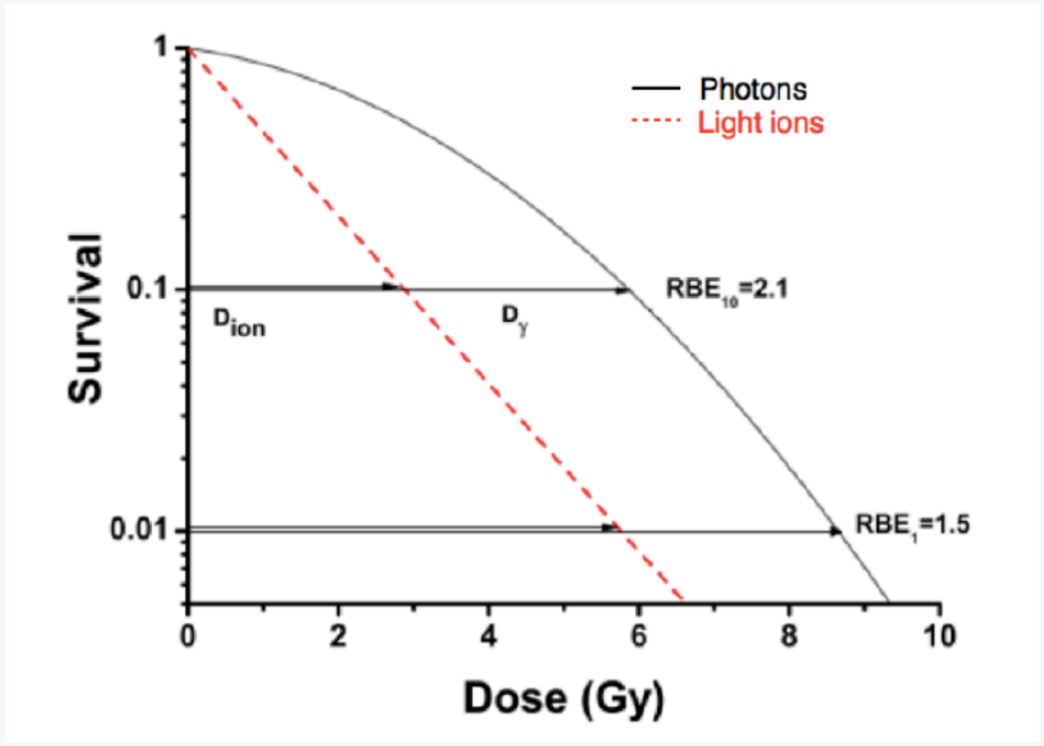


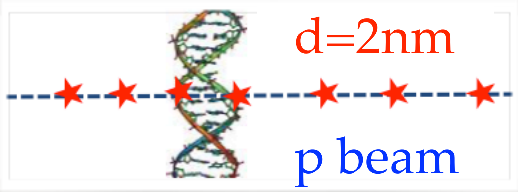
Gamma-index 2mm/3%
pass-rate: 93%
(Dose threshold 1%)

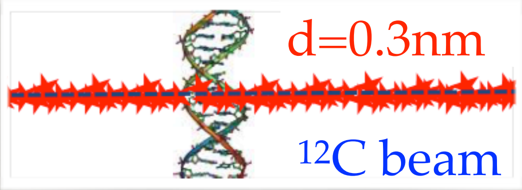
Dbio and RBE.

Biological Dose & Relative Biological Effectiveness

A given amounts of dose has an effects on the cell that depends on the radiation.





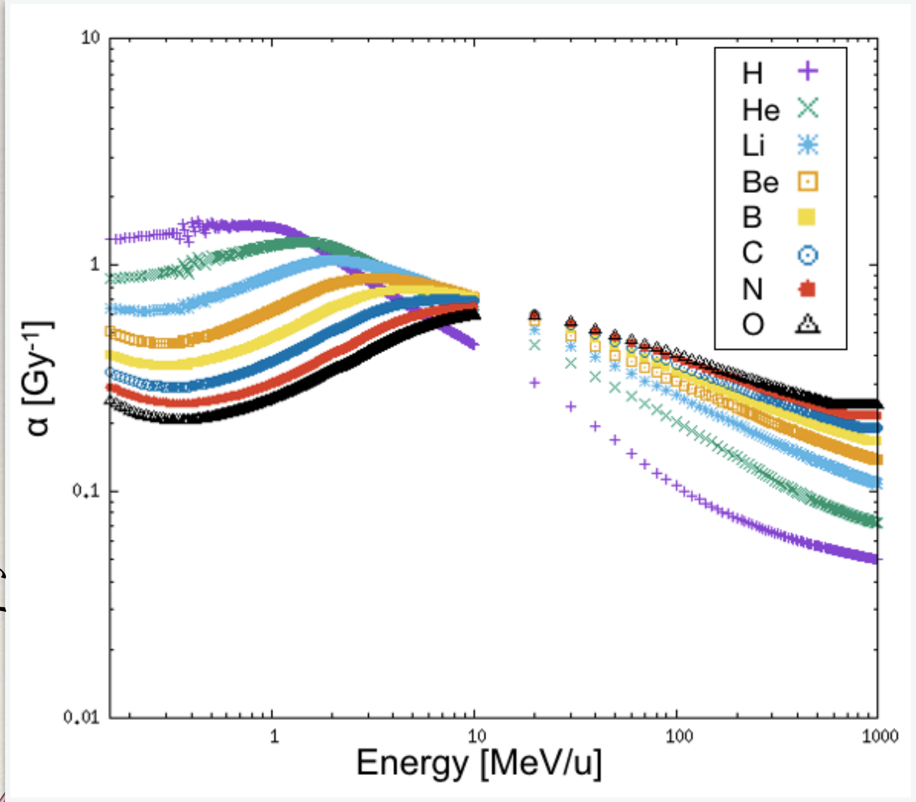


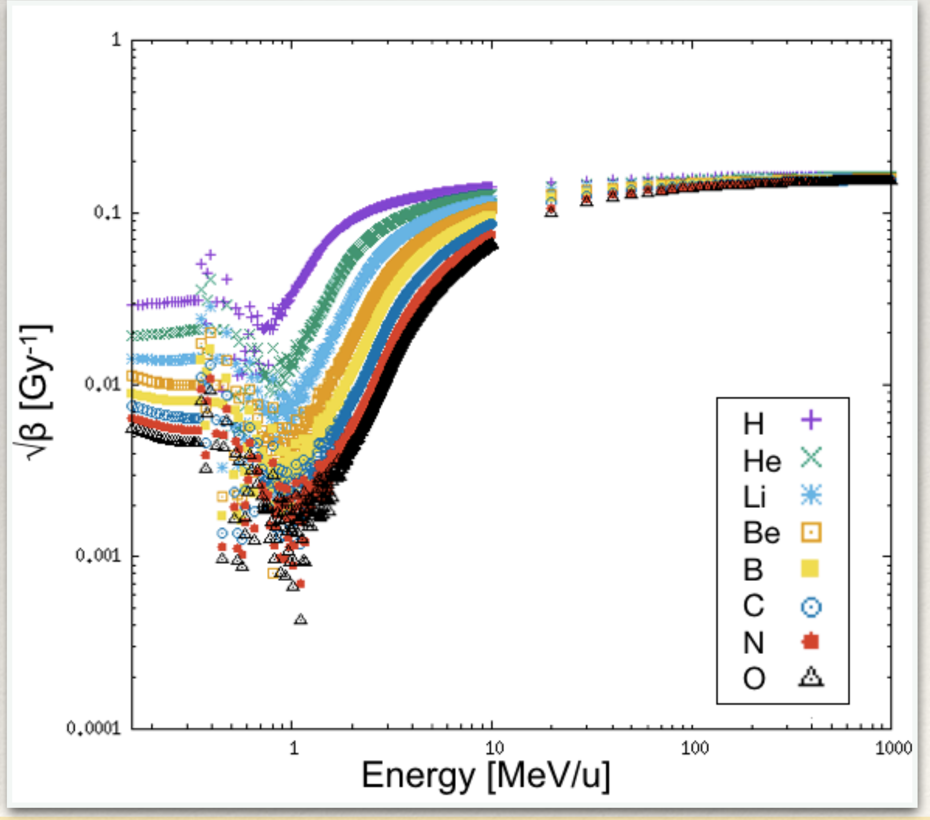
$$S(D) = \frac{N_{survival}}{N_{seed}} = e^{-(\alpha D + \beta D^2)}$$

$$RBE = \left.\frac{D_x}{D_i}\right|_{Isoeffect}$$

D_x = (or **biological dose**) the dose of a photon radiation to caused the same damage of a ion radiation (D_i).

α and β from TOPAS database

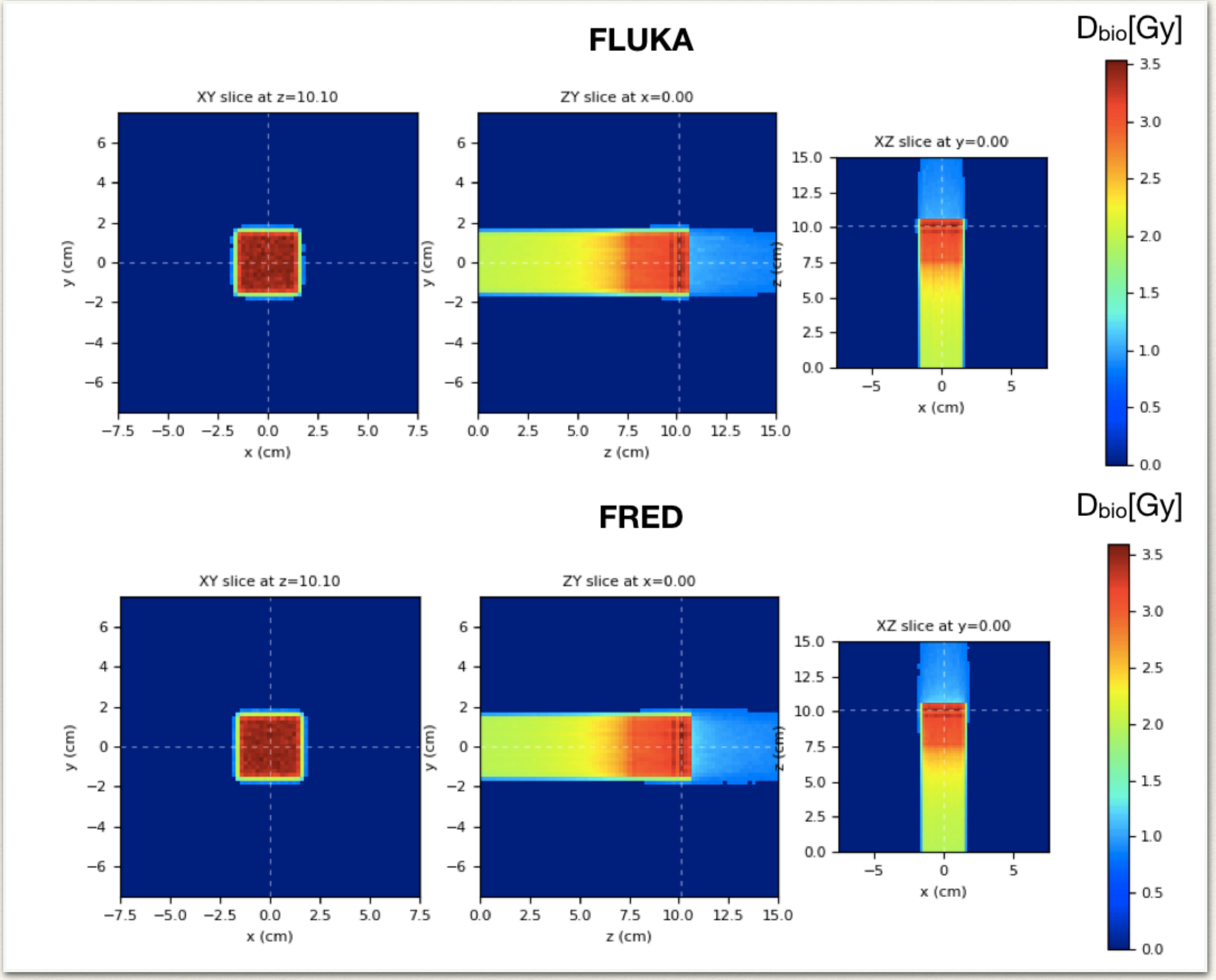




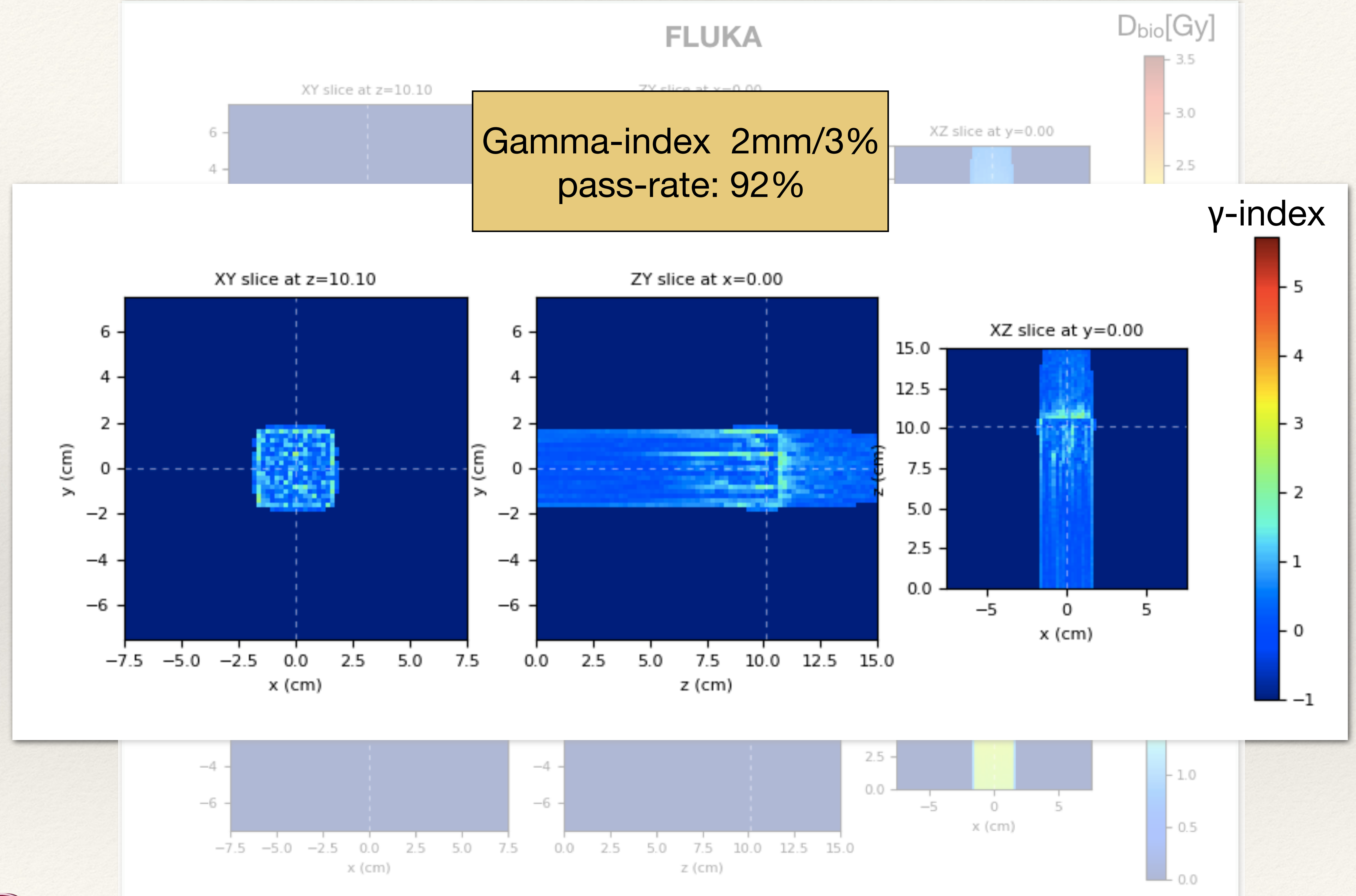
Parameters α and β are strongly correlated to the type of radiation which release dose and its energy.

RBE depends on the fragments and on their energy spectrum.

Biological Dose & Relative Biological Effectiveness



Biological Dose & Relative Biological Effectiveness



Gamma-index 2mm/3%
pass-rate: 92%

Conclusions

☑ Implementation of an entirely **new nuclear interaction model** of carbon on light target nuclei in the fast MC FRED.

☑ **Tested** of the model against the full-MC code **FLUKA**: **excellent agreement**.

- **Single PB**: always within **2.5%** of the total dose deposited in single pencil beams in the 100÷300 MeV/u energy range;
- **SOBP**: agreement of the dose distribution within **1.7%** and the gamma-index 2mm/3% pass rate **93.3%**;
- **Biological dose** and the **RBE** in **good agreement** with FLUKA.

☑ **Comparison** with experiments: **good agreement**.

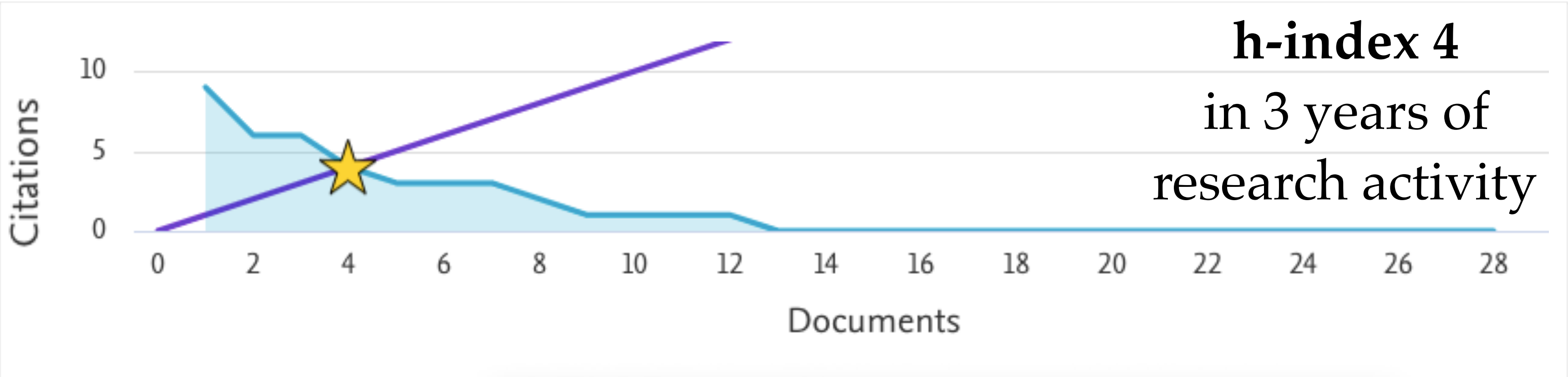
- **GANIL experiment;**
- **Haettner experiment**.

☐ Next steps:

- ☐ Port the model on **GPU**;
- ☐ Comparison of the accuracy of FRED dose recalculation with the CNAO TPS for carbon therapy to achieve **clinical validation**.

Publications

29 publications



h-index 4
in 3 years of
research activity

[1] De Simoni M. et al. "FRED: A fast Monte Carlo code on GPU for quality control in Particle Therapy". In: *Journal of Physics: Conference Series* 1548 (2020), p. 012020. DOI: 10.1088/1742-6596/1548/1/012020

[2] Dong Y. et al. "The Drift Chamber detector of the FOOT experiment: Performance analysis and external calibration". In:*Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 986 (2020), DOI: 10.1016/j.nima.2020.164756

[3] Mattei I. et al. "Charged particles and neutron trackers: Applications to particle therapy". In: *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 954 (2020), DOI: 10.1016/j.nima.2018.09.064

[4] Mattei I. et al. "Measurement of 12C Fragmentation Cross Sections on C, O, and H in the Energy Range of Interest for Particle Therapy Applications". In: *IEEE Transactions on Radiation and Plasma Medical Sciences* 4, pp 269-282 (2020), DOI: 10.1109/TRPMS.2020.2972197

[5] Traini G. et al. "Performance of the ToF detectors in the foot experiment". In: *Nuovo Cimento della Societa Italiana di Fisica C* 43 (2020), DOI: 10.1393/ncc/i2020-20016-5

[6] Morganti S. et al. "Tumor-non-tumor discrimination by a β^- detector for Radio Guided Surgery on ex-vivo neuroendocrine tumors samples", In: *Physica Medica* 72 (2020), pp. 96-102, DOI: 10.1016/j.ejmp.2020.03.021

[7] Collamati F. et al. "Radioguided surgery with β^- radiation in pancreatic Neuroendocrine Tumors: a feasibility study". In:*Scientific Reports* 10 (2020), p. 4015. DOI:10.1038/s41598-020-61075-2

[8] Collamati F. et al. "A DROP-IN beta probe for robot-assisted ^{68}Ga-PSMA radioguided surgery: first ex vivo technology evaluation using prostate cancer specimens". In: *EJNMMI Research* 10,92 (2020). DOI: https://doi.org/10.1186/s13550-020-00682-6

[9] Traini G. et al. "Review and performance of the Dose Profiler, a particle therapy treatments online monitor". In: *Physica Medica* 65 (2019). pp. 84-93. DOI:10.1016/j.ejmp.2019.07.010

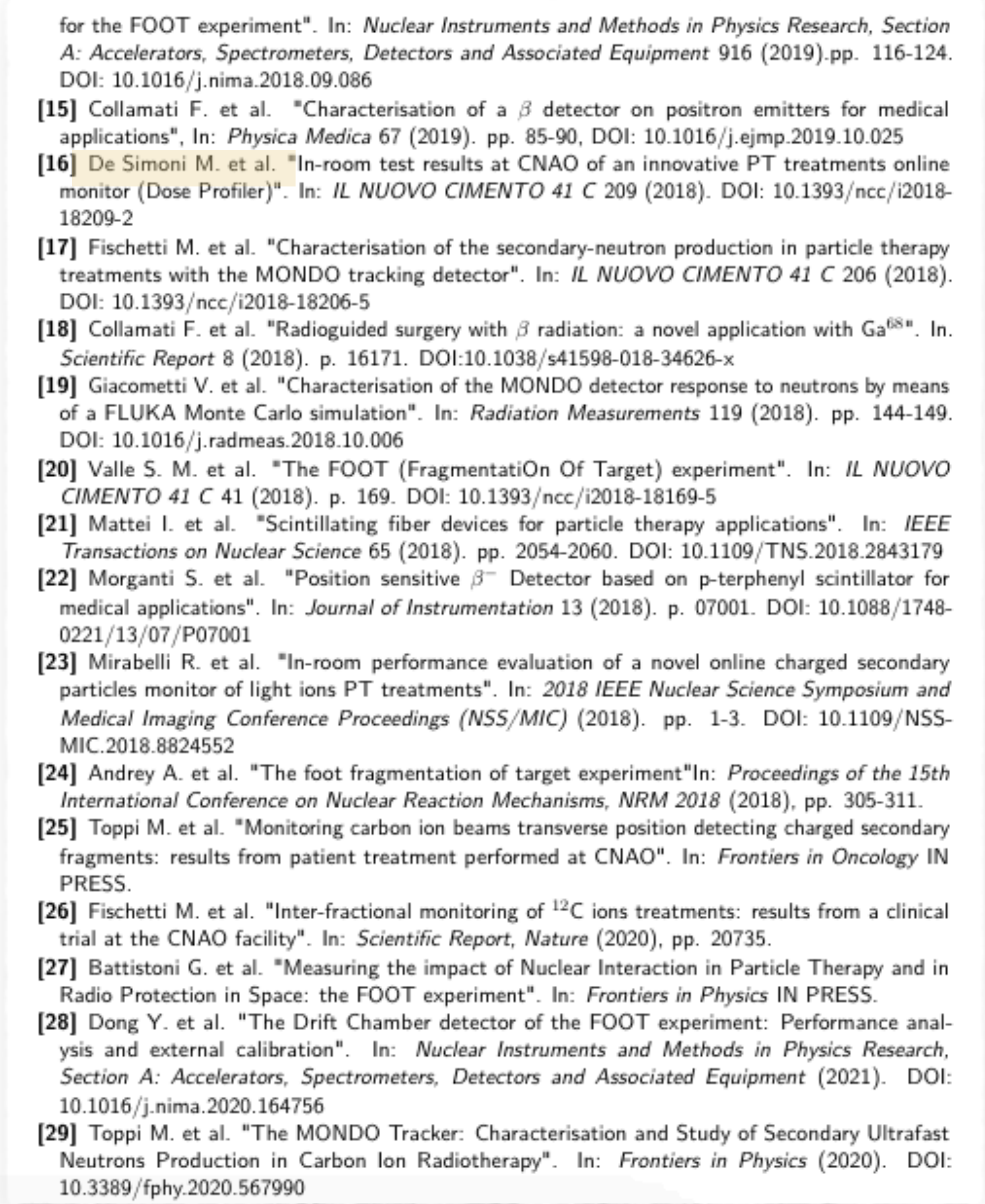
[10] Rucinski A. et al. "Secondary radiation measurements for particle therapy applications: Charged secondaries produced by 16O ion beams in a PMMA target at large angles". In: *Physica Medica* 64 (2019). pp. 45-53. DOI: 10.1016/j.ejmp.2019.06.001

[11] Gioscio E. et al. "Development of a novel neutron tracker for the characterisation of secondary neutrons emitted in Particle Therapy". In: *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 958 (2019). pp. 162862. DOI: 10.1016/j.nima.2019.162862

[12] Manuzzato E. et al. "A 16×18 Digital-SiPM Array with Distributed Trigger Generator for Low SNR Particle Tracking". In: *ESSCIRC 2019 - IEEE 45th European Solid State Circuits Conference* (2019). pp. 75-78. DOI:10.1109/ESSCIRC.2019.8902571

[13] Montesi M. C. et al. "Ion charge separation with new generation of nuclear emulsion films". In: *Open Physics* 17 (2019). pp. 233-240. DOI: 10.1515/phys-2019-0024

[14] Morrocchi M. et al. "Development and characterization of a ΔE-TOF detector prototype



for the FOOT experiment". In: *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 916 (2019).pp. 116-124. DOI: 10.1016/j.nima.2018.09.086

[15] Collamati F. et al. "Characterisation of a β detector on positron emitters for medical applications", In: *Physica Medica* 67 (2019). pp. 85-90, DOI: 10.1016/j.ejmp.2019.10.025

[16] De Simoni M. et al. "In-room test results at CNAO of an innovative PT treatments online monitor (Dose Profiler)". In: *IL NUOVO CIMENTO 41 C* 209 (2018). DOI: 10.1393/ncc/i2018-18209-2

[17] Fischetti M. et al. "Characterisation of the secondary-neutron production in particle therapy treatments with the MONDO tracking detector". In: *IL NUOVO CIMENTO 41 C* 206 (2018). DOI: 10.1393/ncc/i2018-18206-5

[18] Collamati F. et al. "Radioguided surgery with β radiation: a novel application with Ga^{68}". In. *Scientific Report* 8 (2018). p. 16171. DOI:10.1038/s41598-018-34626-x

[19] Giacometti V. et al. "Characterisation of the MONDO detector response to neutrons by means of a FLUKA Monte Carlo simulation". In: *Radiation Measurements* 119 (2018). pp. 144-149. DOI: 10.1016/j.radmeas.2018.10.006

[20] Valle S. M. et al. "The FOOT (FragmentatiOn Of Target) experiment". In: *IL NUOVO CIMENTO 41 C* 41 (2018). p. 169. DOI: 10.1393/ncc/i2018-18169-5

[21] Mattei I. et al. "Scintillating fiber devices for particle therapy applications". In: *IEEE Transactions on Nuclear Science* 65 (2018). pp. 2054-2060. DOI: 10.1109/TNS.2018.2843179

[22] Morganti S. et al. "Position sensitive β^- Detector based on p-terphenyl scintillator for medical applications". In: *Journal of Instrumentation* 13 (2018). p. 07001. DOI: 10.1088/1748-0221/13/07/P07001

[23] Mirabelli R. et al. "In-room performance evaluation of a novel online charged secondary particles monitor of light ions PT treatments". In: *2018 IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC)* (2018). pp. 1-3. DOI: 10.1109/NSS-MIC.2018.8824552

[24] Andrey A. et al. "The foot fragmentation of target experiment"In: *Proceedings of the 15th International Conference on Nuclear Reaction Mechanisms, NRM 2018* (2018), pp. 305-311.

[25] Toppi M. et al. "Monitoring carbon ion beams transverse position detecting charged secondary fragments: results from patient treatment performed at CNAO". In: *Frontiers in Oncology* IN PRESS.

[26] Fischetti M. et al. "Inter-fractional monitoring of ^{12}C ions treatments: results from a clinical trial at the CNAO facility". In: *Scientific Report, Nature* (2020), pp. 20735.

[27] Battistoni G. et al. "Measuring the impact of Nuclear Interaction in Particle Therapy and in Radio Protection in Space: the FOOT experiment". In: *Frontiers in Physics* IN PRESS.

[28] Dong Y. et al. "The Drift Chamber detector of the FOOT experiment: Performance analysis and external calibration". In: *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* (2021). DOI: 10.1016/j.nima.2020.164756

[29] Toppi M. et al. "The MONDO Tracker: Characterisation and Study of Secondary Ultrafast Neutrons Production in Carbon Ion Radiotherapy". In: *Frontiers in Physics* (2020). DOI: 10.3389/fphy.2020.567990

Conferences

9 presentations at international conferences
(5 oral presentations and 4 poster presentations)

Oral Presentations

- **Nov. 2020,** *IEEE Nuclear Science Symposium and Medical Imaging Conference* - Online/Virtual, “In vivo verification of carbon ion therapy treatments at CNAO by means of charged fragments detection”
- **Sept. 2019,** *International Conference on Medical Accelerators and Particle Therapy* - Seville (Spain), ”A data-driven nuclear fragmentation model for a fast Monte-Carlo code, FRED, in Particle Therapy with Carbon beams”
- **Jun. 2019,** *10th Young Researcher Meeting* - Rome (Italy), "FRED: a fast Monte Carlo code on GPU for quality control in Particle Therapy”
- **Jan. 2019**, *57th International Winter Meeting on Nuclear Physics* - Bormio (Italy), "The Dose Profiler tracker: an online Particle Therapy monitor”
- **Sept. 2018**, *Società italiana per le ricerche sulle radiazioni* - Roma (Italy), "In-room characterization, using an anthropomorphic phantom, of a novel detector for on-line dose monitoring in light ions cancer therapy")

Posters Presentations

- **Nov. 2020,** *IEEE Nuclear Science Symposium and Medical Imaging Conference* - Online/Virtual, “Fragmentation model for Treatment Planning System of carbon ions implemented in a fast MC code (FRED)”
- **Nov. 2020,** *IEEE Nuclear Science Symposium and Medical Imaging Conference* - Online/Virtual, “Study of secondary neutron production in PT treatments using MONDO, an innovative ultra-fast neutrons tracker”
- **Sept. 2018,** *Società italiana per le ricerche sulle radiazioni* - Roma (Italy), “Applications in Particle Therapy of FRED, a fast Monte Carlo code on GPUs for energy deposition of proton beams in matter"
- **Sept. 2019,** *International Conference on Medical Accelerators and Particle Therapy* - Seville (Spain), ”Spectrum and flux measurements of secondary ultra-fast neutrons produced in Particle Therapy treatments using the innovative MONDO tracker”


Thank you!
Any questions?