The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences

An Overview of FRED: A GPU-based Monte Carlo Tool for Proton Therapy

A Rucinski[1*], J Baran1[1], G Battistoni[2] , M Durante[3], J Gajewski[1], M Garbacz[1], C Granja[*], R Kopec[1], N Krah[4], G Mierzwinska[1], N Mojzeszek[1], C Oancea[*], V Patera[5], M Pawlik-Niedzwiecka[1], E Pluta[6], I Rinaldi[7], E Scifoni[8], A Skrzypek[1], F Tommasino[8], A Schiavi[5]

(1) Institute of Nuclear Physics PAN, Krakow, Poland
(2) INFN, Milan, Italy
(3) GSI Helmholtzzentrum für Schwerionenforschung, Technische Universität Darmstadt, Germany
(4) University Lyon, CNRS, CREATIS UMR 5220, Centre Lyon Berard, Lyon, France
(5) Sapienza University of Rome, Rome, Italy
(6) M. Sklodowska-Curie Institute OC, Krakow, Poland
(7) ZonPCT/Maastro clinic, Maastricht, Netherlands
(8) TIFPA, Trento, Italy
(*) Advacam, Prague, Czech Republic

ADVACAM Imaging the Unseen

European Funds Smart Growth

Republic of Poland

FNP Foundation for Polish Science

European Union European Regional Development Fund

Outline:

- FRED Monte Carlo code
- Automated implementation of the beam model phase space
- FRED validation
- FRED applications
- Current developments
- Conclusions

Krakow proton beam therapy centre, Poland

- IBA Proteus C-235
- Clinical operation from Oct 2016 **Eclipse TPS v.13.6**
- 2x Gantry (~200 H&N patients treated)
- Eye treatment room
- Experimental hall

Krakow proton beam therapy centre, Poland

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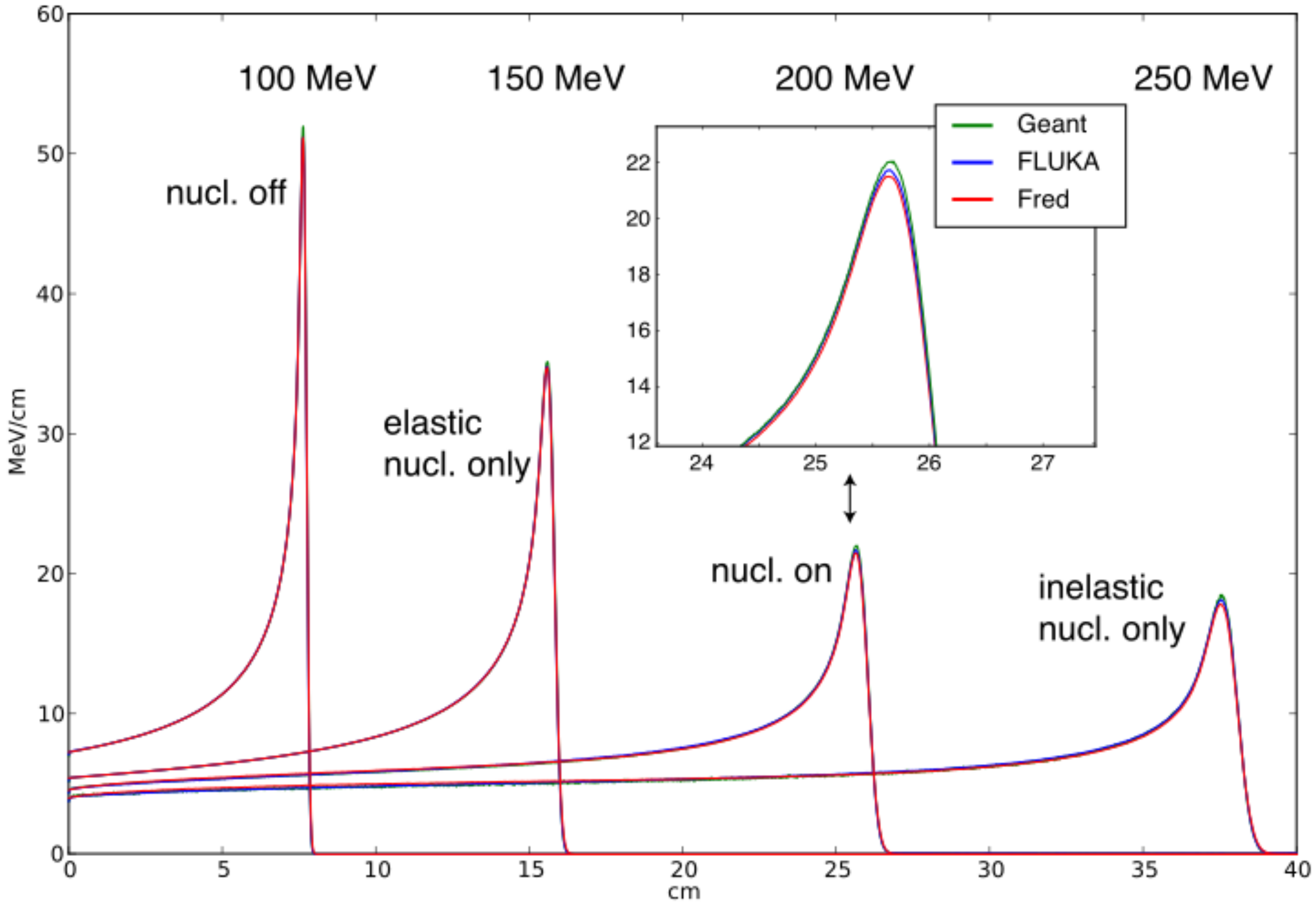
FRED, GPU-accelerated Monte Carlo code

[Schiavi et al. 2017, PMB]

SAPIENZA UNIVERSITÀ DI ROMA

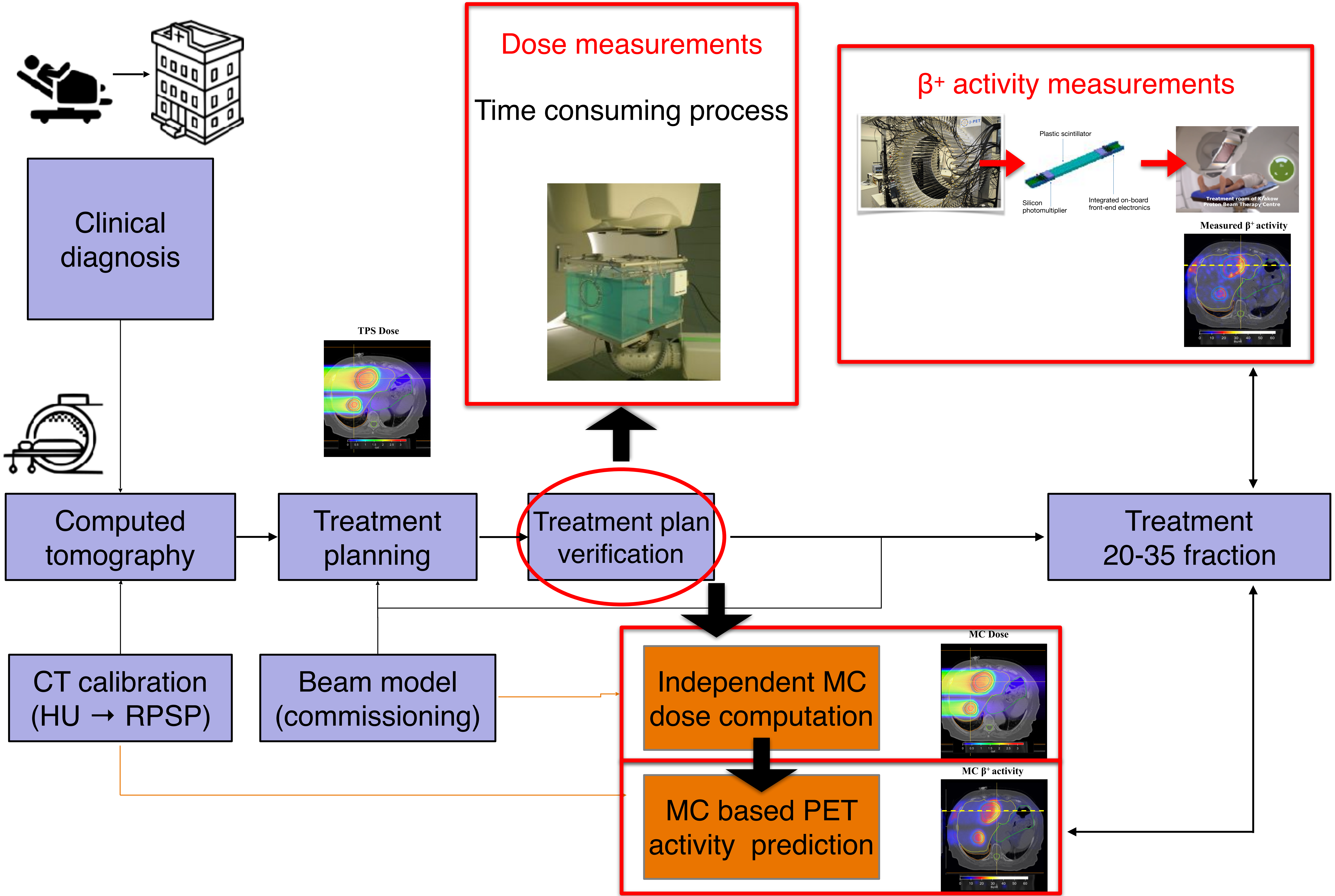
- In-house developed at Sapienza University of Rome
- Condensed history for continuous processes (dE/dx, MCS, energy loss fluctuations)
- Single steps for nuclear events
- **Acceleration x1000 (tracking rate 10^6 p^+/s)**:
  - x10 - physics processes mainly contributing to the proton dose deposition
  - x100 - parallelisation on GPU.

FRED, GPU-accelerated Monte Carlo code



[Schiavi et al. 2017, PMB]

Proton therapy treatment

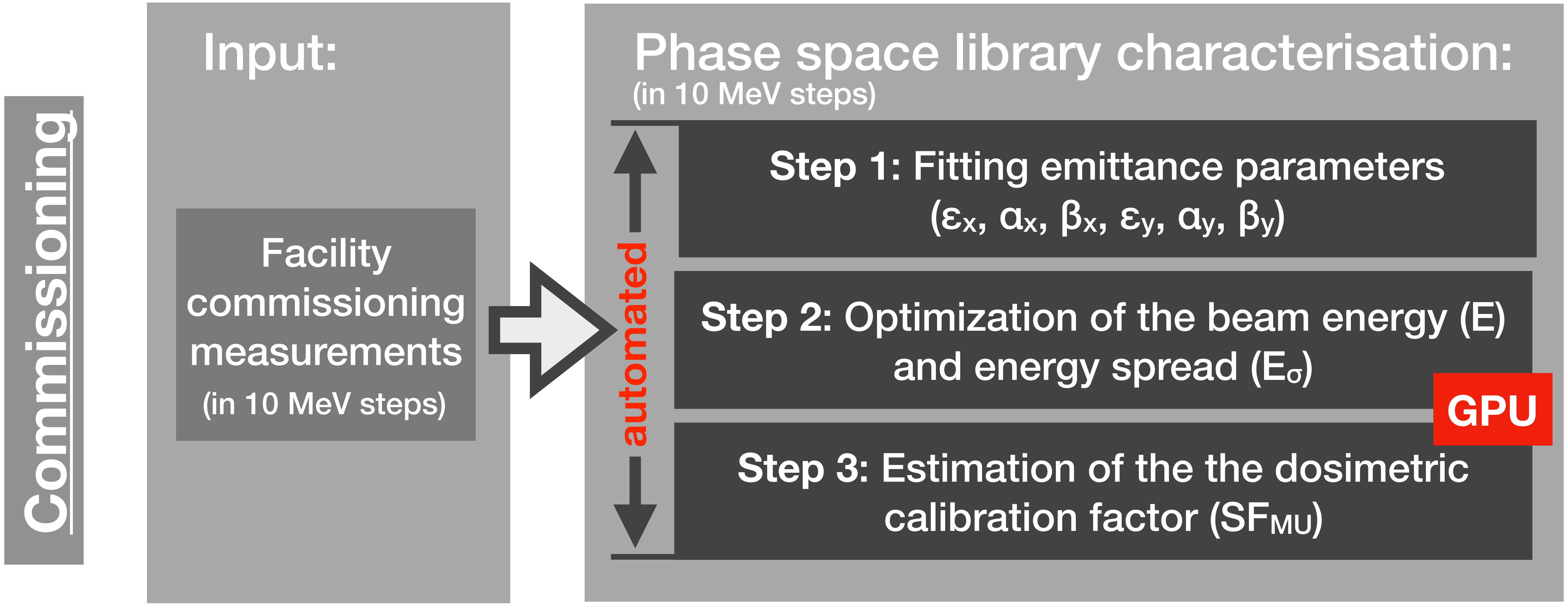


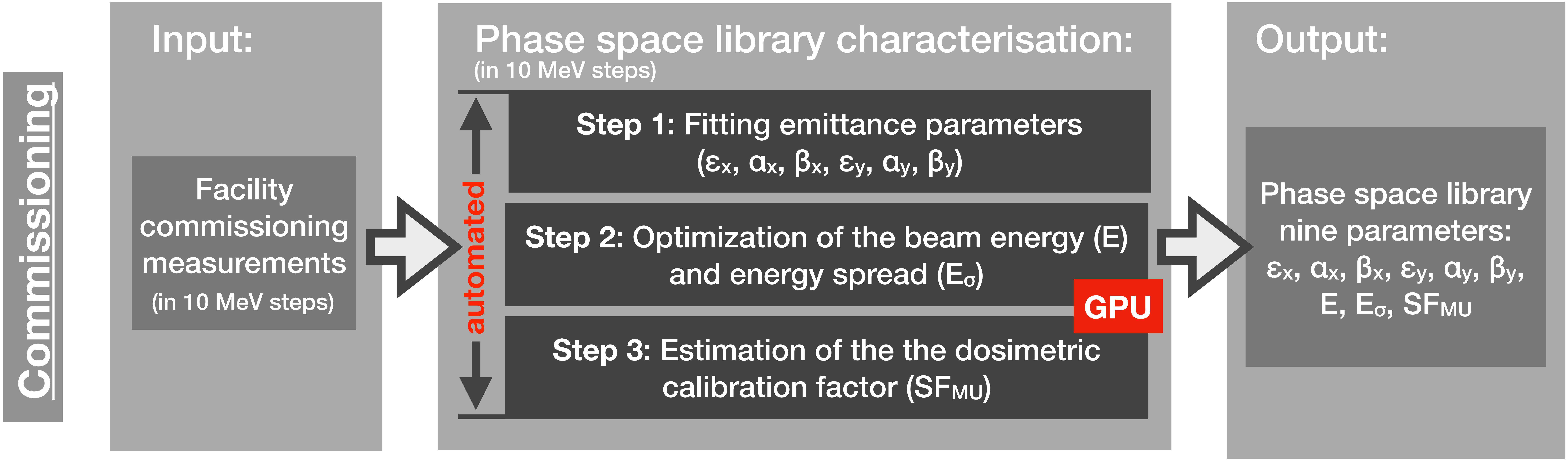
Automated implementation of the beam model phase space library in FRED

Commissioning

Input:

Facility commissioning measurements
(in 10 MeV steps)


Commissioning
Input:
Facility commissioning measurements
(in 10 MeV steps)
Phase space library characterisation:
(in 10 MeV steps)
automated
Step 1: Fitting emittance parameters
(ε_x, α_x, β_x, ε_y, α_y, β_y)
Step 2: Optimization of the beam energy (E)
and energy spread (E_σ)
GPU
Step 3: Estimation of the the dosimetric
calibration factor (SF_{MU})


Commissioning
Input:
Facility commissioning measurements
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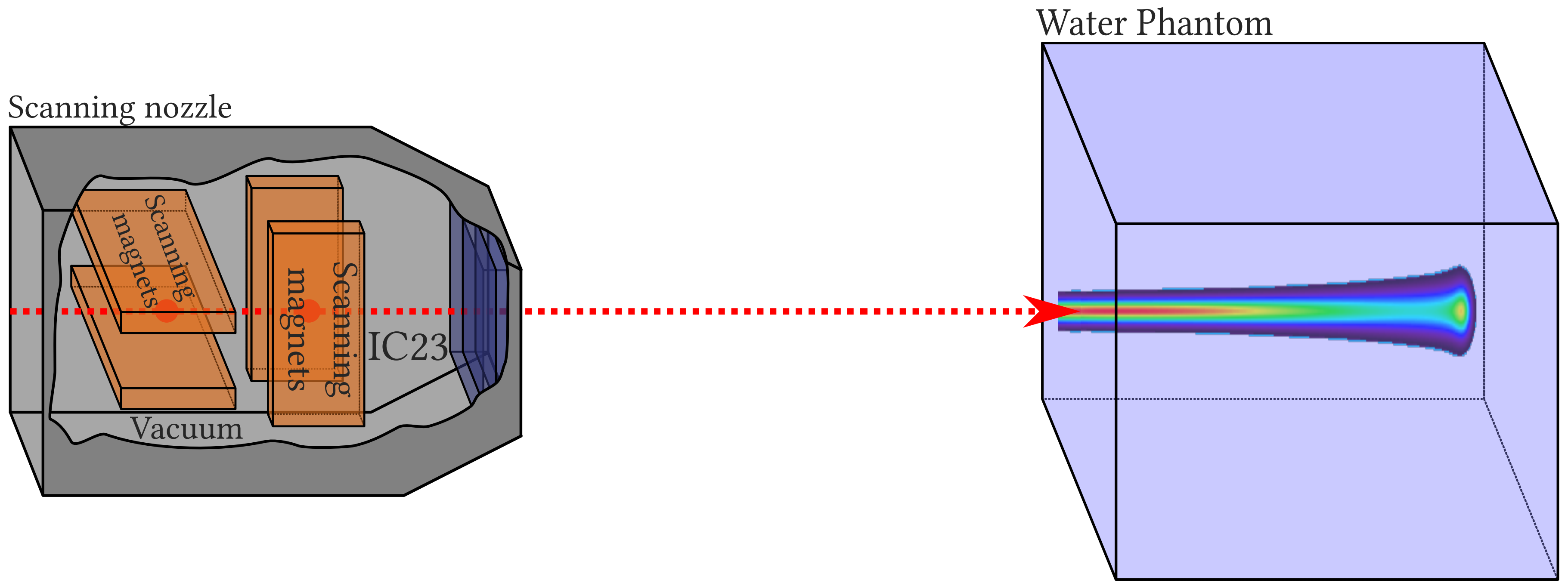
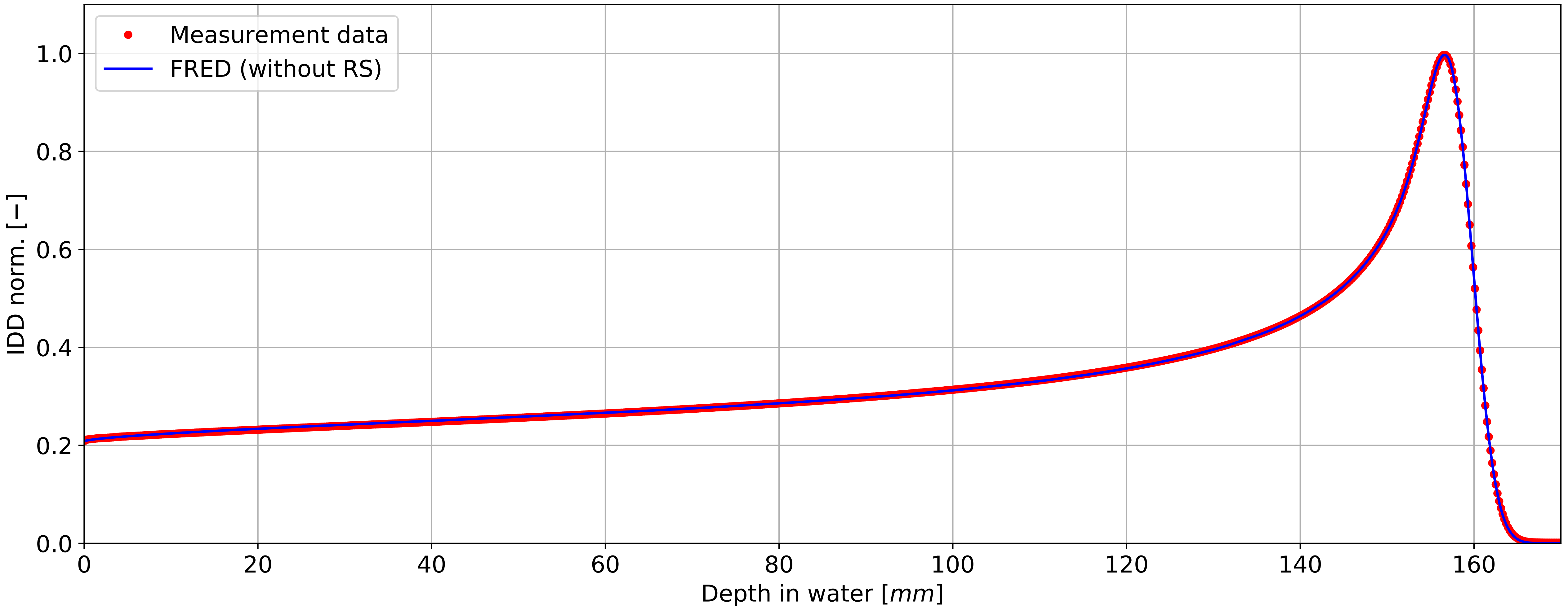
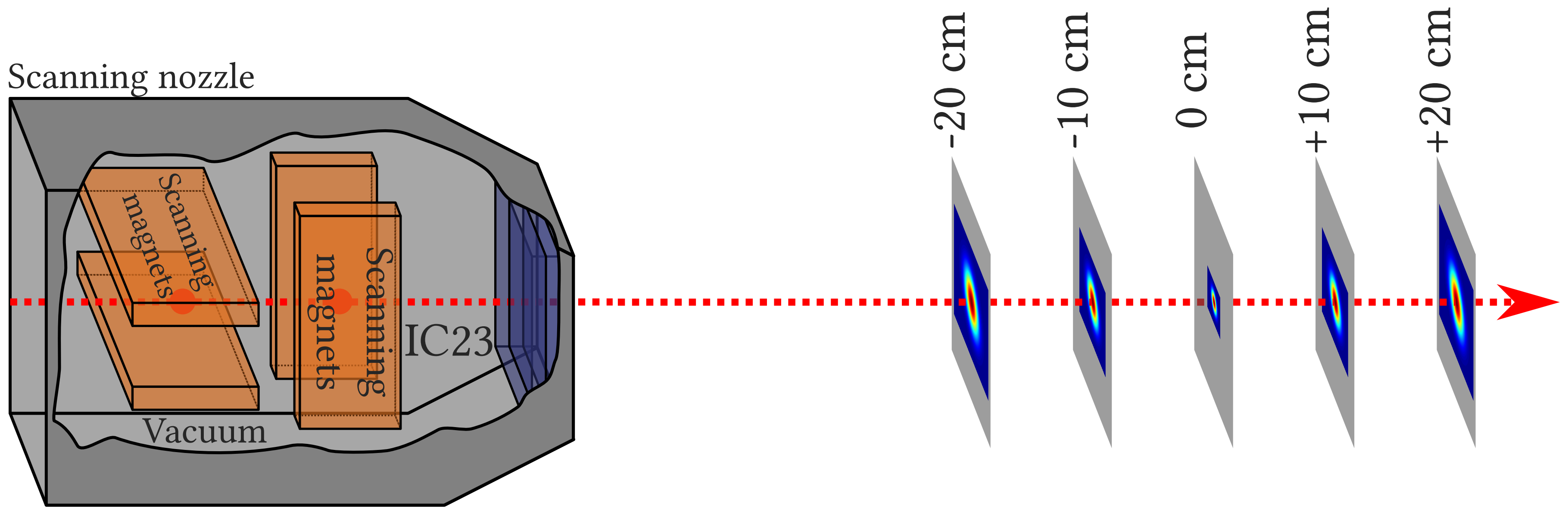
Phase space library characterisation:
(in 10 MeV steps)
automated
Step 1: Fitting emittance parameters
(εx, αx, βx, εy, αy, βy)
Step 2: Optimization of the beam energy (E)
and energy spread (Eσ)
GPU
Step 3: Estimation of the the dosimetric
calibration factor (SFMU)
Output:
Phase space library
nine parameters:
εx, αx, βx, εy, αy, βy,
E, Eσ, SFMU

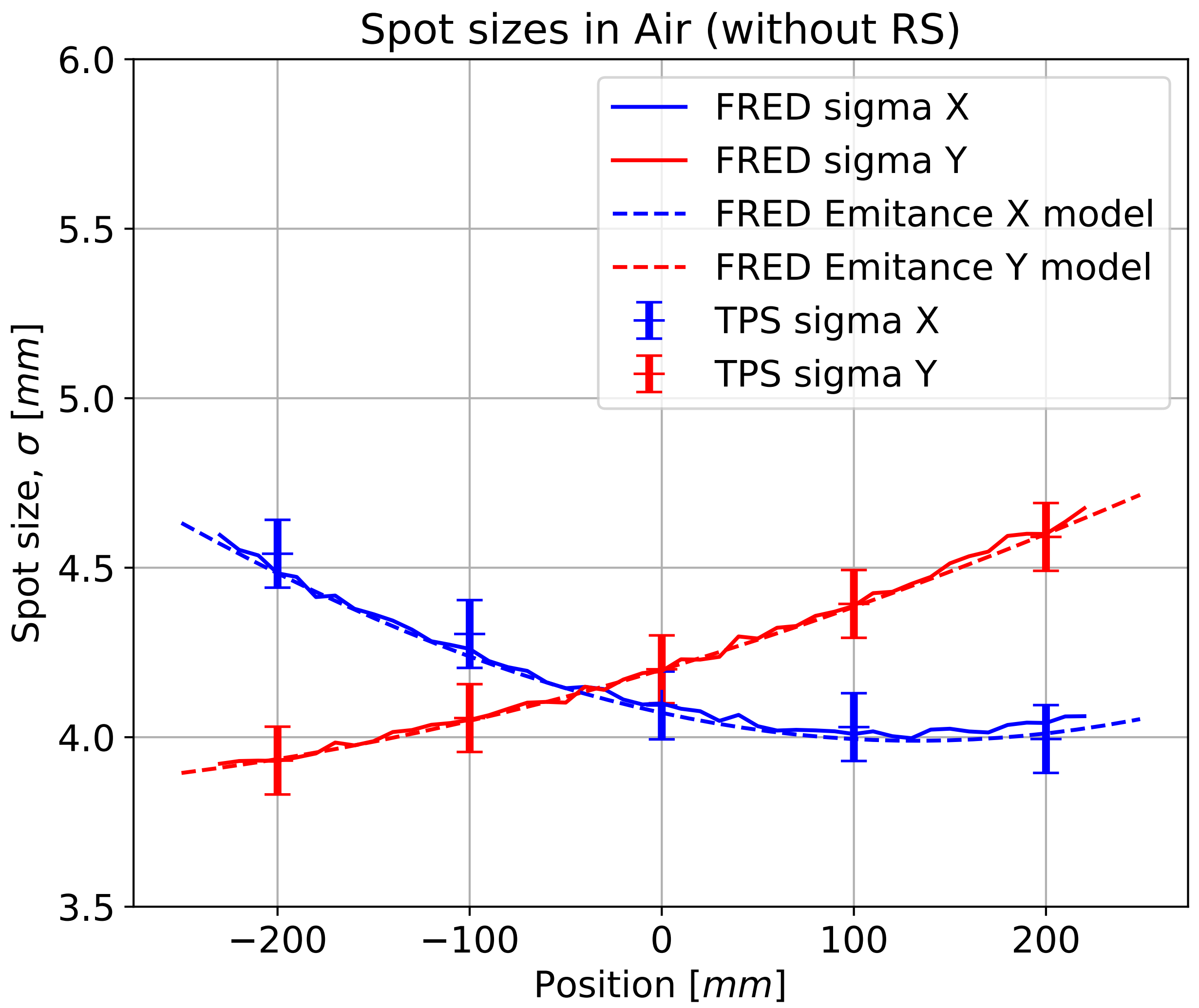
Beam model phase space library in FRED





p⁺ @150 MeV

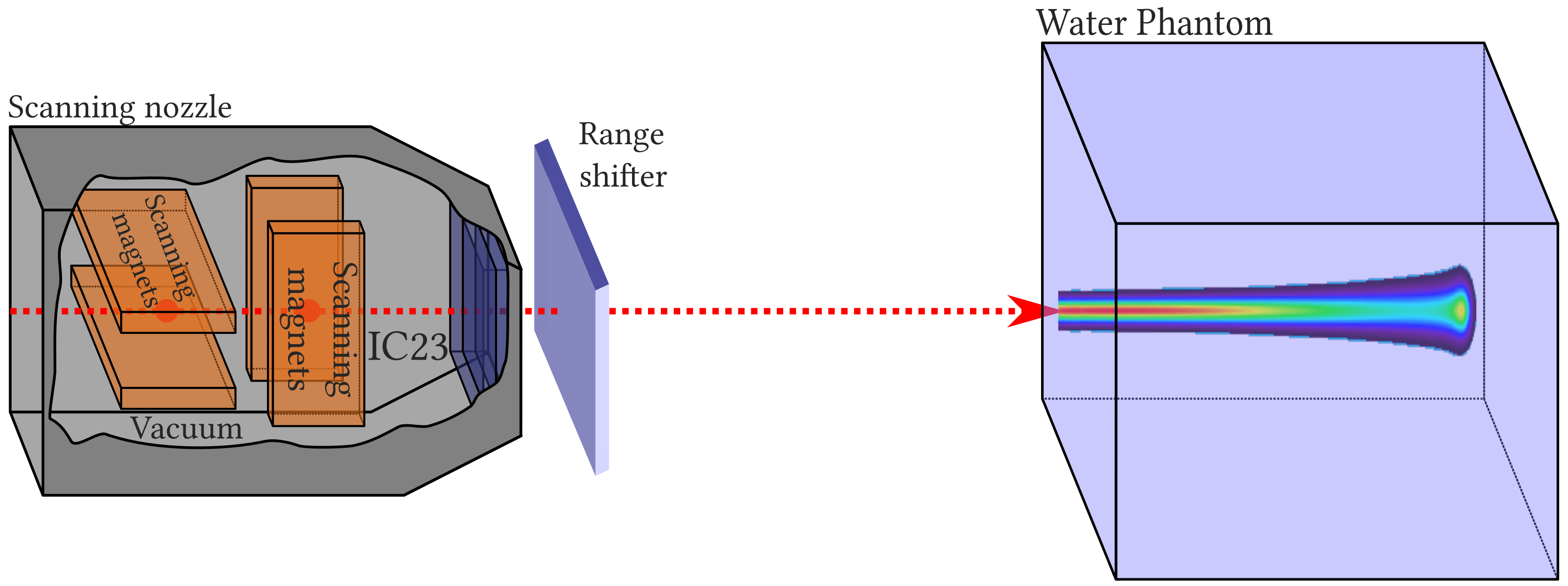


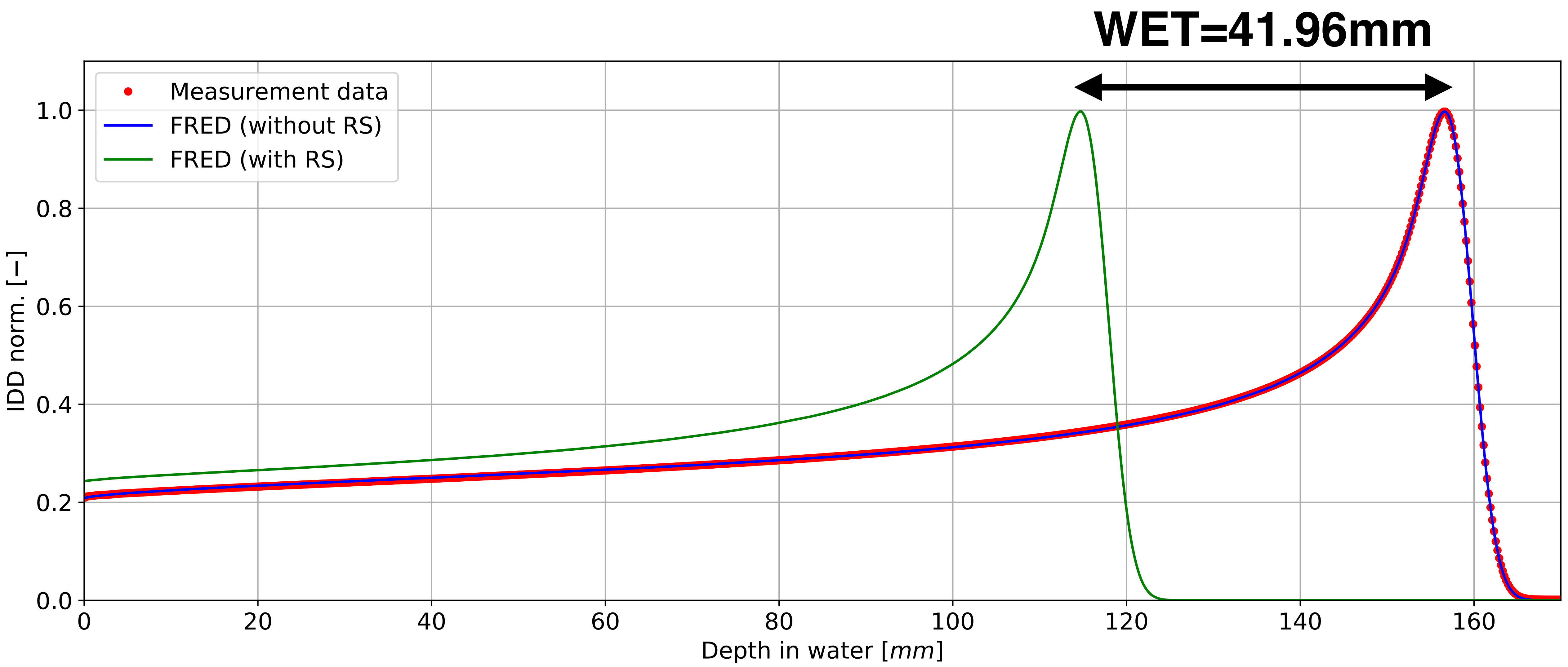


Submillimeter agreement

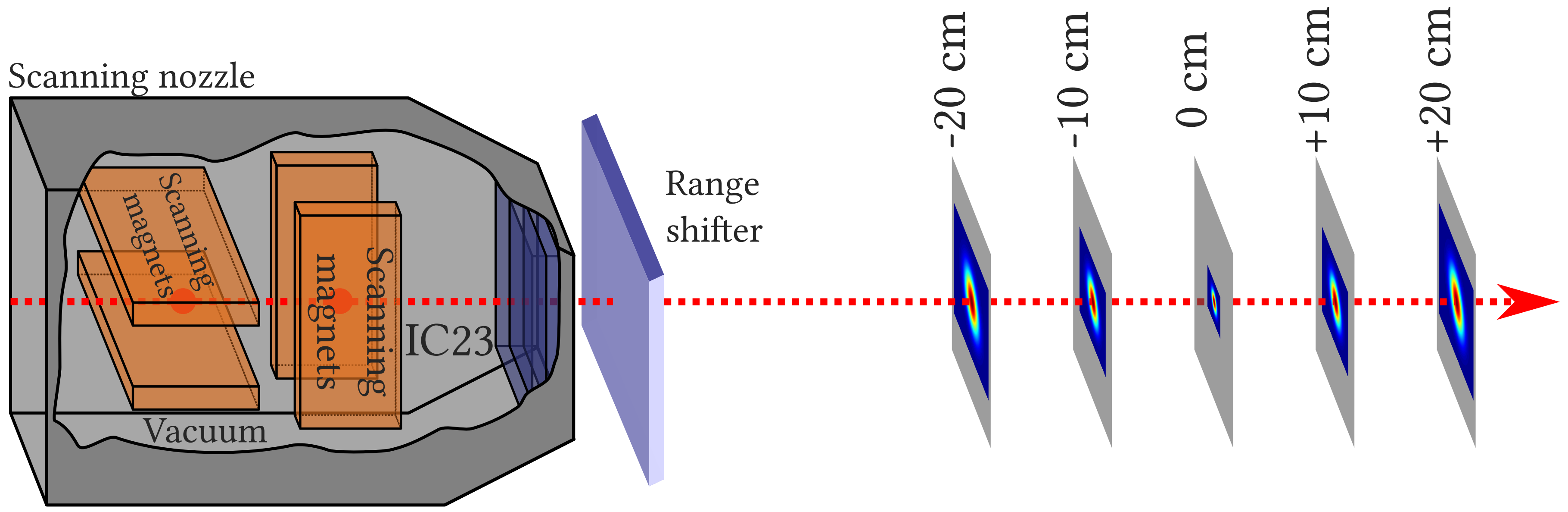
Beam model phase space library in FRED

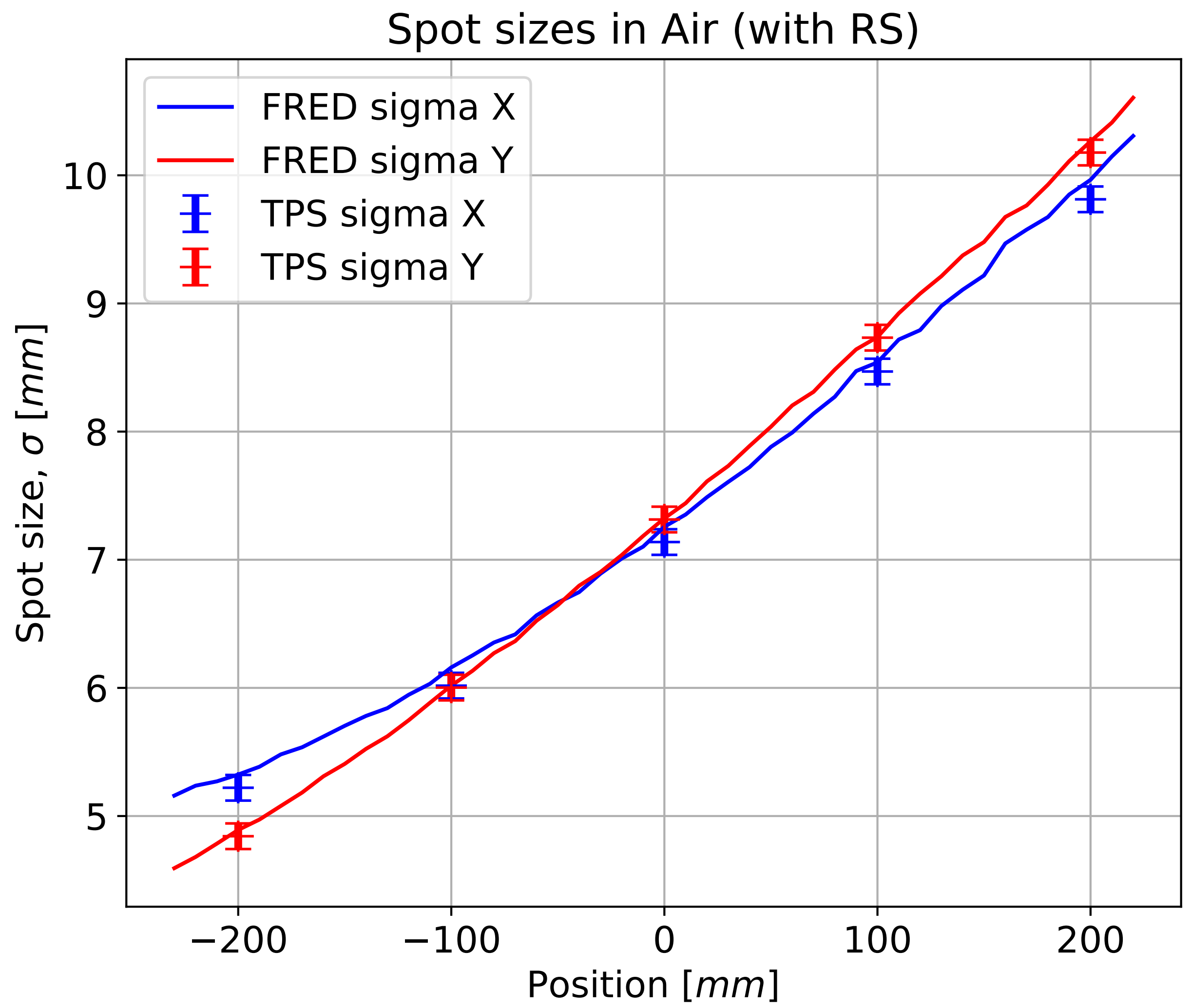
Range Shifter





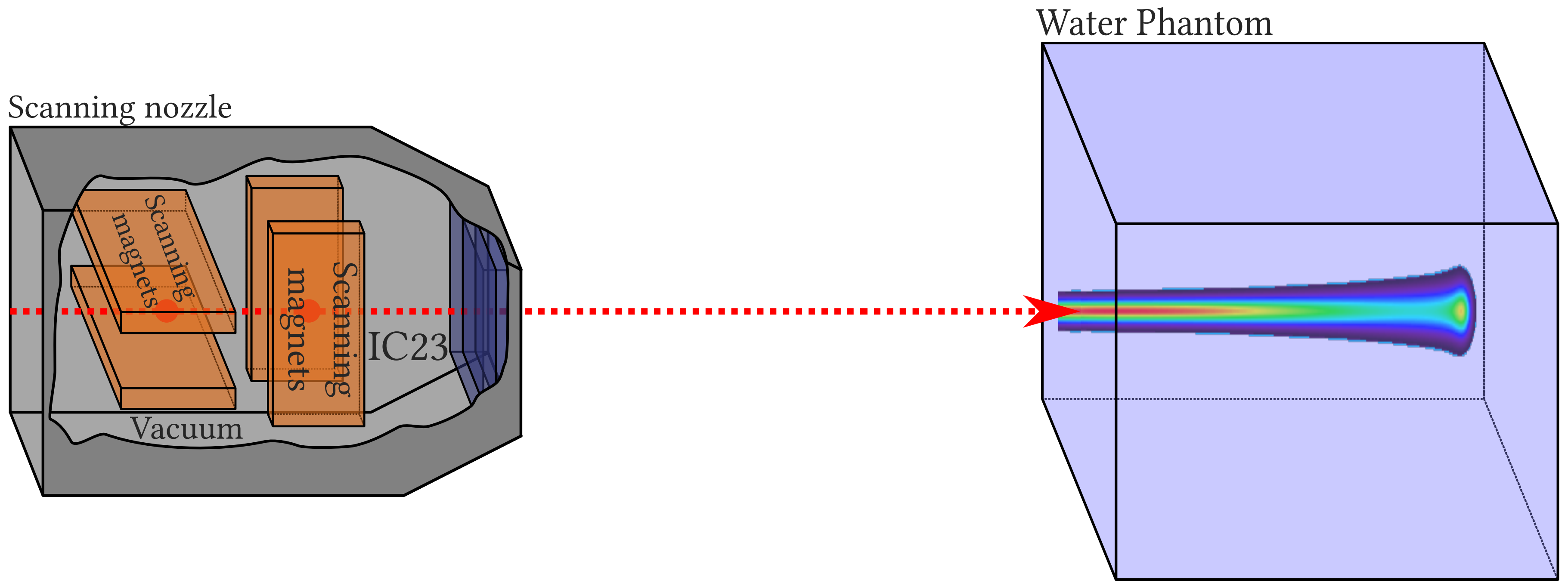
p+ @150 MeV

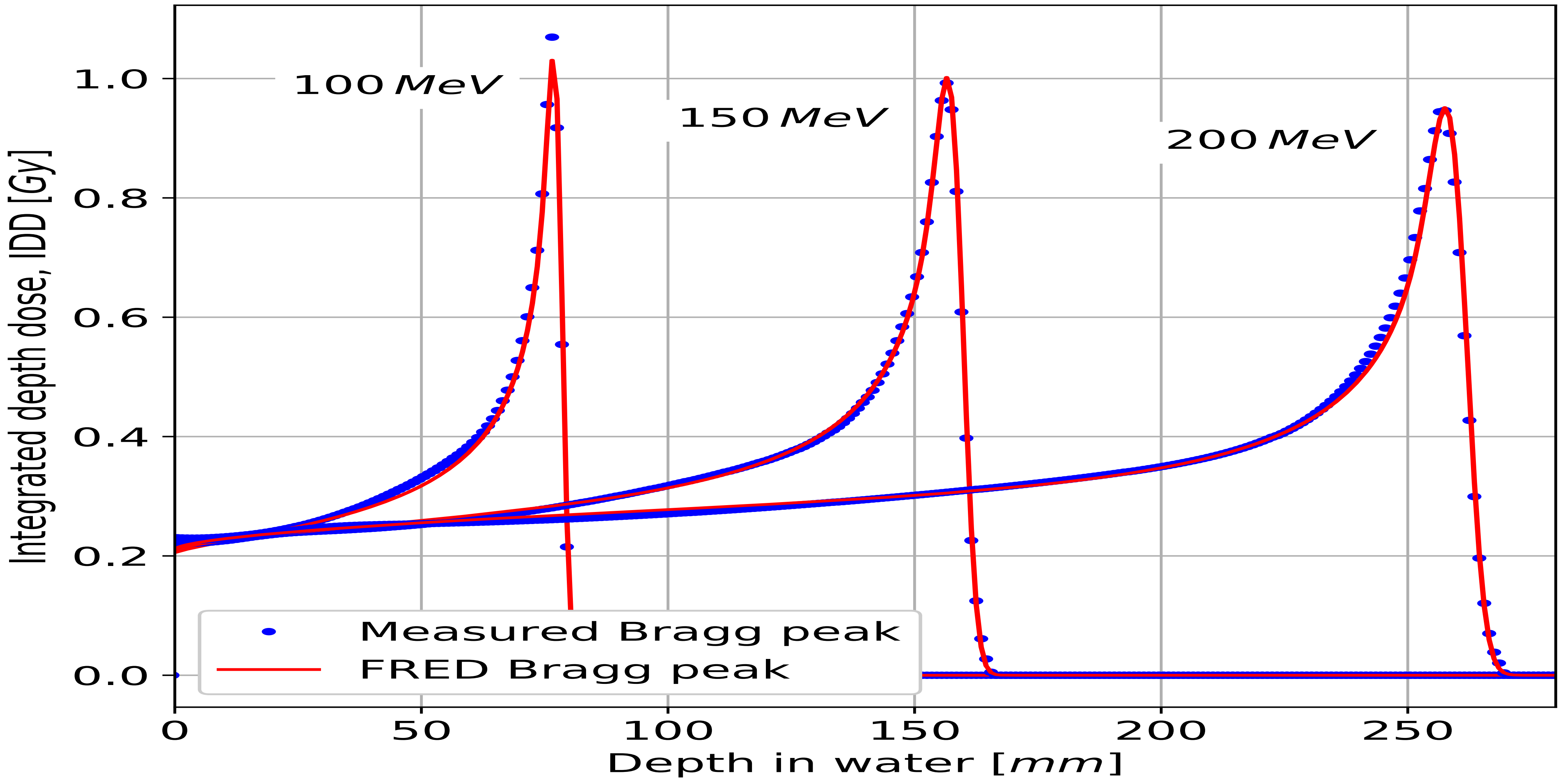




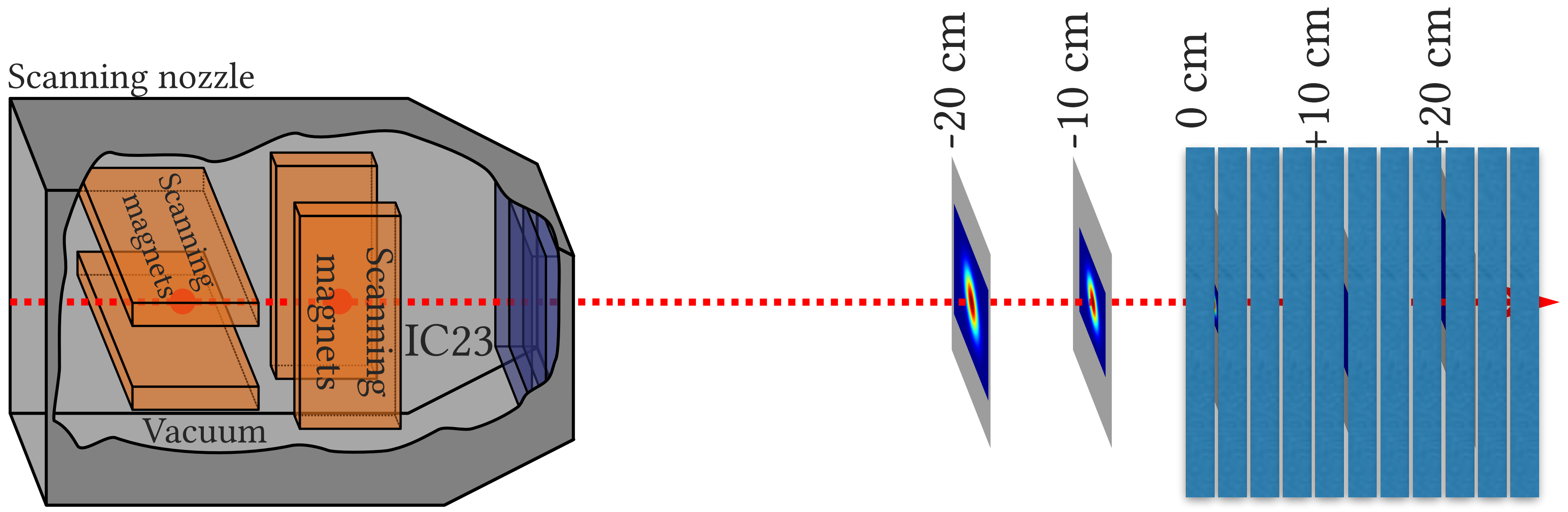
Submillimeter agreement

Beam model phase space library in FRED

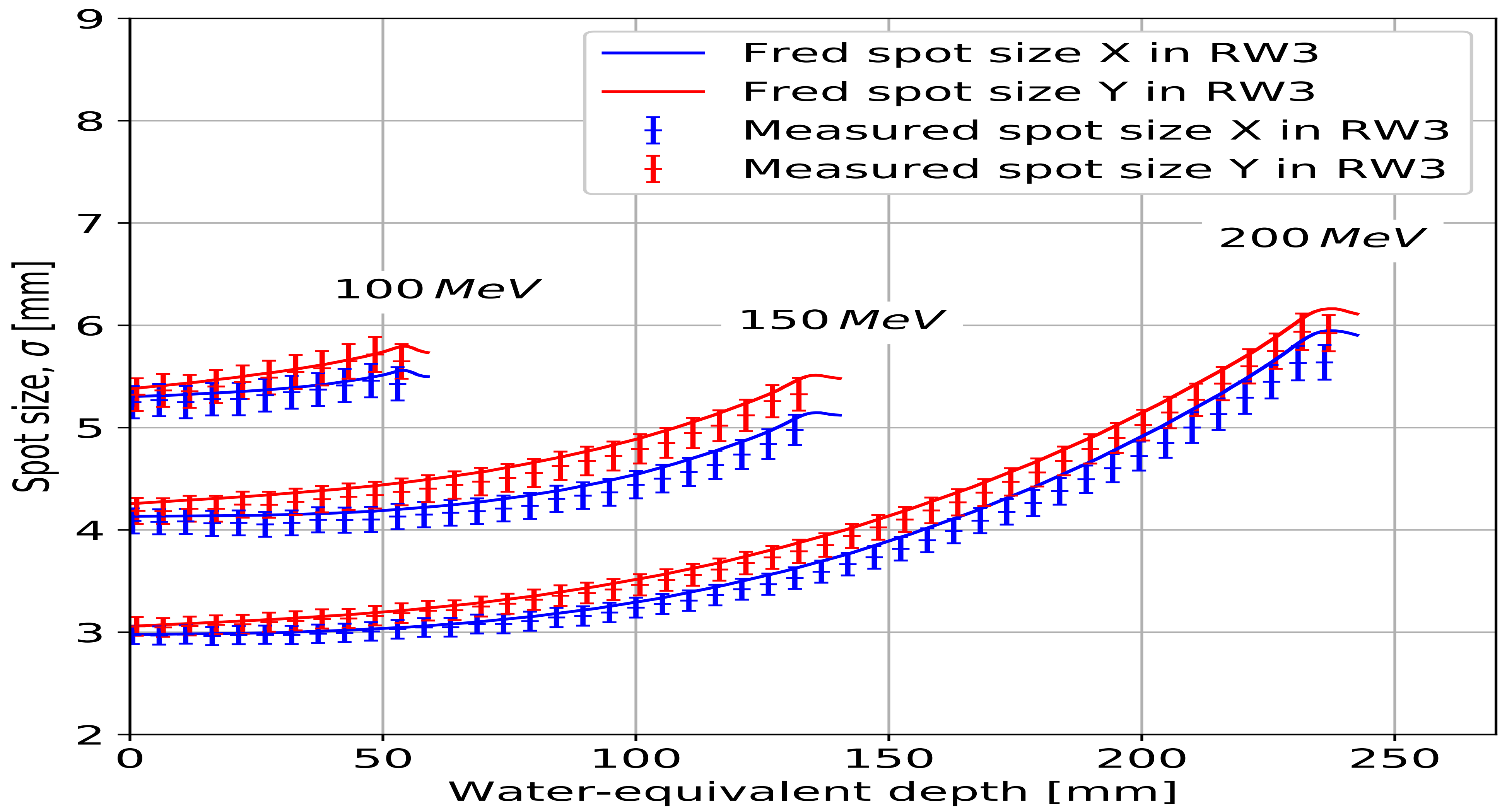




p+ @100, 150, 200 MeV

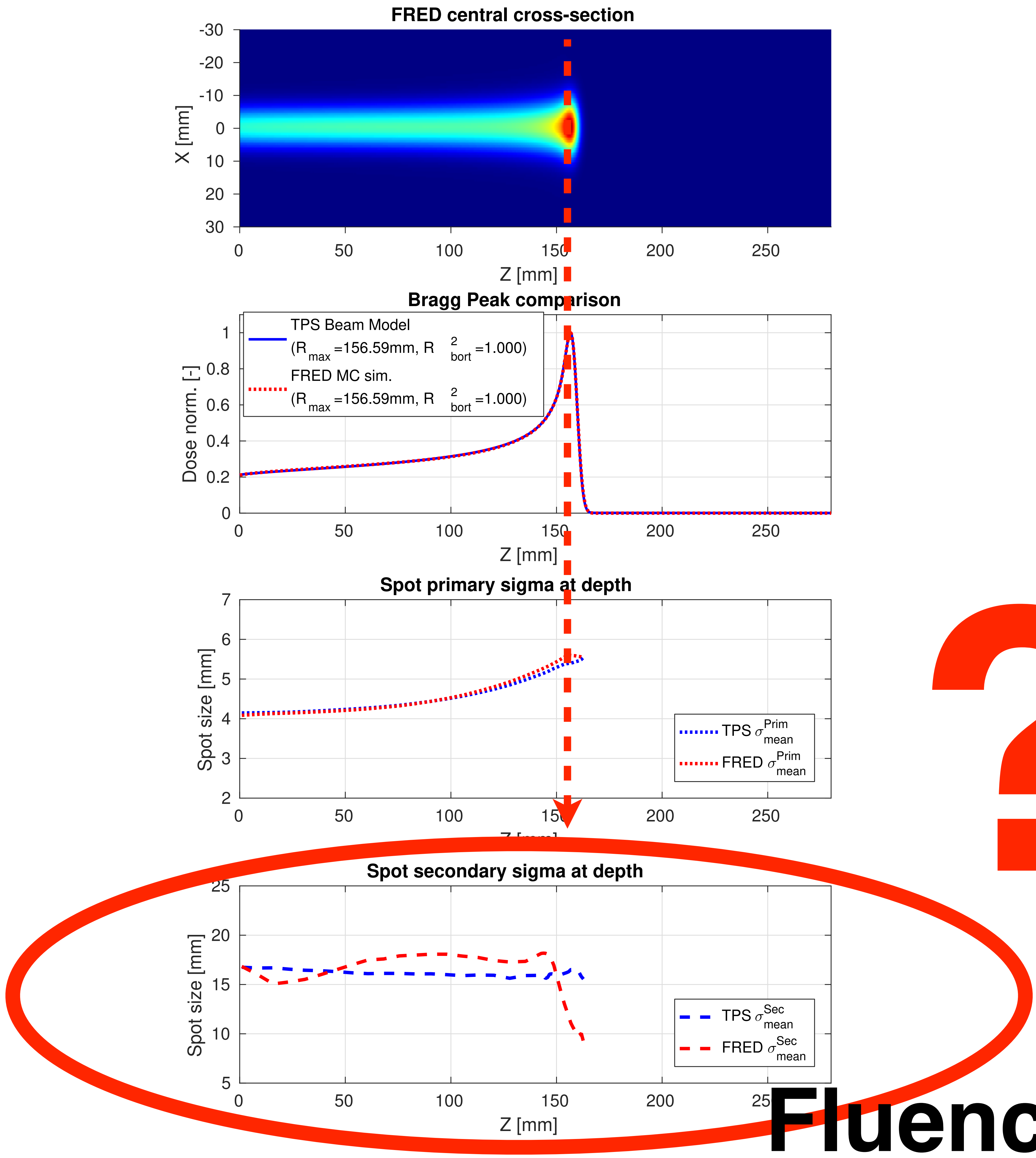


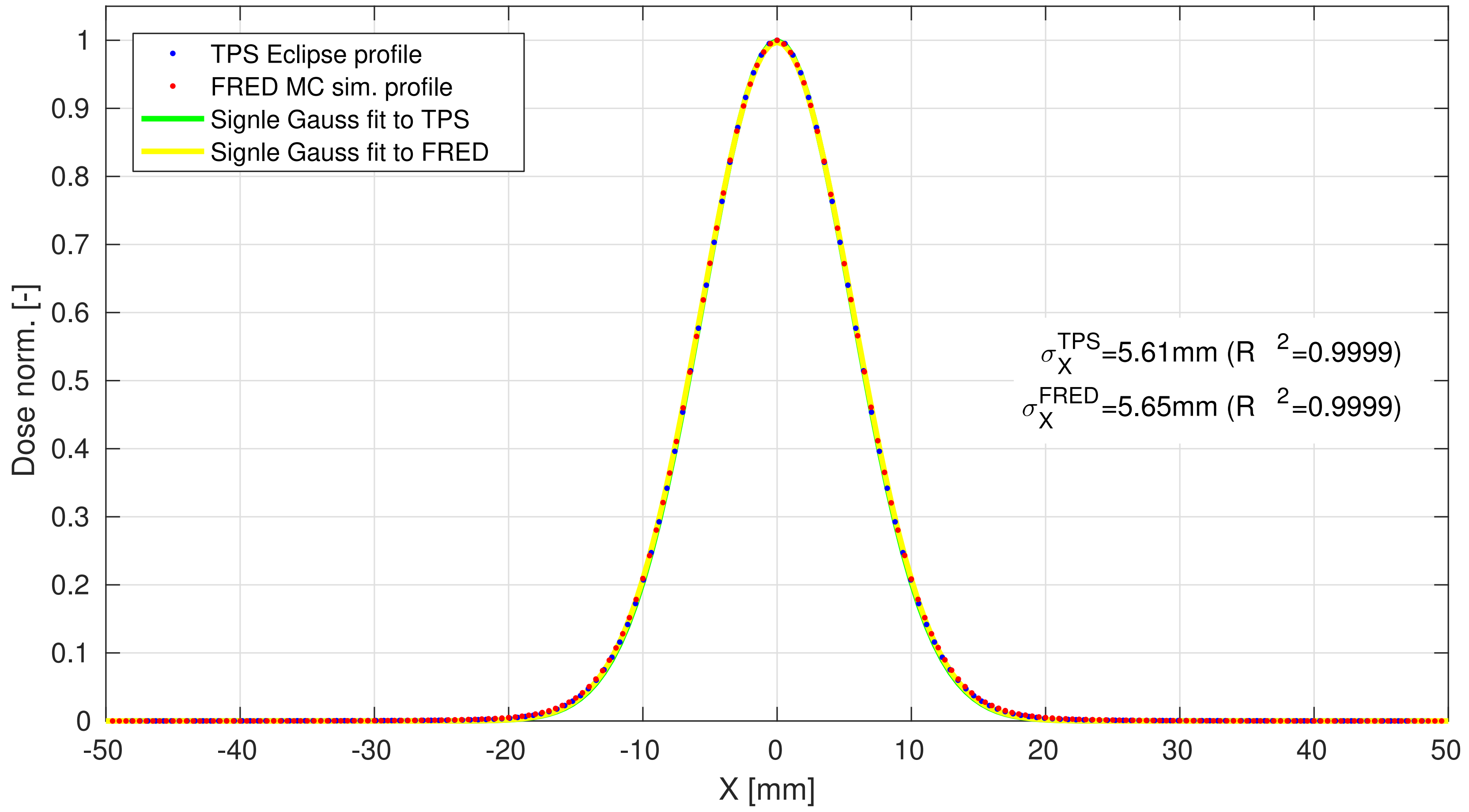
RW3 slab phantom



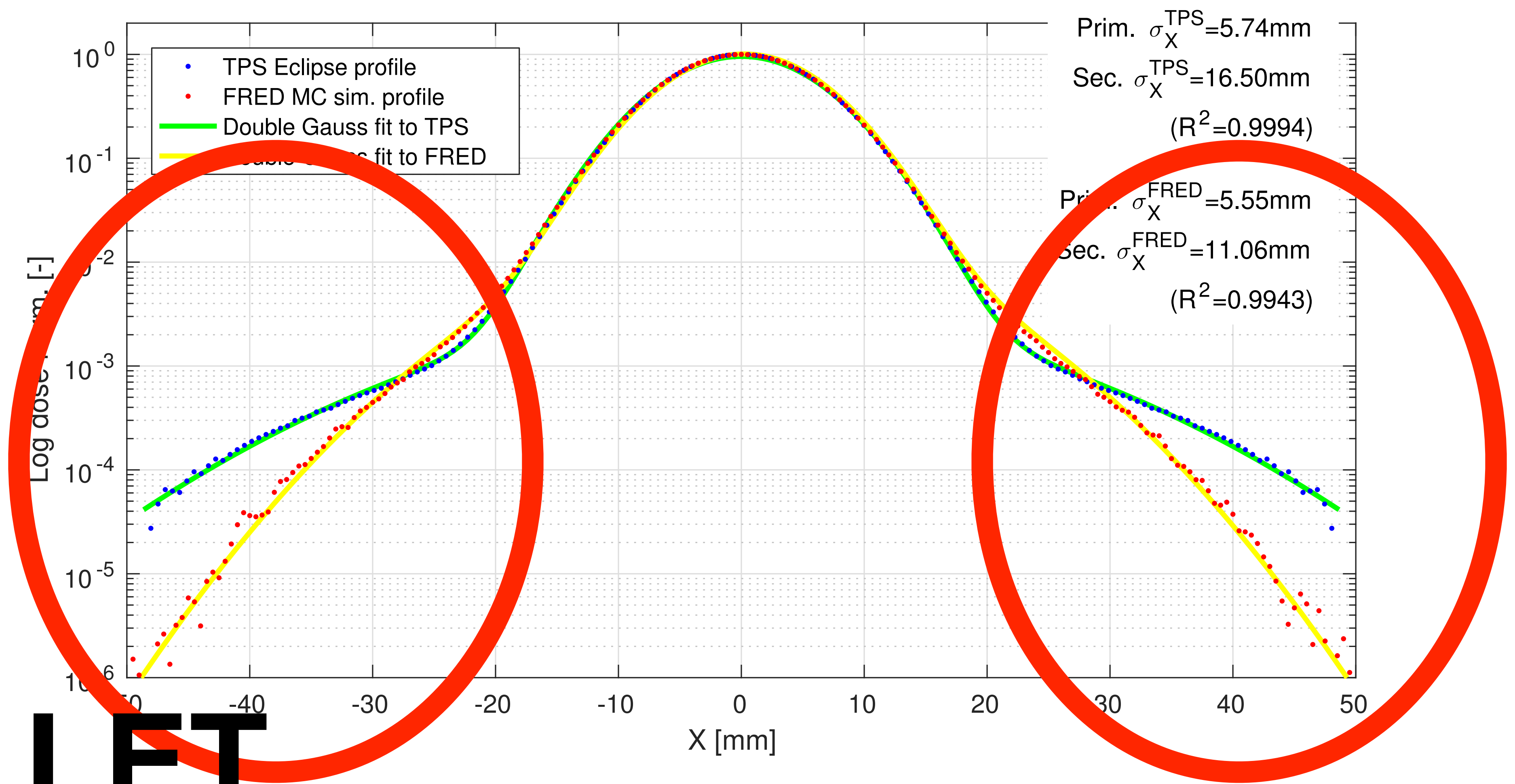
What about the secondary sigma?

p⁺ @150 MeV





?



Fluence, LET

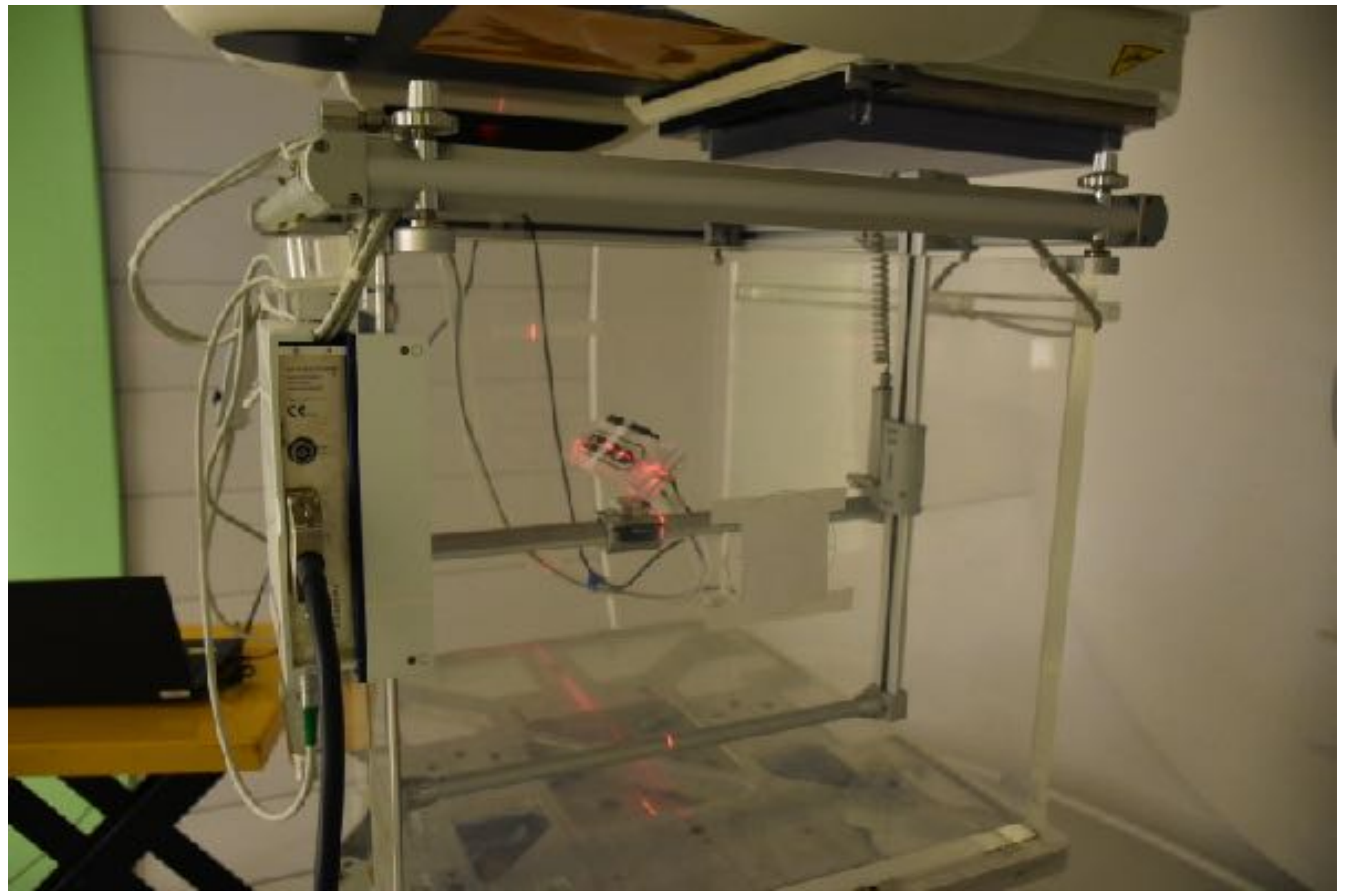
What about the secondary sigma?

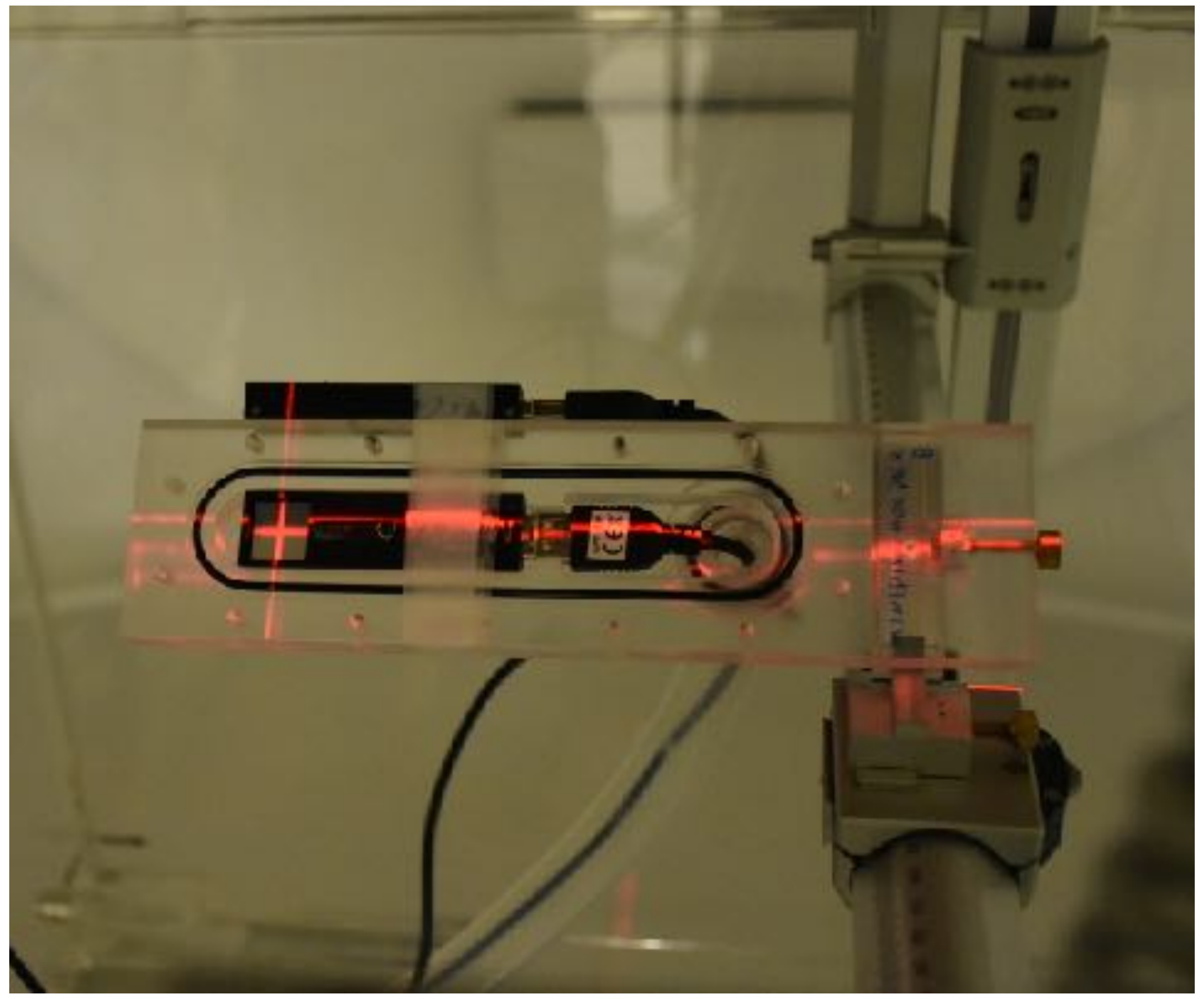
MiniPix TimePix
from Advacam

Sensor Thickness: 300 μm for Si
Sensitive Area: 14 mm x 14 mm
Number of Pixels: 256 x 256
Pixel Pitch: 55 μm
Readout Speed: 45 frames/s

+

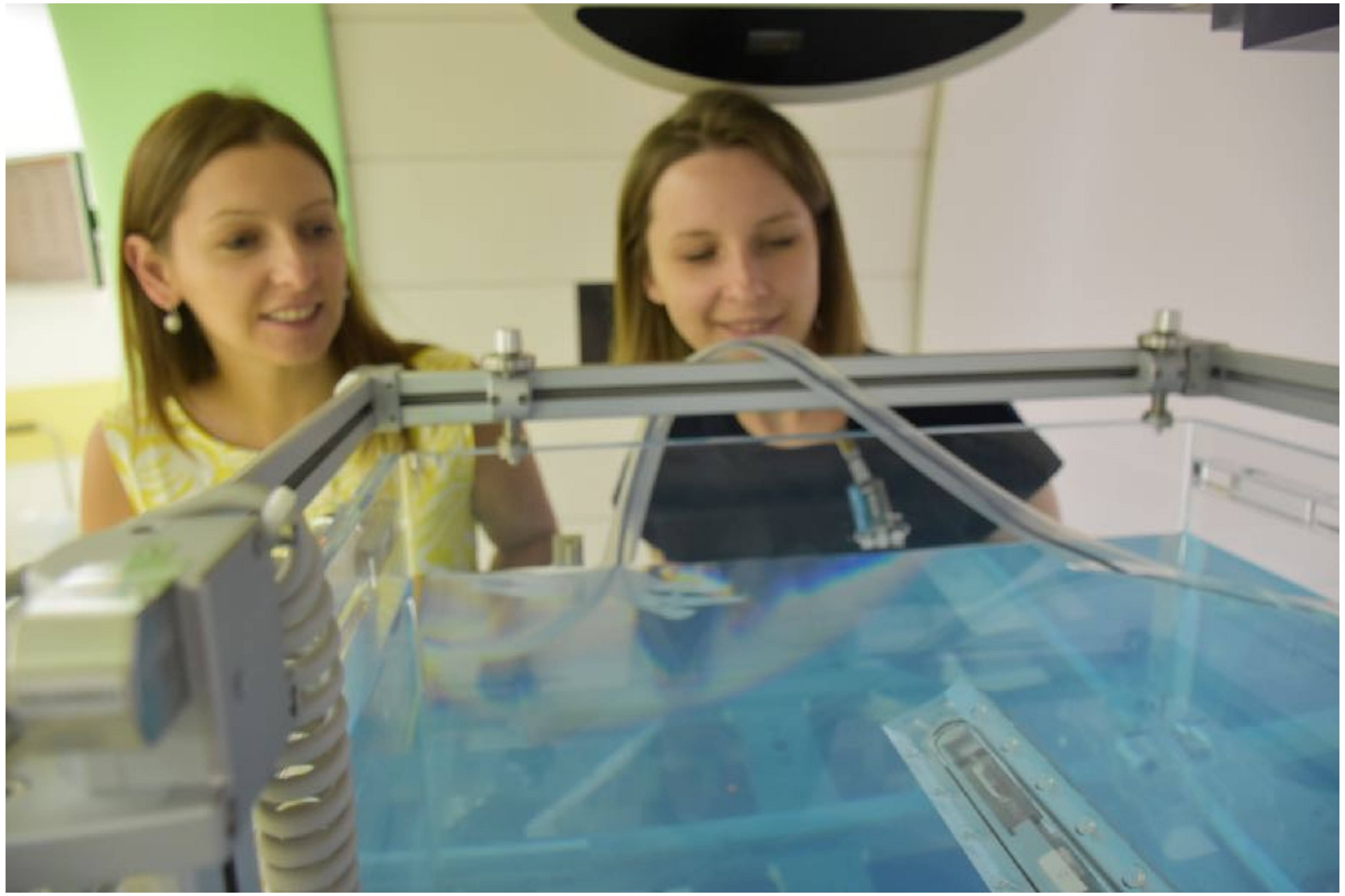
Water phantom
+
Submarine

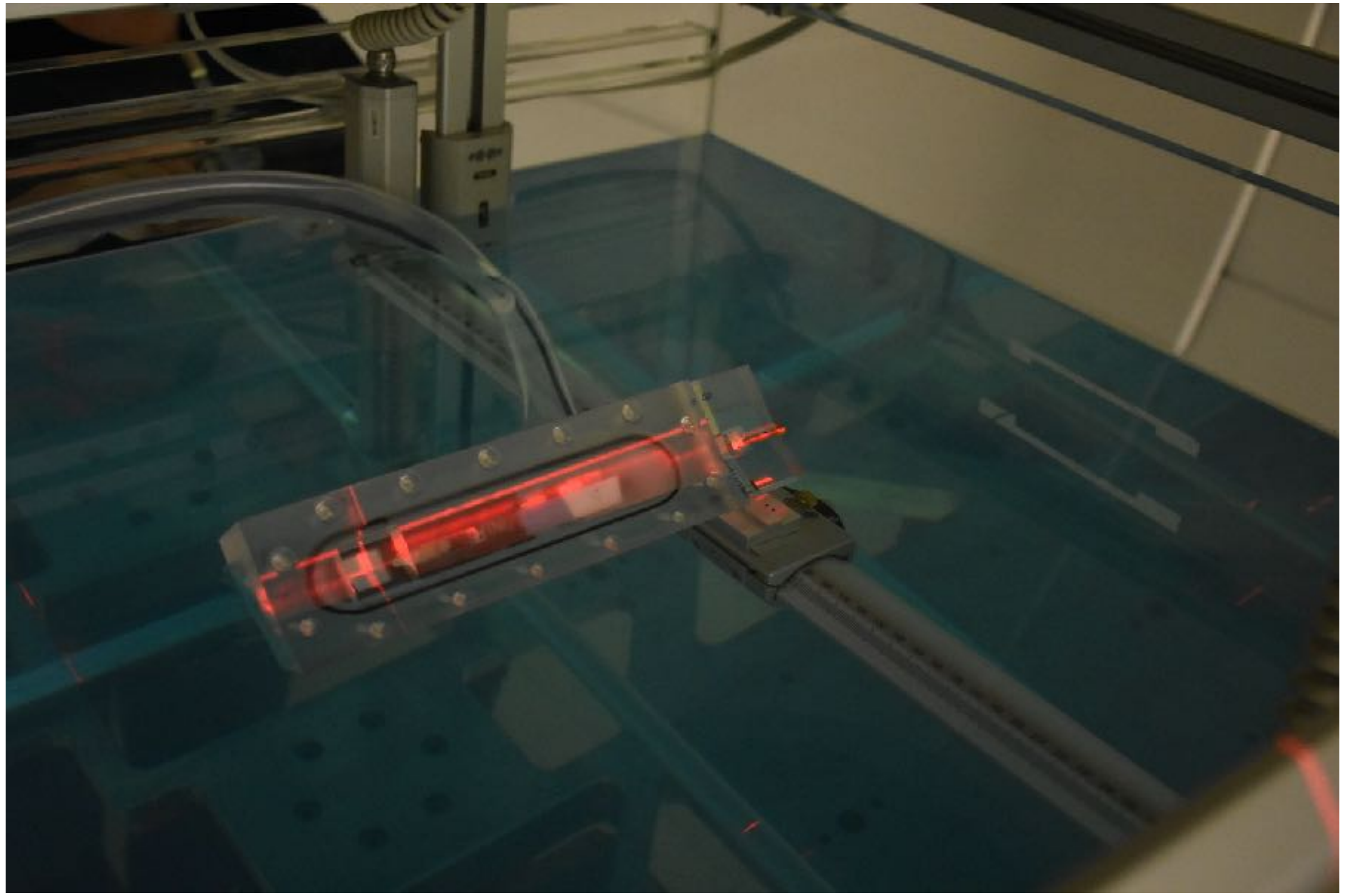




Antoni Rucinski INSTITUTE OF NUCLEAR PHYSICS PAN
antoni.rucinski@ifj.edu.pl antoni.rucinski@gmail.com web: www.ifj.edu.pl/dept/no6/nz62/ar/

Proton beam characterisation in water



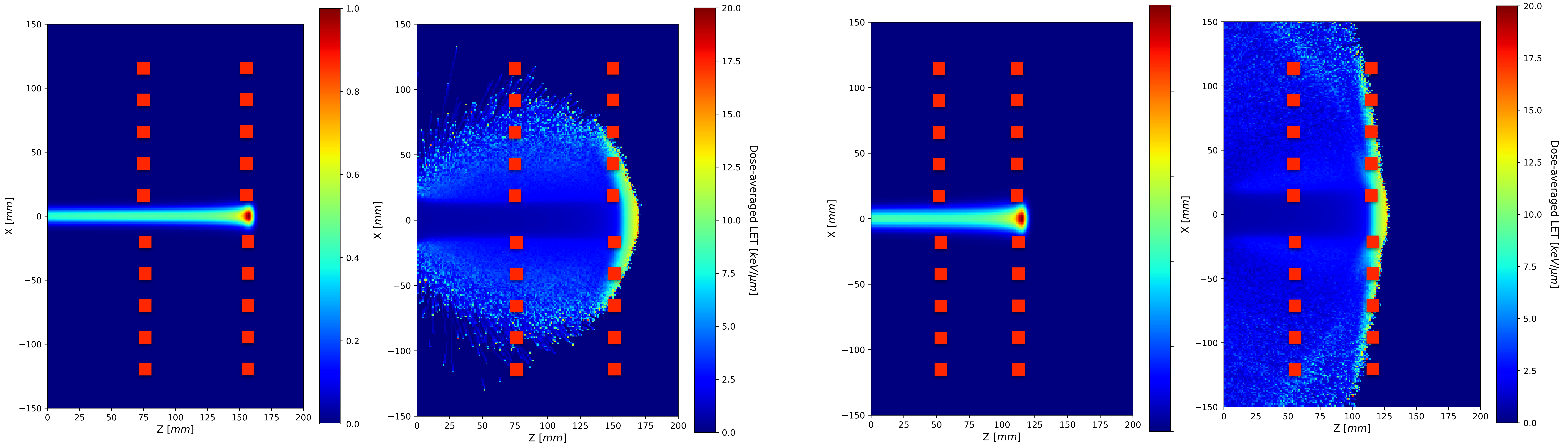


Proton beam characterisation in water

p+, 1nA, clinical mode, 150 MeV

no Range shifter

Range shifter

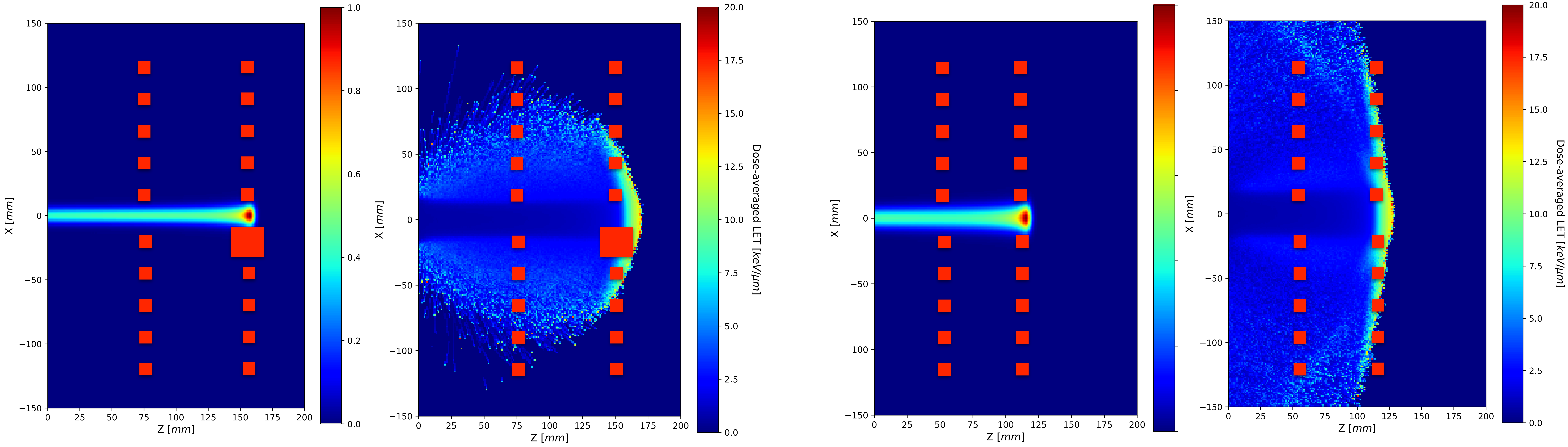


Proton beam characterisation in water

p+, 1nA, clinical mode, 150 MeV

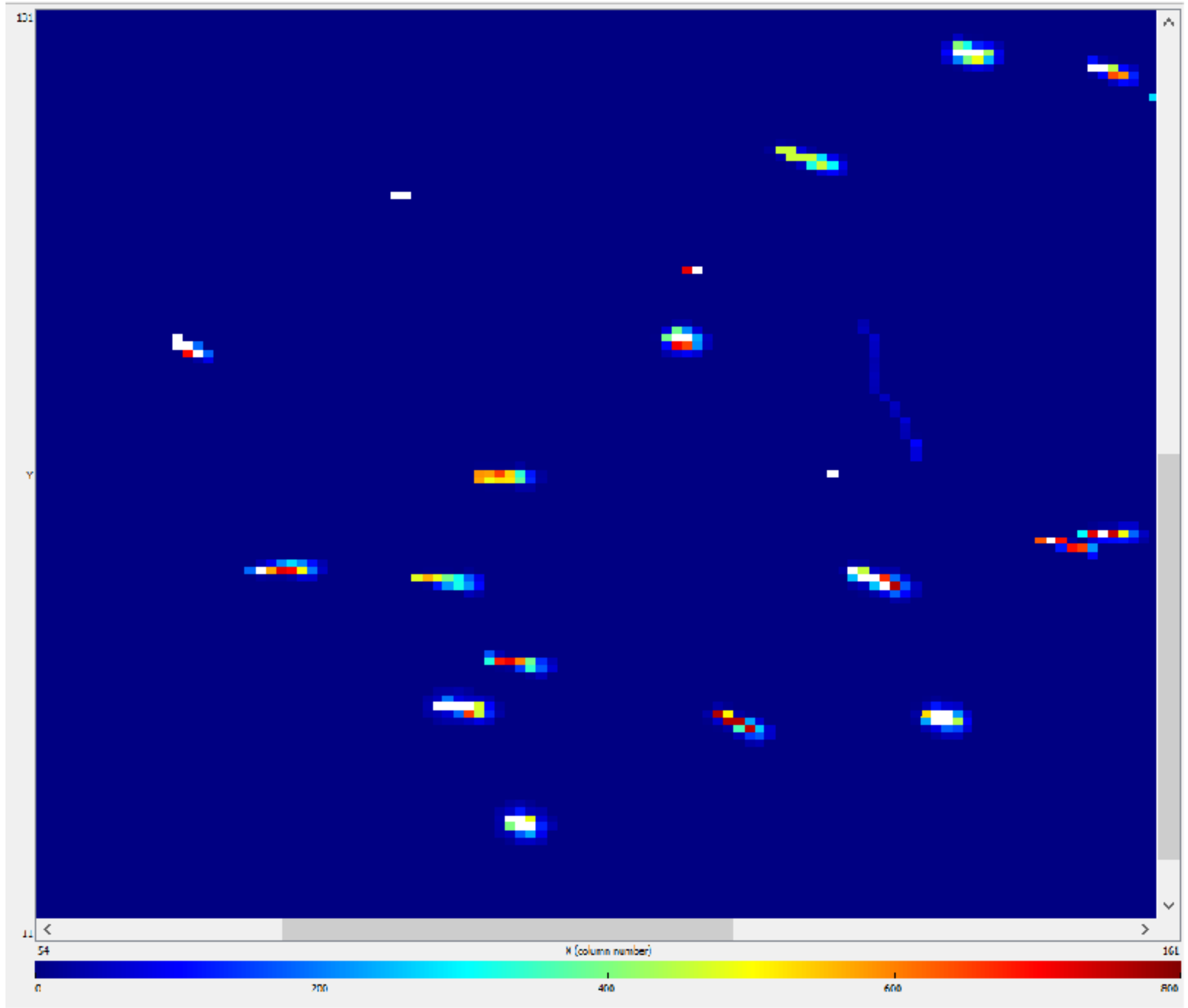
no Range shifter

Range shifter



Pixel detectors Timepix

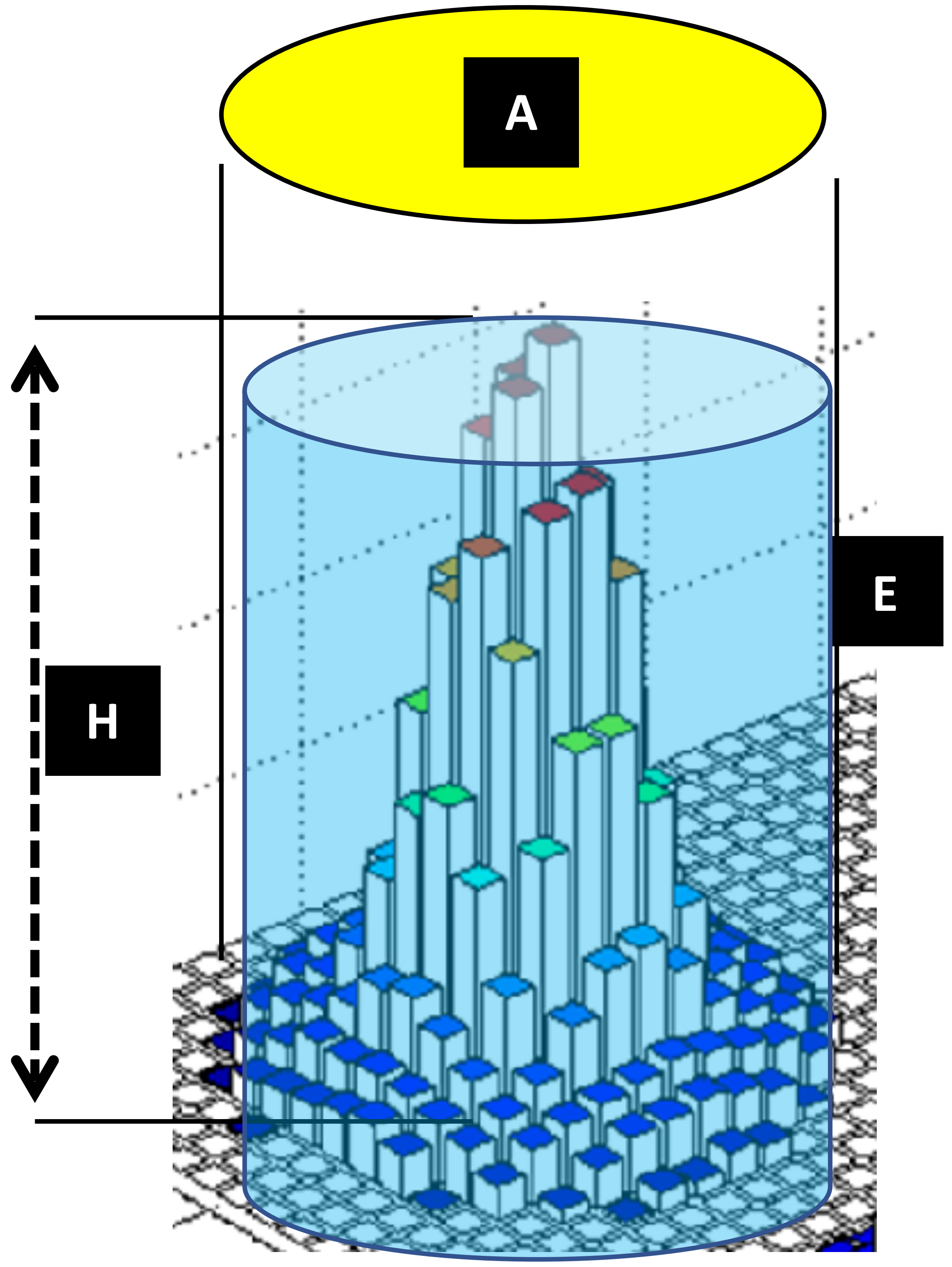
Events display: Mixed Field



Cluster parameters:

- Height [keV], H
- Area [px], A
- Energy [keV/px], E

Pixel cluster analysis

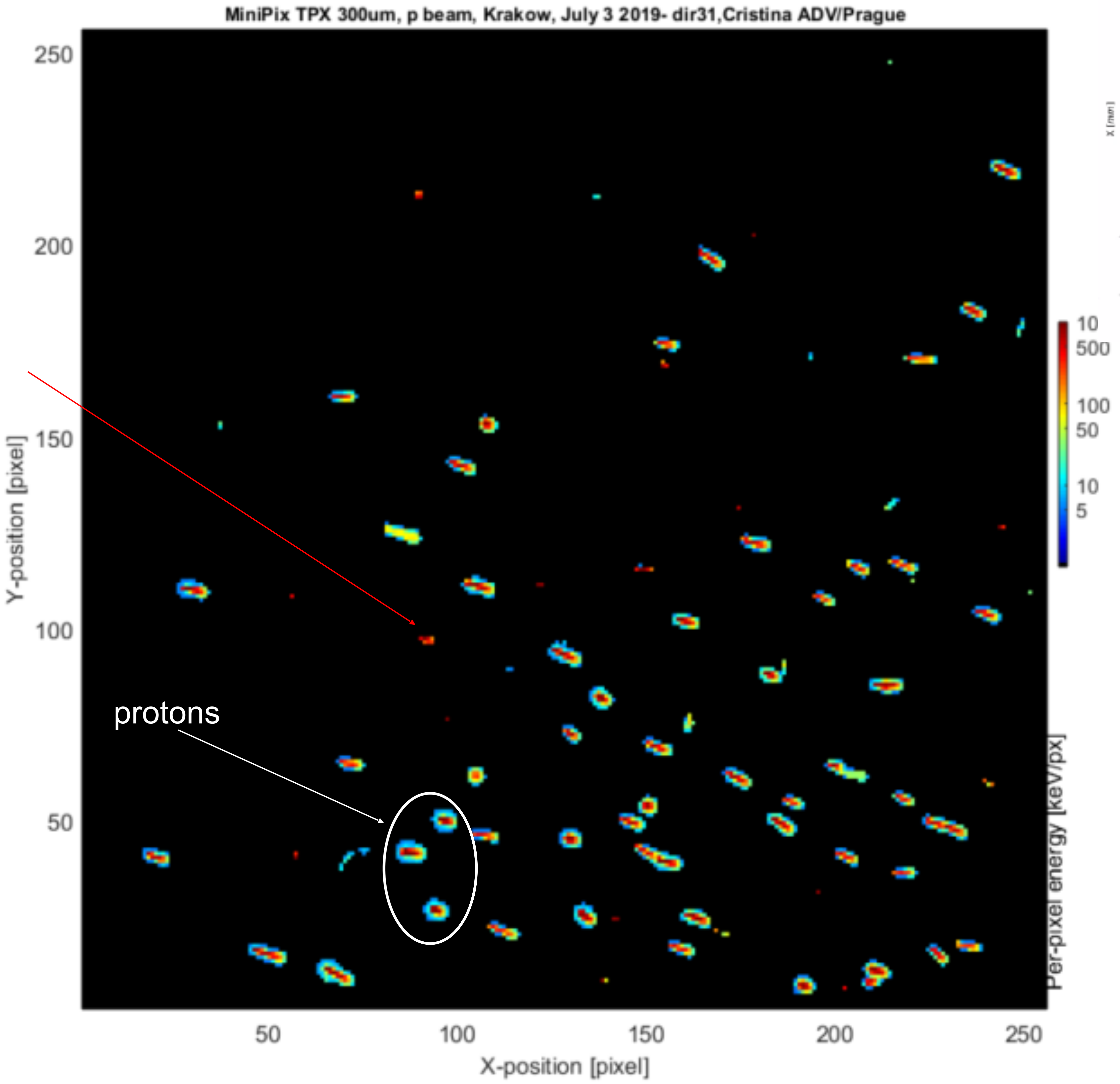


- Detector placed close to the proton beam spot
- Dir 31
- 1 frame
- 256x256 pixels, 14 mm x 14 mm
- Per-Pixel energy deposited
- Mixed field

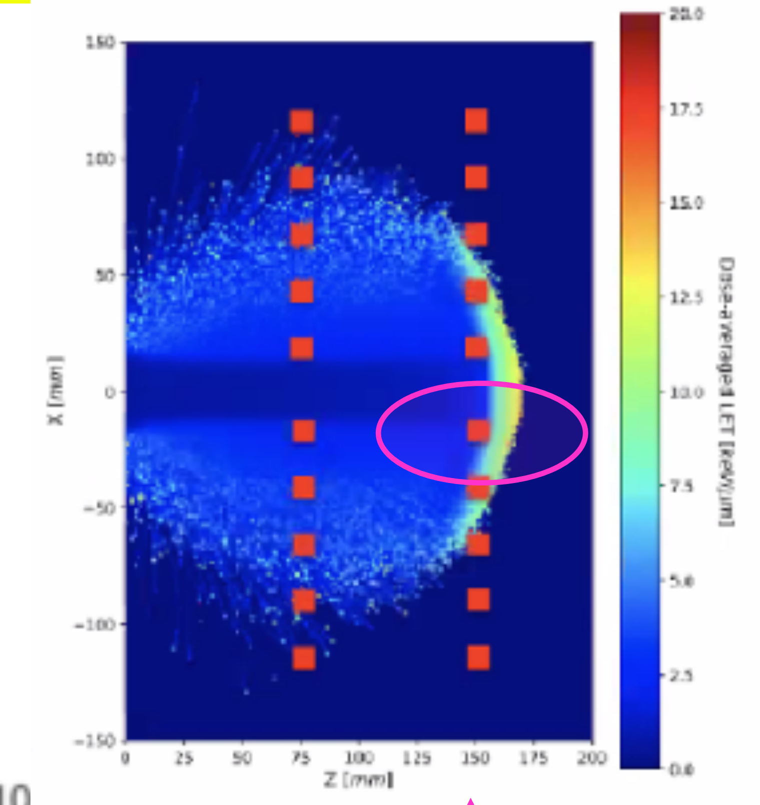
All events	All data no filters
Events A	Height filter **200 to 650 keV** for the 1st peak
Events B	Height filter **800 to 1100 keV** for the 2nd peak

2D visualization of Cluster Energy

Highly energetic charged particles

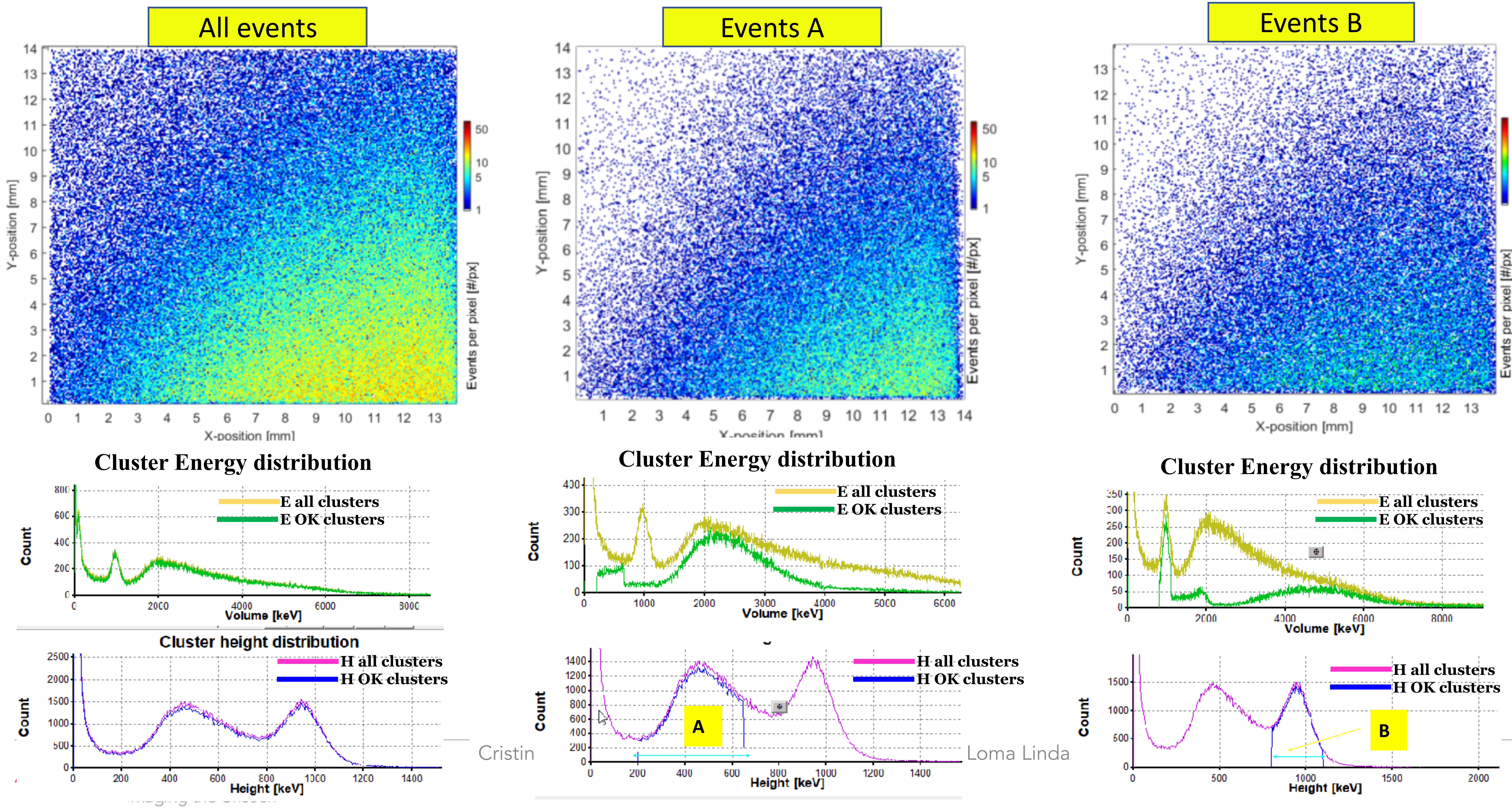


dir 31
Close to the proton beam spot
Minipix Timepix 300μm Si sensor



Spatial distribution of Event counts

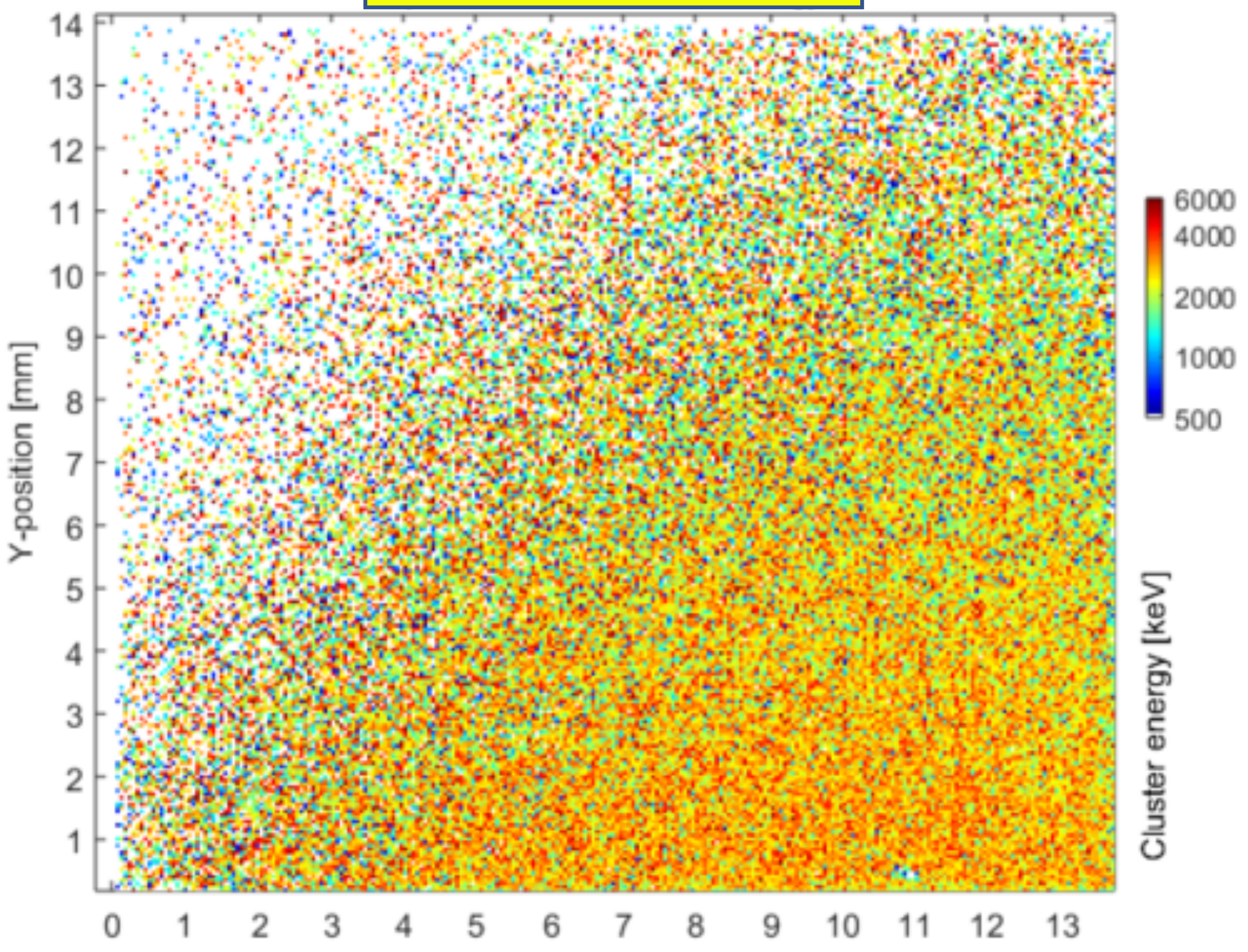
Close to the proton beam spot
Minipix Timepix 300µm Si sensor



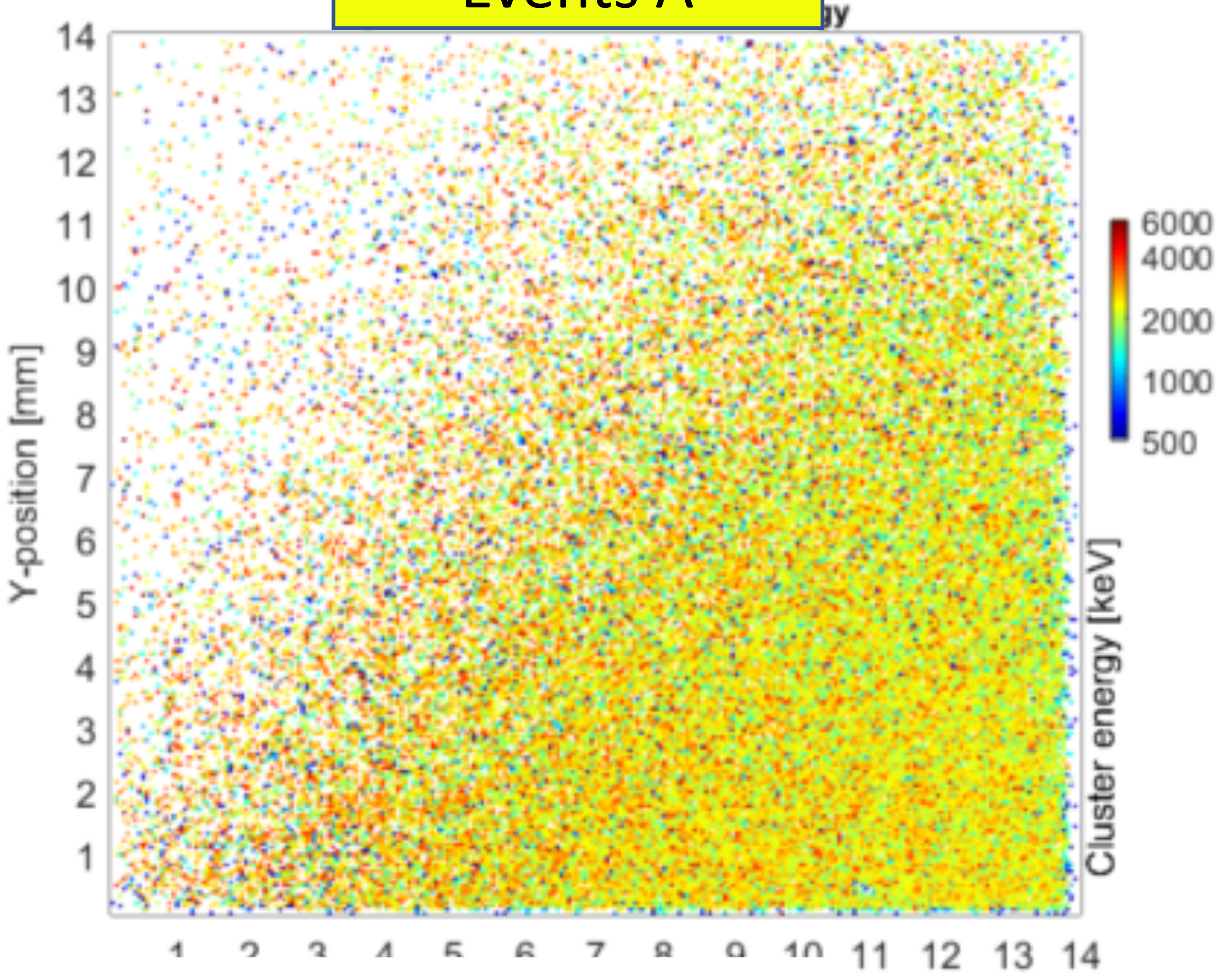
Spatial distribution of events Energy (deposit…)

Close to the proton beam spot
Minipix Timepix 300µm Si sensor

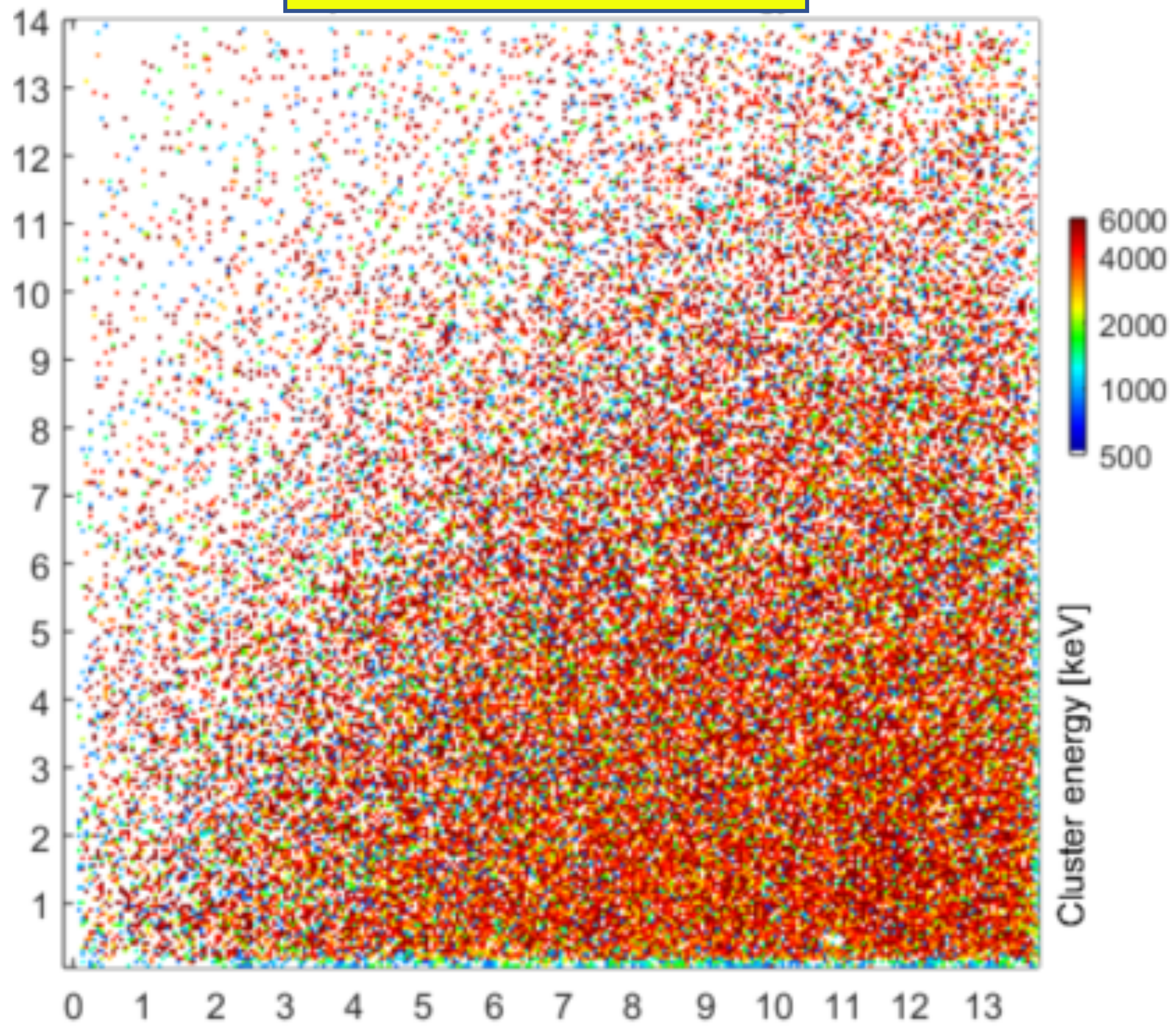
All events



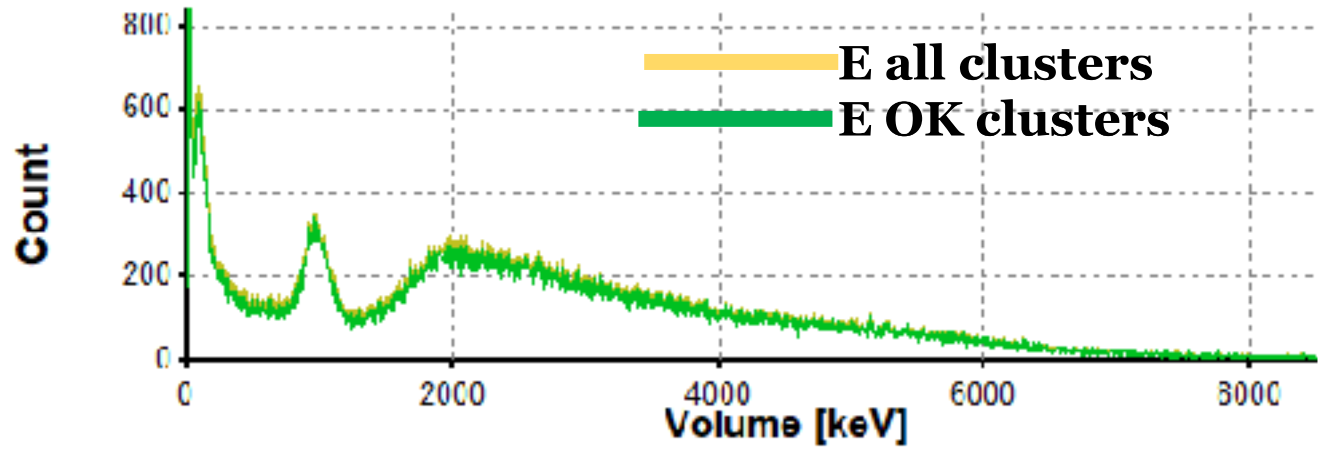
Events A



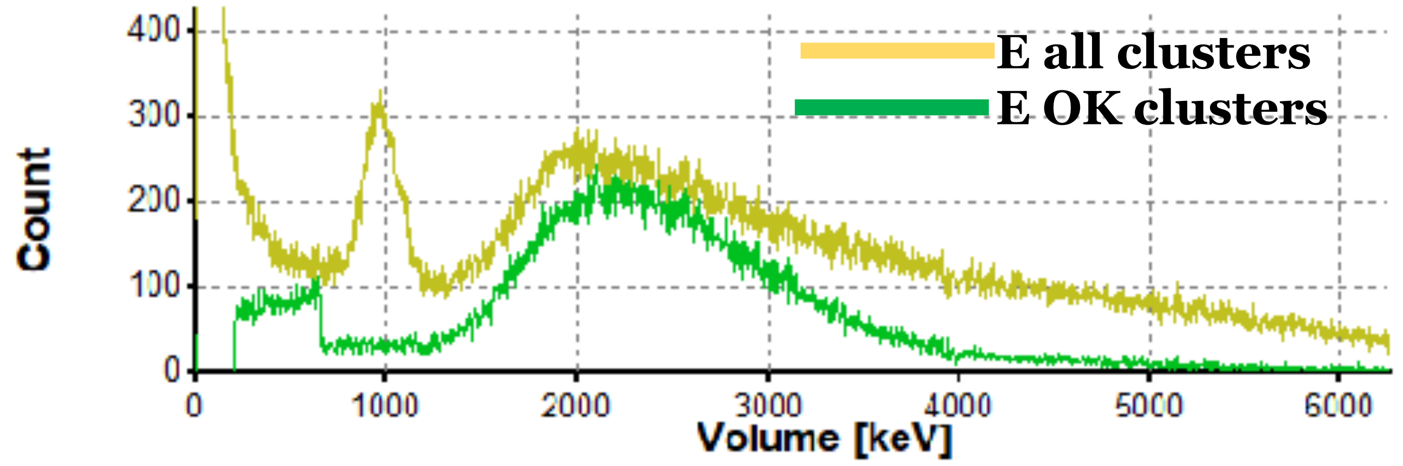
Events B



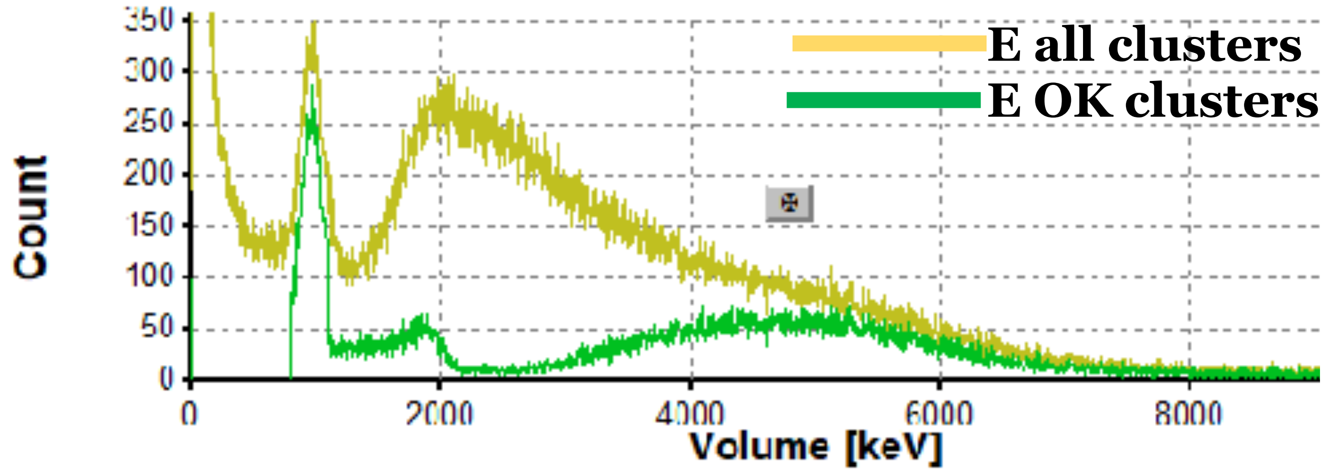
Cluster Energy distribution



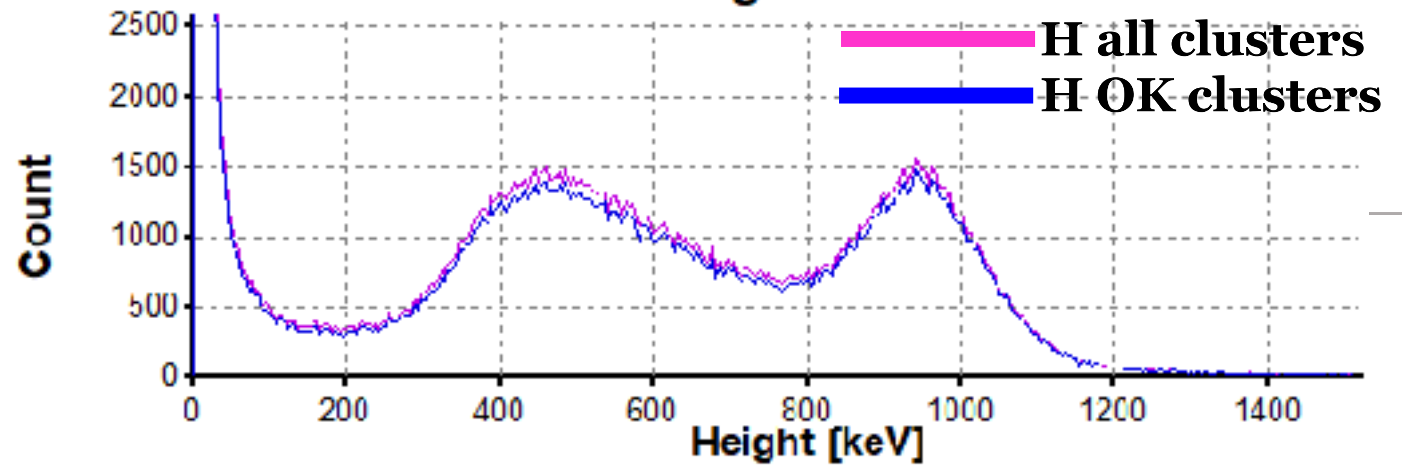
Cluster Energy distribution

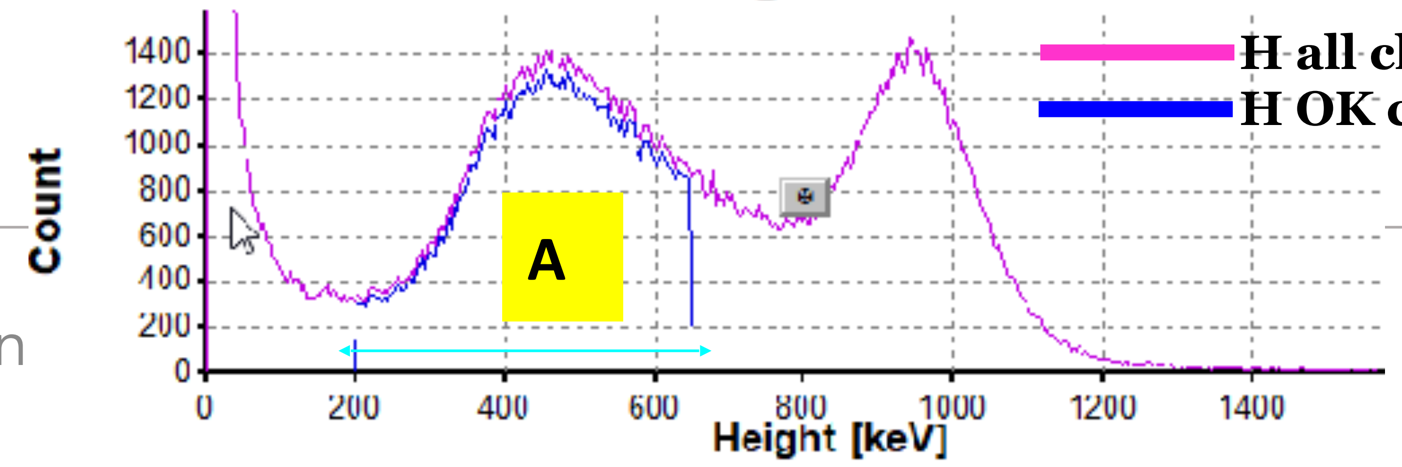


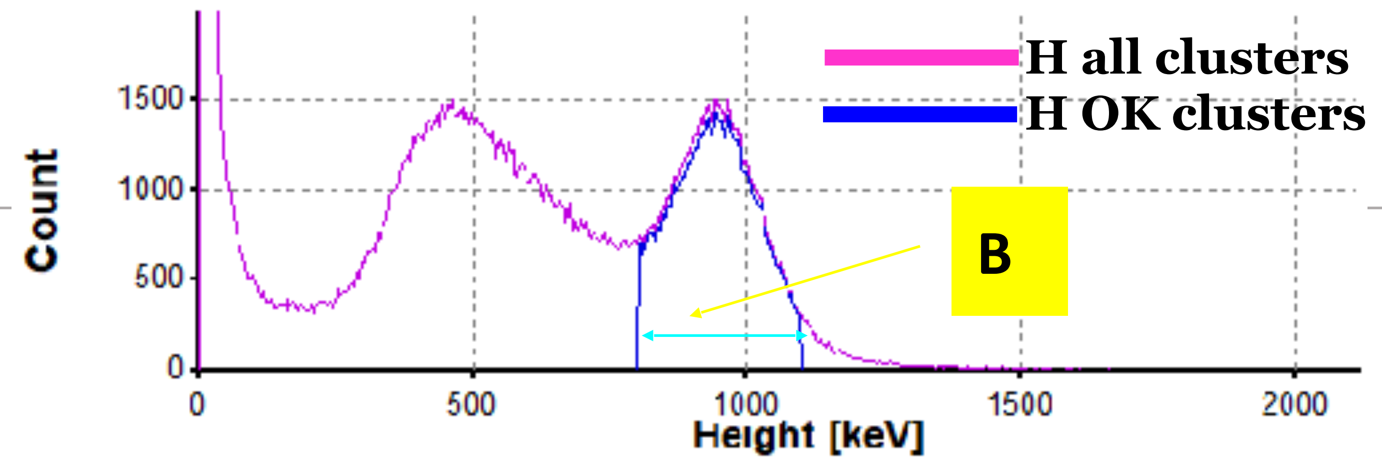
Cluster Energy distribution



Cluster height distribution





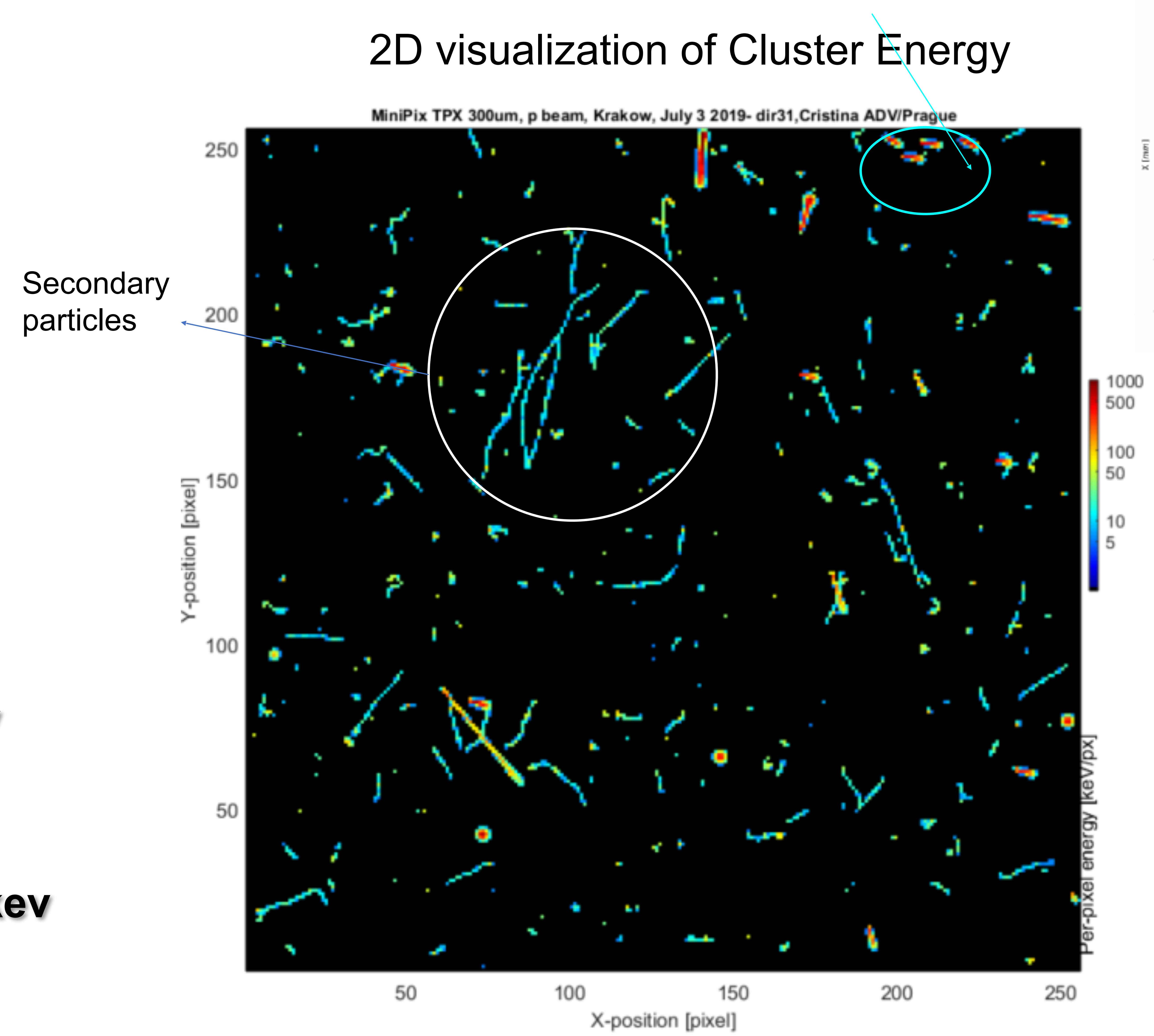


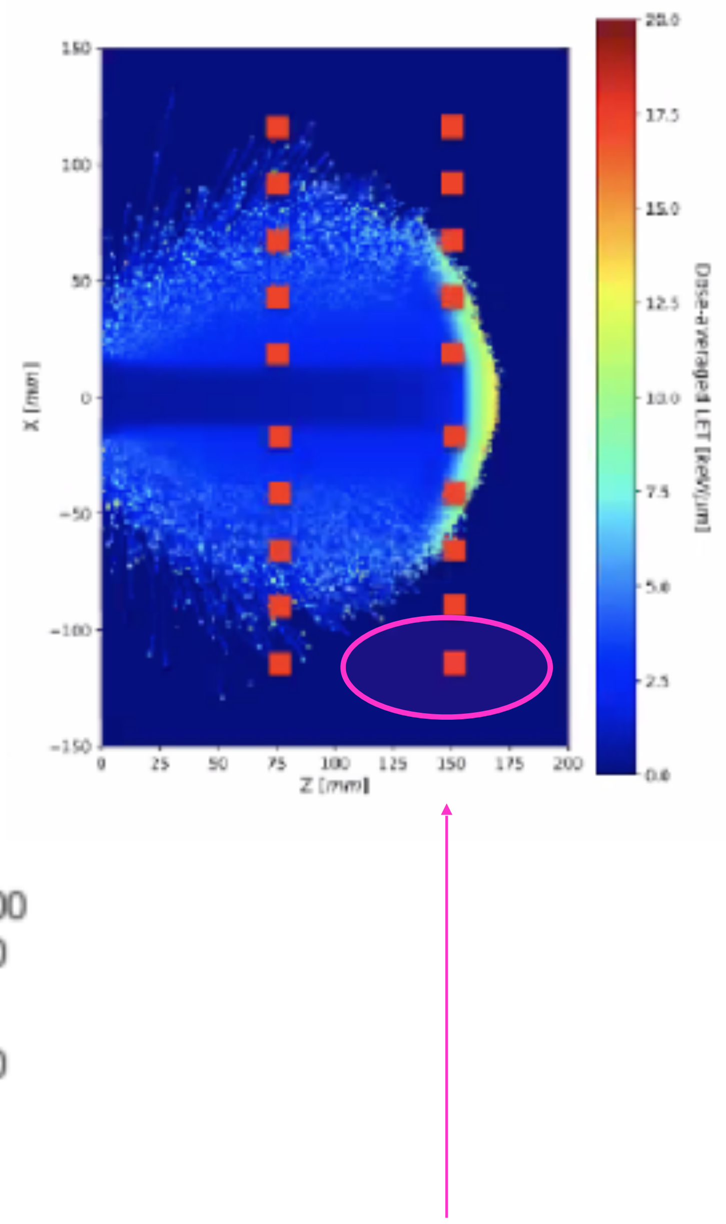
- Detector placed far from the proton beam spot
- Dir 35
- Minipix Timepix Si sensor, 300 μm
- 4 frame
- 256x256 pixels, 14 mm x 14 mm
- Per-Pixel energy deposited
- Mixed field

All events	All data no filters
Events A	Height filter **1 to 11 kev** for the 1st peak
Events B	Height filter **12 to 200 kev** for the 2nd peak

Far from the proton beam spot
Minipix Timepix 300μm Si sensor

2D visualization of Cluster Energy

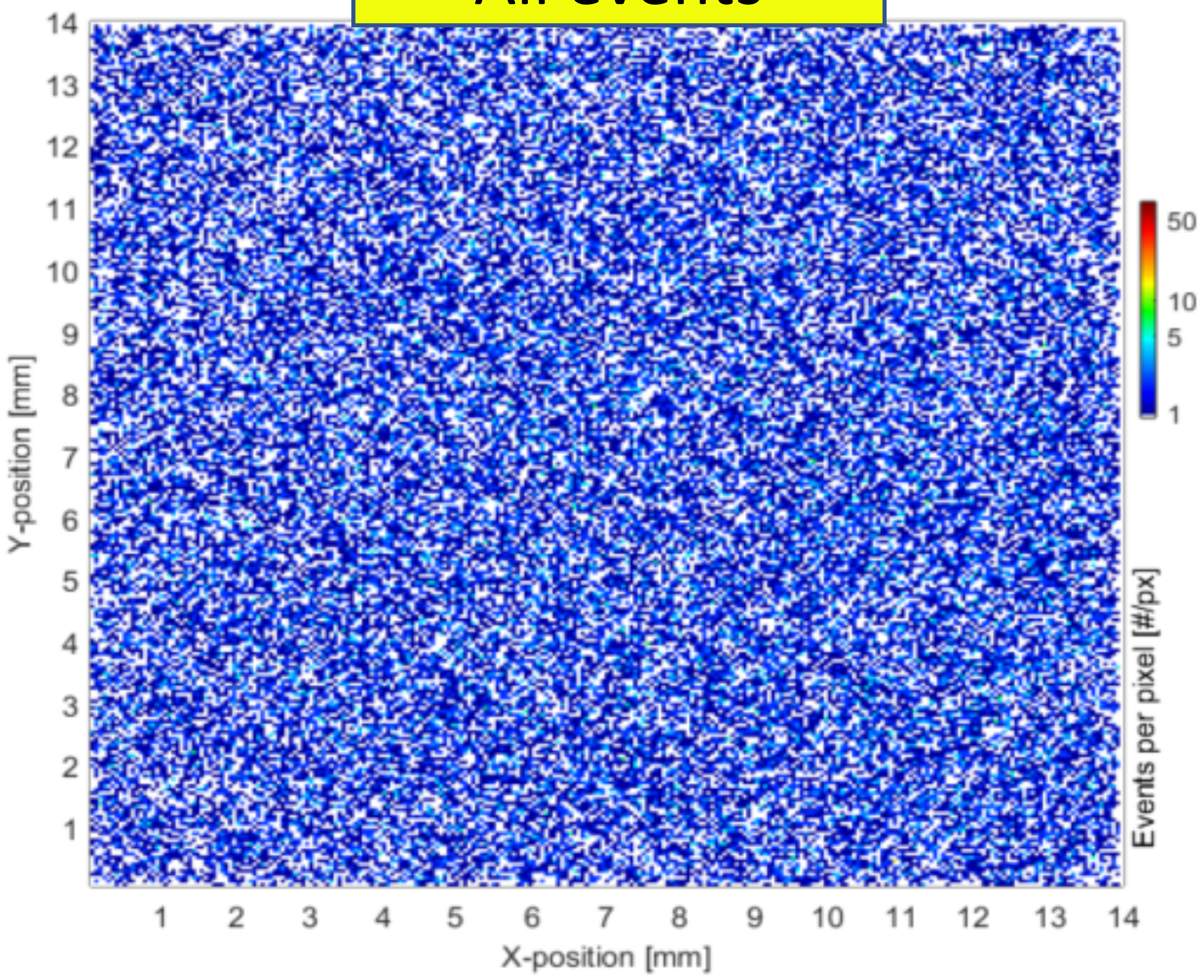


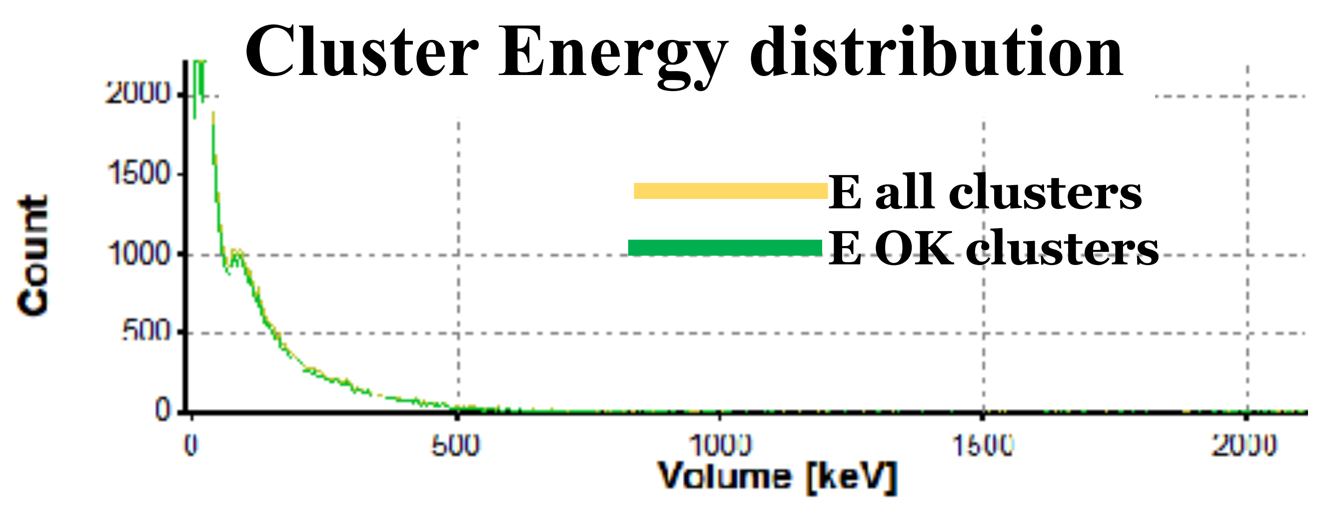


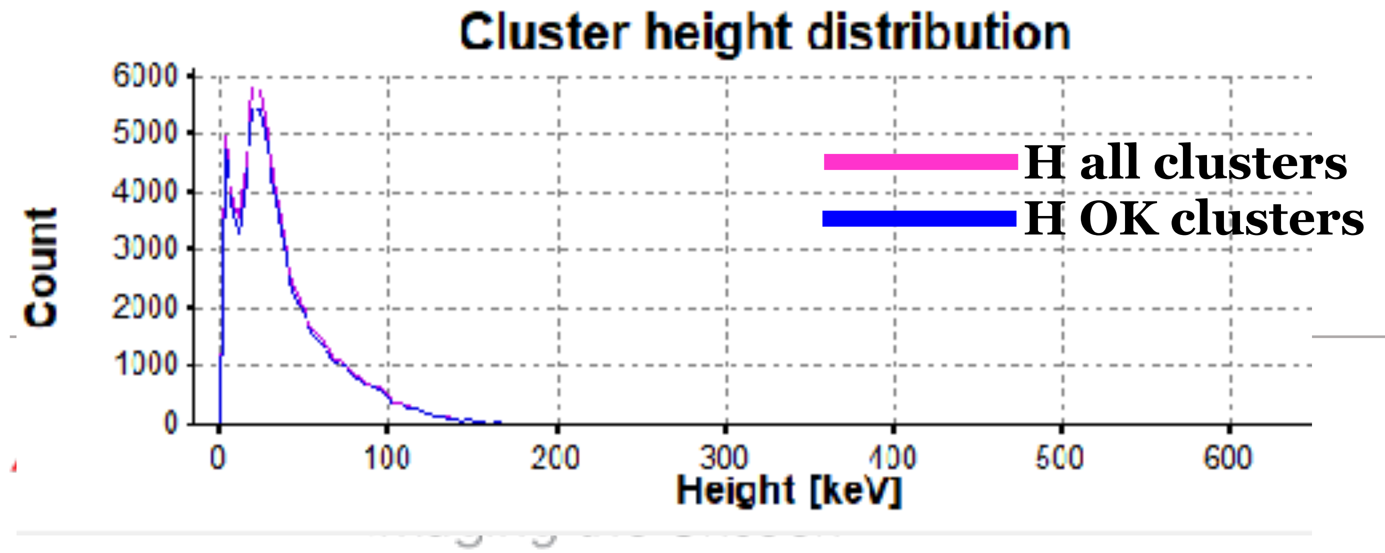
Spatial distribution of Event counts

Far from the proton beam spot
Minipix Timepix 300µm Si sensor

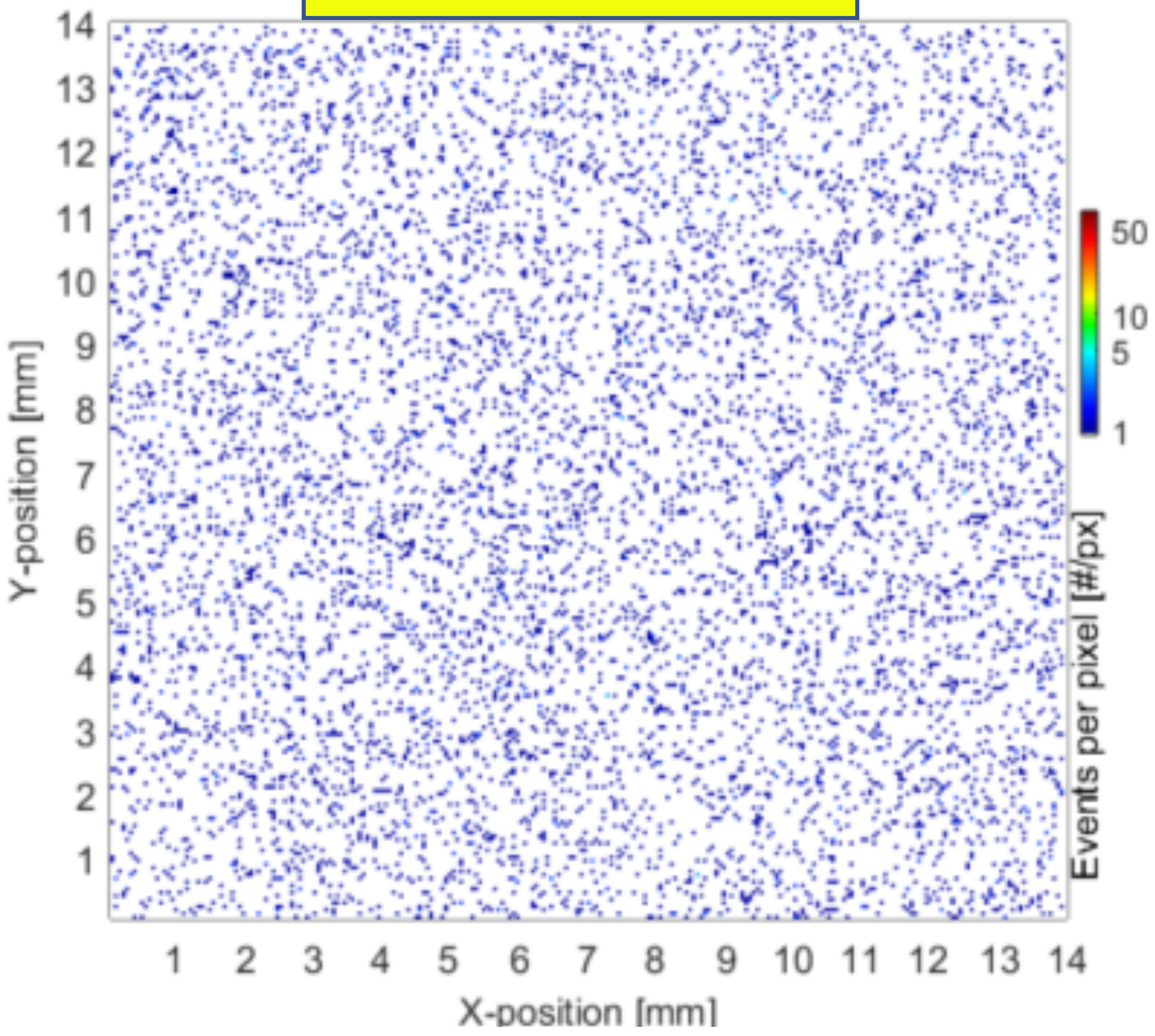
All events

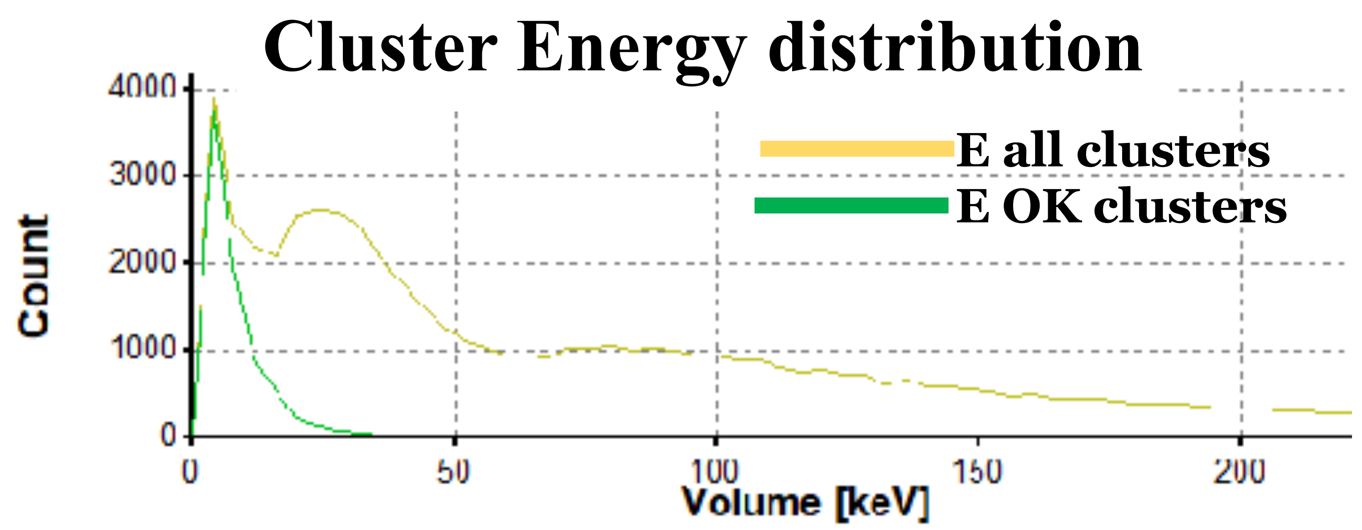


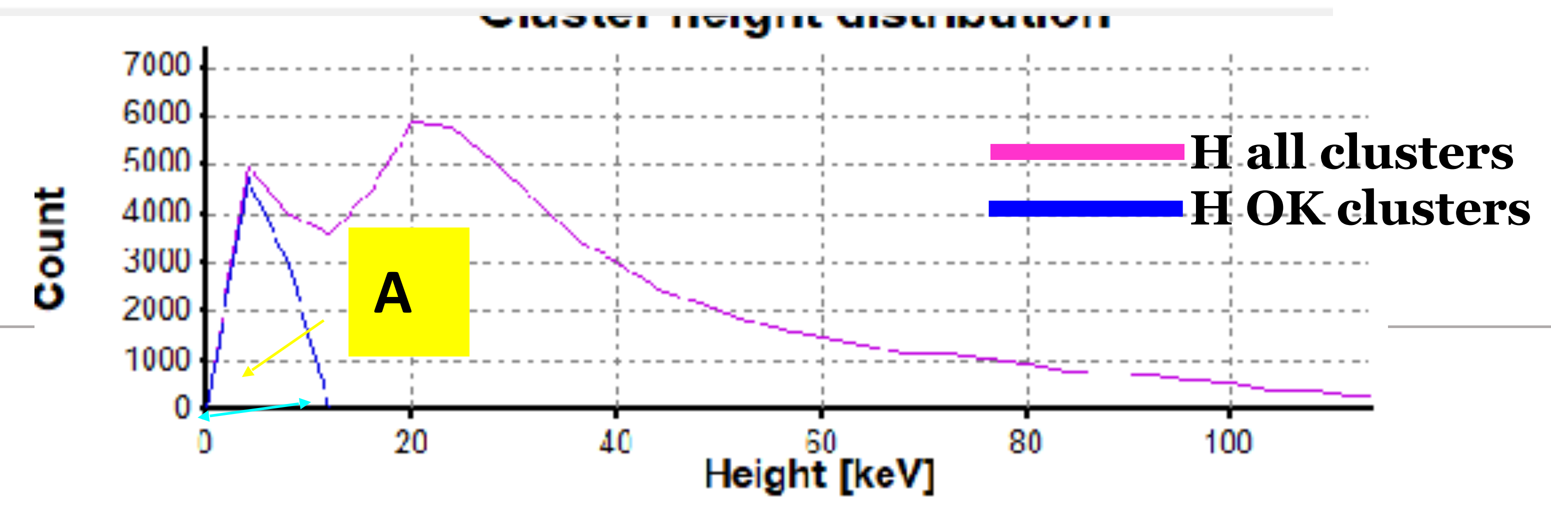




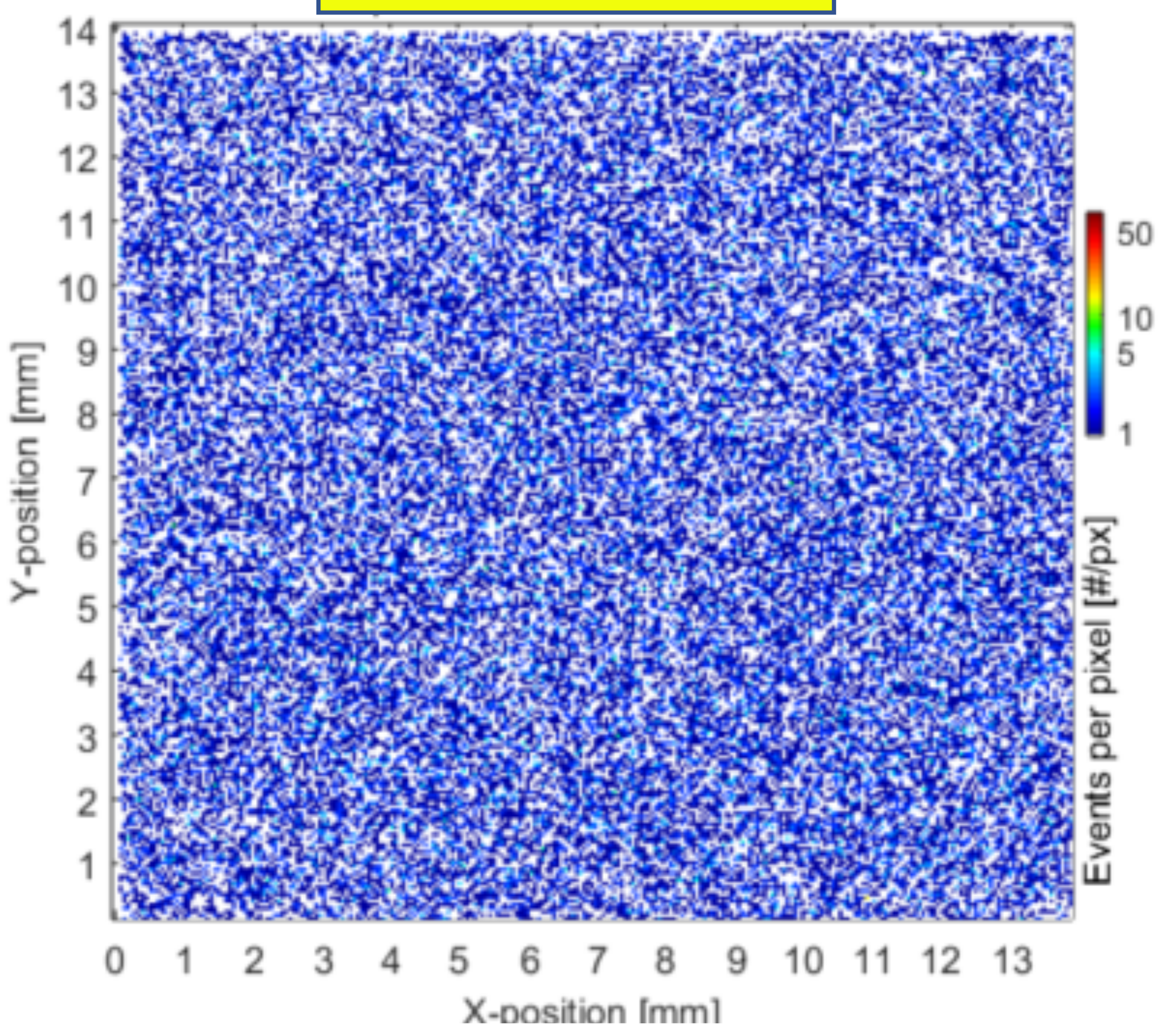
Events A

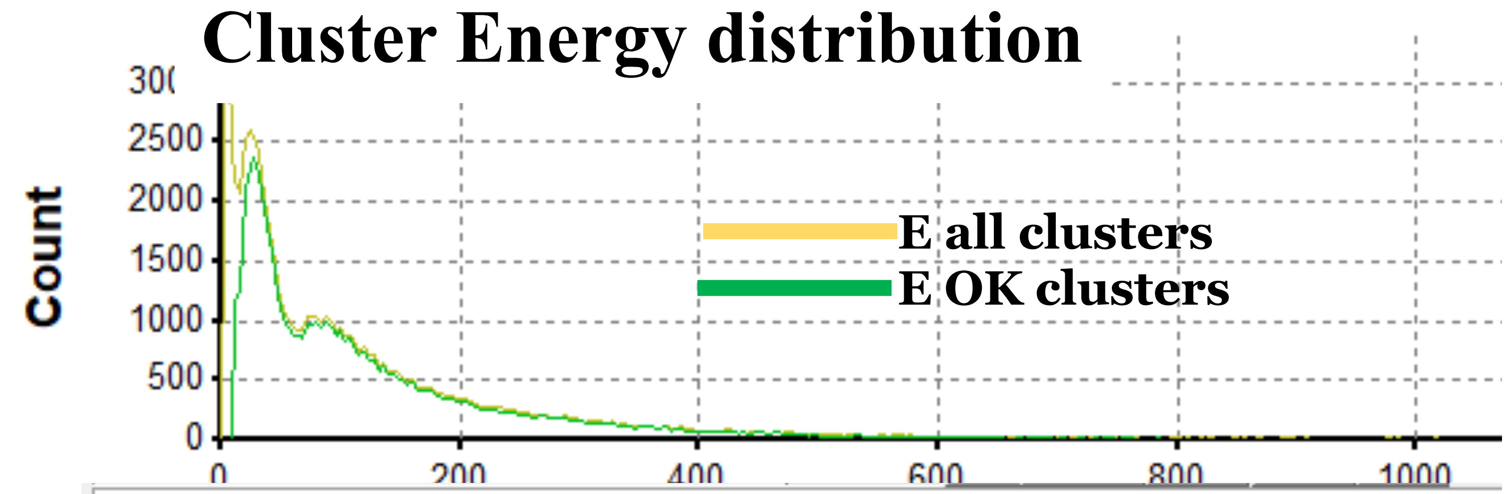


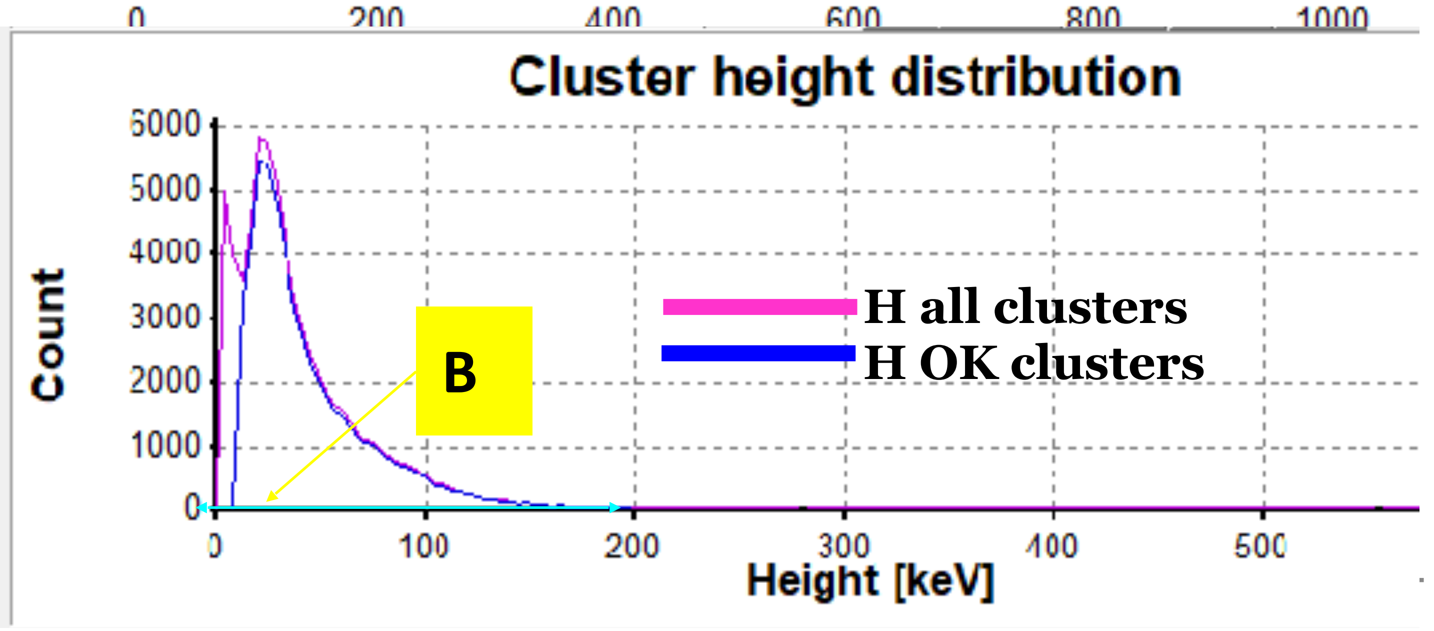




Events B

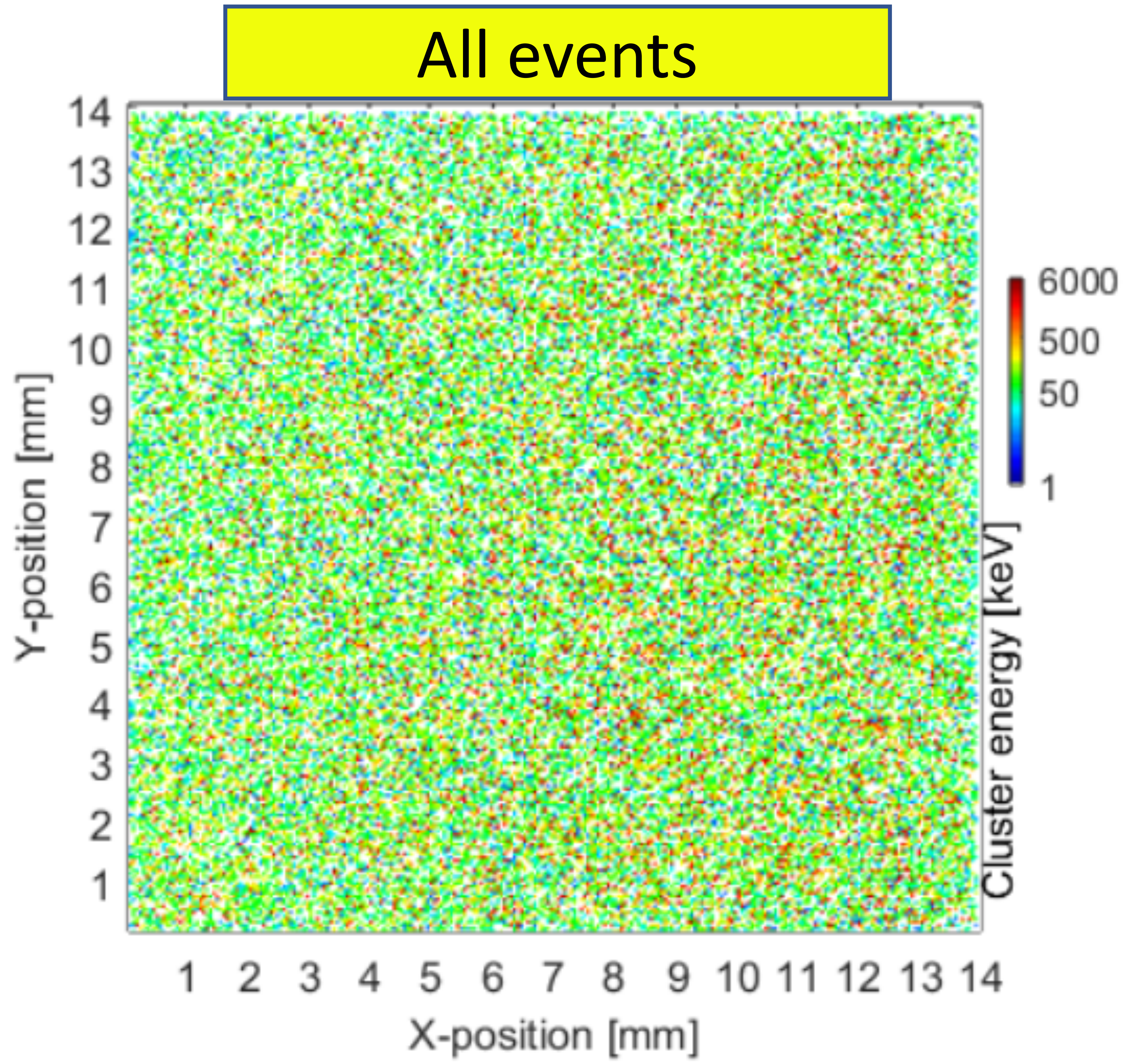


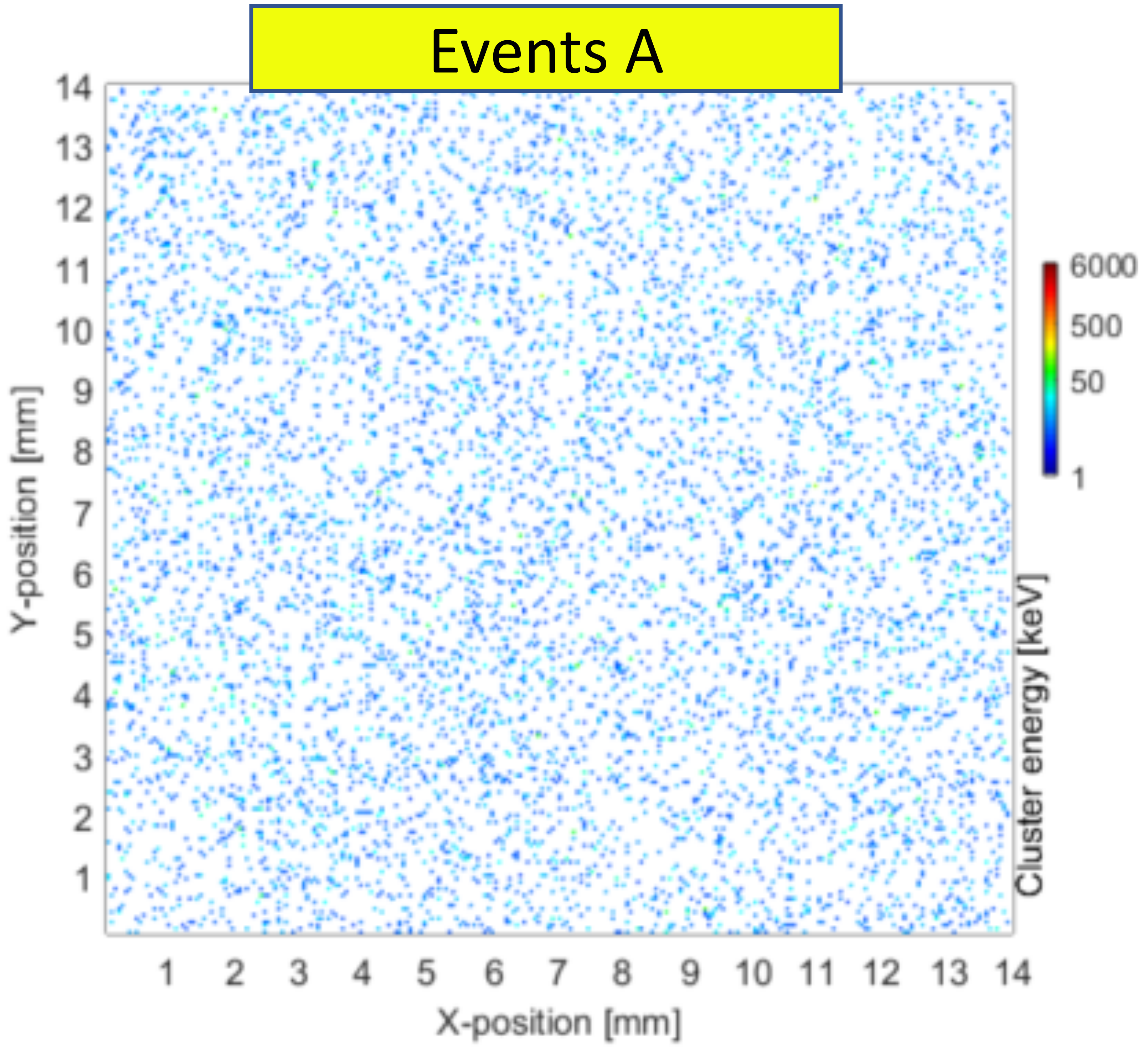


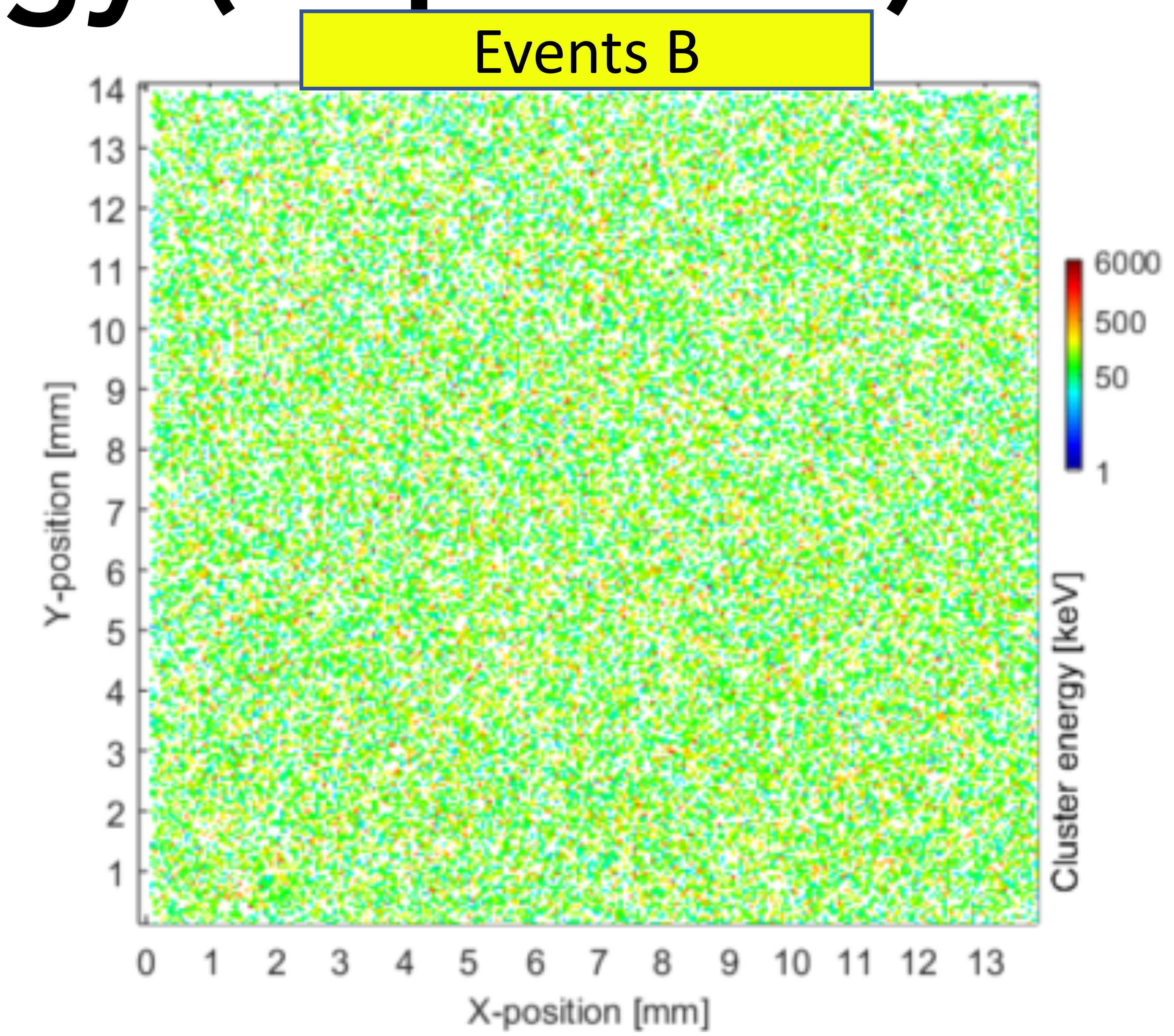


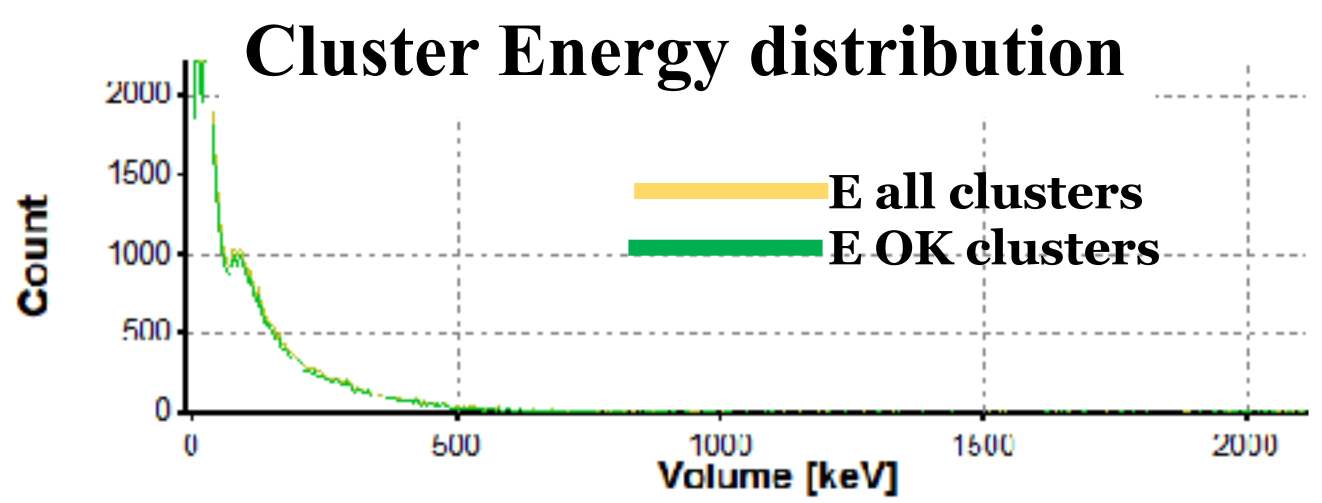
Spatial distribution of Event Energy (deposited)

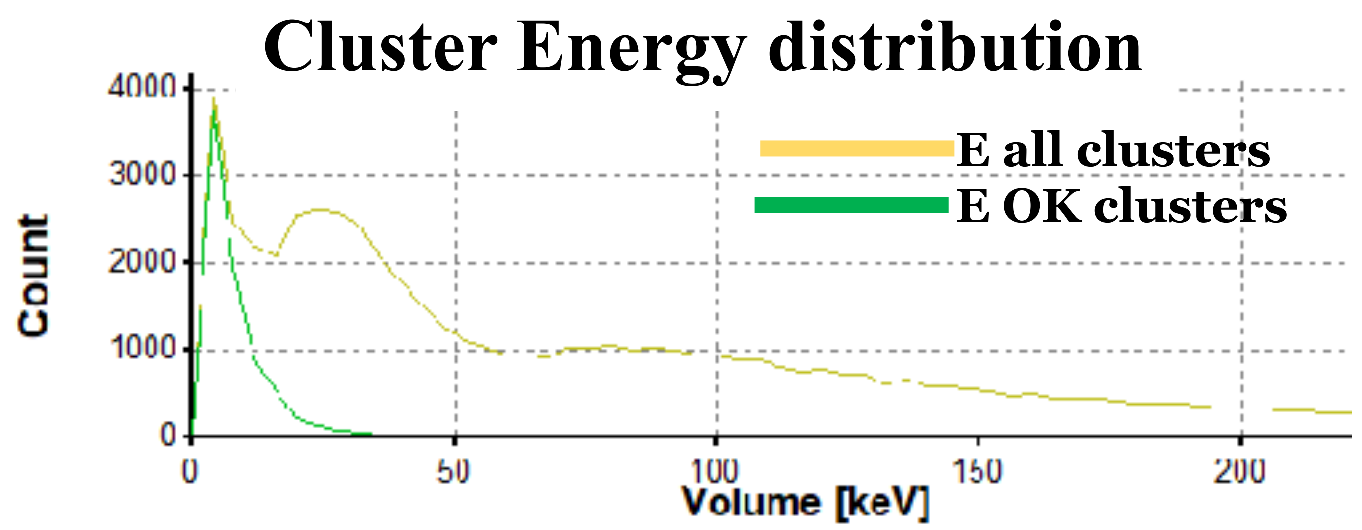
Far from the p beam spot
Minipix Timepix 300μm Si

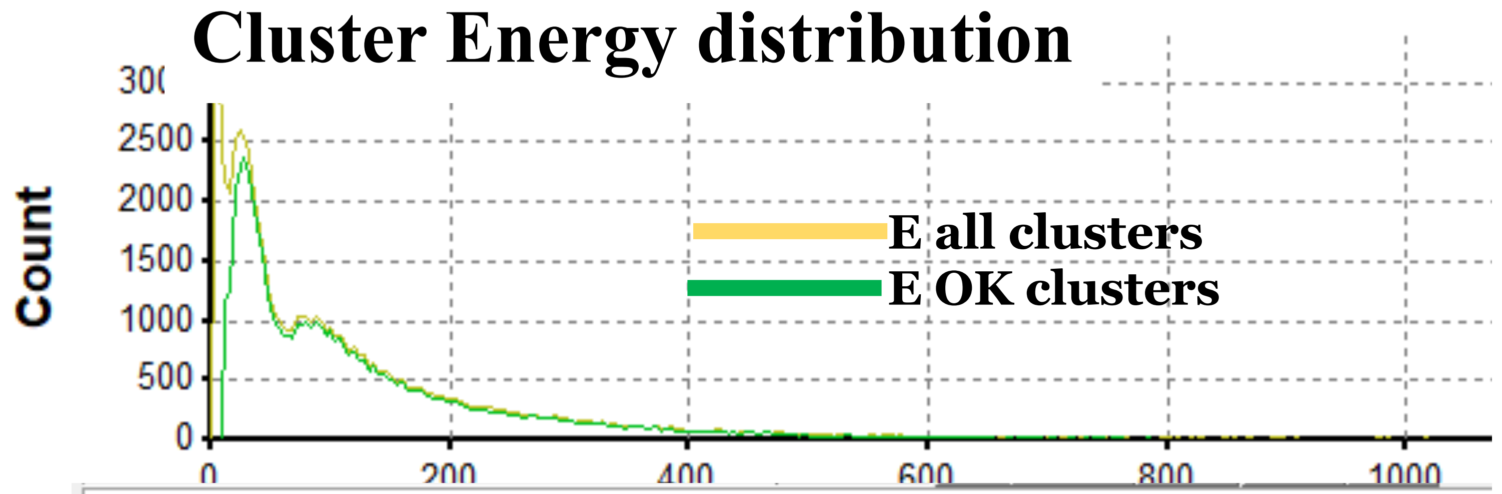


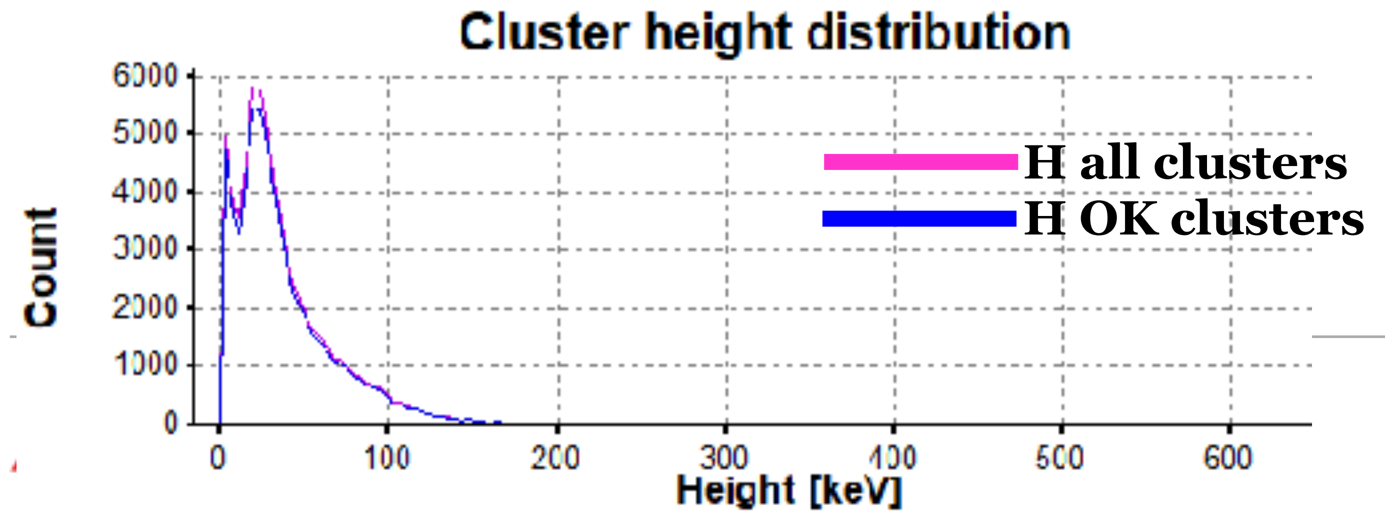


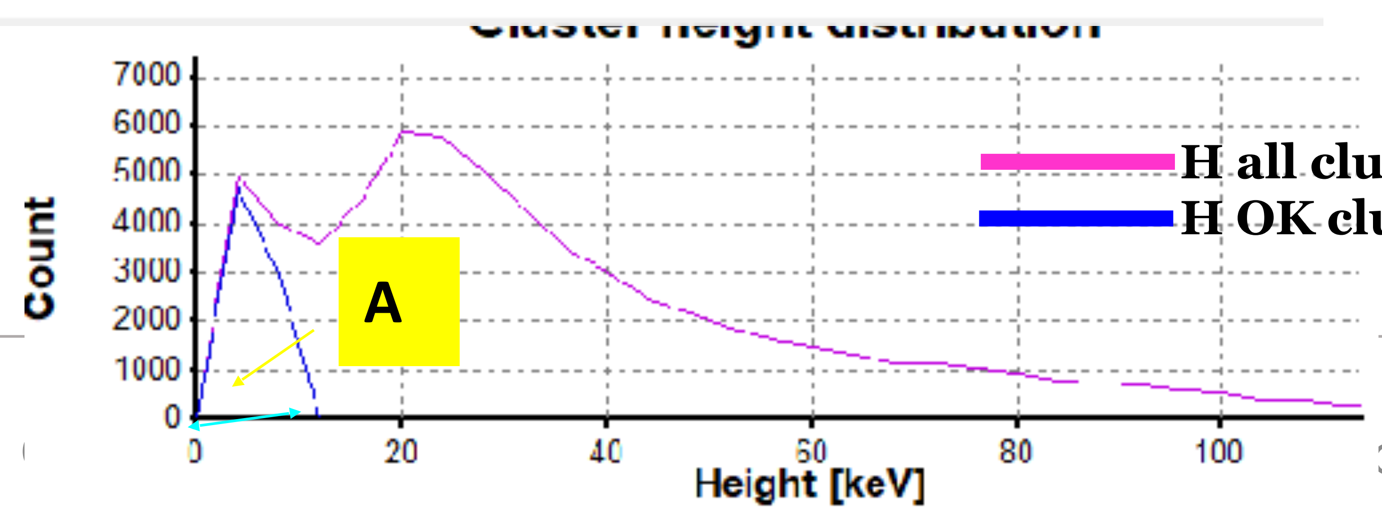


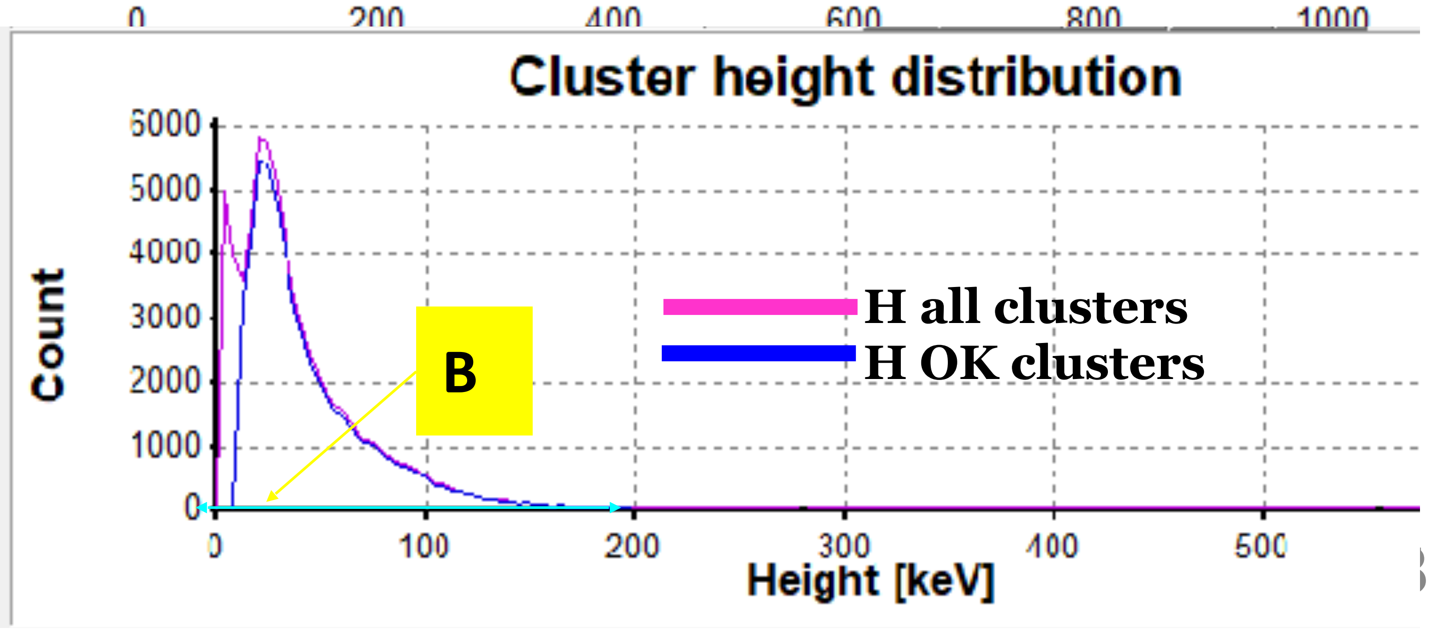













Commissioning
Input:
Facility commissioning measurements
(in 10 MeV steps)
Phase space library characterisation:
(in 10 MeV steps)
automated
Step 1: Fitting emittance parameters
(εx, αx, βx, εy, αy, βy)
Step 2: Optimization of the beam energy (E) and energy spread (Eσ)
GPU
Step 3: Estimation of the the dosimetric calibration factor (SFMU)
Output:
Phase space library nine parameters:
εx, αx, βx, εy, αy, βy, E, Eσ, SFMU
Validation
Input:
Treatment plans
patients & QA
Measurements
patients & QA


Commissioning
Input:
Facility commissioning measurements
(in 10 MeV steps)
Phase space library characterisation:
(in 10 MeV steps)
automated
Step 1: Fitting emittance parameters
(ε_x, α_x, β_x, ε_y, α_y, β_y)
Step 2: Optimization of the beam energy (E) and energy spread (E_σ)
GPU
Step 3: Estimation of the the dosimetric calibration factor (SF_{MU})
Output:
Phase space library nine parameters:
ε_x, α_x, β_x, ε_y, α_y, β_y, E, E_σ, SF_{MU}
Validation
Input:
Treatment plans
patients & QA
Measurements
patients & QA
Conversion and calculation of treatment plans:
Import of the treatment plan accounting for phase space parametrization. Interpolation.
Calculation of Monte Carlo simulations
GPU

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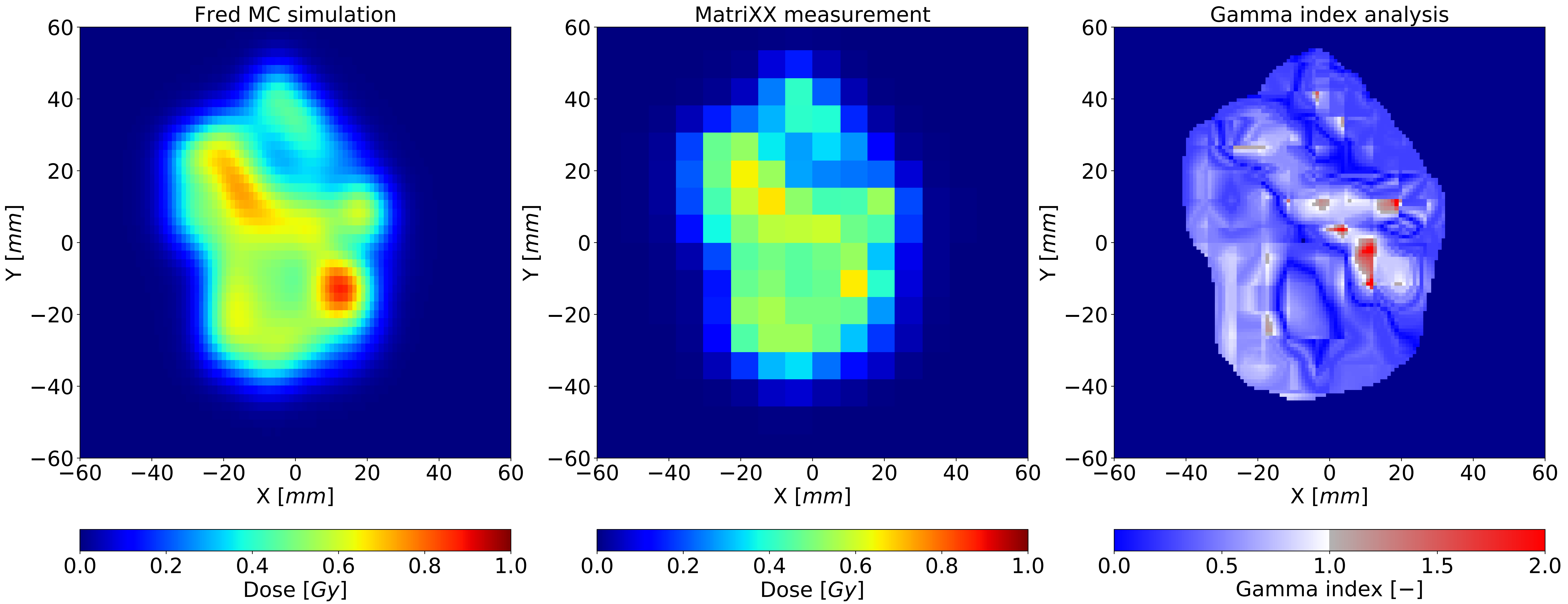
Validation
Input:
Treatment plans
patients & QA
Measurements
patients & QA
Conversion and calculation of treatment plans:
Import of the treatment plan accounting for phase space parametrization. Interpolation.
Calculation of Monte Carlo simulations
GPU
Output:
Validation:
Comparison of measurements and simulations

Phase space validation in water

FRED vs Measurements: **<2%**
TPS vs Measurements: **<4%**

182 simulated and measured layers of **verification plans in water**

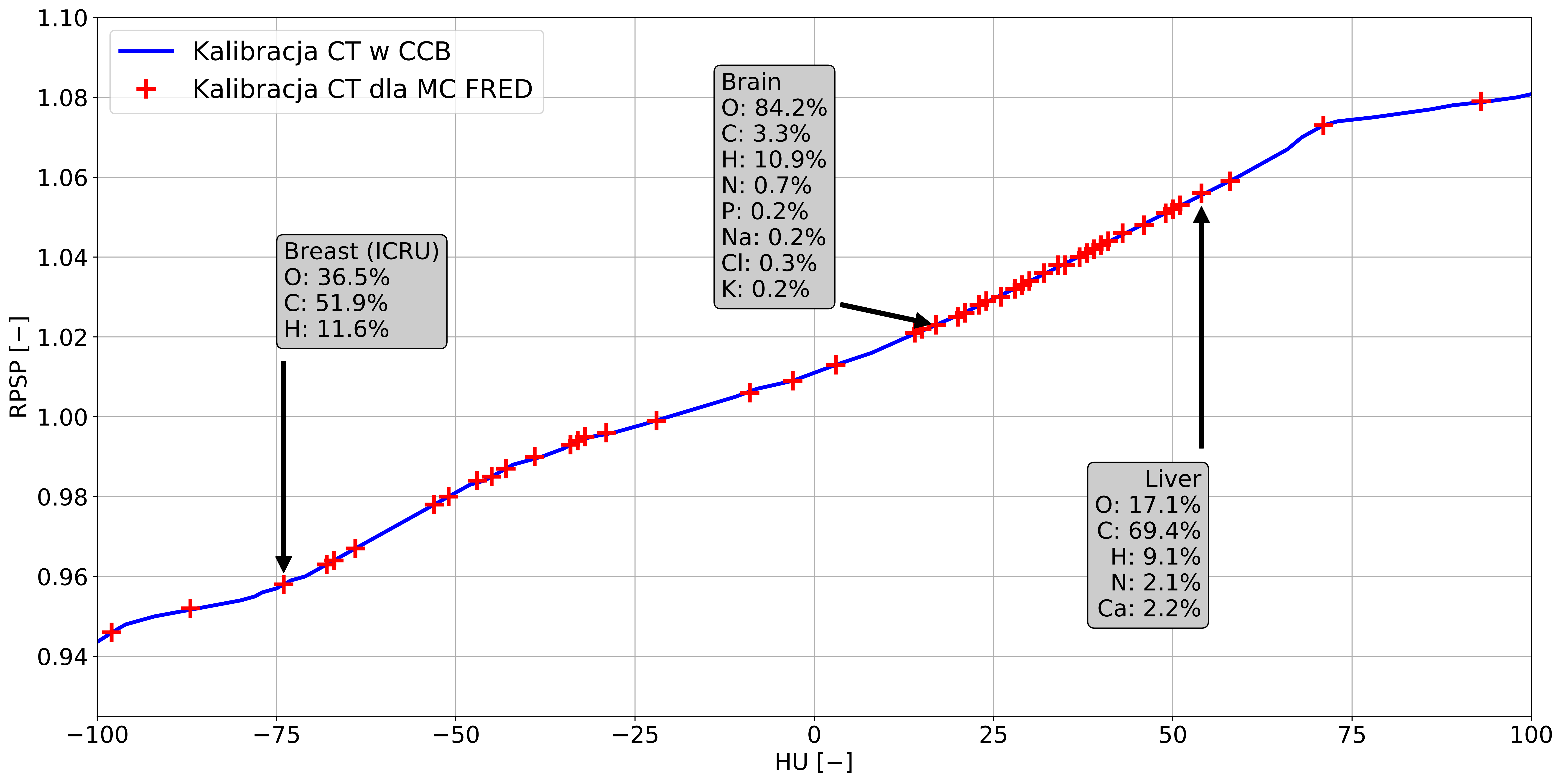
2D plane through the isocenter



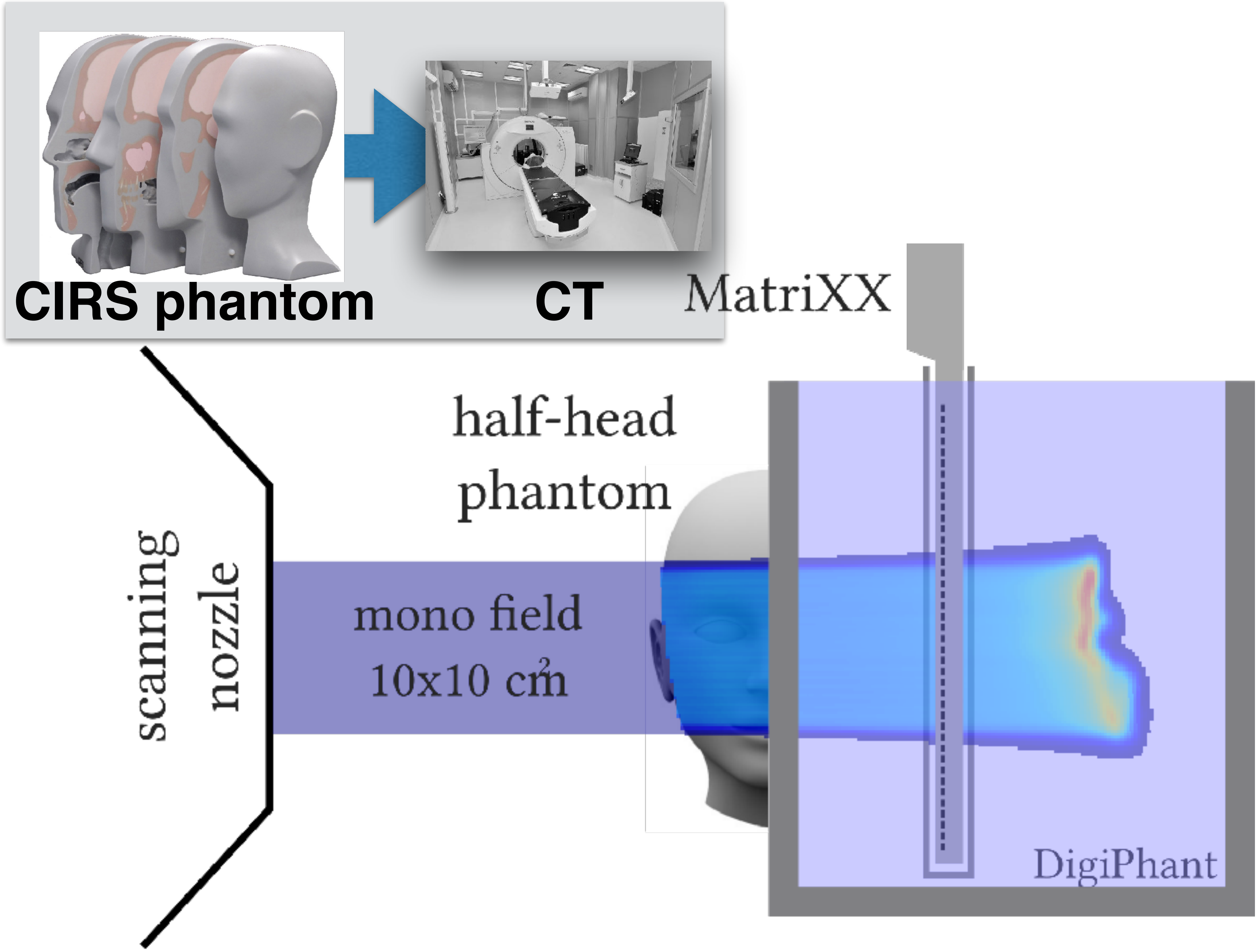
<GI pass rate> (2mm/2% criteria) = **96.3(3.3)%**

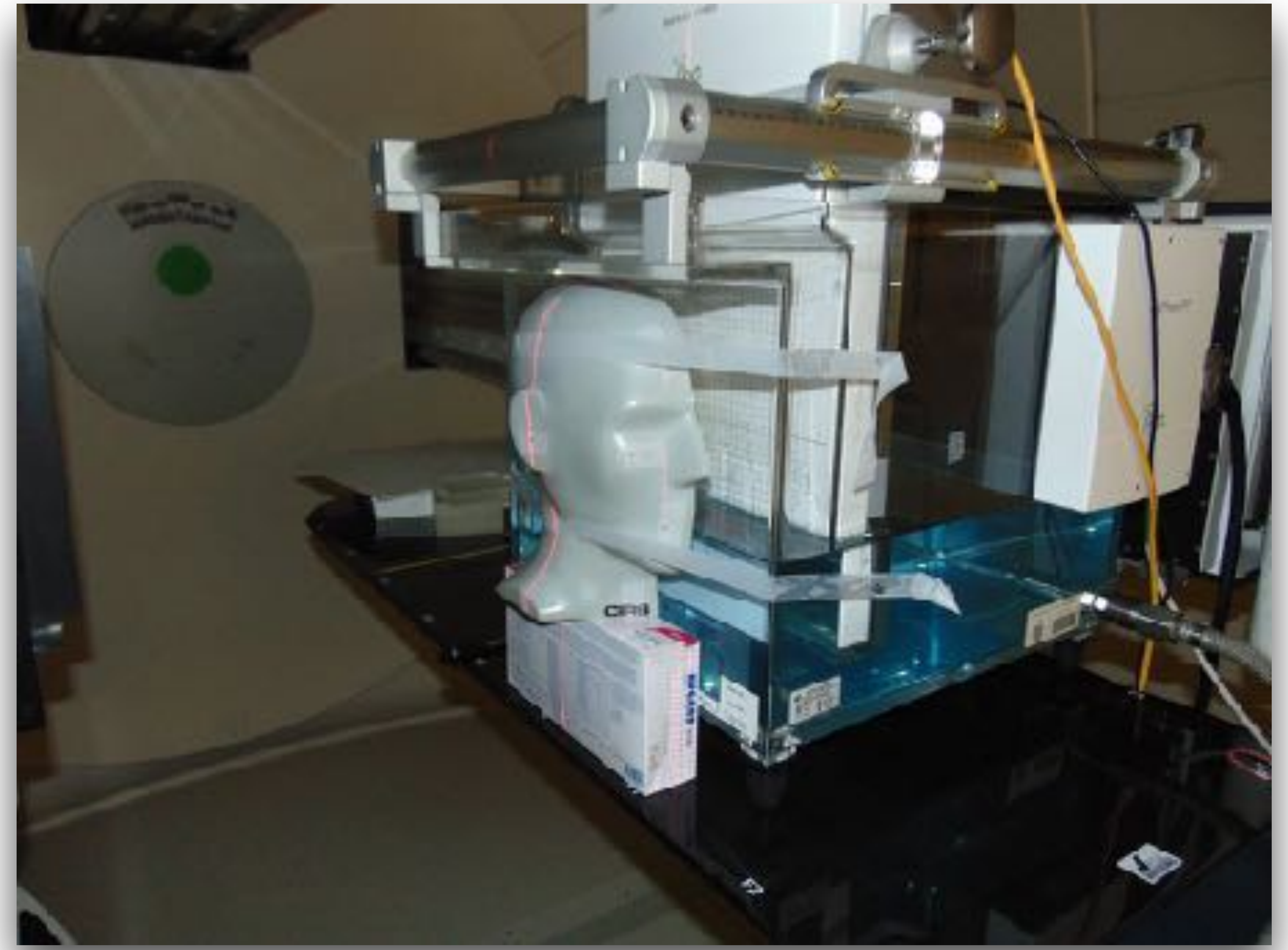
Antoni Rucinski INSTITUTE OF NUCLEAR PHYSICS PAN
antoni.rucinski@ifj.edu.pl antoni.rucinski@gmail.com web: www.ifj.edu.pl/dept/no6/nz62/ar/

CT calibration



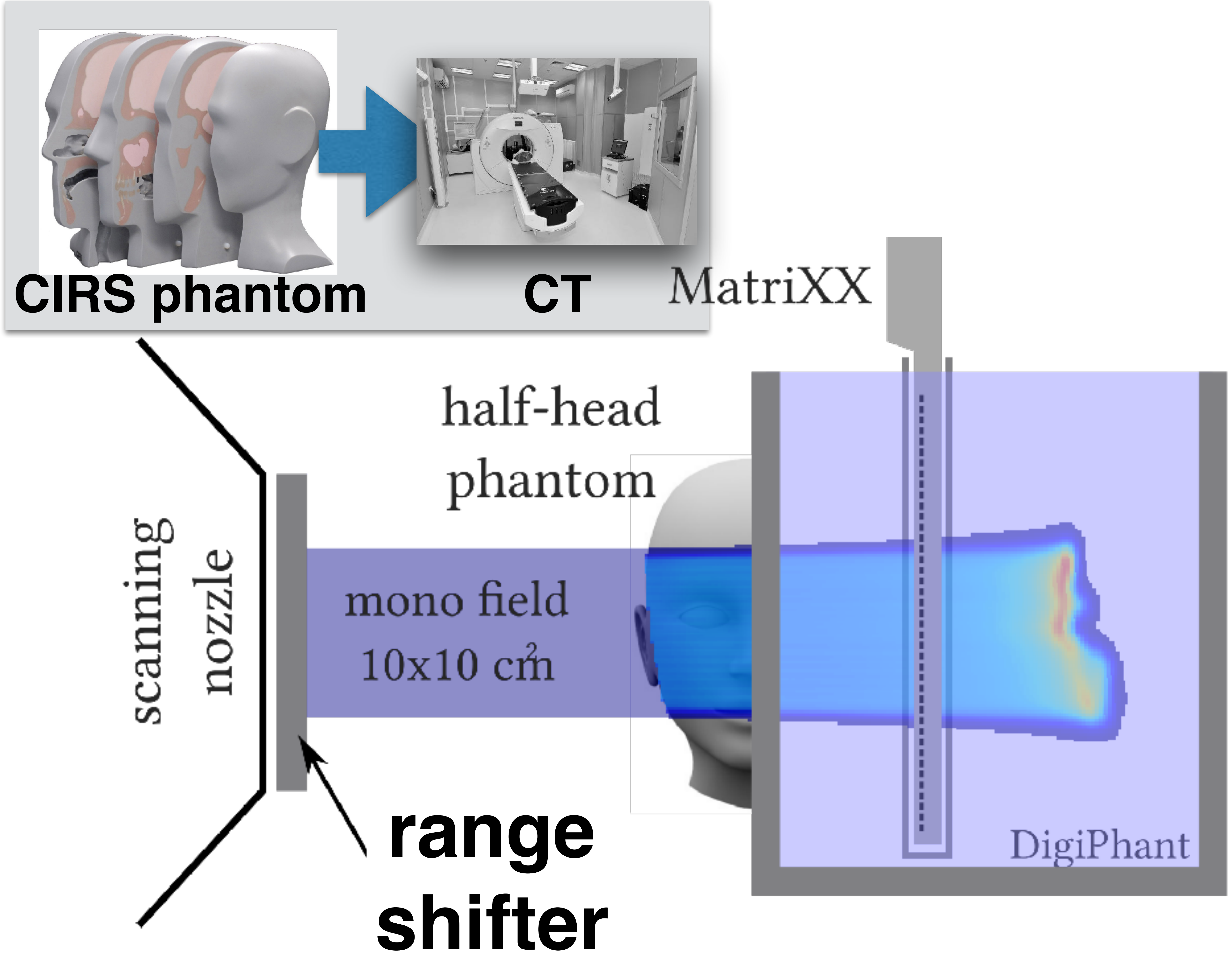
Phase space validation in heterogenous phantom

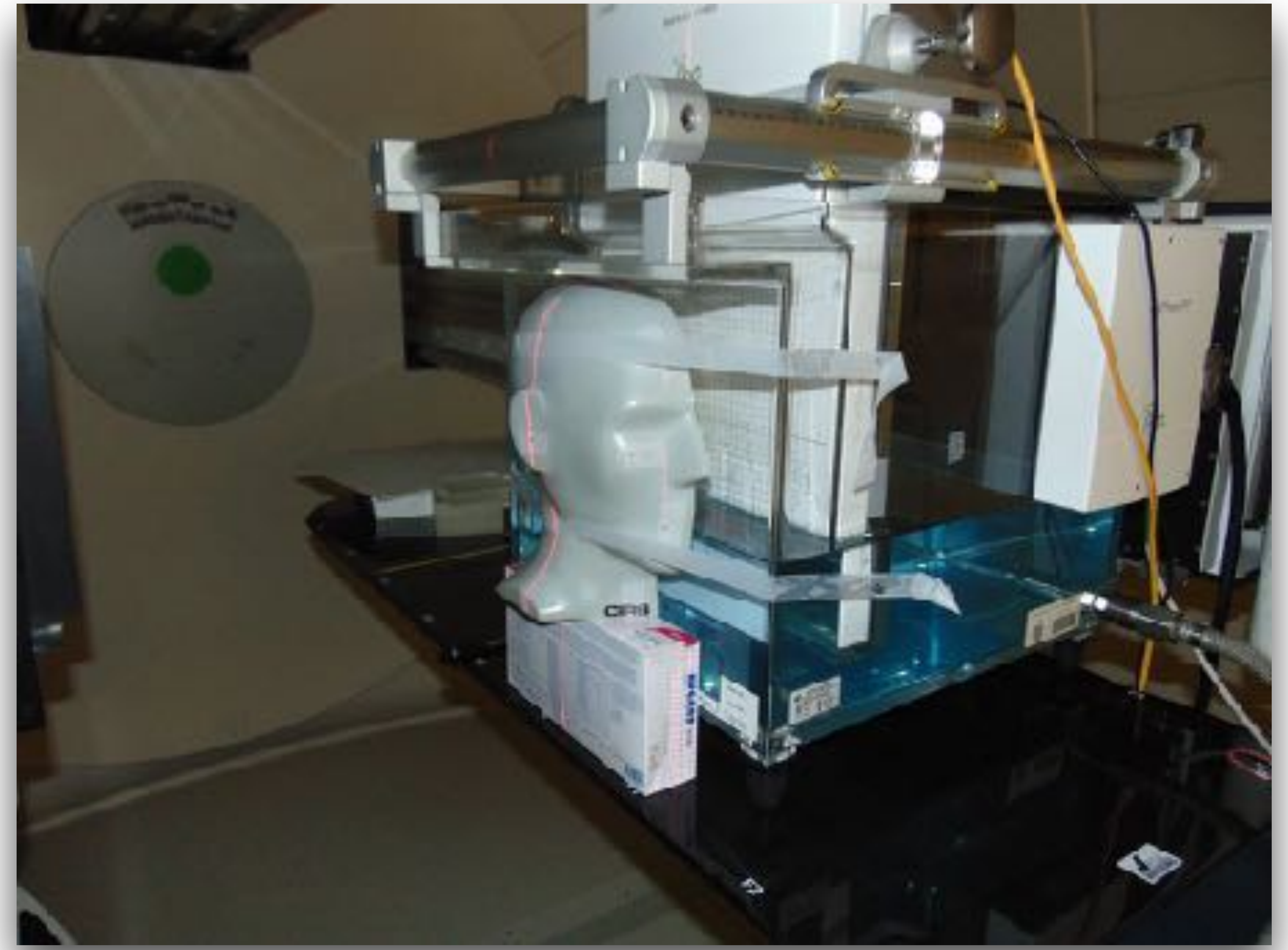




Mono-energetic p+ field: 150 MeV, 10x10cm^2

Phase space validation in heterogenous phantom



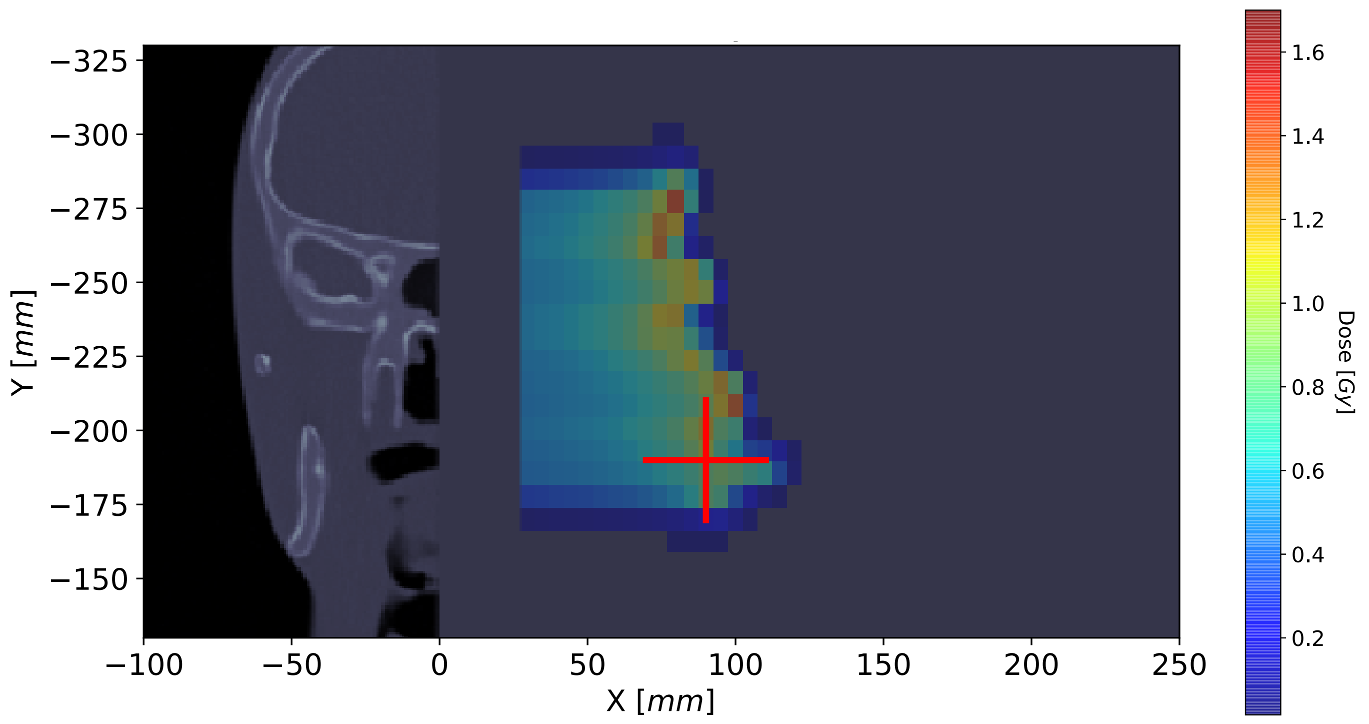


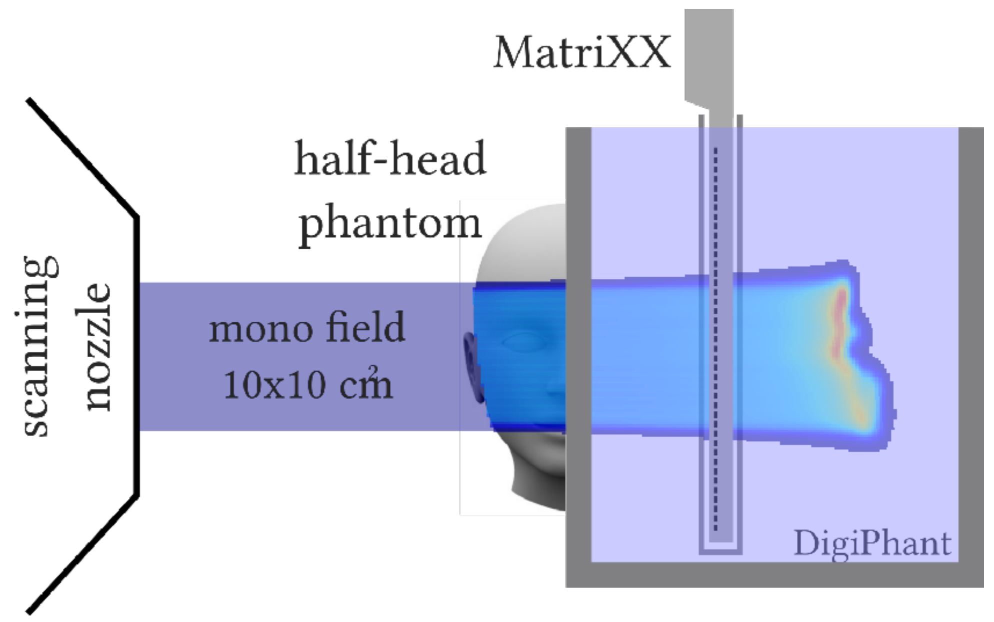
Mono-energetic p^+ field: 150 MeV, $10x10cm^2$

Phase space validation in heterogenous phantom

Measurement

MatriXX



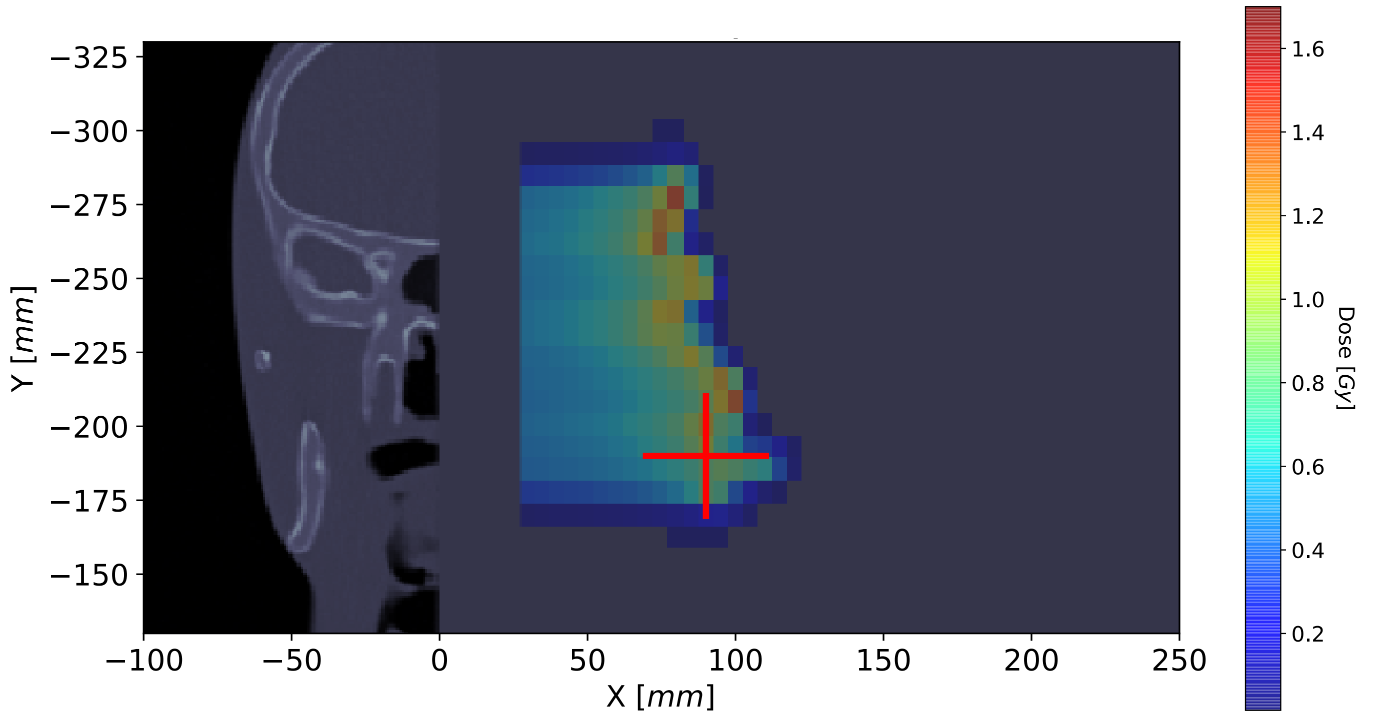


Mono-energetic p+ field: 150 MeV, 10x10cm^2

Phase space validation in heterogenous phantom

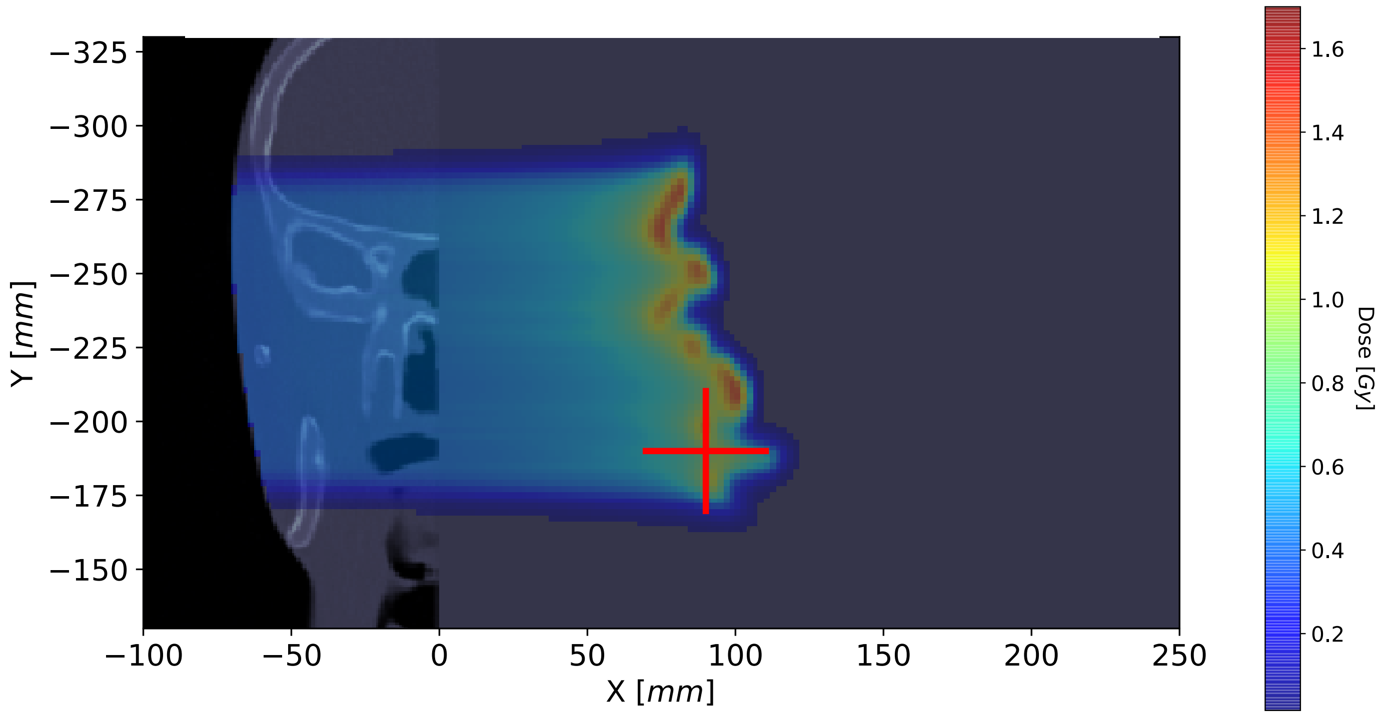
Measurement

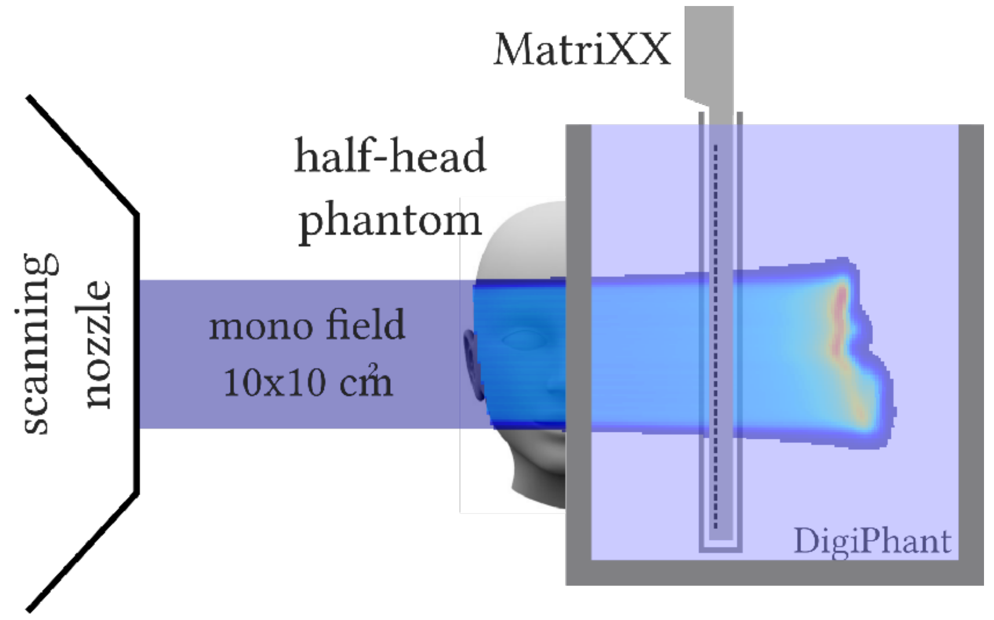
MatriXX



TPS calculation

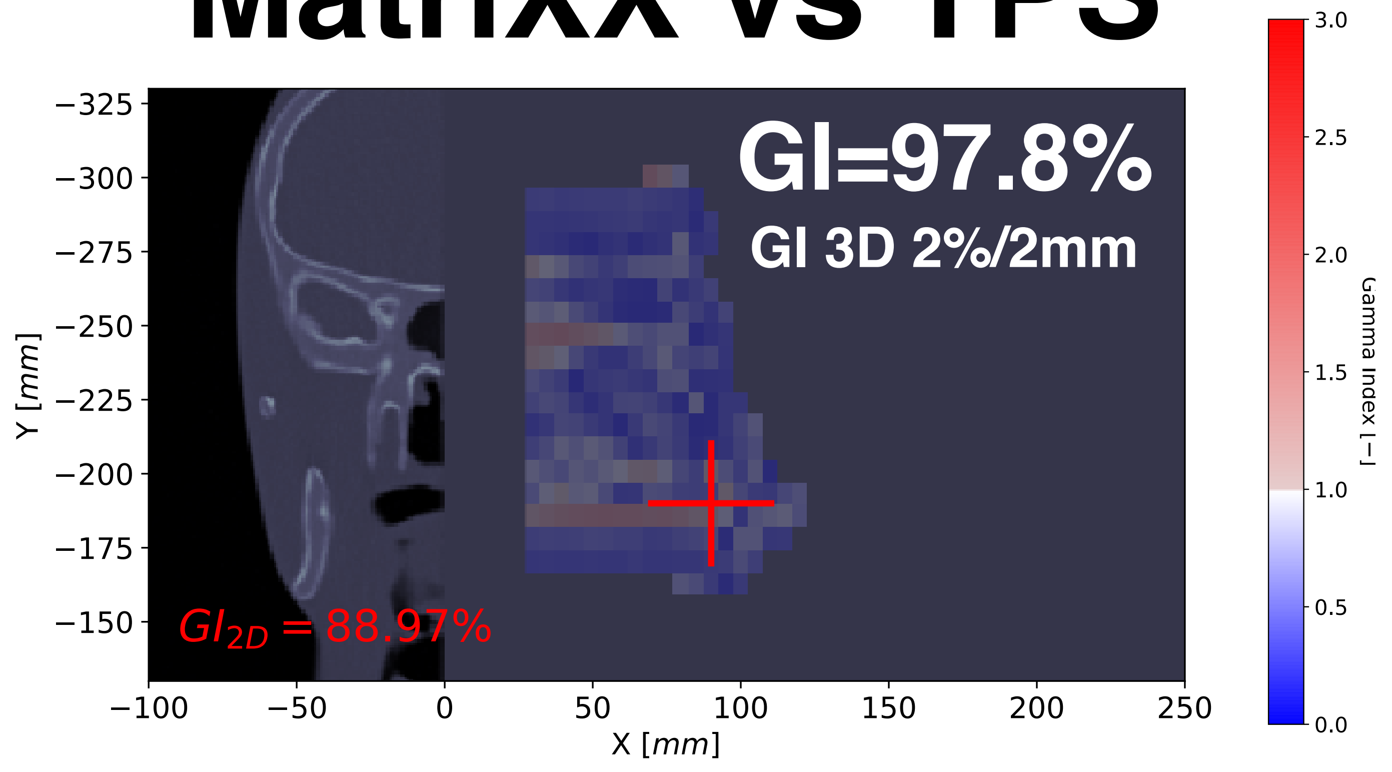
ECLIPSE v13.6





Mono-energetic p^+ field: 150 MeV, 10x10cm^2

MatriXX vs TPS

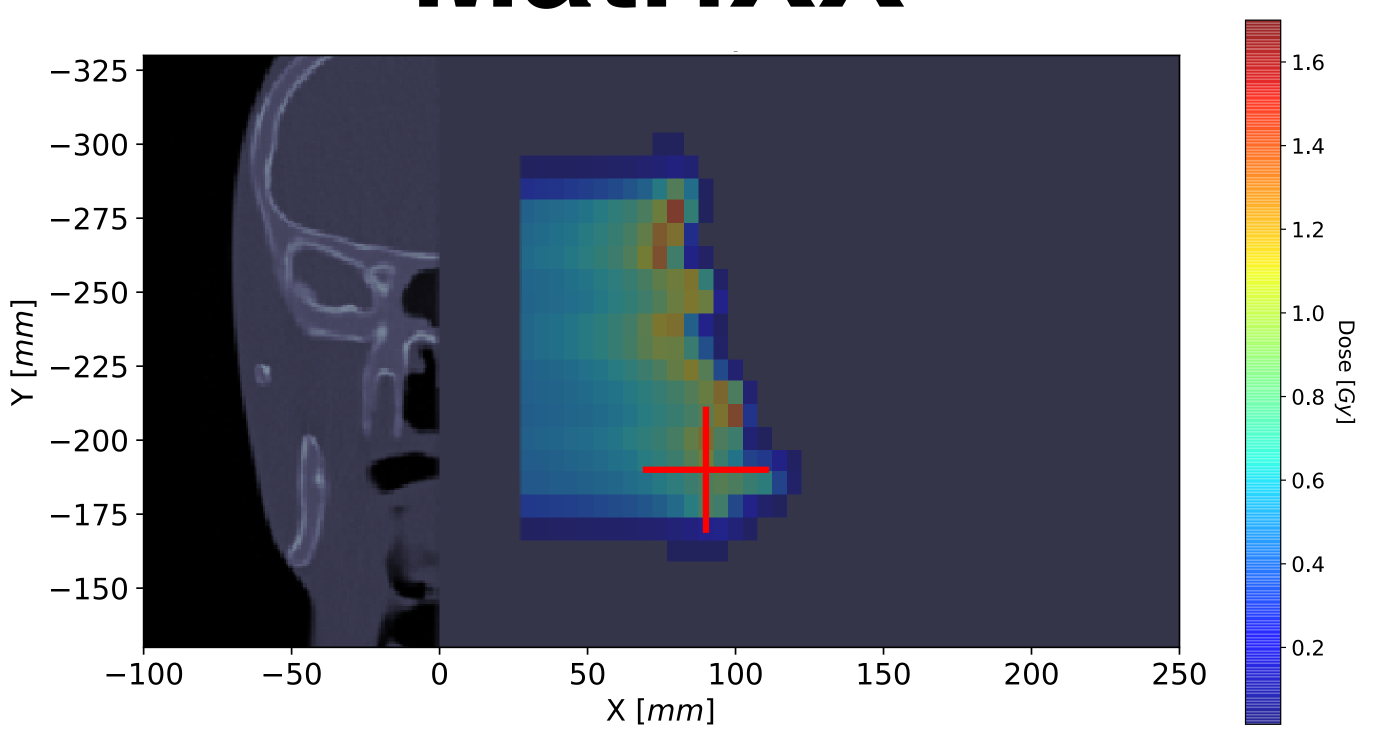


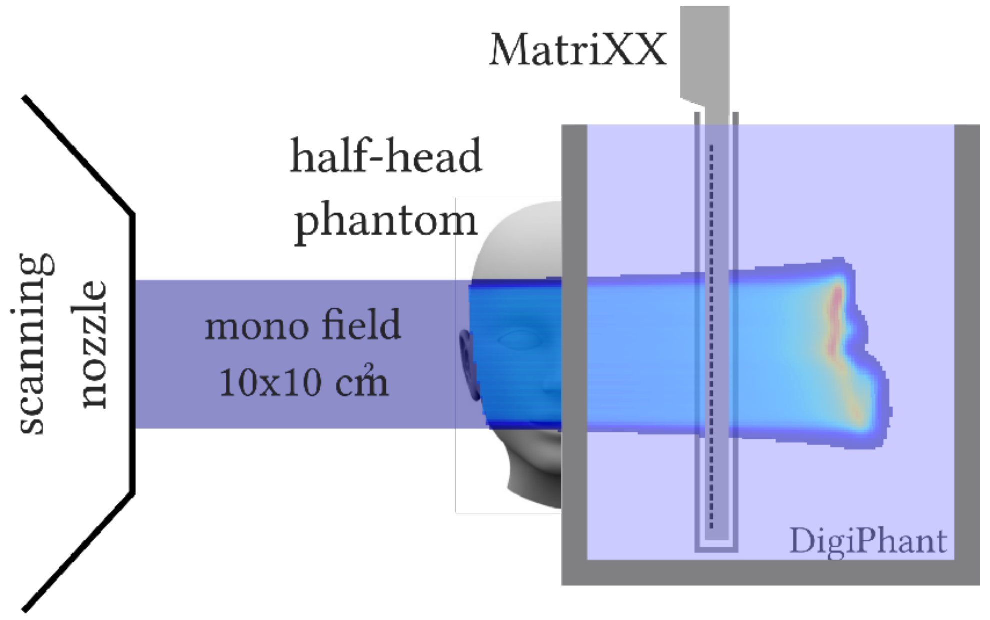
Gamma Index tools: https://pymedphys.com

Phase space validation in heterogenous phantom

Measurement

MatriXX

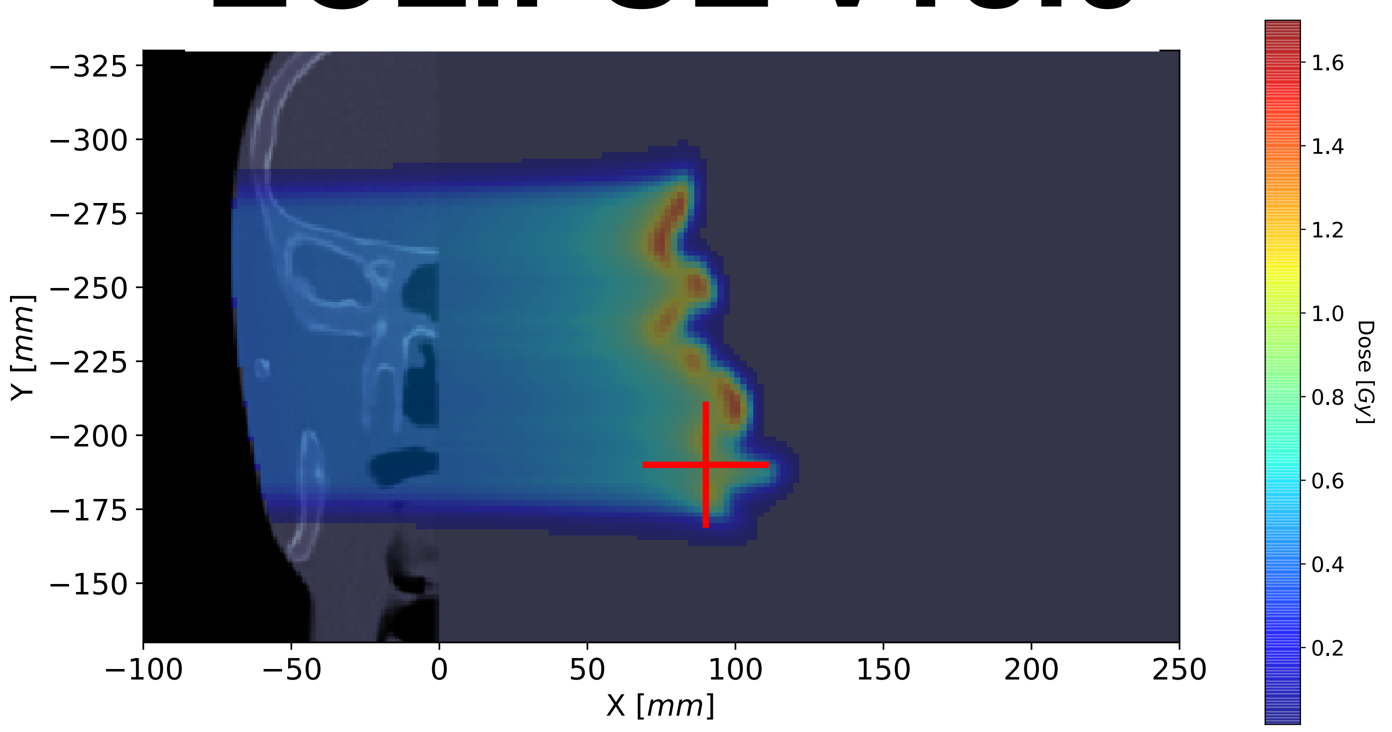




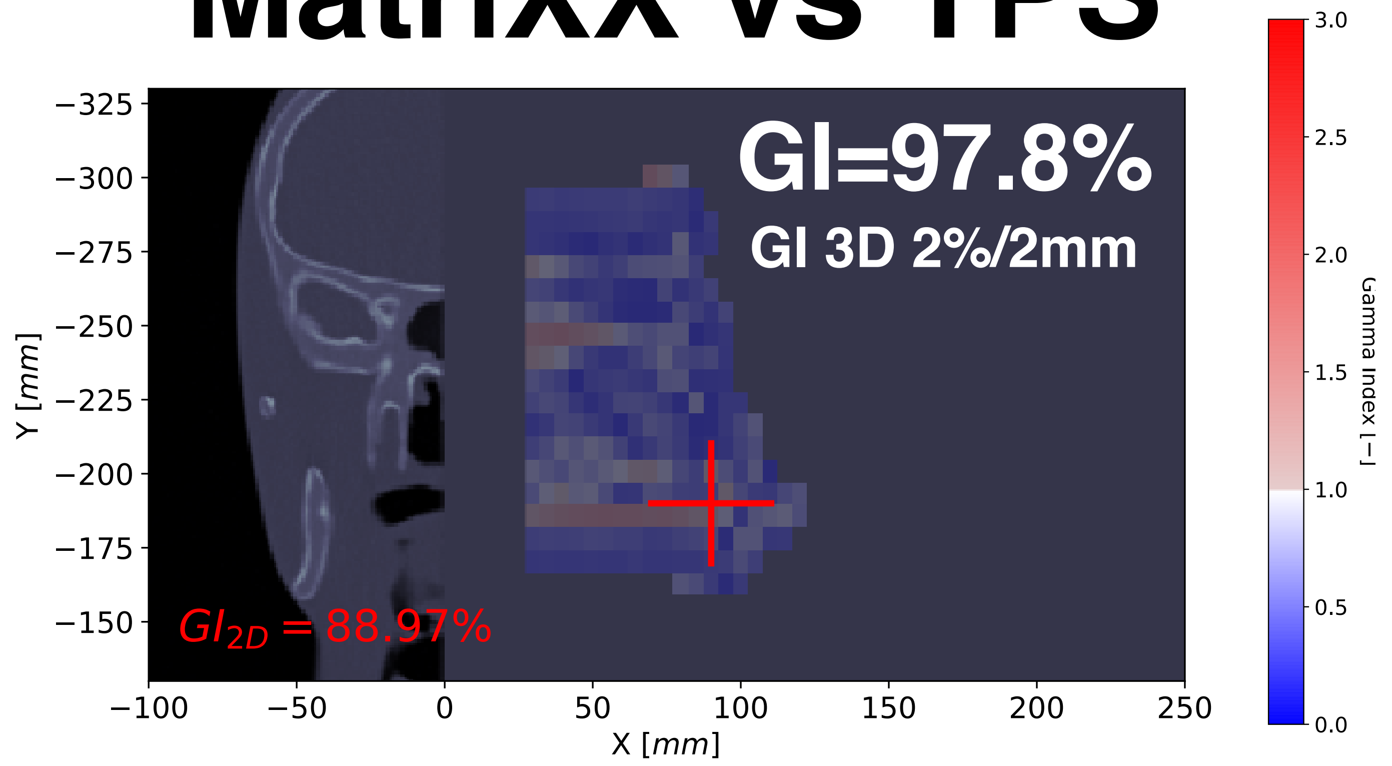
Mono-energetic p+ field: 150 MeV, 10x10cm²

TPS calculation

ECLIPSE v13.6



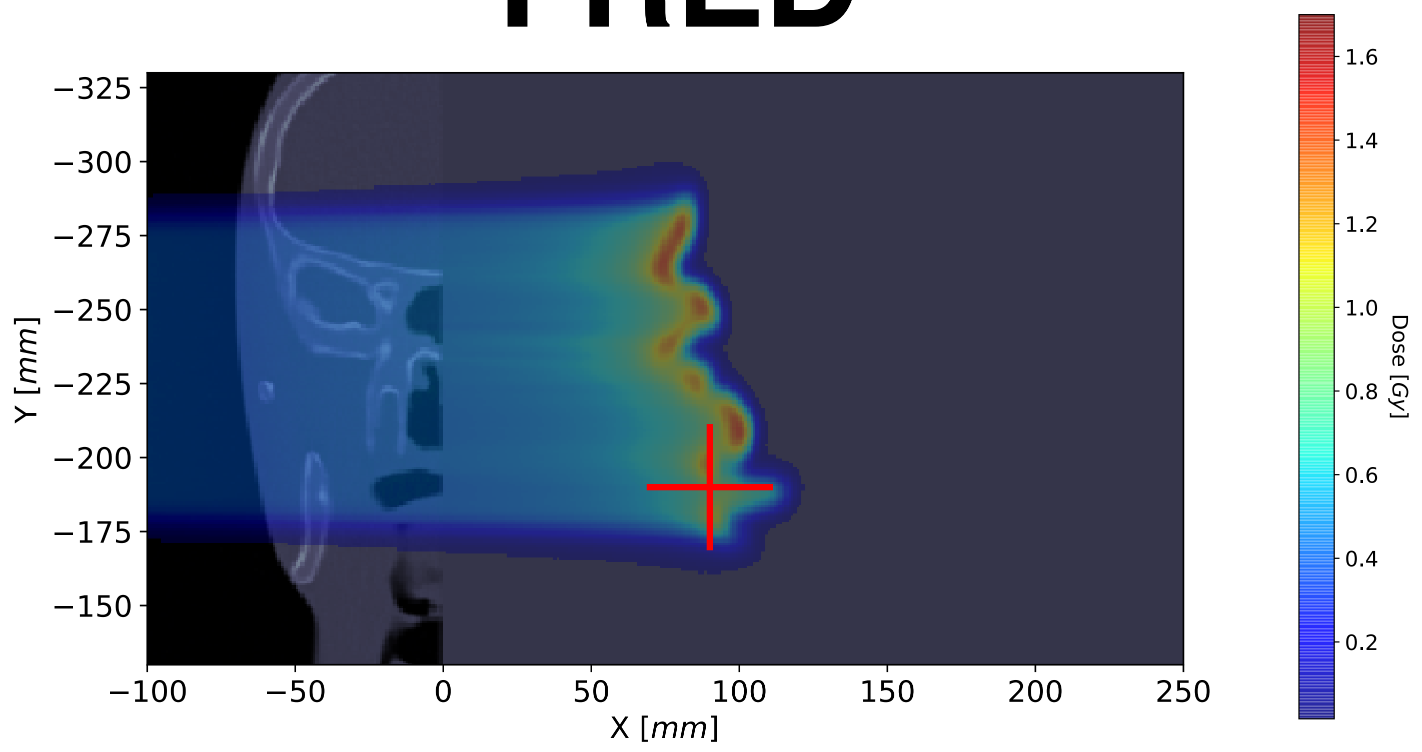
MatriXX vs TPS



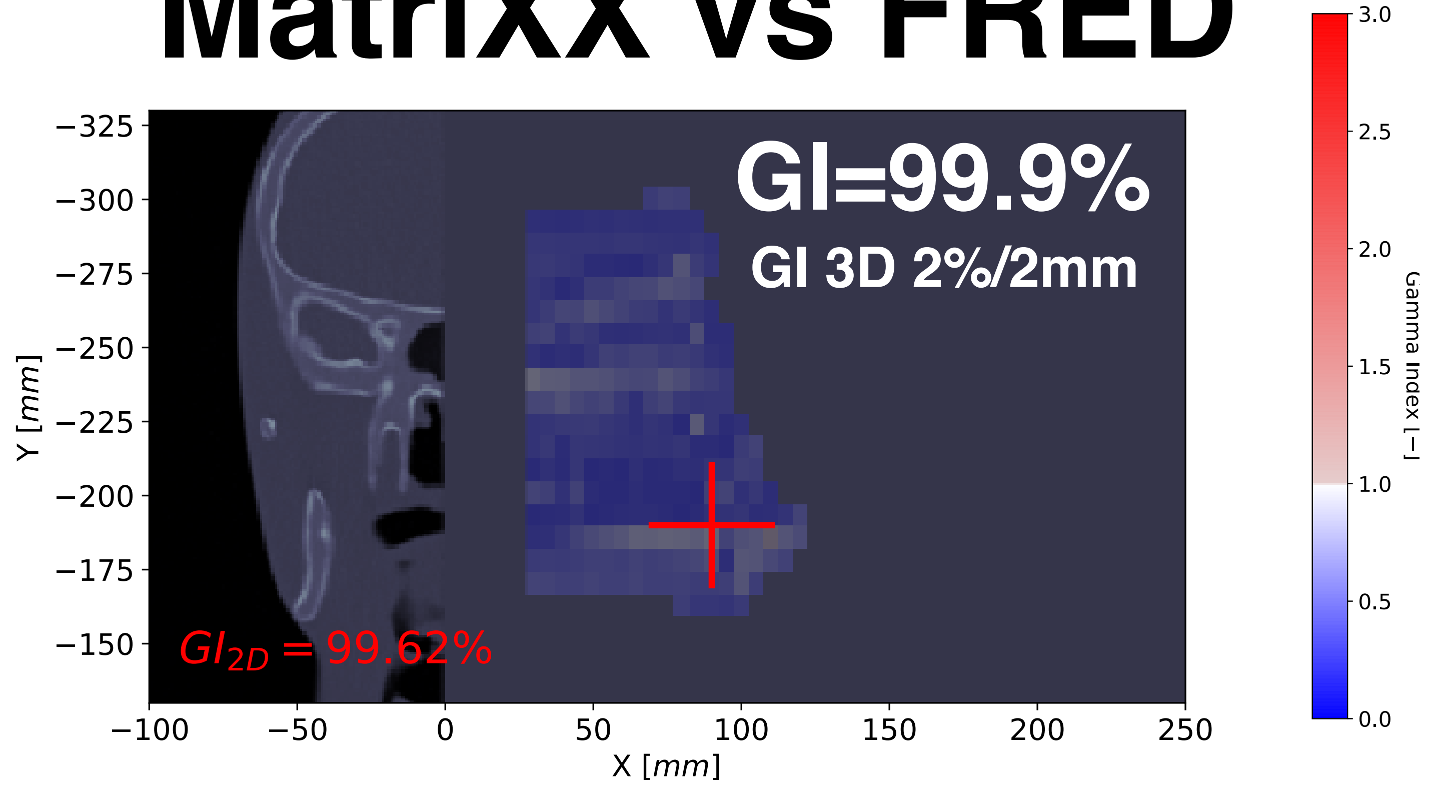
Gamma Index tools: https://pymedphys.com

FRED calculation

FRED



MatriXX vs FRED



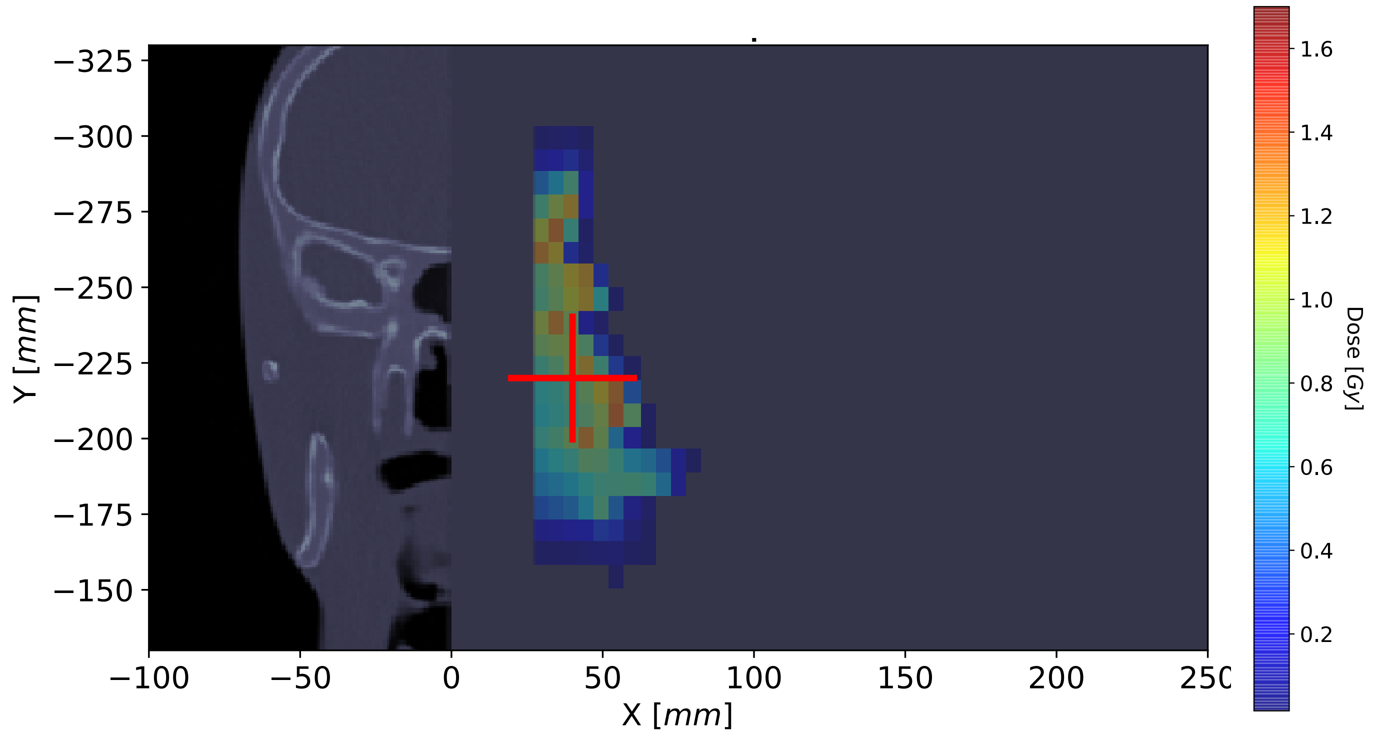
10^5 p+/spot , total sim. time 2’

Phase space validation in heterogenous phantom

Range shifter

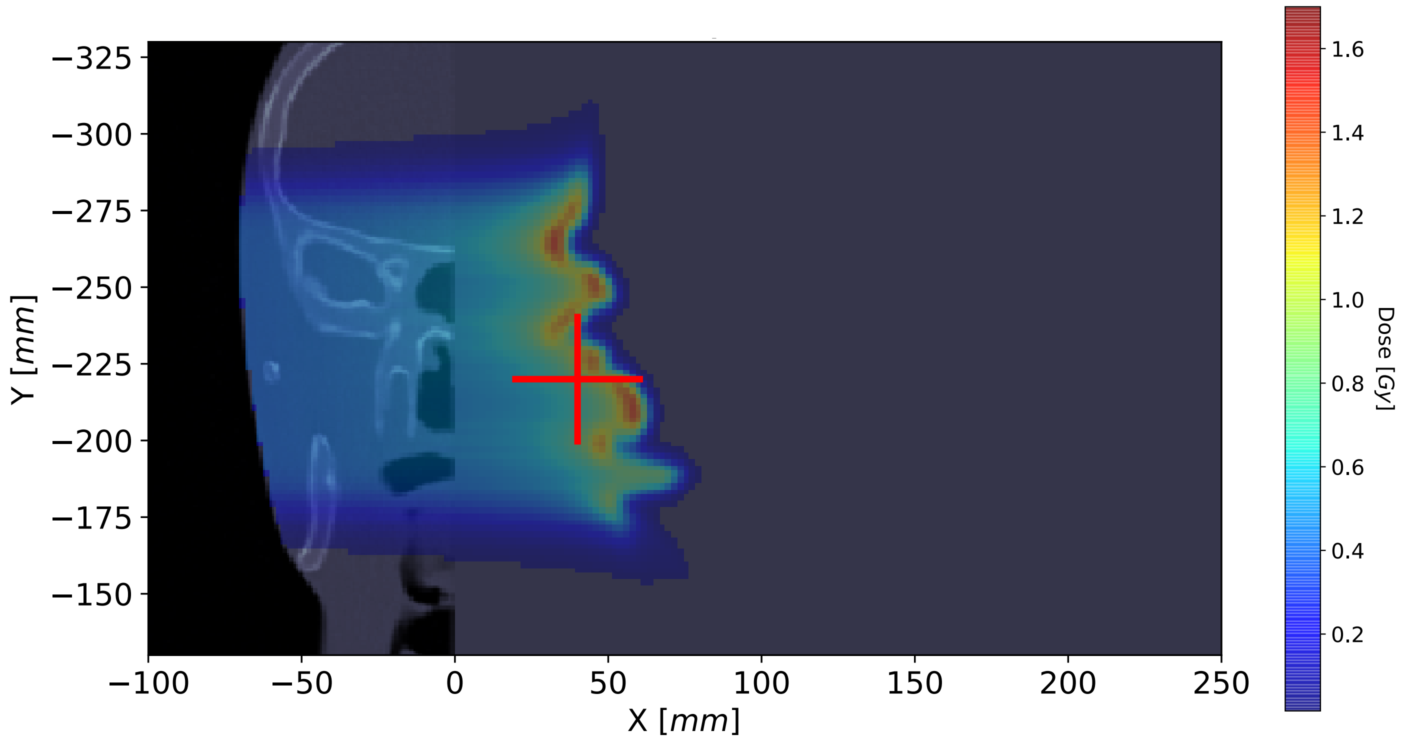
Measurement

MatriXX



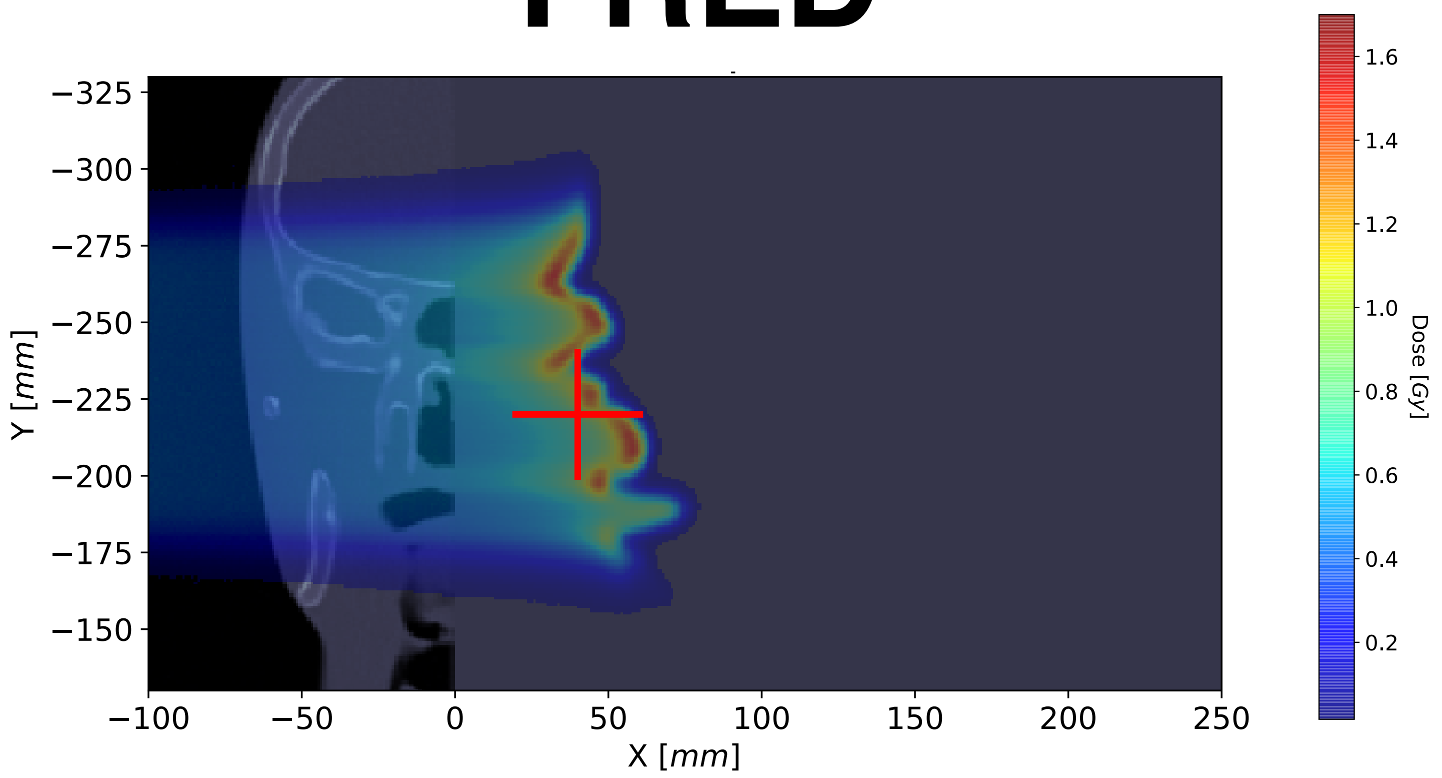
TPS calculation

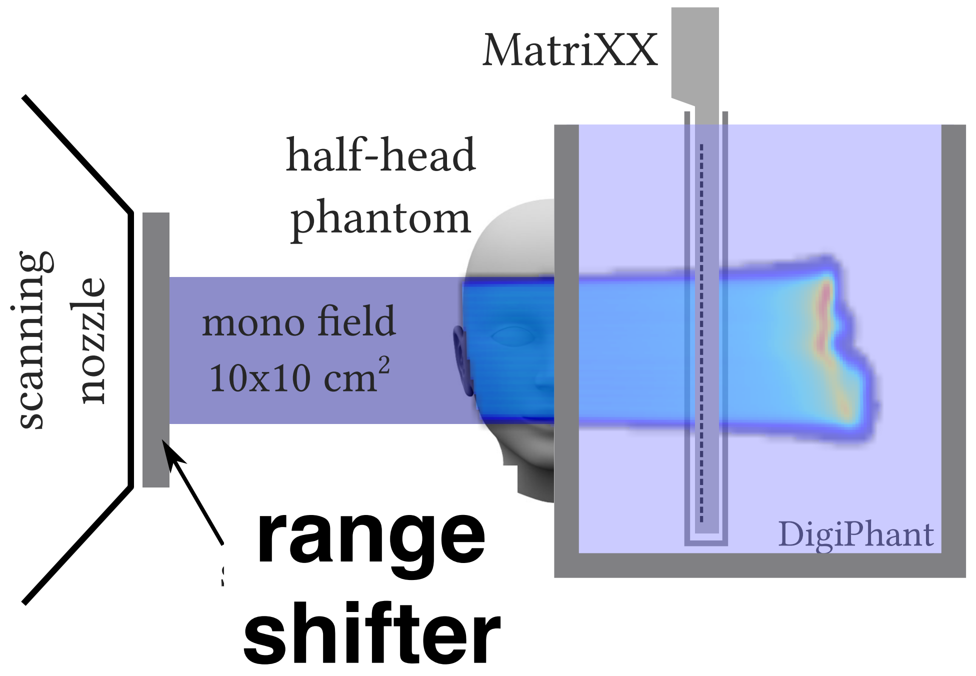
ECLIPSE v13.6



FRED calculation

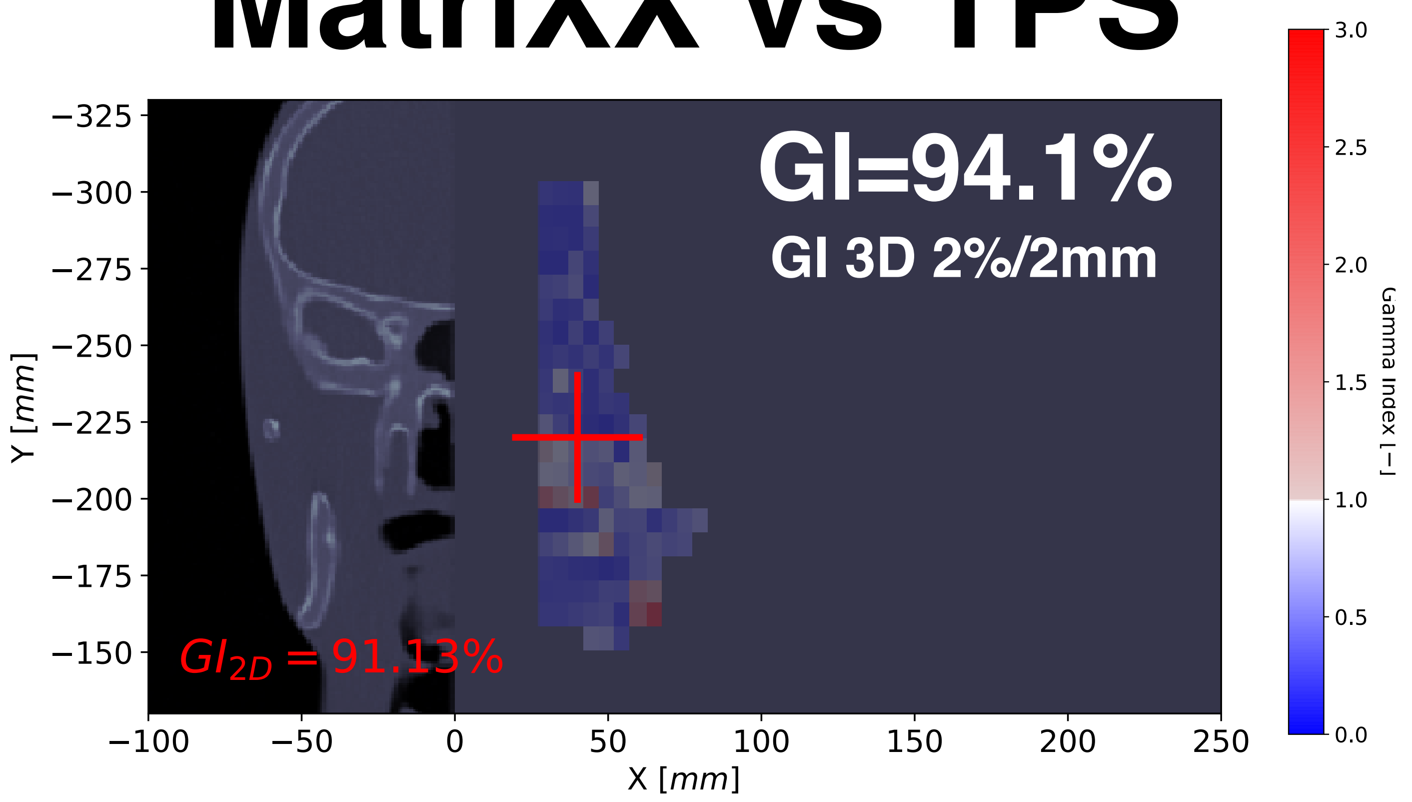
FRED



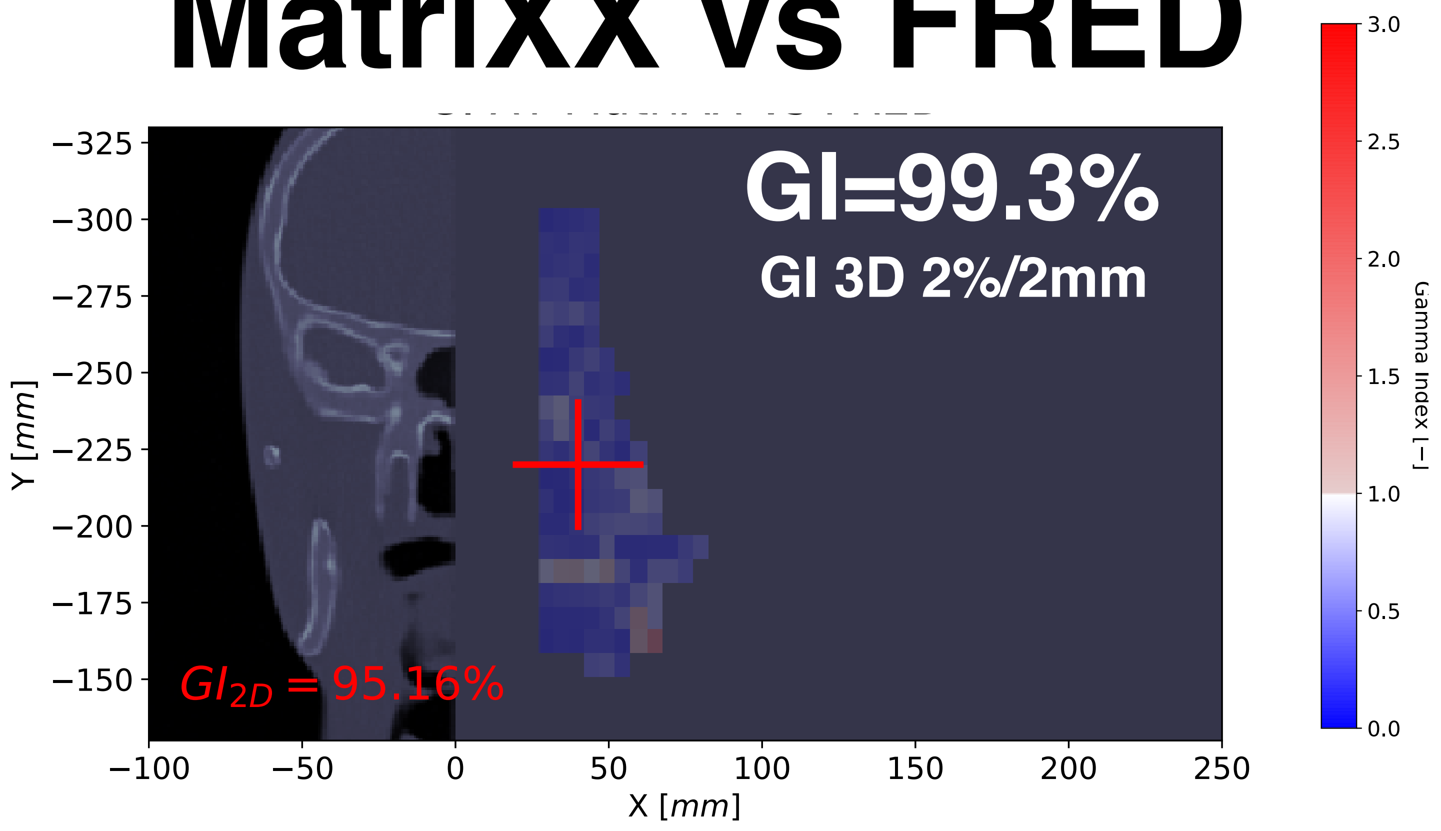


Mono-energetic p⁺ field: 150 MeV, 10x10cm²

MatriXX vs TPS



MatriXX vs FRED



Gamma Index tools: https://pymedphys.com

Antoni Rucinski INSTITUTE OF NUCLEAR PHYSICS PAN
antoni.rucinski@ifj.edu.pl antoni.rucinski@gmail.com web: www.ifj.edu.pl/dept/no6/nz62/ar/

Photons
TCP/NTCP

$$D_{bio} = D_{phys} \cdot RBE_{(D,\, LET,\, \alpha/\beta)}$$

Protons
TCP/NTCP

Physical

Biological

range uncertainties

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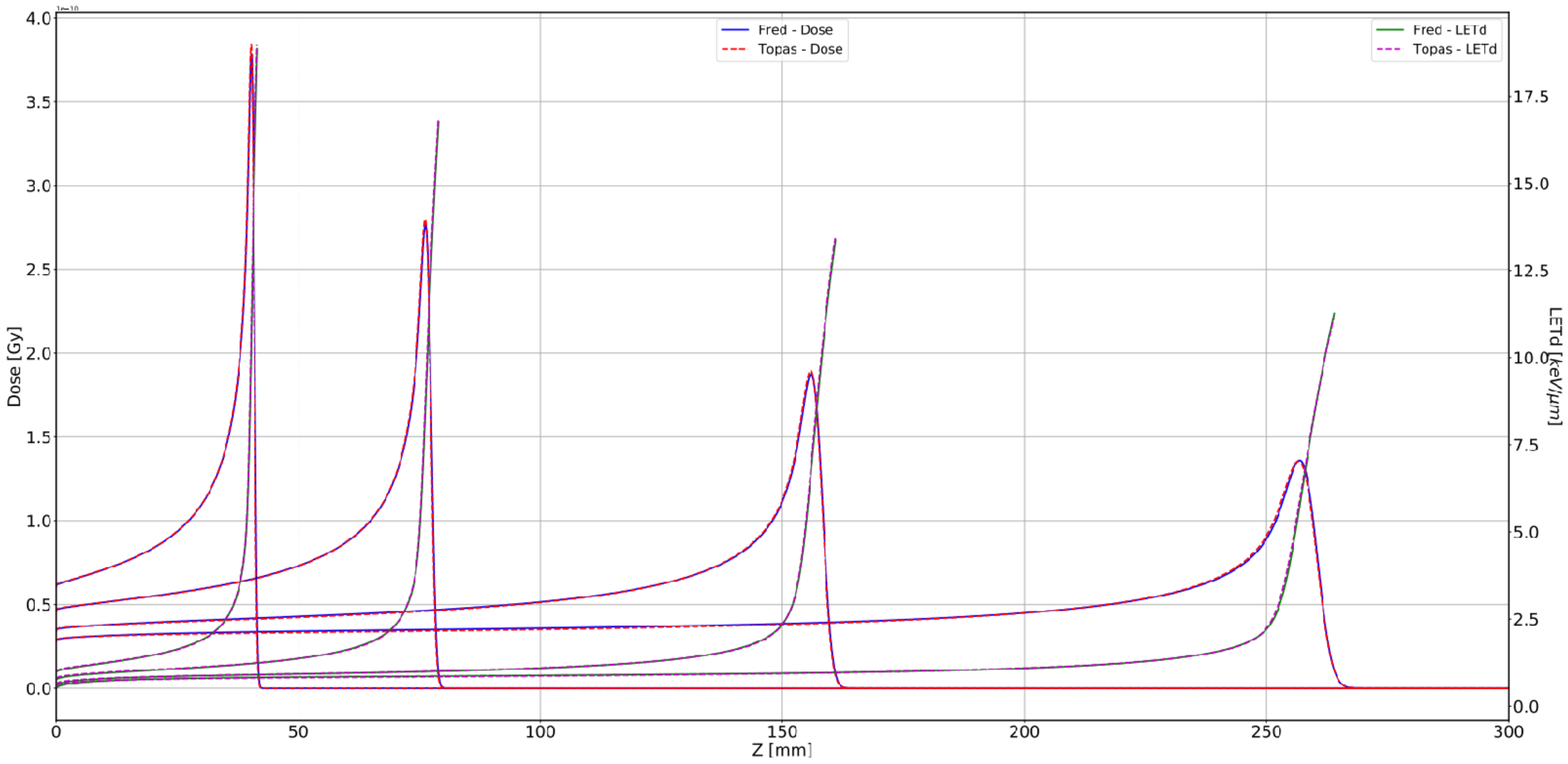
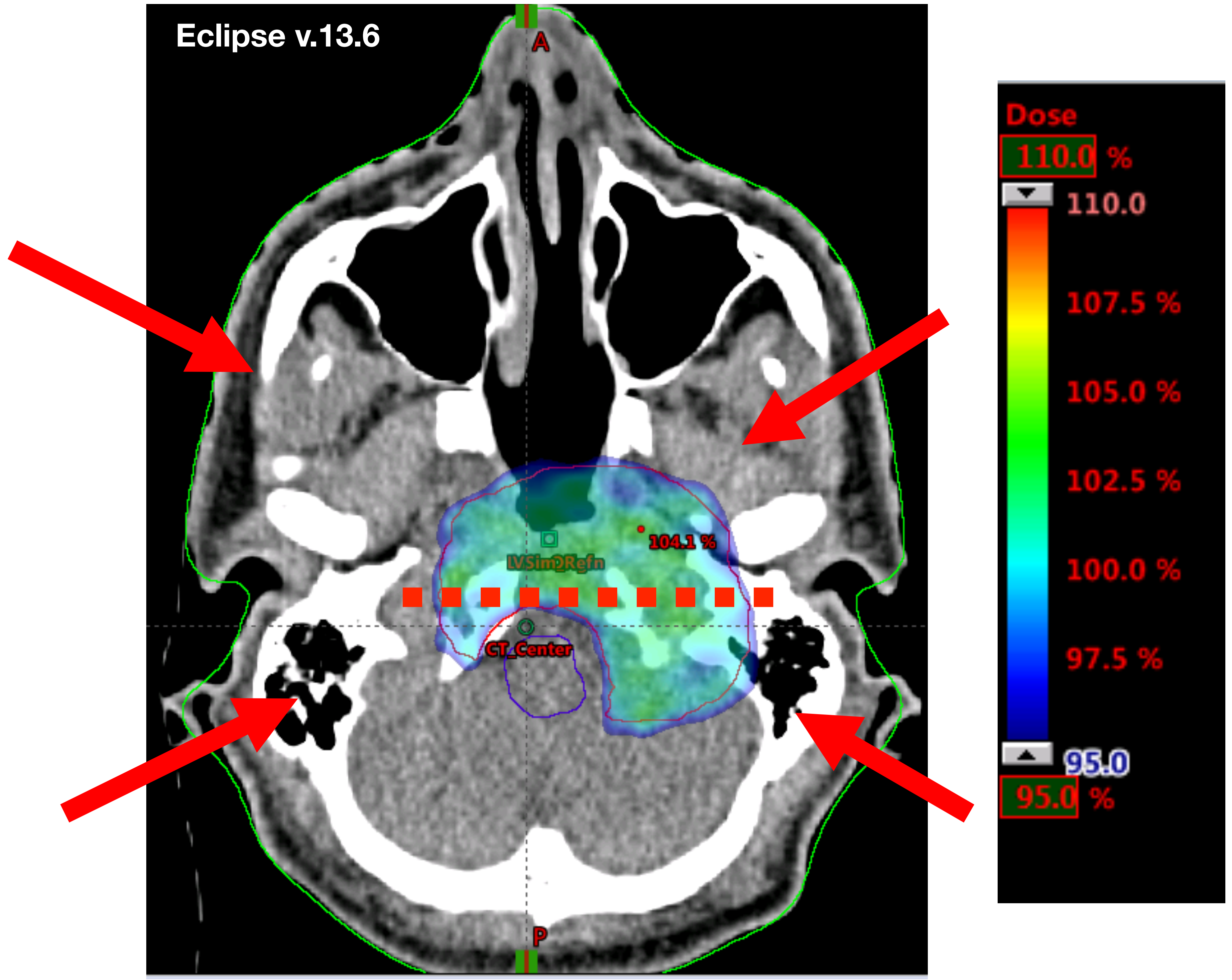
LET validation: FRED vs TOPAS



FRED for independent dose calculation and treatment planing studies

Radiobiological dose
TPS RBE=1.1



Radiobiological dose
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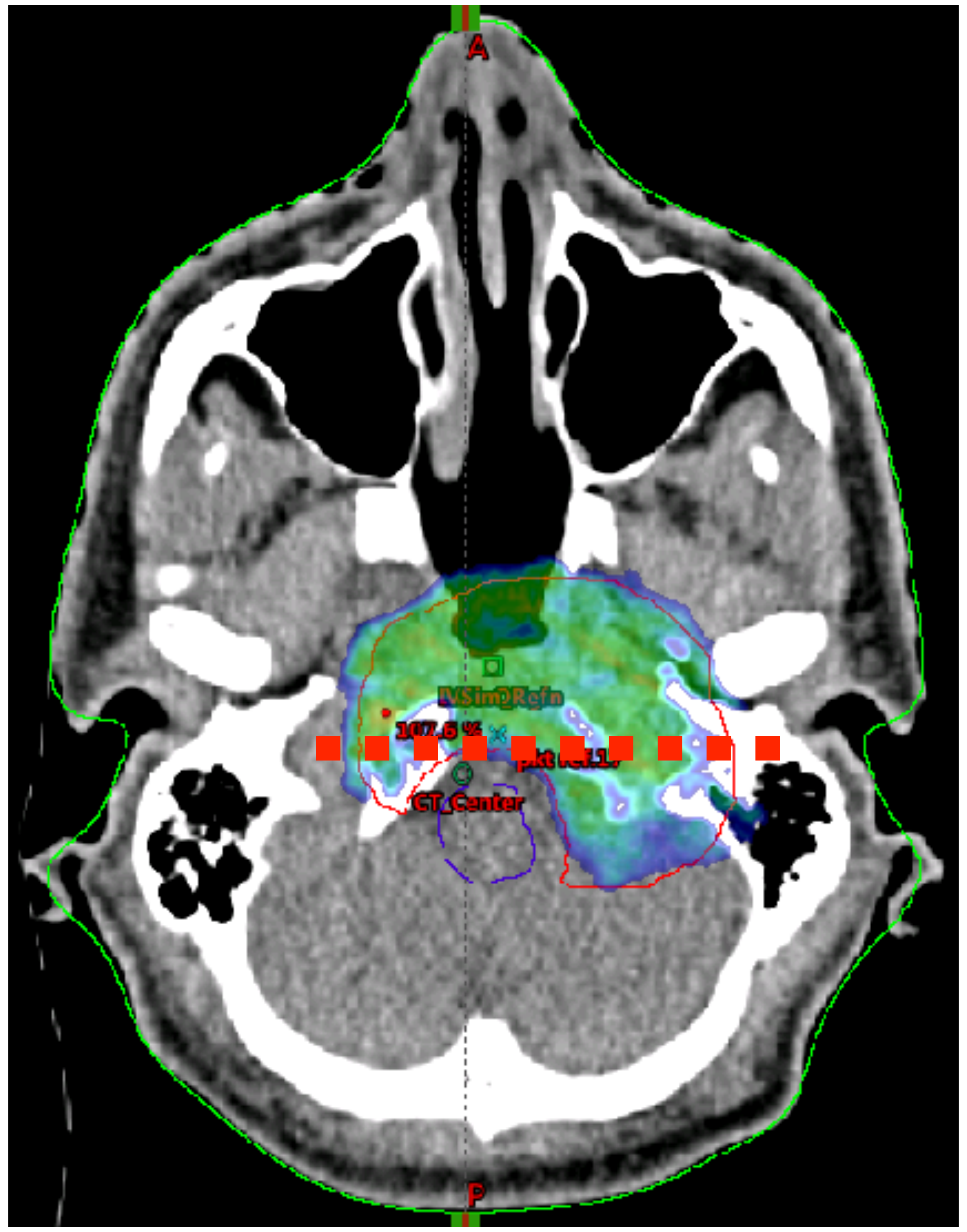
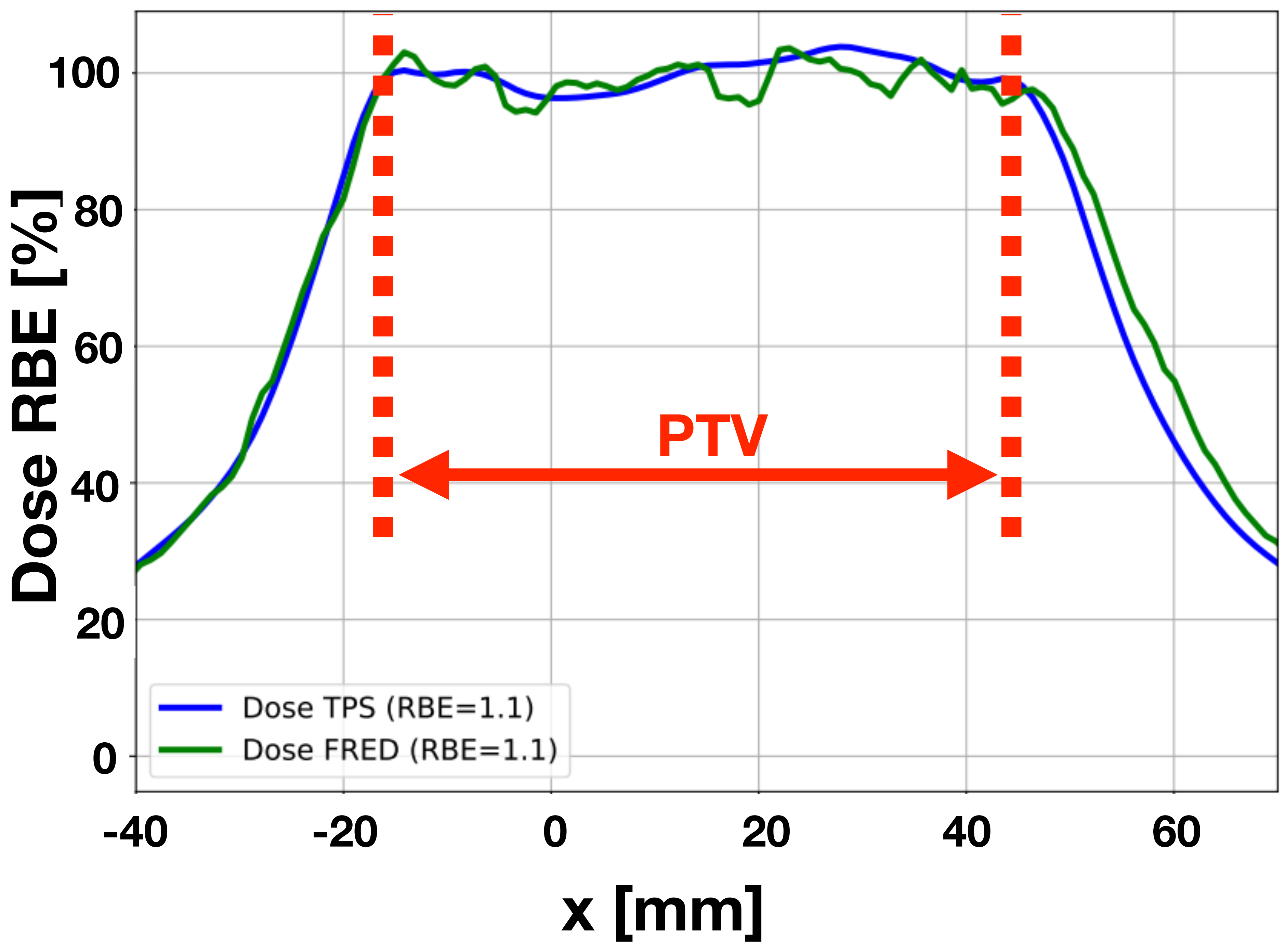


TPS$_{RBE=1.1}$ vs FRED$_{RBE=1.1}$



FRED for independent dose calculation and treatment planing studies

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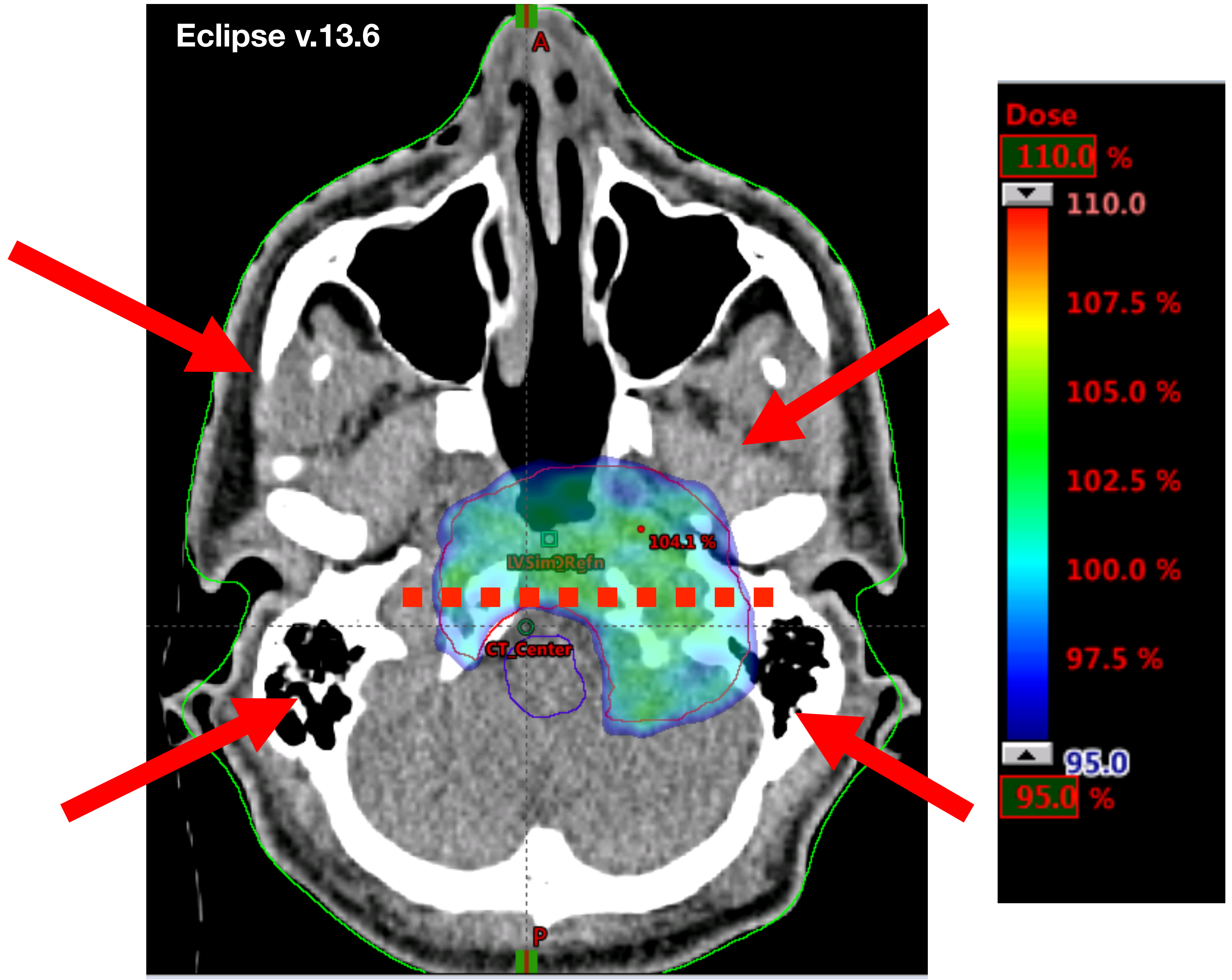
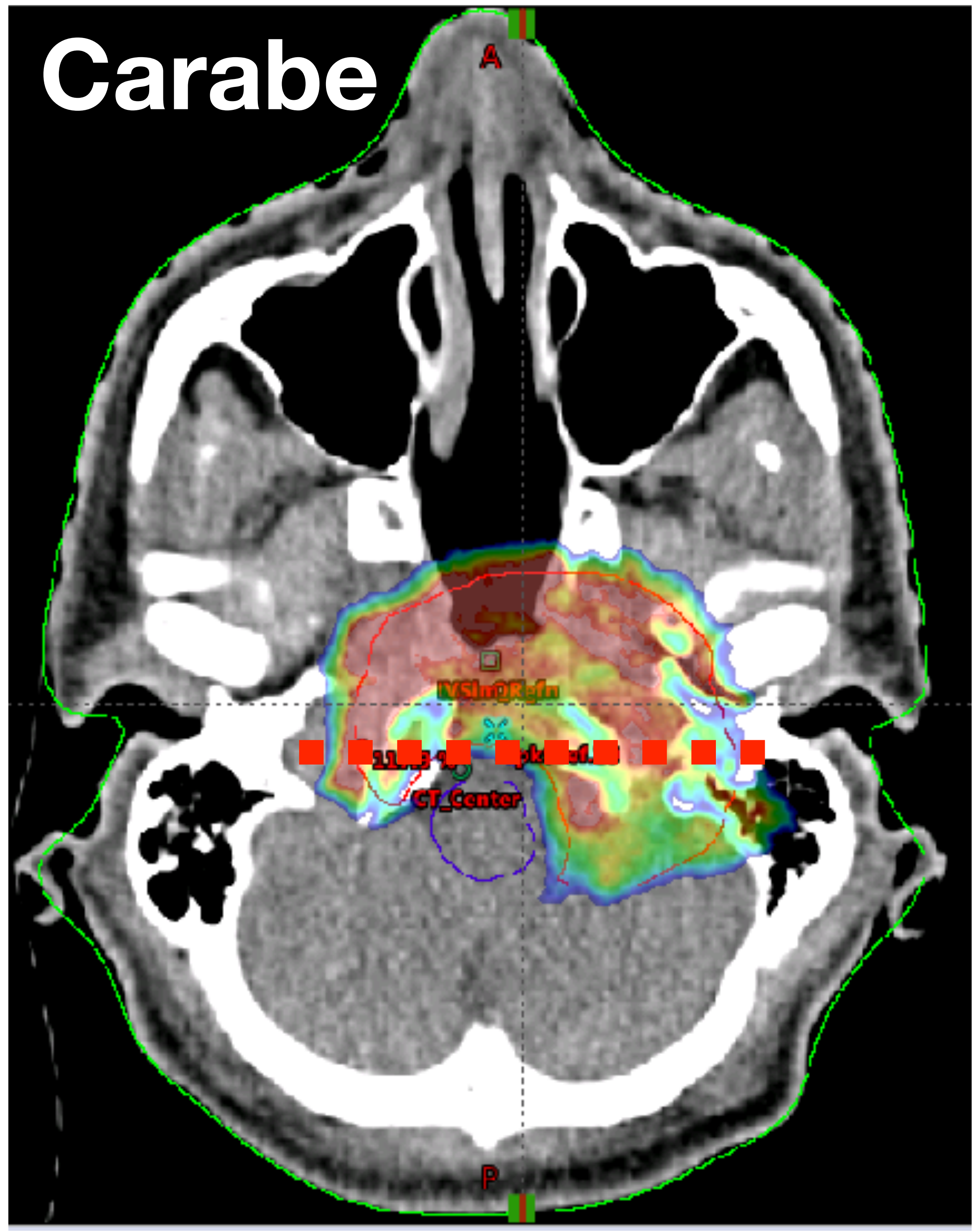
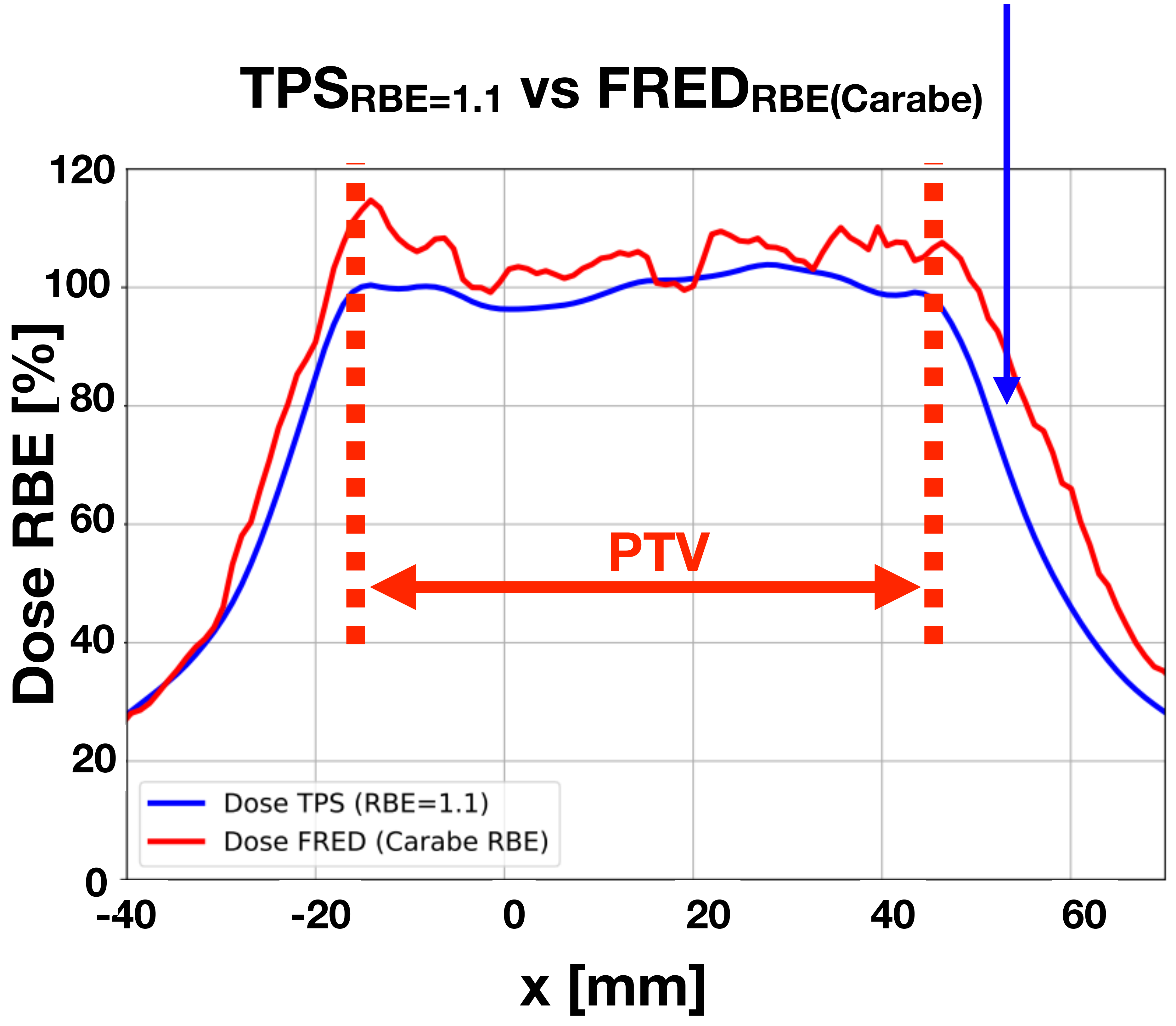


Radiobiological dose
FRED variable RBE

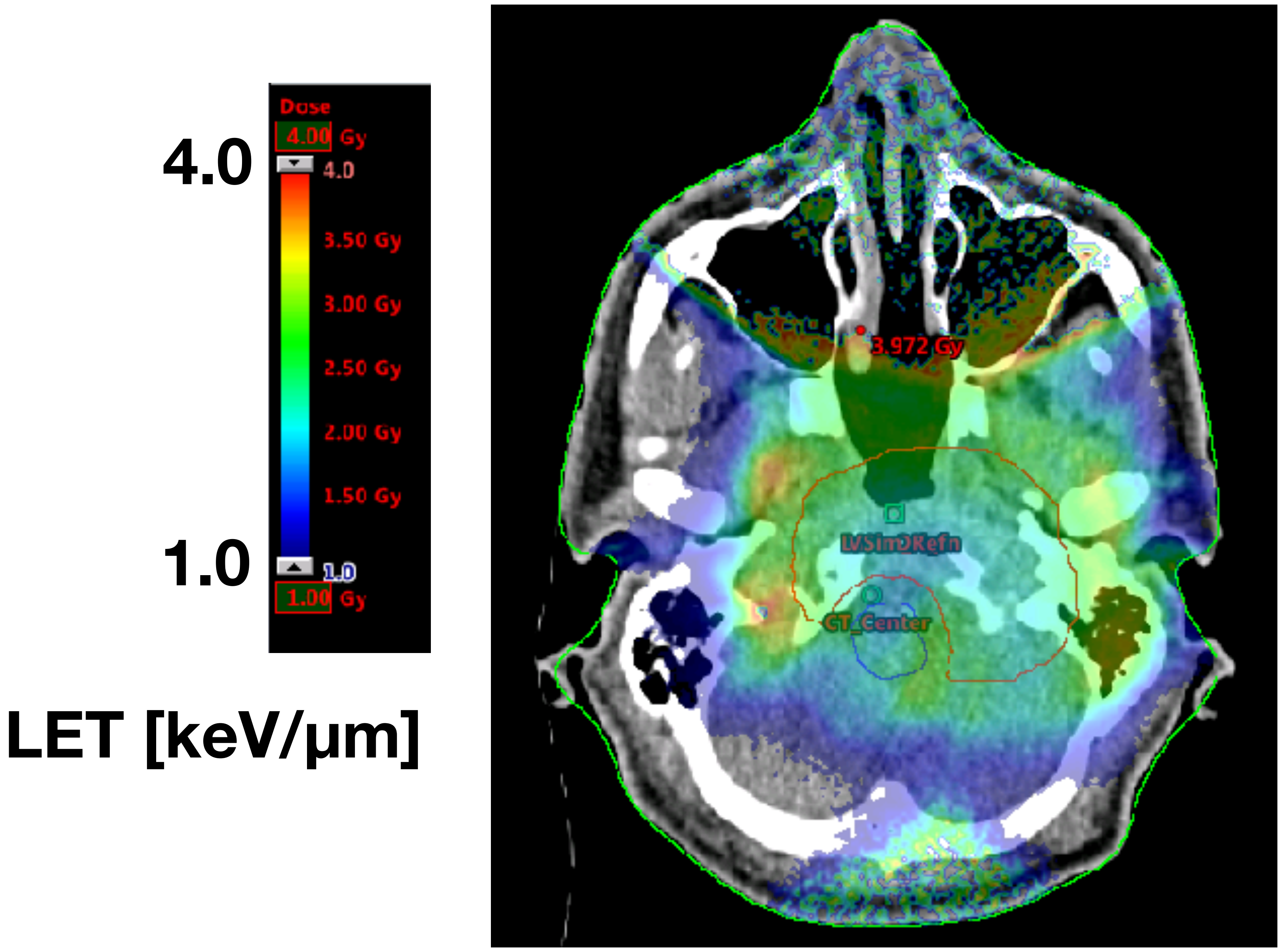


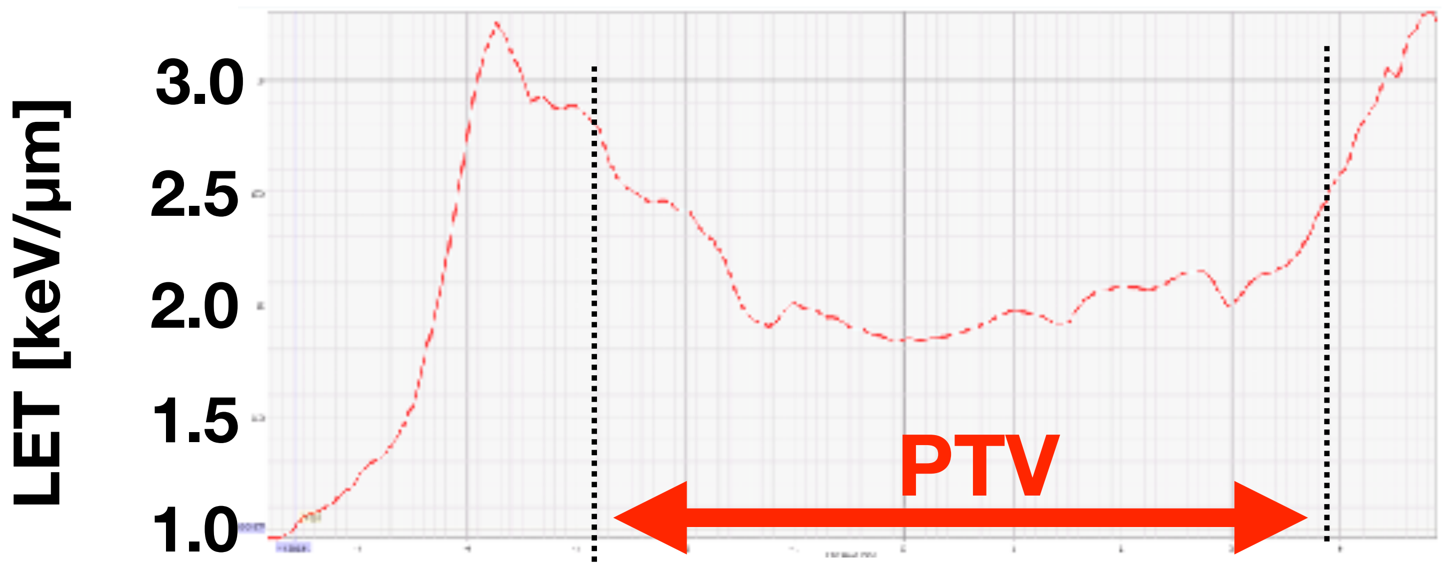
5mm range difference



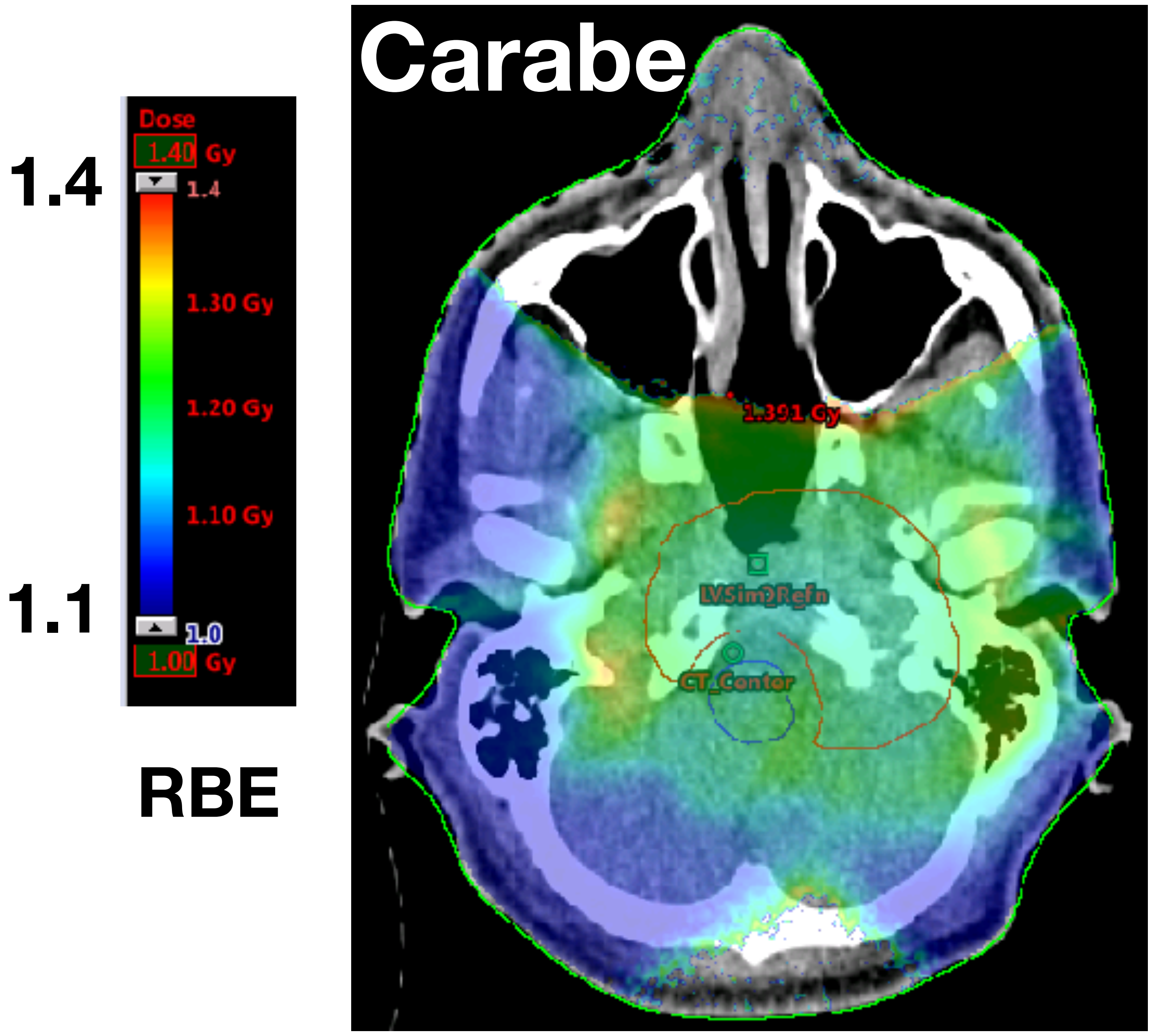
LET and RBE distributions for variable RBE dose calculations

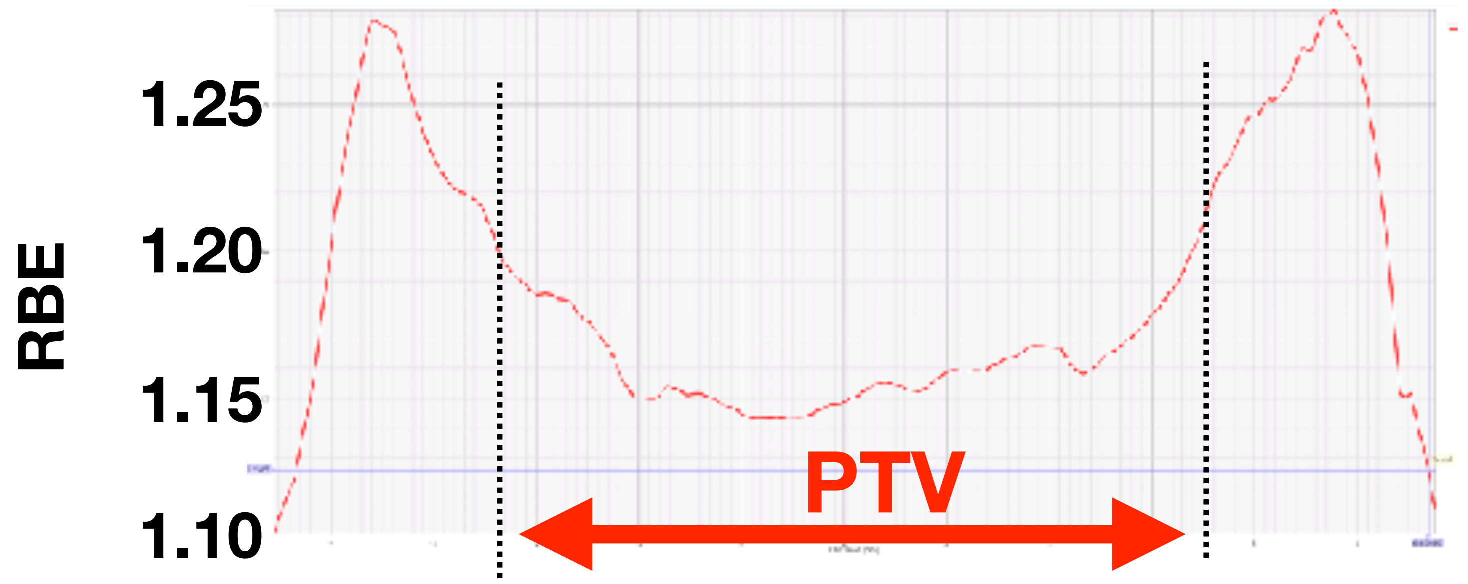
LET distribution





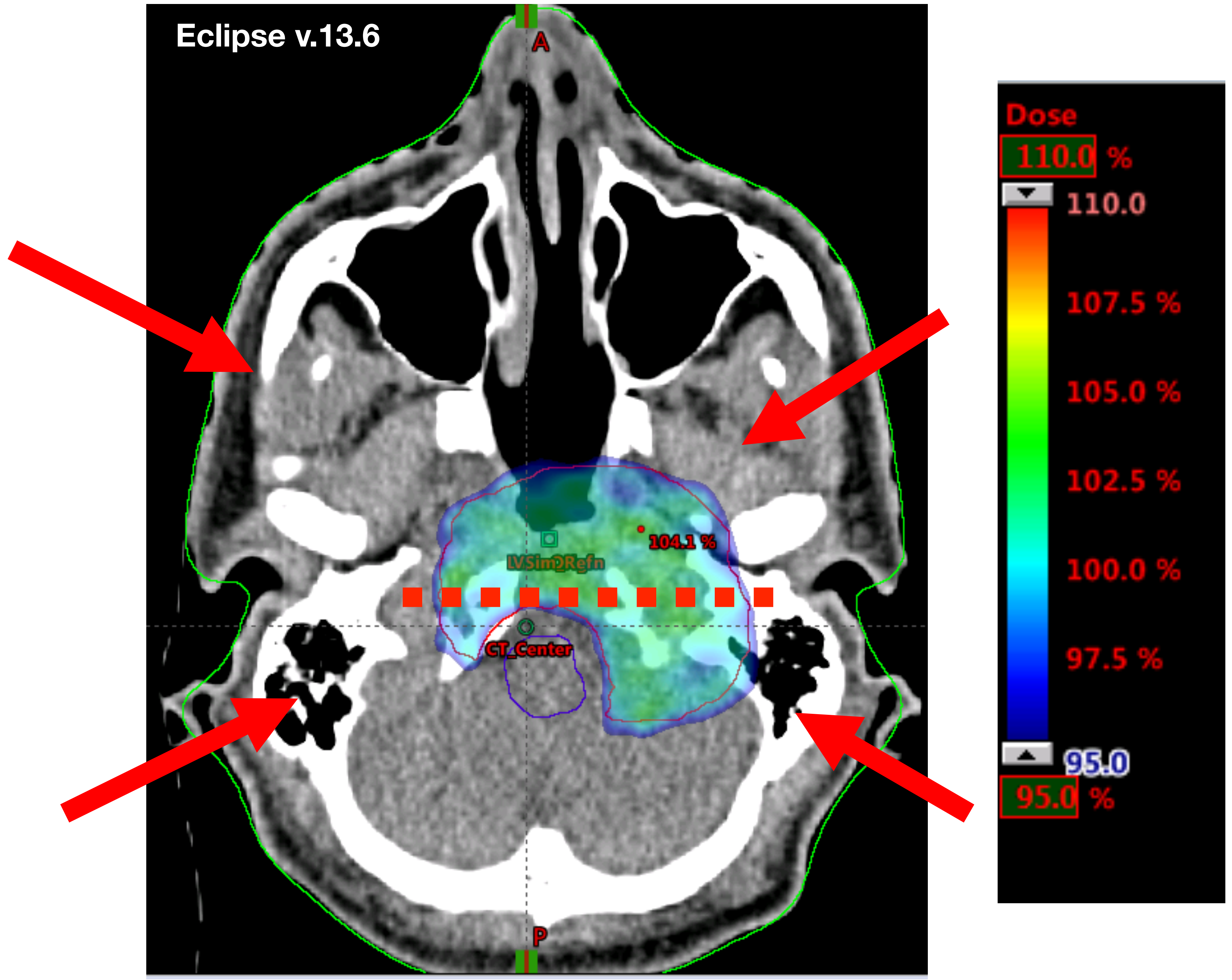
RBE distribution



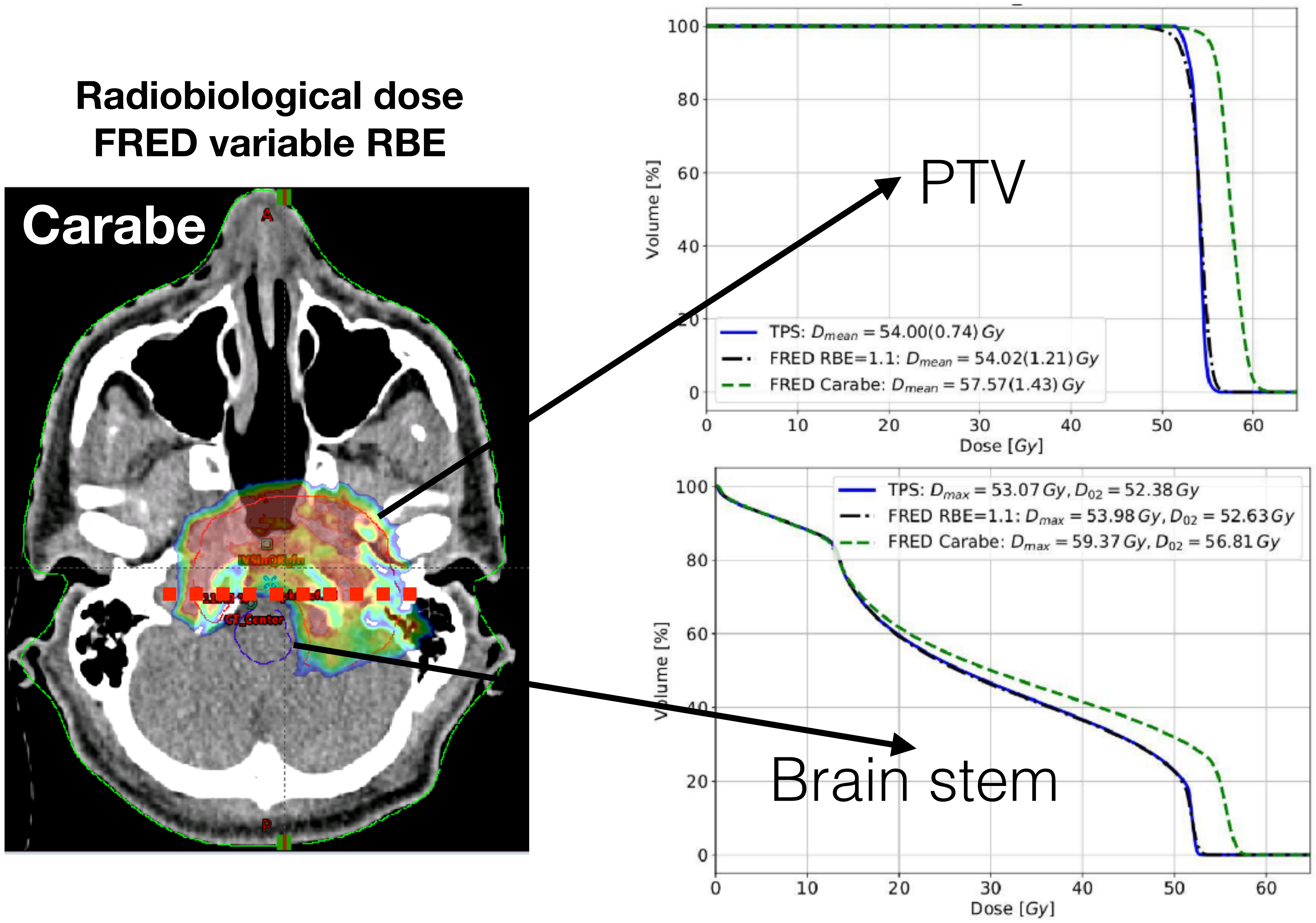


FRED for independent dose calculation and treatment planing studies

Radiobiological dose
TPS RBE=1.1



Radiobiological dose
FRED variable RBE



Treatment planing studies

10 Head&Neck patients treated in Krakow

PTV	RBE=1.1	Carabe RBE
Dmean	100.1% (0.0%)	107.9% (0.8%)

Brain stem	RBE=1.1 [Gy(RBE)]	Carabe RBE [Gy(RBE)]
D_{02}	50.8 (1.8)	55.6 (2.1)

- PTV D_{mean} up to ~8% higher that prescribed dose
- OAR (brain stem) D_{02} up to ~5 Gy(RBE) higher than calculated in TPS

Treatment planing studies

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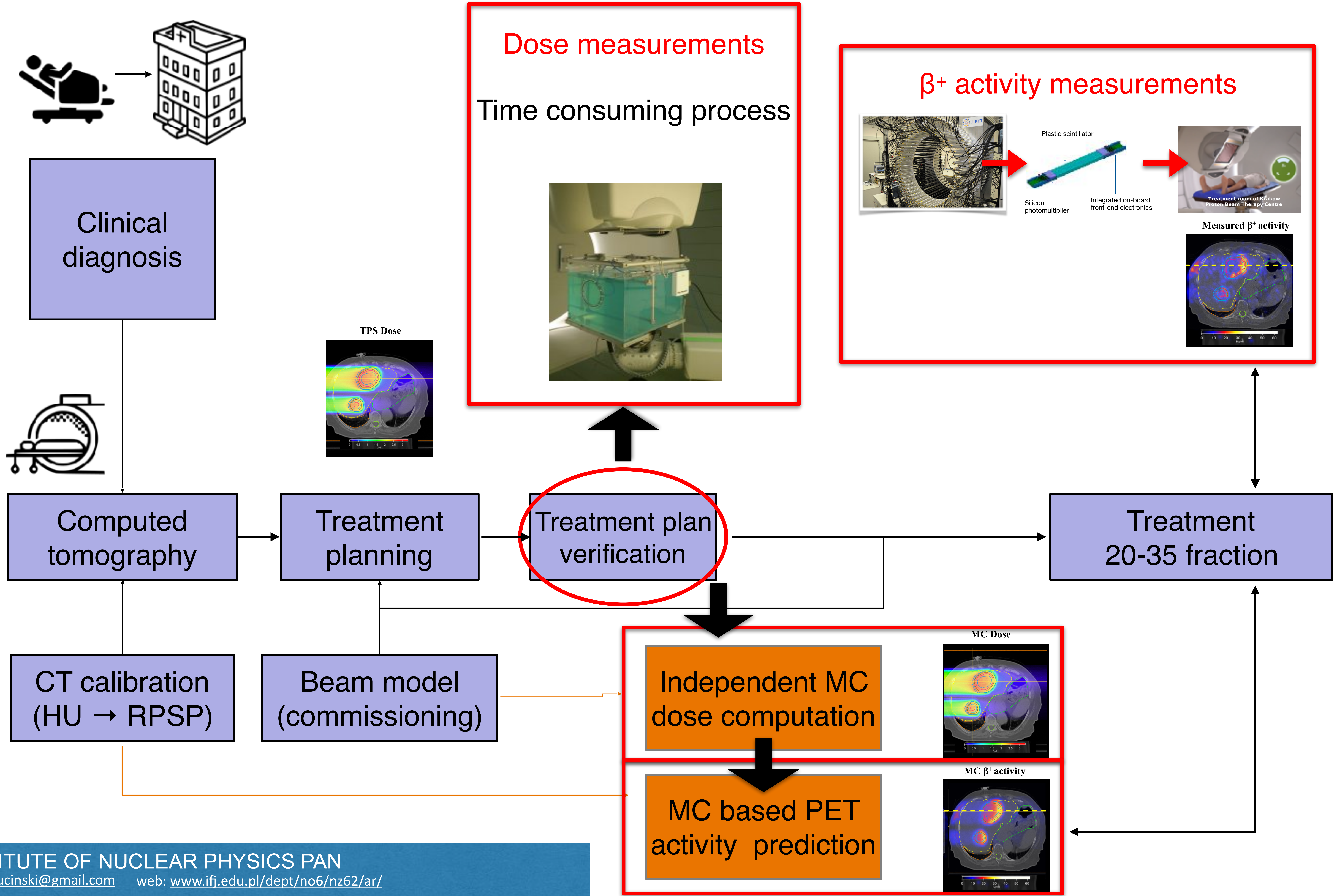
- PTV D_{mean} up to ~8% higher that prescribed dose
- OAR (brain stem) D_{02} up to ~5 Gy(RBE) higher than calculated in TPS
- **The mean time to recalculate a single treatment plan was 3.7 min**
  - 10^5 p/beam
  - 1.2×10^9 p/plan
  - 5.6×10^6 p/s
  - voxel size: 0.7 mm x 0.7 mm x 1.2 mm.

Proton therapy treatment



FRED: New developments and future applications

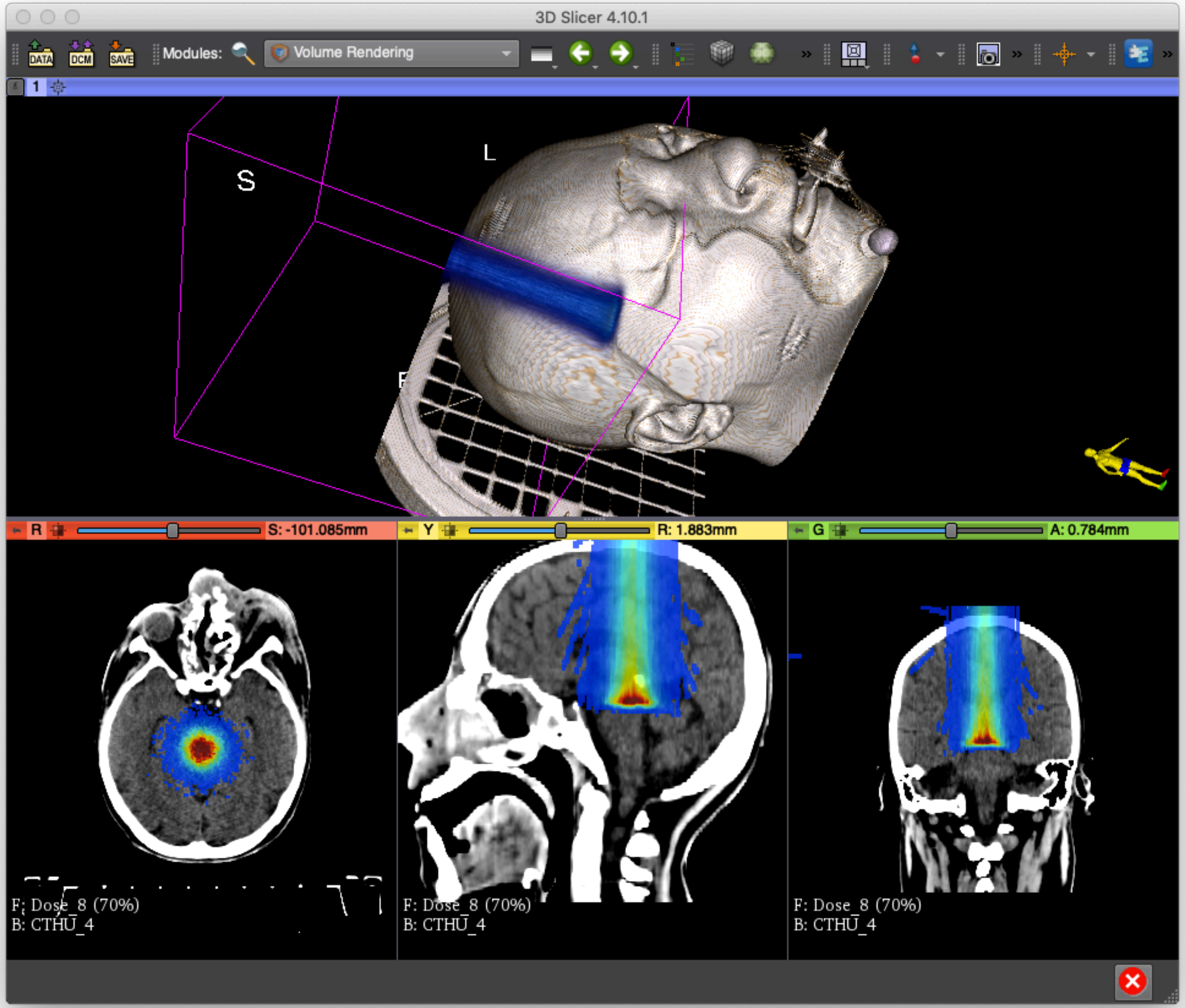
- Interfacing FRED with Eclipse TPS

- We are currently testing FRED for beam models of **IBA, Varian, and Mevion** facilities

- Scoring in multiple regions to enable application of range shifter, dynamic aperture or detector development for range monitoring

- FRED kernel developments: implementation of photon interactions and nuclear models for light and heavy ions.

FRED Interface with Slicer3D



FRED: New developments and future applications

- Potential clinical applications of GPU-accelerated MC code FRED are:
    - independent QA treatment plan recalculation,
    - fast, in-room dose re-calculation based on daily CT images
    - multi-parameter plan optimization (robust, radiobiological, arc optimization).

Conclusions

- These results confirm excellent performance of the physics models implemented in FRED.
- FRED dosimetric accuracy enables its application in clinical routine and potential improvement of patient treatment with protons.

Thank you

J. Baran, K. Czerska, J. Gajewski, M. Garbacz,
L. Grzanka, R. Kopec, A. Krempa, K. Krzempek,
G. Mierzwińska, N. Mojżeszek, E. Pluta, M. Rydygier

Paweł Moskal
Monika Pawlik-Niedźwiecka
& the J-PET collaboration

Nils Krah

Ilaria Rinald

Angelo Schiavi, Giuseppe Battistoni, Vincenzo Patera

Francesco Tommasino, Emanuele Scifoni, Marco Durante

Reinhard Schulte