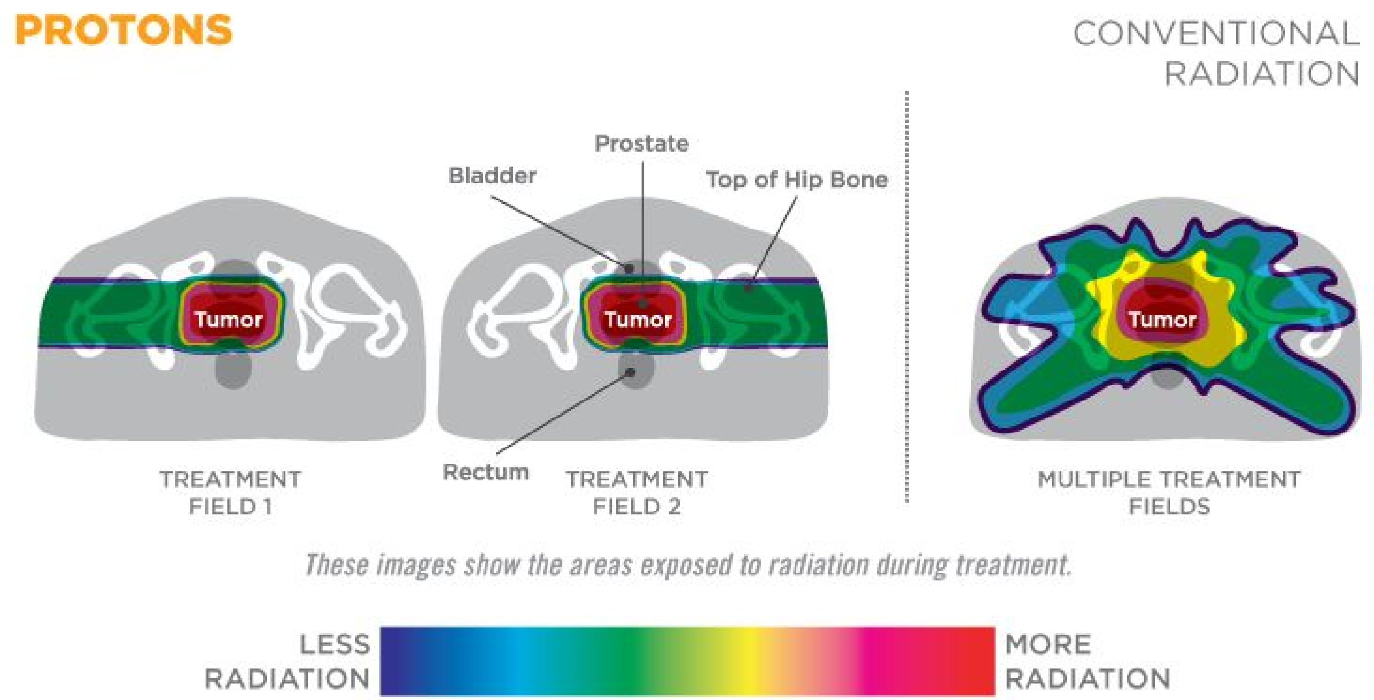
Towards efficient and accurate particle transport simulation in medical applications

L. Grzanka[1,2], M. Kłodowska[1], N. Mojżeszek[1], N. Bassler[3]
[1] Cyclotron Centre Bronowice, Institute of Nuclear Physics (IFJ PAN), Kraków, Poland,
[2] AGH University of Science and Technology, Kraków, Poland,
[3] Stockholm University, Stockholm, Sweden

Leszek.Grzanka@ifj.edu.pl 2017.03.10

Cancer and radiotherapy



- New and innovative technique
- Rare (1 center in Poland)
- <200 patients per year
- Proton beam generated by cyclotron - large facility
- No exit-beam, more healthy tissue spared
- More complexity in physics of the beam

- Long history
- Popular (~120 accelerators)
- ~70000 patients per year
- Beam of X-rays, compact linear accelerator in use
- Simpler physics involved

Proton therapy is booming

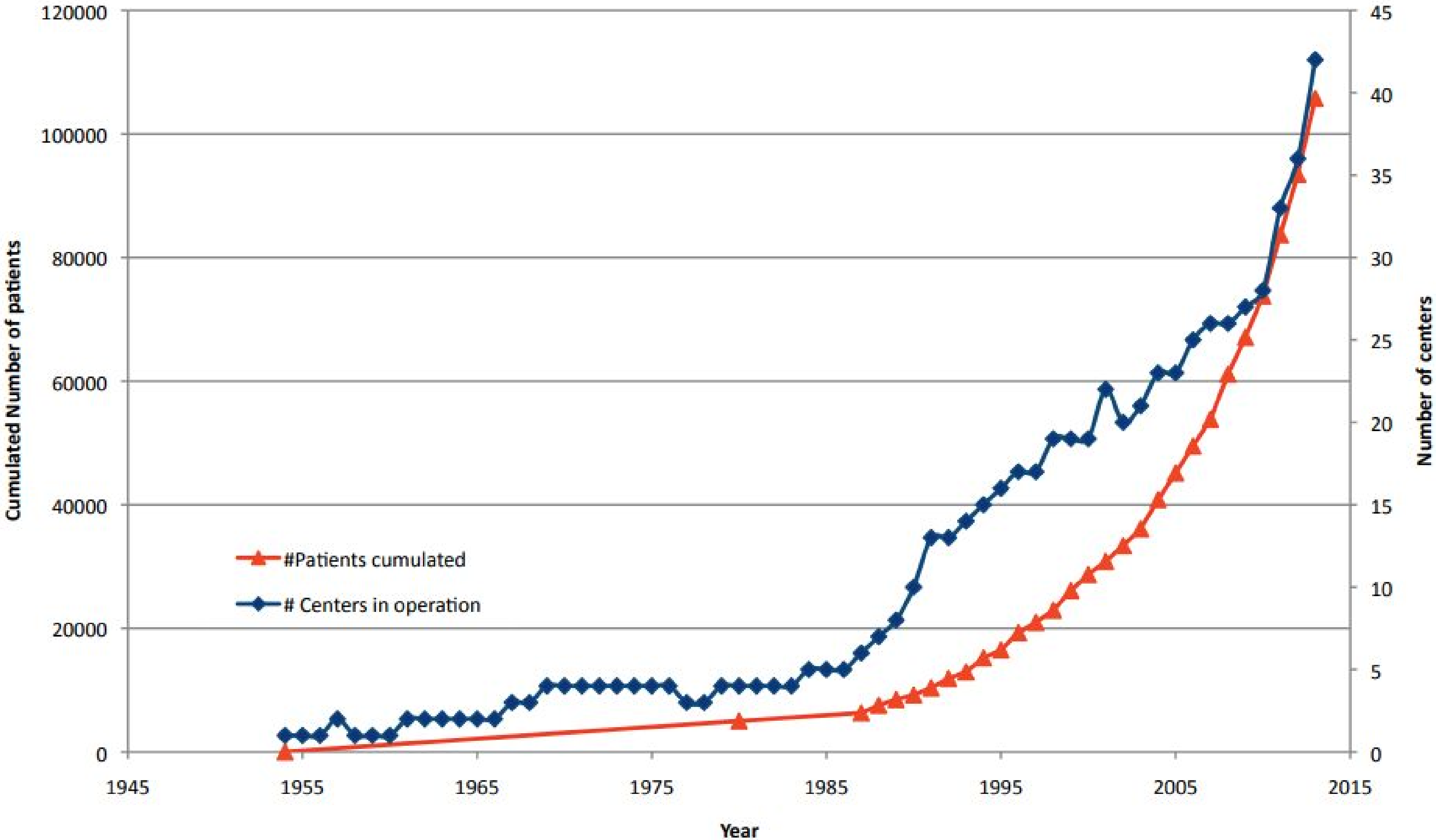
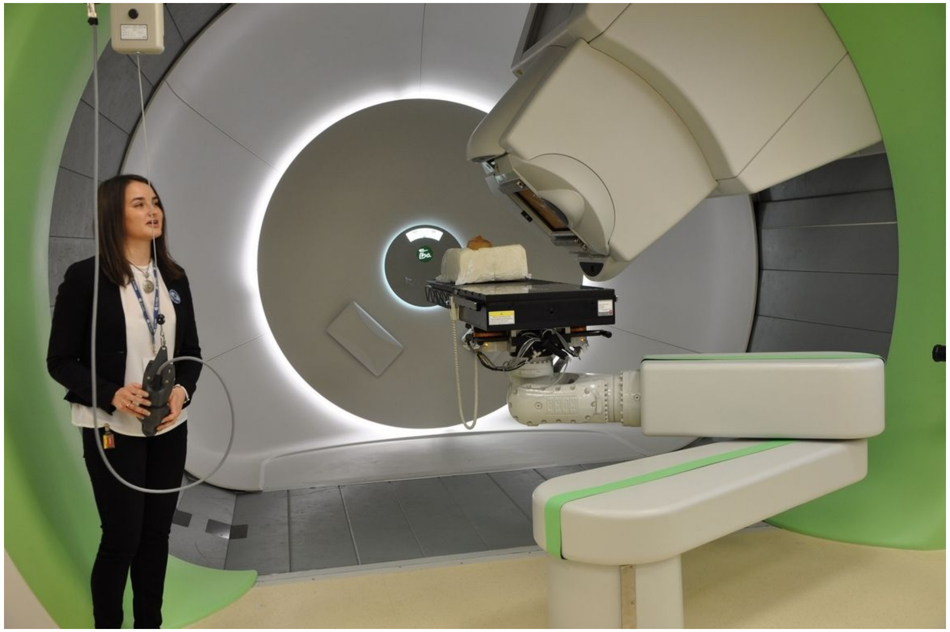


Figure 1.1: Graph representing the evolution of proton therapy centers under clinical operation and the cumulated number of patients treated using proton therapy (Source: PTCOG Website)

Cyclotron Center Bronowice in Krakow



1990 - proton therapy plans

2009 - CCB project starts

2011 - first patients with eye tumors

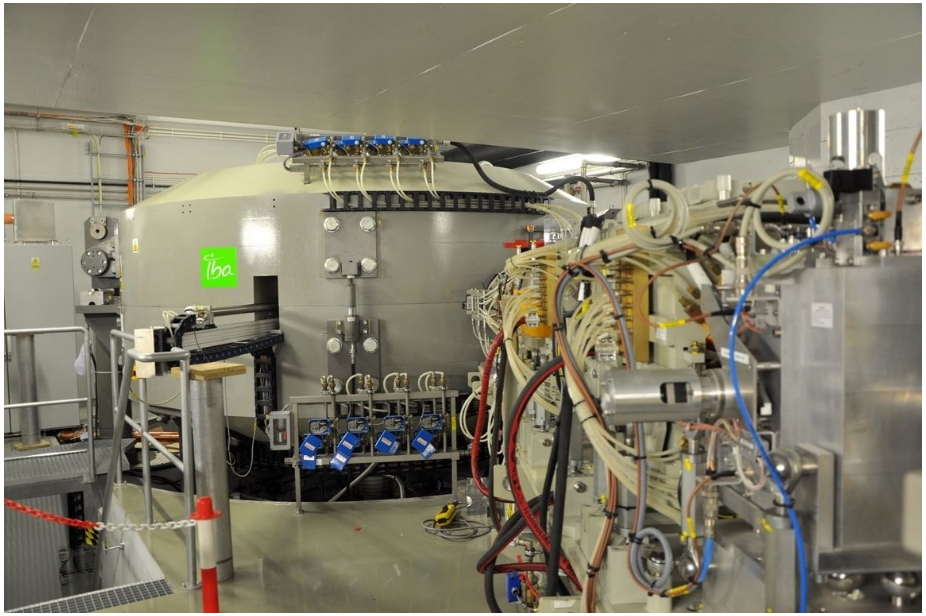
2012 - new cyclotron and building

2016 - first patient treated on gantry

Robotic gantry rotates around the patient

Cyclotron delivers beam of protons with
max energy 230 MeV
(~30 cm range in water)

CCB: patient treatments, experimental
physics research, applied physics

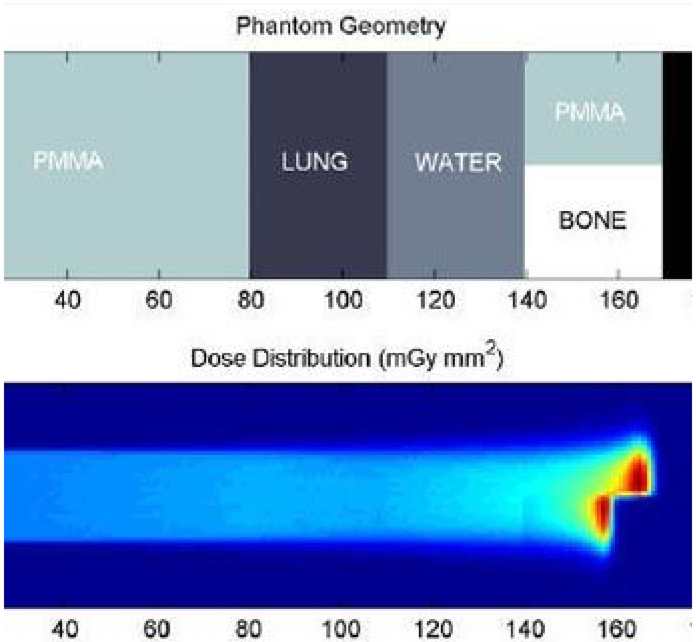


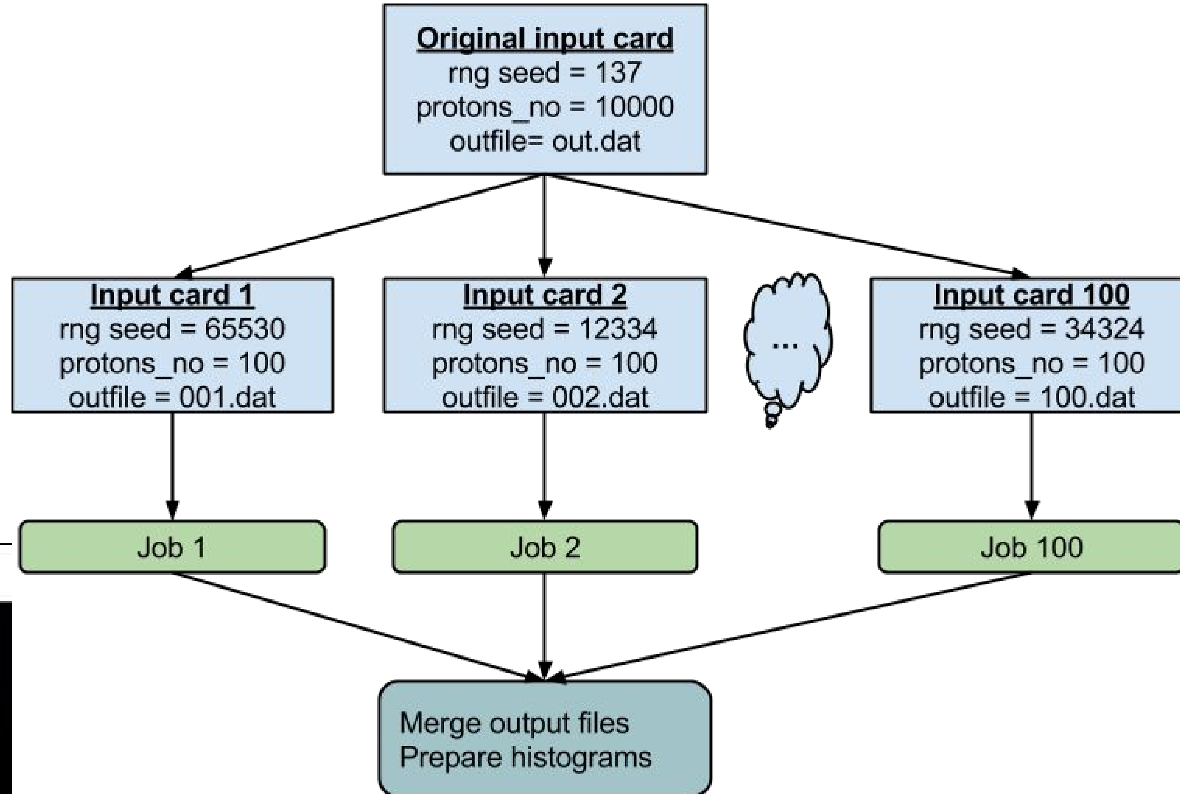
Monte Carlo Simulation of a proton beam

Aim:
simulate proton beam:
- dose spatial distribution
- complex (patient) geometry

Tools:
Monte Carlo transport codes:
- Fluka 2011.2
- Geant4.96

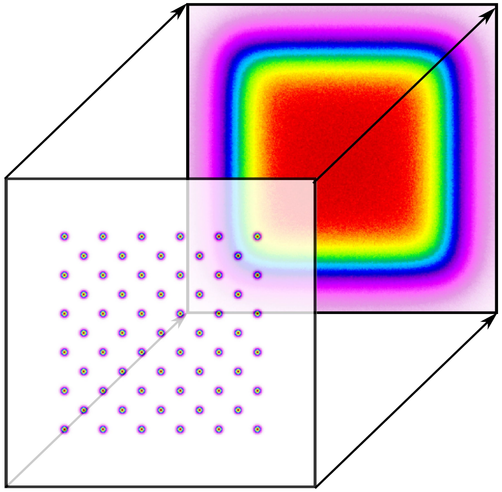
Time consuming simulation of particle interactions with matter





(Embarrassingly) parallelization - procedure

Proton microbeam radiotherapy



- New concept: broad beam filtered by slits.
  Close to skin damage in narrow channels - benefit from dose-volume effect.
  Beam scattering with depth.

- FLUKA MC code:

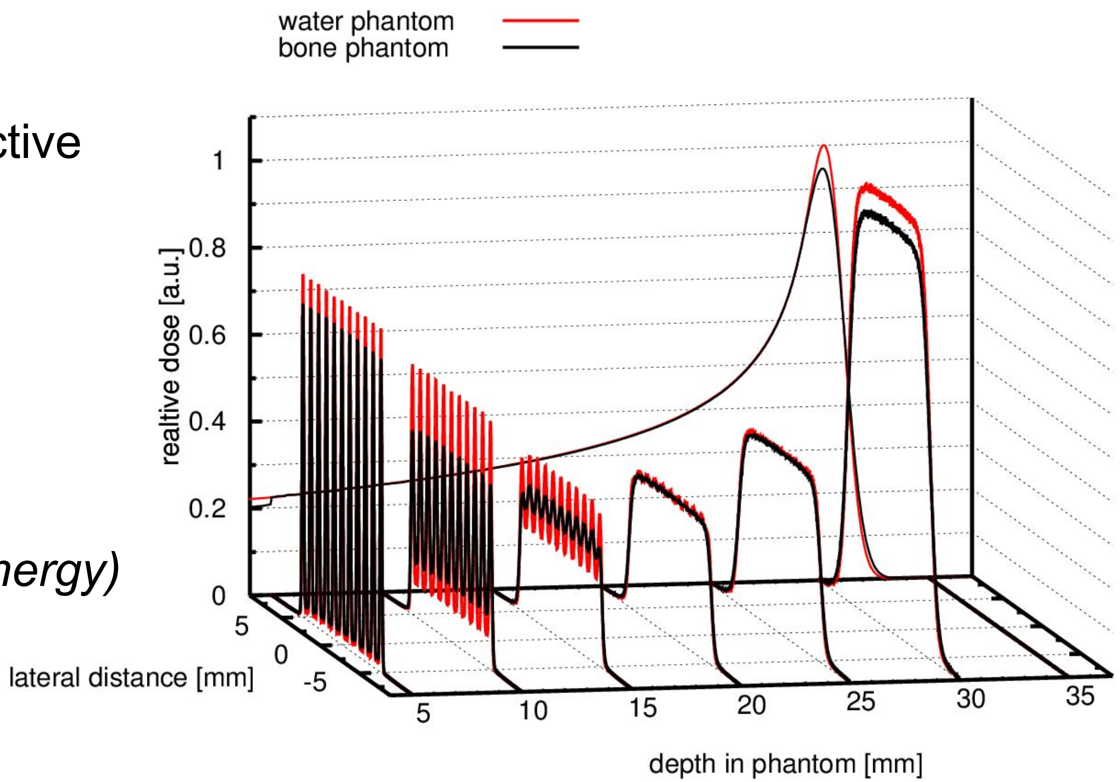
100 µm proton beam with active pencil-beam scanning mode

60-120 MeV,

1-8 mm beam spacing

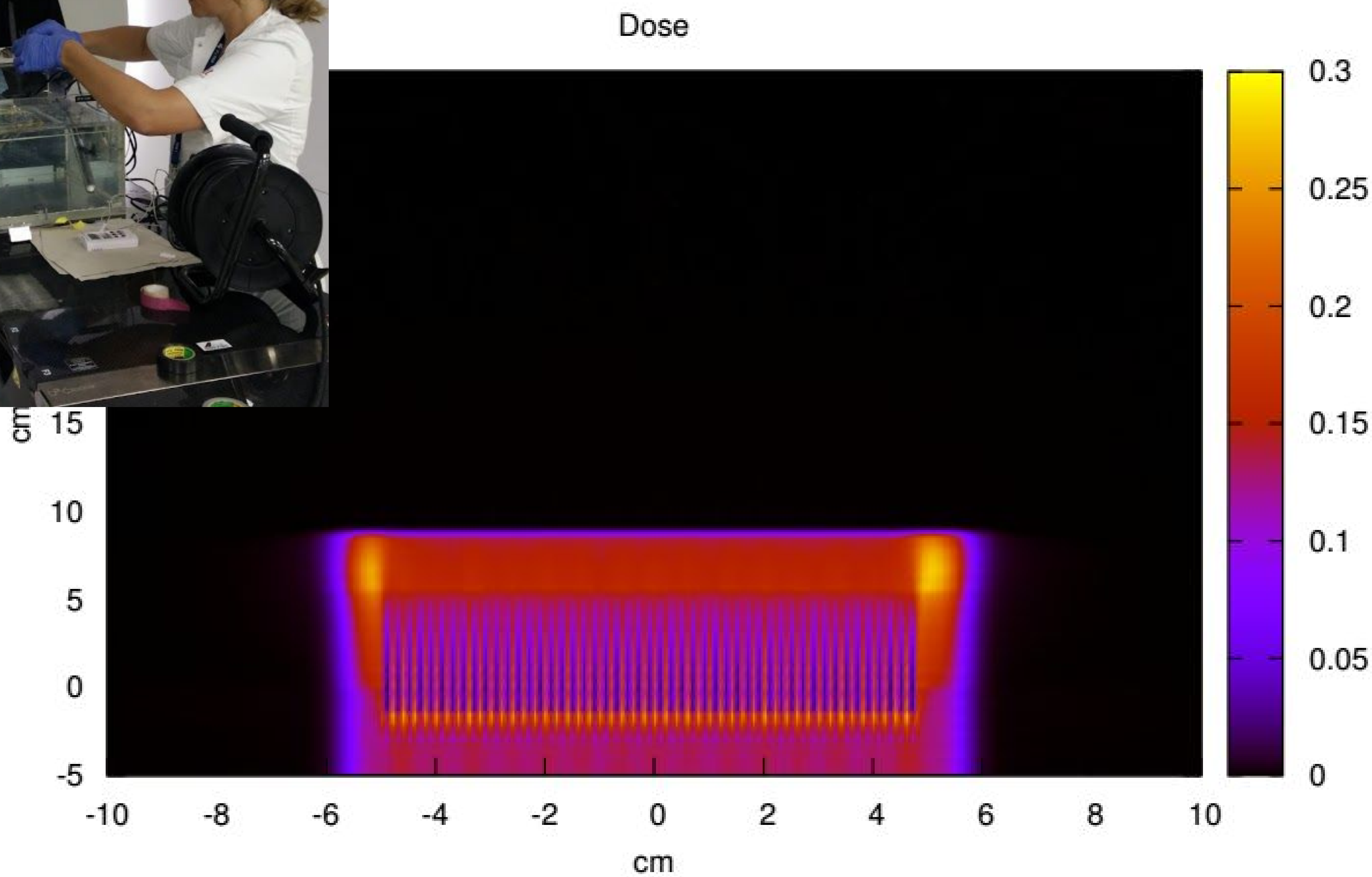
10^5 protons/spot

in 10 runs (60-221 spots / energy)



Proton spatially fractionated radiotherapy

5*10^8 particles simulated (SHIELD-HIT12A code)
500 parallel jobs, each 6hours of CPU time



Simulation of dose distribution delivered by beam available in CCB (IFJ PAN Krakow), filtered by 1mm slit collimator. Geometry represents setup used in radiobiology experiment.

Verification of a proton pencil beam model in the treatment planning system (TPS)

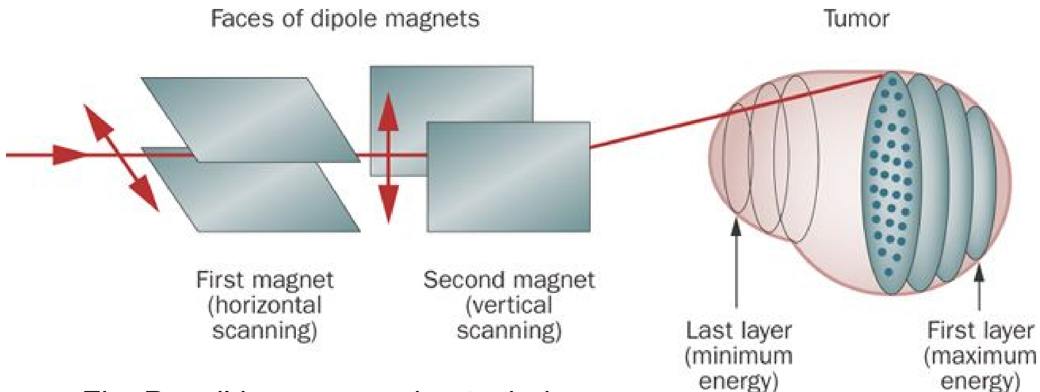


Fig. Pencil beam scanning technique.

http://www.nature.com/nrclinonc/journal/v7/n1/images/nrclinonc.2009.183-f4.jpg

Parameters like **position**, **energy** and **weight** of each **proton pencil beam** are calculated in the treatment planning system (TPS) and optimized to achieve uniform dose distribution in the tumour while sparing healthy organs in close region to the irradiated volume.

Dose distribution calculated in the TPS

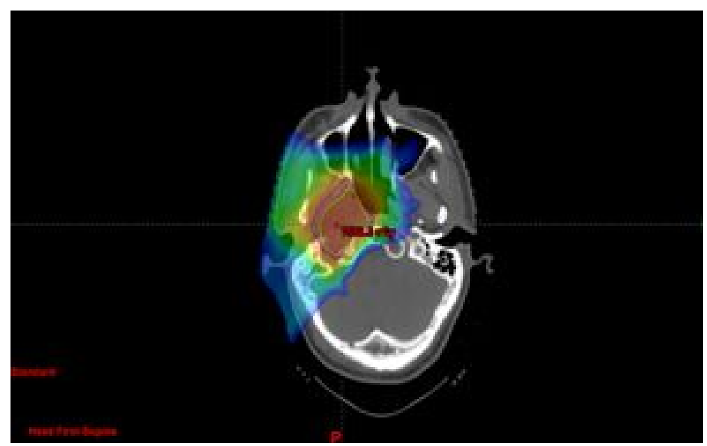
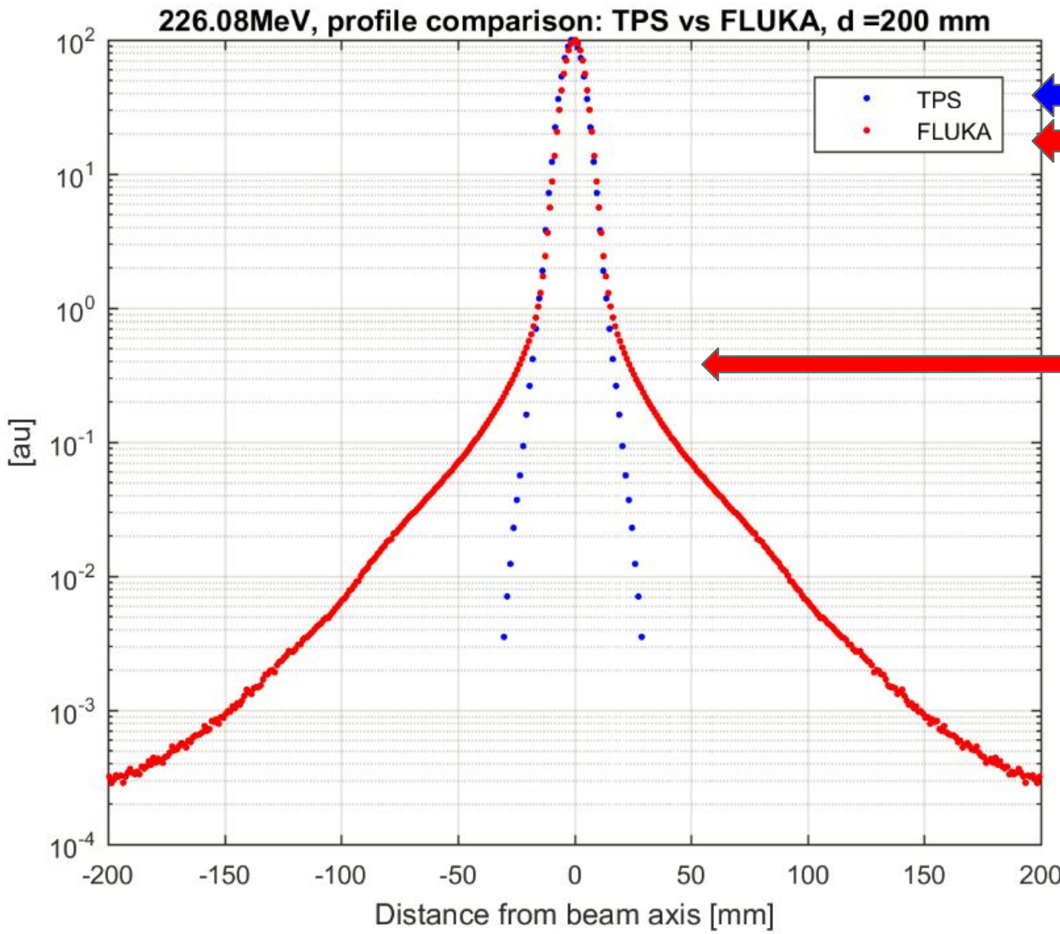


Fig. Dose distribution calculated in the treatment planning system.

TPS - analytical algorithms based on **simplified** physical models (gaussian scattering in water and air). Some disagreement with measurement is observed.

Verification of a proton pencil beam model in the treatment planning system (TPS)



Treatment planning system

Monte Carlo transport code

2*10^8 particles in 25 runs

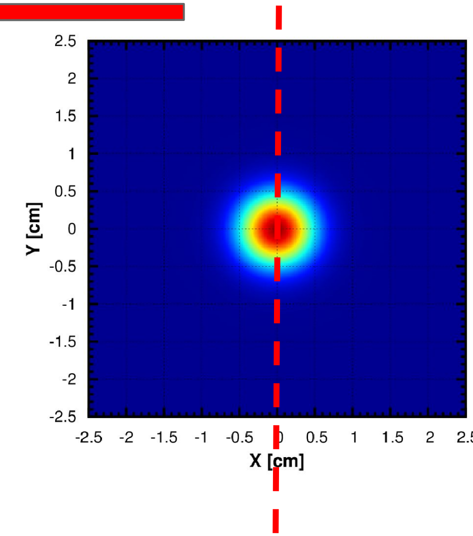
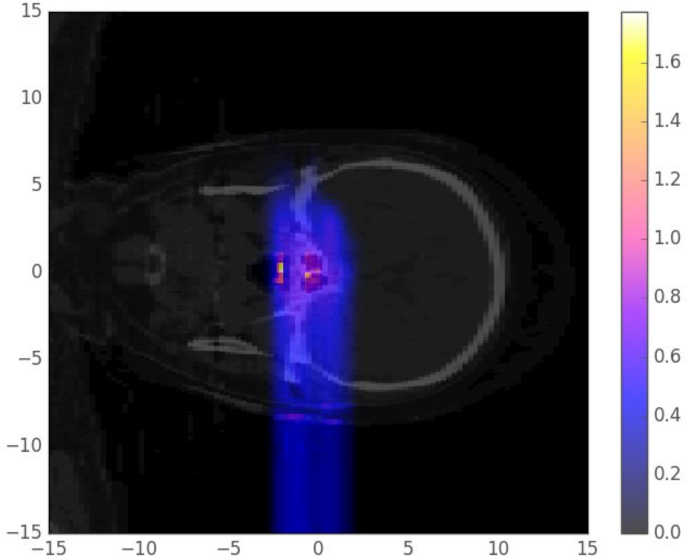


Fig. Lateral beam profiles in water at depth of 200 mm of a single pencil beam of energy 226.08 MeV calculated in FLUKA Monte Carlo code and in Eclipse treatment planning system.

Towards Monte-Carlo based treatment planning



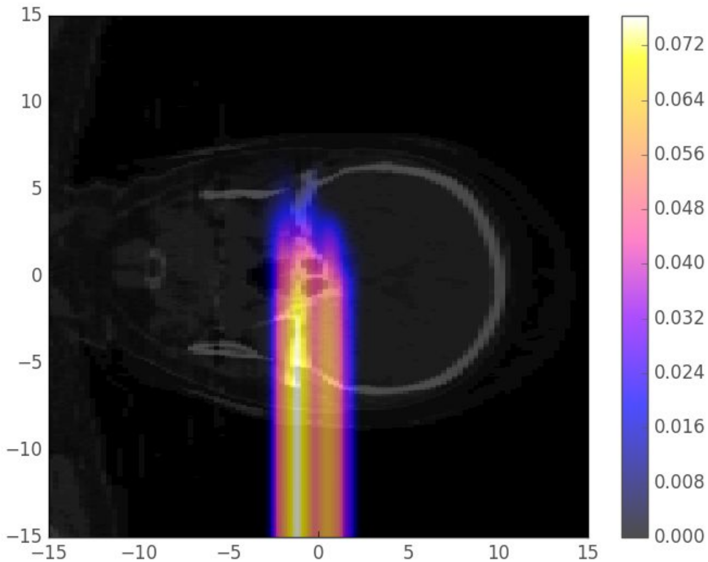
Dose distribution

Simulations of particle interaction in geometries based on patient CT scans.

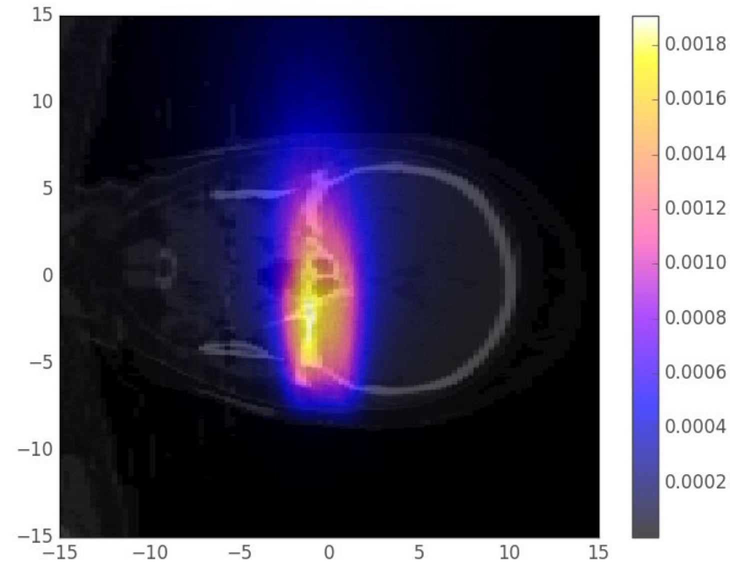
Novel algorithm implemented in SHIELD-HIT12A MC transport code.

Time and memory consuming calculations:

- ~ 10GB RAM per node
- 10^8 particles
- 3h of CPU time on 100 nodes



Proton fluence

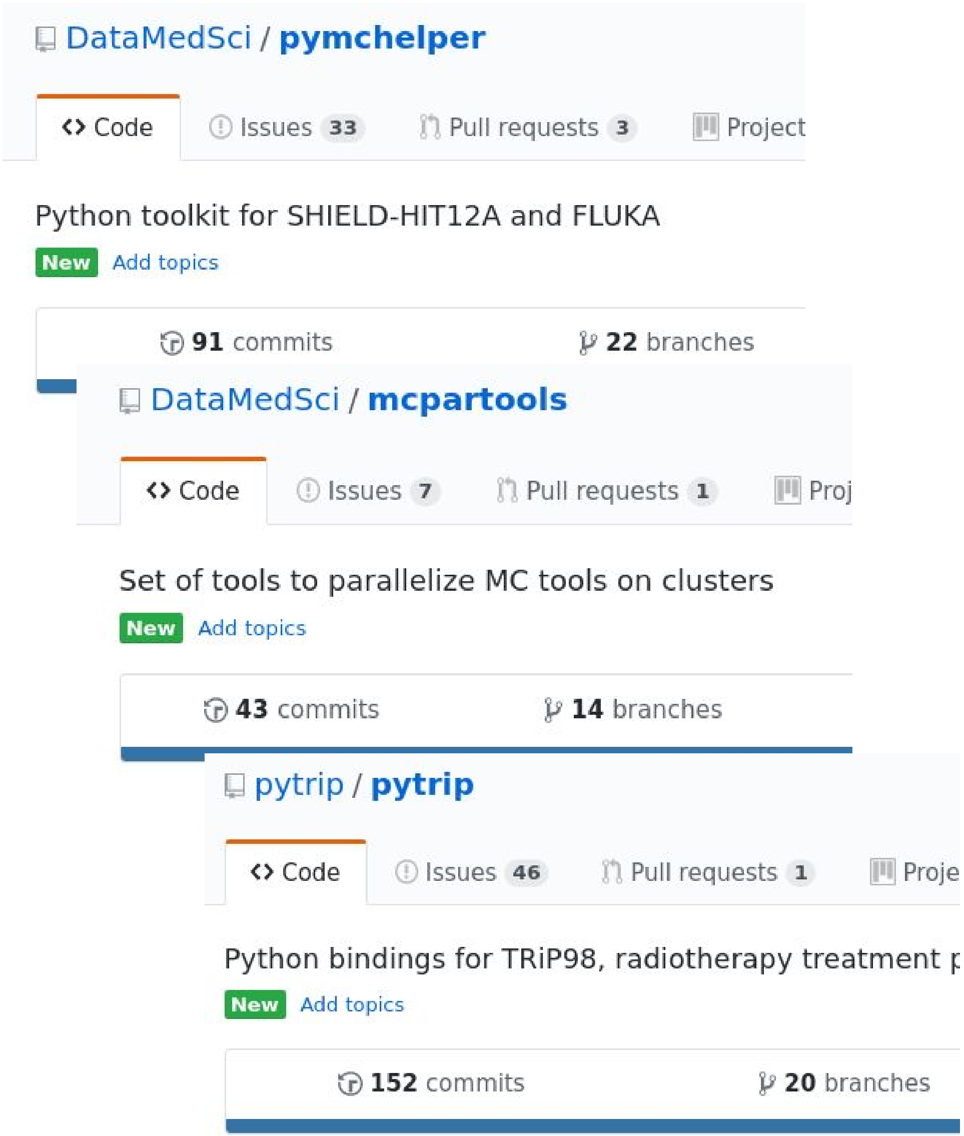


Neutron fluence

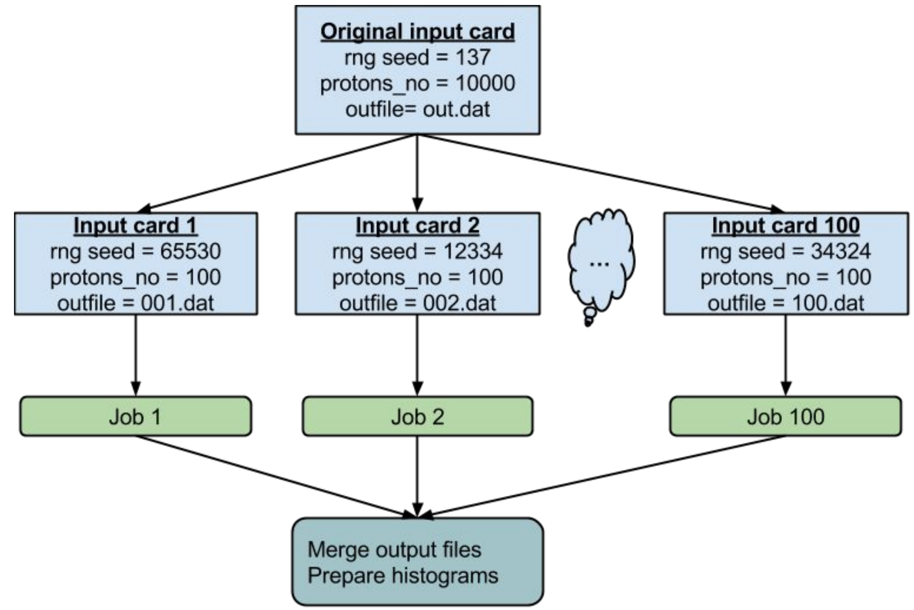
Ecosystem of tools, codes and projects

Monte Carlo particle transport codes:

Tools and toolkits essential for users



Simplifying "embarassing" parallelization



Development: L. Grzanka, A. Rudnicka

➜ `generatemc -j 100 -p 10000 beam.conf`

Single-file executable (no external deps)

No of jobs

Particles per job

Input file

Minimizing total computing time

How to parallelize ?

- 10^6 protons on 1000 nodes, or
- 10^7 protons on 100 nodes, or
- 10^8 protons on 10 nodes ?

$$T(n) = \frac{\alpha p}{n} + \beta n + \gamma$$

Concept from https://arxiv.org/pdf/1009.5282.pdf

Implementation in mcpartools - in progress
(P. Ociepka)

T(n) - total computing time

n - number of nodes

p - number of particles

α - calc. time per particle

β*n - initialization and merging results

time (linear)

γ - initialization time (fixed)

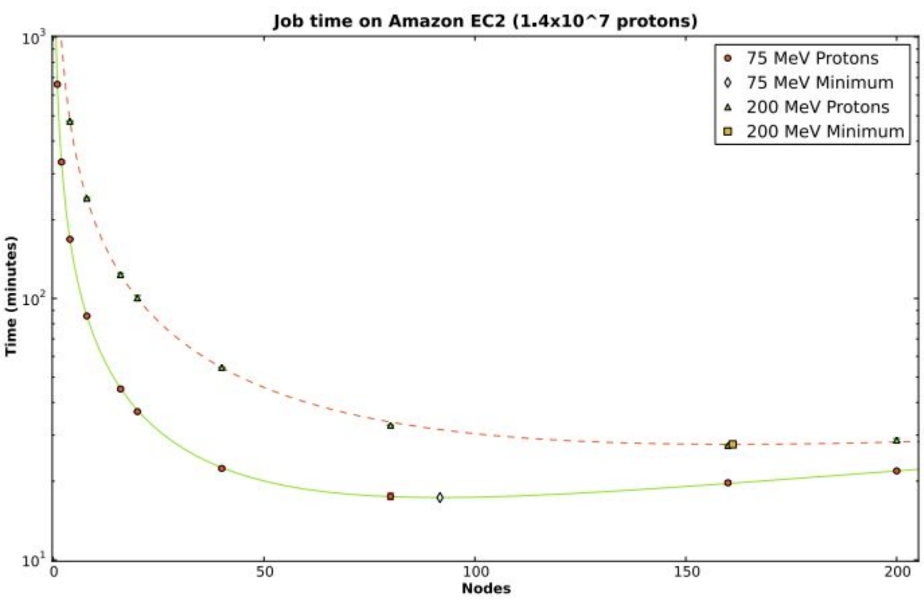


Figure 4. Calculation time versus number of virtual nodes for proton depth-dose curves on Amazon's EC2 cloud service. The calculation time is modelled with Eq.1.

Thank you for attention !