Development and Performance Evaluation of a Simultaneous PET-MR Detector based on the ClearPEM Technology
The ClearPEM breast imaging scanner

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**Abstract**

We present results on the characterization of the ClearPEM breast imaging scanner. ClearPEM is a small-footprint prototype scanning scanner using NaI-based detectors modules that are capable of measuring the depth of interaction (DOI) with a resolution of 2 mm at 511 keV crystals. This new system comprises 128 detector modules with a total of 1536 NaI(Tl) crystals and 288 32-pixel NaI(Tl) arrays read out by a custom analog and digital readout electronics. The software implements calibration and data acquisition electronics, image reconstruction and image reconstruction algorithms.

The scanner's technical characteristics, the calibration strategies, and the performance in terms of spatial and energy resolution were presented as well as the images obtained with point sources and with a microfocus phantom. The image resolution was found to be of the order of 3.5-4.0 mm full width at half-maximum (FWHM) and the DOI capability has shown to have a strong impact on the image sharpness. An example of the first clinical experience was also presented at the conference.

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1. Introduction

Breast cancer is the most common cancer affecting women, with an incidence rate of about 1.2 million females per year worldwide. Positron emission tomography has demonstrated large potential for cancer detection since the radionuclide injected into the patient behaves in tumor cells and its biodistribution can be measured by the temporal coincidence detection of the 2γ photons resulting from the positron-electron annihilation when the radionuclide decays. Here, we present the ClearPEM—a breast cancer imaging scanner developed by the Portuguese PET consortium under the framework of the Crystal Clear Collaboration [1].

CT and ClearPEM images of a Bioscan mini-Jaszczak phantom
(by Benjamin A. FRISCH)

ClearPEM - Detection and Imaging Performance

Energy Resolution
13.3% @ 511 keV (FWHM)

Time Resolution
4.47 ns (FWHM)

Spatial Resolution
< 1.3 mm (FWHM)

“Do not try to develop a PET-MR prototype before build your own PET scanner first...”
Outline

1. Motivations for Combined PET-MR Imaging
2. Electromagnetic Compatibility Issues
3. CIBM/ EPFL Magnet Facility
4. ClearPEM Detectors & Front-end Electronics
5. Mutual Electromagnetic Interference Tests
   5.1. PET: EMI from RF Coils
   5.2. MR: EMI from PET Front-End Electronics
   5.3. PET: Gradients Effects on PET Front-End Electronics
   5.4. MR: Susceptibility Artifacts caused by PET Materials
6. Experimental Proof-of-Principle Prototypes
7. Summary/ take-home message
Why simultaneous PET-MRI?

- Powerful technique for basic biomedical research and pre-clinical studies with small-animal models
- Advantages of multimodality imaging and potential benefits over PET-CT

**PET-CT** vs **PET-MRI**

- anatomical and metabolic mapping
- additional ionizing radiation dose
- image co-registration for sequential scanning

- high spatial resolution
- very high soft tissue contrast
- no additional radiation dose
- simultaneous data acquisition

**Relevant Challenges ...**

- **Hardware: Electromagnetic Compatibility**
- **Software: MR-based Attenuation Correction**
- **Space Constraints**
- **Cost Effectiveness (M€ ??)**
- **Ultimate Clinical Goal / Killer Application**

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[H. SADROZINSKI], Particle Detector Applications in Medicine (VCI 2013, Plenary/ Introductory talk)


[B. Pichler et al, Pre-clinical PET/MR: technological advances and new perspectives in biomedical imaging, Eur J Nucl Med Mol Imaging 36 (S1), 2009]
PET/MR Mutual Electromagnetic Interference

**Interference on PET:** static magnetic field (7T), pulsed RF, switching magnetic field gradients

- Photo-detectors (APDs, SiPMs) are insensitive to B0
- Electromagnetic Interference from pulsed RF Power†
- Induced eddy-current by the time-varying magnetic fields gradients††
- Lorentz forces on electrical conductors parallel magnetic field $\vec{F} = I \int d\vec{l} \wedge \vec{B}$

**Interference on MR:** magnetic susceptibility of PET materials, RF interference, loss of SNR

- Required highly homogeneous B0 (few PPMs) to avoid image susceptibility artifacts
- MRI signal is very low: more susceptible to contaminated high-frequency digital signals from PET
- EMI should be minimized -> loss of SNR -> loss of MRI sensitivity

† Radiated fields from current loops

††switched gradient fields $\mathbf{B}(r,t)$

Faraday’s law: $\varepsilon_{ind}^{\text{Faraday}} = -\frac{\partial \Phi}{\partial t} = -\frac{\partial}{\partial t} \int \vec{B}(t).d\vec{S}$
Experimental EMI/EMC tests were carried out at the EPFL 7 Tesla magnet, Lausanne, Switzerland

- Actively shielded 7 Tesla - 68 cm bore head-only magnet (Magnex Scientific, Oxford - UK)
- Actively shielded head gradient coil
  - 36 cm inner diameter
  - 80 mT/m maximum gradient strength
  - 700 mT/(m.ms) maximum slew rate

Ultra High-Field Magnetic Resonance Imaging

\[ f_0 = \gamma B_0 = \sim 300 \, \text{MHz} \, @ \, 7 \, \text{T} \]

4. ClearPEM Detectors & Front-end Electronics

**LYSO:Ce 2x2x20 mm³**

**4x8 matrix (BaSO₄ walls)**

**Hamamatsu S8550 APDs**

**Detector modules**

**ClearPEM Front-end ASIC**

- **AMS 350 nm CMOS, 70 mm²**
- **Input:** 192 APD readout channels (~30fC input charge)
- **Output:** 2 highest channels (192:2 mux) -> Compton event readout
- **Low noise amplifiers, pulse shaping & analog pipeline memories**
- **Clock frequency 50-100 Mz**
- **Power:** 3.6 mW/channel

**ClearPEM Front-end Electronic Boards**

- **2x Front-end ASICS (50 MHz)**
- **2x free-sampling dual 10-bit ADC (50 MHz)**
- **1x LVDS ChannelLink transmitter (2.4 Gbps)**

**ClearPEM Supermodule**

**Latest developments @ LIP (FP7 EndoTOFPET-US Project)**

- **M. Rolo et al, TOFPET ASIC for PET Applications, JINST, 2013**

**64-channel ASIC for SiPMs (IBM 130nm CMOS)**

(see also next talk by B. FRISCH)
5. Mutual Electromagnetic Interference Tests

5.1. PET: EMI from RF Coils

**1st approach:** Low RF Power (<50W) @ RF LAB

- Pulsed RF tolerance of the front-end electronic boards was assessed as function of the RF Power

- **RF pick-up** (297MHz@7T) was observed on each LVDS analog output of the front-end ASIC. **No EMI shielding was used!**

- For a **RF power < 50W**, the LVDS analog output of the ASIC tends to reject low-amplitude common-mode RF noise pick-up.

\[
P [W] = \frac{V^2}{50 \, \Omega}
\]

\[f(t) = A \left( \frac{t - (T_{\text{max}} - T_{\text{peak}})}{T_{\text{peak}}} \right) \exp \left( -\alpha \frac{t}{T_{\text{peak}}} \right)
\]

- **μ-strip resonator**
  - Resonance frequency: 297MHz
  - Frequency: 1H (7T)

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**Front-end ASIC Analog Output**

- **176Lu events (LYSO)**
- **RF Gate**
- **RF**

**RF Gate/pulse envelope generator**

- TTL 5V, 1ms, 0.1 kHz
- 300 MHz (-10dBm = 100μW)
- 1000 ms
- 300 MHz (50W)

**Pulse samples**

**RF pickup** (297MHz@7T) was observed on each LVDS analog output of the front-end ASIC. **No EMI shielding was used!**

**Analog pipeline memory, SCA**

Dataframes digitized on 10-bit ADCs

**Offline waveform recovery**
5.1. PET: EMI from RF Coils

2\textsuperscript{nd} approach: High RF Power (up to 2.8 kW) @ 7T magnet RF Power Amplifiers

- Pulsed RF tolerance of the front-end electronic boards was assessed as function of the RF Power

- At a maximum RF power = 2.8 kW, we have observed a saturation of the front-end ADCs dynamic range during the RF pulse, and a self-triggering state induced by RF eddy-currents that create a burst of events remaining over 1.2 ms after the RF pulse. No EMI shielding was used!

5.2. MR: EMI from PET Front-End Electronics

1st approach: Spectrum Analyzer measurements

Noise pick-up measurements with PET front-end electronics close to the RF coils shows an important EMI contribution from digital electronics. No EMI shielding was used!

The 300 MHz harmonic from the 50 MHz system Clock was detected to enter in the narrow dynamic range of the RF preamplifiers, being responsible for the noise propagation into the RF receiver chain (SNR degradation)
2nd approach: Analysis of pick-up noise on acquired MR images

- MR images from a water-filled phantom were acquired with a surface RF coil with the PET front-end electronics in its vicinity turned OFF and turned ON. No EMI Shielding was used!

- Coherent results with Spectrum Analyser measurements showing the contribution of high-frequency Clock harmonics propagated into the RF receiver chain

- A shift on the system Clock frequency from 50 to 52.5MHz was proposed to eliminate pick-up noise from the front-end digital electronics
Magnetic Field Gradients: linearly varying magnetic fields applied in addition to the main magnetic field $B_0$ to achieve spatial encoding

$$G_x = \frac{dB}{dx}, \quad G_y = \frac{dB}{dy}, \quad G_z = \frac{dB}{dz}$$

EPFL 7T magnet - Actively shielded head gradient coil
- 80 mT/m maximum gradient strength
- 700 mT/(m.ms) maximum slew-rate $\frac{dB}{dxdt}$

- Gradients effects on front-end electronics were studied with a EPI sequence
High slew-rate gradient transitions were found to be responsible for induced eddy-currents on front-end boards power/ground planes which causes ASIC baseline distortions and bursts of spurious events with a characteristic saturated/flat waveform.

- The expected time scale for the eddy-currents is compatible with the exponential decay time of the ringing distortion of the ASIC baseline (~600us)
5.4. MR: Susceptibility Artifacts caused by PET Materials

- B0 field phase-difference mapping (susceptibility image)
- The ClearPEM module was placed close to a oil-filled spherical phantom (~25 cm diameter) inside a head coil
- B0 field distortions below 10 ppm were observed over an extension of 5 cm

\[ \delta B_0(\text{ppm}) = \frac{\delta B_0(\text{Hz})}{42.58 B_0(T)} \]

_13th Vienna Conference on Instrumentation_  
_J. F. Schenck, The role of magnetic susceptibility in magnetic resonance imaging, Med. Phys. 23 (6), 1996_
5.4. MR: Susceptibility Artifacts caused by PET Materials

- B0 field distortions caused by front-end board materials were also evaluated by the homogeneity analysis of a water-filled spherical phantom (~25 cm diameter)
- A ClearPEM front-end board was positioned in different points to assess its influence on B0 distortion
- Nickel plated APD connectors were found to be responsible for the observed B0 field lines distortions
6. Experimental Proof-of-Principle Prototypes

- Small-animal PET insert for UHF PET-MR
- Detector ring of 12 or 24 APD+LYSO modules
- <140 mm outer Ø / 85 mm inner Ø
- Axial FOV = 19.5 mm
- LYSO crystals matrices in single-ended scintillation light readout mode
- APD charge signals transmitted to the front-end ASIC by via flexible flat-cables (~150 mm length)
6. Experimental Proof-of-Principle Prototypes

Small-animal PET insert for UHF PET-MR

5.06 ns FWHM

5.49 ns FWHM

80 mm length FFC

22 % FWHM @ 511 keV

Hamamatsu S8550 4x8 APD array
LYSO crystal matrix 4x8 (2x2x20 mm³)

Home-made FFCs
32 signal lines + 2 HVs

APD-coupled flexible flat-cable for LYSO scintillation light readout


Non-significant degradation on Time and Energy Resolution was observed with the FFC introduction
RF Coil Design: Coupled Microstrip Line Transverse Electromagnetic (TEM) Resonator

- Microstrip TEM resonator: best compromise for UHF (≥ 7 T)
- 8 Conductor elements (copper 38 μm thick)
- Air/ PMMA dielectric substrate
- Cylindrical shield (current return paths)
  - Segmented shielding at lower frequencies (kHz range)
    - to block the propagation of eddy currents induced by the switching magnetic field gradients
  - Continuous RF shielding at high-frequency (MHz range)
- 2 Driving elements in ‘quadrature’
- Mutual inductive coupling between elements
- Matching to 50 Ω and individual tuning to 297.2 MHz (7T)
- FDTD/ FEM Electromagnetic Simulation
  - CST Microwave Studio ®
  - E/H field distribution
  - Resonant Modes
  - S-parameters/ Q-factor

\[
\begin{align*}
\mathbf{E}(x, y, z) &= E(x, y)e^{i(wt-k_z z)} \\
\mathbf{H}(x, y, z) &= H(x, y)e^{i(wt-k_z z)}
\end{align*}
\]

MR compatibility of the ClearPEM front-end electronics was assessed by evaluating the mutual EMI mechanisms into a 7T MRI system;

The presented results demonstrate that the front-end electronics withstands to pulsed RF power and to the strong magnetic field gradients, introducing some impact upon MR signal acquisition (careful EMI shielding needed);

A new design for UHF small-animal PET-MR was proposed by using long flexible flat cables to transmit the APD charge signals to the ClearPEM front-end ASIC;

Proof-of-principle prototypes are being tested;

A new dedicated RF coil for UHF was designed intending to demonstrate the simultaneous PET-MR acquisition with minimal interference between both systems.

:) Thank you!