Development of an in-beam time-of-flight positron emission tomograph for monitoring proton therapy

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Abstract

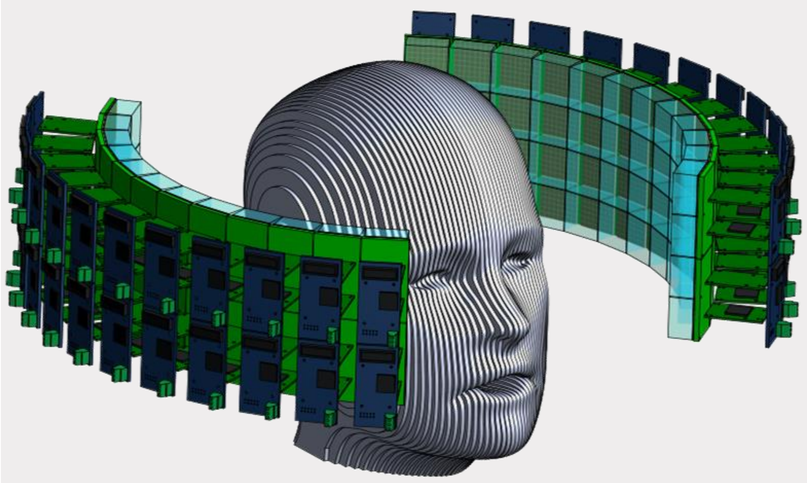
The TPPT (in-beam time-of-flight positron emission tomography for proton therapy) consortium is, since January 2020, thriving efforts in order to construct an in-beam TOF-PET system onto one of the therapeutic proton beam lines in the MD Anderson Cancer Center (MDACC) in Houston, Texas, USA (University of Texas). The team at LIP is responsible for the simulations that will allow a comparison between measured beta+ activity distributions versus the expected ones. Member of the consortium are: PETsys Electronics (leading company in Tagus Park), LIP (divisions of Coimbra and Lisbon), University of Lisbon (FCUL, C2TN & IST), University of Coimbra (ICNAS), University of Texas at Austin, and MDACC. In a first stage the team at LIP is developing code with the Monte-Carlo package called GEANT4. Nuclear cross-sections are being compared with experimental ones, patient computed tomograms (which are proportional to electron density) are being adapted to GEANT4 (which includes tissue density and stoichiometry), and gamma-ray detectors and readout electronics are being also simulated. In a later stage, the simulation code will be accelerated via a routine to be developed in-house that focus solely on the production of beta+ activity and scoring the dose accumulated in the patient, together with positron annihilation and the spreading of the corresponding gamma rays onto the surrounding detector assembly. These results will be interfaced with a dedicated reconstruction routine being developed within the consortium (ICNAS/UC). Finally, head-and-neck patient irradiations with proton beams will be monitored with this TPPT system.

Members of the Consortium

- **PETsys Electronics**, Lisbon, Portugal (leading company).
- **MD Anderson Cancer Center** (MDACC), Houston, Texas, USA (University of Texas).
- **LIP** (Laboratório de Instrumentação e Física Experimental de Partículas – divisions of Coimbra and Lisbon), Portugal.
- **University of Coimbra: ICNAS** (Instituto de Ciências Nucleares Aplicadas à Saúde), Portugal.
- **University of Lisbon: IST** (Instituto Superior Técnico); **C2TN** (Centro de Ciências e Tecnologias Nucleares); and **FCUL** (Faculdade de Ciências da Universidade de Lisboa), Portugal.
- **University of Texas**, Austin, USA.

System under development

A PET system prototype to be used in a proton therapy equipment, suitable for radiation monitoring of the head and neck cancers



- Based on the detection of back-to-back photons (511 keV) resulting from $e^- e^+$ annihilation;
- In proton therapy, the positron arises from β^+ emitters (mainly ^{11}C and ^{15}O) generated by nuclear interaction between protons and the patient tissue

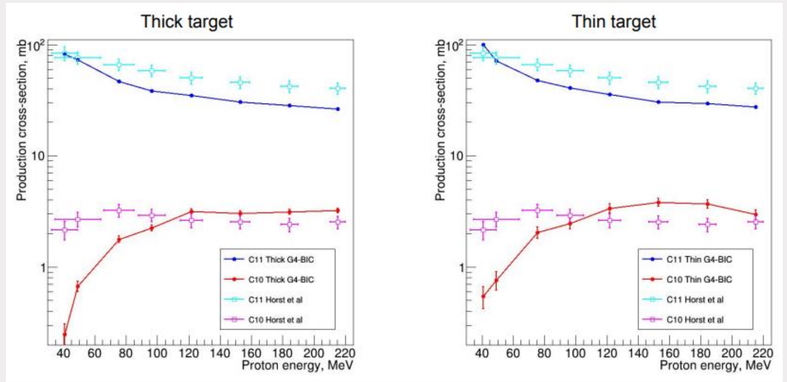
LIP contribution

LIP is responsible for the simulations that will allow a comparison between measured β+ activity distributions versus the expected ones. Some steps of this work are:

- Comparison of simulated nuclear cross-sections with experimental ones:
- Adaptation of patient treatment plan to GEANT4 (including the patient computed tomogram and the irradiation beam);
- Importation of computer-aided design (CAD) draws into GEANT4 (simulation of all detector system components).

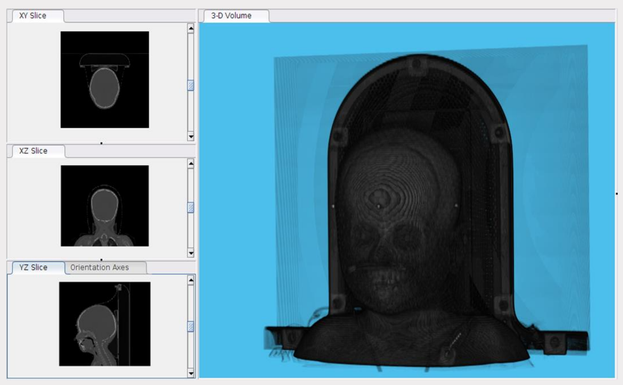
β^+ emitters production cross-sections

- Isotope production cross-section obtained in GEANT4 simulations (QGSP-BIC reference physics list) were compared with those measured by F. Horst *et al*, (Phys. Med. Biol. 64 2019 205012).

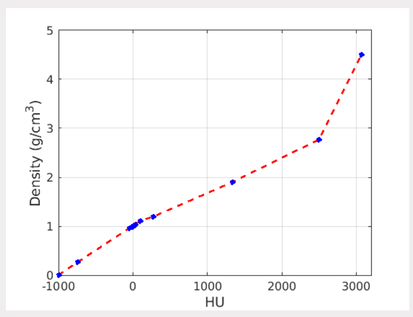


Implementation of treatment plan into GEANT4

- Adapt patient computed tomograms to GEANT4 simulation



- Convert CT numbers into Geant4 materials



Step 1: convert the Hounsfield Unit (HU) values from DICOM (Digital Imaging and Communications in Medicine Digital) files to density

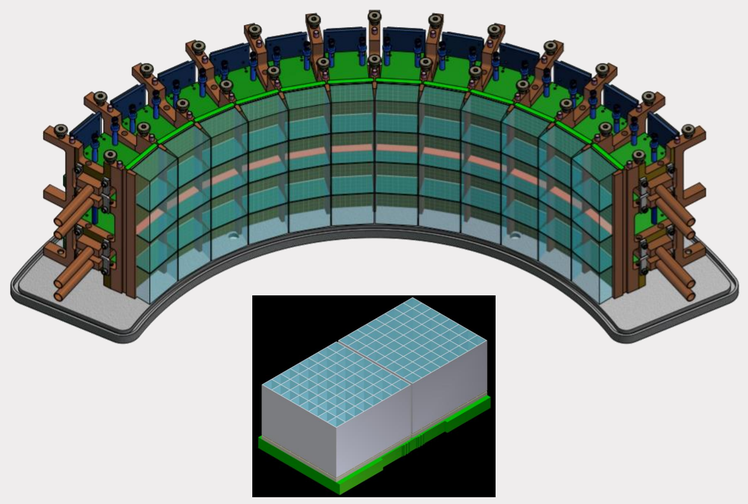
RayStation 10A Reference Manual

Material	Until to (density g/cm³)
Air	0.25
Lung	0.50
Adipose	0.95
Muscle	1.05
Cartilage	1.10
2/3 Cartilage, 1/3 Bone	1.35
1/3 Cartilage, 2/3 Bone	1.60
Bone	1.85
Denser Bone	2.10
1/3 Bone, 2/3 Aluminum	2.40
Aluminum	2.70
Denser Aluminum	2.83
Iron	7.87

Step 2: assign a tissue material (with a specific stoichiometry) to each patient CT voxel

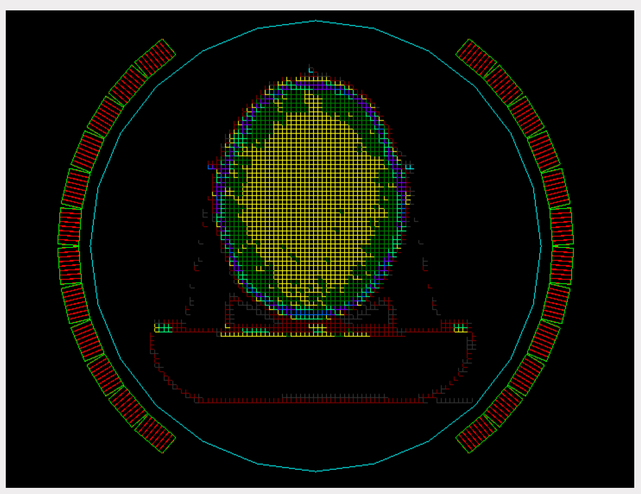
Import CAD draws information into GEANT4

- GUIMesh tool (M. Pinto and P. Gonçalves, 2019, https://doi.org/10.1016/j.cpc.2019.01.02) is used to convert CAD files into GDML (Geometry Description Markup Language) files, compatible with GEANT4.



Simulation geometry implemented into GEANT4

- A simulation geometry, including the detector and a phantom adapted from real patient data, is already implemented into GEANT4.



Ongoing work

Some ongoing tasks are:

- Implementation of the planned beam into the GEANT4 simulation (time structure of the beam is extremely important to such technique).
- Simulation of dose/fluence in detector system components (analisys of electronics damage induced by radiation).
- Development of software rotines to superimpose simulated dose over CT data.
- Documentation of GEANT4 simulation procedure (make the code public to other members of the Consortium).

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