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Energy Resolution of LaBr₃(Ce) Gamma-Ray spectrometer for Fusion Plasma Studies on JET

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ABSTRACT.

A new high efficiency, high resolution, fast γ -ray spectrometer was recently installed at the JET tokamak. The spectrometer is based on a $\text{LaBr}_3(\text{Ce})$ scintillator coupled to a photo multiplier tube. A digital data acquisition system is used to allow spectrometry with event rates in excess of 1MHz expected in future JET DT plasmas. However at the lower rates typical of present day experiments digitization can degrade the energy resolution of the system depending on the algorithms used for extracting pulse height information from the digitized pulses. In this paper the digital and analog spectrometry methods were compared for different experimental conditions. An algorithm based on pulse shape fitting was developed providing energy resolution equivalent to the traditional analog spectrometry method.

1. INTRODUCTION

Gamma Ray Spectrometry (GRS) is used on the JET fusion device for observation of reactions between energetic ions and plasma impurities [1,2,3]. Different γ -ray spectrometers are available since 2009:

- i) A High purity Germanium (HpGe) was installed because of its very high energy resolution [4]. The crystal is sensitive to neutron damage, which limits the use of this detector in a fusion environment. When used, it provides data of excellent quality in the γ -ray energy range up to 5MeV.
- ii) Bismuth Germanate (BGO) and Sodium Iodide (NaI) detectors. These detectors were used at JET for a number of years [3] because of their high efficiency and reasonably good energy resolution over a broad range of γ -ray energies.
- iii) The latest addition to the GRS instrument suite is a Lanthanum Bromide (Brilliance) detector. $\text{LaBr}_3(\text{Ce})$ is a new scintillating material [5] delivering a very high light yield and hence energy resolution. It is also fast (see pulse shape in Fig.1) and insensitive to neutrons. Our 3'' \times 6'' $\text{LaBr}_3(\text{Ce})$ crystal is coupled to a Hamamatsu Photo Multiplier Tube (PMT) designed to allow operations at rates up to 2MHz [6]. The PMT signal is fed into a fast pre-amplifier with $\times 5$ gain before being digitized. High rate capability is enabled by a dedicated pulse digitization data acquisition system [7] based on the ATCA platform with a sampling frequency up to 400MSPS and a nominal 14-bit resolution. The acquisition board has channels with AC or DC coupling. A threshold on the signal coming from the PMT is set to avoid noise peak-up. When the signal exceeds the threshold a trigger is set and a data segment is stored consisting of 128 samples. The first 30 sample points are taken immediately before the trigger. This provides the baseline level for each event. The remaining points contain the actual digitized pulse. Each digitized event has an associated time-stamp to allow for time resolved data analysis.

The digital data acquisition system is used to allow for spectrometry measurements with event rates in excess of 1MHz, expected in future JET DT plasmas. However at the lower rates typical of

present day experiments digitization can degrade the energy resolution of the system depending on the algorithms used for extracting pulse height information from the digitized pulses. The effect of digitization and different processing algorithms are studied here by comparing the results of digital and analog spectrometry for different experimental conditions.

2. SPECTRUM RECONSTRUCTION ALGORITHMS

Dedicated algorithms were developed to build the event pulse height spectrum.

A first algorithm named MAIA (Maximum Algorithm for Intershot Analysis) was written with the aim of providing a spectrum immediately after a JET discharge. The code is written in C and takes about 15 seconds to reconstruct a spectrum made of 10^5 events when running on a computer of the JET Analysis Cluster (JAC). The event pulse height is extracted from the corresponding data segment by taking the difference between the sample with maximum height inside the segment and the baseline. The latter is evaluated as an average of the first 20 points of the segment.

A second algorithm named ORSA (Offline Reconstruction Simple Algorithm) was developed to better cope with noisy data. The absence of an hardware noise filtering stage between the PMT and the ATCA implies that baseline noise is reflected into the sampled pulse. Moreover, amplitude walks can introduce an uncertainty on the baseline value determined as average of the first 20 points of each segment. Noise filtering is achieved in ORSA by pulse fitting. The shape $S(t)$ of each digitized event is described as

$$S(t) = \begin{cases} y_0 & \text{if } t < t_0 \\ y_0 + N(1 - \exp(-(t-t_0)/\tau_1))^P & \text{if } t > t_0 \end{cases} \quad (1)$$

where y_0, N, t_0 , are fit parameters. τ_1, τ_2 and P are instead determined by a pre-fit and kept constant for all the pulses; i.e. the pulse shape is assumed not to depend on γ -ray energy. Best values for these parameters were found to be $\tau_1 = 31.6\text{ns}$, $\tau_2 = 23.8\text{ns}$ and $P = 3.5$ when the accelerating voltage VHV between the anode and the photocathode of the PMT was 800 V. τ_1 was found to have a slight dependence on VHV, while τ_2 and P were independent of VHV. An example of the fit accuracy is shown in Figure 1. Like MAIA, the pulse height of each event is determined from the difference between the maximum and the baseline, but now the fitted pulse shape is used instead of the raw data. ORSA is slow compared to MAIA but provides better results.

3. RESULTS

The pulse height resolution of the system was investigated in laboratory tests and compared to that of an analog spectrometry chain consisting of a preamplifier+shaping amplifier and an ADC unit. The PMT was operated with $V_{\text{HV}} = 800\text{V}$. Gamma rays from ^{137}Cs and ^{60}Co radioactive sources were detected and the pulse height spectrum reconstructed using both ORSA and MAIA algorithms.

The reconstructed ^{137}Cs peak at 661.66 keV is shown in Fig.2 as resulting from the three approaches in the case of measurements performed in low noise laboratory conditions. Pulse height resolution (FWHM) values at the three calibration peaks can be compared in Table 1. One can see that the values obtained with the ORSA algorithm are close to the analog spectrometry values. This is an important result since it shows that digitization in itself does not degrade the resolution of the measurement. On the other hand it is essential for enabling spectrometry at high rates. The results obtained with MAIA, although not optimal, are still better than the NaI and BGO detectors previously used at JET: they feature a resolution of about 7% at the same energy.

Figure 3 shows the achieved resolution (FWHM in keV and in %) of the ^{137}Cs line at 661.66keV during experiments at a Tandem accelerator for different photo multiplier voltage. For comparison the best resolution obtained with an analog chain in low noise laboratory conditions is also shown. Again the analog spectrometry chain and the ORSA algorithm are found to provide similar results. Optimal resolution is achieved when $V_{\text{HV}} \geq 800\text{V}$, with no significant improvement in resolution at higher PMT operating voltages. Resolution with the MAIA algorithm is instead improved by choosing a higher voltage value. This suggests that cable noise is the main cause for resolution deterioration and is partly compensated for by increasing the signal amplitude.

The LaBr_3 spectrometer was successfully used at JET to measure γ -ray spectra in recent experiments where fast ions were produced by Ion Cyclotron Resonance Heating (ICRH). The digital data acquisition proved to be high reliable with practically no loss of data due to malfunction. Figure 4 shows a pulse height spectrum measured during an experiment in a (^3He)H plasma meant to study minority and mode conversion heating in inverted (^3He)H scenarios [8, 9] of relevance for the non-active phase of ITER [10]. First harmonic ICRH was tuned to fundamental ^3He frequency. When the ^3He concentration was sufficiently low, high energy tails in the ^3He distribution function were created as a result of ICRH heating. These fast ions in turn induced γ -ray emission when interacting with impurities inside the machine (typically ^{12}C and ^9Be at JET)[3]. In (^3He)H plasmas γ -rays from the reaction $^9\text{Be}(^3\text{He}, p\gamma)^{11}\text{B}$ were expected to be observed. These are represented by the peak at 4.44 MeV in Figure 4, due to a transition from the second to ground state of ^{11}B . However, γ -ray emission from the reaction $^{12}\text{C}(d, p)^{13}\text{C}$ was also observed, which implied production of deuterons with energy greater than 0.5MeV [3]. This unexpected event is represented by the peak at 3.09MeV in figure 4 due to transition from the first to ground state of ^{13}C . The two peaks at lower energies are instead due to calibration sources (the peak at 661.66keV is due to ^{137}Cs) or to the detector intrinsic radioactivity (peak at 1473keV due to excited ^{138}Ba , produced after electron capture on ^{138}La). Figure 5 shows the temporal evolution of signal proportional to the γ -ray emission due to the reactions $^9\text{Be}(^3\text{He}, p\gamma)^{11}\text{B}$ and $^{12}\text{C}(d, p)^{13}\text{C}$. The coherent trend shows that ^3He and d ions were both accelerated by the applied ICRH and illustrates the time resolution achieved with the new LaBr_3 spectrometry system. Much higher rates and better time resolutions are expected from this system when plasmas with alpha particles and ^9Be impurities are available e.g. in DT fusion experiments in JET and ITER.

CONCLUSIONS

A LaBr₃(Ce) scintillator with fully digital data acquisition designed for high rate operation was installed at JET. Dedicated spectrum reconstruction algorithms were written to allow for immediate visualization of the measured γ -ray spectrum or to provide pulse height resolution matching the best resolution available from conventional analog spectrometry chains. The system was successfully used during recent JET experiments where it provided data at relatively low rates. Much higher rates are envisaged in future DT plasmas due to the presence of energetic alpha particles.

REFERENCES

- [1]. F.E. Cecil *et al.*, Nucl. Instrum. Methods **221**, 449 (1984)
- [2]. V. G. Kiptily *et al.*, Rev. Sci. Instrum. **74**, 1753 (2003)
- [3]. V.G. Kiptily *et al.*, Nucl Fus. **42**, 999 (2002)
- [4]. A.Murari *et al.*, *New Developments in the Diagnostics for the Fusion Products on JET in preparation for ITER*, these Proceedings
- [5]. E.V.D. Van Loef *et al.*, Nucl. Instr. Meth. A **486**, 254 (2002)
- [6]. M. Tardocchi *et al.*, Rev. Sci. Instrum. **79**, 10E524 (2008)
- [7]. R.C. Pereira *et al.*, Fusion Eng. Des. **83**, 341 (2008).
- [8]. M.-L. Mayoral *et al.*, Nucl. Fus. **46**, S550-S563 (2006)
- [9]. E. Lerche *et al.*, *Experimental investigation of ICRF heating scenarios for ITER's half-field phase performed in JET*, in Proc. 37th EPS Conference on Plasma Phys. and Contr. Fusion Dublin, Ireland, 21-25 June 2010, to be published
- [11]. ITER Physics Basis Editors, ITER Physics Expert Group Chairs and Co-Chairs and ITER Joint Central Team and Physics Integration Unit *Nucl. Fusion* **39** 12 (1999)

Gamma ray peak	MAIA	ORSA	Analog Chain
662 keV (¹³⁷ Cs)	4.4%	3.3%	3.2%
1173 keV (⁶⁰ Co)	3.2%	2.5%	2.4%
1333 keV (⁶⁰ Co)	3.0%	2.4%	2.3%

Table 1: Comparison of pulse height resolution values obtained with the digital spectrometry system and the ORSA and MAIA algorithms described in the text for characteristic calibration γ -ray peaks. Results from an analog spectrometry chain are also shown for comparison.

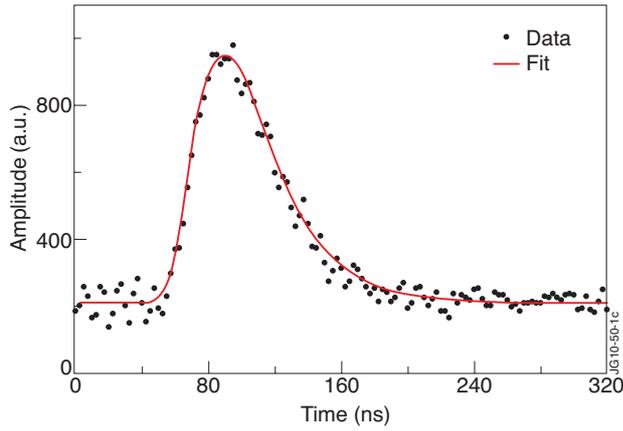


Figure 1: Example of $\text{LaBr}_3(\text{Ce})$ digitized pulse from a 1.5 MeV γ -ray. The solid line is the best fit to the data using Eq. 1.

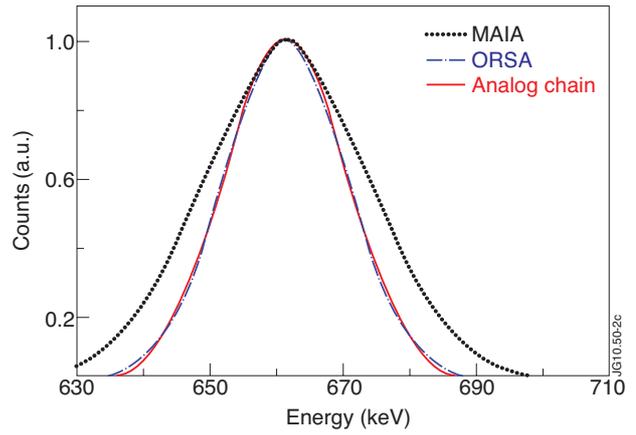


Figure 2: Comparison of a reconstructed ^{137}Cs peak at 661.66 keV using the digitized data processed with the MAIA (dashed) and ORSA (dash-dotted) algorithms. Results from an analog spectrometry chain are also shown for comparison (full line). Measurements performed in low noise laboratory conditions.

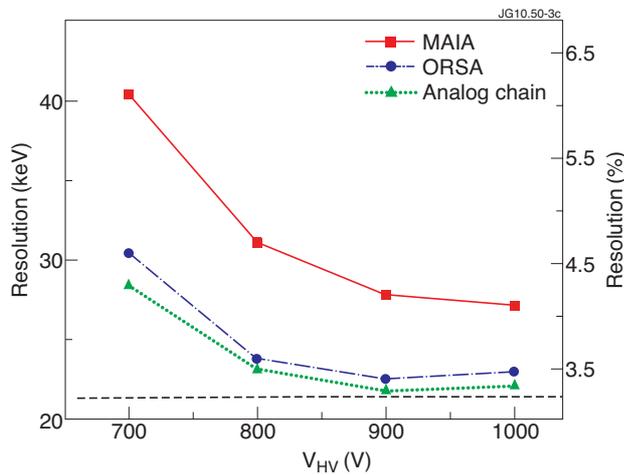


Figure 3: Resolution (FWHM in keV and in %) of the ^{137}Cs line at 661.66 keV during experiments at a Tandem accelerator for different photo multiplier voltage. The analog spectrometry chain (triangles) and the ORSA algorithm (circles) provide similar results. The MAIA algorithm (squares) is somewhat worse. The dashed line represents the best resolution obtained with an analog chain in low noise laboratory conditions.

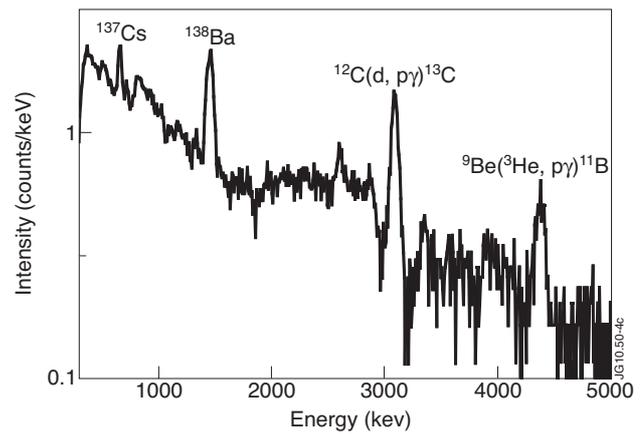


Figure 4: Gamma ray spectrum from JET Pulse No: 79352 obtained with the digital spectrometry system and the ORSA algorithm described in the text. Gamma ray peaks due to the $^{12}\text{C}(d, p)^{13}\text{C}$ and $^9\text{Be}(^3\text{He}, p)^{11}\text{B}$ reactions are marked. Other peaks due to calibration sources or intrinsic detector radioactivity can also be identified.

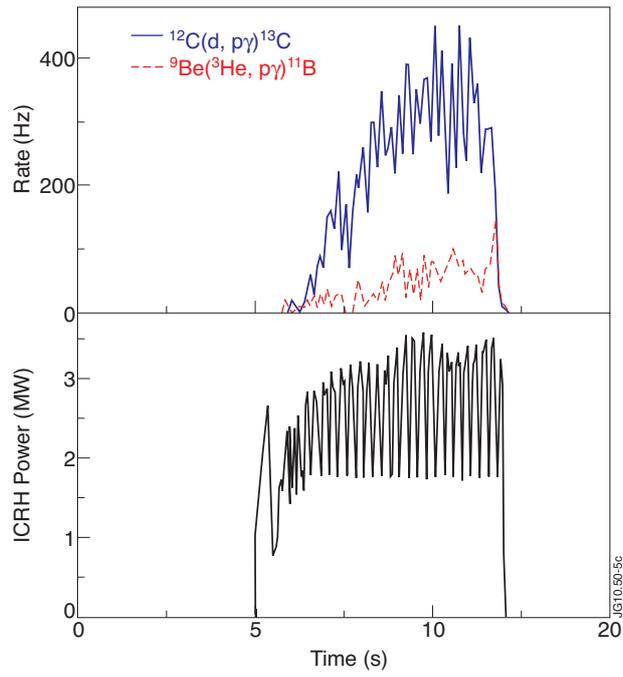


Figure 5: Time traces of measured rates in the pulse height energy regions $E=3.0\text{-}3.2\text{MeV}$ and $E=4.3\text{-}4.6\text{MeV}$ corresponding to g-ray peaks from the reactions $^{12}\text{C}(d, p\gamma)^{13}\text{C}$ and $^9\text{Be}(^3\text{He}, p\gamma)^{11}\text{B}$ observed in JET Pulse No: 79352. The corresponding ICRH power time trace is also shown for comparison.