Dose computation with a GPU-based fast Monte Carlo for an IOeRT mobile electron linear accelerator

Sezione 5 - Biofisica e fisica medica

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IOeRT Technique

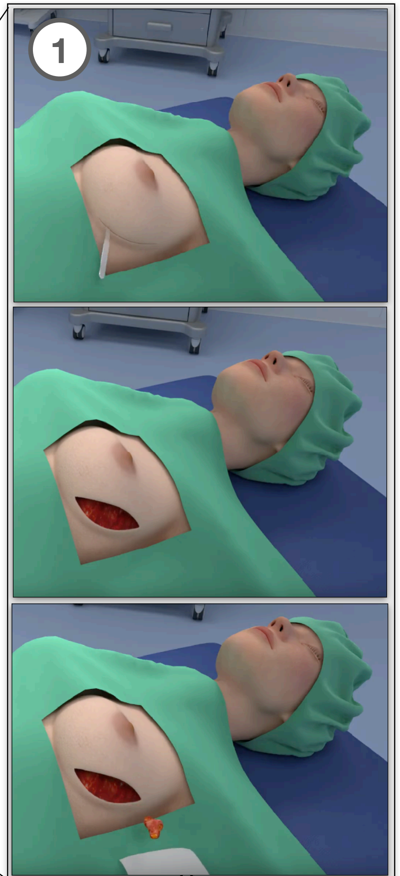
The Intra Operative Radio Therapy with electron (**IOeRT**) is a technique that, after the surgical tumour removal, delivers a dose of ionising radiation directly to the surgery bed [1]. The goal is to eradicate the microscopic residual tumour cells that surgery was not able to remove completely.

1. The patient is surgically treated and the tumour is removed by the medical personal.

A protective disk is applied in order to preserve the organs from the undesired dose.

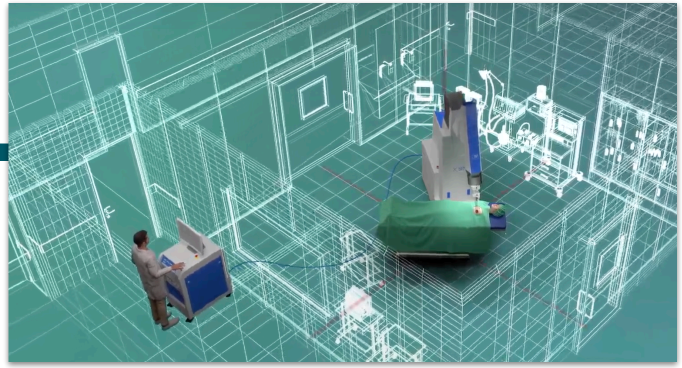
The beam is passively collimated by means of PMMA hollow tubes (applicator), targeting only the tumour cells while preserving the surrounding healthy tissues.

The dose is provided by a uniform electron beam produced by a miniaturised LINAC accelerator with energy between 4 and 12 MeV.



[1] *Intraoperative Irradiation. Techniques and Results, Calvo FA, Gunderson LL et al., Current Clinical Oncology, Second Edition, 2011*

IOeRT Technique



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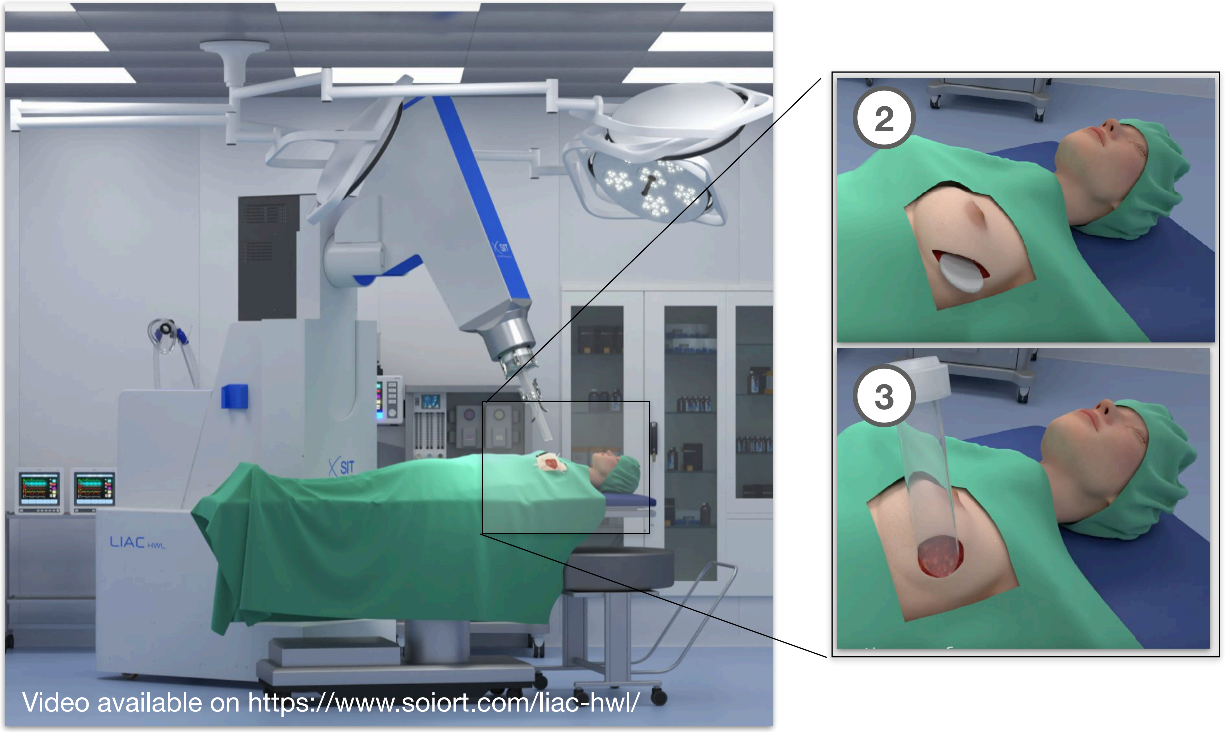

Video available on https://www.soiort.com/liac-hwl/

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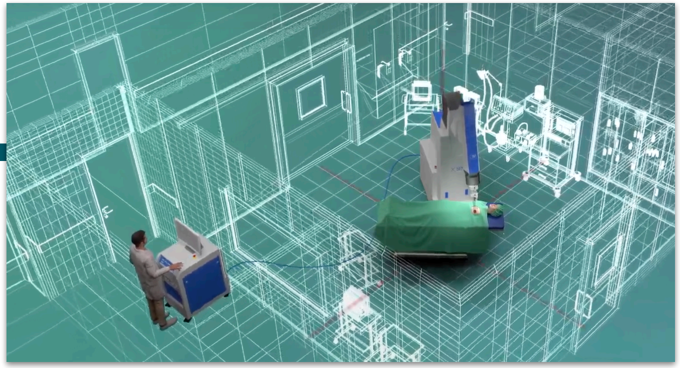

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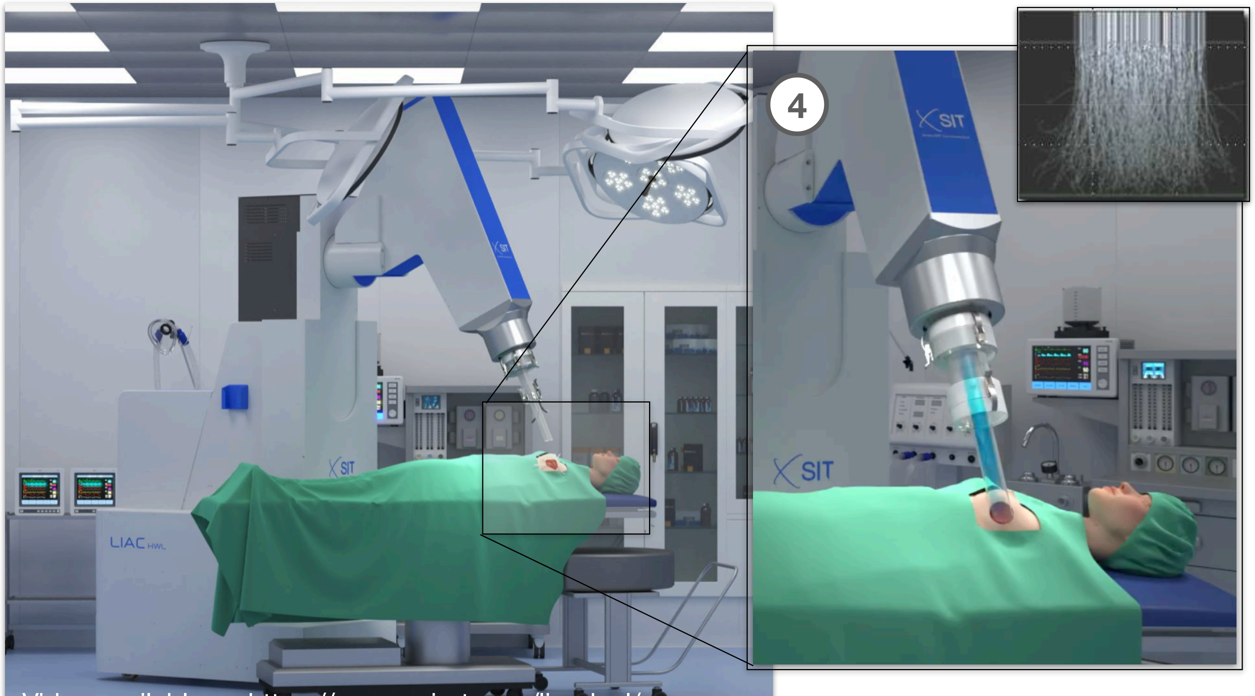

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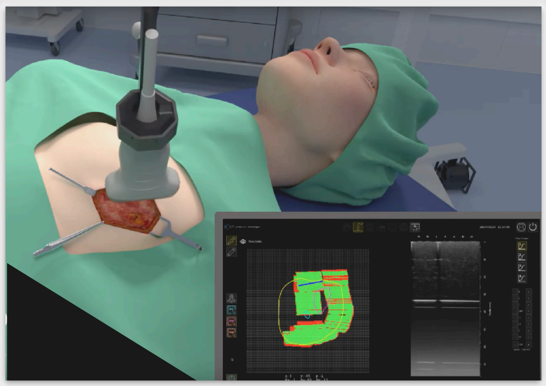
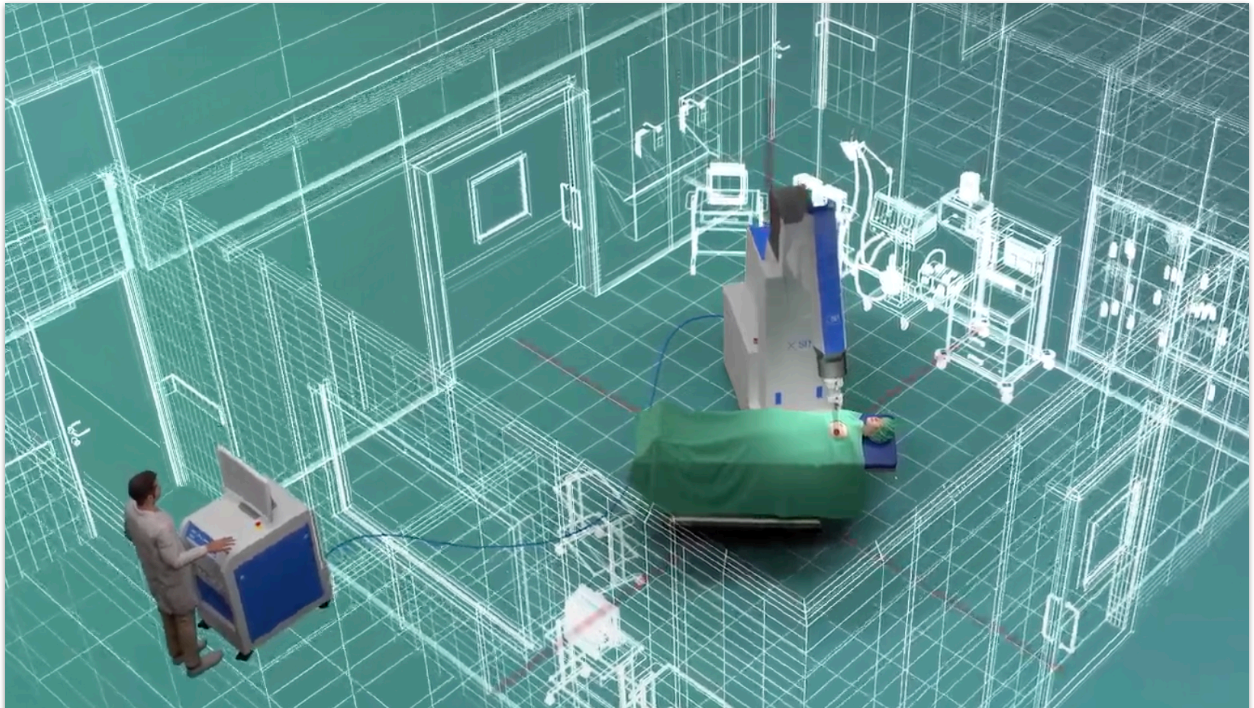
IOeRT Accelerator

From 2020, the low (European 2013/59/EURATOM, Italian D.Lgs 101/2020) asks to provide a dosimetric report after each diagnostic exam/treatement that involve radiations surges. **The report has to includes all the organs at risk involved in the exam/treatement.**

- For IOeRT, the dose report is full-filled evaluating analytically the dose to the patient.
- In order to increase the accuracy a dedicated software is needed. As the patient undergoes surgical removal of the primary tumour a **real-time imaging** (ecography) and an extremely **TPS** are required.
- **The fast TPS must be able to exploit the aforementioned imaging as input.**





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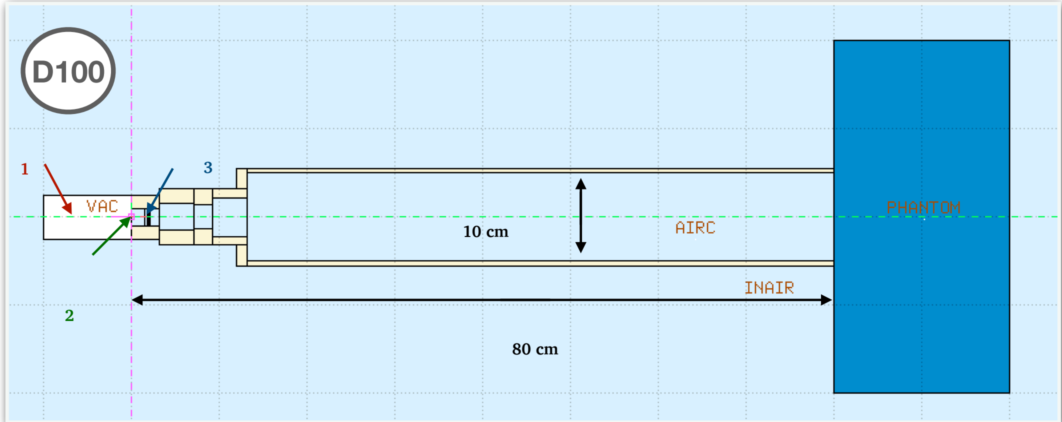
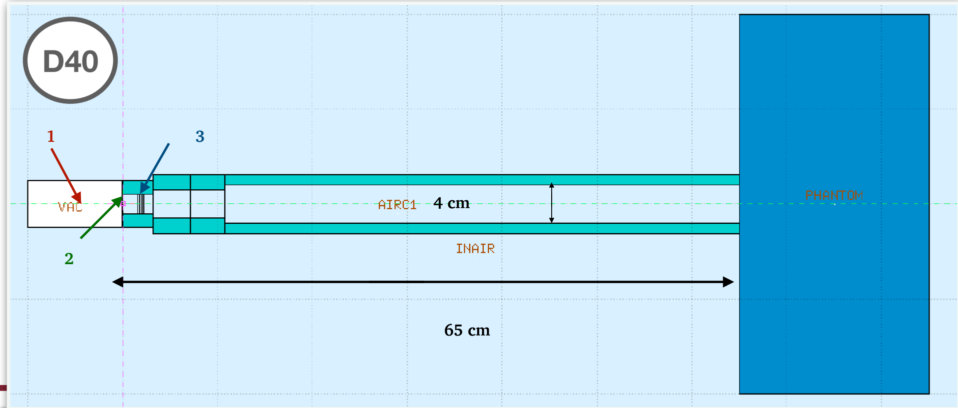
IOeRT Accelerator

The mobile electron linear accelerator **NOVAC 11** (SIT, Aprilia, Italy) [2] maximum energy is 10 MeV which allows treating targets with a thickness up to 2.6 cm inside the 90% isodose (3.0 cm inside the 80% isodose). The device delivers the full treatment in 100 seconds (up to 21 Gy at 90% isodose) and can be installed in any standard operating room with no need of lateral shielding.



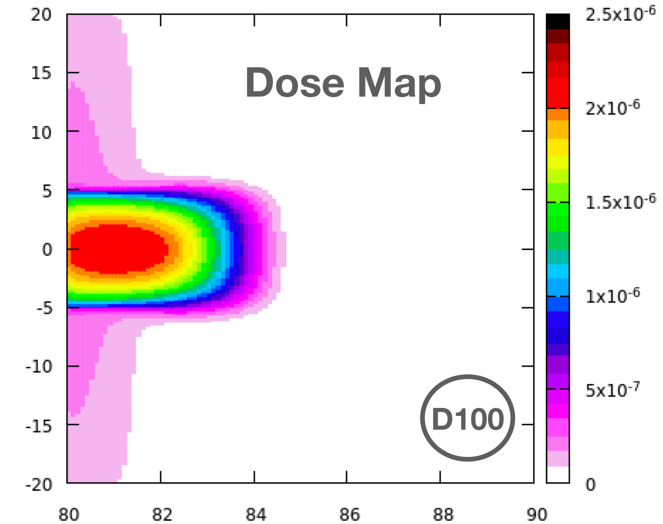
The first **characterisation of the linear accelerator in therms of delivered dose** has been performed with a Monte Carlo simulation developed in FLUKA [3] for a 10 MeV electrons beam.
In particular the **accelerator beam optics** that begins from the titanium window (at the end of the vacuum guide) and finishes at the end of the PMMA applicator **has been simulated to evaluate the dose released by the beam in a water phantom**, with two different applicators with different diameters (d= 100 and 40 mm).

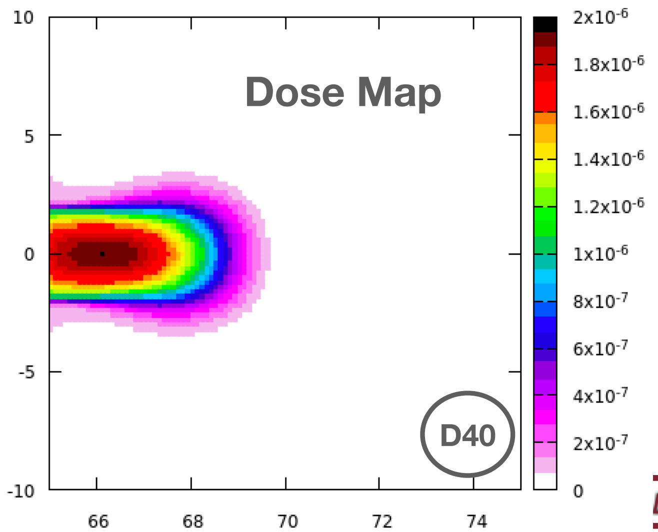


[2] S.I.T. Sordina IORT technologies SpA

[3] Fassò A. Ranft J. Ferrari A., Sala P. Fluka: a multi-particle transport code. Technical Report CERN-2005-10, 2005. INFN/TC 05/11, SLAC-R-773, CERN, INFN, SLAC.

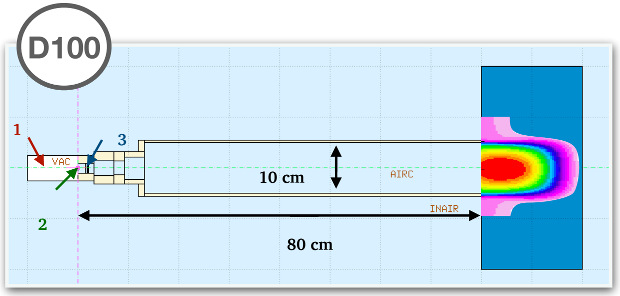
IOeRT Accelerator in MC



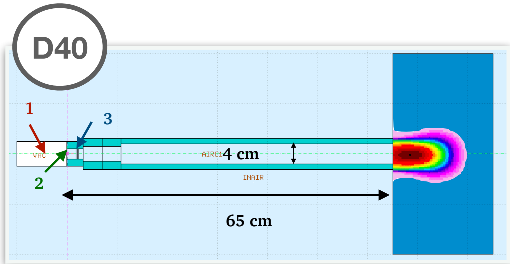


SIMULATION PARAMETERS:

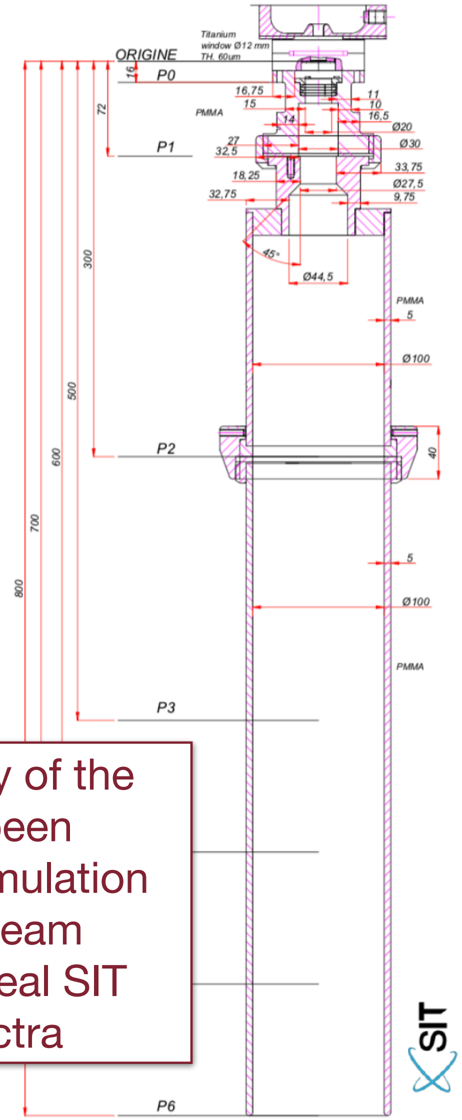
- **10 MeV** electron beam;
- Gauss section with **FWHM=0.13 cm**;
- Transport and production energy cut = **10 keV**;



1. Linac
2. Titanium window
3. Steel planes of the ionization chamber

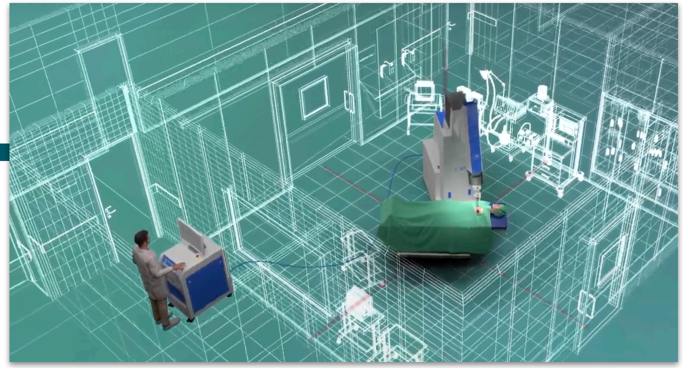


The specific geometry of the applicators have been implemented in the simulation together with the beam parameters and the real SIT beam energy spectra

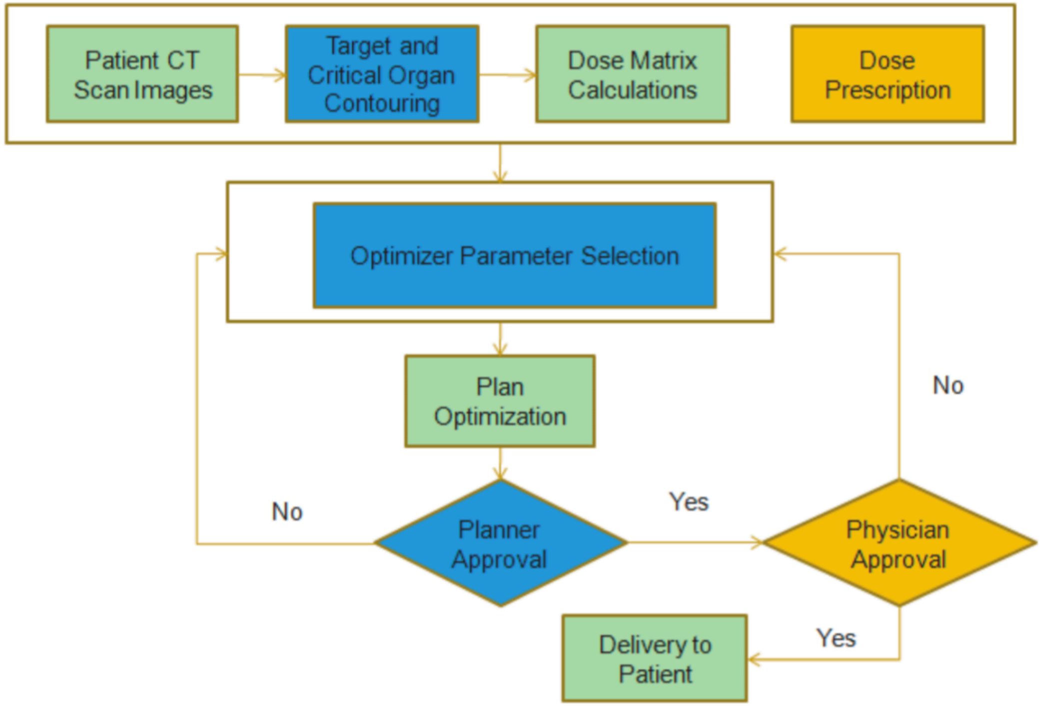


SIT
S.I.T. - Sordina IORT Technologies S.p.A.

IOeRT - TPS

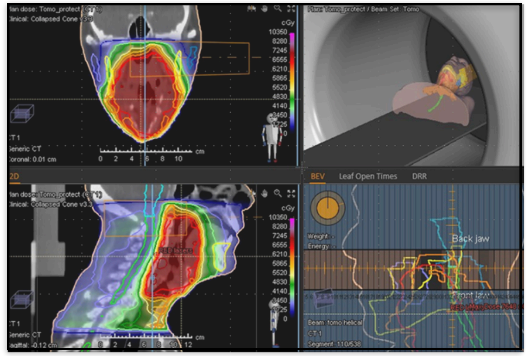


The Treatement Planning System (**TPS**) combines the nuclear models of the particles at the energies of interest with the accelerator machine parameters to be applied in order to optimise the dose distribution to the patient. In radio-particle therapy it can be analytic or MonteCarlo driven.



The TPS provides information to the beam control system:

- Position
- Intensity
- Direction



Radiotherapy TPS

For the **IOeRT technique no TPS is available** => the time to obtain the images and to produce the TPS is very very short: the volume to be treated is accessible only during the surgery procedure.

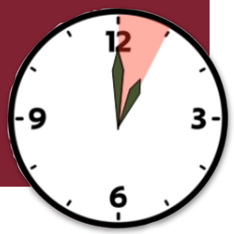
IOeRT and Fast MC

In order to realise a fast and precise TPS for IOeRT it is mandatory to exploits a very fast MC tool.

ANALYTICAL ALGORITHMS

- Reasonable times for calculating the TPS
- Simplified representation of the tissue: the geometry of the patient is represented in an equivalent volume of water, neglecting the real atomic composition of the tissues.
- **Not high accuracy**

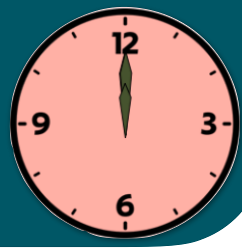
Ex. Proton TPS
~ 1 h/core



MONTE CARLO METHODS

- Realistic assessment of body composition
- Extracts accuracy in the description of the transport and the interaction of the particles with matter
- **Long times for calculating the TPS**

Ex. Proton TPS
~ days/core



FRED MONTE CARLO

- High accuracy in the description of the transport and of the interaction of particles with matter
- Realistic assessment of body composition
- **Very fast calculation of TPS**

Ex. Proton TPS
~ minutes

FRED: Fast paRticle thErapy Dose evaluator

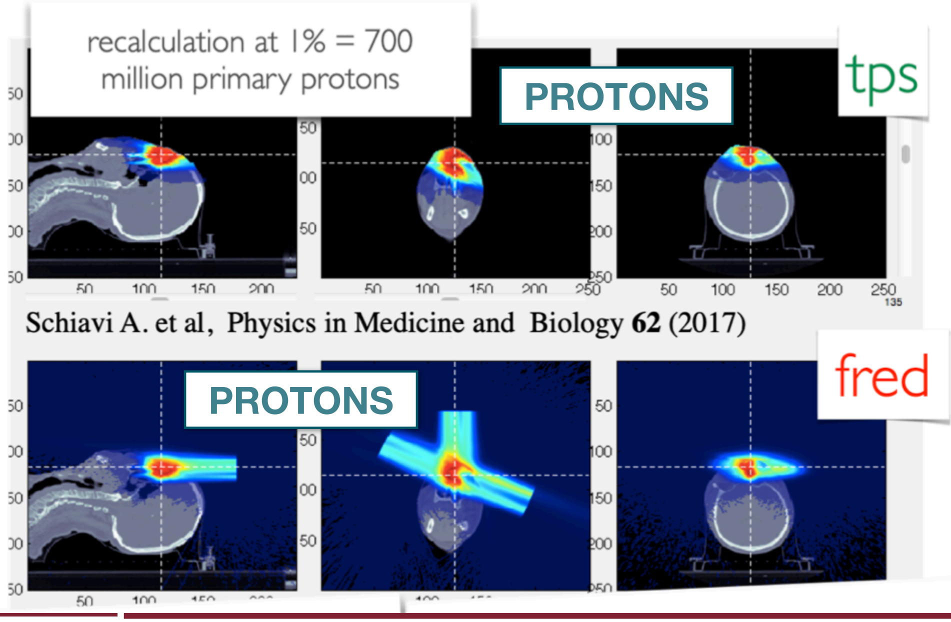
FRED [4] is a fast Monte Carlo code for the transport of particles in heterogeneous media that allows for a quick recalculation of the deposition of the dose. It has been developed in the context of Particle Therapy.

FRED has been developed to work on GPU (Graphics Processing Unit) and it reduce the simulation time by a factor of 1000 compared to a standard MC.

Today FRED protons is used as a tool for the **quality control of TPS** in various medical and research centres throughout Europe.

- MedAustron (Vienna),
- APSS (Trento),
- MAASTRO (Maastricht)
- CNAO (Pavia).

[4] A. Schiavi et al. "FRED: a GPU-accelerated fast-Monte Carlo code for rapid treatment plan recalculation in ion beam therapy" PMB 62 (2017) 18 doi:10.1088/1361-6560/aa8134



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- **Very fast calculation of TPS**
- developed on GPU

Ex. Proton TPS ~ minutes

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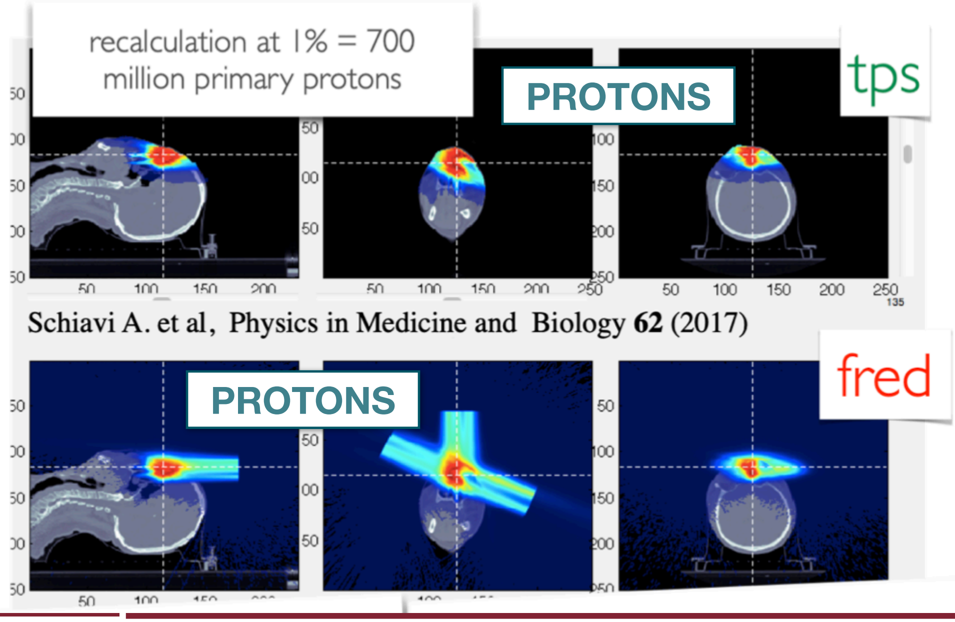
To develop a FRED TPS for IOeRT we need to implement in FRED the physics models, i.e. electromagnetic interactions, relevant for the positron and electron interaction and production.



FRED MONTE CARLO

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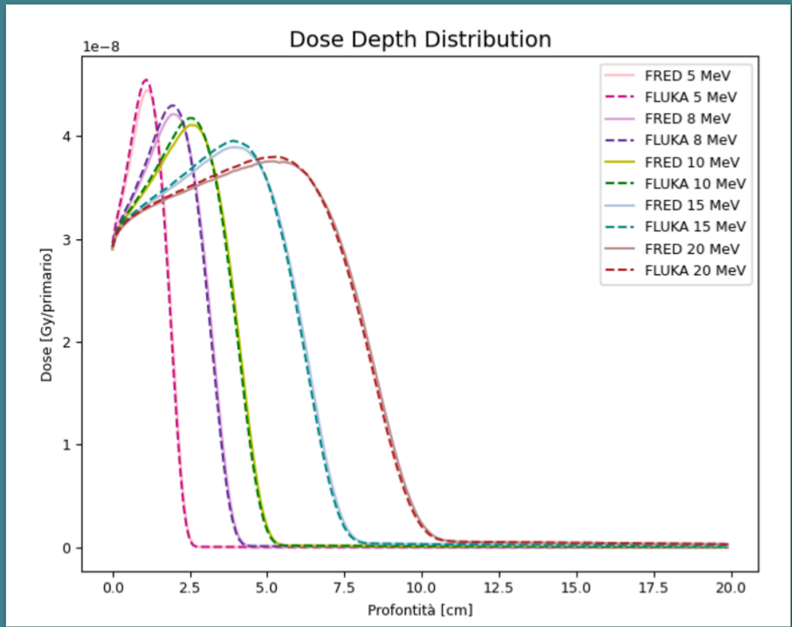
- Realistic assessment of body composition
- **Very fast calculation of TPS**

Ex. Proton TPS ~ minutes

Electromagnetic Model in FRED

All the interactions between electrons, photons and positrons and matter useful for medical applications have been inserted and tested comparing the result with FLUKA:

- ◉ Bremsstrahlung
- ◉ Scattering Moller/Bhabha
- ◉ Positron Annihilation
- ◉ Compton Effect
- ◉ Photoelectric Effect
- ◉ Pair Production
- ◉ Coherent Scattering



In first evaluation study FRED has been used to simulate the SIT mobile IOeRT-NOVAC 11 accelerator with different applicators to compare with results obtained from a FLUKA MC simulation.

SIT

Electromagnetic Model in FRED

	FLUKA [Gy/e]	FRED [Gy/e]	DIFF
D_{max}	3.67e-9	3.57e-9	2.7%
D_{media}	1.10e-7	1.09e-7	0.9%

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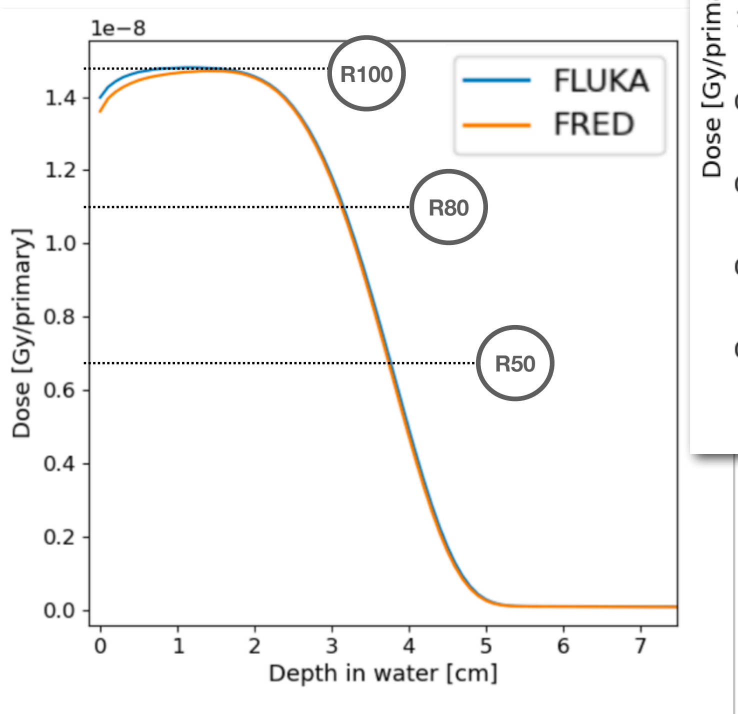
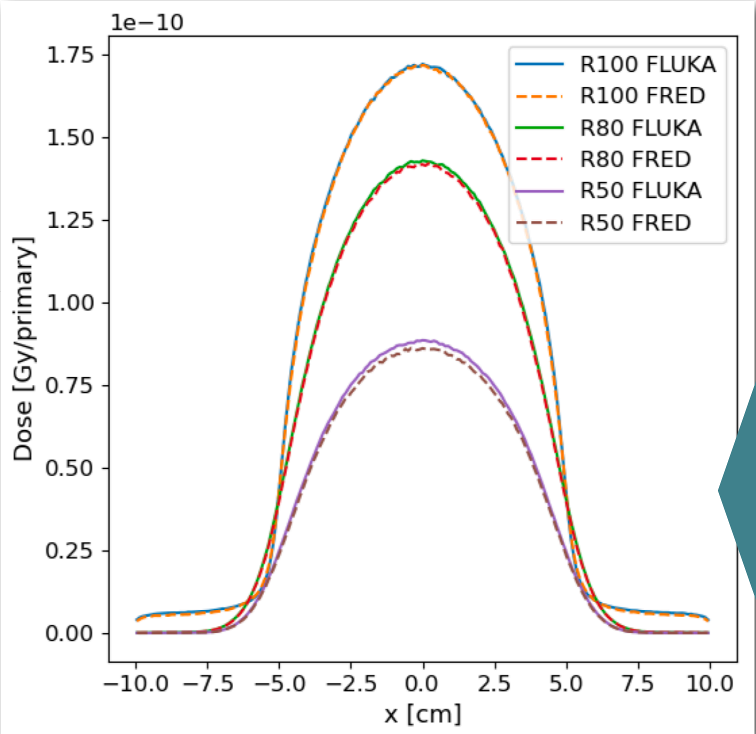


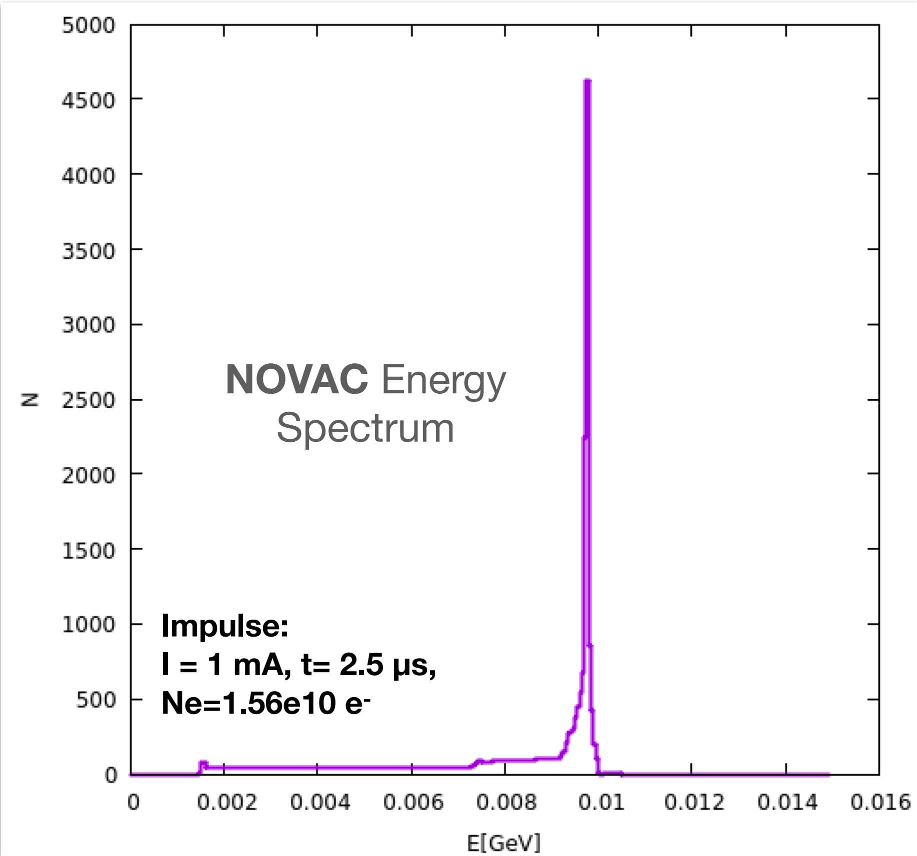


- ☑ Beam 10 MeV (mono-energetic)
- ☑ longitudinal and transversal profiles of the beam

SIT

FRED for IOeRT

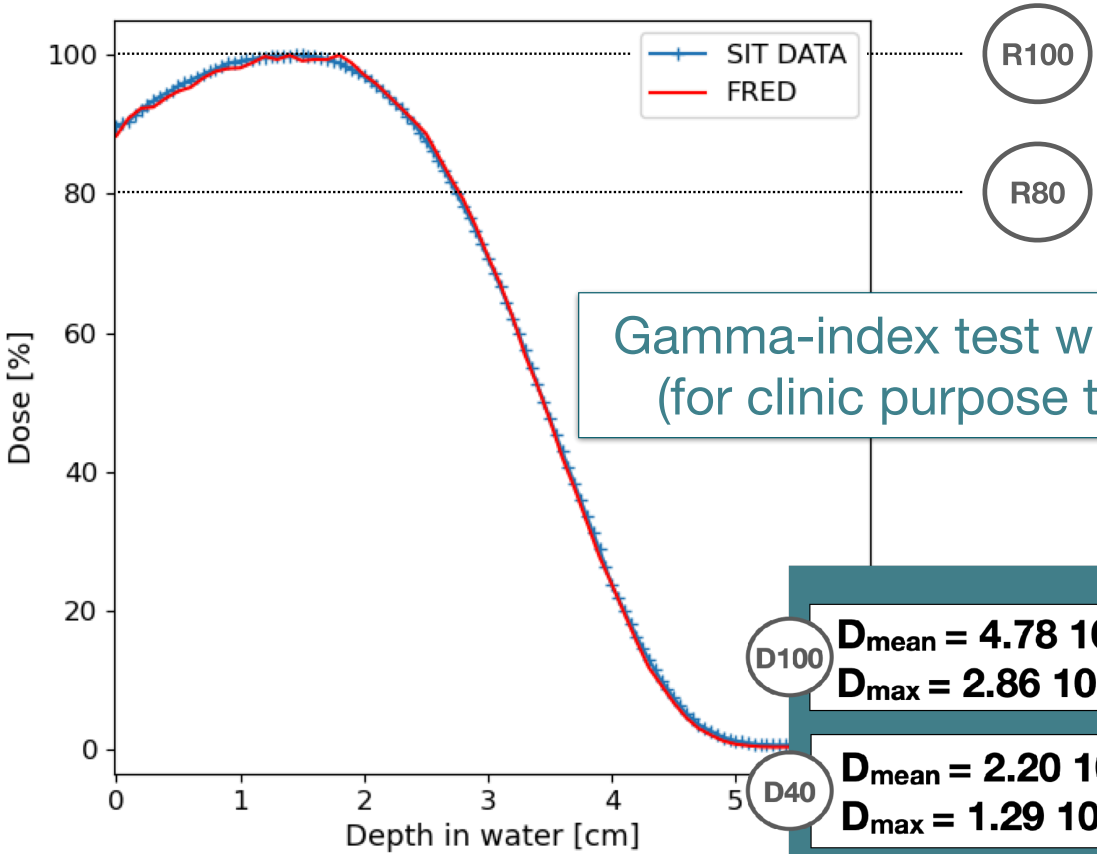
In order to compare with real data the dose has been evaluated along the water target, that is 20 cm thick, in a transverse area of 2x2 mm^2.

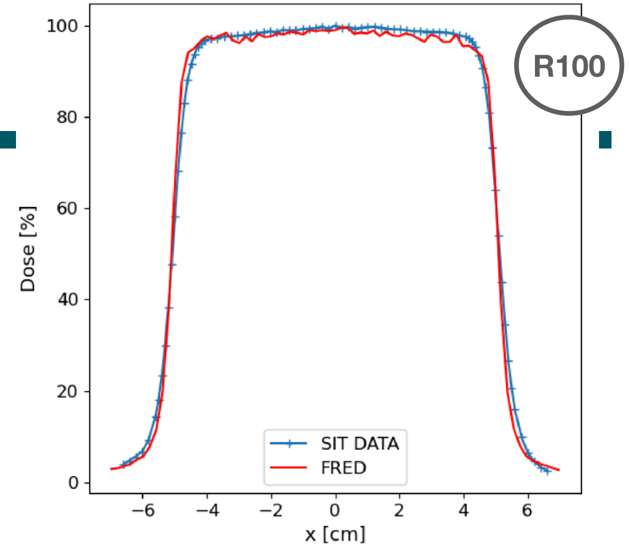


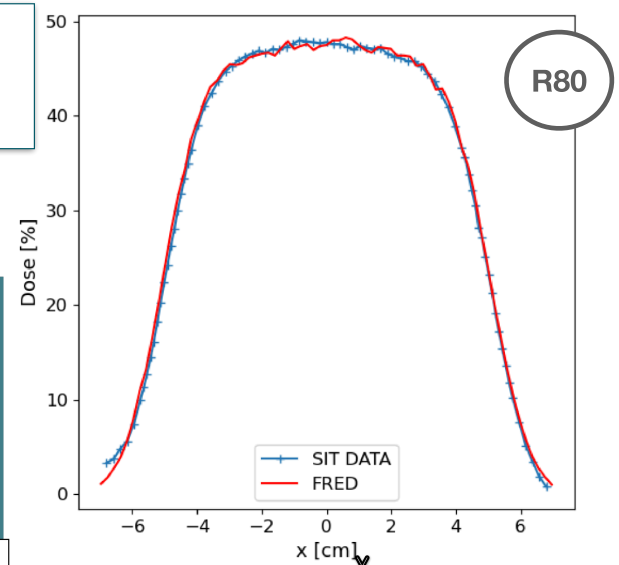
Measurements have been performed by SIT operators with a diode of 4 mm^2 placed inside a water tank.

FRED for IOeRT

The data-MC comparison shows excellent agreement. This promising study is the groundwork for the development of a fast IORT dedicated TPS with FRED.







Gamma-index test with a pass-rate: 98.1%
(for clinic purpose the >96% is needed)

D100

D_{mean} = 4.78 10^{-12} Gy/electron
D_{max} = 2.86 10^{-12} Gy/electron

D_{imp} = 2cGy

D40

D_{mean} = 2.20 10^{-13} Gy/electron
D_{max} = 1.29 10^{-12} Gy/electron

D_{imp} = 4.5cGy

FRED on GPU for IOeRT

The computational time in this application is particularly crucial. We evaluate the computational time achievable with FRED (models and energy of interest of IOeRT). For an electron beam of 10 MeV impinging on a water phantom of 10 x 10 x 50 cm3 we obtain:

FLUKA 1 CORE	FRED 1 GPU
10^3 primary/s	10^5 primary/s

The thresholds chosen (for both MC tools) to track and produce particles are of major impact. For this study we use 50 keV for the tracking and production of electrons and positions and 10 keV for photons.
NB: The threshold choice do not impact the dose evaluation

Exercise with10^8 primary electrons

FLUKA 1 CORE	FLUKA 5 CORE	FRED 1 GPU	FRED 5 GPU
27 hours	6 hours	16 minutes	3 minutes

The level of accuracy is driven by the number of primaries AND by the imaging capability.

Towards fast IOeRT TPS

- Since 2020 in Italy the dosimetric report is needed after each treatement providing information about all the organs at risk.
- A fast and trustable TPS has to be implemented in order to evaluate the real absorbed dose to the patient's organs.
- From the collaboration of SBAI with SIT- Sordina IORT Technologies we develop a MC capable of fully simulate the electron accelerator beam optics and the different tools that are exploited during the treatments.
- The results obtained by the comparison of dose measurements with FRED - a fast MC developed to work on GPU - have shown a very promising agreement.
- From preliminary evaluation the computational time of FRED for IOeRT purpose full fill the requirements with an expected simulation capability of about 100k particles/s per GPU.
- The input from clinic will be of paramount importance.

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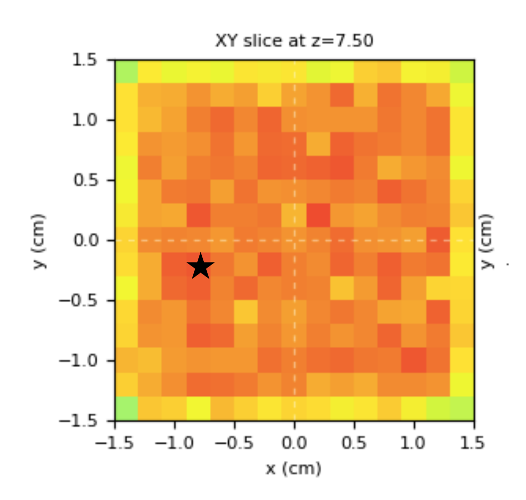
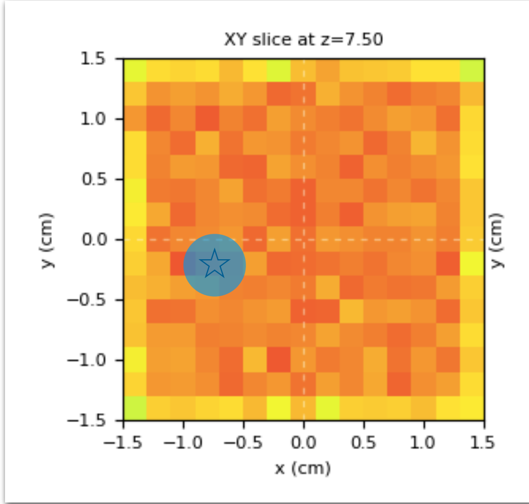
GRAZIE

Gamma index analysis

Reference Map



Under evaluation Map



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)

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

$\gamma \leq 1$ = test passed

$\gamma > 1$ = test NOT passed

pass rate ≥ 96%
clinical acceptance