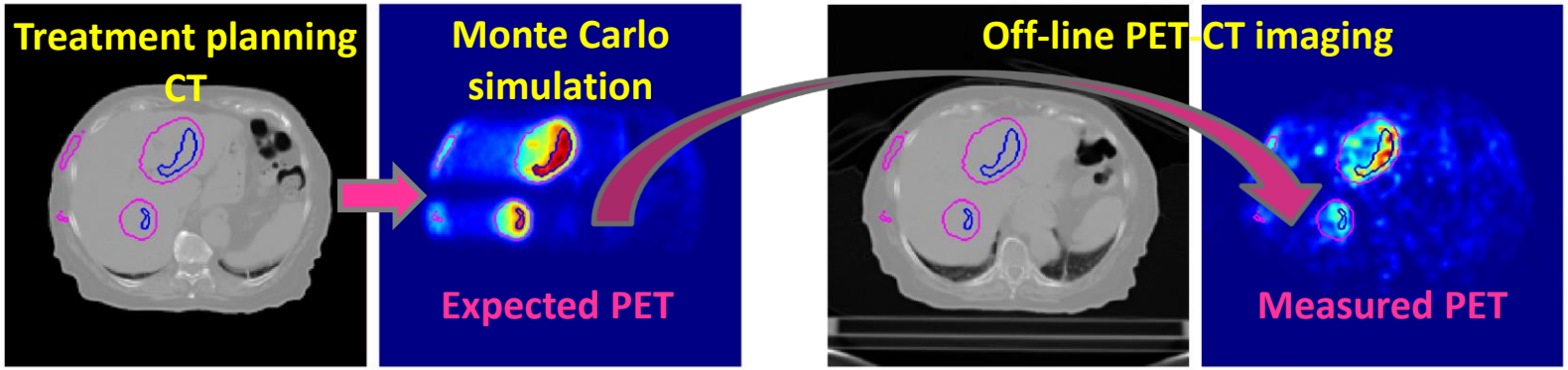
Geometrical Interpretation of TOF PET raw data in commercial PET-CT scanner for SNR optimization

Chiara Gianoli[1], Elisabetta De Bernardi[2], Christopher Kurz[1], Marco Riboldi[3], Guido Baroni[3], Katia Parodi[4]

[1]Department of Experimental Physics - Medical Physics and Department of Radiation Oncology, Ludwig Maximilian University of Munich, Germany; Department of Radiation Oncology, Heidelberg University Hospital, Germany
[2]Tecnomed Foundation, University of Milano-Bicocca, Milan, Italy
[3]Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB), Politecnico di Milano, Italy
[4]Department of Experimental Physics - Medical Physics, Ludwig Maximilian University of Munich, Germany; Department of Radiation Oncology, Heidelberg University Hospital, Germany

PET-based treatment verification in ion beam therapy

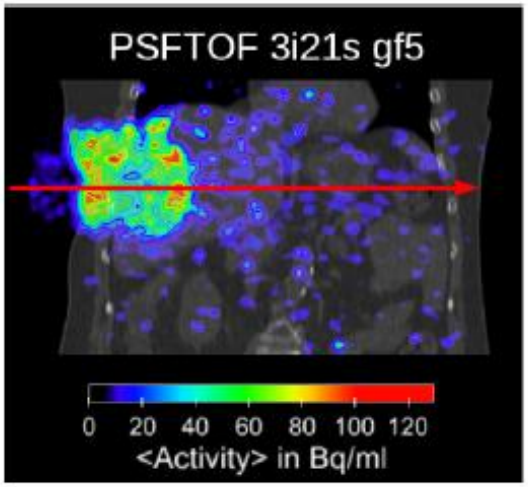
- Detect possible mismatches with respect to the treatment planning (i.e., patient positioning, intra- and inter-fractional anatomical changes)
- Imaging of secondary radiation of the ion beam treatment
- PET-CT comparison in terms of activity-anatomy

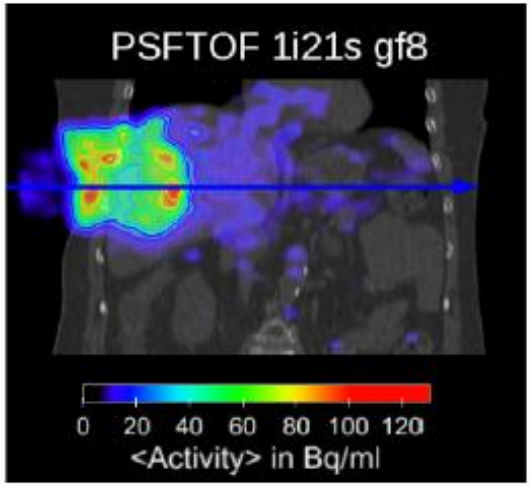


- Researchers are moving the scanner into the treatment room (in-beam PET or in-room PET) but commercial PET scanners are used in clinical applications (off-line PET) (Bauer et al. 2013 Radiother Oncol)

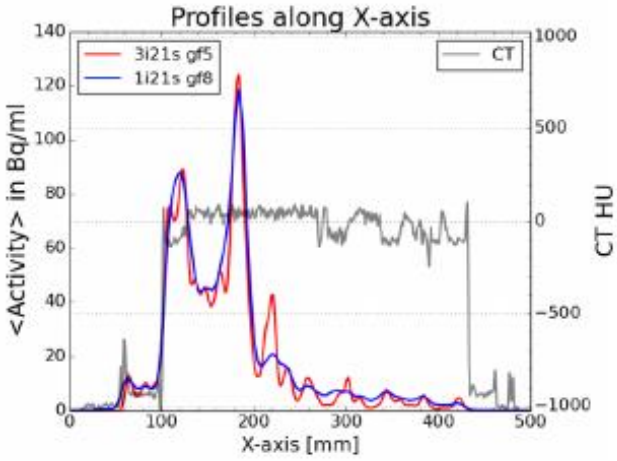
Commercial PET scanners for PET-based treatment verification in ion beam therapy

- Commercial reconstruction requires optimization for extremely low count statistics scenario of PET-based treatment verification
- TOF reconstruction of PET-CT *Siemens mCT* scanner installed at the *Heidelberg Ion beam Therapy* (HIT) center needs to be stopped before convergence and filtered





Measured PET

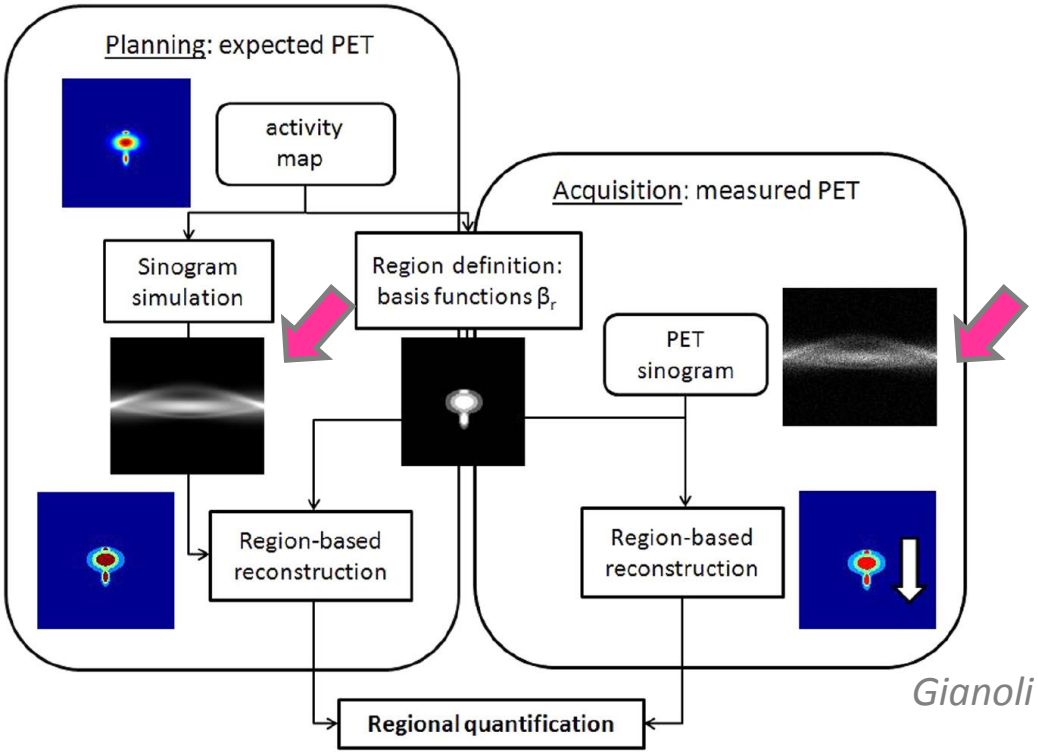


Kurz et al. 2015 Med Phys

Chiara Gianoli

Commercial PET scanners for PET-based treatment verification in ion beam therapy

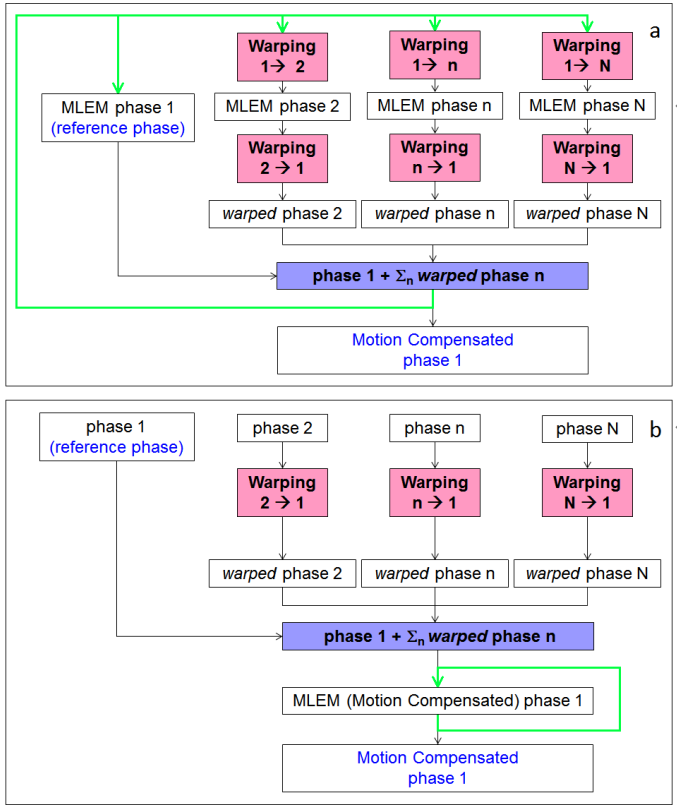
- Dedicated reconstruction methods requires accessibility to PET raw data
  - e.g. Noise robust 3D regional reconstruction of the Measured PET according to the "regional features" of the Expected PET



Gianoli et al. 2014 Phys Med Biol

Commercial PET scanners for PET-based treatment verification in ion beam therapy

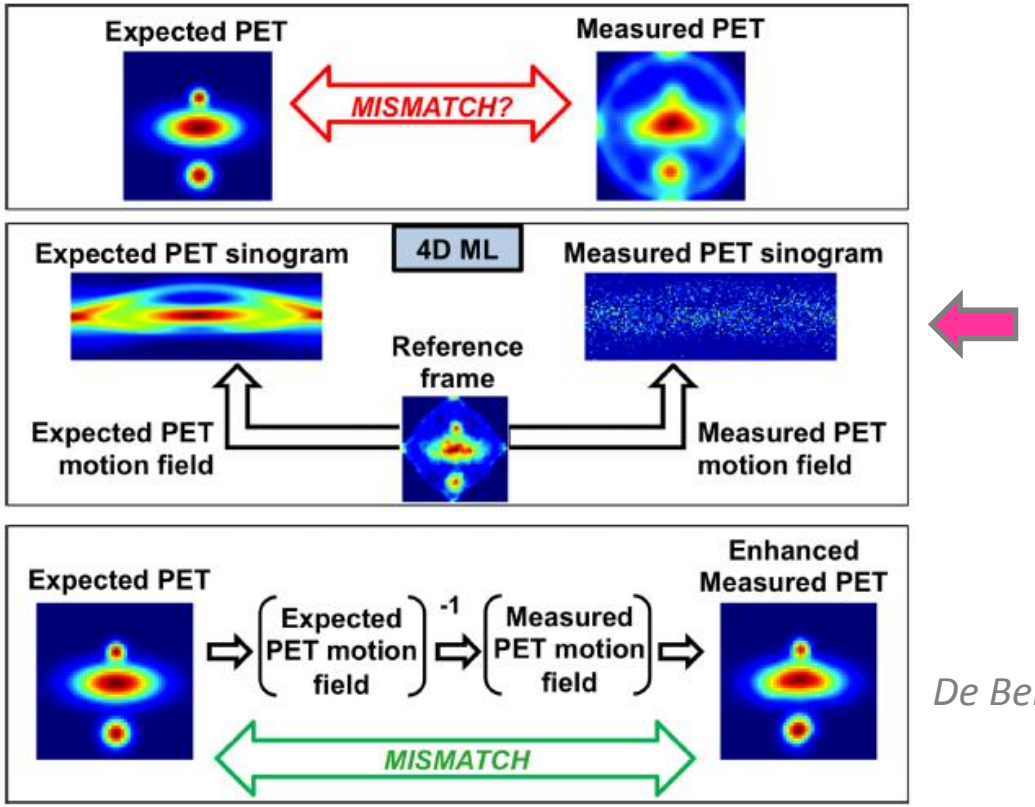
- Dedicated reconstruction methods requires accessibility to PET raw data
  - e.g. Motion compensated 4D reconstruction: 4D-MLEM and pre-reconstruction sinogram warping strategy



Stützer et al. 2013 Phys Med Biol; Gianoli et al. 2015 Med Biol Eng Comput; Gianoli et al. under revision in Phys Med Biol

Commercial PET scanners for PET-based treatment verification in ion beam therapy

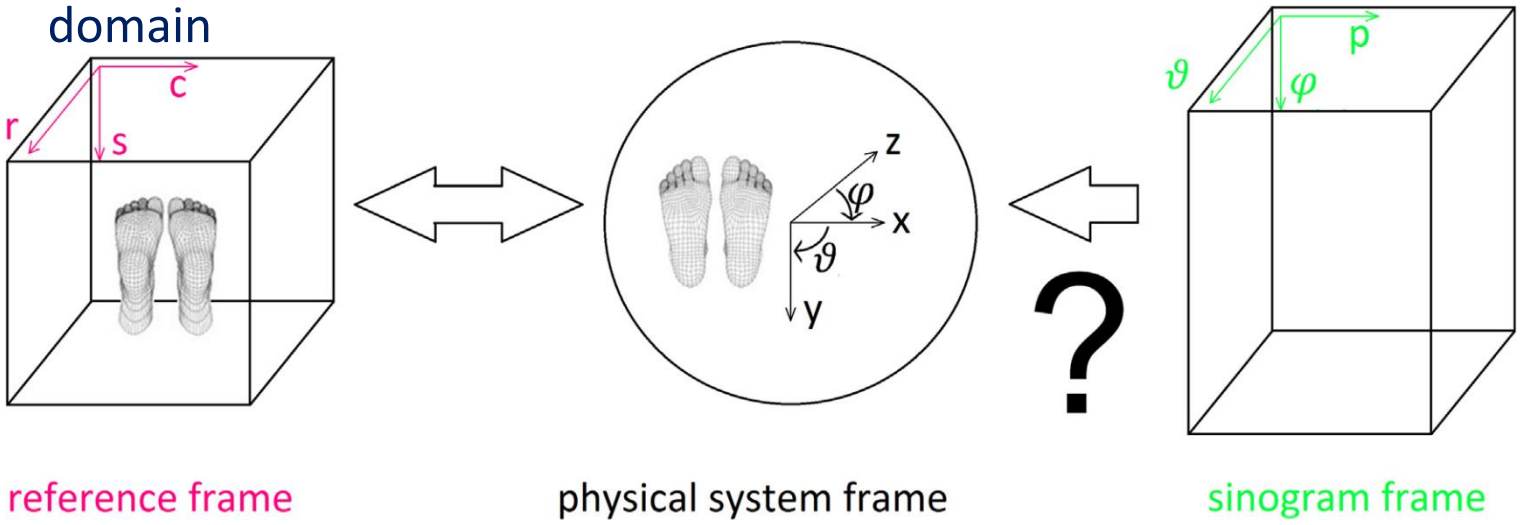
- Dedicated reconstruction methods requires accessibility to PET raw data
  - e.g. Joint reconstruction of image and motion which estimates the Measured PET as deformation of the Expected PET



De Bernardi et al. 2016 Med Phys

Geometrical interpretation of PET raw data

- Development of reverse engineering procedures to define the geometrical correspondence between image domain and sinogram domain

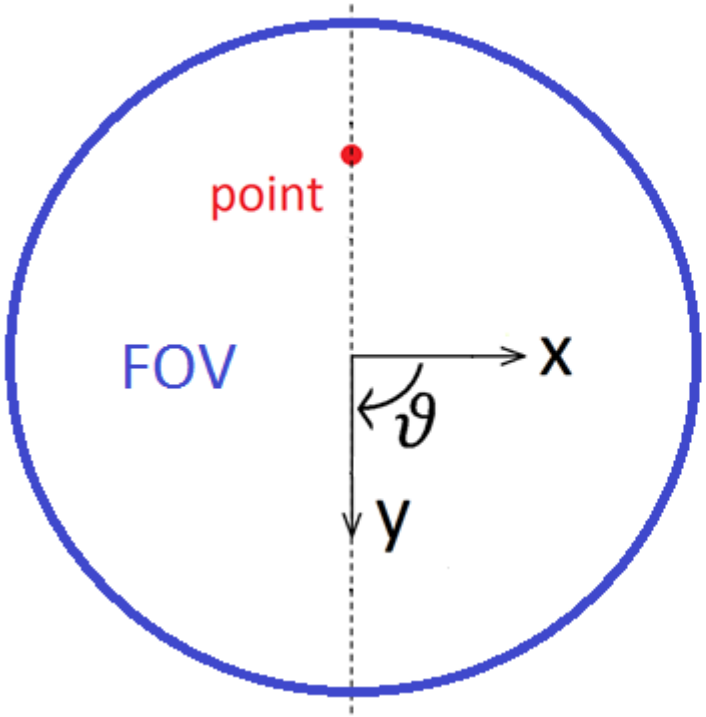


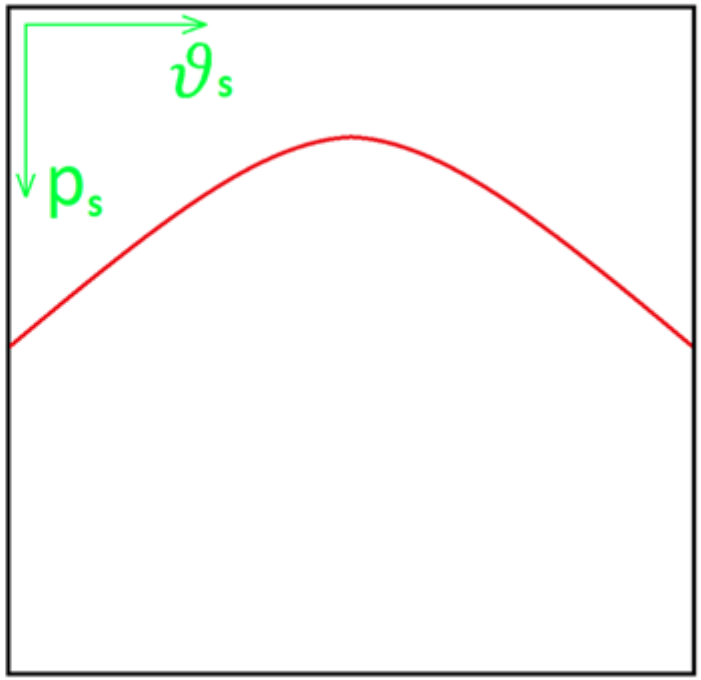
Gianoli et al. 2014 Comput Med Imag Grap

- PET-CT acquisitions of point sources and cylindrical phantoms (QA "materials") placed in different positions *(x,y)* of the Field of View (FOV) of the PET-CT scanner (*Siemens mCT* scanner installed at HIT)
- Implementation of PET acquisition simulators (without TOF)

TOF geometrical interpretation of PET raw data

- PET raw data are organized in *b* TOF bins, where *b=1:13*
- Each TOF bin is a sinogram parameterized in *(p,ϑ,φ)*, collecting PET counts a function of *projection line p*, *azimuthal projection angle ϑ* and *polar angle φ* for each slice

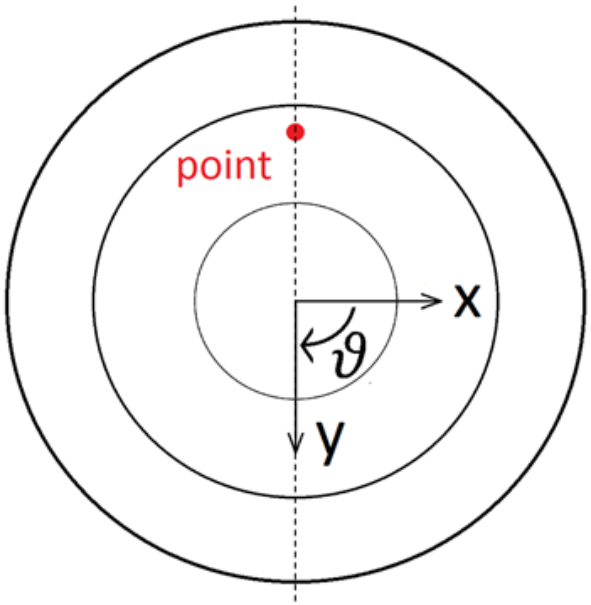




TOF geometrical interpretation of PET raw data

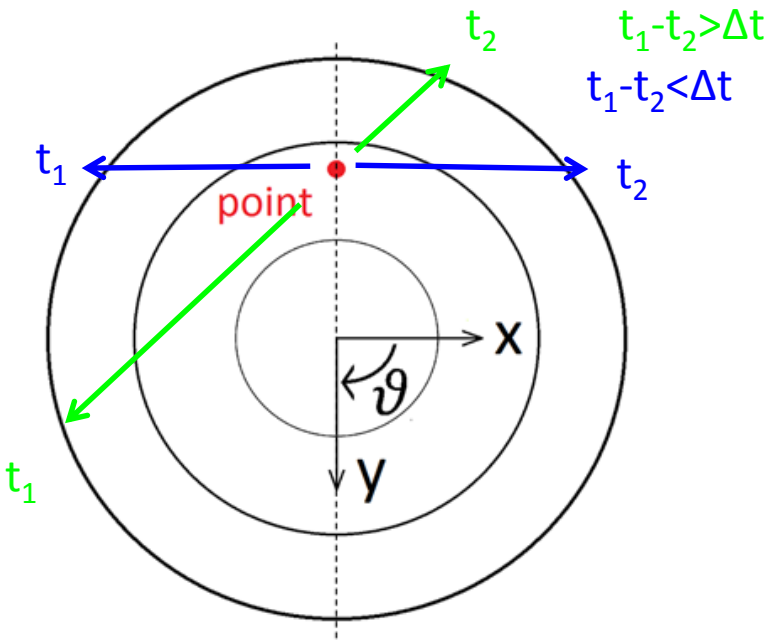
Question: what TOF bins do correspond to?

Hypothesis: axial Field of View (FOV) partitioned as “shooting target”, central full ring-shaped region surrounded by half ring shaped regions

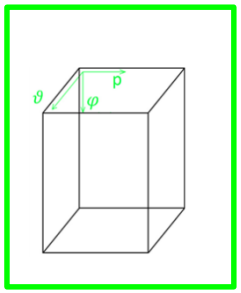


the image partitioning is exclusively encoded in the *projection angle ϑ*

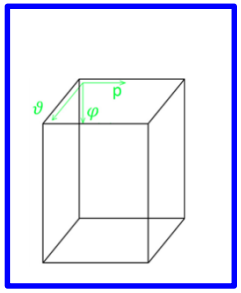
TOF geometrical interpretation of PET raw data



TOF bin, b=2

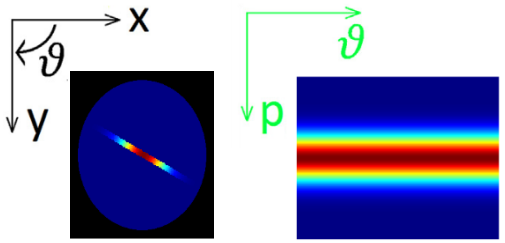


TOF bin, b=1

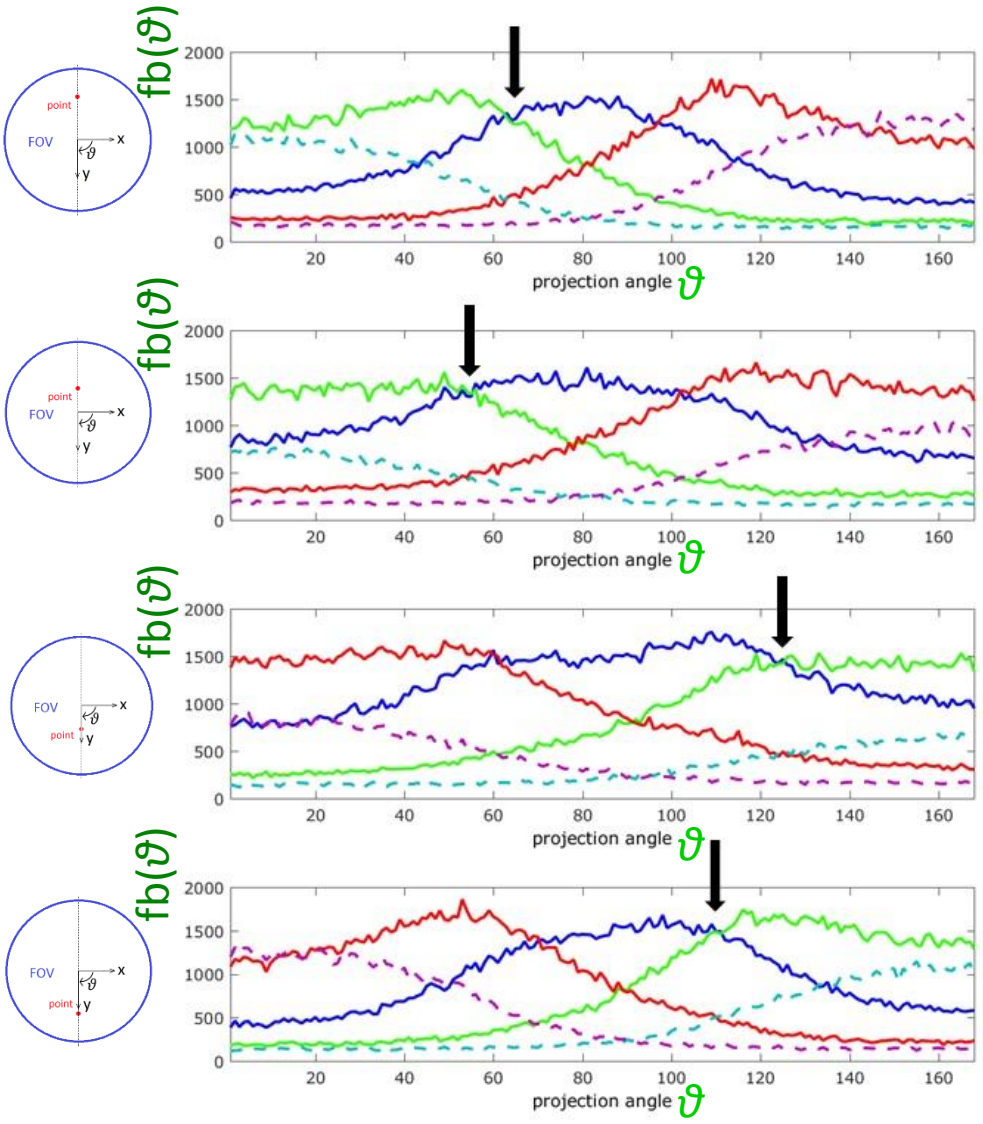


- Δt is defined by timing performance of the scintillator (fast scintillator, low Δt)
- Image reconstruction is confined within Δd ($\Delta d = c\Delta t$), thus:

$$SNR_{TOF} \sim \sqrt{D/\Delta d}\, SNR_{no\ TOF}$$



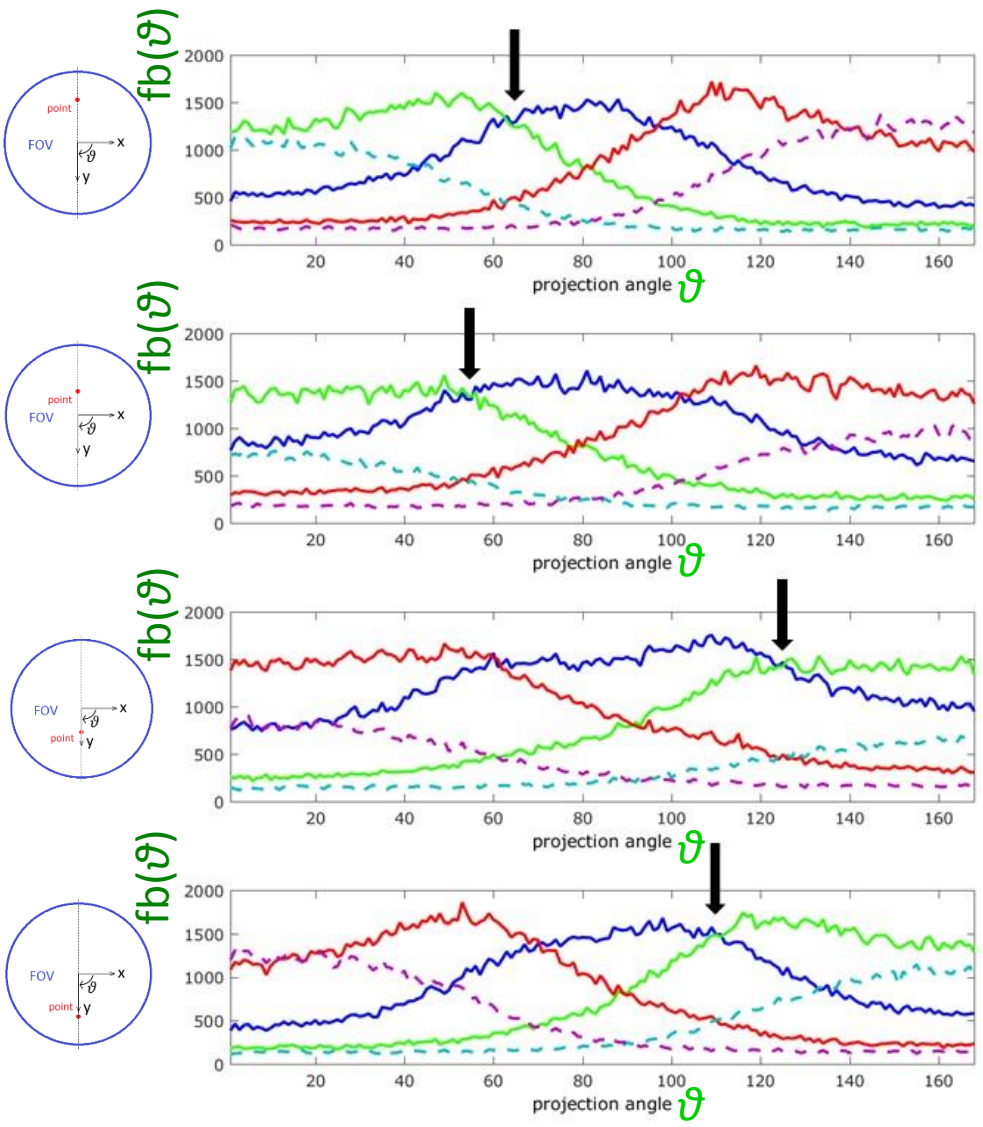
TOF geometrical interpretation of PET raw data



- The fraction of PET counts in each TOF bin b is expressed as a function of ϑ (fb(ϑ))
- Each TOF bin is represented by a color
- The projection angle corresponding to the intersection between fb(ϑ) of adjacent TOF bins defines the ϑ encoding the region interface.

Chiara Gianoli

TOF geometrical interpretation of PET raw data



- The radial position relevant to the interface is calculated according to the source-to-detector distance (d(ϑ))

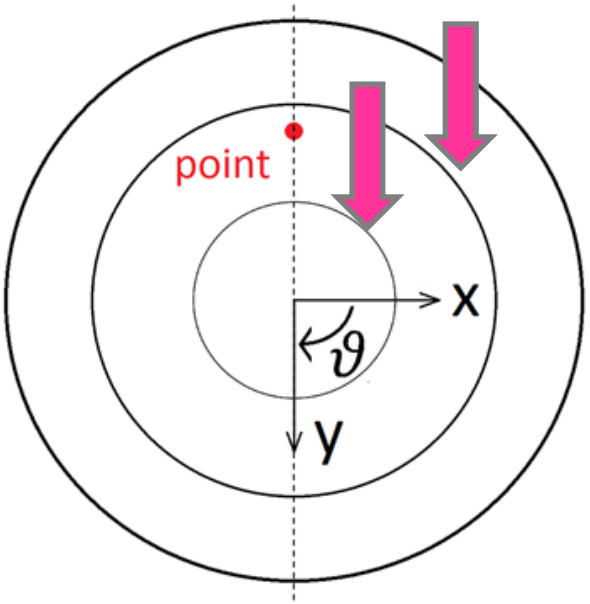
$$d(\vartheta) = x \times \cos\left(\vartheta + \frac{\pi}{2}\right) + y \times \sin\left(\vartheta + \frac{\pi}{2}\right)$$

Chiara Gianoli

ENVISION

TOF geometrical interpretation of PET raw data

- The mean value of radial partitioning resulted in d(ϑ)≈26 pixels (≈52 mm) for the first TOF bin, which coincides with the ray of the central full ring-shaped region
- The mean value of radial partitioning resulted in d(ϑ)≈46 pixels (≈92 mm) for the second and the third TOF bins



- For external TOF bins, the results are affected by a large standard deviation (noise due to the reduced number of PET counts)
- The approximation depends on the adopted fitting to determine the fb(ϑ) intersections

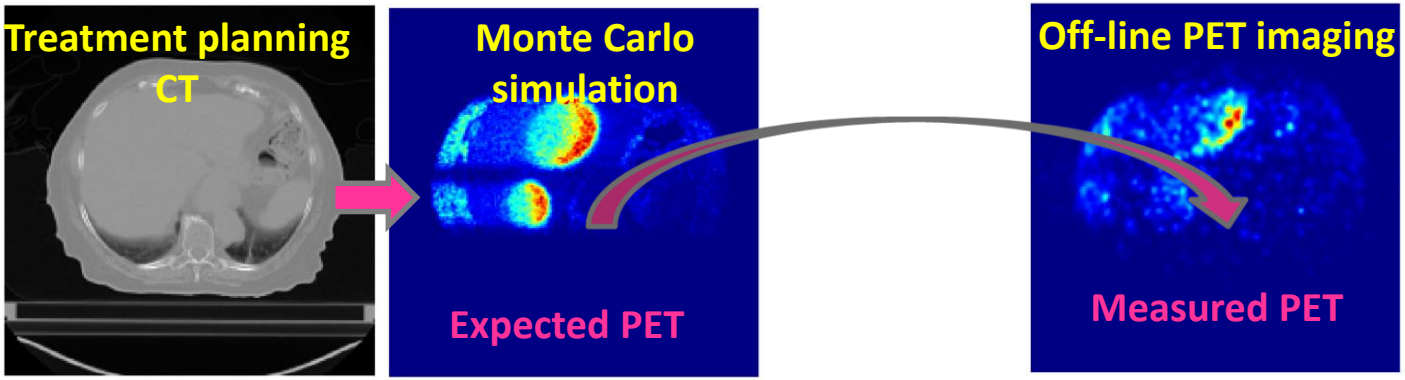
Conclusions

- In PET-based treatment verification, PET activity is distributed in proximity of the tumor target, which is typically centered in the FOV
- In future investigations, external TOF bins (b>5) will be intentionally neglected, since they contain scatter (which has a TOF dependency (Moses 2003 IEEE Trans Nucl Sci)) and random contributions (intrinsic LSO radioactivity)
  - Targeted reconstruction to account for the intrinsic LSO radioactivity in external TOF bins (GE patent 2010)
  - TOF reconstruction only for the central TOF bins

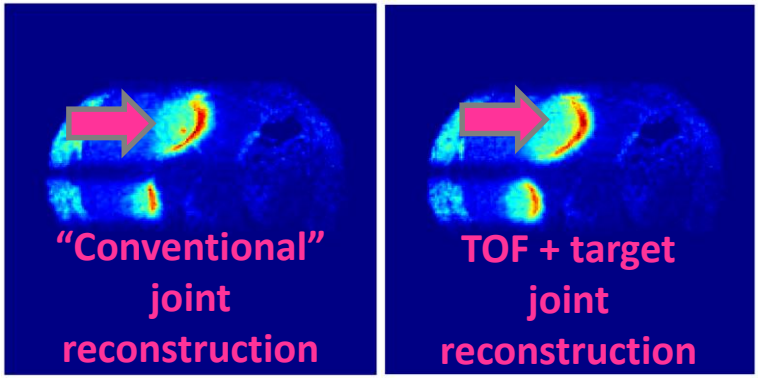
increase of the SNR of TOF 3D reconstruction with computational optimization

Outcomes of the work

- Joint reconstruction of image and motion which estimates the Measured PET as deformation of the Expected PET



Katia Parodi: ICTR-PHE 2016, Oral poster presentation, miscellaneous (Friday)



Outlook

- New commercial PET technologies embed TOF hardware and TOF software
- The geometrical interpretation of TOF PET raw data extracted from a commercial PET-CT scanner allowed understanding the image partitioning due to TOF, thus complementing the geometrical characterization of PET raw data in terms of image and sinogram correspondence
- The characterization enables to implement vendor-independent TOF 3D reconstruction algorithms for SNR enhancement in extremely low count statistics imaging scenarios, like those encountered in off-line PET-based treatment verification in ion beam therapy