Narodowe Centrum Badań Jądrowych
National Centre for Nuclear Research
Świerk

Detectors for Gamma-ray Diagnostics in Plasma

Izabella Zychor

National Centre for Nuclear Research (NCBJ)
Otwock – Świerk, Poland

X-rays and gamma rays in plasma measurements with energies varying from keV up to MeV

$$\mathbf{D} + \mathbf{T} \rightarrow \boldsymbol{\alpha} + \mathbf{n}$$

$$^{9}\mathrm{Be} + \alpha \rightarrow {}^{13}\mathrm{C} \overset{n}{\rightarrow} {}^{12}\mathrm{C}^{*} \xrightarrow{\gamma(4.44\ \mathrm{MeV})} {}^{12}\mathrm{C}_{\mathrm{g.s.}}$$

$$^{16}\mathrm{O} + \mathrm{n} \rightarrow {}^{16}\mathrm{N} + \mathrm{p}, \qquad {}^{16}\mathrm{N} \overset{\beta}{\rightarrow} {}^{16}\mathrm{O}^{*} \xrightarrow{\gamma(6.13\ \mathrm{MeV})} {}^{16}\mathrm{O}_{\mathrm{g.s.}}$$

$$\mathbf{D} + \mathbf{T} \rightarrow \gamma(17\ \mathrm{MeV}) + {}^{5}\mathbf{He}$$

In lab conditions we need radioactive sources to test detector systems

- standard γ-ray sources
  - ^{137}Cs, ^{22}Na, ^{60}Co and many other
- PuBe with 4.44 MeV γ-ray
- PuC with 6.1 MeV γ-ray

DETECTOR OVERVIEW

The choice of a particular detector type for an application depends upon the X-ray or gamma energy range of interest and the resolution and efficiency requirements.

Additional considerations include (high) count rate performance, the suitability of the detector for timing experiments and price (of course).

Main detector for gamma-ray diagnostics:

- **gas-filled detectors**
- **scintillation detectors**
- **semiconductor detectors**

Scintillation detectors use crystals that emit light when gamma rays interact with the atoms in the crystals (photoelectric effect, Compton effect, pair production).

The intensity of the light produced is proportional to the energy deposited in the crystal by the gamma ray.

The detectors are coupled to photodetectors that convert light into electrons and then amplify the electrical signal provided by those electrons.

Scintillation detectors can also be used to detect alpha- and beta-radiation as well as neutrons.

The most important scintillator parameters include a detector resolution and a detector efficiency.

Scintillators

- $CeBr_3$, $LaBr_3$:Ce, NaI, CsI, GAGG, BGO, YAP, …
- dimensions: 10×10×5 mm^3 to 3”×3”
- cuboid and cyllinder shapes

Photodetectors

- pin-diode (PiN)
- photomultiplier (PMT)
- silicon photomultiplier (multi pixel photon counter MPPC)

PROPERTIES

PMT

Advantages

- fast response enabling measurements at high counting rates
- high gain and extremely low excess noise factor resulting in good energy resolution
- large photosensitive area
- large linear dynamic range in which an output signal is proportional to a registered energy

Main drawback

- sensitivity to magnetic field

PiN

Advantages

- small dimensions
- low operating voltage
- immunity to magnetic field

Main drawback

- gain = 1

MPPC

Advantages

- fast response
- high gain resulting in good energy resolution
- immunity to magnetic field

Main drawbacks

- gain sensitivity to temperature and voltage bias
- limited dynamic range

Silicon-based photodetectors

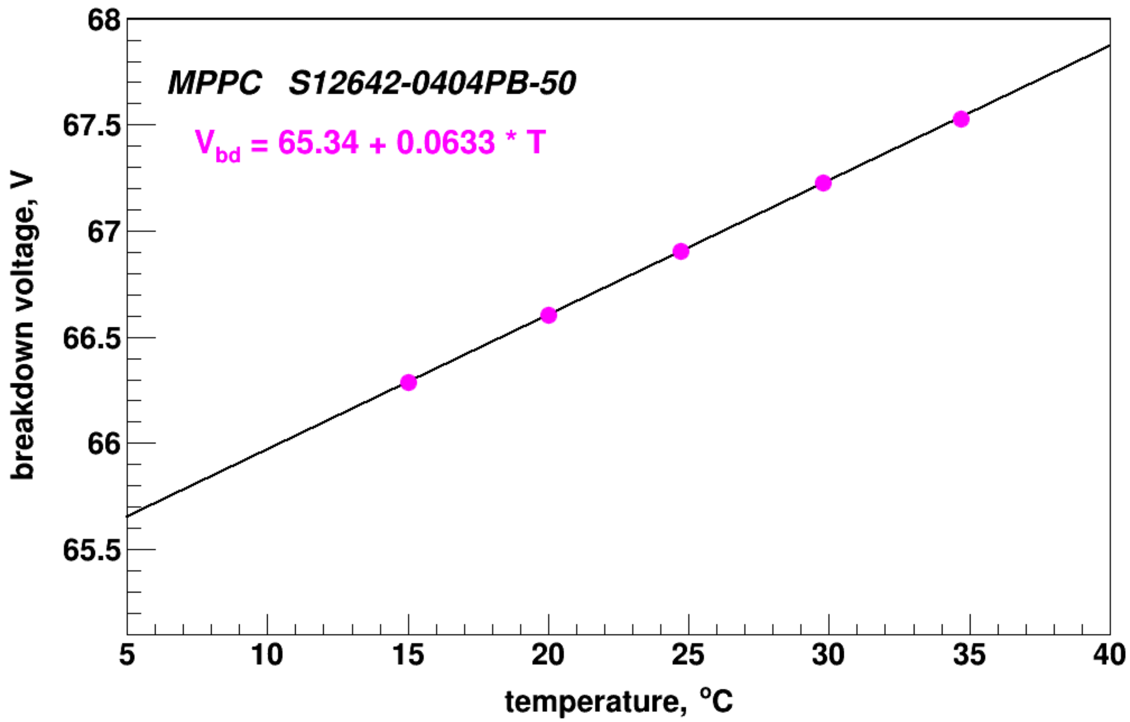
MPPC - Multi-Pixel Photon Counter – is a silicon-based monolithic array of micro-pixel avalanche diodes operating in a Geiger mode.

MPPC is characterized by large internal gain, high photon detection efficiency, high-speed response, excellent time resolution, wide spectral response, immunity to magnetic fields, resistance to mechanical shocks, low power/voltage operation and compactness.

MPPC is therefore an alternative to a photomultiplier tube if operating at high count rate in harsh radiation environment.

Due to the fact that properties of MPPC are strongly affected by temperature, it is necessary to stabilize MPPC operation under temperature variations.

Temperature and bias voltage dependence of the MPPC detectors



scintillator

PMT

detector capsule

photodiode

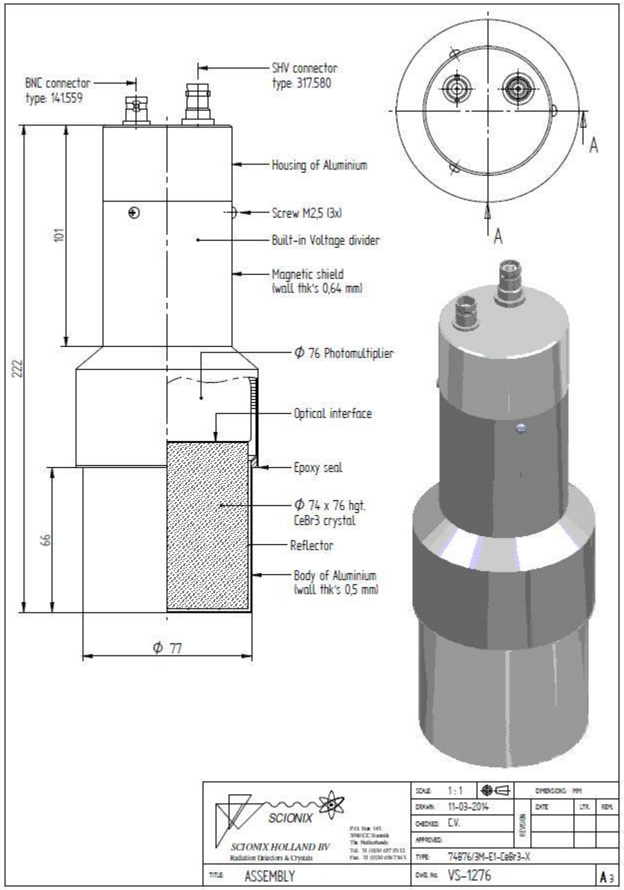
$CeBr_3$ scintillators from SCIONIX

20 mm × **20** mm

with outer dimensions of

28 mm × **24** mm

3” × 3” $CeBr_3$ from SCIONIX



voltage divider

PMT
Hamamatsu
R233-100

scintillator

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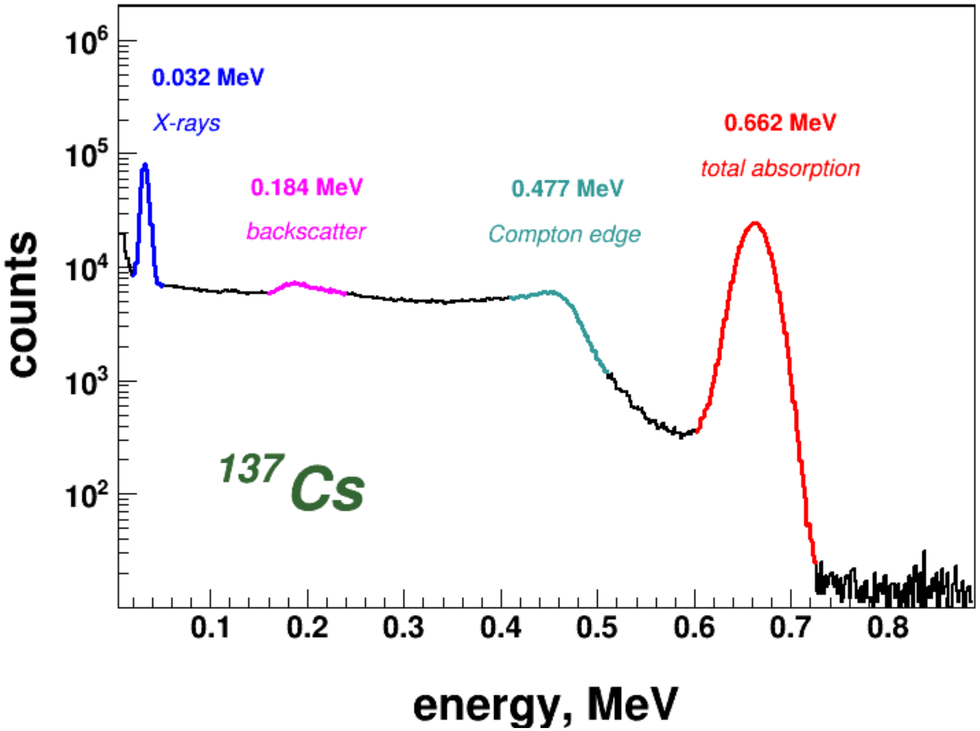
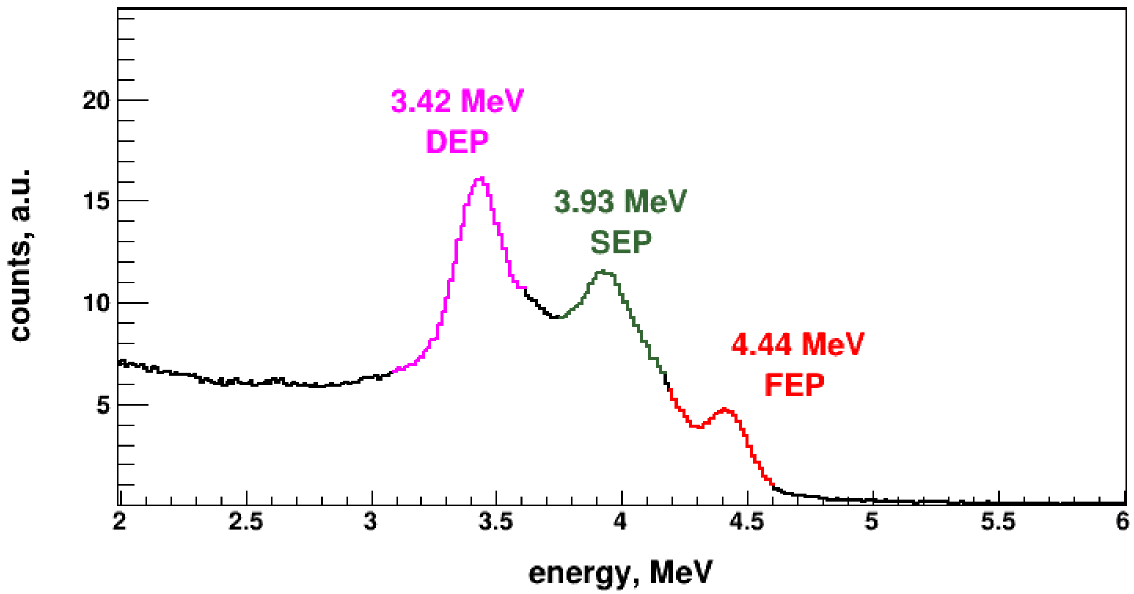
Energy spectrum of 0.662 MeV γ-rays from a ^{137}Cs source measured with 1”×1” $CeBr_3$ scintillator

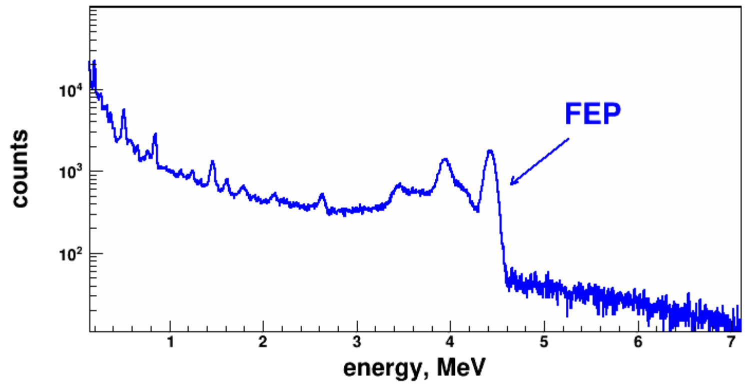


Response of 1”×1” $CeBr_3$ scintillator to PuBe source emitting 4.44 MeV γ-rays



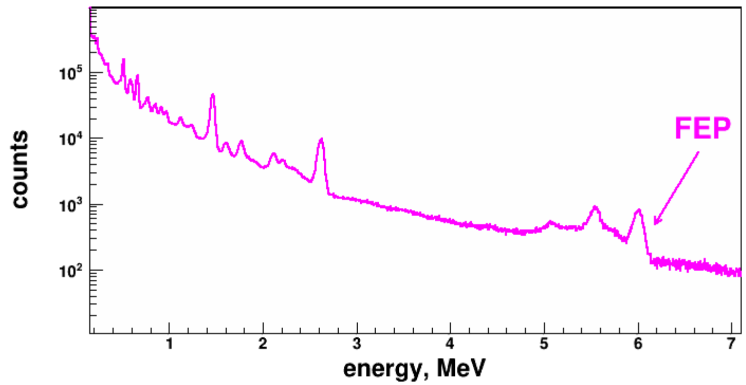
FEP (full energy peak) is detected at 4.44 MeV.
After annihilation of a positron inside the crystal, two 0.511 MeV photons are emitted. It is possible that one or two of those photons can escape a scintillator, which gives rise to the single escape peak (SEP) at 3.42 MeV and double escape peak (DEP) at 3.93 MeV.

3” x 3” $CeBr_3$ + PMT



PuBe

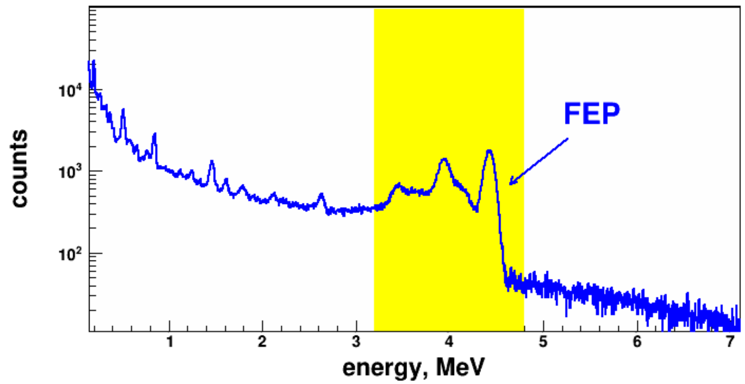
FEP at E_γ = 4.44 MeV



PuC

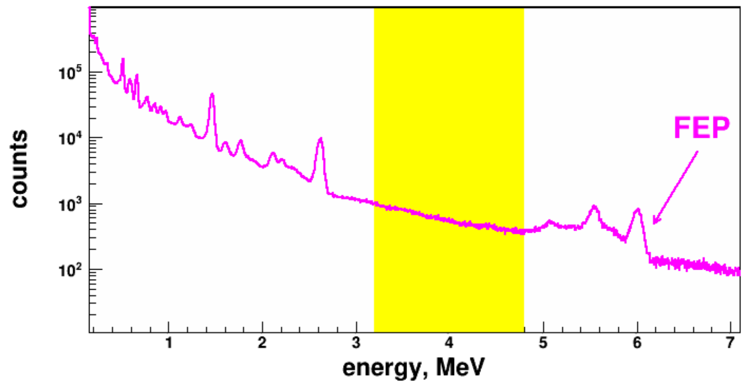
FEP at E_γ = 6.13 MeV

3” x 3” $CeBr_3$ + PMT



PuBe

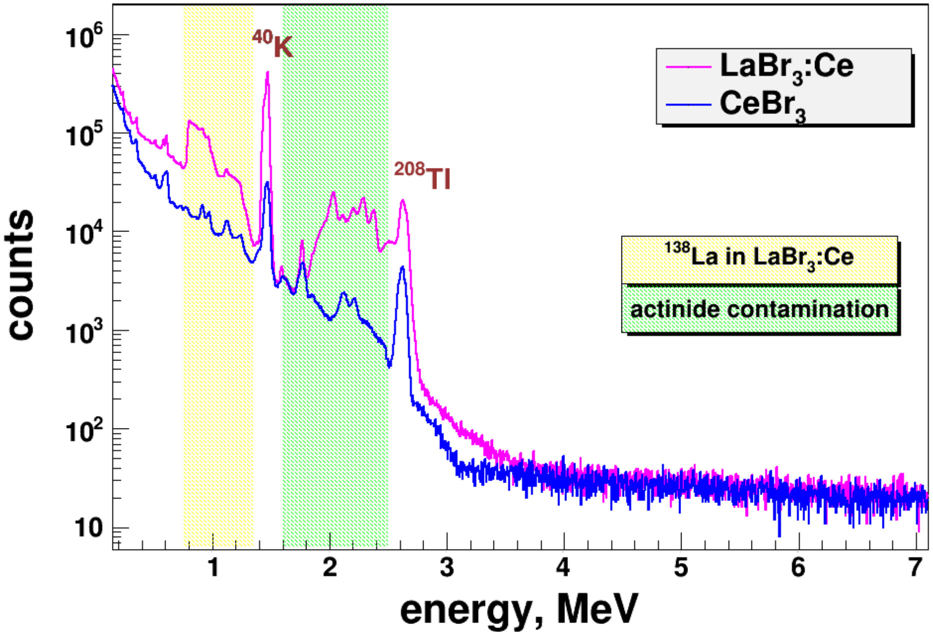
FEP at E_γ = 4.44 MeV



PuC

FEP at E_γ = 6.13 MeV

Response of $CeBr_3$ and $LaBr_3$:Ce to natural background radiation

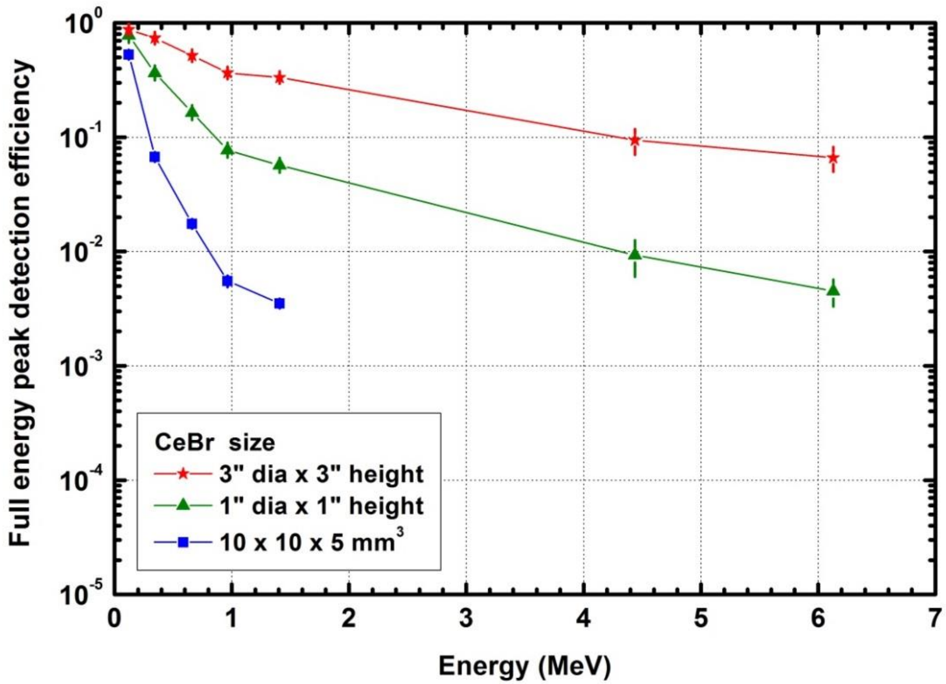


Natural background: ^{40}K (1.461 MeV), ^{208}Tl (2.615 MeV)

$LaBr_3$:Ce is contaminated also with naturally occurring ^{138}La decaying by electron capture or β– decay

Events due to internal contamination by actinides: 1.5-2.5 MeV

Detection efficiency *vs.* detector size

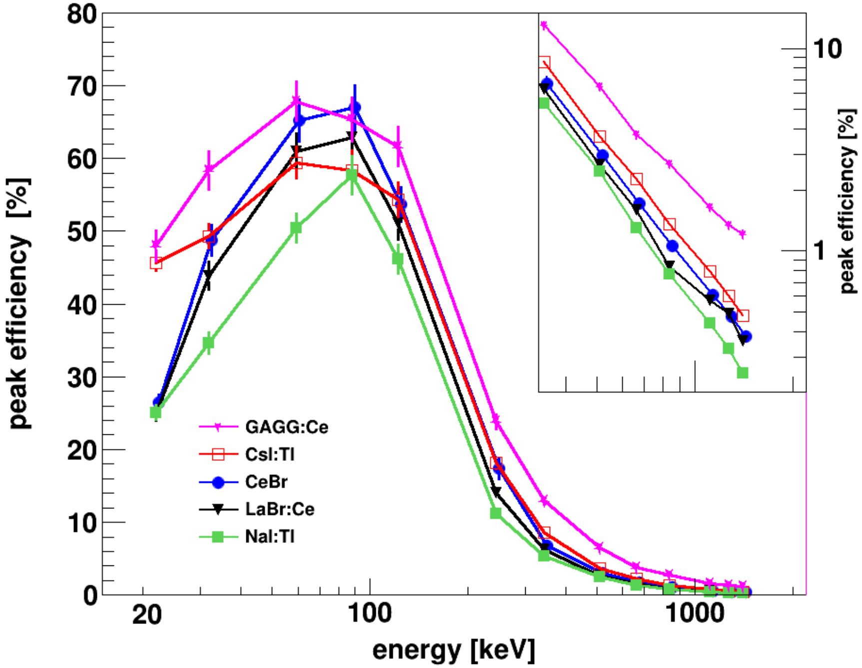


FEP detection efficiency measured for $CeBr_3$ scintillators

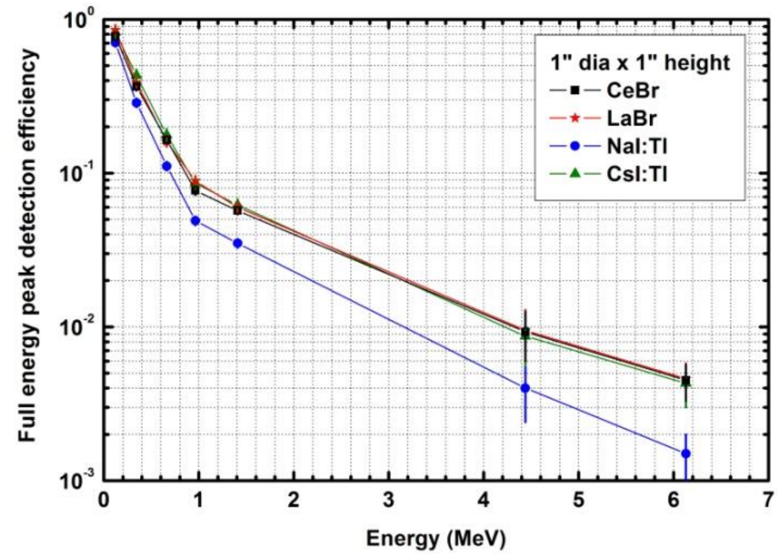
The results for 4.44 MeV and 6.13 MeV γ-rays are not available for the smallest sample because the mean free path is too long to produce FEP is in this scintillator during acceptable acquisition time.

Detection efficiency for different scintillators

10×10×5 mm^3



1”×1”



FEP detection efficiency different scintillators

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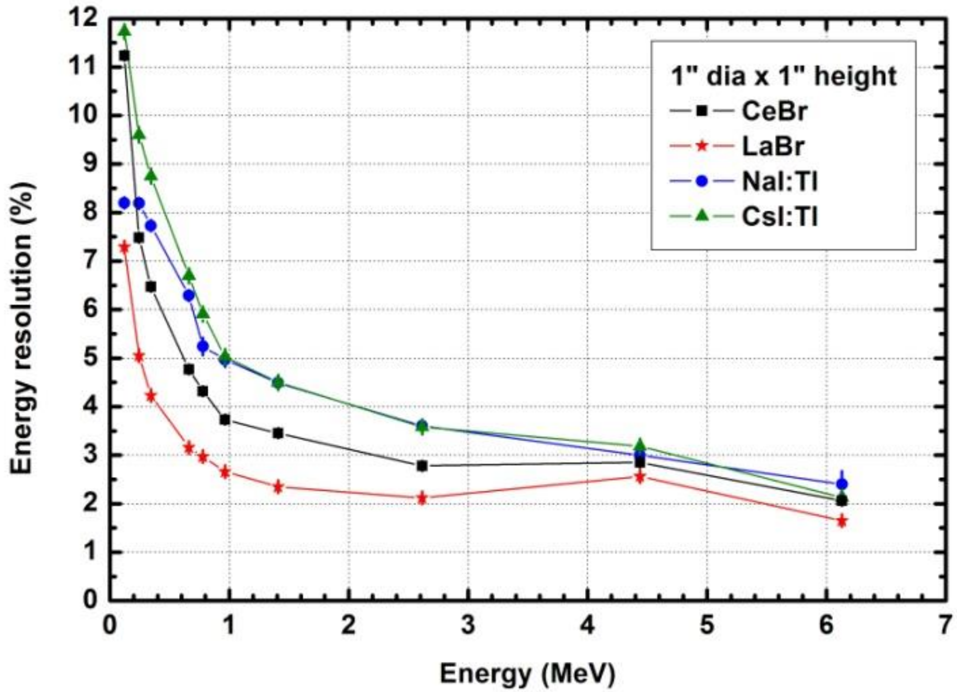
Energy resolution

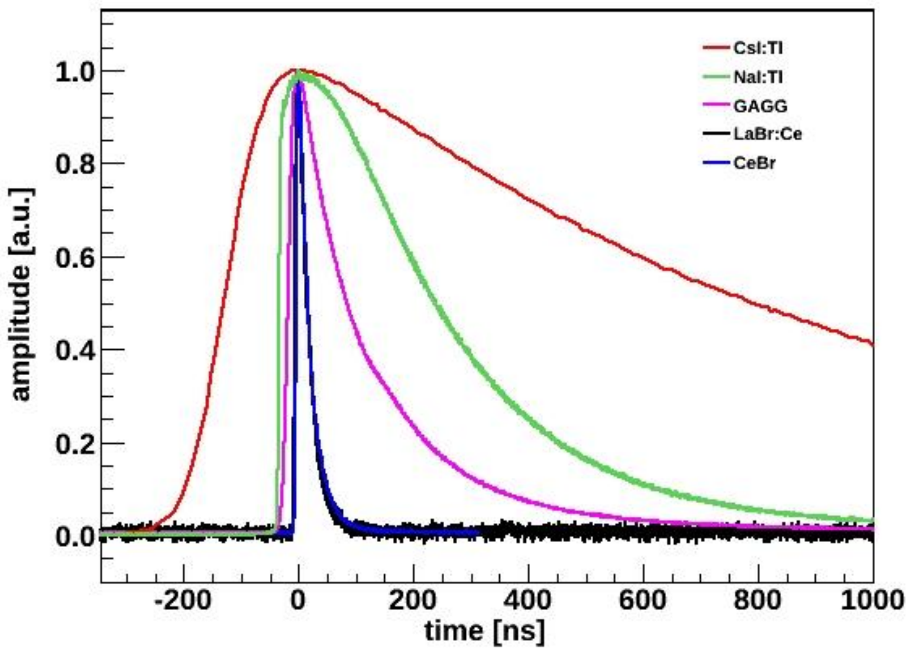


Energy resolution for 1”×1” scintillators

in the γ -ray energy range between 0.1 and 6.13 MeV

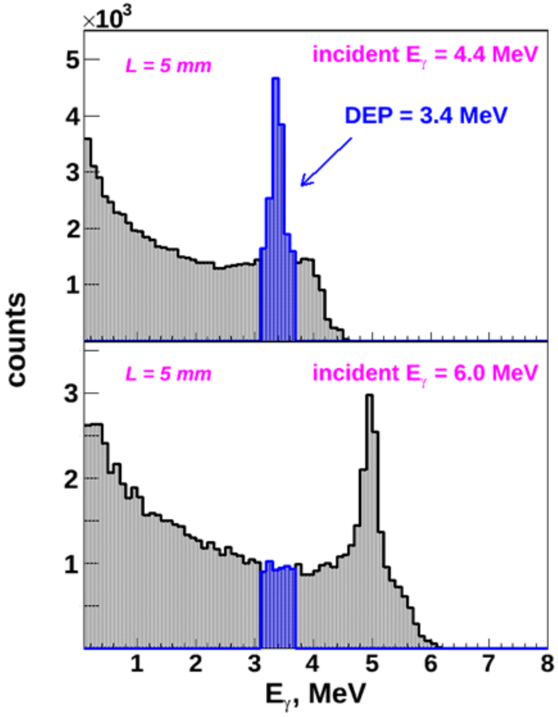
Doppler broadening effect linked to the emission of 4.44 MeV γ-rays from the excited state of ^{12}C

Pulse shape

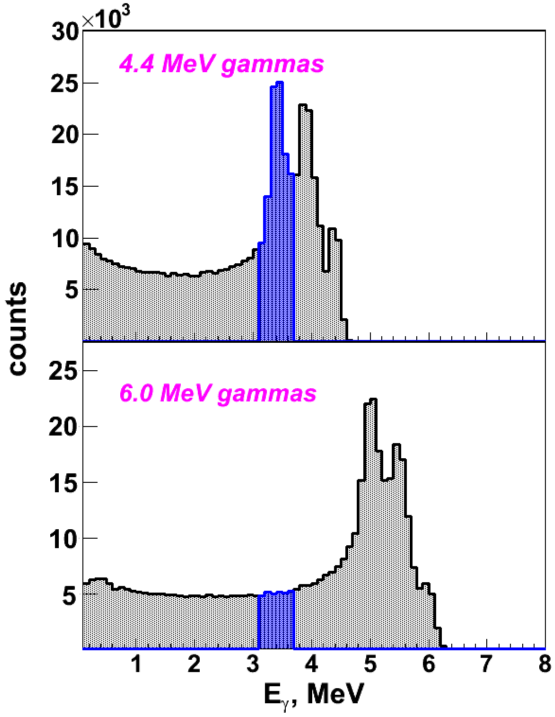


fast scintillator: 20 ns,   low: 300 ns

Monte Carlo simulations with Geant4



L = 5 mm, ϕ = 20 mm



L = 35 mm, ϕ = 35 mm

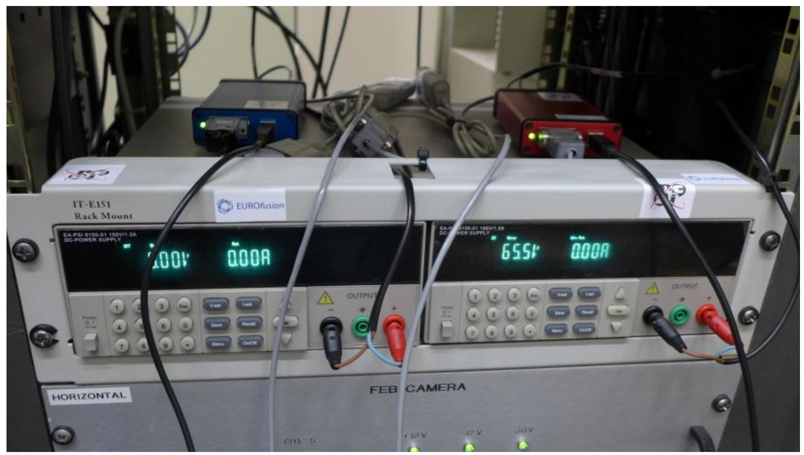
Elements of a complete system for gamma diagnostics

- **detector**
- **electronics, e.g., to optimize a detection setup**
- **DAQ – data acquisition system for high count rates**

MTCD@ NCBJ

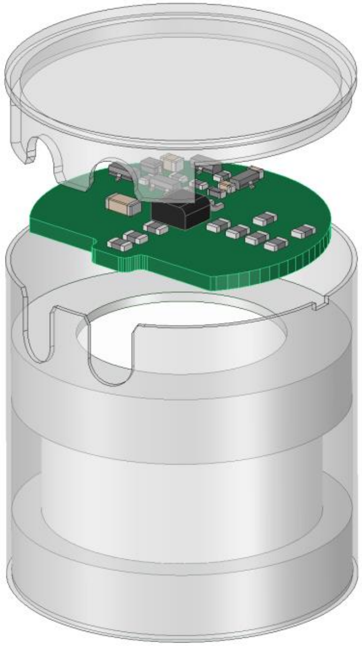
MPPC Temperature Compensation Device

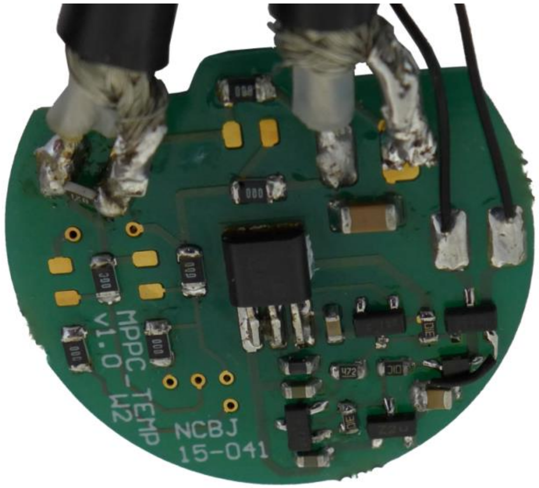
for real-time temperature monitoring and MPPC gain stabilization, necessary due to the fact that properties of MPPC are strongly affected by temperature

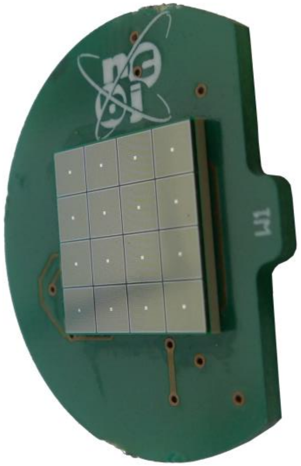


installed at JET in May 2015

providing a current limitation and filtering of the MPPC bias voltage and is using a measured dependence of a bias voltage on temperature to maintain a constant value of the MPPC gain







Dedicated MPPC PCB for detectors installed at JET in May 2015

DIGITAL NEUTRON GAMMA
DNG@NCBJ

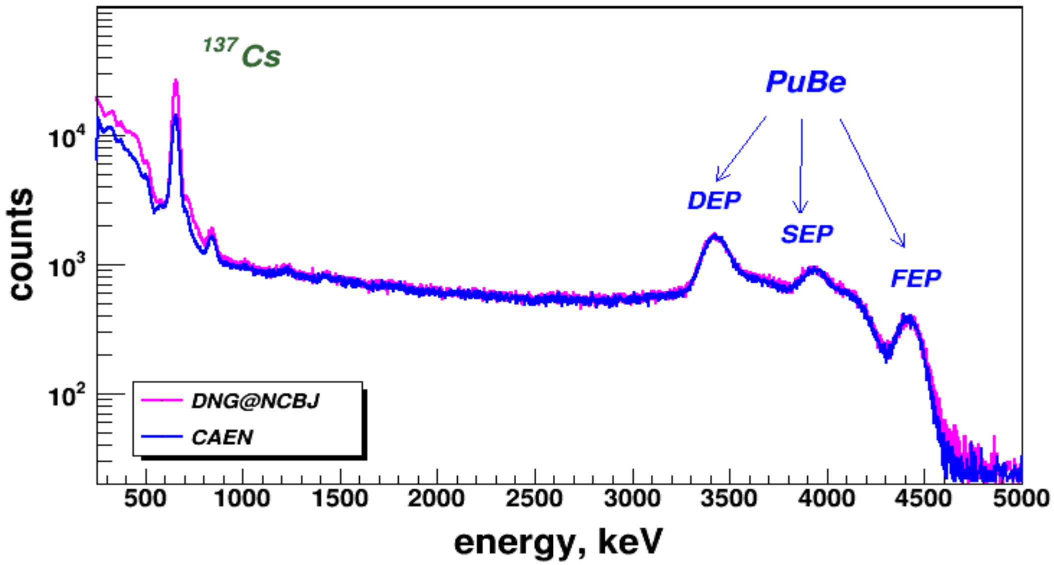
data acquisition system

for high resolution spectrometry measurements at Mcps event rates

- **DNG@NCBJ integrated into a single compact unit**
- **Measurements with DNG@NCBJ performed up to 2.2 Mcps**
- **Almost identical spectra obtained with DNG@NCBJ and commercially available CAEN Desktop Digitizer DT5720**
- **Easy to create data acquisition system for a multi-detector setup**
- **Off-line processing for setting optimization**

FWHM with DNG@NCBJ

at 661.7 keV: 5.4%, at 3.4 MeV: 4.3%, at 4.4 MeV: 3.3%



Measurements performed with DNG@NCBJ and CAEN Desktop Digitizer DT5720 at count rate of 0.2 Mcps

Detection systems for gamma-ray diagnostics

- **design of gamma-ray detection systems meeting requirements of a particular experiment**

- **single detectors**

- **detectors in setups**
  - **gamma camera - for spatial characteristics**
  - **gamma spectrometer - for energetic characteristics**

GCU **Gamma Ray Camera Upgrade**
GSU **Gamma Ray Spectrometer Upgrade**
LRM **Lost Alpha Gamma Rays Monitor**

Three projects implemented under the EUROFusion Consortium in 2014-2017

JET Enhancements Programme WPJET4

Collaboration between NCBJ and IPPLM

S.Mianowski
G.Boltruczyk
M.Gosk
S.Korolczuk
P.Sibczynski
L.Swiderski

and colleagues from
Nuclear Techniques & Equipment Department (NCBJ)

60 years
National Centre for Nuclear Research (NCBJ)

NCBJ pure/applied research profile combines nuclear power-related studies with various fields of sub-atomic physics (elementary particle physics, nuclear physics, hot plasma physics etc.).