A GPU Monte Carlo Platform

Innovative Computational Technologies

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Implementation and functionality

Commissioning and validation

iba MEVION medical systems VARIAN medical systems PAUL SCHERRER INSTITUT PSI

Ongoing developments

Treatment plan optimization

4D applications

FRED Electromagnetic

FRED Carbon

Fred protons

Applications

Quality assurance
Secondary dose calculation engine

Treatment planning studies
Multi-parameter studies on patient data

Treatment planning
Computation of dose, LET, vRBE

PET imaging
Simulations of proton beam induced beta+ activity

Proton CT imaging

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Monte Carlo code for research and QA in PBT

Fast paRticle thErapy Dose Evaluator

Physics implementation

- Models contributing to dose in proton therapy
  - Proton tracking
  - Local deposition (heavy ions, delta rays)
- II class Monte Carlo algorithm
  - Condensed history
    - tabulated total stopping power (PSTAR-NIST)
    - energy straggling (Gaussian+Landau-Vavilov)
    - MCS models (Gauss+Rutherford)
  - Step-by-step implementation of nuclear interactions (elastic and inelastic, fragmentation)

Validated against FLUKA

Functionality

- Speed: 1000x faster than general purpose MC
- CT import: HU to density conversion (Schneider-Parodi)
- Flexible voxelized geometry (CT+multiple user defined structures)
- Calculations of dose, LET, and vRBE (McNamara, Wedenberg, Carabe, Wilkens, Chen, etc.)
- Executable on multi-CPU/GPU systems and clusters
- Dose optimization
- C++ plugins

Accuracy, time performance, flexibility

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A. Schiavi et al. PMB (2017)

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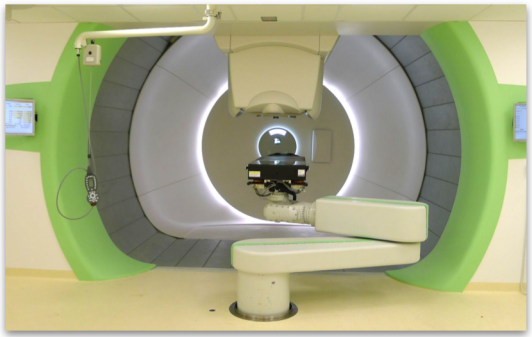
Automated FRED commissioning for various beam line designs



Kraków, Poland

Maastricht,
the Netherlands

Atlanta, US

Villingen, Switzerland

~10h for automated optimization of parameter space over entire proton beam energy range (new beam model or beam model update)

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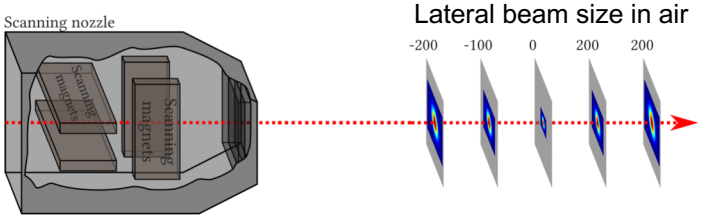
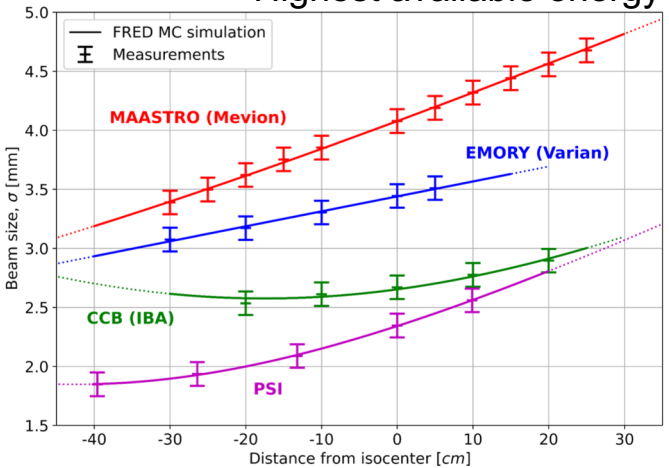
TPS commissioning for proton beams

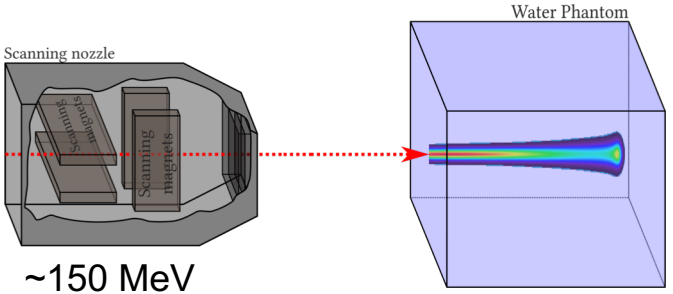


Highest available energy

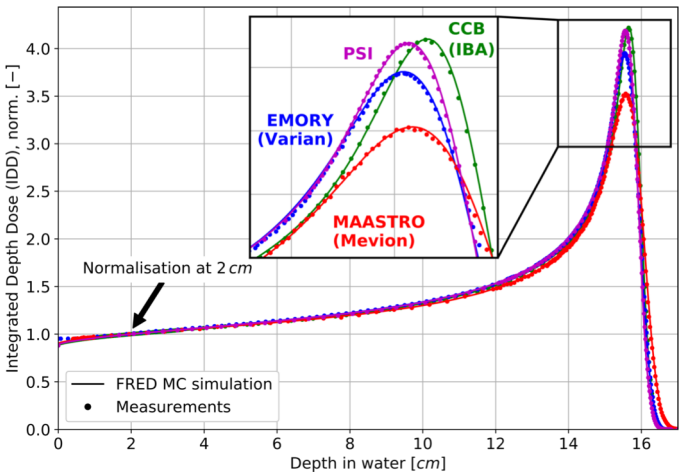


Exp. vs FRED: <0.1mm

Bragg peak in water



~150 MeV



Exp. vs FRED: Dose <2%,
BP range & FWHM <0.1 mm

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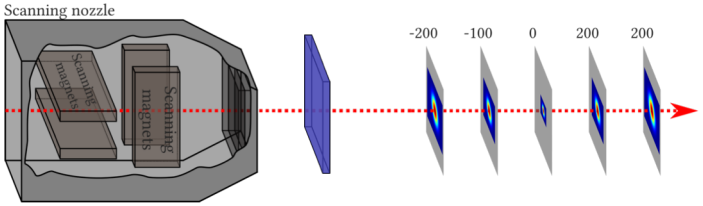
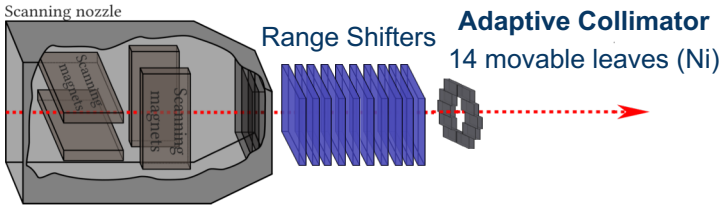
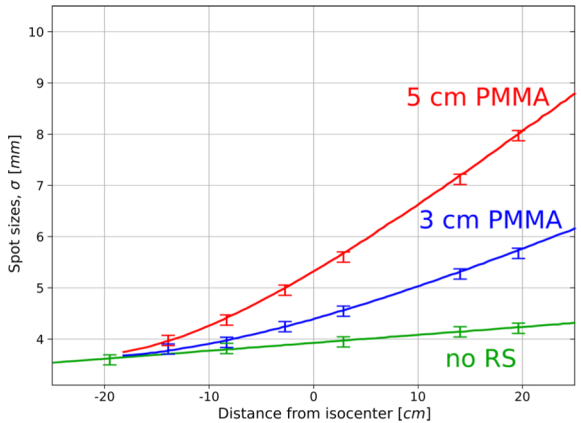
J. Gajewski et al., Front. Phys. (2020 & 2021) www.fred-mc.org

FRED commissioning: range shifters and ext. nozzles

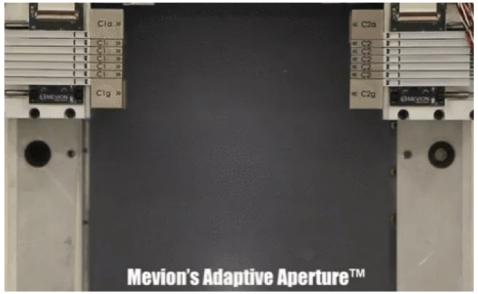




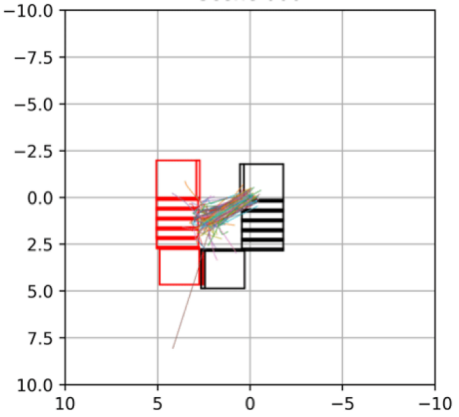
VARIAN medical systems | EMORY | WINSHIP CANCER INSTITUTE



MEVION medical systems | Maastro



Particle tracking in multiple geometries simultaneously handled by GPU



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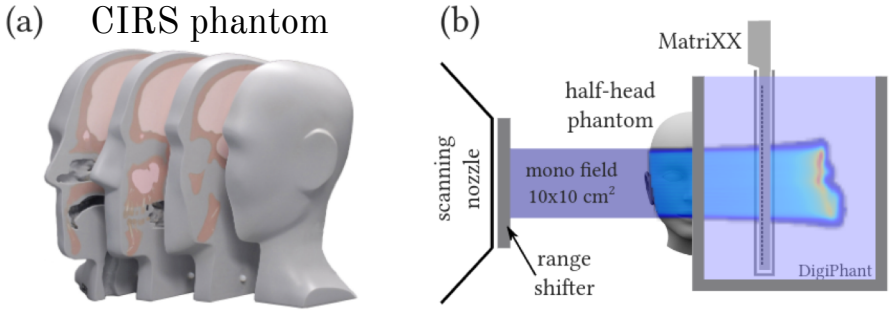
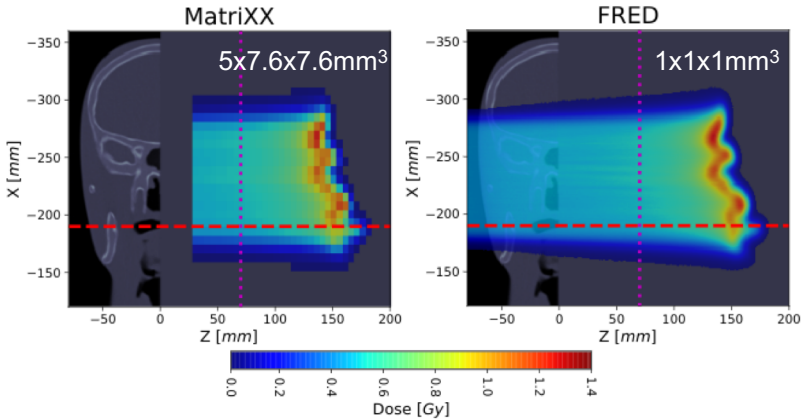
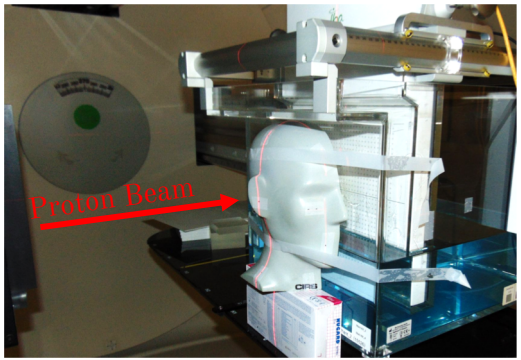
J. Gajewski et al., Front. Phys. (2020 & 2021) www.fred-mc.org

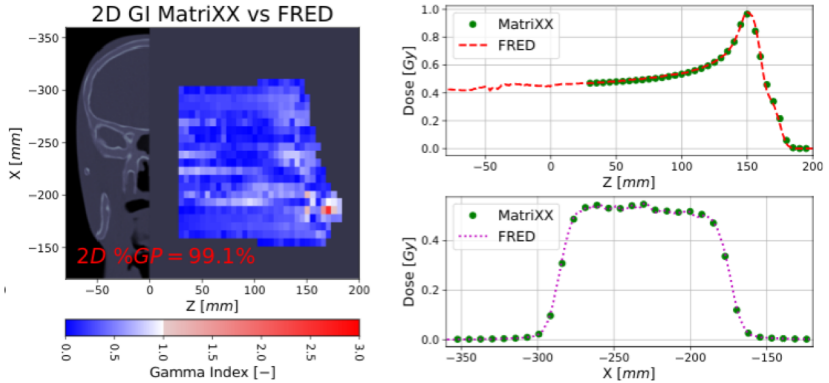
FRED experimental validation







Mono layers:
100/150/200 MeV



3D GI pass rate (2%/2 mm/2%) >99%

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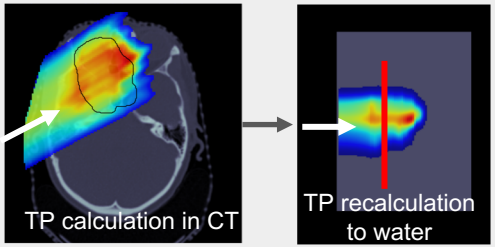
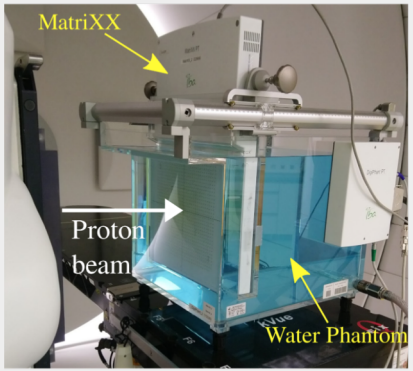
J. Gajewski et al., Front. Phys. (2020) www.fred-mc.org

FRED for patient specific QA

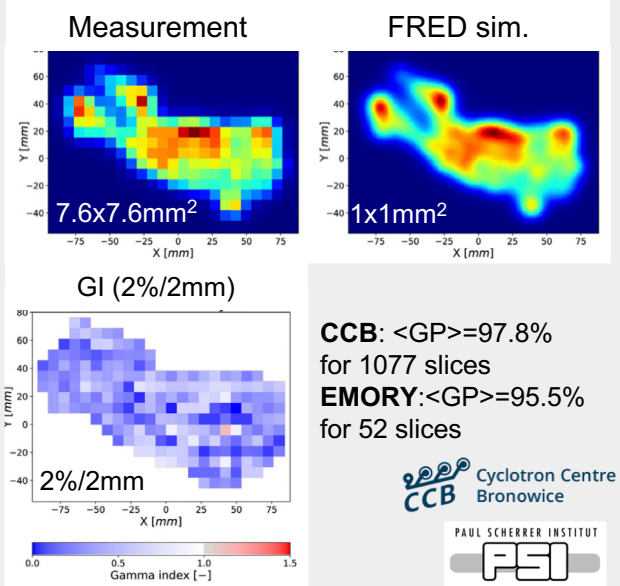
Multiple time consuming measurements per field





2.5 min
$3.4 \cdot 10^6$ pps

FRED dose calculation vs measurements in water



CCB: <GP>=97.8% for 1077 slices
EMORY:<GP>=95.5% for 52 slices

Cyclotron Centre Bronowice

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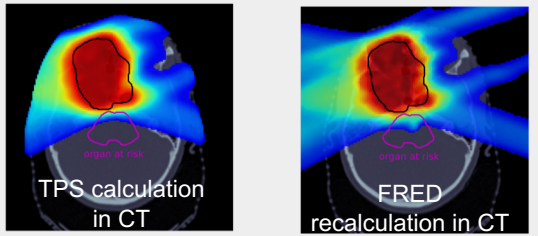
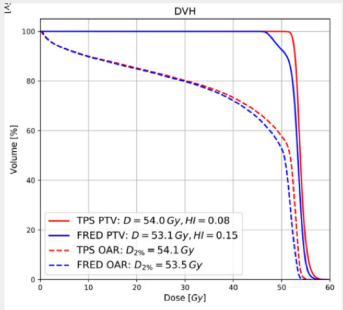
2.5 min
$3.4 \cdot 10^6$ pps

FRED dose calculation in patient





FRED sim:
Res: 1.5x1.5x1.5 mm³
Stat: 10^4 p+/PB
(1% uncertainty)

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2.5 min [20s;6.5min]
$2.9 \cdot 10^5$ pps

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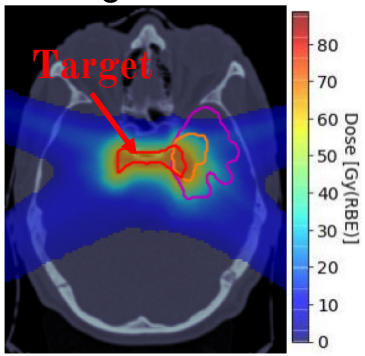
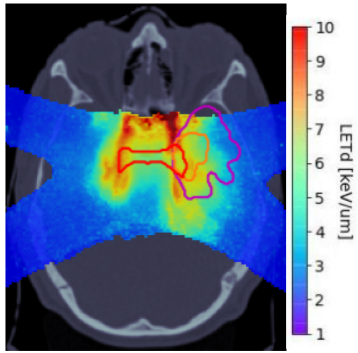
FRED to support treatment planning

cRBE-weighted biological dose



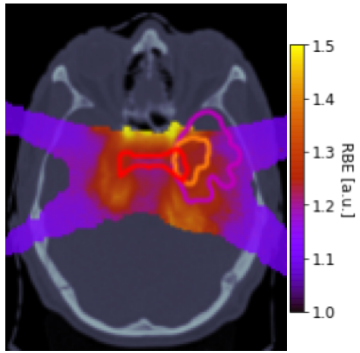
Dose-averaged LET

Cortes-Giraldo et al., PMB (2015)
Granville et al., PMB (2015)

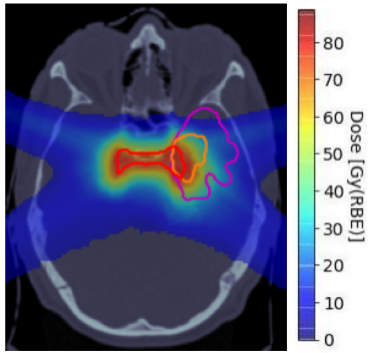


Variable RBE

McNamara et al., PMB (2015)

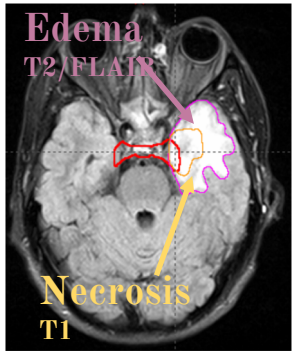


vRBE-weighted biological dose



MRI

3-6 m after treatment



Patient data base:
95 brain and skull base tumors patients
11.2016-09.2018 CCB Krakow proton centre

LET and RBE scoring does not increase simulation time

$vRBE_{PTV\text{-}brain\ (\alpha/\beta = 6\ Gy)}$	1.11 [1.07; 1.31]
$vRBE_{PTV\text{-}skull\ base\ (\alpha/\beta = 4\ Gy)}$	1.15 [1.09; 1.49]
$vRBE_{max@OAR\ (\alpha/\beta = 2\ Gy)}$	2.2-2.7

vRBE induced biol. range extension: 4.5mm

M. Garbacz et al., to be submitted to Cancers

FRED for research - treatment planning studies

Physical vs. biological dose/range uncertainty (vRBE vs robustness)

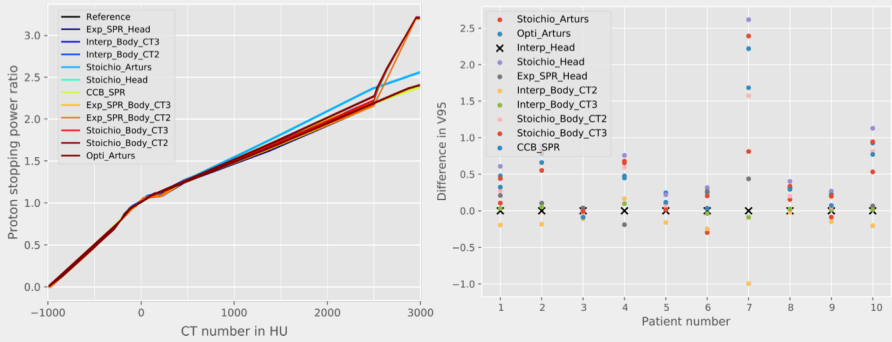
Brain (50 patients)	Maximum diff. $D95_{PTV}$ [Gy(RBE)]	Maximum diff. $D05_{OAR\text{-}brain\ stem}$ [Gy(RBE)]
Robustness (12 x translations + 2 x CT calib.)	1.5(1.2)	1.4(2.0)
RBE-weighted dose (cRBE vs vRBE)	4.1(0.7)	4.5(2.3)

M. Garbacz et al. to be submitted to Cancers

15 sim. x 50 patients = 750 sim.
24 h

Dosimetric impact of CT calibration

12 CT calib. curves
10 patients



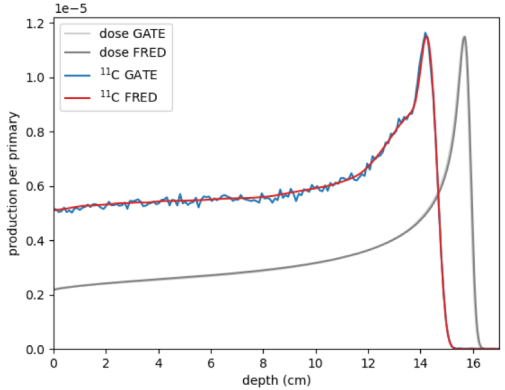
I. Rinaldi, N. Krah, J. Gajewski

12 sim. x 10 patients = 120 sim.
4 h

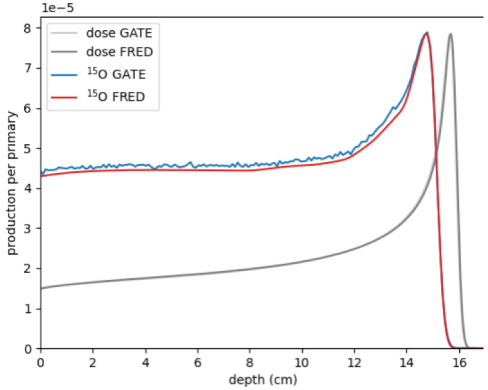
If we find a mistake, we just run FRED again

FRED for research - PET imaging

150 MeV ^{11}C



150 MeV ^{15}O



PETITION

ETH zürich

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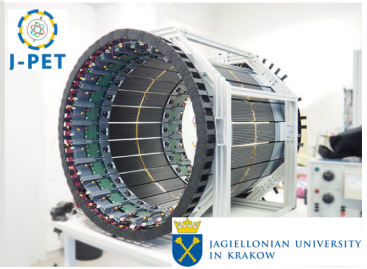
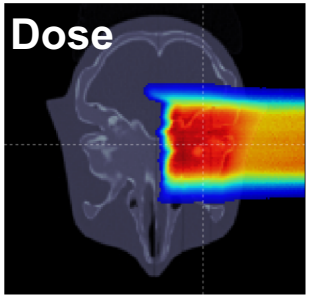
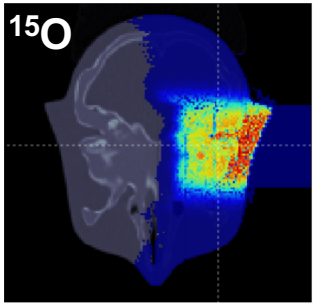
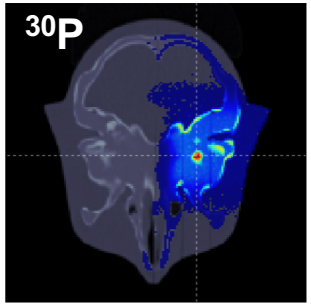


- Continuous scoring of any PET isotope on GPU
- Under validation against GATE/Geant4







2 min
dose & ^{10}C, ^{11}C, ^{13}N, ^{14}O, ^{15}O, ^{30}P, ^{38}K
(~20% decrease wrt dose alone)

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Keegan McNamara, PETITION project,
Swiss National Science Foundation, Grant No. CRSII5189969

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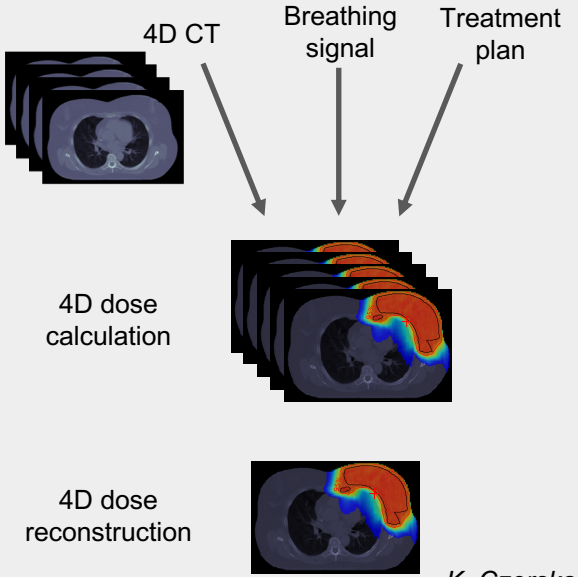
FRED: ongoing developments for new applications

4D applications

Multiple geometries handled on GPU simultaneously

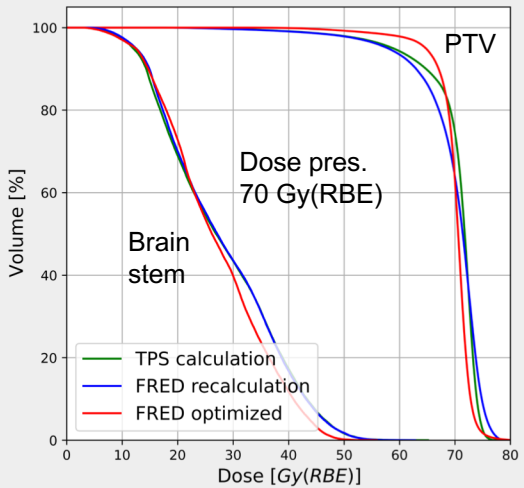


K. Czerska

Fully GPU-based optimization

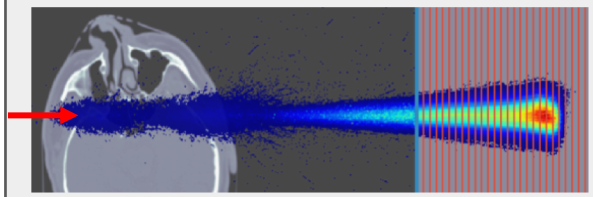
- MC-based influence matrix
- Inverse optimization algorithm

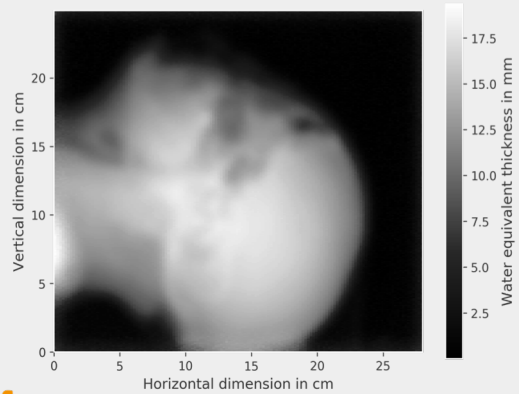
A. Lomax 1999 PMB 44 185–205



M. Dudek

Proton radiography and tomography





Maastro CREATIS *I. Rinaldi, N. Krah*

8.5 min for influence matrix computation

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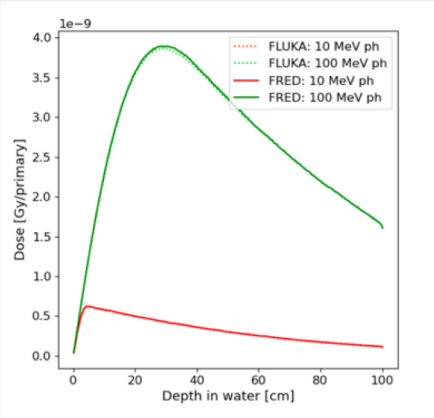
FRED: ongoing developments of the code engine

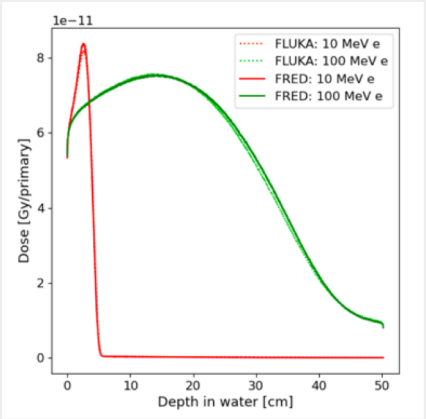
FRED electromagnetic: e-, e+, γ

Continuous processes (e-, e+): dE/dx+straggling, MCS
Discrete interactions (e-, e+, γ): Bremsstrahlung, Möller/Bhabha scattering, e+ annihilation at rest/in flight, Photoelectric, Compton, Coherent scattering, Pair production

Photon dose profile

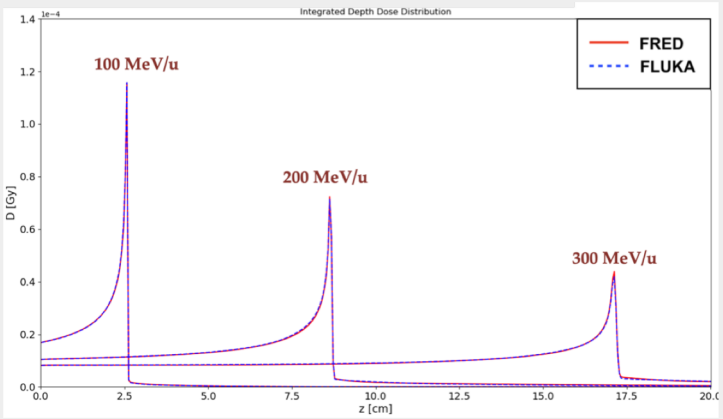


Electron dose profile



FRED carbon

Continuous processes: dE/dx+straggling, MCS
Discrete interactions: nuclear model, i.e., sampling of the fragments, their energy and angular distributions, mass attenuation coefficient to decide between elastic and non-elastic event
RBE-weighted dose: LEM1 model



Merging GPU implementation of FRED proton, carbon and electromagnetic

Conclusions

- FRED is a GPU-accelerated (not only) proton Monte Carlo code for clinical and research applications
- Automated commissioning and validation procedure against measurements
  for three beam line designs (IBA, Varian, Mevion, PSI)
- FRED computes a single proton treatment plan within minutes
- Current applications (QA, TP, PET production)
- Ongoing developments (TP optimization, pCT, 4D applications, electromagnetic and carbon models)

Fred

Collaboration & acknowledgments

SAPIENZA UNIVERSITÀ DI ROMA





V. Patera **A. Schiavi** **M. De Simoni** **G. Franciosini** **G. Traini**

M. Palma, P. De Maria

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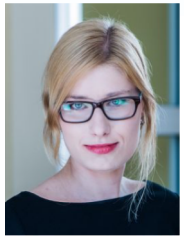

J. Gajewski **M. Garbacz** **A. Rucinski** **M. Dudek**

J. Baran, D. Borys, K. Brzeziński, K. Czerska, J. Drwal, R. Kopeć, N. Krawczyk, K. Krzempek, D. Krzempek, G. Mierzwińska, N. Mojżeszek, A. Skrzypek, P. Olko, E. Pluta, M. Rydygier, B.Sas.-Korczyńska, P. Stasica, T. Skóra

European Funds Smart Growth | Republic of Poland | FNP Foundation for Polish Science | European Union European Regional Development Fund

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C. Chang
L. Lin

PETITION

Swiss National Science Foundation
Grant No. CRSII5189969