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Introduction

In the investigation of Ignitor physics, an important role is played by neutron diagnostics, which should provide information on the plasma parameters and on the plasma response to external controls, such as heating power, fuelling, etc. When significant fusion rates are achieved, neutron diagnostics could give some insight into the α-particle behavior (confinement, thermalization rate) and their effects on the background plasma (heating rate, instabilities). Apart from information on ion density and temperature, the high neutron flux levels expected for Ignitor will allow measurements with good space, time and energy resolution, providing information on plasma profiles and on the ion velocity distribution function. Neutron diagnostics can also provide useful information on α-particle issues, like the total a power $P\alpha(t)$ and its spatial distribution.

There are several technical reasons for developing neutron diagnostics for Ignitor in addition to other diagnostics:

1) the high radiation level accompanying high fusion power is of concern to diagnostics. For neutron diagnostics this is ameliorated by the fact that the signal to background ratio is not deteriorated and the intense neutron signal would improve the counting statistics;
2) the interface between the diagnostics and the tokamak is generally a difficult problem curtailing the information output. Neutron diagnostics have fewer interface problems than most other installations;
3) finally, access to the plasma (port space) is limited with a high value of the benefit/cost ratio.

The diagnostic capabilities of neutron measurements in Ignitor have been investigated in a study [1], by means of a calculation model of the device. The analysis was based on a calculation model of the Ignitor device using the 3-D Monte Carlo code MCNP [2], used to anticipate the neutron flux levels and the related energy spectra in different parts of the device, which are of interest for the diagnostic project and exploitation. In this model all the main device components are represented (plasma chamber, TF coils, PF coils, C-clamp, central post, press, ports etc.). The model has been used to simulate a 14 MeV neutron source, with a gaussian spectrum with a FWHM of 560 keV corresponding to T = 10 keV. The Ignitor plasma was represented by an extended neutron source with equi-emissivity surfaces having D-shaped cross section with the same ellipticity and triangularity as the plasma chamber. The source spatial distribution was given by a generalized parabola with exponent equal to 7. The numerical results have been used for the design of a complete set of neutron diagnostics including:

1) the counters and the activation technique to measure the total neutron yield;
2) the multicollimator array to measure the radial distribution of the neutron emissivity;
3) the high resolution spectrometers to measure the neutron energy distribution.

1. Total Neutron Yield Measurements

The planned plasma scenarios for the Ignitor D-T phase scan from low to extreme parameter regimes, where the neutron production rate can vary by more than two orders of magnitude, from about $Y_n(\mathrm{t}) \approx 10^{17}$ to about 10^{20} n/s. Large variations are also expected in single discharges: for example, the rise phase of the plasma current, lasting 4 seconds, is characterized by a strong rate of ohmic heating up to relatively high temperatures. The neutron production rates vary by several orders of magnitude in this phase, from $Y_n(\mathrm{t}) \approx 10^{15}$ to about 10^{20} n/s in the extreme regime. In this regime, the current flat top phase lasts 4 seconds during which the neutron production rate may well exceed the expected value of Y_n at ignition ($Y_n \approx 3 \times 10^{19}$ n/s).

The primary piece of information obtainable by the measurement of $Y_n(\mathrm{t})$ is either the ion temperature or the ion density time variation, provided that the other one is known independently. The limited use of auxiliary heating (which can cause strong supra thermal neutron production) would mean prevailing thermal plasma conditions in Ignitor, favorable to the interpretation of neutron measurements. The other important aspect is that, in ignited plasmas, the measurement of $Y_n(\mathrm{t})$ is essential for monitoring the total fusion power $P_\alpha(\mathrm{t})$ carried by the α-particles, which are produced concurrently with the 14 MeV neutrons. Hence, the quality of the total neutron yield measuring system is mainly defined by two aspects, i.e., the achievable time resolution and the absolute calibration of detectors.

In present fusion devices, characterized by $Y_n(\mathrm{t}) \geq 10^{13}$ n/s, like for example JET, TFTR and also FTU, the neutron yield measuring systems involve the use of fission chambers. For instance, ^{235}U fission chambers are sensitive to thermal neutrons (since the fission cross section for ^{235}U is highest at neutron thermal energies) and are embedded in suitable moderators. In the presence of very high flux levels, fission chambers sensitive to fast neutrons are also used; these employ isotopes which do not fission thermally, like ^{238}U for which the fission reaction has a threshold at about 1 MeV. ^{238}U chambers are about 2-3000 times less sensitive than ^{235}U fission chambers with equal amount of fissile material. In both cases the count rate capability limit is $C^{MAX} = 1$ MHz (in pulse mode), while the minimum acceptable count rate is determined by the desired time resolution and statistical accuracy.

In ignited plasmas, the slowing-down time of fusion α-particles ($\tau_{s,\alpha} \approx 50$ ms in Ignitor) can be assumed as a typical time scale of variation of $Y_n(t)$. A time resolution $\Delta t \approx 100$ ms and a statistical accuracy $\sigma = \pm 13$ % or better, determine a minimum number of counts $N \approx 1000$ in Δt, hence determine a minimum count rate $C^{MIN} = 10$ kHz. This implies that the useful dynamic range is $D = C^{MAX} / C^{MIN} = 100$. The detector efficiencies ε (in units of cm^2) are defined as the ratio, $\varepsilon=C/F$, of the count rate over the neutron flux F at the detector location (in units of n/s cm^2), which vary proportionally with $Y_n(t)$. In order to cover a variation of five orders of magnitude in the neutron production rate, detectors of different efficiencies will be required.

The fluxes F have been calculated by MCNP [2] at various locations on the external surface of the cryostat. For example, the calculated neutron flux on the mid plane far from the horizontal ports is $F \approx 10^{-7} \times Y_n(t)$ cm^{-2} (only 10% of this flux consists of neutrons with energy > 1 MeV). Assuming $C^{MIN}= 10^4$ c/s for a minimum neutron production rate $Y_n(t) = 10^{15}$ n/s, a ^{235}U fission chamber in this position must have an efficiency $\varepsilon \geq 10^{-4}$ cm^2. On the other hand, a ^{235}U fission chamber with a lower efficiency must be employed at the same location to ensure a measurement up to the maximum neutron production rate $Y_n(t) \approx 10^{20}$ n/s. These efficiency values are standard for fission chambers. The dynamic range of fission chambers can be increased by several orders of magnitude considering also the current mode. However, the good discrimination against γ radiation is lost in passing from the pulse mode to the current mode [3].

It should be mentioned that non-fusion neutrons can be generated by photo-production caused by the interaction of runaway electrons with the wall. However, since this interaction is localized, photo neutrons can be discriminated against fusion neutrons employing several detectors at different toroidal angles around the device. On the other hand, the measurement of the photo neutron yield, provided by the neutron counters, can provide important information on the energy carried by the runaway electrons that is useful for evaluating the wall damage, especially during plasma disruptions.

Considering now the second aspect, the requirements on the accuracy in the absolute value of $Y_n(t)$ are very demanding, $\Delta Y_n/Y_n = 10$ % or better, and suggest the use of different and independent diagnostics [4].

Usually, absolute calibrations of neutron counters are obtained by employing neutron sources or generators with a well-known intensity and situated in several toroidal and poloidal locations inside the plasma chamber (in order to simulate the extended plasma source). This technique, called *in situ* calibration, has been routinely used in present devices operating with D plasmas, including FT and FTU [5]. The experience gained here suggests that many source locations are necessary to obtain an accurate calibration, since the streaming of neutrons through narrow penetrations, especially in compact devices, may give rise to non-symmetric response functions of the detectors with respect to the toroidal location of the source. An example of response function to 2.5 MeV neutrons of one of the FTU fission chambers is given in FIG. 1 and reference [2]. In Ignitor, the compactness of the device and the small port width (0.17 m), will limit the application of the *in situ* technique that, in this case, would require the use of a 14 MeV neutron tube. Here, neutron transport calculations may be usefully employed to study some problems encountered in the *in situ* calibration, such as the choice of the most suitable detector location, the experimental design and the integration of a limited set of experimental data.

The calibration of neutron counters remains however a difficult task. For example, D-T generators are typically much less intense than the plasma source (by a factor at least 10^{-7} in the Ignitor case), so that only the most sensitive detectors can be directly calibrated *in situ*; other detectors can only be cross-calibrated varying the plasma neutron source in the appropriate ranges. In addition, changes in the machine auxiliary components near the tokamak may significantly change the detector response. Thus, periodic recalibrations are necessary. For these reasons the Foil Activation Technique appears the most suitable mean to obtain an accurate absolute measurement of the (time integrated) neutron yield Y_n(t). This method has already been used in many tokamaks, both for 2.5 MeV and for 14 MeV neutrons (from triton burn-up), including FT, FTU and JET (see [6], [7] and references therein). It requires the exposure of foils of suitable materials to the neutron flux close to the plasma chamber wall during a whole single discharge and the analysis of the induced radioactivity shortly afterward. For neutron yields from D-T plasmas, useful reactions must have threshold energies somewhat below 14 MeV, to reduce the contribution of scattered neutrons to the total activation. Since this contribution cannot be avoided but only reduced, the relationship between local fluence at the foil location and the emitted neutron yield must be calculated numerically. A recent benchmark experiment performed on FTU with 2.5 MeV neutrons [8], has shown that the activation technique can give an accurate measurement of Y_n(t) provided that the foils are exposed in a simple casing as close as possible to the plasma, to minimize the contribution of collided neutrons to the total local fluence, and to simplify the numerical simulation. Moreover, the accuracy in modeling the real geometry of the scattering masses close to the foil irradiation position is decisive for the accuracy of the calculation. In order to obtain this, it is mandatory to integrate the Neutron Activation System (at least 4 irradiation ends at different poloidal angles through vertical tubes should be employed to correct for plasma displacement effects) in the Ignitor design from its initial phases.

Activation measurements at 14 MeV will be very useful also in the D operation phase, to verify the single particle behavior of α's in Ignitor plasmas, through triton burn-up studies. These studies have been successfully performed in a number of devices operating in deuterium, including FT [9] and JET [10].

Another important application of the activation technique is the determination of the neutron energy spectrum at the irradiation position, close to the first wall. This can be obtained making use of materials and reactions with different energy thresholds. This information would be useful for checking the evaluations of radiation damage and the activation of the structures close to the plasma.

Finally, the total neutron yield can be determined by integration of the neutron camera measurements (see below). The accuracy is limited by the absolute calibration of the detectors and by geometrical factors [11].

2. Neutron Emissivity Profile Measurements

Ignitor will produce intense collimated neutron fluxes. As a consequence, collimated neutron measurements (time and space differential) may be expected to gain in importance. This calls for neutron detectors of high performance, with regard to count rate capability (> 1 MHz), calibration accuracy (≈ 1%) and energy resolution, to form the basis for new designs of neutron spectrometers and collimator arrays [12, 13, 14, 15].

The neutron emissivity in thermonuclear plasmas is related to the ion temperature and density through the relation $S(r,\vartheta) = n_T\, n_D\, \langle\sigma v\rangle$, where the maxwellian reactivity $\langle\sigma v\rangle$ is a function of the ion temperature and can be approximated for simplicity as $\langle\sigma v\rangle \approx T^{\gamma}$. For example, for the D-T maxwellian reactivity, $\gamma \approx 5$ for $1 < T < 5$ keV and $\gamma \approx 3$ for $5 < T < 15$ keV. If the ion temperature and density can be modeled as: $n_T= n_D= n_o\, (1-\rho^2)^{\alpha_n}$, $T=T_o\, (1-\rho^2)^{\alpha_T}$ where $\rho=r/r_p(\vartheta)$ and $r_p(\vartheta)$ describes the plasma D-shaped edge, then the neutron emissivity can be modeled as $S(\rho)=S_o\, (1-\rho^2)^{\alpha}$ where $\alpha = 2\, \alpha_n + \gamma\alpha_T$ and $S_o = n_D(0)\, n_T(0)\, \langle\sigma v\rangle_{T=T_o}$ is the emissivity on the axis.

The measurement of the spatial distribution of the neutron emission employs arrays of collimators and detectors (neutron cameras) that receive the neutron emission from well defined chordal volumes of the plasma in one plane, usually the poloidal plane. The number of channels must be such as to view most of the emitting plasma, extending symmetrically from the center of the plasma outwards as far as there is sufficient neutron intensity to be measured; the practical limit is ≈ 10^2 the central peak intensity. Every single collimator defines a line of sight, or a chord through the plasma, as sketched in FIG. 2; collimated measurements should aim at a spatial resolution $\Delta x < a/10$, where a is the plasma minor radius. Usually, $\Delta x \approx 5 \div 10$ cm must be maintained in order not to sacrifice the count rate and the time resolution, especially in a plasma region where the local emissivity is low. When two orthogonal cameras (vertical and horizontal) are available, a tomographic reconstruction of the emissivity profile is possible. In Ignitor it will be possible to implement only a horizontal camera, viewing the plasma through one of the horizontal ports; hence only the line integrated emissivity could be obtained and the complete reconstruction of the emissivity profile must rely upon the knowledge of the shape of the magnetic flux surfaces from magnetic measurements and equilibrium calculations. These measurements are usually less accurate in the plasma center where most of the neutrons are emitted. Therefore, the presence of a few vertical channels would be very useful for obtaining the elongation of the hot plasma core.

Under thermal plasma conditions, the first information derived from the camera measurements is the product $n_T \times n_D$ (line averaged, or local values if profile reconstruction is possible) when the ion temperature profile T_i is known independently from spectroscopic measurements. The other important piece of information is the α particle birth profile [16] which, for the plasma currents typical of Ignitor discharges, should be very close to the α-particle heating deposition unless significant radial diffusion occurs. These pieces of information are fundamental to understanding the physics of burning plasma.

As a preliminary design, a set of horizontal collimators is considered with a length L = 4.6 m and a circular cross section of area $A_c = 10$ cm^2 (see FIG. 2 and references [1]-[14]). The detectors may be located behind the bunker wall, which can be used as part of the shield. The detector distance from the plasma center in this case is D = 7.5 m. Given the Ignitor port size, it is possible to employ a fan type collimator with 9 channels, covering 65% of the whole plasma. The FWHM of the viewed plasma volume Δx is approximately $\Delta x = 6.5$ cm. Given the collimation geometry, the number of neutrons Y_i generated in the volume seen by i-th channel can be calculated for particular values of the peaking factor α of the neutron emissivity [1]. The fluxes at the detectors are then given by $F_i = Y_i / 4\pi^2$ (n/cm^{2}s). For the chosen collimator geometry, F_i varies from around $10^{-10}\, Y_n$ in the central channel to $10^{-11}\, Y_n \div Y_n\, 10^{-13}$ in the peripheral channel for $\alpha = 4 \div 14$. These numbers can be used to determine the detector characteristics. Given the large variation of Y_n during the initial transient phase of the discharge, the range of operation of the multicollimator could be fixed to start with T > 4 keV, hence in the range $10^{18} < Y_n < 10^{20}$ n/s. A detector in the central channel, with a sensible area equal to the channel cross section, having an efficiency $\varepsilon = 10^{-3}$ cm^2 will have $C \approx 10^{-13} \times Y_n$ counts/s, that is $C \approx 10^5 \div 10^7$ counts/s in the range of interest. The flux in the most external channel can vary from 10^{-1} to 10^{-3} times the flux in the central one, depending on the profile. For this channel the additional factor > 100 in the profile changes should be added to the given 10^2 variation in the neutron production rate, hence the corresponding detector should have a dynamic range of at least 10^4. For example, a detector with $\varepsilon = 10^{-3}$ cm^2, will have $C \approx 10^2 \div 10^6$ counts/s in the ranges of interest of Y_n and α.

The shielding material and configuration for collimated (and spectral) neutron measurements require a careful analysis. In fact, the experience made in present tokamaks with 2.5 MeV neutrons has shown the presence of high levels of gamma radiation with energy of several MeV, mostly generated by neutron capture in the shielding materials surrounding the detectors. The JET DT experience shows that the problem does not ameliorate in passing from 2.5 to 14 MeV neutrons. The captured gamma radiation can be strongly reduced by an appropriate choice of shielding material; suitable detectors to be used in the multicollimator should however be intrinsically insensitive to gamma radiation.

The detectors should also have sufficient energy resolution to discriminate against background neutrons back scattered from the inner first wall that will inevitably contaminate the measurement to a non negligible amount [1]. Examples of neutron spectra in the central channel and in a peripheral channel are given in FIG. 3.

The use of Magnetic Proton Recoil detectors (MPR) as counters in the camera meets all requirements for measurements of D-T neutrons [10]. The MPR technique (described in the next section) is free of gamma contamination and should provide passively the required energy discrimination. For the camera counters, an energy resolution $\delta E_R/E = 15\%$ is needed in order to discriminate against scattered, energy degraded neutrons, especially in the peripheral channels. Efficiencies up to 10^{-3} cm^2 can be achieved, as required.

3. Neutron Spectrometry Measurements

The basic plasma information that can be obtained in spectrometric measurements, especially in burning D-T plasmas at ignition but also in D-T plasmas at lower fusion power and in D-D plasmas, are:

1) the ion temperature T_i ;
2) the fuel density product $n_D \times n_T$;
3) the fusion spectrum composition in terms of thermal and supra-thermal components.

Below, a neutron spectrometer system is described, that is designed to provide this information over a broad range of Ignitor plasma conditions.

During the ignition phase, the spectrometer must operate at high count rate [17] to afford sufficient time resolution; it should also have an energy resolution (δE_R) matching the ion temperature of these plasmas, $\delta E_R/E = 2.5$ % corresponding to $T_i = 4$ keV or higher [15]. The experiments devoted to burn condition formation will involve numerous discharges of lower temperatures and neutron yields and this will require spectrometers of better resolution ($\delta E_R/E=1.8\%$, corresponding to $T_i = 2$ keV) and also high efficiency. Moreover, it can be anticipated that neutron spectrometry measurements of 2.5 MeV neutrons from D-D reactions will be desirable because much of the operation would be with D-D plasmas including those with very small amounts of tritium seeding. This would call for spectrometers with very high efficiency to maintain high count rate at rather low neutron fluxes; the resolution should be $\delta E_R/E = 4.8$ %, corresponding to $T_i = 2$ keV.

The choice of detection methods for 14 MeV neutrons with energy resolution is rather limited. The Magnetic Proton Recoil spectrometer (MPR) has been preferred for Ignitor because of its ability to handle high count rates and is the only method that can make full use of the high fluxes expected from Ignitor [18]. It would ensure data of the highest possible quality during the plasma burn period of the discharge, relying on count rates in the range 0.1 to 1 MHz and being able to cope with any overshoots into the 1 ÷ 100 MHz range.

The MPR consists of a magnetic spectrograph viewing the recoil protons produced by the neutron beam impinging on a thin CH_2 foil. The protons are focused, deflected and momentum analysed in a magnet system and detected in a proton counter array at the spectrometer exit [19].

The incoming neutron energy is recorded in a histogram as a function of counter number. Specifications of the MPR spectrometer are given in Table I.

$\varepsilon = 7\times10^{-3}$ cm^2	detector efficiency
$\delta E_R/E \leq 2.5\%^*$	energy resolution
$C_n^{CAP} = 25 - 100$ MHz**	count rate capability
$F_n^{MAX} = 1\text{-}5\times10^{12}$ n/scm^2	maximum neutron flux

Table I *Parameter for MPR spectrometer for 14 MeV neutrons.*

* *This corresponds to Doppler broadening of d+t-ions at* T_i*=3.9 keV.*

** *Depending on width of neutron spectrum.*

A prototype MPR spectrometer has been in use at JET since 1996 [20]. A similar design could also be used for Ignitor.

For D-D neutrons high detection efficiency and corresponding count rate capability are the main priority. This can be achieved with the Time of Flight (TOF) technique. This is used for measuring neutron spectra in nuclear physics experiments where the neutron TOF can be determined relative to the time structure of a pulsed beam. For fusion neutrons, dual timing signals must be used. The first comes from a scintillation detector in the neutron beam (S_1) where the $n+p_H \rightarrow n'+p$ scatterings are manifested through the proton recoil signal. The second signal comes from another scintillator (S_2) for the scattered neutron having traveled a known flight path distance.

A TOF spectrometer of the in-beam geometry has been used at JET [21]. The documented JET experience suggests that the count rate capability C_n^{CAP} is one of the principal handicaps [15]. The intrinsic upper count limit of a TOF spectrometer is $C_n^{CAP} = 5$ MHz in a pure neutron beam (in the case of 2.5 MeV neutrons from thermal D+D reactions). This is a theoretical limit which is approached in proportion to a value of the catching factor $\chi \rightarrow 1$ (the catching factor is defined as the fraction of the selected events in S_1 that is also recorded in S_2). The JET spectrometer has $\chi < 10^{-3}$ and has $C_n^{CAP} \approx 10$ kHz. The usefulness of the TOF spectrometer for Ignitor depends crucially on being able to boost the catching factor some two orders of magnitude to $\chi \geq 0.05$. This is the aim of the TOFOR (Time of Flight - Optimized Rate) spectrometer which is presently under design and has been approved for installation on JET in 2004 [22,23]. It is expected to reach $\chi = 0.07$ giving $C_n^{CAP} = 350$ kHz. This requires a special design where the S_2 scintillator is shaped to follow the curved surface on the constant TOF sphere. The specification of the TOF_p spectrometer proposed for the Ignitor measurements are given in Table II.

$\varepsilon = 1\times10^{-2}$ cm^2	detector efficiency
$\delta E_R/E \leq 5\%^*$	energy resolution
$C_n^{CAP} = 350$ kHz	count rate capability
$F_n^{MAX} = 3.5\times10^7$ n/scm^2	maximum neutron flux
$\chi = 0.07$	catching factor

Table II Parameter for TOF_p spectrometer for 2.5 MeV neutrons.
* Corresponds to Doppler broadening of D-ions at T_i=2.2 keV.

The studies of ignition plasma formation in Ignitor would entail lower neutron flux so that high detection efficiency ($\varepsilon = 10^{-3}$ cm^2) is a priority property for a complement to MPR. This can also be provided by the TOF method. For 14 MeV neutrons it is best to use a deuterated in-beam scintillator relying on $n+D_T \rightarrow n'+D$ scattering reaction in the back angle scattering geometry. The TOF_d spectrometer has been described earlier in a design for JET [24] and here the design should be adapted for operation with a narrowly collimated neutron beam (area A_c = 10 cm^2) so that it could share the beam line with MPR [15]. The TOF spectrometer can be operated with different combinations of resolution and efficiency. For Ignitor one could mainly consider operation in a high resolution mode. The corresponding specifications are given in Table III.

A suitable location for the MPR + TOF_D + TOF_p spectrometer system envisaged for Ignitor would be outside the bunker wall, at a distance of about 7 m from the plasma. A collimator (aperture $A_c = 10\ \text{cm}^2$ and length about $L_c = 2$ m) would provide an effective plasma viewing area of $A_p = 100\ \text{cm}^2$ through a diagnostic port of the machine (FIG. 4).

$\varepsilon = 7\times10^{-4}\ \text{cm}^2$	detector efficiency
$\delta E_R/E \leq 1.8\%^*$	energy resolution
$C_n^{CAP} = 80$ kHz	count rate capability
$F_n^{MAX} = 1\times10^8\ \text{n/scm}^2$	maximum neutron flux
$\chi = 0.03$	catching factor

Table III *Parameter for TOF$_d$ spectrometer for 14 MeV neutrons.*

** Corresponds to Doppler broadening of D+T-ions at T_i=2 keV.*

This would represent an adequate spatial resolution in the transverse direction and it would also satisfy the desire for high neutron fluxes ($F_n^{MAX} = 2 \times 10^{10}$ n/(s cm^2)) for the fusion yield at ignition $Y_n^{MAX} = 3 \times 10^{19}$ n/s) in order to exploit the count rate capability of the MPR spectrometer. All spectrometers can be located at the same port and collimation aperture. The remote location combined with the large information output (they provide information on both temperature and density) makes them quite acceptable for use in Ignitor on space economy grounds. Moreover, the neutron spectrometers suggested should be able to operate well within the experimental conditions around Ignitor. Although Ignitor may produce high radiation fluxes, the fluences should be rather limited by the short pulse lengths to be used. Therefore, the use of in-beam scintillators should be acceptable.

Although the MPR technique is most effective for 14 MeV neutrons, it could be used also for 2.5 MeV neutrons. A tandem MPR spectrometer system [25] could simultaneously measure the 2.5 MeV neutron minority flux (from d+d reactions in D-T plasmas) and the 14 MeV flux. Similarly, the MPR counter in the camera could be modified for use in the D-D phase operation, which is especially attractive for determining Y_n of D and D-T plasmas on the same footing.

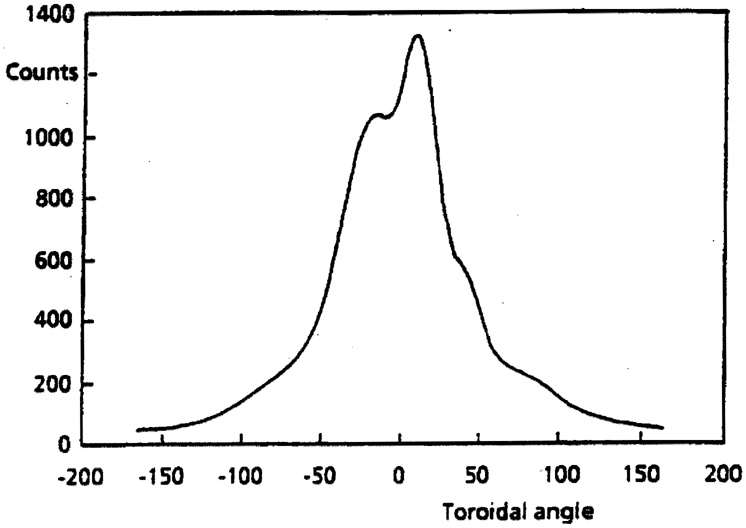

FIG. 1 Geometrical efficiency of one of the FTU fission chambers (^{235}U), obtained in the 1989 calibration, as a function of the location of the ^{252}Cf source in the torus. The fission chamber is located outside the FTU cryostat. The non-symmetric response of the detectors with respect to the toroidal location of the source is clearly evident.

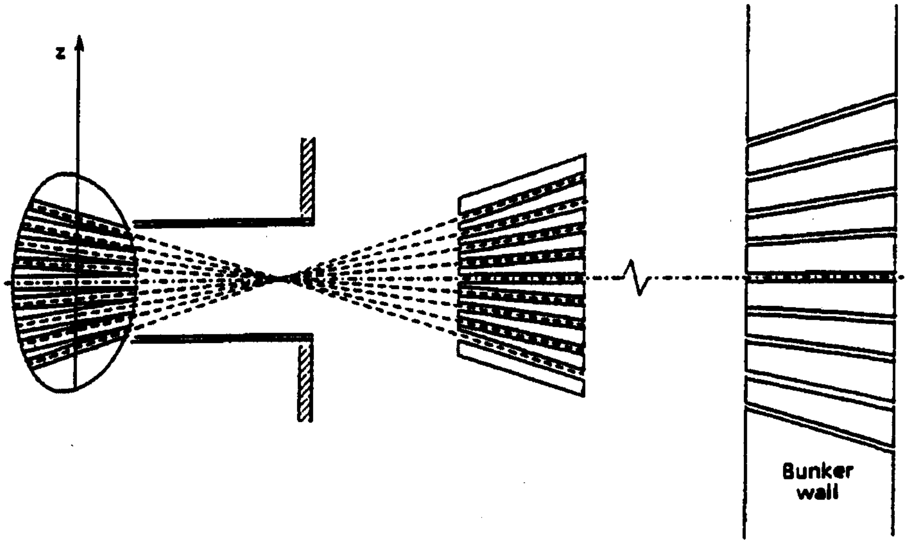

FIG. 2. Meridian cross section of the plasma, horizontal port and layout of the multichannel collimator.

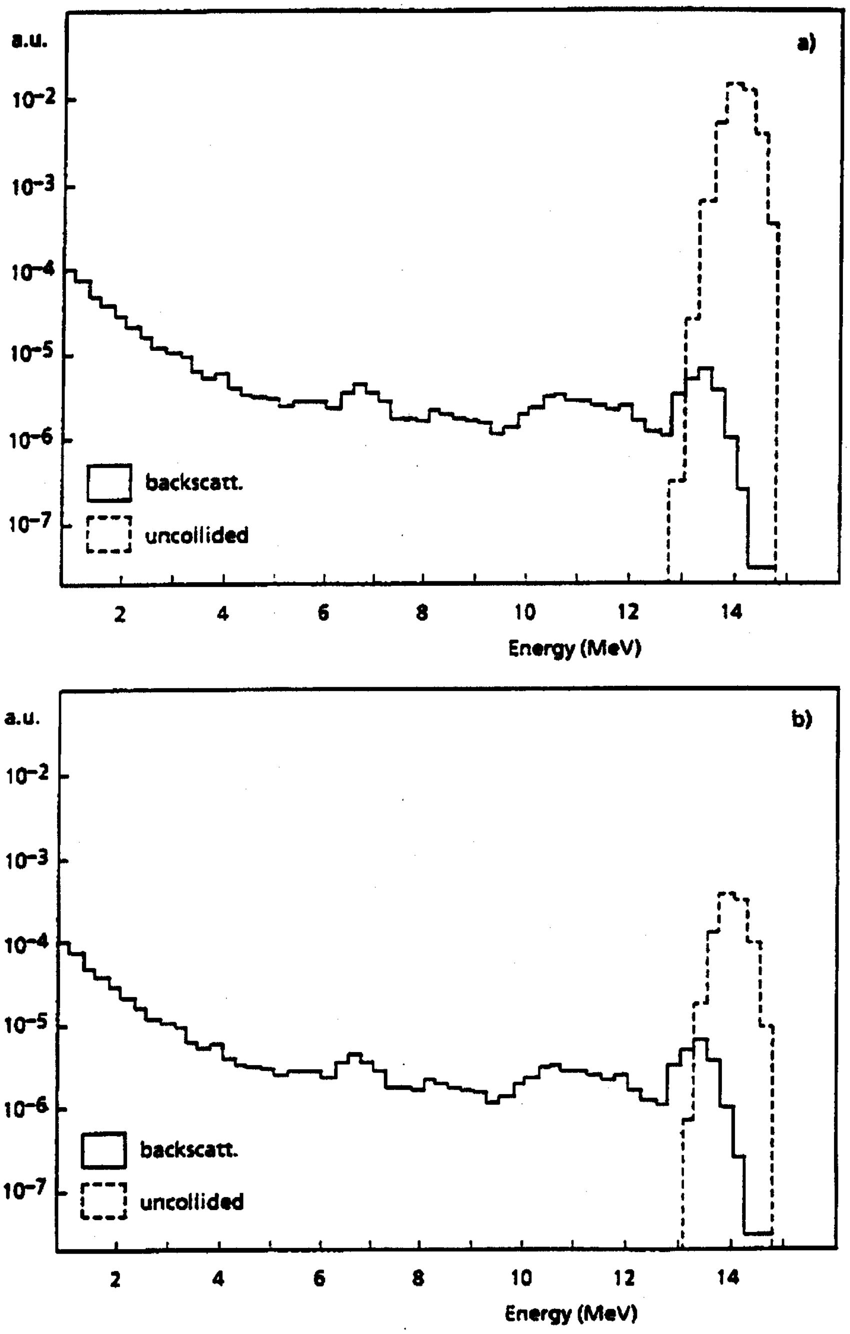

FIG. 3 Calculated energy spectra of neutrons impinging (a) in the central and (b) in the peripheral channel of the Ignitor multicollimator. The hatched line represents the uncollided flux from the plasma source with T=10 keV, while the solid line represent the flux backscattered from the inboard first wall.

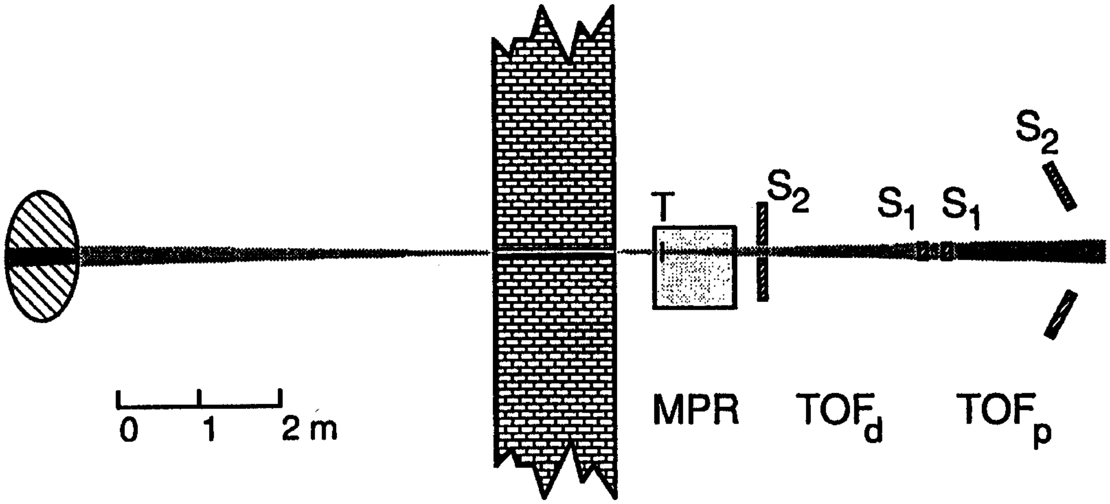

FIG. 4. Poloidal cross section of the plasma, the bunker wall and layout of the MPR+TOF_D+TOF_p spectrometer system.

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