Corrections for Quantitative Image Reconstruction with *pheno*PET, a Plant Dedicated PET Scanner

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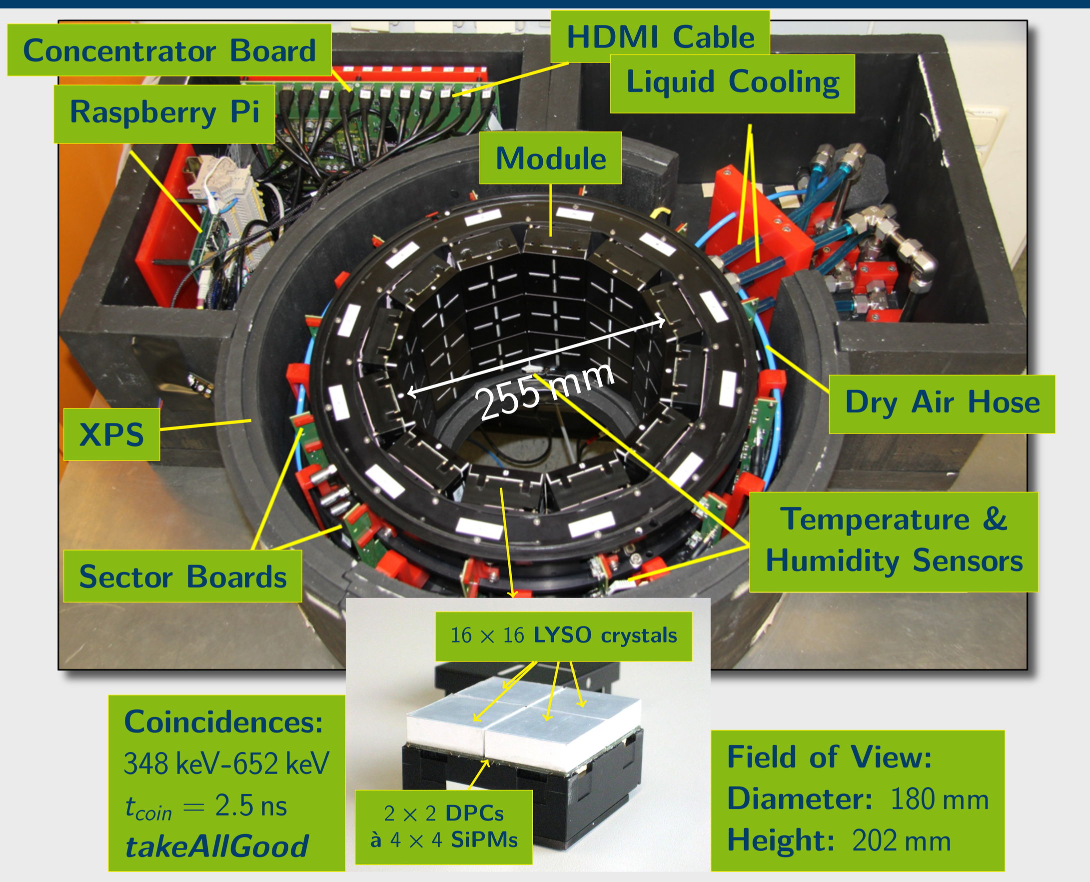
Scientific Motivation

The application of [^{11}C]CO_2 to plant leaves allows the labeling of photo-assimilates. Positron Emission Tomography (PET) enables the non-invasive and quantitative imaging of the *in vivo* transport and allocation of these photo-assimilates in the root systems and below ground storage organs in 3D [1]. The short half life of ^{11}C permits repetitive administration and measurement with PET to study the response to a treatment (e.g. administration of fertilizer [2], temperature changes, drought).

We operate the PET scanner *pheno*PET, which is dedicated for plant sciences. *pheno*PET was developed within German Plant Phenotyping Network (DPPN) and operates Digital Photon Counter (DPC) by Philips (digital Silicon photomultiplier) reading out LYSO crystals. We apply a Line-of-Response (LOR) based image reconstruction with PRESTO [3]. Here, we present the implemented corrections required for quantitative image reconstruction: **static sensitivities**, **dynamic sensitivities**, **attenuation correction** and **scatter correction**.

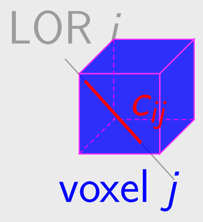
Setup



Energy (FWHM)	Timing (FWHM)	Spatial
16.6 %@511 keV	0.73 ns-0.80 ns	up to 1.6 mm

Background: Emission Reconstruction

Ordinary Poisson Maximum Likelihood Expectation-Maximization (OP-MLEM)



$$\lambda_j^{(n+1)} = \frac{\lambda_j^{(n)}}{\sum_i^{N_i} c_{ij} s_i a_i} \sum_i^{N_j} c_{ij} s_i a_i \frac{p_i}{\hat{p}_i^{(n)}}$$

$$\hat{p}_i^{(n)} = s_i a_i \cdot \left[\sum_j^{N_i} c_{ij} \lambda_j^{(n)} \right] + VRR_i + SE_i$$

$$s_i = s_i^{dyn} s_i^{static}$$

- $\lambda_j^{(n)}$ activity in voxel j
- p_i *prompts* for LOR i
- c_{ij} matrix element between voxel j and LOR i
- VRR_i Variance Reduced Randoms for LOR i
- s_i^{static} component based normalization for LOR i
- s_i^{dyn} count rate corrections
- a_i attenuation correction for LOR i
- SE_i scatter estimates for LOR i

Background: Transmission Reconstruction

Maximum Likelihood for Transmission Reconstruction (MLTR) [4]

$$\mu_j^{(m+1)} = \mu_j^{(m)} + \alpha_{relax} \frac{\sum_i c_{ij} B_i a_i^{(m)} \left(1 - p_i / \hat{p}_i^{(m)}\right)}{\sum_i c_{ij} \left(B_i a_i^{(m)}\right)^2 / \hat{p}_i^{(m)}}$$

$$\hat{p}_i^{(m)} = a_i^{(m)} B_i + VRR_i + SE_i$$

$$a_i^{(m)} = \exp\left(- \sum_j c_{ij} \mu_j^{(m)} \right)$$

- $\mu_j^{(m)}$ attenuation coefficient of voxel j and iteration m
- B_i expected *trues* without object

Our Default Measurement Durations

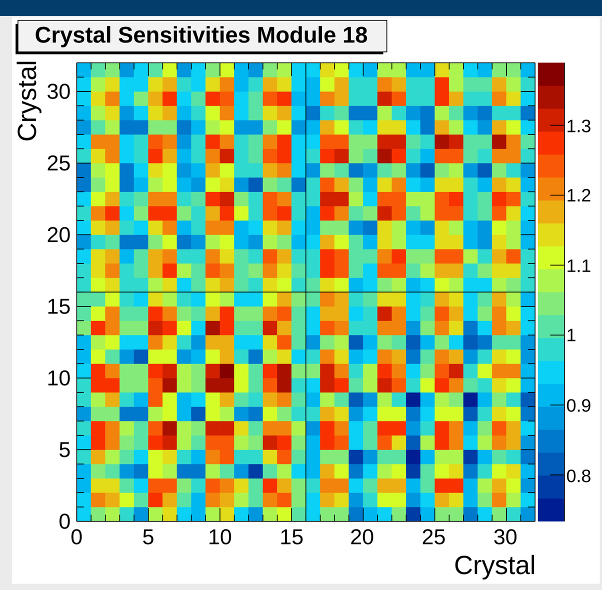
- Emission Scan ^{11}C: 30 frames à 5 min=2.5 h
- Transmission Scan: 15 min ^{68}Ge rod source @ 25 MBq
- Blank Scan: 2 h ^{68}Ge rod source @ 25 MBq

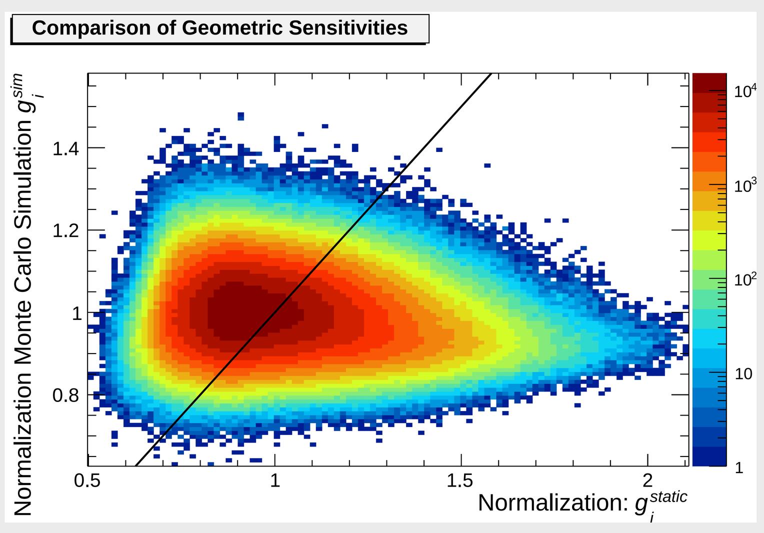
Static Sensitivities: s_i^{static} & s_i^{sim}

Maximum-likelihood fit for component-based normalizations [5]:

$$\hat{t} = s_i \cdot t_i^{ideal} = \epsilon_a \epsilon_b g_i \cdot t_i^{ideal}$$

- s_i s_i^{static} or s_i^{sim}
- g_i geometric sensitivity (sets of 48 LORs)
- ϵ_a sensitivity of crystal a
- t_i^{ideal} ideal expected values from forward projection/simulation





Scatter Estimates SE_i

Monte Carlo (MC) Simulation [6]

$$SE_i = \frac{\sum_j \left(p_j^{meas} - VRR_j^{meas}\right)}{\sum_j \left(s_j^{\epsilon} g_j^{sim} t_j^{sim} + s_j^{\epsilon} sca_j^{sim}\right)} \cdot s_i^{\epsilon} sca_i^{sim}$$

$$s_i^{\epsilon} = \epsilon_a^{sim} \epsilon_b^{sim}$$

- t_i^{sim} *trues* from MC simulation for LOR i
- sca_i^{sim} *scattered* from MC simulation for LOR i

- Emission: 12 × 10^8 primaries for with one iteration
- MLTR: 12 × 10^9 or 30 × 10^9 primaries with three iterations

Dynamic Sensitivities s_i^{dyn}

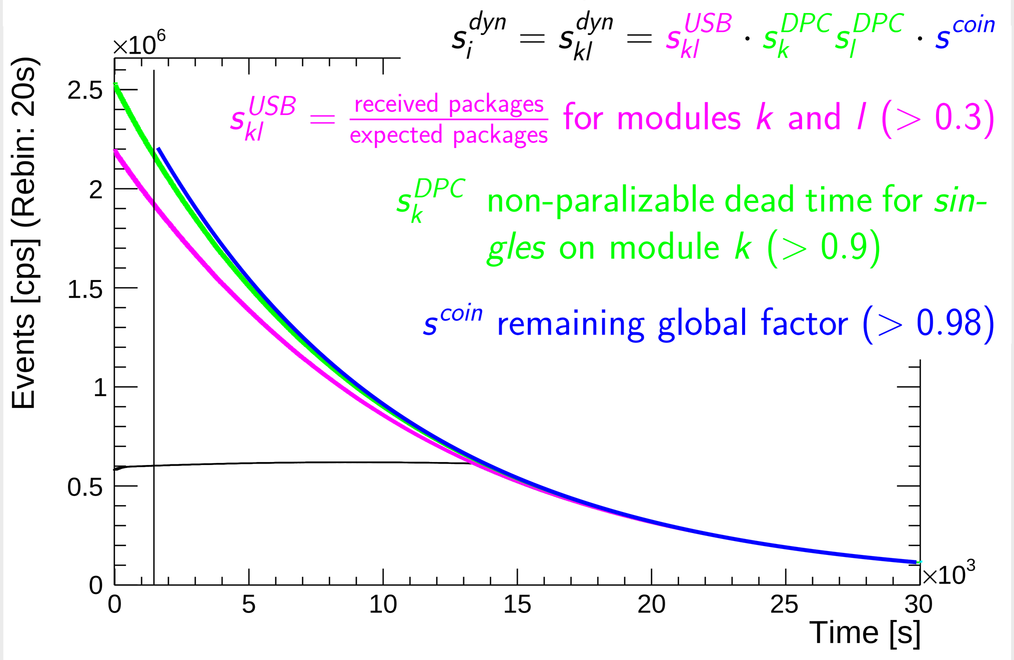
$$eT(t) = \sum_i \frac{p_i - VRR_i}{s_i^{dyn}}$$

$$s_i^{dyn} = s_{kl}^{dyn} = s_{kl}^{USB} \cdot s_k^{DPC} s_l^{DPC} \cdot s^{coin}$$

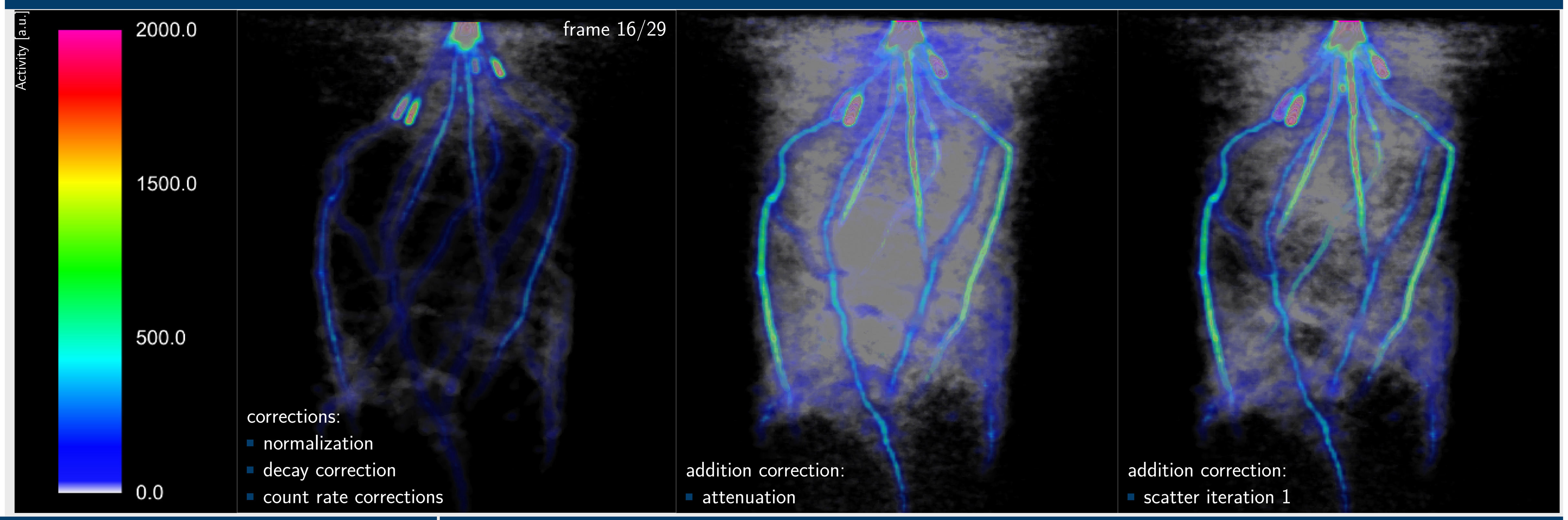
$s_{kl}^{USB} = \frac{\text{received packages}}{\text{expected packages}}$ for modules k and l ($>$ 0.3)

s_k^{DPC} non-paralizable dead time for *singles* on module k ($>$ 0.9)

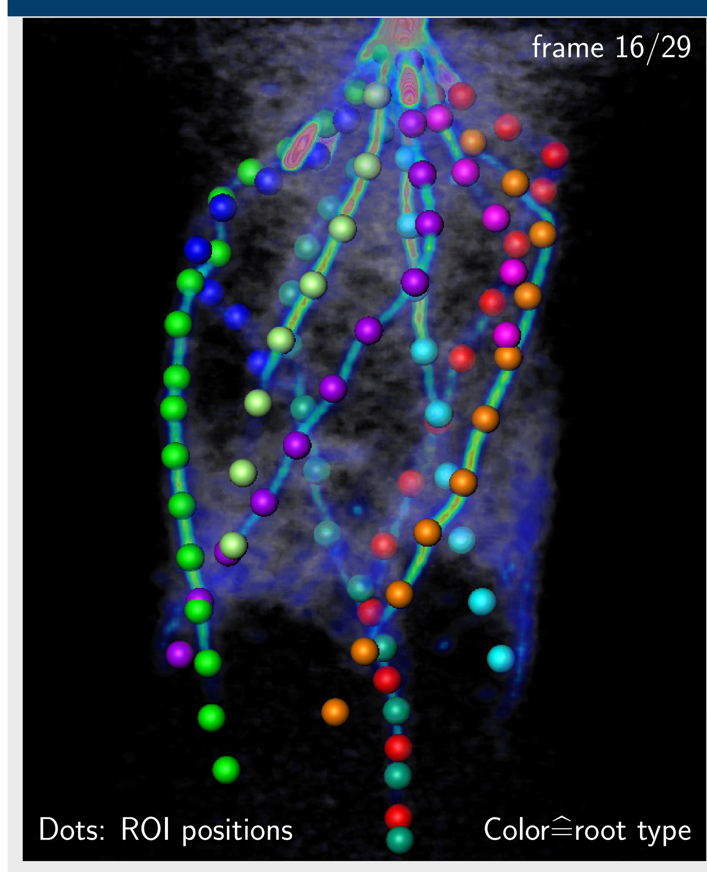
s^{coin} remaining global factor ($>$ 0.98)

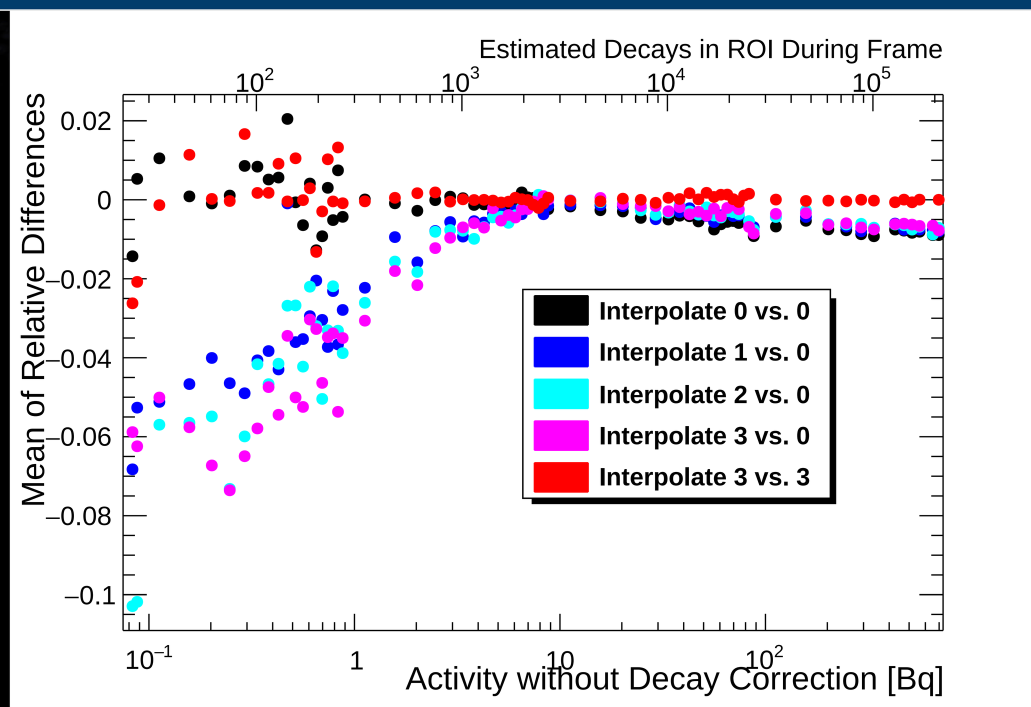


Attenuation and Scatter Correction for Root System of Maize Plant Labeled with [^{11}C]CO_2



Bias by Linear Interpolation for Speedup of Scatter Correction





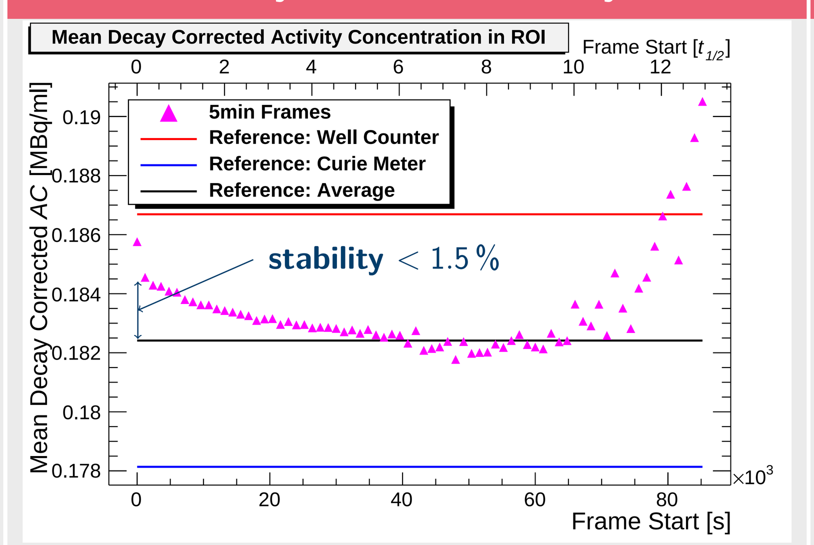
Bias due to linear interpolation of scatter simulations for different interpolations. Mean relative differences for all ROIs and all frames.
Other option: Have a sister institute with a cluster and free capcities.

- Analysis of all 30 frames of a plant measurement (labeling with ^{11}C during 1st frame)
- Integration of activity in Regions of Interest (ROI)
- Ignoring time points before activity reaches a ROI

Speedup of Reconstruction by Linear Interpolation of Scatter for 3 Frames

Threads	Frame Data & 1st OP-MLEM	Scatter Simulation	Calculation of SE_i	Second OP-MLEM	Total	Comment
phenoreco: 46@2.3 GHz	3 h 57 min	17 h 13 min	38 min	3 h 57 min	25 h 47 min	no interpolation
phenoreco: 46@2.3 GHz	2 h 7 min	5 h 27 min	46 min	4 h 13 min	12 h 33 min	
100 TB RAID: 30@2.4 GHz	0 h 44 min[1]	6 h 27 min	38 min	4 h 49 min	12 h 38 min	[1]fewer voxels (-90 %)

Achieved Dynamic Stability



Cylinder phantom (≈ 500 mL) filled with ^{18}F

Summary: Established Measurements

- Study of flow velocities
  - Dynamic corrections essential
  - Stem: Activity not quantitative due to escaping positrons
- Quantitative study of ^{11}C allocation
  - Main addition: attenuation correction
  - Normalization and scatter correction resolve remaining bias
- Routine operation for several projects:
  - Experiments over 2-6 weeks
  - 2-4 measurements per day
  - Minimum 3 Biological replicates

Literature

[1] Siegfried Jahnke et al. "Combined MRI-PET dissects dynamic changes in plant structures and functions". In: *The Plant Journal* 59.4 (Aug. 2009), pp. 634–644.

[2] Ralf Metzner et al. "In Vivo Imaging and Quantification of Carbon Tracer Dynamics in Nodulated Root Systems of Pea Plants". In: *Plants* 11.5 (2022). ISSN: 2223-7747.

[3] J. J. Scheins et al. "High performance volume-of-intersection projectors for 3D-PET image reconstruction based on polar symmetries and SIMD vectorisation". In: *Physics in Medicine and Biology* 60.24 (Nov. 2015), pp. 9349–9375.

[4] Harold Rothfuss et al. "LSO background radiation as a transmission source using time of flight". In: *Physics in Medicine and Biology* 59.18 (Aug. 2014), pp. 5483–5500.

[5] D. Hogg et al. "Maximum-likelihood estimation of normalisation factors for PET". In: *Proc. IEEE Nuclear Science Symp. Conf. Record (Cat. No.01CH37310)*. Vol. 4. 2001, pp. 2065–2069.

[6] J. J. Scheins et al. "High-throughput, accurate Monte Carlo simulation on CPU hardware for PET applications". In: *Physics in Medicine & Biology* 66.18 (Nov. 2021), p. 185001.

Acknowledgements

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