JAERI - M
83-141

ACTIVE BEAM SCATTERING APPARATUS AND ITS APPLICATION TO JFT-2 TOKAMAK

September 1983

Hiroshi TAKEUCHI, Toshiaki MATSUDA, Takeo NISHITANI
Makoto SHIHO, Chikara KONAGAI*, Hironobu KIMURA*
and Hikosuke MAEDA

日 本 原 子 力 研 究 所
Japan Atomic Energy Research Institute

JAERI-M レポートは，日本原子力研究所が不定期に公刊している研究報告書です。

入手の問合わせは，日本原子力研究所技術情報部情報資料課（〒319−11 茨城県那珂郡東海村）あて，お申しこしください。なお，このほかに財団法人原子力弘済会資料センター（〒319−11 茨城県那珂郡東海村日本原子力研究所内）で複写による実費頒布をおこなっております。

JAERI-M reports are issued irregularly.

Inquiries about availabiljty of the reports should be addressed to Information Section, Division of Technical Information, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319−11, Japan.

編集兼発行　日本原子力研究所
印　　刷　㈱原子力資料サービス

JAERI-M 83-141

Active Beam Scattering Apparatus
and
its Application to JFT-2 Tokamak

Hiroshi TAKEUCHI, Toshiaki MATSUDA[+], Takeo NISHITANI
Makoto SHIHO, Chikara KONAGAI[*], Hironobu KIMURA[*],
and Hikosuke MAEDA

Department of Large Tokamak Development,
Tokai Research Establishment, JAERI

(Received August 9, 1983)

The capability to assess the ion temperatures using a neutral beam scattering system is investigated on the JFT-2 tokamak. The neutral beam scattering system consists of a 15 KeV neutral hydrogen atom beam and a momentum analyser with silicon surface barrier detectors. The energy analysis of scattered particles on the scattering angle of 4° gives the estimation of ion temperatures, which agree well with the one deduced from passive charge-exchange neutral measurements. The influence of impurity ions to the scattering spectrum is not observed and the results of gas scattering experiments suggests that this phenomenon occurs because of the ionization of neutral beam due to the collisions with impurity ions.

Keywords: Active Beam Scattering, Ion Temperature, Neutral Beam,
JFT-2 Tokamak, Impurity Ion

[+] Department of Thermonuclear Fusion Research, Tokai, JAERI

[*] Toshiba Corporation, Kawasaki, Kanagawa

能動粒子線散乱装置とそのＪＦＴ－２トカマクへの適用

日本原子力研究所東海研究所大型トカマク開発部
竹内　浩・松田俊明[+]・西谷健夫・志甫　諒
小長井主税[*]・木村博信[*]・前田彦祐

（１９８３年８月９日受理）

トカマクプラズマのイオン温度を測定するための能動粒子線計測法がＪＦＴ－２トカマクに適用されジュール加熱時のイオン温度が求められた。測定には15keVの水素原子ビームが用いられ，散乱粒子のエネルギー分析と検出は，散乱角4°で運動量分析器とシリコン障壁型の半導体検出器によって行なわれた。得られたイオン温度は受動的な荷電交換中性粒子計測法で得られた値と一致した。また散乱スペクトラムへの不純物への影響も調べられ，ラザフォード散乱から予想された強度と観測された散乱強度の間の差はターゲット粒子の原子数の増大とともに増加することがわかった。その結果，散乱強度に不純物イオンが寄与しない現象は中性粒子ビームの不純物イオとの衝突によるイオン化により起ることがわかった。

[+] 核融合研究部

[*] 東芝

Contents

目次

1. Introduction

Until now the ion temperature in the tokamak plasma has been determined by the energy spectrum of charge-exchanged neutral efflux1), Doppler broadening of impurity ion lines2) and 2.45 MeV neutron intensity produced with d-d reaction3). In the reactor scale tokamak plasma, it will be difficult to determine accurately the ion temperature of plasma center with above-mentioned method. Because the charge-exchanged neutrals produced in the neighborhood of plasma center are hardly emitted to the outside, as the mean free path for the reionization is smaller than the plasma dimension. The impurity ions which may give line emissions at plasma center will not always exist because the low Z material, which could be fully stripped at plasma center, will be applied to the wall material of tokamak device to reduce high Z impurity ions in the plasma. If the quantity of deuteron will be measured, the center ion temperature can be infered from d-d reaction neutron intensity. As we have not presently the method of measurement of deuteron density in the plasma center, the accurate absolute value of center ion temperature can not be determined from neutron intensity measurement. In order to measure neutron Doppler broadening, it is necessary to develop high resolution neutron energy spectrometer. Far infrared Laser scattering4) is thought one of attractive method, but is not presently applied to the measurement of high temperature plasma because of plasma fluctuation and insufficient laser power5).

Form these circumstances, the neutral beam scattering method to measure an energy spread of injected high energy neutral beam due to collisions with plasma ions, is one of the most reliable method for ion temperature measurement in the next generation tokamak. The possibility of this method was proved by V.G. Abramov6), et al., and the application to tokamak was made first by E.V. Aleksandrov, et al.7) and E.L. Berezovskii8) in the T-4 tokamak. In these experiment, the ion temperature has been successfully determined and the energy spread of injected particles due to collisions with plasma ions agreed with the theoretical value beased on Rutherford scattering. In spite of the successful use of the method there still remain some discrepancies between theoretical prediction and experimental result. In the scattering spectrum, the peak for impurity ions was expected to appear from the theory, but was not observed even when a plasma was contaminated by oxygen ions of 1%. As the peak intensity for 1% oxygen ion estimated from Rutherford scattering process is five times larger than that for protons in this case, the scattering spectrum of protons could be piled up with that of oxygens.

Though the contribution of impurity ions has not been observed in the measurement performed up to this time, the method seems to give the correct ion temperatures so far. Therefore when this scattering method is applied to the diagnostic system for an ion temperature determination, the reason for this absence of peak for impurity ions must be clarified.

At Japan Atomic Energy Research Institute, the 200 keV neutral beam scattering system is now being developed to provide ion temperature measurement for reactor-like plasmas$^{9)}$. In order to confirm the capability of the method, the prototype scattering system has been constructed and tested on JFT-2 tokamak.

Purposes of this paper are to confirm the capability of this method determining the ion temperature and to investigate the influence of impurity ions to the energy spectrum. In the next section, the scattering theory is reviewed and the experimental set-up is described in section 3. Section 4 is devoted to the present experimental result and discussion of scattering spectrum and the influence of impurity ions. In section 5, we summarize this paper.

2. Fundamental Principles

We consider the system as shown in Fig. 1. A beam with velocity V_1 and mass m is injected into a plasma ions with velocity distribution $f(V_2)$ and mass m_2 and the beam particles scattered by plasma ions are measured. The relation of the velocity distribution between plasma ions and scattered particles is given by

$$\rho(V_1') = n_1 \frac{b^2}{q} \int f(V_2)\sigma(u,\chi)d^2u_\perp \qquad (1)$$

as shown in Ref. (6), where $\rho(V_1')$ is the velocity distribution function for scattered particles; $\sigma(u,\chi)$ is the scattering cross section in the center of mass system; χ is the scattering angle in the center of mass system, u is relative velocity of particle collision and $u_\perp$ is the component of this velocity lying in the plane perpendicular to vector oxygen ions of 1%. As the peak intensity for 1% oxygen ion estimated from Rutherford scattering process is five times larger than that for protons in this case, the scattering spectrum of protons could be piled up with that of oxygens.

Though the contribution of impurity ions has not been observed in the measurement performed up to this time, the method seems to give the correct ion temperatures so far. Therefore when this scattering method is applied to the diagnostic system for an ion temperature determination, the reason for this absence of peak for impurity ions must be clarified.

At Japan Atomic Energy Research Institute, the 200 keV neutral beam scattering system is now being developed to provide ion temperature measurement for reactor-like plasmas[9]. In order to confirm the capability of the method, the prototype scattering system has been constructed and tested on JFT-2 tokamak.

Purposes of this paper are to confirm the capability of this method determining the ion temperature and to investigate the influence of impurity ions to the energy spectrum. In the next section, the scattering theory is reviewed and the experimental set-up is described in section 3. Section 4 is devoted to the present experimental result and discussion of scattering spectrum and the influence of impurity ions. In section 5, we summarize this paper.

2. Fundamental Principles

We consider the system as shown in Fig. 1. A beam with velocity V_1 and mass m is injected into a plasma ions with velocity distribution $f(V_2)$ and mass m_2 and the beam particles scattered by plasma ions are measured. The relation of the velocity distribution between plasma ions and scattered particles is given by

$$\rho(V_1') = n_1 \frac{b^2}{q} \int f(V_2)\sigma(u,\chi)d^2u_\perp \qquad (1)$$

as shown in Ref. (6), where $\rho(V_1')$ is the velocity distribution function for scattered particles; $\sigma(u,\chi)$ is the scattering cross section in the center of mass system; χ is the scattering angle in the center of mass system, u is relative velocity of particle collision and $u_\perp$ is the component of this velocity lying in the plane perpendicular to vector

q ; $q = v_1 - v_1'$ is the change in the velocity of beam particle on the collision of plasma ions; v_1 and v_1' are the velocity of the beam particles, respectively, before and after the collision; v_2 is the plasma ion velocity before the scattering; $b = 1 + \frac{m_1}{m_2}$ is a coefficient determined by the mass ratio. n_1 is the density of incident particels.

Assuming Maxwellian target particles with small thermal velocity ($v_2 << v_1$), the half-maximum width ΔE of an energy spectrum of the scattered particles with the small scattering angle is related to the ion temperature T_i by the following equation$^{6)}$

$$T_i \simeq \left(\frac{\Delta E}{4\theta} \right)^2 \frac{m_2}{E \, \ell n \, 2 \, m_1} \quad , \qquad (2)$$

where E is the energy of the injected particles, and θ is the scattering angle in the larboratory system. The energy E_p of peak value of scattered profile corresponding to plasma ion species of mass m_2 was given by$^{10)}$

$$E_p = E \, [1 - (m_1/m_2)\sin^2\theta] \quad . \qquad (3)$$

Therefore the ion temperature is obtained by measuring the half width of scattering profile and target mass number determined by equation (3).

3. Neutral Beam Scattering System

In Fig. 2 is shown the schematic diagram of a neutral beam scattering system installed in JFT-2 tokamak. We used a duoplasmatron type ion source as an injector which was capable of operating continuously at an accelerating voltage of 20 kV and a drain current of 10 mA. In the neutralizer, the neutralization of the ion beam emitted from the ion source is performed by the collision with the cold neutral gas which flows out of the ion source. The residual ions in the neutralizer are removed by the toroidal magnetic field in the tokamak operation. These ions did not deteriorate plasma operation in this experiment. The pressure of neutralizer at the operation is maintained at 1×10^{-4} Torr by the turbo molecular pump of 500 ℓ/sec. The injector is magnetically shielded with two layers of μ metal an one layer of iron. The injection angle and position can be changed over the range from -5 to +5 degree and from -8 to +8 cm, respectively. The neutral beam was

q ; $q = v_1 - v_1'$ is the change in the velocity of beam particle on the collision of plasma ions; v_1 and v_1' are the velocity of the beam particles, respectively, before and after the collision; v_2 is the plasma ion velocity before the scattering; $b = 1 + \frac{m_1}{m_2}$ is a coefficient determined by the mass ratio. n_1 is the density of incident particels.

Assuming Maxwellian target particles with small thermal velocity ($v_2 << v_1$), the half-maximum width ΔE of an energy spectrum of the scattered particles with the small scattering angle is related to the ion temperature T_i by the following equation[6)]

$$T_i \simeq \left(\frac{\Delta E}{4\theta} \right)^2 \frac{m_2}{E \ \ell n\ 2\ m_1} \quad , \qquad (2)$$

where E is the energy of the injected particles, and θ is the scattering angle in the larboratory system. The energy E_p of peak value of scattered profile corresponding to plasma ion species of mass m_2 was given by[10)]

$$E_p = E\,[1 - (m_1/m_2)\sin^2\theta] \quad . \qquad (3)$$

Therefore the ion temperature is obtained by measuring the half width of scattering profile and target mass number determined by equation (3).

3. Neutral Beam Scattering System

In Fig. 2 is shown the schematic diagram of a neutral beam scattering system installed in JFT-2 tokamak. We used a duoplasmatron type ion source as an injector which was capable of operating continuously at an accelerating voltage of 20 kV and a drain current of 10 mA. In the neutralizer, the neutralization of the ion beam emitted from the ion source is performed by the collision with the cold neutral gas which flows out of the ion source. The residual ions in the neutralizer are removed by the toroidal magnetic field in the tokamak operation. These ions did not deteriorate plasma operation in this experiment. The pressure of neutralizer at the operation is maintained at 1×10^{-4} Torr by the turbo molecular pump of 500 ℓ/sec. The injector is magnetically shielded with two layers of μ metal an one layer of iron. The injection angle and position can be changed over the range from -5 to +5 degree and from -8 to +8 cm, respectively. The neutral beam was collimated by diaphrams to a diameter of 2 cm and was continuously injected into the plasma.

The energy spread of the scattered neutral beam was measured by the detection system which consists of a stripping cell, a momentum analyser and an energy analyser. The tilting angle of detection system can be also scanned from 0 to 5 degree for the perpendicular line to the equatorial plane and is also magnetically shielded with two layers of μ metal and one layer of iron. The scattered particles enter the detection system and become ionized due to the collision with H_2 gas reserved in the stripping cell. The differential pumping in the stripping cell is performed with the turbo molecular pump of pumping speed 500 ℓ/s for H_2 gas. The length and bore of stripping cell are 15 cm and 5 cm respectively. The aperture slit has the length of 2 cm and the diameter of 4 mm. The pressure in the analyser is maintained lower than that of the stripping cell by 2 orders of magnitude.

The particles ionized in the stripping cell enter the magnetic field of momentum analyser, and thereafter an electrostatic energy analyser. The energy analysis and detection of ions is performed by a silicon surface barrier detector (hereafter, abbreviated to SSD) which is installed behind the electrostatic energy analyser with the deflection plate of a stainless steel mesh.

The output signals from SSD are fed to the detector counting system as shown in Fig. 3. The signals are amplified by the pre-amp (CANBERRA 2001) and linear amp (CANBERRA 1413), and analysed by the multi-channel pulse height analyser. The SSD and FET of the first stage of preamplifier are cooled by liquid nitrogen.

The detection system has been calibrated with respect to particle momentum, the current of magnet coil, incident beam energy and output pulse height of SSD. The calibration experiment for the conversion efficiency of the stripping cell has not been performed. Because it is already known that in the energy range above 0.4 keV, the conversion efficiency[11)] of stripping cell is in good agreement with the value estimated from cross sections of charge-stripping and electron-capture processes.

Fig. 4 shows SSD signals when exposed to the 30 keV hydrogen ion beam extracted from duoplasmatron ion source. The ions of 30 keV are directly extracted from ion source. The ions with the energy of 15 keV and 10 keV are produced by dissociation from bi-atomic and tri-atomic molecualr ions respectively. The energy resolution of SSD is 11% at 30 keV. In Fig. 5, the relation between incident energy and pulse height is shown. The linear relation holds over the energy range of 8 keV to 30 keV. However, zero pulse height point corresponds to 1.2 keV because the energy of incident particle is lossed by passing through the collector plate of SSD.

It has been confirmed that the SSD has a sufficient capability for an energy analysis above 8 keV. Accordingly in this detection system, the mass separation of hydrogen, deuterium and helium which are used as operation gas of plasma become sufficient with the SSD.

4. Experimental Results and Discussion

The scattering spectrum has been observed in the JFT-2 tokamak operated at the conditions of a toroidal magnetic field of 13 kG, a line averaged electron density of $1.2 \sim 1.5 \times 10^{13}$ cm^{-3} and a plasma current of 100 kA. The obtained scattering spectrum for hydrogen plasma is shown in Fig. 6. In the experiment, the injector was operated with a hydrogen beam of an energy of 15.6 keV, and a drain current of 2 mA. The meassurement of a scattered beam was made at the scattering angle of 4° in order to attain reasonable energy resolution and signal-to-noise ratio.

The scattered particles were counted with the time interval of 100 ms by an electric counter. As SSD is also sensitive to photon, the photons emitted from plasma become the main cause of background noise. Scattering spectra were determined by measuring the particle signals in a discharge and the background noises in the following discharge in turn. Accordingly in order to obtain one energy point of scattered spectrum, two discharges were necessary at least. The net scattered signal was obtained by subtracting background noise from the scattered signal. The fluctuation of background noise mainly contributed to the scattered data point of spectrum in Fig. 6. The observed scattering intensity obtained by these procedure cosists with the value estiamted from Rutherford scattering process of proton to proton.

The beam profile measured by this detection system is also shown in Fig. 6. As the energy of injection beam is stabilized to 10^{-4} order, the beam spread corresponds to the instrumental width of this momentum molecualr ions respectively. The energy resolution of SSD is 11% at 30 keV. In Fig. 5, the relation between incident energy and pulse height is shown. The linear relation holds over the energy range of 8 keV to 30 keV. However, zero pulse height point corresponds to 1.2 keV because the energy of incident particle is lossed by passing through the collector plate of SSD.

It has been confirmed that the SSD has a sufficient capability for an energy analysis above 8 keV. Accordingly in this detection system, the mass separation of hydrogen, deuterium and helium which are used as operation gas of plasma become sufficient with the SSD.

4. Experimental Results and Discussion

The scattering spectrum has been observed in the JFT-2 tokamak operated at the conditions of a toroidal magnetic field of 13 kG, a line averaged electron density of $1.2 \sim 1.5 \times 10^{13}$ cm^{-3} and a plasma current of 100 kA. The obtained scattering spectrum for hydrogen plasma is shown in Fig. 6. In the experiment, the injector was operated with a hydrogen beam of an energy of 15.6 keV, and a drain current of 2 mA. The meassurement of a scattered beam was made at the scattering angle of 4° in order to attain reasonable energy resolution and signal-to-noise ratio.

The scattered particles were counted with the time interval of 100 ms by an electric counter. As SSD is also sensitive to photon, the photons emitted from plasma become the main cause of background noise. Scattering spectra were determined by measuring the particle signals in a discharge and the background noises in the following discharge in turn. Accordingly in order to obtain one energy point of scattered spectrum, two discharges were necessary at least. The net scattered signal was obtained by subtracting background noise from the scattered signal. The fluctuation of background noise mainly contributed to the scattered data point of spectrum in Fig. 6. The observed scattering intensity obtained by these procedure cosists with the value estiamted from Rutherford scattering process of proton to proton.

The beam profile measured by this detection system is also shown in Fig. 6. As the energy of injection beam is stabilized to 10^{-4} order, the beam spread corresponds to the instrumental width of this momentum analyser. The energy resolution of this analyser is 4%. This is in agreement with the value estimated from the exit slit of this analyser. Accordingly the ion temperature was determined by considering the full half width of scattered spctrum of plasma ion and the instrumental width. The obtained ion temperature is 315 eV in this case. In order to compare the ion temperature obtained by this scattering method with one from the measurement of charge-exchange neutrals, 10-ch neutral particle energy analyser was used simultaneouly. Both ion temperatures coincide within ±10% in the present case.

The scattering spectrum for impurity ions could not be observed in this experiment. The estimated peak energy difference between proton and oxygen impurity is 70 eV from Eq. (3). As the energy resolution of this analyser is 4%, the peak profiles for both ions can not be investigated by this analyser system in detail. In this case, it is infered that 1% oxygen ions to plasma proton existed at least in the plasma[12)]. From Rutherford scattering theory, the scattered intensity for 1% oxygen ion is 5 times larger than for proton. Therefore it is considered that impurity ions could contribute the detected scattering intensity besides protons. However, the scattering intensity is in agreement with the intensity for proton estimated from Rutherford scattering. The results suggest that impurity ions do not contribute to the intensity of scattering spectrum. The same phenomenon had also been observed in the T-4 experiment.[7)]

When this scattering method is applied to determine ion temperatures of a tokamak plasma, the influence of impurity ions on the measurement must be investigated in more detail. In order to simulate the scattering process in proton plasma with impurity ions, scattering experiments for various gas target (H_2, He, Ne, Ar) were performed by injecting proton beam into the JFT-2 vacuum chamber filled with a target gas. In the experiments the target is neutral gas and injected particles are protons, while in the measurement of ion temperatures the target is ionized gas and injected particles are hydrogen atoms. However, as the impact parameter of Rutherford scattering is much smaller than Bohr radius, it is considered for Rutherford scattering that this gas scattering process is equivalent to the scattering in the plasma.

The scattered proton was measured by evacuating the stripping cell in order to avoid measuring hydrogen atoms which might be produced under charge-transfer reactions during Rutherford scattering. In Fig. 7

is shown the time behavior of the scattering signal of proton beam for hydrogen gas injected by a gas puffing. The obtained scattered intensities for various target gases of mass, m and square of charge, Z^2 are plotted in Figs. 8 and 9 respectively. In these figures, solid lines are experimental results and dotted lines are the values estimated from Ruthreford scattering theory. The difference between the experimental and theoretical results becomes large as m and Z^2 increase.

In this gas collision process, the proton beam undergoes a charge transfer reaction besides Rutherford scattering. The obtained intensity for gas scattering is smaller than the estimated value from Rutherford scattering only. The cross section of charge transfer[13,14,15,16) increases with the atomic number in this collision at energy of 15 keV. The trend of the data shown in Figs. 8 and 9 is consistent with the cross section data.

In the measurement of plasma, the inverse phenomenon of this gas scattering process occurs. The injected neutral beam also undergoes charge transfer and impact ionization reactions during Rutherford scattering. Ionized particles through the scattering process are unable to escape from the plasma because there is a toroidal magnetic field and therefore might have no contributions to scattering spectrum.

This gas scattering result is applied to the interpretation of contribution of 1% oxygen ions of main impurity to the scattering intensity of 15 keV hydrogen atom in this hydrogen plasma experiment. The scattering intensity estimated from Rutherford theory for 1% oxygen ions is 5 times larger than for protons and the gas scattering intensity for oxygen infered from the gas scattering result of Fig. 9 reduces to 1/6 in comparison with the intensity estimated from Rutherford scatterring process only. On the other hand the ionization cross section[17,18) (2.4×10^{-15} cm^3 including charge transfer and impact ionization) of 15 keV hydrogen atom by oxygen ions in the plasma is larger than the charge transfer cross section[14) (3.2×10^{-16} cm^2) of 15 keV proton to oxygen O_2 in gas scattering. Accordingly the scattering intensity for oxygen ion O^{8+} in the plasma must be smaller than that for oxygen O_2 scattering. As the gas scattering intensity for Ar whose the charge transfer cross section to 15 keV proton is 8×10^{-16} cm^2[16) reduces to 1/20 in Fig. 9, it is infered from this gas scattering data that in the plasma the scattering intensity for O^{8+} reduces over 1/20. Therefore in the plasma scattering experiment, the intensity for oxygen ions

is buried in the spectrum of hydrogen ion. As a result, the contribution of oxygen ions to scattering spectrum has not been observed.

The influence of impurity ion on the scattering spectrum in the plasma has been simulated by this gas scattering experiment. It has been made clear from this experiment that the influence of impurity ion was not present in the scattering spectrum.

Until now the effect of impurity ions to the scattering sectrum is indistinct, but the absence of the peak for impurity ions in the scattering spectrum in recent tokamak experiments could be resonably understood from the results of this gas scattering experiments.

5. Summary

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

(1) The active beam scattering system has been developed and constructed to measure high ion temperatures of JFT-2 tokamak.

(2) Using SSD for low energy particle, the detection of particle signal in the scattering experiment has been successfully performed.

(3) The obtained ion temperature consists with the passive charge exchange measurement.

(4) The influence of impurity to the scattering spectrum has been investigated by gas scattering experiment.

(5) The measured scattering intensity is smaller than the estimated value from Rutherford scattering theory, because the ionization process exists in the collision process.

(6) The method of estimating impurity effect has been established on the application of this scattering method.

Acknowledgements

The authors are grateful to members of JFT-2 and JFT-2 operating groups for their discussions and efforts. In particular we appreciate many fruitful suggestions and co-operation to our experiment by Drs. A. Funahashi and T. Kimura. We would like to express our gratitude to Drs. Y. Shimomura, Y. Tanaka, Y. Suzuki, M. Tanaka, and M. Yoshikawa for their continuous encouragement to the present work.

is buried in the spectrum of hydrogen ion. As a result, the contribution of oxygen ions to scattering spectrum has not been observed.

The influence of impurity ion on the scattering spectrum in the plasma has been simulated by this gas scattering experiment. It has been made clear from this experiment that the influence of impurity ion was not present in the scattering spectrum.

Until now the effect of impurity ions to the scattering sectrum is indistinct, but the absence of the peak for impurity ions in the scattering spectrum in recent tokamak experiments could be resonably understood from the results of this gas scattering experiments.

5. Summary

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

1. (1) The active beam scattering system has been developed and constructed to measure high ion temperatures of JFT-2 tokamak.
2. (2) Using SSD for low energy particle, the detection of particle signal in the scattering experiment has been successfully performed.
3. (3) The obtained ion temperature consists with the passive charge exchange measurement.
4. (4) The influence of impurity to the scattering spectrum has been investigated by gas scattering experiment.
5. (5) The measured scattering intensity is smaller than the estimated value from Rutherford scattering theory, because the ionization process exists in the collision process.
6. (6) The method of estimating impurity effect has been established on the application of this scattering method.

Acknowledgements

The authors are grateful to members of JFT-2 and JFT-2 operating groups for their discussions and efforts. In particular we appreciate many fruitful suggestions and co-operation to our experiment by Drs. A. Funahashi and T. Kimura. We would like to express our gratitude to Drs. Y. Shimomura, Y. Tanaka, Y. Suzuki, M. Tanaka, and M. Yoshikawa for their continuous encouragement to the present work.

is buried in the spectrum of hydrogen ion. As a result, the contribution of oxygen ions to scattering spectrum has not been observed.

The influence of impurity ion on the scattering spectrum in the plasma has been simulated by this gas scattering experiment. It has been made clear from this experiment that the influence of impurity ion was not present in the scattering spectrum.

Until now the effect of impurity ions to the scattering sectrum is indistinct, but the absence of the peak for impurity ions in the scattering spectrum in recent tokamak experiments could be resonably understood from the results of this gas scattering experiments.

5. Summary

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

(1) The active beam scattering system has been developed and constructed to measure high ion temperatures of JFT-2 tokamak.

(2) Using SSD for low energy particle, the detection of particle signal in the scattering experiment has been successfully performed.

(3) The obtained ion temperature consists with the passive charge exchange measurement.

(4) The influence of impurity to the scattering spectrum has been investigated by gas scattering experiment.

(5) The measured scattering intensity is smaller than the estimated value from Rutherford scattering theory, because the ionization process exists in the collision process.

(6) The method of estimating impurity effect has been established on the application of this scattering method.

Acknowledgements

The authors are grateful to members of JFT-2 and JFT-2 operating groups for their discussions and efforts. In particular we appreciate many fruitful suggestions and co-operation to our experiment by Drs. A. Funahashi and T. Kimura. We would like to express our gratitude to Drs. Y. Shimomura, Y. Tanaka, Y. Suzuki, M. Tanaka, and M. Yoshikawa for their continuous encouragement to the present work.

References

1) H. Takeuchi, A. Funahashi, K. Takahashi, H. Shirakata, and S. Yano: Japan. J. Appl. Phys. 16, (1977) 139.

2) T. Sugie, H. Takeuchi, S. Kasai, A. Funahashi, K. Takahashi, and H. Kimura: J. Phys. Soc. Japan. 44, (1978) 1960.

3) A.L. Berry, A.C. England, J.F. Lyon, and G.L. Mogan: ORNL-TM-5054 (1975)

4) D.E. Evans. J. Katzenstein: Rep. Progress Phys. 32, (1969) 207.

5) P. Woskoboinikow, H.C. Praddaude, W.J. Mulligan, D.R. Cohn, B. Lax, and H.R. Fetterman: Sixth International Conference on Infrared and Millimeter waves, IEEE CAT, No. 81 CH1645-1 MIT

6) V.G. Abramov, V.V. Afrosimov, I.P. Gladkovskii, A.I. Kislyakov, and V.I. Perel: Sov. Phys.-Tech. Phys: 16, (1972) 1520.

7) E.V. Aleksandrov, V.V. Afrosimov, E.L. Berezovskii, A.B. Izvozchikov, V.I. Marasev, A.I. Kislyakov, E.A. Mikhailov, M.L. Petrov, and G.V. Roslyakov: JETP Lett., 29, (1979) 1.

8) E.L. Berezovskii, A.I. Kislyakov. S. Ya. Petrov, and G.V. Kislyakov: Sov. J. Plasma Phys., 6, (1980) 760.

9) Annual Report of JAERI Fusion Research and Development Center: JAERI-M 9421 (1981)

10) V.V. Afrosimov, I.P. Gladkovskii and A.I. Kislyakov: Sov. Tech. Phys. Lett. 3, (1977) 3.

11) N. Noda: J. Phys. Soc. Japan 41, 625 (1976)

12) S. Konoshima, et al., J. Nucl. Materials 76, 581 (1978)

13) F.J. deHeer, J. Schutten and H. Moustafa: Physica 32, 1768 (1966)

14) P.M. Stier and C.F. Barnett: Phys. Rev. 103, 896 (1956)

15) G.W. McClure: Phys. Rev. 130, 1852 (1963)

16) J.F. Williams: Phys. Rev. 150, 7 (1966)

17) A. Salop and R.E. Olson: Phys. Rev. A 13, 1312 (1976)

18) R.E. Olson and A. Salop: Phys. Rev. A 16, 531 (1977)

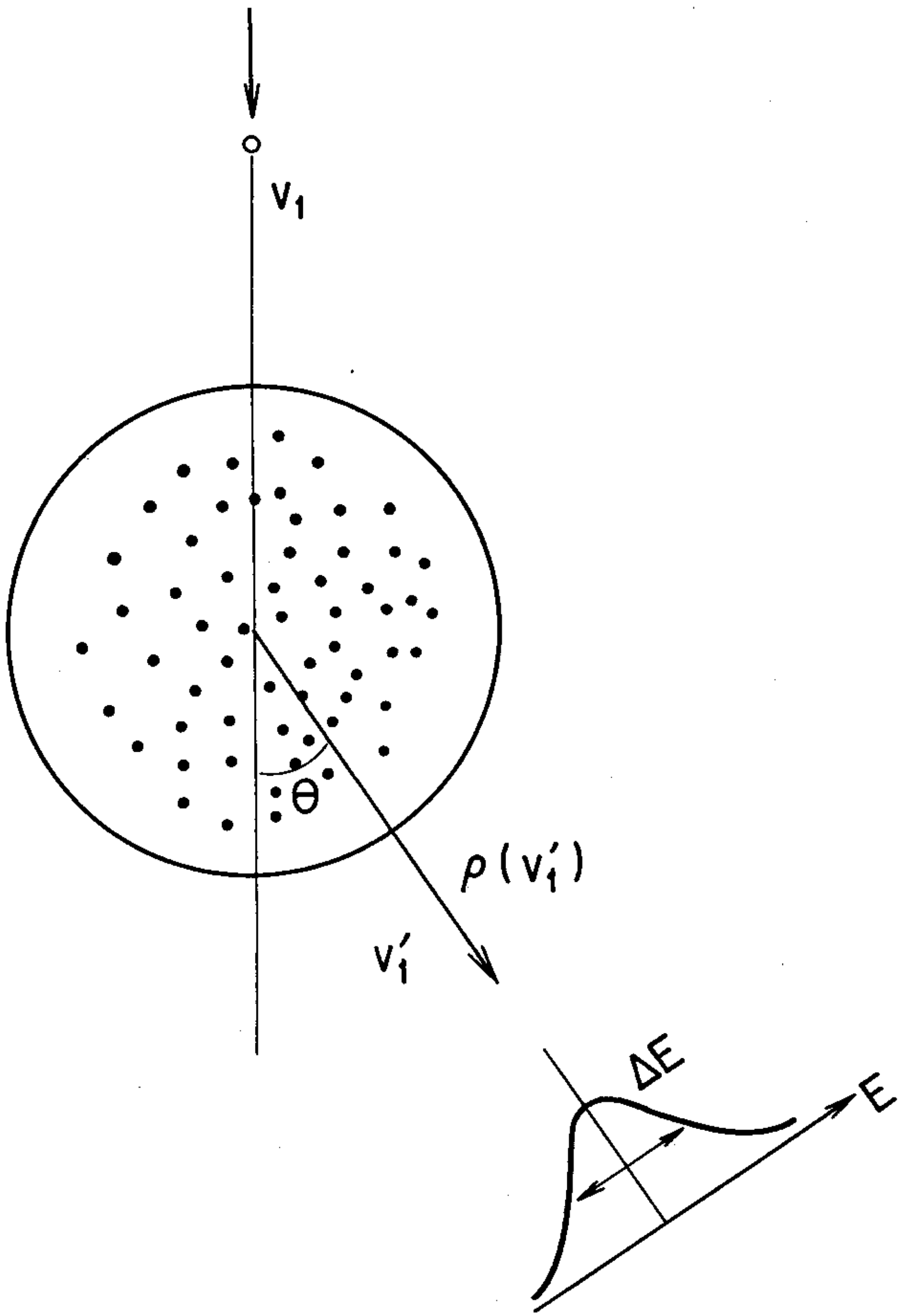

Fig. 1 Schematic diagram of neutral beam scattering method for measurement of plasma ion temperature, v_1: beam velocity, v_1': scattered beam velocity, θ : scattering angle, ΔE: energy spread of scattered particle, T_i: ion temperature.

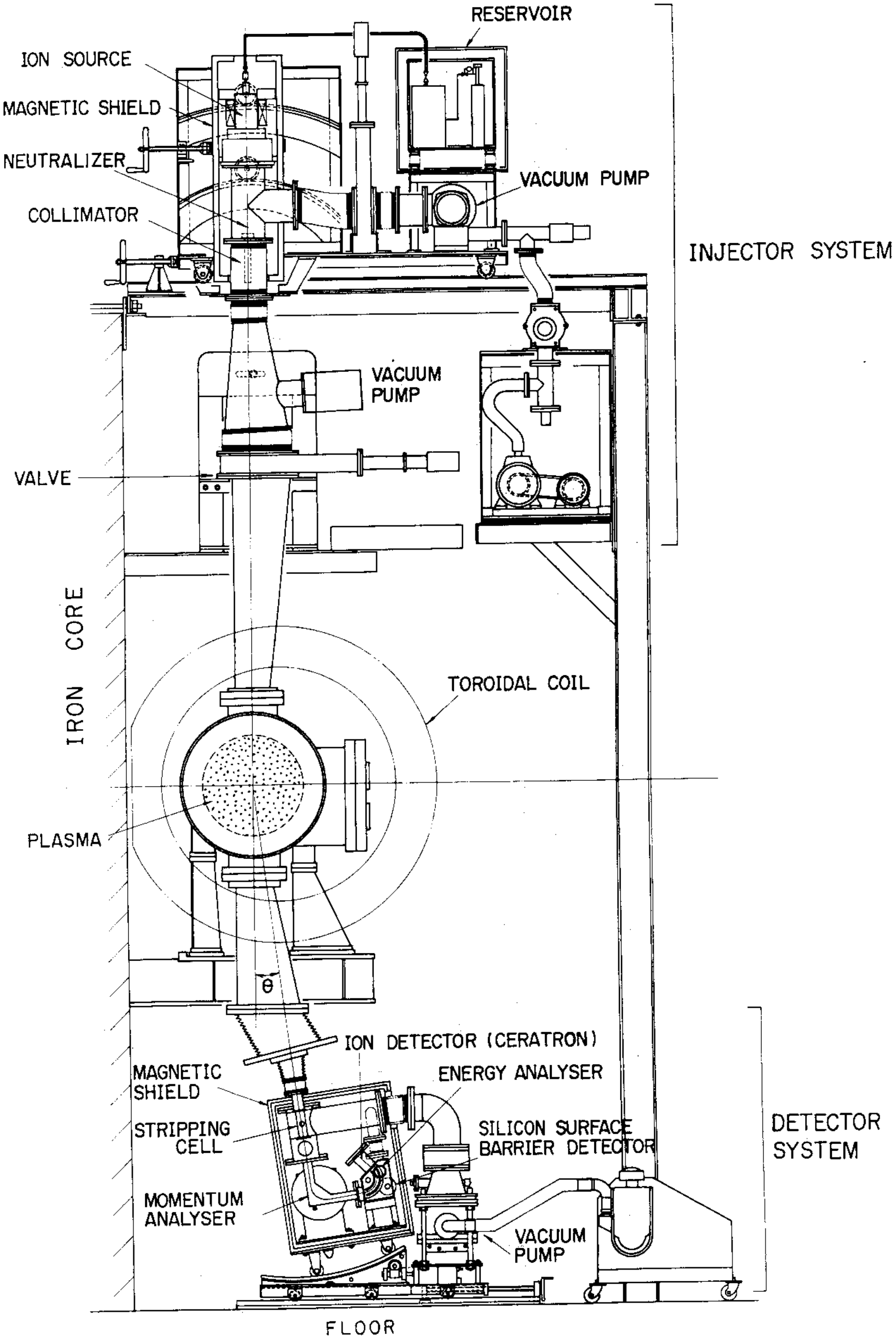

Fig. 2 Neutral beam scattering system installed in JFT-2 tokamak.

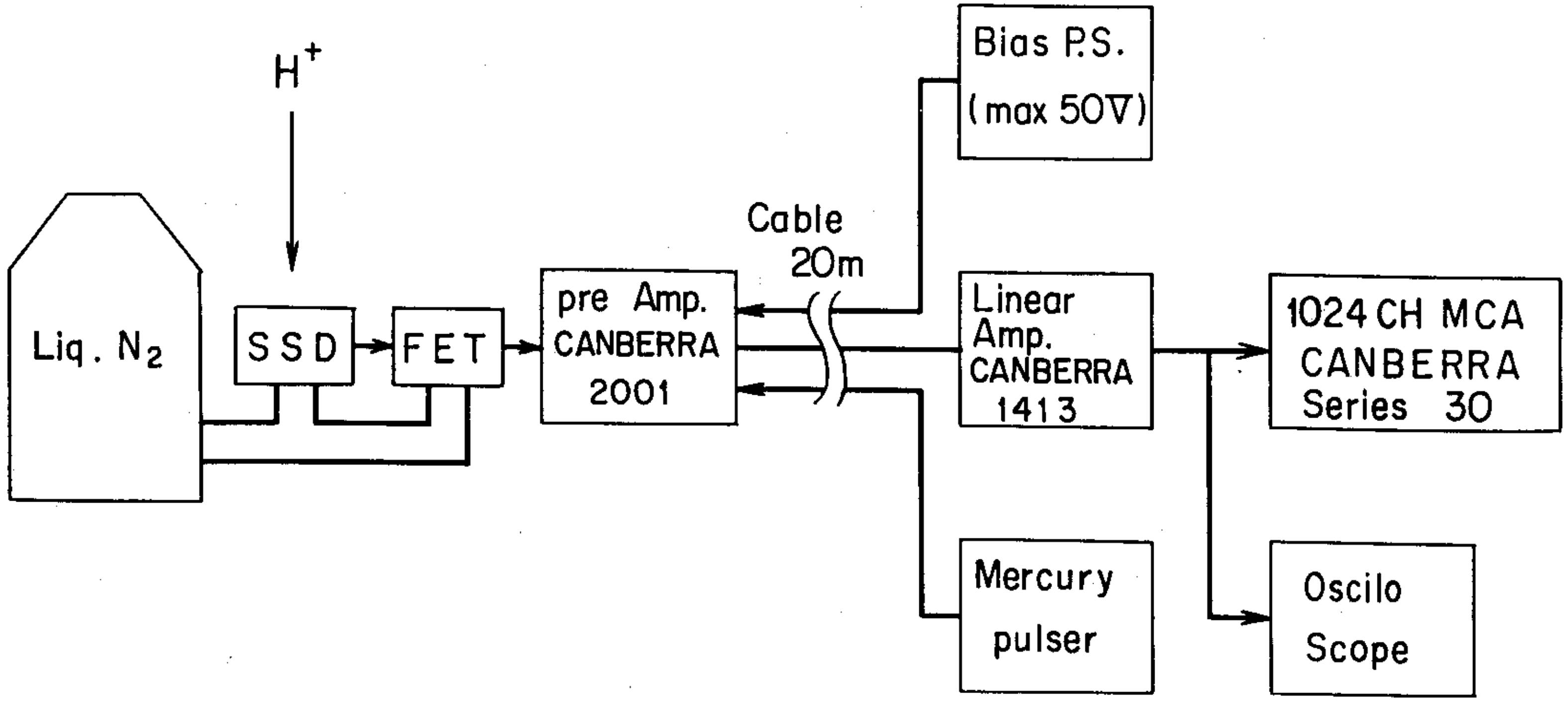

Fig. 3 Detector counting system.

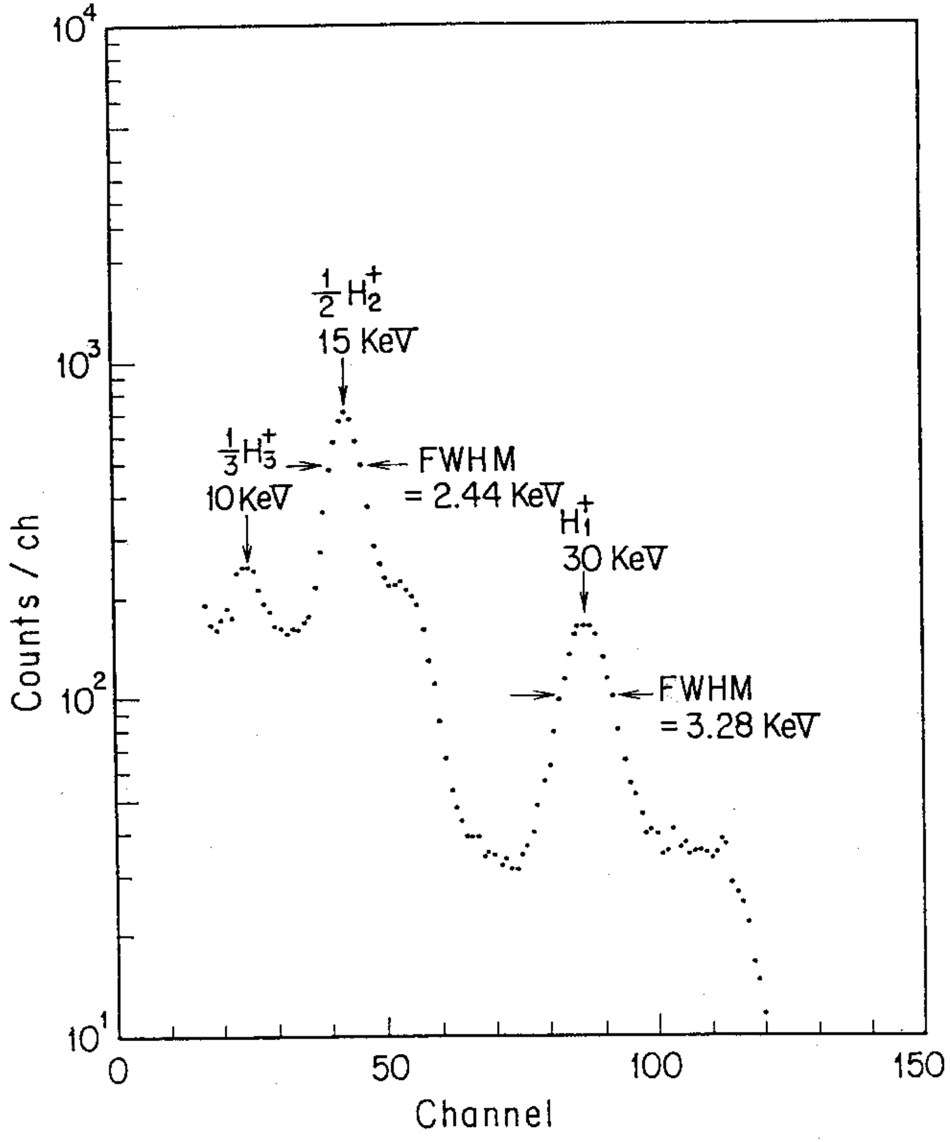

Fig. 4 SSD detection characteristics in the radiation of hydrogen ions emitted from ion source accelerated at 30 keV.

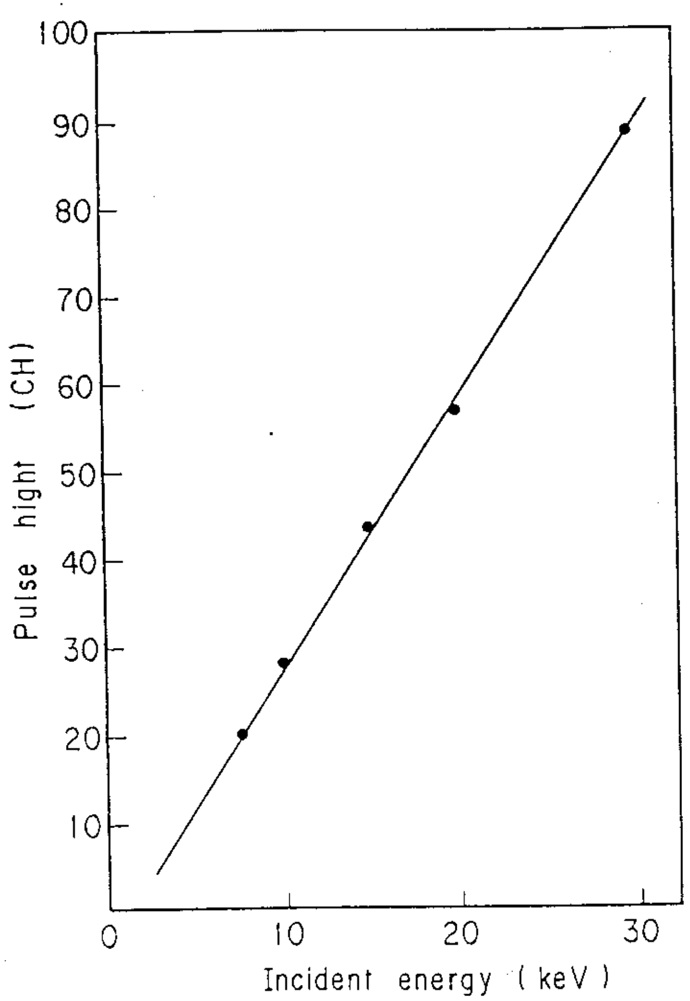

Fig. 5 Pulse hight characteristics of SSD V.S. incident energy.

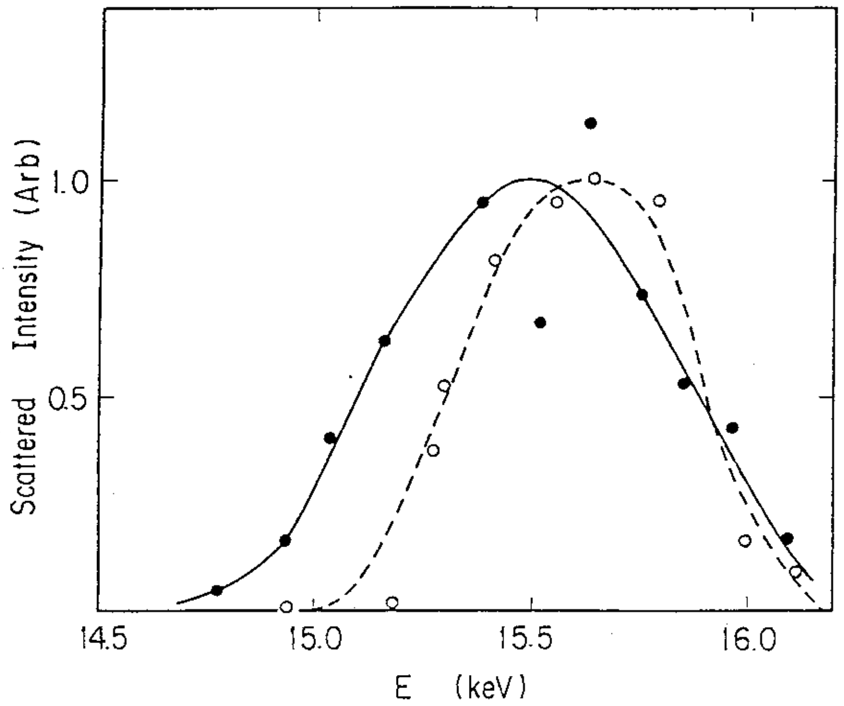

Fig. 6 Scattering spectrum obtained by this scattering system. Solid line is spectrum of hydrogen plasma and dashed line is beam profile.

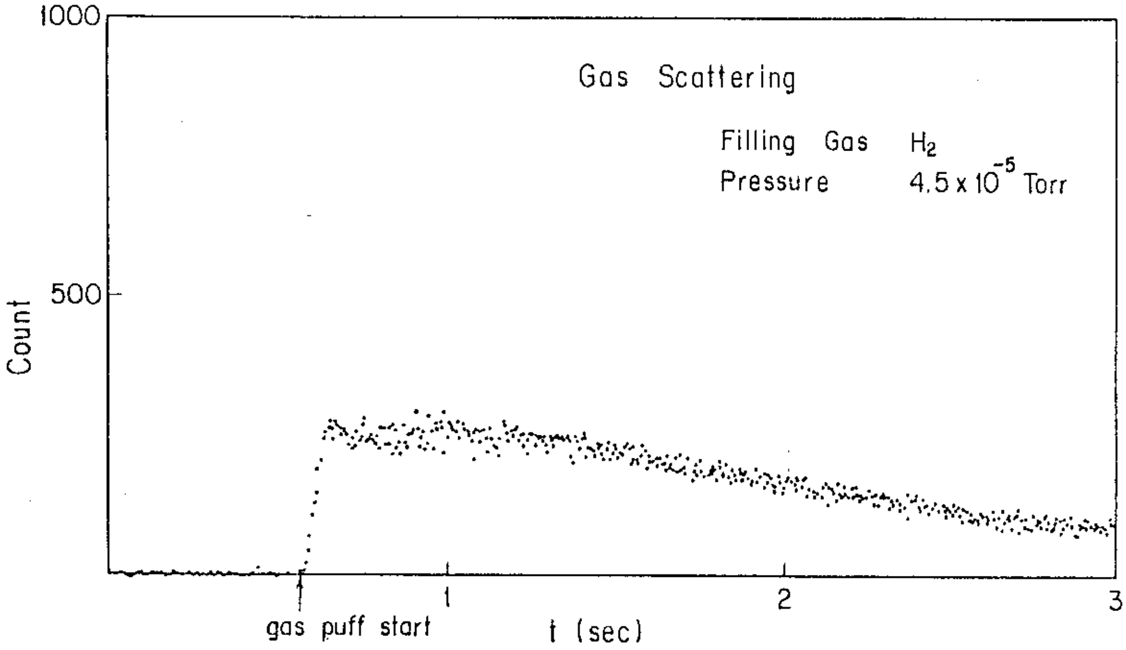

Fig. 7 Time variation of scattering intensity of hydrogen beam for the hydrogen gas puff.

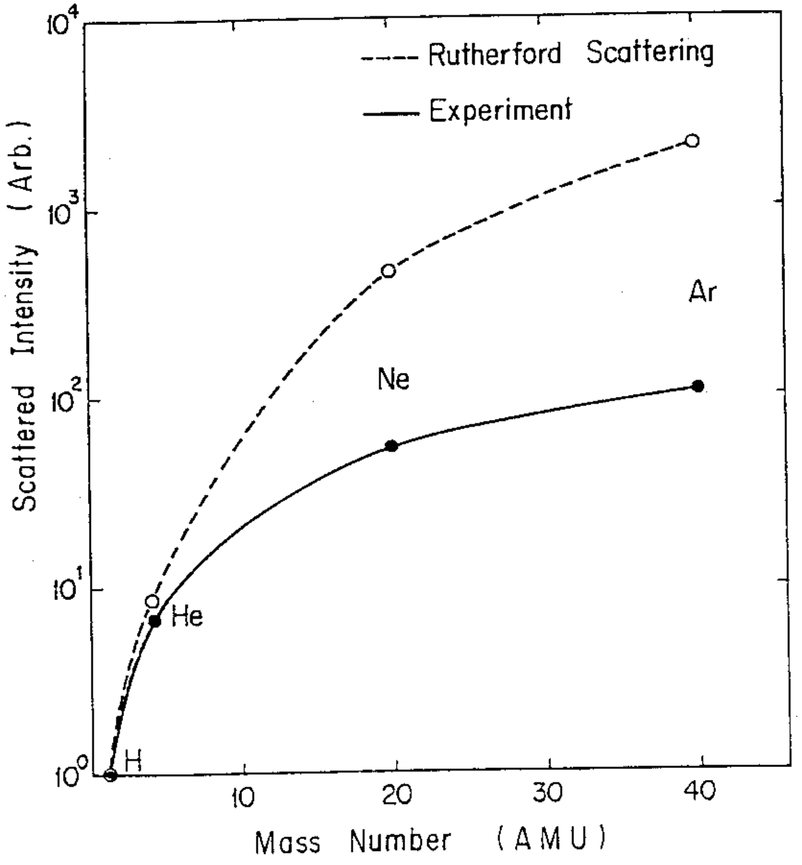

Fig. 8 Comparison of scattered intensity with mass variation between the gas scattering experiment and Rutherford scattering theory.

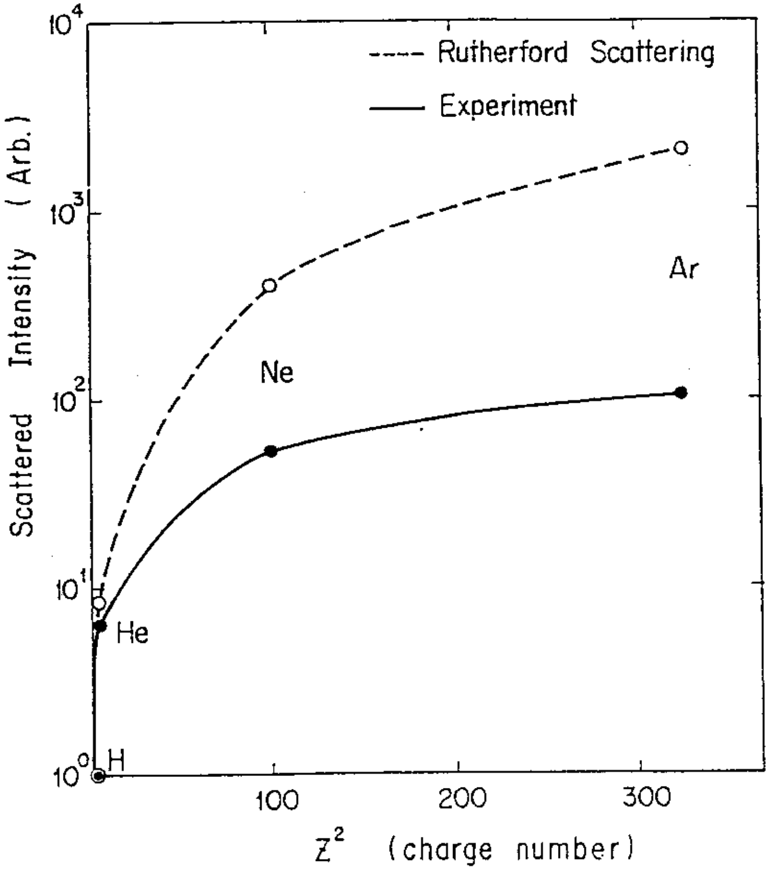

Fig. 9 Comparison of scattered intensity with charge number variation between gas scattering experiment and Rutherford scattering theory.