Proton CT R&D

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# Transmission imaging using therapeutic ion beams

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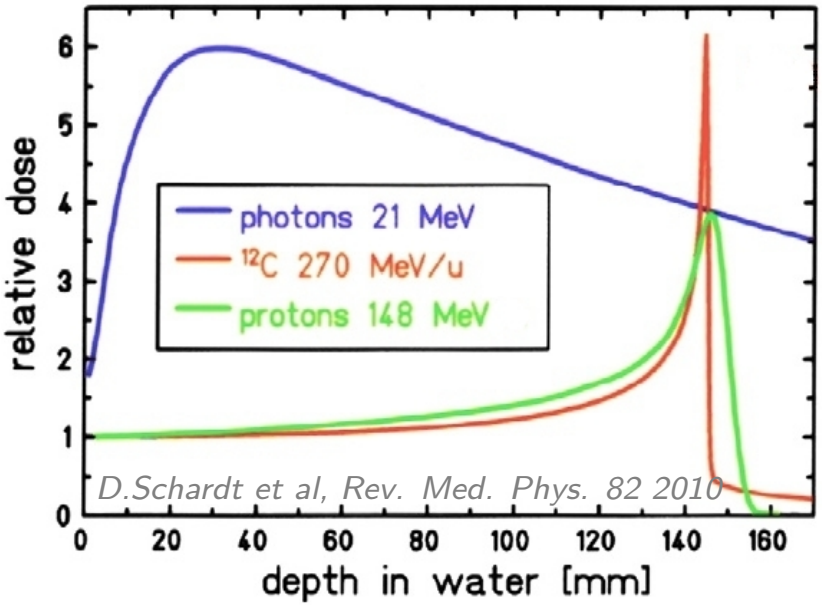
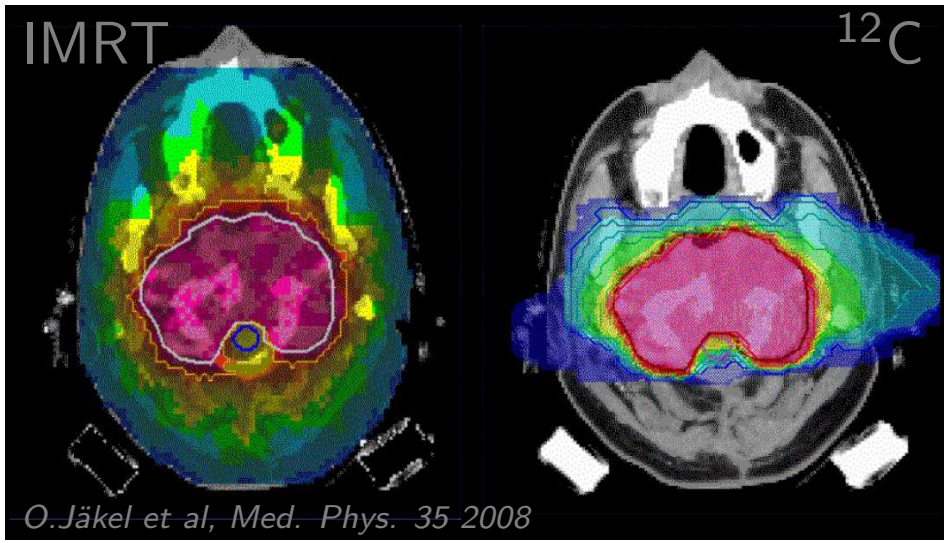
# Introduction
## Ions vs. Photons






**$^{12}$C ions exhibit**

- Inverted depth-dose profile
- Finite range

**$^{12}$C ions allow**

superior tumor-dose conformality

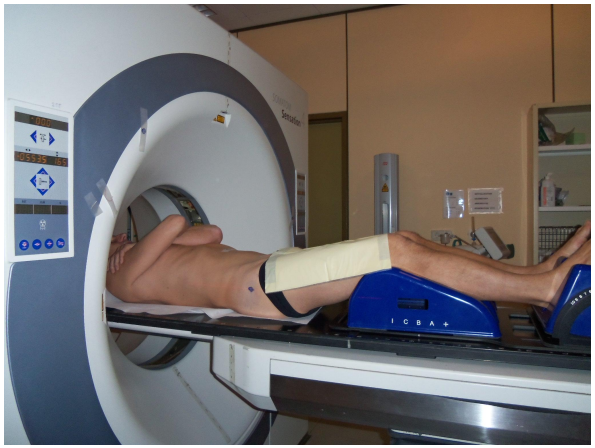
**$^{12}$C ions introduce**

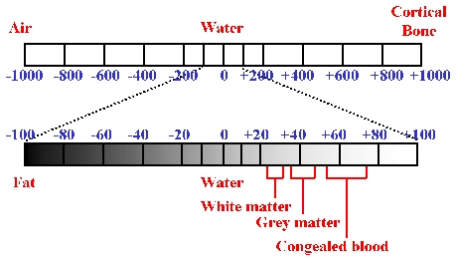
increased sensibility to range uncertainties

# Introduction
## Transmission imaging – The motivation



**X-ray planning CT**

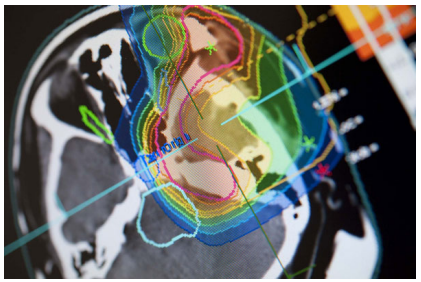





?

⇒

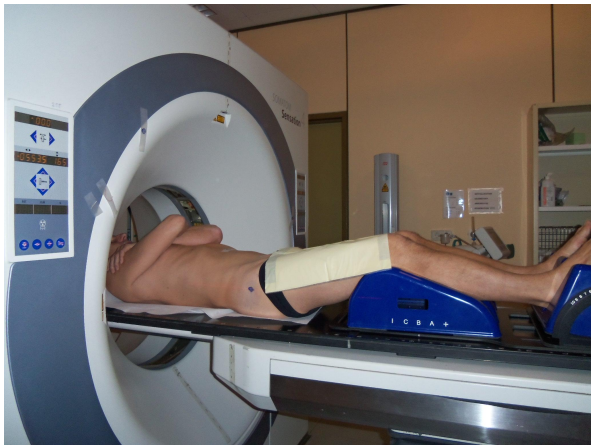
**Ion treatment**

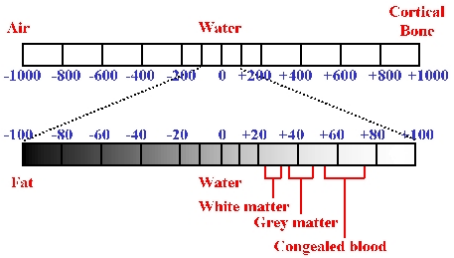


Ilaria Rinaldi



## X-ray planning CT



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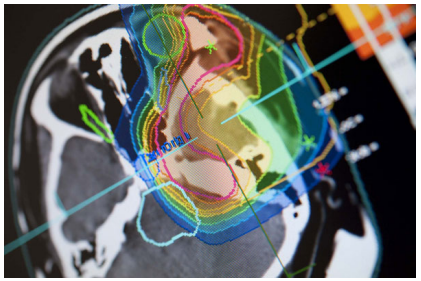
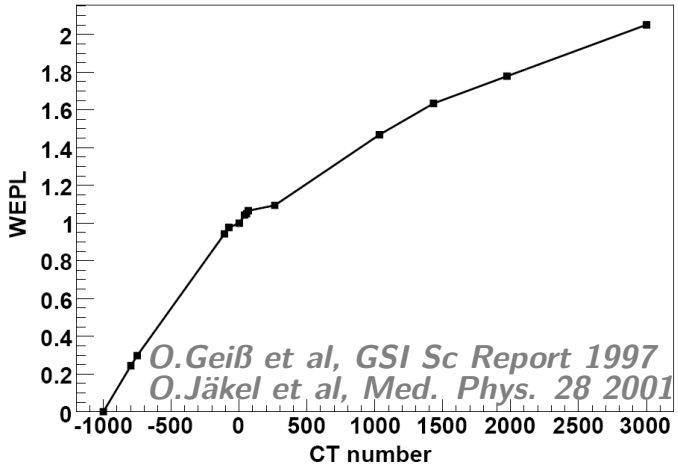
⇒

## Ion treatment



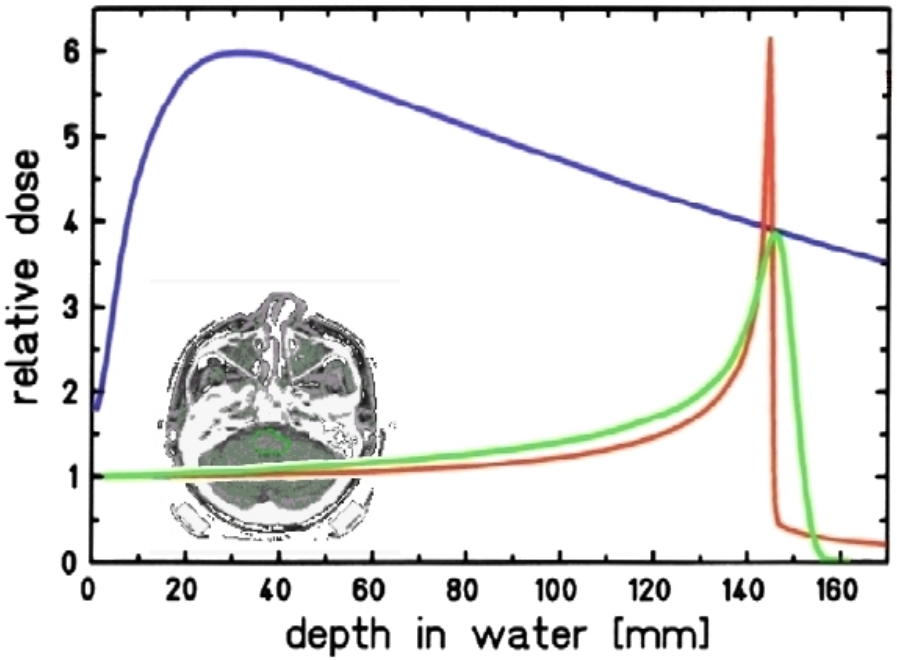
## Experimental calibration curves




⇒ **1-3% range uncertainties**

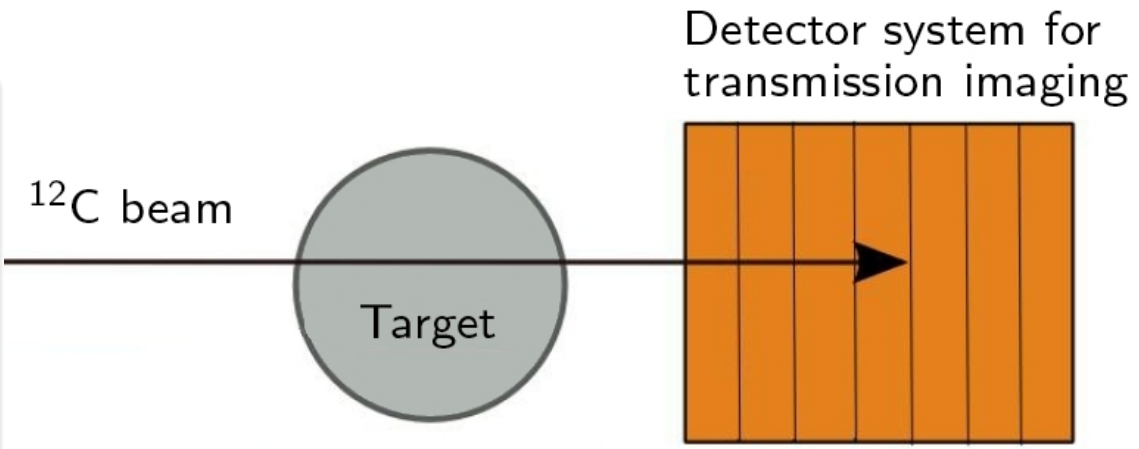
# Introduction
## Transmission imaging – The idea






- use of energetic ion beams prior to or even in-between the treatment
- low dose to the patient

position of the Bragg peak depends on the characteristics of the transversed materials



State of the art of transmission imaging at the beginning of my PhD:

- Proton

  $\Rightarrow$began already since 1968

  $\Rightarrow$PSI (Switzerland) and LLUMC (USA) set-ups

  $\Rightarrow$not yet used in the clinical routine

- Carbon ion

  $\Rightarrow$CHIBA (Japan) set-ups

State of the art of transmission imaging at the beginning of my PhD:

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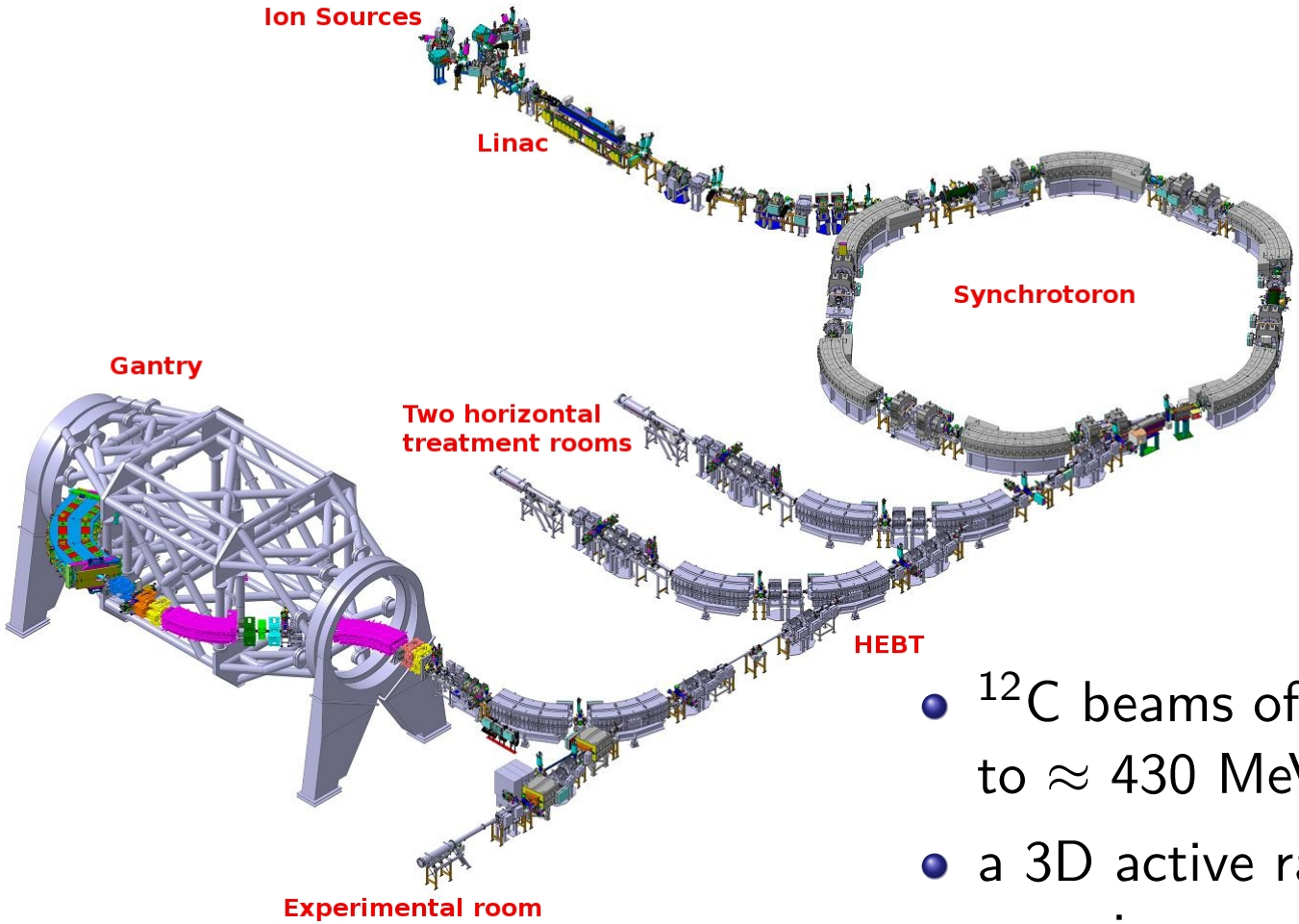
  ⇒not yet used in the clinical routine
- Carbon ion
  ⇒CHIBA (Japan) set-ups

**What should a good detector provide?**

- low dose to the patient
- good image quality
- fast data acquisition
- fine resolution
- large covered range

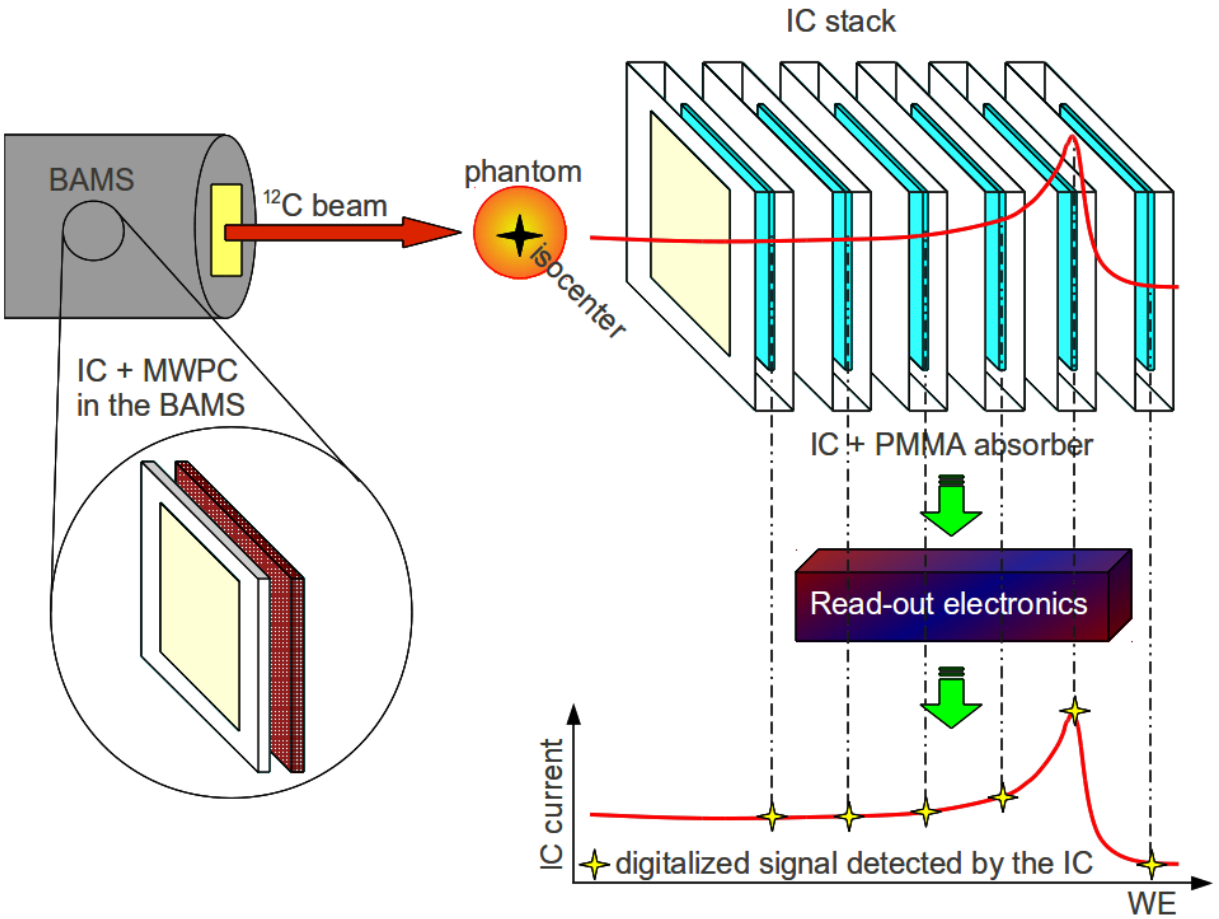
# Introduction
## Transmission imaging at HIT

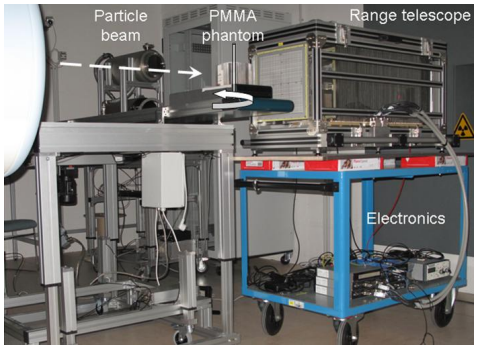


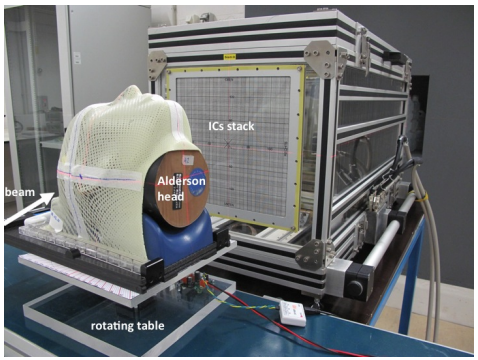



- $^{12}C$ beams of energy up to $\approx$ 430 MeV/u
- a 3D active raster scanning
- the worldwide first heavy ion gantry

## Carbon ion radiography and tomography



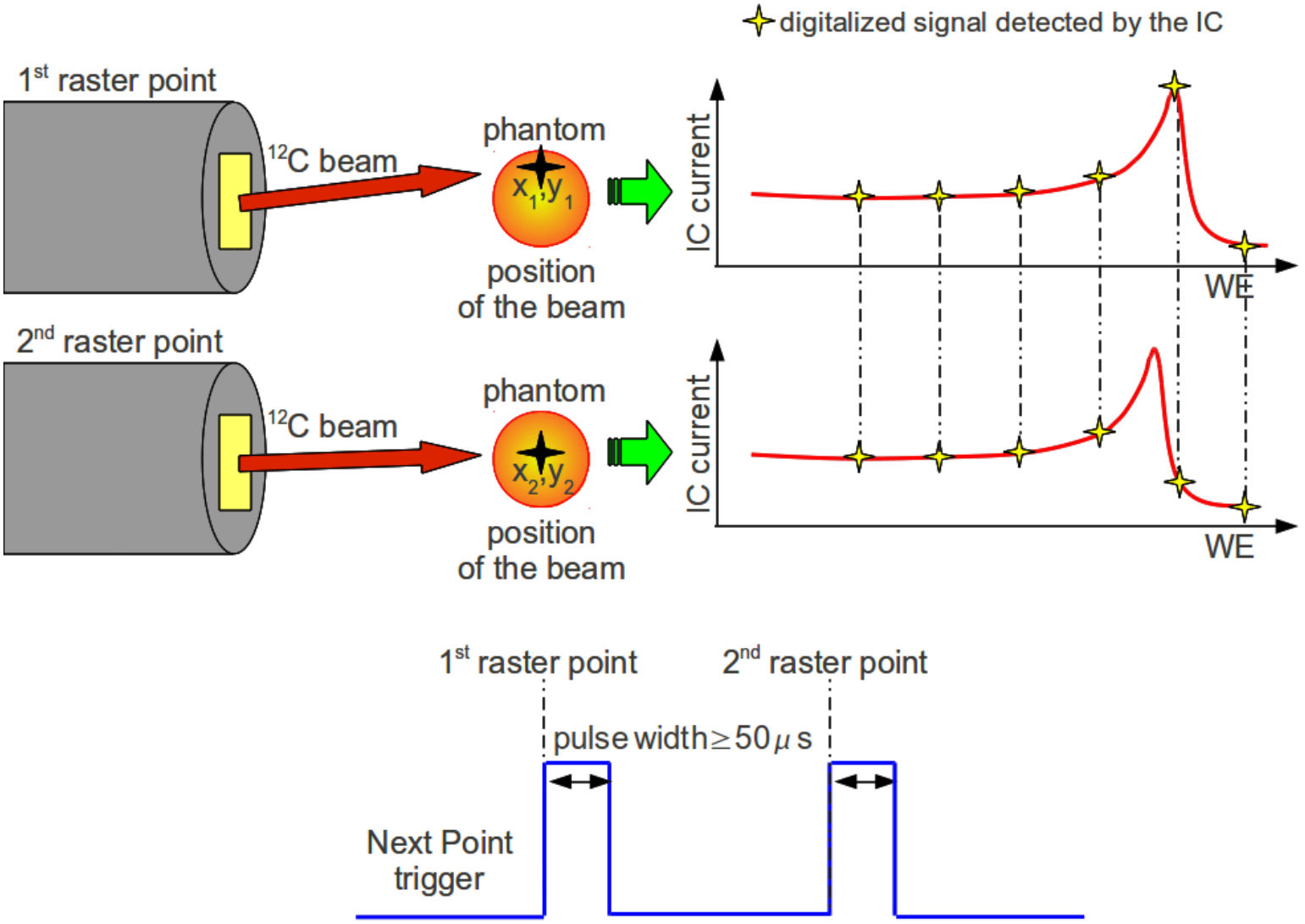




*I. Rinaldi et al, PMB 58 (2013), 413*

# Set-up
## Data acquisition technique



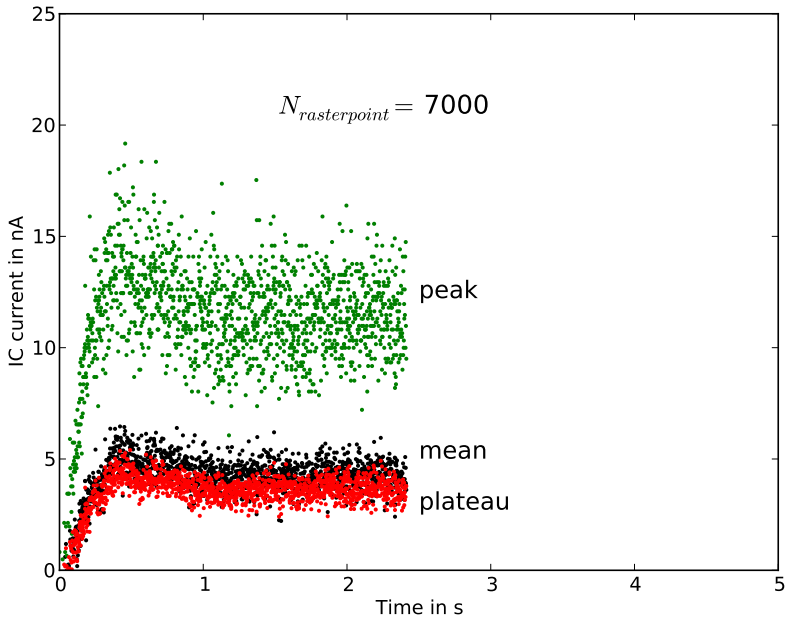


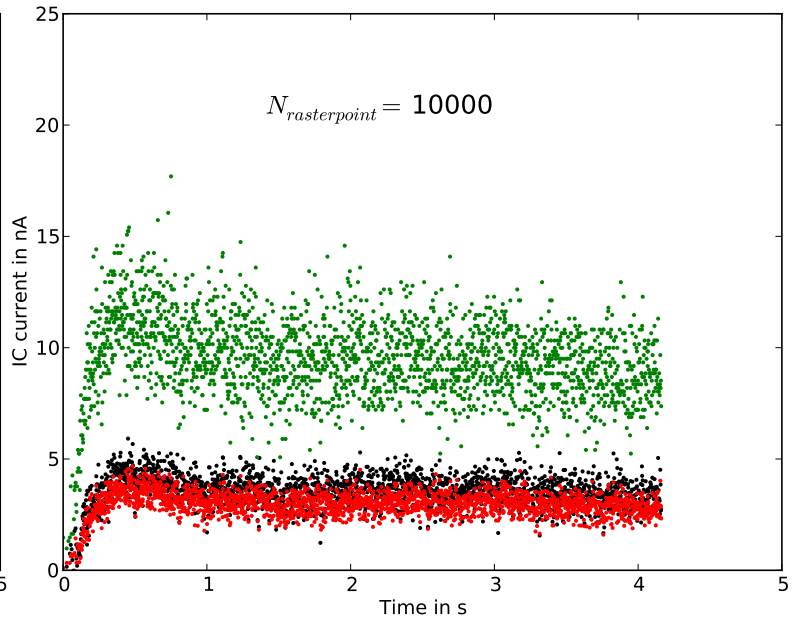

*I. Rinaldi et al, PMB 58 (2013), 413*

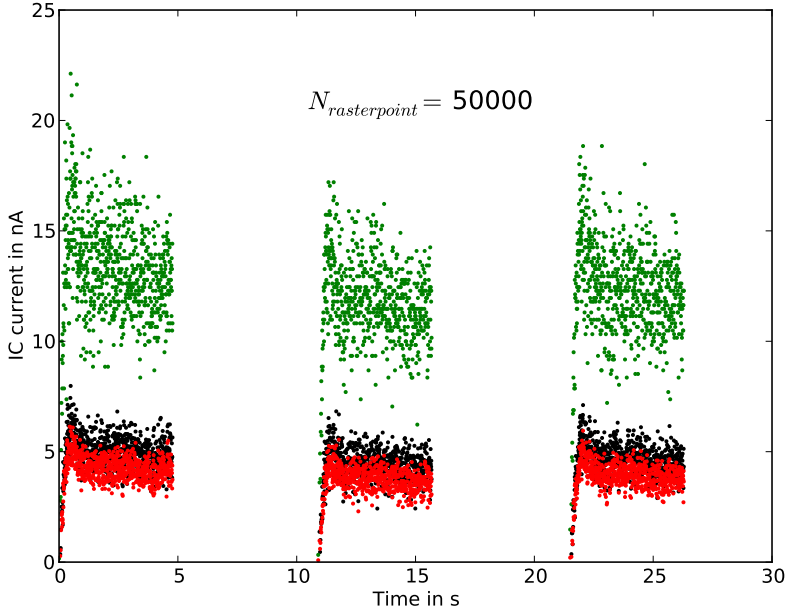
# Set-up

## Dependence of ICs stack response on number of particles per raster point





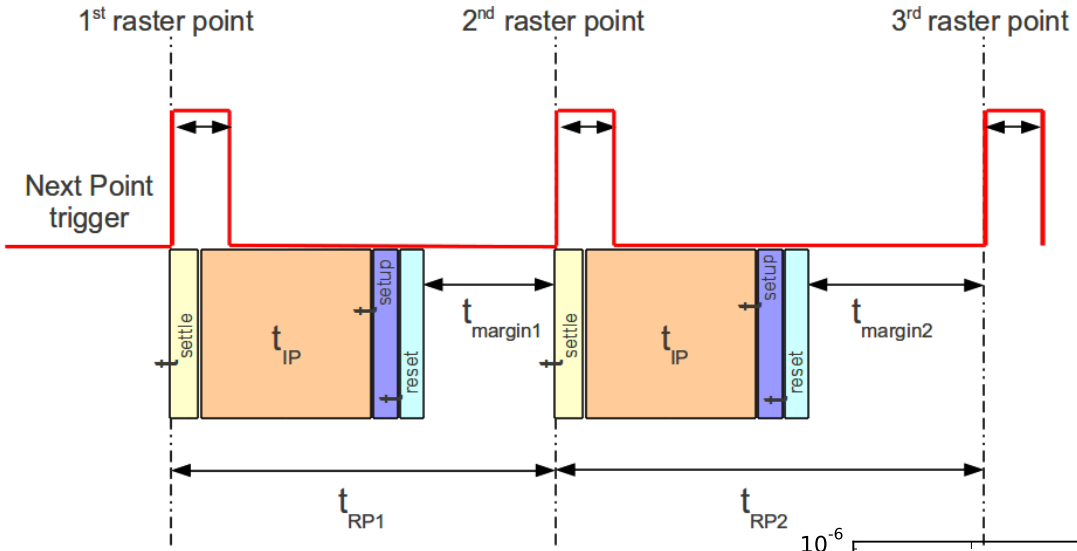

- ICs signal independent of delivered number of particles if $t_{IP} \leq t_{RP}$
- To minimize dose
  $\Rightarrow$ Reduce $N_{RP}$

*I. Rinaldi et al, PMB 58 (2013), 413*

# Set-up

## Dependence of ICs stack response on electronics and beam intensity



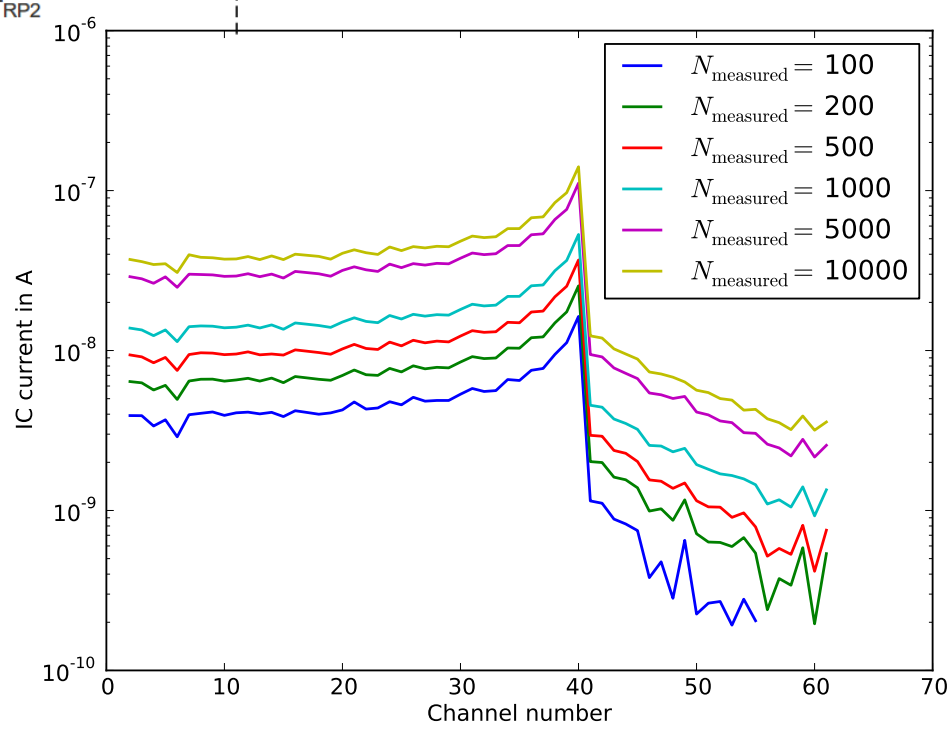



$$\frac{N_{measured}}{N_{delivered}} = \frac{t_{IP}}{t_{RP}}$$

$$N_{measured} = I \cdot t_{IP}$$

$$N_{delivered} = I \cdot t_{RP}$$

- To speed up scan time
  $\Rightarrow$ High beam intensity
- To optimize delivered number of particles
  $\Rightarrow$ Minimize idle and lost time

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# Experimental characterization
## Calibration phantom



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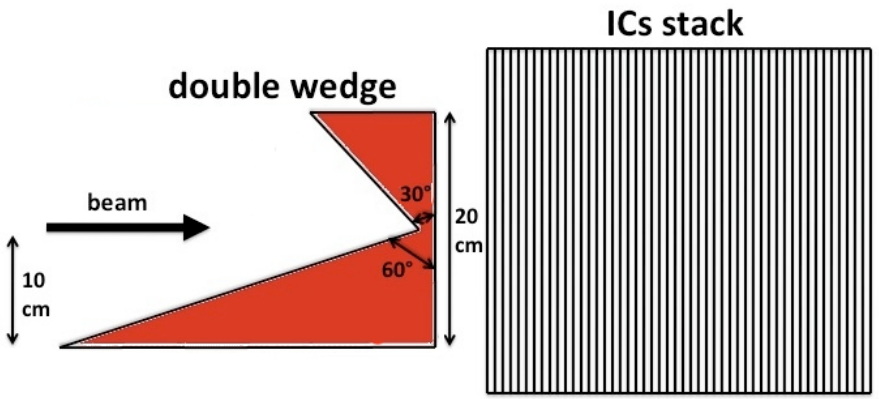
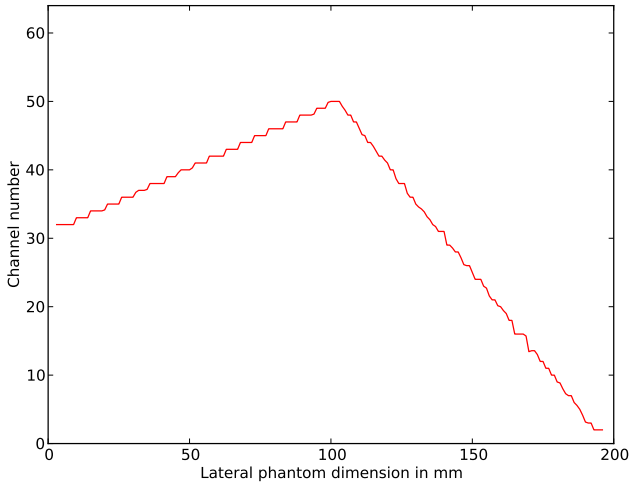
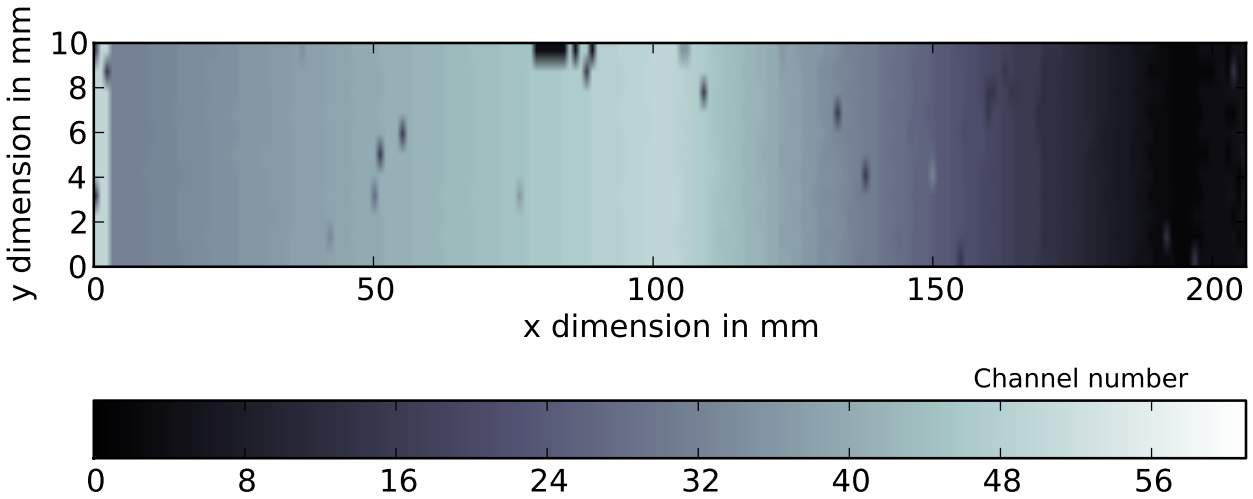


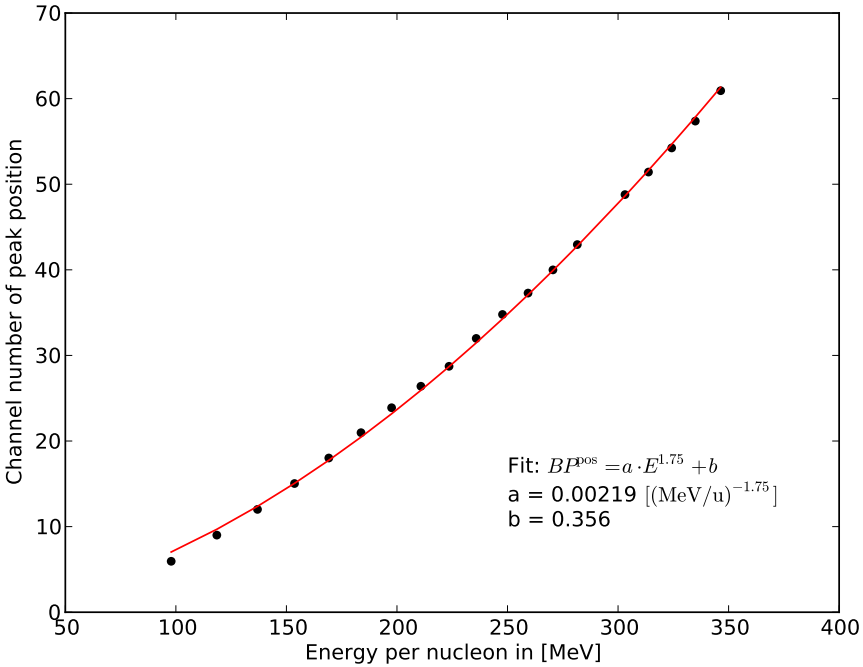



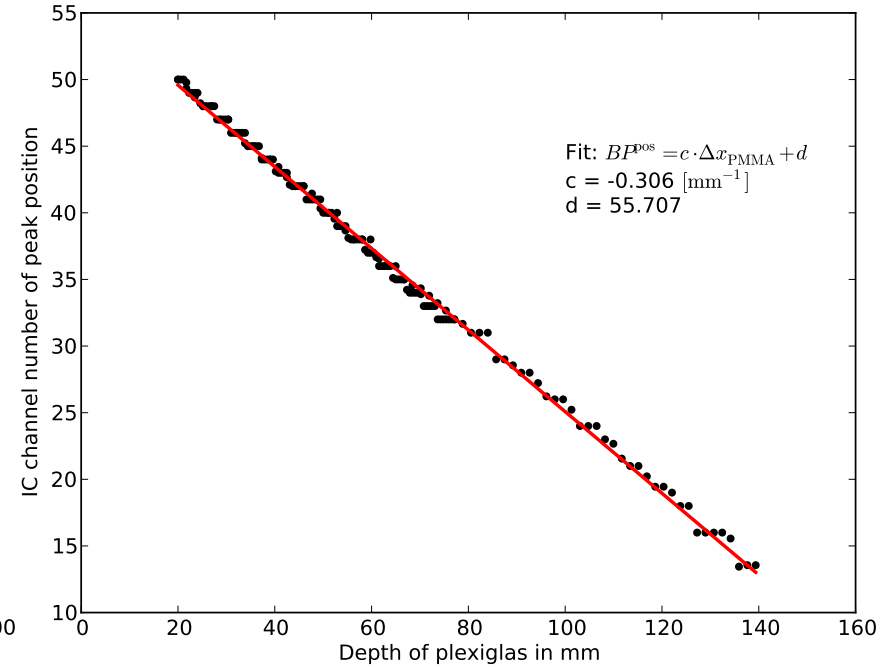
# Experimental characterization

## Bragg peak position in the ICs stack as function of beam energy and target thickness

*I. Rinaldi et al, PMB 58 (2013), 413*





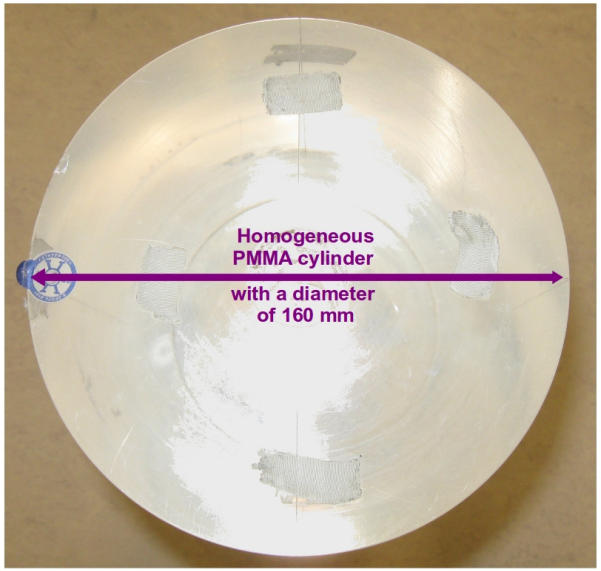

## Re-elaboration of radiography in WE:

$$\mathrm{WEPL}^{\mathrm{HIT}}_{\mathrm{PMMA}} = 1.165 \Rightarrow \Delta x_{\mathrm{WE}} \approx \mathrm{WEPL}_{\mathrm{PMMA}} \cdot \Delta x_{\mathrm{PMMA}}$$

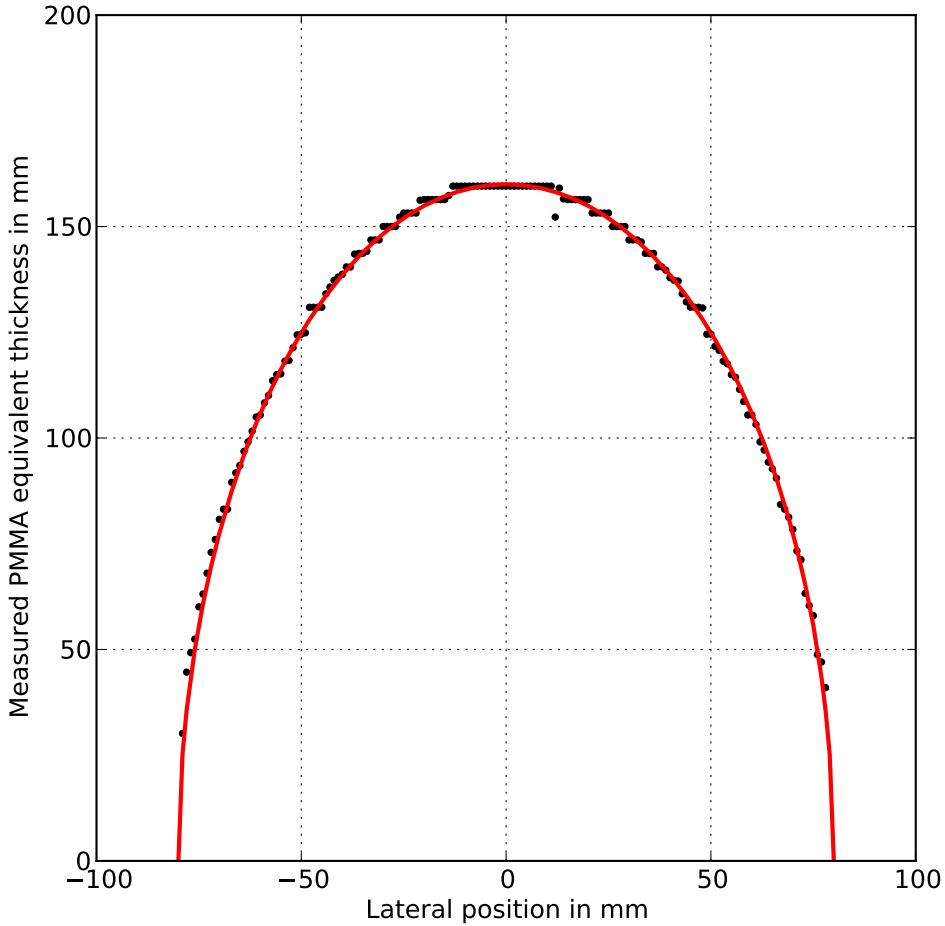
$$\Delta x_{\mathrm{WE}} = WEPL_{\mathrm{PMMA}} \cdot \left\{ \frac{1}{c} \cdot \left[ \left( BP^{\mathrm{pos}}_{\mathrm{measured}} - b \right) \cdot \left( \frac{E_{\mathrm{ref}}}{E_{\mathrm{measured}}} \right)^{1.75} + b \right] - \frac{d}{c} \right\}$$

# Experimental characterization
## Homogeneus PMMA phantom






*I. Rinaldi et al, PMB 2013b, submitted*



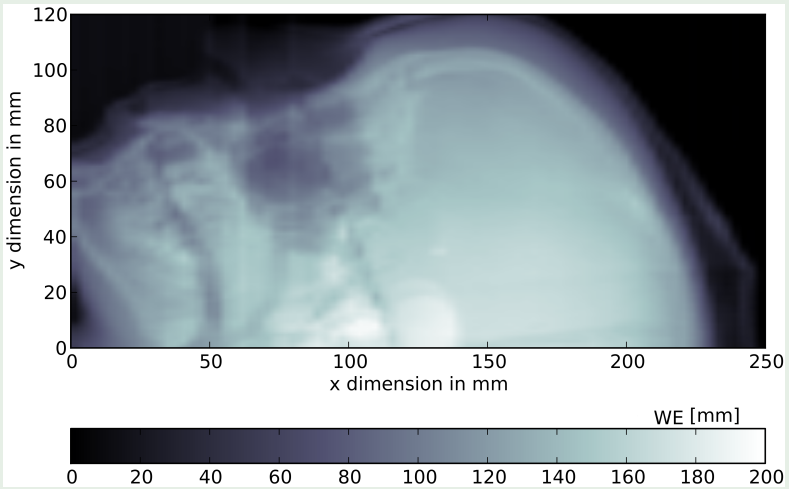
# Radiography

## X-ray vs. $^{12}$C radiography expressed in Water Equivalent (WE) thickness

*I. Rinaldi et al, PMB 2013b, submitted*

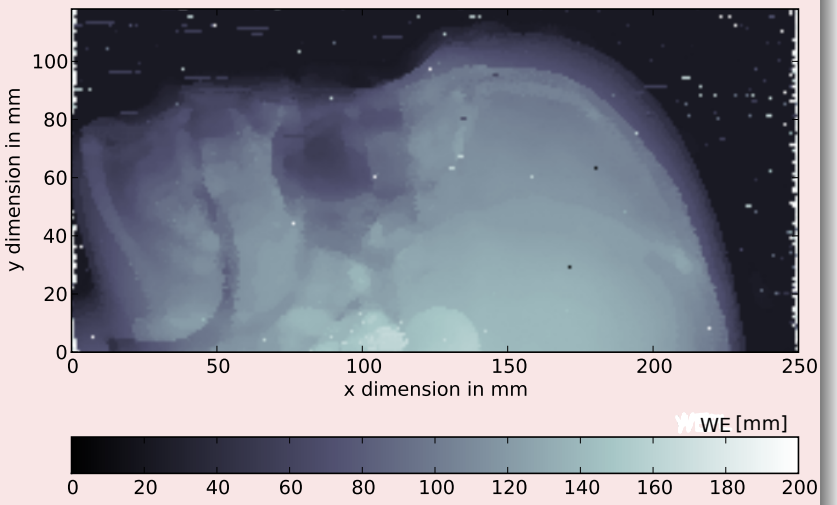


### X-ray projection from CT




- X-ray of 120 kV
- pixel resolution of $(3 \times 0.6\,\mathrm{mm}^2)$

### $^{12}$C



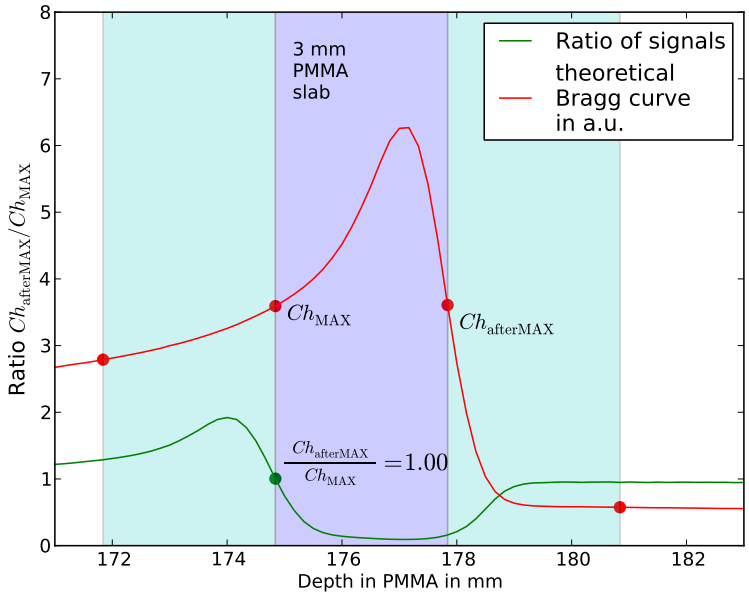

- $^{12}$C beam of 375.32 MeV/u
- 3.5 mm FWHM spot size (focus)
- pixel resolution of $(1 \times 1\,\mathrm{mm}^2)$

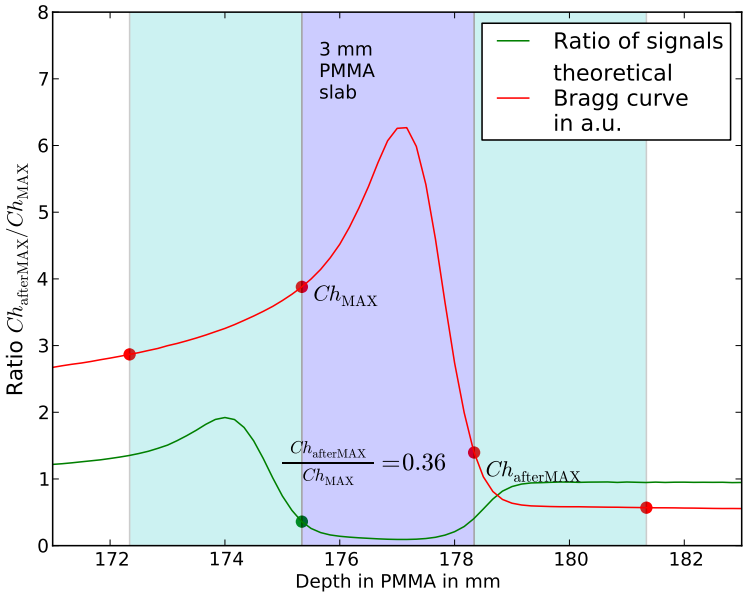
# Radiography

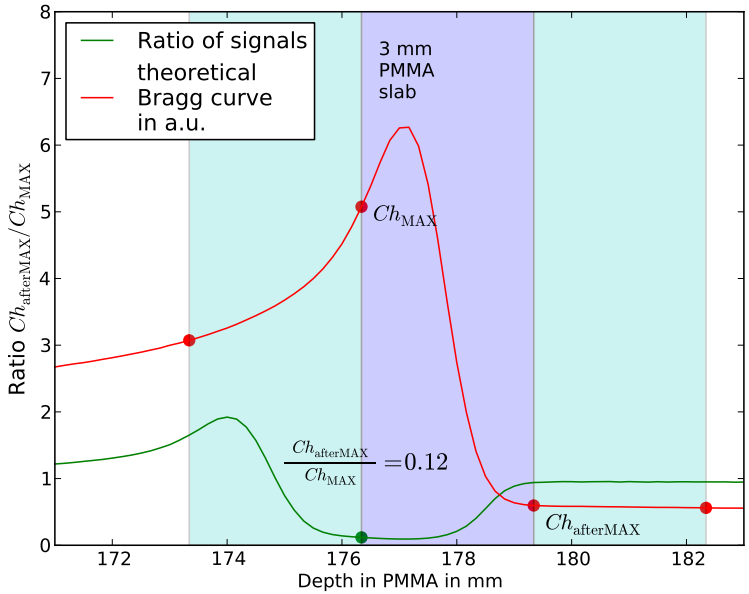
## Method to vitually increased the nominal resolution of the ICs stack

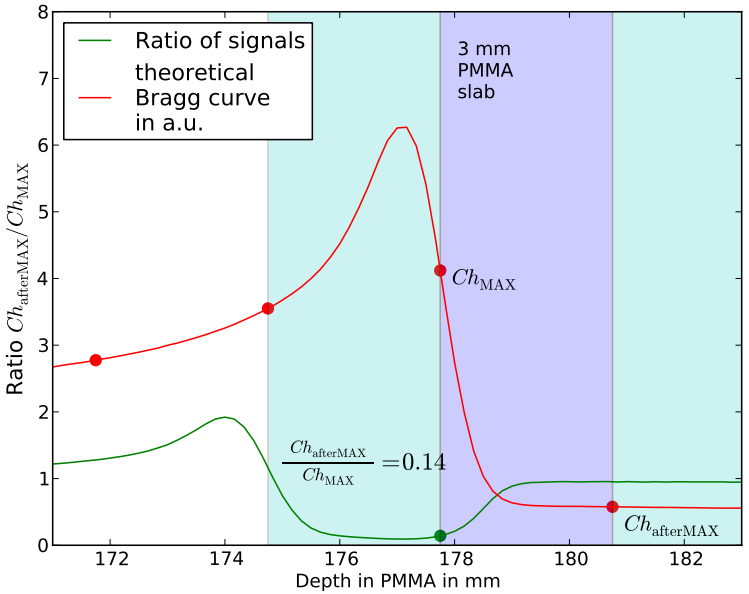
*I. Rinaldi, PhD Thesis 2011*





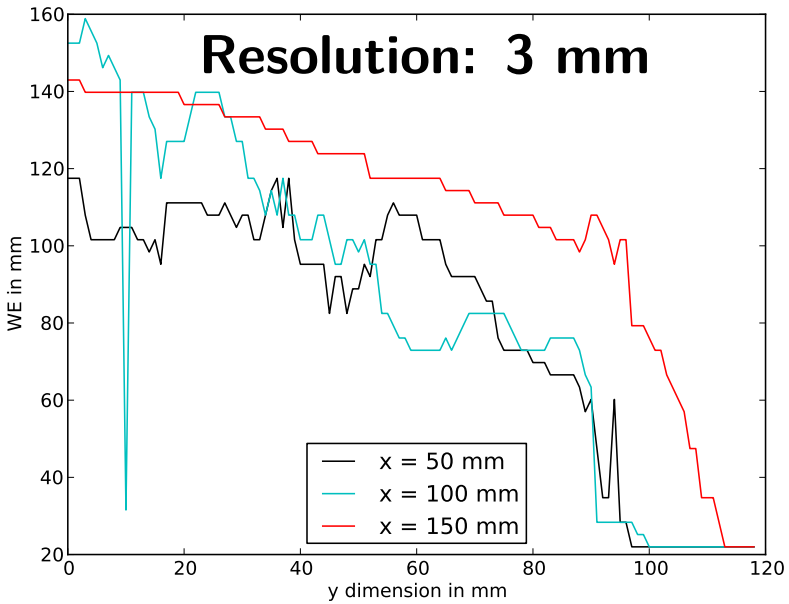



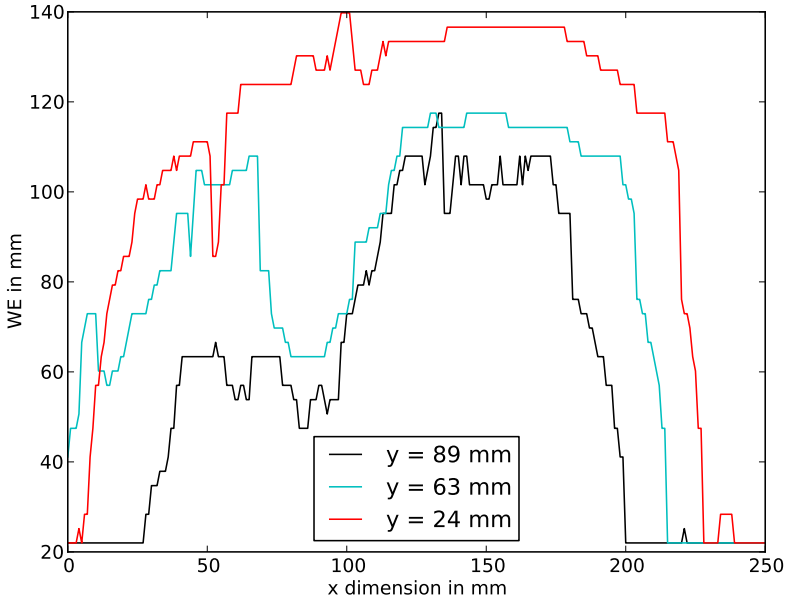
# Radiography

## Sections throught the radiography of the Alderson head phantom

*I. Rinaldi, PhD Thesis 2011*





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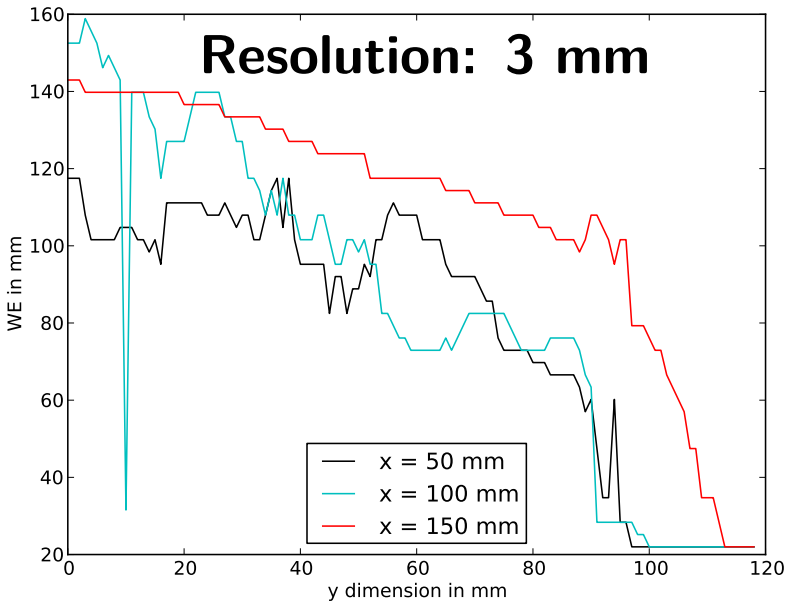


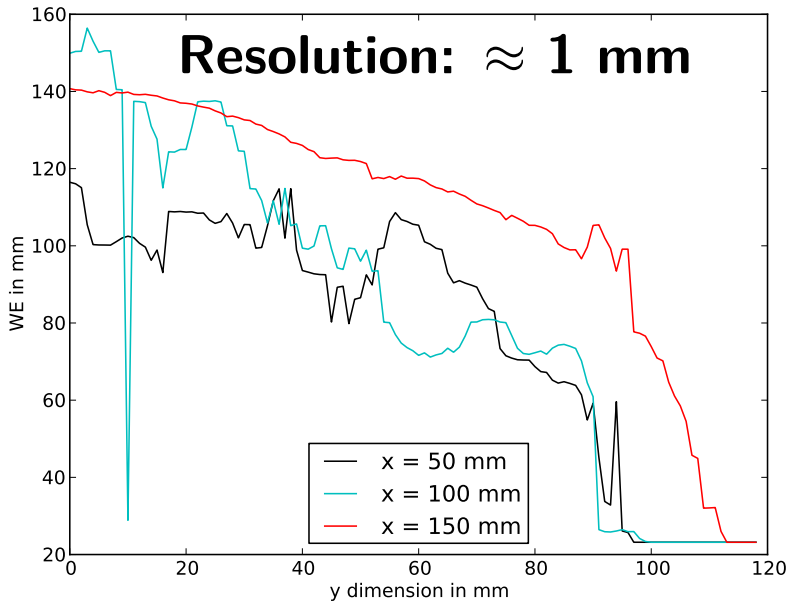


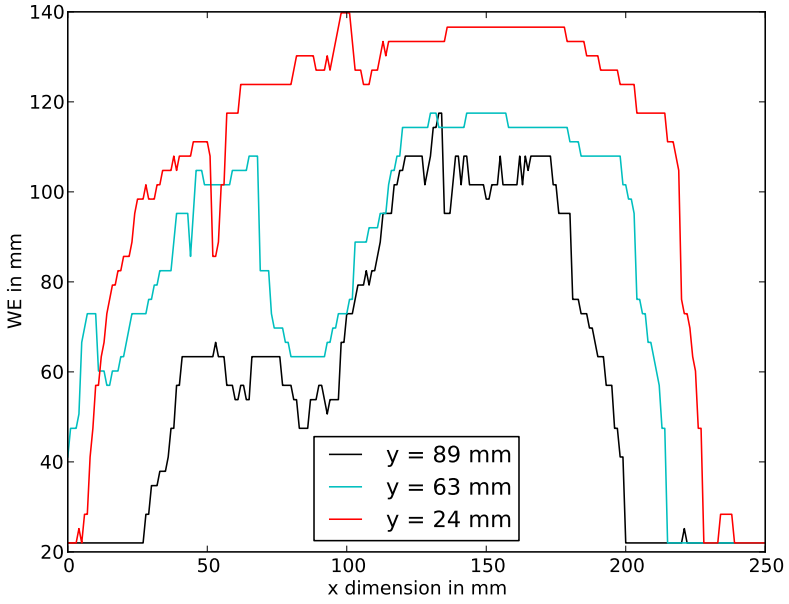


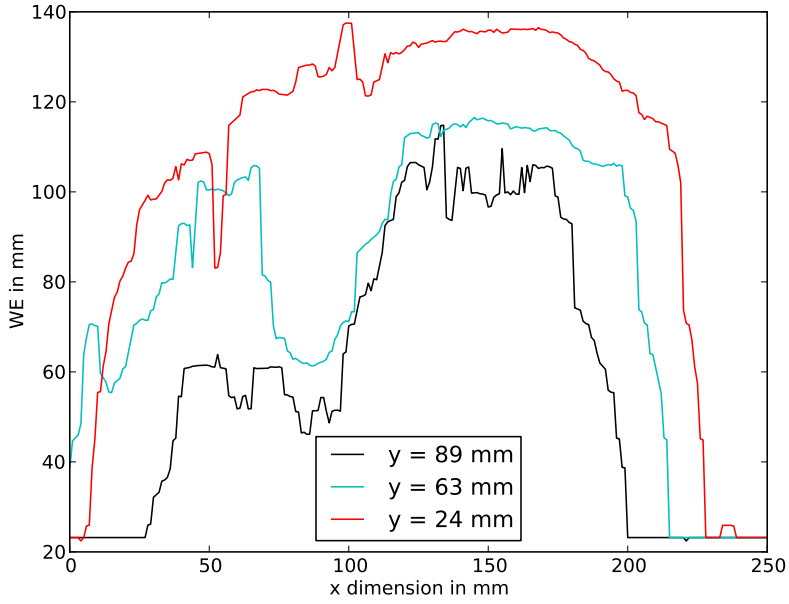

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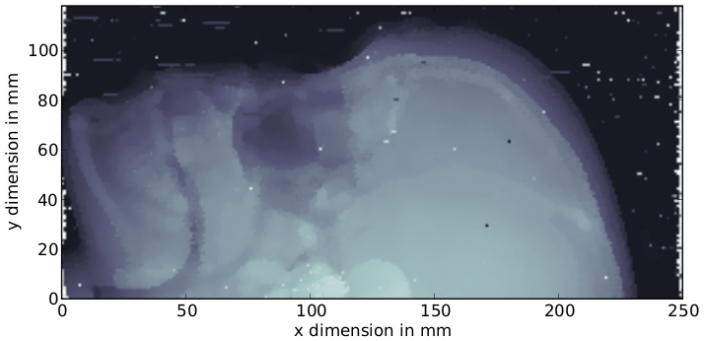
**Radiography acquired with $^{12}$C beam of 375.32 MeV/u**

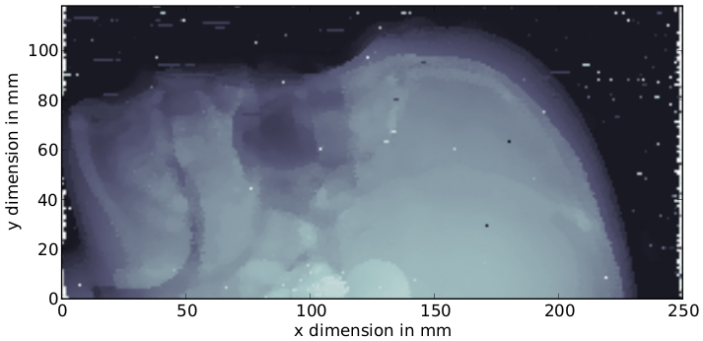



$\Rightarrow$ Different reconstruction stategies

Ilaria Rinaldi

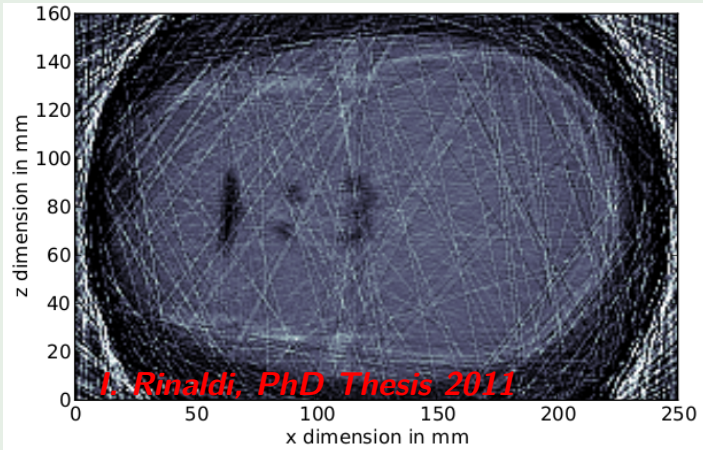


**Radiography acquired with $^{12}$C beam of 375.32 MeV/u**

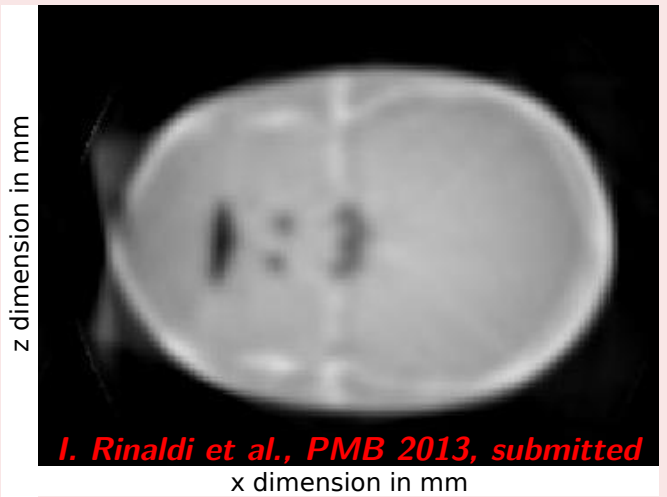



$\Rightarrow$ Different reconstruction stategies

## Filtered Back-Projection




## Algebraic Reconstruction Technique



# The project
## Nowadays

The DFG grants a collaboration project between:
University Hospital/HIT Heidelberg
GSI Darmstadt
LMU München

on

A novel imaging technique for ion beam therapy:
Ion Computed Tomography

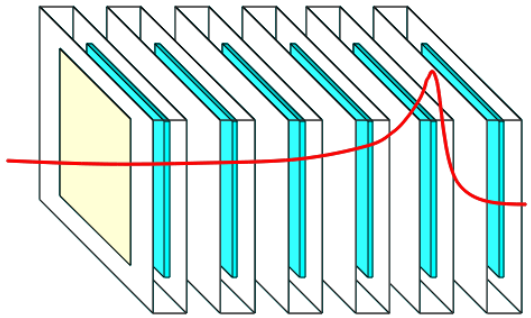
Started on February 2013

1 Post-doc

2 PhD students

**Not only carbon ions, but also protons!!!**

## New advanced detector set-up



IC stack

+

?

Beam tagging hodoscope + Thin silicon pixel detector + Dedicated fast electronics

=

**Powerful and versatile dedicated set-up for carbon ion and proton based 2D and 3D imaging**

# Conclusion & Outlook



This work shows promising proof of principle of ion based transmission imaging

Ongoing work:

- Technical improvements of the current experimental set-up (e.g, data acquisition system, electronics, . . . )
- Development of deconvolution and data processing techniques
- Further experimental studies
- Investigation of robust reconstruction algorithms
- . . .

# Acknowledgments

- Helmholtz Association of German Research Centers on the framework of the "Virtual Institute" project under the contract number VH-VI 303 and German Research Foundation to support this work
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- M. Testa of MGH Boston

# Thank you for your attention!!!