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# TOF-PET scanner configurations for quality assurance in proton therapy: a patient case study

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ICTR-PHE 2014 Geneva, 13 February 2014

# QA via in-vivo dose delivery verification

**Full exploitation of the dosimetric benefits of proton therapy needs in-vivo dose delivery verification !**

**Dose delivery verification:**

- **adds to quality assurance**
- **potentially allows**
  - **better treatment plans**
  - **treating new patient categories**

**How ? Imaging of secondary radiation:**

- **positron emission tomography (PET)**
- **imaging of prompt gamma rays**

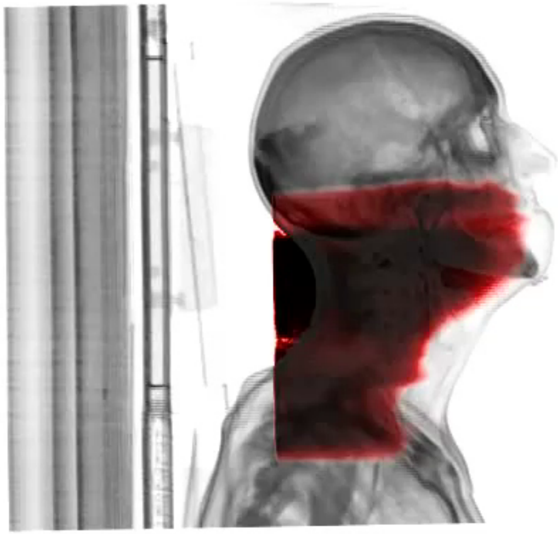
**Work presented today:**

- **Monte Carlo simulation of a real patient case**
- **compare different time-of-flight PET scanners**
  - **geometry**
  - **coincidence resolving time**

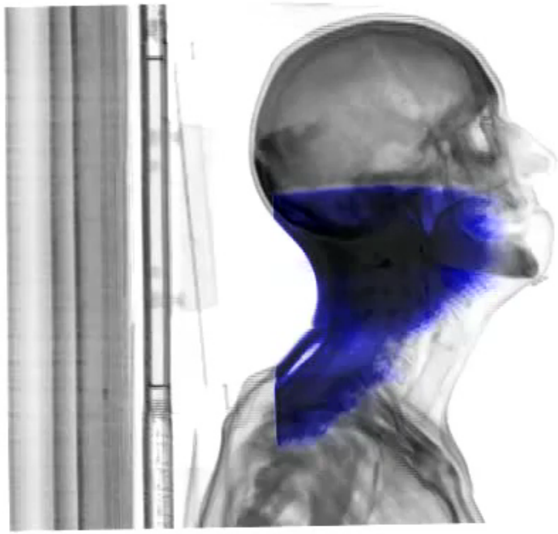
# Simulations

- **planning CT translation to**
  - **density**
  - **elemental composition**
- **Geant4 simulation of**
  - **dose**
  - **secondary radiation**
- **positron emitters produced on C, N, O, P, Ca:**
  - **$^{15}O$, $^{11}C$, $^{14}O$, $^{10}C$, $^{13}N$, $^{30}P$, $^{38}K$**
  - **experimental production cross sections**
  - **decay during irradiation**
  - **no biological washout**
- **PET scan simulation using GATE**

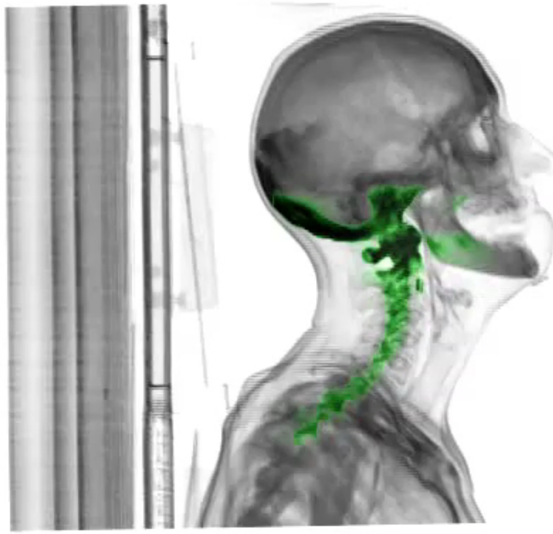
**treatment planning CT**
**simulated dose, 1 field**



**treatment planning CT**
**oxygen-15 production**

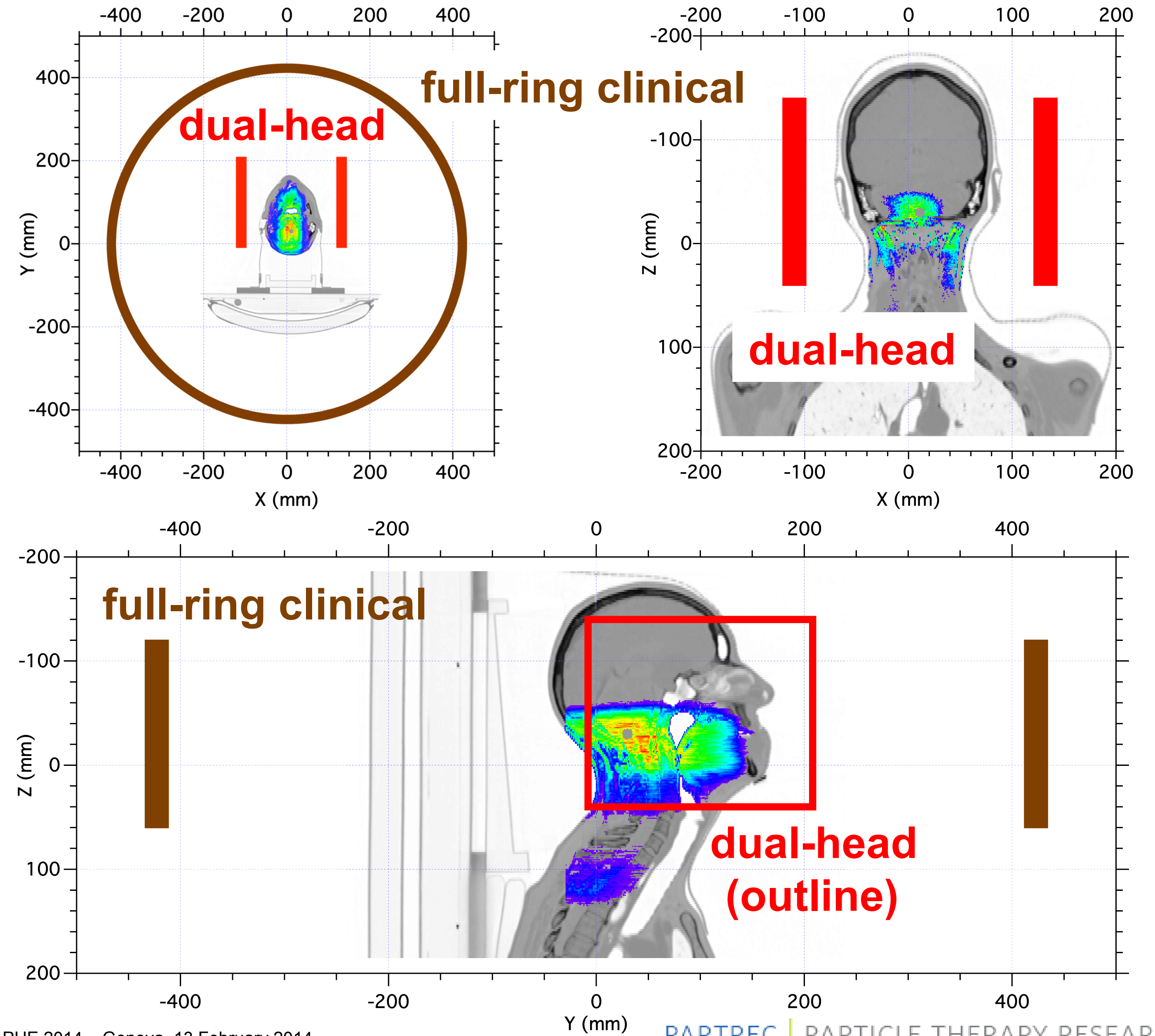


**treatment planning CT**
**potassium-38 production**



**spot scanning (Elekta XiO)**

# Clinical and dual-head scanner geometries



# PET scanner details and scan protocols

- ***in-situ*:**
  - **no delay after irradiation**
  - **clinical scanner, angular coverage 1, 2/3, 1/2**
  - **dual-head scanner (has an angular coverage of 1/2)**
- ***in-room*:**
  - **delay after irradiation: 30, 60 s**
  - **full-ring clinical scanner**

- **scan duration: 120 s**

- **LSO crystals: 4x4x22 mm$^3$**
- **energy window: 435-650 keV**
- **coincidence time window: 4.1 ns**
- **coincidence resolving time (CRT): 600, 300, 150 ps**

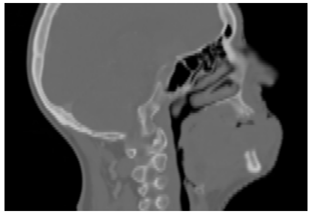
**600 ps: first generation, since about 2006**

**300 ps: present generation, arriving to the clinic**

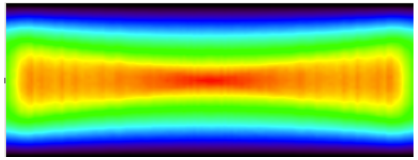
**150 ps: following generation (cfr. talk D.R. Schaart)**

# MLEM image reconstruction

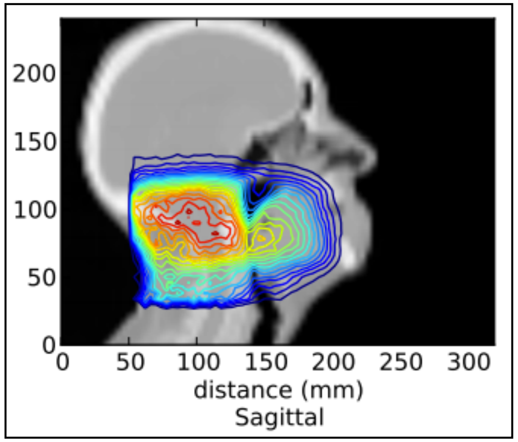

list mode data



attenuation map



sensitivity map




reconstructed image

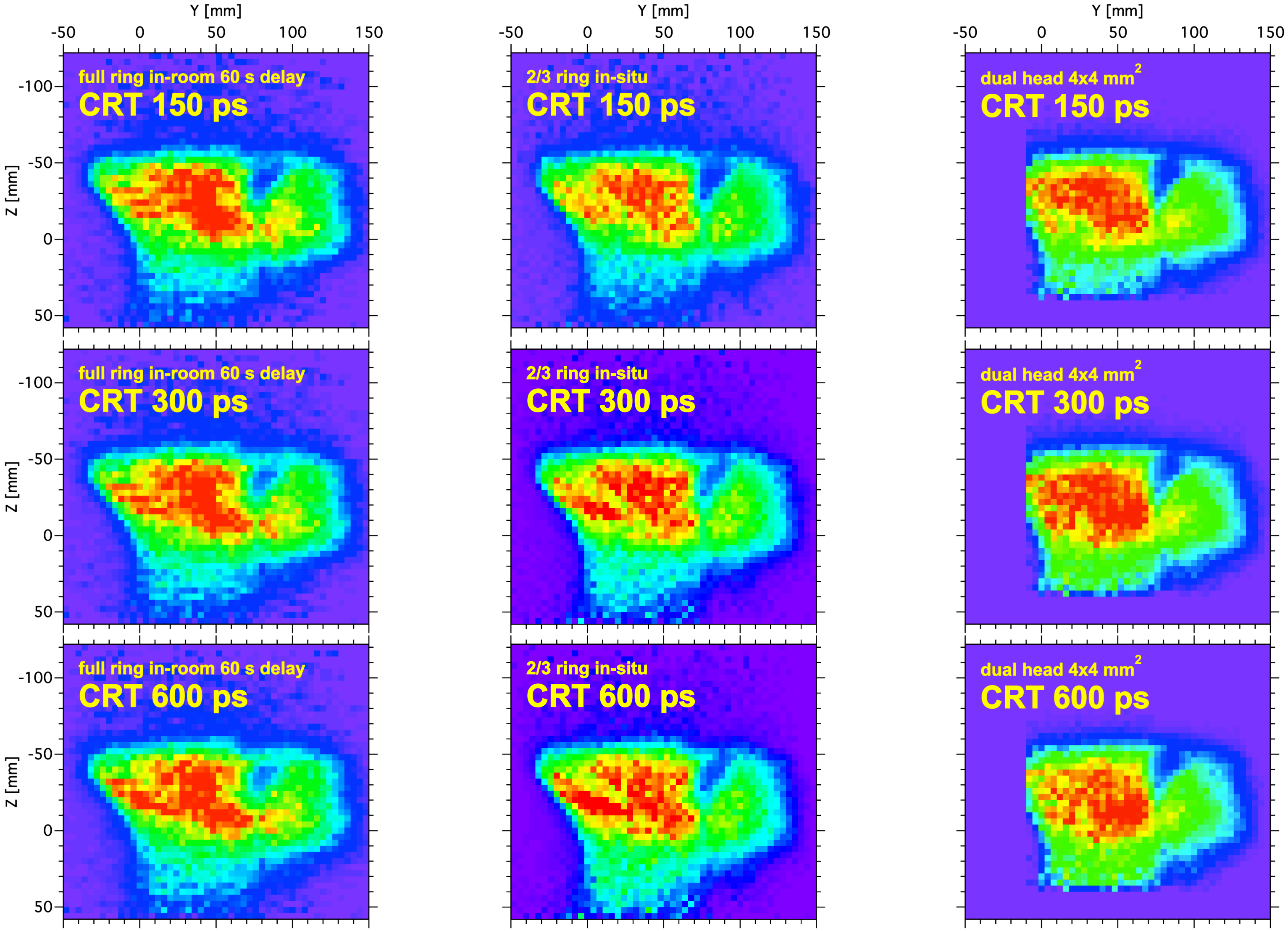
**Maximum Likelihood Expectation Maximization (MLEM)**

- **attenuation correction using CT**
- **TOF information**
- **ray tracing based on Siddon algorithm**
- **2 mm and 4 mm voxel size**

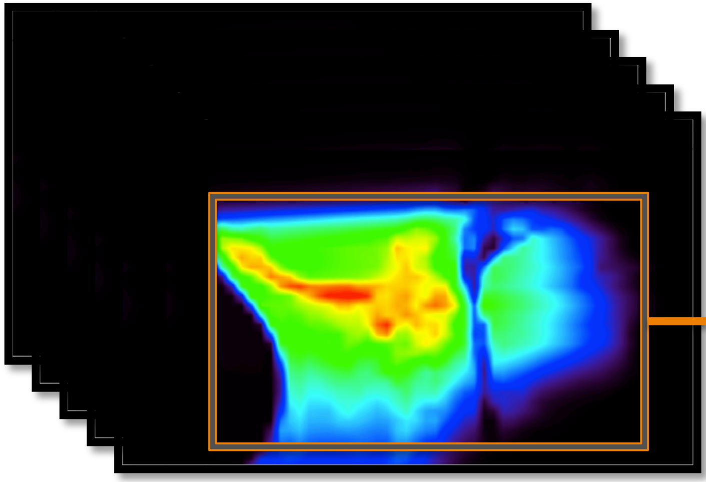
$$f_i^{k+1} = \frac{f_i^k}{\sum_{j'=1}^{M} a_{ij} H_{ij}} \sum_{j=1}^{M} a_{ij} H_{ij} \frac{p_j}{\sum_{i=1}^{N} a_{ij} H_{ij} f_i^k}$$

# Comparison of PET images

| full-ring *in-room* 60 s delay | 2/3 ring *in-situ* no delay | dual head *in-situ* no delay |
|---|---|---|

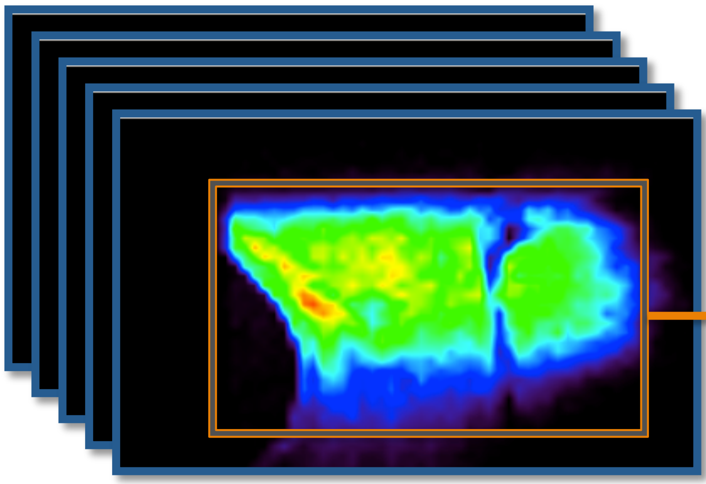


# Correlation images - source



ROI

reference distribution:
decays of positron emitters

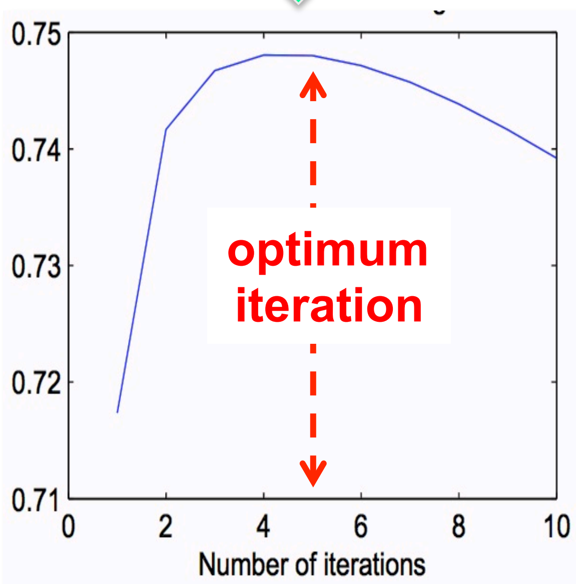


ROI

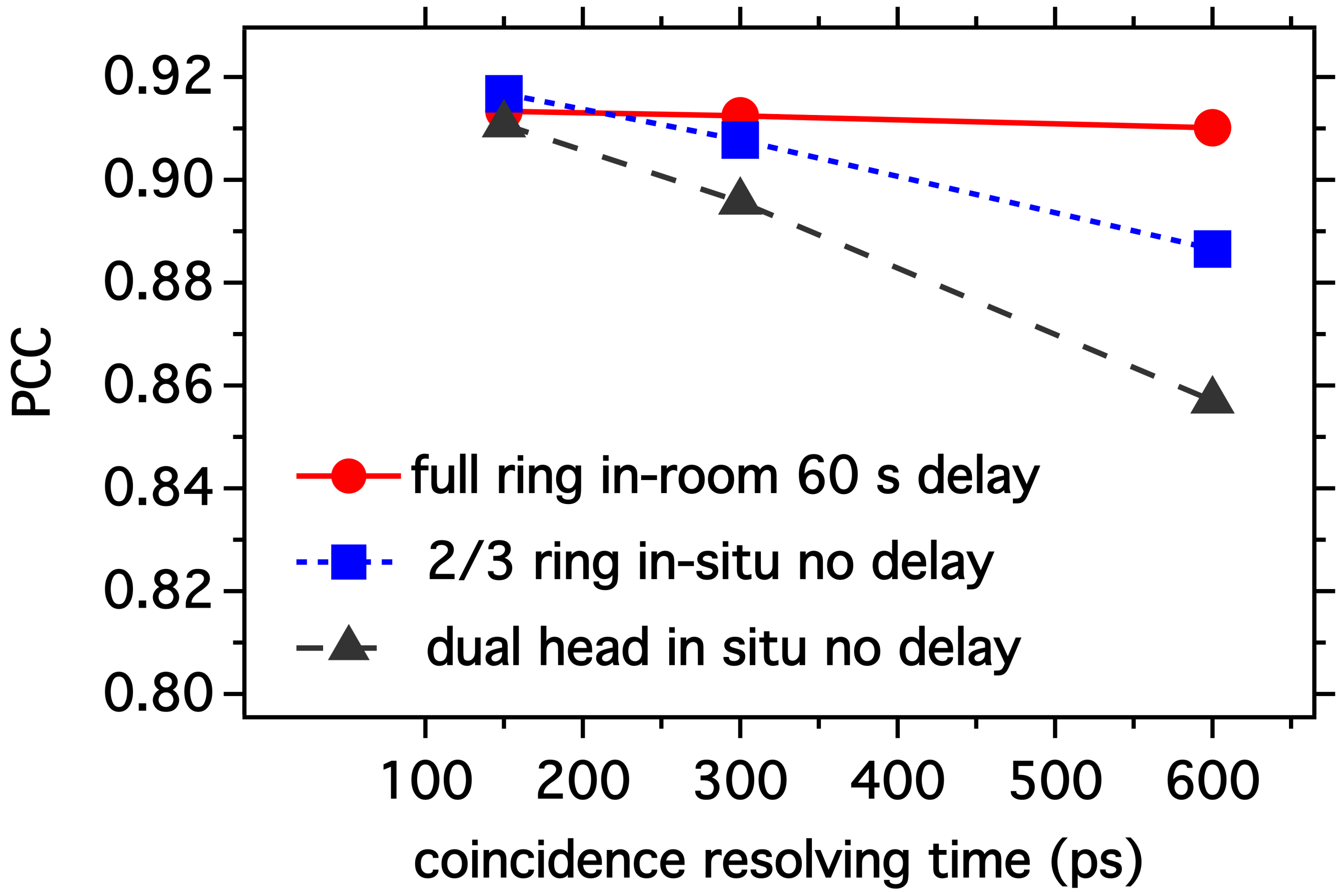
reconstruction

**Pearson correlation coefficient**

$$r = \frac{\sum_{i=1}^{n}\left((x_i-\bar{x})(y_i-\bar{y})\right)}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2\sum_{i=1}^{n}(y_i-\bar{y})^2}}$$



# Improvement with better CRT




**Pearson's correlation coefficient (PCC) between TOF-PET image and positron emitter decay distribution (for each geometry/protocol)**

# Number of coincidence events

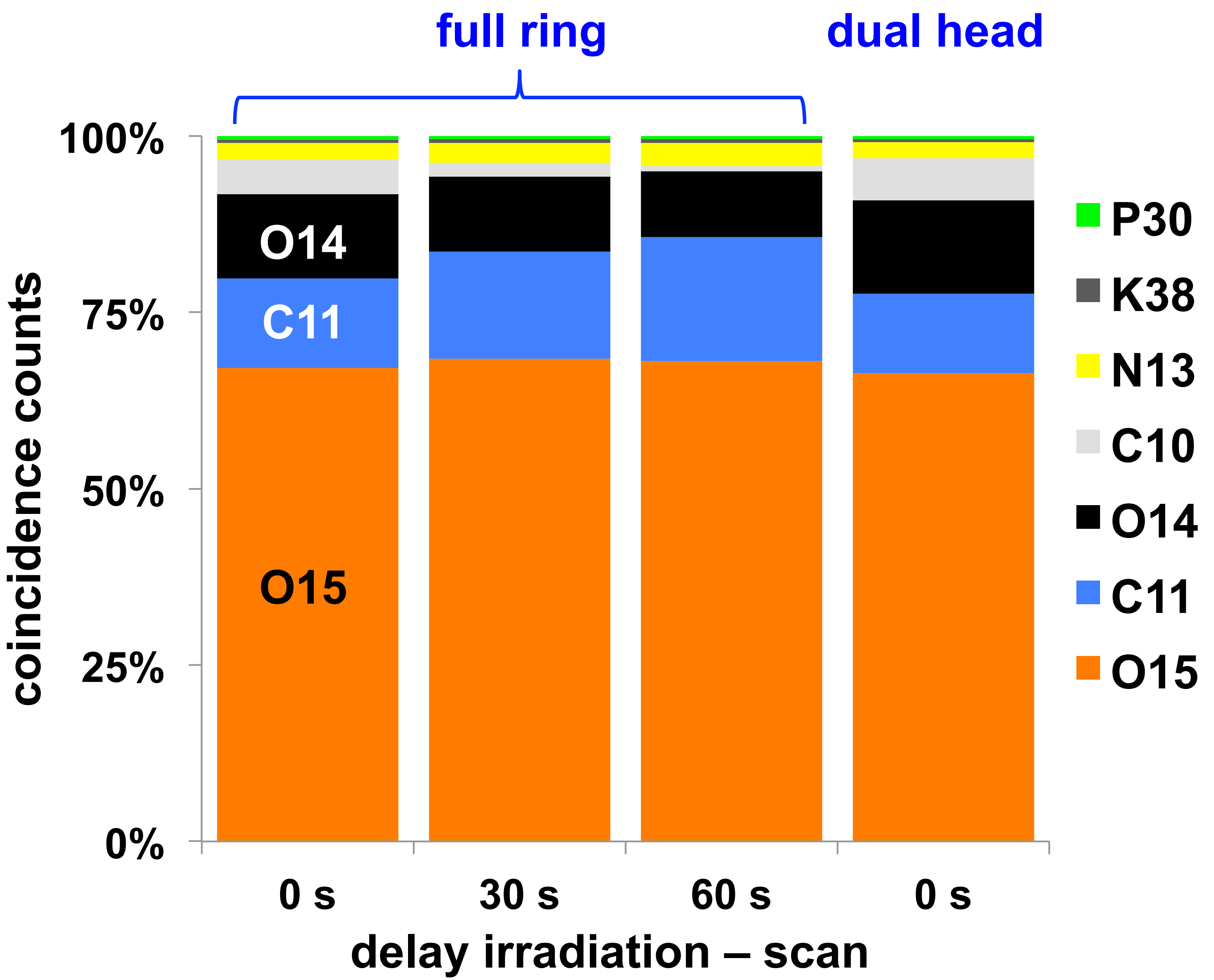
| geometry/ protocol | relative number of coincidences* |
|---|---|
| ***in-situ*** | |
| dual-head | 77 |
| full ring | 100 |
| 2/3 ring | 68 |
| 1/2 ring | 51 |
| ***in-room* full ring** | |
| 30 s delay | 83 |
| 60 s delay | 70 |

~3/4

~45 s

***relative to the *in-situ* full ring with $3.36 \times 10^6$ coincidences for an SOBP dose of 0.46 Gy**

# Relative counts of each PET isotope



# Conclusions

- **dual-head *in-situ* and *in-room* full-ring clinical TOF-PET scanner deliver comparable image quality:**
  - **they detect a comparable number of coincidences**
  - **state-of-the-art TOF detector performance [1] can eliminate the limited-angle image artifacts of the dual-head scanner**
- **advantages of the dual-head *in-situ* configuration:**
  - **minimizes the effect of biological washout**
  - **an economic solution: 1/6$^{th}$ detector area of a full-ring scanner**

[1] CRT < 200 ps, van Dam H et al. 2013 Phys Med Biol **58** 3243

**Acknowledgements**

Funded in part by the foundation for Fundamental Research on Matter (FOM), grant 09NIG18. We thank the staff of the Millipede cluster of the University of Groningen (www.rug.nl/cit/hpcv/faciliteiten/HPCCluster) where the simulations were performed.

# Outlook

- **under final analysis:**
  - **effect of smaller detector crystals**
  - **effect of depth-of-interaction capability**
  - **correlation of the detectability of unacceptable dose delivery errors (e.g. due to anatomical changes) with scanner properties**
  - **comparison production distributions PET and prompt gamma**
- **outlook:**
  - **implementation of biological washout**
  - **studying different categories of patient cases**
  - **experimental verification with state-of-the-art TOF-PET hardware**