

Advanced Data Acquisition System for Gamma-Ray Spectrometry in JET

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Gamma-ray spectrometry, comprising *NaI(Tl)* and *BGO* detectors, is a routine JET diagnostic used for fast-ion and α -particle physics studies [1-3]. Measurements of fusion-born α -particles in JET ‘trace tritium’ discharges showed that an upgrade of the data acquisition system (DAQ) is needed to improve the energy and temporal resolution of the γ -ray measurements in high performance *dd*- and *dt*-discharges.

The JET DAQ system for γ -ray measurements based on conventional ADCs has a relatively low counting rate limit, about 50-kHz. This limitation is linked to dead-time losses during the data collection, due to pulse height analysis (PHA) and pile-up effects.

To improve the counting rate characteristics, a DAQ system, exploiting new signal processing technique, has been developed in the Ioffe Institute [4,5]. It is based on a 2-channels PCI transient recorder for digitising incoming signal at a sampling rate of 25 MHz with an amplitude resolution of 14-bit at maximum average pulse rate 1MHz. The module provides 2 Gbytes of on-board memory, which covers the acquisition time during the JET discharge. This advanced DAQ contains fast ADCs, which digitise the continuous detector signal with a high sampling rate. The recorded data are processed by a special code after the discharge. The main advantages of the developed system are PHA at high counting rates and gain stabilisation that is crucial at the fast count-rate variations. It is important to note that the DAQ system allows avoidance of the pile-up effects, which distort the γ -ray spectra, and may cause a misinterpretation of the data.

Figure 1 illustrates the procedure for the data analysis. The first stage is a pulse calibration, which has to be done during the experiment preparation. A digitised single pulse is used for parameterisation of the spectrometer output. For this purpose the following function is used:

$$U(V, t) = A(V)[1 - \exp(-(t - t_0) / \tau_1)]^P \exp(-(t - t_0) / \tau_2).$$

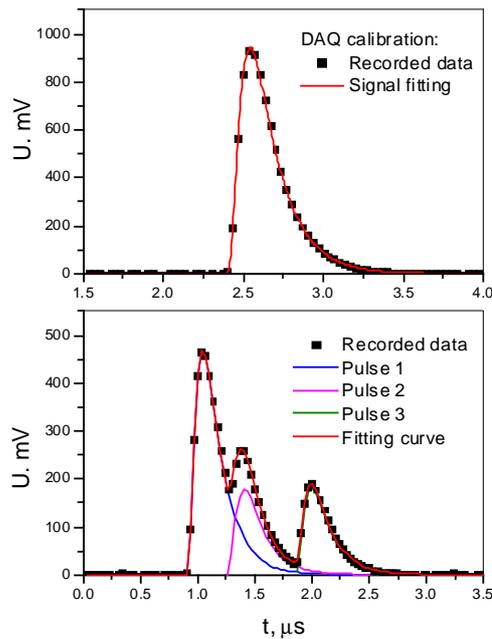


Fig.1 Signals recorded with the NaI(Tl) detector and fitting results for the calibration and analysis.

It is well known that there is a gain instability problem at high count-rate variations, which takes place during measurements with spectrometers based on photo-multipliers. The gain instability has strong dependence on high voltage (HV) applied to the photo-multiplier. Count-rate characteristics of the JET detectors were investigated at different HVs. A considerable gain instability of the NaI(Tl) photo-multiplier was found; the gain noticeably raised with counting rate at rather low HV. To avoid this problem a novel algorithm of the amplitude correction was developed. The correction is performed during the digital processing of data. An efficiency of the gain correction procedure is shown in Fig.2.

Here, $A(V)$ is amplitude of the signal, which is proportional to the measured γ -ray energy; t_0 is the signal start time; and τ_1 , τ_2 and P are parameters that depend on the particular analog modules settings and the scintillator de-excitation time characteristics. In the post-discharge period a spectrum reconstruction procedure is started. The pulses are recognised, and then data are fitted with two parameters t_0 and A for every pulse. An example of the separation of overlapped pulses is given in Fig.1. The best-fit data are stored in a PC memory and transferred to the JET database.

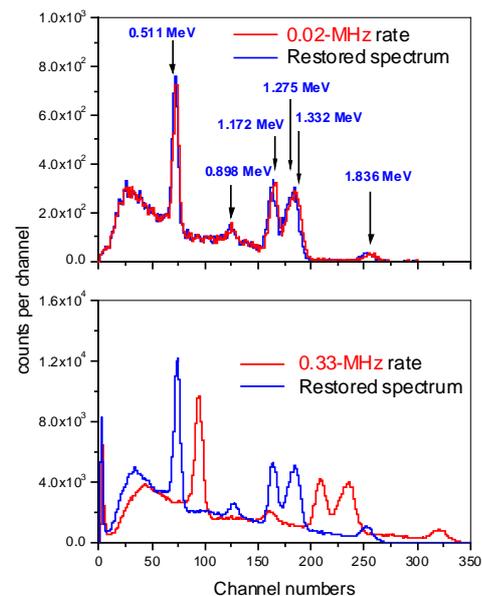


Fig.2 Comparison of the γ -ray spectra recorded (red) with radioactive sources (^{22}Na , ^{60}Co , ^{88}Y) at different counting rates and restored spectra (blue). It is clearly seen that severe distorted spectrum at 0.33-MHz rate is properly corrected by means of the digital stabilisation procedure.

The developed DAQ was tested in beam experiments with ^4He -ions, accelerated to 3.5 MeV in the Ioffe cyclotron. The $^9\text{Be}(\alpha, n\gamma)^{12}\text{C}$ nuclear reaction, used in JET for the α -particle diagnostic, has been chosen to produce an intensive source of the 4.44-MeV γ -rays. Measurements were carried out with a $\text{NaI}(\text{Tl})$ detector ($\text{Ø}150\times 100$ mm) which is similar to the JET one. The counting rate was varied in the range from 10 kHz to 1 MHz, changing the beam current. As can be seen from Fig.3, the experiments have demonstrated that the gain of the spectrometer with this DAQ system is stable, and the energy resolution changes are rather low in the count-rate range up to 0.6 MHz. A counting efficiency of the DAQ at 0.6 MHz rate is about 65%.

This advanced DAQ has been installed in JET and connected to the JET Datanet. Now, it is fully operational, collecting data from two spectrometers, $\text{NaI}(\text{Tl})$ and BGO . Gamma-ray spectra can be recorded during a whole JET discharge with any integration time from 1 ms. A variation of the γ -ray emission detected by $\text{NaI}(\text{Tl})$ spectrometer during the discharge with 20-MW NBI heating is presented in Fig.4. Fusion products, p (3 MeV), T (1 MeV), and ^3He (0.8 MeV) provide main contributions to

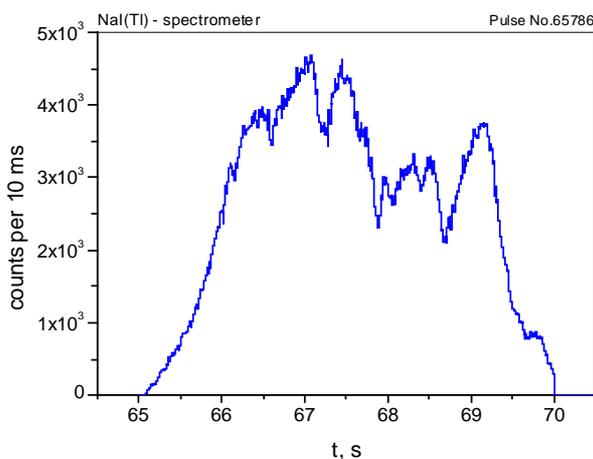


Fig.4 A time evolution of the γ -ray emission recorded by the new DAQ with 10-ms integration time.

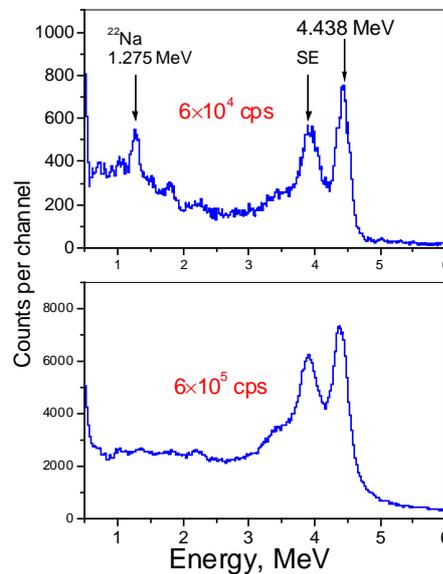


Fig.3 Spectra recorded by the $\text{NaI}(\text{Tl})$ detector with developed DAQ in experiments on the Ioffe Cyclotron (SE - single escape peak).

the γ -ray emission due to nuclear reactions with plasma impurities, C and Be .

An example of the γ -ray spectrum recorded by the $\text{NaI}(\text{Tl})$ -detector with new DAQ system during the JET discharge with the H -minority ICRF heating is shown in Fig.5. The γ -ray emission from two nuclear reactions, $^{12}\text{C}(p,p'\gamma)^{12}\text{C}$, $^{12}\text{C}(d,p\gamma)^{13}\text{C}$, have been observed. The inelastic scattering of protons on carbon is a typical threshold reaction which takes place in JET

plasma with ICRF-heating tuned to hydrogen. Excitation of the first level of the nucleus ^{12}C , 4.44 MeV, is energetically allowed for protons with energies of 5 MeV. Observation of γ -rays de-exciting this state is evidence for the threshold crossing. In the case of the reaction $^{12}\text{C}(d,p\gamma)^{13}\text{C}$, the deuterons accelerated in JET with 2nd harmonic ICRF-heating react with ^{12}C to yield ^{13}C in excited states with the energies 3.09, 3.68 and 3.85

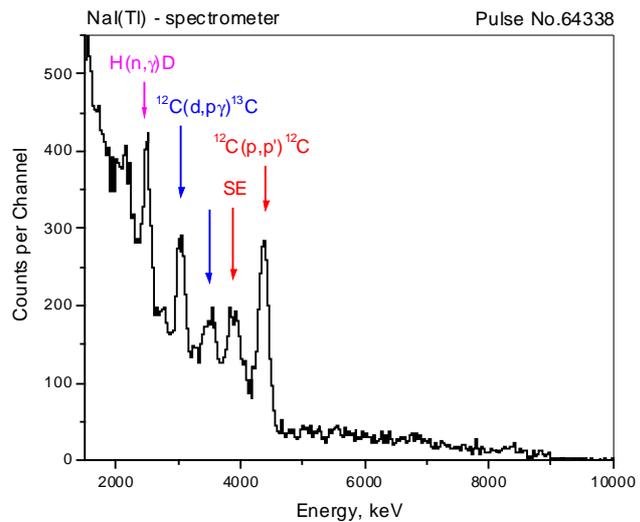


Fig.5 A gamma-ray spectrum recorded by the NaI(Tl) detector with new DAQ in the JET discharge with ICRF heating.

MeV. Observation of the γ -rays de-exciting these levels requires necessarily deuterons with energies exceeding the threshold energies of 0.5 MeV.

The development of the advanced DAQ system on JET has shown that the main limitation for further improving their counting rate capabilities with *NaI(Tl)* and *BGO*-detectors is their scintillation times, 250 ns and 300 ns, respectively. There is a plan to replace these detectors by fast heavy scintillators: *LaBr₃(Ce)*, known as "BriLanCe" (Sait-Gobain Ceramics & Plastics, Inc.) and *Lu_{1.8}Y_{0.2}SiO₅(Ce)* - "LYSO". These new developed high-Z scintillators have a short decay-time, 16 ns and 40 ns, and a high yield of photons, 63 keV⁻¹ and 27 keV⁻¹, respectively (e.g. *NaI(Tl)* scintillator - 38 keV⁻¹). Their outstanding properties open the possibility both to extend the counting rate limit beyond the 5 MHz and to improve the energy resolution for γ -ray spectrometry in the range 2 - 30 MeV.

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