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The energetic atomic hydrogen in an MeV range produced by the ion cyclotron range of frequency heating in JT-60U plasma was directly measured with a charge-exchange neutral particle analyzer. Particle signals from the detector were successfully separated from the neutron and $\gamma$ ray background by the pulse height analysis (PHA) method used first in all detector channels. The net flux of atomic hydrogen was easily obtained by summing counted numbers of PHA channels over the peak formed by atomic hydrogen.

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Keywords: JT-60U, Alpha Particle, Neutral Particle Analyzer, Ioffe Institute, ICRF, Atomic Hydrogen, Neutron, $\gamma$ Ray, Pulse Height Analysis.

# JT-60UのICRF加熱プラズマにおける荷電交換中性粒子分析器を用いたMeV領域水素原子の直接測定

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JT-60Uプラズマにおけるイオンサイクロトロン周波数帯加熱によって生成されたMeV領域の高エネルギー水素原子を荷電交換中性粒子分析器を用いて直接測定した。初めて検出器の全チャンネルに用いた波高分析法によって、検出器からの粒子信号を中性子及びガンマ線によるノイズと分離することに成功した。水素原子によって形成されたピークにわたり波高分析チャンネルのカウント数を足し合わせることによって、正味の水素原子束を容易に得ることができた。

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## 1. Introduction

Charge-exchange (CX) neutral particle measurement[1] is the most reliable diagnostic method to evaluate an energy distribution of ions in a plasma. In recent years, the CX diagnostic method has been applied to the measurement of MeV-range ions in JET[2, 3] and TFTR[4, 5] to predict alpha particle behavior in a next-step fusion device like ITER[6] and a tokamak fusion reactor.

In JT-60U, alpha particle behavior is planned to be investigated in a D-$^3$He plasma heated by neutral beams of 500 keV and by the ion cyclotron range of frequency (ICRF) waves. In recent experiments, the toroidal Alfvén eigenmodes (TAE mode)[7, 8, 9] have been intensively studied with MeV protons produced by the ICRF heating. Direct measurement of the MeV protons during the TAE excitation became important. For these studies, a charge-exchange neutral particle analyzer covering the energy up to 4 MeV for alpha particles has been developed and installed in JT-60U under the collaboration between the A. F. Ioffe Physical-technical Institute, Russia, and the Japan Atomic Energy Research Institute(JAERI). A pulse height analysis (PHA) method has been used first in all detector channels to distinguish particle signals from neutron and $\gamma$ ray background.[10] In this report, first results of the measurement of energetic atomic hydrogen up to 1 MeV using the analyzer in the ICRF heating are presented.

## 2. Characteristics and setup of the analyzer

Energetic neutral particles entering the analyzer are ionized by stripping in a thin carbon foil of thickness 400 Å. The energy and mass of secondary ions are separated by a combination of magnetic and electrostatic fields(E//B type). The analyzer has eight detectors consisting of CsI(Tl) scintillators of thickness 10 $\mu$m and photomultiplier tubes (PMT). The detectable energy range for alpha particles is 0.5-4 MeV. The ratio of the highest energy channel to the lowest energy channel($E_8/E_1$) is 4.08. The energy resolution of the analyzer is 6-11%. The absolute detection efficiency, defined as a ratio of detected particle number to the particle number entering the analyzer, is 30-40% for alpha particle energies over 1 MeV. The setup and line-of-sight for the neutral particle analyzer on JT-60U is shown in Fig. 1 and Fig. 2, respectively. The analyzer views the JT-60U plasma vertically at the major radius of 3.56 m.

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The analyzer has a special feature in the data processing system. A pulse counting system is widely used in neutral particle analyzers because the system is simple and useful when a sufficient neutral particle flux is expected and the background noise arising from neutrons and $\gamma$ rays is negligible. However, a pulse counting system is not feasible when the neutral particle flux is small and the noise level is high. Therefore, a 16-channel pulse height analysis system has been adopted in all detector channels of this analyzer.[10] Our new system distinguishes pulses from energetic ions from the background due to neutrons, $\gamma$ rays and optical lights from the plasma by utilizing the different pulse heights. The voltages to each PMT are adjusted for the particle species and energies of each detector channel in order to separate pulses of the particles from the background.

## 3. Measurement results and discussion

The measurement of energetic protons was carried out in a plasma heated by deuterium neutral beams and ICRF waves. The plasma current was 3.5 MA and the toroidal magnetic field at the center of the vacuum vessel was 4 T. The frequency of the ICRF waves was 116 MHz and the $2\omega_{cH}$ resonance layer of the ICRF waves was located at 3.5 m of major radius, which is near the center of the plasma. The resonance layer was located at the sight volume of the analyzer. Figure 3 shows time evolutions of (a) line-averaged electron density, central ion and electron temperatures, (b) deuterium neutral beam power and ICRF power, (c) neutron yield. The line-averaged electron density was $2.3\times10^{19}$ $m^{-3}$ at 8 sec. Neutral beam and ICRF power was 15 MW and 4 MW, respectively.

The magnetic and electric fields of the analyzer were adjusted to measure energetic atomic hydrogen of 0.25 MeV (Ch1) to 1 MeV (Ch8) in this discharge. Moreover, photomultiplier voltages were applied to measure each energy of protons, following the calibrated formula $A/E=k(U/U_0)^\beta$ (A: pulse height, E: particle energy, U: photomultiplier voltage) with a coefficient k for protons and a power $\beta$ for each photomultiplier.[10] Figure 3 (d) shows temporal behavior of total count rate of Ch8 of the analyzer. As the neutron yield built up by neutral beam injection, the detector started to count signal pulses. The total count of Ch8 increased ~30% by injection of the ICRF waves. Meanwhile, an increment in neutron emission was ~20%. This result means that the detector of the analyzer counted not only neutrons and $\gamma$ rays but particle flux produced by the ICRF heating. Other detectors showed similar time evolution.

Figure 4 compares pulse height distributions of Ch2, Ch4, Ch6 and Ch8 at the NBI alone phase (7.3 s) and at the NBI + ICRF phase (7.8 s). The sampling time duration was 50 ms. In the NBI alone phase, neutrons and $\gamma$

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The full width of the half maximum of a proton peak in Fig. 4 is 4-5 PHA channels, which corresponds to ~40% of energy of each detector channel. Calibration experiment showed that scintillator detectors of this analyzer had a broadening of 35%-40%, 20%-30% and 15%-25% for 0.2 MeV, 0.4 MeV and 0.95 MeV of mono-energetic protons, respectively. The measured broadening is a little wider than that obtained from the calibration experiment. The cause of this broadening is now under investigation.

## 4. Summary

Charge-exchange (CX) neutral particle measurement in an MeV energy range was performed in a combined heating with deuterium beam and ICRF waves, using a CX diagnostics system developed under collaboration between Ioffe Institute, Russia, and JAERI. In order to distinguish the pulses of the alpha particles and protons from the background due to neutrons, γ rays and optical lights from the plasma, the pulse height analyzer was introduced to the signal processing system. Pulse signals due to energetic atomic hydrogen were successfully separated from the neutron and γ ray background as expected, using the pulse height analysis system. The net flux of proton was easily obtained by summing rays were detected with a high count number at low PHA channels. The background signal decays in 6 PHA channels for Ch2 and in 3-4 PHA channels for Ch4 to Ch8. It should be noted that the background noise level was negligibly low at PHA channels above the background detected by low PHA channels. On the other hand, a clear peak was observed at central PHA channels in the NBI+ICRF phase. In the experiment, the deflection magnetic and electrostatic fields and photomultiplier voltages were applied for the measurement of protons. From this reason, we could conclude that the observed peak in each pulse height distribution was formed by energetic protons. It was confirmed from Fig. 4 that pulses from energetic ions could be successfully distinguished from neutron and $\gamma$ ray background by the introduction of the PHA method. Therefore, we could directly obtain a net flux of the energetic atomic hydrogen by summing the counted numbers of PHA channels over the peak due to protons. A time evolution of atomic hydrogen flux of 1 MeV is shown in Fig. 3 (d). The background noise included in the evaluated net flux of atomic hydrogen was less than 1%. Energetic protons can be observed only in the ICRF heating phase. It was found from this measurement that minority protons were accelerated up to an MeV range by the ICRF wave.

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## References

[1] V. V. Afrosimov and M. P. Petrov, Sov. Phys. Tech. Phys. **12**, 1467 (1968).

[2] A. B. Izvozchikov, A. V. Khudoleev, M. P. Petrov, S. Ya. Petrov, S. S. Kozlovskij, S. Corti, and A. Gondhalekar, JET Joint European Torus Report, JET-R(91)12, 1991.

[3] JET TEAM, in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 14th Int. Conf. Würzburg, 1992), Vol. 1, IAEA, Vienna (1993) 429.

[4] S. S. Medley, R. K. Fisher, A. V. Khudoleev, D. K. Mansfield, J. M. McChesney, P. B. Parks, M. P. Petrov, C. K. Phillips, A. L. Requemore, and K. M. Young, in Proc. of 20th Eur. Conf. on Controlled Fusion and Plasma Physics, Lisboa(1993), Vol. 17C, Part III, p. III-1183, European Physical Society, 1993.

[5] R. J. Hawryluk, H. Adler, P. Alling, C. Ancher, H. Anderson, et al., 15th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Seville, Spain, 1994, IAEA-CN-60/A-1-I-1.

[6] ITER Conceptual Design Report, ITER Documentation Series No. 18, IAEA, Vienna, 1991.

[7] C. Z. Chen and M. S. Chance, Phys. Fluids 29, (1986) 3695.

[8] H. Kimura, M. Saigusa, S. Moriyama, T. Nishitani, T. Kondoh, et al., submitted to Phys. Rev. Lett and references therein.

[9] M. Saigusa, H. Kimura, T. Fujii, S. Moriyama, M. Satoh, et al., 15th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Seville, Spain, 1994, IAEA-CN-60/A-3-I-5.

[10] Y. Kusama, M. Nemoto, M. Satoh, Y. Tsukahara, K. Tobita, H. Takeuchi, S. Petrov, V. Afanassiev, S. Kozlovskij, A. Kislyakov, M. Petrov, Rev. Sci. Instrum., Jan. 1995 (in press).

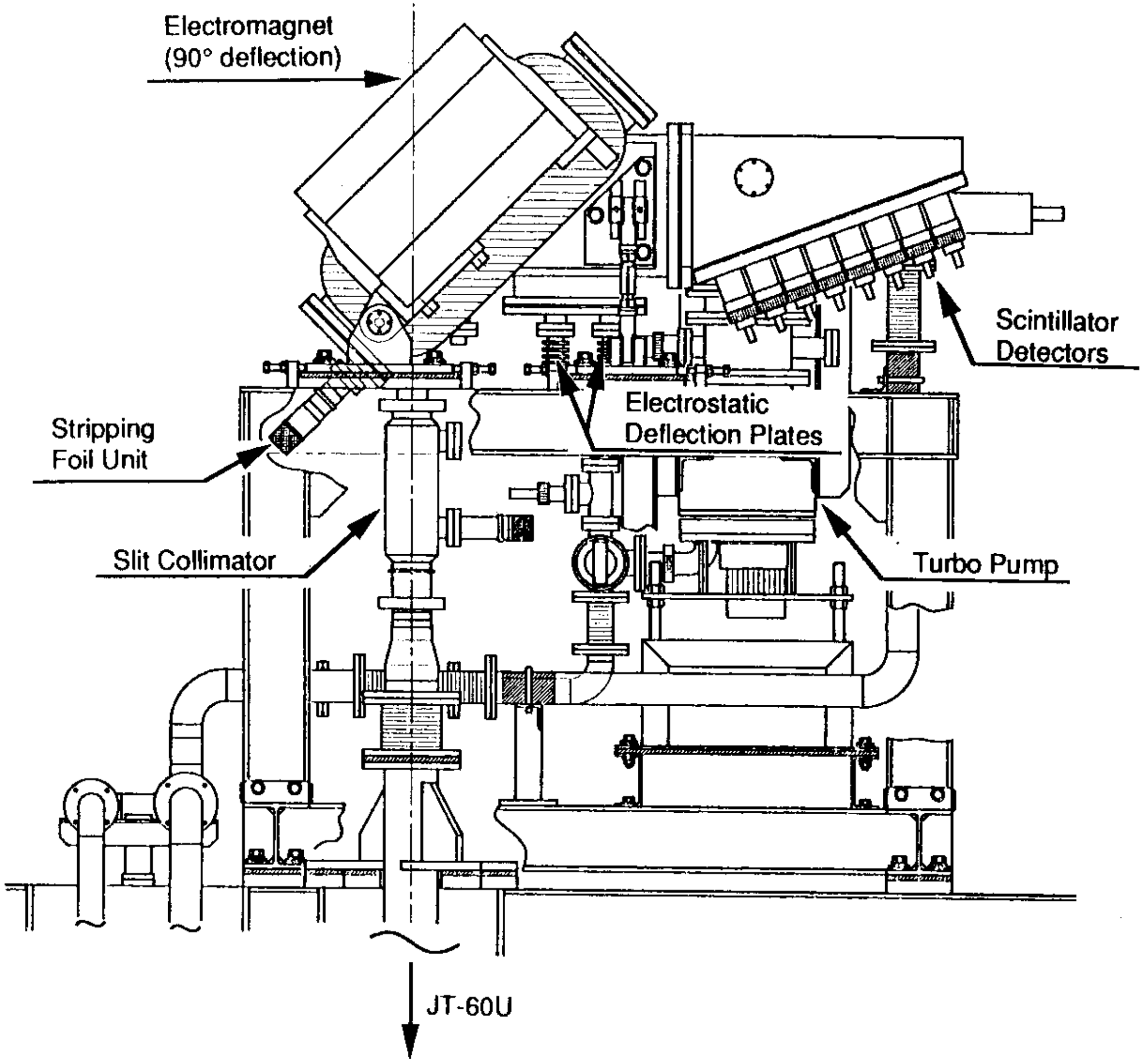

Fig. 1 Schematic diagram of the charge-exchange neutral particle analyzer with a pumping system and a support structure on JT-60U.

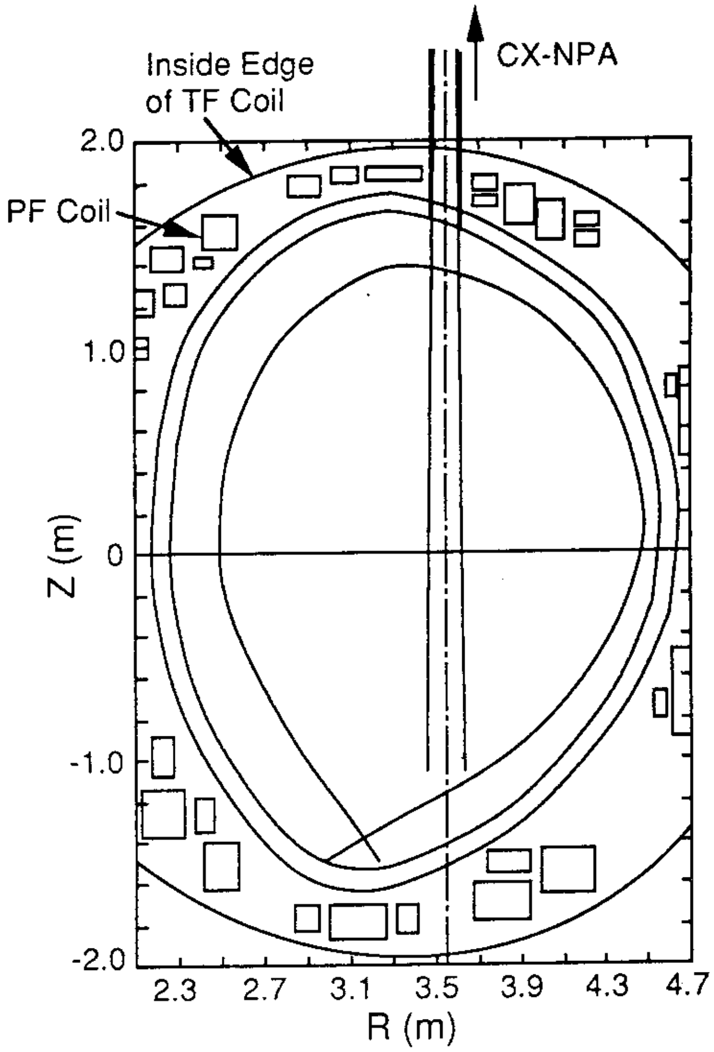

Fig. 2 Line-of-sight for the charge-exchange neutral particle analyzer (CX-NPA) on JT-60U.

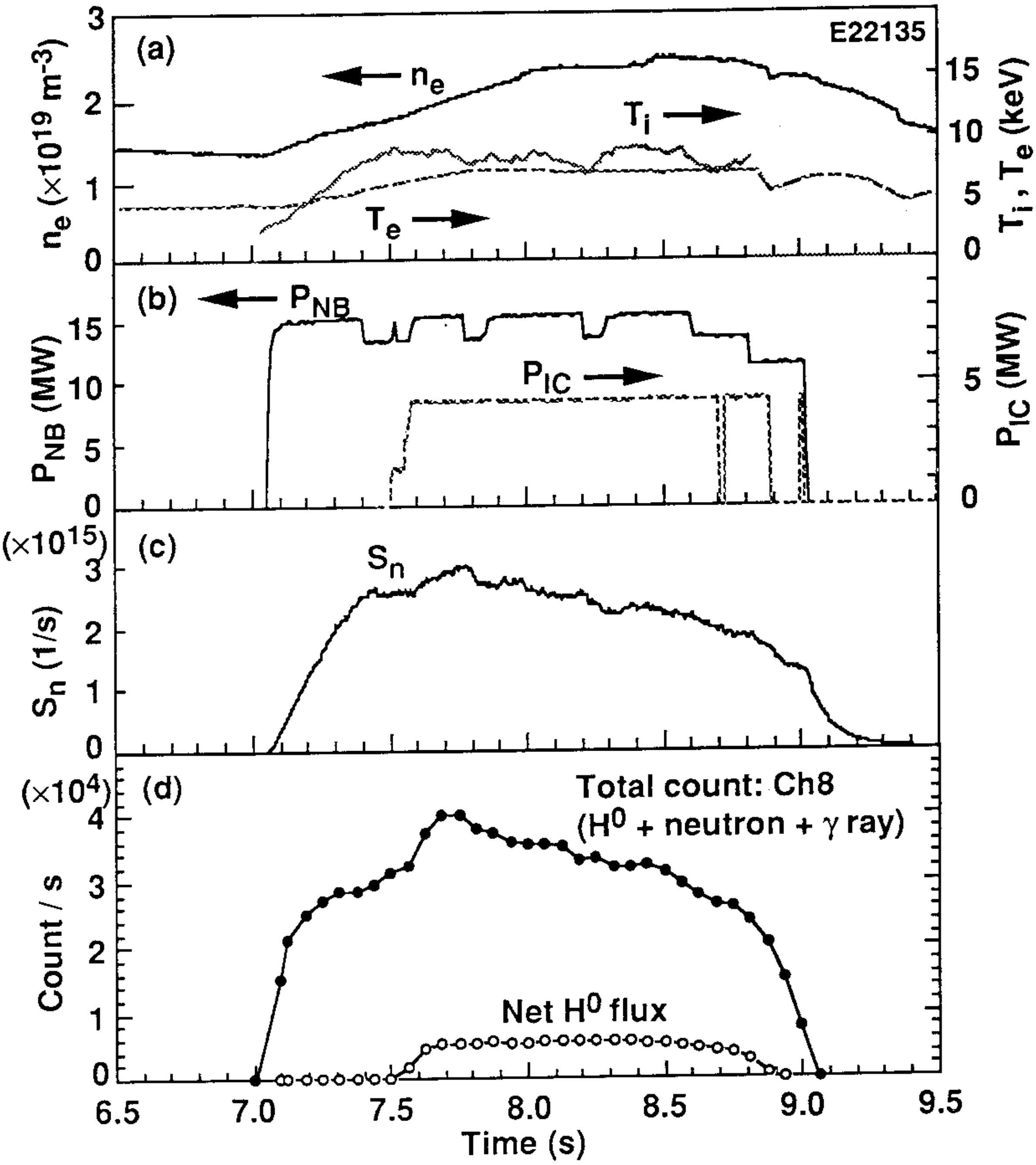

Fig. 3 Time evolution of (a) line-averaged electron density($n_e$), central ion and electron temperatures($T_i$, $T_e$), (b) neutral beam power ($P_{NB}$) and ICRF power($P_{IC}$), (c) neutron emission rate($S_n$), (d) total count rate of Ch8 and net count rate of energetic atomic hydrogen (1 MeV) detected by Ch8.

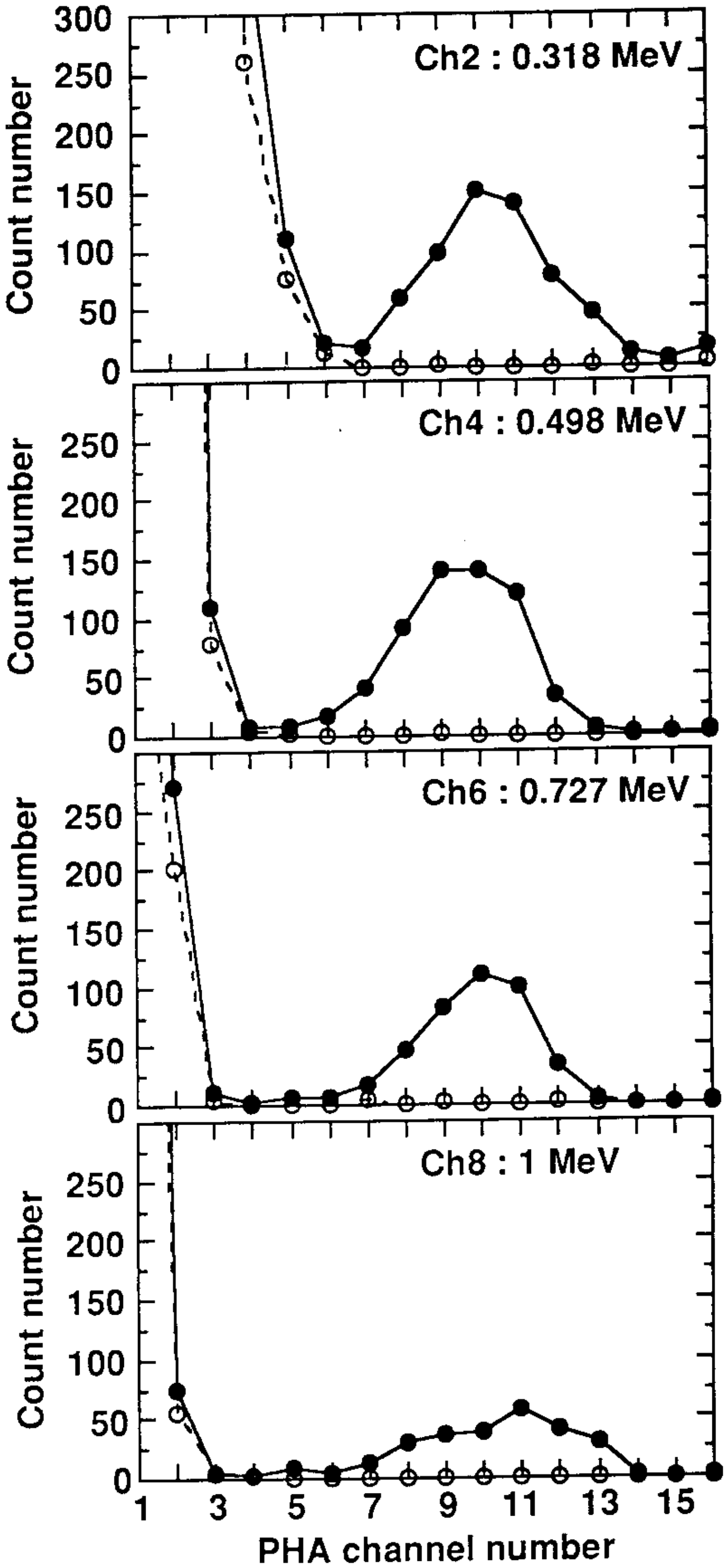

Fig. 4 Pulse height distributions of Ch2, Ch4, Ch6 and Ch8 at the NBI alone phase (7.3 s, open circles) and at the NBI+ICRF phase (7.8 s, filled circles).