International Conference on Medical Accelerators and Particle Therapy

A data-driven nuclear fragmentation model for a fast Monte-Carlo code, **FRED**, in Particle Therapy with Carbon beams.

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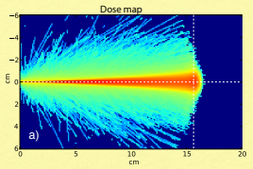
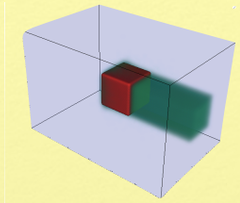
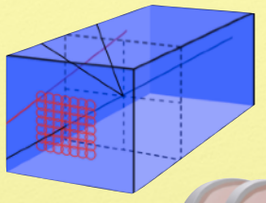
"Sapienza" University of Rome and INFN (Italy)

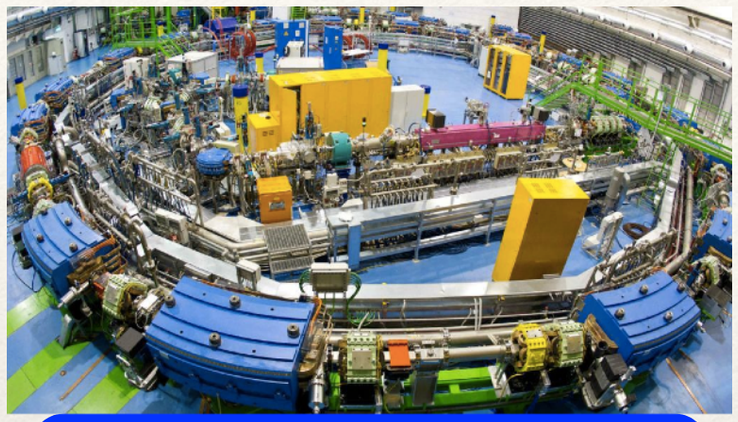
Collaboration Network:

Summary

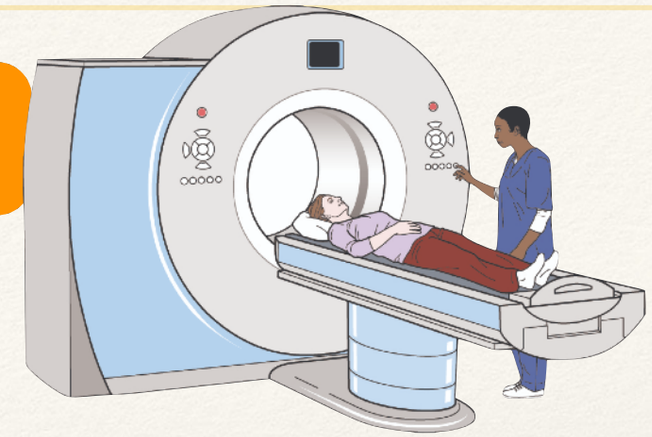
- Development of FRED
- FRED quality check:
  - Single pencil beam 

  - SOBP QA 
  - Field Size Factor test 
  - Heterogeneous material 
- RBE model implementation
- Execution of FRED and its performance
- Input of FRED
- Implementation of nuclear fragmentation (work in progress)

Treatment Planning System (TPS) currently used



Patient Data



Accelerators Parameters

TPS

Physician Prescription

ANALYTICS TPS

- Faster
- Simplified beam-body interaction model using a 3D water equivalent representation of the patient morphology

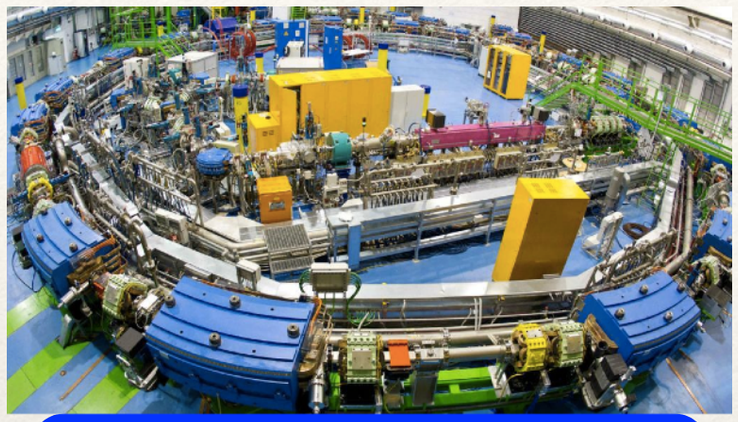
Used routinely in PT treatment

MC TPS (FLUKA and TOPAS/Geant4)

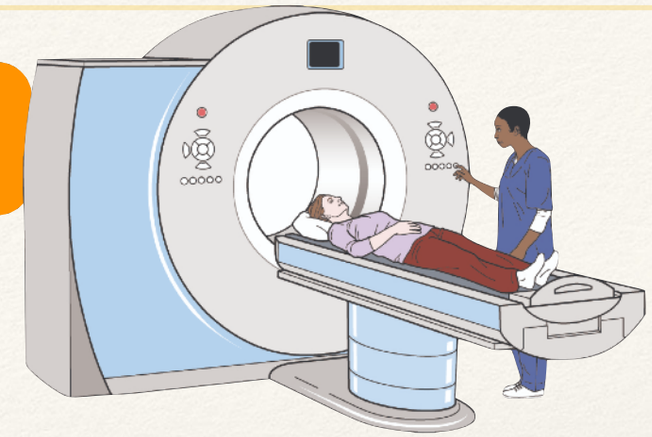
- Slower
- Explicitly take into account the details in the interaction of particles with human tissues

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

Treatment Planning System (TPS) currently used



Patient Data



Accelerators Parameters

TPS

Physician Prescription

ANALYTIC

- Faster
- Simplified beam-bo model using a 3D w equivalent represen patient morpholog

Used routinely in PT ti

FAST MC: FRED

NEW!!

- Faster
- Takes into account the details in the interaction of particles with human tissues that are needed for a TPS

Using it as Quality Assurance for TPS

and TOPAS/Geant4)

nto account the teraction of uman tissues

treatment plans for a ifficult cases

Fast Monte Carlo: FRED

Fast pa**R**ticle th**E**rapy **D**ose evaluator

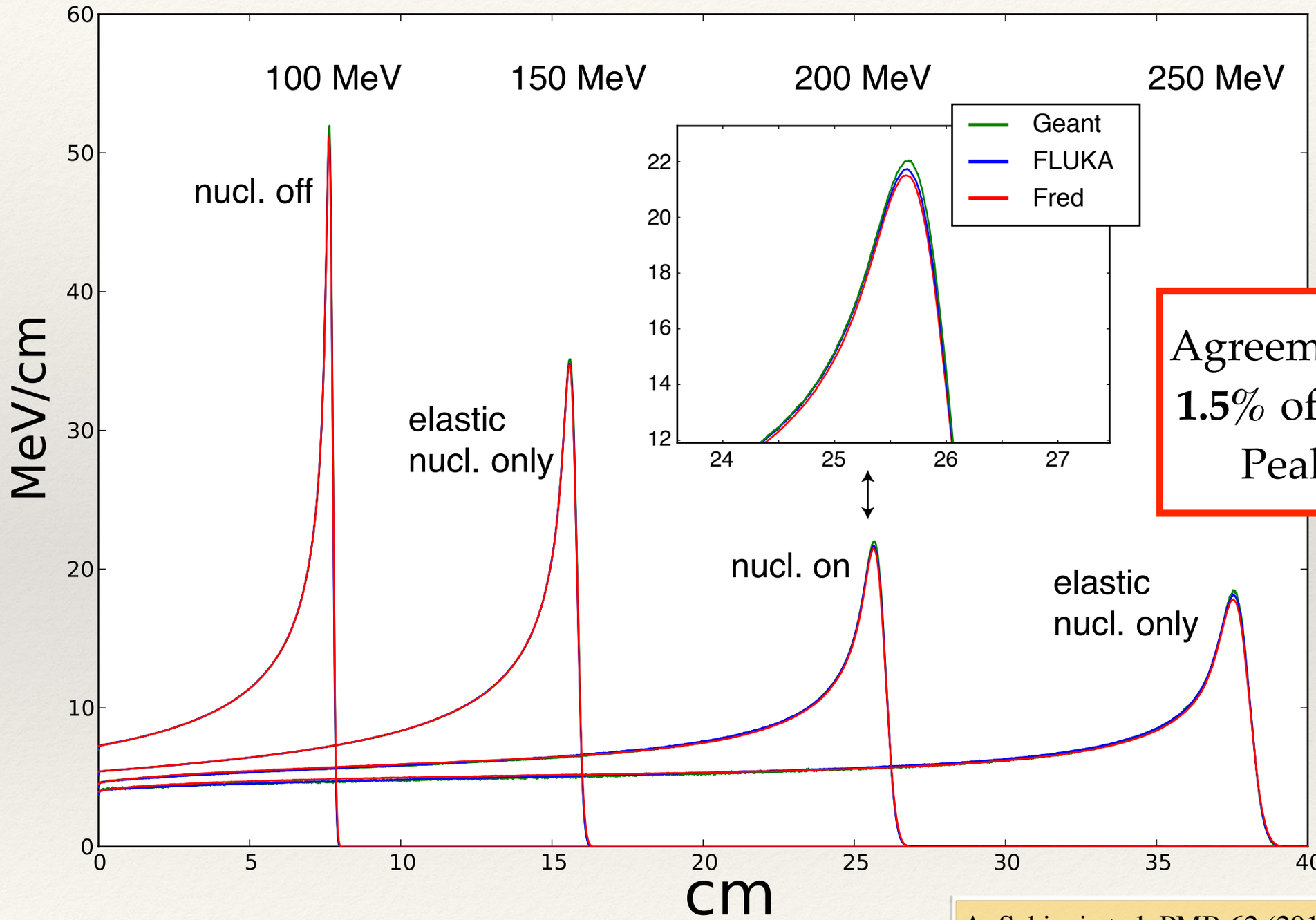
The FRED code has been designed to perform fast and accurate calculations of **energy deposition** in the patient's body during the delivery of a treatment plan.

Main characteristics of FRED:

- Tabulated total **stopping power** in water (PSTAR-NIST), **energy straggling** (Gaussian and Landau-Vavilov regimes)
- **MCS models**: single-,double-,triple-gaussian, 2 gauss + Rutherford
- **Nuclear interactions**: elastic and inelastic; fragmentation; local deposition of heavy ions; tracking of secondary protons and deuterons
- **RBE models** = fixed 1.1, LETd-based (Wedenberg, Carabe, Wilkens, Chen)

Comparison with other MC tools

Proton beams at different energies in a water target have been simulated with FRED, FLUKA and GEANT4 switching on and off different models.

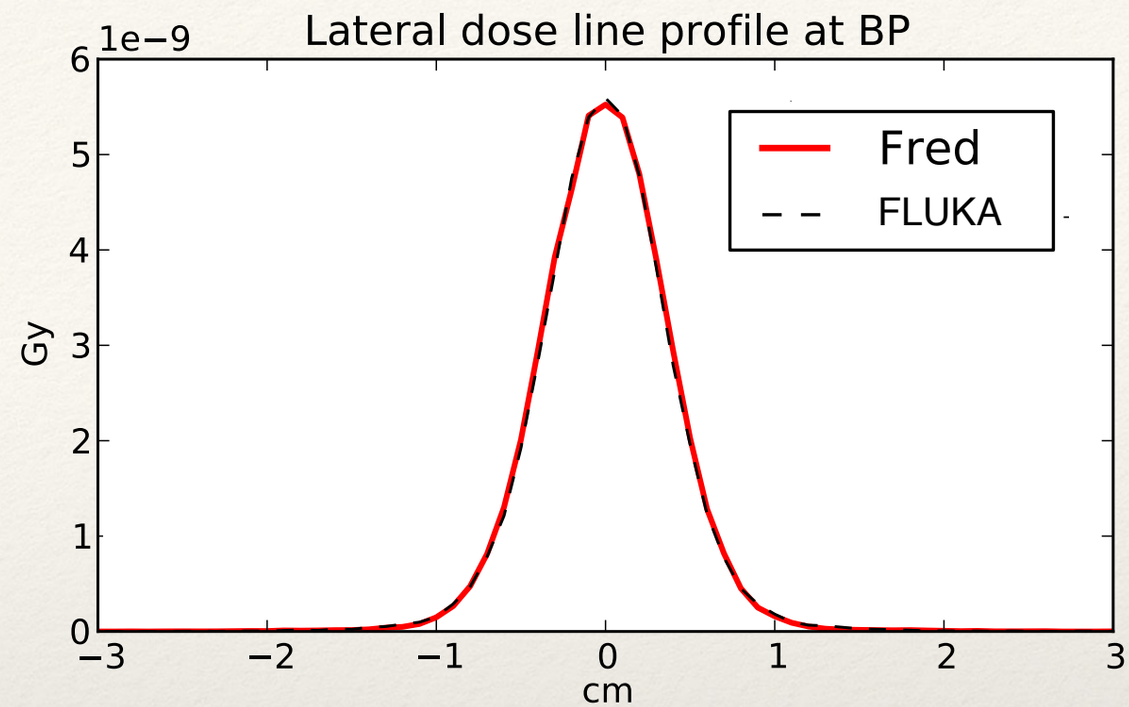


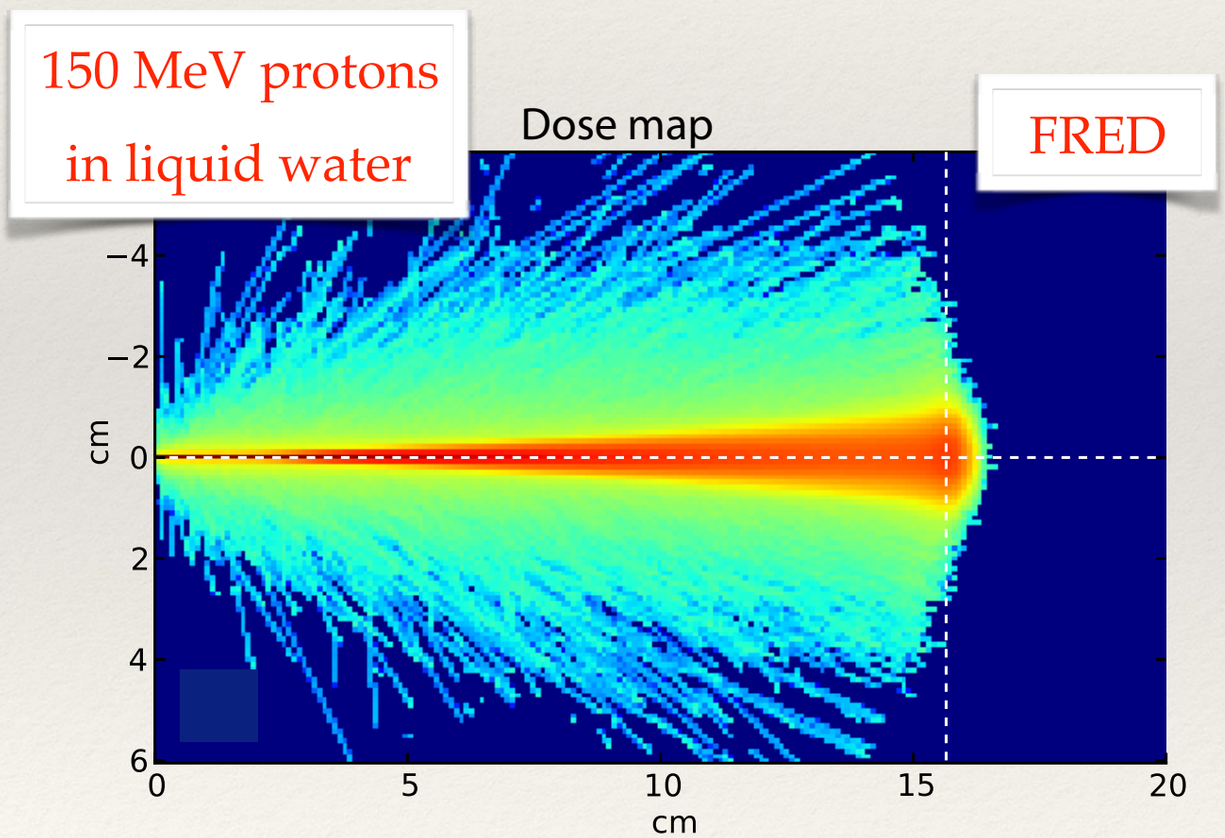
Agreement within **1.5%** of the Bragg Peak value

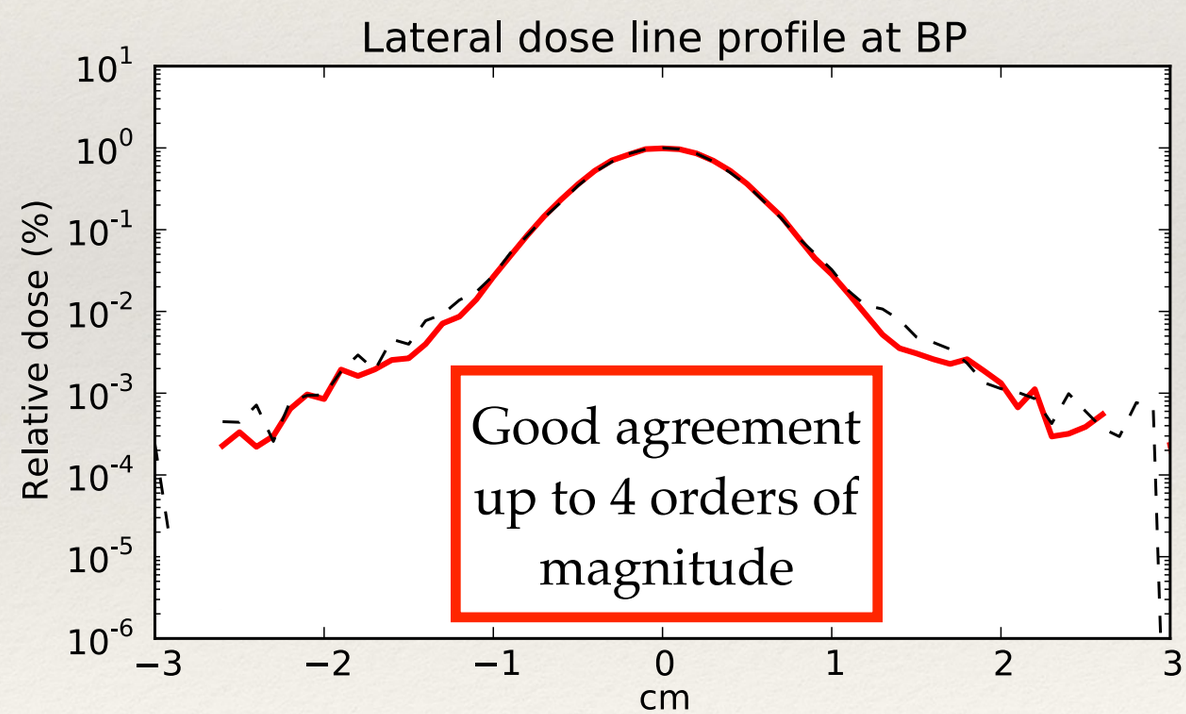
A. Schiavi et al, PMB 62 (2017) 7482–7504

Lateral dose distribution

The accuracy of the lateral dose distribution is very important for PT applications, since the dose value in a single voxel is dependent on contributions from many thousands of pencil beams closely bundled in the transverse direction



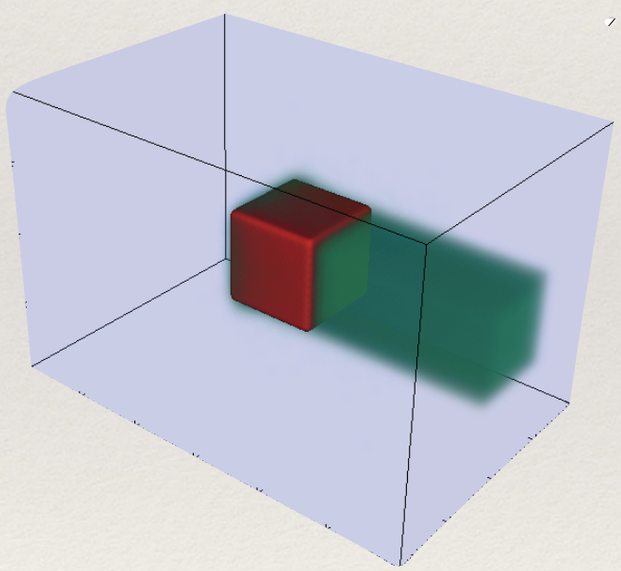


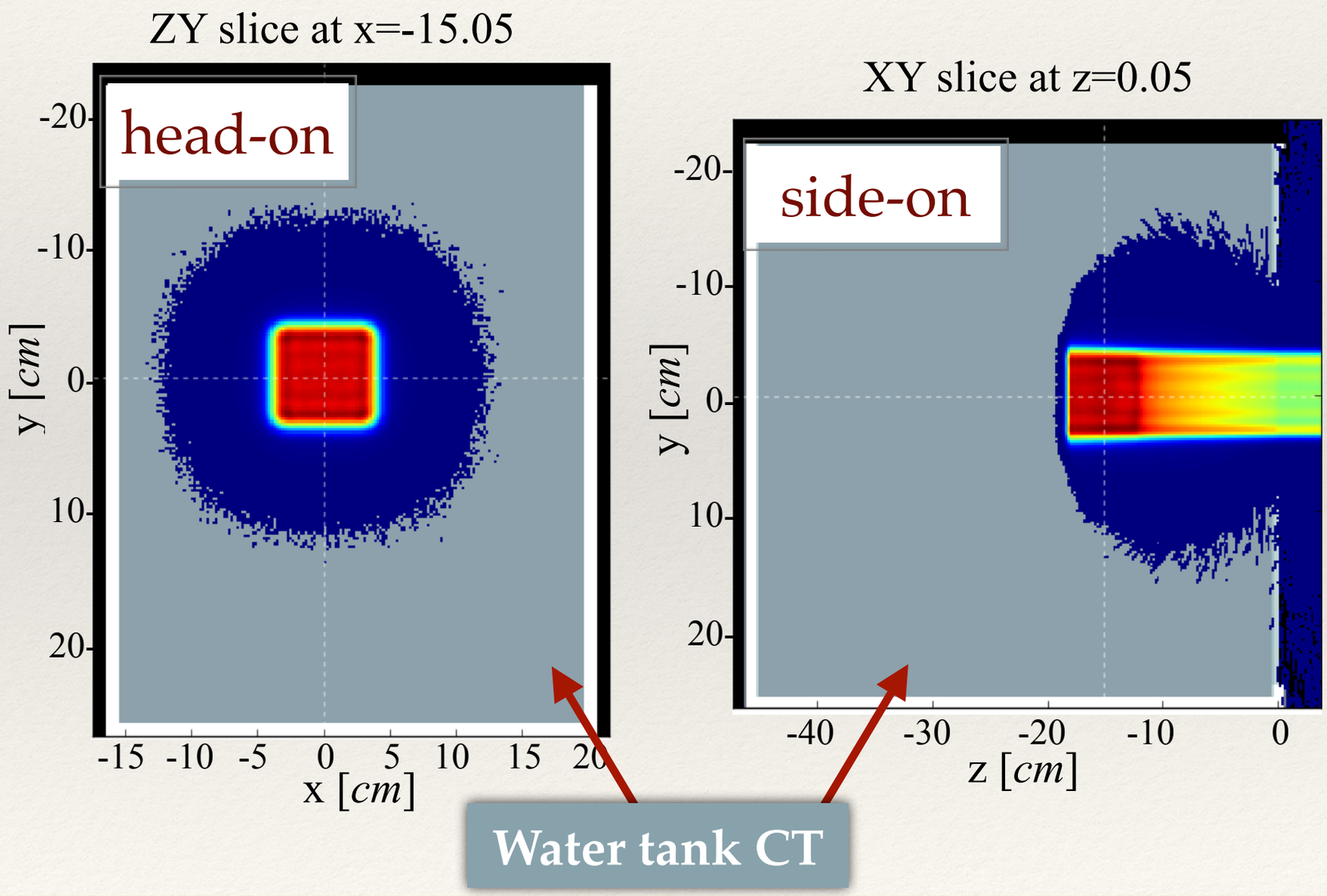


Performance: QA SOBP

SOBP QA: set of 6 *cm*-sided cubic volumes, planned and verified in water with the same dosimetric system applied for patient-specific QA -> routine at CNAO

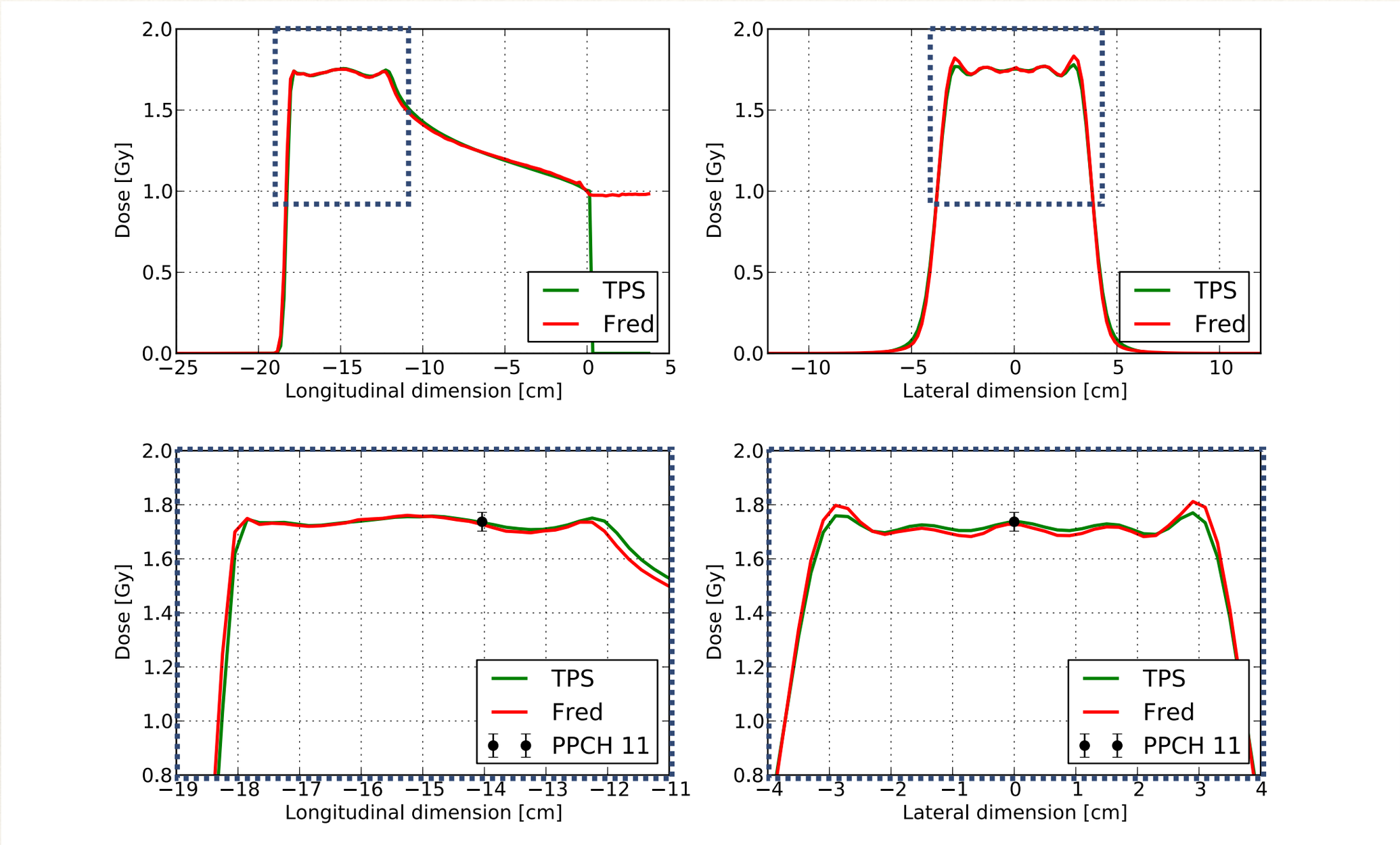
Irradiation geometry and dose map in the longitudinal and transverse planes for the SOBP QA cube at the depth of 15 *cm*





Performance: QA SOBP

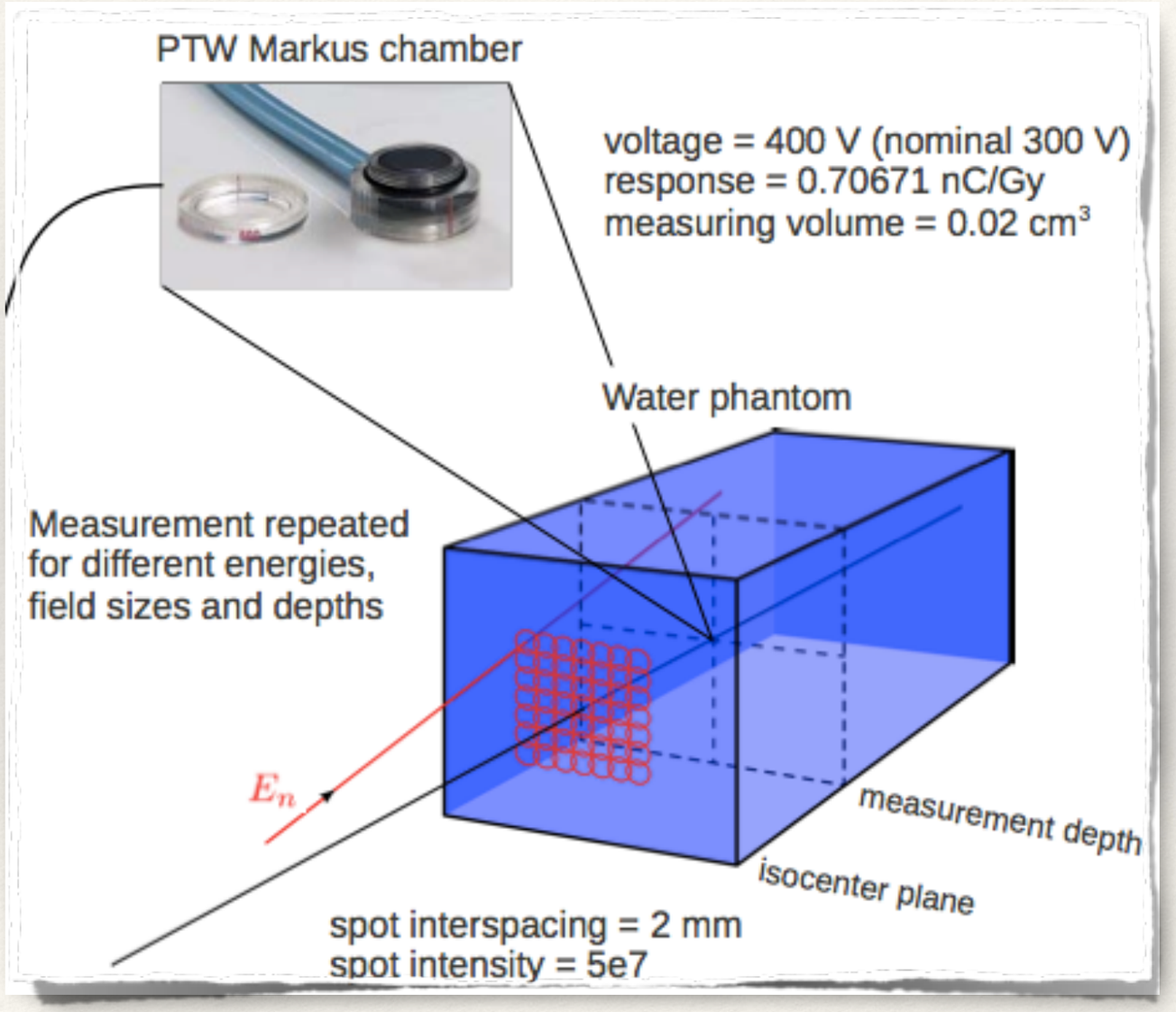
The SOBP QA has been calculated with TPS and then recalculated with FRED. Both have been compared with measurements (PPCH 11).

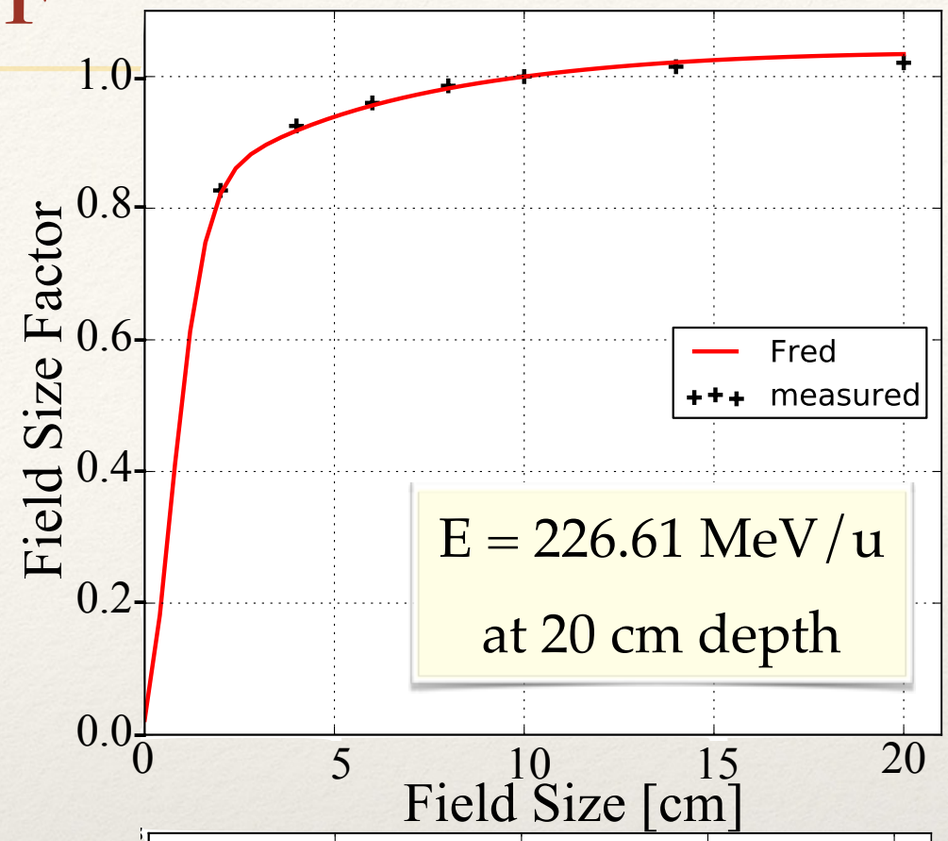


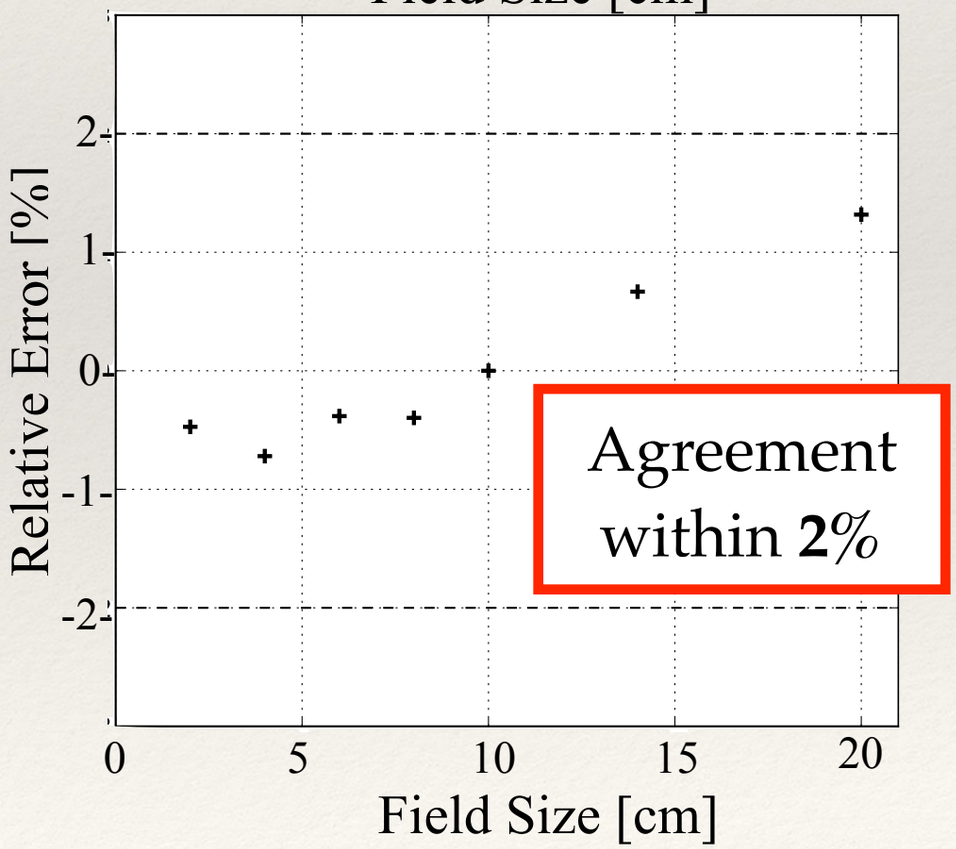
3D Gamma index (2mm/2%) passing rate for all measurements **>99%**

Performance: FSF

Fields Size Factor (FSF) test: technique that allows to directly measure the contribution of long range lateral tails in the dose distribution



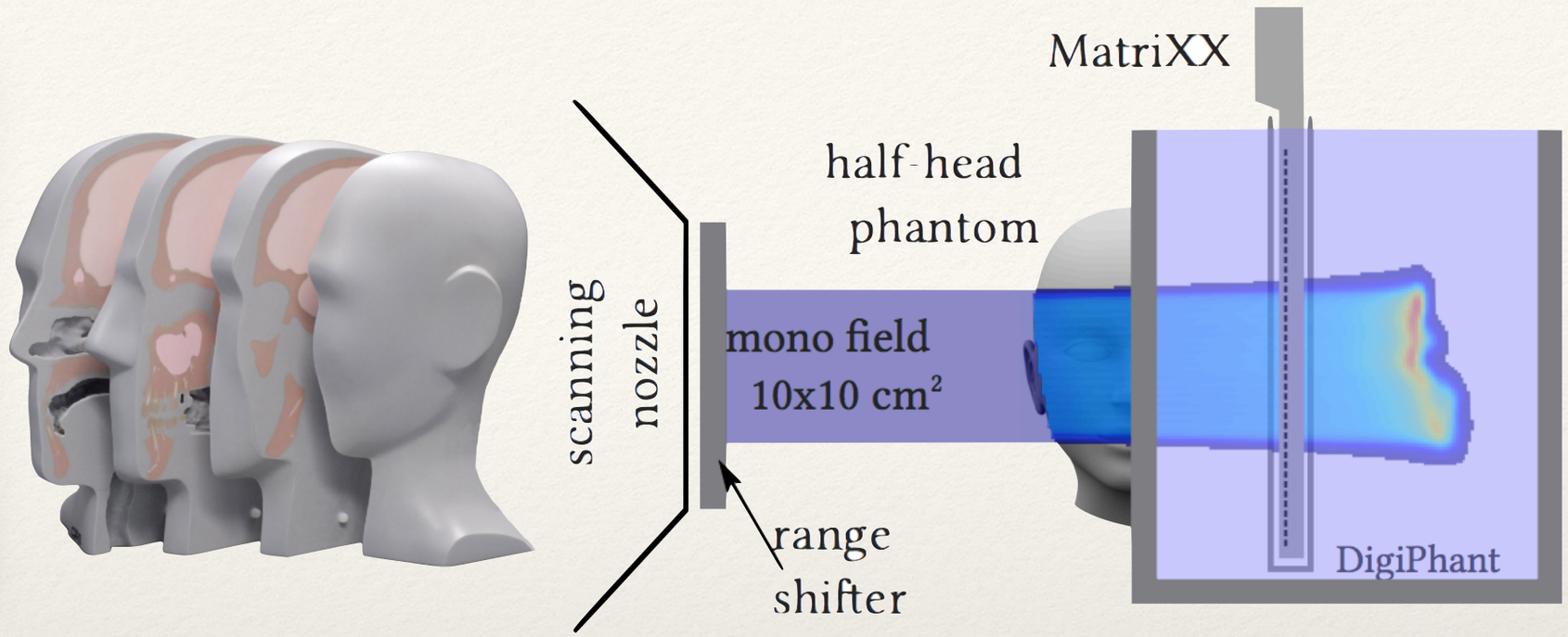


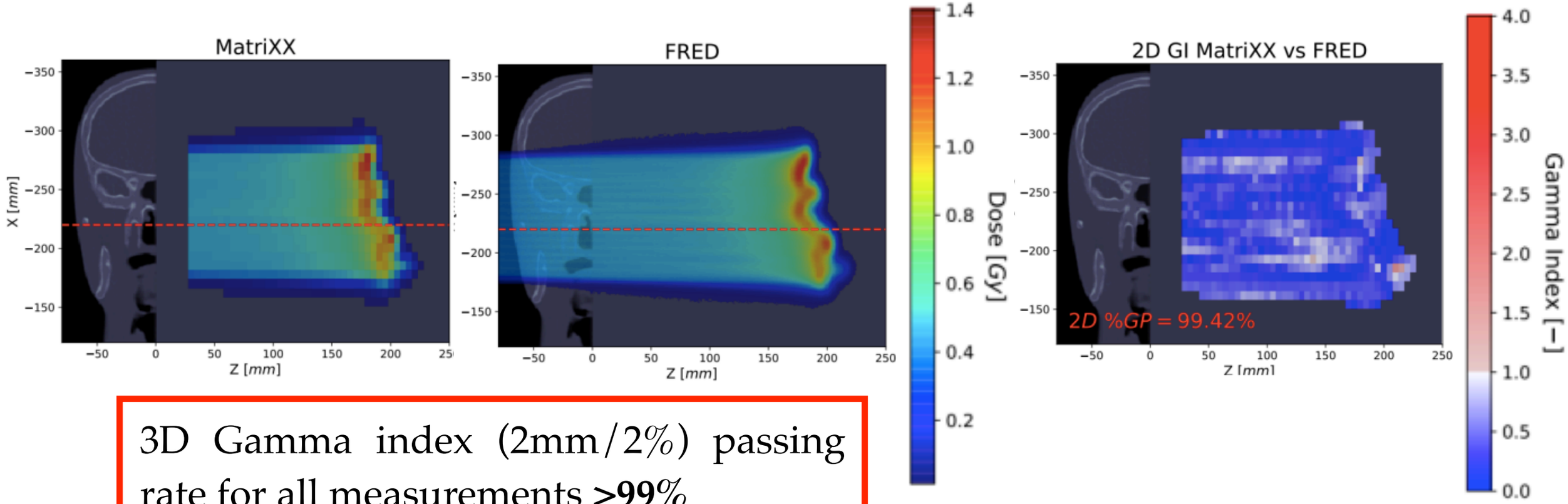


Excellent reproduction of nuclear tails

Performance: Validation in heterogeneous media

- Heterogeneous head phantom
- MatriXX measurement in water
- Single energy: 100, 150 and 200 MeV
- Range shifter





3D Gamma index (2mm/2%) passing rate for all measurements **>99%**

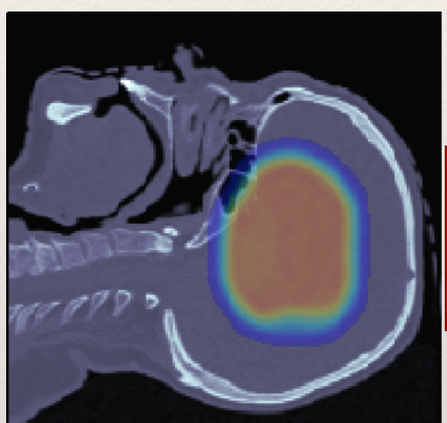
Performance: Biological dose with variable RBE

Function of LET

$$\mathrm{RBE}\left(D_p, \overbrace{\frac{\alpha_p}{\alpha_x}, \frac{\beta_p}{\beta_x}}, \left(\frac{\alpha}{\beta}\right)_x\right) = \frac{D_x}{D_p} = \frac{\sqrt{\left(\frac{\alpha}{\beta}\right)_x^2 + 4\frac{\alpha_p}{\alpha_x}\left(\frac{\alpha}{\beta}\right)_x D_p + 4\frac{\beta_p}{\beta_x} D_p^2} - \left(\frac{\alpha}{\beta}\right)_x}{2D_p}$$

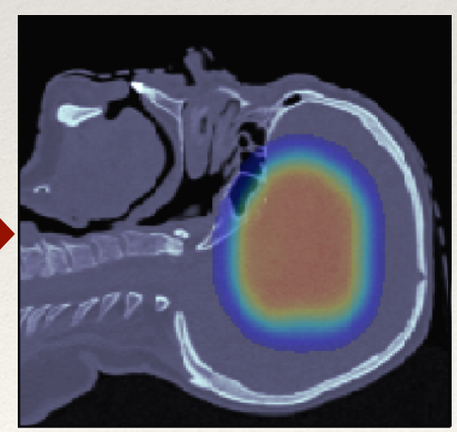
Variable RBE models:
Wedenberg (Wedenberg et al. 2013)
Wilkens (Wilkens and Oelfke 2004)
Chen (Chen and Ahmad 2012)
Carabe (Carabe at al. 2012)

Physical Dose



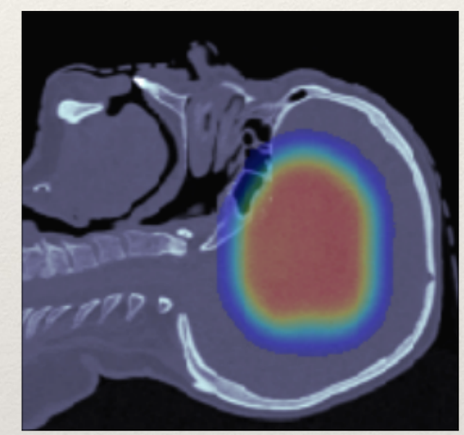
LET and variable RBE

RBE=1.1

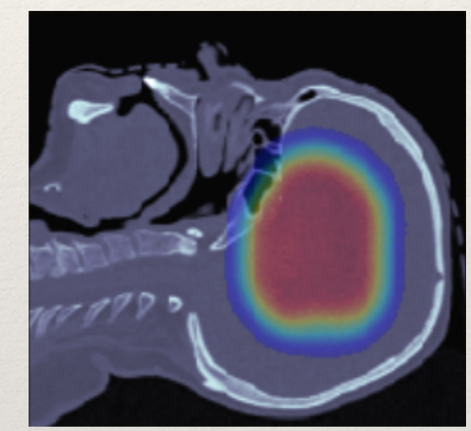


Biological Dose

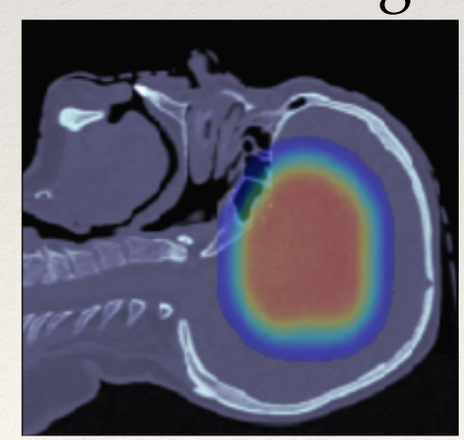
Carabe



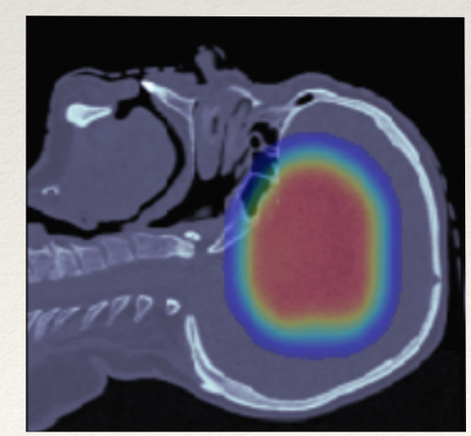
Chen



Wedenberg

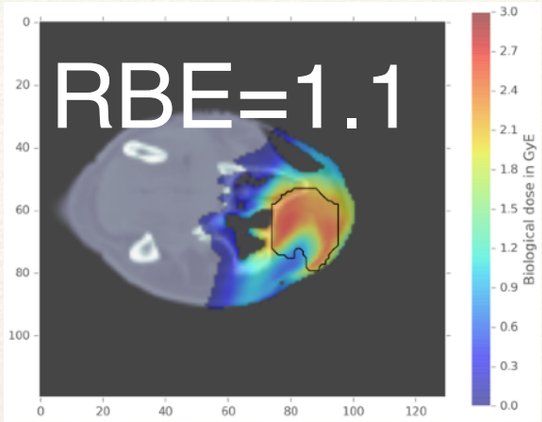


Wilkens



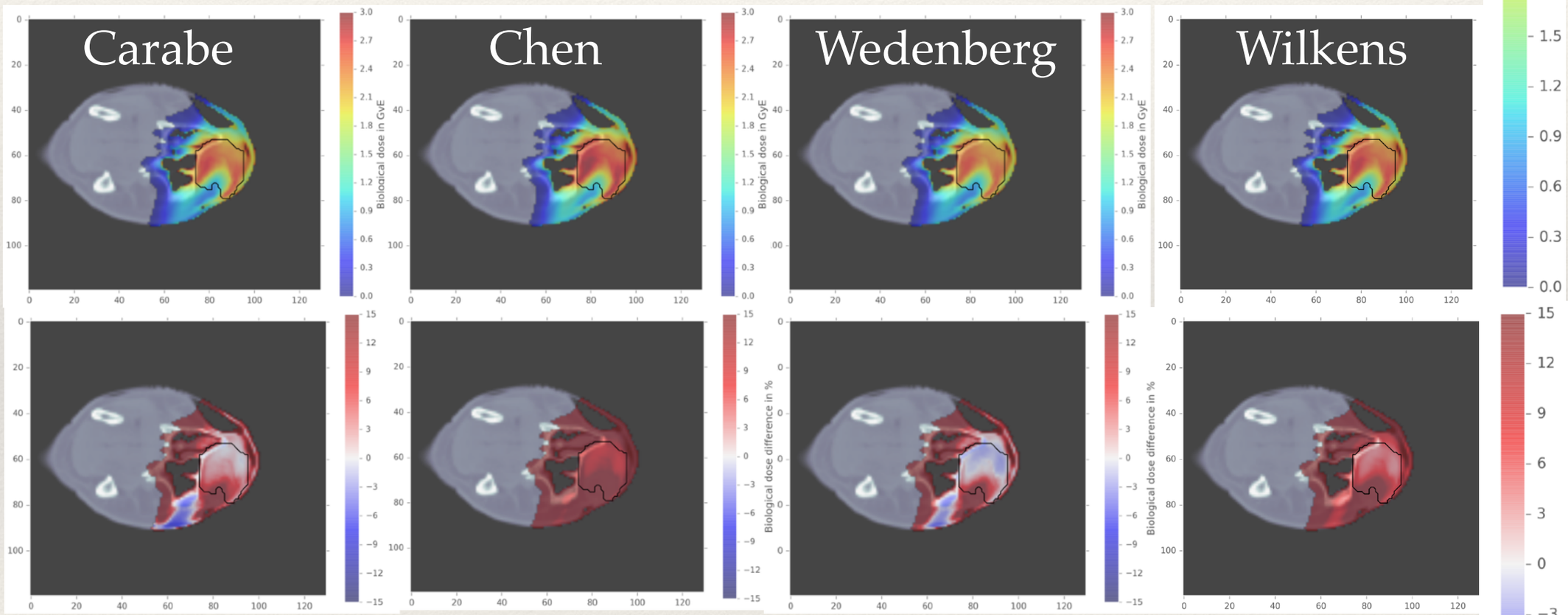
Performance: Biological modelling

Generic RBE clinic

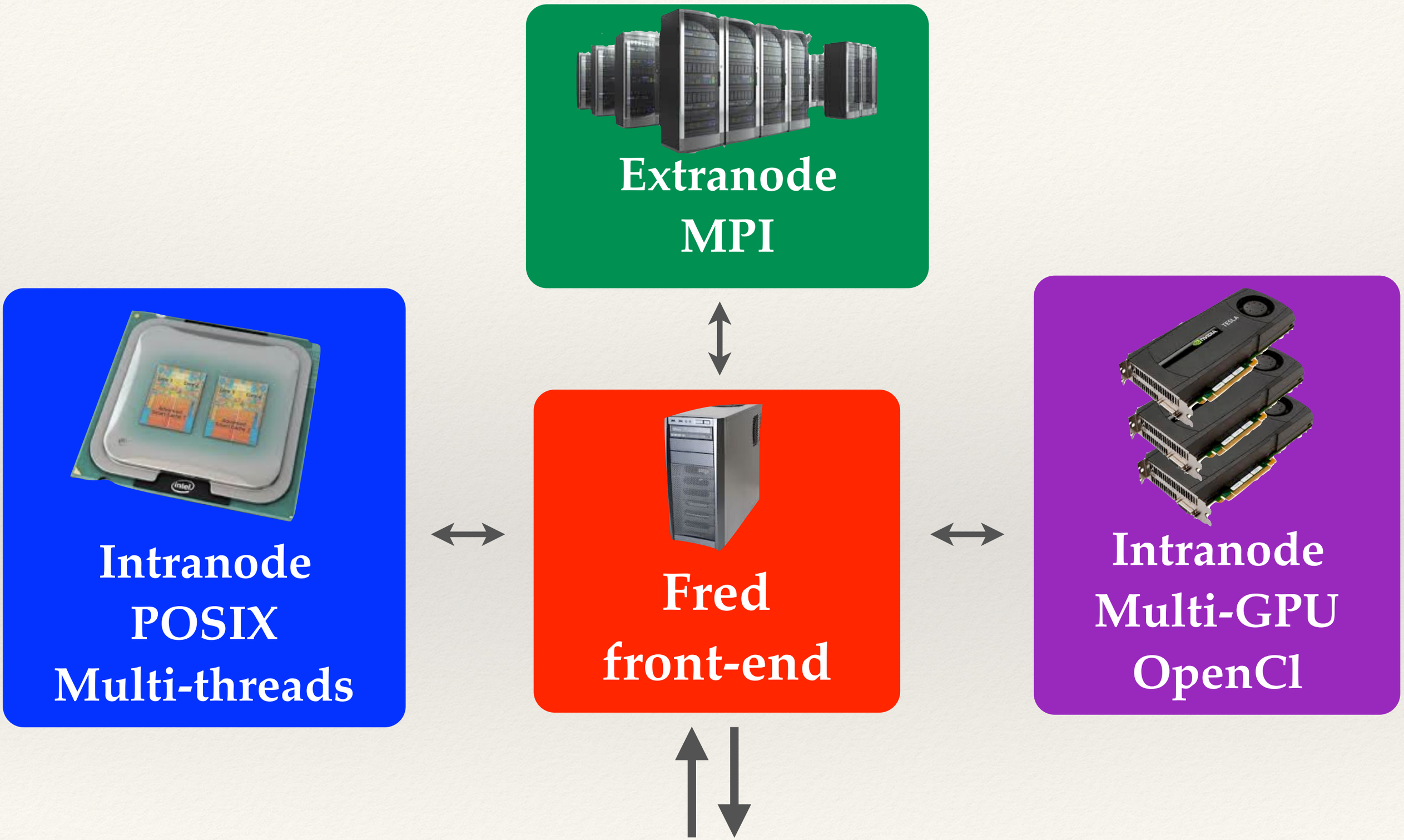


The user can choose the RBE model

Variable RBE



Parallel execution model in Fred



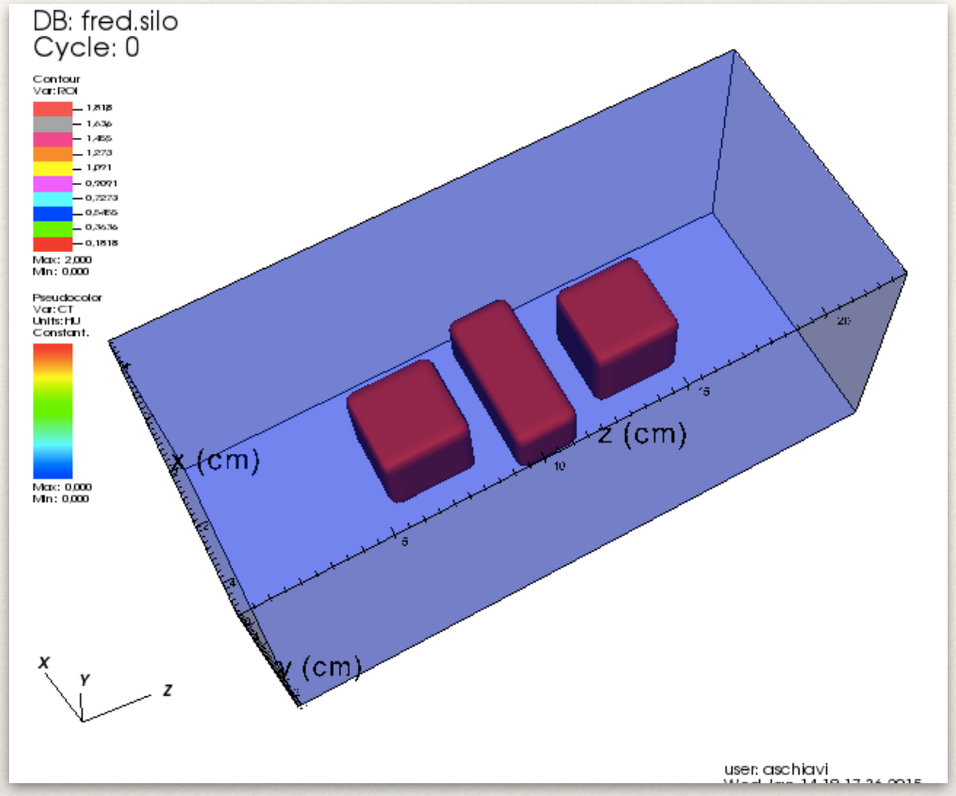
Tracking Performance

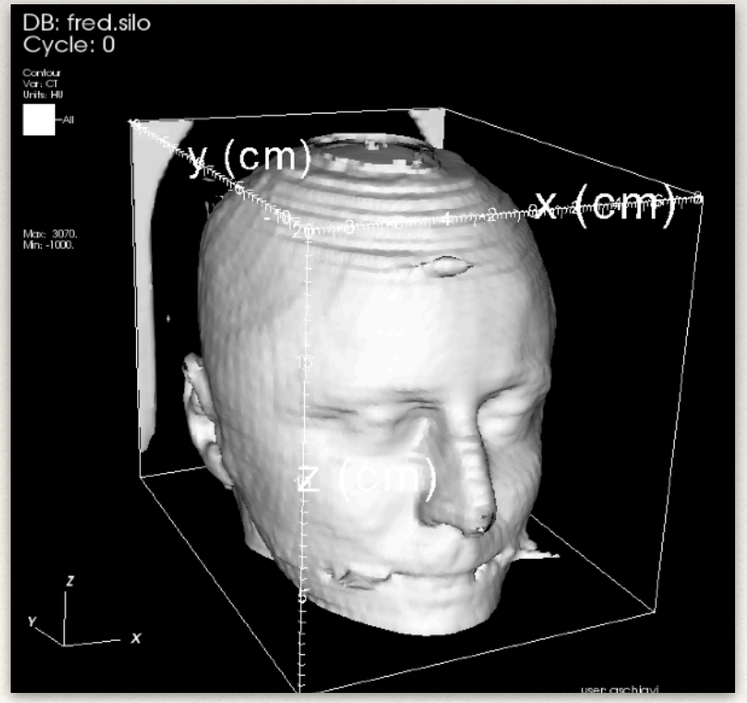
Dose calculation for 150 MeV protons in liquid water phantom with 2 mm voxel resolution.

	Hardware	Primary / s	μs / primary
FLUKA/ GEANT4	single CPU core	0.75 k	1340
FRED	single CPU core	15 k	68
FRED	single GPU card (NVIDIA GTX 980)	800 k	1.35
FRED	4 GPU cards (NVIDIA GTX 980)	20000 k	0.05

Excellent performance with proton beams

INPUT

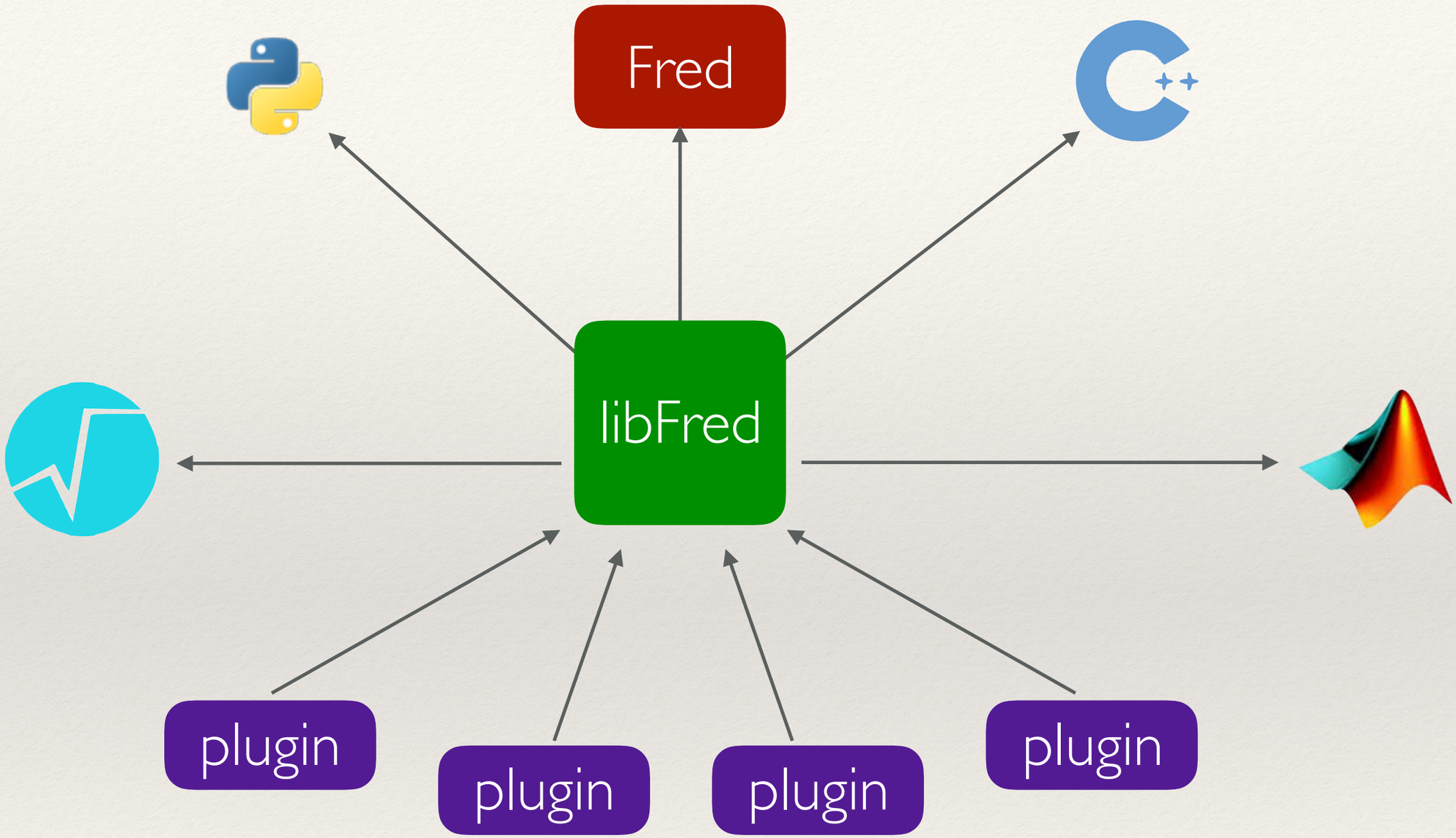




- text input file (energy and type of the projectile, voxel resolution, model switched on,etc.)
- geometry and ROIs definition
- machine file (accelerator settings)
- voxel resampling and optimization parameters (if it is used as TPS)

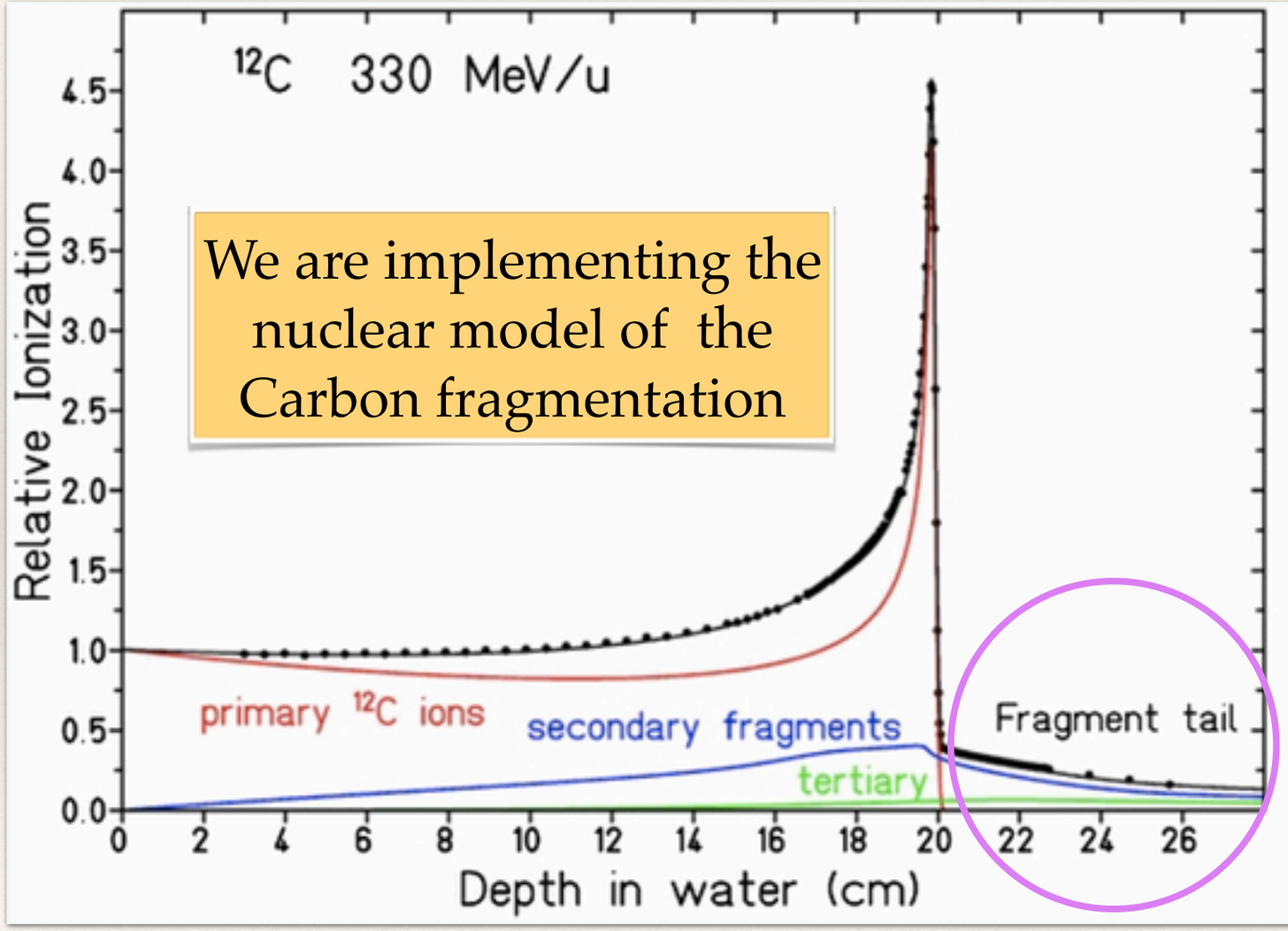
- DICOM import (Patient CT)
- RTSTRUCT (Physician Prescription: PTV,OAR,etc.)
- RTPLAN (raster file)

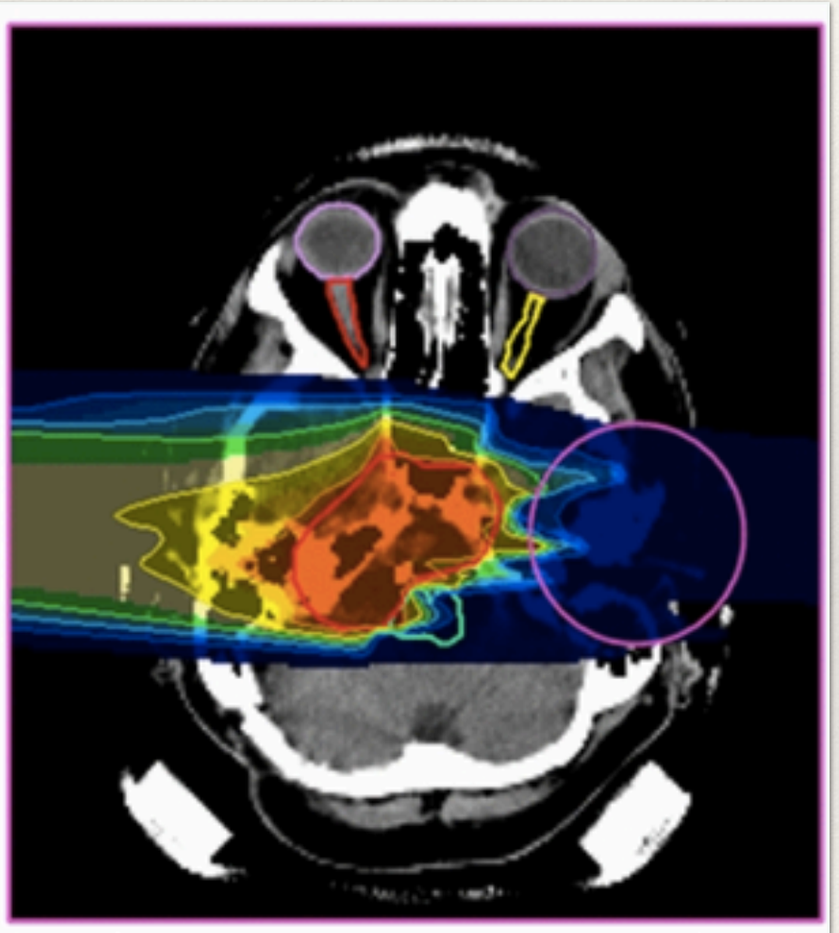
Library



Heavy Ion Beams

The simulation of the fragmentation of the ions of the beam, actually not considered in the code, gives an important contribution for the dose deposition for heavy ion treatments.

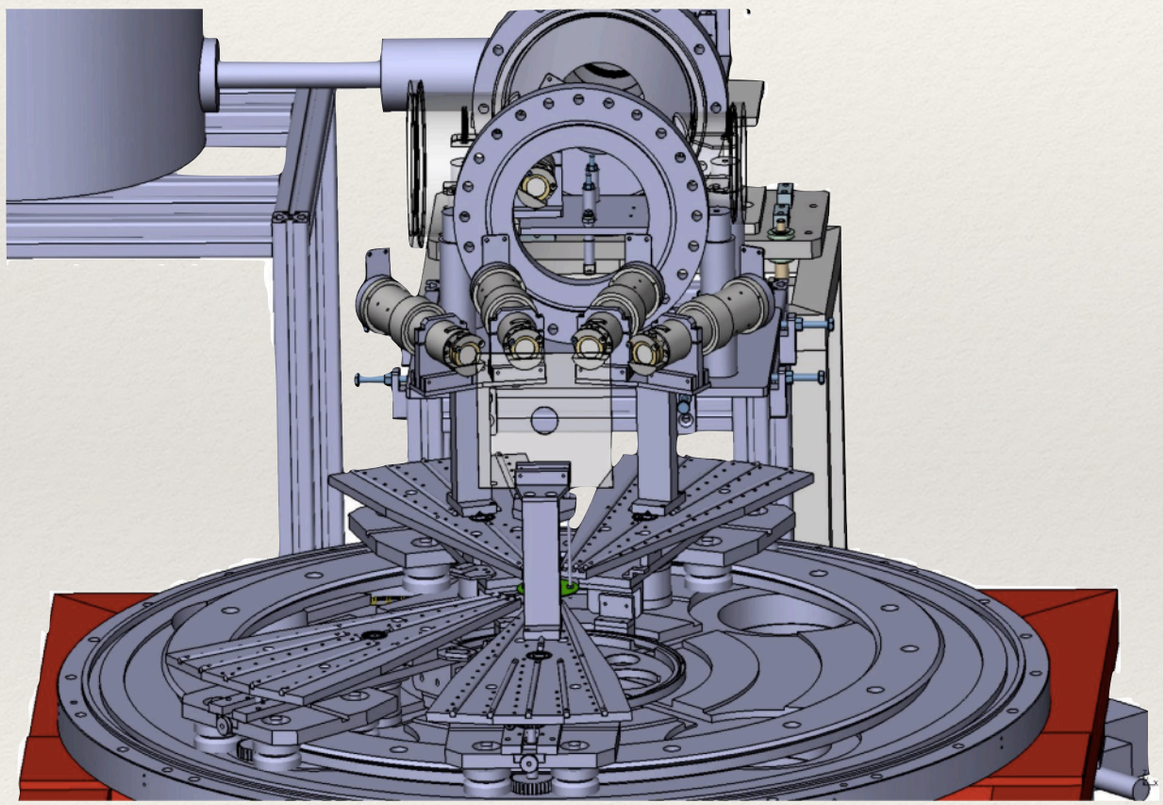


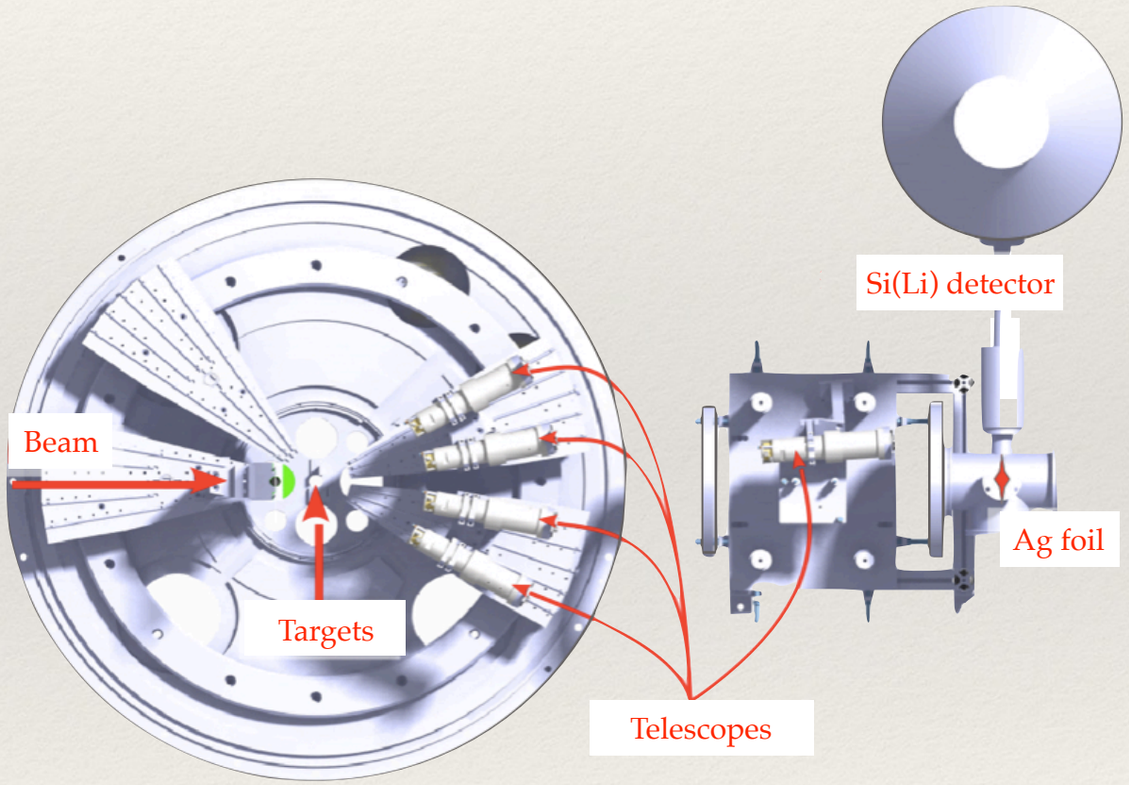


Ganil Experiment

Development of the model using data taken during experiments to study the fragmentation of ^{12}C beams on thin targets at GANIL (laboratory of CAEN, France, 2011-2017).

Data consist on: **energy and angular cross-section** distributions on H, C, O, Al, and Ti with beams of ^{12}C with energies of 50 and 95 MeV/n with a detection angle [-43°,+43°]



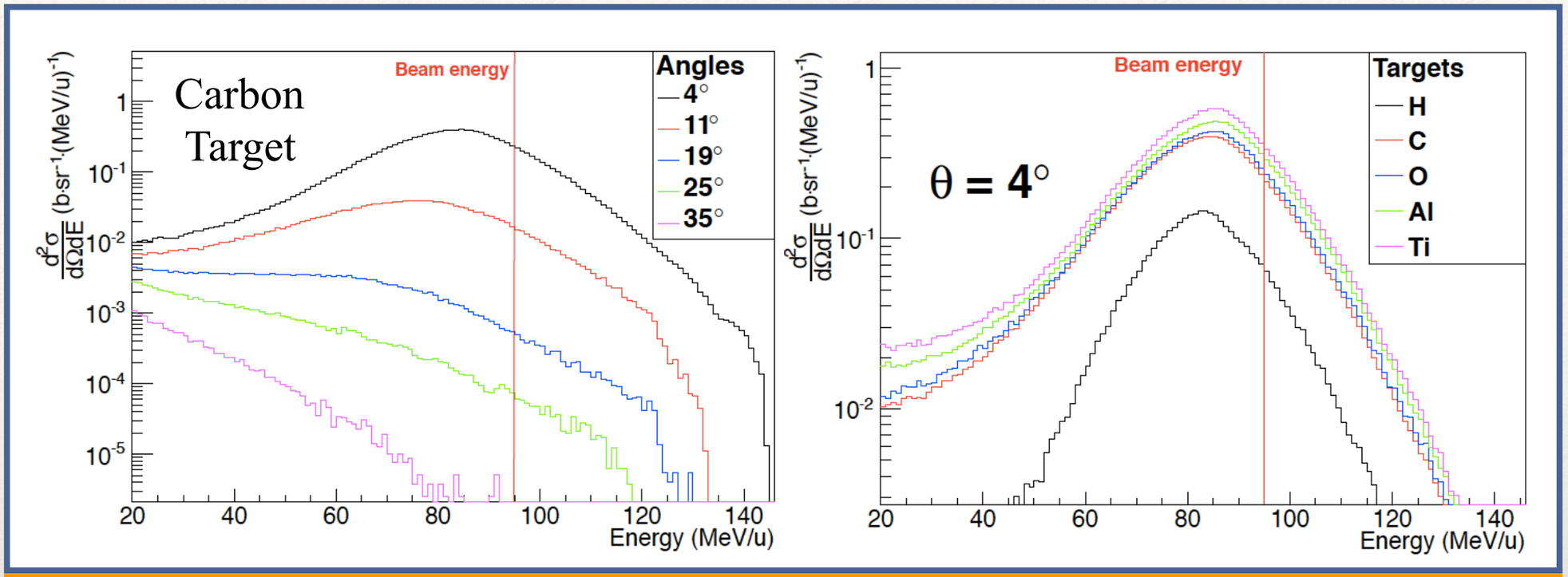


J. Dudouet, et al, C, PHYSICAL REVIEW American Physical Society, 2013

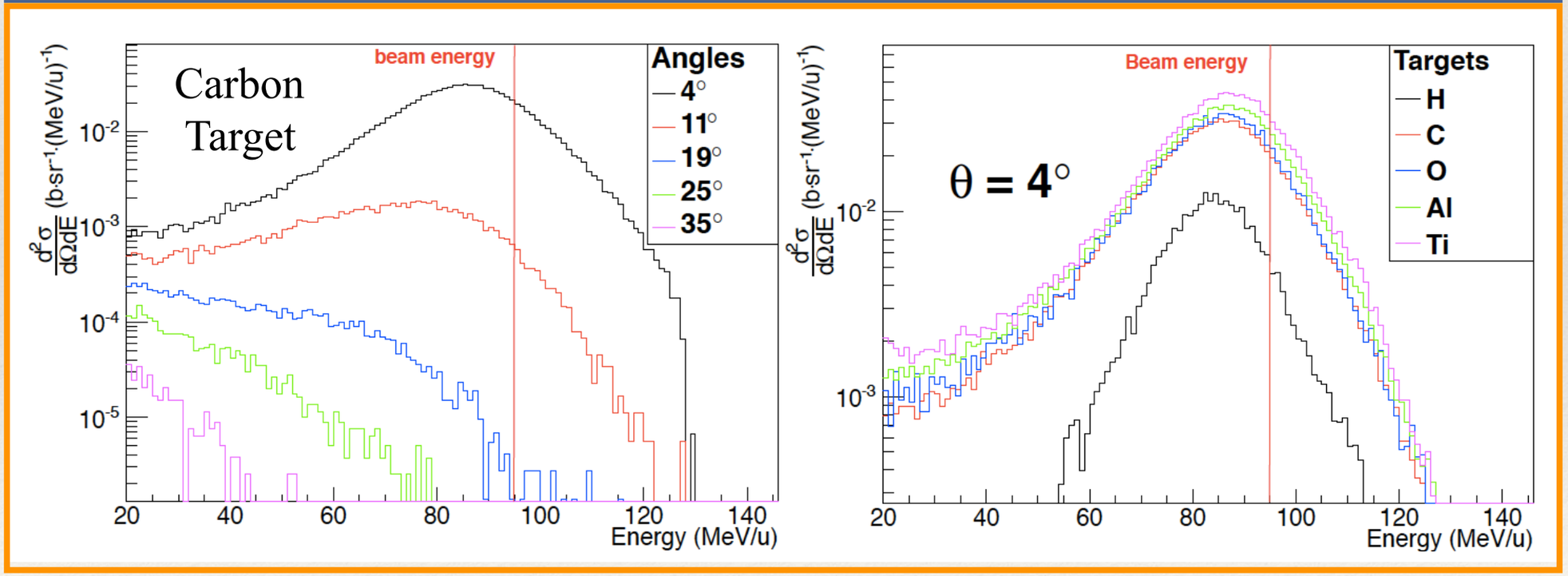
C. Divay et al, PHYSICAL REVIEW C 95, 044602 (2017)

Implementation of the ions fragmentation

^{4}He energy distribution
Beam:
^{12}C [95MeV/u]



^{6}Li energy distribution
Beam:
^{12}C [95MeV/u]



J. Dudouet, et al, C, PHYSICAL REVIEW American Physical Society, 2013

Implementation of the ions fragmentation

Limitation of GANIL Data:

- Beam Energy: only ^{12}C 50 MeV/u and 95 MeV/u
- Angle: [-43°,43°]

Scaling of fragments **kinetic energy**:

$$K_f = K_f^{Ganil} R$$

Scaling of fragments **angle emission**:

$$\theta_f \propto \sqrt{\frac{p_f}{p_b}} \simeq \sqrt{\frac{K_f}{K_b}}$$

$$R = \frac{K_b}{K_b^{Ganil}}$$

$K_f =$ Kinetic Energy of fragments produced by a beam with kinetic energy K_b

$K_f^{Ganil} =$ Kinetic Energy of fragments produced by the beam used in the GANIL experiment

$K_b =$ Kinetic Energy of the beam

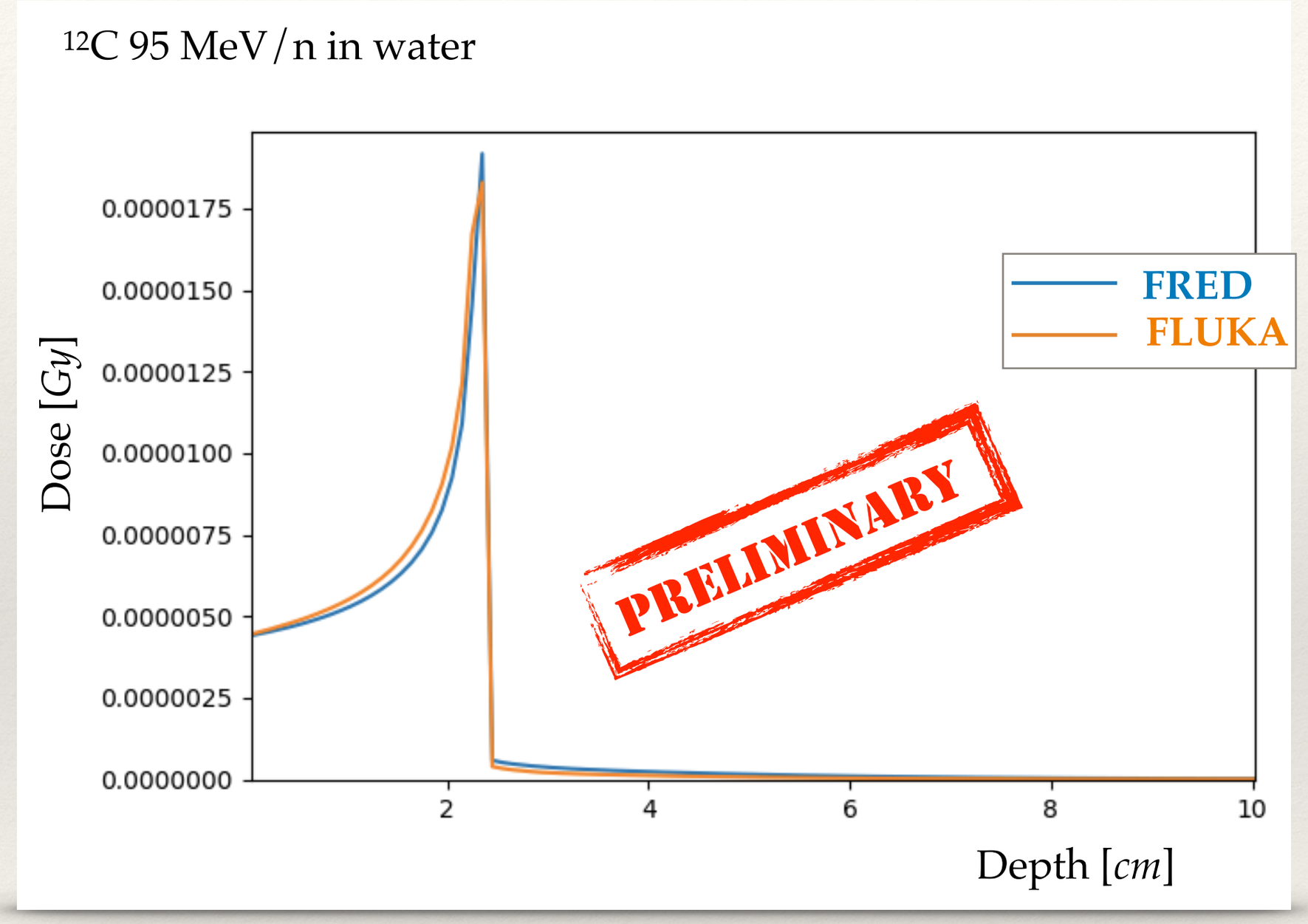
$K_b^{Ganiil} =$ Kinetic Energy of the beam used in the GANIL experiment

$\theta_f =$ Angle of fragmentation with a beam of kinetic energy K_b

$p_f =$ Transverse momentum of the fragment

$p_b =$ Transverse momentum of the beam

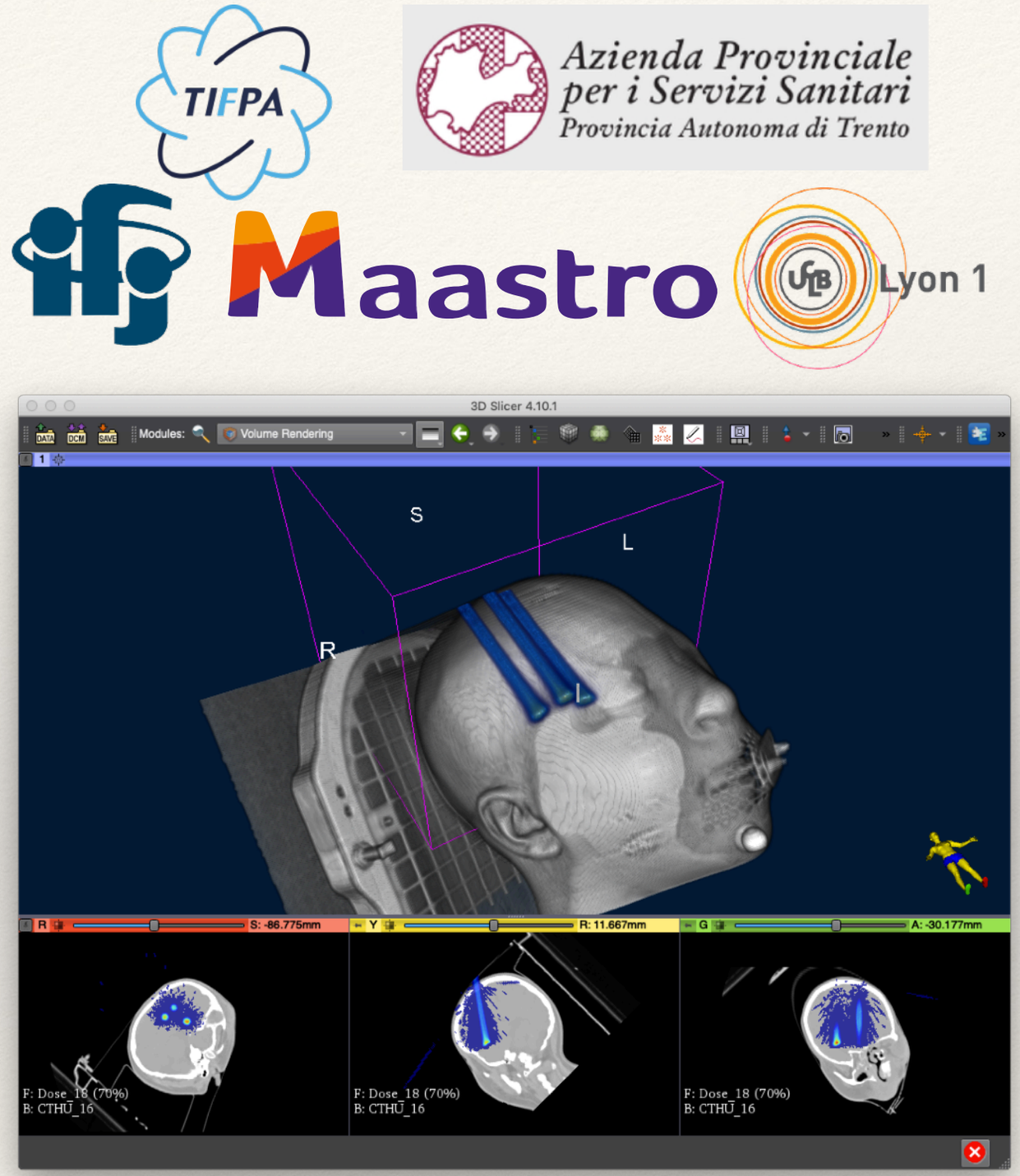
Waiting for new data



The model will be implemented using new data from other experiments of our group such the one shown in the poster of Y. Dong *"Beam and target fragmentation in hadrontherapy: The FOOT experiment"*

Conclusion

- FRED is used as research tool at several clinical and research centres in Europe (Krakow, Trento, Maastricht, Lyon)
- Running on GPU hardware it is possible to recalculate a complete treatment plan within minutes
- Excellent performances with **Proton** beams
- Work in progress for the implementation of nuclear models in order to use FRED also with **Carbon ion** beams



Graphic interface of FRED

Thanks!

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vincenzo.patera@uniroma1.it