Tokamak Neutron Calibration at High Yields Using Combined Nuclear Emulsion Measurements, Indium Activation, and VINIA-3DAMC Simulation

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IPP III/132 August 1989

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IPP III/132 August 1989

Contribution to the
Neutron Calibration Techniques Workshop
Princton Plasma Physics Laboratory
August 1-3, 1989

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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

This is a cooperative work by MPI für Plasmaphysik,
Universität Heidelberg, Universität Düsseldorf, and ENEA

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1. Principle

Our concept for absolute calibration at high neutron yields is based on absolute measurement of the neutron fluence Φ at a suitable position and on a Monte Carlo calculation of the specific fluence φ, i.e. the ratio between the fluence Φ and the total neutron production Y in the plasma. These two results immediately give the absolute yield Y.

Absolute measurement of a neutron fluence requires an absolutely calibrated detector and unfolding of the response of the detector or an additional Monte Carlo simulation of its response to the specific fluence φ. At present, we are using nuclear emulsions and indium activation; though the treatment of emulsions is very time-consuming, they enable us to restrict the procedure to an appropriate interval of the neutron energy spectrum.

Monte Carlo calculation of the specific fluence $\varphi = \Phi/Y$ is started from the spectral local neutron birth rate, which is determined by means of our NR code from the measured plasma data for the discharges used for calibration. Starting from this plasma neutron source, the VINIA-3DAMC software is used to follow migration and scattering of neutrons through the full tokamak device, and the specific neutron fluence arriving in the active detector volume is determined.

This paper summarizes the work we have done on this line during the past few years. The first section treats problems concerning the arrangement of the detectors at a tokamak and relevant properties of the detectors. The second section describes the numerical input and output of the different types of software. The third section summarizes the results obtained so far for ASDEX and JET. The last section contains some comments about detector calibration and software checks.

2. Numerical input and output

The VINIA-3DAMC software [1] needs as input a description of the neutron source and a model of the tokamak facility. Starting from this source, the software stochastically generates neutrons, follows their migration through the facility, and delivers as output the specific spectral neutron fluence φ arriving in the detecting volume.

2.1 Plasma neutron source

Our NR code [2] is used to determine the plasma neutron source from measured plasma data of the discharges considered. This software was developed as a general code for interpreting and predicting the neutron emission rate. Here it is used to calculate the normalized neutron emission profile. For this the following measurements are used:

electron density profile	from interferometer or Thomson scattering
electron temperature profile	from ECE measurement or Thomson scattering
Z_{eff}	from Bremsstrahlung
deuteron density	from CX measurements
deuteron temperature	from CX measurements
injection energy and species mix	from injection data
deposition profile	from FREYA or PENCIL calculations

When CX measurements are not available, the deuteron parameters are determined from the electron parameters by taking advantage of parameter studies for the relations between the two. So far the fast particle energy distribution function, for the injected deuterons, was calculated by a relaxation-time model, which was demonstrated to be applicable to the ASDEX plasma parameters. Recently, for application to JET the code was extended by including a Fokker-Planck calculation of this distribution function.

2.2 Tokamak model

The Monte Carlo calculations use a full 3-dimensional model of the tokamak. The intention in preparing our models is always to distribute all essential masses as realistically as possible without taking into account all minor geometrical details except in the vincinity of the detectors. As many details from there as possible are included in the model in order to make sure that absorption and scattering near the detector are properly taken into account. The constituents of the detector device are always absorbing but are usually considered to be collisionless. In fact, their masses are very small and they contribute little to the scattered neutron flux, but their absorption is essential in determining the absolute neutron fluence arriving in the detecting volume.

2.3 PTO output files

The PTO (point contribution output) files from the VINIA-3DAMC software are very detailed. They contain the coordinates of each point of neutron emission or collision, the coordinates of the corresponding point of detection in the active volume of the detector, and the energy and weight of the contribution to the specific fluence.

2.4 Nuclear emulsion response

The response of the nuclear emulsion plates (NEP) to the contributions stored in the PTO files is simulated by the special Monte Carlo software NEPMC [1]. This program stochastically creates for each contribution a predefined number of protons with different scattering angles with respect to the true direction of incidence of the neutron. From the corresponding proton energy the track length is determined and stochastically distorted according to the effect of range straggling and to the errors in the measurement of track length and angles. Finally, the resulting proton energy spectrum is converted into an apparent neutron energy spectrum which is to be compared with the measured spectrum.

Owing to the limited energy resolution of the emulsion the apparent neutron spectrum is broadened in relation to the incoming specific neutron fluence φ. Off-axis incidence of the neutron - which also exists to a small degree in collimated measurements - causes additional unsymmetric broadening and a small shift to lower energies. Thus the integrated neutron fluence in a certain energy interval is somewhat reduced by the emulsion response function. For the energy range between 2.1 and 3 MeV, which is used in the calibration procedure, this effect is of the order of 5 to 15%, depending on the aperture angle of the collimator.

2.5 Indium activation response

To treat the response of the indium sample, we are at present using a very simple approach. From the data in the PTO files just the total number of activated nuclei $^{115}In^{m}$ is calculated.

A more sophisticated Monte Carlo treatment has to be developed in future, stochastically treating, like in the NEPMC program, the generation of $^{115}In^{m}$ nuclei, their decay by γ emission, the γ absorption in the sample, the detector housing and detector crystal, and, finally, the response of the Ge crystal to the γ quanta.

3. Experimental problems

3.1 Arrangements and positions

We are using nuclear emulsions for spectrally resolved measurements and indium activation for spectrally integrated measurements. Emulsions can be used with either collimated or uncollimated neutron incidence. For collimated measurements some basic aspects concerning a suitable choice of position of the collimator and the orientation of its line of sight have to be considered.

First of all, tangential orientation of the collimator does not seem to be recommendable, because the observed section of the plasma is rather complicated and the results would be very sensitive to the plasma neutron emission profile. However, our results for ASDEX demonstrate that even such positions could be used, provided that the neutron plasma source is well known.

In radially orientated measurements, the full cross-section of the plasma neutron source should be observed in order to make the measurements insensitive to the details of emission profiles. The ideal position for the collimator would be above (or below) the tokamak, because in such measurements radial motions of the plasma would not affect the results. Unfortunately, it is practically impossible on large tokamaks to obtain such access to the device. Usually, vertical observations must be restricted to a small part of the plasma cross-section and can thus become sensitive to the emission profile and plasma position. However, for our nuclear emulsion spectrometer at JET, located in such a position in the roof laboratory, preliminary numerical studies show that a variation of ±5 cm in the Shafranov shift results in a change of only ±5% in the direct neutron flux arriving in the emulsion.

Nevertheless, the best solution in practice is horizontal radial observation, which, in principle, is what we are doing at ASDEX. As the plasma position is well measured, problems due to the radial Shafranov shift of the plasma need not be expected.

In our first designs, the horizontal aperture of the collimators was adjusted to observe the full plasma cross-section of 40 cm radius. In future the aperture of collimator **2** will be reduced to a region of 25 cm radius. This still covers more than 95% of the neutron emission and - as predicted by the numerical results - will improve the ratio of direct to scattered neutron fluxes arriving at the emulsion by a factor of about 1.6.

Uncollimated emulsion measurements and indium activation measurements should be made as near the plasma as possible. Positions near the vessel or a port are usually easily accessible, but our experience shows that such positions cause

trouble in the form of large contributions from collided neutrons scattered in the vicinity of the detector. For this reason we have now installed at ASDEX the new measuring position 6 (Fig. 1), using a tube inside the vessel and a transport system for both the emulsions and the indium samples.

3.2 Determination of relevant number of counts

As experimental result the detectors yield a certain number of counts; for the emulsion these are the proton tracks and for the activated indium sample the counts from the Ge counter. The first problem is to determine the absolute number of relevant counts; the second is to relate the number of counts to the corresponding absolute value of the neutron fluence (or neutron flux) which arrived in the active volume of the detector during the exposure time.

It should be mentioned here that the proposed procedure of absolute calibration at high yields is not restricted to the use of emulsions and indium activation; it could be done with any detector for which one is able to solve the two problems of determining the absolute response and its conversion into a neutron flux.

The problems in determining the absolute number of proton tracks arise from three effects:

1) some tracks leave the emulsion and cannot be measured;
2) some tracks are distorted by encounters of the proton with other nuclei in the emulsion;
3) in principle, it is not possible to measure the parameters of either short proton tracks or of tracks at large angles to the plane of the emulsion.

An analytical expression was determined to correct for the number of escaping tracks. The correction factor for distorted tracks has to be determined during the scanning of the emulsions. The measurement of the track parameters is restricted to a maximum scattering angle and a minimum track length. Then the total track number is extrapolated, advantage being taken of the general properties of the proton energy distribution or the proton angle distribution. All these procedures are now well established.

The determination of the absolute number of activated indium nuclei is essentially a question of the calibration of the Ge counter, usually used for counting the γ decays, and the correction for both the background counts caused by radiation of the environment of the counter and the Compton effect in the Ge crystal. The calibration of the Ge counter has to take into account not only the absolute response of the detector, but also two effects introduced by the thickness of the indium samples, namely γ-ray absorption in the indium and

the dependence of the counter efficiency on the distance between the Ge crystal and the point of γ emission. A serious problem which we have not studied in detail so far arises from the fact that the efficiency of the counter is not homogeneous over the area of the Ge crystal, and that the indium samples will not generally be homogeneously activated. In order to consider this problem, we have to develop the Monte Carlo simulation mentioned in section 1.5.

3.3 Conversion of detector response into neutron fluence

The spectral response of the nuclear emulsion allows direct unfolding of the number of proton tracks into the apparent neutron spectrum and thus into the apparent neutron fluence. For this one needs only the cross-section for the n-p collision, which is well known, and the number of protons present in the emulsion during exposure. Here we depend on the specifications of the producer, Ilford, and the uncertainty in the emulsion thickness gives the largest contribution to the final error.

As the spectral information is lost in the activated Indium sample and the nuclear cross-section is strongly energy-dependent, here conversion of the number of counts into neutron fluence is impossible and we have to use the opposite way of calculating the number of activated nuclei from the spectral distribution of the specific fluence φ.

3.4 Measurement of the scattered neutron spectrum

Our experimental results demonstrate that due to the strong decrease of the activation cross-section for indium (Fig. 2) the numerical results for the activity of the sample depend remarkably on the structure of the calculated spectrum of the scattered fluence. Therefore the application of indium activation for neutron yield calibration needs not only a carefull calculation but also a measurement of the scattered spectrum.

For this reason we will use collimator 2A - the improved version of collimator 2 mentioned in section 3.1 - for indium activation and emulsion measurement of the spectrum at the same place. Thus we will be able to confirm the calculation of the scattered spectrum for this position. Because activation measurements in collimator 2A need long shot series with deuterium injection into deuterium plasmas whereas position 6 is expected to be used for single discharges, finaly, a relation between the activation in collimator 2A and at the new position 6 has to be determined by simultaneous measurements.

4. Results for absolute neutron yield

This section summerizes the results obtained so far for ASDEX and JET. At ASDEX we used a sequence of different positions with stepwise improvement of the ASDEX model, the software and the evaluation of the results. The work for JET is still at an early stage, and so the results should be considered as preliminary.

For all nuclear emulsion measurements the results for the ratio Y/Y_c, of the neutron yield Y determined by our procedure and the yield Y_c obtained by the counters are between 1.0 and 1.2 with an error of the order of 30%. Thus, within the error bars we get excellent agreement between the two results.

The result for Indium activation suffers essentially from the fact that we have to use here the full energy range between 0.3 and 3 MeV in the Monte Carlo simulation. For the calculations we have done so far, the statistical error in the simulation of the direct fluence is only about 3% and for the collided fluence it is about 13%, but owing to strong peaks in the neutron spectrum caused by near scatterers the error in the activation is in the order of 30%. The situation is illustrated in Fig. 3 which gives the neutron yield per shot as a function of the Indium activity per gramme and shot. The two solid lines indicate the limits for the VINIA calculations; nearly all experimental points and their error bars are between these two lines and in this sence we get also here a good agreement.

Our method is about to be applied to a more appropriate position 6 inside the vessel. There we expect improvement by a factor of about 6 for the ratio of the direct to the collided fluence for the emulsion measurement and by a factor of 2.5 for the Indium activation.

4.1 Collimated nuclear emulsion measurements in the energy range between 2.1 and 3.0 MeV

1) ASDEX, <u>position 1:</u> collimated horizontal radial measurement in front of the quartz window for the Thomson scattering system (Fig. 4), distance torus axis - detector: 282 cm, window - detector: 174 cm discharge no. 16910, D injection into D plasma

Φ from NEP	3.0×10^5 ±12%	neutr./cm^2	
φ from VINIA	2.2×10^{-8} ± 2%	cm^{-2}	
direct part	1.5×10^{-8} cm^{-2},	scatt. part	0.7×10^{-8} cm^{-2}
$Y = \Phi/\varphi$	1.4×10^{13} ±12%	neutrons	
Y_c from counters	1.3×10^{13} ±25%	neutrons	$Y / Y_c = 1.1 \pm 28\%$

2) ASDEX, position 2: collimated horizontal radial measurement in front of vacuum vessel (Fig. 4),
distance torus axis - detector: 163 cm, vessel - detector: 99 cm,
discharge no. 19611, D injection into D plasma

Φ from NEP	2.7×10^{6} ±12%	neutr./cm^2	
φ from VINIA	7.5×10^{-8} ± 7%	cm^{-2}	
direct part	4.4×10^{-8} cm^{-2},	scatt. part	3.1×10^{-8} cm^{-2}
$Y = \Phi / \varphi$	3.6×10^{13} ±14%	neutrons	
Y_c from counters	3.2×10^{13} ±25%	neutrons	$Y / Y_c = 1.1 \pm 29\%$

Comment: Scattered part of neutron fluence enlarged in relation to position 1 owing to the short distance to the vacuum vessel

3) ASDEX, position 3: forward tangential measurement near the quartz window (Figs. 4, 6)
distance torus axis - detector: 129 cm, window - detector: 48 cm,
discharge no. 16744-16748, H injection into D plasma

Φ from NEP	4.0×10^{5} ±11%	neutr./cm^2	
φ from VINIA	6.4×10^{-8} ±12%	cm^{-2}	
direct part	5.5×10^{-8} cm^{-2},	scatt. part	0.9×10^{-8} cm^{-2}
$Y = \Phi / \varphi$	6.3×10^{13} ±16%	neutrons	
Y_c from counters	5.7×10^{13} ±25%	neutrons	$Y / Y_c = 1.1 \pm 30\%$

4) ASDEX, position 4: forward tangential measurement near the quartz window, other data same as for position 3 (Figs. 4, 6)

Φ from NEP	5.2×10^{5} ±11%	neutr./cm^2	
φ from VINIA	7.5×10^{-8} ± 8%	cm^{-2}	
direct part	6.8×10^{-8} cm^{-2},	scatt. part	0.7×10^{-8} cm^{-2}
$Y = \Phi / \varphi$	6.9×10^{13} ±14%	neutrons	
Y_c from counters	5.7×10^{13} ±25%	neutrons	$Y / Y_c = 1.2 \pm 28\%$

Comment: The difference in the absolute values of the neutron fluence for positions 3 and 4 is caused by the plasma rotation and the resulting different absorption in the quartz owing to the shifted neutron energies [3].

5) JET: collimated vertical radial measurement in the roof laboratory with precollimator in torus hall (Fig. 5),
distance torus axis - detector: 1976 cm
discharge no. 13797-13814, D injection and ICRH in D plasma

Φ from NEP	9.0×10^{5}	±12%	neutr./cm^2	
φ from VINIA				
direct part	3.4×10^{-11}	± 5%	cm^{-2}	
$Y = \Phi / \varphi$	2.6×10^{13}	±13%	neutrons	
Y_c from counters	2.7×10^{13}	±10%	neutrons	$Y / Y_c = 1.0 \pm 16\%$

Comment: Monte Carlo simulation of the scattered part of the specific fluence φ is still not available; it is expected to be of the order of a few per cent of the direct fluence and will not change the results appreciably.

4.2 Uncollimated nuclear emulsion measurements
in the energy range between 2.3 and 3.0 MeV

6) ASDEX, position 5: measurement near the quartz window (Fig. 6),
distance torus axis - detector: 110cm, window - detector: 8 cm,
discharge no. 18949-18959, H injection into D plasma

Φ from NEP	6.7×10^{6}	±11%	neutr./cm^2	
φ from VINIA	6.2×10^{-7}	±12%	cm^{-2}	
direct part 3.7×10^{-7} cm^{-2}, scatt. part 2.5×10^{-7} cm^{-2}				
$Y = \Phi / \varphi$	10.8×10^{12}	±16%	neutrons	
Y_c from counters	10.6×10^{12}	±20%	neutrons	$Y / Y_c = 1.1 \pm 26\%$

Comment: Determination of the yield suffers from the large error in the scattered part of the calculated neutron fluence, this being caused by the very near scatterers.

4.3 Indium activation measurement

7) ASDEX Position 5: near quartz window (Fig. 7)

A/Y from VINIA	$5.4 \ldots 3.5 \times 10^{-14}$		Bq/g neutron	
A/Y_c from counters	4.8×10^{-14}	±15%	Bq/g neutron	$Y / Y_c = 0.9 \ldots 1.4$

Comment: The activity A of the indium is devided, for convinience, by the mass of the sample; A/Y gives the numerical result; A/Y_c is the indium activation measurement divided by the yield determined by the counters.

5. Detector calibration and software checks

5.1 Monoenergetic neutron sources and simple geometry

For the procedure of absolute neutron yield determination considered here, it is necessary that the detectors used be absolutely calibrated. This has to be done with a well- calibrated neutron source and a well-known neutron emission spectrum. The best way is to use an accelerator. We are going to use the facility of the PTB in Braunschweig (German National Standards Laboratory), for which the neutron yield is determined with an error of ≤3% and the energy spectrum with a resolution of 1.5%.

Besides calibrating the absolute response, a calibrated accelerator also provides a check of the software by means of quite simple geometric arrangements. We are preparing such a check for the VINIA-3DAMC software, using a simple scatterer and calibrated neutron spectrometers installed at PTB. Such measurements will be done with scatterers from different materials, thus also providing a check of the most important cross-section data in our calculations. Furthermore, these arrangements will also be used for basic checks of the combination VINIA-3DAMC software and either emulsions or indium activation.

5.2 In-situ calibration in the tokamak

Having successfully confirmed the basic features of the detectors and of the software used, it is worthwhile to do an in-situ calibration using a neutron source inside the tokamak. Usually, and at least for all positions so far used at ASDEX and at JET, this would be impossible since the required source strength is neither available nor treatable. But in our new position 6 the detector is located at a distance of only about 50 cm from the plasma centre and here an in-situ calibration using a conventional neutron source seems possible. As the emitted neutron rate and spectrum of such a source is well known, we shall not only get an absolute calibration of the neutron fluence, but also be able to treat this arrangement with the VINIA-3DAMC software for an in-situ check of the whole procedure which we are using for the neutron yield determination.

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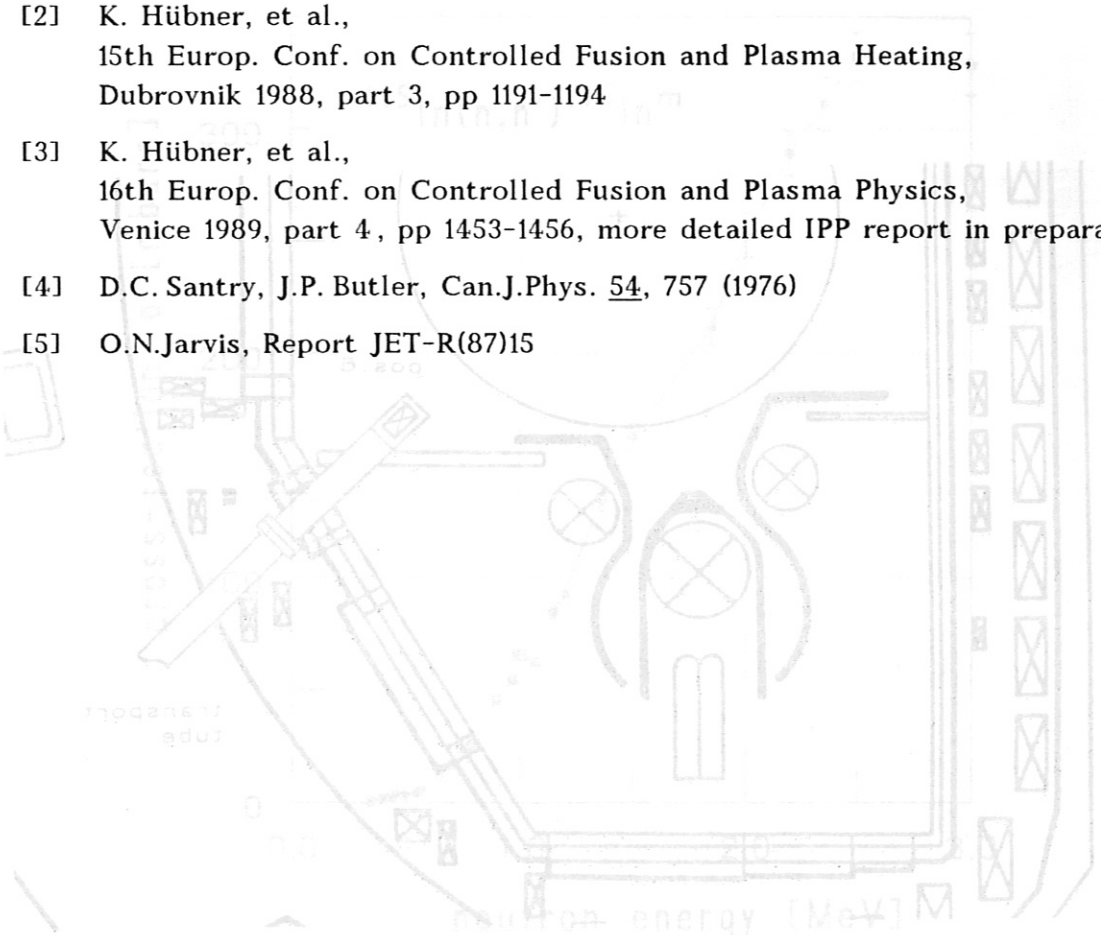

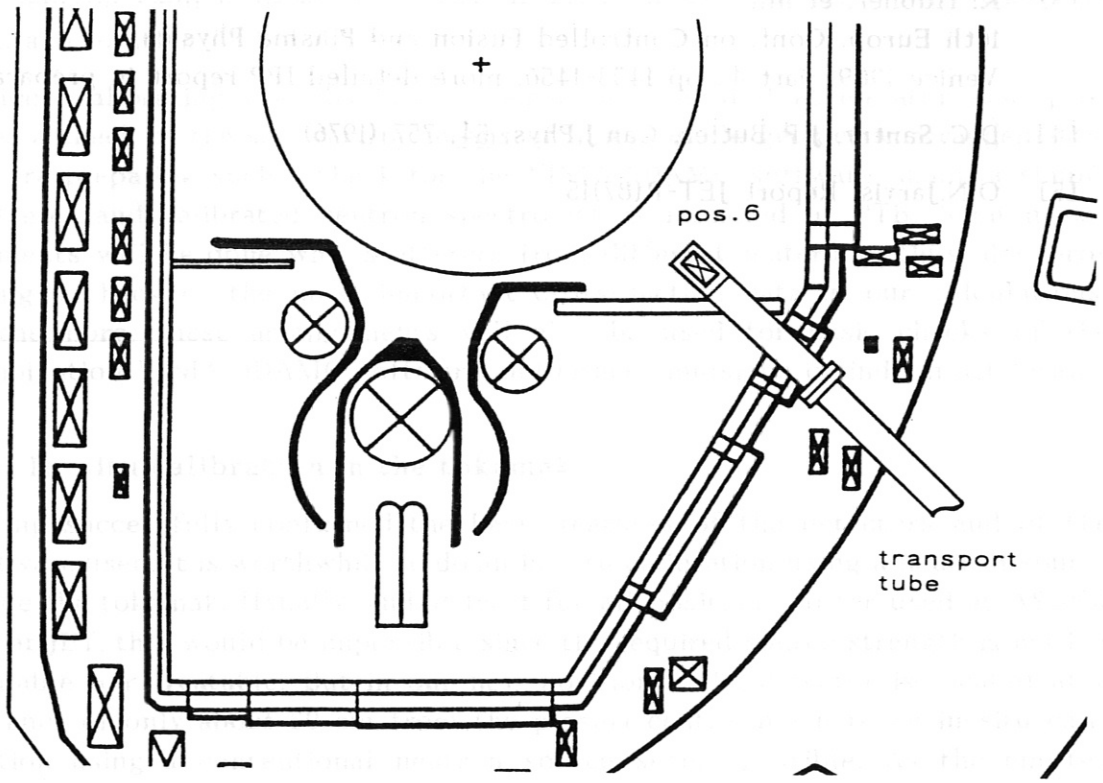

Fig. 1: New position 6 at ASDEX inside the vessel for indium activation and nuclear emulsion measurements

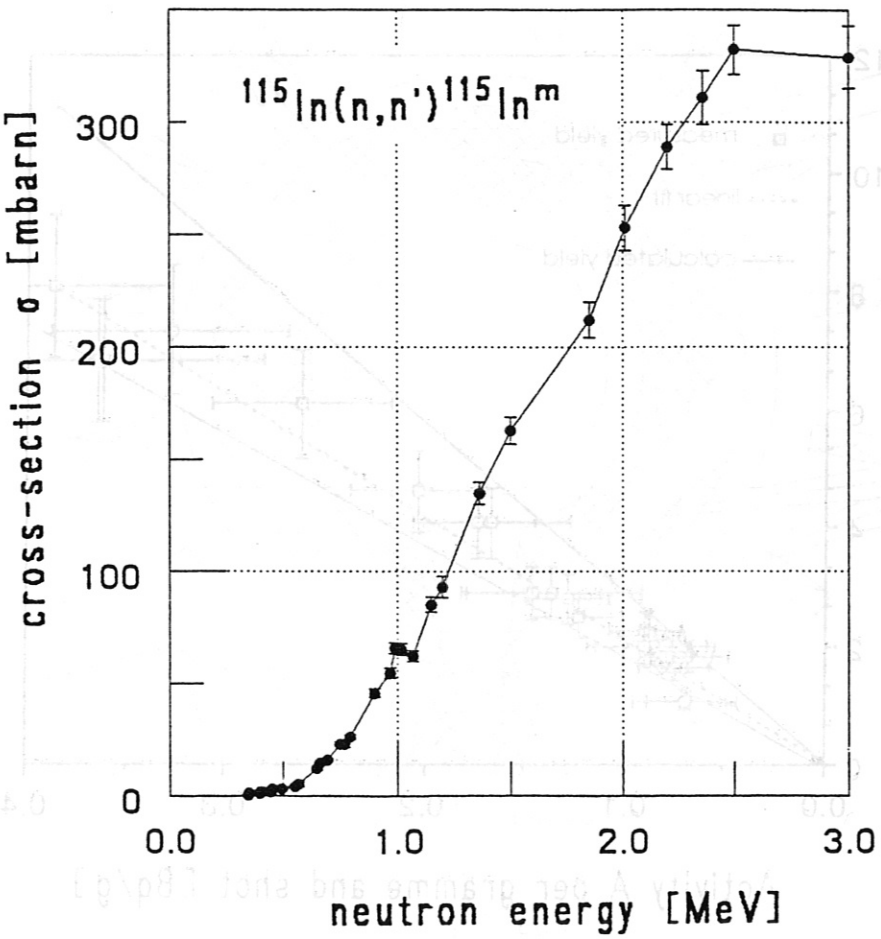

Fig. 2: Cross-section for indium activation [4]

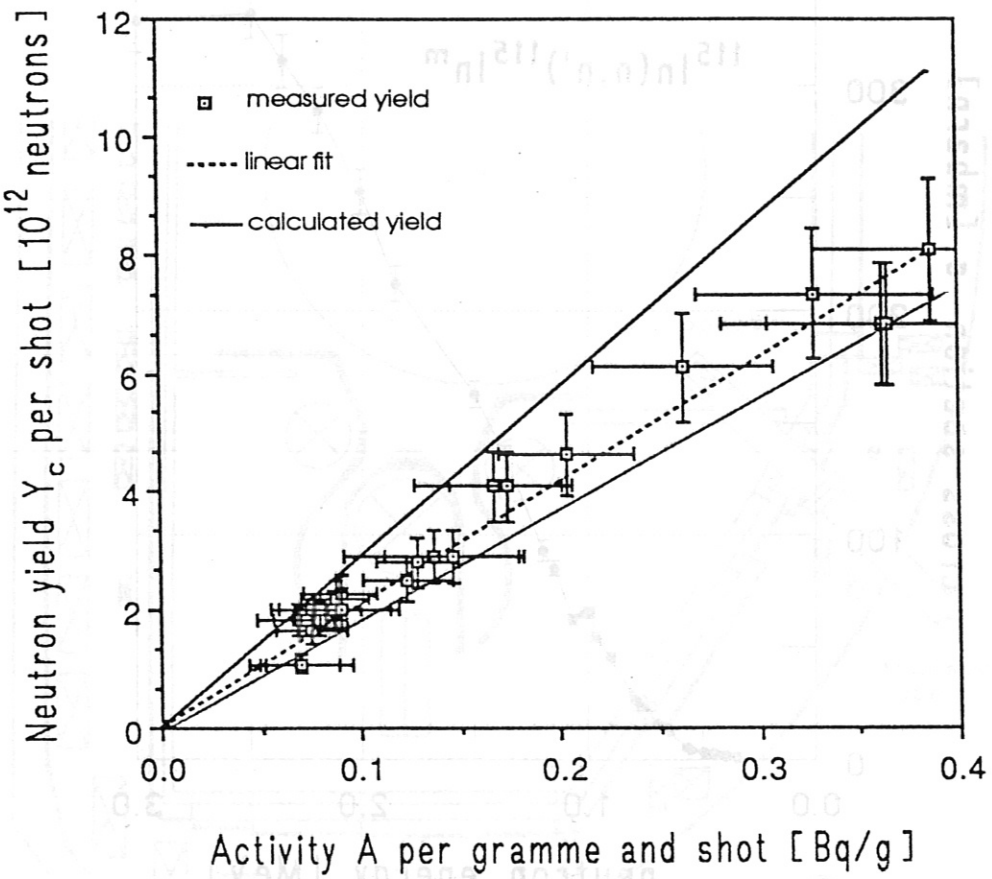

Fig. 3: Neutron yield Y_c from counters as a function of sample activity A

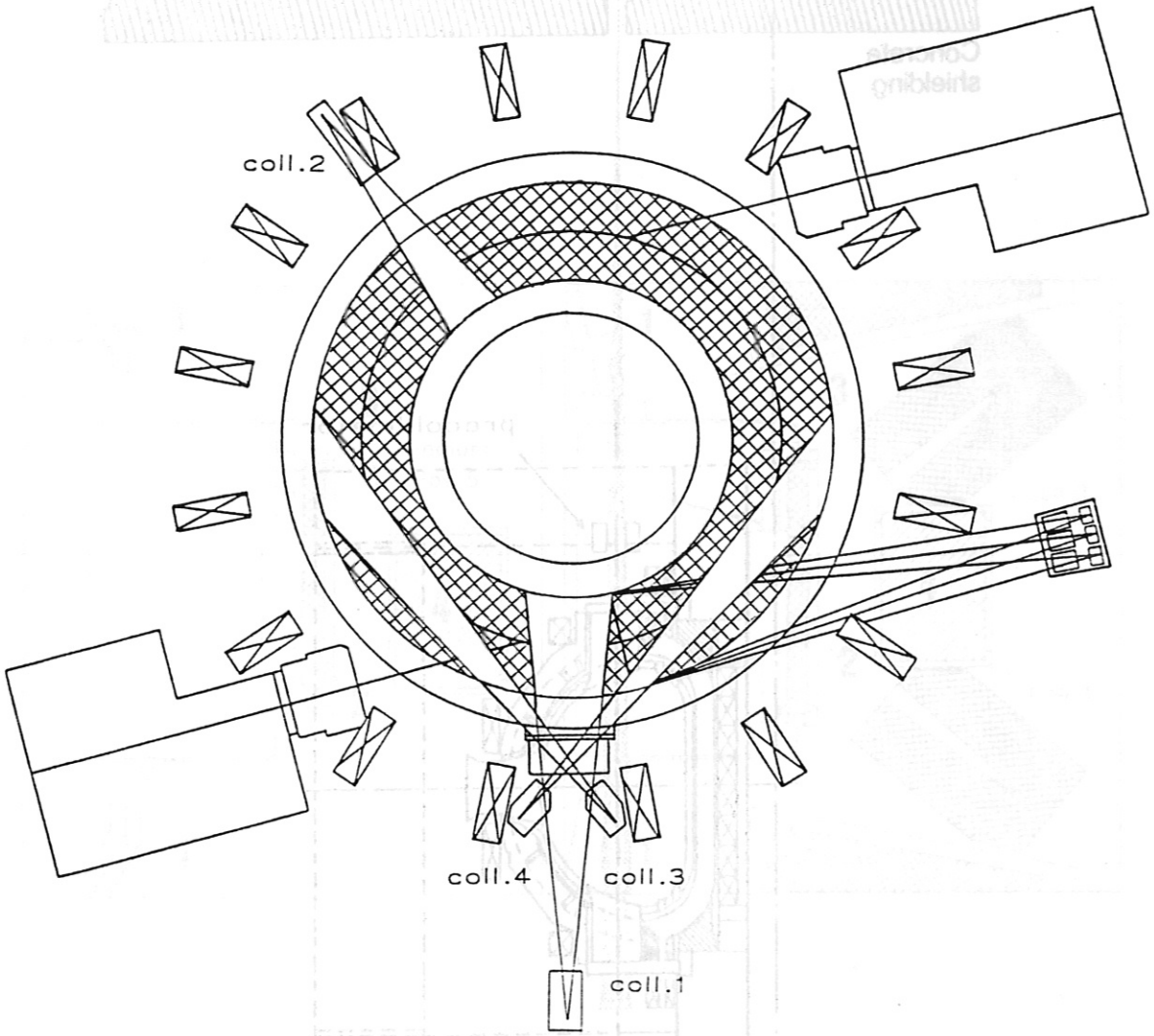

Fig. 4: Positions of collimators 1, 2, 3, and 4 at ASDEX

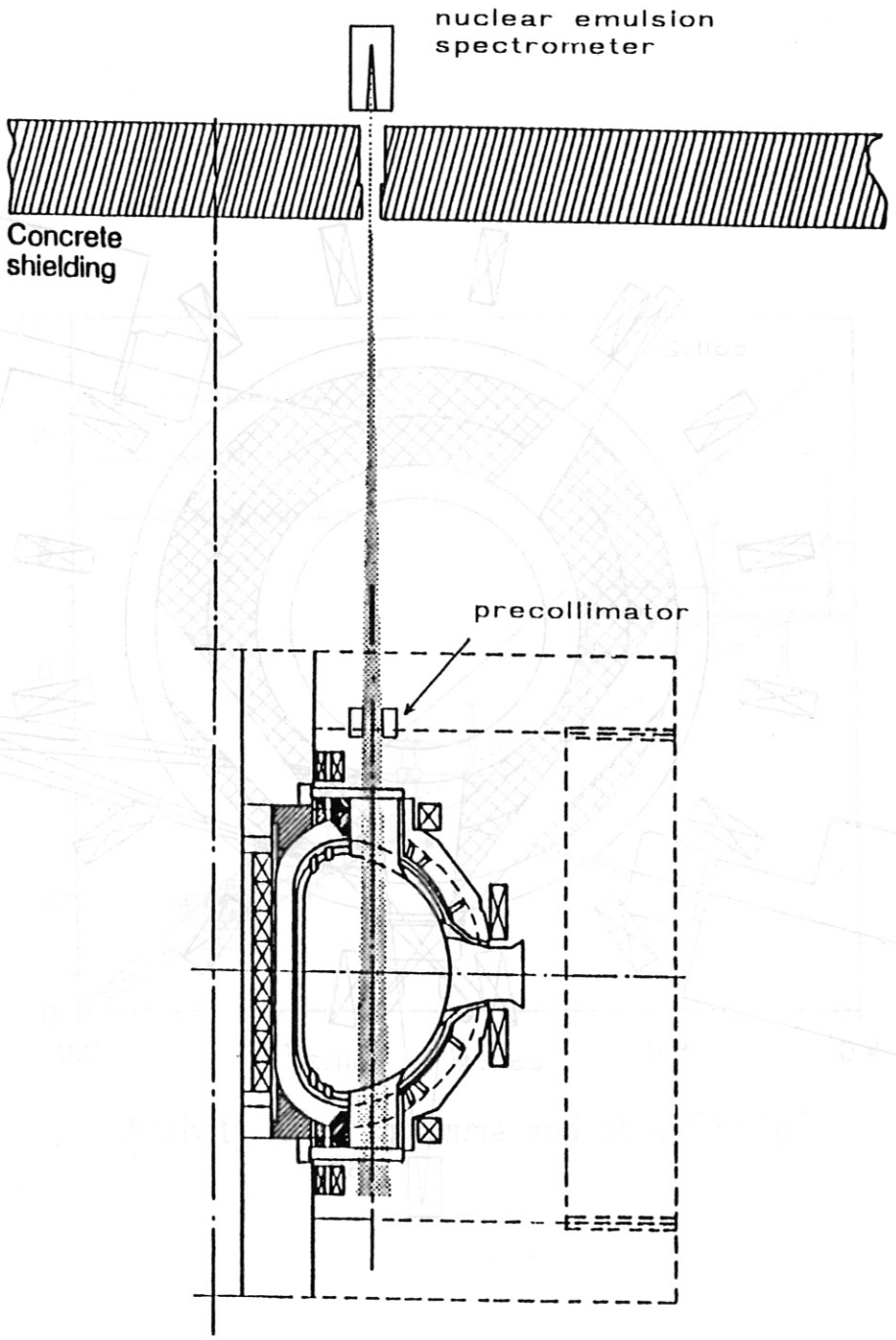

Fig. 5: Arrangement of precollimator and nuclear emulsion spectrometer at JET,
drawing after [5] (not to scale)

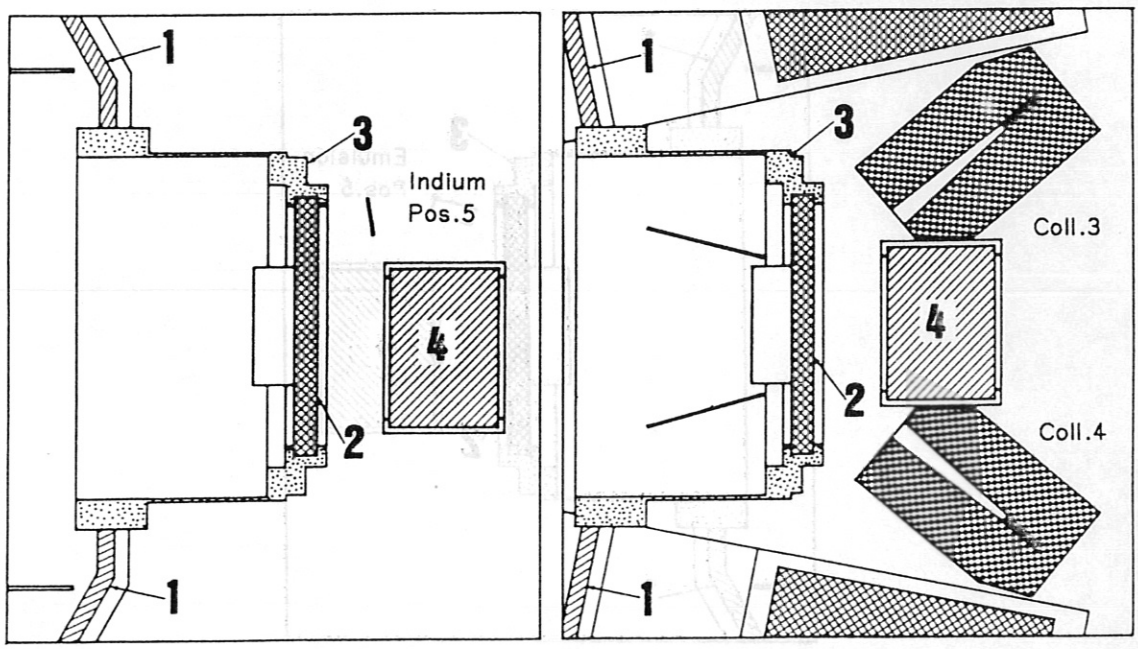

Fig. 6: a) Vertical cross-section through the quartz window and indium sample at position 5
b) horizontal cross-section through the quartz window and collimators 3 and 4
1: vessel, 2: quartz window, 3: window support,
4: glass lense for Thomson scattering

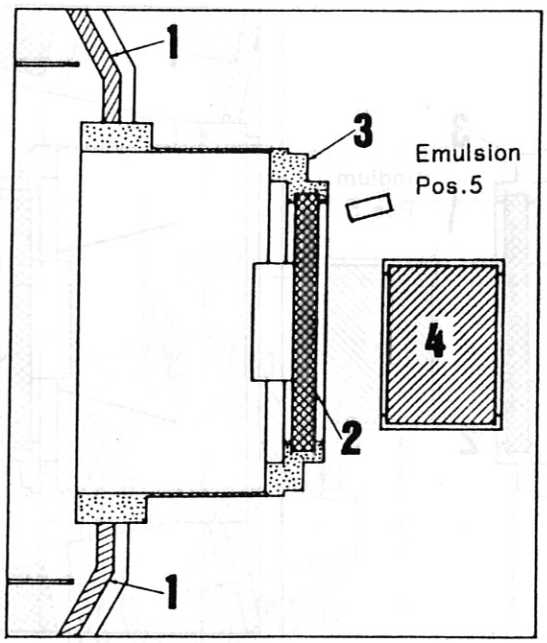

Fig. 7: Vertical cross-section through the quartz window and nuclear emulsion box at position 5
1: vessel, 2: quartz window, 3: window support,
4: glass lense for Thomson scattering