Nuclear Instruments and Methods in Physics Research A 732 (2013) 384–387

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

$LaBr_3$ 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], G. Gorini [a,b], A. Weller [c], 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

ARTICLE INFO

Available online 11 June 2013

Keywords:
X- and γ−ray spectroscopy
Scintillation detectors

ABSTRACT

The γ−ray spectroscopy is a promising method for diagnosing fast ions and confined α particles in a fusion plasma device. This application requires γ−ray detectors with high energy resolution (say a few percent for γ−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.

1. Introduction

A confined thermonuclear plasma is heated by α 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-hydro-dynamics (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 provides diagnostic information on the reactants' energy distribution, and can be used for fast ion studies, as demonstrated with measurements in present day tokamaks [1–5]. More recently, γ−ray spectroscopy demonstrated to be a candidate diagnostics for confined fast ions observations [6–8]. The 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 tokamak's first wall. Most promising for diagnosis of α particles is the reaction $n\gamma)^9$Be(α, nγ)^{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 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 63 000 photons per MeV) [11,12]. $LaBr_3$ spectrometers were designed to be able to cope with high counting rate measurements (up to a few MHz), with an ad hoc developed active voltage divider for the photomultiplier tube and a fast digital data acquisition (see [13]).

* Corresponding author at: Istituto di Fisica del Plasma Piero Caldirola – CNR, Milano, Italy. Tel.: +39 0266173458.
E-mail addresses: carlo.cazzaniga@mib.infn.it, cazzaniga.carlo87@gmail.com (C. Cazzaniga).

0168-9002/$ - see front matter
http://dx.doi.org/10.1016/j.nima.2013.05.055

2. Performance of the new $LaBr_3$ spectrometer

A 3 in. × 6 in. (diameter × height) $LaBr_3$ scintillator was developed for measurements at the JET tokamak in the United Kingdom. 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, which 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 ($R = \mathrm{FWHM}/E$) is 3.3% at the 662 keV peak, 2.5% at the 1173 keV peak and 2.4% at the 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 in 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 determining 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 in. × 6 in. $LaBr_3$ scintillator has a very high efficiency thanks to high effective Z, high density and big volume.

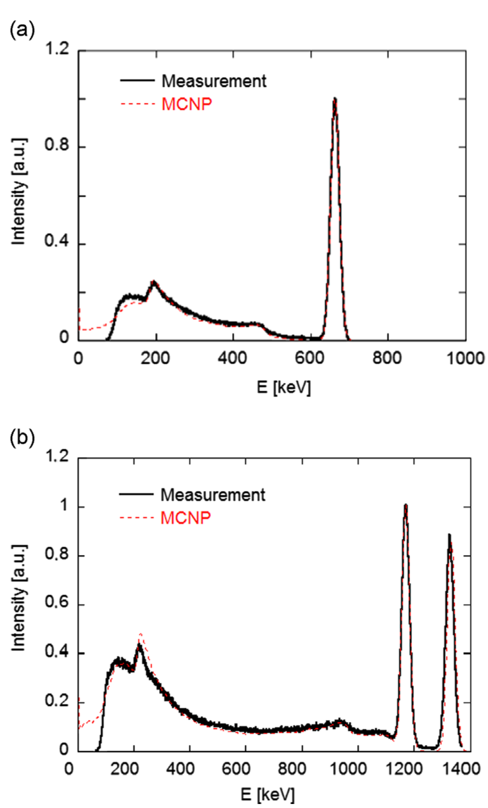

Fig. 1. Simulated and measured energy spectrum using a $LaBr_3$ scintillator for a ^{137}Cs (a) and a ^{60}Co (b) radioactive source.

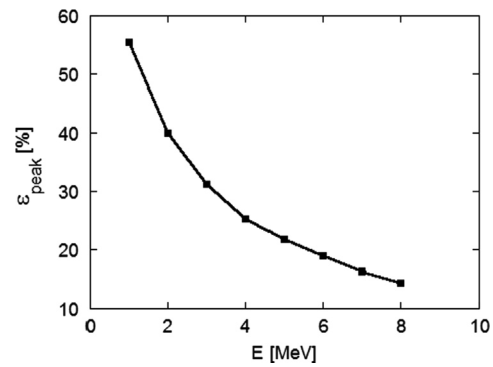

Fig. 2. Simulated full-energy-peak efficiency as a function of the γ−ray energy for a 3 in. × 6 in. $LaBr_3$ scintillator.

Full-energy-peak efficiency is 25% at 4.44 MeV, which is the energy of γ−rays from the reaction $^9\mathrm{Be}(\alpha, n\gamma)^{12}\mathrm{C}$.

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 photomultiplier-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 2.7×10^5. The gain stability was tested as a function of the frequency using a LED source for different values of the HV (see [15]).

The detector's 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 $E_\gamma = 3$ MeV), using HV=−800 V. 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 [18]). High rate capability has been further verified during tokamak discharges. Experiments were performed at the ASDEX Upgrade (AUG) tokamak in Garching (Germany), where the detector was installed on a collimated line of sight, 12 m away from the plasma [19,23]. The detector allowed the first γ−ray spectroscopy measurements of confined fast ions on AUG [20]. AUG operates 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 1.7×10^4 neutrons/s/cm^2 considering a typical discharge with 7.4 MW of NBI (92 kV deuterons). These kind of plasmas are poor in 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.