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FLUKA applications in the medical field

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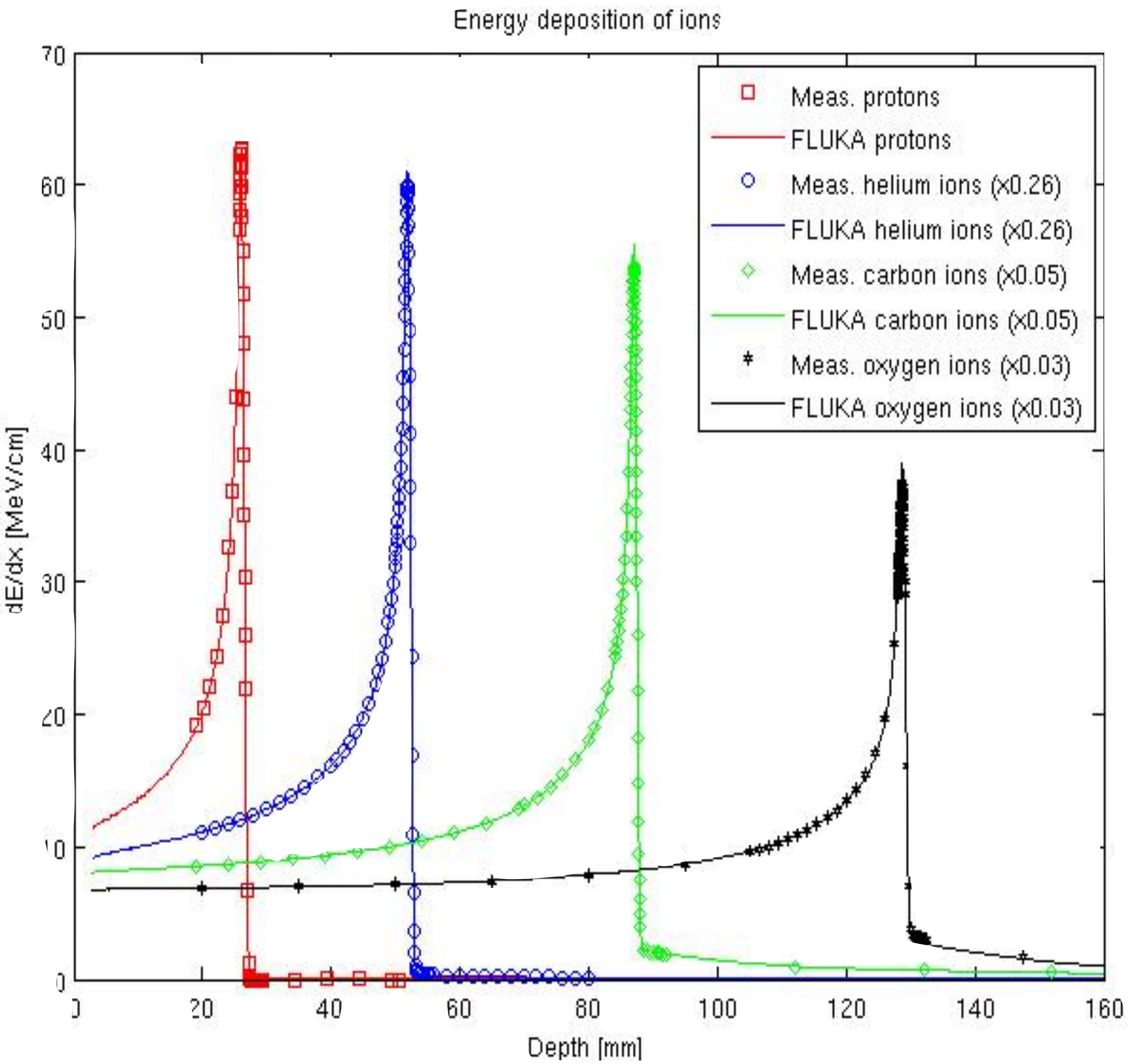
on behalf of the FLUKA team

FLUKA[1][2] and its GUI Flair[3]

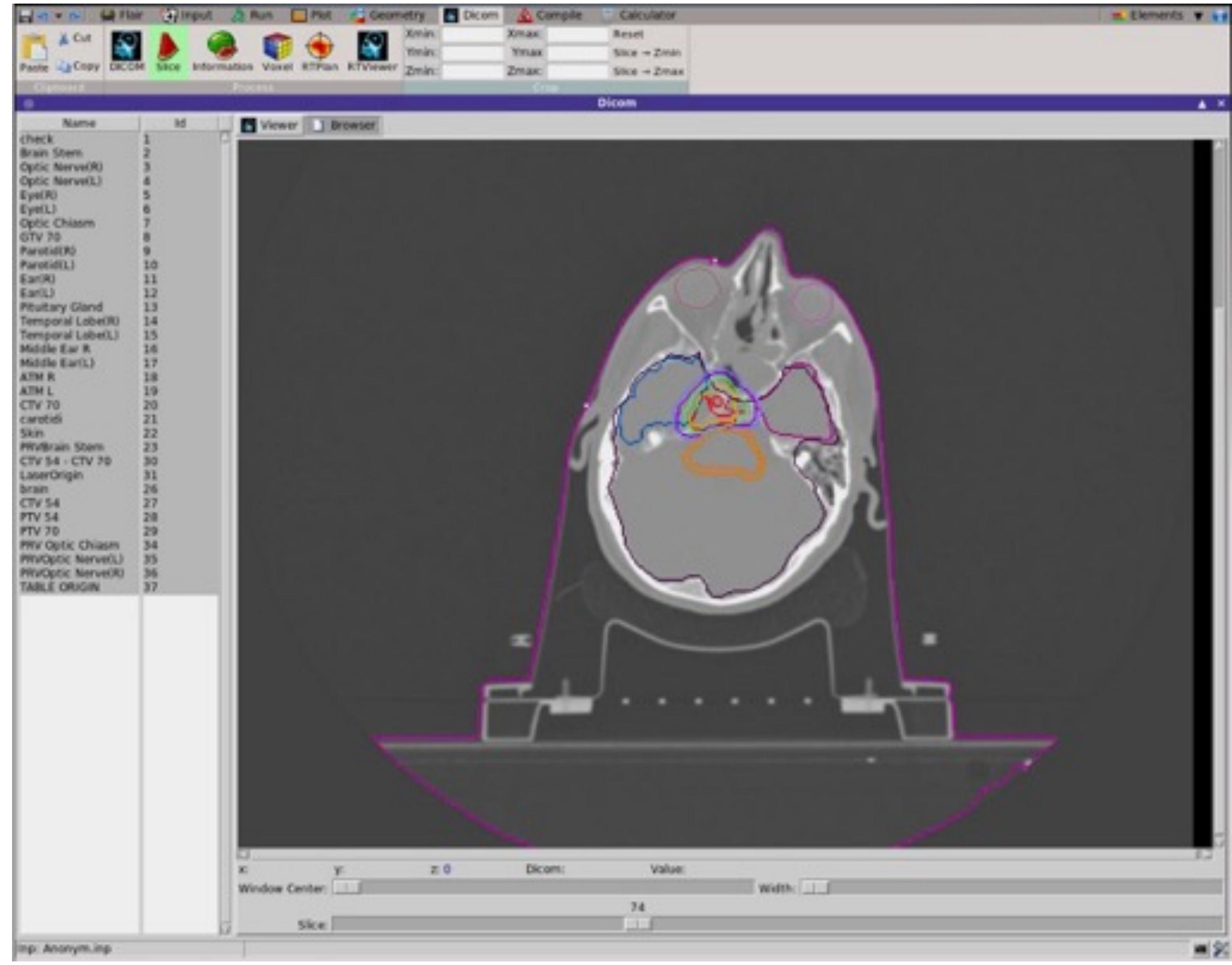
- Developed by **CERN and INFN** with support of international collaborators
- General purpose MC code simulating **particle transport and interactions with matter**
  - all hadrons, electromagnetic, nucleus-nucleus, low energy neutrons, full mixed field capability, radiation damage predictions, transport in magnetic field etc.
- Thoroughly **benchmarked** at single interaction level; i.a. **against depth–dose data and lateral-dose profiles** used for proton and ion-beam therapy

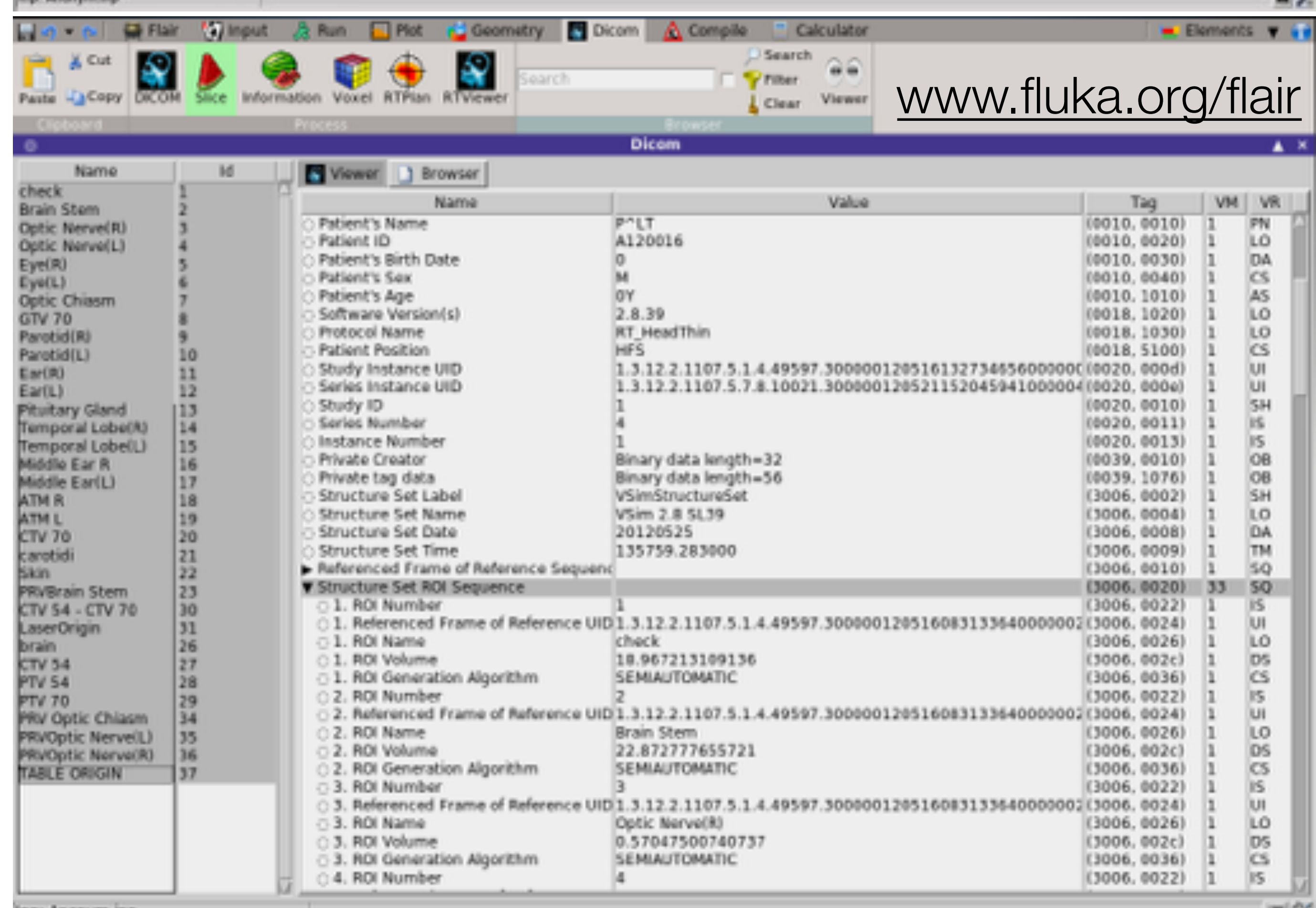


FLUKA simulations of depth–dose profiles of protons and light ions with therapeutic ranges in comparison with measured data at HIT [10]

FLUKA and its GUI Flair

- **Flair** provides an IDE for all stages of **FLUKA simulations**
  - input editing
  - geometry editor
  - running monitoring
  - post-processing
  - output visualization
- For medical application:
  - Process **DICOM standard files**
  - Provides tool for **treatment plan re-simulation** and comparisons
  - Automatic **PET scanner generation** from user provided parameters
  - User defined **coincidence scoring routines** with different **reconstruction algorithms**





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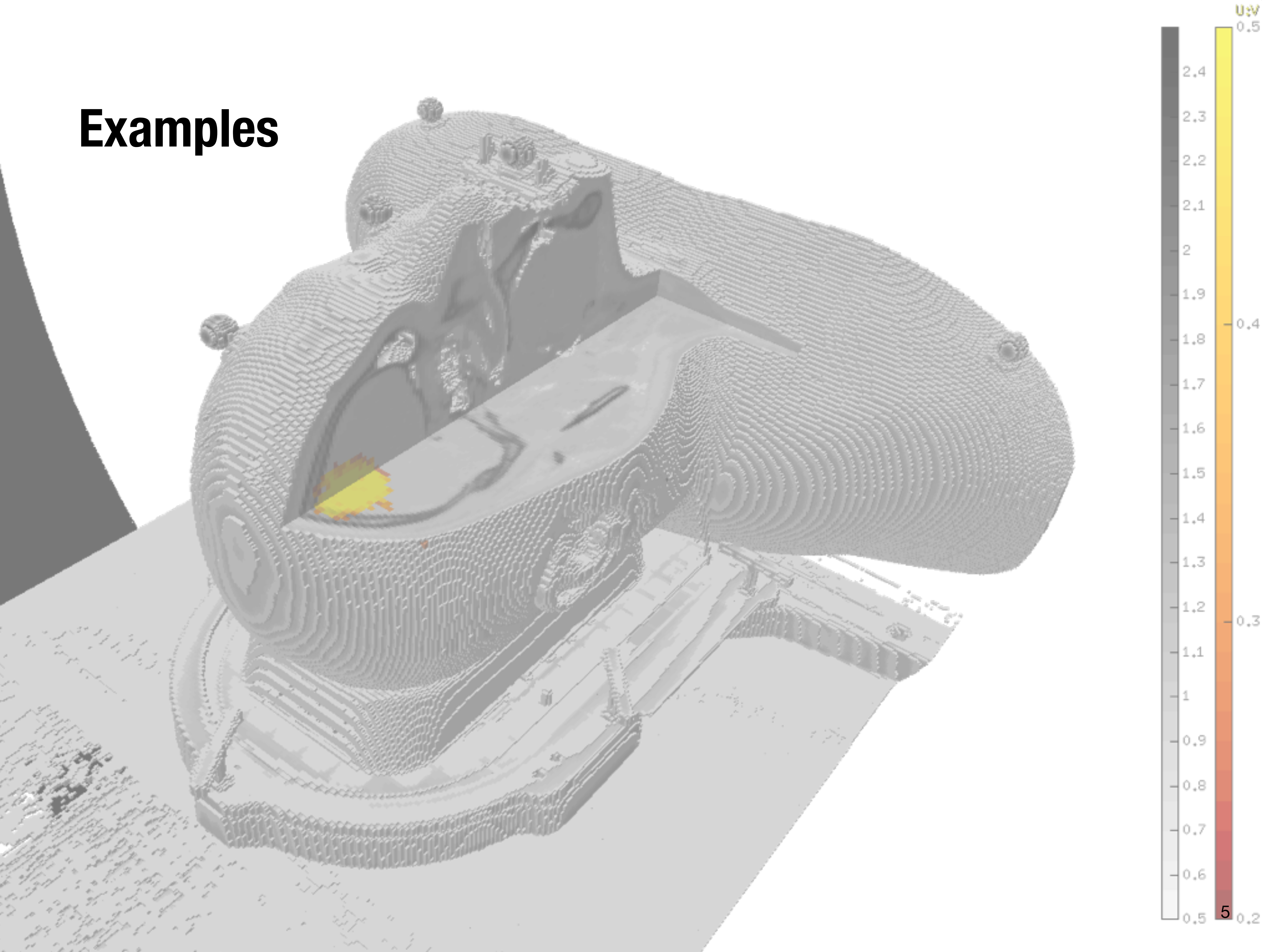
Monte Carlo in Medicine

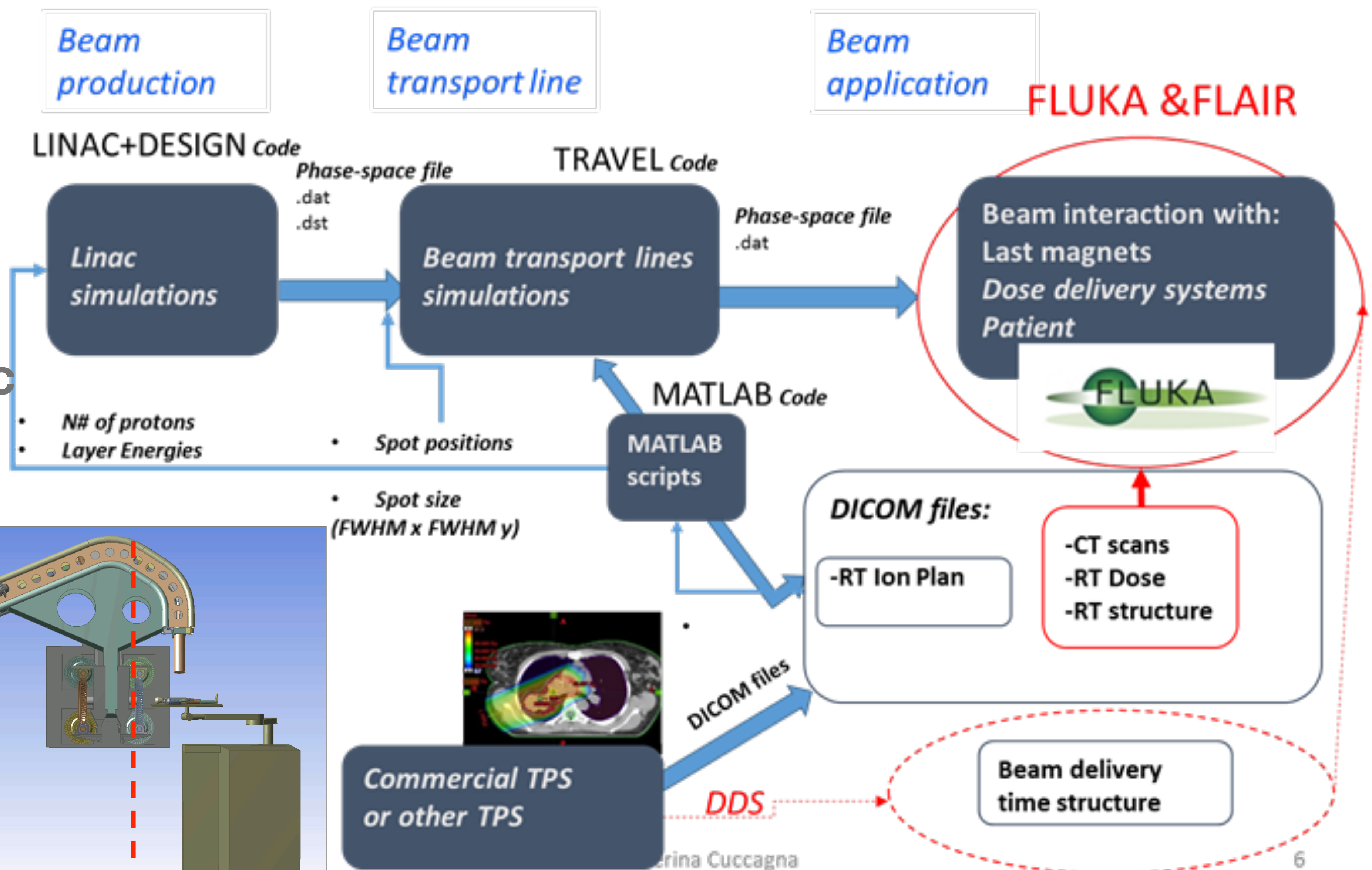
- Faithful consideration of **radiation transport and interactions with matter:**
  - energy losses through collisions with atomic electrons (Bethe- Bloch formula with its corrections)
  - nuclear reactions (i.a. fragmentation tails, other secondary particles..)
  - Multiple Coulomb Scattering (mostly elastic scattering - deflection)
- **Capable of handling all components** of the expected **radiation field**
- **Realistic atomic composition** of the patient tissue, limited by the HU (Hounsfield Unit) to tissue conversion method
- Scoring not only physical dose, but also **RBE (relative biological effective) weighted dose, LET (linear energy transfer)**
- Accurate prediction of **emerging secondaries** for in vivo studies

Monte Carlo Simulations are considered as a gold standard for dosimetric calculations in medical physics, although time is the main issue

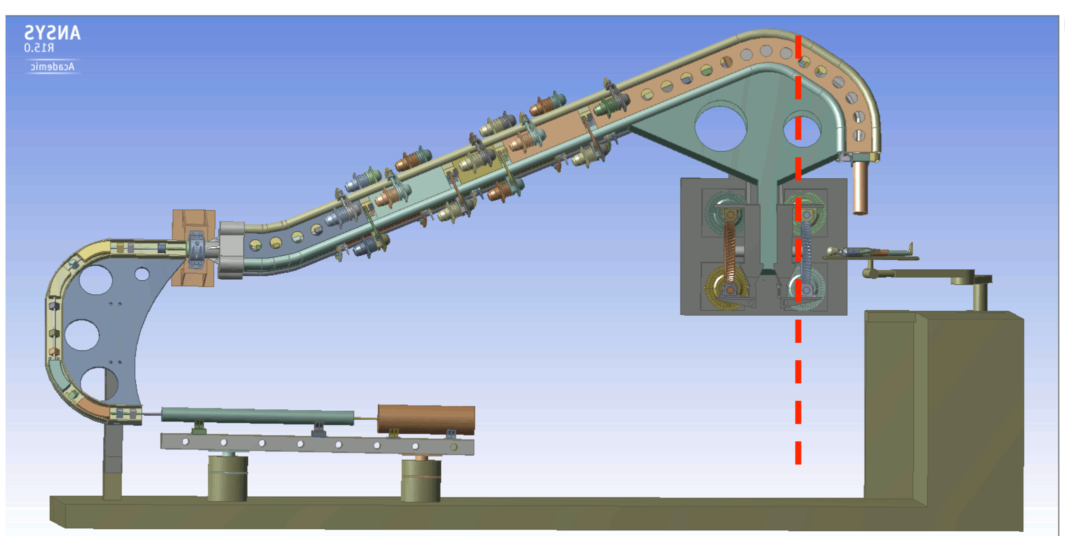
Examples



Full Monte Carlo Simulations for new accelerator complex in Hadrontherapy TERA Foundation



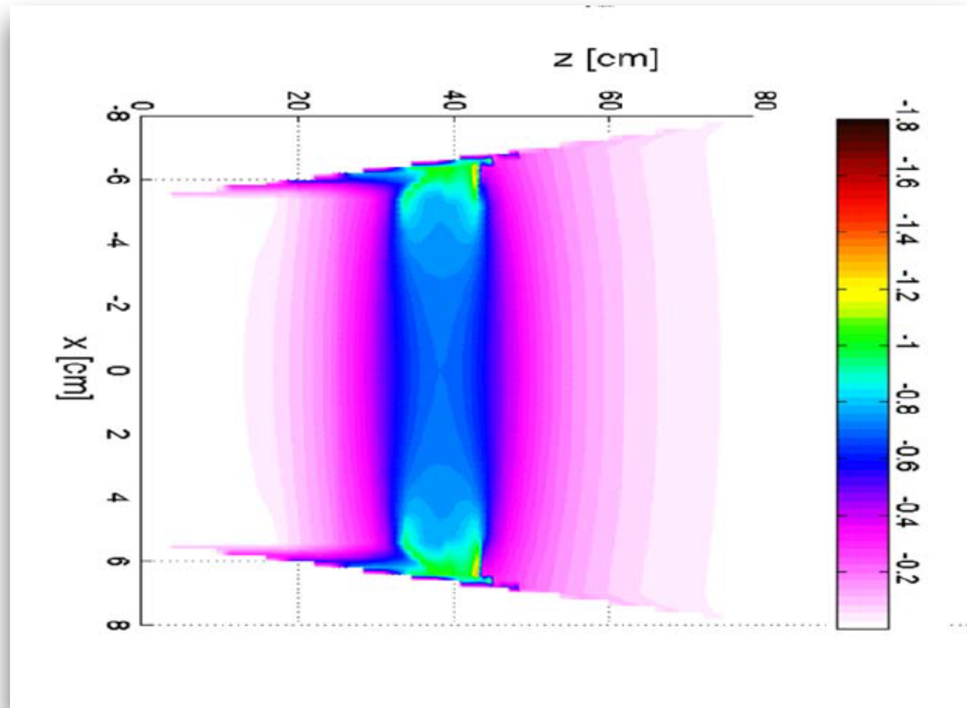
TULIP- TUrning Linac for Protontherapy

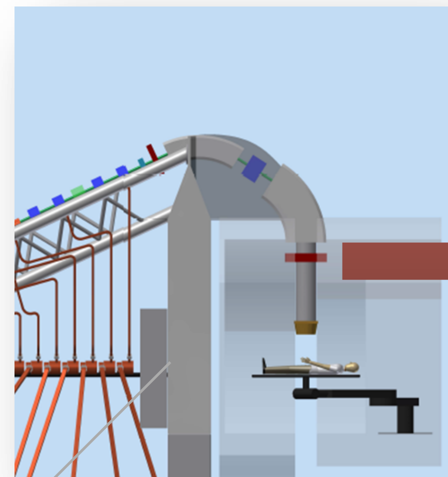


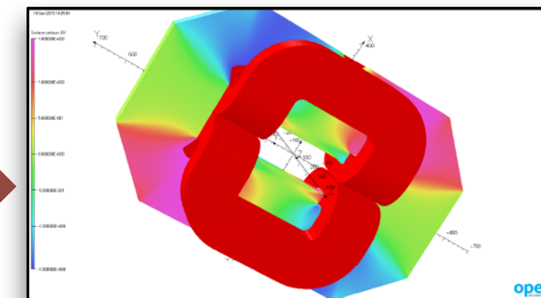
Courtesy of: Caterina Cuccagna (TERA Foundation)

Scanning Magnet Fluka simulation -TERA Foundation

Opera Code

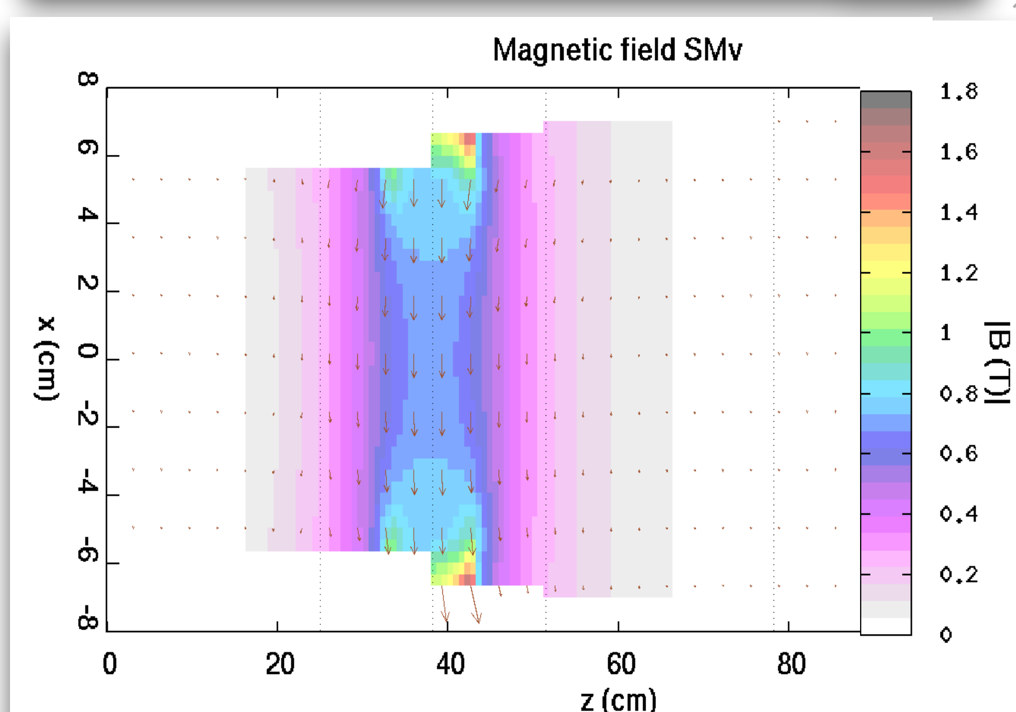


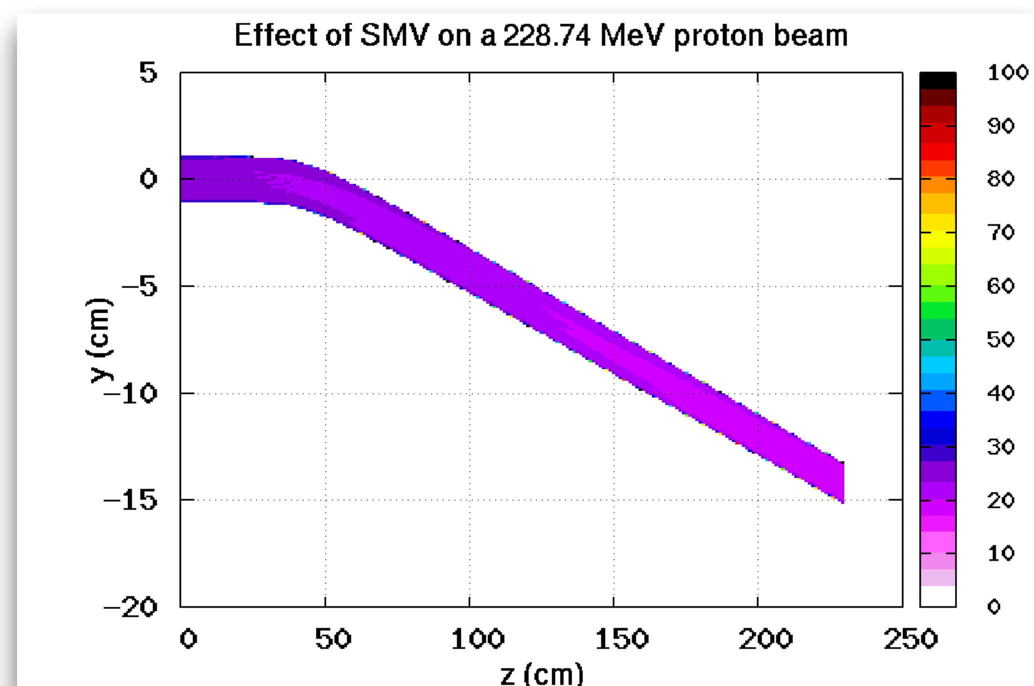




Courtesy of R.Lopez TE-MSC-MNC

FLUKA

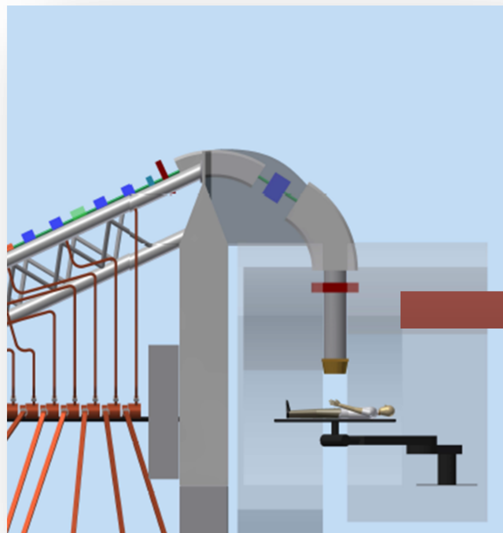


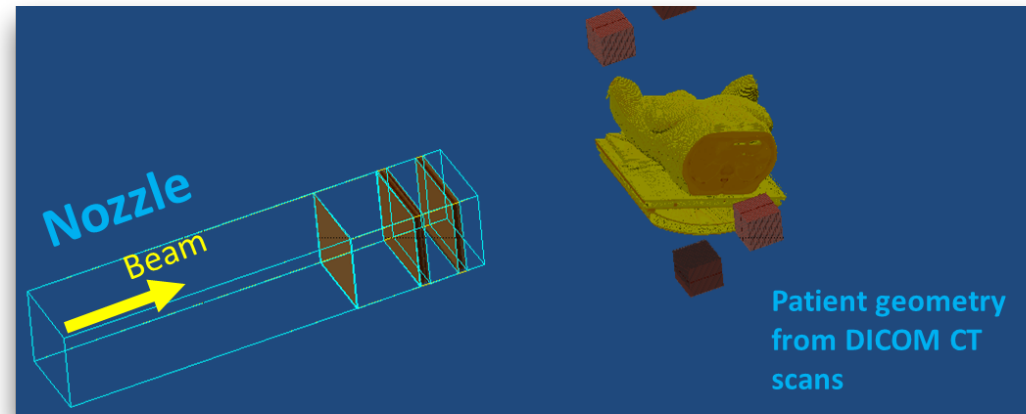


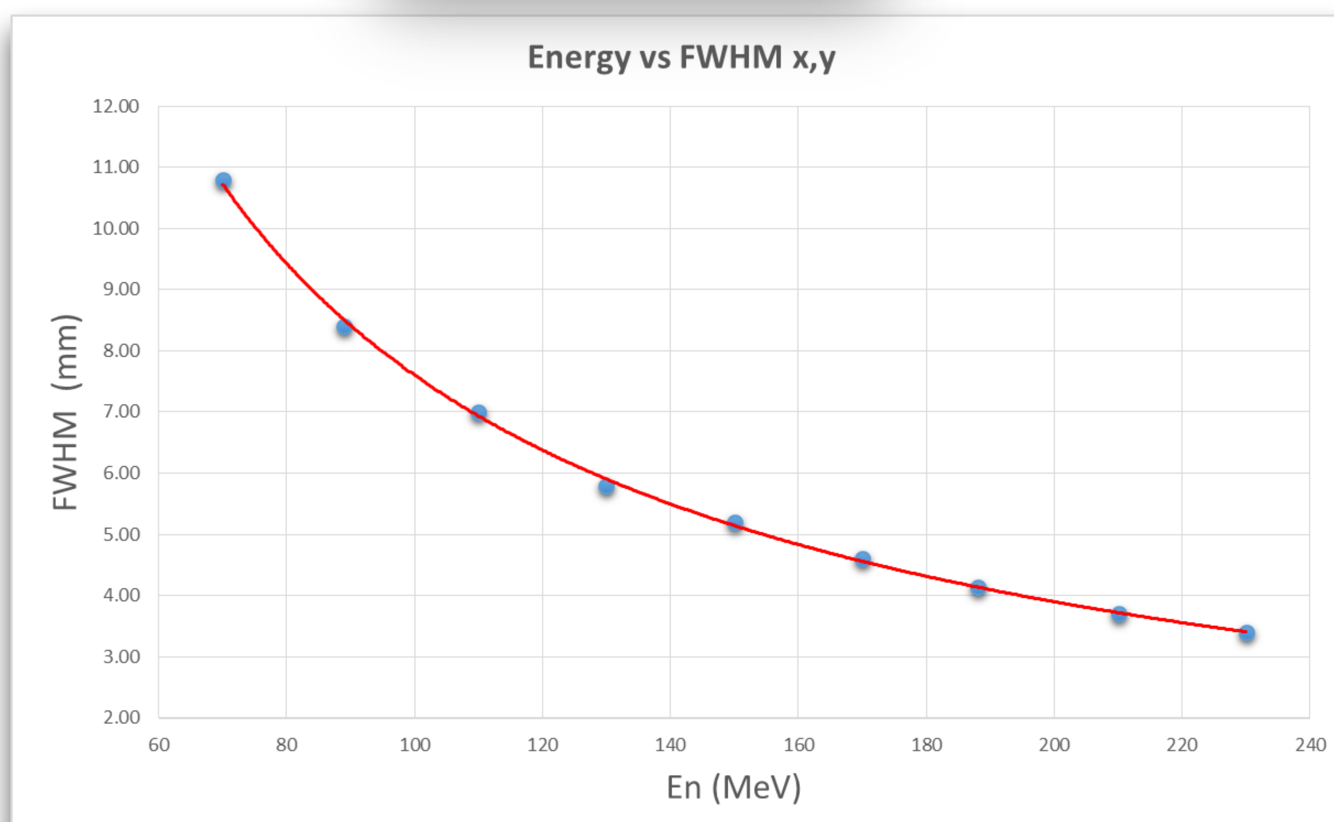
Bending effect on the beam in Fluka

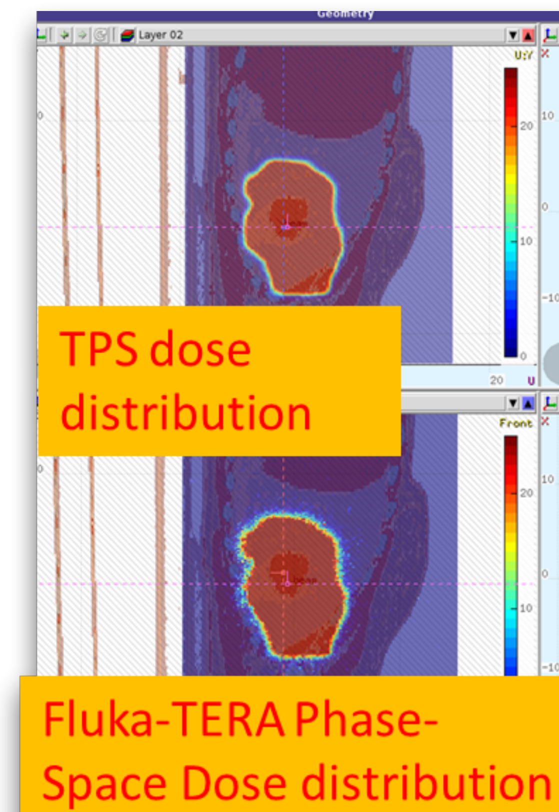
Courtesy of: Caterina Cuccagna (TERA Foundation)

Nozzle simulation - TERA Foundation





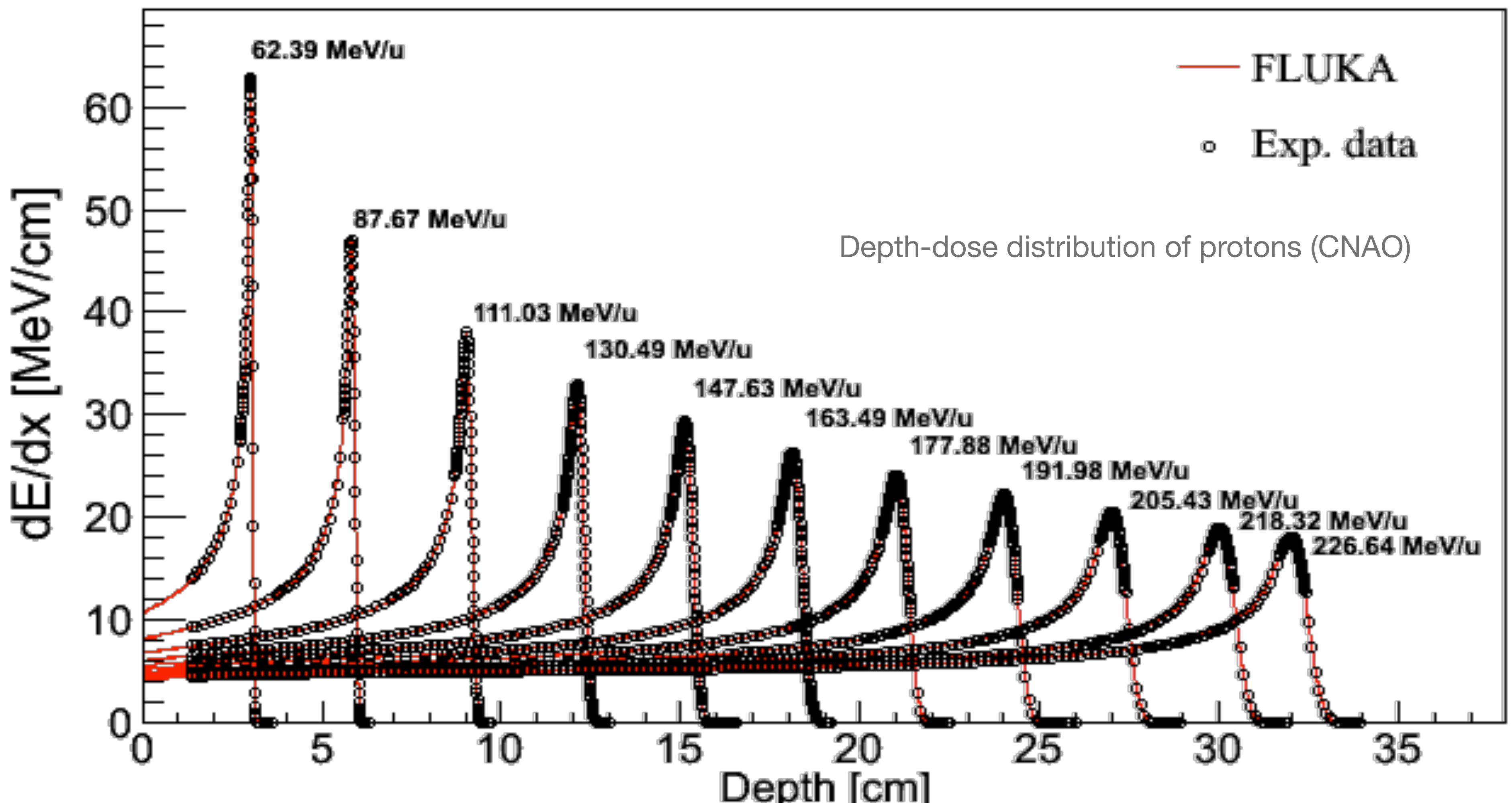




Courtesy of: Caterina Cuccagna (TERA Foundation)

Generating depth-dose distribution of protons (CNAO)

- Generated for TP databases
- In water with/without RiFi for 147 energies

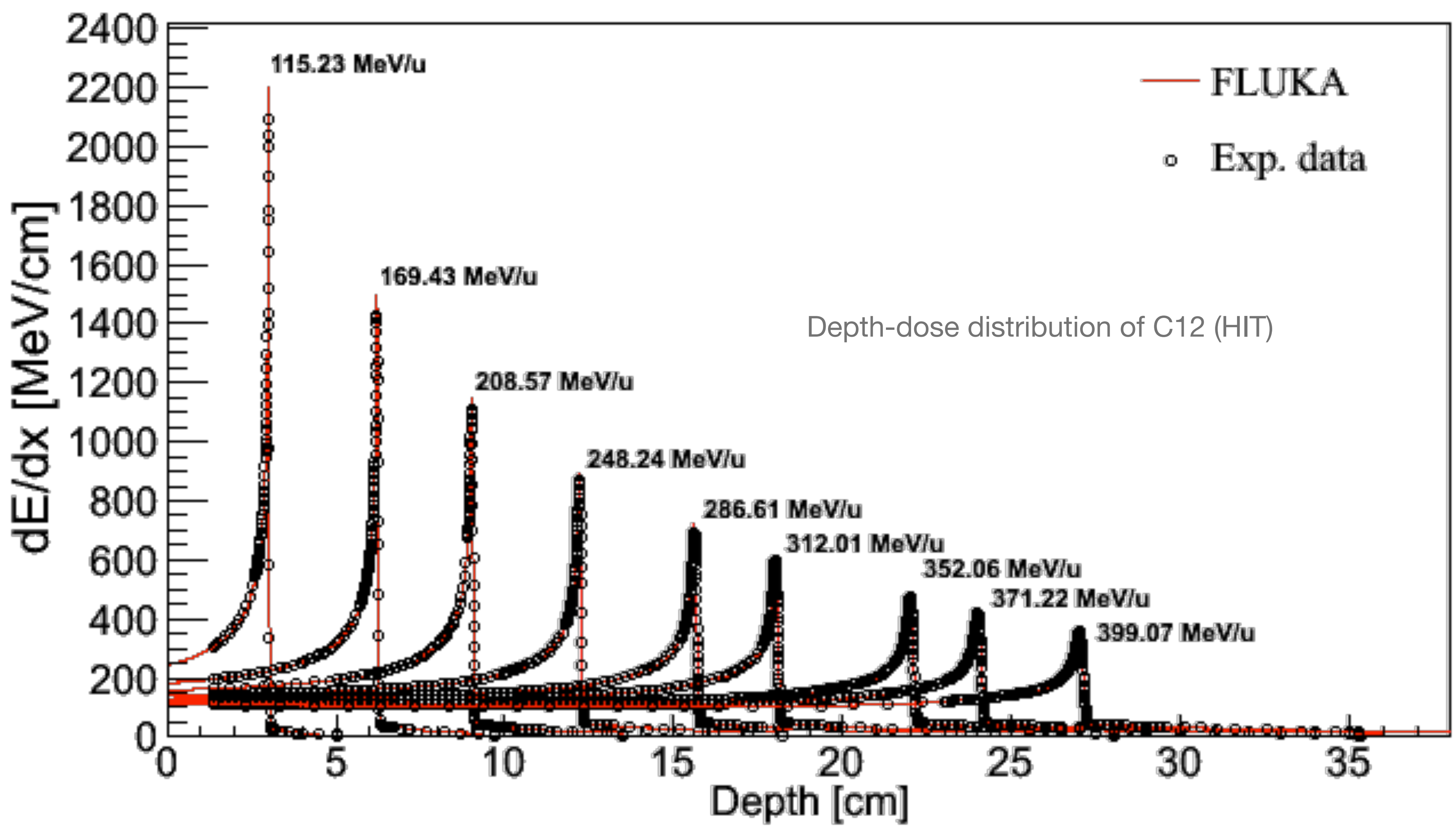


Mairani, Varenna 2012

Courtesy of: Med Phys Group at CNAO

Generating depth-dose distribution of 12C (HIT)

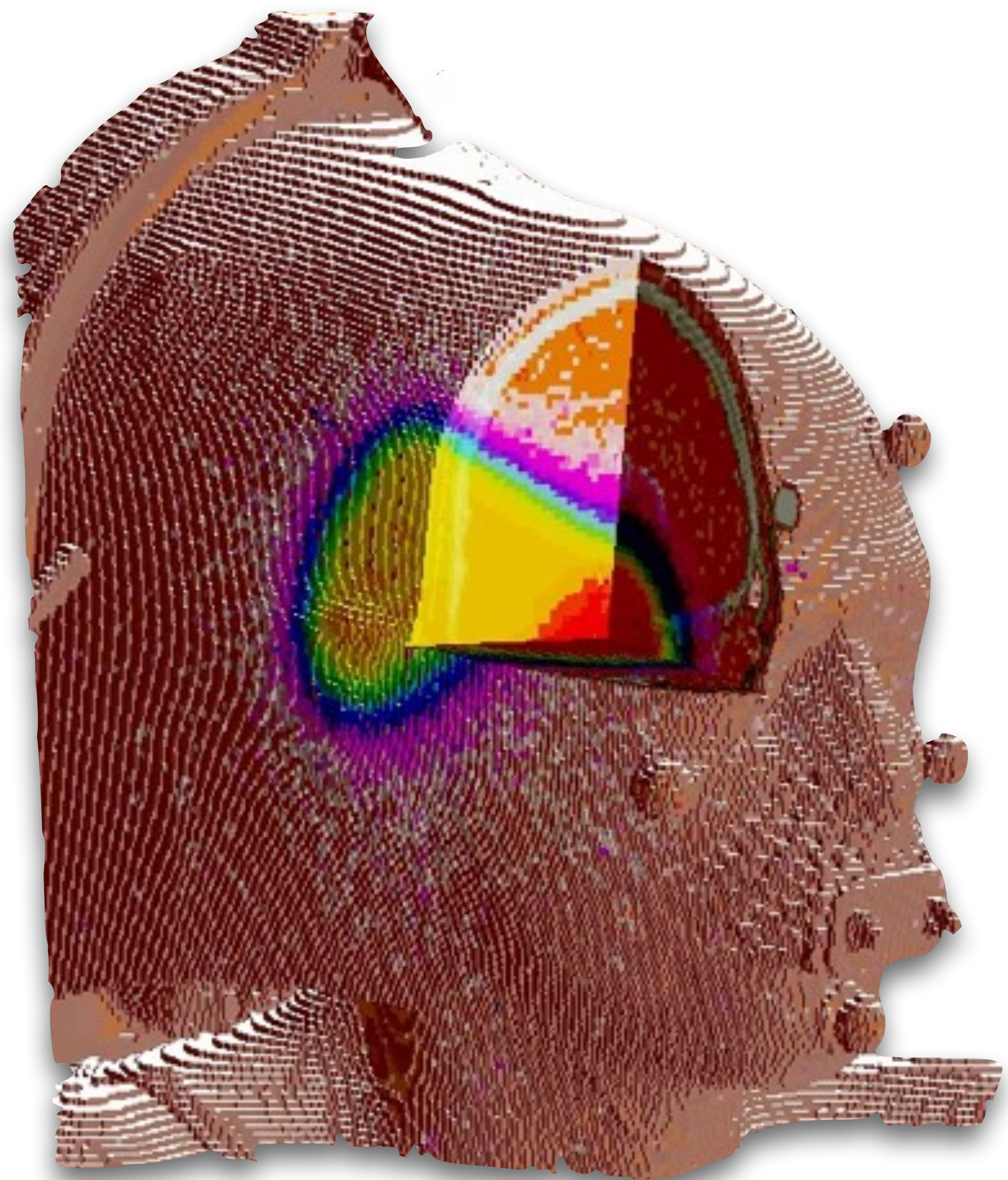
- Generated for TP databases

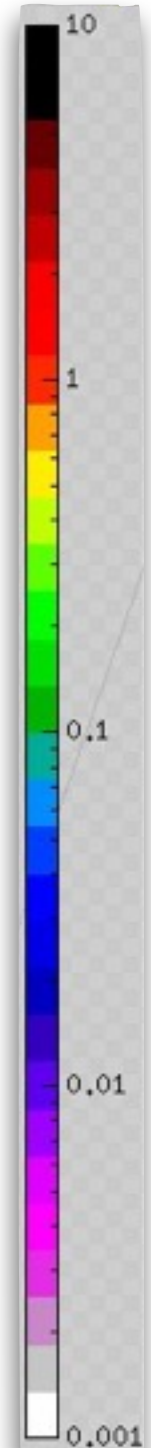


Depth-dose distribution of C12 (HIT)

Courtesy of: Med Phys Group at HIT

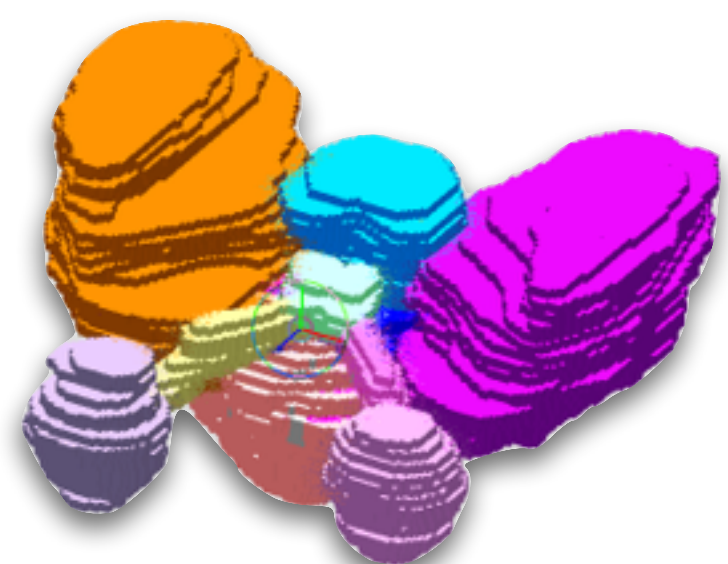
Dose deposition in patient





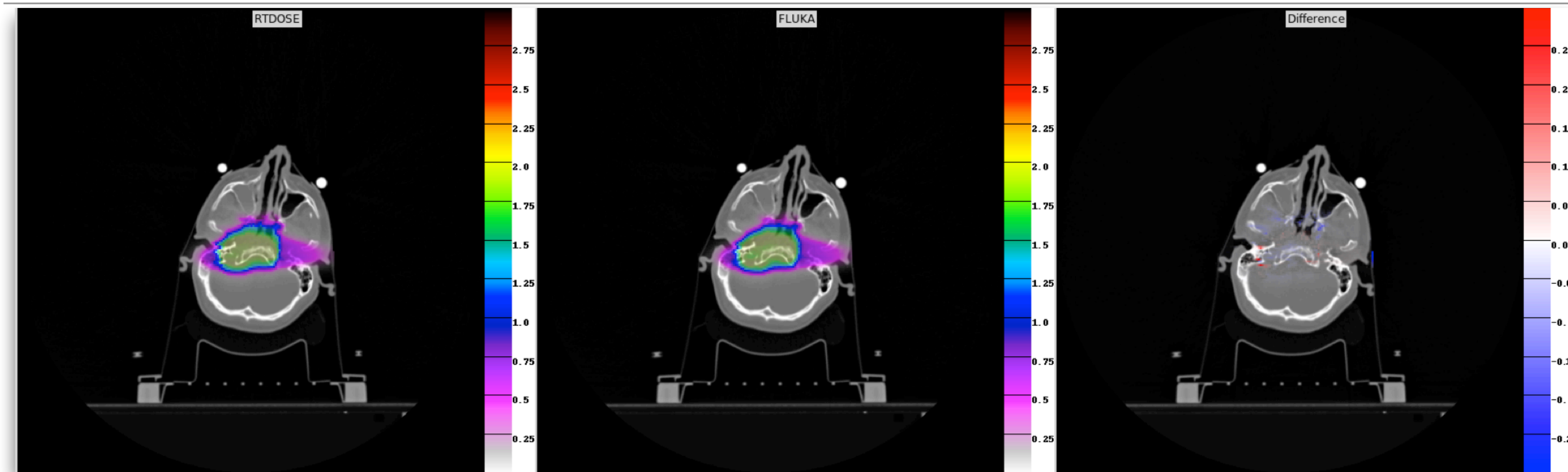
- Provides easy-to use tool for **treatment plan re-simulation** and quantitative comparison
- Enables precise description of patient model and beam delivery system

Regions of interest (ROI)

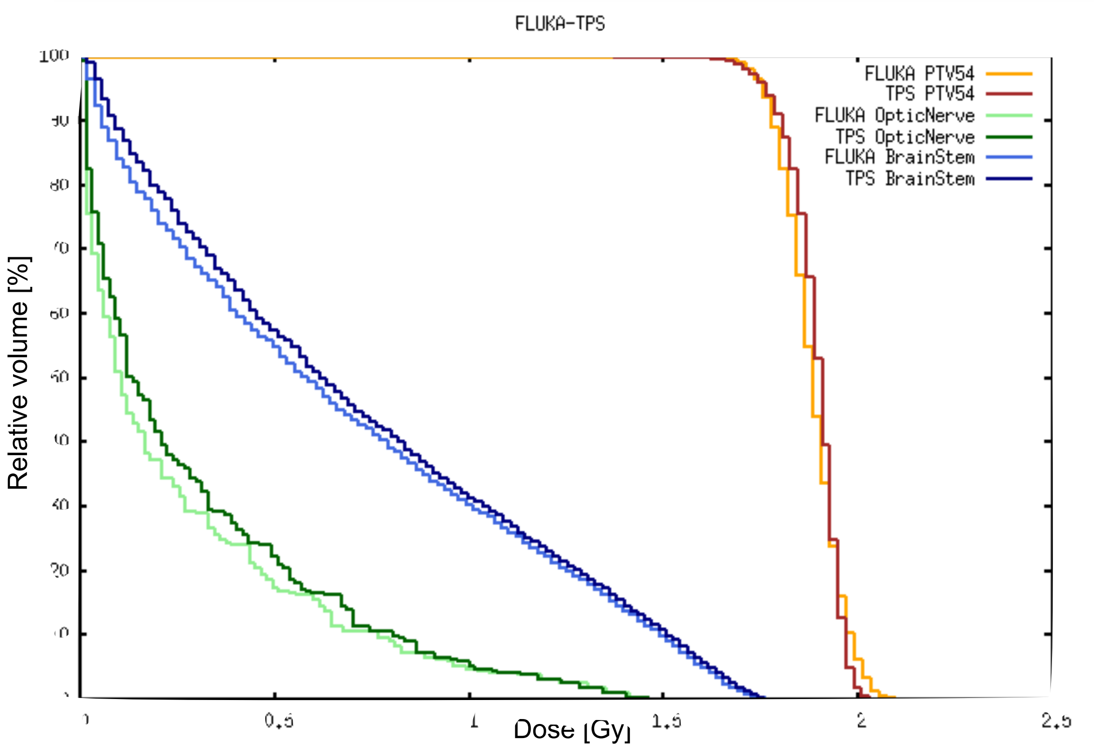


FLUKA and its GUI Flair for Hadrontherapy TPS

Monte Carlo Treatment Plan recalculations for hadrontherapy / sensitivity studies



Proton chordoma patient case (CNAO)



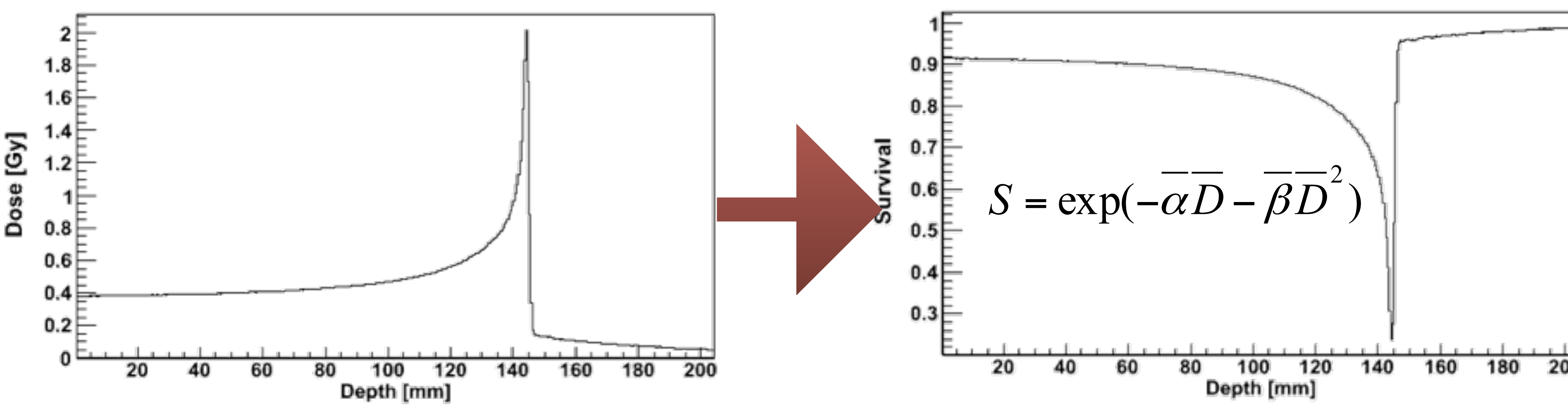
- Calibration of HU to density
- HU to tissue conversion methods
- Ionization potentials of tissue materials
- Accuracy of primary beam description
- Biological dose and LET calculations

Biologically Oriented Scoring

- Under the standard assumption of a **linear-quadratic dose-effect relationship**, for each energy deposition i, FLUKA interpolates from a radiobiological database the αD,i and βD,i parameters for the **specific ion with a certain charge at a certain energy**.
- Then FLUKA **sums up properly the mixed radiation effect applying the Kellerer and Rossi theory** of dual radiation action

Physical dose

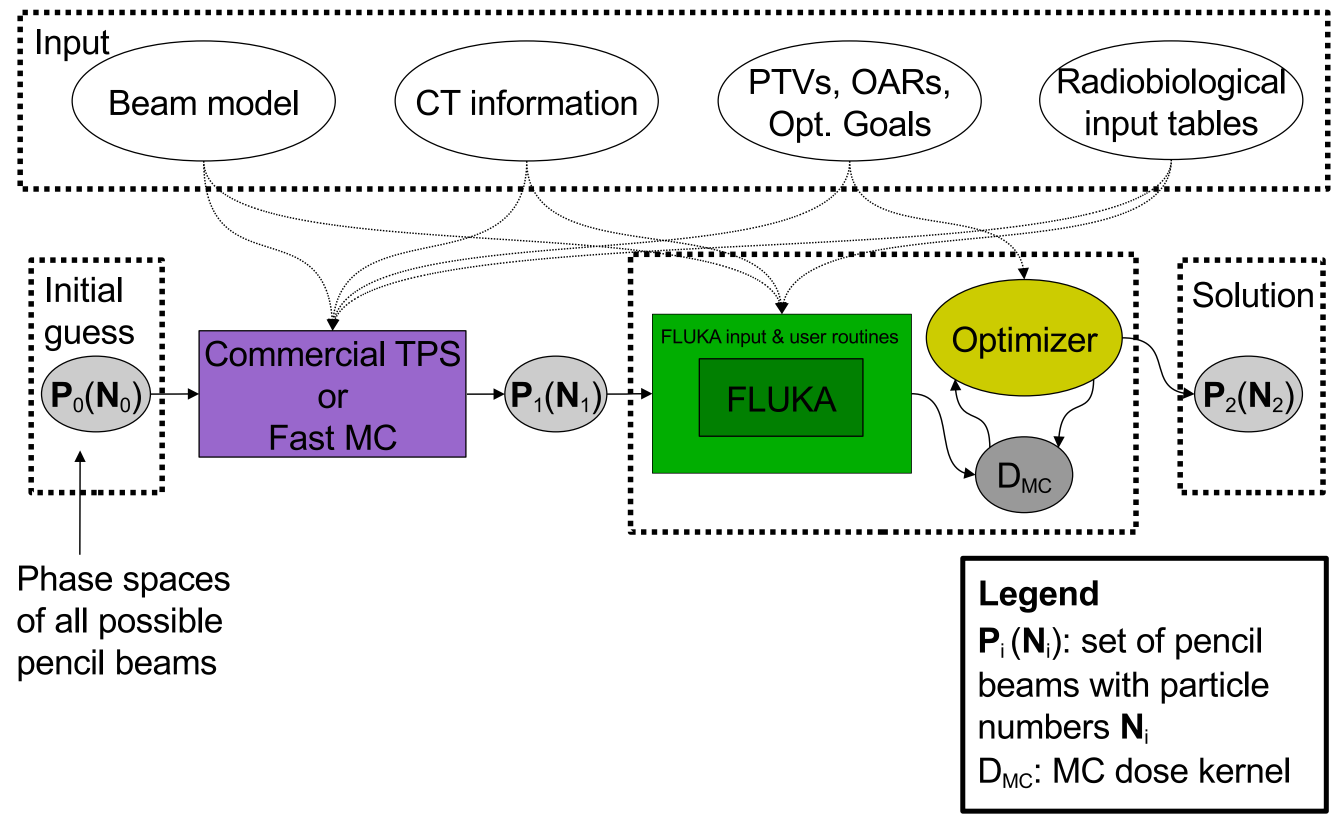
Final result survival curve



270 MeV/u 12C ions on V79 cell line

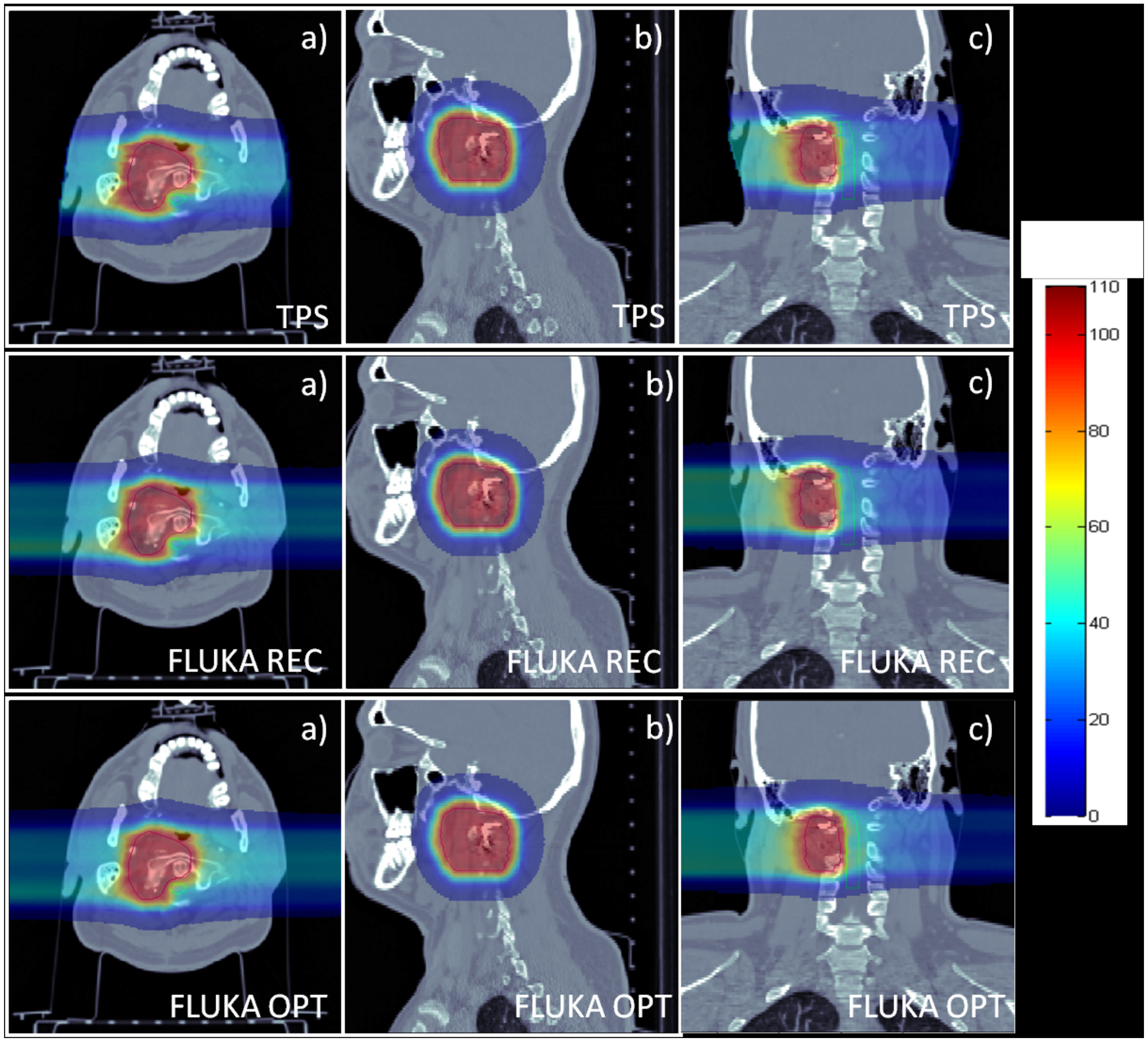
FLUKA based MC Treatment Planing

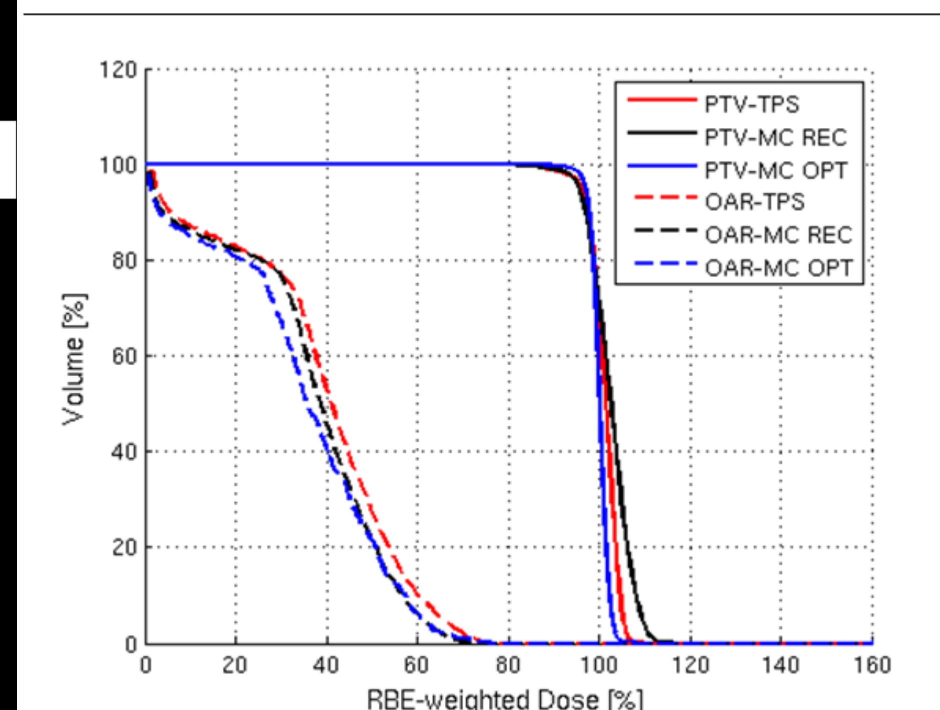
- To **account for geometry and material details and applying realistic treatment conditions** within acceptable CPU time
- To **check a given plan** but also **suggest a better solutions**
- To be used **stand-alone** or as **post re-optimization** of TPS plans
- To be **used in research**: New ions and combined ion fields, testing of new biomodels and algorithms, to predict secondary fluxes



Software architecture of the FLUKA MC TPS [4]

FLUKA based MC Treatment Planing



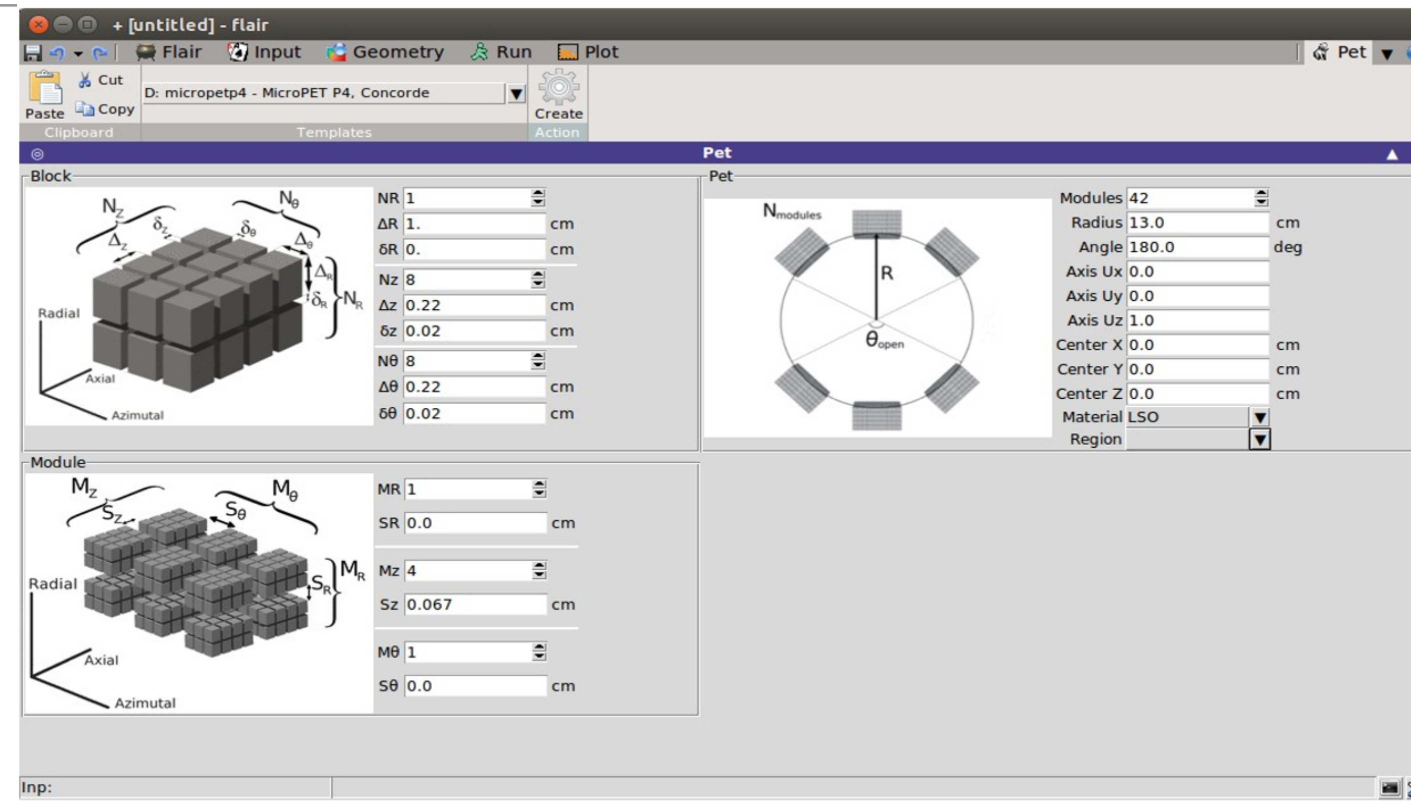


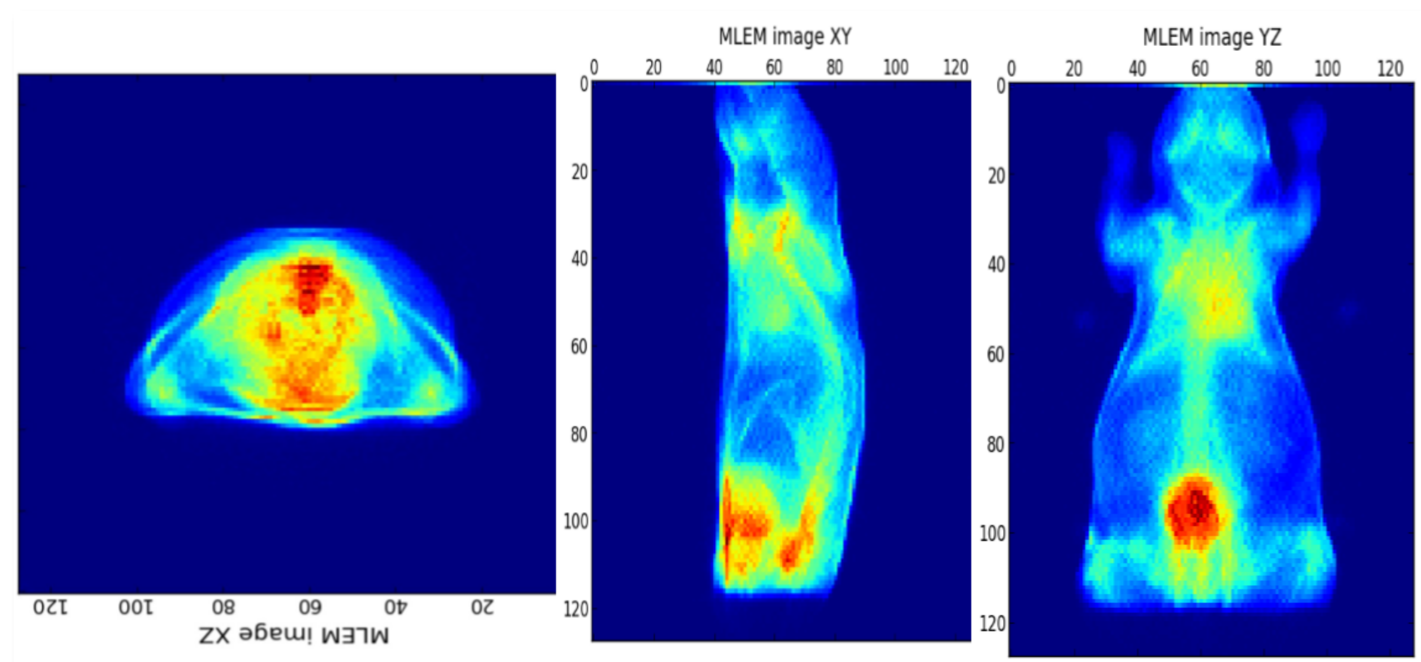
FLUKA RECalculation and FLUKA OPTimization of a proton TP at CNAO[4]

PET simulations

- Incorporated **dedicated PET scanner tool**, covering all steps from PET **ring creation** to the **reconstruction** of the image from coincidence events

- Useful for:
    - Inferring the dose map from the β+ emitter distribution
    - New PET design

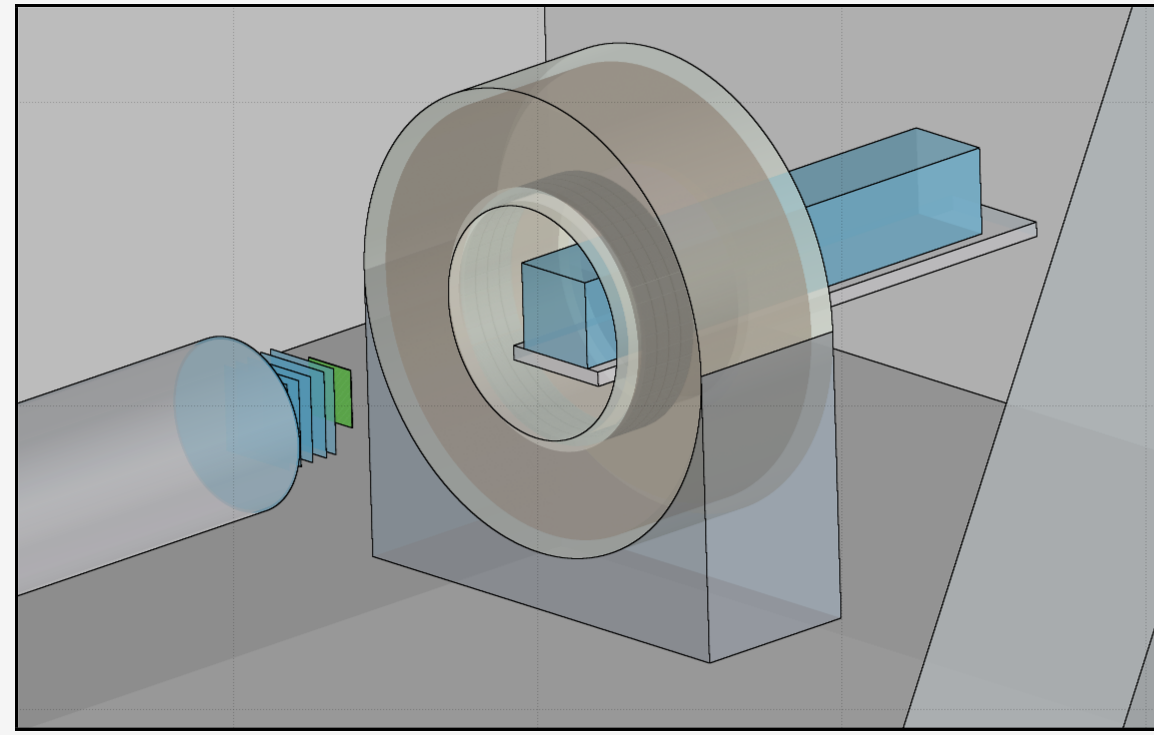




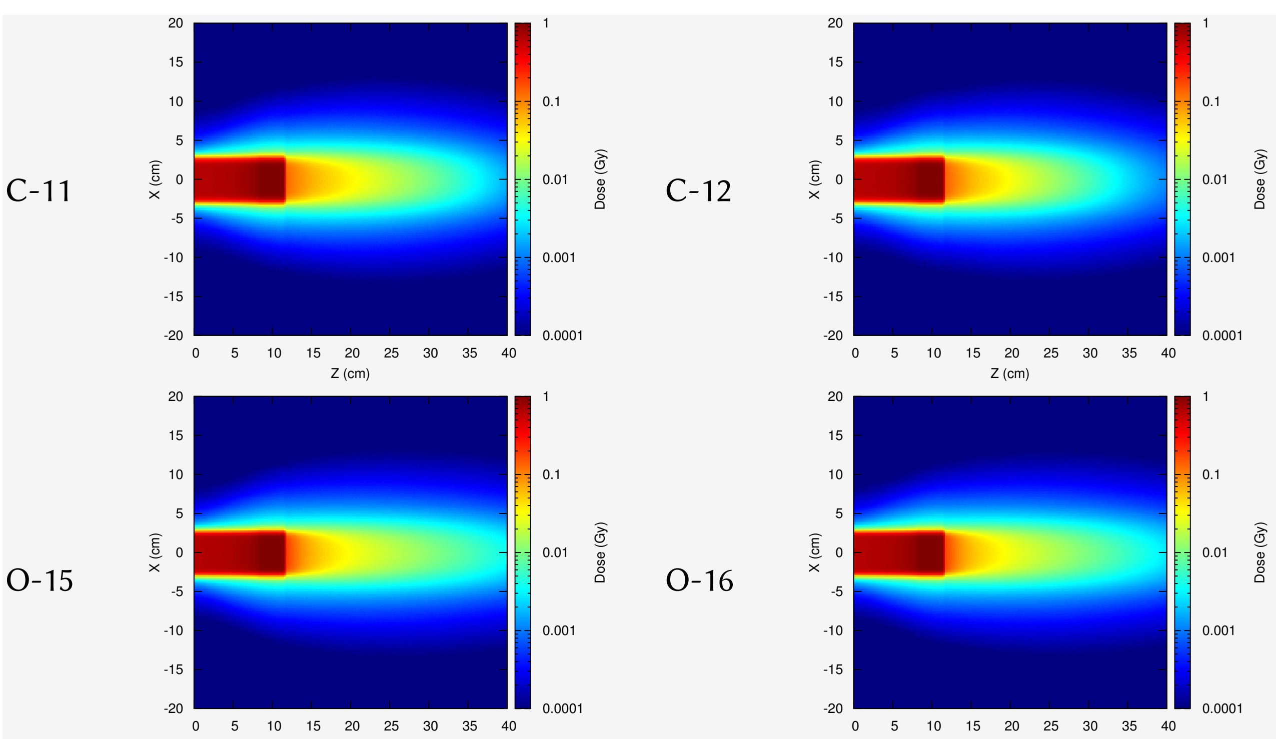
Courtesy of: Pablo Garcia Ortega (Universidad de Valencia, Institut de Fisica Corpuscular)

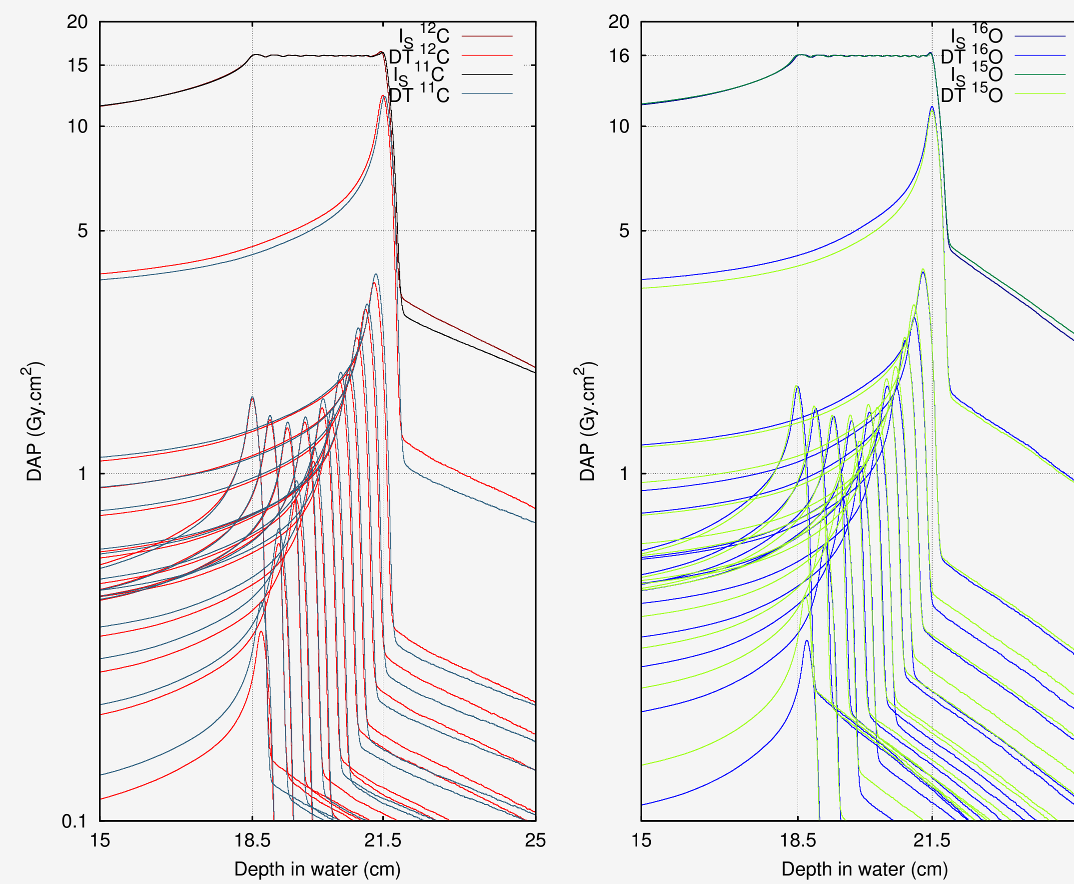
Radioactive ion Beams in Clinical Scenarios

- Studies in water with different ions, under realistic (HIT) conditions:
- Almost equivalent dosimetric performance. **Radioactive ion beam can be a valid alternative**



Disentaglement of different Pristine Bragg Peaks (DT) from simulated (I_S) SOBP.



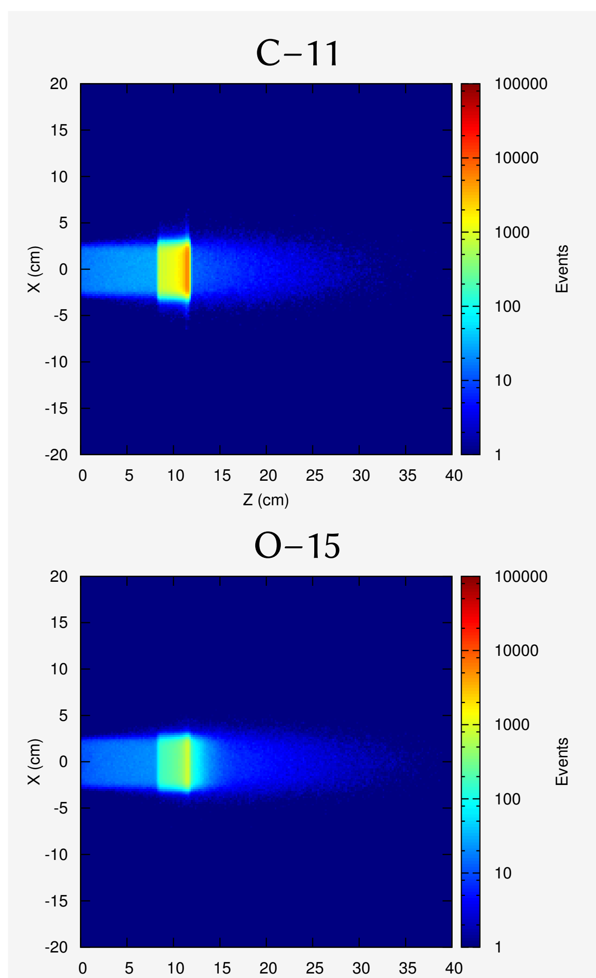


Courtesy of: Ricardo dos Santos Augusto (CERN/LMU)

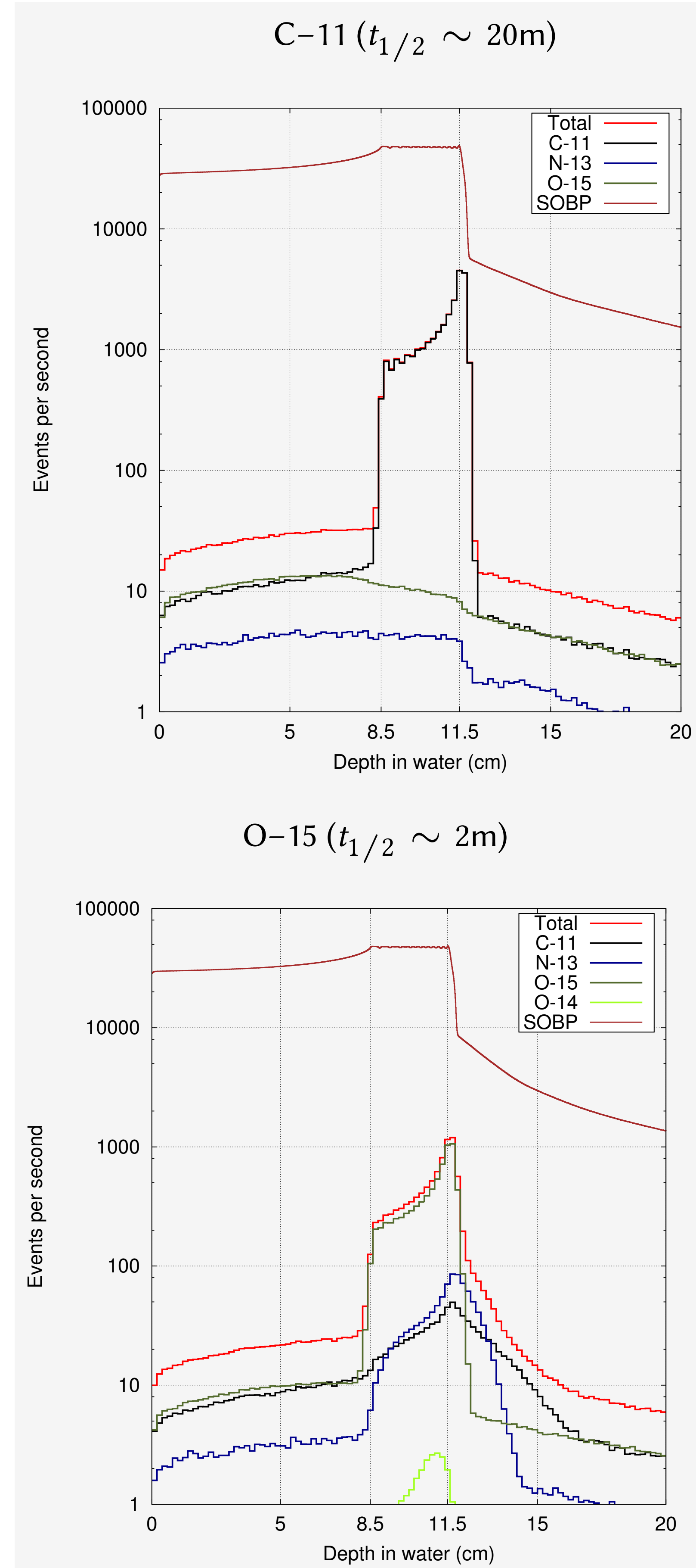
Imaging potential and parent isotope study

- Different RIB have **different imaging potentialities**, depending of their **half-life and the half life of produced fragments**

Annihilation Events at Rest, 12 minutes End-of-Beam



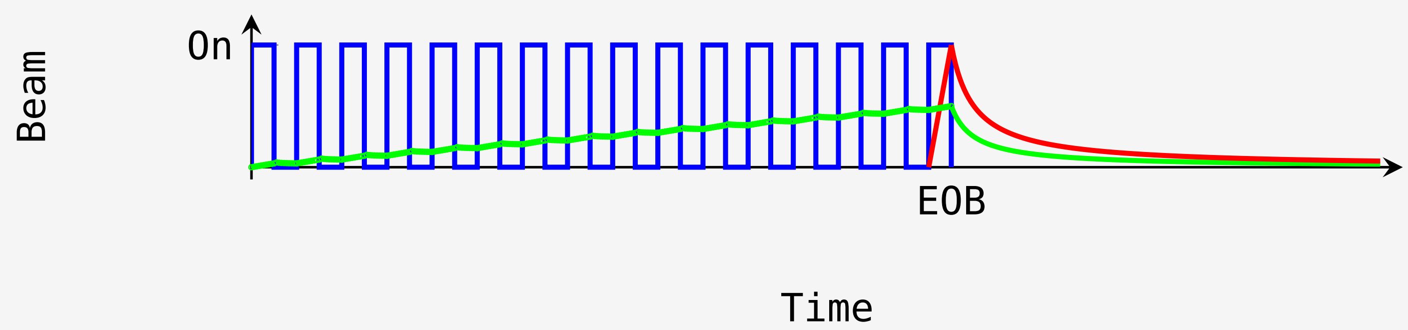
Parent isotope contribution to the overall Annihilation Events' rate



Courtesy of: Ricardo dos Santos Augusto (CERN/LMU)

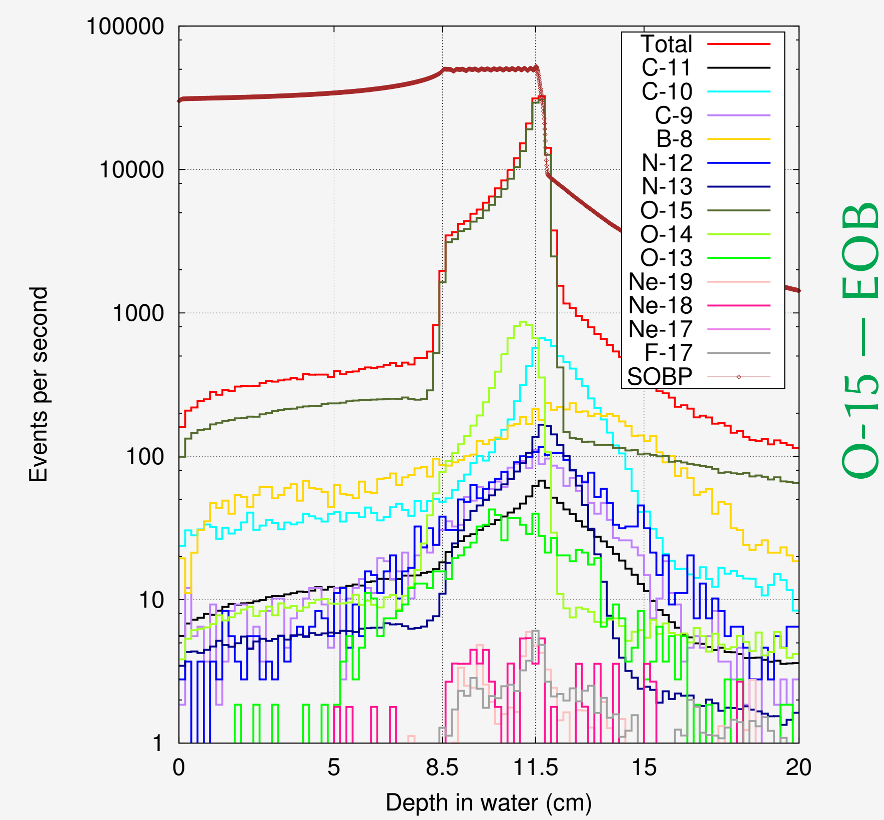
Accounting for the beam time structure

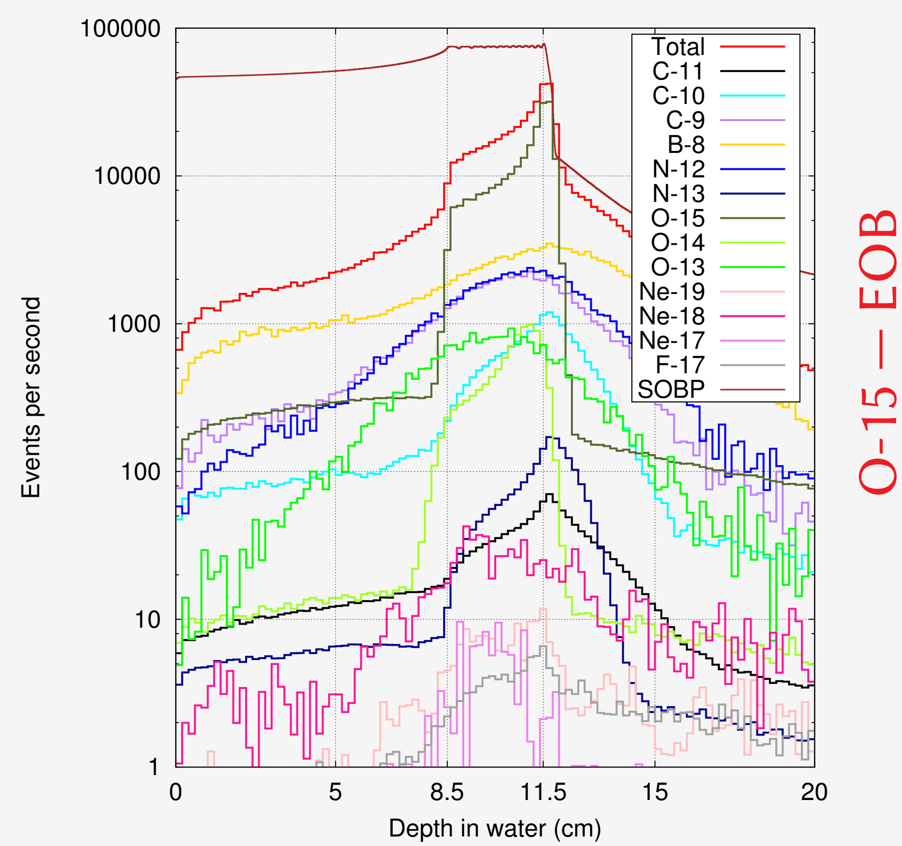
- It is essential to account for the **decay impact during beam time**:



Note: The diagram above is only a scheme and is *NOT* numerically accurate.

- Ongoing work on quantifying imaging based on the **realistic (HIT) irradiation** & PET models





Courtesy of: Ricardo dos Santos Augusto (CERN/LMU)

Summary

Ongoing work:

- Ion fragmentation (also space radiation)
- Very light "special" ions: 3He, α, 6Li, 7Li, develop/check the nuclear model physics
- Different radiobiological parameters/models (eg health tissue/tumor)
- Monte Carlo based TPS
- Direct scoring on Region-Of-Interest
- In-beam PET for Radioactive Ion Beams
- (Software) acceleration techniques

Questions?

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- [1] Böhlen, T. T., Cerutti, F., Chin, M. P. W., Fassò, A., Ferrari, A., Ortega, P. G., Mairani, A., Sala, P. R.,Smirnov, G., Vlachoudis, V. (2014). *The FLUKA Code: Developments and challenges for high energy and medical applications*. Nuclear Data Sheets, 120, 211-214

- [2] Ferrari, A., Sala, P. R., Fasso, A., & Ranft, J. (2005). *FLUKA: A Multi-Particle Transport Code*. CERN 2005-10 (2005), INFN/TC_05/11, SLAC-R-773

- [3] Vlachoudis, V. (2009). *FLAIR: A Powerful But User Friendly Graphical Interface For FLUKA*. Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York

- [4] Mairani, A., Böhlen, T. T., Schiavi, A., Tessonnier, T., Molinelli, S., Brons, S., Battistoni, G.,Parodi K., Patera, V. (2013). *A Monte Carlo-based treatment planning tool for proton therapy*. Physics in Medicine and Biology, *58*(8), 2471–2490

- [5] Battistoni, G., Bauer, J., Böhlen, T. T., Cerutti, F., Chin, M. P. W., Dos Santos Augusto, R., Ferrari, A., Ortega, P. G., Kozlowska, W., Magro G., Mairani A., Parodi K., Sala P. R., Schoofs P., Tessonnier T., Vlachoudis, V. (2016). *The FLUKA Code: An Accurate Simulation Tool for Particle Therapy.* Frontiers in Oncology, 6.