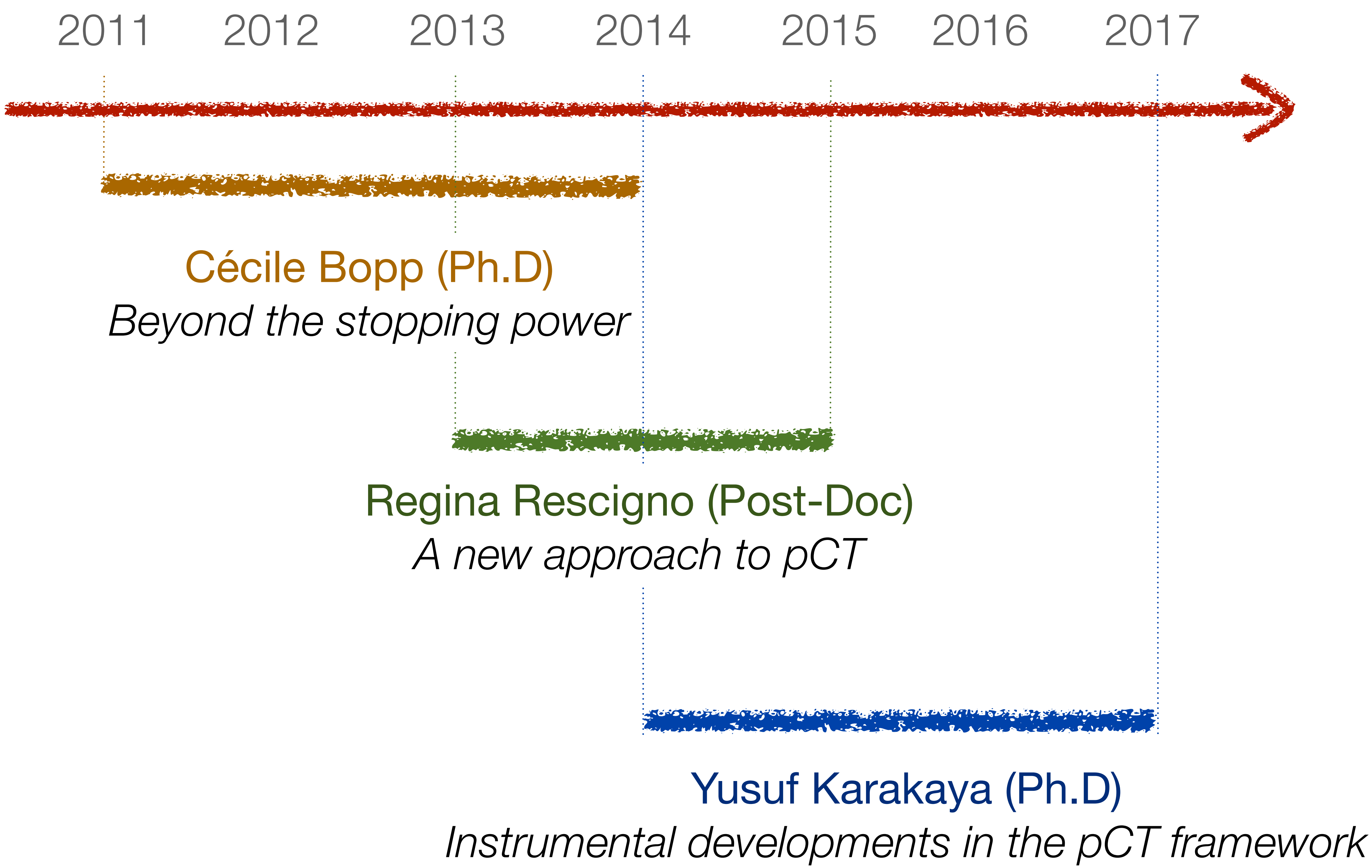
Développements autour de l'imagerie proton à l'IPHC

R. Rescigno, C. Bopp, D. Brasse, C. Finck, Y. Karakaya, M. Rousseau et M. Vanstalle

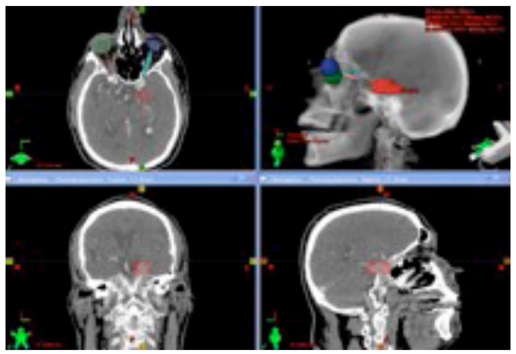
Assemblée Générale du GDR MI2B, Marseille, 09-04-2015

Timeline


2011
2012
2013
2014
2015
2016
2017
Cécile Bopp (Ph.D)
Beyond the stopping power
Regina Rescigno (Post-Doc)
A new approach to pCT
Yusuf Karakaya (Ph.D)
Instrumental developments in the pCT framework

Analytical TPS

x-ray CT scan



Extrapolated information

- Relative Stopping Power (RSP)
- Nuclear Interaction Cross Section (NICS)
- Scattering Power

Clinical Application

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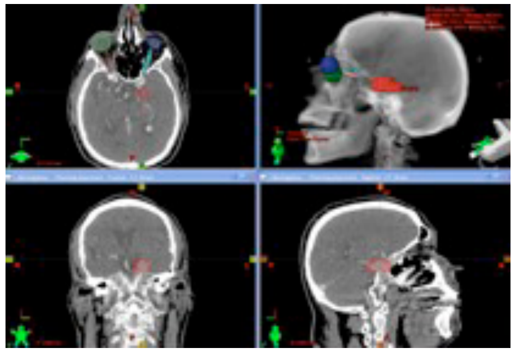

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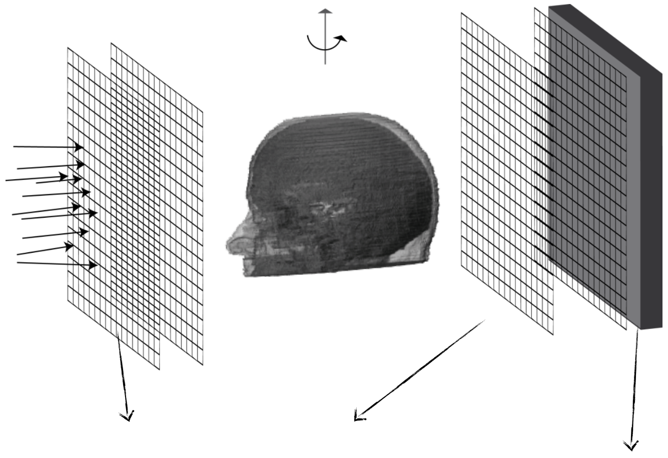

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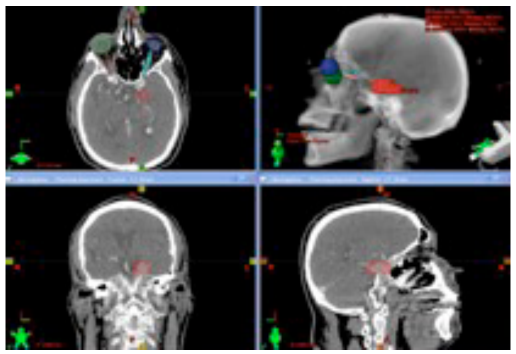

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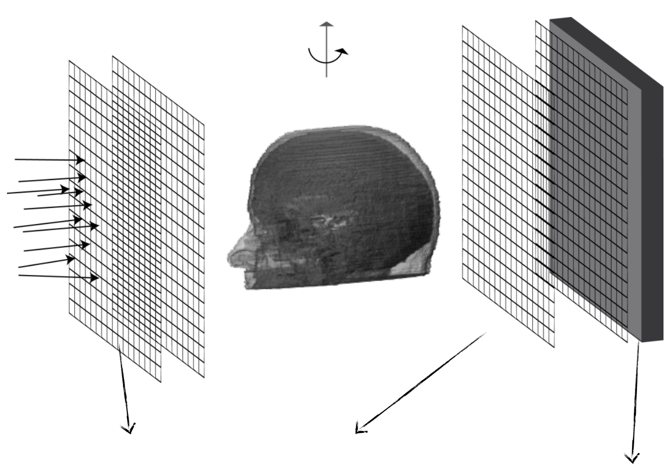


Tracker planes

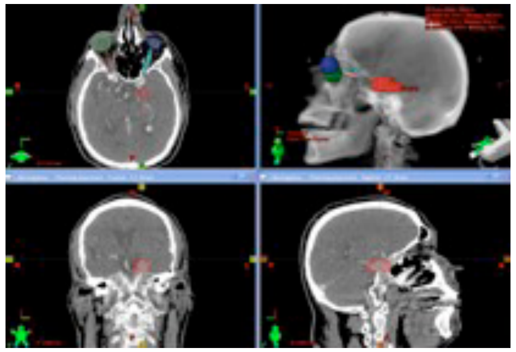
Calorimeter or range-meter

From **residual energy** measurements

Cécile Bopp

Analytical TPS

x-ray CT scan



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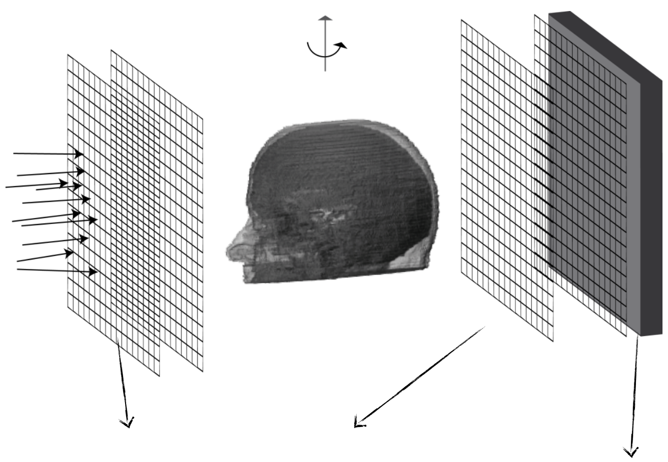


From **residual energy** measurements

Is it possible to extract **quantitative** information about **NICS** using **transmission rate** measurments?

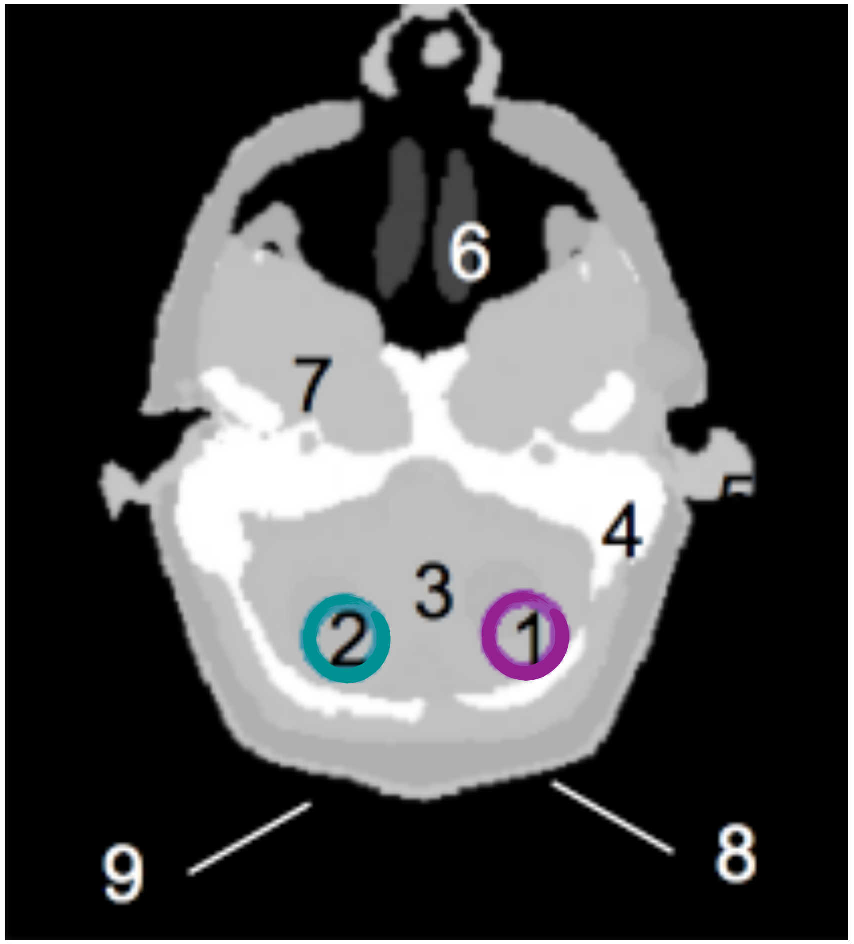
Transmission Rate Imaging

like in X-ray imaging

$$\Phi = \Phi_0 e^{-\int_\ell \boxed{\kappa(x,y,z,E)} d\ell}$$

Nuclear interactions macroscopic cross-section

Transverse slice of RSP head phantom



1: Right carcinoma RSP:1 (65% O)
2: Left carcinoma RSP: 1 (35 % O)
3: Brain and withe matter RSP: 1.04
4: Bone RSP: 1.48

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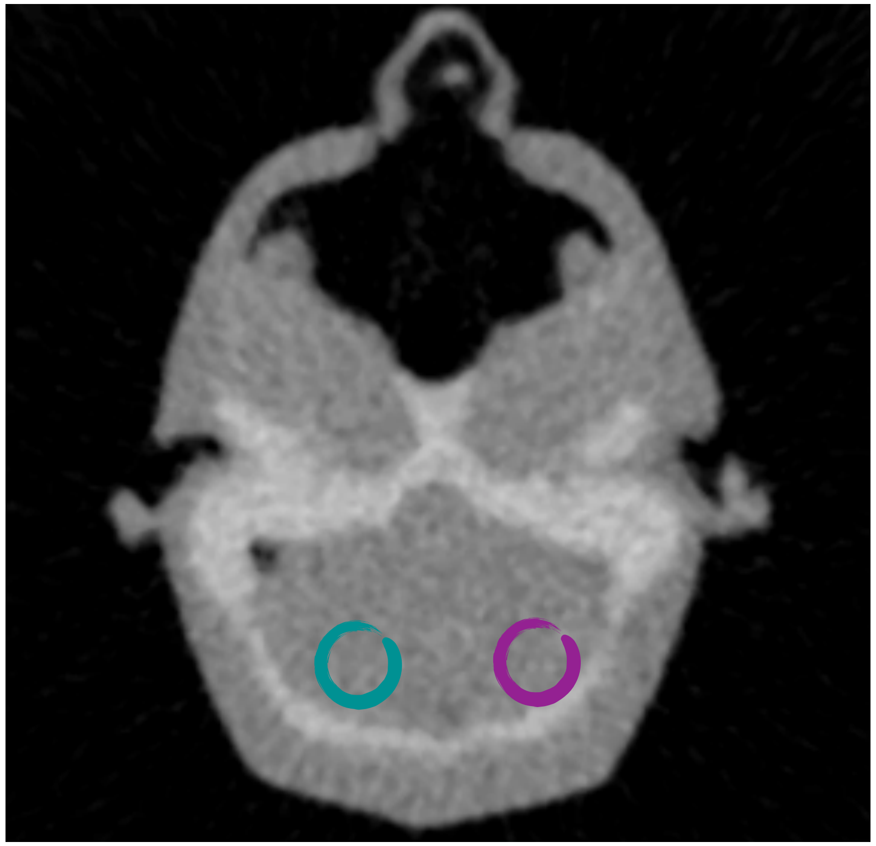

Data binned upstream tracker
Analytical reconstruction (FBP)
1000 protons/mm^2 - 256 projections

- Can distinguish bone soft-tissues air
- Can not see the tumors

C. Bopp et al., Quantitative proton imaging from multiple physics processes, PMB 2015

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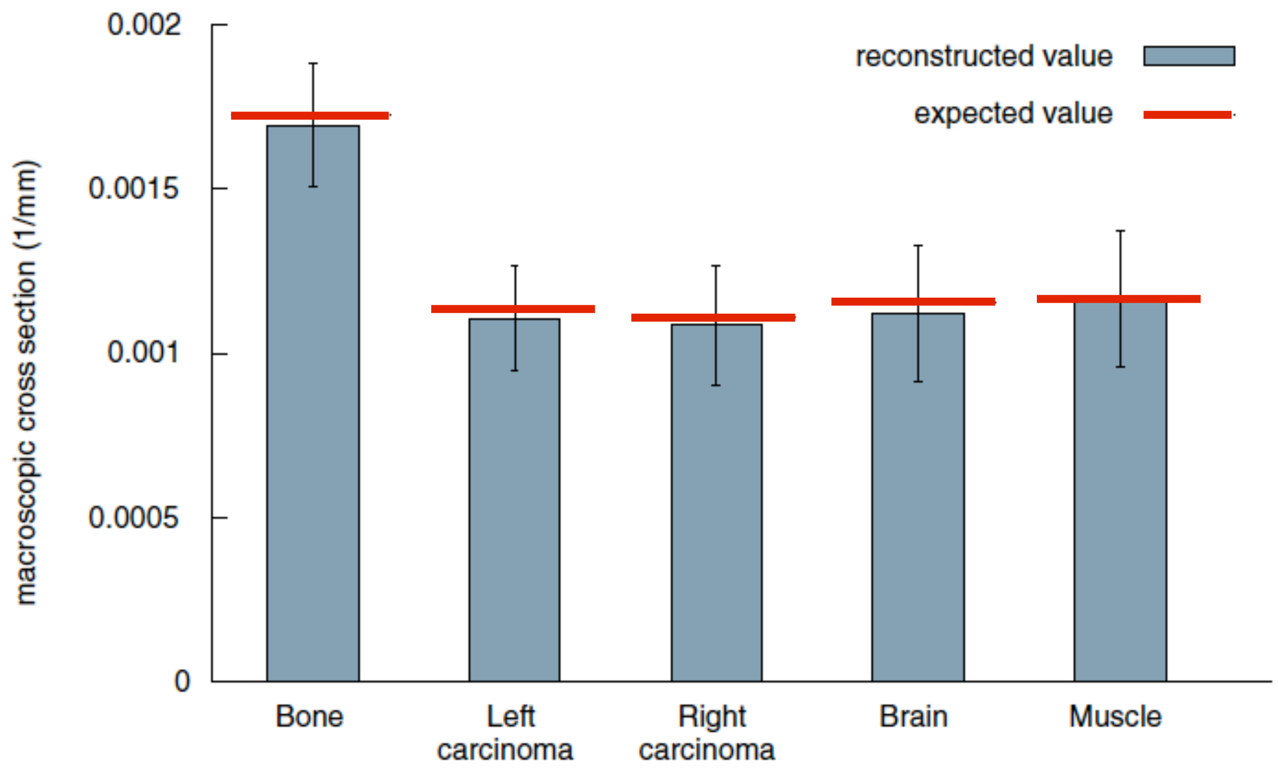

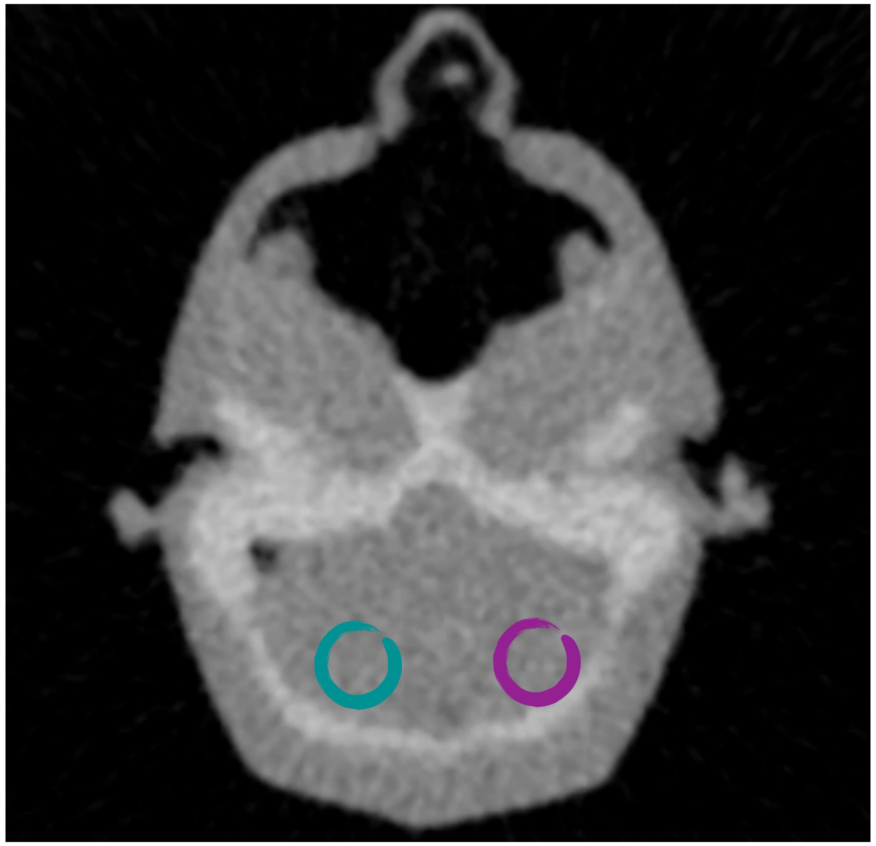

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Quantitative imaging from transmission rate

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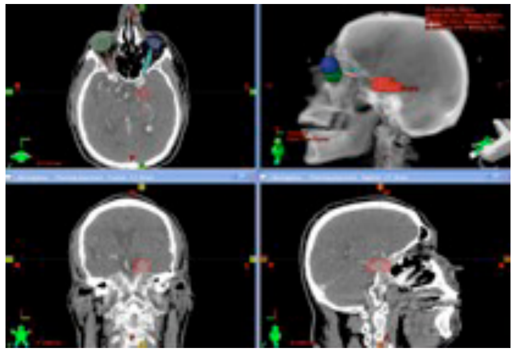

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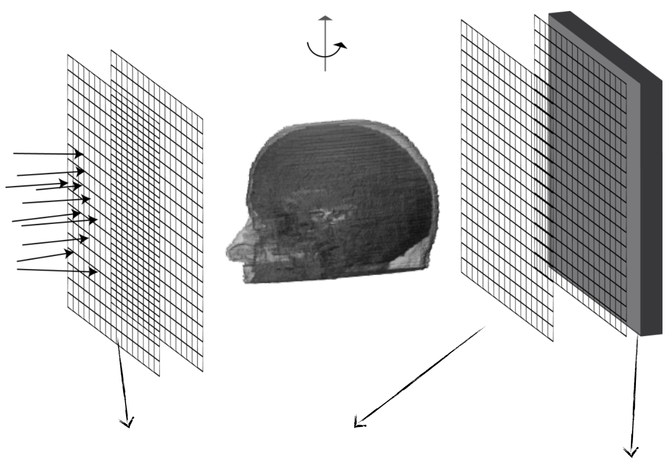

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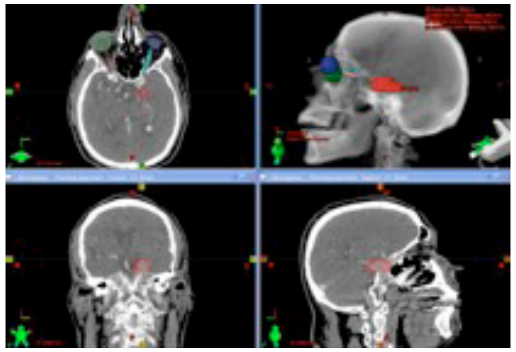

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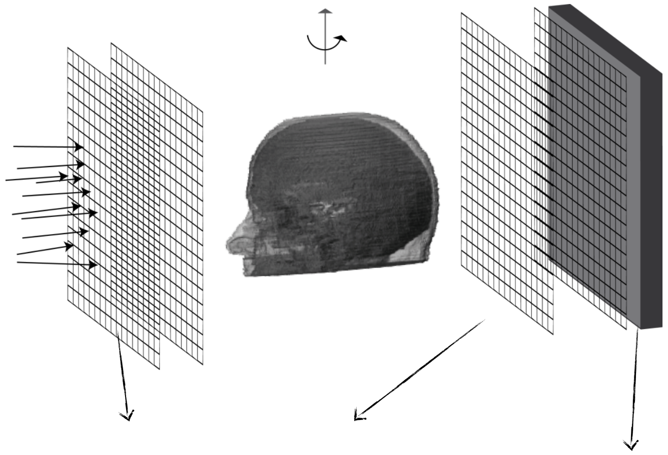


From **residual energy** measurements

From **transmission rate** measurements

Is it possible to extract **quantitative** information about **Scattering Power** using **angular spread** measurments?

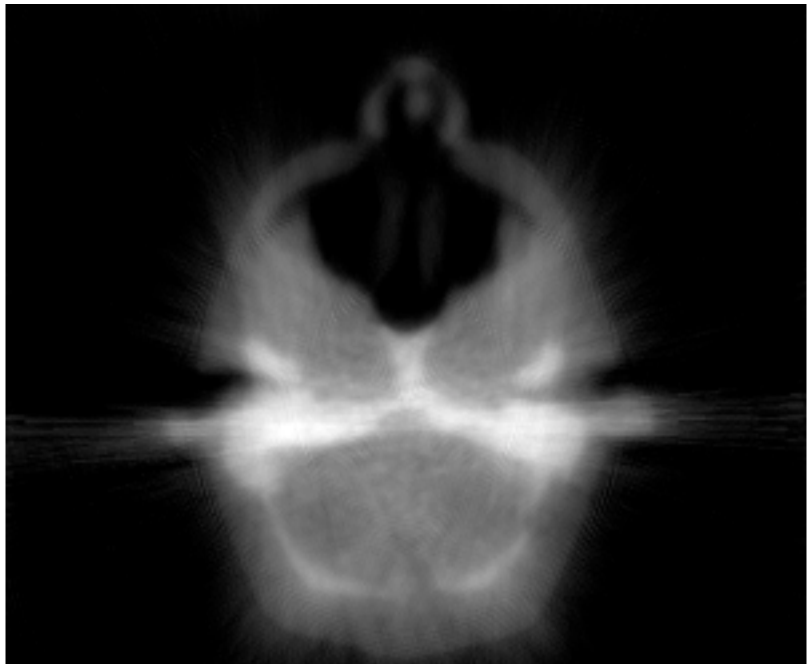
Scattering Imaging

$$\underbrace{\boxed{<\theta_{proj}^2>}}_{\text{Measured angular spread}} = \int_0^x \underbrace{\boxed{f_{dM}(pv, p_1v_1)\left(\frac{E_S}{pv}\right)}}_{\text{Energy dependent term}} \underbrace{\boxed{\frac{1}{X_s}}}_{\text{Reconstructed quantity}} du$$

Reconstruction is in two steps

- RSP image reconstruction
- Scattering Length reconstruction

Transverse slice of $1/X_S$ head phantom



From projections
ART algorithm
1000 protons/mm^2 - 256 projections

C. Bopp et al., Quantitative proton imaging from multiple physics processes, PMB 2015

Scattering Imaging

- Reconstruction process still needs to be optimized
- Can distingush the tumor from the brain

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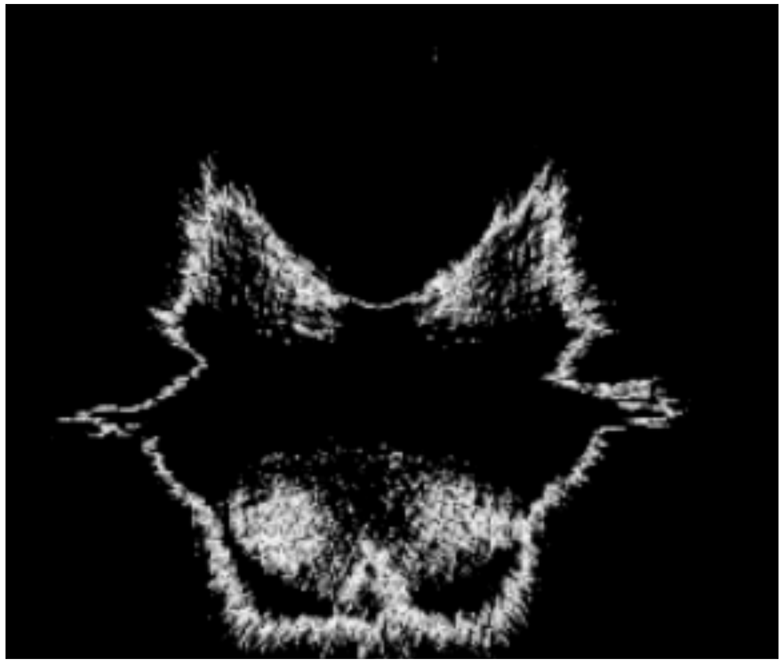

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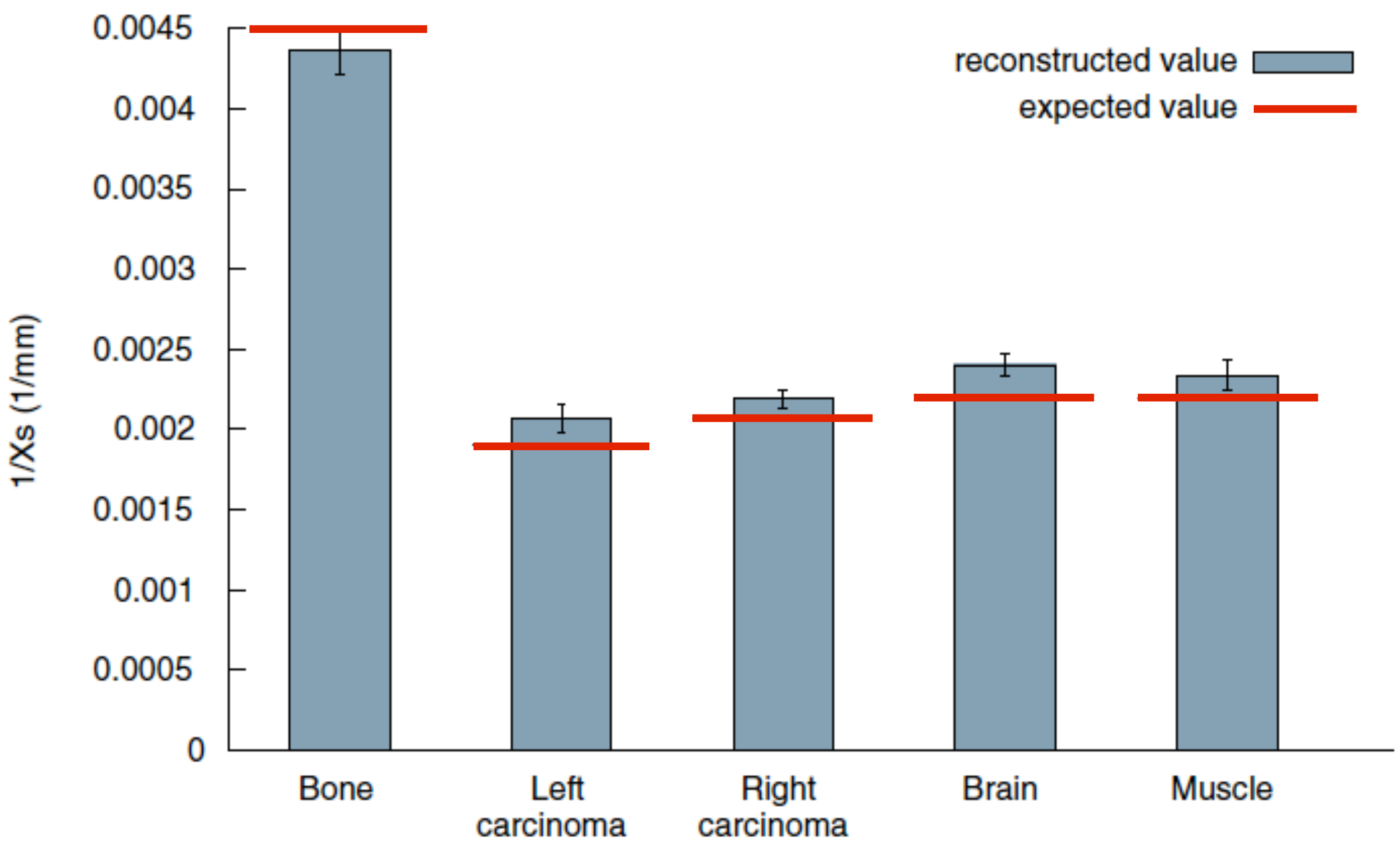

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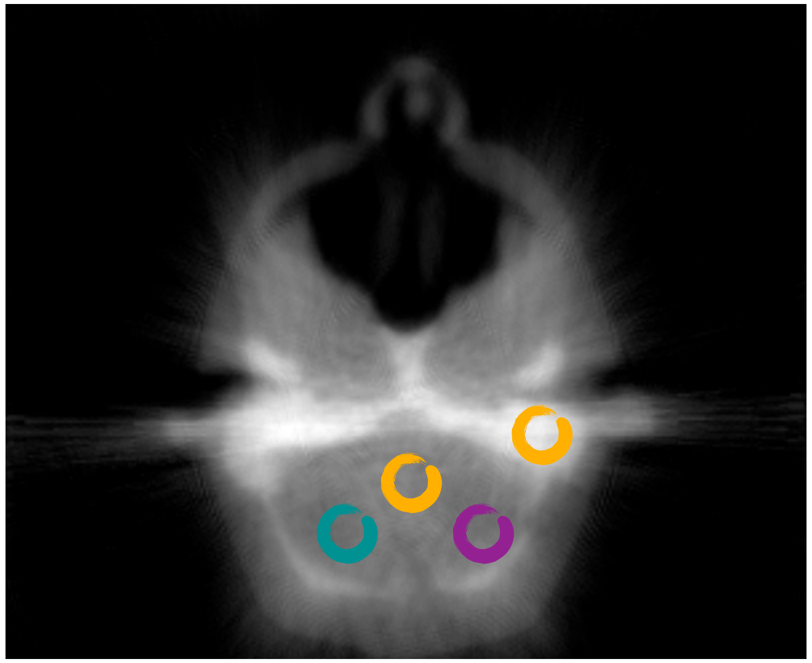

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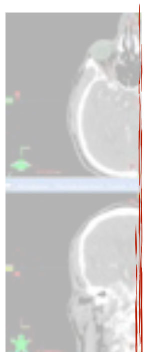
Quantitative imaging from scattering

C. Bopp et al., Quant

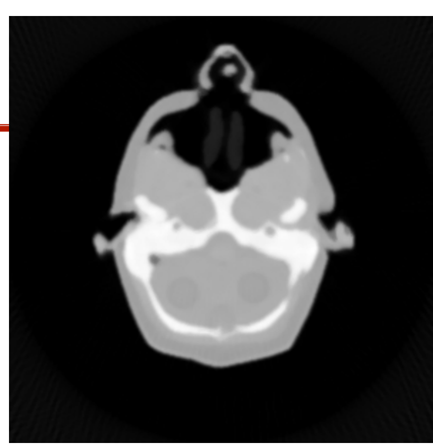
x-ray CT scan



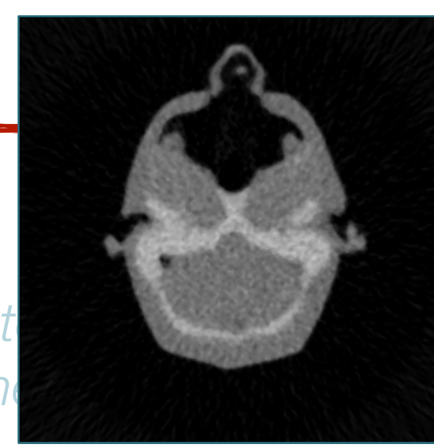
Conclusions

There is information in scattering and transmission rate of protons.

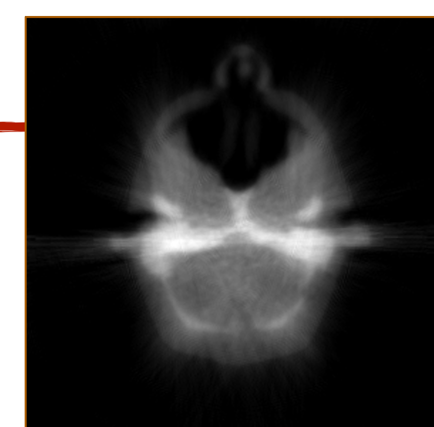
- Used to reconstruct images, <u>qualitative</u> and <u>quantitative</u>
- Could be of use in analytical treatment planning
- Not enough to fully characterize the composition of materials
- <u>Can provide additional constraints for a conversion</u>



Relative Stopping Power



Transmission



Inverse scattering length

Analytical TPS

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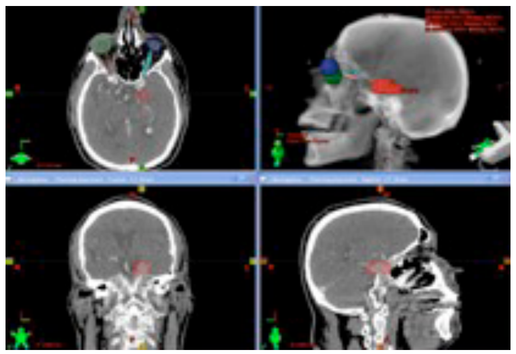

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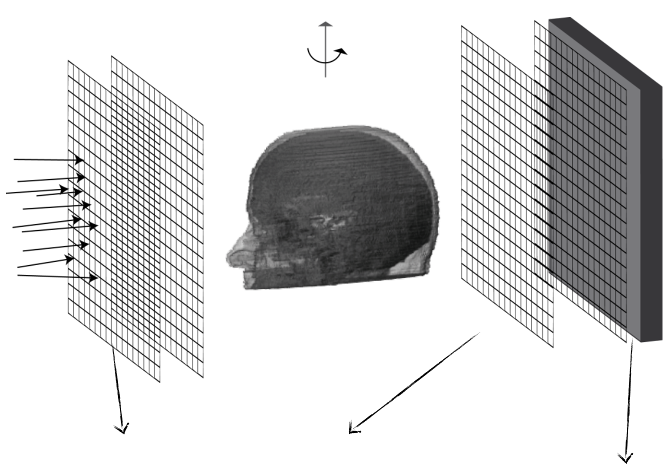

From **residual energy** measurements
From **transmission rate** measurements
From **angular spread** measurements

Analytical TPS

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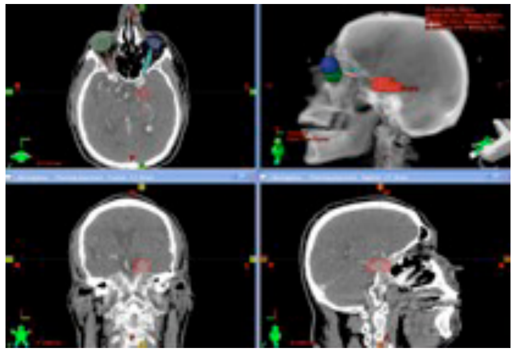

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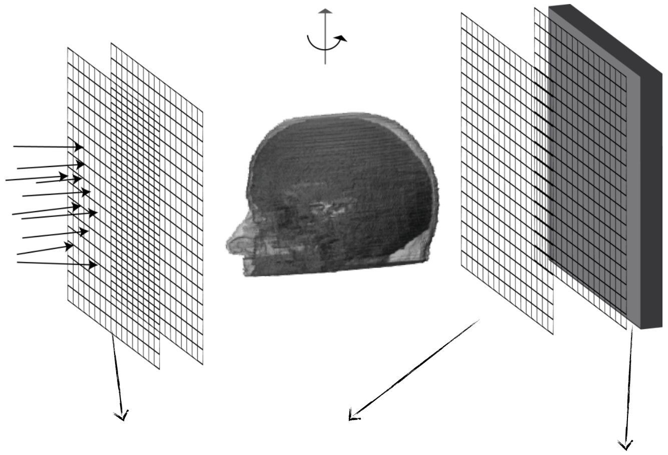

From **residual energy** measurements

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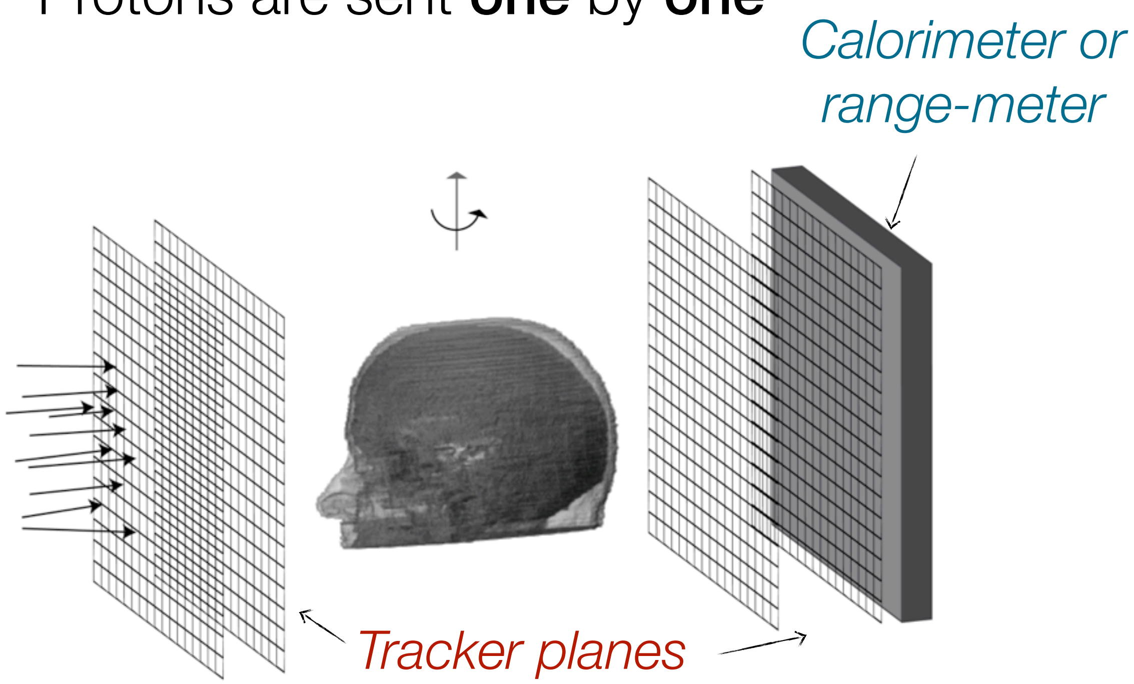
Why is there no pCT scanner **in clinical routine**

Classical approach to pCT

Protons are sent **one** by **one**



For each proton, measurement of:

- Initial and final positions and directions
- Final energy

Requirements:

- ~ 100 protons/voxels
- ~ 5-10 min acquisition time

Mean data rate to sustain ~ 1-2 MHz

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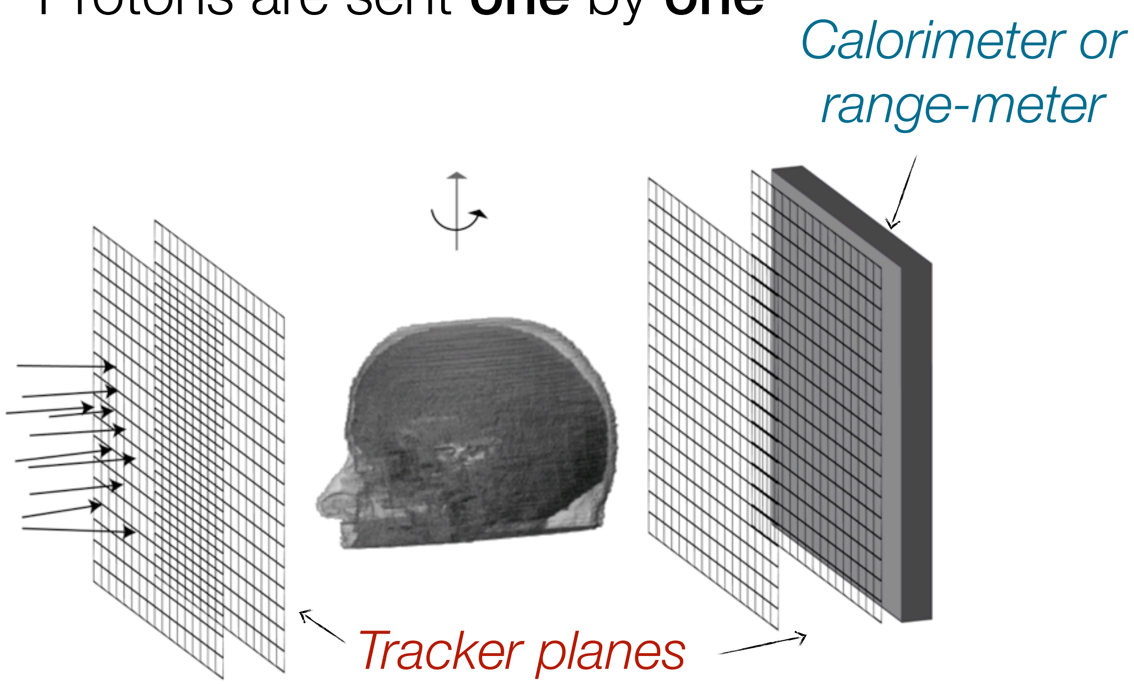

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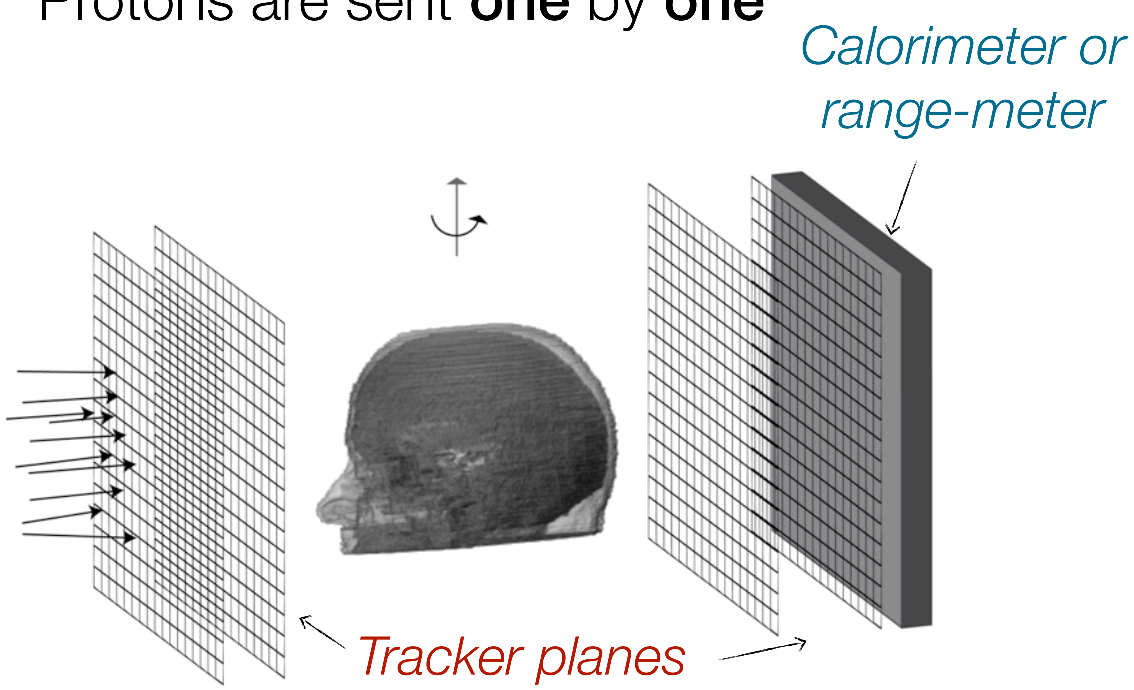

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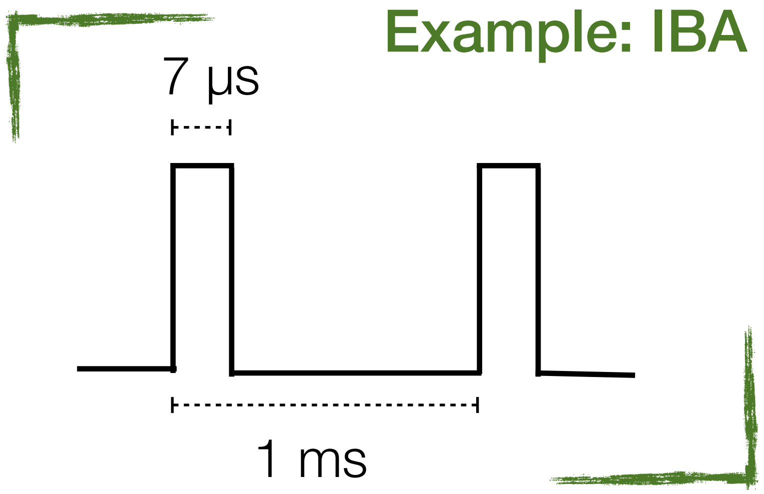

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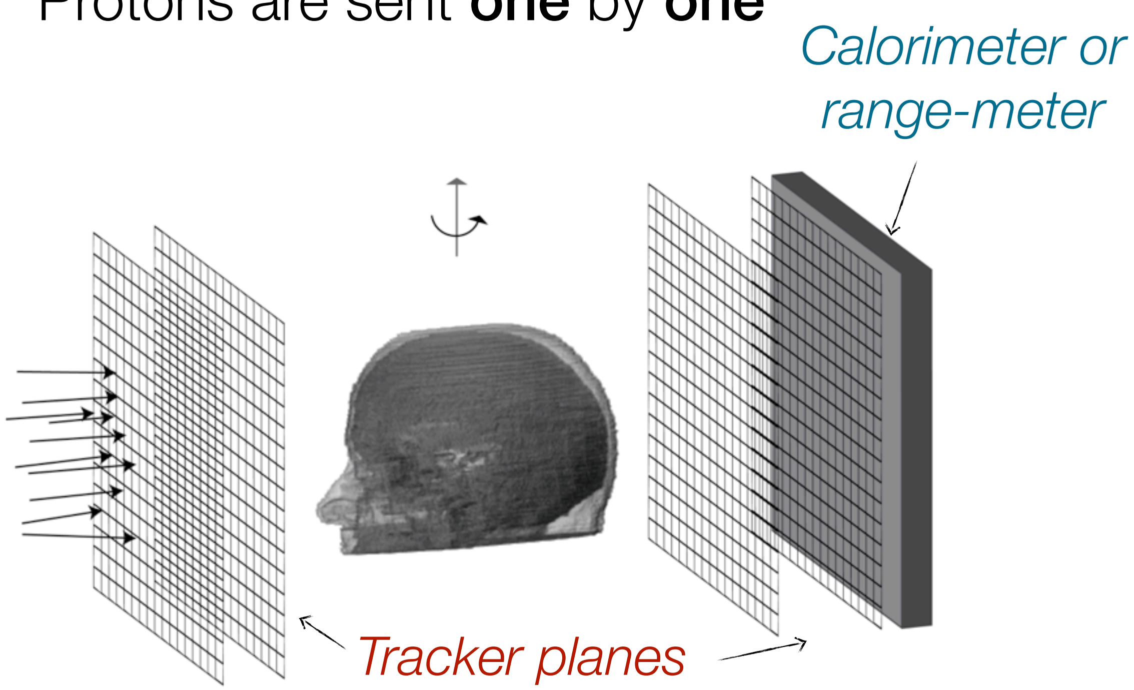

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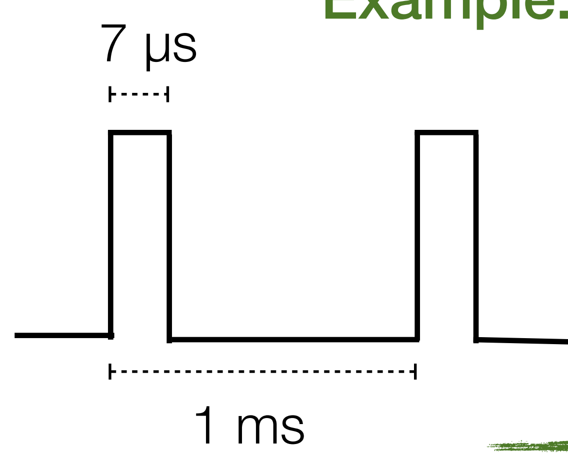

Data rate to sustain ~ 200 MHz (during the bunch)

Classical vs. "new" approach

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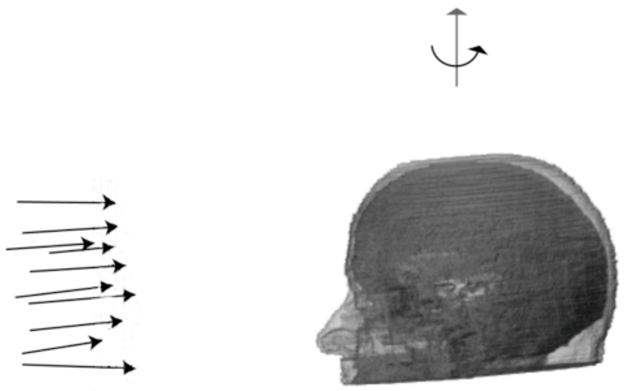

Unknown RSP

$$\boxed{\rho(\vec{r})}$$

Classical vs. “new” approach

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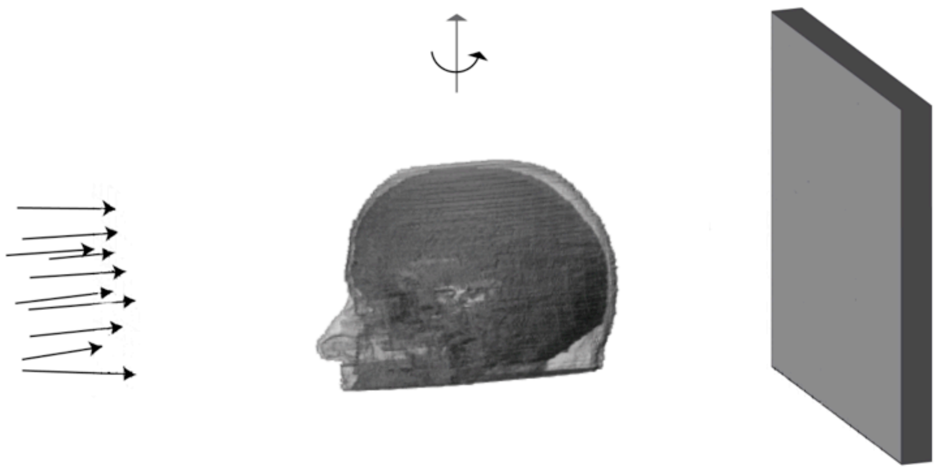
Calorimeter or range-meter



WEPL

Unknown RSP

$$\boxed{\int_{E_{in}}^{E_{out}} \frac{dE}{S_{water}(I_w, E)}} = \int_l \boxed{\rho(\vec{r})}\, dl$$

Bethe and Bloch formula

Classical vs. "new" approach

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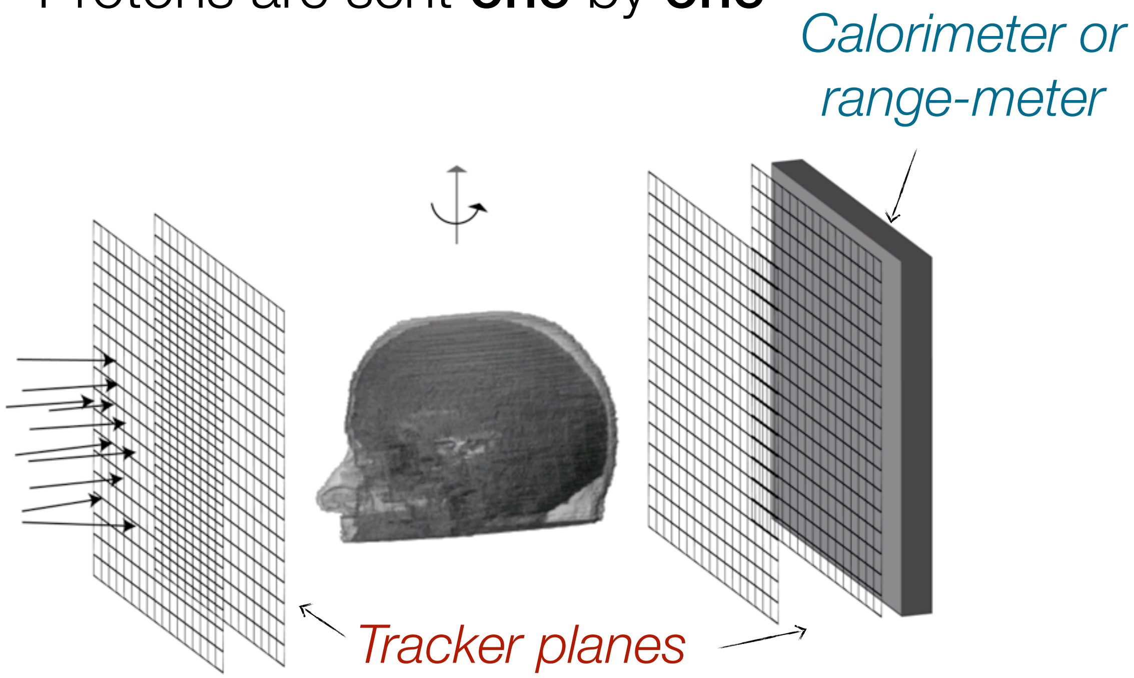

Reconstruction problem

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Proton path

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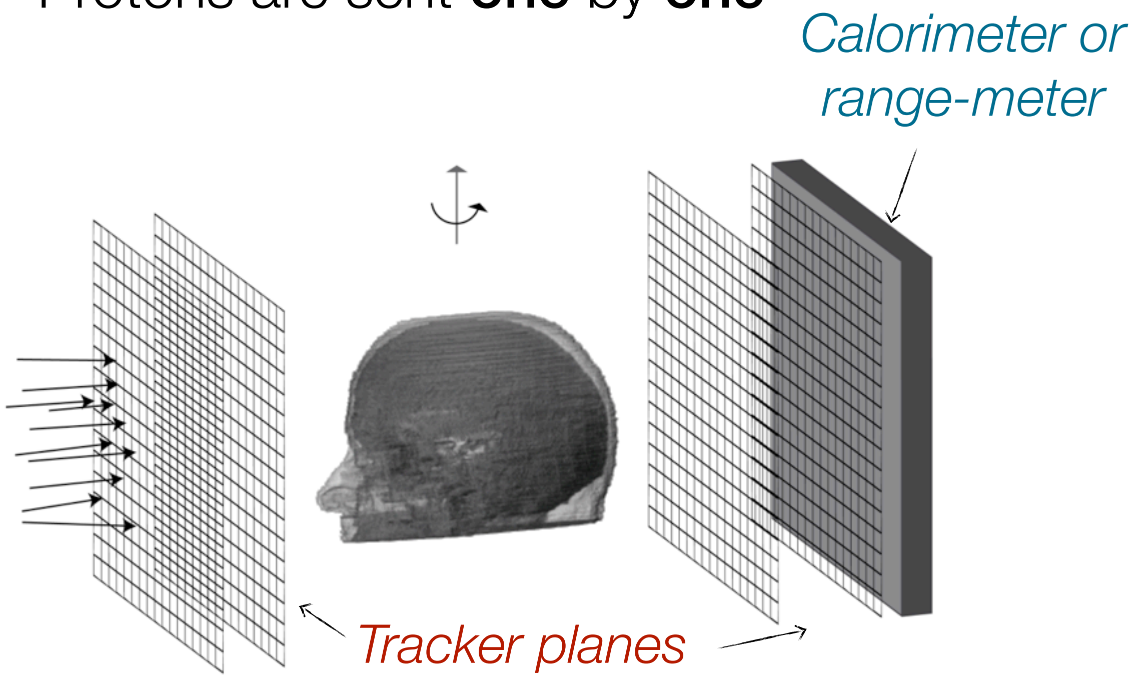
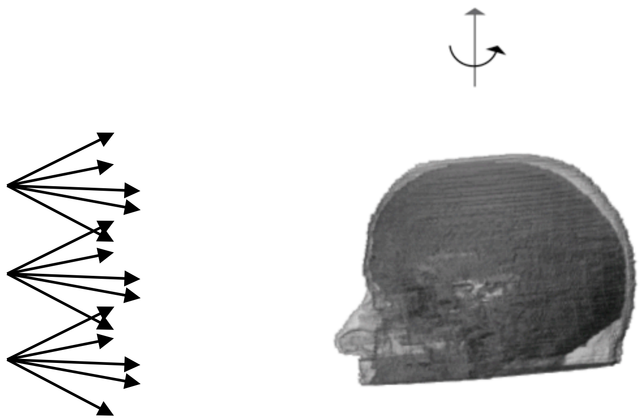


Protons are sent **bunch** by **bunch**



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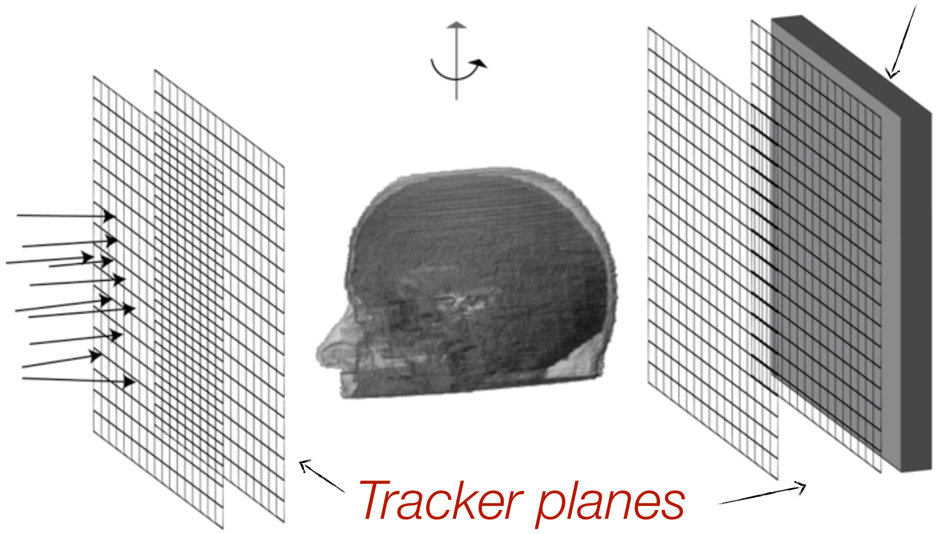

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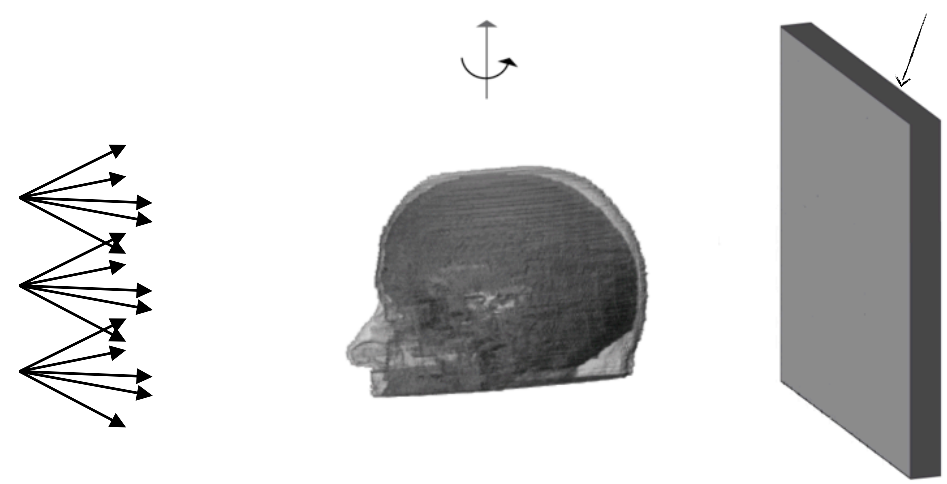

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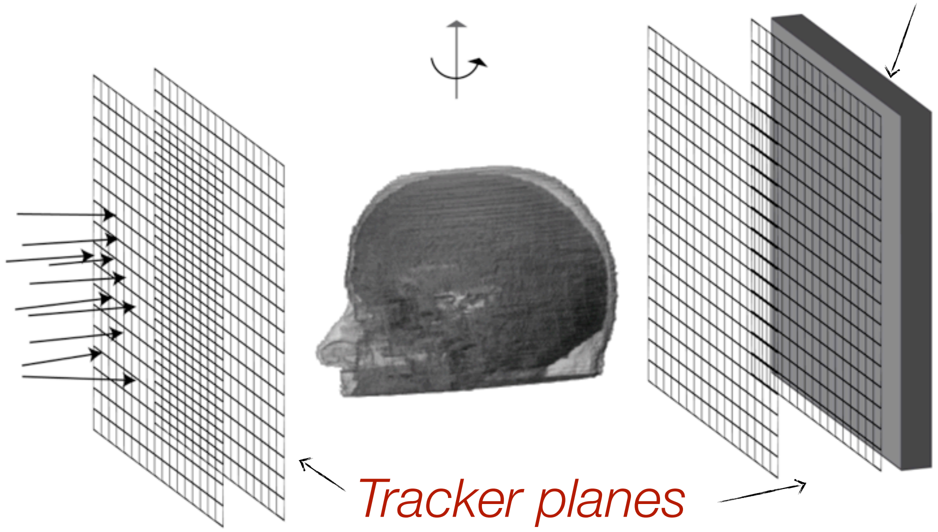

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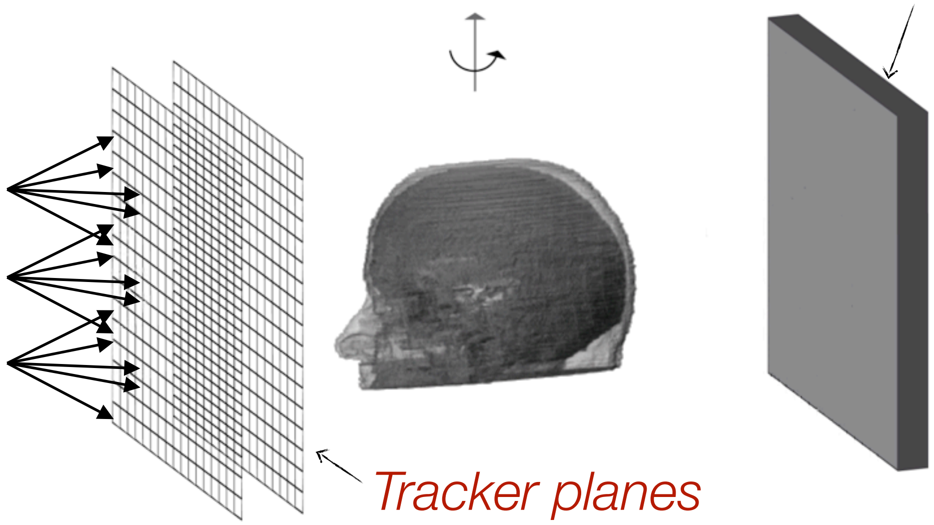
Range-meter



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Bethe and Bloch formula

Mean beam path

Pencil Beam (PB) approach to pCT

- **Analytical** description of the **beam**
- **Propagation of the beam** in matter described by the **Fermi-Eyges** theory

Mean Beam Path

Probability map of the beam passage in a volume

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→

Mean Beam Path

Probability map of the beam passage in a volume

PB approach philosophy

- Each beam seen as a "**super-proton**"
- Probability map used to estimate the "**beam position**"
- Analytical or iterative algorithm can be used to reconstruct the image

R.Rescigno et al, Pencil Beam approach to proton computed tomography, accepted Medical Physics 2015

Classical vs. PB

Beam characteristics

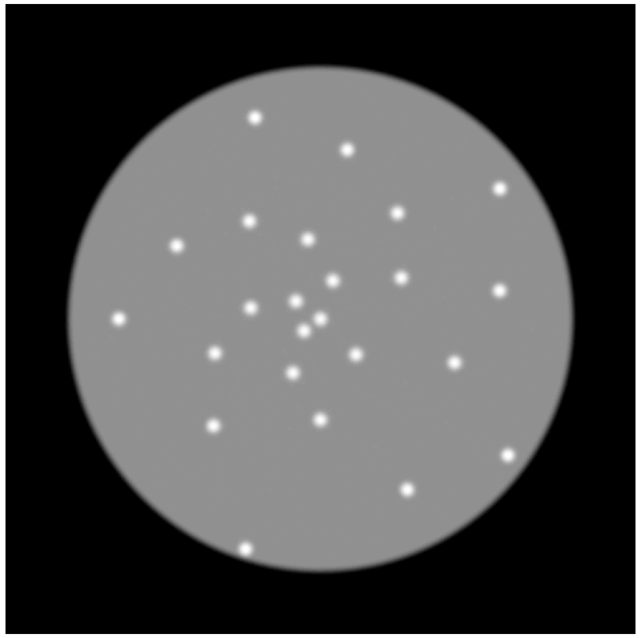
- Rectangular beam of 1 x 1 mm^2
- Beam spacing: 1 mm
- N particles/beam: 500

Reconstruction parameters

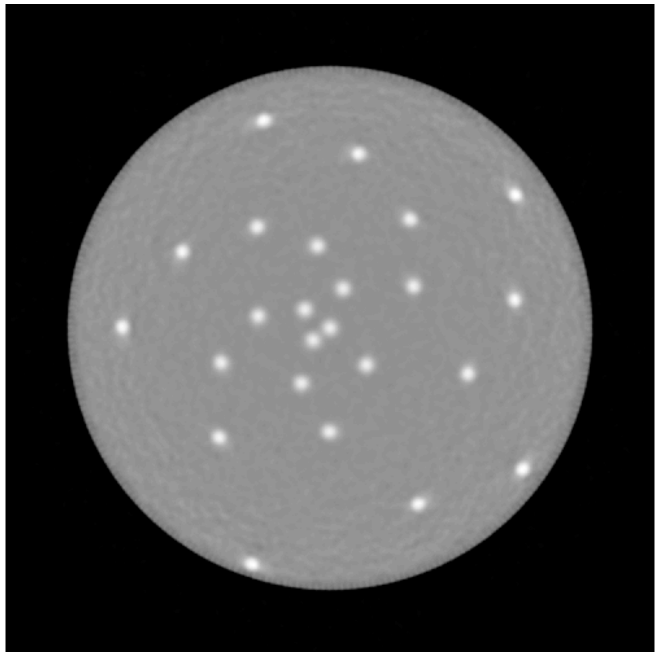
- 500 $protons/mm^2$
- 256 projections over Pi

Arbitrarily chosen!
Optimization ongoing

Classical approach



PB approach



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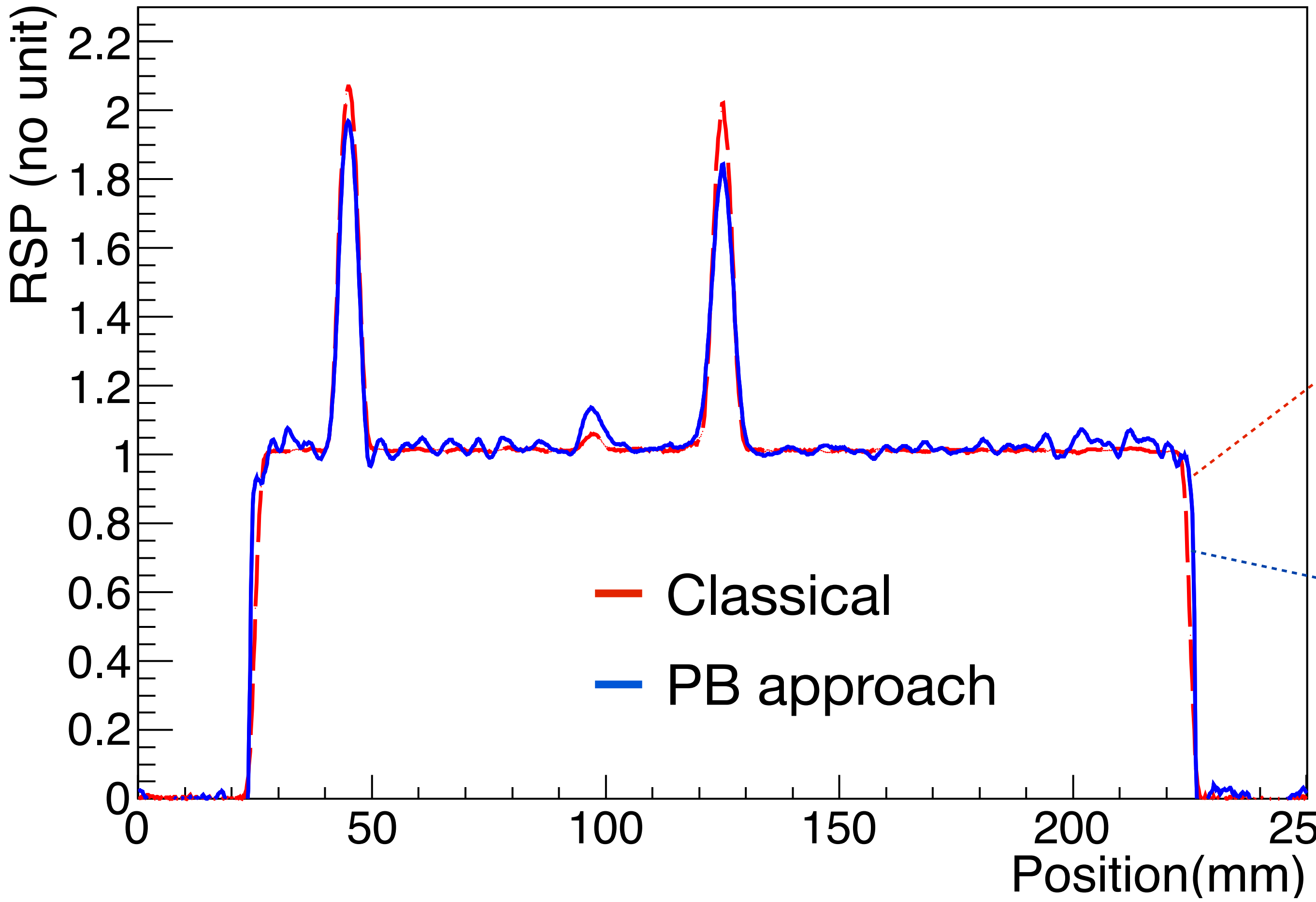
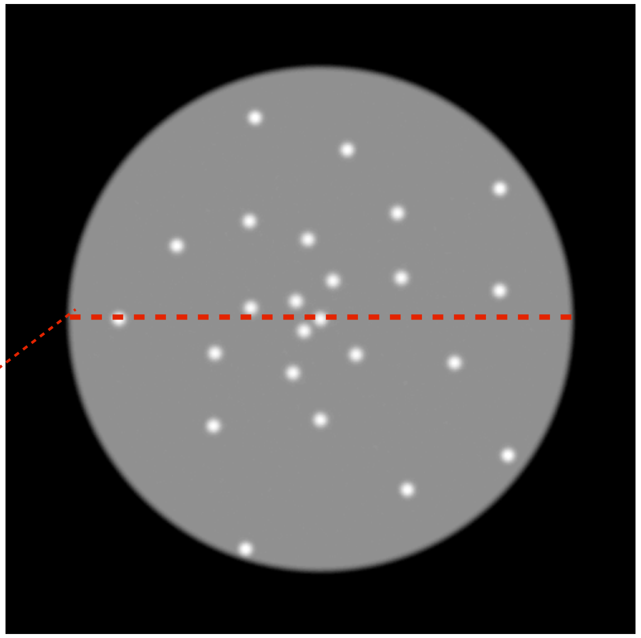
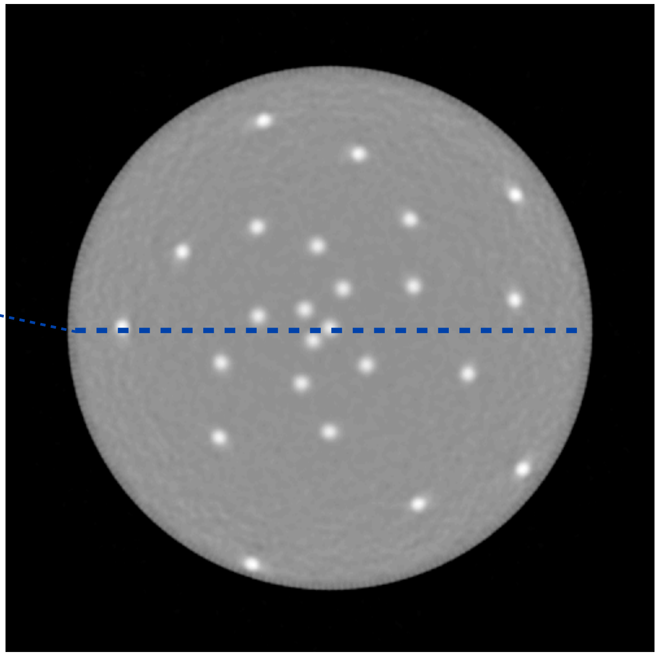


Classical approach

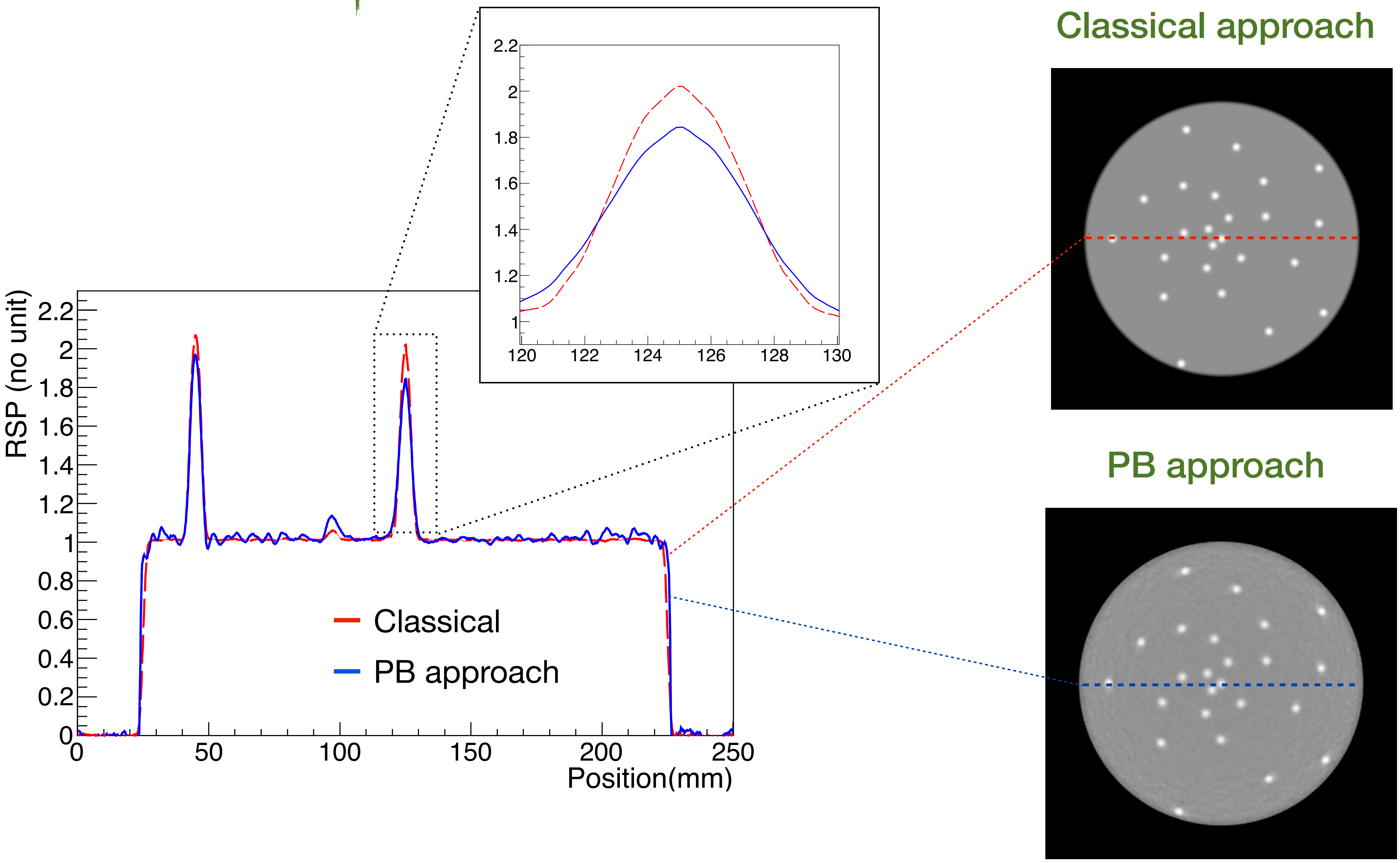


PB approach



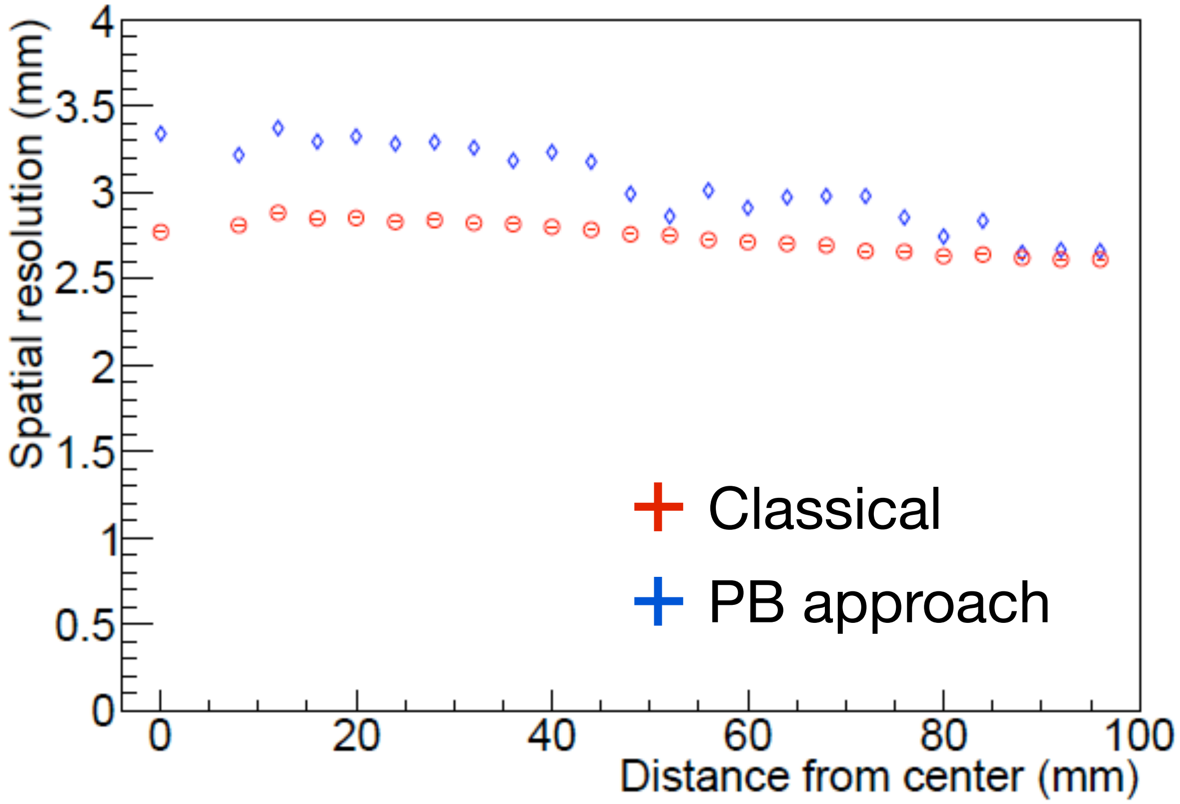
R.Rescigno et al, Pencil Beam approach to proton computed tomography, accepted Medical Physics 2015

Classical vs. PB

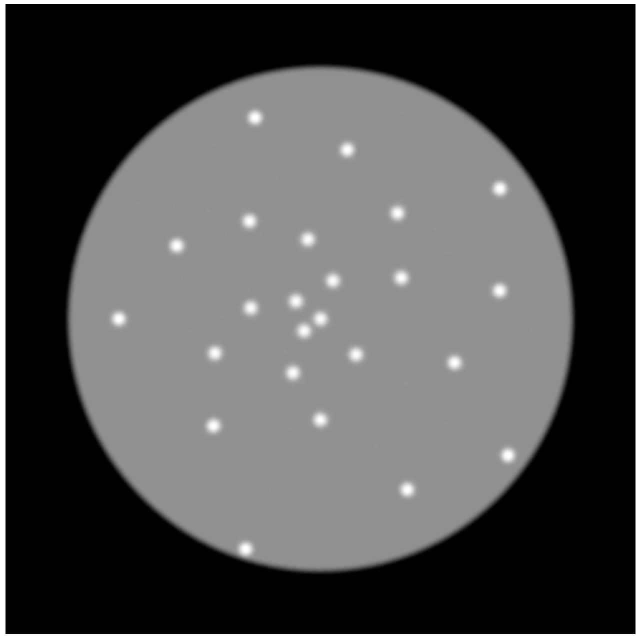


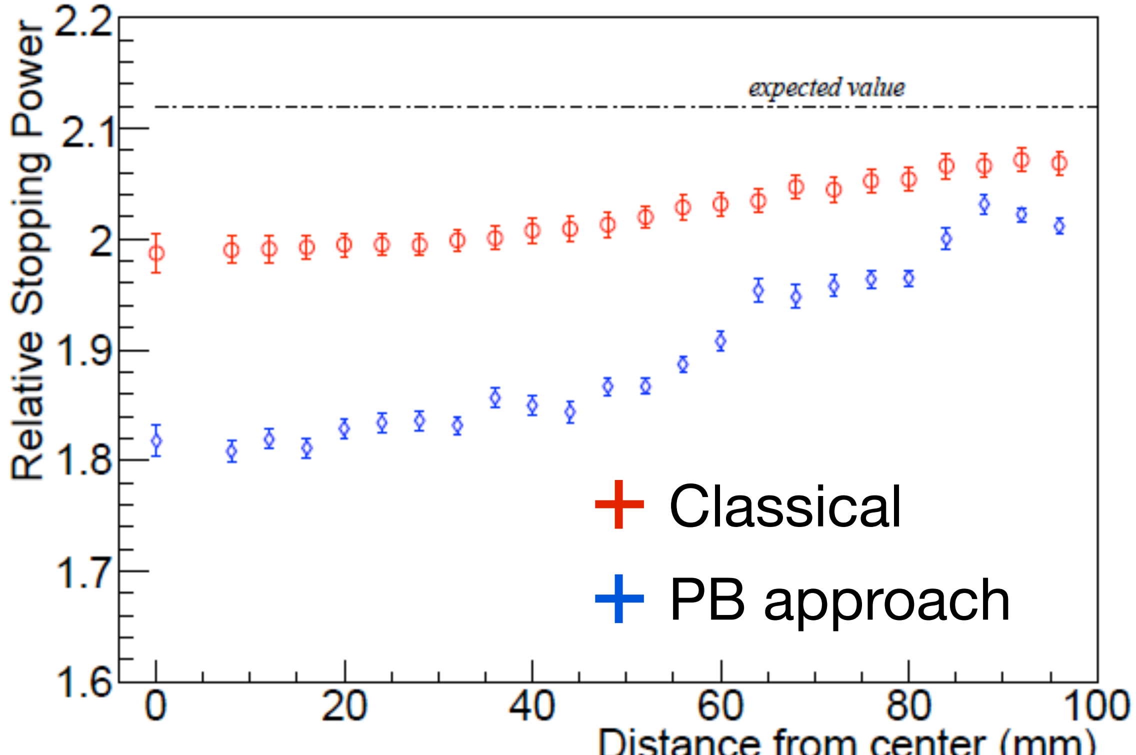
R.Rescigno et al, Pencil Beam approach to proton computed tomography, accepted Medical Physics 2015

Classical vs. PB

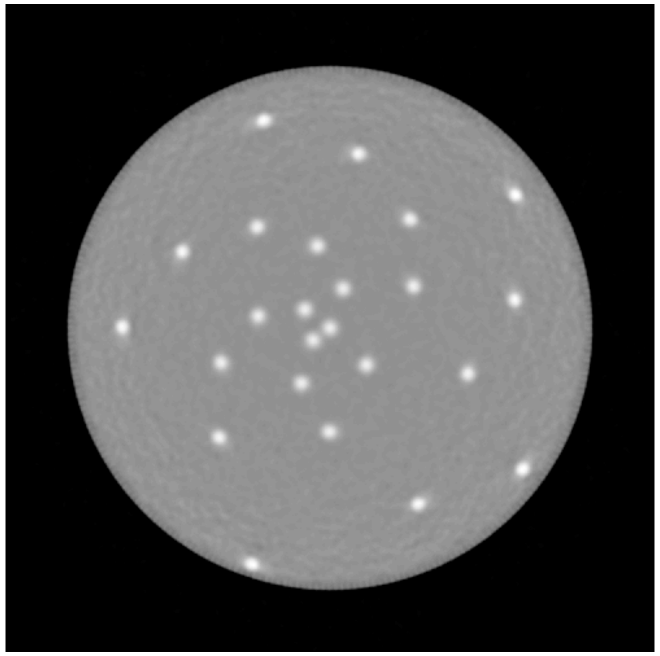


Classical approach





PB approach



R.Rescigno et al, IEEE NSS/MIC 2015

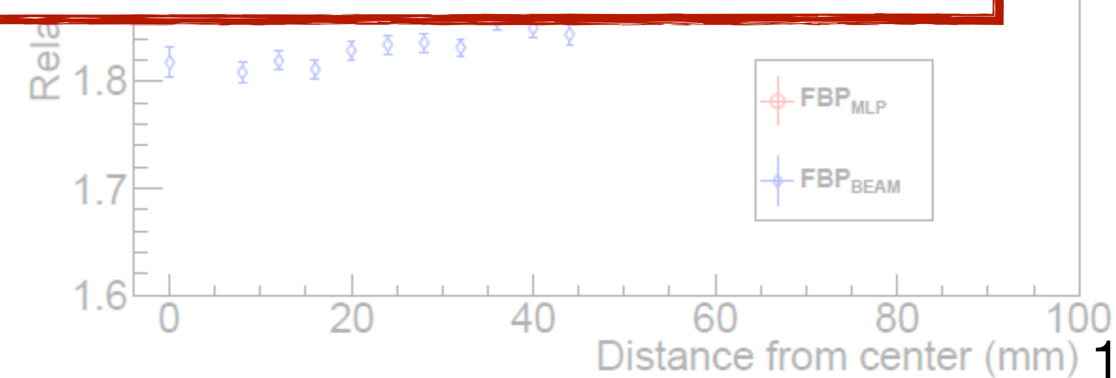
Classical vs. PB

Conclusions

It is possible to use a “statistical” approach to pCT without neglecting MCS effects

- Mathematical formalism well defined
- Results very promising
- <u>Optimization study is ongoing</u>

PB



R.Rescigno et al, IEEE NSS/MIC 2015

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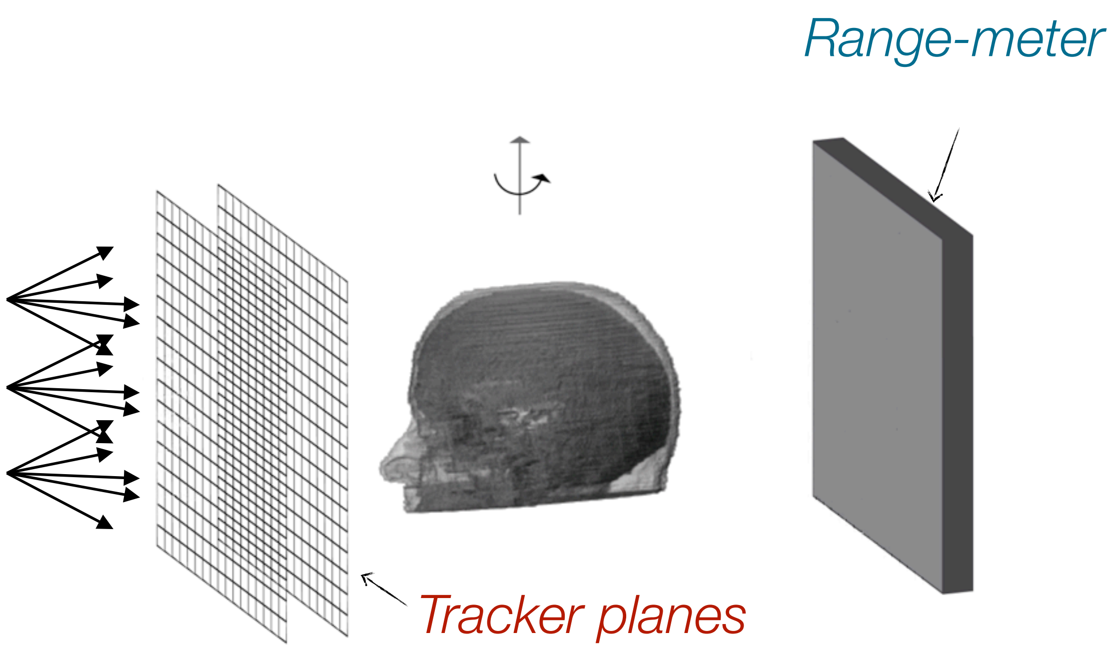
PB approach - what is needed?

Protons are sent **bunch** by **bunch**



Physical observables

Initial

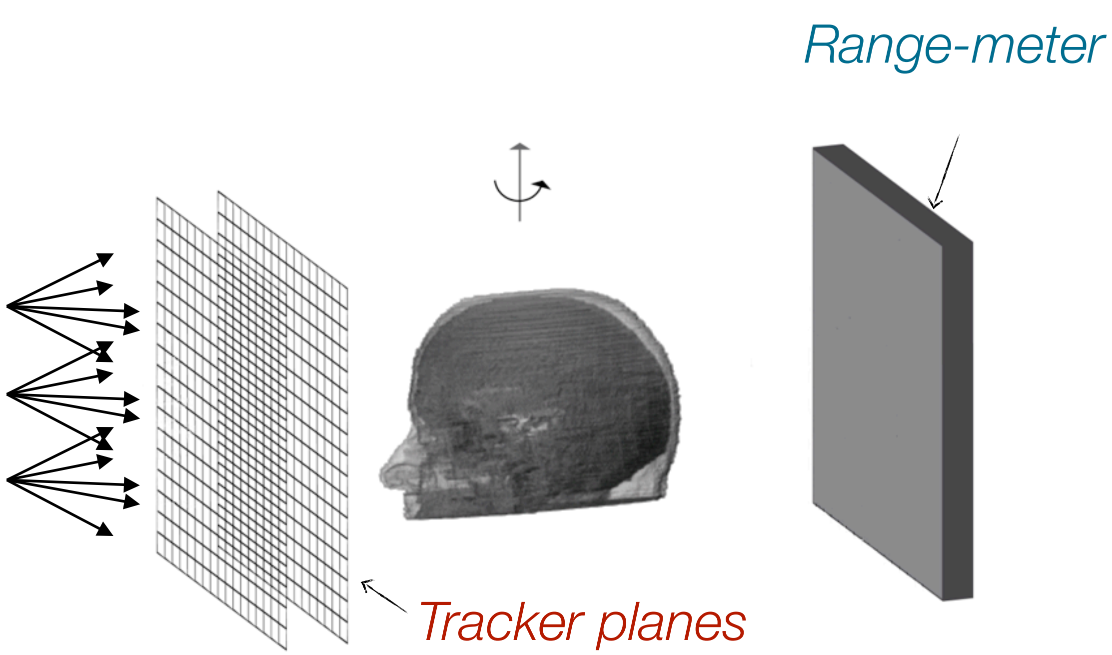
- **Mean** beam **position** in x and y
- **Angular** and **spatial spread** of the beam
- **Intensity** of the beam
- **Mean energy**

Final

- **Residual range**

PB approach - what is needed?

Protons are sent **bunch** by **bunch**

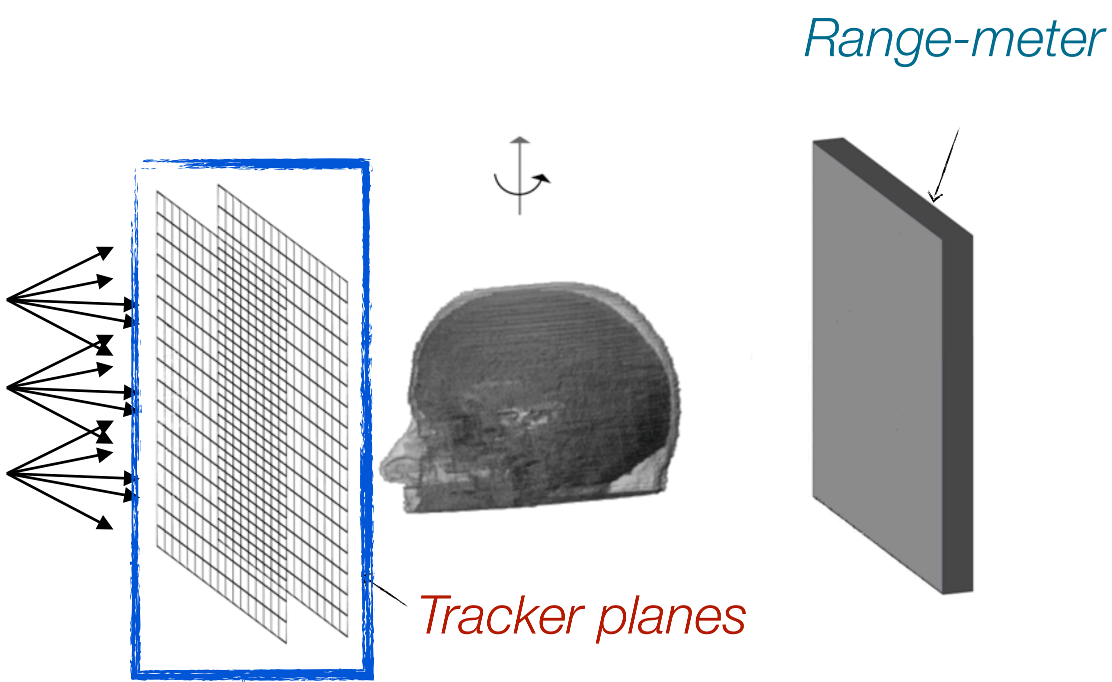


Which **detector** for **tracker** planes?

Which **detector** for **residual range** measurement?

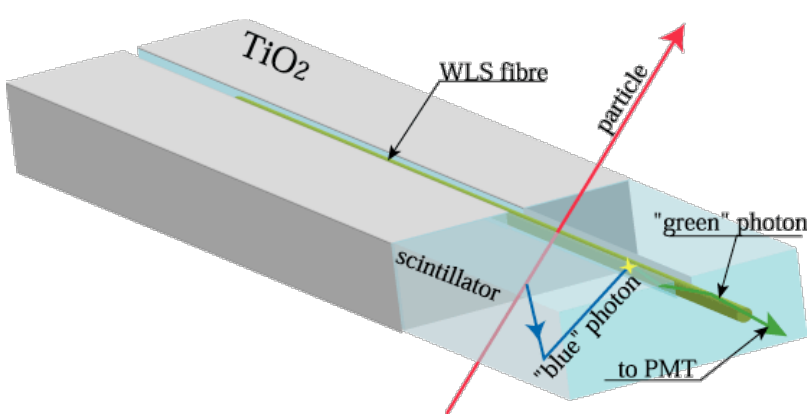
PB approach - what is needed?

Protons are sent **bunch** by **bunch**



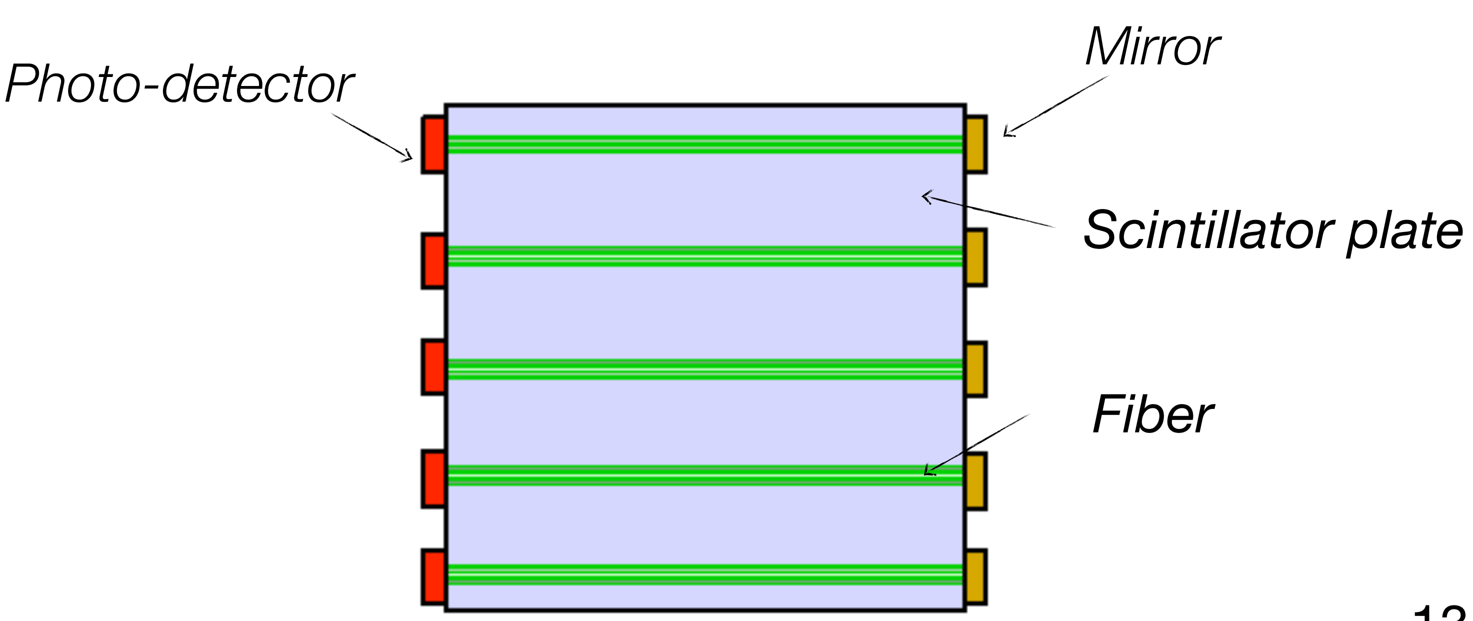
Which detector for tracker planes?

Which detector for residual range measurement?



From **OPERA**

To a **pCT tracker** used in integration mode



Yusuf Karakaya

PB approach - what is needed?

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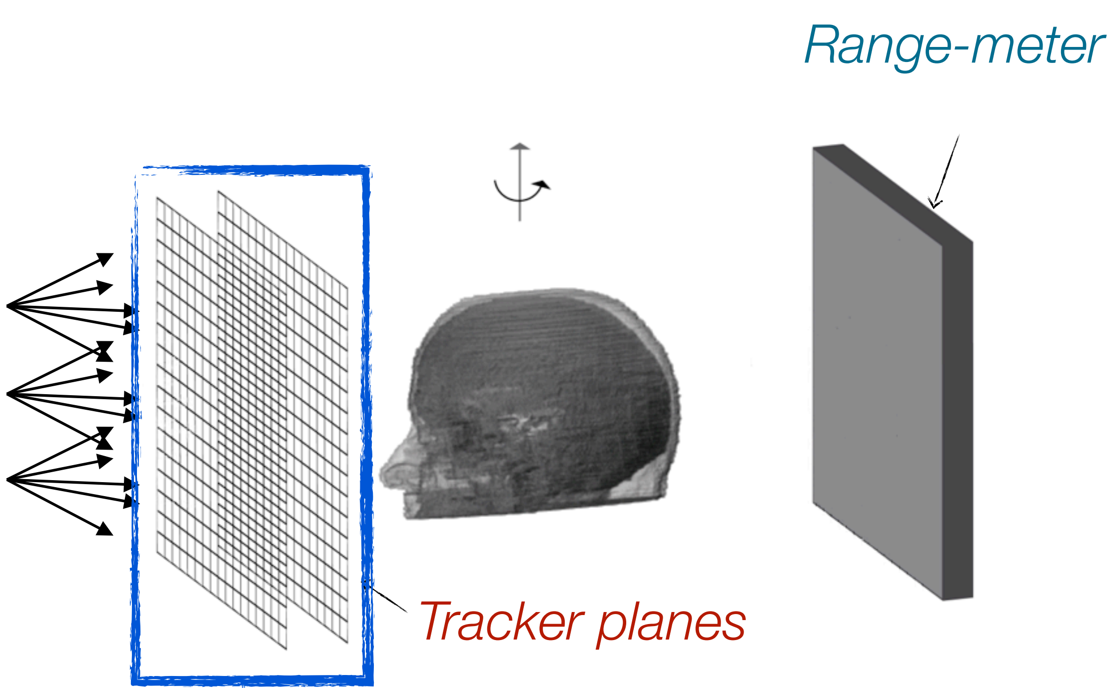

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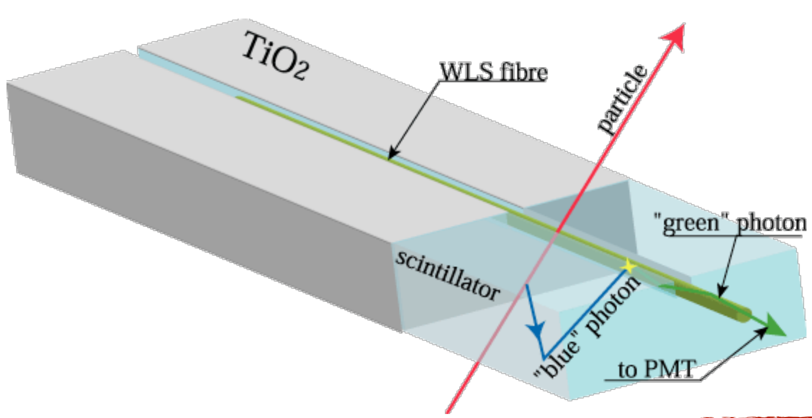

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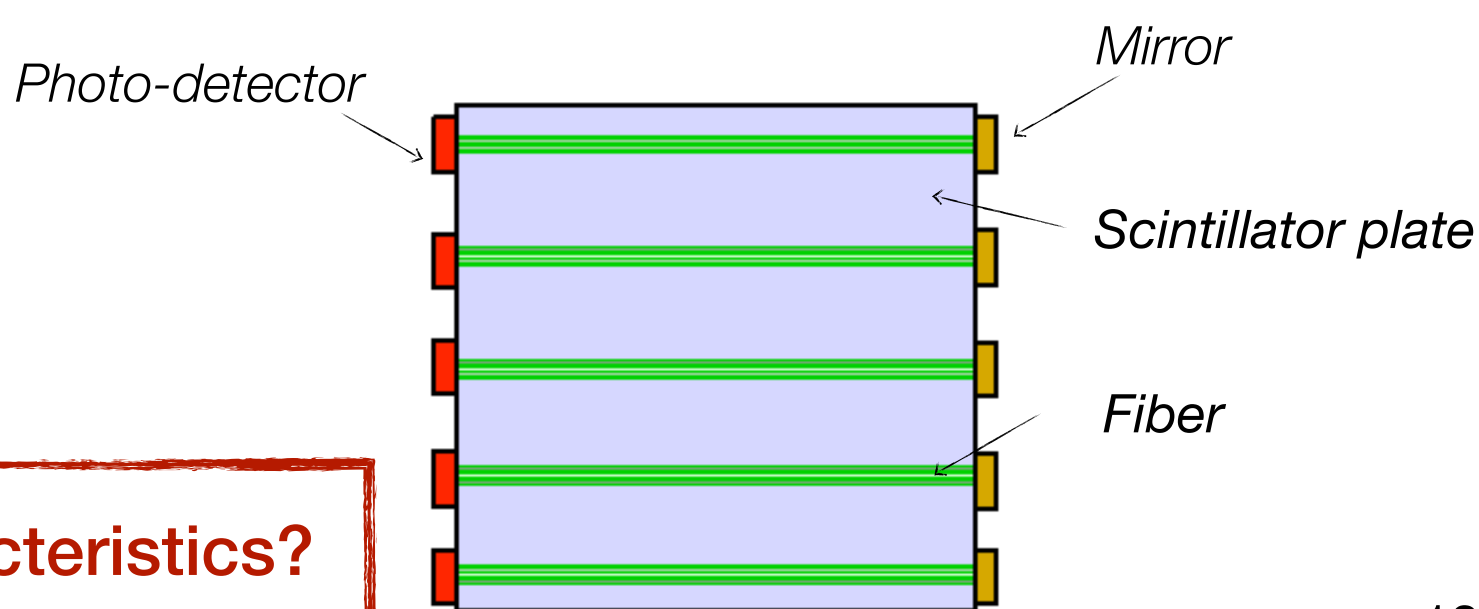

Which characteristics?

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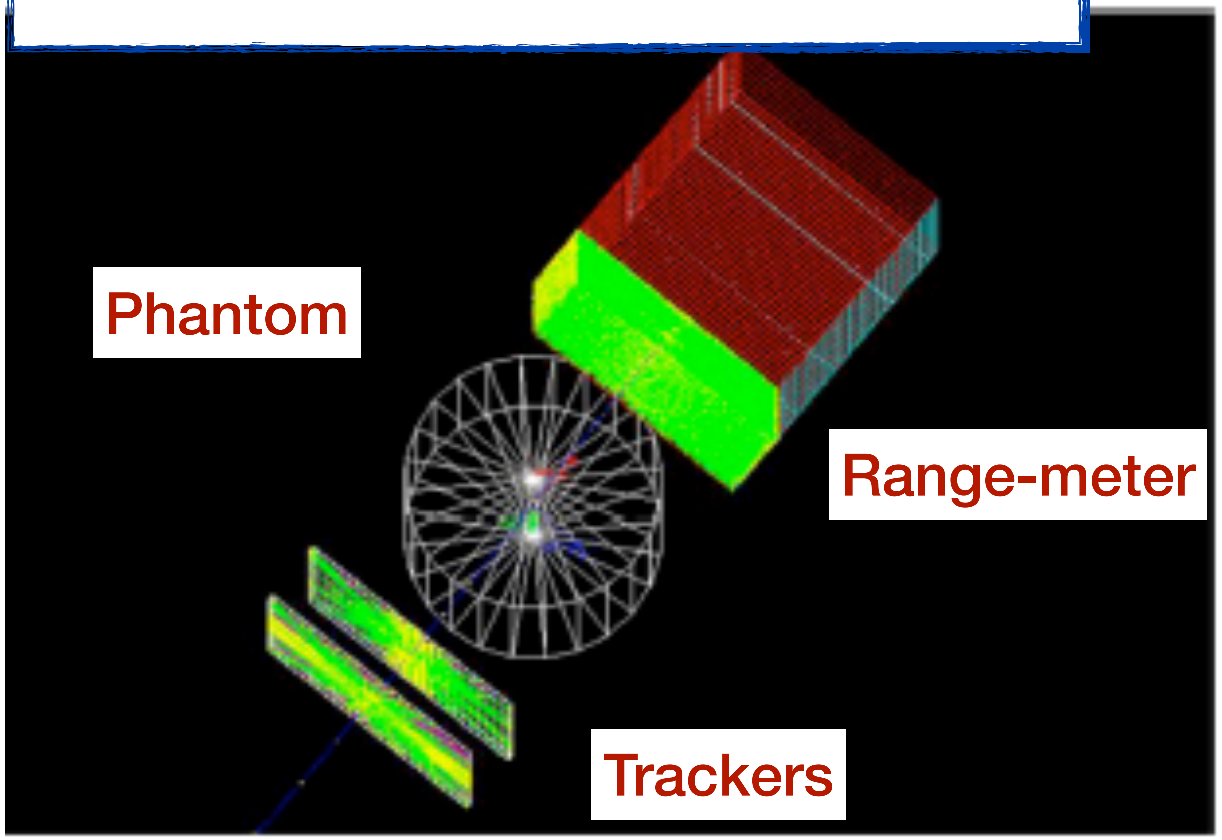
Monte Carlo simulations

GEANT4 simulation platform



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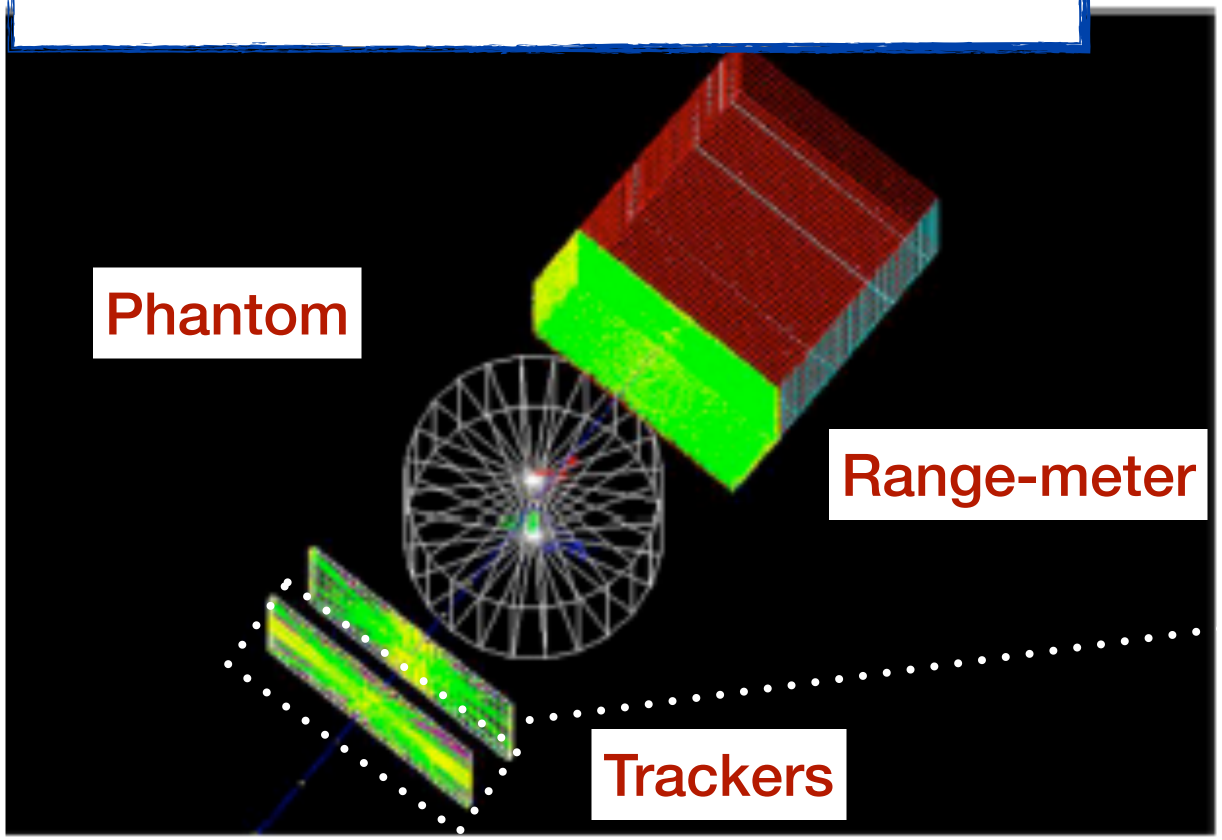
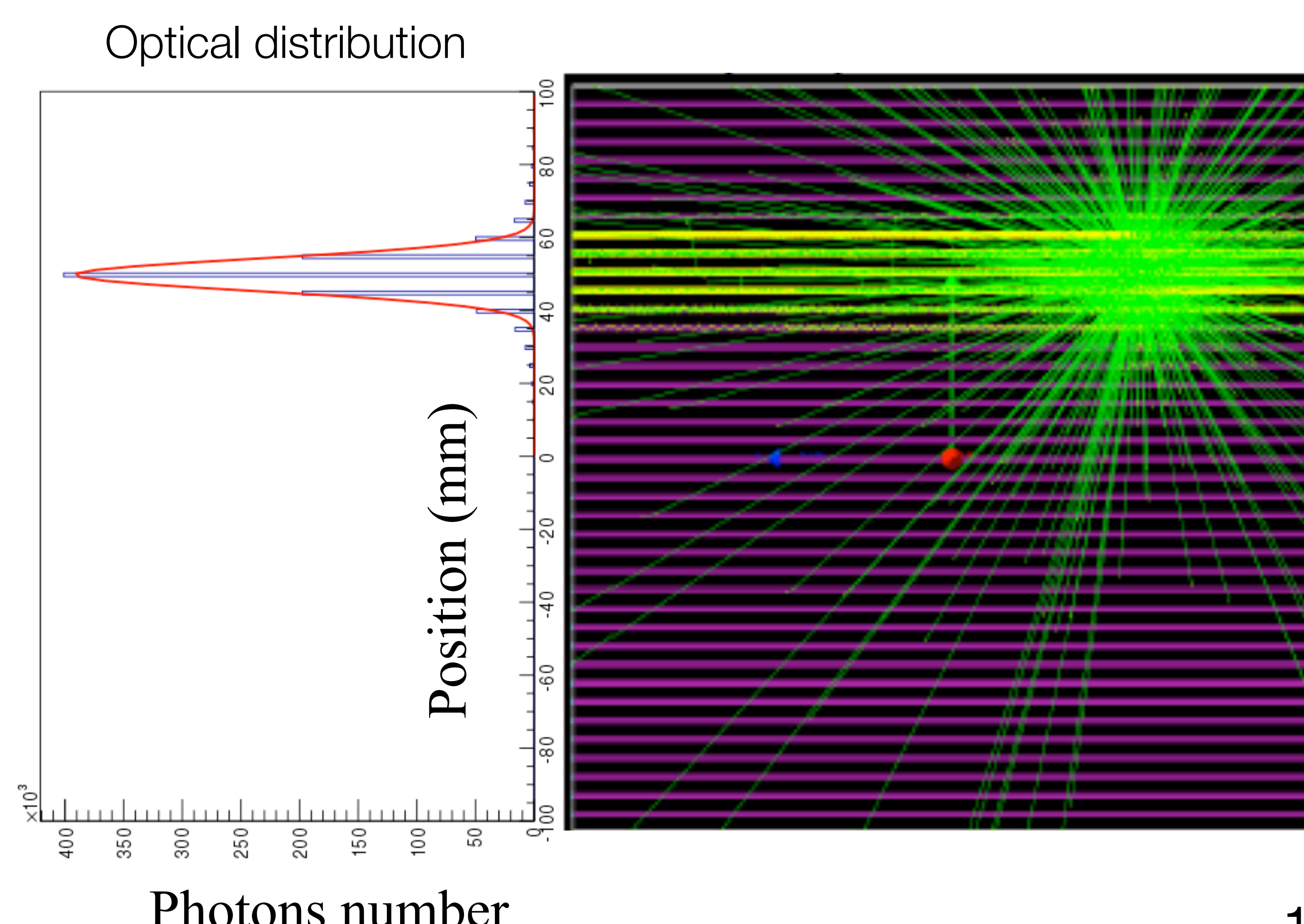
Monte Carlo simulations

GEANT4 simulation platform





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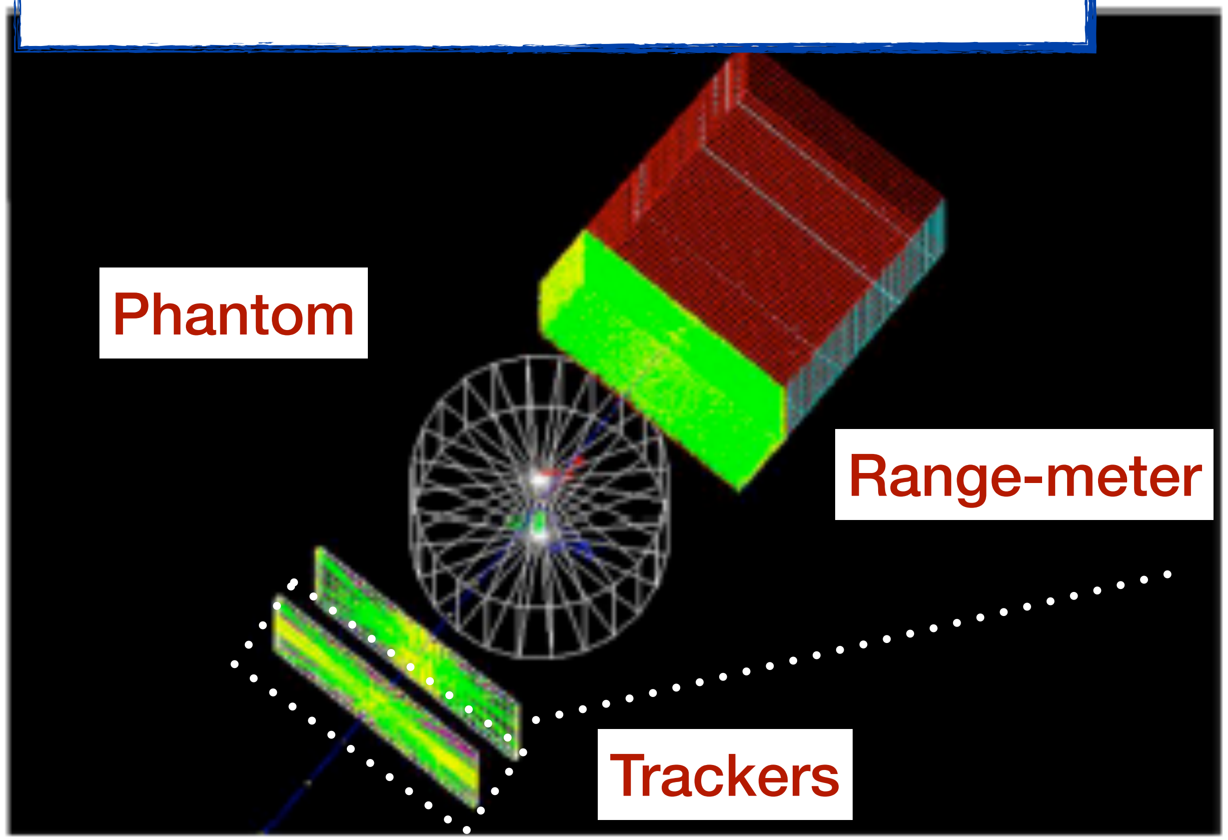
Monte Carlo simulations

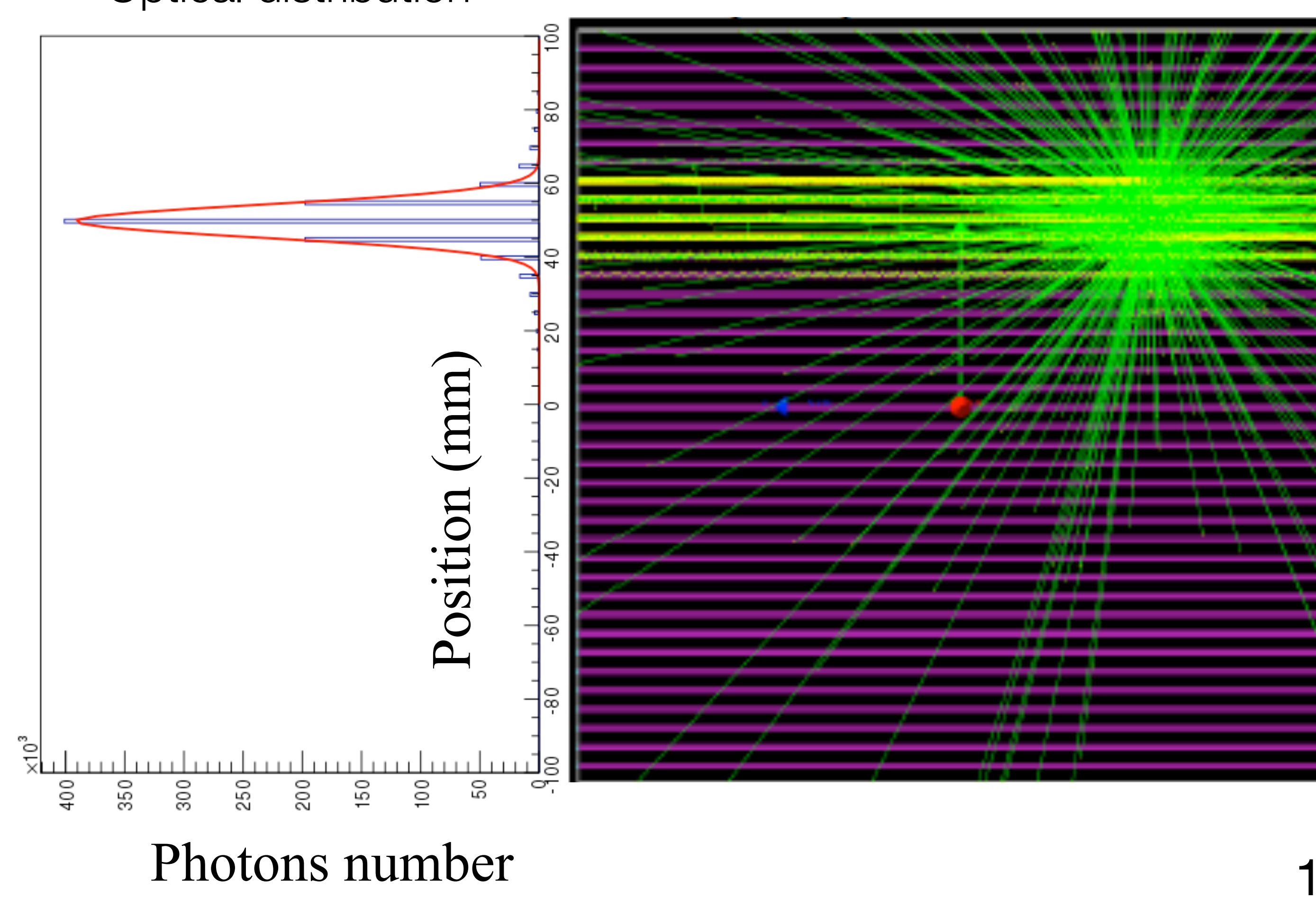
GEANT4 simulation platform



Investigated parameters

- Scintillator material and dimension
- Different **fibers (types, shapes and dimensions)**
- **Inter-fiber spacing**
- **Transversal fiber position** in bulk
- Mirror/no mirror impact
- Cover scintillator material

Optical distribution



Optimization criteria

Minimization of:

- Resolution on **mean beam position**
- Resolution on **beam spread**

Optimization example

- Bulk material: Plastic
- Thickness: 3 mm
- Fiber type and dimension: Circular WLS - 1 mm

- Gaussian beam
- Spread: 3 mm
- # of particles: 500
- Energy: 200 MeV

Observable: Inter-fiber spacing

Optimization example

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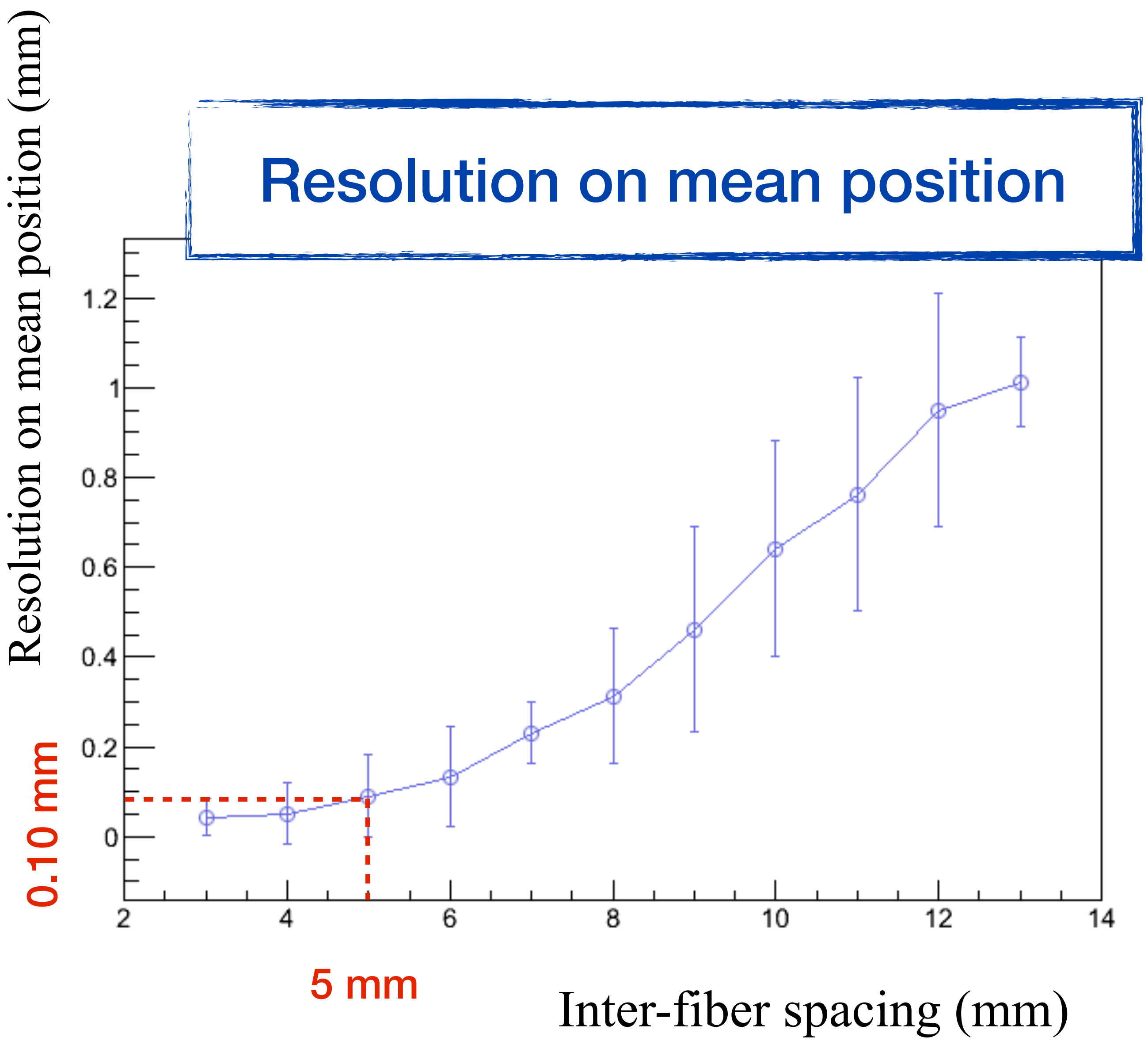

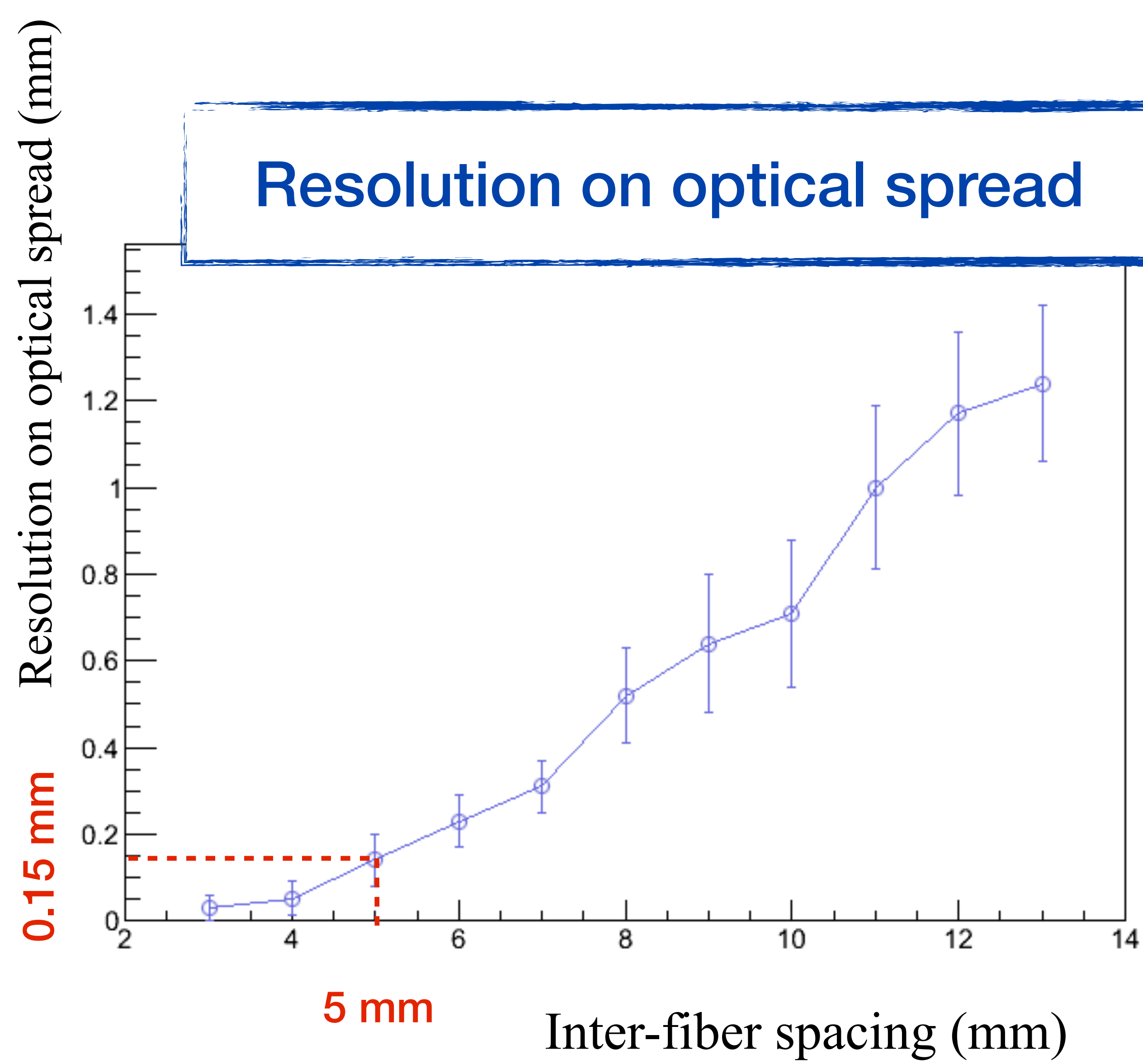

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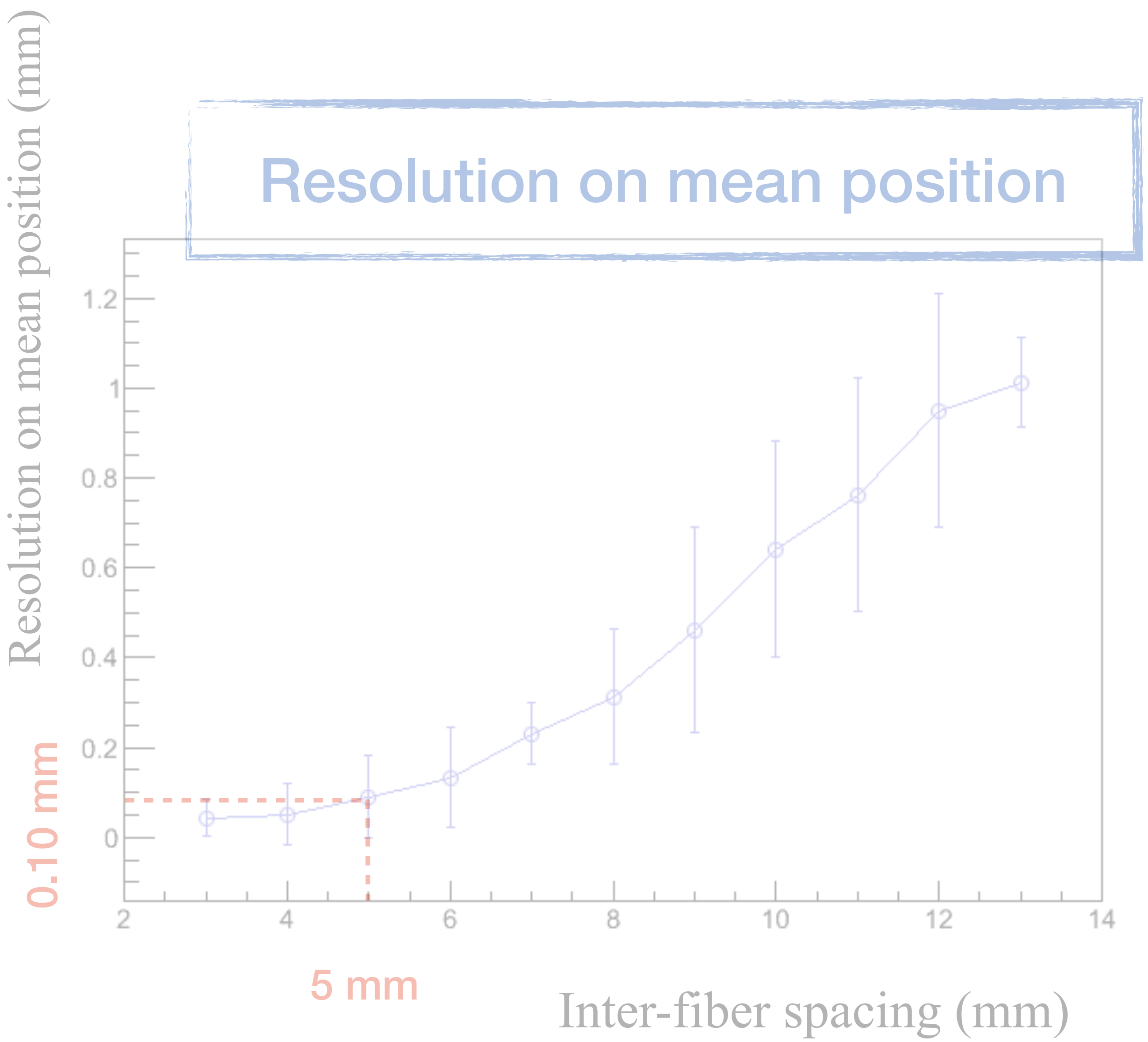
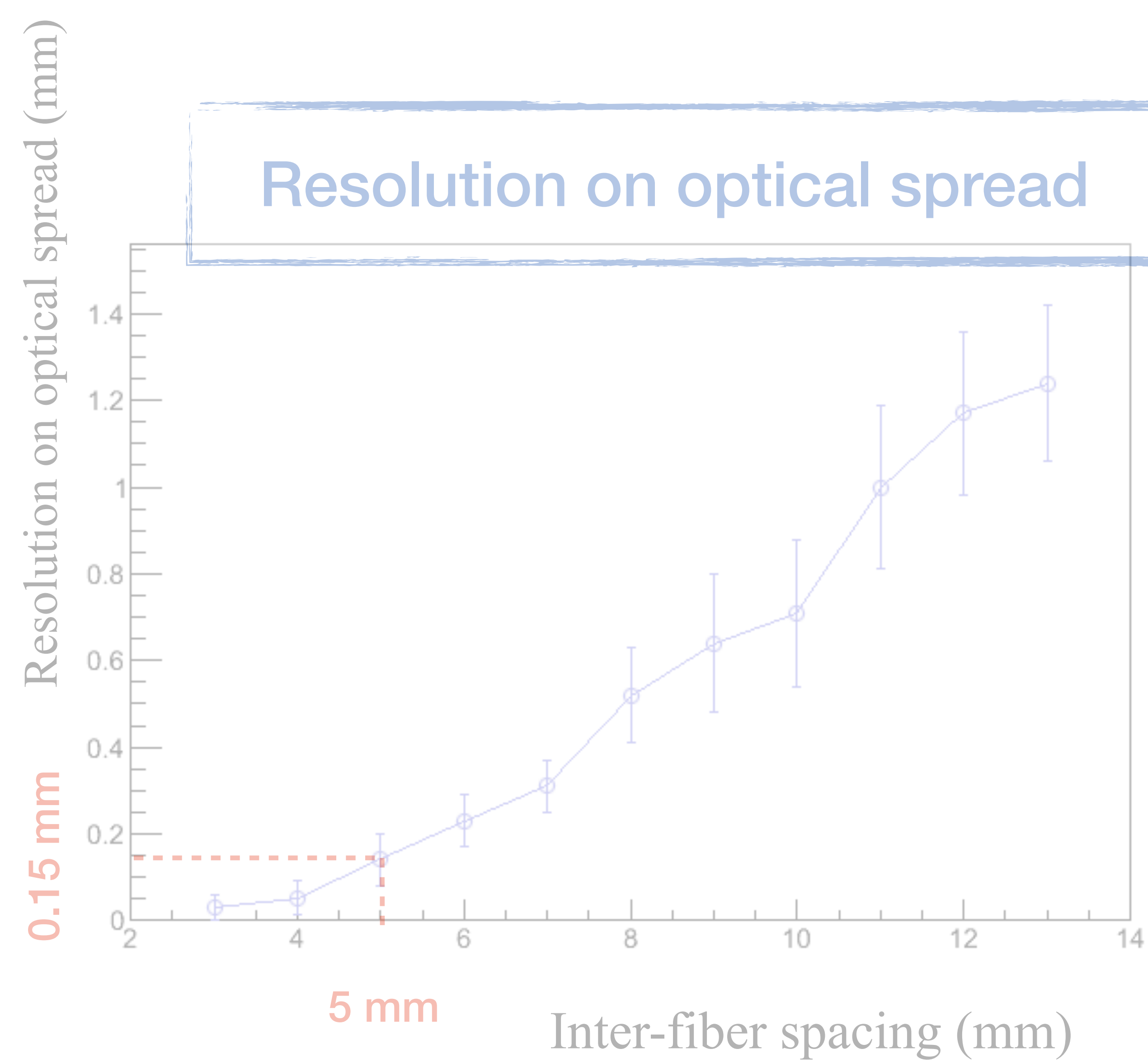
Retained parameters

- Bulk material: **Plastic**
- Dimension: **200 x 200 x 3 mm**
- Fiber type and dimension: **Circular WLS - 1mm**
- Inter-fiber spacing: **5 mm**
- **With mirror**
- **Absorbing cover material**

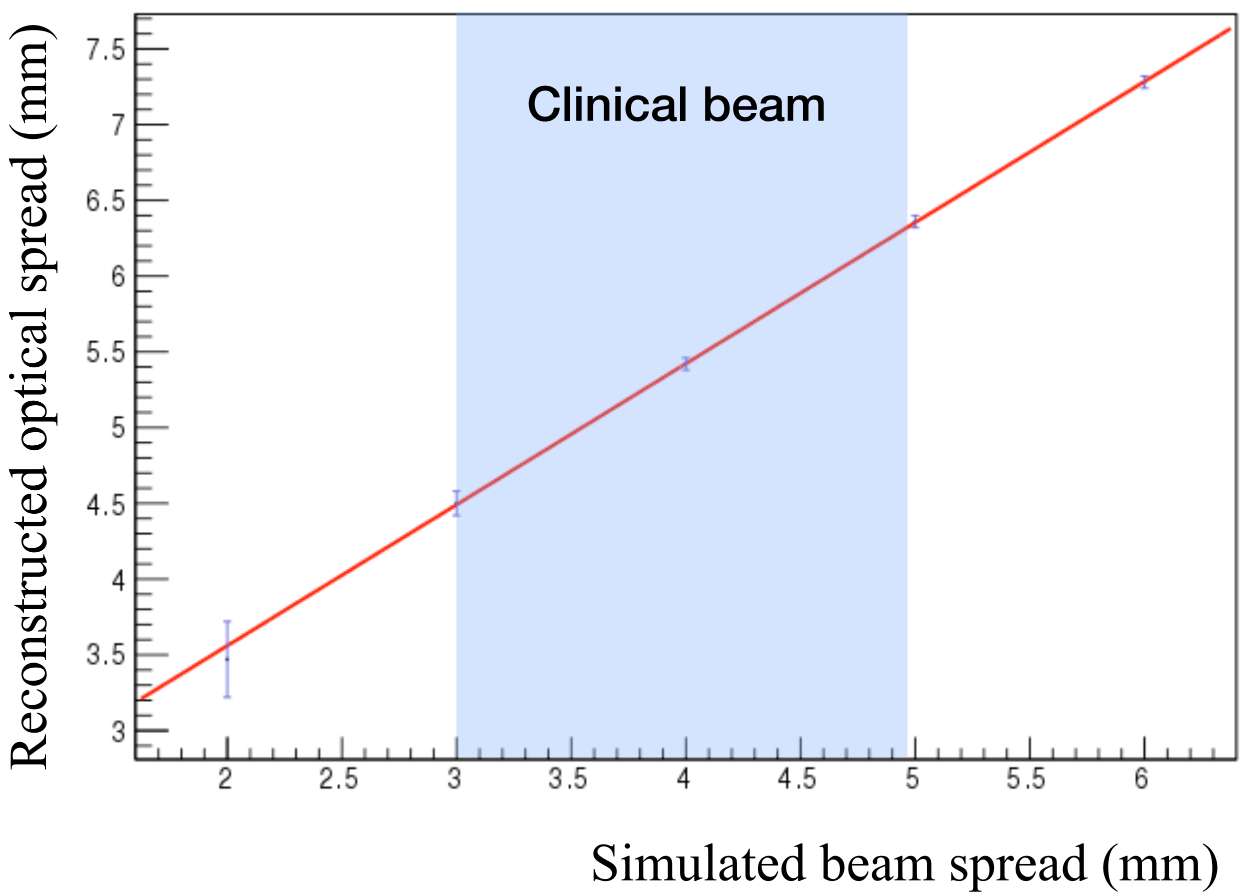
Observable: Inter-fiber spacing



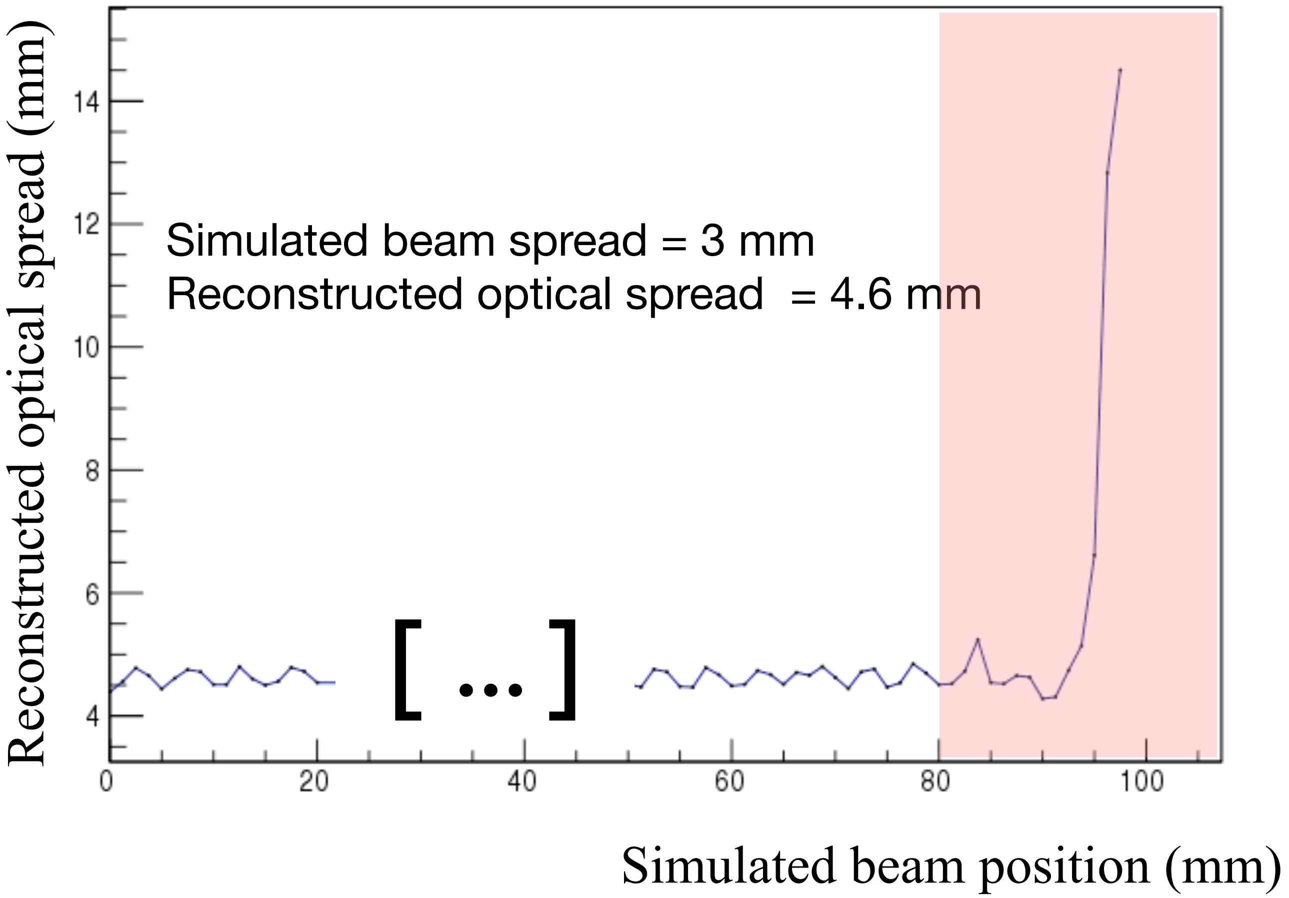


Detector performances

Linear correlation between *beam* and *optical* spread



Field of view reduced (20 %) because of edge effect



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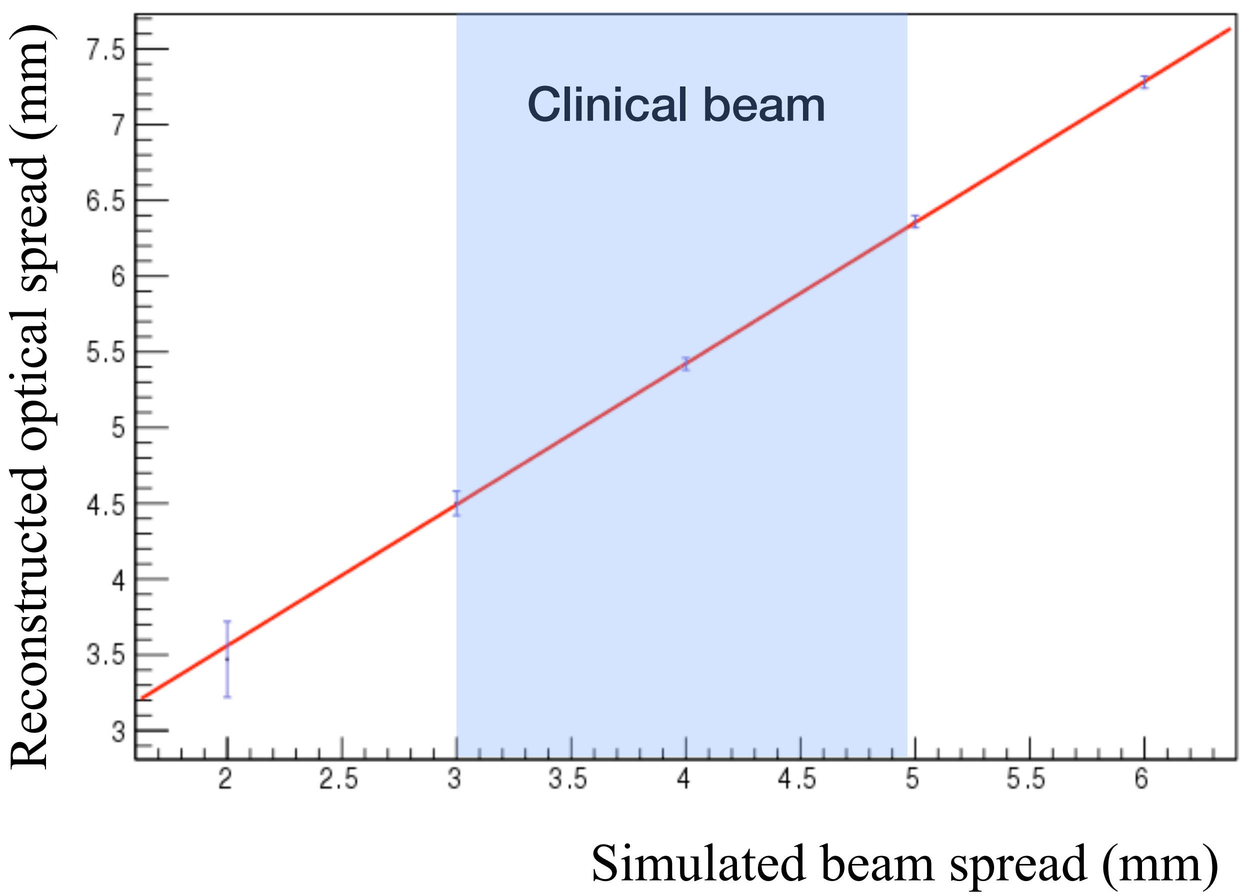
Detector performances

Linear correlation between *beam* and *optical* spread



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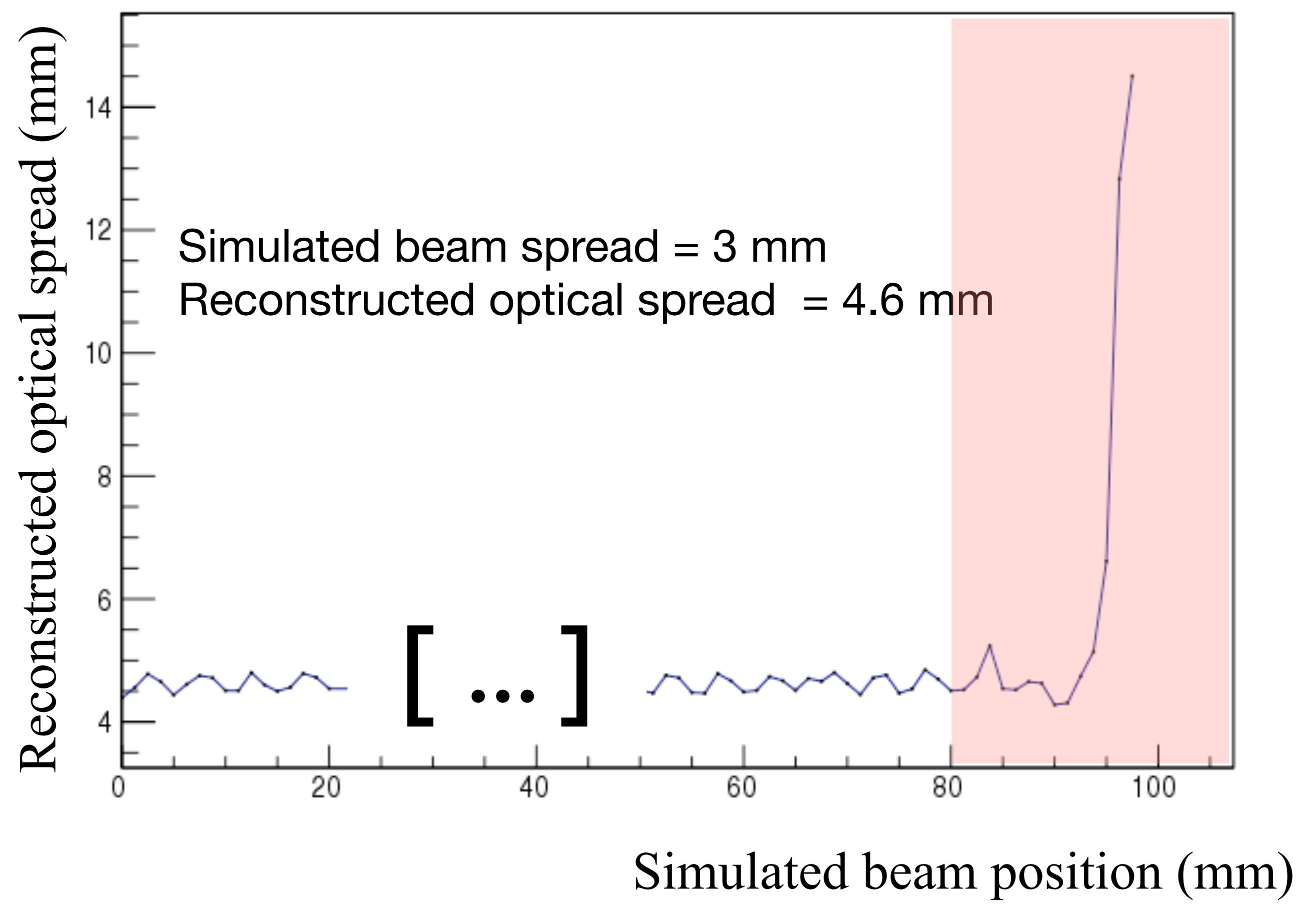


Resolution on beam position ~ 0.2 mm
Resolution on beam spread ~ 0.4 mm

Detector performances

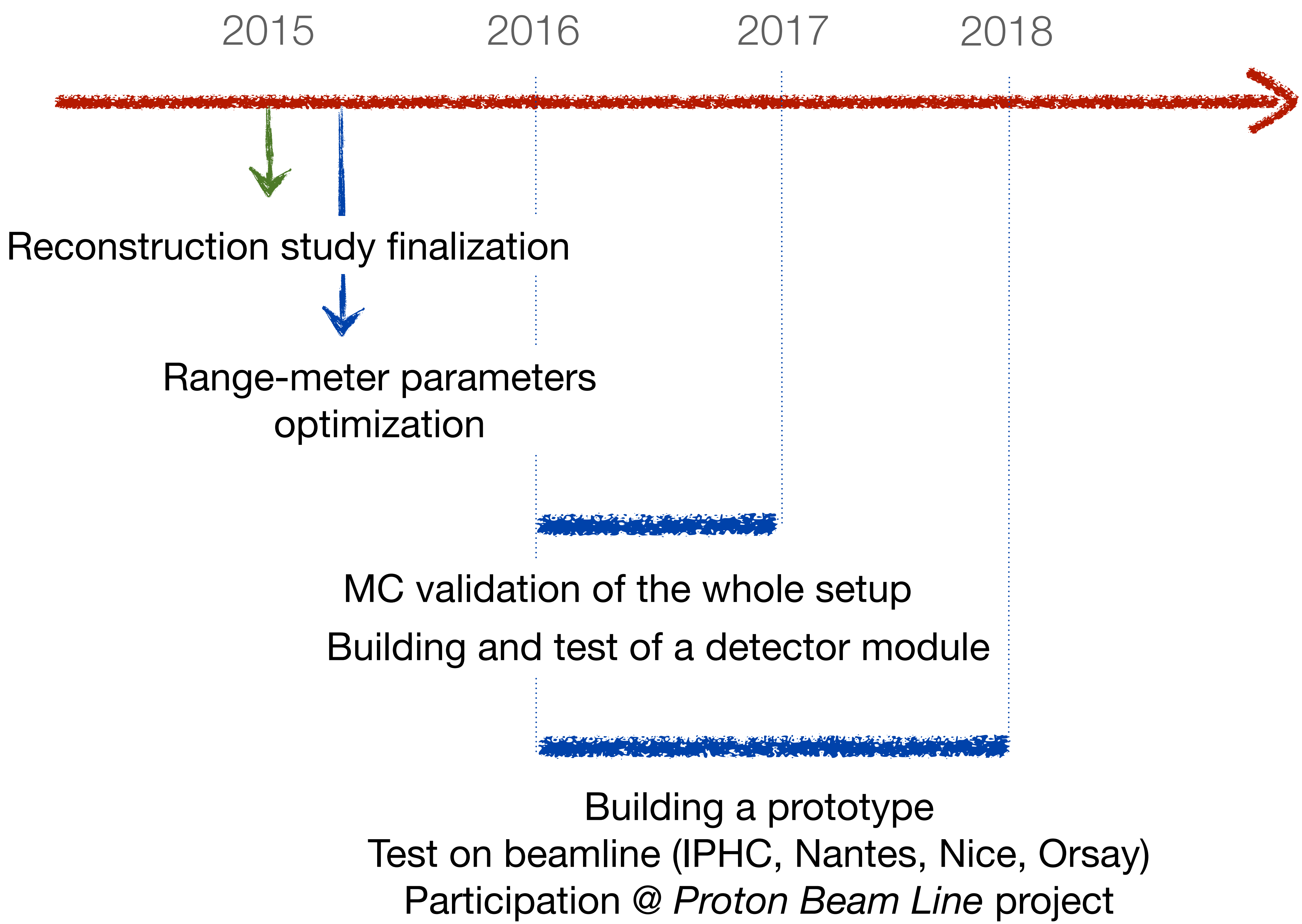
Conclusions

Tracker detector for pCT scanner using PB approach defined

- Detector parameters optimized by MC
- Good resolution on physical observables (beam position and spread)
- <u>Range-meter study is ongoing</u>

Resolution on beam position ~ 0.2 mm
Resolution on beam spread ~ 0.4 mm

Perspectives



Publications, communications and funding

- C. Bopp, Proton Computed tomography for multiple physics processes, PMB 2013
- C.Bopp, The impact of tracking system properties on the most likely path estimation in proton CT, PMB 2014
- C. Bopp, Quantitative proton imaging from multiple physics processes, PMB 2015
- R.Rescigno, Pencil Beam approach to proton computed tomography, accepted Medical Physics 2015

- IEEE NSS/MIC, Workshop on new technologies in hadron therapy, Anaheim, 2012
- IEEE NSS/MIC, Proton computed tomography: beyond the stopping power, 2014
- SFP, Développement d’un scanner pour l’imagerie proton, 2015
- IEEE NSS/MIC, Pencil Beam approach to proton computed tomography: a performance study, 2015

- Physique cancer INCa (ProTom - 2012/2013)
- IdEx Stasbourg (2013-2015)