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Introduction

Neutrons are widely used in several research laboratories all around the world to investigate the structures of both biological and inorganic samples at atomic level. The process involved is the scattering of neutrons on the nuclei. The large cross section for hydrogen-neutron interaction makes neutrons a valid alternative to synchrotron radiation in those cases in which hydrogenated materials are involved. In these cases, in fact, synchrotron radiation is less effective because the X-rays scatter on the shell-electrons and not on the nuclei. Moreover, neutrons can distinguish isotopes of the same element.

Being uncharged particles, neutrons cannot be accelerated in a traditional synchrotron, thus neutron beams must be created in a different way. A continuous flux of neutrons can be obtained in an experimental fission reactor; a pulsed beam is instead realized for instance through a Spallation Neutron Source (SNS). SNSs are facilities in which bunches of protons are accelerated in a synchrotron and then made collide on a solid heavy target, like for example Tungsten or Tantalum. Neutrons released in the process are then collimated, giving rise to different beamlines to be used by the researchers. The characterization of these neutrons beamlines is therefore of primary interest to fully understand the experimental results. Because the main physical, biological and chemical studies are made using thermal (En ≈ 0.025 eV) and epithermal (1 eV ≤ En ≤ 1 keV) neutrons, detectors for the characterization of these "slow" neutrons are more widely used than fast neutron detectors (En up to many MeV). Fast neutrons are useful as well, because they can be used in other applications, such as the study of radiation damage in electronic chips. So, as in the thermal neutron case, the fast neutron flux must be carefully monitored and characterized, using dedicated detectors. Taking advantage of the pulsed source, the characterization of the neutron beam can be performed through time of flight (ToF) measurements. In this way, for each bunch, the neutron energy distribution can be naturally monitored by measuring the neutrons arrival time.

The aim of this application note is to show how this characterization of a fast neutron beam took place at the ISIS facility (**Fig. 1**) through the use of a fast CAEN digitizer, model DT5751 1 and 2 GS/s, 10 bit. Measurements were made together with Marco Tardocchi of IFP-CNR Milan and Marica Rebai of University of Milano-Bicocca.
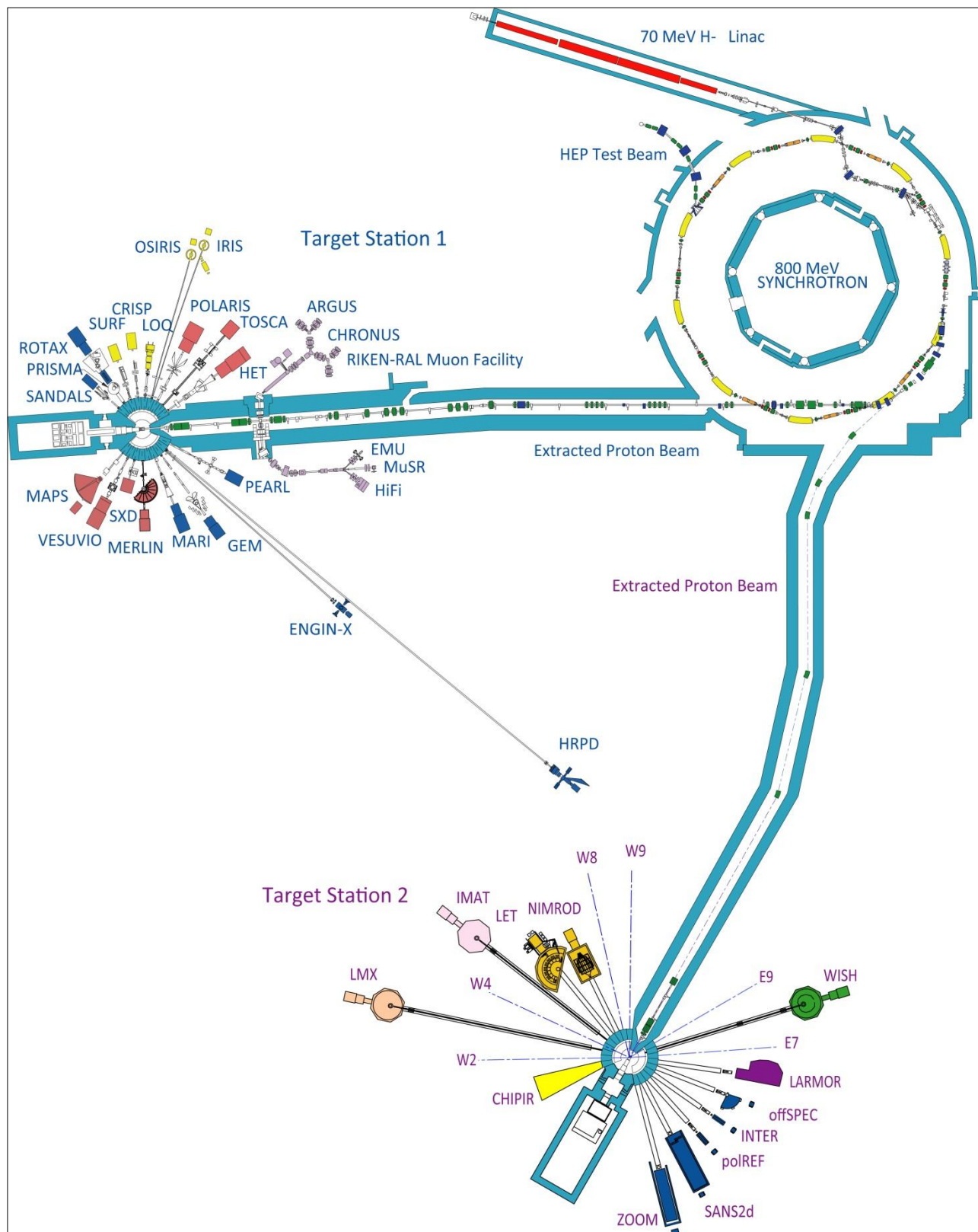
CAEN
Tools for Discovery

Fig. 1: The ISIS neutron source. In the picture the linac, the synchrotron, the target station 1 and the beam lines are shown.

Neutron Detection with Diamond Detectors

Diamonds are well known radiation detectors since several years, but only today their features are becoming widely available, thanks to the technological development in building cost-effective devices. Diamonds can detect any kind of ionizing radiation, from photons to every charged particle. They show a very high radiation hardness and low noise, thanks to the wider band gap (5.5 eV) in comparison with Germanium or Silicon detectors. Moreover, the very fast signals generated (typical rise time ≈ 100 ps) make them ideal for timing measurements. All these features make them very attractive detectors in several applications and the beam monitoring is one of the most promising.

Neutrons can interact in a diamond detector via different nuclear reactions that generate direct ionizing particles such protons, alphas and heavy ions. The rate of these reactions is proportional to their cross sections at different incoming neutron energies.

The three main reactions involved inside the detector are [1]

- the elastic scattering, in which a neutron hits a carbon atom. The carbon atom recoils with an energy equal to $E^{max}_R = 0.28 (\cos^2\theta)E_n$, where θ is the recoiling angle.
- the $^{12}C(n, a)^9Be$ reaction (*n-alpha reaction*), in which a neutron breaks the carbon nucleus into an alpha particle and a ^9Be atom. The energy threshold for this reaction is 6.17 MeV, the Q-value being negative and equal to -5.7 MeV.
- the $^{12}C(n,n')3a$ reaction (*n-3alpha reaction*) in which the carbon nucleus breaks up into three alpha particles. The energy threshold for this reaction is 7.9 MeV, the Q-value is 7.3 MeV.

These three combined reactions make possible the detection of neutrons above 1 MeV, thus diamonds are ideal detectors for fast neutron beam monitoring.

Set-Up description

The picture in **Fig. 2** shows the set-up as mounted in the ROTAX experimental hall at ISIS.

The neutron beam comes from the left and the detector is placed directly into the beam. At the end of the beam line, the preamplifier is placed close to the detector, and the signal is acquired outside the experimental hall.
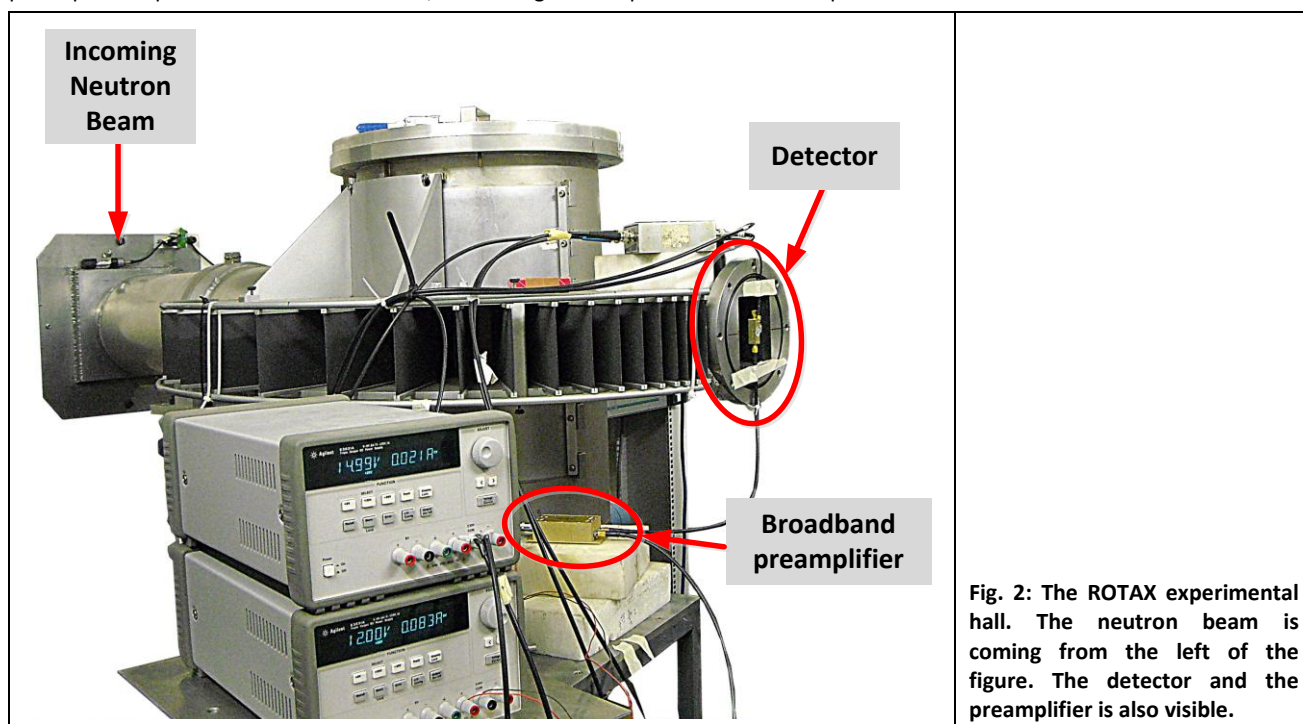

Incoming Neutron Beam

Detector

Broadband preamplifier

Fig. 2: The ROTAX experimental hall. The neutron beam is coming from the left of the figure. The detector and the preamplifier is also visible.

Two bunches of protons (322 ns apart and 50 ns wide) are generated by the ISIS accelerator with a frequency of 50 Hz and an energy of 800 MeV. The neutron beam obtained after spallation on the target is characterized by a white energy spectrum varying from 0 to 800 MeV. Neutrons are then collimated to the ROTAX experimental hall.

The detector chosen for the present experiment is a 500 μm thick, 4.5 x 4.5 mm^2 active area single crystal diamond (SCD) by Diamond Detectors Ltd, and it is biased with +400 V. Fig. 3 shows the experimental setup used in these measurements.
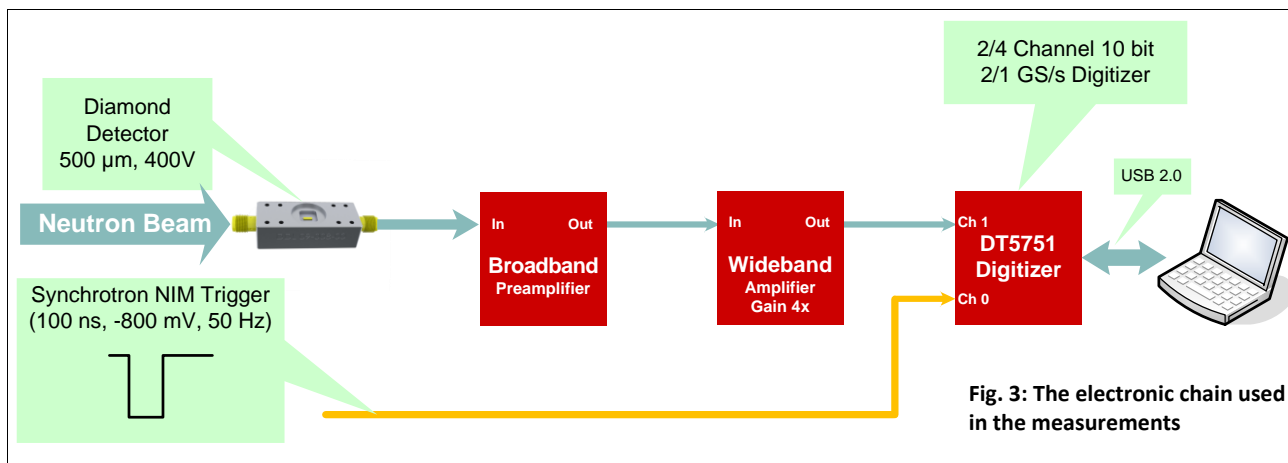
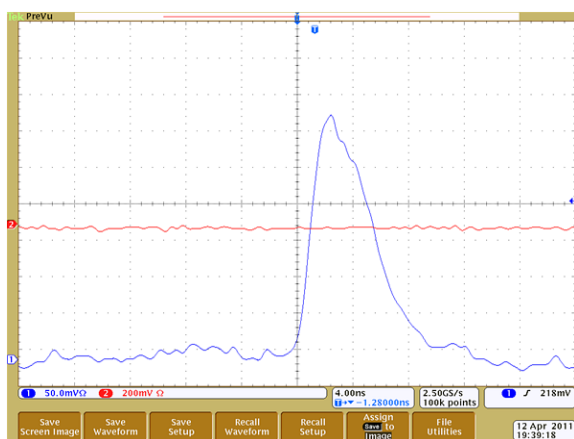Fig. 3: The electronic chain used in the measurements

Fig. 4: A typical signal from the preamplifier

The signal from the detector is then sent into a double amplification stage realized with a Broadband DBA III preamplifier, designed at GSI [2], and a custom made wideband amplifier with a fixed gain of 4. This amplification stage gives rise to a slightly shaped signal with a rise time of 2 ns and a width of 10 ns, as shown in **Fig. 4**.

The amplitude of the signal is variable according to the neutron energy and to the reaction involved, but typical signals (from tens to hundreds of mV) perfectly fit the input range of the digitizer.

The chosen digitizer is the fast DT5751 model, with 1 and 2 GS/s sampling rate, 10 bits of resolution and 1 Vpp input range. The desktop configuration of the digitizer allows for a very compact system, avoiding the need of any kind of crate.

Calibration

In order to characterize the neutron beam it is necessary to measure the correlation between the incoming neutron energy (from the ToF measurement) and the energy released in the detector. For the latter purpose an energy calibration is needed and it has been done using an alpha source (^{241}Am, E_α =5.5 MeV). The source was placed in front of the detector and the resulting calibration spectrum is shown in **Fig. 5**. In the calibration process, the signal was acquired with the DT5751 self-triggering on the input pulses.
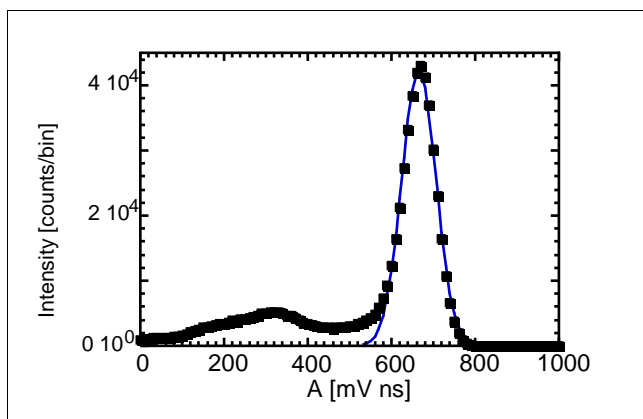

Fig. 5: Calibration peak with ^{241}Am source. The line is a Gaussian fit to the data. The Gaussian parameters are height I= 4.5·10^4, FWHM= 96 mVns, position A=665.5 mVns.

Measurments

During the measurements, the data acquisition was triggered by a NIM logic signal generated by the ISIS synchrotron, which represents the neutron start time. Such a signal reaches the digitizer with a 5 µs delay respect to fast neutrons signals.

As shown in the scheme in section 3, the signal from the detector is sent to Channel 1 of the digitizer while the trigger signal is sent to Channel 0. Digitizing the trigger signal (instead of sending it in the TRG-IN connector on the front panel) it is possible to achieve a time resolution of 1 ns (at 1GS/s sampling rate, 500 ps at 2GS/s). In Figure 6 a typical acquisition window taken with the CAEN WAVEDUMP acquisition software is shown.
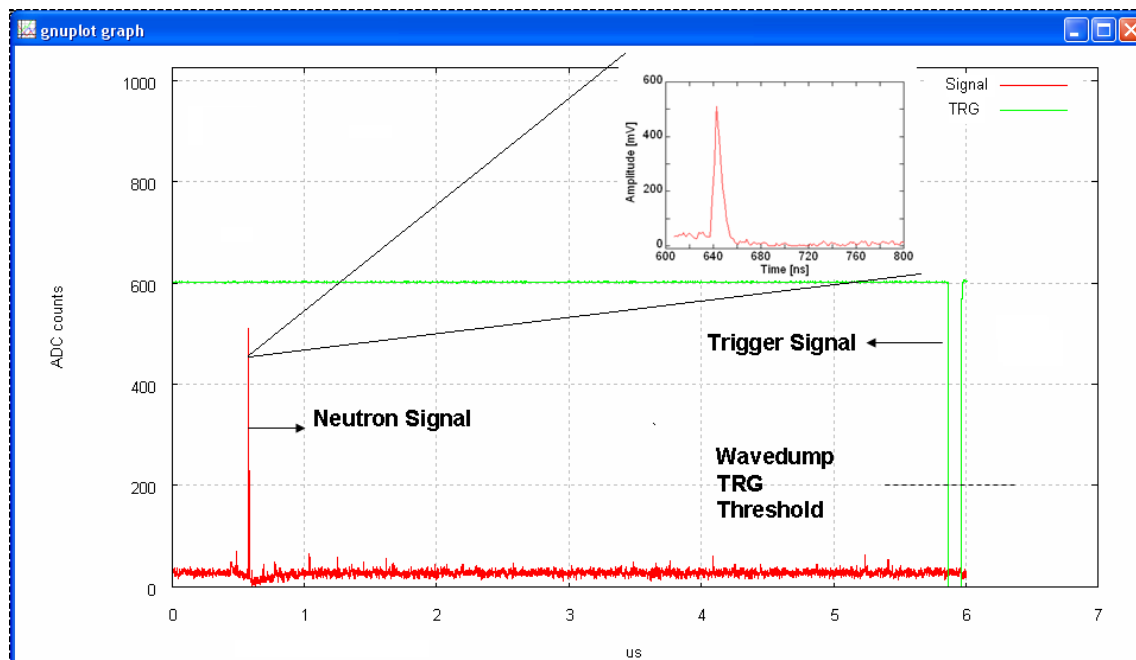

Fig. 6: The figure shows the data acquisition technique. The red line represent the signal from the detector, the green line is the machine trigger.

This acquisition technique is made possible by the common trigger feature of the digitizer standard firmware. In this modality, every channel is enabled to trigger according to a programmable threshold and this trigger signal is then propagated to the other channels, which freeze their memories and acquire the set acquisition window.

For this acquisition the Channel 0 (green signal in Fig.6) trigger threshold parameter is set to 200 ADC counts, while the Channel 1 (red signal) trigger is disabled. With this setting it is Channel 0 only, i.e. the machine sync signal, that triggers the acquisition. The acquisition window length is set to 6 µs, in order to take account of the delay of the trigger and a value of 1% of post trigger is set (i.e. the percentage of samples after the trigger acquired in an acquisition window).

In this way the digitizer can "look back in time" allowing the storage of pulses coming from the detector digitized before the trigger arrival. Every event like the one represented in figure 6 is saved in binary format on a file that can be retrieved in order to perform off-line analysis. In this case a custom made software reads every event and calculate the time difference between the trigger signal and the maximum of the detector signal, that is the neutron ToF. In addition the area of each pulse, that is proportional to the energy deposited in the detector, is calculated and saved too. These two information make possible the creation of a biparametric contour plot. The only ToF measurement, in fact, is not enough for a full characterization of the neutron beam, because the slow neutrons of the first bunch can be overtaken by the fast neutrons of the second one.

The use of the DT5751 Digitizer allows the user to combine the information from both ToF measurement and deposited energy in the detector and so it is possible to place a threshold on the deposited energy in order to distinguish neutrons from the two bunches.

Data analysis

Figure 7 shows the biparametric (ToF - deposited energy, Ed) contour plot of the acquired data. The structure of the event distribution in the contour plot reflects the time structure of the two bunches in the ISIS proton beam. The events from the two bunches are well separated in time only for deposited energies Ed>10 MeV. For lower Ed values the two bunches overlap.

Some peak structures with a number of events higher than 3000 events-per-bin can be recognized at Ed values below 5 MeV. The peak at about (ToF=49 ns, Ed=2 MeV) is associated with a strong flash of gamma-rays, coming directly from the moderator and

spallation target. This peak was used for synchronization of the ToF axis since it provides a more stable reference than the proton signal from the accelerator. An identical peak is visible about 320 ns later and is due to the second proton bunch. Two broader peaks are also visible at longer ToF: approximately at 600 ns and at 900 ns. These peaks are due to the less energetic neutrons which interact via elastic scattering with carbon atoms, thus depositing few energy.

The black and green lines in **Fig. 7** provide a guide for understanding the observed events distribution in the ToF - Ed space. Let the reader consider for instance the black line: at a given ToF corresponds a specific neutron kinetic energy K; a neutron with kinetic energy K can release a variable amount Ed of energy in the detector via n-alpha reaction: the full black lines (one for each proton bunch) represent the maximum possible deposited energy for this reaction. The corresponding dashed black lines represent the same amount but considering the uncertainty of neutron kinetic energy due to the 50 ns broadening of each proton bunch. The green lines represent the same quantities but for the elastic reaction mentioned before.
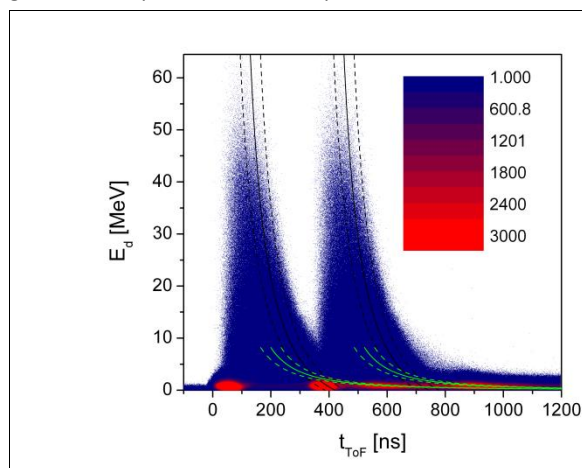

Fig. 7: Contour plot of the event density in the (ToF, Ed) plane. The total number of events in the plot is 3 10^7. Data collection time of 65h.
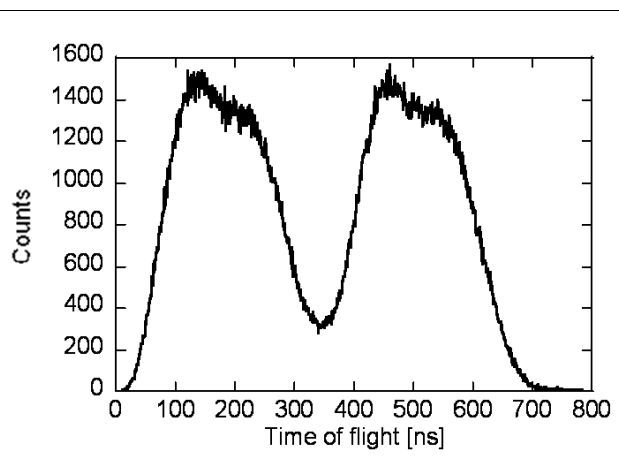
Fig. 8: A Time of Flight spectrum obtained from the waveforms acquired during the last session of measurements at the ISIS spallation source.

In **Fig. 8** a typical ToF spectrum is shown, which is the projection of the data shown in Figure 7 on the x-axis considering only events with Ed > 5 MeV. As said, the two peaks correspond to the two bunches of protons accelerated by the synchrotron. The width of the two bunches is the sum of the width of the proton bunches broadened by the neutron ToF. The less energetic the neutron is, the longer is the ToF. This figure, combined with Figure 7, shows the capability of diamond detectors and CAEN DT5751 Digitizer to fully characterize a fast neutron beam.

Further details can be found in reference [3].

References

[1] http://www-nds.iaea.org/exfor/exfor.htm.

[2] P. Moritz, Broadband Preamplifiers for Fast Particle Detectors, GSI - Gesellschaft für Schwerionenforschung mbH, Planckstr. 1, D-64291 Darmstadt, Germany.

[3] M. Rebai et al., Diamond detectors for fast neutron measurements at pulsed spallation sources, 2012, JINST 7 C05015.

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