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The Development of a Spectrometer for 14 MeV Neutrons from Fusion

by
Dan Aronsson

Department of Reactor Physics
Göteborg 1991

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Abstract

A spectrometer for 14 MeV neutrons, to be used for fusion plasma diagnostics at JET, was developed at the Department of Reactor Physics at Chalmers. The spectrometer utilizes neutron scattering in a polyethylene foil with the detection of the scattered neutron and its associated recoil proton. This thesis describes the contributions by the author to the development of the spectrometer.

For the detection of 12 MeV protons we have tested silicon surface barrier detectors, lithium-drifted silicon detectors and high purity germanium detectors. The lithium-drifted detectors were finally selected for use in the spectrometer. The lithium-drifted silicon diodes have also been used for direct spectrometry, utilizing the neutron induced charged particle reactions in silicon. The methods used for the energy calibration and the timing calibration of the diodes, both during the installation of the spectrometer and during operation, are described. Coincident gamma radiation from a cobalt source is used to calibrate the timing scales of the proton detectors to that of the neutron detectors.

The detection of 2 MeV neutrons is done by fast plastic scintillators. Since the neutron generator which was used to test the detectors supplies 14 MeV or 2.5 MeV neutrons only, a neutron energy converter ha · be constructed to study the detectors at other neutron energies. In the actual spectrometer an array of scintillation neutron detectors is used. A method of calibrating such an array of detectors with a gamma source was elaborated and is also described here. The result of the calibration is a set of parameters that can be used to determine the high voltage settings and the discriminator levels that are needed to achieve homogeneous sensitivity for all the detectors of the array. The energy scale itself was then calibrated by using gamma sources of various energies.

To test the spectrometer as a whole at a neutron generator, a test bed was constructed. A lithium-drifted silicon diode was used to measure the neutron flux and the neutron energy resolution in the test bed.

Keywords: Neutron detection, neutron spectrometer, associated particle spectrometer, time–of–flight spectrometer, JET tokamak, fusion reactor instrumentation, plasma diagnostics, proton recoil detector, proton detection.

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PAPERS

This thesis is based on work contained in the following papers:

I C Grosshög, D. Aronsson, K.–H. Beimer, R. Rydz, N. G. Sjöstrand, L. O. Pekkari and Ö. Skeppstedt, The Use of the Neutron – Proton Scattering Reaction for D–T Fusion Spectrometry, Nucl. Instr. Meth. A249(1986)468.

II D. Aronsson and S. Singkarat, A Neutron Energy Converter for a Small Laboratory Neutron generator, Nucl. Instr. Meth. A245(1986)426.

III K. Drozdowicz, M. Hoek and D. Aronsson, Energy Calibration of Neutron Detectors for the Neutron Spectrometer TANSY, Nucl. Instr. Meth. A306(1991)315.

IV D. Aronsson, Selection and Calibration of Proton Detectors for Use in the TANSY Neutron Spectrometer, Report CTH–RF–73, Göteborg (1990).

V D. Aronsson, SiLi–Detector Used for Calibration of 14 MeV Neutron Flux, Report CTH–RF–78, Göteborg (1991).

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1. Introduction

The interest in fusion research has led to the construction of very large experiments for developing the technology of magnetic confinement of fusion plasmas. The experiments measuring on the plasmas produced bear the common name fusion diagnostics and supply the experimentalists with information about different properties of the plasma, such as power, plasma current, electron density, neutron production, neutron spectrum and so on. Another aim for plasma diagnostics is to investigate the different signals from the plasma to see if they can be used as feedback signals for controlling a burning plasma. Such features will be required for the possible energy production by fusion.

From the neutron physics point-of-view a large experiment fusion plasma may be an interesting source for 14 MeV neutrons. The high intensities that are likely to be attained may open new fields for research.

The Department of Reactor Physics at Chalmers University of Technology became involved in neutron spectrometry for fusion plasma diagnostics in 1982. The specific task was to investigate the feasibility of using the proton-recoil method for a 14 MeV neutron spectrometer with 1 per cent resolution. The spectrometer should be used for diagnostics on pulsed deuterium - tritium plasmas at the Joint European Torus (JET). The study was successful and gave as a result a proposal for a neutron spectrometer [1].

The feasibility study was evaluated together with other suggestions and was selected by JET as one of the proposals that should be investigated in a design study. During the development of this second study the original proposal was revised and further refined at the same time as the aspects of manufacturing the instrument and operating it in the JET laboratory environment were considered. The design proposal was published as a report in 1985, see reference 2. The research leading to the reports in 1983 and in 1985 was summarized in paper I. During the development of the spectrometer this was given the name "TANSY".

Based on the design proposal, JET placed a construction contract for TANSY with our department. The actual construction started in 1987 and the spectrometer was completed and sent to JET in the autumn of 1990. The further developments done during the construction and the results from the calibrations are reported as parts of the documentation of the instrument, which will be published as several department reports. Some results will be described briefly below to illustrate the measurements done. Since JET has prolonged the present state of deuterium-deuterium operation, the tritium phase is postponed and TANSY will probably be used in 1994.

My involvement started during the background research which is described in references 1, 2 and is also reported in paper I. Chapter 2 of the present work describes the background. The leading subject of my work has been the proton detectors, which I deal with in chapter 3, and which is based on the contents of papers I, IV and V. The detection of the scattered neutrons uses scintillators. In the development of the scintillation detectors a neutron energy converter, "Tebene", was used. I took part in the design of "Tebene" and in the measurements. This is described in chapter 4.1, which is based on paper II. The calibration of the scintillator detector arrays in TANSY is described in chapter 4.2, which is based on paper III. My contribution to that work is mainly with the absolute calibration measurement. The work I have done on the spectrometer system in general is described in chapter 5. That is based partly on papers IV and V but also on not yet published material [22].

To gain experience of the JET operations and the laboratory environment, I have taken part in the work at JET under a so called task agreement. The task has been neutron diagnostics and has in particular dealt with the 2.5 MeV neutron spectrometer that is used during the deuterium-deuterium operation of JET [3].

2. Neutron spectrometers for fusion diagnostics

The JET machine has been operated for several years with deuterium plasmas giving 2.5 MeV neutrons. For measuring neutron spectra several instruments are used. These are ^{3}He-spectrometers, ionization chambers, silicon diodes and a time-of-flight spectrometer.

The time-of-flight spectrometer uses a scintillator positioned in the neutron beam as scatterer. Neutrons that are scattered in the correct direction will hit a battery of scintillators. The time-of-flight of the scattered neutron is measured and as the flight path and the scattering angle are known, the energy of the original neutron can be calculated. The instrument and the data analysis as well as results are described in reference 3.

2.1 Feasibility study

A plasma with a mixture of deuterium and tritium will emit neutrons of about 14 MeV energy. Since several other types of diagnostics will be impossible in such a plasma, the neutron measurements will be of very high importance and the energy resolution requirement has been set as high as 1.5 per cent. Another spectrometer design than the one above is therefore necessary.

In thorough pre-studies JET has investigated several alternatives for 14 MeV neutron spectrometry. The work has been performed at several laboratories around Europe and the different alternatives have been evaluated in workshop meetings at JET. The final choice was to use two types of spectrometers. One type is the combined proton-recoil and neutron time-of-flight spectrometer, TANSY, which is described in this work. The other type is a proton recoil spectrometer using annular scatterers and a centrally positioned proton detector.

TANSY measures the energy of the recoil proton from a scattering reaction against hydrogen. The scattered neutron is also measured and used as a correction to the energy measurement. This idea was presented by Elevant and Lorenzen [4], [5], and it was developed for JET usage by our department in the feasibility study [1].

It appears that there are no reports in the literature about any instruments using this method. However, some conventional proton recoil instruments have been interesting and inspiring for our work. Keith Furr and Runyon [6] presented an idea which was adopted for the TANSY annular design of scatterer in the feasibility study. In their work a beam of neutrons hits an annular scatterer and the recoiling protons impinge on a centrally positioned diode detector. The diode is protected from the direct neutrons by a central shadow bar. Chung [7] suggested several designs for a spectrum monitor. One of them uses an annular scatterer of the same kind as Keith Furr and Runyon. Chung mentioned also a spectrum monitor with a coincidence requirement between the proton detector and a scintillator detecting the scattered neutron. However, he neither described the instrument nor gave any results from using it.

In the feasibility study the annular scatterer idea was developed to include detection also of the scattered neutron in a circular set of neutron detectors. See figure 3 of paper I. The proton energy would be registered in the centrally positioned diode and a start signal would go for the time-of-flight measurement of the scattered neutron. The contribution from the scattered neutron would be used as a correction factor to the energy measurement. There would of course be a coincidence requirement between the two measurements. This instrument was planned to look at the plasma from the side of the torus, i.e. it should have been placed in the diagnostics hall. In the next paragraph the reason why this design was later replaced is described. The intended position in the diagnostic hall has been occupied by other equipment and a position in the roof laboratory was assumed in the design study.

An interesting two detector telescope was designed by Geller et al. [8]. The energy loss of the proton within a stilbene scatterer is measured and used for correction of the total energy measurement in a proton detector.

Another fruitful idea was found from the paper by Potenza and Rubbino [9]. The barrel-shaped scatterer they suggest was used for the proton detector tests described in chapter 11 of reference 1. The test bench Tebene which is described in chapter 4.1 was based upon the same principles, but with the development that Tebene uses the pulsed neutron generator for a time-of-flight measurement of the neutron.

2.2 Design study development

The annular design which was the product of the feasibility study would have made maximum use of the proton detector area. All of the 100 cm^2 annular scatterer would have recoil protons detected in 3 cm^2 area of the proton detector. A drawback of this design was that the collimator had the same large cross-section, 100 cm^2. This large opening would lead to a considerable background from all the unscattered neutrons that would pass through the large but thin foil.

To make better use of the neutrons passing the collimator a radical redesign of TANSY was done in the design study. The cross-section area of the collimator was decreased, giving a lower background while the sensitivity of the spectrometer was increased by a factor 10. The total signal-to-background ratio was improved by a factor 33. This improvement was made at the expense of a little worse resolution and a more complex detector system using six proton detectors instead of only one. Another advantage gained is improved reliability as the spectrometer does not depend on the function of one single proton detector. Furthermore, it is possible to completely separate the spectrometer in two independent halves.

In the new design the foil is positioned parallel to the neutron beam and right in the middle of it. Figure 7 of paper I shows the geometry in detail. The design gives a less favourable angle for the protons exiting the foil which causes a somewhat worse resolution. On the other hand, the amount of foil is much better utilized and a higher fraction of the recoil protons is likely to reach a detector.

3. Proton detectors

Semiconductor diode detectors have been used for measuring ionizing radiation since the early sixties. The technology offers good energy resolution and has the advantage that the detectors occupy only small volumes. Today high–purity germanium detectors are widely used for gamma spectroscopy. Lithium-drifted silicon detectors are used for less penetrating radiation such as soft gamma and X–rays. Silicon detectors dominate the detection of charged particles. The semiconductor detectors for photons usually require cooling, whereas some types of charged particle detectors require cooling and some not. The diodes used for charged particle detection can be made very small and there are types available for special purposes.

Semiconductor detectors have often been used in proton-recoil detection. The history was reviewed in the first report [1]. The advantage is the small volume of the detector which gives a good angular definition. For the present work it was natural to investigate semiconductor detectors further. The types of detectors that have been considered are silicon surface-barrier detectors, lithium-drifted silicon detectors and high purity germanium detectors. Aspects such as energy resolution, timing resolution and reliability were studied. From the experiments we learnt how to separate the proton signals from the background signals of neutron induced reactions. Different electronics set-ups were tested and methods of calibration and testing have been developed. The final choice of detector type was a lithium-drifted silicon detector selected for sufficient timing purposes. The development work is described in paper IV.

A feature of a silicon detector is that it may itself be used as a neutron spectrometer, using the neutron reactions in silicon giving charged particles [10],[11]. This was utilized for determining the neutron flux at the neutron generator at Chalmers (paper V).

3.1 Selection of the proton detectors for TANSY

The electric field applied to a semiconductor diode creates a region normally depleted of charge carriers, i.e. electrons and "holes" that are free to move with the electric field. When a charged particle enters the semiconductor material it causes ionizations that give charge carriers. The number of charge carriers created by a certain amount of energy is significant for how good energy resolution it is possible to achieve with the detector material. Furthermore, it is essential that the detector has a homogeneous electric field so that all the charge carriers are efficiently collected to the electrodes.

When a charged particle enters the detector through the front contact the electronic pulse starts instantly since the first charge carriers are produced immediately behind the contact. For a particle resulting from a neutron reaction within the bulk detector material, or for gamma radiation causing ionization in the detector, all charge carriers will have to travel a certain distance in the detector before reaching the electrodes. In this case the start of the electronic pulse is less well defined and the time distribution for such pulses is broader than for charged particles entering through the front window. This difference has been useful in the detector studies for separating the proton events from the neutron induced background events in the bulk of the silicon. The measurements are described in paper IV, chapter 2.

The thick detectors necessary for fully stopping protons of 10 - 20 MeV energy will have slow pulse rise times due to the long charge collection time. Long rise time is a disadvantage when making precise timing measurements since the timing signal uses the differentiated pulse. The timing signal will then have a low amplitude for long rise-time pulses. The situation improves with increasing bias of the detector [12] as the higher electric field of the detector shortens the charge collection time. To fulfil the timing requirement the thick detectors selected for the TANSY application require higher voltages than standard detectors do.

Sometimes pulses occur with extremely long rise times. These are due to defective regions within the detector which give poor charge collection in the detector [13]. Such pulses can be rejected through an optional circuit in the constant fraction discriminator[1], slow rise time rejection (SRT), which is used in TANSY.

An arrangement quite often used to achieve good timing is a set of two detectors, one thin transmission detector in front and one thick energy detector behind. This gives a good timing signal from the transmission detector while the major part of the energy signal comes from the second detector. The arrangement was considered for the TANSY spectrometer but was rejected because the energy resolution would be poor when adding the energy spread from two detectors. For timing purposes the detector should be thin, typical thickness 100–300 μm. In this

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[1] EG & G Ortec model 584.

case, even when using a thick timing detector, 500 μm, the energy detector must still be 2 mm thick. For such thicknesses a lithium–drifted silicon detector is the only realistic alternative with the relatively poor resolution which is the main drawback of that type of detector. Then adding the energy spread of another detector would make it even worse.

The measurements done for the selection were reported in paper IV. The detector types that were tested are described in the following paragraphs.

3.1.1 Silicon surface-barrier detectors

Silicon surface-barrier detectors are made from very pure silicon. The rectifying contact is made from gold that is evaporated onto the silicon surface. The gold layer is very thin, typically 40 $\mu g/cm^2$, which minimizes the energy loss of particles coming in through it. The leakage current of a surface-barrier detector is very low, typically less than 1 μA. The detectors have low noise and consequently the resolution is high.

In the feasibility study [1] some experiments were done with an Ortec ruggedized detector, type R. This type is reversed with the silicon-gold junction at the rear and an aluminium contact in front. Through a protective coating it can be used in a hydrogen environment, an option that was considered in the feasibility study. The aluminium front window is thicker than for the normal gold window detector which gives a higher energy loss for particles penetrating the window.

The tests for the design study [2] included a normal surface-barrier detector 2 mm thick and 1.0 cm^2 in area. This was an expensive specimen and, as we realized later, also rare. The extremely pure silicon needed to make such thick detectors is normally not available.

3.1.2 High purity germanium detector

High purity germanium is well known as a material for gamma radiation detectors. It is possible to use the same technology to make detectors for medium energy charged particles. Compared to a silicon surface-barrier detector the germanium detector will take higher energies of the particles due to the higher density of the material and the range of thicknesses available. It is necessary to cool the detector to liquid nitrogen temperature when it is under bias. Operated at these conditions the detector offers equally good resolution as the best surface-barrier detectors of similar area.

It was suggested to us to use a germanium detector because the cross-section for neutron induced charged-particle reactions of germanium is much lower than it is for silicon. This was, however, not useful for us because the commercially available detectors are too thick for our purpose. Due to the total volume the number of reactions in a detector will then anyhow be high despite the lower cross-section. Furthermore, the cooling requirement introduced a lot of complications such as cleaner vacuum at lower pressure and long cycles of evacuation and ventilation to allow the detector to cool down and to warm up to room temperature, respectively.

The alternative of using germanium detectors was rejected because of the complications described above.

3.1.3 Lithium-drifted silicon detectors

The lithium-drifted silicon detectors are p–i–n diodes where the intrinsic region is formed by silicon compensated by lithium that has been drifted into the material. This is used for making charged particle detectors thicker than circa 2 mm. The detectors can be operated at room temperature and thicknesses of up to several mm are available. The front contact consists of a thin surface layer of gold and a thin region of heavily doped material. The energy loss for a 5.5 MeV alpha particle is about twice that in a surface barrier detector. The leakage current is in the order of a few μA and the resolution is consequently worse than for a surface-barrier detector at room temperature. If the detector is cooled to -30°C the resolution is improved to the level of a surface-barrier detector.

When it became clear that surface–barrier detectors were hard to find and that germanium detectors were impractical to use, the next alternative was to investigate lithium-compensated silicon detectors. During the design study several standard detectors were tested. The detector performance was, however, insufficient and after a discussion with the manufacturer[2] it was decided instead to use specially selected detectors with better time properties. This choice of detectors stands higher voltage which improves the charge collection time of the detectors.

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[2] At that time Enertec, today Intertechnique.

3.2 Set–up for TANSY

The six proton detectors of TANSY are placed in the vacuum vessel. Their positions have been carefully calculated [2] to be just off the neutron beam. This is important to avoid background in the proton detectors from direct neutrons as well as in the neutron detectors from neutrons scattered in the proton detectors. The vacuum required to operate the proton detectors is easily kept by a turbomolecular pump.

The detectors are connected to the preamplifiers that are outside the vacuum vessel. The cables and the vacuum feed–through connectors have a total length of circa 30 cm for each detector. The signal from the preamplifier is led to the main electronics through 30 m long cables. The energy signal is used for deriving the timing signal as well as for the pulse height analysis. The full technical description of the TANSY proton detection system is given in reference 14.

A pulse generator is connected to each proton detector channel. It is a low–priced model which is continuously in operation. The stability is good but the precision of the setting is, however, not good enough for our purpose and therefore it is necessary to calibrate this low–precision system from time to time using a high precision pulse generator.

Through the continuously operating pulse generator it is possible to collect calibration data whenever the spectrometer TANSY is idle. The alpha particles from the americium source and the signals from the pulse generator give the points that are necessary to calibrate the energy scale in the pulse height spectrum. After a JET pulse the up-to-date calibration data are saved together with the pulse data. After each JET pulse the collection of calibration data is restarted in the same spectrum. Each calibration result can be compared to previous values to observe changes in the system. Since the periods of time between JET pulses can vary considerably, the number of counts in the channels may well exceed the maximum capacity of the system. Therefore, to avoid distortion of the collected spectrum, the contents of every channel is divided by two every time any channel reaches the maximum limit. The advantage of this calibration system is that the spectrum will always contain recently collected and useful data in a sufficient amount. The older data successively lose in importance since they will be divided by two, several times. The full description of the calibration methods is given in paper IV.

3.3 Direct spectrometry with diodes

When silicon is irradiated with fast neutrons there occur (n,α) and (n,p) reactions within the silicon. In a silicon diode the charged particles from these reactions give signals that can be recorded. Since the Q–values of the reactions are known the spectrum recorded can be used for analysis of the neutron spectrum. The method has been described by several authors, e.g. in references 10, 11, and 15.

Paragraph 5.3 treats how this method was used for measuring the energy spread of the collimated beam of neutrons in the test bed experiments and an attempt made to use the neutron induced reactions in silicon for determination of the total neutron flux at the scatterer position in the spectrometer TANSY.

4. Neutron detectors

The properties required for the TANSY neutron detectors were specified in reference 1. The neutron detectors should be fast, they should have low background sensitivity and they should have a high sensitivity for neutrons in the low MeV energy range [1]. The type of detector best to fulfil these requirements was plastic scintillators.

To test the detectors a test bench was constructed as described in paper II. The detector construction for TANSY was based on measurements done in the test bench [2]. The relation between the signal amplitudes from neutrons and the signal amplitudes from electrons was determined from the test bench measurements.

A procedure for determination of the high voltage settings and the discrimination levels for an array of neutron detectors is described in paper III. The method has been developed for and applied in the calibration measurements for TANSY.

4.1 Scintillator measurements

4.1.1 Test bench

The response of a scintillator depends on the energy of the neutrons. A test of a neutron detector must therefore be done using neutrons of relevant energies. However, from a small laboratory neutron generator there are only two energies available. The $^{2}D(d,n)^{3}He$ reaction gives neutrons of about 2.5 MeV energy and the $^{3}T(d,n)^{4}He$ gives about 14 MeV energy. These two energies are not enough to test the detector performance.

A way of making tests with several energies would have been to make the experiments at a van de Graaff generator. For repeated experiments with several different detector constructions this would have been very expensive and the step by step development would not have been possible.

Instead it was decided at our department to use our own neutron generator and a system of concentric scatterers around a central shadow bar. The principle of this test bench has been described and analysed in paper II. The method utilizes neutron scattering against hydrogen for converting source neutrons to lower energies. To achieve a reasonable yield of scattered neutrons a large scattering volume is required. A scatterer shaped as a special surface of revolution fulfils this without causing too large spread in the scattering angles. When using only a ring of scattering material the flight-paths from scatterer to detector are equal for all neutrons. With a pulsed neutron generator, time-of-flight analysis of the scattered neutrons is possible for verifying the energies of the neutrons. In the experiments four polyethylene rings were used as scatterers. They gave neutrons of energies 1.0, 1.8, 2.8 and 4.0 MeV for a source neutron energy of 14 MeV. The idea sprung from the proton detector tests done in the feasibility study, see reference 1, and the test bench was nicknamed Tebene.

The work has been continued by Singkarat, who analysed the effect of multiple scattering in Tebene using the Monte Carlo method [23].

4.1.2 Scintillator design

The first TANSY design [1] suggested long scintillators connected to the photomultiplier with large light guides. An alternative was to use two photomultipliers in coincidence, one at each end of the scintillator. Both solutions were shown to have problems as the light signal is attenuated on its way from the point of interaction to the photomultiplier. The longer the path for the light, the weaker the light signal to the photocathode of the multiplier will be.

The Tebene test bench was used for developing the neutron detector construction for TANSY. Scintillators with long light guides were tested as well as those that were coupled directly to the photomultiplier. The experiments clearly showed that for TANSY it was necessary to use a scintillator close to the photomultiplier. The tests have been described in reference 2.

4.2 Calibration of the detector array

The aim with the calibration of the neutron detectors is to be able to control the individual detectors so that they give a homogeneous response to neutrons in the interesting range of energy. The high voltage of the photomultiplier tube and the setting of the constant fraction discriminator are the two factors that are used for controlling the response of a scintillator detector. The total response is also affected by several other factors that can not be controlled such as the optical coupling and individualities of the photomultiplier.

Through the method described in paper III the neutron detectors were calibrated for their optimal operation. A complete description and detailed results are available in references 16 and 17. First a relative calibration was done where all detectors were mapped and a set of two calibration parameters for each detector was calculated. This was done from measurements of the detector count rate response to a gamma radiation source. The count rate was measured as a function of high voltage at several discriminator levels. The discriminator level was then fixed at 150 mV. Using the measurement data the high voltage for each detector was thereafter set so that the energy response was the same for all detectors.

The absolute energy calibration relates the response of the detector to the neutron energy. The scintillator response is different for different types of radiation interaction. The neutrons react through proton recoils and the gamma radiation through gamma-electron interactions, e.g. Compton scattering. In the gamma calibration experiment the electron energy scale in the scintillator was related to the ^{60}Co gamma energy. This was verified in separate measurements with several gamma sources. The energy scale for neutrons was related to the scale for gamma radiation, using data from the Tebene measurements, published in reference 2, page 63, and data from Madey et al.[18].

With the knowledge from this method it is possible to set the discriminators at any energy level without having to make any new calibration. From that it is possible to make a good sensitivity calculation for the neutron detectors.

5. Spectrometer system

The TANSY spectrometer measures two properties of each event. They are the energy of the recoil proton and the time difference between the detection of the proton and the detection of the scattered neutron. From this difference the time-of-flight of the neutron can be calculated since the proton energy and the flight lengths are known [2]. To measure the time difference correctly it is necessary to calibrate the time scales of the proton detectors to that of the neutron detectors. The spectrometer system has been tested using the neutron generator at our department as a neutron source.

5.1 System calibration

The timing walk must be adjusted for the proton detector constant fraction discriminator. If the walk is properly adjusted the timing will be the same independent of the amplitude of the signal that is fed to the constant fraction discriminator. To do this it would be useful to have a radiation source that emits radiation of all energies within the range of interest, in coincidence with a fixed amplitude triggering signal. No such source is available and the best substitute we could use was a precision pulse generator[3]. In this pulse generator the trigger signal is unaffected by the attenuation switches if the same number of switches is used all the time. After a suitable amplitude was set, pairs of the attenuators were applied to give amplitudes that together cover the interesting range of amplitudes.

The perfect walk adjustment is seldom possible to achieve. For the proton detectors it was not possible to get a completely homogeneous response for all energies. A homogeneous response would have been useful since a cobalt source is used for the timing calibration. The signal amplitudes from the ≈ 1 MeV gamma radiation of cobalt are considerably lower than the amplitudes from the protons. The aim was therefore set to have a homogeneous response over the interesting energy range of the protons. The difference from the relative time calibration is compensated through a constant which can be calculated from the neutron measurements. The walk adjustment and its results for the proton detectors are described in paper IV.

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[3] EG & G Ortec model 448.

For the timing intercalibration of the proton detectors and the neutron detectors it was first considered to use a ^{207}Bi source which emits a conversion electron in coincidence with a gamma ray. ^{207}Bi is, however, no longer a standard off-the-shelf nuclide and it would have been expensive to have such a source made. Instead it was decided to make use of a strong ^{60}Co gamma radiation source. This source emits two coincident gamma rays of ≈ 1 MeV energy each. The silicon diodes have small volumes and the sensitivity for gamma radiation is therefore low. This is an advantage in normal operation as it keeps the background count rate down. For this calibration it was, however, a major drawback as the measurement time has to be very long, more than a day, to compensate for the low sensitivity. The neutron detectors have good sensitivity for gamma radiation. The source was therefore positioned close to the proton detectors. By placing the source in the foil-centre position we also gained the advantage of the gamma rays coming from the same point as the neutrons will come in the measurement.

The time distribution was measured using the proton detector for the start signals and the neutron detector signals as stops. For each detector combination a coincidence peak occurs as in figure 4.2 of paper IV. The timing distribution for the coincidence peak is not very well defined. This is due to the distributed points of interaction in the proton detectors. For an interaction in the bulk of the material the charge collection time is longer than for an interaction starting near a detector electrode. Correlation techniques are used to get the best timing precision. The calibration done this way will only give a time scale common for all neutron detectors. The absolute time scale will have to be analysed from the measurement data itself. This procedure is described in reference 19.

5.2 Test bed

The environment at the neutron generator in Gothenburg is very different from that at JET. The conditions differ when it comes to source properties, radiation background, data collection etc. For the tests of TANSY a test bed was constructed around the neutron generator. The test bed is shown in figure 1. The neutron generator was operated in continuous mode at a moderate intensity of typically total yield 10^9 n/s. The flux of neutrons from the neutron generator is much lower than from the JET fusion plasma. It was therefore necessary to have the spectrometer much closer to the source. In fact one had to come so close that the 2 m long collimator [2] could not be used at these tests. The source to foil distance in the test bed defines the geometry. The source to foil centre distance was chosen to be 40 cm, which left 20 cm of space available for a simple straight slot collimator. A detail of the test bed arrangement around the target is shown in figure 2.

The neutron generator target could be treated as a point source as it produces a divergent flux of neutrons. The flux leaving the collimator is still divergent. This condition is a major difference from the conditions at JET where the flux from the distant source, after leaving the long collimator, is essentially parallel.

A floor was constructed around the neutron generator, at the level corresponding to the floor level at JET roof laboratory. The floor was made from aluminium scaffolding and in the experiments it was used to imitate the JET conditions as much as possible. The central part that supports all the shielding consists of steel plates resting on water filled concrete rings. That acts as a shield for those neutrons that go towards the floor from the target.

The 20 cm collimator is much too short to give proper shielding. To protect the proton detectors from excessive radiation damage an extra steel shield was put in the line-of-sight between the detectors and the target. To shield the neutron detectors from direct neutrons and gamma radiation the space available between them and the target was filled with as much concrete blocks as possible. The vacuum pump was moved from below the base plate to the top of the vessel to give space to the shielding. The volume closest to the target and around the drift tube was filled with polyethylene granulate. Furthermore, neutrons escaping downwards were stopped in the shield mentioned above. A photograph of the test bed is shown in figure 3.

5.3 Measurements in the test bed

The test bed was used for a long period of the TANSY test runs. The tests were done with one half of the spectrometer at a time. The two halves of the spectrometer work independently of each other and it was natural to divide it that way. During the measurements with the first half (branch A) the development and testing of methods was done. The hardware was tested and the software for the data collection was developed and debugged in this work. The software for the data analysis was also developed in parallel. The software is described by Grosshög [20] and Grosshög et al.[21].

The experiments with branch B were done for a short period before closing the experiments. This measurement series was a function test of the hardware of branch B but it also served as a test of the software that was developed earlier.

In the acceptance test for branch A, a resolution of 334 keV for 2.4 mg/cm^2 foil thickness was achieved, according to the preliminary evaluation. In the acceptance test for branch B a resolution of 252 keV was achieved for a 0.95 mg/cm^2 foil, which is also a preliminary result. The final evaluation of the measurements will be published together with Monte Carlo calculations on the spectrometer [22].

The resolution depends to a great extent on the foil thickness, which explains the considerable difference between the two results above. A normal series of experiments included using many different foil thicknesses. A thicker foil gives higher efficiency and many experiments were made with thick foils. The design value of the thickness is 1 mg/cm^2 [2].

In the measurements described in paper V the neutron generator energy spread was measured to a value 138 or 163 keV, depending on what assumption is done about the intrinsic resolution of the silicon diode. Quadratic subtraction of these values from the measurement result for a 0.95 mg/cm^2 foil gives a net resolution for the spectrometer of 207 keV and 192 keV, respectively. The experiment agrees well with the theoretical value of the resolution which has been calculated to 200 keV for a 1 mg/cm^2 foil [2].

The efficiency of branch B of the spectrometer was also measured using a silicon diode. The efficiency measurements are described in paper V. The results give an efficiency of $3 \cdot 10^{-6}$ cm^2 for a 1 mg/cm^2 foil when using the preliminary evaluations of the measurement data. The calculated value is $5 \cdot 10^{-6}$ cm^2 [2]. There was only time to make one diode measurement for this purpose. There are several possible reasons for the difference between calculation and measurement. The dominating error in the measurement is the uncertainty in the values of the cross sections, which are known only within 25 per cent. Furthermore, there is a very strong variation of the cross section with the energy of the incoming neutron. Other factors of uncertainty are indicated in paper V. The preliminary analysis of the TANSY data for the spectrum may also be insufficient.

At a measurement in the test bed it took typically several hours to collect a sufficient number of counts for a spectrum. This low intensity should be compared to the short duration of a JET pulse, only a few minutes. On the other hand, due to the position close to the target, the background problems in the test bed were considerable. In this way valuable experience was gained for the JET operation of the spectrometer.

6. Final remarks

The present work has described the detector development that has been done as a part of the design and construction of the neutron spectrometer TANSY. The work has also involved development of calibration methods for individual detectors as well as for the spectrometer system in total. The parts and methods described in this work have been used successfully in the spectrometer system. The measurements in the test bed at the neutron generator in Gothenburg verified that the spectrometer works at its specifications. The spectrometer has passed the tests and it has been accepted by JET.

The project of design and construction of the spectrometer TANSY shows that a relatively large task can be fulfilled also in a small university laboratory. The work done also demonstrates how a small laboratory neutron generator can be very useful in the development of neutron detectors. The neutron generator is the most important experimental equipment at the department of Reactor Physics in Gothenburg and without that this project would not have been possible. Large international scientific schemes such as the European JET project require national resources such as the neutron generator in Gothenburg for the development of components and for preliminary investigations of possible projects.

Unfortunately, the basic working tools of a small university laboratory are often insufficient for complex tasks. This is due to the small economical resources which do not make it possible to keep the laboratories with up-to-date equipment. In parallel to the actual work on the spectrometer and its components a large effort has therefore been put into creating hardware and software tools necessary for the different experiments. A considerable fraction of the work has dealt with the development of the data collection system. Software for the control and the data analysis was developed for the CAMAC computer "Starburst"[4]. By tradition in a university much of the work is done within the local organization instead of buying ready-to-use solutions. An advantage with this is, of course, the full control of all details and that the possibilities can be exploited. The disadvantage is that it costs time and work. All this technical background work put into the TANSY development has been time consuming but the character of the work makes it impossible to describe in the different reports or published papers.

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[4] Made by CES, Geneva.

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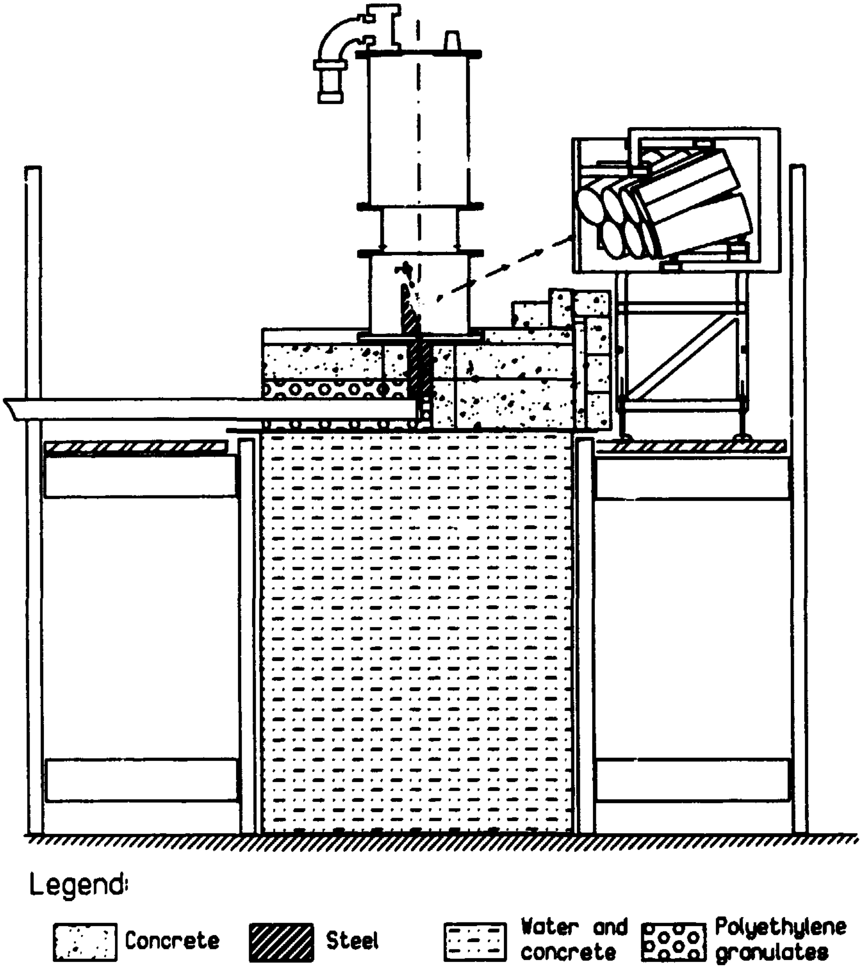

Figure 1. The test bed

For the tests of TANSY a test bed was constructed around the neutron generator. The spectrometer was modified with a short collimator and the vacuum equipment was moved from the base plate to the top plate of the vacuum vessel. Compare with figure 1 of paper III. This was done to make room for the shielding. The shielding was constructed so that it was possible to change the target of the neutron generator without moving the spectrometer.

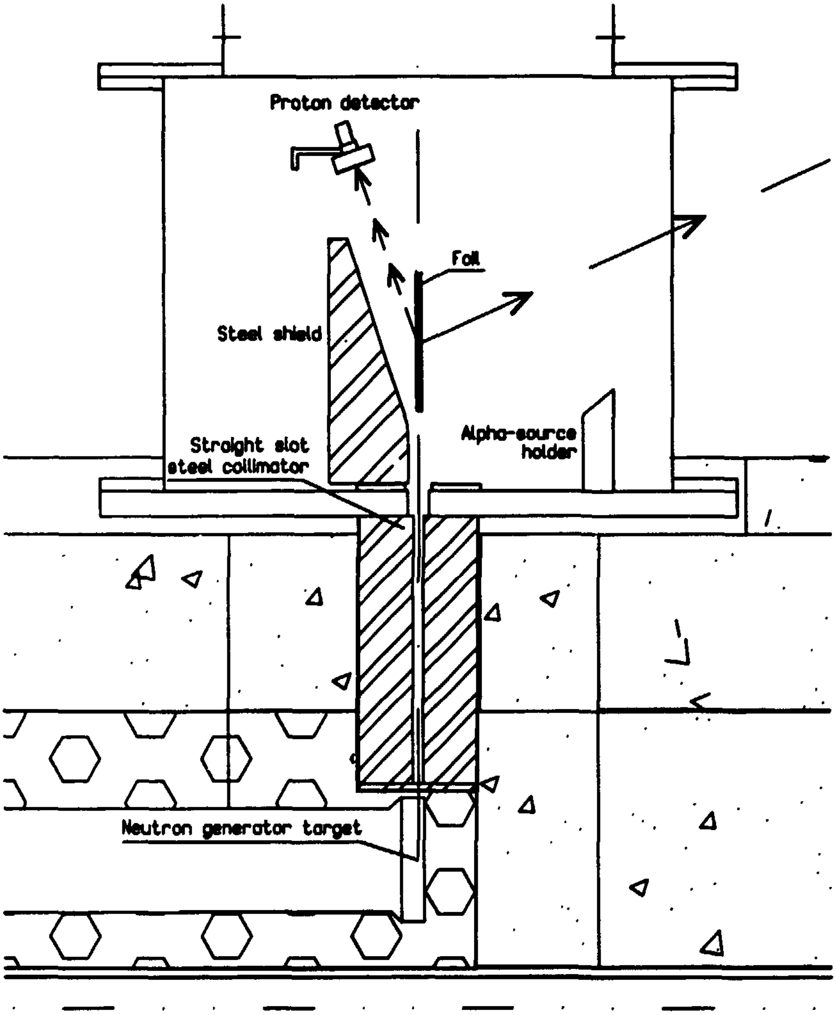

Figure 2. Details of the spectrometer in the test bed
The area around the target and the scattering foil of the spectrometer. The calibration alpha radiation source had to be put in a special source holder since the position intended for it in the final use was occupied by the steel shield.

Figure 3. Photograph of the test bed at the neutron generator in Gothenburg. For the photographer, both branches of TANSY have been arranged in the test bed. Actually, experiments were never run with both branches simultaneously.