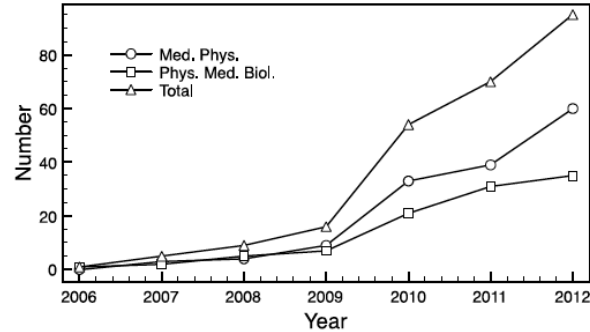
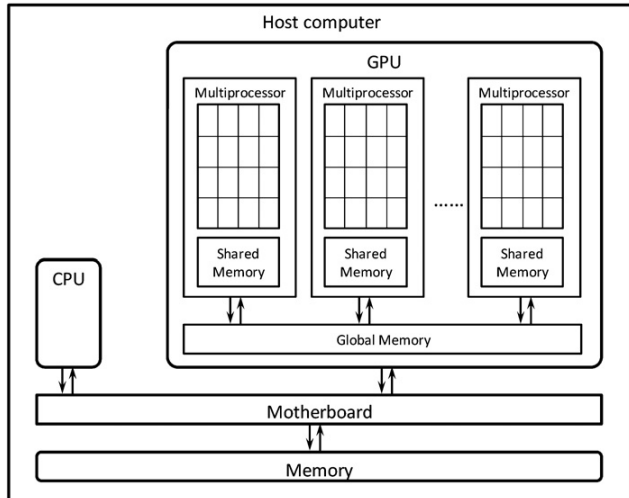


# New Technological Developments for Fast Calculations: the GPU MC – 1`

The progress in the use of graphics processing units (GPU) allowed for the development of techniques for general purpose computing exploiting the high degree of parallel operation which characterize these hardware units.

This has brought to the approach denominated “General Purpose computing with Graphics Processing Units” (GPGPU) which includes MC code and their application in medicine, mostly for dose calculations.

High degree of parallelism: events may be processed in many different cores at the same time.



For a review about GPU proton dose calculations see: *Jia et al. Proton therapy dose calculations on GPU: advances and challenges. Transl. Canc Res. (2012). 1, 207–16.*

# New Technological Developments for Fast Calculations: the GPU MC - 2

Limits such as the size of global and shared memory, maximum number of threads per block, and number of stream multiprocessors are GPU dependent. In the case of MC simulations, there exist some limitations to the effective number of parallel threads in a GPU. The large number of cores (typically thousands) cannot, in practice, be totally exploited at all times.

**However, the achievable gain factor remains in any case significant.**

Programming mostly in C/C++, using the CUDA® (Compute Unified Device Architecture) platform or the OpenCL (Open Computing Language) software libraries

# Example of a GPU MC for medical applications: FRED (Fast paRticle thERapy Dose evaluator)

[www.fred-mc.org](http://www.fred-mc.org)

The logo for FRED, featuring the word "Fred" in a stylized, glowing font with a blue and yellow gradient, set against a dark blue background.

## 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

## Recent developments

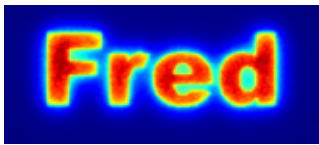
FRED Electromagnetic

FRED Carbon

## Ongoing developments

Treatment plan  
optimization

4D applications



# 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

# FRED performances in terms of computation speed

*A. Schiavi et al. 2017 Phys. Med. Biol. 62 , 7482*

MC	Hardware	Primary/s	$\mu s$ /primary
FLUKA	single CPU core	0.75k	1340
FRED	single CPU core	15k	68
FRED	single GPU cards	800k	1.35
FRED	4 GPU cards	20000k	0.05

# Automated FRED commissioning for various beam line designs

CCB Cyclotron Centre Bronowice

Iba



Kraków, Poland

Maastrro

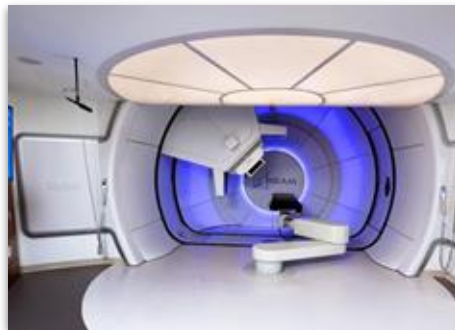
MEVION medical systems



Maastricht,  
the Netherlands

EMORY WINSHIP CANCER INSTITUTE

VARIAN medical systems



Atlanta, US

PAUL SCHERRER INSTITUT PSI

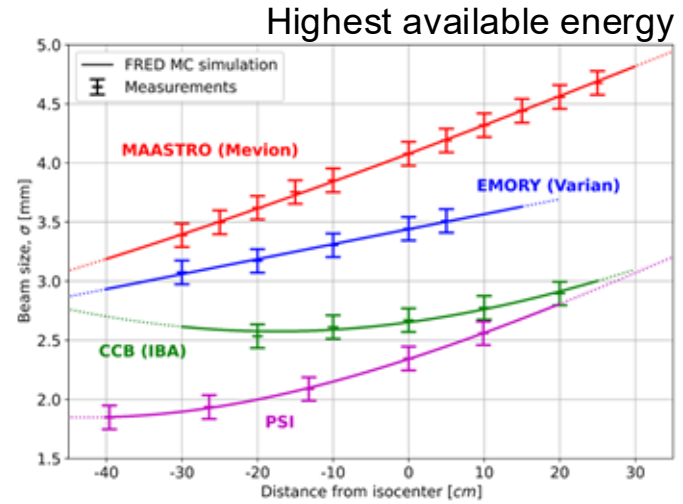
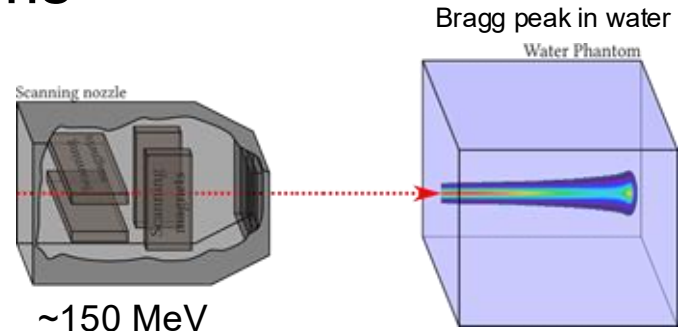
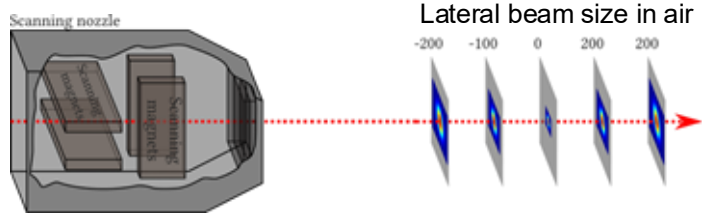


Villingen, Switzerland

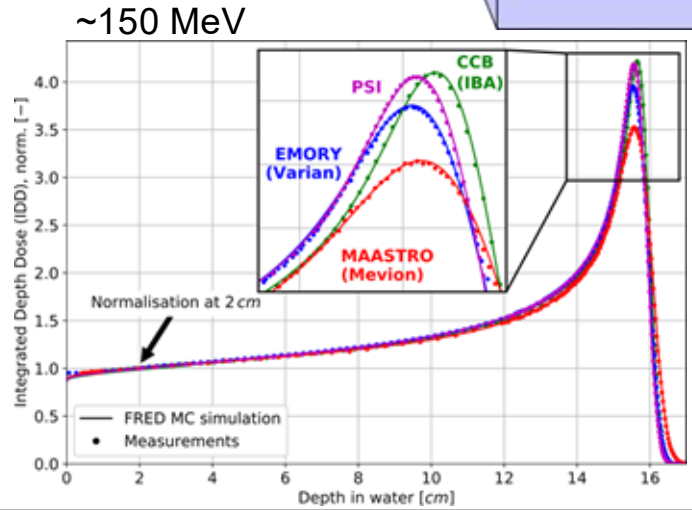


~10h for automated optimization of parameter space over entire proton beam energy range (new beam model or beam model update)

# TPS commissioning for proton beams

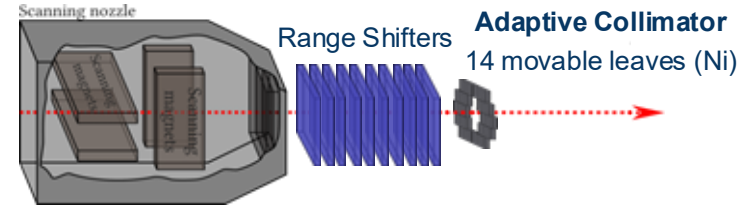
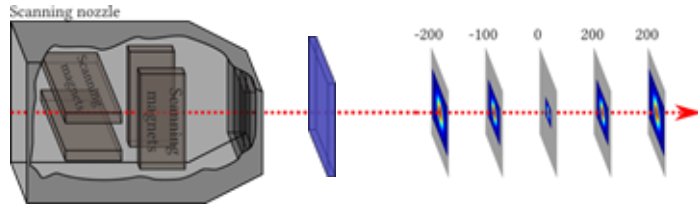


Exp. vs FRED: <0.1mm

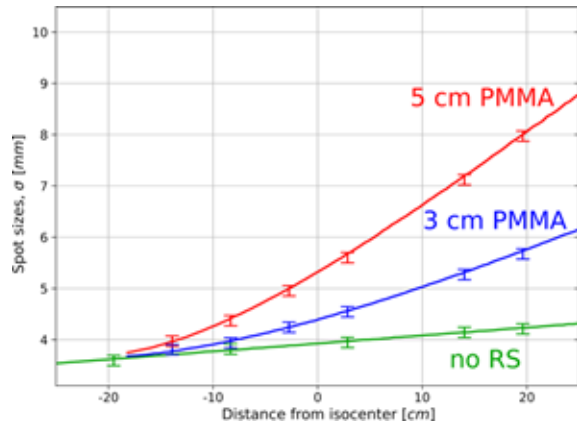


Exp. vs FRED: Dose <2%,  
 BP range & FWHM <0.1 mm

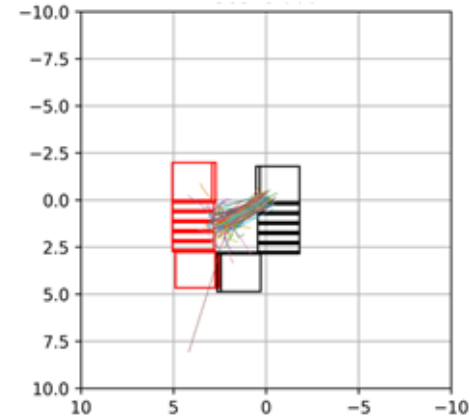
# FRED commissioning: range shifters and ext. nozzles



VARIAN medical systems | EMORY | WINSHIP CANCER INSTITUTE



Particle tracking in multiple geometries simultaneously handled by GPU

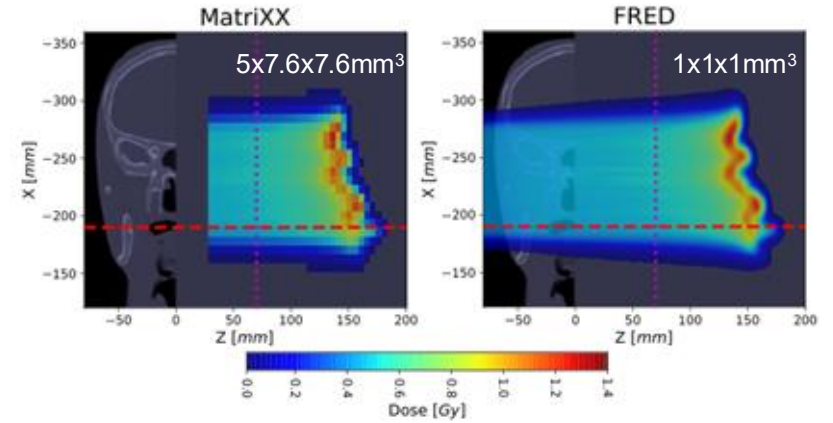
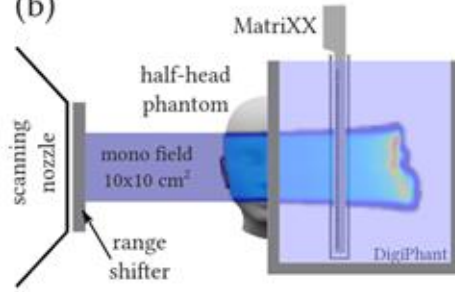


# FRED experimental validation

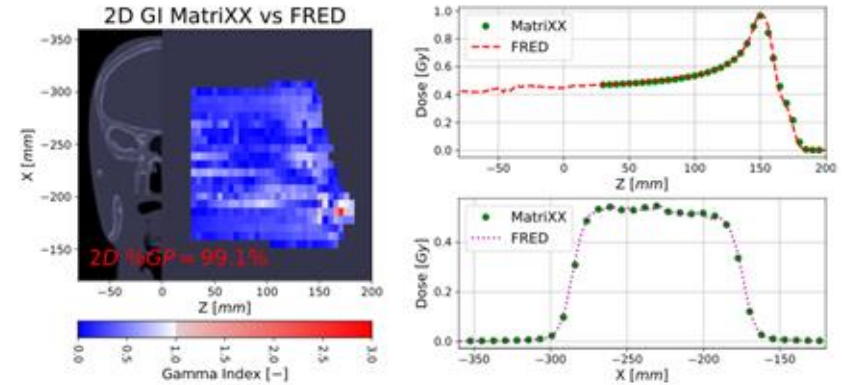
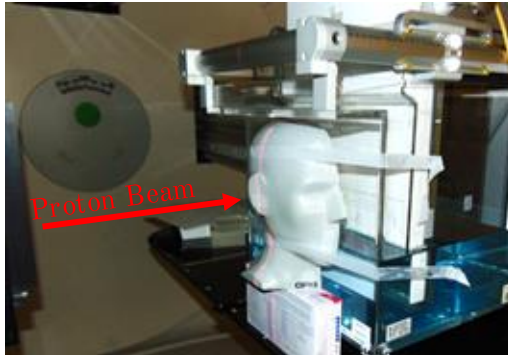
(a) CIRS phantom



(b)



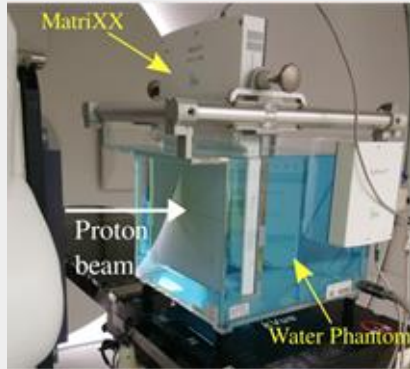
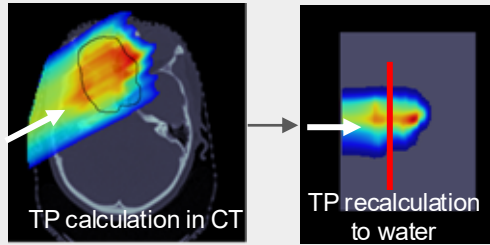
Mono layers:  
100/150/200 MeV



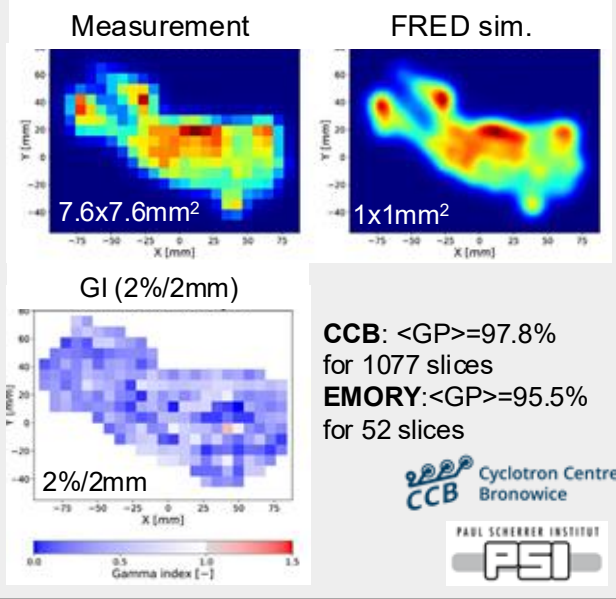
3D GI pass rate (2%/2 mm/2%) >99%


# FRED for patient specific QA

Multiple time consuming measurements per field

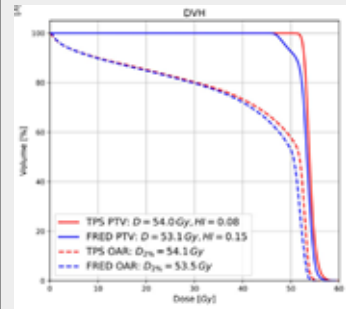
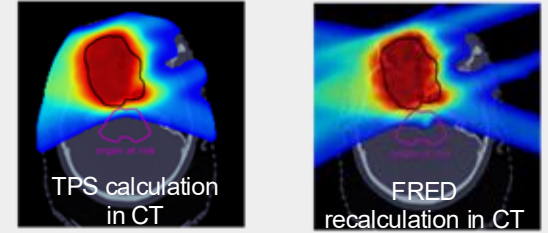


FRED dose calculation vs measurements in water




 2.5 min  
 $3.4 \cdot 10^6$  pps

FRED dose calculation in patient



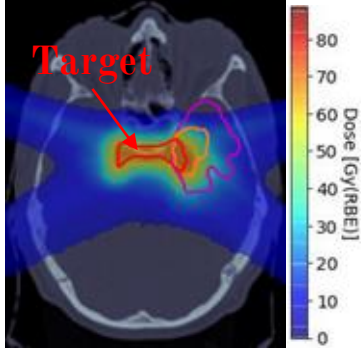
FRED sim:  
Res:  $1.5 \times 1.5 \times 1.5 \text{ mm}^3$   
Stat:  $10^4$  p+/PB  
(1% uncertainty)

**Maastr**

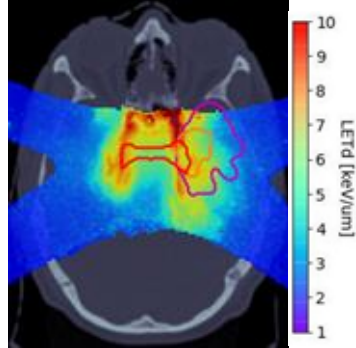
 2.5 min [20s; 6.5min]  
 $2.9 \cdot 10^5$  pps

# FRED to support treatment planning

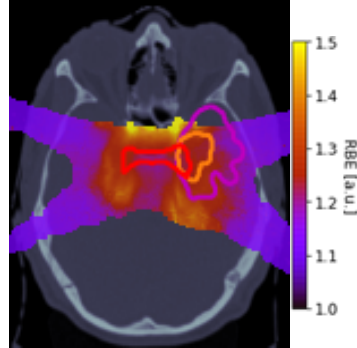
cRBE-weighted  
biological dose



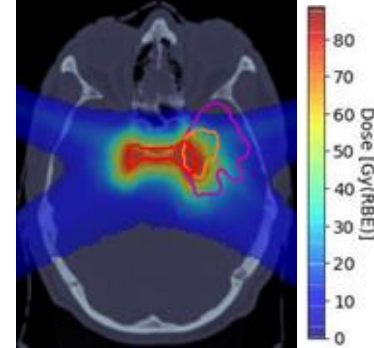
Dose-averaged LET  
Cortes-Giraldo et al., PMB (2015)  
Granville et al., PMB (2015)



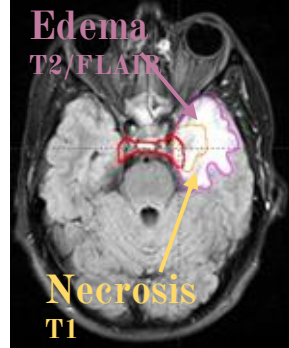
Variable RBE  
McNamara et al., PMB (2015)



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

$vRBE_{PTV-brain}$ ( $\alpha/\beta = 6$ Gy)	1.11 [1.07; 1.31]
$vRBE_{PTV-skull\ base}$ ( $\alpha/\beta = 4$ 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

# FRED for research - treatment planning studies

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



Brain (50 patients)	Maximum diff. D95 <sub>PTV</sub> [Gy(RBE)]	Maximum diff. D05 <sub>OAR-bra in stem</sub> [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*

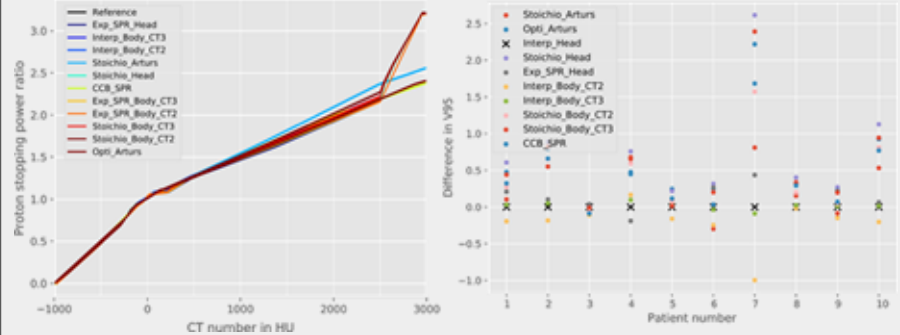


15 sim. x 50 patients = 750 sim.  
24 h

Dosimetric impact of CT calibration



12 CT calib. curves  
10 patients



*I. Rinaldi, N. Krahl, J. Gajewski*



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

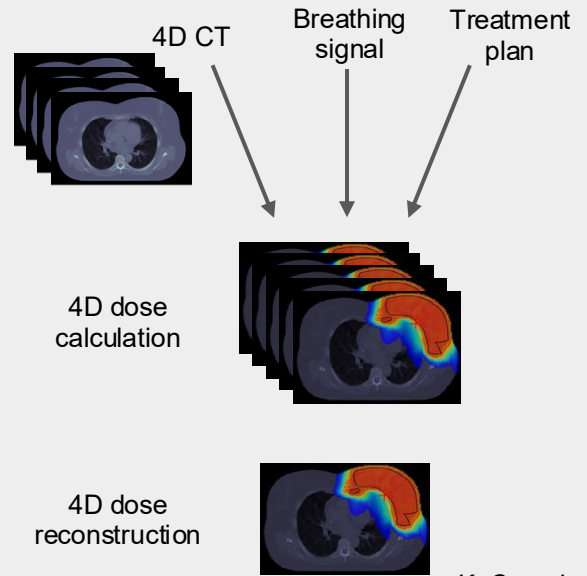


If we find a mistake, we just run FRED again

# FRED: ongoing developments for new applications

## 4D applications

Multiple geometries handled on GPU simultaneously

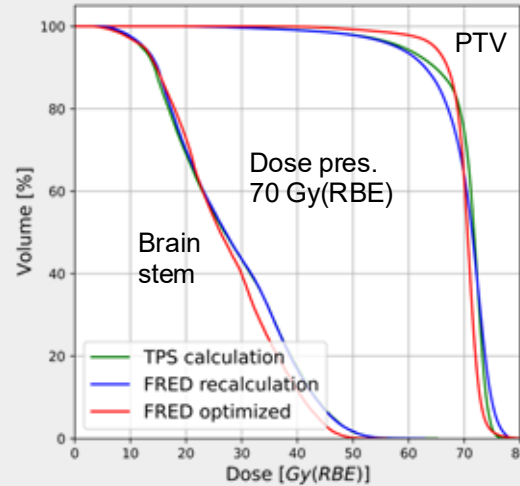


K. Czerska

## Fully GPU-based optimization

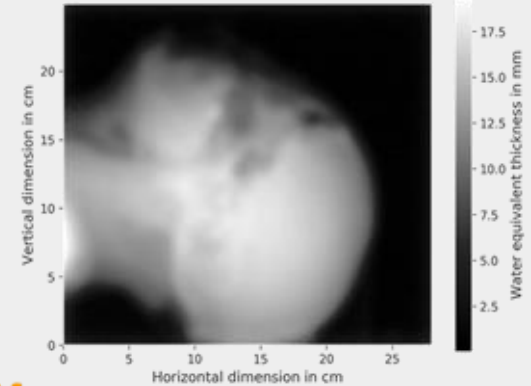
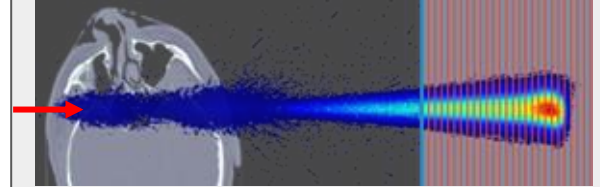
- MC-based influence matrix
- Inverse optimization algorithm

*A. Lomax 1999 PMB 44 185–205*



M. Dudek

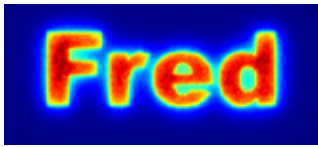
## Proton radiography and tomography



**Maastro** **CREATIS** *I. Rinaldi, N. Krahl*



8.5 min for influence matrix computation



# Collaboration



**V. Patera    A. Schiavi    M. De Simoni    G. Franciosini    G. Traini**  
**M. Palma, P. De Maria**



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

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S. Makkar  
J. Hrbacek  
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D. C. Weber



**I. Rinaldi    N. Krah**  
G. Vilches-Freixas

**C. Winterhalter    K. McNamara**

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