Neutron Diagnostics for W7-X: A Long Term Plan for the Period 1996-2005.

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ABSTRACT

Deuterium plasmas in the Wendelstein 7-X Stellarator are estimated to generate 10^{12} to 10^{16} neutrons per second depending on the heating scenario applied. Under such circumstances it becomes feasible to evaluate information on plasma parameters like ion velocity distributions, ion densities, reaction fluctuations and thermal reaction fractional contribution from the neutron emission rate and energy distribution.

Methods for measurements of neutron total yield and energy distributions are discussed and suitable techniques, line-of-sight requirements, operating ranges and on-line data evaluation procedures are described. Measurements of total reaction yield are performed through two independent techniques, viz a set of standard neutron counters for time-dependent measurements and an activation system for time-integrated measurements. For time-dependent measurements several counters with different sensitivities will be used in order to cover six orders of magnitudes in neutron emission. Numerical simulations of the neutron transport will be carried out in order to optimise the detector locations with respect to a low scattering background and little neutron shadowing and screening in the line-of-sights of the detectors. Methods based on activation measurements for evaluation of toroidal non-symmetric neutron emission are also discussed. Usage of neutron spectrometry for evaluation of central ion temperatures and thermal reaction rates is described. A profile monitor utilising a new type of fast response detectors is suggested for measurements of neutron emission profiles and fluctuations of 30-40 kHz. Provisions are suggested for measurements of gamma radiation and charge fusion products. Necessary codes to be used for data analysis, interpretation, simulations and on-line representation of evaluated parameters like total neutron emission rate, thermal fractional contribution and central ion temperature are described.

A ten year plan for realisation of the neutron diagnostic systems is outlined with each system schedules divided into three phases. The first phase comprises preparations, decisions and design. The second includes construction, testing, calibration and preparation of software and the third installation and commissioning on W7-X. Estimated necessary personnel and financial resources are given for the specific systems proposed.

1 INTRODUCTION

Fusion plasma experiments generate fusion products like neutrons and charge particles, which, through their emission rate and energy distribution, carry information about the energy distribution of the reacting ions. Magnetic fusion experiments involving deuterium plasmas, with ion temperatures exceeding 1 keV, deuterium densities equal to a few times 10^{14} cm^{-3} and with plasma volumes of a few m^3 will generate 10^{12} or more neutrons per second. At this emission level it becomes feasible to extract information by making use of various techniques measuring fluxes and energy distribution of fusion products. Furthermore, gamma radiation can be emitted through bremsstrahlung from superthermal electrons during ECRF heating. Gamma emission is also generated through reactions between fast hydrogen ions and nuclei of impurities. These reactions are often of threshold type and therefore gamma energy spectra provide coarse information on the energies of the reacting particles. Through analysis of emission rates and energy spectra of fusion products and gamma emission, several pieces of information can be obtained. For plasmas with Maxwellian energy distributions, information on ion temperature and fuel density can be evaluated. Under auxiliary heating conditions, ion distribution functions and ratios of non-thermal versus thermal and non-fusion versus fusion reaction rates are deducible. Prompt losses, confinement and slowing down of charge fusion products in deuterium plasmas can also be evaluated. Furthermore, with some ingenuity, information on particle transport and MHD effects can be extracted. For a review article on neutron diagnostics and extraction of plasma parameters see [1].

This report describes diagnostic system based on measurements of neutrons, gamma emission and charge fusion products suitable for the Wendelstein 7-X Stellarator, see Table 1. The obtainable information in terms of plasma parameters and operating ranges is specified. Also described is a 10-year long term plan for realisation of the diagnostic systems. The plan describes the different items to be carried out for each system suggested, advises on a suitable laboratory where tests and calibrations can be performed and provides estimates on required financial and personnel resources. Three laboratories, IPP, University of Heidelberg and the Royal Institute of Technology take part in the realisation of the neutron diagnostic systems. The responsibilities and share of work are given in the description of each subsystem and in the time-plan respectively. The plan also provides a tentative time schedule. Because of the long time involved the timing can not be planned in detail but the report servers as a guide-line for the forthcoming work. It has also the significance of listing all the details and to give an overview of the whole project. The planned work is divided into three phases for each subsystem; Phase I includes preparation and decision, phase II is a design and construction phase and phase III concerns the installation and commissioning. Phase I comprises also all necessary R&D work to be performed prior to the decision on employing the system. The phase I and II work can normally be performed at the home laboratory while the phase III work essentially has to be made at the W7-X site. Section 2 gives an overview of the proposed fusion product diagnostics. Special considerations have been made due to the semi-continues character of the discharges. Section 3 to 8 describes the planned work and a time schedule for the major systems. In section 9 are the planned work on the interpretation codes and the interfaces between the diagnostic systems and W7-X described. Section 10 contains a summary of the long term plan.

2 NEUTRON DIAGNOSTIC SYSTEMS

In this section are the aims of the proposed diagnostic systems described. Several measurement methods have been considered and some have been rejected on practical or technical grounds. The links between the diagnostic systems and the computer data acquisition system are outlined.

2.1 Proposed systems

A set of fusion product and gamma diagnostics for the W7-X Stellarator are here described, see Table 1.

2.1.1 Diagnostic system objects

The objectives with the diagnostic systems are;

- To obtain information on the total neutron emission rate with an absolute accuracy of 10% and with a temporal resolution of 10 ms.
- To determine central ion temperatures in Maxwellian plasmas with an accuracy of 10% and a temporal resolution of 100 ms.
- To determine distribution functions of fast reacting ions during auxiliary heating such as neutral beam- and ICRF-heating with a temporal resolution of 100 ms.
- To determine non-thermal versus thermal and non-fusion versus fusion reaction rates under auxiliary heating conditions with a resolution of 20% and a temporal resolution of 100 ms.
- To study MHD activities and other fluctuations associated with fast particle behaviour.
- To evaluate and present data on total neutron emission rate, thermal reaction fractional contribution and possibly deuterium concentration on-line with resolution and time-lag of 100 ms.

And optionally:

- To monitor the presence of superthermal electrons through measurements of gamma radiation generated by bremsstrahlung and with a temporal resolution of 100 ms.
- To study prompt losses, confinement and slowing-down of fast charge fusion products with an accuracy of 20% and a temporal resolution of 100 ms.

This will be achieved by means of an integrated analysis of data provided by the neutron- and magnetic diagnostic systems.

2.1.2 Proposed neutron diagnostic systems

The proposed neutron diagnostic system is conveniently divided into six hardware systems and one package of software:

1. **A set of 8 neutron BF_3-counters, fission chambers and ^{3}He Bonner spheres [2], measuring the time resolved total neutron emission rate.**
2. **An activation system measuring time integrated total neutron yield.**
3. **A time-of-flight spectrometer [3-6], measuring neutron energy spectra.**
4. **A profile camera measuring neutron emission profiles by means of fast (1-3 MHz) detectors.**
5. **Furthermore, a package of analysis and presentation software will be developed for the purpose of analysis of data and on-line presentation.**

And optionally:

6. **A set of charge particle detectors measuring fluxes and energy spectra of escaping charge fusion products, optional.**
7. **A gamma detector measuring gamma energy spectra, optional.**

Subsystem 1) will on its own provide data on time-resolved neutron emission rate. Subsystems 1), 3) and 4) constitute a set of neutron diagnostics comprising major instruments. Integrated analysis of data from these subsystems provides time resolved information on ion temperatures for Maxwellian plasmas. For non-Maxwellian plasmas, energy distributions of high energy ions, generated by auxiliary heating, and different fractional neutron source contributions can be evaluated. Furthermore, fast fluctuations ($\nu < 40$ kHz) in local neutron emissivity are measurable by the neutron camera. Subsystem 2) is a major installation and will be the primary technique to determine the absolute total reaction yield. Subsystem 6) is a minor instrument and will provide information of energy distribution and fluxes of lost charge fusion products. Subsystem 7) is also a minor installation and may provide information on fast ions generated during ICRF-heating and of presence of superthermal electrons during ECRF-heating. Table 1 gives an overview of the measurement systems, information on plasma parameter obtainable and number and type of detectors proposed.

2.2 Other systems considered

Several measurement techniques have previously been considered and also used in the context of fusion plasma diagnostics. For various reasons given below some of these methods are not regarded suitable as diagnostics for the W7-X Stellarator, while others are not planned for use although they are regarded suitable.

2.2.1 Scintillating detector

The main uncertainties in the determination of neutron yield by activation measurements are due to, firstly, the uncertainty in cross-sections and, secondly, to the Monte Carlo calculation of the scattered neutron fluence. The problem of cross-sections is considered in section 9. The problem of the calculation of the scattered fluence can be essentially reduced by restricting the measured energy range of the neutrons. As far as possible this is done through the choice of activation materials with suitable energy thresholds. However, the ideal material with a sharp threshold between 2.3 and 2.4 MeV does not exist. Thus, the use of an energy resolving detector would be advantageous. The NE 213 scintillator is a good choice for this purpose, it has a sufficient energy resolution of about 10% [9]. A liquid scintillator, like NE 213, has to be used in a collimator with adjustable aperture at ports similar to the activation's ports in order to allow direct comparison of results. Obviously, it is not practicable to use a set of scintillators for measurements of total emission rates. One scintillator might be useful at a later stage for a cross-check of the activation results.

The utilization of a single fast (5 - 10 MHz) detector for studies of MHD activities and their interaction with fast particles is planned. One suitable detector is based on scintillating fibers and would need some development work (see sec. 6). The detector provides fast simple amplitude discrimination between neutron and gamma events. Located in a small shielding it would respond to MHD activities with frequencies up to approximately 40 kHz.

2.2.2 Activation measurements using delayed neutrons

For measurements at plasmas with high neutron yield delayed neutron technique with thorium samples is sometimes used instead or parallel to activation measurements [7]. This would also be possible with the proposed transport system at W7-X without changes. However, delayed neutron measurements require extra samples and transport capsules and additional counting systems for the neutrons. The arrangement of transport capsule, sample and detector must be calibrated absolutely and an extra software for data evaluation is needed. The additional costs would be extensive and the resources can be used more efficiently if allocated to other neutron diagnostics.

2.2.3 Nuclear emulsion measurements

Nuclear emulsion measurements in combination with the activation measurements would allow to measure the neutron energy spectrum at the different positions used for the exposure of the activation samples [8]. This would give an experimental proof of the neutron spectra determined by the Monte Carlo calculations. At the present state of the systems the scanning of the emulsions could be done automatically, but the use of nuclear emulsions requires significant work-force. One person will be needed for manufacturing the emulsions, which are no more commercially available, and for the scanning hardware. A second person is needed for the scanning software and for data evaluations. Therefore, nuclear emulsions are not suitable for W7-X.

2.3 Diagnostic data interface with the W7-X data acquisition system

Presently only preliminary concepts for the W7-X data acquisition and computer system are discussed [10]. Particular requirements arise from quasi-continuous operation (20 seconds to 20 minutes). The interface between subsystems has eventually to be well defined because of national and international co-operation and the involvement of external contractors. Specific hardware components for data acquisition and control as well as software platforms have not yet been defined. However, a number of guidelines already exist:

- Electronic and computing hardware and commercial software components should be specified as late as possible.
- Commercially available products should be utilised.
- All electromechanical systems should be fully under computer control.
- All hardware components should be connected via glass fibre cable exclusively.
- The system should be flexible to allow for a large variety of hardware interfacing systems connected to a standard computer network.
- Each subsystem will be supplied by trigger and clock pulses for synchronisation of various measurements.
- Continuous monitoring of data and diagnostics operating state should be possible.
- Data processing components should support real-time operations.
- Execution of remote control commands should be possible at any time.

A common set of tools based on expert systems should be available for data storage and management, data analysis and computation, graphics, software development and hardware testing.

3 NEUTRON COUNTERS

A description of the system, physics information obtainable, accuracy in measurements, work and estimated resources in terms of work-force and financial support is given below. A schedule of all the foreseen issues to be undertaken is shown in Table 2.

3.1 Purpose and description of system

A set of standard neutron counters is needed for measurements of the time-dependent total neutron emission rate. The system consists of 8 units of BF_3 , fission counters and Bonner spheres comprising a ^{3}He counter. Each counter is surrounded by a several cm thick moderating layer. This is to make calibration with a neutron source (e.g. AmBe or AmB [11]), with a well-known strength, useful in spite the fact that this source does not generate the same energy spectrum as fusion reactions do.

Usage of BF_3- and ^{3}He counters and fission chambers in counting mode has shown to be very reliable. However, current mode operation, with signals in the nano ampere range, can be difficult in harsh electromagnetic environment. Therefore it is proposed to make use of counters with different sensitivities and to operate them in counting mode only. The system would then allow coverage of emission rates ranging from 10^{12} to 10^{16} neutrons per second. These detectors operate without any extra shielding although a moderator will be used.

The Bonner sphere consists of a spherical ^{3}He proportional counter and a moderator sphere made of polyethylene [12]. Bonner spheres have the advantage of an almost isotropic response and can cover the whole energy range from thermal to a few hundred MeV. Since the energy dependence of the fluence response changes with the sphere diameter, Bonner spheres have been used as a wide range neutron spectrometer with rather poor energy resolution. The response functions of the Bonner spheres for various diameters of the moderator have both been measured and calculated by using a MCNP Monte Carlo simulation [13]. Bonner spheres can also be used as simple neutron flux monitors. By selecting the moderator diameter the sensitivity can be optimised to the experimental neutron spectrum [14]. This can be strongly degraded outside the W7-X vessel due to scattering processes.

3.1.1 Accuracy and resolutions

The accuracy in emission measurements is estimated to 15-20%. The main contribution comes from the uncertainty in the difference of the attenuation of neutrons in the structure materials due to different energy distributions, i.e. from DD-reactions and from calibrated neutron sources. Another uncertainty is caused by different detector sensitivities due to different energy distributions. The time resolution aimed at is 10 ms or better. This can be achieved with the system suggested.

3.1.2 Necessary R&D-work

The plan is to design, construct and test a prototype detector. After calibration, three more units will be constructed and tested. For this purpose, a detector configuration, moderator material and thickness must be selected. The detector sensitivity for different energies has to be assessed through neutron transport calculations and calibration measurements. A Monte Carlo code MCNP [15] will be made available for this purpose. A neutron laboratory with the possibility of producing neutrons of 2.45 MeV, 14.1 MeV and fission energy spectra is made available for tests and calibration purposes.

3.1.3 Decision points and influence from R&D work on the design

The technique of using neutron detectors with almost flat response is well known and used, e.g. at JET. No further information is needed before a decision on employing such a system can be made. Only details in the design may be effected by further calculations and calibration work.

3.1.4 Detector location

The counters will be strategically distributed near the torus, see fig.1, such that alteration of large devices, which will influence the flux on one or two counters, will cause a minimum of perturbation to the others. One obvious location is in the middle of the torus where several counters will be placed in one moderator. Further three positions evenly distributed around the torus horizontal midplane are suggested. Each position will have one moderator accommodating two counters and with the provision of housing a third counter.

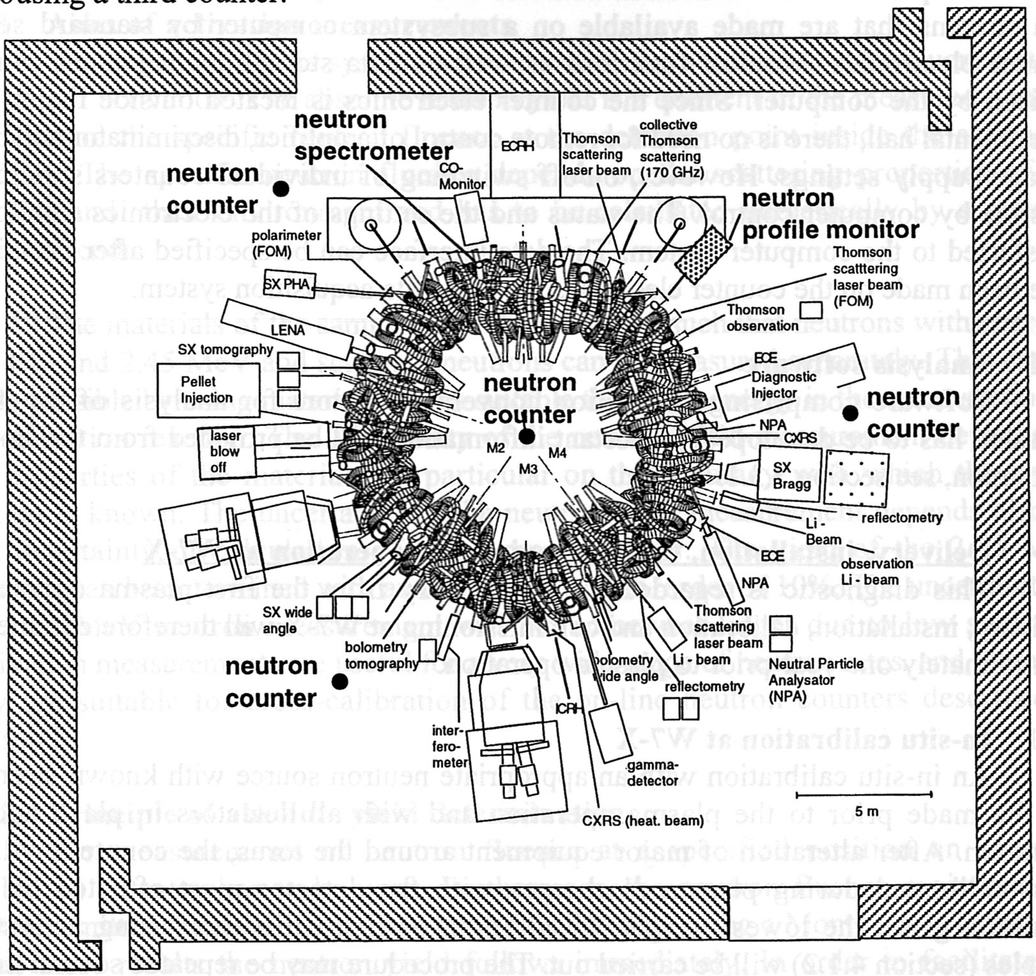

Figure 1. Locations of the four sets of BF_3- or fission counters and Bonner sphere are shown in relation to the vessel.

3.1.5 Choice of detectors

Reliability is a priority in this context. Therefore only standard neutron BF_3 and high pressure ^3He counters or fission chambers will be considered. The detector sensitivity has to be selected after an estimate of the fluxes at the detector positions have been made. The most sensitive detector, preferably located in the centre position, needs to have a sensitivity estimated to 5 c/(n cm^{-2}).

3.2 Design and construction

The design should allow for replacement of detectors with different sensitivities and slightly different geometry. This will be of importance at a later stage when the total emission is expected to increase and use of less sensitive detectors will be more appropriate.

3.2.1 Tests and calibration at a neutron laboratory

Functional tests will be made by means of a neutron generator and neutron sources in a laboratory in Sweden. Final flux calibration of all counters and response function measurements will be carried out at the Physikalisch-Technische Bundesanstalt, Braunschweig (PTB).

3.2.2 Interface with the W7-X data acquisition system

The pulses from the neutron counters can be easily converted into continuous data streams that are made available on a subsystem computer by standard serial counter electronics. Monitor functions as well as data storage management can be realised by the computer. Since the counter electronics is located outside the W7-X experimental hall, there is no need for remote control of amplifier, discriminator and high voltage supply settings. However, on/off switching of individual counters should be possible by computer control. The status and the settings of the electronics should be transferred to the computer system. The data interface can be specified after decisions have been made on the counter electronics and the data acquisition system.

3.2.3 Analysis software

Software comprising calibration conversion factors for analysis of the total emission has to be developed. Important information will be provided from the in-situ calibration, see section 3.3.1.

3.3 Delivery, installation, commissioning and operation at W7-X

This diagnostic is regarded to be necessary from the first plasma operation. Delivery, installation, calibration and commissioning at W7-X will therefore commence approximately one year prior to plasma operation.

3.3.1 In-situ calibration at W7-X

An in-situ calibration with an appropriate neutron source with known strength will be made prior to the plasma operation and with all detectors in place and in operation. After alteration of major equipment around the torus, the counters will be cross-calibrated during plasma discharges with the detector most effected by the alteration given the lowest weight. In addition, on-line calibration using activation samples (section 4.1.2) will be carried out. The procedure may be repeated several times but eventually a re-calibration must be performed.

3.3.2 Operation of the systems at W7-X

Continuous monitoring and presentation of neutron emission rate during operation are envisaged. The time lag and resolution will be of the order of 100 ms.

3.4 Resources needed, personnel, financial and other

The resources needed are given in Table 2. Approximately 0.5 professional man-year per year is estimated for the development work up to and including commissioning at W7-X. Thereafter only a fraction of a man-year will be needed for monitoring the system and refinements of the presentation software. Occasionally more intensive efforts will be needed for in-situ calibrations, approximately once every 2-3 year. Financial support will be needed for the neutron transport calculations by means of a Monte Carlo code. Furthermore, financial support will be needed for purchasing and manufacturing of the detectors, moderators, detector holders, signal counting electronics, high voltage power supplies and necessary tests.

4 ACTIVATION SYSTEM

A description of the system and the physics information are given below. A schedule listing all the foreseen issues to be undertaken, resources needed and cost estimates is given in Table 3 and details are provided in Table 4.

4.1 Physics background and objectives

4.1.1 Aims of activation measurements

The objective of this system is to determine the absolute neutron fluence at the position of activation. The absolute neutron yield is a quotient of the measured neutron fluence and the specific neutron fluence at the detection point inside the activation samples. The specific neutron fluence depends on the scattering properties of the samples and their environment and has to be calculated numerically by a neutron transport code.

The materials of the samples have to be chosen such that neutrons with energies of 14.1- and 2.45 MeV and scattered neutrons can be measured separately. This can be made possible by using materials with a suitable threshold energy in the cross-section of the activation reaction. The uncertainty of the neutron yield measurement depends on the properties of the materials, in particular on the accuracy with which the cross-section is known. The uncertainty of the neutron yield measurement depends also on the uncertainty of calculation of the geometry-factor. The yield of the 2.45 MeV neutrons can be determined with an uncertainty of the order of 10%. The uncertainty of the 14.1 MeV neutron measurement will be somewhat larger due to low statistics. Activation measurements are useful for a very wide range of neutron rates, and therefore they are suitable for cross-calibration of the on-line neutron counters described in section 3.

4.1.2 Principle of absolute yield determination

For measurements of neutron fluence at a specified position an absolute calibrated detector has to be used. Furthermore, the neutron fluence registered per neutron emitted from the plasma has to be calculated by using a Monte Carlo technique. From these results the neutron yield follows immediately. In order to facilitate the Monte Carlo calculations and to make their results as reliable as possible the detector set-up has to fulfil an additional set of fundamental requirements;

- The scattered neutron background should contribute as little as possible to the measurements.
- The measurement should be as insensitive as possible to changes in plasma parameters.
- The detector should observe a representative part of the plasma.
- The detecting system should not introduce essential additional problems for the simulation.

The contribution from the scattered background can be made small by several means. Firstly, one can use a measuring position inside the vessel where the scattered neutrons will reach the detector after comparably few collisions. Secondly, one has to use detectors with a suitable energy threshold. Here, activation materials offer a lot of possibilities. Furthermore, observation of a representative part of the plasma is essential as otherwise the Monte Carlo simulation would depend strongly on plasma shape, position and emission profiles. Here too, a measuring position inside the vessel near the plasma boundary is advantageous. Systems outside the vessel should be able to observe a full poloidal cross-section.

The detecting system should be as simple as possible in order to reduce neutron scattering near the detector. As less and thin materials as possible have to be used for positions inside the vessel. Systems outside the vessel need a good shielding and usually make use a collimator. The properties of the detector have to be known very well as they must be taken into account in the Monte Carlo simulation. In particular, for activation materials the relevant cross-section must be known accurately.

4.1.3 On-line calibration of neutron counters

On-line calibration of the neutron counters requires a shot-to-shot determination of the absolute neutron yield using activation samples with sufficiently short decay times. Suitable materials are yttrium and gold as shown in Table 5. Owing to the short decay time, the measurements of the activity have to be done fully automatically.

4.1.4 Toroidal variations in neutron production

Activation samples can be used for very cost-effective measurements of toroidal asymmetries in the neutron production due to the Stellarator plasma geometry and heating. Therefore, simultaneous measurements at similar ports in different modules have to be performed. At least four ports in different modules have to be allocated for these measurements, preferably at the same poloidal position. The best choices in descending order would be the ports Z1, R1 and S1. Furthermore, it would be desirable to carry out measurements at the position of the profile cameras for their absolute calibration.

4.1.5 Triton burn-up measurements

A small fraction of the total number of tritons, produced by the DD-reactions, undergoes burn-up $T(d,n)^4He$-reactions. The confinement and slowing down of the tritons can be diagnosed by measuring emission of the 14.1 MeV neutrons produced. The time-integrated 14.1 MeV neutron flux and the 2.45 MeV neutron flux can be measured simultaneously by using appropriate activation double samples. The burn-up fraction then follows directly from the ratio of the corresponding activities.

4.1.6 Local fluence measurements

Sometimes it is of interest to know the neutron fluence at a particular point at the experiment. Since it might not be practical to carry out neutron transport calculations, accurate localised measurements are needed. This can be achieved by positioning of activation samples with a flexible pipe connected to the transport system, i.e. a pipe that is not permanently attached to a fixed position.

4.2 Necessary R&D-work

Presently, it is difficult to set up a complete plan for the necessary R&D-work. However, for some activation materials, e.g. yttrium and gold, new cross-section measurements are required. This will be done in co-operation with the neutron laboratory of the PTB in Braunschweig.

4.3 Design and construction criteria

4.3.1 Piping

One line of the pneumatic transport system for activation samples consists of a suitable PE tube ranging from the irradiation position to the γ-counting station. At both ends, metal pipes of 1-2 m length are fitted which provide the air cushions to slow down the fast moving capsules of about 25x75 mm in size. The length of the PE tube can range from 10 to 300 m. The obtainable minimum bending radius should be as small as possible with little deformation of the cross-section. For sufficient stability, the PE tube should have a wall thickness of about 4-5 mm. Two cross-sections are suitable (see figure 2):

(i) Circular cross-section of about 43-45 mm in diameter.

Advantages:

- It is easy to manufacture and the tubes are readily available.
- It is easy to manufacture the circular metal end pipes.

Disadvantages:

- The minimum bending radius is rather large and, thus, installation is complicated.
- The capsule can rotate inside the tube and therefore its orientation during the exposure is unknown.

(ii) Oval or elliptical cross-section of about 43x33 mm in size.

Advantages:

- The minimum bending radius (50 cm) is rather small and the tube can be twisted to simplify the installation.
- The orientation of the activation sample during its exposure is known.
- The construction of junctions for blowing of venting is fairly simple.

Disadvantages:

- Manufacturing the tube is complicated since a dedicated extraction line is needed.
- The metal end pipes have to be welded from suitable pieces of circular pipes.

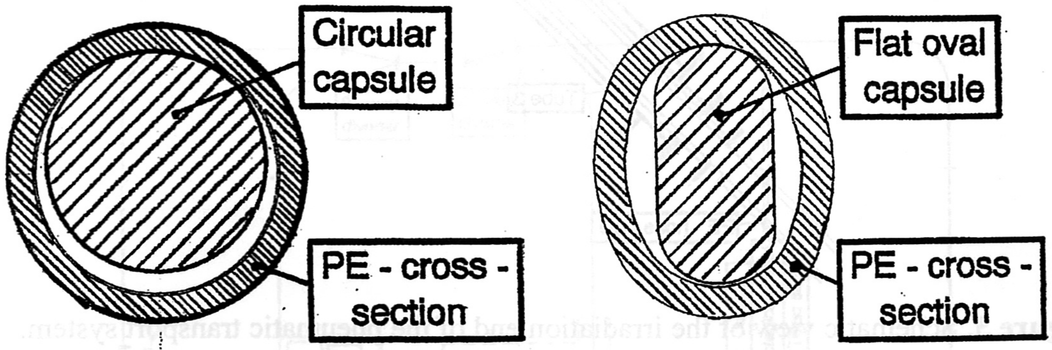

Figure 2. Possible cross-section for the tubes of the pneumatic transport system and the corresponding capsules of the activation samples.

Thus, it is more advantageous to use a transport system with oval shaped tubes. Furthermore, the problems of manufacturing the oval PE tube and the metal end pipes have already been solved for the pneumatic transport system at ASDEX and TEXTOR.

4.3.2 Biological shield penetration

Passing a five-pipes system through the concrete wall of the biological shield can be done by a straight bore of about 15x15 cm that is not aiming directly at the neutron source. However, a circular bore hole requires less filling and absorption material to fill the gaps, resulting in a smaller area. Thus, circular bore hole is preferred.

4.3.3 Remote counting stations

Since the activity of the samples usually is very low the counting process is rather sensitive to neutrons or high energy gamma radiation. Although the γ-counting stations are shielded with 5-10 cm lead, they should therefore be located in a well-shielded area in order to avoid interference of the measurements during plasma discharges.

4.3.4 Mechanical interface to W7-X

An irradiation end for activation samples consists of three coaxial tubes reaching as close to the plasma as possible (see figure 3). The „tube 1“ (circular) is counter-flanged to a port flange and is therefore the only vacuum relevant part. Its wall thickness in the front facing the plasma should not exceed 1 mm. The „tube 2“ (circular) and the „tube 3“ (oval) are made of even thinner steel pipes. The removal of these pipes, i.e. the whole irradiation ends, is possible without braking the vacuum. The minimum diameter of the first tube is about 45 mm and therefore even the smallest ports are suitable. There is no technical restriction on the port orientation. However, there should be sufficient space (at least 50 cm) for access and installation.

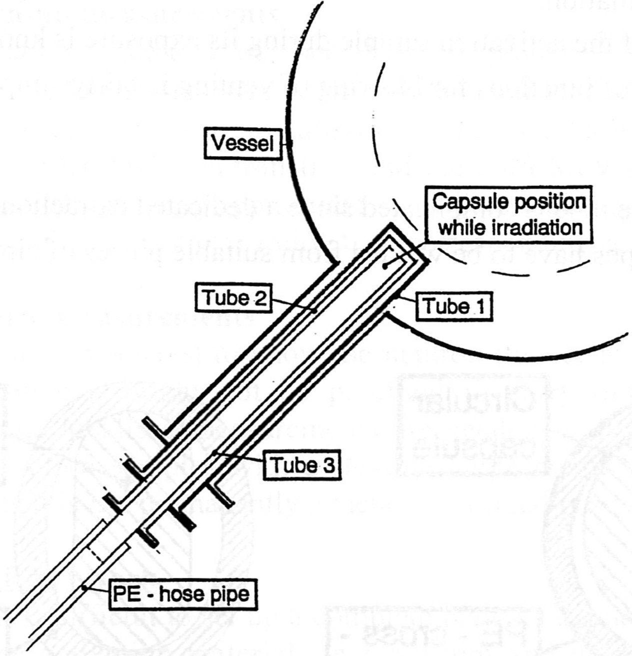

Figure 3. Schematic view of the irradiation end of the pneumatic transport system.

4.3.5 Electrical interface to W7-X

The complete system will be installed in a R-connection, i.e. each station inside the torus hall is connected to a corresponding station outside the hall through a multi-wire control cable. The electrical potential is the one of the station outside the hall. Any galvanic connection from the outside to the inside systems will be prevented by usage

1.5 keV separation relays. Each irradiation end in the torus hall requires a mains supply of 220 V~ and ≈ 2 Ampere and its own supply of 7-8 bar pressurised air. This can be achieved by using standard 12-15 mm hose connected to the general compressed air supply.

4.3.6 Design and construction

As shown schematically in figure 4, a basic unit of the proposed transport system consists of three sub-units, the manual capsule loader, the irradiation end and the PE tube. The complete system consists of five similar systems with the possibility of manual or automatic loading and unloading as indicated in figure 5. In order to achieve this, two-way divertors will be used. Although revolving systems can be used, divertors can be pre-set well in advance and therefore the transportation can be done much faster when using revolving systems

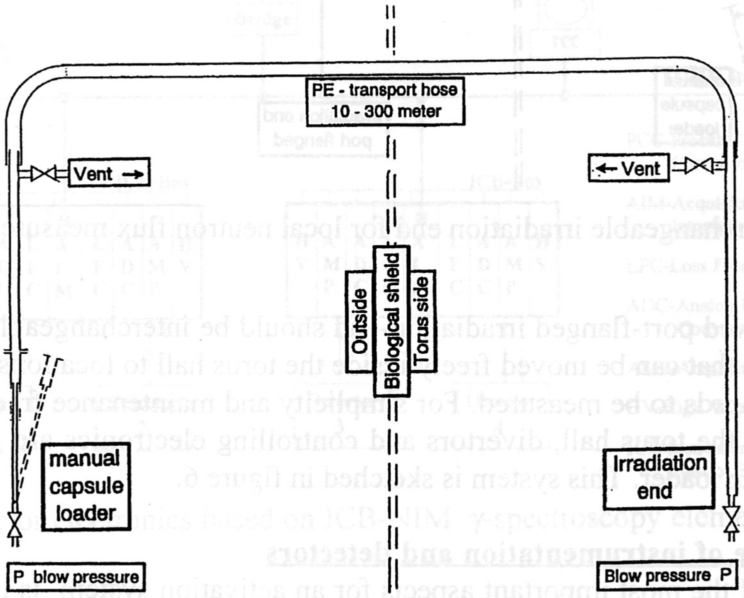

Figure 4. Basic units of the transport system.

The automatic loader may be a linear or circular system. In case samples accumulate in an automatic counting system, unwanted activation would occur which have to decay before reuse.

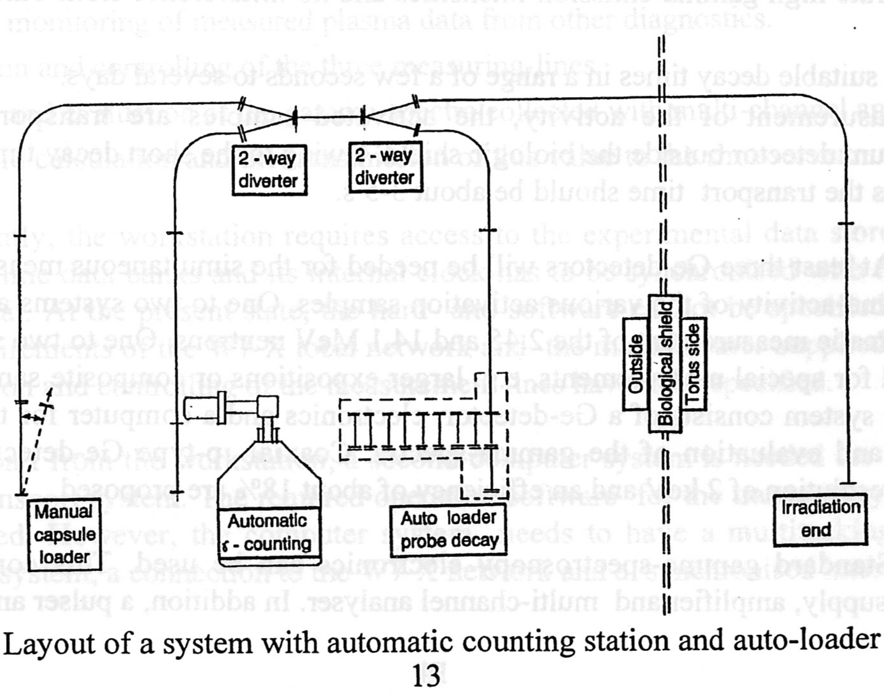

Figure 5. Layout of a system with automatic counting station and auto-loader station.

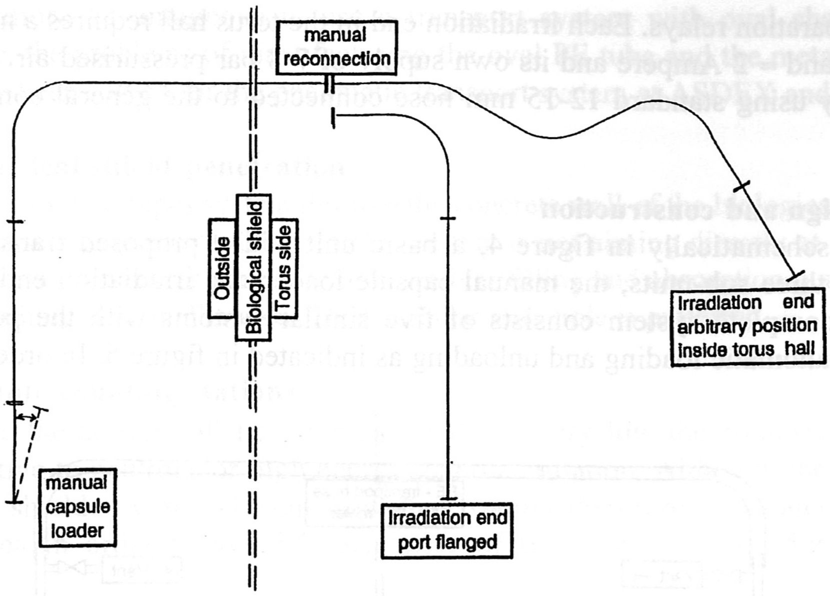

Figure 6. Interchangeable irradiation end for local neutron flux measurements inside the torus hall.

The fixed port-flanged irradiation-end should be interchangeable by means of a special device that can be moved freely inside the torus hall to locations where the local neutron flux needs to be measured. For simplicity and maintenance free function of the system inside the torus hall, divertors and controlling electronics are located near the manual capsule loader. This system is sketched in figure 6.

4.4 Choice of instrumentation and detectors

One of the most important aspects for an activation system is the choice of the sample materials. Table 5 summarises typical materials that can be used for neutron measurements at fusion experiments. They have to meet the following criteria:

- Posses large cross-sections for neutron reactions with 2.45 MeV or 14.1 MeV neutrons.
- Have small cross-section at lower energies to minimise the influence of scattered neutrons.
- Generate high gamma-emission intensities and no interference from other gamma-lines.
- Have suitable decay times in a range of a few seconds to several days.

For measurement of the activity, the activated samples are transported to the germanium detector outside the biologic shield. Owing to the short decay times of some materials the transport time should be about 3-5 s.

At least three Ge-detectors will be needed for the simultaneous measurement of the gamma-activity of the various activation samples. One to two systems are required for automatic measurement of the 2.45 and 14.1 MeV neutrons. One to two systems are required for special measurements, e.g. larger expositions or composite samples. Each detector system consists of a Ge-detector, electronics and a computer for the detector control and evaluation of the gamma-spectra. Coaxial p-type Ge-detectors with a typical resolution of 2 keV and an efficiency of about 18% are proposed.

Standard gamma-spectroscopy electronics can be used. This contains high voltage supply, amplifier and multi-channel analyser. In addition, a pulser and a counter shown in figure 7 are needed in order to carry out necessary death-time corrections. The gamma-spectra evaluation and the detector control are performed by a local dedicated computer system. In order to obtain a practical user interface both the transport system and the three detector systems should be controlled through a central computer system that will also be used for analyses of spectra.

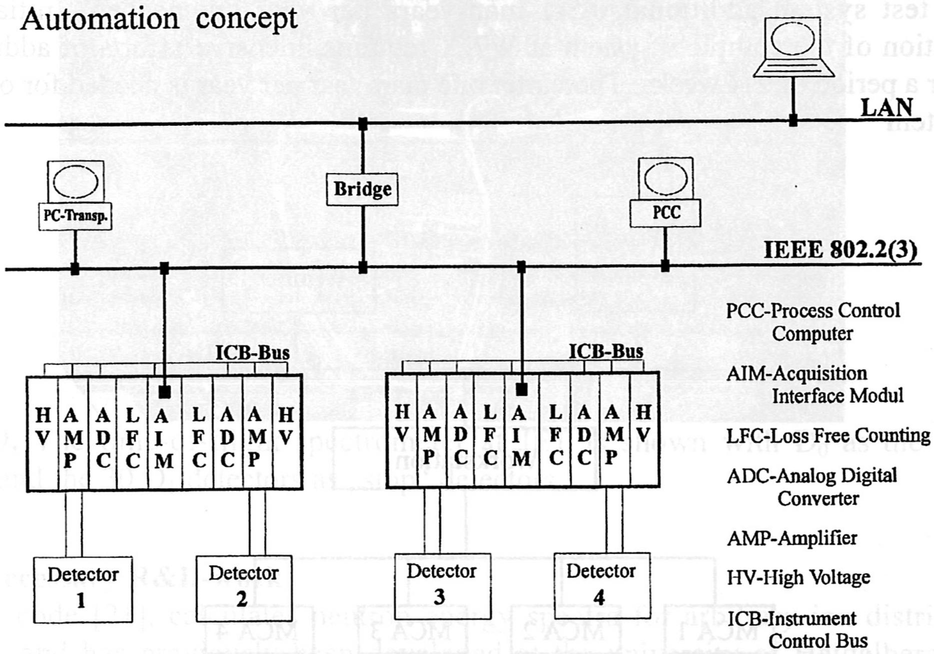

Figure 7. Detector electronics based on ICB-NIM γ-spectroscopy elements.

4.5 Interface to W7-X data acquisition system

Here, the data handling structure of the activation system and its links to the experiment will be discussed. A simple and central operation of the activation system as well as a fast evaluation of the experimental data is required. Therefore, the entire system needs to be fully atomised. This could be done with the structure given in the block diagram in figure 8.

A workstation is suggested to be used for;

- On-line monitoring of measured plasma data from other diagnostics.
- Operation and controlling of the three measuring-lines.
- Storage and evaluation of the gamma-spectra collected with multi-channel analysers.
- The yield calculation and the transmission of this value to the shot-server.

Consequently, the workstation requires access to the experimental data stored on the public on-line data banks and its internal clock has to be synchronised with the W7-X timer signal. At the present state, the hard- and software cannot be specified in detail since requirements of the W7-X local network and the manufacturer-supplied software for operation and controlling of the measurement lines have to be specified.

Apart from the workstation, a second computer system is needed for operation of the transport system. The required operation software for the transport system will be supplied. However, the computer system needs to have a multitasking capable operating system, a connection to the W7-X network and a synchronised internal clock.

4.6 Resources needed, personnel, financial and other

The resources needed are summarised in Table 3 while in Table 4 a more detailed compilation is presented. One professional man-year is needed for the development work and for supervising the construction of the test system. In addition, 1 man-year per year is needed for the installation of the test system. For the cross-section measurements at the Physikalisch-Technische Bundesanstalt (PTB) and the operation of the test system additional 0.5-1 man-years per year are needed. Initially, the installation of the complete system at W7-X requires intensive efforts of additional 3 men for a period of 2-4 weeks. Thereafter one man-year per year is needed for operating the system

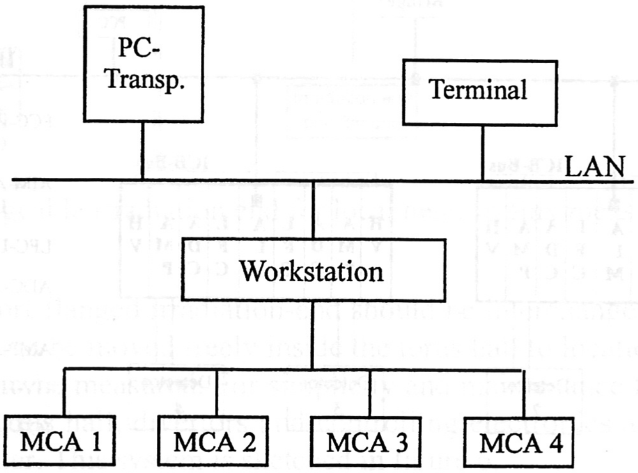

Figure 8. Hardware structure for the data handling of the activation system.

The measurements of the cross-sections, the operation of the test-system and associated works are foreseen as a Ph.D. task.
Financial support will be needed for the cross-section measurements (measurement time and travel). Financial support will also be needed for purchasing and manufacturing of the different components of the activation systems, the activation samples and for the associated travel expenses.

5 NEUTRON ENERGY SPECTROMETER

A description of the system, physics information obtainable and all work and estimated resources required in terms of work-force and financial support is given below. A schedule of all the foreseen issues to be undertaken, required personnel and cost estimates are shown in Table 6.

5.1 Purpose and description of system

Measurement of neutron energy spectra can be used for evaluation of ion temperatures, high energy tails and thermal reaction fractions. A self contained time-of-flight spectrometer shown in figure 9 with the line-of-sight intersecting the plasma centre, is planned to be used. It consists mainly of two sets of hydrogen based scintillators. Time elapsed between correlated neutron elastic scattering in the two detector sets are registered and the neutron energy is evaluated, see refs.[3,4]. To enable analysis of 3 keV ion temperatures, a resolution better than 4% and an efficiency of $5 \cdot 10^{-2}$ cm^2 will be necessary. The aim is to achieve a time resolution of 100 ms.

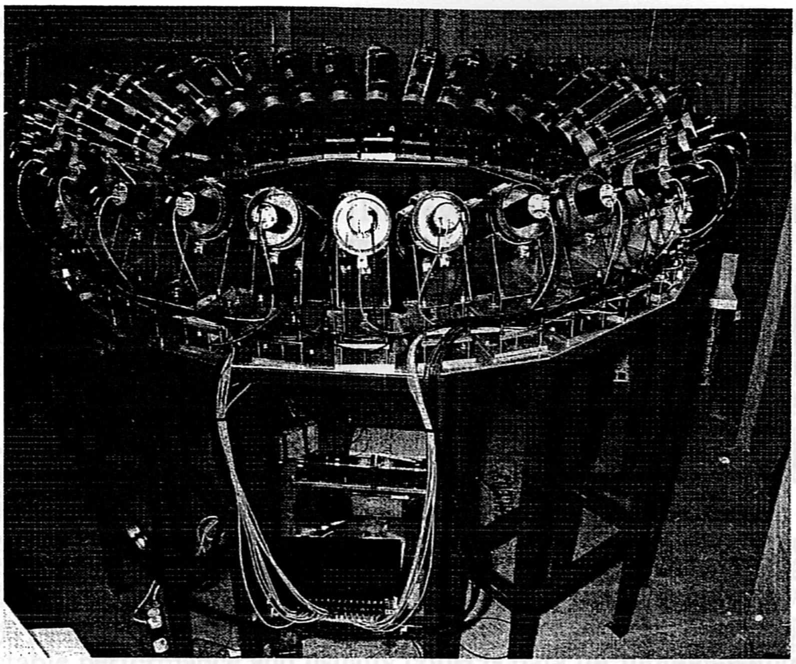

Figure 9. The time-of-flight spectrometer at JET is shown with D_0 as the "start" detector and the 30 D_1 detectors as „stop" detectors.

5.1.1 Necessary R&D-work

A code [21], calculates neutron energy spectra for arbitrary ion distribution functions and has previously been developed at the university of Heidelberg. It is written for tokamak configuration. Modified for Stellarator configurations it will be used for prediction as well as interpretation purposes, see section 9. The code takes into account the reaction kinematics and the velocity distributions of the reacting ions and calculates the resulting neutron energy distribution in a defined collimator. Applied to several plasma volumes, energy spectra of neutrons emitted along a line-of-sight are superimposed. Because this is a line integrated measurement, a correction factor to the measured ion temperature has to be applied to obtain the maximum ion temperature along a particular line-of-sight. Calculations show that this factor is equal to 1.10 ± 0.05 and rather independent of the emission profile shape. The code has been utilised for calculations of neutron energy spectra from neutral beam heated plasmas in JET [22].

As the spectrometer has been in operation at JET for several years [5,6] no particular development work is needed. However, new development in high rate signal timing electronics will be tested and possibly employed.

5.1.2 Decision points and influence from R&D work on the design

This diagnostic system has been in operation at JET for many years and the kind of information obtainable is well known. Calculations on toroidal symmetry in ion distribution functions may be of value prior to a decision to assess the generality of the measured neutron energy spectra.

5.1.3 Design criteria and port allocation

It is a clear advantage if the biological shield with a dedicated penetration (cross-section area ≈50 cm^2), could be used for shielding of the spectrometer. To obtain a well-defined line-of-sight a pre-collimator has to be located in the torus hall, the realignment precision of which is ± 0.5 cm. The spectrometer may saturate at high neutron fluxes and some technique for reduction of either the flux or the active detector volume must be used. At JET this has been solved by using an adjustable pre-collimator. The technique to be used here has to be determined at a later stage. Location of the spectrometer in the basement underneath the machine seems a very suitable option but only if sufficient shielding can be provided, see figure 10.

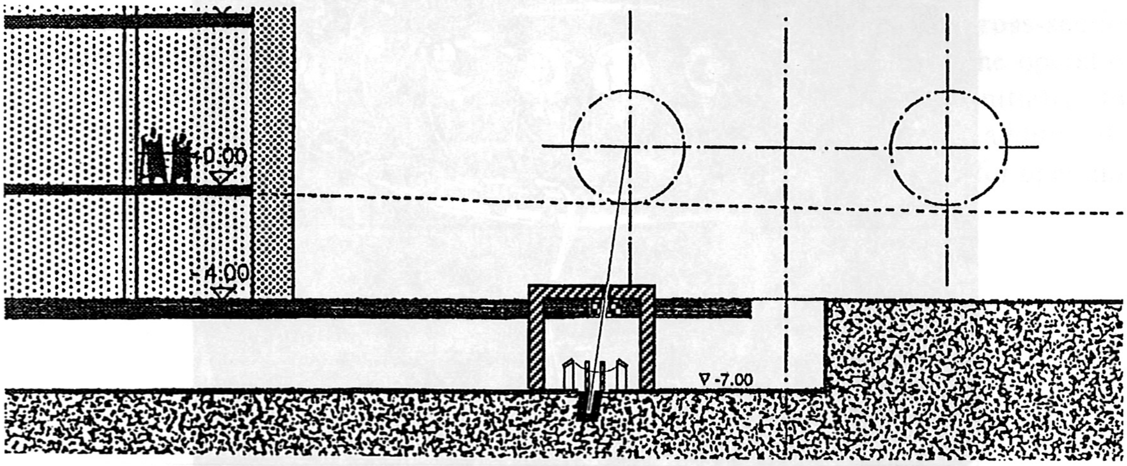

Figure 10. Suggested location of the time-of-flight spectrometer is shown schematically in relation to the W7-X vessel.

5.1.4 Possibilities to inherit instruments from JET

A Time-of-Flight spectrometer is being used at the JET tokamak. By the time it will be of interest to install such a spectrometer at W7-X (around year 2003) it may well have served its purpose at JET. The possibility and formalities to heritage the instrument from JET should be investigated at an earlier stage.

5.1.5 Design and construction

For the spectrometer itself only design and construction of new detector holders are necessary. A collimator through the biological shield must be designed. At high fluxes a pre-collimator or a first detector with reduced volume must be used.

5.1.6 Tests and calibration at a neutron laboratory

The spectrometer will be tested at a neutron generator at a neutron laboratory in Sweden. Tests will be performed with 1/4 of full spectrometer at one time. More detailed calibration of efficiency and energy resolution will be performed at PTB.

5.2 Data acquisition and interpretation

The time of flight coincidence electronics delivers start and stop pulses to standard timer modules together with ID codes for the active channels. The time of flight spectra should be accumulated in data buffers over time windows, which are either pre-defined or set automatically depending on the chosen statistical error. Processed spectra (neutron energy spectra with significant information) should then be stored in the data bank. On/off switching of the spectrometer should be made possible by remote control. The status and the settings of the electronics should be transferred to the computer system. The data interface can be specified after decisions have been made on the spectrometer electronics and the data acquisition system.

5.2.1 Data acquisition software

This software package can only be specified when the data acquisition system has been defined.

5.2.2 Analysis software

An analysis software package has been developed at JET and the main features of this can possibly be used for the necessary development work. It computes the neutron energy distribution from the measured time distribution taking into account the response function of the spectrometer. However, with the ambition to present data on line, see section 9, special requirements will be placed on the software package. The specifications of this can only be defined when the computer system has been specified.

5.3 Delivery, installation, commissioning and calibration at W7-X

Delivery to W7-X is anticipated during year 2004, in good time before the operation of the auxiliary heating systems. Installation and commissioning will require several months of effort. No particular calibration is foreseen, as all the settings will be the same as for the previous test at the PTB laboratory.

5.3.1 Operation of the systems at W7-X

The experience with this system from JET is that once it is in operation it shows very stable performance and usually collects data for months without any special supervision or maintenance.

5.3.2 Resources needed

Depending on the amount of work required for the development of analysis software approximately 0.5- 0.8 man year per year will be needed during the calendar years 2000 to 2005. Financial support will be needed for the new detector holders, new high rate timing electronics, tests and transportation of the instrument. After commissioning only a small effort like a fraction of a man-year per year will be needed for maintenance.

6 NEUTRON PROFILE CAMERA

Description of the system, physics information, accuracy and resolutions obtainable and all work and estimated resources in terms of work-force and financial support are given below. A schedule of all the foreseen issues to be undertaken is shown in Table 7.

6.1 Purpose and description

Information on the neutron emission profiles, and therefore also triton birth profiles, is necessary for evaluation of confinement and slowing down of tritons generated at 1 MeV by fusion reactions [1]. For evaluation of the central ion temperature and thermal reaction fractional contributions from total neutron emissions, information on neutron emission profiles is used as a correction factor. Furthermore, neutron emission profiles vary during MHD activity and other fluctuations. A 1-D profile camera with 3-8 channels is planned for the purpose of these measurements. The channel width can be as small as 5 cm at the plasma centre. The precise number of channels and their dimensions have to be determined at a later stage.

A new type of fast neutron detectors based on scintillating fibres [23,24] is expected to respond to 10% fluctuations in neutron emission with frequencies up to 40 kHz. Using conventional liquid scintillators would give an upper limit of 4 kHz. The detectors will require a massive block of concrete radiation shielding with the approximate weight of 15 tons. The shielding has to be realigned with a precision of ± 0.3 cm. As an illustration a 1D profile camera is shown in figure 11.

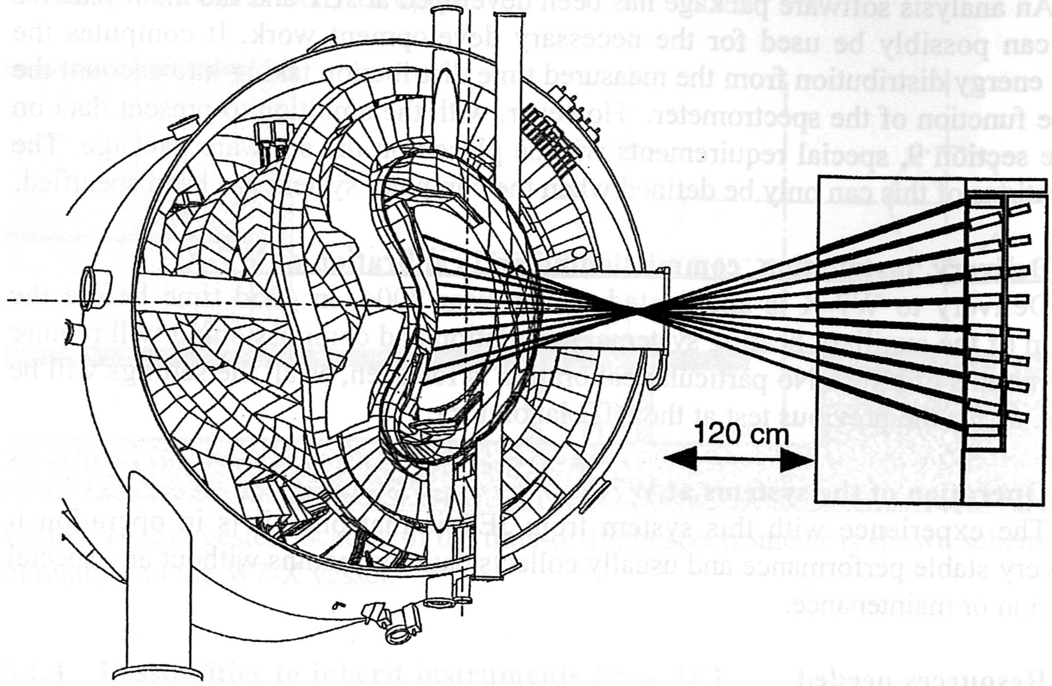

Figure 11. A 1D profile camera is shown in relation to the W7-X vessel.

6.1.1 Necessary code- and detector R&D-work

Calculations of the toroidal symmetry of neutron emission are needed to assess the generality of neutron profile emission measurements. Also simulations of neutron emission from different plasma cross-section area shapes will be needed to assess the need for 1D or 2D measurements. Extensive calculations of the confinement and slowing down of the tritons are needed to simulate the processes and to evaluate the order of magnitude of losses.

A conventional liquid scintillator as detector has the capability to separate signals from neutron and gamma interactions. However, these detectors have a maximum count-rate around 300 kHz. Because approximately only 20 % of the counts are useful the dynamic range and the time resolution are severely restricted. The solution to this problem at the JET tokamak has been to use insert collimators to restrict the neutron flux. An alternative way to extend the dynamic range will be considered for the W7-X Stellarator. A new type of flux detector based on a large number of scintillation fibres is being studied and development work on such a detector is in progress. Tests with gamma- and neutron sources have demonstrated the feasibility to use simple pulse-height discrimination for separation of gamma- and neutron events. This type of detector has a potential useful count-rate of 3-5 MHz. Further development work will be needed previous to a detector design:

1. Detail design of detector and read-out system.
2. Functional tests of fibres, photo-multiplier tubes (PMT) and electronics.
3. Construction of read-out system.
4. Assembly of scintillating fibres and Photo-Multiplier Tubes.
5. Test of read-out system.
6. Test with a neutron source and a generator and possibly at JET.

The choice of detector can be made after this development work has been performed.

6.1.2 Decision points and influence from R&D work on the design

The fast scintillating fibre detector is preferred due to its higher dynamic range and faster response in comparison with what conventional liquid scintillators can provide. The development of this detector will influence the decision and design of the profile camera because some functions of the camera are related to the particular high count-rate capability of this detector.

6.1.3 Port allocation

A bean shaped plasma cross-section is preferred implying port type A1 or possibly E1/E10. This would give the highest possible spatial resolution approximately equal to 5 cm with a 1D camera, see figure 11.

6.1.4 Design and construction

Design of a detector shielding with several collimators is envisaged. The shielding has to attenuate the neutron and gamma flux by a factor of 10^{-4}. This implies a wall thickness of 50 cm in the front and side directions. Detailed neutron transport calculations must be performed to assess the shielding properties.

6.1.5 Tests and calibration at a neutron laboratory

Tests and flux calibrations with a 2.45 MeV neutron generator and a neutron source are envisaged for the detectors. Absolute accuracy is estimated to ± 10% and relative accuracy to ± 5%. When used in the collimator the absolute accuracy will deteriorate to approximately ± 15% due to inaccurate relation between emission rate and flux. The relative accuracy is estimated to ± 10% and will be evaluated in more detail through MCNP calculations.

6.2 Interface with the W7-X data acquisition system

The pulses from the scintillation fibres can be processed by standard serial counter electronics. Monitor functions as well as data storage management can then be realised by the computer. Since the counter electronics is located outside the W7-X experimental hall, there is no need for remote control of amplifier, discriminator and high voltage supply settings. However, on/off switching of individual detectors should be possible by computer control. The status and the settings of the electronics should be transferred to the computer system. The data interface can be specified after decisions have been made on the counter electronics and the data acquisition system.

6.2.1 Analysis software

A package of analysis software needs to be written the purpose of which is to make a reconstruction of the neutron emission profile. The method to be used and the presentation software has to be specified at a later stage.

6.3 Delivery, installation and commissioning at W7-X

The profile camera has to be delivered, installed and commissioned at W7-X prior to operation of auxiliary heating, i.e. around year 2003.

6.3.1 In-situ calibration at W7-X

Only functional tests with a neutron source, e.g. an AmB source, are envisaged at W7-X. These tests will partially serve as a flux calibration provided a similar test has been made in a neutron laboratory, see section 6.1.5.

6.3.2 Operation at W7-X

This system is a major installation and the experience from operation at JET is that monitoring is inevitable.

6.4 Resources needed

During the development phase (year 1998-2004) this system will require 0.5-1.0 man year per year. During installation at least two man year per year will be needed. The detector development work is foreseen as a Ph.D. task. Furthermore, appropriate hardware financial support will be required.

7 MEASUREMENTS OF GAMMA ENERGIES

Through analysis of gamma energy spectra, different threshold reactions can be identified and used for determining the presence of fast protons, deuterons and impurities. This is of particular importance whenever ICRF is used for heating. The size of the detector proposed is approximately 200-400 cm^3. For this purpose it is proposed that provision for a detector (NaI), for measurements of gamma radiation spectra, is taken. A port location and a line-of-sight should be identified and allocated for future use.

8 MEASUREMENTS OF CHARGE FUSION PRODUCTS

The sizes of the larmor radii of the charge fusion products are comparable to the plasma cross-section dimensions. Therefore, diagnostics based on measurements of charge fusion products (particularly 14.7 MeV protons from $D(^3He, p)^4He$ reactions) seems feasible. However, substantial particle orbit calculations have to be carried out prior to the detector design to clarify the interpretation aspects. Candidates for the detectors are e.g. silicon diodes and scintillators. Measuring positions and directions are adjustable and exchangeable from outside the biological shield. The space required is small (10-20 cm^3) and therefore this type of diagnostic may be implemented at a later stage. However, provisions for its implementation in terms of port allocation and space should be made at an early stage.

8.1 General design

8.1.1 Mechanics

The parts of the diagnostic connected to the vessel are built up as a slim tubing assembly on top of a flange. The flange must allow free access to the plasma and should be closeable by a slide valve.

8.1.2 Vacuum

The charge particles pass through a thin foil window (several μm), which is very sensitive to pressure differences on its two sides. Differences of more than a few mbar may destroy the foil and should therefore be avoided. This is accomplished by using high vacuum of both sides of the foil. The inner high vacuum is necessary too in case of foil window breakdown. The inevitable resulting small leakage (from inner high-vacuum to vessel high-vacuum) is easily eliminated by retracting the measuring head beyond the slide valve and closing the valve. For this purpose, a rather long assembly of disc membranes form a bellow, which allows to withdraw the complete inner assembly beyond the slide valve. Repairs or head exchange can also be performed in this way, without breaking the vacuum.

Evacuation and venting of the device must be done very carefully to avoid a pressure difference on the thin foil window. Since only mechanical stresses have to be avoided and there are no valves on the high-vacuum side of the turbo-pump, a suitable connection of the otherwise separated pumping circuits is made on the prevacuum side. A bi-directional pressure differential switch signals in the event of a breakdown of the foil window. The conductors for head adjustments and cables are fed through a differentially pumped vacuum (at the rear side of diagnostic tubing), to keep their technical demands on a low level.

8.2 Detectors and measuring heads

The heads should be constructed as to be fully exchangeable. This ensures the ability to cover demands that could come up in the course of measurements. This also ensures the possibility to adapt the front end to various circumstances of measurements (various directions and several types of particles). Before doing a precise mechanical design, the complete scientific demands must be clear. In particular, the expected gyrational movements of the particles to be measured must be known in order to allow them to reach the detector through the collimator before hitting other parts of the device. A basic design is shown in figure 12. The adjustment of the collimator and the foil window could be done by a steel bellow assembly. This construction allows ultra high vacuum-tightness. Tilting and turning is only allowed for the cooling finger inside,

Figure 12. The main details of the assembly of the charge fusion particle detector are shown.

whereas the outer parts of the bellow will only tilt and tumble. Their connection to the inner part must be done via a rotational bearing (i.e. ball bearing). Estimated costs for the proposed system are given in Table 8.

8.3 Resources needed

The estimated costs of the system are given in Table 8. For construction, installation and commissioning about 3-4 man-years are needed. additional support is required for the orbit calculations.

9 DATA ANALYSIS, INTERPRETATION AND SIMULATION CODES

Optimal performance and use of the different neutron diagnostic systems require three different layers of computational procedures. Firstly, there are the fast dedicated computer programs for the primary data evaluation and for processing the directly measured neutron signals of each detector system. Secondly, there have to be computer codes for interpretation and, thirdly, simulation of these measurements. Interpretation codes are needed to deduce plasma parameters such as deuteron densities and temperatures out of the measured neutron signals. Simulation plays an important role for calibrating different detector systems, in particular the neutron flux detectors.

9.1 Data Analysis

The fast dedicated computer programs for the primary data evaluation and the direct processing of the measured signals are described in the respective subsections for each detector system separately.

9.2 Neutron Transport Code

Because the yield determination from activation measurements relies on the ratio of sample activation to absolute neutron yield, accurate neutron transport calculations are essential. They are helpful for the neutron profile camera and the neutron spectrometer in order to assess effects from neutron scattering and attenuation in the material structure of W7-X on the measured detector data.

9.2.1 Requirements

The requirements for neutron transport calculations can be subdivided in two parts, i.e. modelling requirements and numerical aspects. The modelling requirements are as follows:

- ***A neutron source model.*** This includes the spatial dependence as well as the anisotropy of neutron production and the neutron birth spectra. It is useful not only for neutron transport calculations but also as a stand-alone tool. Its ingredients are the distribution functions of the fusing ions, the fusion reaction cross-sections and adequate numerical methods.

- ***A geometry model of W7-X including material compositions.*** The relevance of the various components for neutron transport calculations and, thus, the accuracy required for their modelling depend on the specific calculation to be performed. Various components have to be considered: major structural components (e.g. inner and outer vacuum vessel, coil systems and support structure), components inside the inner vacuum vessel (e.g. divertor plates) and relevant structural components close to detectors (e.g. diagnostic ports, collimators, detector support structures and detectors).

- ***The cross-sections for the interaction of neutrons with matter.*** In the relevant neutron energy range of 0.5-15 MeV, major concerns are high energy resolution, accurate angular distributions of secondary neutrons and energy-angle coupled distributions of secondary neutrons from inelastic reactions.

- ***The detector response function.*** This can be defined to be the ratio of the detector signal to the neutron flux distribution inside the active volume. It usually depends on neutron energy and may also depend on incident angle and on the position inside the detector.

From the numerical point of view, a decision between numeric-deterministic method and Monte Carlo methods must be made. The convergence rate of Monte Carlo calculations is independent from the dimensionally of the problem, whereas for numeric-deterministic methods it deteriorates with increasing dimensionally. In addition, the treatment of complex geometrical and scattering properties is for numeric-deterministic codes much more difficult than for codes based on Monte Carlo methods. The neutron transport problem at W7-X is fully 3-D and has complex geometry and complex neutron cross-sections. Therefore, from the present point of view, the Monte Carlo method is preferred.

In Monte Carlo neutron transport calculations, the following numerical aspects are the most important to be considered:

- ***Neutron tracking.*** In Monte Carlo calculations with complex geometry, significant time is spent on tracking the simulated neutrons through the geometry model. Therefore, a good algorithm for neutron tracking may significantly reduce the computational time of Monte Carlo calculations.

- ***Variance reduction.*** The variance and therefore the number of Monte Carlo particles required to achieve a certain degree of accuracy can be reduced by applying non-analogue Monte Carlo techniques like importance sampling or particle splitting. In this case the neutron detectors are small compared with the volume relevant for neutron transport. This fact constitutes the main obstacle for achieving a low variance.

9.2.2 Present Status

At present, neutron transport calculations for neutron diagnostics are most frequently performed by using the MCNP code, [15]. Here, the modelling capability, the numerical techniques offered by the MCNP code and the modelling effort required for actual computations is described with respect to W7-X.

- ***Neutron emission.*** The built-in MCNP neutron source is not versatile enough even to provide a rather simple fusion neutron source model. Therefore, most users have written their own subroutines modelling the neutron emission. In these models, realistic flux surface geometry and anisotropic ion distribution functions are usually not taken into account. For the complex geometry of W7-X it is difficult to judge the significance of these simplifications. Therefore, the aim is here to include these dependencies in the description.

- ***Neutron cross-sections.*** Knowledge on neutron cross-sections is based on measurements and is summarised in data banks of evaluated nuclear data such as the ENDF/B-VI system, [25]. Typical uncertainties in neutron cross-sections are 2-3% for total cross-sections and 10-20% for angular distributions. Recent integral experiments indicate that the overall influence of the uncertainties in neutron cross-section data on the accuracy of the neutron transport calculation about 5%. The MCNP code is compatible with most evaluated nuclear data systems.

- ***Geometry.*** The MCNP geometry modelling concept has been designed in the early 1960's and provides a subset of constructive solid geometry. Modelling is done by directly editing the input file that describes the geometry that requires a considerable amount of dedication. Therefore, in most actual calculations, simplified models have been used. Typically, the uncertainty from geometry simplifications constitutes the main contribution in the overall uncertainty of the Monte Carlo result and ranges from 10-20%.

- ***Detector response.*** Detector response functions that only depend on energy can directly be modelled with MCNP. For more complex ones, a user-supplied subprogram is required.

- ***Neutron tracking.*** Neutron tracking means calculating the point of intersection of a ray with a geometry model and is essentially the same as ray tracing in computer graphics. From this point of view, the ray tracing algorithm used in MCNP is rather simple. The computational cost of ray tracing increases strongly when the geometry becomes more complex and therefore it constitutes a limiting factor for geometry complexity.

- ***Variance reduction.*** A variety of non-analogous Monte-Carlo schemes are offered by MCNP, but few of them are appropriate for the specific problems associated with small detectors. Therefore, several millions of events are usually required to achieve a statistical accuracy of a few percentages.

It should be noted that, at the present state, the typical modelling time for a rather strongly simplified problem is in the order of weeks. The typical computer time consumption for a production run is in the order of days on small workstations and the typical overall uncertainty of the Monte Carlo result is about 10-20%. However, mainly due to the very complex geometry, it will be hard to achieve these figures if the present methods are applied to a model of W7-X.

9.2.3 Suggested R&D work

The necessary and the desirable R&D work follows from the discrepancies between the present status and the requirements.

(I) Neutron emission.

A source code needs to be developed which takes into account anisotropic ion distribution functions and realistic flux surface configurations. New measurements of differential fusion cross-sections at low energies are desirable for proper assessment of effects from anisotropic neutron emission.

(ii) Neutron cross-sections.

In order to assess the impact of uncertainties in neutron cross-sections on Monte Carlo results, it is desirable to continue the campaign of integral benchmark experiments at a neutron laboratory. In particular, the measurements should be extended to a broader set of scattering materials and experimental set-ups that are sensitive to large angle scattering should be performed.

(iii) Geometry.

Since the entire W7-X experiment is being modelled by using the CADDS-5 CAD system [26], it is highly desirable to use this geometry model also as an input for the neutron transport calculations. However, this is not feasible together with MCNP, since the geometry modelling concepts of MCNP and CADDS-5 are not compatible.

(iv) Detector response.

The response functions of the relevant detectors have to be measured at a neutron laboratory and corresponding modelling codes have to be developed.

(v) Neutron tracking.

For experiments with very complex geometry such as W7-X, the ray tracing algorithm used in MCNP is not any more appropriate. Instead, a modern ray tracing acceleration technique has to be adopted.

(vi) Variance reduction.

To overcome or at least to alleviate the problems associated with small detectors, new Monte-Carlo algorithms have to be designed.

From the above list, the point concerning the geometry is both the most desirable and the most critical. Since an import of the W7-X geometry as modelled with CADDS-5 into MCNP is not feasible, it follows the need for a completely new Monte-Carlo neutron transport program.

9.2.4 Validation

For validation of the Monte Carlo procedure, dedicated scattering experiments at a neutron laboratory can be performed. Calculations and measurements for realistic geometries can be carried out at W7-AS, TEXTOR, ASDEX-U or JET. The final concept has to be designed and proposed at a later stage.

9.3 Deduction of plasma parameters from measured neutron rates

Using the measured neutron rates, it is possible to evaluate the ion temperature provided the fuel density is known [1]. To treat neutral beam heated plasmas, it is important to use models that describe non-Maxwellian velocity distributions with sufficient accuracy. Sophisticated transport codes, such as TRANSP [27,28], are usually employed to obtain information on the plasma fuel ions in tokamaks. These codes attempt to obtain consistency between all measured plasma parameters within small variations of their values in order to derive transport coefficients. However, they are too time-consuming for routine analysis. In order to carry out routine interpretations of neutron signals, fast dedicated codes are needed. These codes are usually based on time-dependent Fokker-Planck models. Some works on tokamaks, TFTR and PLT, reported of discrepancies of up to a factor 2-3 between calculations and measurements for some cases [29,30]. However, parameter ranges are identified in relation to the errors in the measured input data using a fast steady-state Fokker-Planck model [21]. The main results are as follows. Firstly, in the appropriate parameter ranges the results of interpretation calculations, e.g. the time evolution of the inferred dilution ratio n_D/n_e, were shown to be in good agreement with results of other independent measurements. Secondly, the deduction of the ion temperature solely out of measured neutron rates is not possible for neutral beam heated plasmas. However, for a rather small range of experimental conditions the deuteron temperature could be deduced and shown to be consistent with other independent measurements.

For W7-X we propose two different sets of codes to be used for deduction of plasma parameters:

1. For plasmas with NBI one large code for a refined interpretation analysis of selected time intervals based on the time-dependent Fokker-Planck equation including relevant source and loss terms.

2. For thermal plasmas a fast on-line program for evaluation of the central ion temperature or the central deuterium density.

These codes which for tokamaks are well established will be discussed below.

9.3.1 Fast on-line integrated analysis of measured thermal neutron rates

The thermal reactivity of the D-D fusion reaction strongly depends on the ion temperature and to the square of the deuterium density. Thus, it is possible to determine either the plasma deuterium temperature or the deuterium density from the D-D fusion emission provided the other is known. This is a straightforward procedure and recent works report good agreement with results of other diagnostics [31,32]. This procedure requires an accurate knowledge of the reactivities. They can, in principle, be calculated from the fusion cross-section for any known deuterium velocity distribution. However, for non-thermal distributions, such as those occurring during deuterium neutral beam injection or second harmonic ICRF heating, numerical integration is required. A fast on-line integrated analysis should therefore primarily be applicable to thermal plasmas for which the emitted neutron rate is:

$$R = \frac{1}{2}\int_0^1 n_D^2(\rho)\langle\sigma v\rangle_{DD}\,\Omega(\rho)\,\mathrm{d}\rho \qquad (1)$$

where the deuterium density profile and the fusion reactivity are functions of the flux surface label ρ. Furthermore, Ω denotes the appropriate volume elements for a given flux surface label. The thermal fusion reactivity is a function of the deuterium temperature and can be approximated in the temperature range from 0.2 to 100 keV with an accuracy of 0.3% by the fit formula given by [33]. Due to the T^{κ} dependence of the fusion reactivity with κ ranging from 3-5, the neutron emission is approximately twice as sensitive to the shape of the temperature profile than to the shape of the density profile. Thus it is important to use a sufficiently accurate ion temperature profile in the calculations for determining the central deuterium temperature or the deuterium density.

9.3.2 Refined deduction of plasma parameters during NBI heating

For the refined iterative deduction of the plasma deuteron density n_D, for plasmas with neutral beam injection, the evolution of the 2D velocity distribution $f(\upsilon,\mu,t)$ needs to be calculated using the Fokker-Planck equation

$$\frac{\partial U(v,\mu,t)}{\partial t} = \frac{\partial}{\partial v}\left[-\alpha U + \frac{1}{2}\frac{\partial}{\partial v}(\beta U)\right] + \frac{\gamma}{4v^2}\frac{\partial}{\partial \mu}\left[\left(1-\mu^2\right)\frac{\partial U}{\partial \mu}\right] + S(v,\mu) - L(v) \qquad (2)$$

where $U(\upsilon,\mu,t) = \upsilon^2 f(\upsilon,\mu,t)$, $\mu = \upsilon_{||} / \upsilon$ is the pitch angle variable, S is a source term and L is a loss term. The collision coefficients are given by [34]:

$$\alpha = \langle \Delta\upsilon_{\Pi} \rangle + \frac{1}{2\upsilon}\langle (\Delta\upsilon_{\perp})^2 \rangle, \qquad \beta = \langle (\Delta\upsilon_{\Pi})^2 \rangle, \qquad \gamma = \langle (\Delta\upsilon_{\perp})^2 \rangle. \tag{3}$$

Different models can be used for the loss term. Charge exchange models [35] and models taking into account both finite particle and energy confinement [36] are most frequently employed. A simple Gaussian loss term at thermal velocities is also used [37].

When carrying out the interpretation calculations, the initial value of n_D is obtained from the measured Z_{eff} and n_e profiles. If the Z_{eff} profile is not available, a flat profile and thus, a flat n_D/n_e profile is assumed. In the iteration procedure, the evolution of the distribution function from the previous time-point is calculated by varying the particle loss rate of the thermal particles in the loss-term of the Fokker-Planck equation. This leads to a change in the velocity distribution functions and the total local deuteron densities for the consecutive time point. With the new local distributions and densities, the neutron emission rate is calculated. It should be mentioned that quasi neutrality is always maintained. Thus, when varying n_D, the impurity densities are varied as well. For simplicity, the ratio between the different impurity densities is kept constant. The iteration loop is stopped when the calculated and measured neutron rates agree within the error limit of the measurement, which can be about 10% for the neutron rate measurements. Owing to the n_D^2 dependence of the neutron rate, the agreement between measurement and calculation can after 3-4 iterations become typically better than 5% for reasonable starting values. It should be noted that the output of the interpretation calculation includes the iterated value of the deuteron density and the fractional contributions from thermal, beam-thermal and beam-beam reactions.

The code also allows the prediction of total neutron yields and neutron emission profiles. As shown in [38], the agreement between prediction and measurement is better than 20%, provided input data with sufficient accuracy are available.

9.3.3 Design criteria for the interpretation code

The main conceptual requirements for the interpretation code are as follows:

1. **The interpretation code needs to have a fully modular structure:** A software module, which is easily adapted to changes in central data banks or to newly available diagnostic data, reads all the input data. Except for the neutral beam deposition profile, these data are all measured. The latter is calculated by using a fast appropriate deposition code. The local time-dependent distribution functions, the corresponding reactivities and other important velocity space moments are calculated in the main module.

2. **The code will have to be run in two modes.** It can be used as a predictive code calculating the time-dependent neutron signals from all input data. It can also be used in an interpretative mode yielding the deuteron density through an iterative procedure using the neutron emission as input.

3. **The code has to be sufficiently fast for routine analysis** but the 2D character, i.e. anisotropy, of the velocity distribution has to be fully taken into account in the calculations of the neutron rate. Also it is important to include the time-dependence,

particularly when the background parameters or the injection power varies on a time scale comparable or shorter than the ion-electron slowing-down time. This is often the case for large fusion plasma devices. For such plasmas, a stationary model can substantially overestimate the neutron rate and, therefore cause discrepancies between the inferred deuteron parameters and the measurements.

4. **The code has to provide necessary input data** for the neutron transport calculations, e.g. a sufficiently accurate neutron plasma source.

To meet these requirements the code will be based on a 2D Fokker-Planck model. (Effects and errors due to approximation of the 3D Stellarator flux surface geometry with a 2D model are difficult to estimate but need to be examined at a later stage.) In order to keep the computation time sufficiently short for routine analysis, the 2D Fokker-Planck equation is solved by expanding the distribution in eigenfunctions of the pitch angle scattering operator. Thus the problem is reduced to a set of 1D parabolic differential equations. Typically less than approximately 10 - 15 orders need to be calculated to obtain a reasonable accuracy. The computation time can therefore be fairly short. The 1D equations can be solved with a finite element method as it is flexible and the boundary conditions are easily implemented. Furthermore, a non-uniform grid will be used which is essential for treating NBI with its rather narrow source.

9.3.4 Necessary R&D work

1. *Flux surface geometry.* At present, a Tokamak type flux surface geometry in Lao-Hirshman representation is used in the Neutron rate Fokker-Planck solver (NR-FPS) code. For W7-X a more realistic flux-surface geometry needs to be implemented.
2. *Beam deposition.* The fast beam deposition module SINBAD [39] originally written for Tokamak requires modifications of the surface geometry for treating neutral beam injection into Stellarator plasmas.

9.4 Resources, personnel and time plan

Estimated resources needed and a time plan for implementation of the data analysis, interpretation and simulation codes are given in Table 9.

For design and programming about 3 man-years per year are needed. Most of this work will be done within the framework of Ph.D. tasks. More intensive work is needed for installation, approximately 2-3 man-years. For the final operation and supervision of the codes 1 man-year per year is needed.

Financial support is needed only for travel expenses.

10 SUMMARY

Several techniques for measurements of neutron emission levels and energy distributions have been used at previous magnetic fusion experiments like in JET. For W7-X several systems of neutron diagnostics are here proposed for evaluation of plasma parameters like ion temperature, thermal reaction rate and fuel densities. An overview of the proposed systems is given in Table 1.

For total yield measurements two independent systems are proposed;

1. Conventional BF_3- and ^3He counters and fission chambers surrounded by moderators are suggested for measurements of time dependent total reaction rates. To enable in-situ calibration by means of a well-calibrated neutron source the aim is to obtain detectors with almost flat responses. A system comprising four sets of detectors

covering the emission range from 10^{12} to 10^{16} neutrons per second is outlined. Furthermore, the sets are distributed around the torus to reduce the influences from scatter and shadowing due to major modifications in installations near to the torus or detectors. With this technique the accuracy in total emission rate measurements is estimated to ± 15-20% and the time resolution is 10 ms.

2. As a more accurate technique for total neutron yield measurements an activation system is proposed and suitable activation reactions are listed. This system is envisaged to operate occasionally and mainly for cross-calibrating with the counter system whenever this is needed. The measurement accuracy is estimated to ± 10-15%. The purpose with this system is also, to evaluate possible toroidal non-symmetries in the neutron emission rates and to measure the triton-burn-up rate.

For measurements of neutron energy spectra a time-of-flight spectrometer is proposed. The purpose is to evaluate ion temperatures in Maxwellian plasmas and fast ion distributions and thermal reaction rates during auxiliary heating conditions. Located in the basement, central ion temperatures can be evaluated for $T_i > 3$ keV and $\Delta T_i / T_i < 10\%$ with a time resolution of 100 ms provided the neutron emission rate exceeds 10^{14} n/s. This type of spectrometer has been in operation for several years at JET and only minor modifications before installation at W7-X are foreseen.

A profile camera housing a new type of fast detector based on scintillating fibres is proposed for measurements of neutron emission profiles and their fluctuations with frequencies of up to 40 kHz. The detector development is a significant part of the work. Simulations are necessary to assess the needs for a 1D or 2D camera and the optimum number of lines-of-sight. The camera will yield the birth profile of the neutrons and therefore also of the associated tritons.

It is proposed to make provisions for measurements of gamma radiation to identify reactions between fast (MeV) ions. Furthermore, bremsstrahlung emission can be detected for monitoring existence of fast electrons. The smallness of the detector makes this installation a minor task provided provisions have been taken in terms of port allocations and cable preparations. Also provisions are suggested for a set of detectors to be used for measurements of lost charge fusion products at the first wall. Approximately 10-15 Si-diodes or scintillators will be used and provisional port allocation will be made. Information from this system is useful only in combination with information on reaction profiles from the profile camera, yielding the birth profile of the charge fusion products.

Computational procedures will be used to support the diagnostics for analysis, interpretation, and simulations. Associated with each diagnostic system there will be fast dedicated computer codes aimed at analysis of measured detector signals, for processing, evaluation and simulation. The interpretation will be needed to deduce plasma parameters and for presentation of results. Simulation is of particular importance for calibration of detector systems.

A rather detail time-plan including the necessary preparation work, decisions to be made, R&D needed, construction work and tests, development of software, delivery, installation and commissioning at W7-X is presented for each diagnostic system proposed. The schedule is such that the diagnostic will be ready for operation approximately a year before it will be needed. Estimates of necessary personnel and financial resources are given.

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Table 1. NEUTRON DIAGNOSTICS FOR W7-X

System	Level [A)]	Primary measure-ments	*Plasma parameters*		*Time resol.*	*Radial resol. (cm)*	Detector number and type	Port type / position	Comments	Estimated hardware costs k DM
			Maxwellian	*Non Maxwellian*						
Neutr. counters BF3, ^{3}He, fission	1	$Y_n(t)$	*Reaction rate.* *$T_i(0) < 2$ keV if $n_d(r)$ is known*	*Reaction rate.* *High energy tails.*	10 ms - 100 μs	- - - -	8 x BF3	Machine centre and 3 outboard positions	Total yield $\Delta Y/Y \approx 10\%$. Needs in-situ calibration.	40
Bonner sphere							1 x ^{3}He			20
Activation system [B)]	2	Y_n	*Total reaction yield*		- - - -	- - - -	2-4	Horisontal ports	Total yield $\Delta Y/Y \approx 10\%$. Needs n-transp. calculation.	180-342
Neutron energy spectrometer	2	$Y_n(E,t)$	*$T_i(0) \geq 3$ keV* *$\Delta T_i/T_i \leq 10\%$*	*Fast ion and non-fusion reactions*	100 ms	≈ 30	T-o-F spectro-meter	M 8	Utilises penetration in main shield. Location in basement. From JET?	16
1D/2D/2D neutron profile camera	TBD	$Y_n(t,z)$	*Fast profile fluctuations.* *Triton burn-up profile*		300 ms - 100 μs	≈ 30/ 5	3/10/20 chs. Fast fibre scintillators	A1 or E1 or E10	Detector R&D needed. Needs radiation shielding.	200/ 500/ 1000
Gamma detector	TBD	$Y_\gamma(E,t)$	*Detection of fast electrons*		10 ms - 100 μs	≈ 40	Ge (Li)	Q1	Commercially available	20
Lost triton/ proton detectors	3	$\phi_{t,p}(t,r{=}a)$	*Losses of charge fusion particles*		10 ms - 1 ms		Si-diodes or scintillators	TBD	Extensive particle orbit calculations needed	100-200
Computer codes	1		*Interpret data and present param. on-line*		- - - -	- - - -	- - - -		Software development needed. Aims at 100 ms time lag.	0

A) Level-1: Basic diagnostics for machine operation and plasma characterization.
Level-2: Extension of level-1 set to additional parameters and/or higher spatial/temporal resolution.
Level-3: Special advanced diagnostics/new trends.

B) Unshadowed areas represent responsibilities of the Swedish association and shadowed areas responsibilities of Univ. of Heidelberg.

Table 2. Long term plan for implementation of neutron counters

SUBSYSTEM / YEAR	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
<u>COUNTERS</u>											
<u>Phase I, preparation and decision:</u>											
Port allocation and location of detectors.	x-Δ										
Flux estimates and decision making.	x-Δ										
Calculation of response functions.	x-	Δ									
Decision on instrumentation and detectors.		x-Δ									
Design criteria and detail design.		x--R									
<u>Phase IIa, construction of prototype</u>:											
Construction of moderator.		x	-|								
Purchase of detectors and electronics.			x-|								
Functional tests.			x-|								
Detector assembly.			x	-|							
Tests and flux calibration at a neutron laboratory.				x-R							
<u>Phase IIb, construction of counters</u>:											
Construction of moderator.					x-|						
Purchase of detectors and electronics.					x	-|					
Functional tests.						x-|					
Detector assembly.						x-|					
Tests and flux calibration at a neutron laboratory.						xR					
<u>Data analysis software</u>											
Specifying interfaces with the data acquisition system.							x-|				
Writing and testing of data acquisition software.							x-|				
Installation of data acquisition software.							xR				
Writing and testing of specific analysis software.							x-|				
Installation of specific analysis software.							xR				
<u>Phase III, delivery of hardware to W7-X:</u>											
Installation and commissioning at W7-X.								x--|			
In-situ calibration at W7-X.								xC			
Operation at W7-X.									O---- --	R---	----
<u>Data evaluation and presentation software</u>											
Specification of software.							x-|				
Writing and testing of software.								x---|			
Installation of software.								x	---R		
<u>Personel MY</u> (prof. + PhD stud.)											
W7-X staff							0.3	0.5			
Swedish Association staff		0.3	0.5	0.3	0.5	0.5	0.5	0.5	0.5	0.5	
Heidelberg staff						0.5					
<u>Cost estimates, kDM</u>											
Hardware		12	10		11	27					
Travel	2	9	15	10	5	5	10				

x: Starting point, R: Reporting, Δ: Decision point, C: Calibration, O: Start of operation.

Table 3. Long term plan for implementation of neutron activation system.

SUBSYSTEM / YEAR	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
ACTIVATION SYSTEM											
Phase Ia, test transport system:											
Planning		x-Δ									
Port allocation and location of irradiation ends.		x-Δ									
Flux estimates and decision making.		x-	-Δ								
Construction		x	- R								
Calibration and cross-section measurements		x---	——	——	—R						
Phase Ib, test transport system:											
Installation at TEXTOR or W7-AS			x	-- Δ							
Operation				x--	R						
Phase II, final system:											
Planning					x-|						
Purchase of detectors and electronics.					x|						
Functional tests.						x-|					
Detector assembly.						x-|					
Final construction work						xR					
Phase III, delivery of final system to W7-X:											
Installation and commissioning at W7-X.							x-- Δ				
In-situ calibration at W7-X.								xC			
Operation at W7-X.								O	-—R		——
Data evaluation and presentation software											
Specification of software.							x-|				
Writing and testing of software.								x---|			
Installation of software.								x	---R		
Personel MY (prof. + PhD stud.)											
W7-X staff		0.5	0.5	1	1	1	1.5	1.5	1	1	1
Heidelberg staff	1	1	2	1	1	1	1	1			
Cost estimates, kDM, (detailes are listed in Tab. 4)											
Hardware		11	115		156	20					
Cross-section measurements		5	5	5	5						
Travel		2	3	5	4	2	2				

x: Starting point, R: Reporting, Δ: Decision point, C: Calibration, O: Start of operation.

Table 4. Resources needed and expected costs for the activation system.

Year	Type of work	Item/Resources	Costs kDM
1997-1998	Planning and construction of test system	Labor	Heidelberg
		Labor	Heidelberg
		Workshop time (220h)	Heidelberg
		Material	15
		Activation samples	5
		1 PC system	5
		1 Workstation	12
		1 AIM module with NIM-crate	16
		1 set of electronics	20
		1 Detector	25
		Software	28
1997-2000	Calibration and cross-section measurement in a neutron lab. PTB	Labor	Heidelberg W7-X
		Measurement time (0.3-0.7 kDM/h)	15-20
		Travel expences	8
1998/1999	Installation of test system	Labor	Heidelberg
		Travel expences	3
1999/2000	Operation of test system	Post-doc.	W7-X
		Travel expences	2
2000-2001	Planning of final system	Labor	Heidelberg
	Final construction work	Labor	Heidelberg
		Workshop time (500h)	40
		Travel expences	3
		Material + act. samples	25
		3 Detectors	75
		1 AIM module with NIM crate	16
		3 sets of electronics	60
2002	Installation	Labor (3 people 100 - 150 h each)	W7-X
	Operation	Travel expences	2
		1 staff	W7-X

Table 5. List of possible activation materials for 2.45 MeV and 14.1 MeV neutrons.

2.45 MeV material	σ [mb]	γ-energy [MeV]	Threshold energy [MeV]	Decay time	Remarks 1)	Ref.
Indium	340.5	336	0.3	4.5 h	N(2), Res (30)	[16], [17]
Nickel	101.6	811	0.5	71 d	N(700)	[16], [17]
Titanium	22.9	159	0.7	3.3 d	N(30)	[16], [17]
Yttrium	360	909	0.9	16 s	S(3), Res(5)	[16], [19]
Zinc	26.8	511	0.5	12.7 h	N(5)	[16], [17]
Gold	1300(?)	279	0.5(?)	7.5 s	S(3), Res(5)	[20]

14.1 MeV material	σ [mb]	γ-energy [MeV]	Threshold energy [MeV]	Decay time	Remarks	Ref.
Copper	456	511	10.6	9.4 min	N(6), Res(60)	[16], [17]
Cerium	969	754	10	56 s	S(3), Res(5)	[18], [17]
Silicon	279	1779	4.5	2.25 min	S(3), Res(5)	[18], [17]
Aluminium	122	1370	5	14.9 h	N(6)	[16], [17]
Titanium	61	983	5	43.7 h	N(20)	[16], [17]

1) N(k): Normal measurements (integration over 1 second to one hour), the sample can be used again after k days for next measurement. S(k): Short time measurement (at least one second), the sample can be reused after k minutes for next measurement. Res(k): The result of the measurement is known after k seconds.

Table 6. Long term plan for implementation of neutron Time-of-Flight spectrometer.

SUBSYSTEM /YEAR	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
TOF-SPECTROMETER											
Phase I, preparation and decision:											
Flux estimates.	x--|										
Port allocation and location of detectors.	x-Δ										
Assessment of value of information.		x--|									
Decision making.		Δ									
Procedure for inheritage from JET.			x-|								
Phase II, construction:											
Detail design and construction of new detector support.					x-|						
Functional tests of support structure.					x-|						
Disassembly at JET.					x-|						
Transport to Sweden.					x-|						
Detector assembly.						x-|					
Tests and calibration at a neutron laboratory.						x--R					
Data analysis software:											
Specifying interfaces with data acquision system.								x|			
Writing of data acquisition software.								x--|			
Test of data acquisition software.								x-|			
Installation of data acquisition software.									x-R		
Writing of analysis software.								x-|			
Test of analysis software.								x--|			
Installation of analysis software.									x-R		
Phase III, delivery to W7-X:											
Installation and commissioning at W7-X.									x--|		
Functional test at W7-X.									x-|		
Operation at W7-X.										O---R-	
Data evaluation and presentation software:											
Specification of software.								x-|			
Writing of software.									x--|		
Tests of software.									x--|		
Installation of software.									x-R		
Personel MY (prof. + PhD stud.)											
W7-X staff								0.3	0.3		
Swedish Association staff	0.1	0.2	0.1		0.5	1.0		0.5	1.0		
Heidelberg staff										0.5	
Cost estimates, kDM											
Hardware [1]					10	6					
Travel					10		1	4	4		

x: Starting point, R: Reporting, Δ: Decision point, C: Calibration, O: Start of operation.

[1] Assumes inheritage of the instrument from JET.

Table 7. Long term plan for implementation of a neutron profile camera.

SUBSYSTEM / YEAR	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
<u>PROFILE CAMERA / FAST COUNTERS</u>											
<u>Phase I, preparation and decision:</u>											
Flux estimates.	x-|										
Port allocation and location of detectors.	x|										
Assessment of value of information.	x|										
Decision making.	Δ										
<u>*Fibre detector prototype R&D*</u>:											
Detail design of detector and read-out system.			x--|								
Purchase of fibres, PMTs and electronics.			x-|								
Functional tests.			x-								
Construction of read-out system.				x-|						
Assembly of detectors.					x-|					
Test of read-out system.					x-|					
Test witht a neutron source and a generator					x-R						
<u>Phase II, construction</u>:											
Decision on instrumentation and detectors.						Δ					
Neutron transport calculations of shielding.						x---|				
Detail design of detectors and shielding.							x--|			
Purchase of detectors, PMTs and electronics.							x-|			
Manufacturing of radiation shielding.							x--|			
Detector assembly.								x--|		
Tests and calibration at a neutron laboratory.								x-R|		
<u>Data analysis software</u>:											
Specifying interface with the data acquisition system.									x|	
Writing and testing of data acquision software.									x-|	
Installation of data acquisition software.									x-R		
Writing and testing of analysis software.									x-|	
Installation of analysis software.									x-R		
<u>Phase III, delivery of detectors and shielding:</u>											
Installation and commissioning at W7-X.										x--|	
Functional test at W7-X.										x-|	
Operation at W7-X.										O---R---	
<u>Data evaluation and presentation software:</u>											
Specification of software.								x-|			
Writing and testing of software.								x--|			
Installation of software.										x---R	
<u>Personel MY</u> (prof. + PhD stud.)											
W7-X staff										0.5	
Swedish Association staff	0.1		0.5	0.5	0.5	0.5	0.5	1.0	1.0	1.5	
Heidelberg staff						0.5					
<u>Cost estimates, kDM</u>											
Hardware [1)]			80	5	3	100/ 200/ 500	100/ 300/ 500				
Travel			1	1	1	1	1				

x: Starting point, R: Reporting, Δ: Decision point, C: Calibration, O: Start of operation.

[1)] The numbers refere to 3, 10 and 20 channels respectively.

Table 8. Estimated costs for the charge fusion product measurement system.

Item	Estimated costs kDM
Mechanical components	
pumps	20
vacuum meters	12
other mechanics (motors etc.)	25
Electronics, detectors	40
Total	97

Table 9. Long term plan for implementation of a data analysis, interpretation and simulation codes.

SUBSYSTEM / YEAR	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
COMPUTER CODES											
Design and programming:		x-----	——	——	—R						
Testing and benchmarking:						x---R					
Installation and operation:						x---R					
Personel MY (prof. + PhD stud.)											
W7-X staff						2-3					
Heidelberg staff		1+2	1+2	1+2	1+2						
Cost estimates, kDM											
Travel		1 - 2	1 - 2	1 - 2	1 - 2						

x: Starting point, R: Reporting, Δ: Decision point, C: Calibration, O: Start of operation.