EUROfusion

High performance detectors for upgraded gamma ray diagnostics for JET DT campaigns

Izabella Zychor

National Centre for Nuclear Research, Otwock, Poland

JET IFPiLM ncbj

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Acknowledgements

G.Boltruczyk[1], A.Burakowska[1], R. Costa Pereira[2], T.Craciunescu[3], A.Fernandes[2], J.Figueiredo[2,4], L.Giacomelli[5], M.Gierlik[1], G.Gorini[5], M.Gosk[1], G.Kaveney[6], V.Kiptily[6], S.Korolczuk[1], R.Kwiatkowski[1], S.Mianowski[1], M.Nocente[5], V.Perseo[5], D.Rigamonti[5], J.Rzadkiewicz[1], S.Soare[7], A.Szydlowski[1], M.Tardocchi[5], A.Urban[1], V.L.Zoita[3] and JET contributors*

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

[1] Narodowe Centrum Badań Jądrowych (NCBJ), 05-400 Otwock-Swierk, Poland
[2] Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Portugal
[3] National Institute for Laser, Plasma and Radiation Physics, Bucharest, Romania
[4] EUROfusion Programme Management Unit, Culham Science Centre, Abingdon, United Kingdom
[5] Istituto di Fisica del Plasma, CNR, Milan, Italy
[6] CCFE, Culham Science Centre, OX14 3DB, Abingdon, UK
[7] National Institute for Cryogenics and Isotope Technology, Rm. Valcea, Romania

**See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

Joint European Tokamak JET

JET investigates the potential of fusion power as a safe, clean, and virtually limitless energy source for future generations. The largest tokamak in the world, it is the only operational fusion experiment capable of producing fusion energy. As a joint venture, JET is collectively used by more than 40 European laboratories. The European Consortium for the Development of Fusion Energy, EUROfusion for short, provides the work platform to exploit JET in an efficient and focused way. As a consequence more than 350 scientists and engineers from all over Europe currently contribute to the JET programme.

Plasma diagnostic aims to determine plasma temperature and density, to measure plasma particle and radiation losses, to find out the magnetic topology and to observe plasma flows and fluctuations.
Physicists observe the plasma from the outside, applying as many different methods as possible and exploiting a great variety of physical phenomena, ranging from atomic effects and nuclear reactions to radiation propagation and electromagnetism.

www.euro-fusion.org

JET

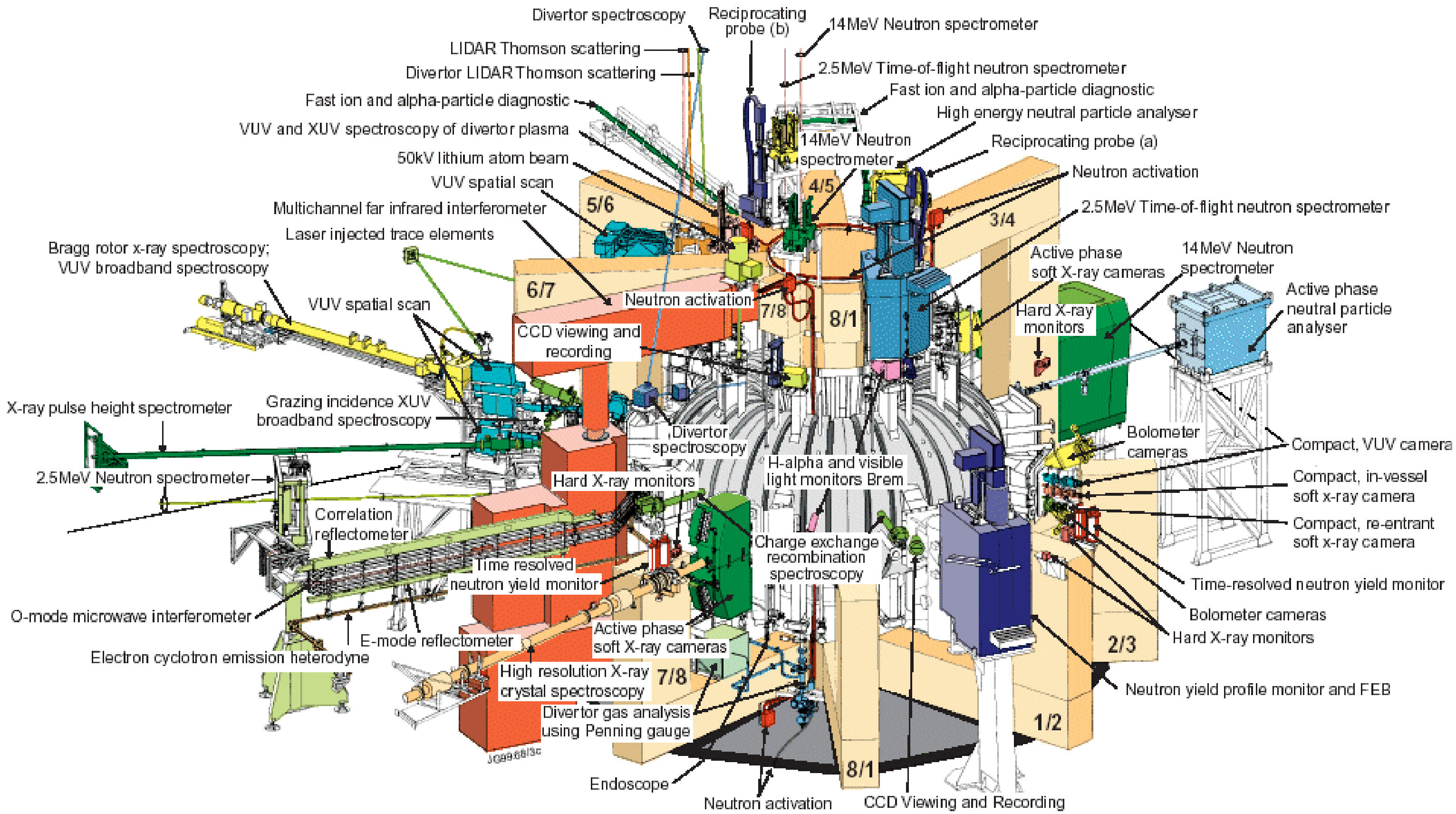
JET DIAGNOSTICS

At JET, signals from all diagnostic systems are digitised and stored in a central database. Every JET pulse produces almost 8 GBytes of raw diagnostics data.

Most of the data need further processing – this is done automatically where possible by dedicated computer codes, but in many cases human intervention and/or data validation is required.

All data are accessible to all scientists on the JET site and, moreover, any scientist from any EUROfusion Research Unit has remote access to the data from their home institute.

JET DIAGNOSTICS



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

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

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

	DTE1@JET	DTE2@JET
year	1997	> 2017
14 MeV neutron budget	2.5×10^{20}	1.7×10^{21} (proposed)
Wall/Divertor	CFC/CFC	Be/W
NBI	~21 MW in D &T ~10 MW in H	~35 MW in D & T ~14 MW in H
ICRH (H-mode)	2-4 MW	3-8 MW (includes ITER-like antenna)
LHCD	2-3 MW	2-3 MW
ITER Scenarios	H-mode at q_{95}~3	H-mode at q_{95}~3, Hybrid, Advance Tokamak
Fusion product diagnostics	2.5 MeV-14 MeV neutron cameras	· New neutron & gamma detectors · Active TAE antennae
Tritium in Active Gas Handling System / JET	20 g / ~100 g (incl. NBI)	60 g / 500-1000 g (incl. NBI)
Fusion Technology tasks	· Long term retention CFC · Activation samples	· Long term fuel retention in Be/W · Activation of ITER materials · Radiation damage in functional materials · Validation of neutronics codes · 14 MeV neutron calibration

H. Weisen et al., AIP Conference Proceedings 1612, 77 (2014)

What do we want to measure in DTE2@JET

Fusion reaction rate:

Neutron and **γ-ray** diagnostics

Spatial α-particle distribution & redistribution effects:

Neutron and **γ-ray** diagnostics

α-particle energy distributions:

γ-ray and neutron spectrometry, neutral particle analyser

α-particle slowing down & confinement:

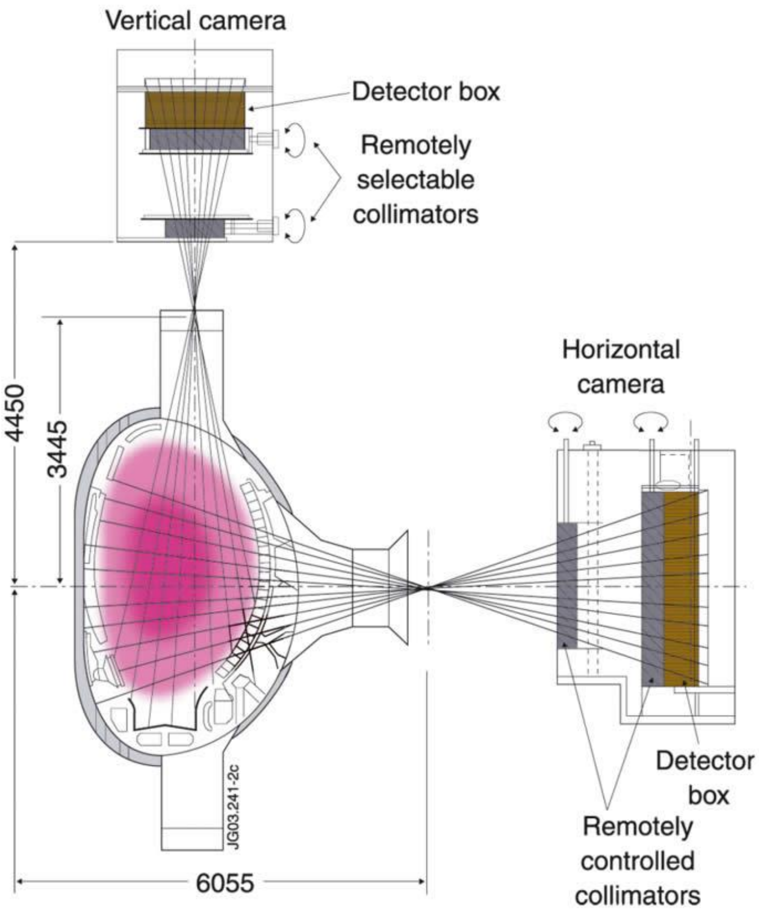
γ-ray diagnostics

α-particle losses:

Scintillator Probe, Faraday Cups, **γ-ray** diagnostics

V.Kiptily, 1st KM6T Group Meeting, 17th May 2013, Culham, UK

Gamma (and neutron) Camera at JET



Two cameras

Vertical: 9 lines-of-sight
Horizontal: 10 lines-of-sight
Remotely controlled collimators
with two apertures (Φ10 and 21 mm)
Space resolution: ~8 (or ~15) cm (in the centre)

Detectors

- NE213 liquid scintillators (2.5 &14 MeV neutrons)
- Bicron-418 plastic scintillators (14 MeV neutrons)
- **CsI:Tl photo-diodes (hard X-rays and γ-rays)**
- Fast digital Data Acquisition system
- Pulse Height Analysis
- Neutron and γ-rates in real time for all channels

JET

Gamma Spectrometer at JET

Tangential Gamma Spectrometer

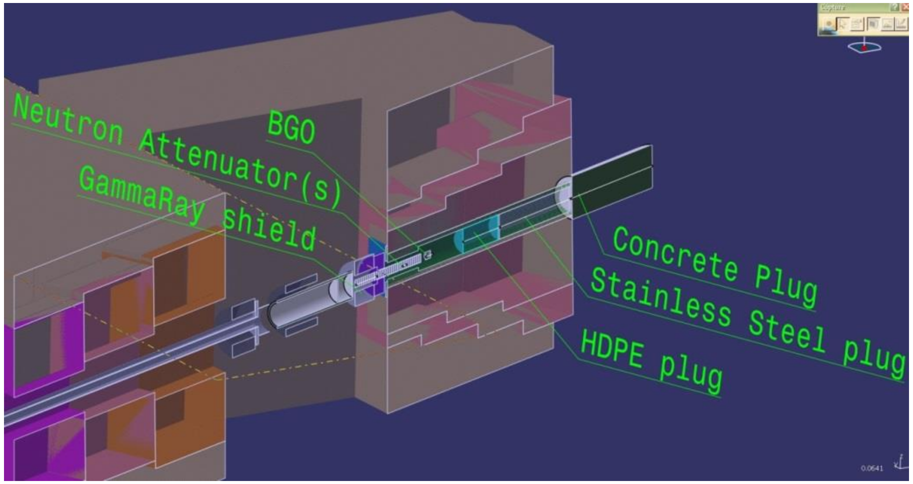
bismuth germanate (BGO) scintillator with a diameter of 3” and a height of 3”.

In order to reduce the neutron flux and the γ-ray background, the front collimator is filled to a depth of 500 mm with polythene.

Behind the scintillation detector, there is an additional 500 mm long dump of polythene and a 1000-mm long steel plug.

The detector's line of sight lies in a horizontal plane about 30 cm below the plasma magnetic axis.

Energy resolution of about 4% at 10 MeV.



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

These projects are implemented under the EUROFusion Consortium for the period
1st January 2014 to 31st December 2017

and they are parts of the JET Enhancements Programme WPJET4

JET

In laboratory conditions radioactive sources used 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**

JET

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.

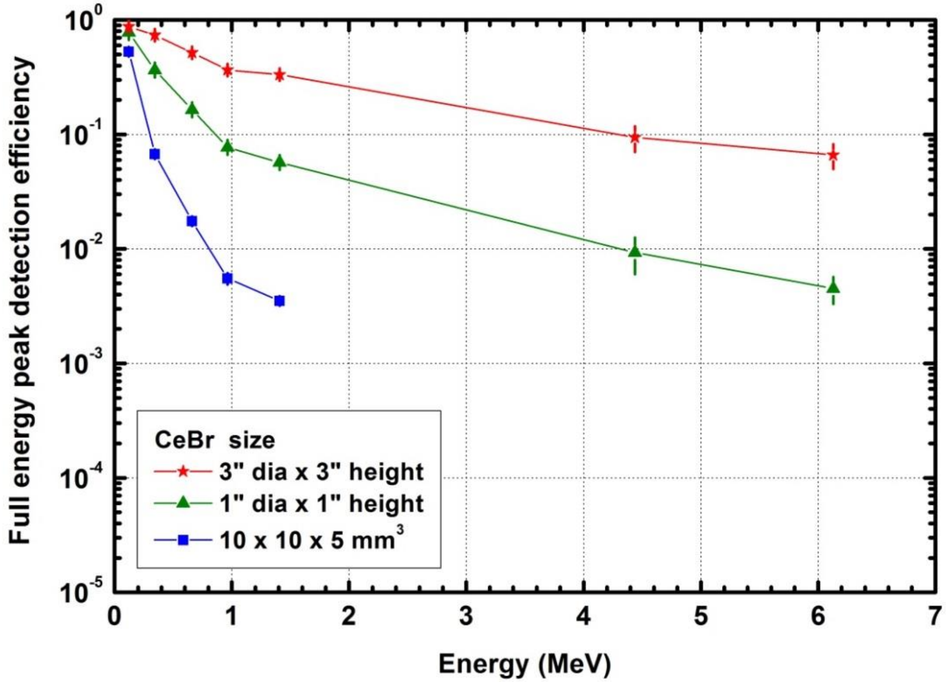
Scintillators

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

Photodetectors

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

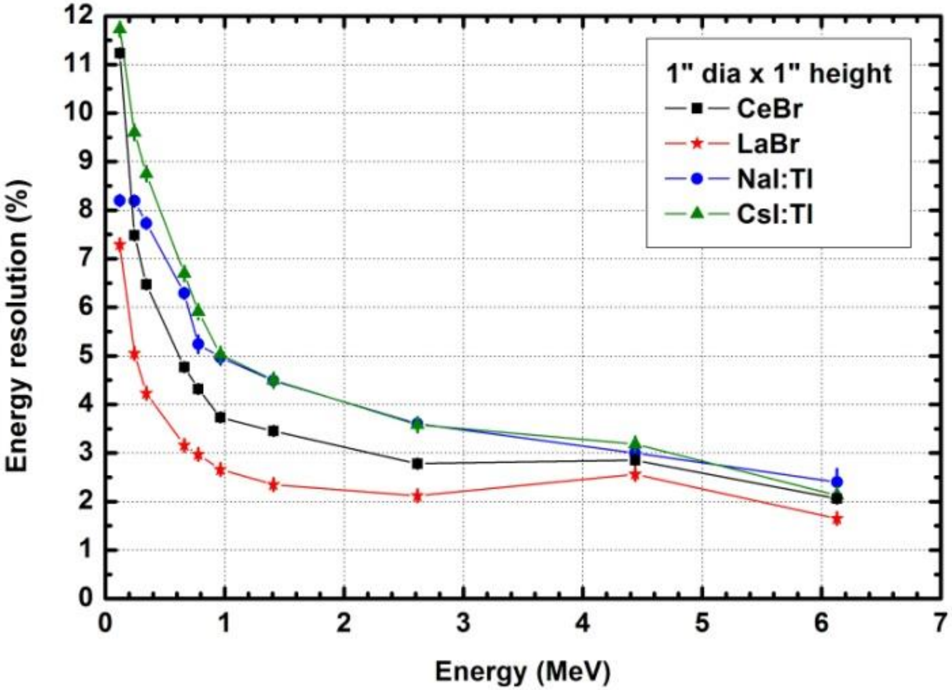
Detection efficiency vs. detector size



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 in this scintillator during acceptable acquisition time.

Energy resolution

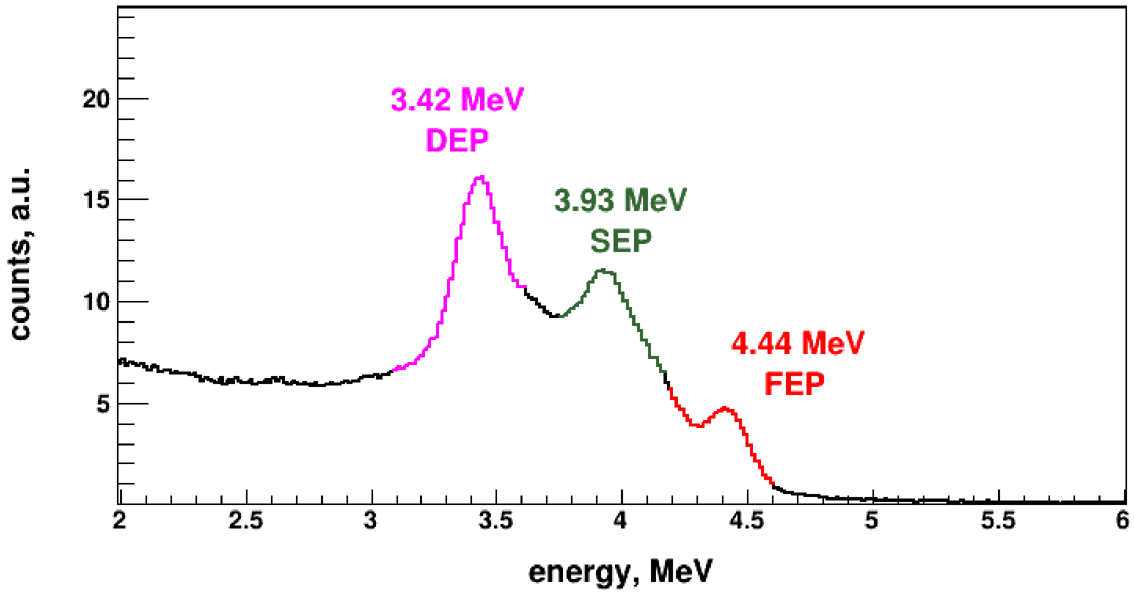


Energy resolution for 1”×1” scintillators

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

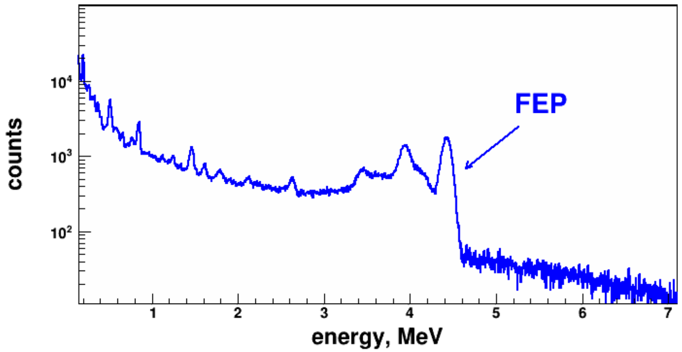
Doppler broadening effect linked to the emission of 4.44 MeV γ-rays from the excited state of ^{12}C

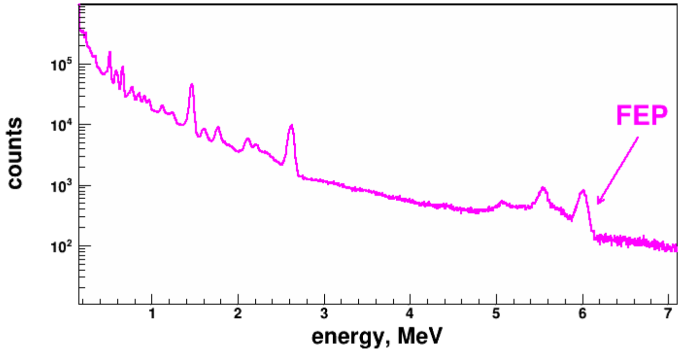
Response of 1”×1” CeBr3 scintillator to PuBe source emitting 4.44 MeV γ-rays



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

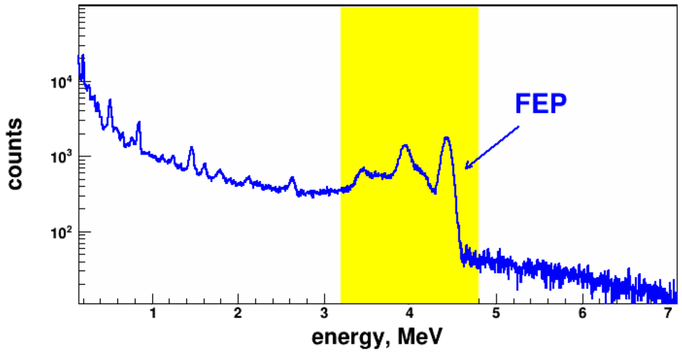
FEP at E_γ = 4.44 MeV

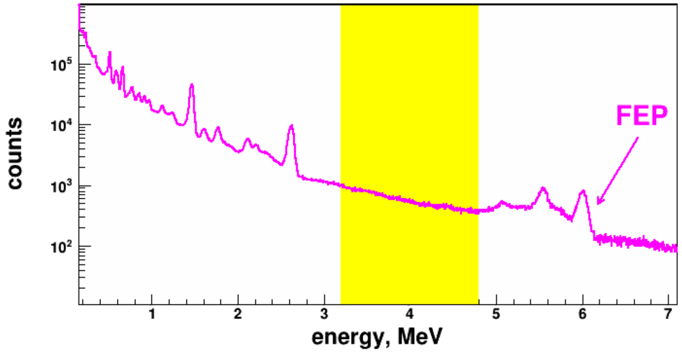
PuC

FEP at E_γ = 6.13 MeV

JET

3” x 3” $CeBr_3$ + PMT





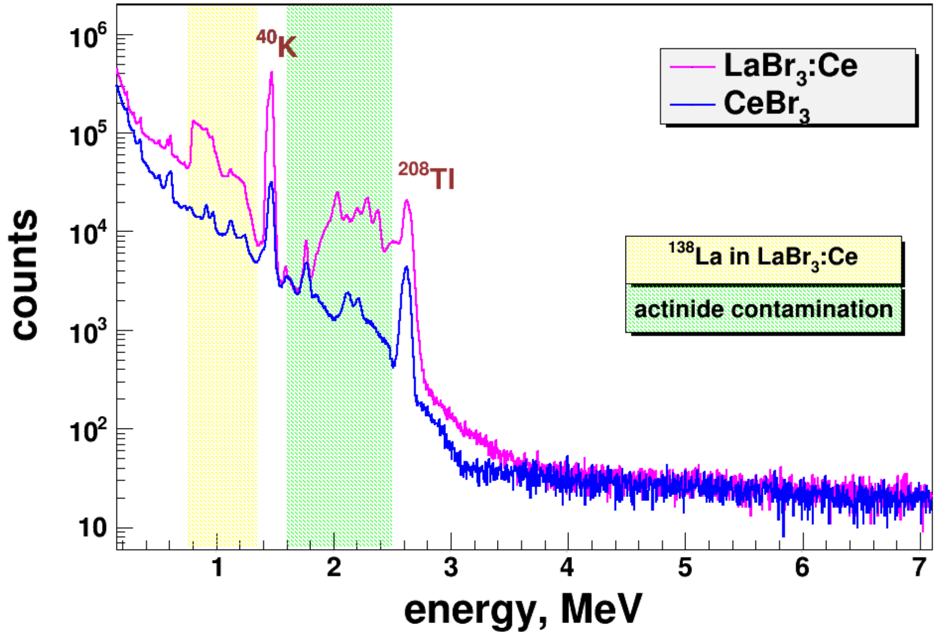
PuBe

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



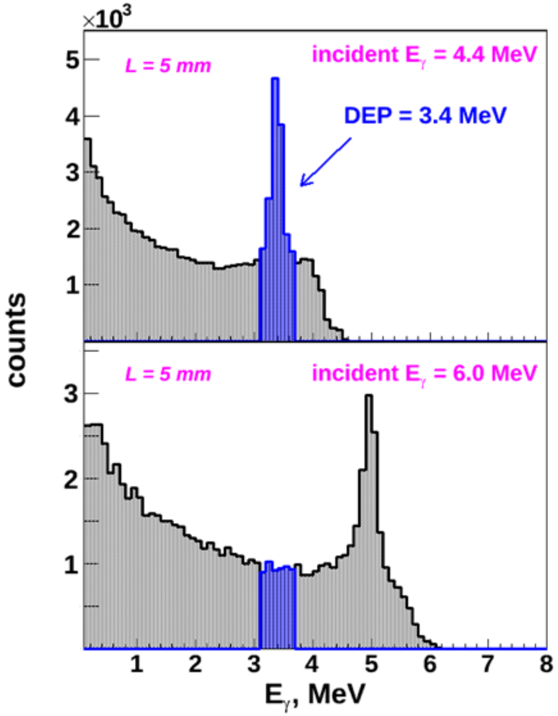
Natural background: ^{40}K (1.461 MeV), ^{208}Tl (2.615 MeV)

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

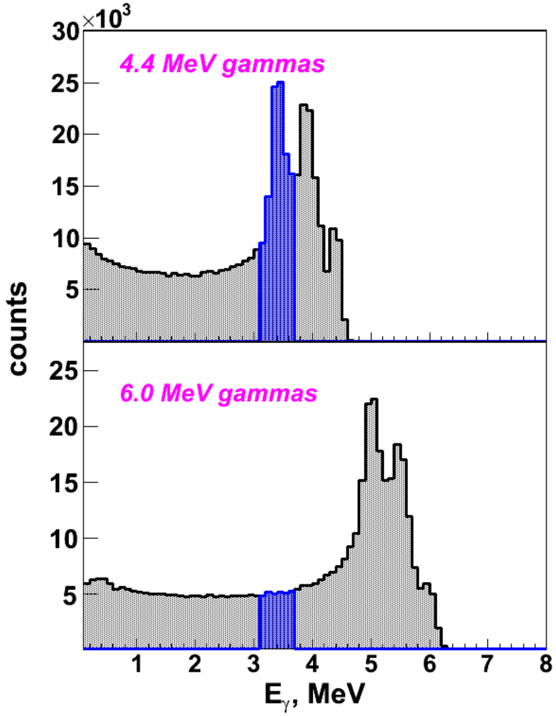
Events due to internal contamination by actinides: 1.5-2.5 MeV

JET

MONTE CARLO SIMULATIONS WITH GEANT4

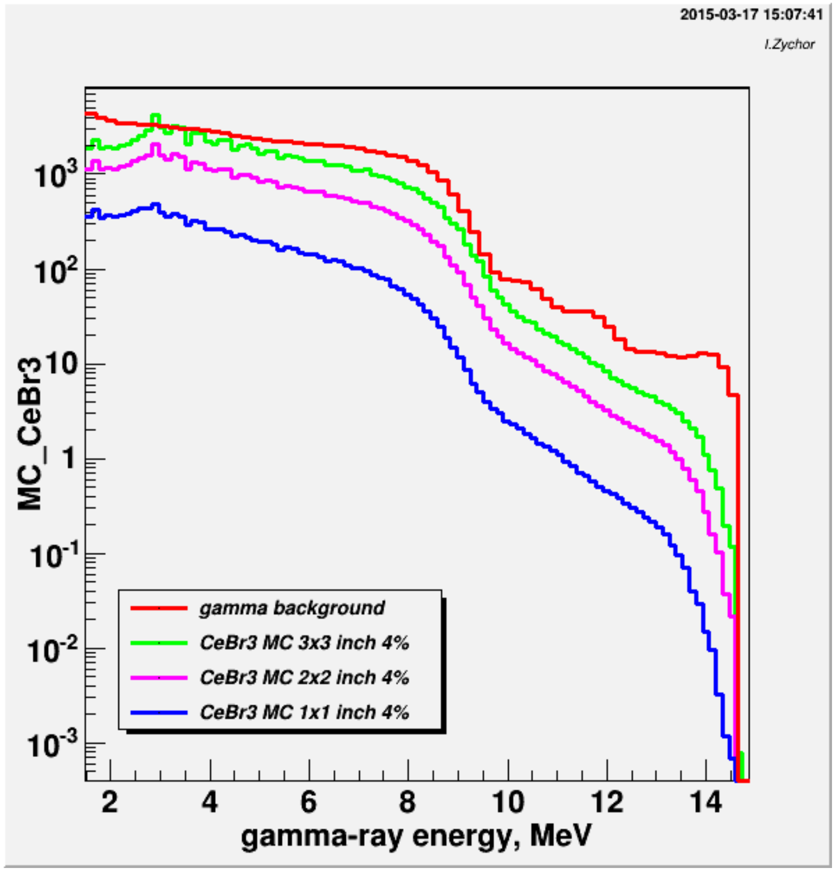


L = 5 mm, ϕ = 20 mm



L = 35 mm, ϕ = 35 mm

JET



Monte Carlo simulations for $CeBr_3$ scintillators with different size performed to evaluate a detector response to gamma radiation in DT experiments

0 approx. gamma-ray background normalised to the integral spectrum provided by V.Kiptily. The spectrum covers a range of gamma ray energy from 1.5 to 14.9 MeV.

$$D + T \rightarrow {}^5He + \gamma\ (16.6\ MeV)$$

$$D + {}^3He \rightarrow {}^5Li + \gamma\ (13.7\ \&\ 16.7\ MeV)$$

A comparison of normalised event numbers obtained from Monte Carlo simulations.

$CeBr_3$ scintillator	average event number	event number at 1.5 MeV	event number at 4.4 MeV	event number at 6.1 MeV
1”x1”	1.0	1.0	**1.0**	1.0
2”x2”	4.1	4.3	**4.6**	5.0
3”x3”	8.1	8.8	**9.4**	10.8

Scintillators

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

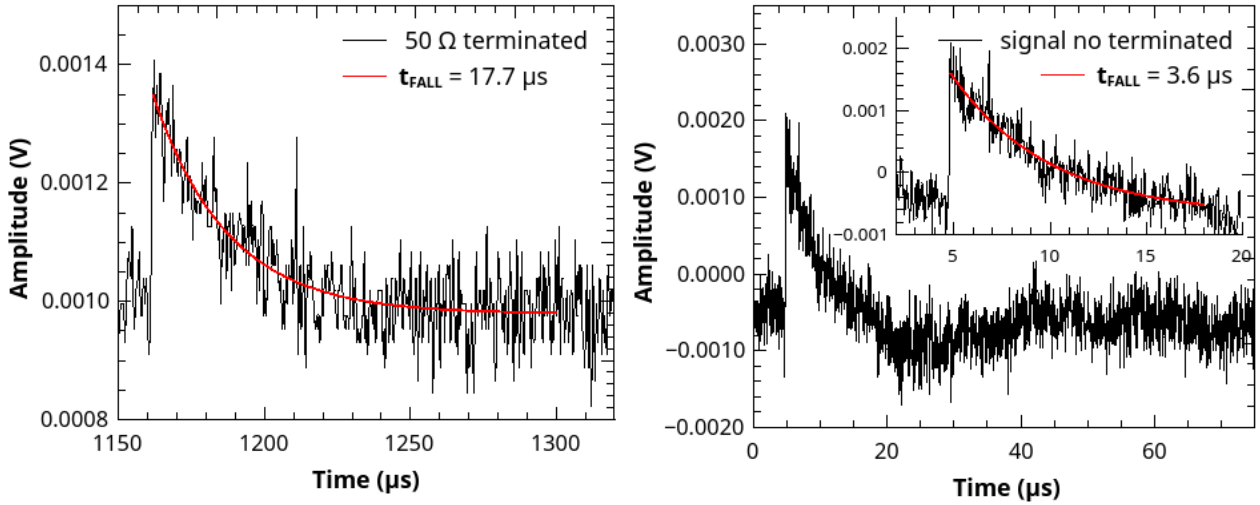
- fast response
- high gain resulting in good energy resolution
- immunity to magnetic field

Main drawbacks

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

Detector setup based on $CeBr_3$ coupled to PiN diode photodetector

1. the observed signals are very similar with the signals from CsI:Tl based detectors, currently installed at JET
2. signals characterized by a very low signal to noise ratio and much longer signal time
3. over 60% worse energy resolution for ^{137}Cs source in comparison with a MPPC based detector



Examples of pulses stored at 2.5 Msps rate with 50 Ω channel termination (left) and without termination (right). Fitted red curves defines a fall time of signals to be equal to 17.7 μs and 3.6 μs, respectively. The time scale is relative.

Silicon-based photodetectors

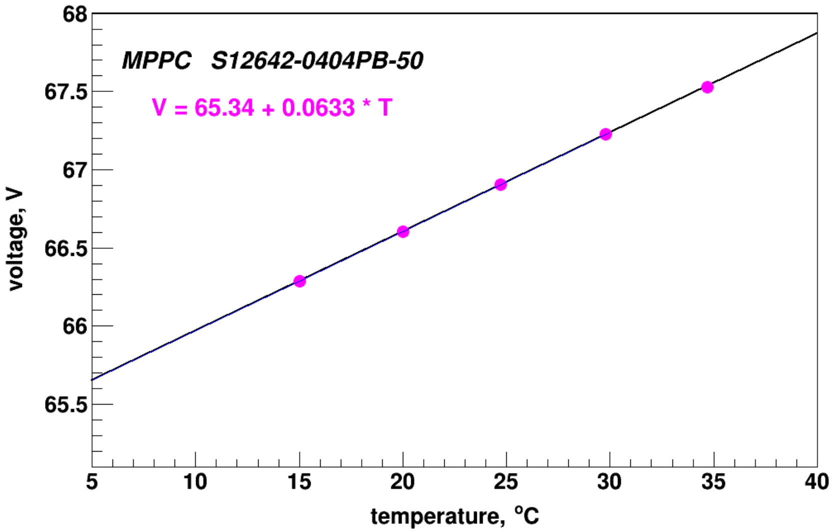
MPPC - Multi-Pixel Photon Counter – is a silicon-based monolithic array of micro-pixel avalanche diodes operating in a Geiger mode.

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.

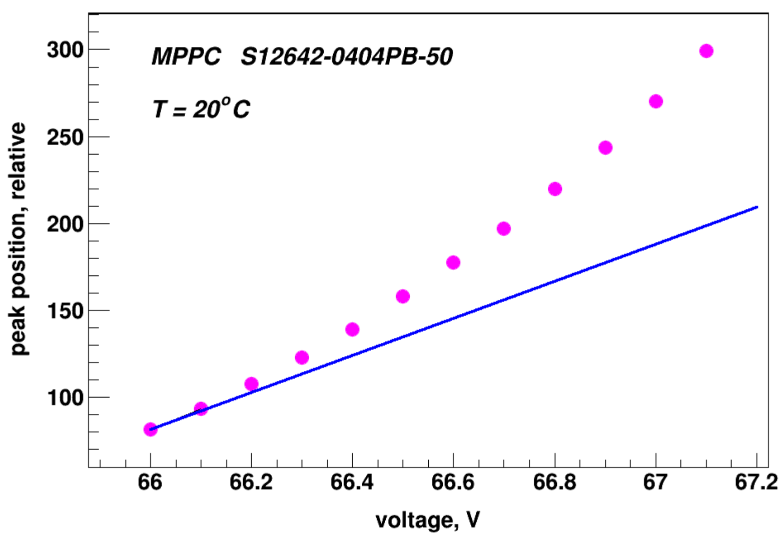
MPPC is therefore an alternative to a photomultiplier tube if operating at high count rate in harsh radiation environment.

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

Temperature and voltage dependence of MPPC detectors

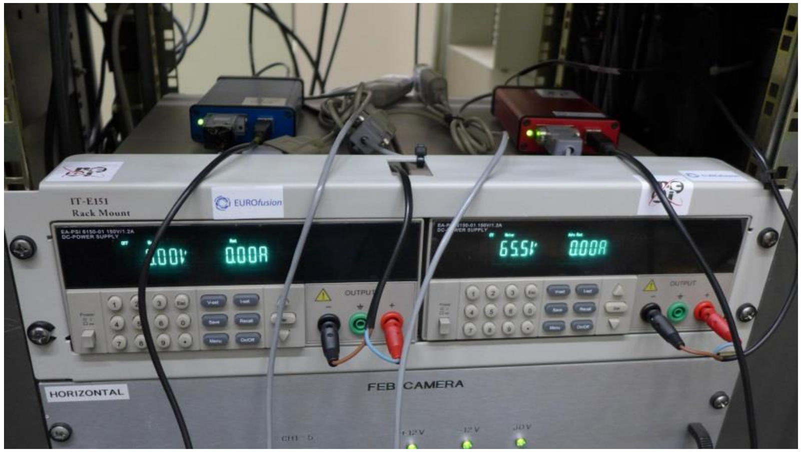


Peak position and voltage dependence of MPPC detectors



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

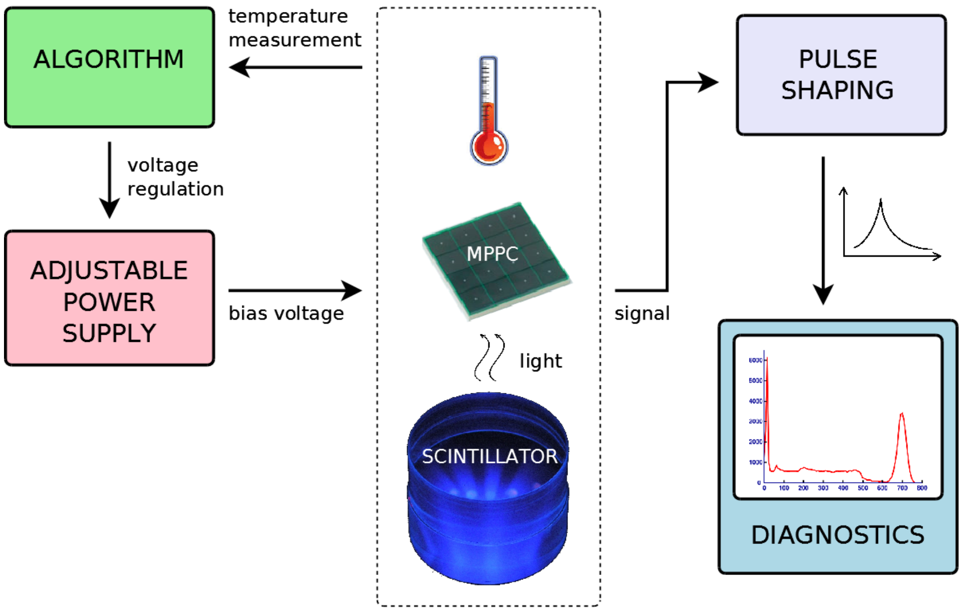


installed at JET in May 2015

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

JET

MTCD@ NCBJ



MTCD@NCBJ, a temperature compensation device, is based on an Atmega128 microcontroller, controlling an EA-PSI6150-01 power supply by an opto-isolated serial interface.

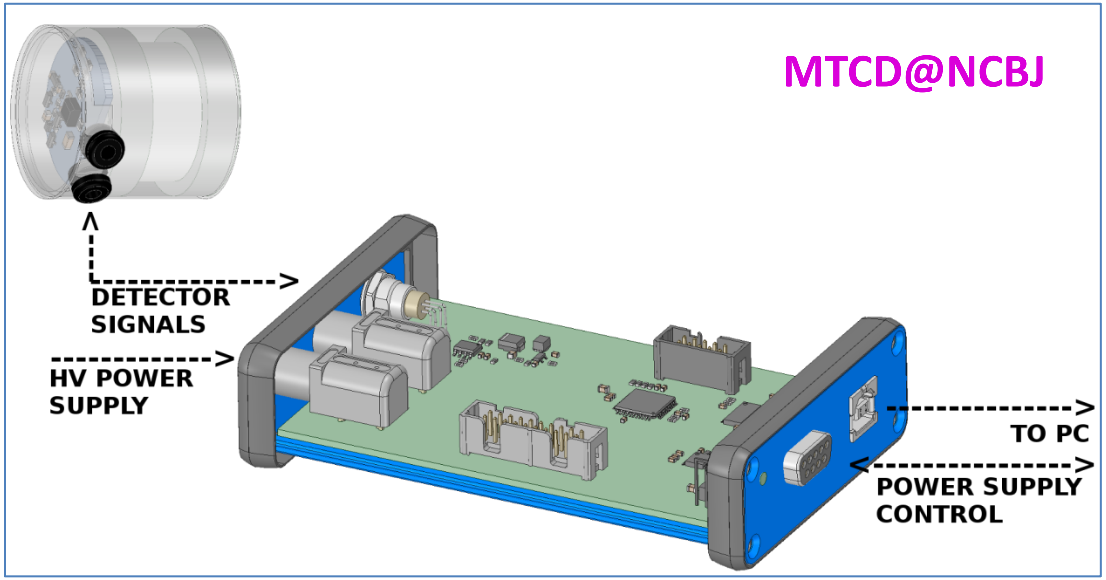
Temperature of the scintillator is measured by a TSIC506F digital thermometer integrated with the detector. The thermometer has an accuracy of ±0.1°C in a temperature range from +5 to +45°C.

MTCD@NCBJ is using a measured dependence of a bias voltage on temperature to maintain a constant value of the MPPC gain. The device can supply an output voltage up to 80 V.

All functions are controlled from a personal computer.

Dedicated MPPC based system for detectors

installed at JET in May 2015



Aluminium cylinder detector capsules

Φ 35 × H 35 mm

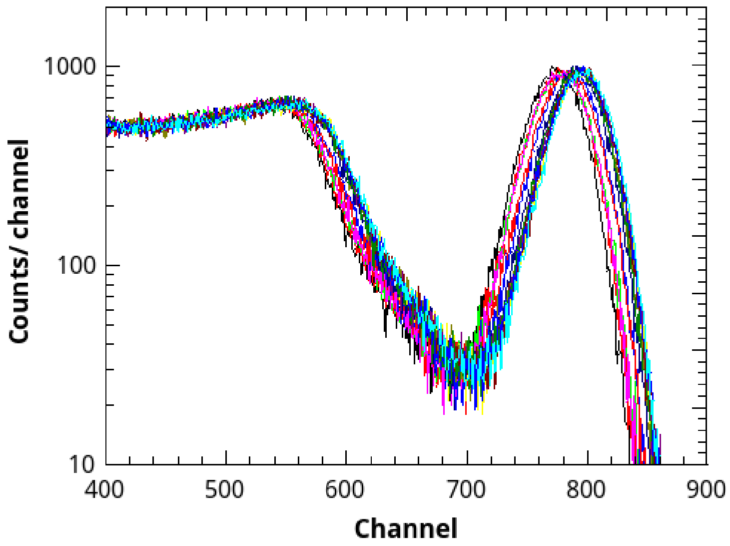
mounted on a slider

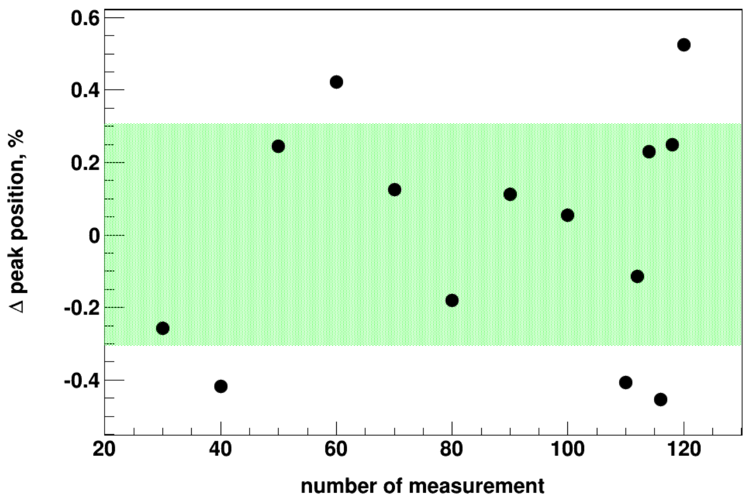
At JET in four conductors of 80 m long electrical cables, 2 conductors were chosen to be used only for MPPC power supply.

Two other conductors were used to send measured temperature values to a C&M system from MTCD@NCBJ.

JET

MTCD@ NCBJ PERFORMANCE

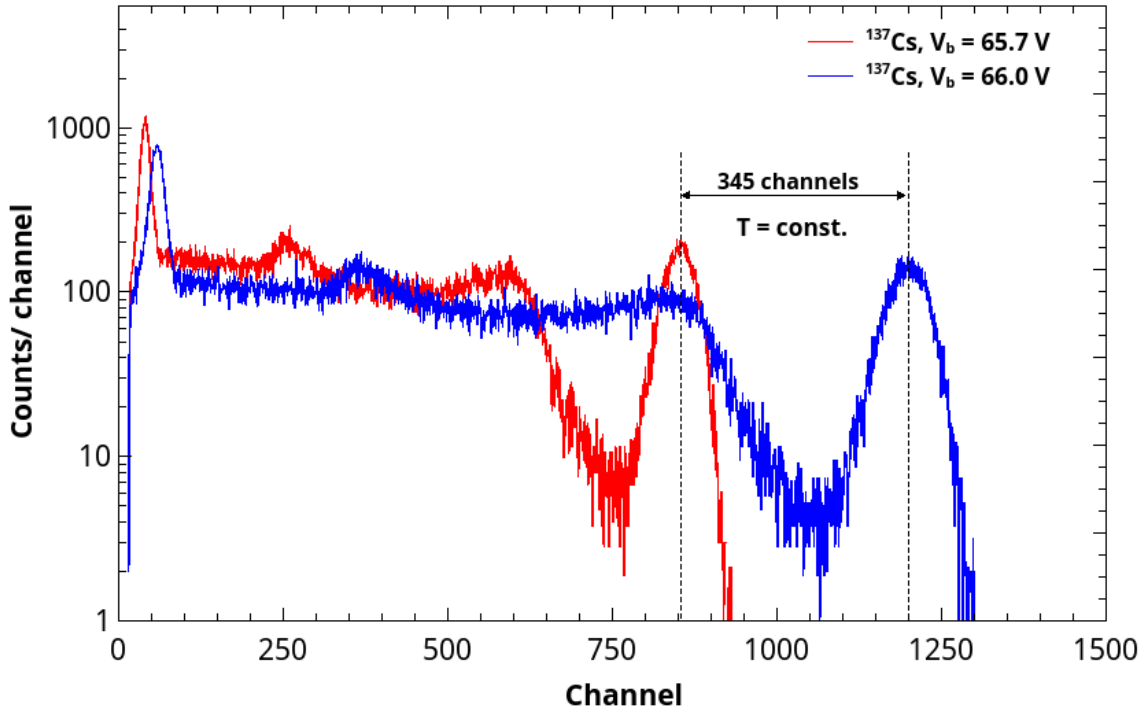




- ***661.7 keV gamma line measured with 20×15 mm $CeBr_3$ scintillator***
- ***120 measurement sessions at NCBJ, each lasted 500 s of live time***
- ***17 hours of measurements during day and night with ΔT=2-3°***
- **change in Full Energy Peak (FEP) position below 1%**

JET

MTCD@ NCBJ PERFORMANCE



^{137}Cs spectra measured at constant room temperature

at different MPPC bias voltage: 65.7 and 66.0 V

ΔU_b=100 mV → ΔFEP ≈ 100 channels

ΔT = 1°C → ΔU_b=70 mV

Gamma Camera Upgrade (GCU)

- The Gamma Ray Camera in JET is equipped with a detector array which comprises 19 CsI:Tl photodiodes with a diameter of 20 mm and a thickness of 15 mm.
- CsI:Tl crystals are characterised by a comparatively long scintillation decay time, around 1000 ns.
- At the expected high counting during DT campaigns (in MHz range) it is required to replace CsI:Tl by detectors with a shorter decay time, e.g., $CeBr_3$ or $LaBr_3$:Ce detectors with a scintillation time around 20 ns.
- New detector material should not contain oxygen to avoid unwanted background due to a reaction on oxygen.
- Resistance to high neutron/gamma fluxes – no degradation in energy resolution

JET REQUIREMENTS

1. **limited space for a MPPC-based scintillation detector → dedicated detector setup fitted to "old" CsI:Tl capsules**
2. **new electronics using existing cabling: 80 m long cables, four wires in a cable**
3. **power supplies and control system put in one box**

JET

Measurements at JET

^{22}Na spectrum measured by CeBr$_3$ coupled to MPPC in the Gamma Camera channel 9 in May 2015

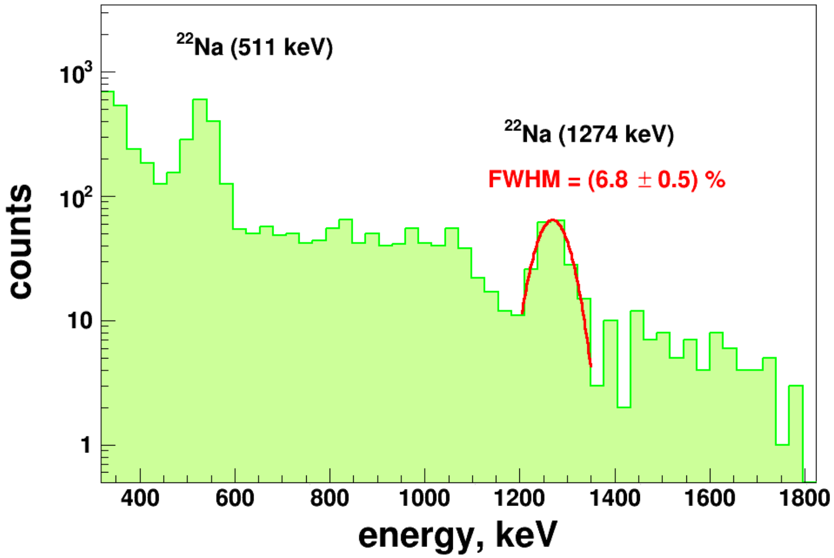
data acquired at ***200 MSPS***

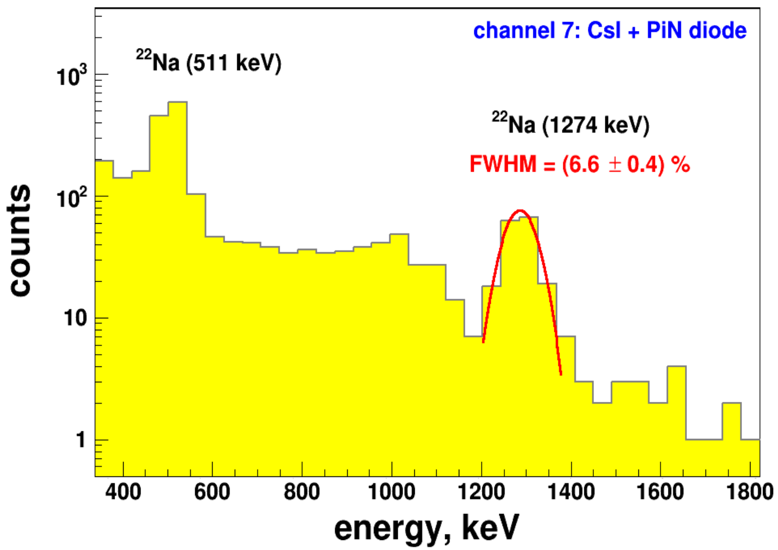
spectra built with a fast, non-optimized algorithm

^{22}Na spectrum measured by CsI:Tl coupled to PiN diode in the Gamma Camera channel 7 in May 2015

data acquired at ***2.5 MSPS***

spectra built with an optimized algorithm for CsI:Tl pulses



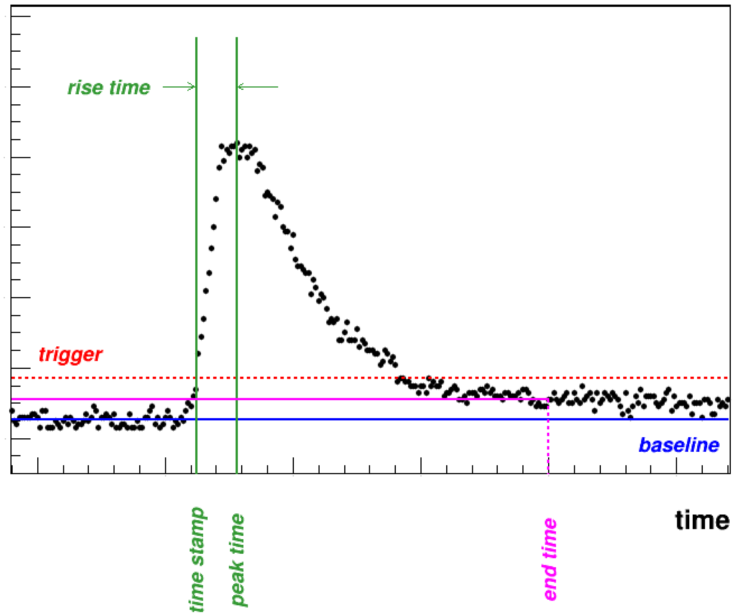


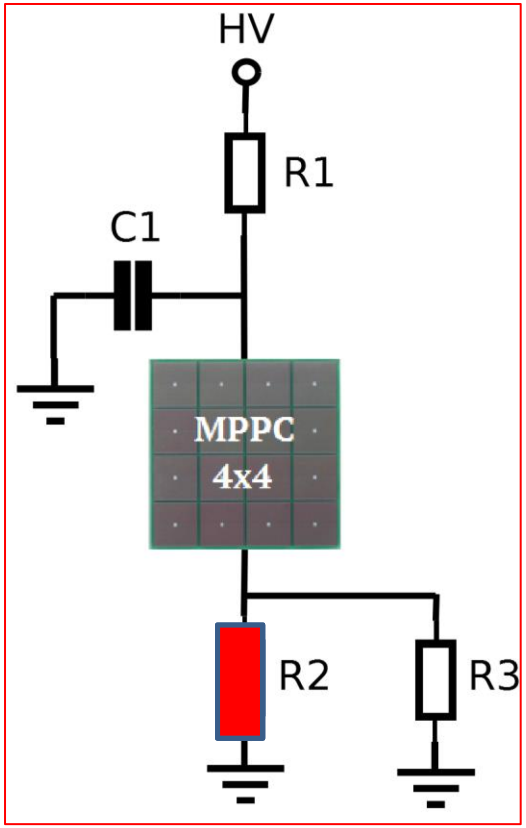
JET

Detectors based on $CeBr_3$ coupled to MPPC

1. Detector signals registered in the setup are characterized by a good signal to noise ratio and short total length.
2. MTCD@NCBJ optimises a detector operation in varying temperatures.
3. MTCD@NCBJ is easily extended to a setup for 19 detector system.
4. 19 MPPC power supplies will be integrated in C&M box.
5. Measured temperature values will be off-line available for further use, including date and time information.

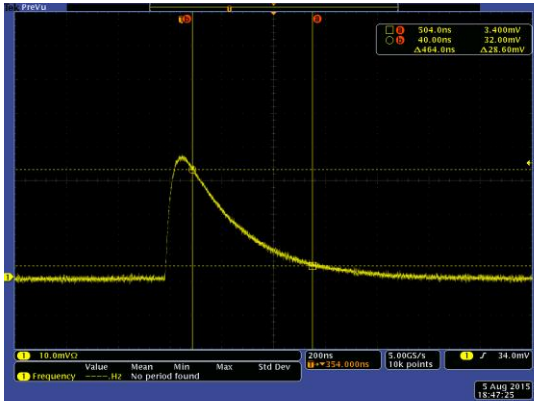
Signal shortening

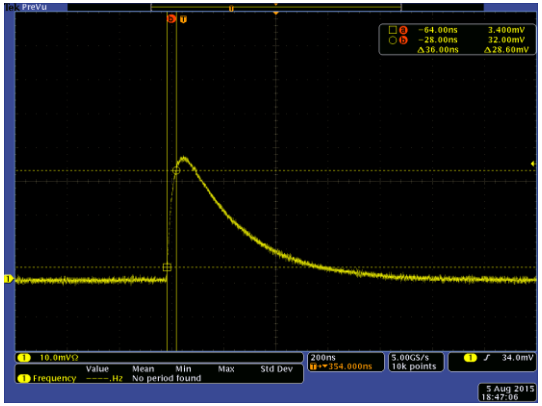




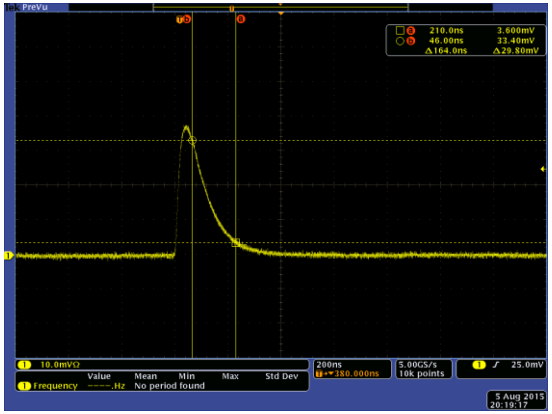
Signal shortening

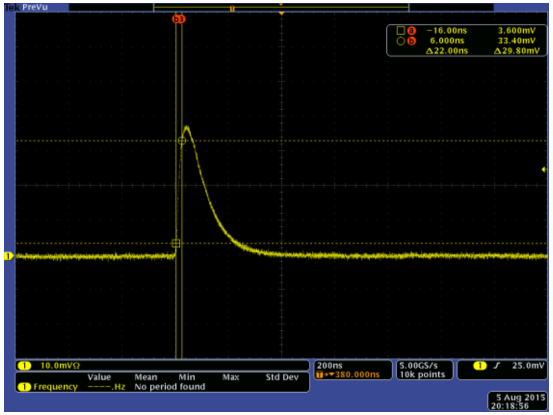
PRELIMINARY – FIRST APPROACH





rise = 36 ns , fall= 464 ns for R_2 = 750 Ω, FWHM(662 keV) = 8.4%

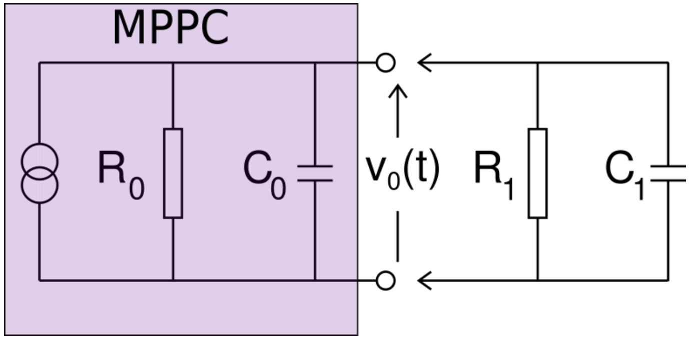


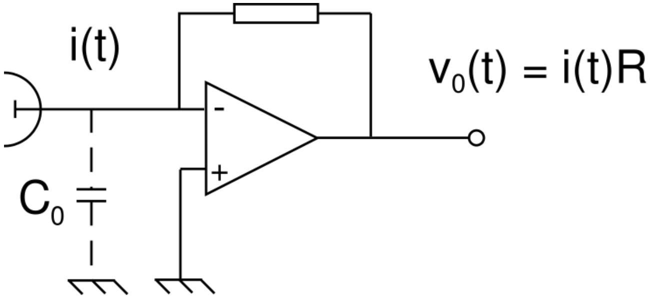


rise = 22 ns , fall = 164 ns for R_2 = 18 Ω, FWHM(662 keV) = 9.7%

JET

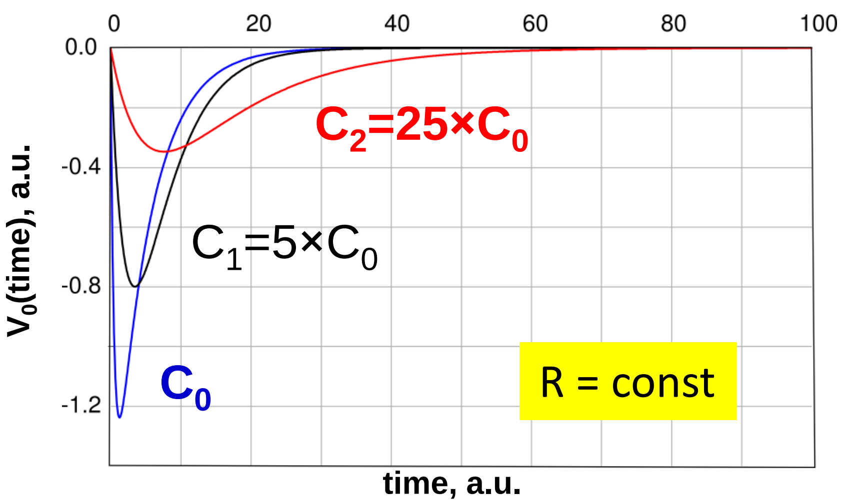
Transimpedance Amplifier (TIA)

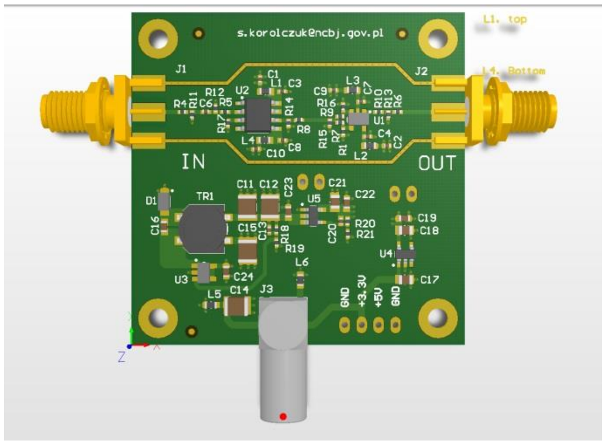




Voltage V_0(time) of the output signal depends on a time constant $\tau = R_1C_1$

TIA isolates MPPC output capacitance from the current i(t) converting resistor



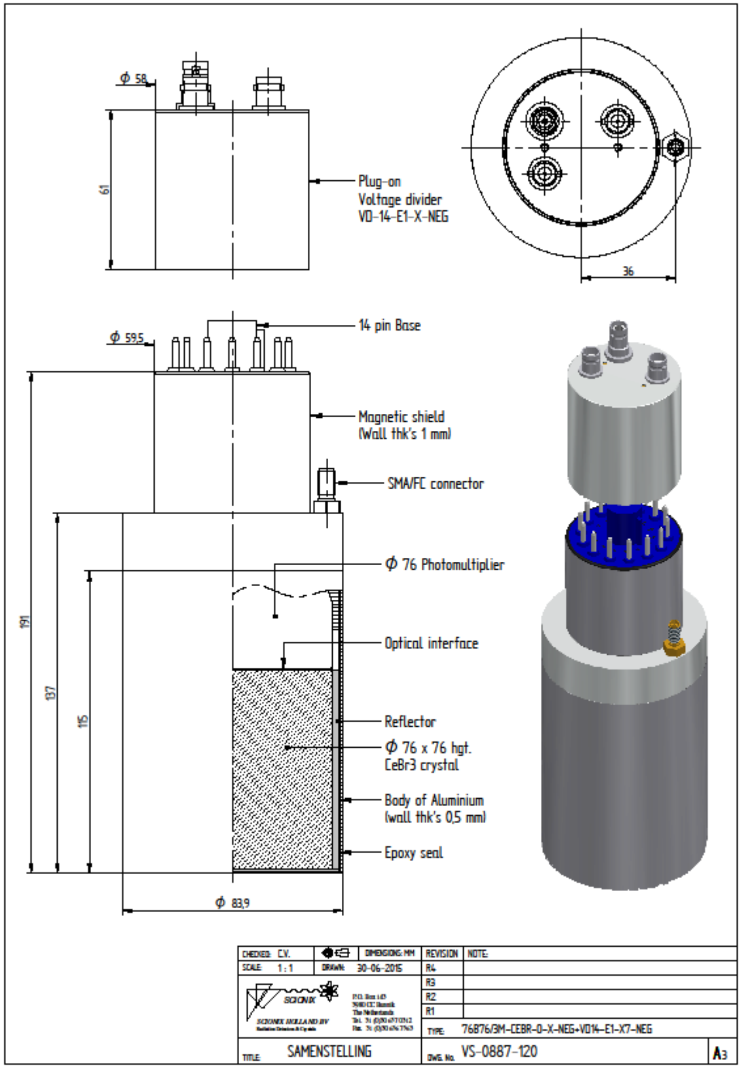


TIA designed at NCBJ

Gamma Spectrometer Upgrade (GSU)

- Replacement of the existing BGO detector in the Gamma Spectrometer
- Gamma ray detector must work at high count rates – detector based on the BGO scintillator has a long decay time and old electronics that does not fulfill requirements for high count rate measurements (DT experiments).
- New material should not contain oxygen to avoid unwanted background.

SCINTILLATOR FOR GSU

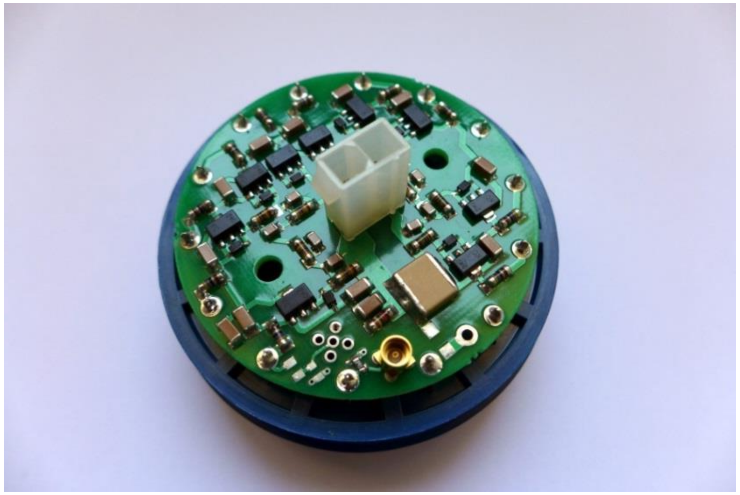


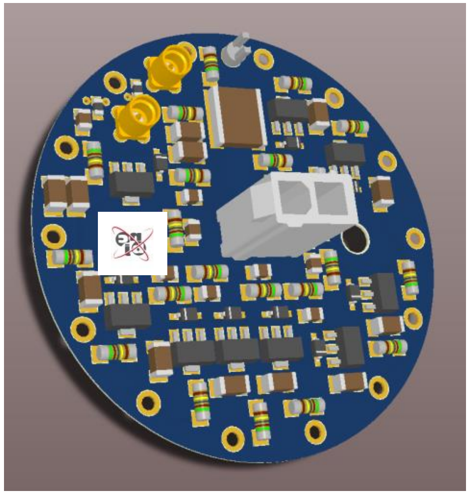
SPECIFICATION

- 3”×3” $CeBr_3$ scintillator
- 0.5 mm aluminium housing
- R6233-100 PMT
- SMA connector
- HV divider
- 1 mm µ-shielding

Dedicated high voltage divider for GSU designed at NCBJ

- HV up to 1.5 kV
- designed for high count rate applications
- for 3" PMT
- 14 pin standard socket
- easy removable to replace components
- fully active design
- anode and last dynode signal output





JET

Lost Alpha Gamma Rays Monitor (LRM)

- **For lost α-particle studies, a new diagnostics is proposed**
- **Early closed project - final decision made on July 3rd, 2015**
- **IPPLM contributions**
  - design, manufacture and installation of two KA4 detectors based on $CeBr_3$, similar to GCU detectors
  - calculation of KA4 detector response function