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A time-of-flight neutron spectrometer is proposed for measurements of neutron energy spectra from deuterium-deuterium reactions in JT-60U tokamak plasmas. The sensitivity of the instrument is $2 \cdot 10^{-2} cm^2$, energy resolution is 4.5% (FWHM) and maximum useful count-rate is 6 kHz. Analysis of neutron energy spectra will provide information on central ion temperatures larger than $\sim$ 4 keV with an accuracy of ± 10%, and neutron source fraction from reactions between thermal ions with an accuracy of ± 15%. The minimum time required for data acquisition is 0.1 s.

Keywords: Magnetic Fusion Plasmas, JT-60U, Neutron, Plasma Diagnostics, Energy Spectra, Time-of-flight Spectrometer

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** STA fellowship

ＪＴ－60Ｕ用飛行時間法による中性子スペクトロメーターの設計に関する研究

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（1993年5月19日受理）

重水素放電を行うＪＴ－60Ｕトカマクプラズマにおいて，中性子エネルギースペクトル測定用に飛行時間法による中性子スペクトロメーターを設計した。この装置の感度，エネルギー分解能，使用可能な計数率はそれぞれ 2×10^{-2} cm^2，4.5％(FWHM)，6kHzとした。中性子エネルギースペクトルにより，約4keV以上の中心イオン温度の情報と熱化したイオンとの反応による中性子の割合の情報はそれぞれ±10％，±15％の精度で得られる。データ収集に必要な最小時間は，0.1secである。

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1 INTRODUCTION

Neutron energy spectra from reactions in fusion plasma experiments carry information about the energy distribution of the reacting ions. Depending on the heating method employed; ohmic, deuterium Neutral Beam Injection (NBI) or Ion Cyclotron Resonance Frequency (ICRF) heating, different ion distributions emerge, which is reflected in the shape of the neutron energy spectra. A special case is Maxwellian plasmas for which the ion temperature is given by the width of the gaussian shaped neutron energy spectrum. Although different kinds of heating are often used simultaneously, the effect on the neutron energy spectra are discussed in section 2 in a separate form.

Spectrometers based on the $^3He(n,p)T$ reaction are commonly used for spectroscopic measurements of neutrons in the energy range from 0.5 to several MeV and measurements of neutron energy spectra at tokamaks have previously been performed, [1,2,3,4,5]. The technique provides an excellent energy resolution $\approx$ 80 keV, however, due to long integration time, the technique suffers from saturation at a total count-rate of approximately $4 \cdot 10^3$ cps. High sensitivity to thermal and epithermal neutrons limits the useful count-rate to approximately 200 cps. Thus, an integration time for a useful spectrum (consisting of $\approx$ 800 counts) is several seconds, which in practice means integration over several discharges. A different technique, based on time-of-flight (t-o-f) measurements of the neutrons interacting in two plastic scintillators, has been developed and used for several years at the JET tokamak, [6,7,8]. The lay-out and performance of this spectrometer is described in section 3. The maximum count-rate obtained is $17 \cdot 10^3$ cps, the sensitivity $5 \cdot 10^{-2}$ cm^2 and the resolution 110 keV. The spectrometer provides information about central ion temperatures and neutron source fractions from reactions between thermal ions.

It is the purpose of this report to outline a proposal for a spectrometer based on time-of-flight technique for measurements of neutron energy spectra at the JT-60U tokamak. A design, with two detectors, is proposed as described in section 4. Sensitivity and energy resolution have been calculated and the results are presented. Neutron flux conditions at a suitable location for the spectrometer, and thereby obtainable time resolutions, are discussed. Suggested arrangement of the detectors and shielding are described, and an outline for signal electronics, data acquisition and interpretations is provided. For the necessary work associated with completion of an operating spectrometer a number of tasks have to be performed. It includes numerical calculations, detailed design of detectors, performance tests, determination of response functions, design and construction of shielding and construction and installation of the instrument.

This diagnostic will provide direct information on central ion temperatures and neutron source contributions from thermal-thermal reactions with time resolutions between 0.1 and 2.0 seconds, as stated in the summary. In contrast to more conventional ion temperature diagnostics such as charge exchange recombination spectroscopy (CXRS) and X-ray crystal spectroscopy, neither neutral beams nor impurities need to be present. Supportive calculations of shapes of energy spectra, generated by reactions between beam-beam and beam-thermal ions, and adequate data fitting procedures, will be needed for spectrum analysis.

2 NEUTRON ENERGY SPECTRA

Depending on the heating methods employed; ohmic-, deuterium neutral beam- and ICRF heating, different energy spectra will be generated.

2.1 Maxwellian plasmas

In case of a pure Maxwellian plasma the resulting neutron energy spectra have a gaussian shaped distribution with a characteristic width equal to

$$\Delta E\ (\mathrm{keV,FWHM}) = k\bullet T_i^{1/2} \quad (T_i,\ \mathrm{keV}) \tag{1}$$

where k is 82.5 and 177.7 for deuterium and a mixture of deuterium and tritium plasma respectively, [9,10]. There is a weak temperature dependance in the value of k, [11]. With a spectrometer providing a resolution equal to or narrower than the width of the neutron peak, it is possible to evaluate the ion temperature from neutron spectral measurements. Because data collected in this type of measurement are line-of-sight integrated, a correction is needed for evaluation of central temperatures. Due to the reaction rate dependence on temperature and density, the integrated spectrum is heavily weighted towards the hottest and most dense part of the plasma. Contributions from outside this part generate a narrower spectrum. It has been estimated that the correction is 9 to 15 % [12,13], for cases with narrow radial lines of sight. The precise value depends on the ion temperature and the peaking factors of the temperature and density. Usually these quantities are known and the correction term can be determined with an accuracy of 30-50 %.

2.2 Deuterium beam heated plasmas

For deuterium plasmas heated with deuterium neutral beam injection, there are usually three different neutron source contributions. They originate from reactions

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2.3 Deuterium first harmonic ICRF-heated plasmas

Deuterium plasmas heated by first harmonic ICRF generate energy tails with perpendicular ion temperatures, $T_{\perp}$, ranging from the bulk ion temperature to several hundred keV [16]. By employing a perpendicular viewing direction for the neutron spectrometer it may be possible to evaluate the high energy deuteron tail. This is of particular importance for assessment of the deposition of the ICRF power. Furthermore, reactions between fast deuterons and impurities generate gamma events in the MeV range [17], which show the presence of both fast deuterons and impurities [8].

3 T-O-F NEUTRON SPECTROMETER AT JET

A spectrometer based on time-of-flight technique with an energy resolution $\Delta E/E=$ 4.5%, used at the JET tokamak, has shown to be very reliable and sensitive (≈ 0.05 cm^2) and provides high count-rates (up to 17 kHz). This has permitted detailed studies of neutron energy spectra to a degree which was not previously possible. Details of the instrument are given in fig.1 and in refs.[6,7,8]. Some results from measurements with different fuel ion distributions are reported here.

3.1 Thermonuclear plasmas

Good examples of Maxwellian plasmas at high ion temperatures are those heated by ^{3}He-neutral beams and ICRF (^{3}He-minority) heating. Neutrons are generated with thermonuclear origin and possess a gaussian energy distribution. This is utilized for evaluation of ion temperatures and for comparisons with results from more conventional ion temperature diagnostics. Fig. 2a) shows a neutron energy spectrum from an between different ion distributions i.e. thermal-thermal (tt), beam-thermal (bt) and beam-beam (bb) ions. The beam ion distribution function can be calculated [14], and folded with the thermal- or the beam-distribution itself and the corresponding neutron energy spectrum is computed [11]. Calculations include a solution to the Fokker-Planck equation for the beam ion velocity distribution and the use of relativistic kinematics and anisotropic reaction cross sections. Measured spectra may then be compared with the pre-calculated spectra and information can be obtained about the fractional contributions from reactions between tt-, bt- and bb-ions [15]. Because a high number of degrees of freedom is involved, independent information e.g. on the ion temperature, has to be provided from some other diagnostic. For discharges with high densities and low temperatures, the proportion of bb-reactions may be negligible and the ion temperature and tt-fraction can usually be determined solely from neutron energy spectra.

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ICRF(^{3}He)- and ^{3}He-neutral beam heated deuterium plasma, together with a gaussian shaped distribution fitted to the data, yielding an ion temperature equal to 7.7±0.9 keV. In fig. 2b-c) are the absorbed ICRF power and neutron yield for the same discharge shown. Fig. 2d) shows, for comparisons, the ion temperature measured by X-ray crystal spectrometry [18], full line, and the ion temperature evaluated from neutron t-o-f spectrometry measured with 0.5 s integration times.

3.2 Deuterium beam heated plasmas

Whenever high power deuterium neutral beams are employed for heating of deuterium plasmas, the neutron emission is enhanced by one to two orders of magnitude. Under such conditions, high useful count-rates have been achieved with the time-of-flight spectrometer [8]. Through analysis of such spectra together with information from other diagnostics on densities and temperatures, quantities like the tt-neutron source fractions (and thermal Q_{DD}), ion temperature and deuterium concentration can be determined. Results from plasmas heated with different techniques are compared with results from CXRS, with good agreement as shown in fig. 3.

3.3 Deuterium second harmonic ICRF-heated plasmas

Heating of deuterium with ICRF at its second harmonic cyclotron resonance frequency may produce fast deuterons depending on the hydrogen and deuterium concentrations and temperatures [16,19,20]. Reactions will then occur between thermal-thermal, fast-thermal, fast-fast and fast- and impurity ions, generating a complex neutron energy spectrum. However, the population of the fast ions is expected to be small leading to a negligible contribution to the neutron yield from reactions within itself.

With carbon and beryllium as the main impurities there are probabilities for additional reactions between fast deuterons and these impurities, leading to neutrons in the few MeV energy range. The cross-sections for reactions of interest are given by refs. [21,22]. Presence of both high energy deuterons (i.e. $E_D > 1$ MeV) and a large density of impurities ($n_{imp.} \approx n_D$) are necessary if a significant fraction of neutrons from such reactions is to be generated.

Analysis of gamma energy spectra provides an estimate of the energy distribution of the fast deuterons [17], and data from Z_{eff} measurements give a measure of the impurity densities. Thus, by combining neutron and gamma diagnostics, an estimate can be made of the fraction of neutrons generated by fast deuterons reacting with impurities. For illustrative purposes, results from two ICRF-heated discharges with similar heating power (≈ 10 MW), but significantly differing in density and Z_{eff}, have been studied.

Fig.4 shows neutron- and γ-energy spectra for a discharge with low density and high Z_{eff}, while fig.5 shows the corresponding results for a discharge with high density and low Z_{eff}. Due to the apparent large amount of non thermal reactions for discharge #25920, difficulties occur when analyzing the neutron energy spectrum. However, assuming there is a thermal peak on top of a non thermal background, analysis of the peak width gives a temperature $T_i = 7.1 \pm 1.9$ keV. This is in broad agreement with the result provided by the crystal spectrometer providing $T_i = 7.9$ keV. The γ-energy spectrum in fig.4b) shows presence of both ^{12}C ions and fast deuterons. This suggests that there is a large fraction of neutrons from fast deuterons reacting with thermal fuel or impurity ions, consistent with the observation that $Z_{eff} \approx 6.5$. The neutron source fraction from reactions between thermal deuterons is estimated to 10±3 %.

A different situation occurs for the discharge #25117 for which the neutron spectrum has a nearly gaussian shape, but with a weak tail formation at high energies, see fig.5a). Analysis yields a tt-fraction equal to 84±1 %. The measured γ-spectrum, fig.5b), shows low intensities of reactions between fast deuterons and impurities such as ^{12}C and ^{9}Be. This being consistent with the low value of $Z_{eff} \approx 1.3$). For further details of this study see ref. [23].

4 PROPOSED SPECTROMETER.

A further developed Time-of-Flight neutron spectrometer is proposed for JT-60U. The design is based on previous and current work on model and Monte-Carlo calculations on energy resolution and sensitivity and tests of a prototype [24].

4.1 Spectrometer performance.

The spectrometer, shown in figs. 6a) and 6b), has one first detector and one long second detector. Preliminary model and Monte-Carlo calculations yield an energy resolution $\Delta E/E$ equal to 110 keV (FWHM), see fig.7, and a maximum sensitivity of $2 \cdot 10^{-2}$ cm^2. The energy resolution of the spectrometer can be calibrated to 1.2% accuracy (FWHM) by using a narrow energy neutron source (i.e. ≈ 70 keV (FWHM)) and more than 10^4 events. This in its turn enables ion temperatures larger than ≈ 4 keV to be evaluated with an accuracy better than 10% (FWHM) with only 800 counts per spectrum. For the evaluation the expression on ion temperature accuracy in ref. [25] has been used. Estimated count-rates in the first detector and spectrum integration times are given in Table 1.

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4.2 Detectors and signal electronics.

Both detectors utilize fast plastic scintillators. D_0 has a maximum dimension of 5•10•2 cm^3, and its cross-section area, A_0, is determined by maximum acceptable count-rate in D_0 ($\approx 10^6$ cps) and required energy resolution. This provides value of A_0 from 5 to 50 cm^2. The detector is equipped with a 5" diameter photomultiplier tube (PMT,*3) and the scintillator is optically coupled with the 10•2 cm^2 side directly to the PMT. The second detector, D_1, consists of a long scintillator with the dimensions 60•30•2 cm^2, two PMT's, and a mean-timing system as shown in fig. 8. Ongoing investigations of different arrangements is expected to result in detailed proposals for suitable detector and light-guide configurations in the near future [24].

The signal scheme is shown in fig.8. The first detector has a simple fast timing circuit with a differential constant fraction (CFDD) timing unit. Exchange between at least two different scintillator sizes, in order to maintain count-rates close to maximum for different neutron fluxes, should be prepared for. The second detector has a fast timing circuit (with the mean-timing unit, MT) for determination of the timing pulse, and a slow coincidence circuit for amplitude discrimination. In order to maintain the high voltages in the PMT's during high count-rates, their voltage dividers should all be of the stabilized type as described in ref. [26].

4.3 Radiation shielding

Good shielding against neutron and gamma background radiation is of vital importance for successful operation of the spectrometer. The background radiation of neutrons (0.5 MeV $< E_n <$ 4.0 MeV) and gammas (0.05 MeV $< E\gamma <$ 1.0 MeV) must not exceed $1 \cdot 10^3$ $(n+\gamma)/(cm^2 \cdot s)$ at the position of the D_1 detector. It is proposed to utilize the existing shielding of neutron detectors, as shown in fig.9a) and b). The second detector of the spectrometer is then located at a larger major radius than this shield. The detailed design of the shielding has to be determined after evaluations of the radiation background. A collimator insert with the dimensions 5•7 cm^2 has to be used in the 10 cm diameter penetration tube. Other penetrations have to be filled with shielding material to reduce background radiation to a minimum.

4.4 Issues to be addressed

Issues to be considered are given in Table 2. The first point refers to previous and ongoing work [24]. Light collection capabilities, energy resolution and sensitivities for

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*3 R1250, Hamamatsu Photonics K.K., Shizuoka-ken, 438-01 Japan.

different configurations are under investigation. The effects of different scintillator shapes and coatings and optical connections between scintillators and PM-tubes are studied. The aim of this work is to provide a general design of such a spectrometer to be suitable for medium and large sized tokamaks.

The second point refers specifically to the version of the neutron detectors aimed for JT-60U. Included are the selection of the PM-bases to be used and shape and thickness of magnetic shielding. Knowledge of the response functions will be necessary for evaluation of the measured neutron energy spectra and can be obtained by Monte-Carlo calculations. However, experimentally determined response functions for different geometries are desired for checking the validity of the Monte-Carlo code.

The third point regards the design and construction of the radiation shielding. The design should be done in close collaboration with engineers at JT-60U. The fourth point deals with the installation and primary tests at the JT60-U tokamak.

The fifth point deals with the modification of existing codes for the numerical calculations of neutron energy distribution from Maxwellian, beam- and ICRF-heated plasmas. These distributions functions may then be folded with the Monte-Carlo calculated response functions and the results compared with measured spectra. A fitting procedure then yields the ion temperature and the fractions of t-t, b-t and b-b neutrons generated in the plasma.

The last point deals with operation of the complete system. Ion temperatures and tt-neutron source fractions will be the essential results of the analysis.

5 SUMMARY

Analysis of energy spectra of neutrons generated in fusion experiments, provide information on ion temperatures and neutron source fractional contributions from reactions between thermal ions. A self contained time-of-flight neutron spectrometer consisting of two scatter detectors and thirty receiving detectors is used at the JET tokamak. The instrument yields a sensitivity of $5 \bullet 10^{-2}$ cm^2, an energy resolution $\Delta E/E$ = 4.5% (FWHM), a maximum count-rate of 17 kHz and a potential time resolution equal to 40 ms. Obtained results have been compared with results from other diagnostics usually with good agreement.

A further developed version of the time-of-flight spectrometer is proposed for usage at the JT-60U tokamak. The instrument consists of two detectors, one small scatter detector and one long receiver detector. Maximum sensitivity is equal to $2 \bullet 10^{-2}$ cm^2, energy resolution equal to 4.5%, and a maximum count-rate is 6 kHz which would give a time resolution equal to 100 ms. It is suggested to use a replaceable scatter detector in

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Together with an evaluation procedure, e.g. based on neural network principles, and pre-programmed neutron energy spectra, this diagnostics can provide ion temperatures with an accuracy better than ±10% and neutron source fractions from thermal ion reactions with an accuracy equal to ±15% in 0.1 s time intervals.

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Table 1 Spectrometer count-rates and integration times.

ΔE = 110 keV (FWHM) and sensitivity, $\varepsilon_{ff} = A_0 \cdot 4 \cdot 10^{-4}$ cm^2.

n-yield (n/s)	Γ_n 1) (n/(cm^2•s))	A_0 (cm^2)	D_0 count-rate (cps)	Useful count-rate N_s, (cps)	Δt for one spectrum (s)
$5 \cdot 10^{14}$	$1.3 \cdot 10^4$	50	$1.3 \cdot 10^5$	$3 \cdot 10^2$	2.0
$1 \cdot 10^{15}$	$2.5 \cdot 10^4$	50	$2.5 \cdot 10^5$	$6 \cdot 10^2$	1.0
$5 \cdot 10^{15}$	$1.3 \cdot 10^5$	50	$1.3 \cdot 10^6$	$3 \cdot 10^3$	0.2
$1 \cdot 10^{16}$	$2.5 \cdot 10^5$	50	$2.5 \cdot 10^6$	$6 \cdot 10^3$	0.1
$5 \cdot 10^{16}$	$1.3 \cdot 10^6$	5	$1.3 \cdot 10^6$	$3 \cdot 10^3$	0.2

1) The conversion factor between total neutron emission and flux at D_0 is set equal to $2.5 \cdot 10^{-11}$.

Table 2 Issues to be addressed.

Tasks	Remarks
1. Calculations and tests of light collection and timing properties of a large scintillator. Design of a prototype for test purposes. Performance tests of light collection and timing with a γ-source. Tests of energy resolution with a neutron generator. Determination of response functions for a few energies. Compare results from Monte-Carlo calculations for energies from 1.5 to 5.0 MeV.	Ongoing work, [24]. Results estimated at the end of 1993.
2. Design for a JT-60U version. Construction of scintillator and photomultiplier housing and detector holders. Performance tests with a γ-source and possibly also a neutron generator. Determination of response functions.	
3. Design and construction of shielding and supports.	
4. Installation at JT-60U. Tuning and operational tests. Writing and testing of Camac control software. Writing and testing of analysis software.	
5. Implementation of a neutron spectral calculation code such as FPS.	
6. Measurements of neutron energy spectra. Analysis of ion temperatures, neutron source contributions and high energy tails in NBI and RF heated plasmas.	

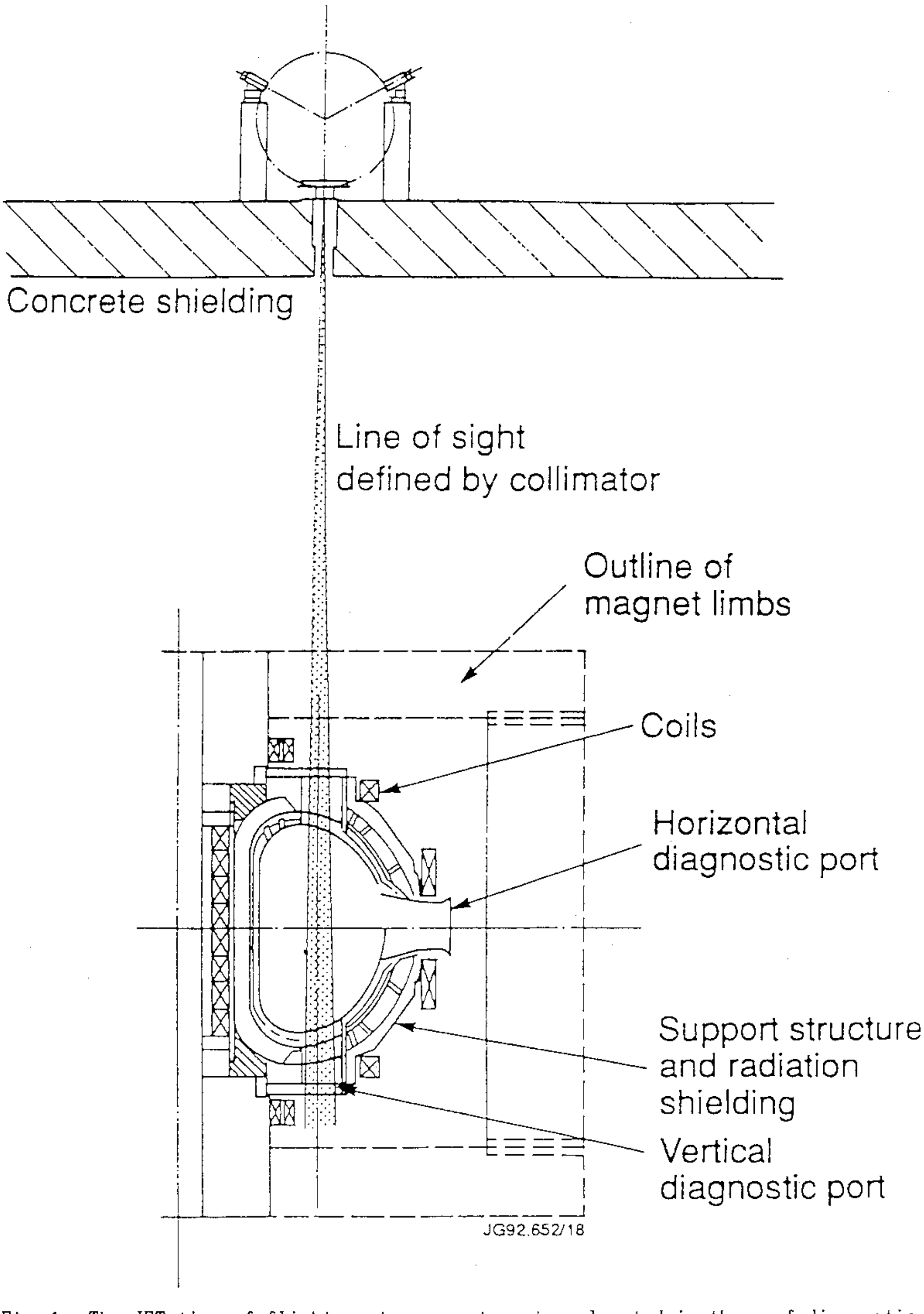


Fig. 1 The JET time-of-flight neutron spectrometer, located in the roof diagnostic hall, and the line-of-sight are shown relative to the torus.

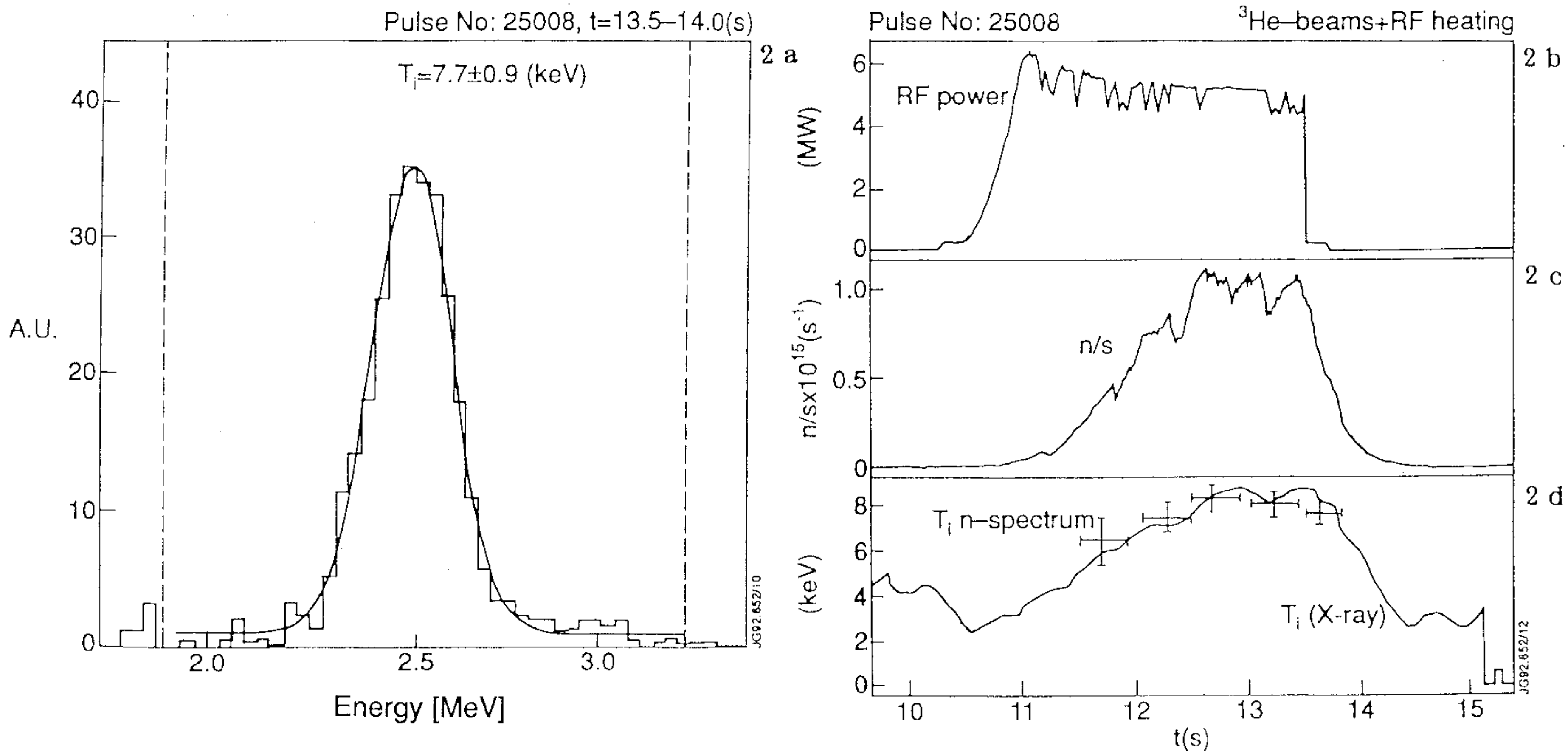


Fig. 2 Some characteristics of a deuterium plasma heated by ^{3}He-beams and ICRF(^{3}He). Shown are in: a) a neutron energy spectrum measured by the time-of-flight spectrometer, b) absorbed ICRH power, c) neutron emission and d) ion temperatures evaluated from X-ray crystal spectrometer (full line) and neutron energy spectra.

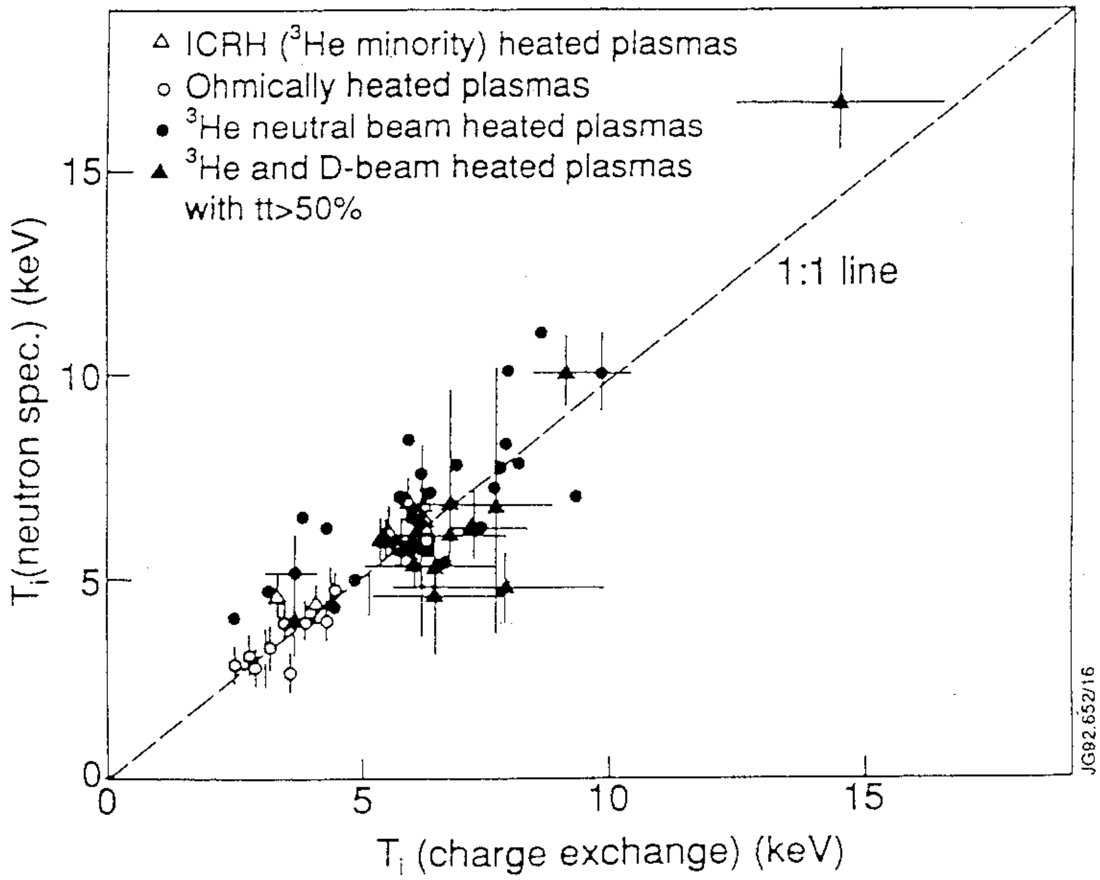


Fig. 3 Comparisons between ion temperatures evaluated from neutron energy spectra, obtained with the time-of-flight spectrometer, and from Charge Exchange Recombination Spectroscopy (CXRS) for plasmas under different heating conditions.

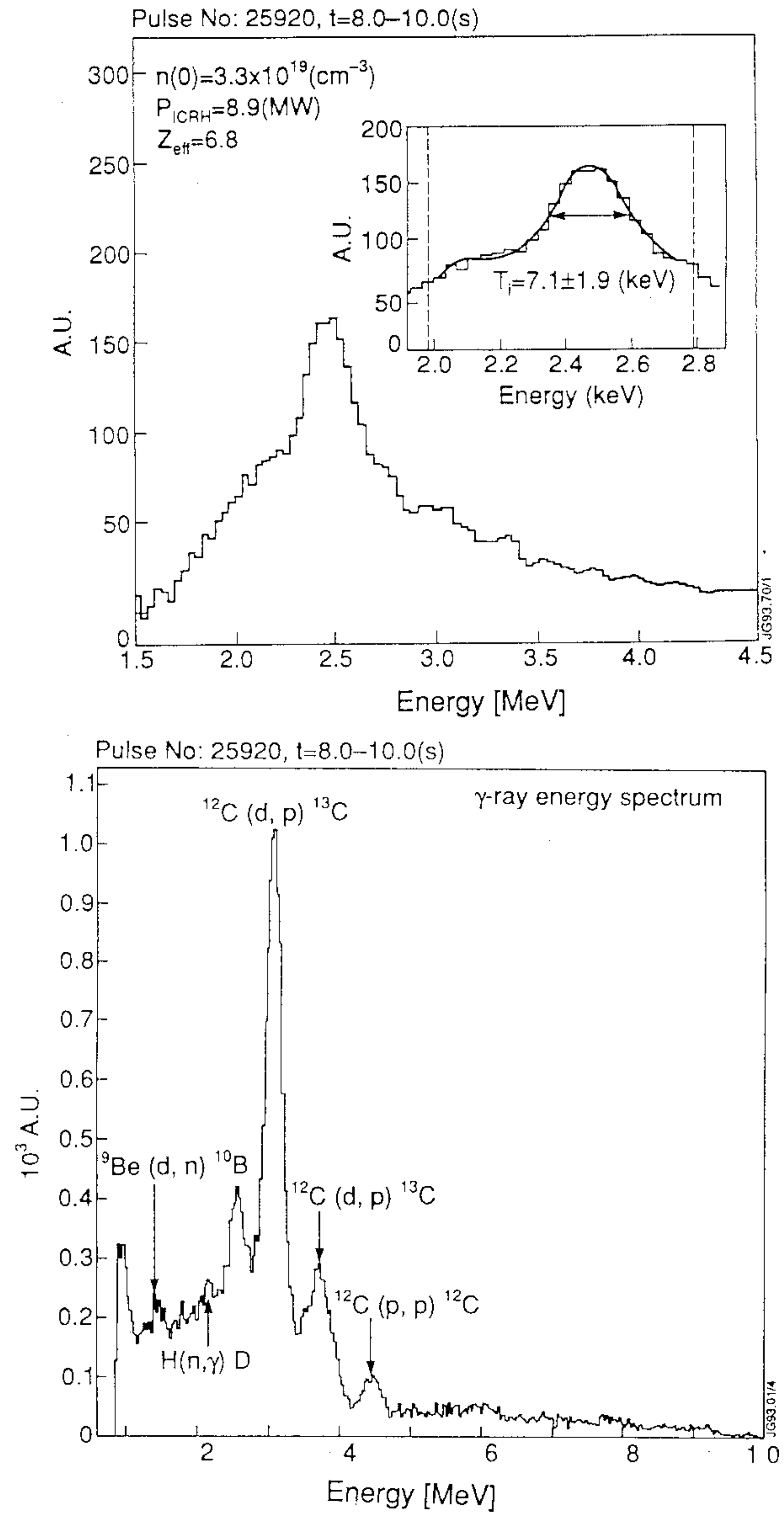
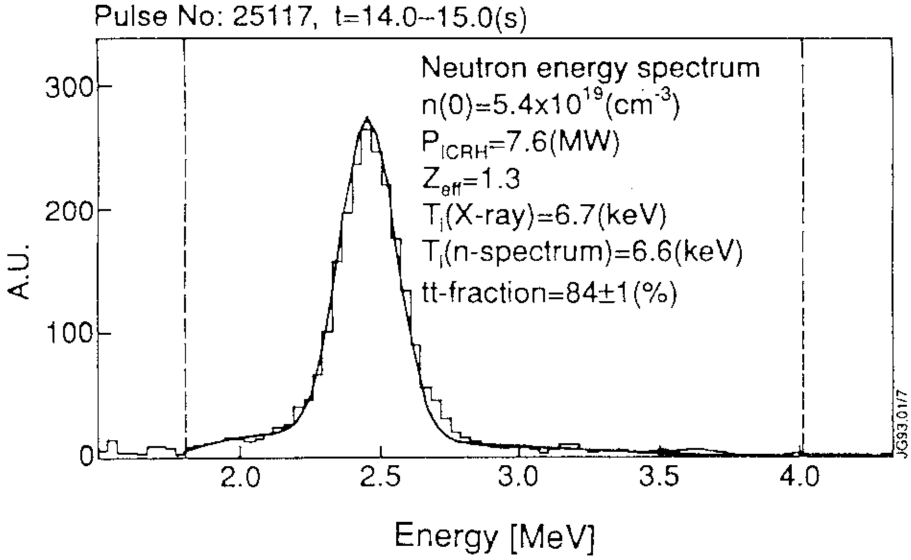


Fig. 4 a) The broad neutron energy spectrum indicates presence of fast deuterons. b) γ-ray energy spectrum shows presence of fast deuterons (E_d > 1.8MeV) and of carbon ions through the reactions $^{12}C(d,p)^{13}C+\gamma$ and $^{12}C(p,p')^{12}C+\gamma$.



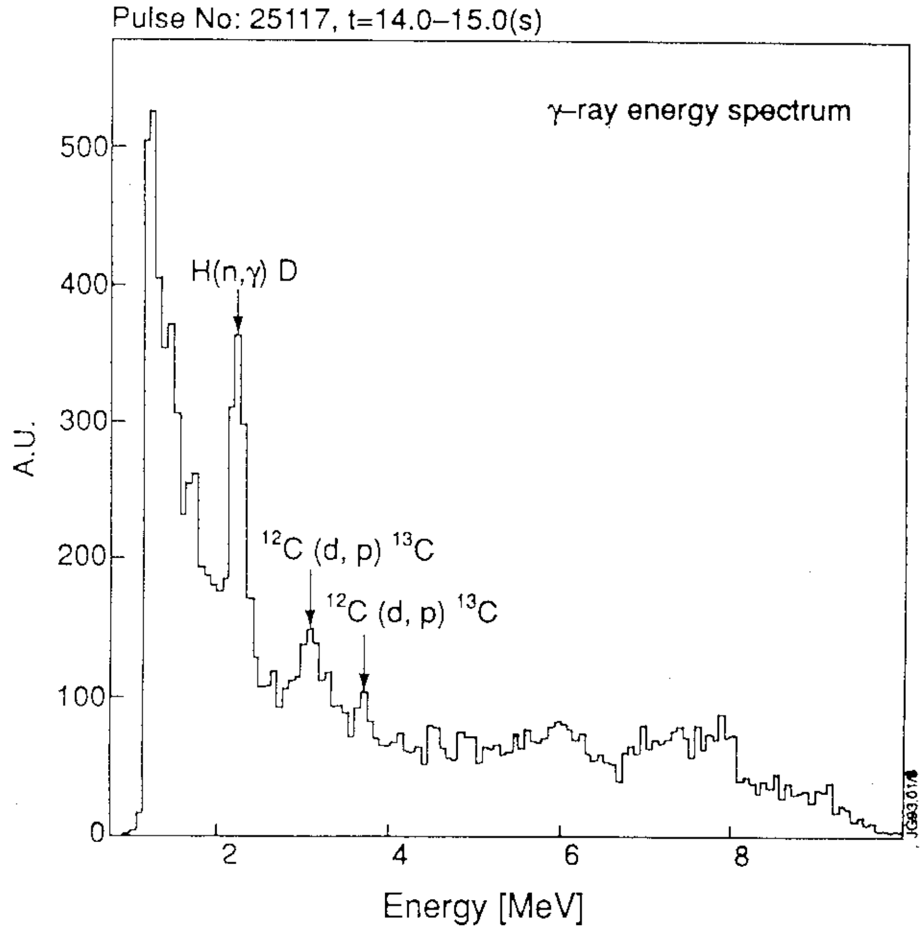


Fig. 5 a) The narrow neutron energy spectrum allows analysis of neutron source fractions yielding a tt-fraction of 84± 1% with an ion temperature equal to 6.6 keV. b) γ-energy spectrum shows only small traces of $^{12}C(d,p)^{13}C+\gamma$ and $^{12}C(p,p')^{12}C+\gamma$ reactions.

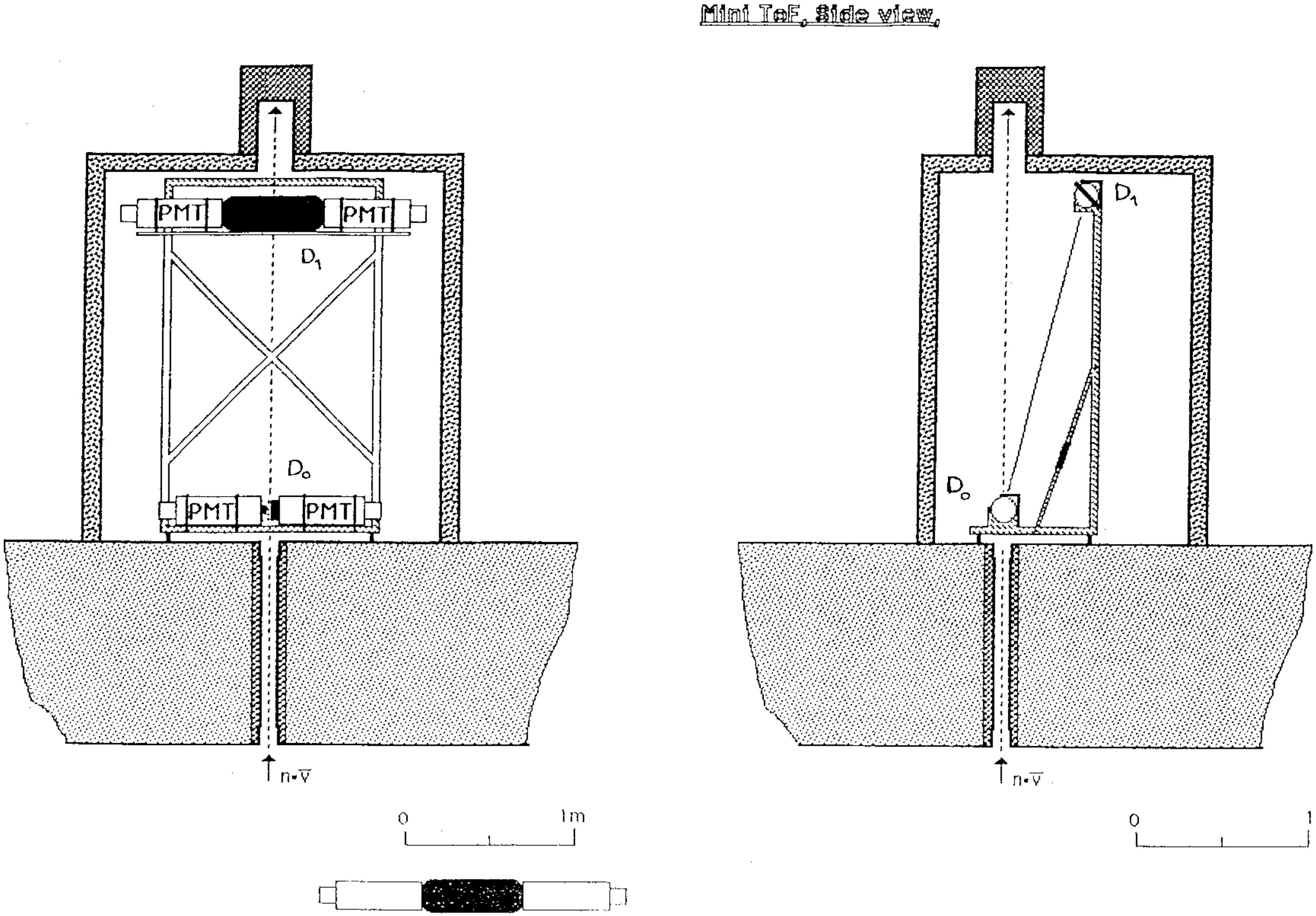


Fig. 6 Detector arrangement, for a t-o-f spectrometer at JT-60U, with the scatter detector D_0 (dimensions 5・10・2 cm³) and receiving detector D_1 (dimensions 60・30・2 cm³) shown in a front view a) and a side view b).

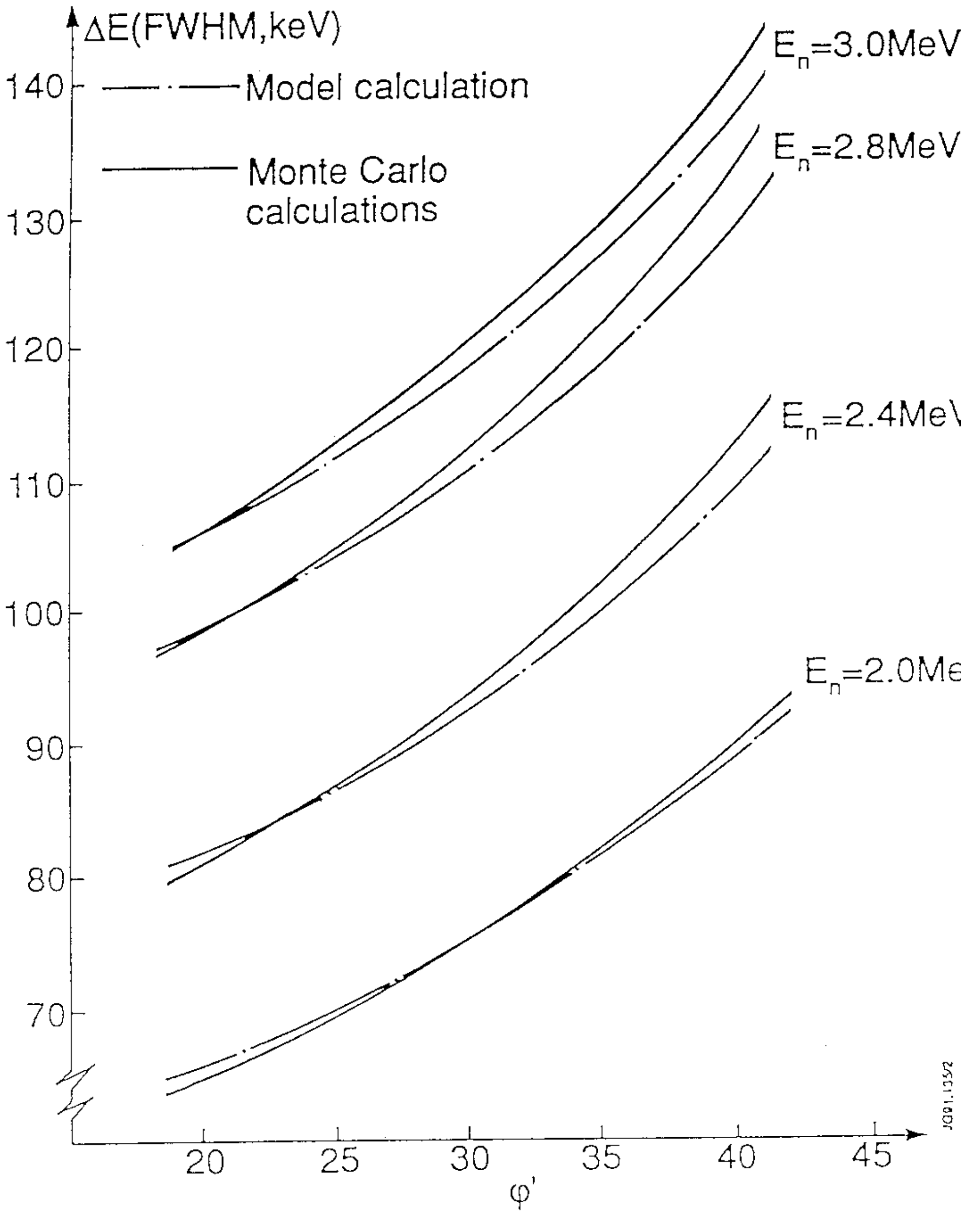


Fig. 7 Energy resolutions (FWHM) obtained with model (－･－) and Monte－Carlo calculations (—) are shown as function of scattering angle for several energies.

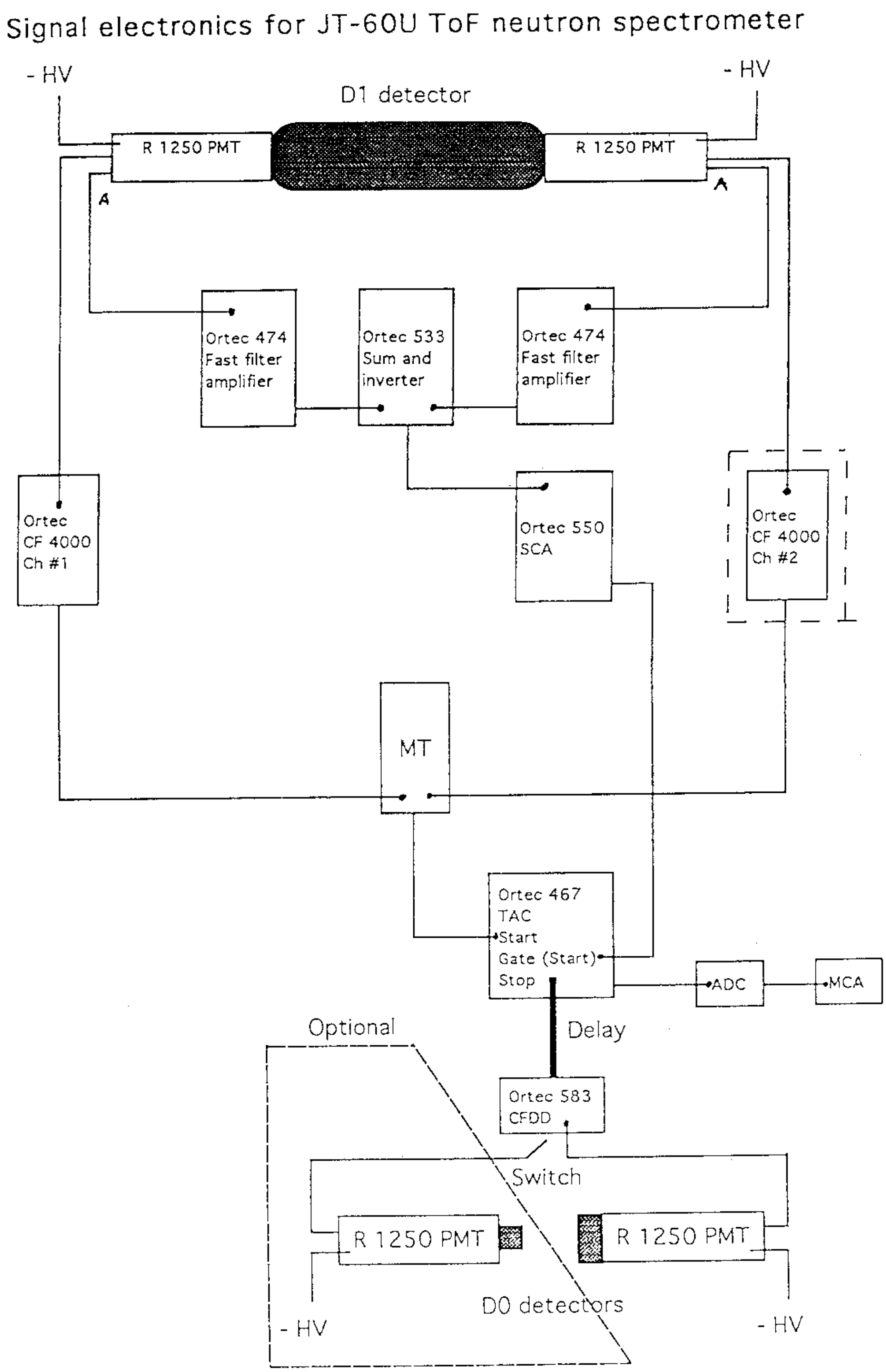


Fig. 8 Signal electronics are shown. The following notations are used: PMT-photomultiplier tubes, SCA-single channel analyzer, CF-constant fraction discriminators, CFDD-constant fraction differential discrimination, MT-mean timer unit and TAC-time to amplitude converter.

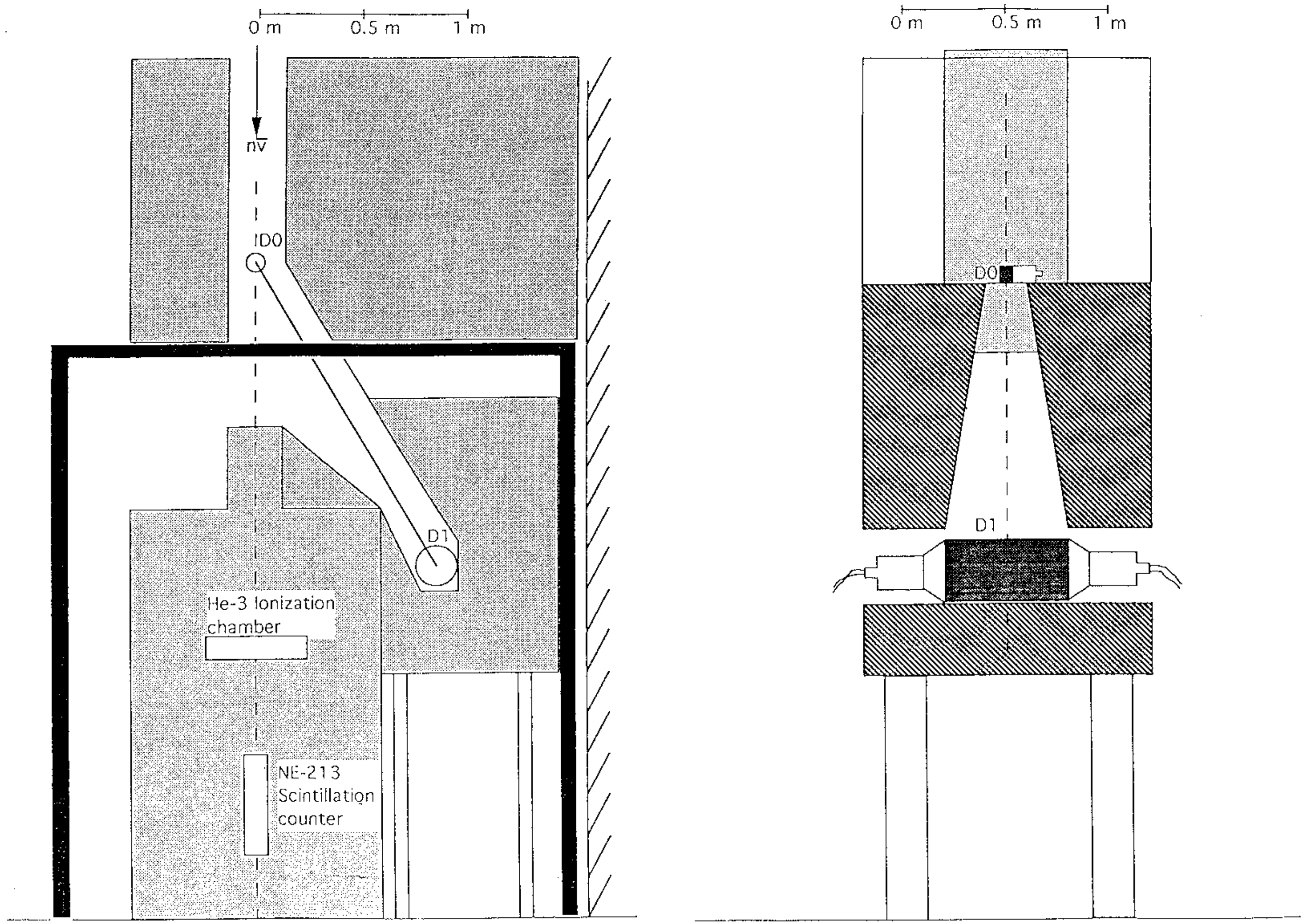


Fig. 9 A lay out of detectors and shielding arrangements are shown in relation to the vertical line-of-sight and the existing shielding for installed neutron diagnostics. a) side view and b) front view.