Recent developments in the SAFIR project: towards the first prototype

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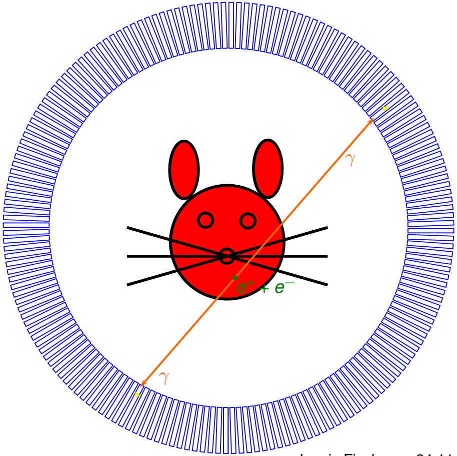
Introduction to PET

Physics

- Positron emitting radiotracer (e.g. ^{15}O-H_2O, ^{18}F-FDG)
- $e^+ + e^- \rightarrow \gamma + \gamma$ (511 keV)
- Detection in coincidence
- Information: Annihilation has taken place on line between detectors (line of response, LOR)
- PET: functional, MR/CT: anatomical

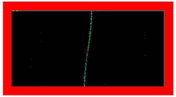


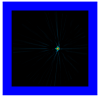
Introduction to PET

Image Reconstruction

Linear model

$\bar{y}_i = \sum_{j=1}^{J} a_{ij} f_j + n_i$





- n_i: noise in the measurement
- $a_{ij} \in \mathbb{R}^{I \times J}$: "system matrix"

- Tracer distribution $\vec{f} = (f_1, \ldots, f_J)^T$
- Mean counts $\vec{\bar{y}} = (\bar{y}_1, \ldots, \bar{y}_I)^T$
- Inverting (a_{ij}) computationally unfeasible
- Maximum Likelihood approach $p(\vec{\bar{y}}|\vec{f}) = \prod_{i=1}^{I} e^{-\bar{y}_i} \frac{\bar{y}_i^{y_i}}{y_i!}$
- Iterative algorithm $f_j^{k+1} = \frac{f_j^k}{\sum_{i=1}^{I} a_{ij}} \sum_{i=1}^{I} a_{ij} \frac{y_i}{\bar{y}_i^k}$

Introduction to PET

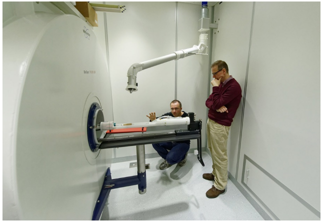
A bit on MR

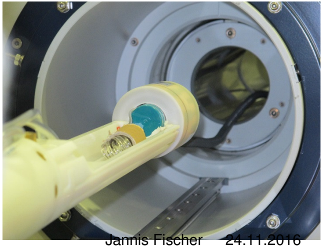
- Static magnetic field (7 T) $\rightarrow$ alignment of spins
- Strong RF pulses
  - Alteration of the spin alignment
  - precession while relaxing back
  - Can measure change of magnetic flux (very small voltage change in receiving coils)
  - Spatial encoding through gradients
- Gradient switching (eddy currents)

The SAFIR Project

Requirements and Challenges

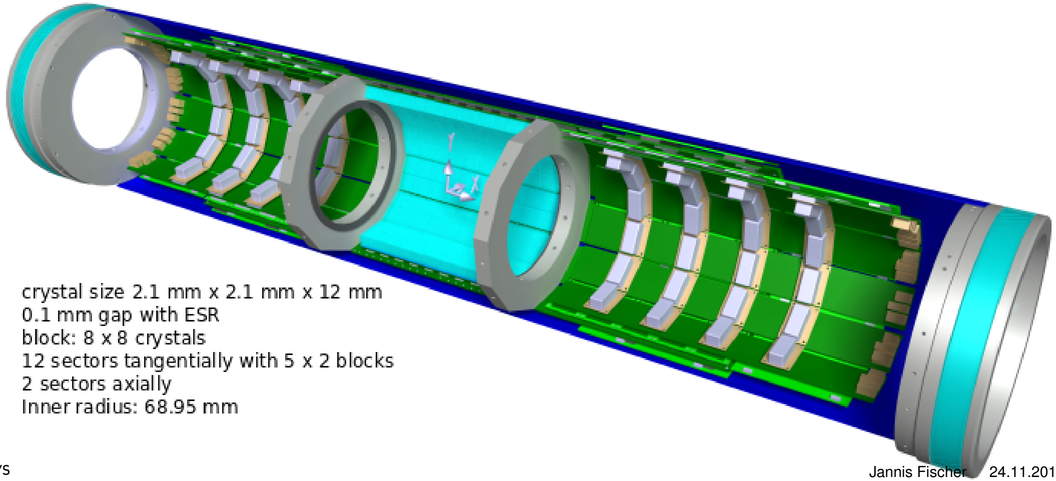
- Target activity injected in mouse: 500 MBq (typical $\leq$ 50 MBq today)
- Insert in Bruker BioSpec 70/30 USR
  - Simultaneous acquisition of PET and MRI data
  - Field strength: 7 T, Larmor frequency: $\approx$ 300 MHz
  - Have to avoid ferromagnetic materials, EMI emission
- Space
  - Gradient coils inner diameter: 200 mm
  - RF coil outer diameter: 112 mm
- Infrastructure
  - Power and cooling ($\approx$ 1 kW)
  - Data out ($\approx$ 5 GB/s) and slow control





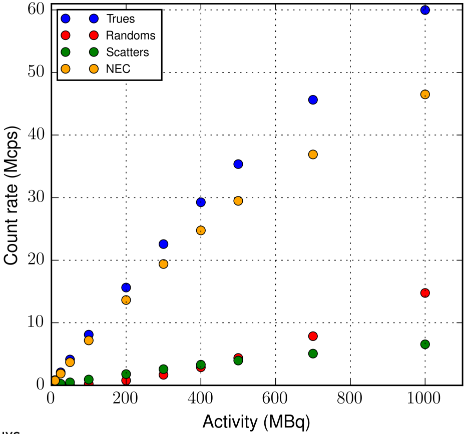
The SAFIR Project

Reference Design



crystal size 2.1 mm x 2.1 mm x 12 mm
0.1 mm gap with ESR
block: 8 x 8 crystals
12 sectors tangentially with 5 x 2 blocks
2 sectors axially
Inner radius: 68.95 mm

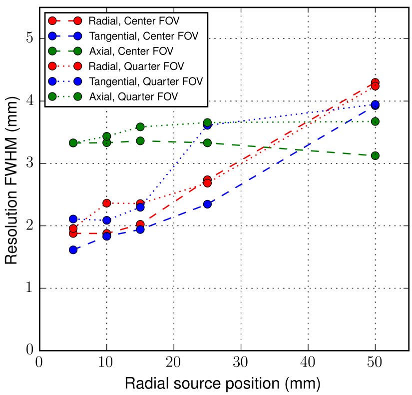
Simulations
NECR

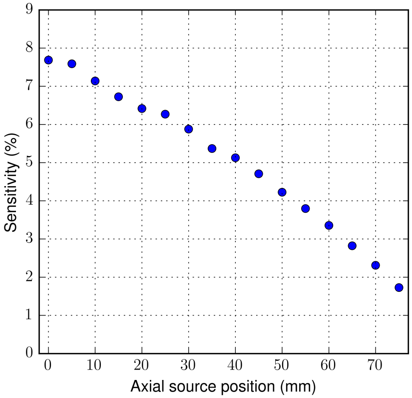


- Noise-equivalent count rate
- $NECR = \frac{T^2}{T+S+R}$
- Coincidence timing resolution: 170 ps σ
- Coincidence window: 400 ps
- Recovery of inter-crystal scattered events

Simulations

Spatial Resolution and Sensitivity

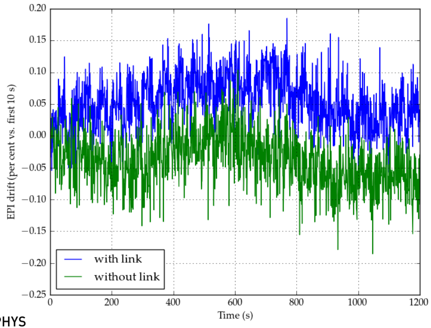




MR Compatibility

Optical Link

Setup	Time (min)	RX BER	RX Bit Count
10 m fiber	64	$9.779 \cdot 10^{-14}$	$1.023 \cdot 10^{13}$
20 m fiber & patch connector	8	$7.914 \cdot 10^{-13}$	$1.264 \cdot 10^{12}$

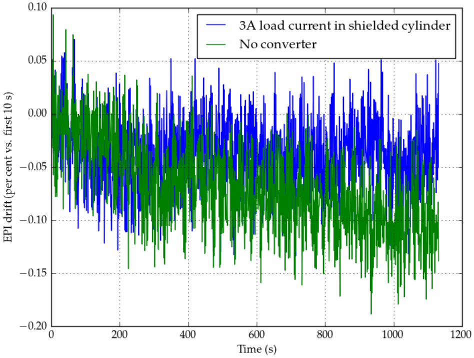


Avago AFBR-57R5APZ

MR signal-to-noise (SNR) measurement

Condition	SNR ($1/mm^3$)
With optical link	3726
Without optical link	3787

MR Compatibility
DC-DC Converter



- CERN FEASTMP_CLP buck converter
- Converter works in MR

MR signal-to-noise (SNR) measurement

Condition	SNR (1/mm^3)
3A load current in shield	3863
No converter	3787

The Prototypes
ASICs

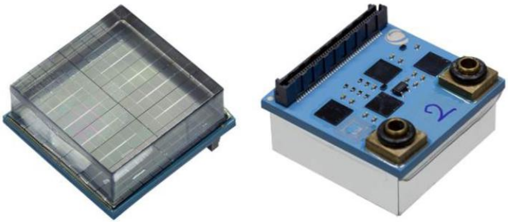
- At first: TOFPET and STiC ASICs, later also PETA
- Decided to build two prototypes with STiCv3.1 and PETA5/6

ASIC	TOFPETv1	STiCv3.1	PETA5
Timing measurement	TAC-ADC	digital	digital
Channels	64	64	36
LVDS output bandwidth	640 Mbit/s	160 Mbit/s	640 Mbit/s
Energy measurement	ToT	ToT	QADC
CRT at high activity[1] (ps σ)	189	131	128

[1] $\geq$500 MBq equivalent activity

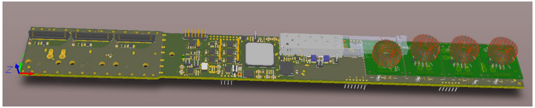
The Prototypes

PETA



LTCC module (*Sacco et al. 2015*)

- LYSO 2.25 mm x 2.25 mm x 10 mm
- FBK SiPM (pitch 2.5 mm)
- 12 x 12 array, 4 PETA on ceramic

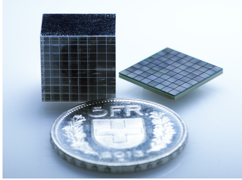


Digital Interface Board (SDIP)

- LTCCs from Mannheim (PETA5, later PETA6)
- SDIP assembled in two weeks
  - Artix7 FPGA
  - Optical Gigabit Ethernet Link
  - Up to 3 LTCCs
  - Power distribution

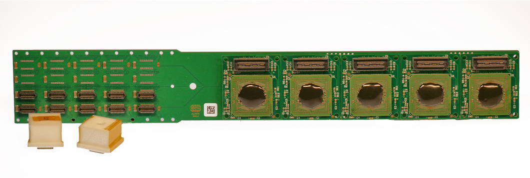
The Prototypes

STiC



LYSO crystal matrix and MPPC

- LYSO 2.1 mm x 2.1 mm x 12 mm
- Hamamatsu MPPC (pitch 2.2 mm)
- 8 x 8 array



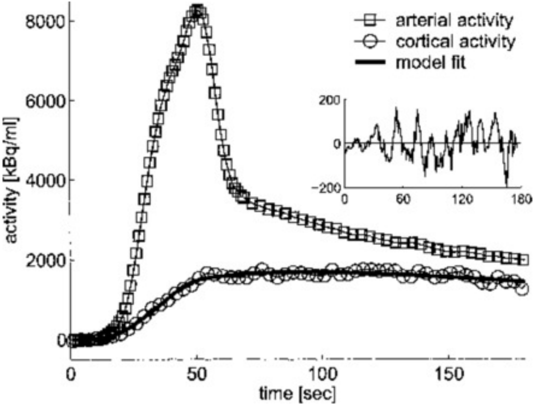
Analog signal (SAS) and STiC boards (SST)

- SAS routes 640 analog signals, ready
- SST hosts 1 STiC (later 2), ready

Next and last board: SDIS (digital interface board)

Outlook

- Next milestone: Working prototypes with timing resolution measurements in the MR
- Overall goal: Measure fast tracer changes with ^{15}-O (not possible with PET so far)



Weber et al. 2003

Thank you