JAERI-M
83-146

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September 1983

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編集兼発行　日本原子力研究所
印　　刷　日立高速印刷株式会社

Mass Separated Neutral Particle Energy Analyser

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(Received August 12, 1983)

A mass separated neutral particle energy analyser which could simultaneously measure hydrogen and deuterium atoms emitted from tokamak plasma was constructed. The analyser was calibrated for the energy and mass separation in the energy range from 0.4 keV to 9 keV. In order to investigate the behavior of deuteron and proton in the JFT-2 tokamak plasma heated with ion cyclotron wave and neutral beam injection, this analyser was installed in JFT-2 tokamak. It was found that the energy spectrum could be determined with sufficient accuracy. The obtained ion temperature and ratio of deuteron and proton density from the energy spectrum were in good agreement with the value deduced from Doppler broadening of TiXIV line and the line intensities of H_α and D_α respectively.

Keywords: Neutral Particle, Energy Analyser,
Ion Cyclotron, Plasma Heated
JFT-2, Tokamak, Ion Temperature
Deuteron, Proton, Calibration

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質量分離型中性粒子エネルギー分析器

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（1983年8月12日受理）

トカマクプラズマから放出される水素と重水素原子を同時に測定可能な質量分離型中性粒子エネルギー分析器が製作され，0.4 KeV～9 KeV のエネルギー範囲で質量とエネルギーに関して較正を行った。そしてイオンサイクロトロン波及び中性粒子ビームの入射によって加熱されたＪＦＴ－２トカマクプラズマにおける重陽子及び陽子の振舞いを調べるために，本分析器をＪＦＴ－２トカマクに装着し，十分な精度をもって各エネルギースペクトルを決定した。またエネルギースペクトルから定められたターゲットプラズマのイオン温度及び，重陽子と陽子との密度比はそれぞれ Ti XIV ラインのドップラー幅からのイオン温度及びH_αとD_αの強度比からの値と一致した。

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1. Introduction

The measurement of charge-exchanged neutral particles emitted from JFT-2 tokamak plasma[1] had been made by an electrostatic energy analyser[2]. Recently JFT-2 tokamak machine have been operated with two kinds of working gas of hydrogen and deuterium in the ion cyclotron resonance heating[3] and neutral beam heating[4]. We have need of the mass separated neutral particle energy analyser for investigating the behavior of each species in these mixed plasma.

Up to this time, the mass separated neutral particle energy analyser which consisted of momentum analyser and cylindrical electrostatic energy analyser were used in the PLT[5] and T-10[6] tokamaks. This type of analyser was not able to detect equal mementum particles at the same time. In addition the mass separation of this analyser was not perfectly performed because mass separated particles which were reflected at the deflection plate entered the detector. Accordingly we have constructed E// B type mass separated neutral particle energy analyser (hereafter abbreviated to E// B type analyser) which removed the above mentioned weak points.

The operation principle of E// B type analyser is similar to one proposed by R. Kaita and S.S. Medley[7]. The proposed method was that analysing magnetic field and electrostatic field were superimposed both in the same space and in the same direction. A large gap space of magnet york was necessary for the mass separation. Therefore the capacity of magnetic coil became large and the magnetic leakage flux disturbed the ion orbit in the region outside of analysing field. Then we separated the electric field from the region of magnetic field. The similar method was also proposed by R. Kaita et al.[8] But their method had the deflection plate of complicate shape. As a result, the determination of the shape of deflection plate and detector position was very difficult. Accordingly, in order to simplify the analyser construction and design, we adopted another configuration that the energy analysis and the mass separation were performed by the 180° bending magnet and the deflection plate of simple shape respectively.

Purposes of the present work are to confirm experimentally its main characteristics and the capability of determining ion temperatures and measuring the behavior of each ions on the further heated JFT-2 tokamak plasma.

A description of principle and structure of E//B type analyser are presented in Section 1. Section 2 describes the calibration experiment method and result and Section 3 presents the measurement on the JFT-2 tokamak heated by the neutral beam and ion cyclotron wave. Section 4 is devoted to the some discussions on this E//B type analyser and the summary of this paper is given in the last section.

2. Description of Mass Separated Neutral Particle Energy Analyser

Fig. 1 shows a schematic diagram of the analyser which consists of a stripping cell, a bending magnet, deflection plates and ion detectors. The stripping cell is 20 cm in length and 5.3 cm in bore with enterance/exit apertures in the form of cylindrical channels, whose diameters are 2 mm and 4 mm, respectively, and each of length 2 cm. The wave-shaped and black-coloured inner surfaces of entrance/exit apertures of stripping cell prevent scattered particles and photons on the inner surfaces from entering analyser. The stripping cell is operated with hydrogen gas at a few mTorr and is pumped out with a 500 ℓ/sec turbomolecular pump. A drift pipe connecting the analyser to JFT-2 device is also pumped out with a sputter ion pump of 80 ℓ/sec. During operation the analyser chamber is maintained at a pressure of two-orders of magnitude less than that of the stripping cell.

The detailed figures of plane and section of the analyser are shown in Fig.2 and Fig.3, respectively. The 4 cm thick iron walls of the vacuum chamber provides both the return yoke for the magnet as well as shielding against the magnetic field in the environment of the JFT-2. The attained shielding factor for the stripping cell with μ metal and iron walls is 3800.

The entering path to the magnetic field is electrostatically shielded with stainless steel against the electric field coming from the adjacent deflection plates. The 180° bending magnet provides a maximum field of 4 kG in a 1 cm gap between the pole faces. The neutral particles which are not ionized in the stripping cell and photons which are emitted from plasma are absorbed by the viewing damp. The viewing damp consists of curved plates of stainless steel. The electrostatic deflection plates consists of two parallel plates. The upper and lower deflection plates are supplied with the positive and negative voltage. The width of the deflection plate is designed to provide the equal transit time for the ions passing through the deflection plates.

Ions entering the magnetic field follows the Larmor orbits according to $mV/R = qB$ for a ion of mass, m charge, q and velocity, V, which R is the Larmor radius, and B is the strength of the magnetic field. The Larmor radius R (cm), for a particle of charged number, Z, mass, A (AMU) and energy, E (eV) satisfies the equation

$$R^2 = 2.088 \times 10^4 \frac{A}{Z^2} \frac{E}{B^2} \quad (1)$$

where B is the magnetic field strength in Gauss. The analyser has 10 channels; the upper 5-channel detectors receive deuterium ions and the lower detectors hydrogen ions. In deuterium channels, the 2nd to 5th channels detect the ions with the energy 2, 3, 4 and 5 times as much as the 1st channel, respectively, and hydrogen channels are arranged in the same way.

Ions enter the electric field between deflection plates after emerging from the magnetic field. The mass analysis is performed with this electric field for the ions of the same momentum. In Fig.4, the displacement Z of ions towards the direction of electric field is given by the following equation

$$Z = \frac{eV}{4E} y_1 (y_1+2y_2) \quad (2)$$

where V is the strength of electric field y_1 and y_2 are flight path in the electric field and free space respectively. The ions with defined mass and energy enter ion detectors. However in order to perform a sufficient mass separation between deuterium and hydrogen, detector positions must satisfy the following condition

$$S \geqq \frac{1}{2} (D_c + D_s) \quad (3)$$

where in Fig.4 D_c is a beam spread width, D_s is a width of entrance of ion detector, and S is determined by the following relation

$$S = \frac{eV}{4} y_1 (y_1 + 2y_2) \left(\frac{1}{E_2} - \frac{1}{E_1}\right) \quad (4)$$

where E_1 and E_2 are hydrogen and deuterium ions energy respectively. Accordingly the designed value of detector position are chosen by Eq.(2) which satisfies (3) and (4).

Channel type secondary electron multiplier, Ceratron[9] is adopted as ion detector. Ceratrons are fixed in the sliding feed through behind the deflection plate. In order to reduce the influence coming from high voltage (-4 kV) applied to Ceratron and protect Ceratron from magnetic field of momentum analyser, Ceratrons are individually put in shield box made of μ metal and the stainless mesh is installed in the entrance of sheild box. Moreover a high transparency grid is installed in the front of core[10] of Ceratron for smoothing the effective collection area.

Ceratron being operated in the pulse saturation mode, a data acquisition system of pulse counting method is adopted. The signal from Ceratron in each channel passes through a preamplifier, and linear amplifier. The signal is separated from a thermal noise level with a discriminator and is counted with a scaler. The counted number is stored in the local memory. After a discharge, the obtained data is transfered to and analyzed with OKITAC 4500 computer system.

3. Calibration Experiment

The analyser was calibrated about the relation between an incident particle energy and the deflection magnetic field for energy analysis and between detector positions and the deflection electric field for mass separation. The calibration experiment for the conversion efficiency of the stripping cell was not performed. Because it was already known that in the energy range above 0.4 keV, the conversion efficiency[2,11] of stripping cell is in agreement with the value estimated from cross sections of charge-stripping and electron-capture processes. Accordingly the calibration experiment was performed about the capability of mass separation and energy analysis.

The experimental arrangement used for calibration of analyser is shown schematically in Fig.5. The calibration ion beam generated in an electron impact ion source. The range and stabilization of accelerating voltage were 0.1 to 10 keV and below 0.1% respectively and the exit aperture was 3 mm . Proton and bi-atomic molecular ion of hydrogen were used for the calibration of hydrogen and deuterium channel respectively.

At the first step, in order to confirm primarily the capability of mass and energy analysis of single species beam, ions with specified energy and mass entered the analyser. The ions were led to a channel by adjusting the current of magnet coil, the voltage of deflecting plate and detector position. At the next, on the condition of the fixed magnet current and deflection voltage of the E//B analyser, ion beam was led to the next channel by controlling the accelerating voltage and magnetic current of mass analyser for generation of calibration ion beam and adjusting detector position. The same procedure was performed for the other channels in turns. From these procedure rough positions of detectors were determined and the capability of mass and energy analysis was preliminarily confirmed.

At the next step, in order to simulate the actual measurement of two species plasma of hydrogen and deuterium, the capability of simultaneous mass and energy analysis of hydrogen and deuterium was investigated by directly entering ions beam emitted by ion source which was installed at the point 60 cm away from the entrance slit of stripping cell without the mass analyser of calibration stand.

Accordingly protons and bi-atomic molecular hydrogen ions with defined energy by accelerating voltage were simultaneously introduced to detectors of hydrogen and deuterium channels, which were set at positions roughly determined by the single species beam measurement. As a slight difference was observed at the detection energy between deuterium and hydrogen channels with the same energy, after this procedure, the detailed detection energy of each channel was determined by adjusting incident energy of calibration ion beam so as to have a maximum intensity at the each channel. The intensity profile of Z direction was measured by scanning the detector position in order to determine more accurately the detector positions and measure beam profiles at Ceratrons. At the next step, the accelerating voltage was varied so as to enter the detector of next channel. The optimum detector position and profile were measured by similar method. The same measurements were made for the other channels by turns. The obtained typical data of detector positions and profiles for each channel are shown in Fig.6. In this figure, the whole profile was not obtained, because the stroke of sliding feed through was short. However the symmetry of beam profile was confirmed by scanning the deflecting voltage. In this figure the solid line and dashed line are data obtained from scanning the detector position and deflecting voltage respectively. Optimum detector positions, for each channel, determined from these profile data are shown in Fig.7. The detector positions shifted to upper position as the Larmor radius of designed value became small. The displacement was caused by the electrostatic fringing field of deflection plate because the deflection plate width became narrow in the lower energy channel.

In each data point of Fig.7, the ranges of Z direction presented by solid lines are widths of beam at the detector position determined by beam profile data. The widths of Z direction of each channel were almost constant within experimental error. From this figure it was found that the enough mass separation was performed by this detector arrangement. The capability of mass separation was also checked by scanning the deflection voltage. Fig.8 shows Z direction profiles of proton beam of 2.75 keV, which was obtained by scanning deflecting voltage, for hydrogen and deuterium channels. Accordingly it was proved from these data that this analyser had a perfect capability of mass separation. Beam profile data for 14 combinations of magnet current and deflection voltage were obtained in the energy range between 0.4 keV and 9 keV. It was confirmed from these measurement that the detector positions and beam profiles did not vary in any combination of magnet current and deflection voltage.

The obtained relations between incident energy and current of magnet coil are shown in Fig.9(a), (b). The relation between magnet current and incident beam energy was in good proportion to the square of magnet current as expected from (1). But the energy difference between ch 1 and ch 5 in hydrogen and deuterium channel were 5.3 and 6.6 which were different from designed values. The discrepancy was caused by the displacement of detector position for the mechanism of sliding feed through, which had difficulty to be set exactly at the designed position. The relation between incident energy and deflection voltage are shown Fig.10(a) and (b). The linear relation among these parameters was in good agreement with the estimated value infered from equation (2).

The energy resolution was measured by scanning the incident beam energy. In Fig.11 the energy resolution obtained from the full half widths of energy profile is plotted for Larmor radius of the ion beam led to each channel. The dotted line in this figure is a curve of s_c/r, s_c is aperture diameter of Ceratron and r is Larmor radius for each channel. It was found from this figure that the dependence of energy resolution differs slightly from 1/r and the resolution of deuterium channel was smaller than that of hydrogen channel. The difference was caused by the phenomena that the change of ion orbit with the variation of incident beam energy resulted in the displacement of not only X but also Z direction in accordance with Larmor radius as shown in Fig. 7. The displacement of Z direction became large as the Larmor radius decreased, and the ratio of change of deuterium channel for Larmor radius was larger than that of hydrogen. Accordingly the effective width of Ceratron became smaller than that of 1/r dependence in decreasing the Larmor radius, and deuterium channel had smaller effective width than hydrogen channel.

4. Experimental Arrangements and Results of Charge-Exchanged Neutral Particle Measurements on JFT-2 Tokamak

In order to demonstrate the capabilities of this analyser, we applied it to JFT-2 tokamak which was operated with the working gas of hydrogen and deuterium. The experimental set-up for measuring charge-exchanged neutral is shown in Fig.12. This analyser was connected to JFT-2 tokamak through the pipe with the aperture slit. This slit prevented the enterance of neutral particle and UV photons reflected on the inner wall of this pipe. The region of this pipe was pumped out by 80 l/sec sputter ion pump and the pressure was maintained at 10^{-6} Torr order. The neutral particles which were not ionized by the stripping cell and the photon emitted from the plasma were absorbed by the viewing damp.

The ratio of signal to noise was obtained to be several thousand by these adequate measures. After installing this analyzer to tokamak, the check of detector efficiency was made by electro-impact ion source which could be removed in the plasma measurement. In the measurements on the JFT-2 tokamak, this analyser was connected to the port capable of horizontal scanning for the small plasma radius distribution. The measurement was made in the Joule heating, neutral beam injection heating, and ion cyclotron resonance heating. Proton and deuteron energy spectra of charge-exchanged neutrals obtained in the Joule heating of the toroidal magnetic field of 14.5 kG, peak plasma current of 100 kA, peak line-averaged electron density of 2.2×10^{13} cm^{-3} and ratio of hydrogen to deuterium of 1:10 are shown in Fig.13(a) and (b). These data were also obtained from successive 6 good reproducible shots which contain 3 cases of magnet current and deflecting voltage. The measurements of each case were performed by measuring the particle signals in a discharge and background noise in the following discharge in turn. The energy spectra of hydrogen and deuterium were in good agreement with Maxwellian distribution which gave ion temperatures of 340 eV and 360 eV respectively.

In Fig.14, (a) and (b) show the energy spectrum of neutral beam injection heating plasma of deuterium which hydrogen beam was injected into at the 36 degree from the perpendicular direction of magnetic axis. As the measurement was made at the perpendicular direction of magnetic axis, the peak of beam component for the dissociated ion of molecular hydrogen atom was not observed. The deuteron ion temperature was obtained to be 570 eV from this energy spectrum.

The energy spectra of deuteron and proton in the ion cyclotron resonance heating plasma with the ratio of hydrogen and deuterium density of 1:10 are shown in Fig.15(a) and (b). Proton and deuteron temperature were obtained to be 530 eV and 880 eV respectively from these spectra. Fig.16 shows an example of time variation in the ion cyclotron resonance heating obtained by this analyser. At the present time, this analyser was used in the routine measurement on the ion cyclotron resonance heating and neutral beam injection heating experiments of JFT-2 tokamak plasma in order to investigate the heating mechanism and ion behavior in these further heating.

5. Discussion

As the capability of mass separation of coventional mass energy analyser consisted of momentum analyser and cyclindrical êlectrostatic energy analyser was insufficient, it was known that the detail investigation of behavior of high energy tail was difficult. Accordingly the capability of mass separation of this analyser was measured in the discharge of hydrogen neutral beam injection experiment into the hydrogen target plasma. Fig.17 shows the time behavior of hydrogen and deuterium signal of ch 2, 3, and 4. In joule heating phase between 90 ms and 100 ms, as the ion temperature was 330 eV, the counts of hydrogen and deuterium channels were negligibly small. As the neutral beam injection started at the 100 ms, the counts of hydrogen channel immediately increased. But the counts of deuterium channel were negligibly small. The few counts of deuterium channel during neutral beam injection seemed to result from the fluctuation of background noise. As a results it was found that the capability of mass separation of this analyser was nearly perfect, as measured by the calibration experiment. This sufficient capability of mass separation increased the reliability of data about behavior of beam component during the neutral beam injection and high energy tail of deuterium during ion cyclotron resonance heating.

The ion temperature on the further heating obtained with this analyser were compared to impurity ion temperature determined by the measurement of Doppler broadening of TiXIV line spectrum. The measurements of TiXIV line broadening were simultaneously made with 1 m Czerny-Turner spectrometer[12)]. It was confirmed by radial distribution measurement that TiXIV line emission placed at 5 cm from plasma center. The bulk ion temperature of central region deduced from energy spectrum of neutral particle was in good agreement with impurity ion temperature determined by Doppler broadening of TiXIV line.

In the minority heating of ion cyclotron wave, the ratio of deuteron and proton density in the inner region of plasma is very important parameter. In the mixed plasma, the ratio of proton and deuteron density at the plasma center region could not be determined in a sufficient accuracy from measurements of H_α and D_α. The determination of the ratio of proton and deuteron was made by the energy spectrum of hydrogen and deuterium emitted from JFT-2 tokamak. The intensity ratio of H_α and

and D_α was simultaneously measured togather with the charge-exchange measurement. In Fig.4 the obtained n_p/n_d from the energy spectrum is shown in comparison with the spectroscopic measurement. As a result, it was found that the ratio of deuteron and proton density in the plasma center was in agreement with the density at the boundary region.

6. Summary

In concluding the present report, we summarize our results as follows.

(1) A mass separated neutral particle energy analyser has been designed and constructed to measure ion temperature and investigate the behavior of hydrogen and deuterium in the further heated JFT-2 tokamak phasma.

(2) Calibration experiments for mass and energy measurements have been performed by the calibration stand.

(3) The mass separated neutral particle energy analyser has been calibrated with proton and bi-atomic molecular hydrogen ion beam of the energy of 0.4 keV to 9 keV. The obtained experiment result is in good agreement with the designed value.

(4) The capability of mass separation has been measured with ion beam and further heated plasma. It is confirmed that this analyser can perfectly separate deuterium beam from hydrogen beam on the ion beam and plasma measurements.

(5) The measurements of hydrogen and deuterium charge-exchanged neutral spectra were made in the JFT-2 plasma of Joule, neutral beam and ion cyclotron resonance heating experiments.

(6) The obtained ion temperature and ratio of deuteron and proton density from the energy spectrum were in good agreement with the value deduced from Doppler broadening of TiXIV line and the line intensities of H_α and D_α respectively.

Acknowledgements

The authors are grateful to Dr. A. Funahashi, and other members of JFT-2 groups for their co-operation and discussions and to Mr. S. Kunieda and his groups for their operation of JFT-2 device and NBI system. We also appreciate the presentation of Doppler broadening data by Dr. T. Sugie. We would like to express our gratitude to Drs. Y. Tanaka, Y. Suzuki, M. Tanaka, M. Yoshikawa, Y. Obata and A. Tomabechi and S. Mori for their continuous encouragement to the present work.

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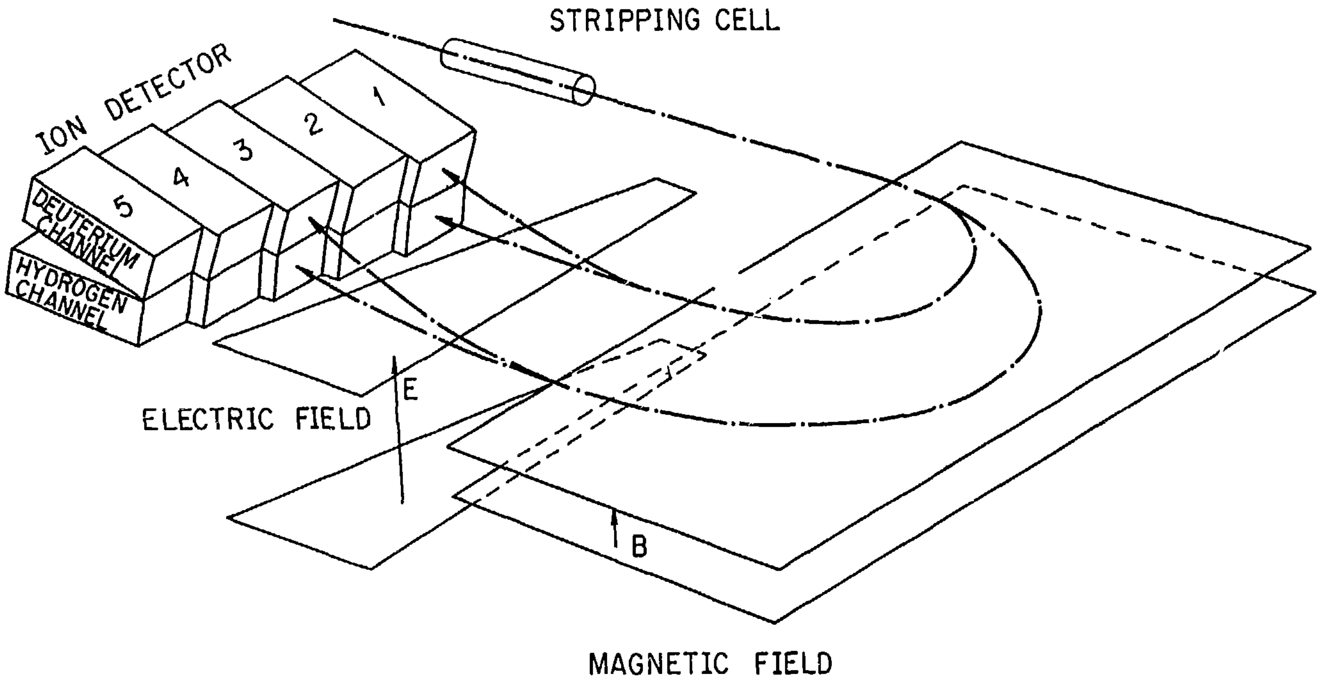

Fig. 1 Schematic diagram of the E//B type mass separated neutral particle energy analyser

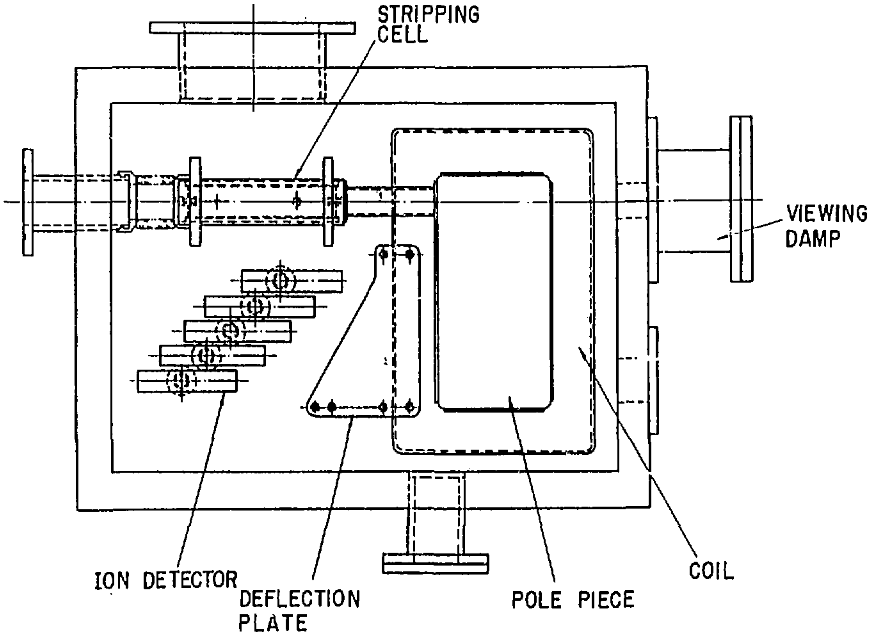

Fig. 2 Sectional plan view of E//B type analyser

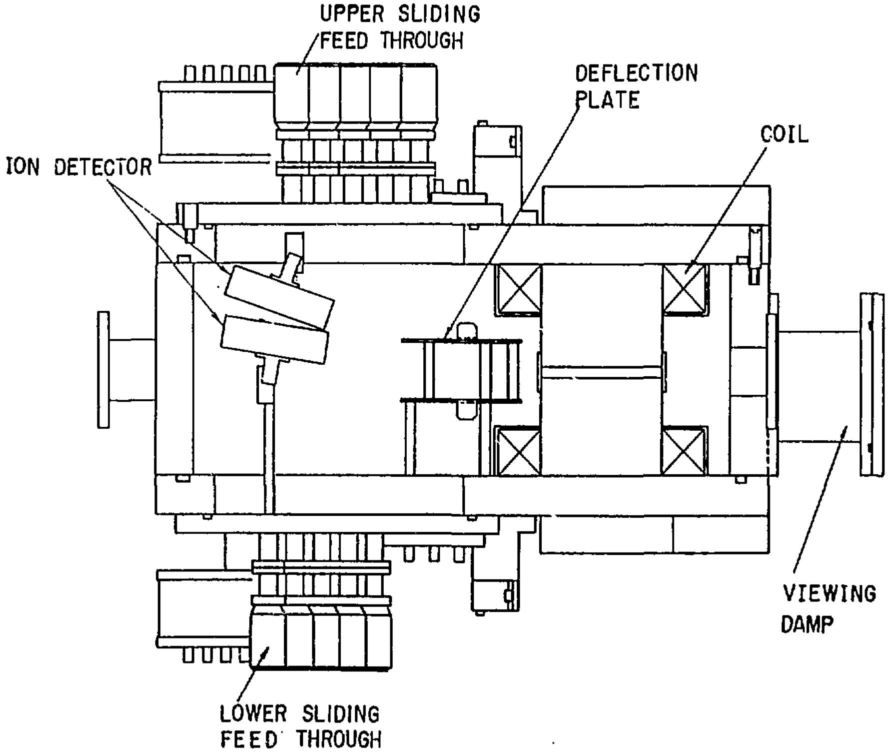

Fig. 3 Sectional side view of E//B type analyser

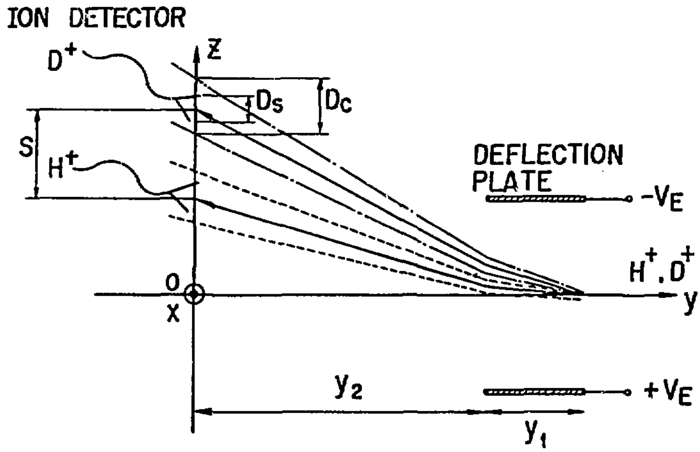

Fig. 4 Diagram explaining the condition of mass separation

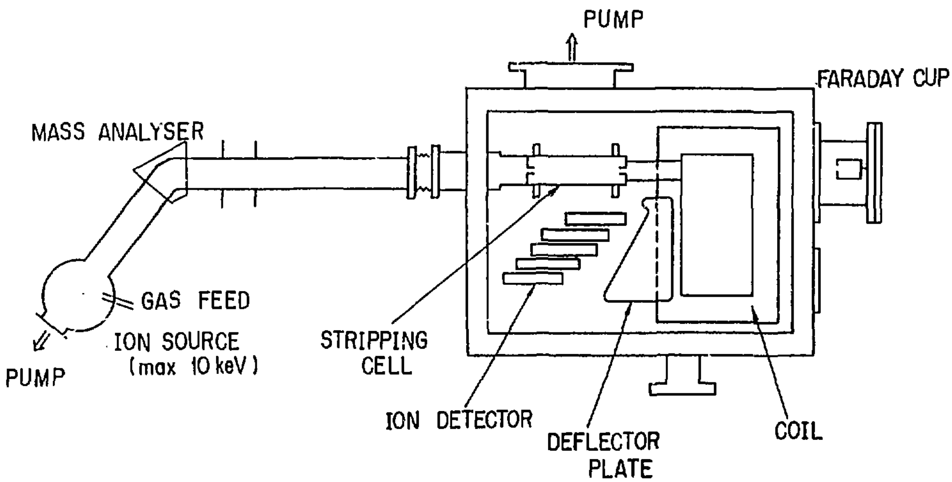

Fig. 5 Schematic diagram of set-up for calibration experiments

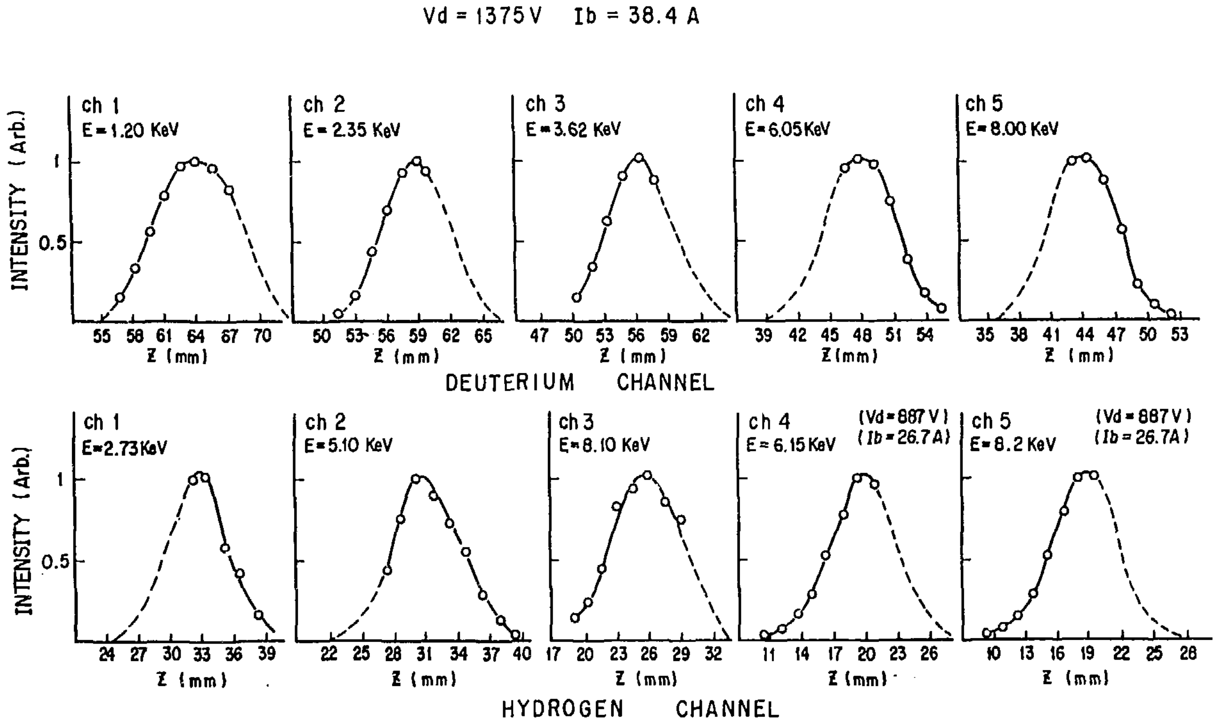

Fig. 6 The obtained Z direction profiles and positions on the condition of magnet current I_b=38.4A and deflection voltage V_d=1375 V. (Data of ch 4 and ch 5 of hydrogen channel were obtained at I_b=26.7A and V_d=887 V)

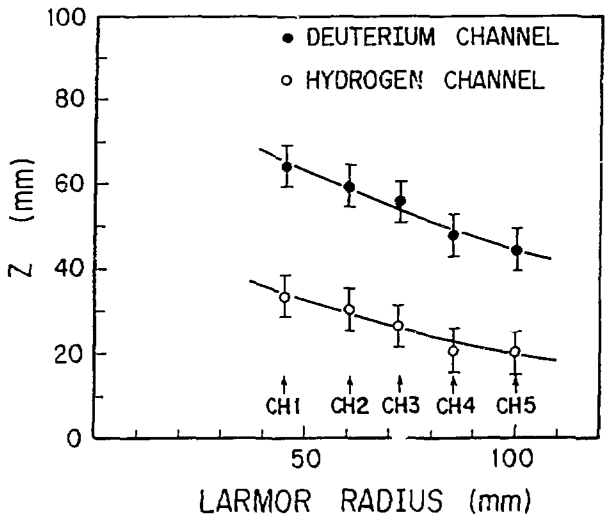

Fig. 7 The variation of detector center position for Larmor radius of designed value. The ranges of Z direction show beam widths determined by profile data of Fig.6.

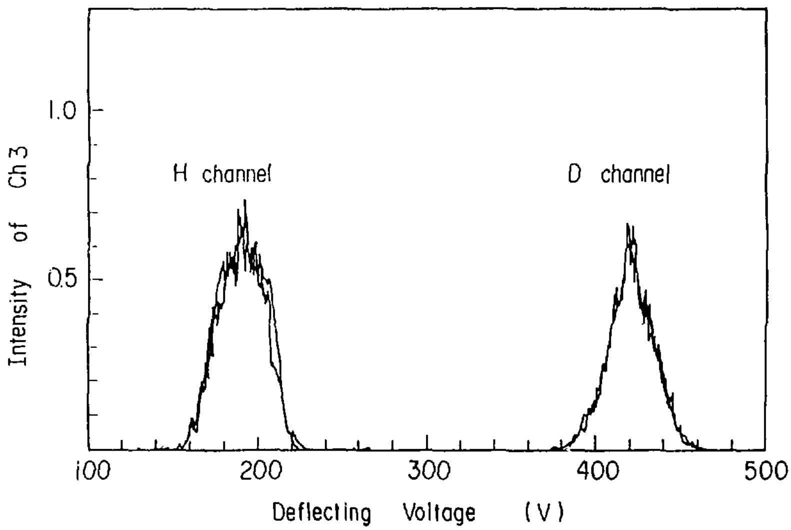

Fig. 8 Relation between deflection voltage and Z direction profile in deuterium and hydrogen channel of ch 3 for the incident of proton beam of 2.75 keV.

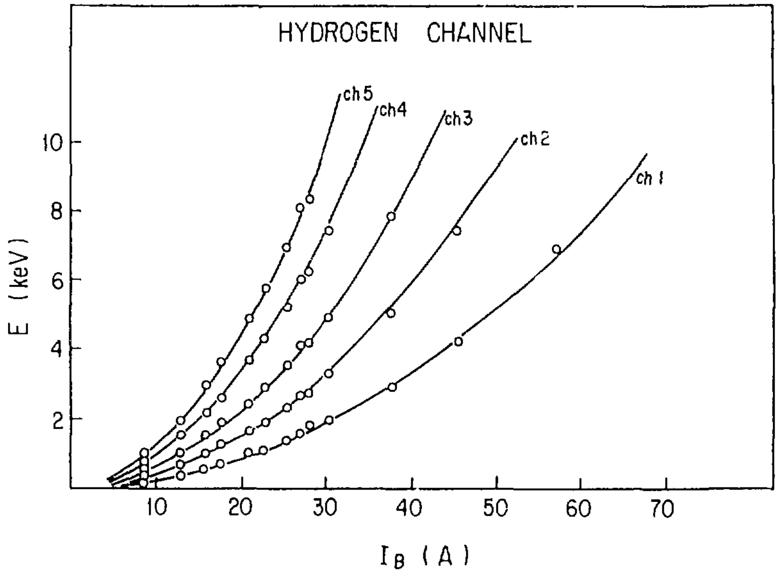

Fig. 9(a) Experimental results of hydrogen channel between incident ion energy and magnet current

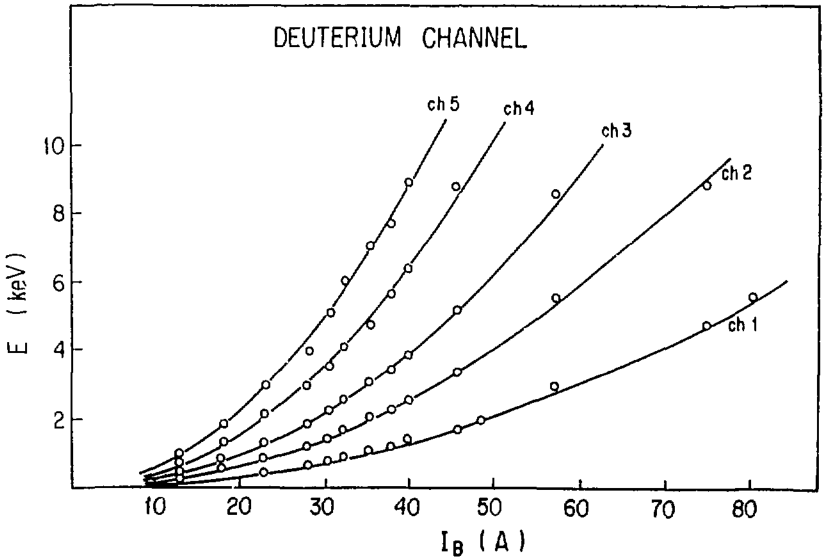

Fig.9(b) Experimental results of deuterium channel between incident ion energy and magnet current

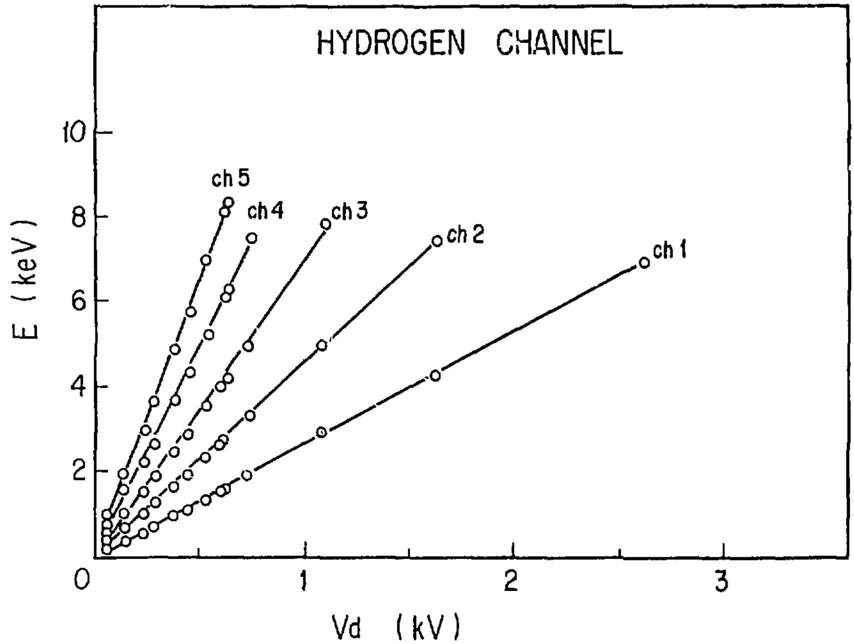

Fig.10(a) Experimental results of hydrogen channel between incident ion energy and deflection voltage

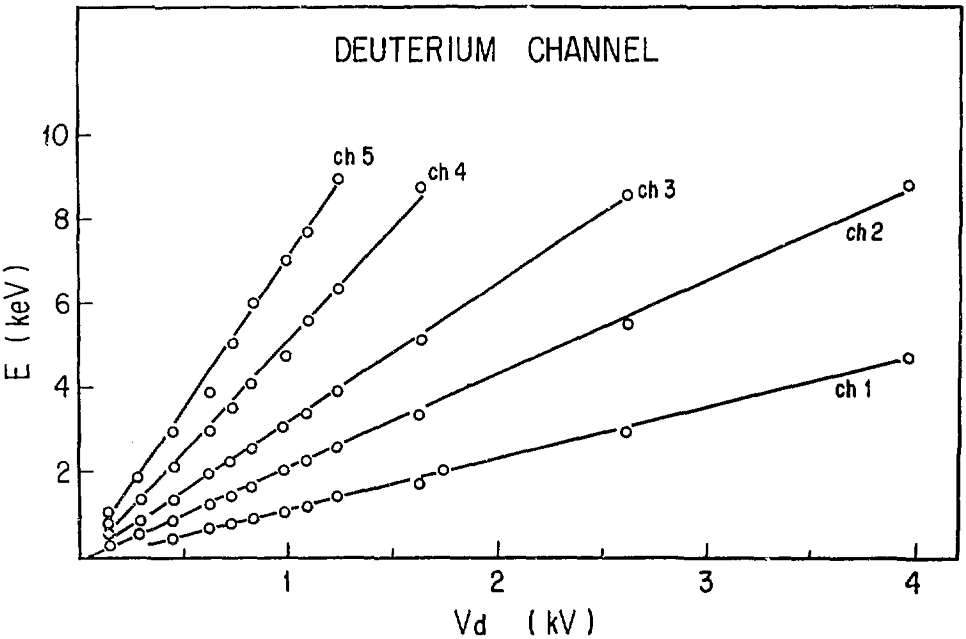

Fig.10(b) Experimental results of deuterium channel between incident ion energy and deflection voltage

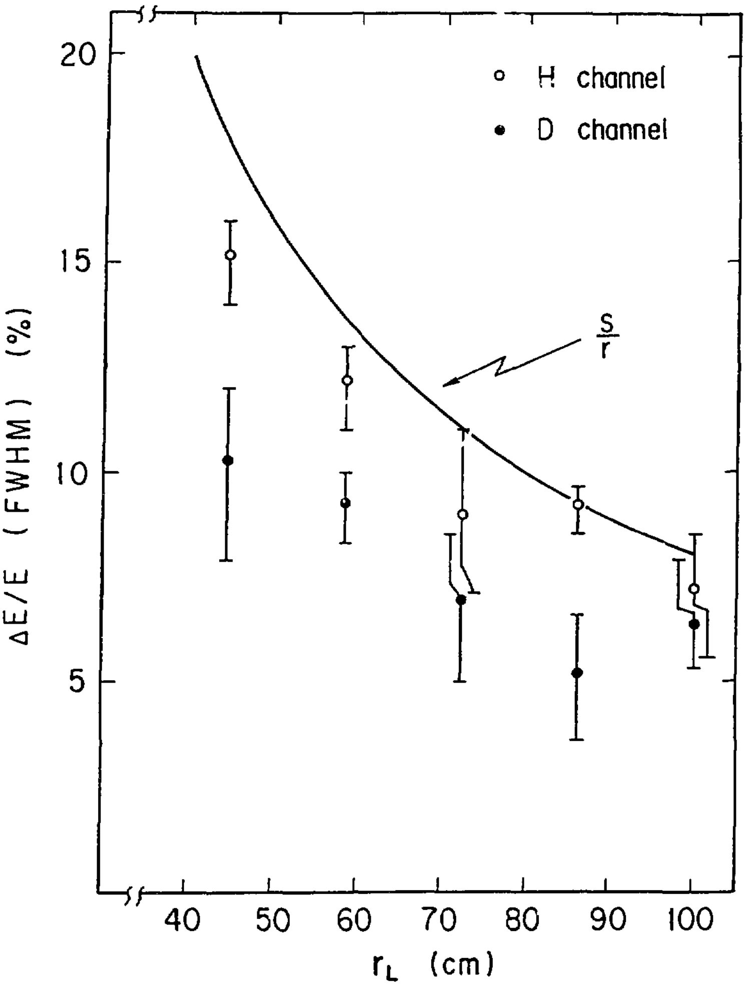

Fig. 11 The variation of energy resolution for Larmor radius of designed value

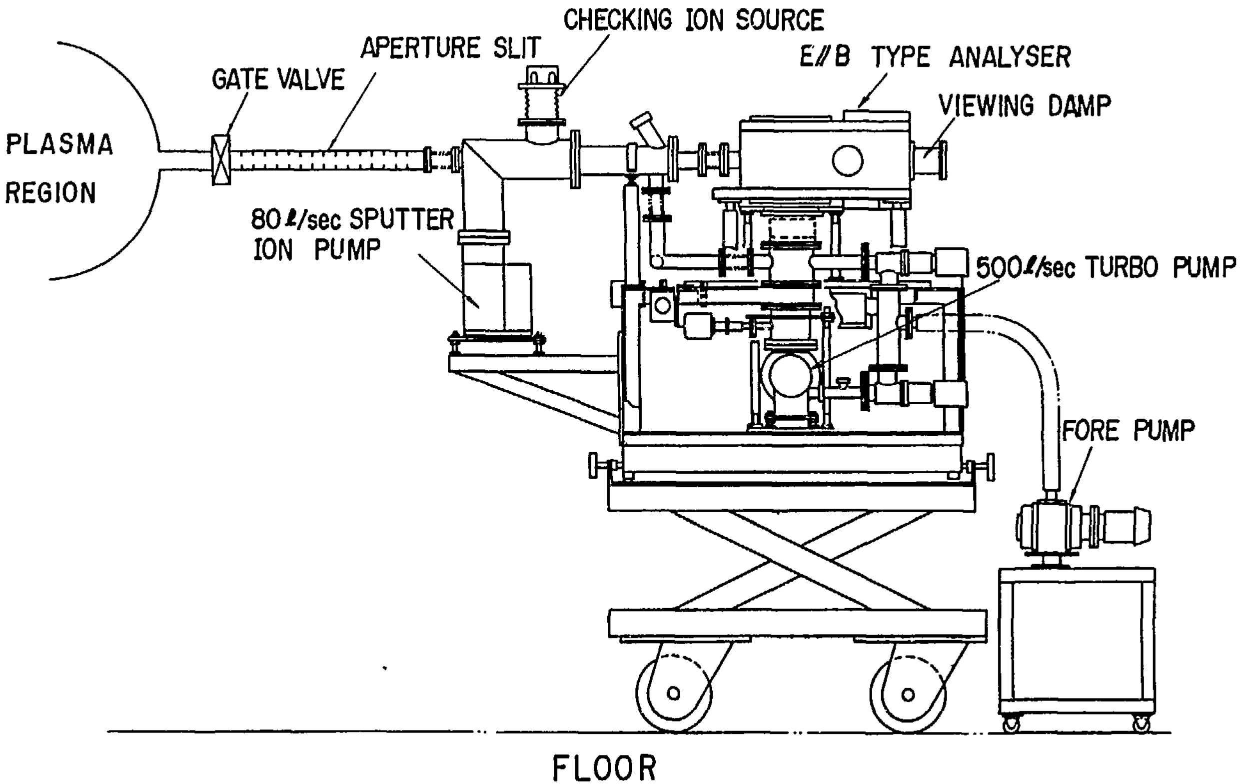

Fig. 12 Experimental set-up for measuring charge-exchanged neutral particle spectrum from the JFT-2 tokamak plasma

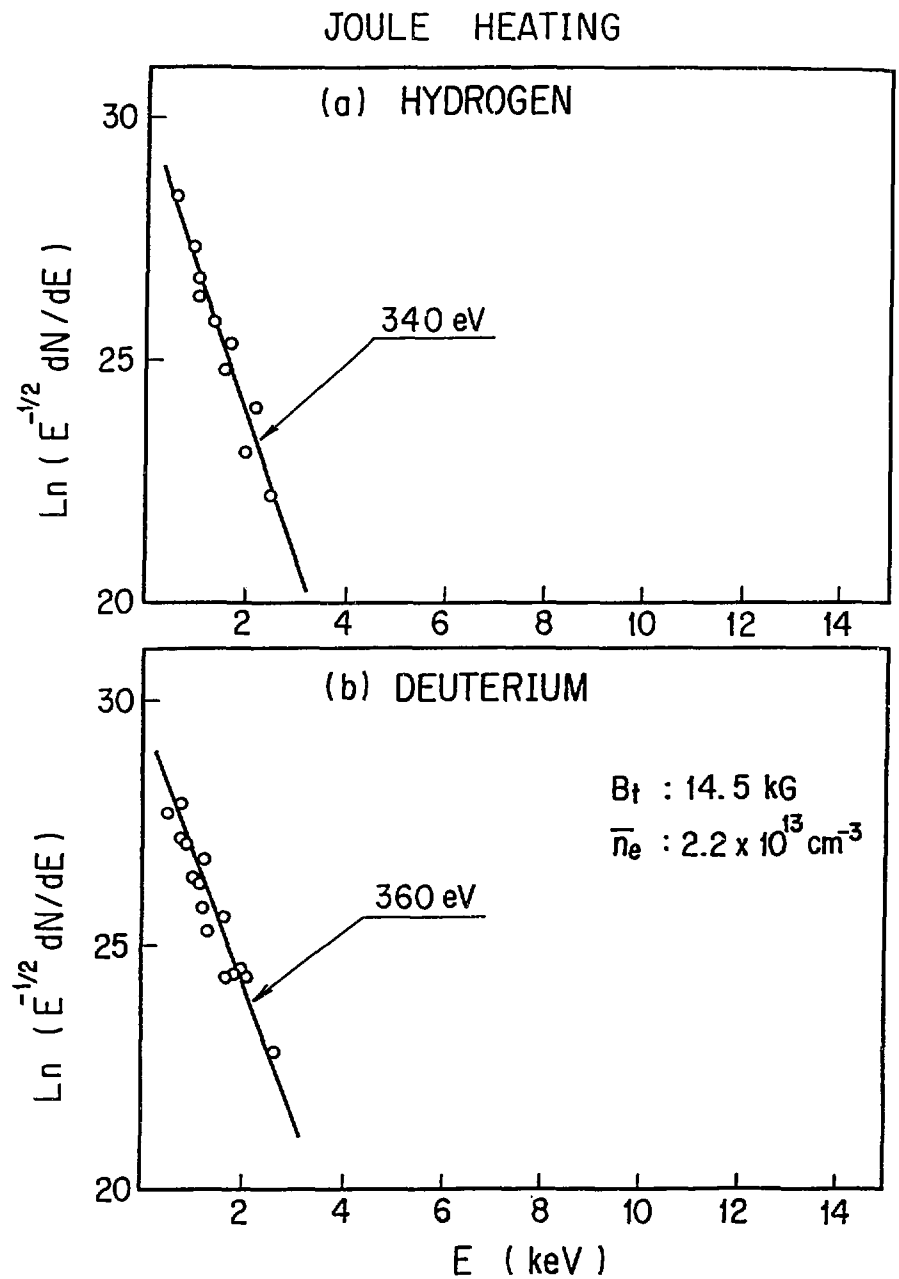

Fig. 13 The obtained energy spectra of (a) hydrogen and (b) deuterium in the discharge of Joule heating

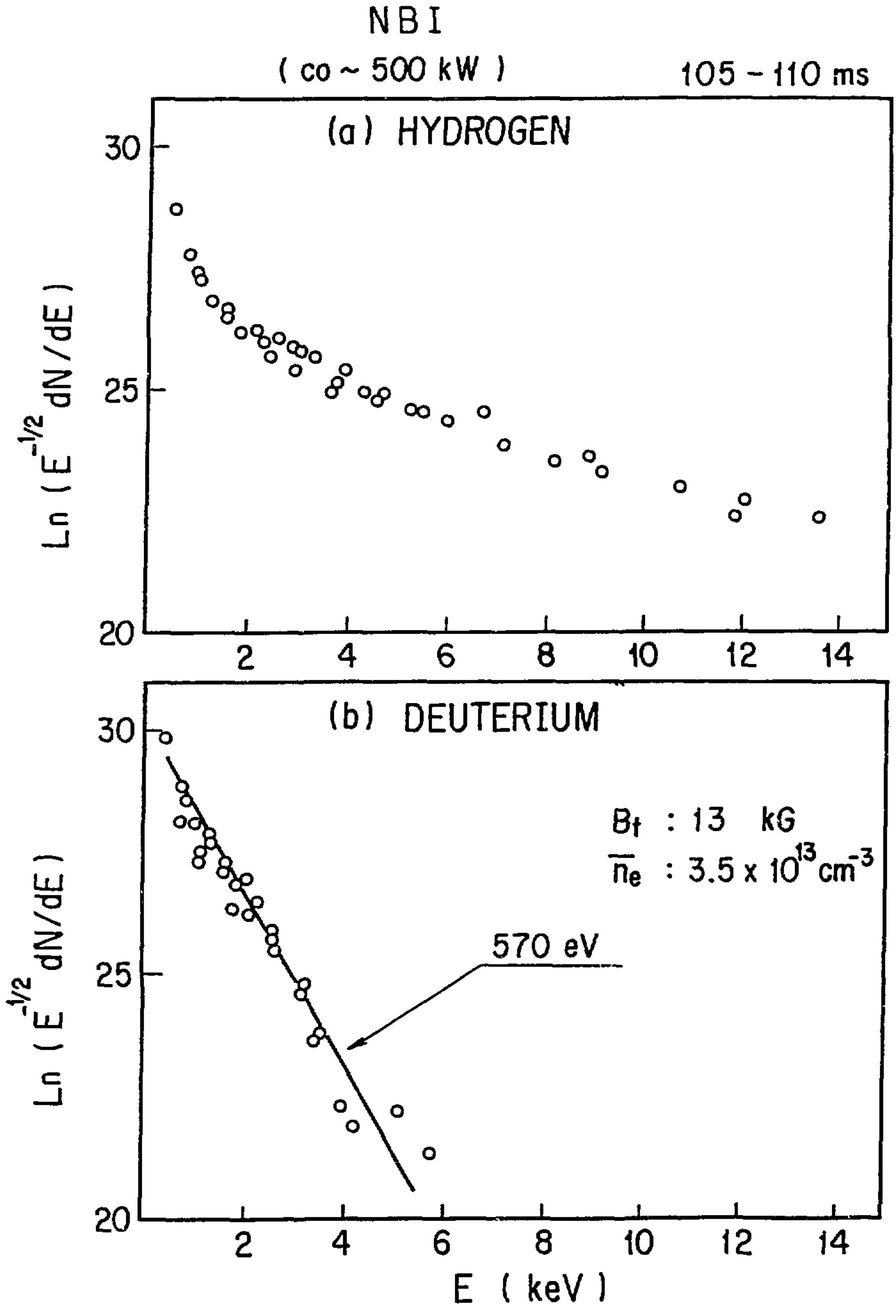

Fig. 14 The obtained energy spectra of (a) hydrogen and (b) deuterium in the discharge where at the co-direction hydrogen beam power of 500 kW was injected into deuterium plasma

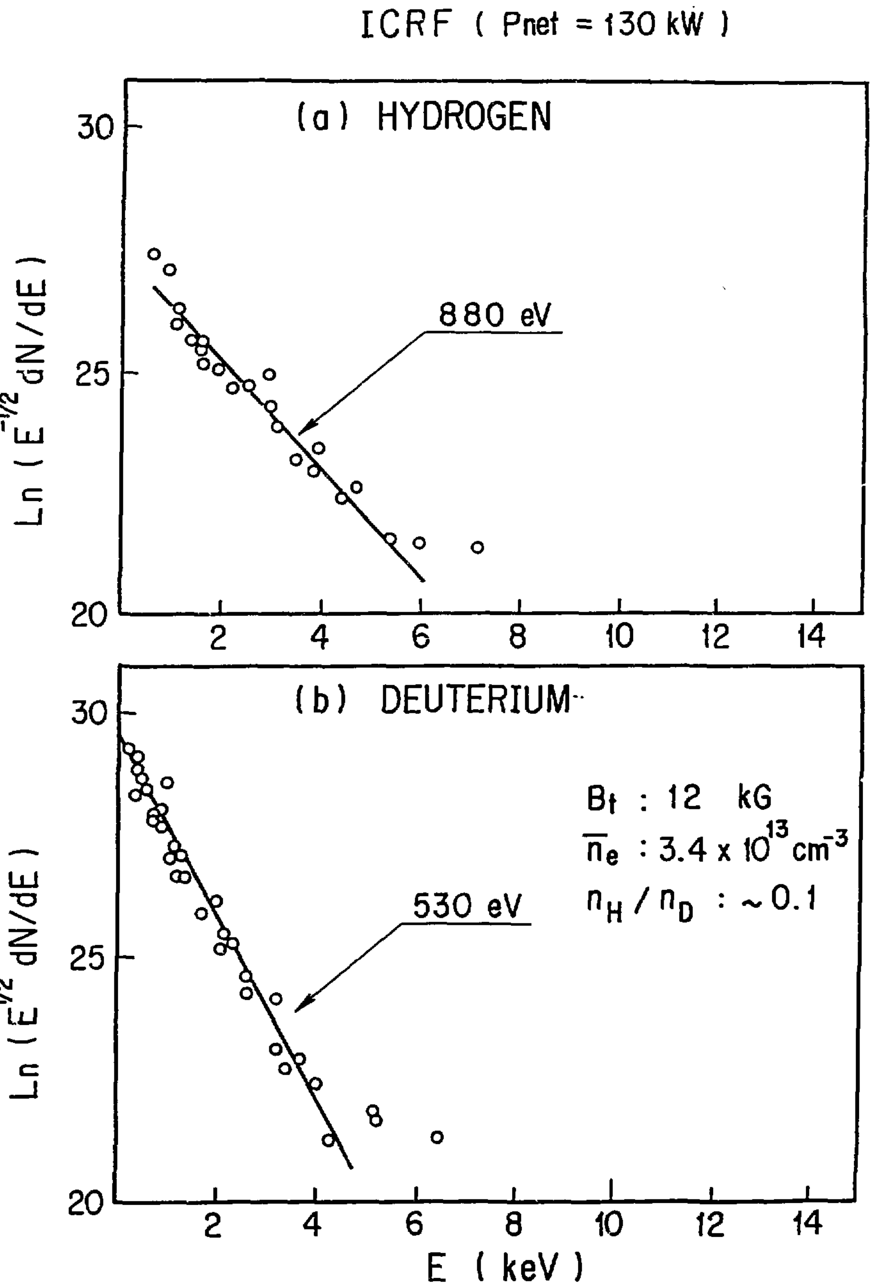

Fig. 15 The obtained energy spectra of (a) hydrogen and (b) dueterium in the discharge of the ratio of hydrogen to deuterium 1:10 which was heated by ion cyclotron wave power of 130 kW.

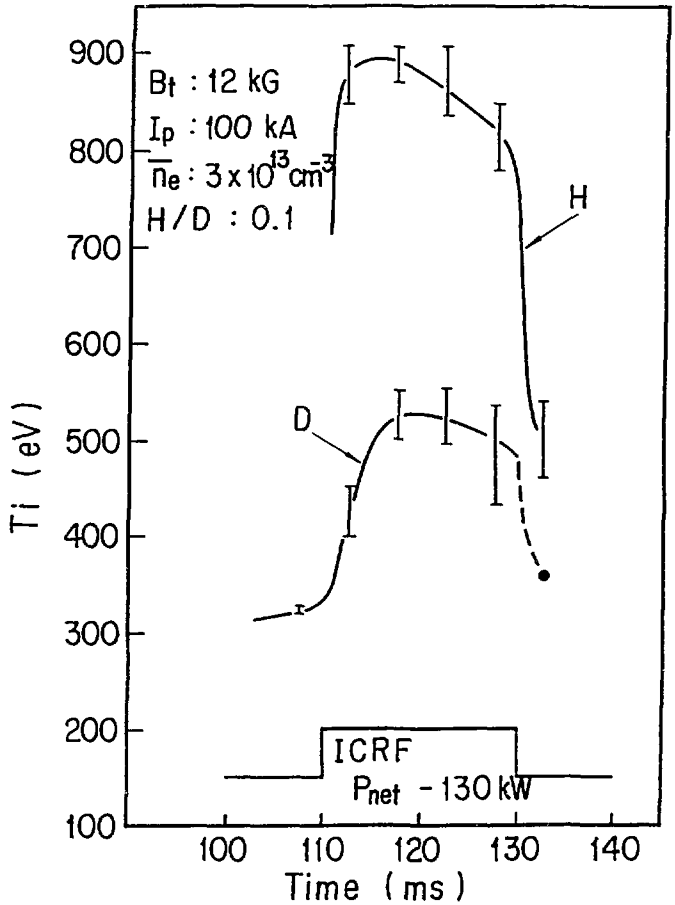

Fig. 16 The time variation of hydrogen and deuterium ion temperature deduced from charge-exchanged neutral energy spectrum in the ion cyclotron resonance heating

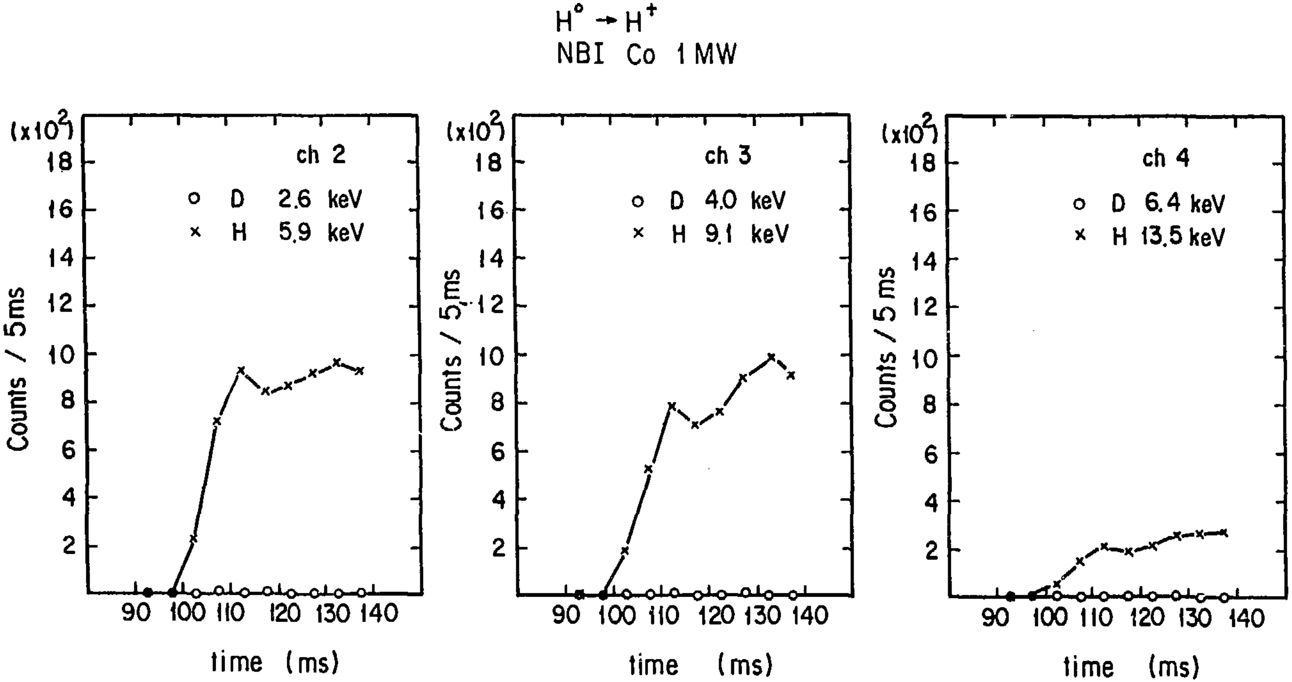

Fig. 17 The time variation of deuterium and hydrogen channel at ch2, 3 and 4 respectively in a hydrogen discharge which was heated by the hydrogen beam

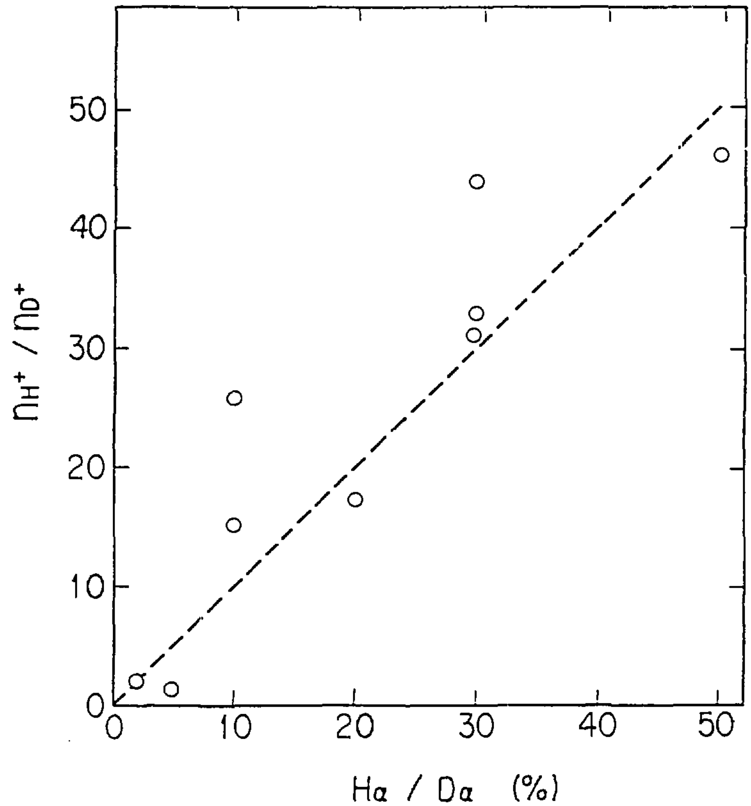

Fig. 18 Comparison of the ratio of deuteron and proton density determined by the energy spectrum with the ratio of hydrogen and deuterium density estimated by H_α and D_α line intensity respectively