$LaBr_3$ scintillator response to admixed neutron and γ-ray fluxes

C. Cazzaniga[a,b,*], G. Croci[b], L. Giacomelli[a], G. Grosso[b], M. Nocente[a,b], M. Tardocchi[b], A. Weller[c], G. Gorini[a,b], ASDEX Upgrade team

[a] *Università degli studi di Milano Bicocca, Milano, Italy*
[b] *Istituto di Fisica del Plasma Piero Caldirola - CNR, Milano, Italy*
[c] *Max-Planck-Institut fuer Plasmaphysik, IPP-EuratomAssociation, Garching, Germany*

Abstract

Gamma ray spectroscopy is a promising method for diagnosing fast ions and confined alpha particles in a fusion plasma device. This application requires γ-ray detectors with high energy resolution (say a few percent for gamma ray energies in the range 1-5 MeV), high efficiency and high count rate capability, ideally up to a few MHz. Furthermore, the detector will have to withstand the high 14 MeV and 2.45 MeV neutron fluxes produced by the main fusion reactions between deuterium and tritium. Experimental results demonstrate that the requirements on energy resolution, efficiency and count rate can be met with a $LaBr_3$(Ce) scintillator detector equipped with fast digital data acquisition. The measured response of the detector to 2.45 MeV neutrons is presented in this paper and discussed in terms of the interaction mechanism between neutrons and detector.

Keywords: X- and γ-ray spectroscopy, Scintillation detectors

1. Introduction

A confined thermonuclear plasma is heated by alpha particles from Deuterium-Tritium (DT) reactions. These particles are produced with an energy of 3.5 MeV, much higher than the plasma bulk temperature (10-20 keV), and must slow down in order to release their energy into the plasma. The study of α-particles and more generally of fast ion confinement is therefore a crucial topic for future thermonuclear plasma experiments, such as ITER. Fast ions induce magneto-hydrodynamics (MHD) instabilities and can lead to the loss of energetic particles, which are potentially harmful for plasma control and for the integrity of the machine. However, very few diagnostic techniques of fast ions are available today for confined energetic particles in the MeV energy range. Neutron spectroscopy provide diagnostic information on the reactants energy distribution, and can be used for fast ion studies, as demonstrated with measurements in present day tokamaks [1][2][3][4][5]. More recently, γ-ray spectroscopy demonstrated to be a candidate diagnostics for confined fast ions observations [6][7][8]. γ-ray emission is typically relevant for fast ion energies of some hundred keV, as a consequence of the underlying cross sections. Many γ-ray emitting reactions are possible between fast ions and impurities in the plasma. Beryllium will be naturally present as an impurity in ITER plasmas, since it is the main component of the tokamak first wall. Most promising for diagnosis of α particles is the $^9Be(\alpha,n\gamma)^{12}C$ [9][10].
A spectrometer suited for this application must have a good energy resolution (say a few percent for γ-ray energies in the range 1-5 MeV) and be able to cope with a few MHz count rate.
Energy resolution is essential to perform spectral analysis that can provide information on the fast ion energy distribution (e.g. Doppler broadening). High rate capability is necessary for time resolved measurements, that are crucial in order to measure fast transients in the γ-ray counting rate associated to MHD instabilities in the plasma.
First observations of γ-ray spectral broadening in fusion plasmas were reported in Ref.[7]. The measurements were performed in radio-frequency heated (^{3}He)D plasmas of the JET tokamak using a High Purity Germanium (HPGe) spectrometer, which permits high energy resolution (<2.8 keV at 1.33 MeV). The measured γ-ray peak shape was reproduced using a physics model that combined the kinetics of the reacting ions with a detailed description of the nuclear reaction differential cross sections and branching ratios.
However, the HPGe detector does not allow for high rate measurements in the MHz range, which is required if one wants to study fast ion dynamics on characteristic time scales of MHD instabilities (a few ms). For this reason a spectrometer based on the $LaBr_3$ scintillator has been specifically developed. High energy resolution is made possible by the high scintillation light yield of the crystal (about 63000 photons per MeV) [11][12]. $LaBr_3$ spectrometers were designed to be able to cope with high counting rate measurements (up to few MHz), with an ad hoc developed active voltage divider for the photomultiplier tube and a fast digital data acquisition (see Ref. [13]).

2. Performances of the new $LaBr_3$ spectrometer

A 3”x6” (diameter x height) $LaBr_3$ scintillator was developed for measurements at the JET tokamak in the United Kingdom.

*carlo.cazzaniga@mib.infn.it

The detector was fully characterized and now regularly takes data during JET plasma experiments. Energy calibration measurements were carried out using radioactive sources, such as ^{137}Cs and ^{60}Co, and were successfully reproduced with Monte Carlo simulations using the MCNPX code [14]. The model used in the simulations included details of the geometry and of the materials surrounding the crystal, such as iron shielding and steel supports, that are important due to the effect of high Z materials on γ-ray scattering. Fig.1 shows a comparison between the measured and simulated spectrum for a ^{137}Cs (a) and a ^{60}Co (b) radioactive source. Spectral broadening due to the finite energy resolution of the spectrometer is included in the simulation. The measured energy resolution (R=FWHM/E) is 3.3% at 662 keV peak, 2.5% at 1173 keV peak and 2.4% at 1333 keV peak. Spectra are normalized to the full-energy-peak height. There is very good agreement between simulation and data, which holds both at the Compton-edge level and at the low energy back-scattering region. Small differences are ascribed to minor details of the actual experimental setup. This confirms the reliability of the MCNPX model of the detector for determination of its response function to γ-rays of different energies. Simulations have been performed using the MCNP model in order to evaluate the efficiency as a function of the γ-ray energy. Full-energy-peak efficiency (ϵ_{peak}) is defined as the number of events in the full-energy-peak divided by the number of photons impinging on the detector. Results are shown in Fig.2. Every point is obtained with a simulation of 10^6 events, resulting in very low relative errors (< 0.2%). The 3"x6" $LaBr_3$ scintillator has a considerably high efficiency thanks to high effective Z, high density and big volume. Full-energy-peak efficiency is 25% at 4.44 MeV, which is the energy of γ-rays from the reaction $^9Be(\alpha, n\gamma)^{12}C$.

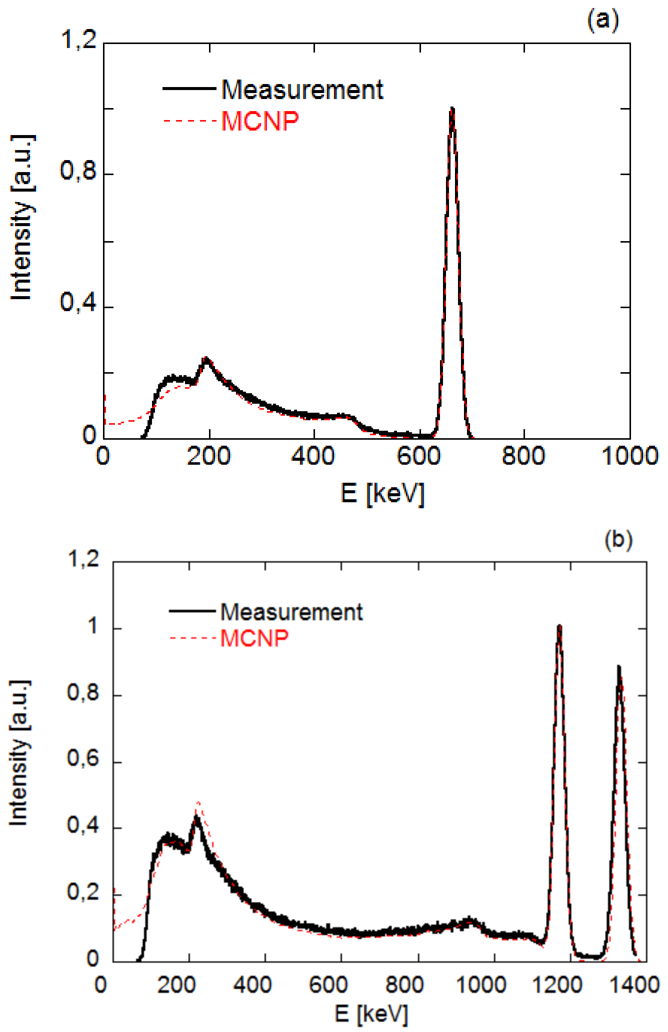

Figure 1: Simulated and measured energy spectrum using a $LaBr_3$ scintillator for a ^{137}Cs (a) and a ^{60}Co (b) radioactive source.

High rate capability was a fundamental goal when the design of the detector was first presented in 2008 [15]. An important hardware component to be carefully optimized is the photo-multiplier-tube (PMT). PMTs are known to be affected by gain drifts when the counting rate of the source varies. This is due to the fact that an increasing mean photoelectric current running between the dynodes results in a voltage drop in the divider chain, which in turn causes a gain modification [16]. A PMT with a custom developed active base, which includes transistors in the last three stages, has been developed and optimized for this application. This PMT is an eight stage Hamamatsu R6233-01 with a length of 223 mm and a diameter of 82 mm. The gain at the nominal High Voltage (HV) of -1000 V is $2.7 \cdot 10^5$. The gain stability was tested as a function of the frequency using a LED source for different values of the HV (see Ref.[15]).

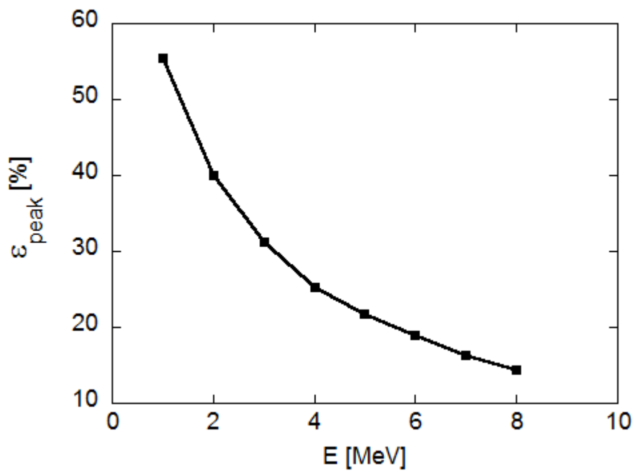

Figure 2: Simulated full-energy-peak efficiency as a function of the γ-ray energy for a 3"x6" $LaBr_3$ scintillator.

The detector high rate capability was demonstrated in dedicated experiments at nuclear accelerators [17][18]. A not significant degradation in energy resolution was found for count rates up to 2.6 MHz (R=2.0 % at E_γ= 3 MeV), using HV=-800V. The mean position of the peaks was also unchanged between measurements at 80 kHz and 2.6 MHz, showing that no appreciable variations of the PMT gain occurred (see Ref.[18]).

High rate capability has been further verified during tokamak discharges. Experiments were performed at the ASDEX Up-

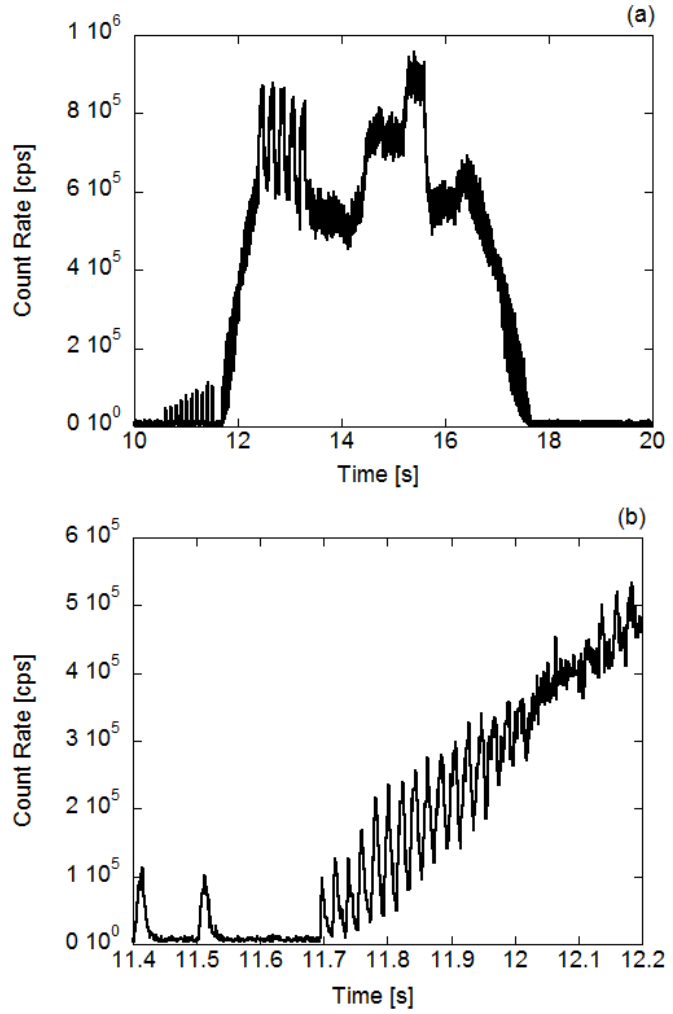

Figure 3: Temporal evolution of the counting rate of the $LaBr_3$ spectrometer as a function of time for AUG discharge # 26328 (a). In (b) a magnification of (a) within 11.4-12.2 s. An offset of about 10 s with respect to the AUG time base is present.

grade (AUG) tokamak in Garching (Germany), where the detector was installed on a collimated line of sight, 12 meters away from the plasma [19],[20]. The detector allowed the first γ-ray spectroscopy measurements of confined fast ions on AUG [21]. AUG operate with deuterium plasmas, which means that the main components of the emitted neutron spectrum are 2.45 MeV neutrons from Deuterium-Deuterium (DD) reactions. Deuterium plasmas with high Neutral Beam Injection (NBI) power have a high neutron yield, mostly from beam-plasma reactions. At AUG the neutron flux at the detector position was about $1.7 \cdot 10^4$ neutrons/sec/cm^2 considering a typical discharge with 7.4 MW of NBI (92 kV deuterons). These kind of plasmas are poor of fast ions in the MeV energy range, which is reflected in a negligible fast ion induced γ-ray emission. However, neutrons produce background γ-rays when they directly interact with the detector or surrounding materials. In Fig.3 temporal variations in the measured counting rate of the $LaBr_3$ spectrometer for a discharge with 7.4 MW NBI are shown. The counting rate reaches values very close to 1 MHz. One can notice long time scale variations (a), due to modulation of the NBI power and RF power. Fast variations (b) can be attributed instead to changes in the power coupling due to bulk plasma instabilities such as, for instance, sawteeth.

3. $LaBr_3$ response to fusion neutrons

In view of γ-ray spectroscopy measurements on fusion burning plasmas, one must consider experimental constraints posed by high neutron fluxes, which will be orders of magnitude larger than in todays tokamak experiments (up to 10^8-10^9 neutrons cm^{-2}s^{-1} at the detector position without neutron filters [22]). 2.45 MeV neutrons emitted from fusion reactions in a deuterium plasma can interact with $LaBr_3$ through nuclear inelastic scattering. As a result of this interaction the constituent nuclei of $LaBr_3$, i.e. ^{139}La, ^{79}Br and ^{81}Br, are left in an excited state that de-excites by emission of (background) γ-rays [23]; the latter can interfere with the γ-signal from nuclear reactions induced by α particles or even paralyse the detector if the count rate saturates the detector capabilities. As said before, the measurements from AUG plasmas heated by NBI power were characterized by intense 2.45 MeV neutron fluxes. These data were then compared to preliminary measurements of the response of the $LaBr_3$ γ-ray spectrometer to 2.45 MeV mono-energetic neutrons performed at the Frascati Neutron Generator (FNG). At FNG a deuteron beam was accelerated on a deuterium target, providing a neutron fluence on the detector surface of about $8 \cdot 10^4$ neutrons per second. Fig.4 shows a comparison between the energy spectra measured at AUG and at FNG. Each spectrum was separately energy-calibrated using radioactive ^{137}Cs and ^{60}Co sources and normalized to a total counting statistics of $1.5{\cdot}10^4$. The measured spectra are fairly similar for E < 1.5 MeV. At larger gamma energies instead, the different neutron energy spectra at AUG and FNG play a role. At AUG, high energy NBI deuterons reacting with the bulk plasma thermal D population give rise to neutrons of energy $E_n = 2.45 \pm 0.3$ MeV. At FNG accelerator with the spectrometer positioned at 90 deg with respect to the deuteron beam impinging onto the target,the neutron energy spectrum is quite narrow around 2.45 MeV. This is probably the reason for the different slope of the spectra for 1.5<E<2.5 MeV (see Fig.4). The events with E > 2.5 MeV are mostly due to γ-rays emitted by neutron capture on surrounding materials. This was different in the two experiments, as it depends on details of the specific environment where the experiment is carried out. However, the fact that there are only few neutron induced events for E>2.45 MeV confirms the 2.45 MeV neutron origin and it is promising, as γ-rays of interest for plasma diagnostics are expected to show up in the energy range E_γ=2-5 MeV.

The role of nuclear inelastic scattering from fusion neutrons was investigated with a preliminary MCNP model in which the interaction process is divided in two steps. In the first one, the energy distribution of γ-rays born from the interaction of a uniform beam of 2.45 MeV neutrons impinging on the $LaBr_3$ crystal is simulated. In the second step, the resulting neutron induced γ-ray spectrum is used as input for a new MCNP simulation aimed at evaluating the interaction of these neutron born

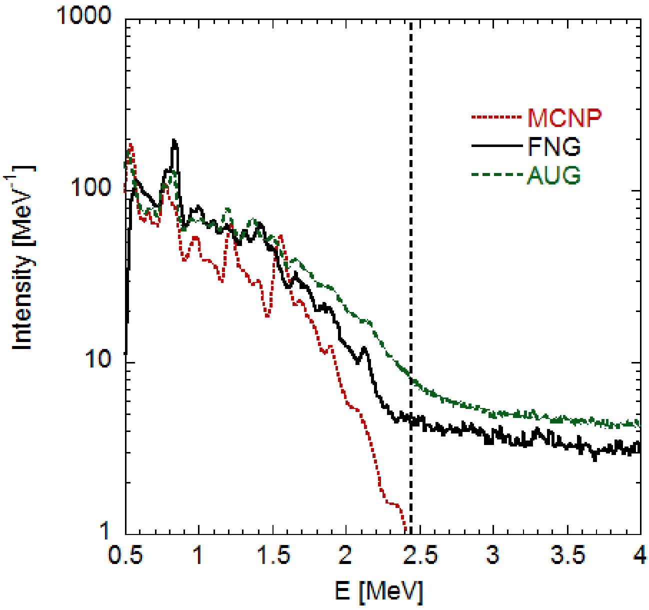

Figure 4: γ-ray energy spectra from 2.45 MeV fusion neutrons interacting on a $LaBr_3$ scintillator, measured at AUG and FNG, and simulated with MCNP. The dashed line indicates the 2.45 MeV energy value.

γ-rays with the crystal. According to MCNP simulation, an average number of 1.14 γ-rays per neutron is produced. Due to the large volume of the crystal, it is likely that the same neutron interacts more than once via inelastic scattering. The average probability of an emitted γ-ray to give a signal, considering a low energy threshold (E > 100 keV) is 65%. It is possible to notice in Fig.4 that the main structure of the measured neutron induced spectra is only partially reproduced in the region E < 2.45 MeV. Differences on single peaks and on details of the spectral structures are explained by the fact that other materials but $LaBr_3$ are not included in the simulation. For the same reason the spectrum region E > 2.5 MeV is not reproduced, since it is due to γ-rays emitted by neutron capture on surrounding materials. A more detailed MCNP model will be implemented in order to reproduce the full spectrum. This model will (1) include surrounding materials and line of sight and (2) consider the complete neutron spectrum emitted by the plasma, rather then just the main 2.45 MeV component. Starting from the understanding of the interaction mechanisms of 2.45 MeV neutrons, one must study the response function of the $LaBr_3$ crystal to 14 MeV neutrons emitted from deuterium-tritium plasmas of a thermonuclear device. Based on cross section values, reactions of the type (n,2n) are expected to play a significant role, which results in an increased sensitivity of the detector to 14 MeV neutrons [23].

4. Conclusions and Outlook

In this paper the energy resolution, efficiency to γ-rays in the MeV energy range and high rate capability of a $LaBr_3$ scintillator have been assessed in view of γ-ray measurements on next step fusion devices. The response of $LaBr_3$ detectors to 2.45 MeV neutrons was presented and compared with a preliminary MCNP simulation. A $LaBr_3$ detector is now installed at the JET tokamak and will collect data with two main goals: (1) γ-ray measurements for confined fast-ion diagnostics at JET, and (2) measurements of the $LaBr_3$ response to fusion neutrons. The reported results provide the basis for the conceptual design of optimized $LaBr_3$ detectors for fusion burning plasmas.

[1] J. Kaellne et al, Phys. Rev. Lett. vol. 85 (2000) p.1246
[2] M. Nocente, G. Gorini, J. Kallne and M. Tardocchi, Nucl. Fus. vol. 51 (2011) p. 063011
[3] C. Hellesen et al, Nucl. Fus. vol. 50 (2010) p. 084006
[4] M. Gatu Johnson et al, Nucl. Fus. vol. 50 (2010) p. 045005
[5] M. Gatu Johnson et al, Rev. Sci. Instrum. vol. 81 (2010) 10D336
[6] Proverbio I. et al, 2010 Rev. Sci. Instrum. 81 10D320
[7] M. Tardocchi et al, Phys. Rev. Lett. 107, 205002 (2011)
[8] M. Nocente et al, Nucl. Fusion 52 (2012) 053009
[9] V. G. Kiptily et al, Nucl. Fusion 42, 999 (2002).
[10] Kiptily V.G. et al, Plasma Phys. Control. Fusion 48 (2006) R59
[11] R. Nicolini, F. Camera et al, Nucl. Instrum. Methods Phys. Res. A 582, 554-561 (2007)
[12] E. V. D. van Loef et al, Nucl. Instrum. Methods Phys. Res. A 486, 254 (2002)
[13] M. Nocente et al, Rev. Sci. Instrum. 81, 10D321 (2010)
[14] The MCNPX website: http://mcnpx.lanl.gov/
[15] M. Tardocchi et al, Rev. Sci. Instrum. 79, 10E524 (2008)
[16] M. Tardocchi et al, Nuclear Instruments and Methods in Physics Research A 485 (2002) 624
[17] M. Nocente et al, 2013 accepted for publ. to IEEE Trans. on Nucl. Science
[18] M. Nocente et al, 2011 IEEE Nuclear Science Symposium Conference Record (2011)
[19] L.Giacomelli et al, Rev. Sci. Instrum. vol. 82, 123504 (2011)
[20] M. Tardini et al, JINST 7 (2012), C03004
[21] M. Nocente et al, Nucl. Fusion 52 (2012) 094021
[22] I.N. Chugunov et al, Nuclear Fusion 51, 083010 (2011)
[23] Cross Section Database http://atom.kaeri.re.kr/