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ABSTRACT

Confinement of ripple-trapped energetic ions is studied in a low-aspect-ratio helical system using a neutral beam with variable injection angle. The heating efficiency was found to be very low for the perpendicular injection compared with the tangential one, in the magnetic field configuration which is optimized for the global confinement for the tangential NBI plasmas. Confinement of beam ions was improved by shifting the magnetic axis inward, which was confirmed by the measurement of their energy spectrum. The results are consistent with the calculation of Monte Carlo beam-ion-thermalization code. The poloidal rotation near plasma edge is measured for different injection angles which shows larger value for the perpendicular injection.

The fast wave ICRF heating is applied to a low-aspect-ratio helical system. Substantial energy increase is obtained for the NBI taget plasma. High energy ion tail is observed in the limited range of pitch angles.

Keywords : Low-aspect-ratio, Fast ions, Orbit loss, Trapped particles, Neutral particle energy analyzer, Electric field, ICRF heating

Introduction

In helical systems, the transport related with the magnetic field ripple is one of the most important problems. It appears as direct orbit losses of high energy particles which are trapped in the magnetic field ripple, as well as additional non-axisymmetric terms in the neo-classical transport calculations. In low-aspect-ratio heliotron/torsatrons, because the drift orbits of trapped particles largely deviate from the magnetic surfaces, the problem of the orbit losses is more important [1]. It is possible, however, to improve the confinement of trapped particles by optimizing the magnetic field configuration [2]. This paper gives the experimental studies of these problems by comparing the heating efficiencies of tangential and perpendicular neutral beam injection for different magnetic field configurations.

The radial electric field in the plasma has been receiving attention especially for helical systems in relation to the confinement improvement [3,4]. The electric field is determined primarily by the bulk plasma density and temperature profiles but additional particle loss channels are also important to determine the electric field. In particular, orbit losses of trapped ions possibly contribute to the generation of the electric field in plasmas.

The ICRF heating has been successful in tokamak research. In helical systems, it was successful so far in Heliotron-E which has a high aspect-ratio [5]. The applicability of ICRF heating to low-aspect-ratio machines has been in discussion because of the uncertainty of the sufficient confinement of high energy ions produced by ICRF waves. The actual experiments are necessary.

NBI experiments with variable injection angle

CHS (Compact Helical System) [6] is a low-aspect-ratio heliotron/torsatron which has an aspect ratio 5 (major radius: $R = 1$ m, minor radius: $a = 0.2$ m) and the toroidal period number : $m = 8$. The maximum magnetic field on axis is $B_t = 2$ T. Two neutral beam injectors are installed. NBI-1 ($E_0 = 36$ keV, port-through power $P_{NBI-1} = 0.9$ MW) is movable and its injection angle is varied from tangential to perpendicular. NBI-2 ($E_0 = 32$ keV, $P_{NBI-2} = 0.6$ MW) is fixed for the tangential injection making the balanced injection possible with NBI-1. The NBI-1 beam was injected onto a target plasma produced by the NBI-2. The magnetic axis position R_{ax} was 92.1 cm (in vacuum field) which gives the best global energy confinement for tangential NBI plasmas in CHS. It is possible to make the plasma density constant by shaping a gas puffing throughout the discharge. The parameters of the target plasma were : diamagnetic energy $W_{dia} = 2.5$ kJ, $n_e(0) = 5 \times 10^{13}$ cm^{-3}, $T_e(0) = 250$ eV, $B_t = 1.5$ T.

Figure 1(a) shows the incremental energies produced by the additional heating of NBI-1 as a function of injection angle (α_{inj} : angle formed by the beam ray and the magnetic axis). The incremental energy for the tangential injection of NBI-1 is almost the same as the expectation from the power scaling law : $W \propto P_{net}^{0.4}$ (P_{net} is the net input power) [7]. When the injection angles of NBI-1 were $19° < \alpha_{inj} < 44°$, almost the same heating efficiency was obtained. It is because most beam ions are not trapped in the magnetic field ripple for these angles. The heating efficiency decreases for α_{inj} > 44° and almost no global heating effect is found for the case $\alpha_{inj} = 74°$.

In this paper, the injection with $\alpha_{inj} = 74°$ is referred to as a perpendicular injection because the pitch angles of beam ions are almost 90° in the plasma edge region owing to the bumpy structure of the helical field. Calculations of collisionless orbits show that the injected ions are completely lost when they are born in the region r/a > 0.4 (a: plasma radius) on the outboard side of the torus.

In order to estimate beam ions dynamics more quantitatively, calculation is made with the Monte Carlo code HELIOS [8] which traces particles in realistic magnetic field configuration. Fast ions are traced in the entire vacuum vessel including the region outside of the plasma. Figure 1(a) shows the calculated fractions of injected beam power : shine-through, orbit loss and the power thermalized in the bulk plasma. The calculated value for the charge exchange power loss is less than 15 % for $\alpha_{inj} = 29°$ and still lower for the perpendicular injection. The simulation results are consistent with the experiments.

The beam ion energy spectra are obtained by a fast neutral particle energy analyzer (FNA) which is capable of scanning the observation angle. For the perpendicular injection, the fast neutral flux was reduced significantly and the energy spectrum of beam ions shows a large drop in the range $E_0/2 < E < E_0$ indicating the orbits losses during the thermalization process (R_{ax} = 92.1 cm case in Fig. 1(b)). Since the radial electric field was negative in this experiment, the helical resonance increases the orbit loss of trapped ions. The Monte Carlo simulation shows some effects of electric field for $E_0/2$ and $E_0/3$ ions but very little for E_0 ions.

It is shown by the orbit analysis that the confinement of trapped ions can be improved by controlling the magnetic field configuration especially by shifting the magnetic axis position. With the inward shift of the magnetic axis, the deviation of the orbits of trapped particles from the magnetic surfaces becomes smaller. Figure 1(b) shows the energy spectra of beam ions measured by FNA for three different positions of magnetic axis. The observed fast ion flux increased with the inward shift of magnetic axis especially in the energy range $E_0/2 < E < E_0$. The incremental energy increased for the inward shifted configuration even though the plasma volume decreases and hence the shine-through power increases. ΔW = 0.4 kJ is obtained with the perpendicular injection for the case R_{ax} = 87.8 cm.

To investigate the correlation between the beam ion loss and the radial electric field, the poloidal rotation of the plasma was measured by CXRS [9] for the experiments shown in Fig. 1(a). The measurement takes CVI impurity line emission (λ = 5292 Å) which is induced by the charge exchange process with the residual neutrals in the plasma instead of beam neutrals, because the NBI-1 beam path is varied. Figure 2(a) shows the product of the poloidal rotation speed and the local toroidal magnetic field in the plasma edge region (r/a = 0.7 - 0.8) for the different injection angles of

NBI-1. The ion pressure gradient term is about 40 V/cm for these plasmas. The electron temperature and density profiles are shown in Fig. 2(b) for $\alpha_{inj} = 19°$ (tangential injection) and 74° (perpendicular) cases. The density profiles are almost the same and the difference in temperature profiles corresponds to the total energy difference. For $\alpha_{inj} = 74°$ case, the electron temperature did not increase with the NBI-1 additional injection. In these experiments, an increase of the electric field in the outer region ($r/a \sim 0.8$) was observed for the perpendicular injection of NBI-1, but no substantial change in the global confinement was found.

ICRF heating experiments

Two-ion hybrid (H or ^{3}He minorities in D) fast wave heating experiments were successful in CHS using two poloidal half-turn antennas. The antenna position was determined to fit the plasma with $R_{ax} = 92.1$ cm configuration. With ECH initial target plasmas, plasmas are heated solely by ICRF (P = 300 kW) and the resultant stored energy was 0.65 kJ for the plasma density of 2×10^{13} cm^{-3} ($B_t = 1$ T, $f_{ICRF} = 14$ MHz). But the radiation loss was increasing during the discharge (20 ms heating pulse length). Ion temperature was 200 - 350 eV which was comparable to the electron temperature. Figure 3(a) shows the time traces of plasma parameters for the combined heating experiments using NBI target plasmas ($B_t = 1.4$ T, $f_{ICRF} = 22$ MHz). The increase in an stored energy was 0.85 kJ with 500 kW ICRF power for the initial plasma energy of 1.2 kJ.

The ion energy spectrum was measured by FNA for different observation angles. The spectrum shows two-component Maxwellian type and the tail component extends to 10 keV energy (shown in Fig. 3(b)). The tail formation was observed at the same time as the bulk ion heating occurred for various experimental conditions. The energy ratio of tail and bulk components has a pitch angle dependence as shown in Fig. 3(c), though the tail temperature is almost constant. With the assumption of the adiabatic motion of fast ions, this dependence reflects the difference of magnetic field strength between the observation points and the ion cyclotron resonance points where the ions are accelerated perpendicularly. It is supposed that the thermalization of high energy ions is not sufficient in the configuration with $R_{ax} = 92.1$ cm. The similar optimization of the magnetic field configuration by shifting R_{ax} inward should be effective for a better confinement of high energy ions in ICRF heating.

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FIGURE CAPTIONS

Fig. 1 (a) Dependence of the incremental energy ΔW_{dia} on the NBI-1 injection angle α_{inj}. Monte Carlo calculation results for the fractions of injected beam power are plotted with thinner lines as the function of α_{inj}. (b) Energy spectra of beam ions for the perpendicular injection measured by a neutral particle energy analyzer (FNA) for three different magnetic axis positions R_{ax}. The observation angle is the same as the beam injection angle $\alpha_{inj} = 74°$. The injection energy was $E_0 = 36$ keV.

Fig. 2 (a) Dependence of the poloidal rotation on the injection angle of NBI-1 at two different radial positions for $R_{ax} = 92.1$ cm configuraion. The outboard boundary of the plasma is $R \sim 108$ cm. (b) Profiles of electron temperature and density for $\alpha_{inj} = 19°$ (tangential injection) and 74° (perpendicular injection). Density of the target plasma produced by NBI-2 shows hollow profile which is different from both profiles in this figure.

Fig. 3 (a) Time traces of heating power and gas puff (upper), diamagnetic energy W_{dia} and radiation power (middle) and average density (lower). Traces for two shots with and without the additional ICRF heating for NBI plasma are overlapped for the comparison. (b) Spectrum of fast neutral particles measured by FNA in ICRF heating experiment. (c) Dependence of energy ratio of tail to bulk component and tail component temperature on the observation angle.

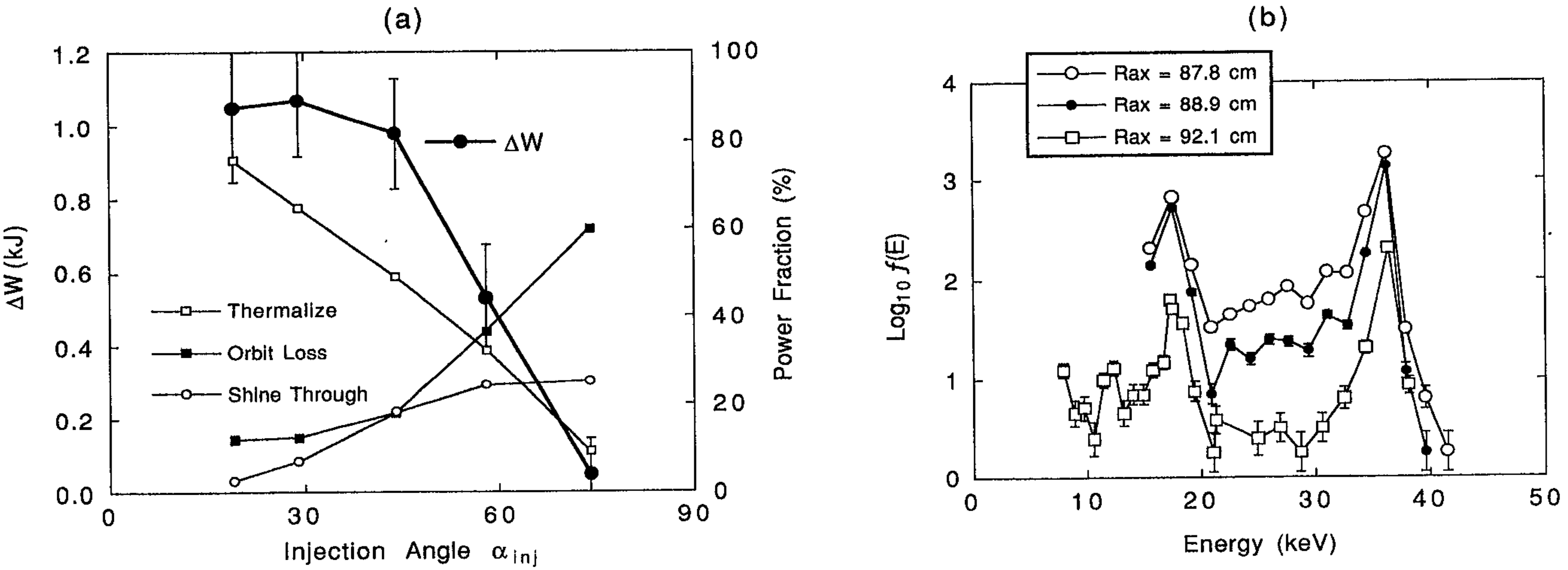
(a)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
ΔW (kJ)
100
80
60
40
20
0
Power Fraction (%)
ΔW
Thermalize
Orbit Loss
Shine Through
0
30
60
90
Injection Angle α_{inj}
(b)
Rax = 87.8 cm
Rax = 88.9 cm
Rax = 92.1 cm
4
3
2
1
0
$\log_{10} f(E)$
0
10
20
30
40
50
Energy (keV)

Fig. 1

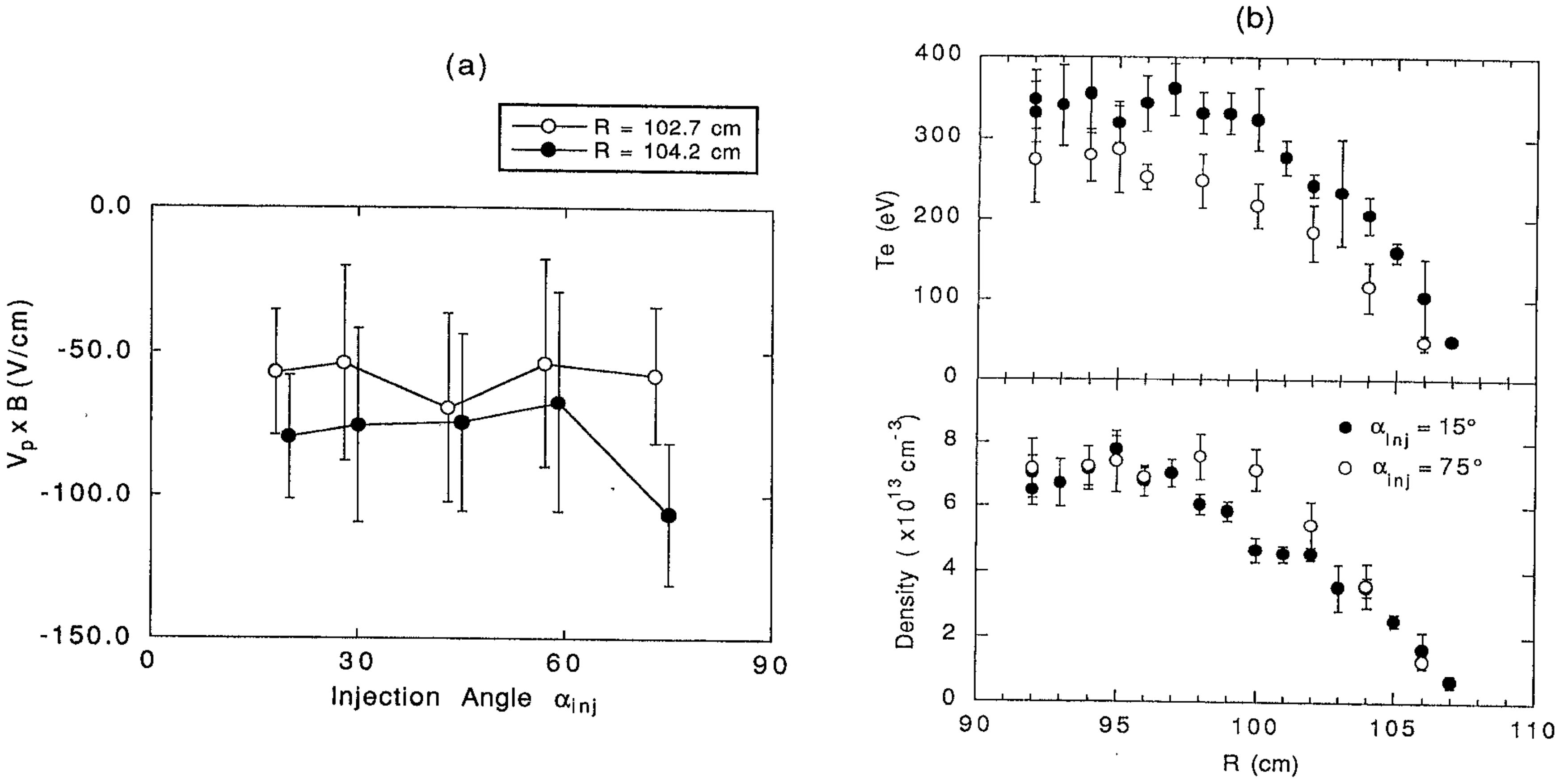
(a)
R = 102.7 cm
R = 104.2 cm
$V_p \times B$ (V/cm)
0.0
-50.0
-100.0
-150.0
0
30
60
90
Injection Angle α_{inj}
(b)
Te (eV)
400
300
200
100
0
Density ($\times 10^{13}$ cm^{-3})
8
6
4
2
0
● α_{inj} = 15°
○ α_{inj} = 75°
90
95
100
105
110
R (cm)

Fig. 2

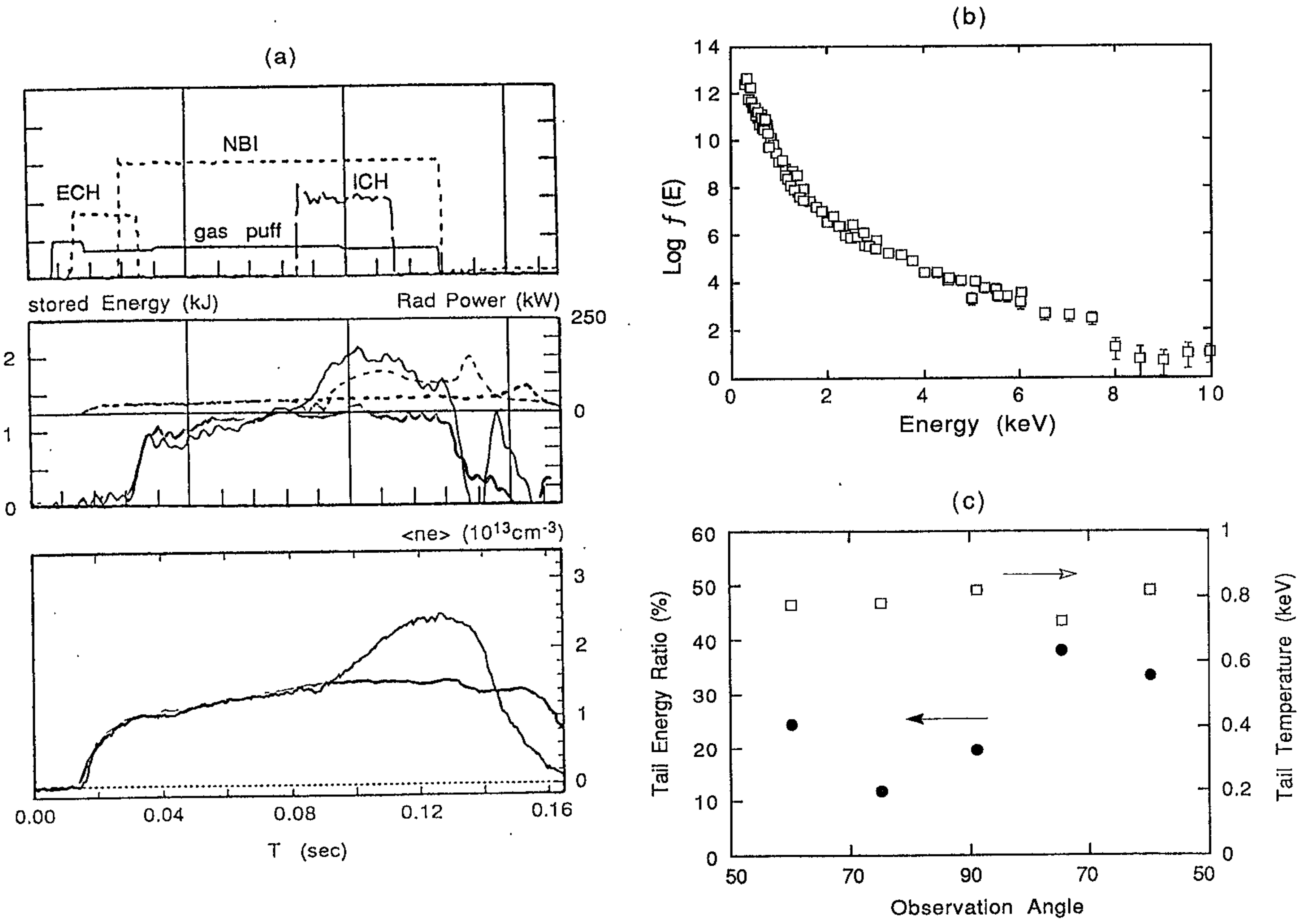
(a)
NBI
ECH
ICH
gas puff
stored Energy (kJ)
Rad Power (kW)
250
0
2
1
0
<ne> (10^{13}cm^{-3})
3
2
1
0
0.00
0.04
0.08
0.12
0.16
T (sec)
(b)
Log f (E)
14
12
10
8
6
4
2
0
Energy (keV)
0
2
4
6
8
10
(c)
Tail Energy Ratio (%)
60
50
40
30
20
10
0
Tail Temperature (keV)
1
0.8
0.6
0.4
0.2
0
Observation Angle
50
70
90
70
50

Fig. 3

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