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PSI

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Validation of activation calculations during proton therapy in the GPU Monte Carlo code FRED using GATE

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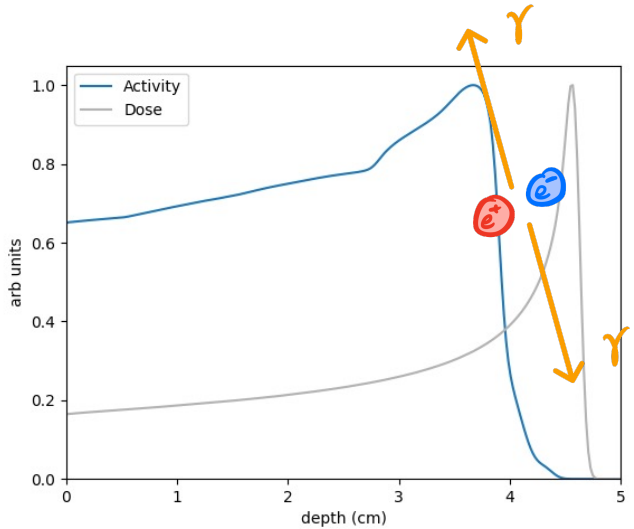
Range verification in proton therapy

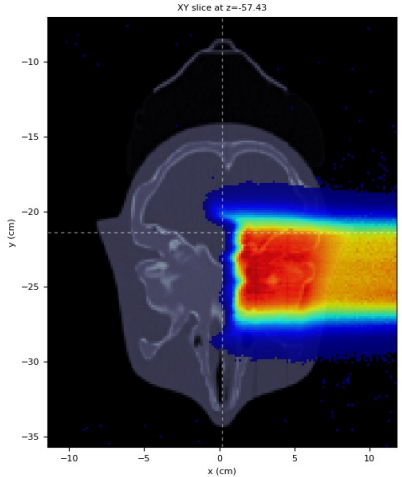
- Positron emitting isotopes are produced during irradiation, e.g.

$$^{16}O + p \rightarrow {}^{15}O + p + n, \quad Q = -15.7\ \text{MeV}, \quad t_{1/2} = 122\ \text{s}$$

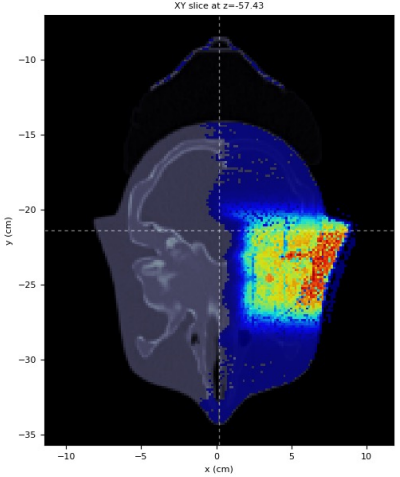
- Measure resulting activity with a PET detector, verify range, detect interfractional changes



Dose



^{15}O



GATE & FRED for proton therapy

- GATE/Geant4 widely accepted accurate Monte Carlo toolkit for medical physics
  - Full physics setup (EM models, nuclear cascade, etc.)
  - CPU based code
  - “Ground truth”

- FRED, optimised for proton therapy, A. Schiavi *et al.* PMB (2017)
  - Models contributing dose in proton therapy
    - Proton & deuteron tracking
    - Local energy deposition (alphas, heavy ions, etc.)
  - GPU based, x1000 speed up WRT general purpose MC codes

Full physics isotope production

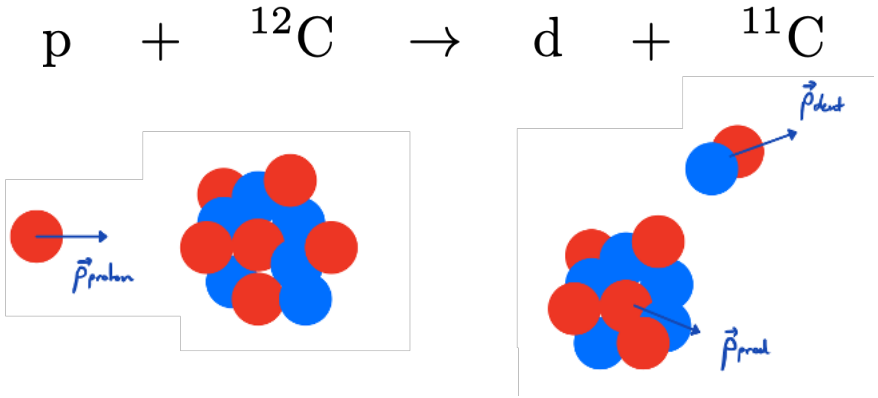
1) Decide if an inelastic event occurs (1% of protons per cm)
2) If yes: decide which atom in the material it occurs on
3) Run nuclear cascade model to determine the outcome of the reaction
4) Score the produced β^+ emitters

Pros:

- Accurate physics processes*
- Contains momentum information**

Cons:

- Slow
- Large number of protons needed



Continuous scoring in FRED

- Instead of treating isotope production as a discrete process allow ‘build up’

$$x_O \sigma_{O \rightarrow {}^{15}O}(E_s) l_s N_V$$

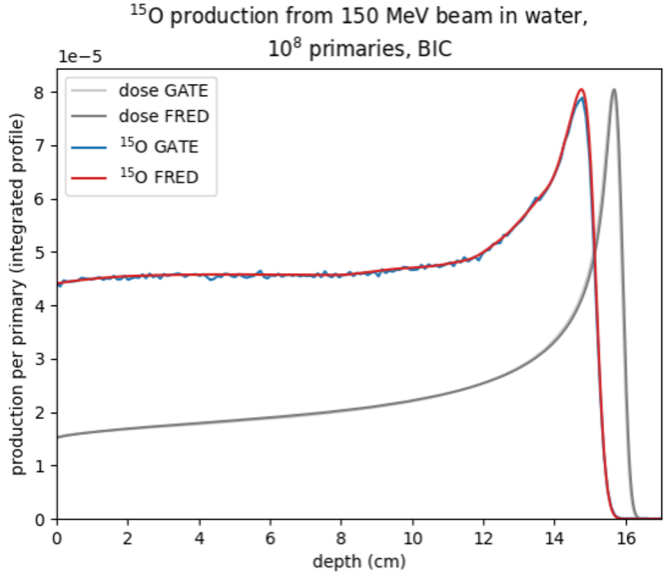
- Every proton adds a fractional amount of isotope to each voxel
- Takes advantage of GPU parallelism, shaders, memory structure

Pros:

- Very fast
- Smooth, quicker convergence
- Can easily update cross sections

Cons:

- Missing some physical processes



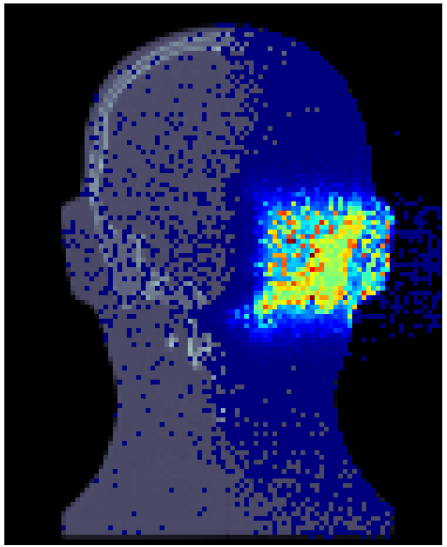
Fred:
10^5 protons

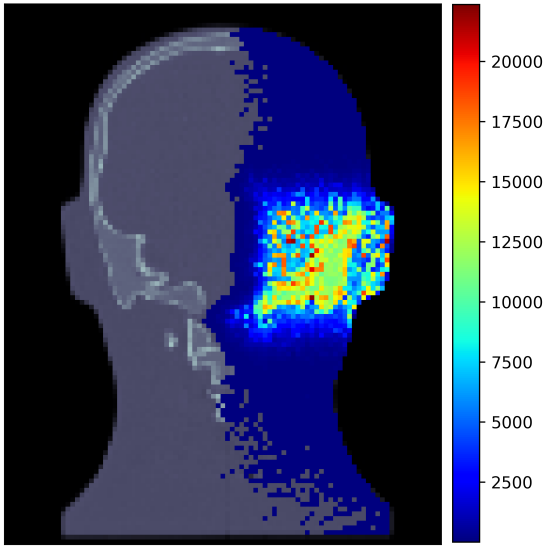
Isotope production validation

- Neutrons not tracked in Fred, <1% of production
- Compare voxel by voxel

$$\left| \frac{\mu^f - \mu^g}{\sigma^g} \right| < 1$$

- Some small deviations due to differences in proton flux
- Deviations weakly correlated to dose differences





GATE

Fred

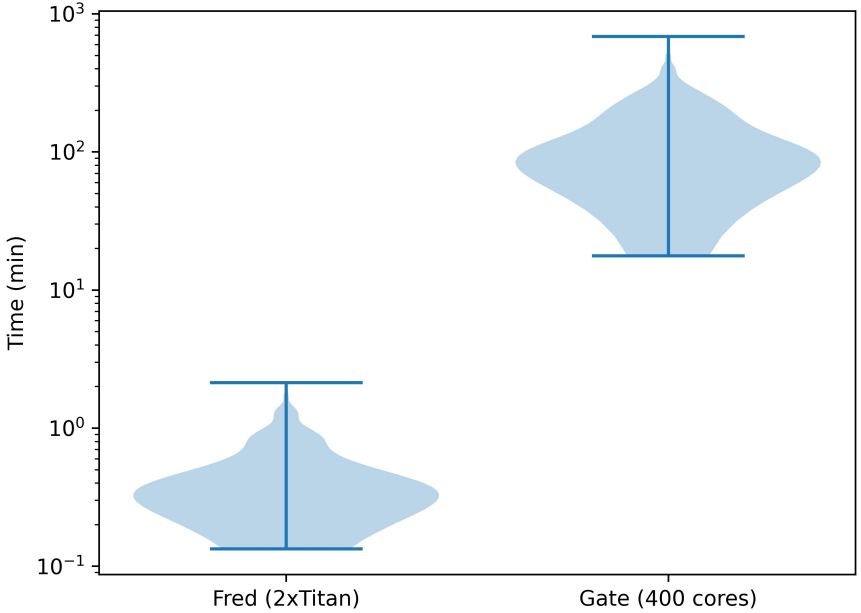
Speed comparison

- Simulation of a full field in a phantom, 4.8×10^{10} protons
- Scoring dose, ^{10}C, ^{11}C, ^{13}N, ^{14}O, ^{15}O, ^{30}P, & ^{38}K

Monte Carlo engine	Primaries/sec	10% of protons	0.3% of protons
GATE (1 CPU core)	870	>64 days	2.2 days
GATE (400 CPU cores)	350,000	>4 hours	9 minutes
FRED (NVIDIA Quadro P2200 GPU)	290,000	4.5 hours	10 minutes
FRED (2x TITAN GPUs)	1,400,000	1 hour	2 minutes

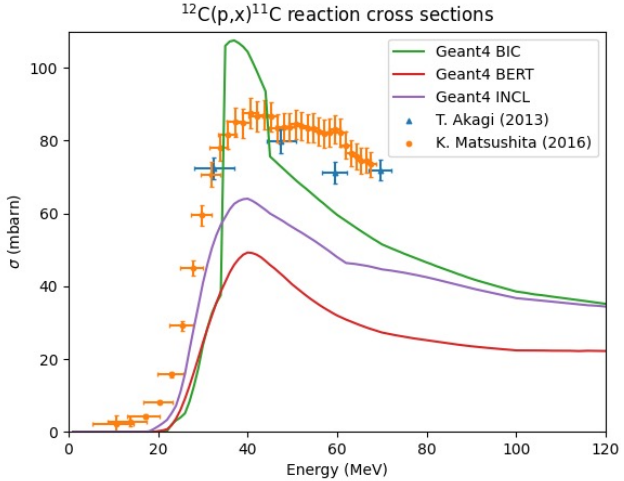
Speed comparison

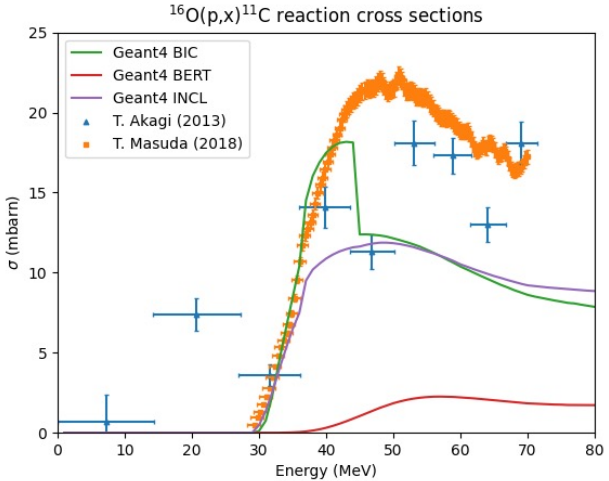
- 108 patient plans, 390 total fields
- All FRED calculations performed on 2 NVIDIA TITAN GPUs:
  - Avg 30 sec/field
  - Avg 3.0×10^{7} prim/field
  - Total time 3.3 hours
- All GATE calculations performed on 400 CPU cores:
  - Avg 2.3 hours/field
  - Avg 1.9×10^{9} prim/field
  - Total time 38 days

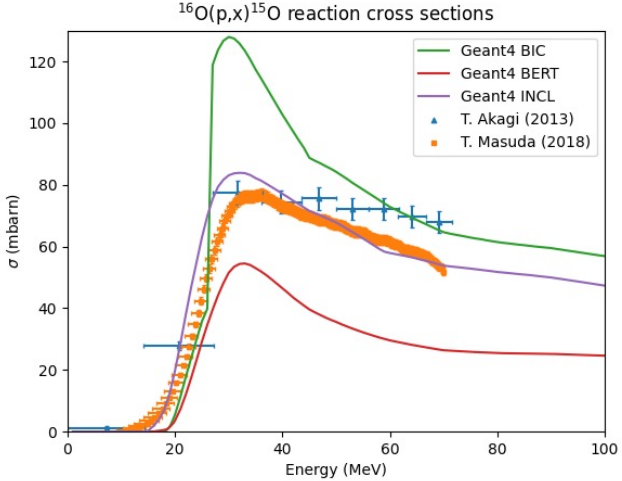


Colaboration with CCB Krakow
Antoni Rucinski

Physics & cross sections







Cross sections extracted from Geant4.10.06.03 (Hadr03)

Wir schaffen Wissen – heute für morgen

Conclusions

- Fred has been validated against Geant4 (GATE) for activation calculations
- Good agreement
- Massive speedup with fewer computational resources required

Outlook

- Combined FRED & GATE workflow and detector modelling