INSTITUTE OF PLASMA PHYSICS

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RESEARCH REPORT

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ABSTRACT

A hydrogen beam of 16 kV, 4 A was co-injected into hydrogen plasmas and coupled to an rf of 800 MHz, up to 150 kW. It has been observed with the measurement of parallel charge-exchange neutrals that the fast ions above 16 keV are enhanced by the interaction with the lower hybrid waves. The enhancement is critically reduced when the line-averaged electron density is higher than 1.6×10^{13} cm^{-3} both in the toroidal fields of 22 kG and 16 kG. For the 22 kG case, the cause of the reduction may be related to the location of the turning point of the incident waves; that is, the turning point, in higher densities, locates outside the region where the fast ions produced by NBI are relatively abundant. For the 16 kG case, however, this interpretation is valid only when a part of the incident wave energy is transferred into waves of shorter wavelengthes. The ion-temperature increment in the simultaneous heating agrees with the sum of those in the individual heatings even when the beam-rf interaction is considerably strong.

1. INTRODUCTION

Simultaneous heating by rf and neutral-beam injection (NBI) is interesting from a viewpoint of improvement in the heating efficiency. It is possible in a future tokamak that the direct interaction of the rf waves with the fast ions produced by NBI raises power-deposition efficiency inside the plasma and the energized ions make D-T reaction rate higher through bulk-ion heating and/or Two-Component-Torus (TCT) effect.

Some experimental studies have been reported on the simultaneous injection of rf and neutral-beam. In the ATC, it has been observed that fast deuterium ions generated by NBI of as small as 100 mA are heated by the interaction with lower hybrid waves (LHW) [1]. It has been also reported by the PLT group that neutral-beam-injected minority ions are energized by ion-cyclotron waves (ICRF) [2]. In these experiments, enhancement of charge-exchange neutral flux is observed in the energies higher than the incident beam. We may expect an improvement of the heating efficiency because the energy of waves, which otherwise transmits, may couple to an enough number of the fast ions.

On the efficiency of bulk-ion heating, however, it has been shown in JIPP T-II experiments that the ion temperature increment in the combined heating is sum of those in the separately heating cases [3]. Also in the PLT, the increment due to NBI and ICRF heating is found to be linearly additive [4]. No investigation has been reported, however, on the correlation between the strength of the beam-rf interaction and the heating efficiency. In order to understand the interaction and heating mechanisms in the simultaneous injection and to assess effectiveness of the combined heating in future tokamaks, it is necessary to find conditions where rf closely interacts with fast ions. It is also important to understand whether the increment of the bulk-ion temperature is linearly additive or not in the cases where beam-rf interaction is strong.

We have made an experiment in the JIPP T-II on these problems for a combination of lower hybrid waves and neutral beam injection of moderate power. We studied the interaction of LHW with NBI in toroidal fields of 22 kG and 16 kG, and in various plasma densities because the propagating characteristics of the incident LHW are affected by these parameters. We used NBI of up to 64 kW in order to compare the temperature increment in the combined heating to those in the separate heatings.

2. EXPERIMENTAL

The JIPP T-II is a toroidal machine, of which the major radius is 91 cm and the minor radius is 17 cm [5]. A hydrogen neutral beam of 64 kW (16 kV, 4 A) is co-injected into the hydrogen plasma. The frequency of the incident rf is 800 MHz and injected power is 150 kW at the maximum. The ohmic input power of the target plasma is around 150 kW. The electron temperature of the background plasma is around 700 eV and the ion temperature 240 eV. Line averaged electron density $\overline{n_e}$ has been varied from 1.2×10^{13} cm^{-3} to 2.2×10^{13} cm^{-3} for 16 kG and 22 kG of the toroidal field B_0 on the plasma axis. Two charge-exchange neutral analyzers are used to investigate energy distribution of ions in parallel and perpendicular directions to the magnetic axis. The arrangement of the heating devices and the neutral analyzers is shown in Fig. 1.

The heatings are applied to the plasmas in both tokamak and stellarator operations. Figure 2 shows typical waveform of plasma parameters in the stellarator operation, where the rotational transform (ι_h) due to the external helical coil is 0.14. The rf power is injected from 70 ms to 110 ms and NBI from 80 ms to 100 ms. The plasma density increases during the rf injection, and the amount of density-rise depends on the rf power. The density-rise is attributed to the enhanced flux of light impurities from the wall, not cleaned enough, due to perpendicularly accelerated ions by LHW. Time variations of parallel ion temperature are also shown in the figure.

3. EXPERIMENTAL RESULTS

Figure 3 shows energy spectra of charge-exchange neutrals in the parallel direction. The injected power of NBI is 64 kW (16 kV, 4 A) and the rf is 58 kW. The line averaged electron density $\overline{n_e}$ is 1.6×10^{13} cm^{-3} and B_0 is 22 kG in this case. In the figure, we can see that the particle flux increases above 16 keV, which is the injected neutral beam energy. Three maximums corresponding to H, H_2 and H_3 components in the beam are recognized in the spectrum. It is worth to note that the particles around those maximums are reduced in the case of simultaneous injection compared with the case of NBI alone. It is surmised that the particles of these energies are accelerated by rf into the higher energies and appear as the high energy component above 16 keV. The increment of the fast ions above the beam energy is an evidence of the direct interaction of incident rf power with beam ions. Figure 4 shows the time behavior of the energy spectrum. It is remarkable that the high energy ions around 30 keV are confined for more than 25 ms after both of the injections are terminated. The results shown in Fig. 3 and Fig. 4 are obtained in the stellarator operation. Similar results are obtained also in the tokamak operation.

On the spectra of neutrals perpendicular to the magnetic field, no appreciable change is observed between the case of simultaneous injection and of the LHW alone. This reason is that the number of fast ions produced by NBI is much smaller than the one by LHW in the perpendicular directions since the neutral-beam is injected tangentially.

Figure 5 shows the relation between rf power and intensity of the parallel neutral flux. While the flux slightly decreases with rf power in the energies below 16 keV, it increases in higher energies for relatively small power of the incident rf and saturates for the rf powers above 20 kW. This saturation is observed in both cases where the equivalent current of NBI is 4 A and 2 A. This feature of the saturation is observed also in the ATC experiment, where the beam current is as small as 100 mA [1]. These results suggest that the saturation occurs independent of the density of fast ions in the plasma. The cause of the saturation cannot be explained, but it may be related to nonlinear processes in the interaction of rf waves with beam ions. The results shown in Fig. 5 are obtained for B_0= 22 kG, $\overline{n_e}$ = 1.4 ~ 1.8 X 10^{13} cm^{-3}. The electron density varies with the incident rf power and the relation is shown in the figure. The decrement of high energy components for high rf powers may be due to weakening of the beam-rf interaction in the high density regime, which will be mentioned later.

The intensity of charge-exchange neutrals was investigated for various electron densities of the ambient plasma. The results for B_0= 22 kG is plotted in Fig 6 a), and for B_0= 16 kG is in Fig. 6 b). The incident rf power is 58 kW and the parameters of the injected neutral beam are 16 kV, 4 A. A noticeable feature of the results is that the enhancement of the high energy ions extremely decrease at the densities higher than 1.6 X 10^{13} cm^{-3} in the both cases of the toroidal field. Since the fluxes with energies lower than 16 keV are not changed over the density range considered, the decrement in higher energies cannot be attributed to the increase in ionization rate because of the higher densities. The results in Fig. 6 indicate the presence of a critical density in the beam-rf interaction.

The relation between bulk-ion heating and beam-rf interaction was investigated. The results are shown in Fig. 7. These are obtained in the conditions $\overline{n_e}$ = 1.4 ~ 1.8 X 10^{13} cm^{-3}, NBI of 16 kV, 4 A, B_0 = 22 kG. In these conditions, it is recognized from the results in Fig. 6 a) that the interaction of rf with NBI is considerably strong. The results in Fig. 7 show that the temperature increment is linearly additive with the power of NBI and rf. There is no profit in heating efficiency even in the conditions where the beam-rf interaction is strong.

4. DISCUSSION

The presence of the critical density is one of the important findings in this experiment. It is probable that the interaction between rf and fast ions is independent of the ambient plasma parameters if the rf reaches the region where the fast ions due to NBI is relatively abundant. Then the fact that the interaction varies depending on the plasma density indicates that the extinction in the interaction appeared in Fig. 6 is owing to the propagating characteristics of LHW in the bulk plasma and does not relate to the inherent mechanisms of the beam-rf interaction. The radius r_b of the fast-ion abundant region is estimated to be 7 cm on the basis of deposition profile of the incident neutral beam. When the turning point of LHW locates outside the region, the interaction between rf and fast ions must be weak. In the linear theory, location of the turning point of LHW is determined from a relation [6]

$$N_{/\!/}\sqrt{T_i} = 6.5(\omega^2/\omega_{LH}^2 - 1) \quad ,$$

where $N_{/\!/}$ is the refractive index parallel to the magnetic axis, $\omega/2\pi$ the frequency of the incident wave, $\omega_{LH}/2\pi$ that of the lower hybrid resonance and T_i the ion temperature in keV. This relation is drawn on B - n_e space and shown in Fig. 8, where B is magnetic field strength in kG. In the figure, toroidal field strength at r = + r_b (7cm) is indicated by an arrow for each case of B_0 = 22 kG and 16 kG. Assuming that the density profile is parabolic, $n_e(r_b)$ is equal to 1.17 X $\overline{n_e}$. The density $n_e(r_b)$ corresponding to the critical $\overline{n_e}$ is indicated by a broken line in the figure, where 1.6 X 10^{13} cm^{-3} (see Fig. 6) is taken as the value of the critical $\overline{n_e}$. Assuming parabolic profile in the ion temperature, we have $T_i(r_b)$ = 0.78 X $T_i(0)$, where $T_i(0)$ is the central ion temperature measured with the charge-exchange neutral analyzer. Using these values and the equation above described, the refractive index $N_{/\!/}$ is determined uniquely on the condition that the turning point locates just at r = r_b, that is, at the boundary of the fast-ion abundant region. The values of $N_{/\!/}$ thus obtained are 2.16 for B_0 = 22 kG, and 6.75 for 16 kG (see Fig. 8). Hence if the spectrum of LHW would vary with the toroidal field strength without changing the location of the turning point, the extinction of the beam-rf interaction in the higher densities could be understandable. It is possible that the incident wave decays into the ion cyclotron waves and the cold LHW, which generates LHW of shorter wave length [7]. But it is hard to believe that the decay into high $N_{/\!/}$ waves occurs only in the case of 16 kG and does not in the 22 kG case.

We note that the density corresponding to the ion-plasma frequency of 800 MHz is 1.45 X 10^{13} cm^{-3}, which nearly coincides with the critical value of the line-averaged electron density, 1.6 X 10^{13} cm^{-3}. This fact suggests that the ion motion unaffected by magnetic force may play an essential role in the present phenomenon.

As is shown in Fig. 7, the heating efficiency differs in the region of rf power higher than 20 kW from the one below 20 kW. This feature may be related to the fact that the particle flux saturates at around 20 kW as is seen in Fig. 5. The heating in the low power region is considered to be dominated by linear interactions. On the other hand, the heating in the high power region is to be affected by nonlinear processes, for example, the parametric decay [8,9], which reduces the effective power in the bulk-ion heating. The presence of the non-linear effect around 20 kW is supported by an observation of ion-cyclotron waves with an electrostatic probe. The amplitude of the ion-cyclotron waves excited by parametric decay grows as the rf power is raised and saturates around 40 kW. Although the heating efficiency is reduced, the bulk-ion temperature rises as rf power is increased up to 150 kW, which was the maximum power applied in this experiment. We have expected that the efficiency of the bulk-ion heating rises through the interactions of LHW with fast ions due to NBI. Improvement in the efficiency is not observed, however, even under the conditions where the interaction of LHW with NBI is strong. This suggests that the interaction predominates over ions which occupy a small part of the velocity distribution and that only small fraction of the incident rf power is absorbed by fast ions. Another possible reason is that, since the slowing-down time of an accelerated ion is longer than the confinement time of the plasma particles, there rarely occurs the energy transfer in between. If we provide a device with a longer confinement time and use more intense NBI, we may clarify the improvement of the heating efficiency and furthermore the contribution of the beam-rf interaction upon the TCT effect.

5. SUMMARY

An experiment was carried out on the simultaneous injection of neutral beam and lower hybrid waves into the plasma for the purpose of finding the conditions where the beam-rf interaction is strong. Tangential observation of charge-exchange neutrals shows that, when the line-averaged plasma density is less than 1.6 X 10^{13} cm^{-3}, the fast ions due to the neutral-beam injection are scattered by rf into the energies higher than the incident beam. This confirms the presence of the interaction between fast ions produced by NBI and lower hybrid waves, which was previously observed in the ATC. An important finding in our experiment is that the interaction critically decreases for the densities above 1.6 X 10^{13} cm^{-3}, and this feature is independent of the toroidal field strength. The dependence of the critical density on magnetic field strength is inconsistent with the location of the turning point predicted assuming constant refractive index.

The heating efficiency was also investigated in the simultaneous injection and compared to the cases of individual heatings. The results show that the heating efficiency does not vary compared to the individual heatings even in the case where the beam-rf interaction is considerably strong.

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FIGURE CAPTIONS

Fig. 1 Arrangement of the heating devices and the charge-exchange neutral analyzers.

Fig. 2 Waveforms of loop-voltage V_p, plasma current I_p, and line-averaged electron density $\bar{n}_e$. The NBI is injected from 80 ms to 100ms and the rf from 70 ms to 110 ms. The plasma density rises during the rf-injection, which is shown by a solid line in the figure. A broken line shows $\bar{n}_e$ without heatings. The bottom is time variations of the ion temperature obtained with the parallel charge-exchange measurement, where solid points show the temperature with the simultaneous heating and open ones with Ohmic heating only.

Fig. 3 Energy spectra of parallel charge-exchange neutrals in the cases of NBI only, rf only and simultaneous injection. The power of NBI is 64 kw (16 kV, 4 A), and that of rf is 58 kW. The strength of the toroidal field B_0 is 22 kG and the condition of the target plasma is shown in Fig.1. The squares correspond to the data in the case of the simultaneous injection.

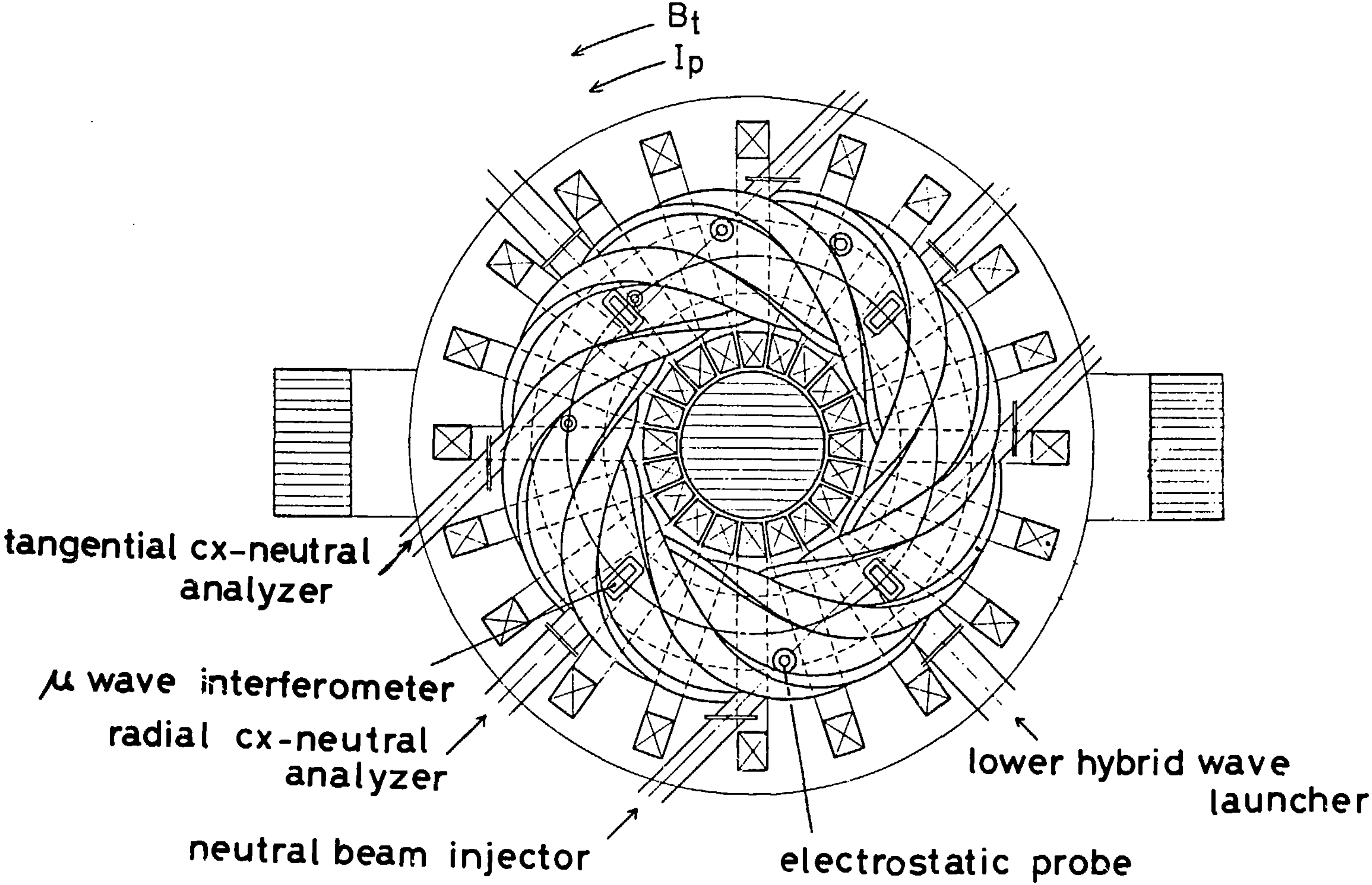
Fig. 4 Time evolution of the spectrum of charge-exchange neutrals in the parallel direction. Solid circles show the spectra in the period where both of the heatings are applied, circles with central dots those in the period where only rf is injected, and open circles those after both of the heatings are terminated.

Fig. 5 Relation between the neutral flux and the injected rf power P_{rf}. Line-averaged electron density is also shown as a function of rf power.

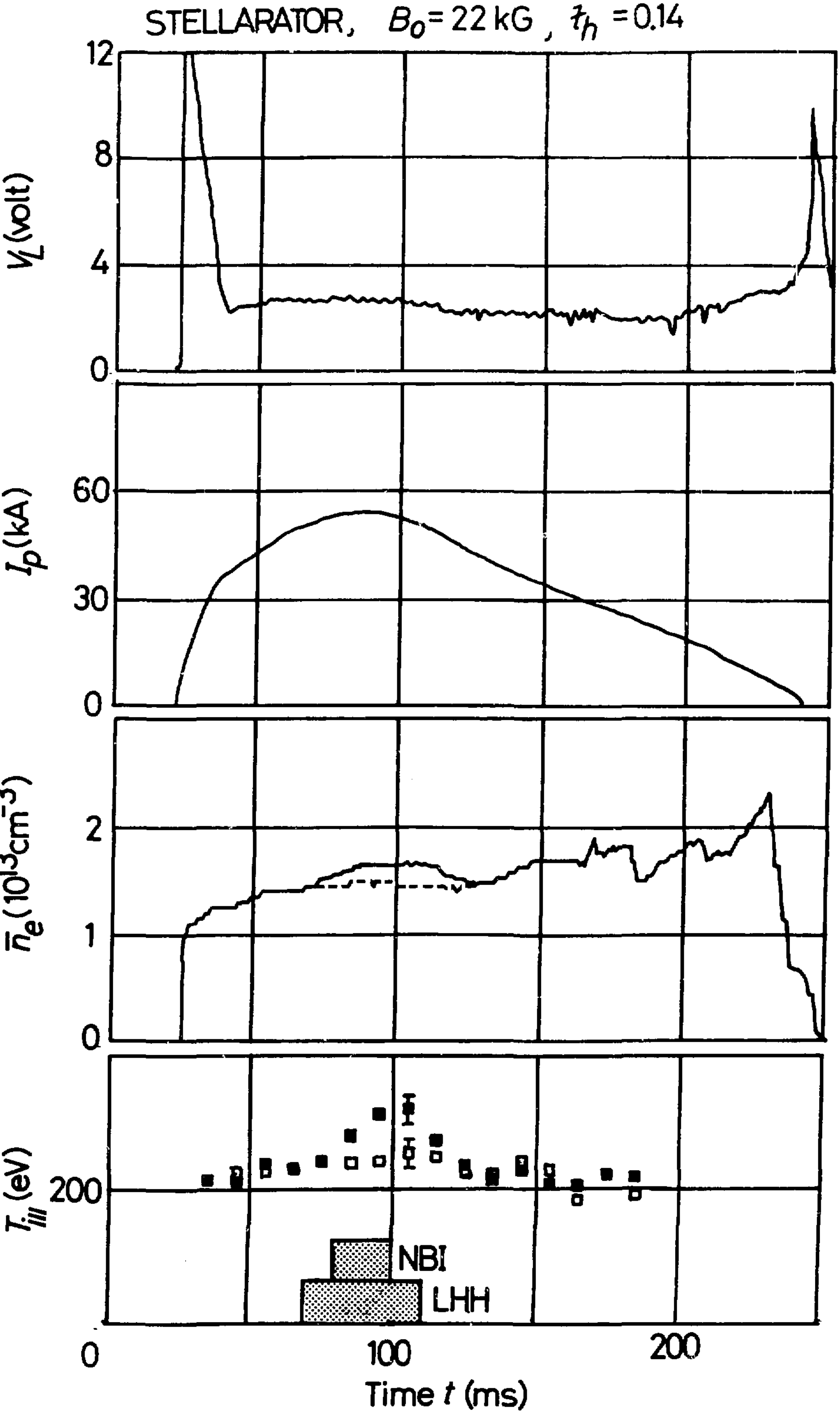
Fig. 6 Relations between the neutral flux and the line-averaged electron density. a) B_0 = 22 kG, b) B_0 = 16 kG.

Fig. 7 Ion temperature as a function of rf power P_{rf} with and without NBI. Solid lines correspond to heating efficiency for large P_{rf} and dotted ones for small P_{rf}. A broken line shows the temperature with Ohmic heating only.

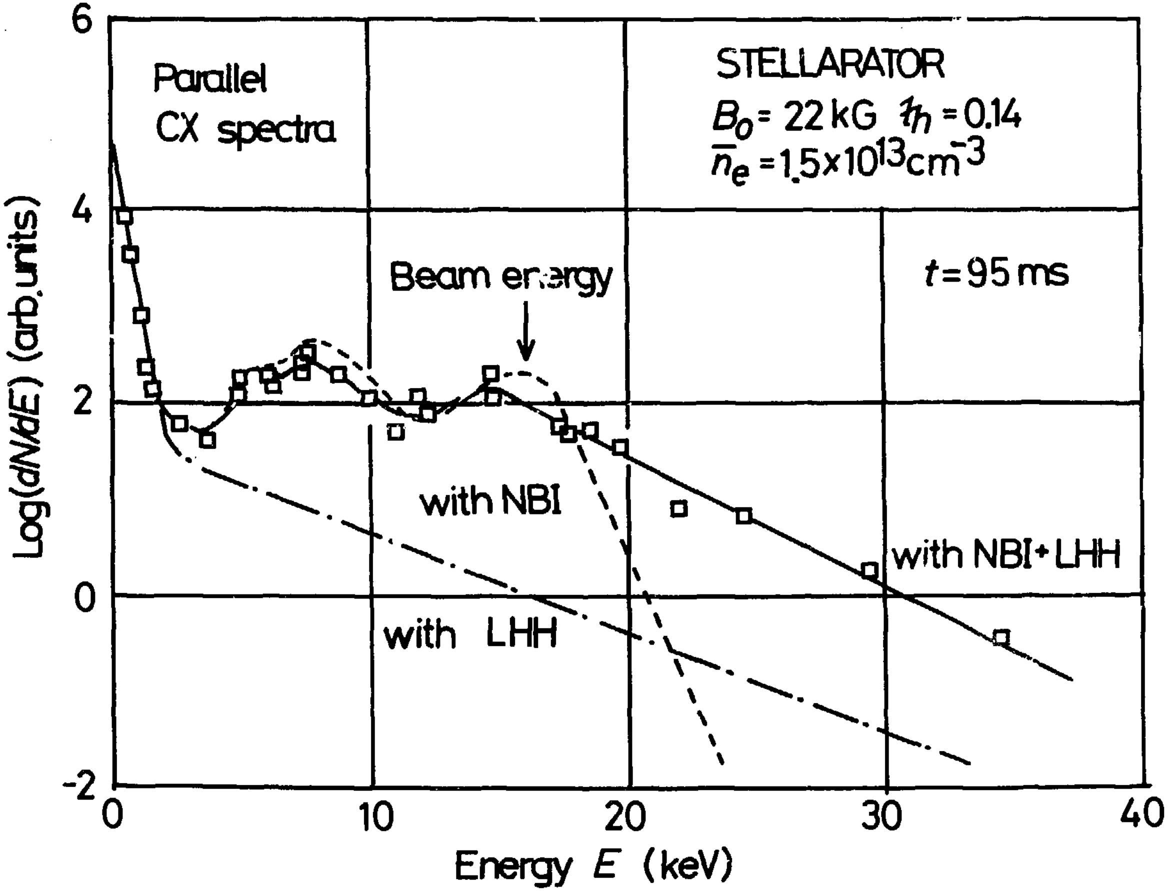
Fig. 8 The relation between electron density and magnetic field strength which gives the turning point for given $N_{/\!/}$ and T_i. The field strength at r = + 7 cm is indicated by an arrow for each case of B_0 = 22 kG and 16 kG. Broken line shows the electron density at r = 7 cm estimated from n_e of 1.6 X 10^{13} cm^{-3} , which is the critical density in the interaction between NBI and LHW.



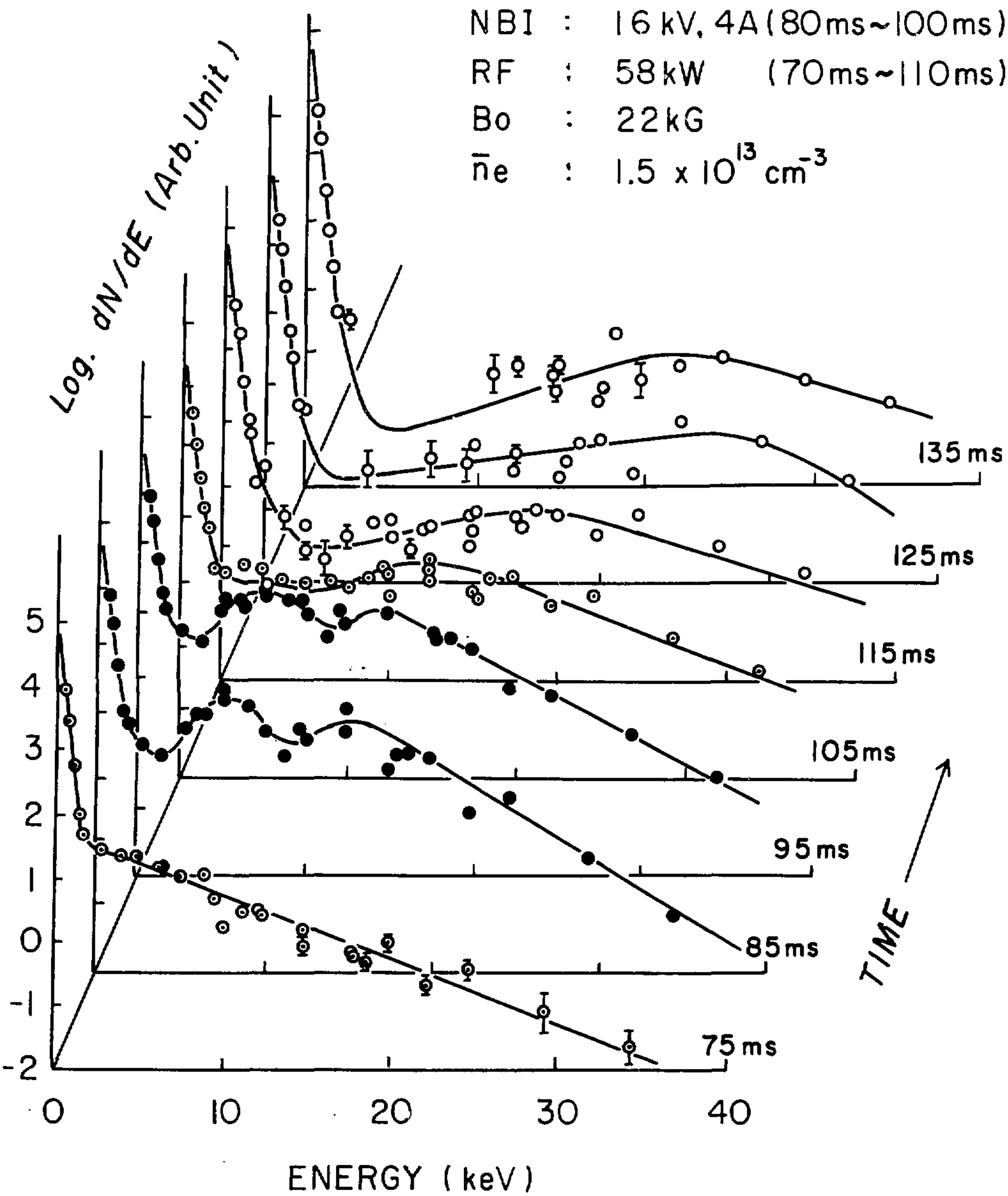
Bt
Ip
tangential cx-neutral analyzer
μ wave interferometer
radial cx-neutral analyzer
neutral beam injector
electrostatic probe
lower hybrid wave launcher



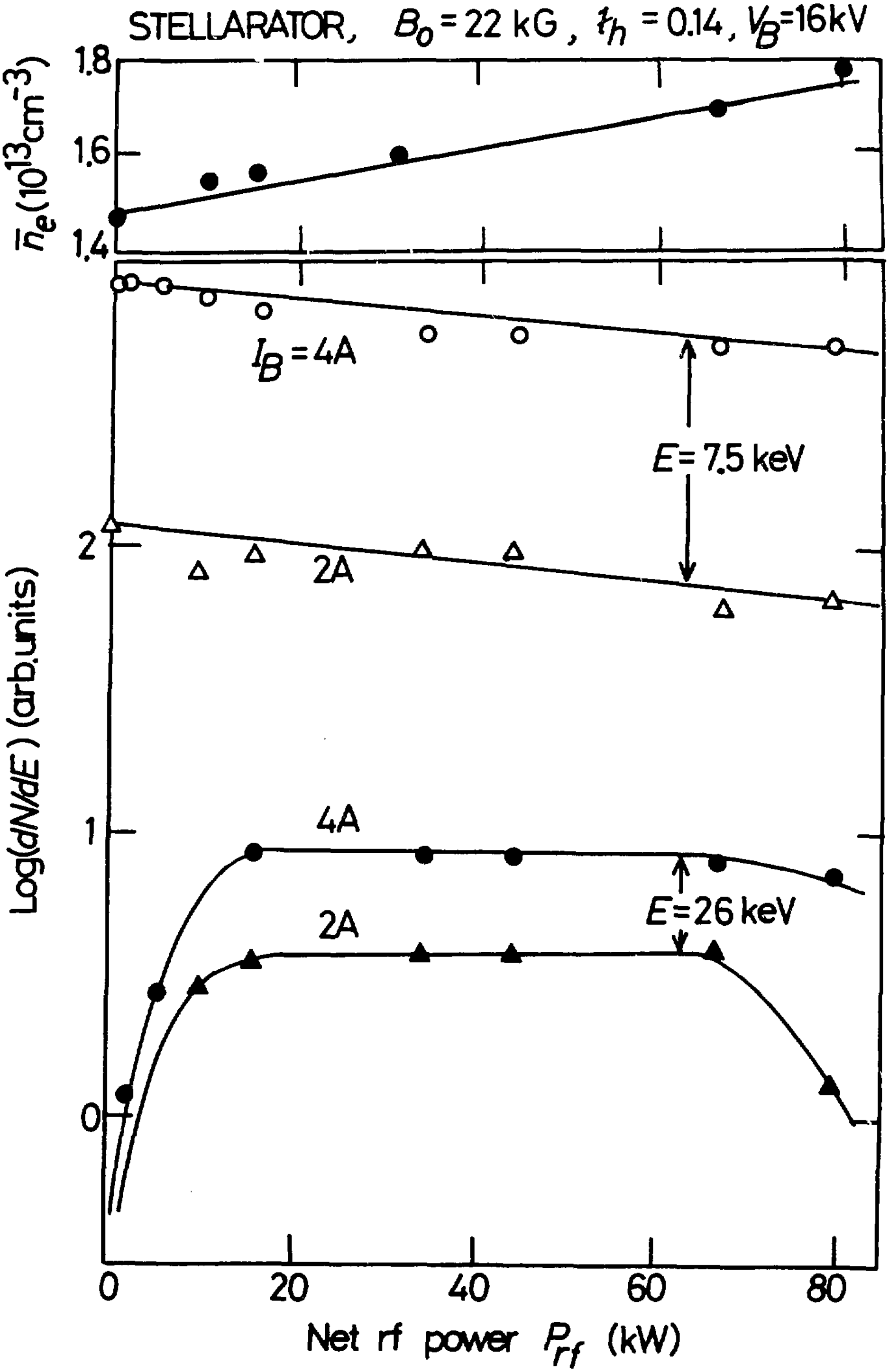
STELLARATOR, $B_0 = 22$ kG , $ι_h = 0.14$
12
8
4
0
V_L(volt)
60
30
0
I_p(kA)
2
1
0
$\bar{n}_e(10^{13}cm^{-3})$
200
$T_{i\parallel}$(eV)
NBI
LHH
0
100
200
Time t (ms)



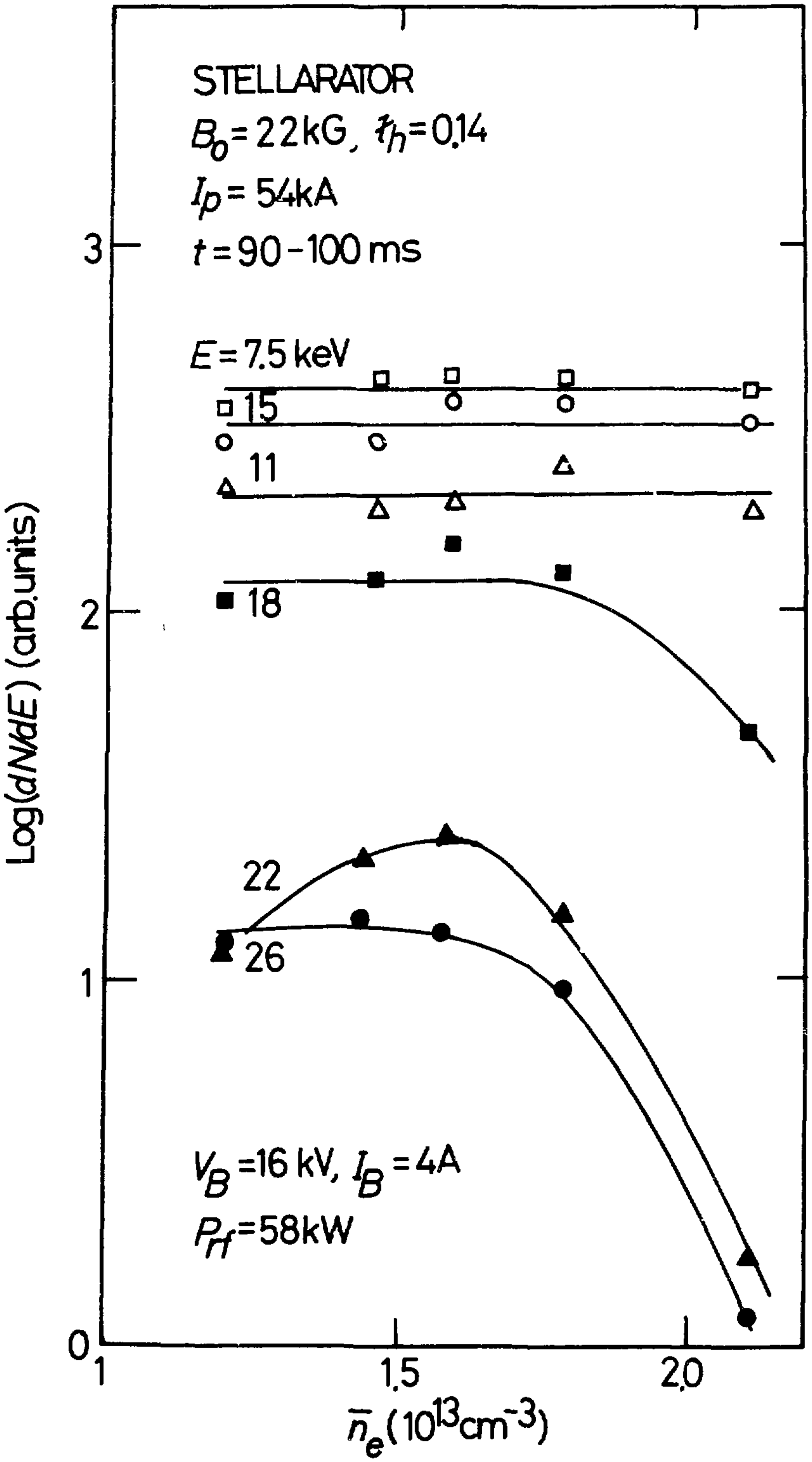
Parallel
CX spectra
STELLARATOR
B_0 = 22 kG $ι_h$ = 0.14
$\bar{n}_e$ = 1.5×10^{13}cm^{-3}
t = 95 ms
Beam energy
with NBI
with NBI+LHH
with LHH
Log(dN/dE) (arb.units)
Energy E (keV)
6
4
2
0
-2
0
10
20
30
40

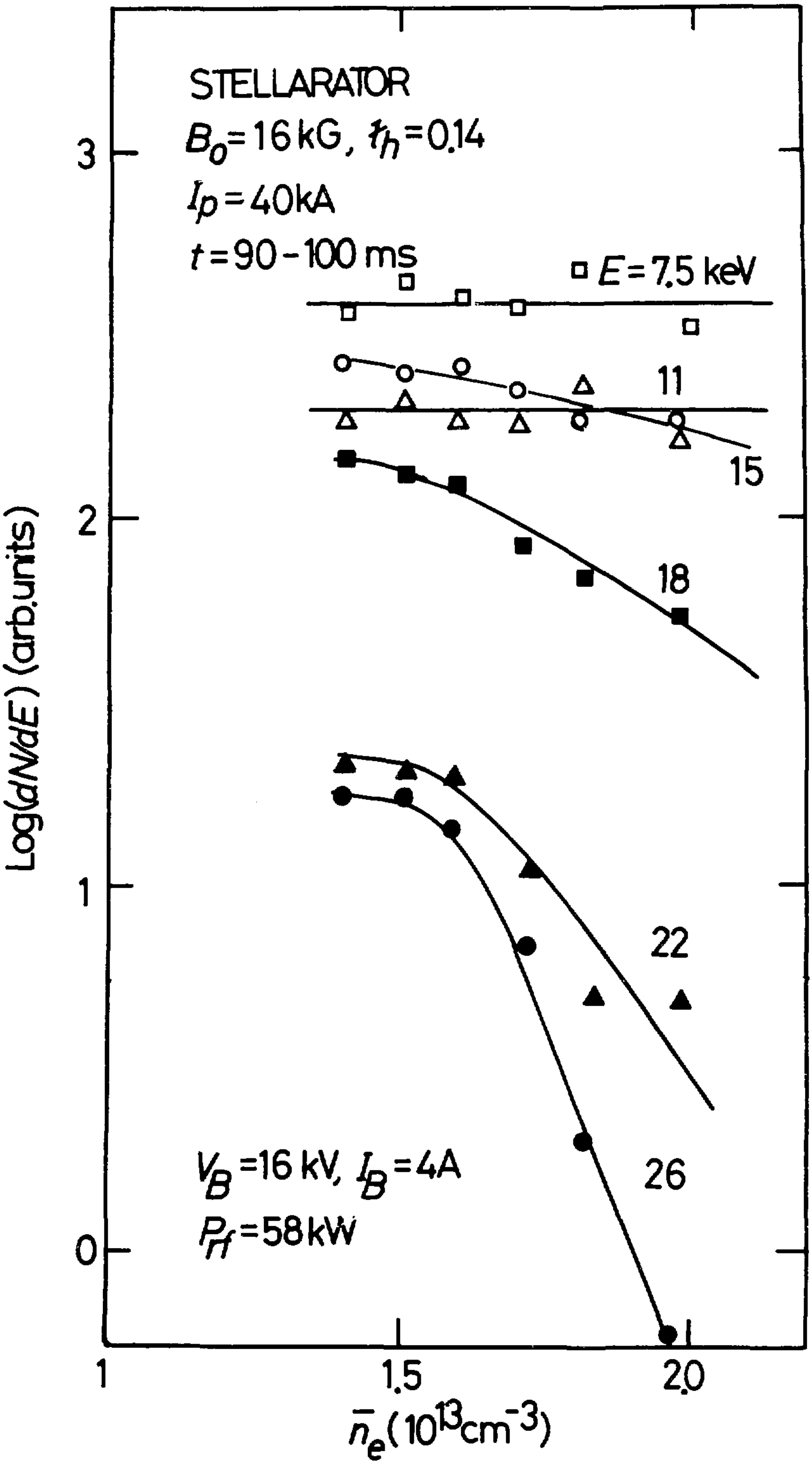


NBI : 16 kV, 4A (80ms~100ms)
RF : 58 kW (70ms~110ms)
Bo : 22 kG
$\bar{n}_e$: 1.5×10^{13} cm^{-3}
Log. dN/dE (Arb. Unit)
5
4
3
2
1
0
-1
-2
0
10
20
30
40
ENERGY (keV)
135 ms
125 ms
115 ms
105 ms
95 ms
85 ms
75 ms
TIME

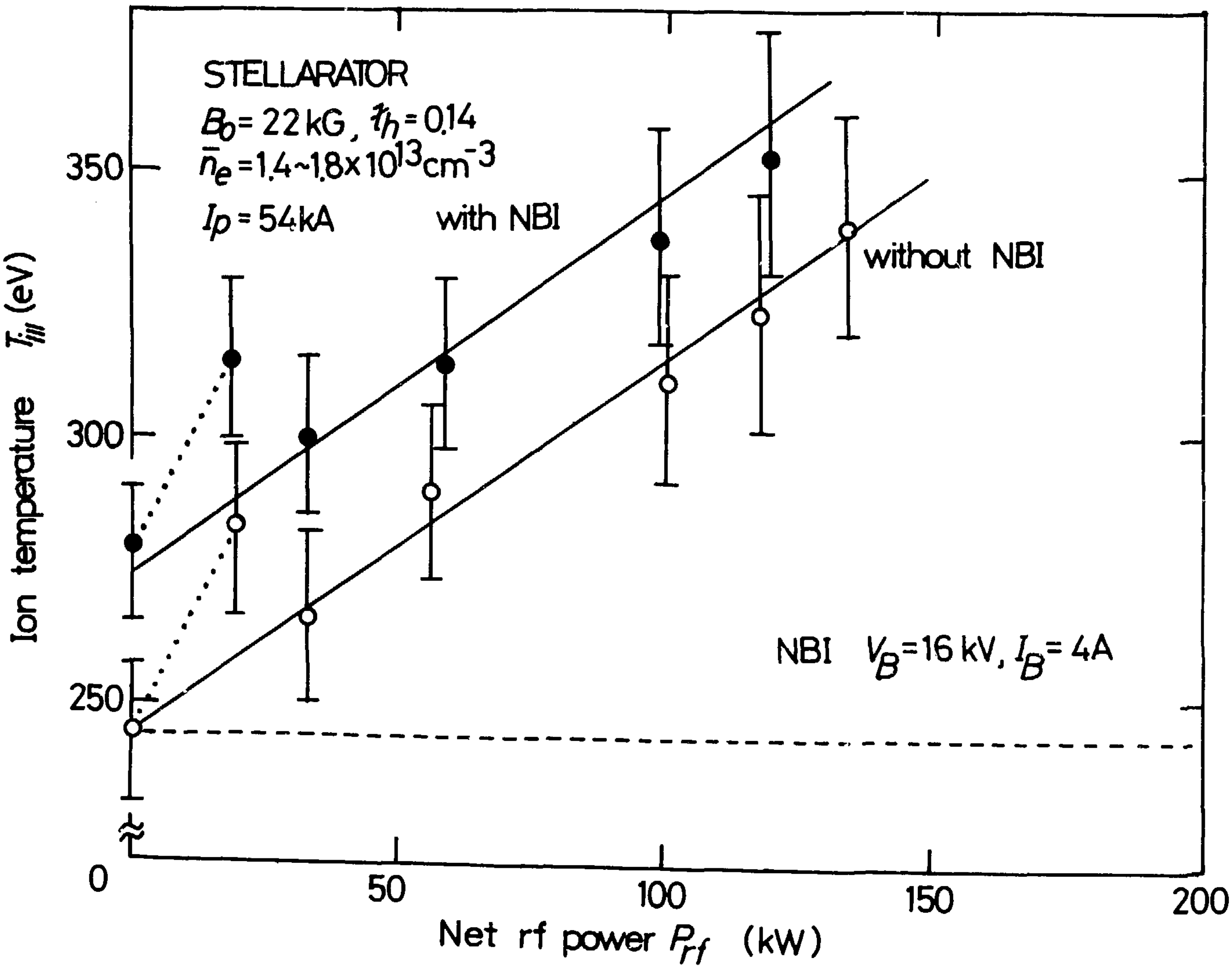


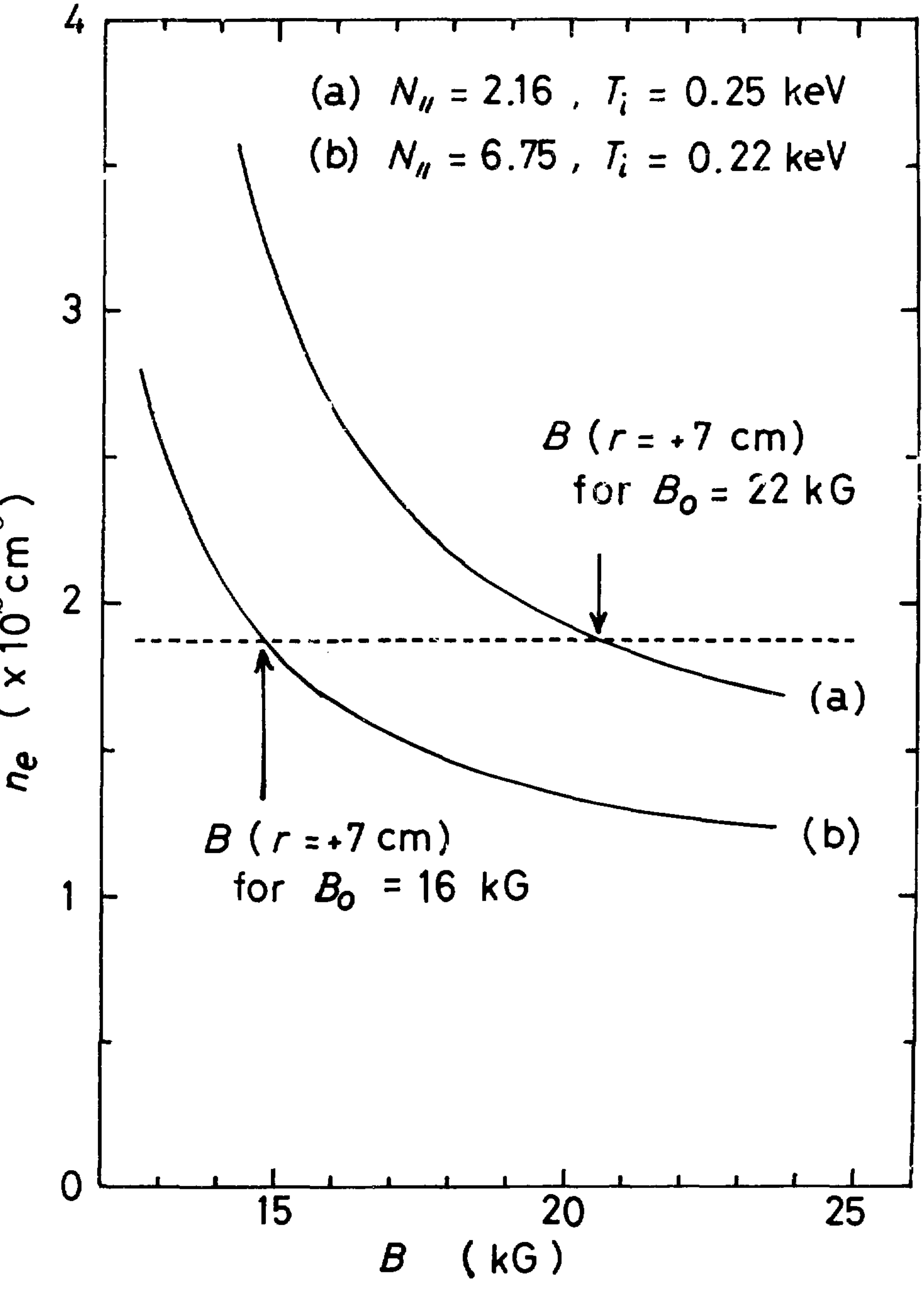
STELLARATOR, B_0 = 22 kG , $ι_h$ = 0.14 , V_B=16kV
$\bar{n}_e$ (10^{13}cm^{-3})
1.8
1.6
1.4
I_B = 4A
E = 7.5 keV
2A
4A
E = 26 keV
2A
Log(dN/dE) (arb.units)
2
1
0
0
20
40
60
80
Net rf power P_{rf} (kW)


STELLARATOR
B0 = 22 kG, ι/h = 0.14
Ip = 54 kA
t = 90-100 ms
E = 7.5 keV
15
11
18
22
26
VB = 16 kV, IB = 4A
Prf = 58 kW
Log(dN/dE) (arb.units)
0
1
2
3
1
1.5
2.0
n̄e (10^13 cm^-3)



STELLARATOR
B_0=16 kG, $ɫ_h$=0.14
I_p=40kA
t=90-100 ms
E=7.5 keV
11
15
18
22
26
V_B=16 kV, I_B=4A
P_{rf}=58kW
Log(dN/dE) (arb.units)
3
2
1
0
1
1.5
2.0
$\bar{n}_e$ (10^{13}cm^{-3})


STELLARATOR
B_0 = 22 kG , ι_h = 0.14
$\bar{n}_e$ = 1.4~1.8 x 10^{13} cm^{-3}
I_p = 54 kA
with NBI
without NBI
NBI V_B = 16 kV, I_B = 4A
Ion temperature $T_{i\parallel}$ (eV)
350
300
250
0
50
100
150
200
Net rf power P_{rf} (kW)



4
3
2
1
0
(a) $N_{//}$ = 2.16 , T_i = 0.25 keV
(b) $N_{//}$ = 6.75 , T_i = 0.22 keV
B (r = +7 cm)
for B_o = 22 kG
(a)
(b)
B (r = +7 cm)
for B_o = 16 kG
n_e (x 10^{13} cm^{-3})
15
20
25
B (kG)