Characterization of scintillators for gamma-ray spectrometry of fusion plasma

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Hard X-ray and γ-ray diagnostics in magnetically confined plasmas, investigated presently at various tokamaks and foreseen for the International Thermonuclear Reactor (ITER), provide crucial information on behaviour of fast electrons, fusion reaction products and other fast ions.

The energetic ions give rise to the intense γ-ray emission reacting with either fuel ions or the main plasma impurities, including beryllium admixtures.

Gamma-ray intensities and their energy spectra recorded with collimated spectrometers provide information on the energy and spatial distributions of fast electrons and ions in plasmas by means of reconstruction of measured 2D γ-ray emission profiles.

Time resolved γ-ray profile measurements provide important information on the time evolution of processes taking place in the plasma volume during high temperature discharges.

Parameters of γ-ray detector in tokamak experiments

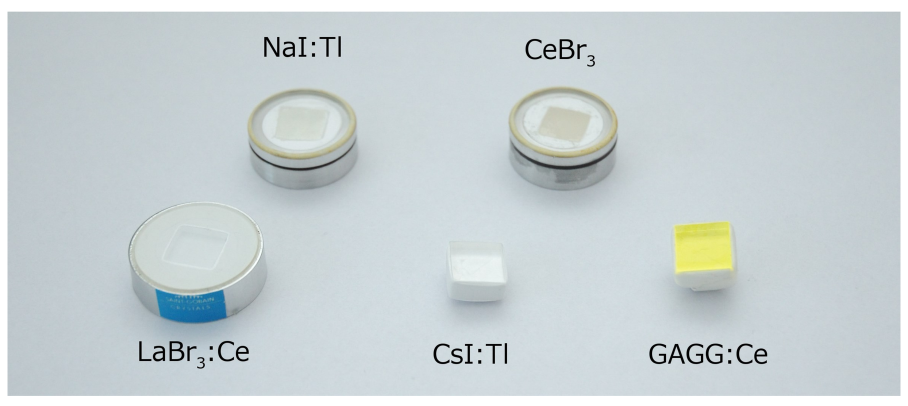
- **fast response** to incident radiation, especially important for deuterium-tritium (DT) experiments with expected high counting rates up to a few Mcps,
- **high energy resolution** depending on detector material,
- **proportionality** of the output signal to absorbed γ-ray energy,
- **high efficiency** of the γ radiation detector.

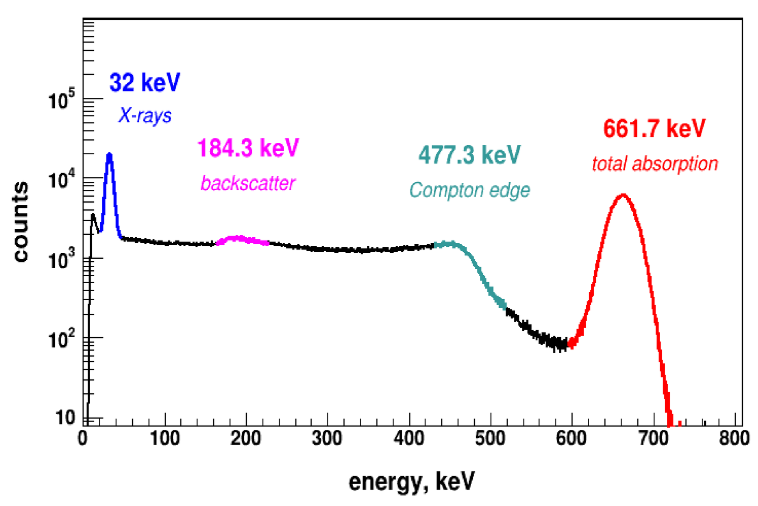
Scintillators:

good candidates for tokamak experiments

Since decay time, energy resolution and proportionality only slightly depend on a crystal size, presented results are used to limit number of scintillator samples investigated in the next step of our work.

All scintillators used in this study have the same size of 10×10×5 mm^3 and a cuboid shape. Due to a hygroscopic nature of NaI:Tl, $CeBr_3$ and $LaBr_3$:Ce materials, these crystals were assembled by manufacturers in aluminum containers with a glass window.





Energy spectrum of 661.7 keV γ-rays emitted from a ^{137}Cs source measured with the $CeBr_3$ scintillator.

The full energy peak (total absorption peak) appears at 661.7 keV.

If the photon is not absorbed, it deposits a part of its energy in a Compton continuum, with a Compton edge equal to 477.3 keV.

The backscatter peak is also noticeable at 184.3 keV.

An absorption peak of 32 keV KX-rays emitted by the ^{137}Cs source is seen.

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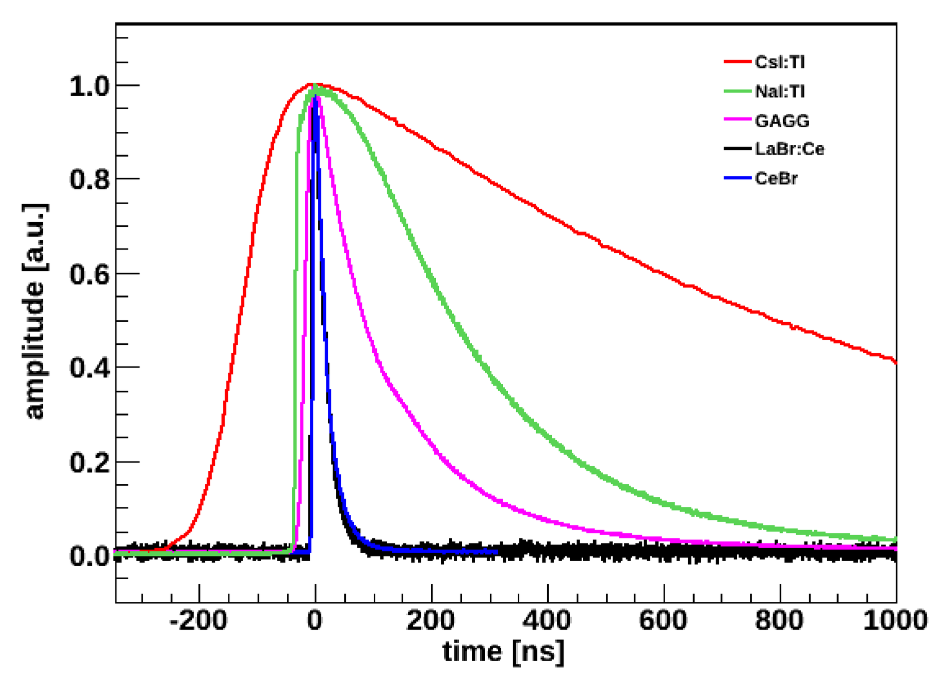
Decay time

The decay time of the scintillation materials plays crucial role in registration of large amount of events emitted during operation of tokamak. Slow response of a scintillator can results in significant contribution of pile-up events under tokamak operation at high count rate up to a few Mcps.

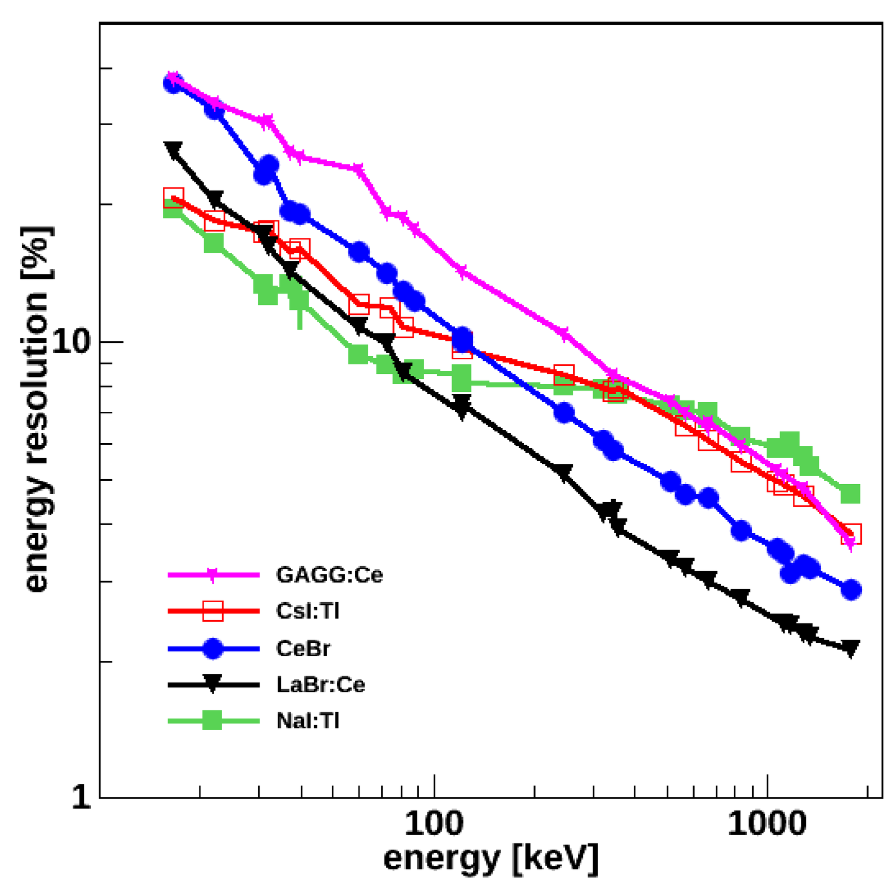


The fastest response is observed for $LaBr_3$:Ce and $CeBr_3$ scintillators.

The response of GAGG:Ce and NaI:Tl is one order of magnitude slower, however the decay time is still moderate.

Because of slow response observed for CsI:Tl, detectors based on this crystals are less useful for high performance tokamak plasma diagnostics.

Energy resolution



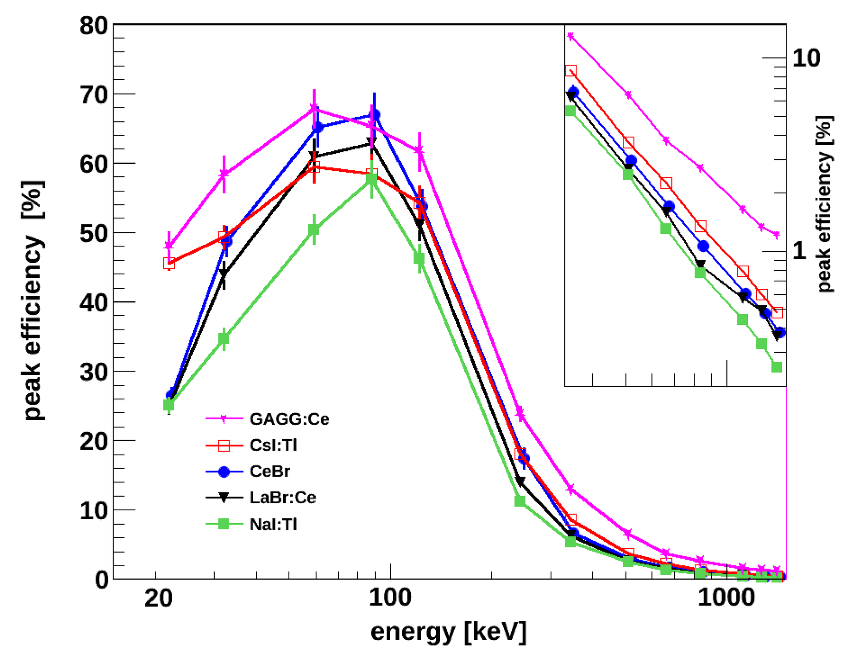
crystal	59.5 keV ^{241}Am	1115.5 keV ^{65}Zn	1770.2 keV ^{207}Bi
CsI:Tl	(12.5 ± 0.3) %	(4.9 ± 0.1) %	(3.8 ± 0.1) %
NaI:Tl	(9.4 ± 0.2) %	(5.9 ± 0.2) %	(4.6 ± 0.1) %
$LaBr_3$:Ce	(10.8 ± 0.3) %	(2.4 ± 0.1) %	(2.1 ± 0.1) %
$CeBr_3$	(15.7 ± 0.4) %	(3.4 ± 0.1) %	(2.9 ± 0.1) %
GAGG:Ce	(23.9 ± 1.0) %	(3.7 ± 0.2) %	(3.7 ± 0.1) %

The $LaBr_3$:Ce scintillator with an energy resolution equal to 2.9% at 661.7 keV and 2.1% at 1770 keV offers the best performance for gamma rays of energy above 100 keV.

This is due to: high light output, good matching of the emission spectrum with a photomultiplier quantum efficiency resulting in a high photoelectron yield and a linear response to gamma rays of energy from a broad range.

In the low energy range, CsI:Tl and NaI:Tl show similar performance to $LaBr_3$:Ce.

Full energy peak detection efficiency



Full energy peak detection efficiency.

For higher energies the dependence is also shown in the inset in a double logarithmic scale.

The full energy peak detection efficiency was calculated for gamma-ray sources with energies from 22 keV up to 1770 keV.

The measurements were performed for identical setup.

The full energy peak detection efficiency ε is determined by a number N of net counts in the full energy peak, a source activity A, a measurement time τ, a detection solid angle Ω and a branching ratio B of the reaction resulting in gamma-ray emission:

$$\varepsilon = \frac{N}{A \times \tau \times \Omega \times B}$$

Photoelectron yield

crystal	$N_{phe/MeV}$ (±3%)	$\tau_{shaping}$ (μs)
CsI:Tl	8900	6.0
NaI:Tl	12500	2.0
$LaBr_3$:Ce	20500	0.5
$CeBr_3$	17300	0.5
GAGG:Ce	5900	2.0

SUMMARY

We present a study of characteristic parameters describing 10×10×5 mm^3 cuboid scintillators, $LaBr_3$:Ce, $CeBr_3$, GAGG:Ce, CsI:Tl and NaI:Tl. Crystals were irradiated by gamma rays with energies from 16 keV up to 1770 keV.

Measurements were performed in the same experimental conditions with optimally matched photomultipliers. This kind of study allows us to draw general conclusions on possible use of scintillators in hard X-ray and gamma-ray tokamak plasma diagnostics dedicated for high count rate measurements.

$LaBr_3$:Ce and $CeBr_3$ scintillators are the best candidates for experiments in which a fast response of detectors is required, independent of gamma-ray energy.

For low count rates and lower energies, well-known and widely used CsI:Tl and NaI:Tl scintillators are still a reasonable option.

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