# Ion Temperature Measurement and Energy Balance
# in Detached Plasmas in the Divertor Simulator, NAGDIS-II

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## 1. Introduction

Recent studies in fusion-related divertor plasma experiments indicate that volumetric plasma recombination plays an essential role in detached plasmas. Continuum and a series of line emissions from highly excited levels were observed in several tokamaks and linear divertor simulators, showing that dominating process is three-body recombination[1-3].

In the linear divertor simulator NAGDIS-II ( NAGoya DIvertor Simulator), the electron-ion energy exchange process followed by the ion-neutral charge exchange is thought to be a key mechanism responsible for the electron temperature drop along the magnetic field to lead $T_e$ below 1 eV, which was predicted by 2D fluid code[4].

In order to reveal the energy balance between electrons, ions and neutrals experimentally, precise measurement of ion temperature $T_i$ as well as $T_e$ in the detached plasmas should be required. In this report, we present the neutral pressure's dependence of $T_i$ measured by Doppler broadening of HeII line (468.6nm).

On the other hand, relatively high ion temperature around 10 eV, which can't be expected in a conventional DC discharge system, was also observed at lower neutral pressure. This heating mechanism will be also discussed.

## 2. Experimental Set-up

The experiment was performed in the linear divertor simulator, NAGDIS-II[2] as shown in Fig. 1. Helium plasmas are produced by modified TP-D type DC discharge. The neutral pressure $P$ in the divertor test region can be con-
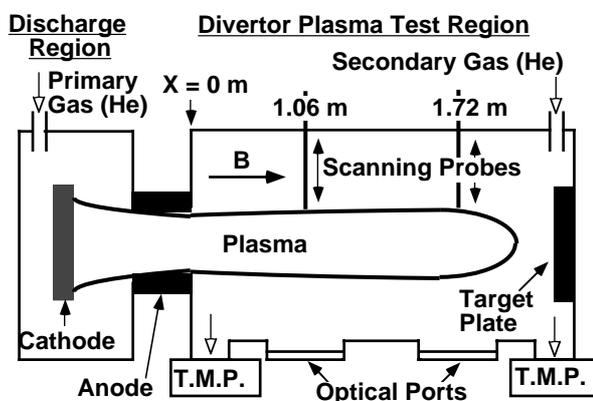


*FIG. 1 Schematics of experimental set-up.*

trolled from 1 mtorr to 20 mtorr by feeding a secondary gas. It should be noted that the change of $P$ in the divertor test region has no effect on the plasma production in the plasma source region due to the substantial pressure difference between the plasma source and the divertor test region. Spectra of light emission are detected at two different positions of $X = 1.06$ m and 1.72 m from the anode. Fast scanning probes are also set at the same positions to measure plasma parameters.

## 3. Experimental Results and Discussion

### (a) Change of Ion Temperature from Attached to Detached Plasmas

Helium plasma was produced at a discharge current $I_d = 60$ A without any secondary gas puff, where the electron density $n_e$ and $T_e$ in the upstream ($X = 1.06$ m) are $8 \times 10^{18}$ m$^{-3}$ and 7 eV, respectively. With an increase in the neutral gas pressure $P$, $n_e$ is increasing both in the upstream and downstream region ($X = 1.72$ m) as shown in Fig. 2(b). Above $P \sim 6$ mtorr, that is a critical value for the plasma to start to detach from the target plate, $n_e$ in the downstream is found to be rapidly reduced. We can see a series of prominent line emissions from highly excited levels associated with three-body recombination.

Figure 2(a) shows that the electron temperature $T_e$ in the downstream rapidly decreases with $P$. On the ohter hand, the ion temperature $T_i$ is gradually decreasing to be compared with $T_e$.



FIG. 2 Dependence of (a):electron temperature $T_e$ and ion temperature $T_i$ ; (b): electron density $n_e$ on the neutral gas pressure P measured at upstream ( X =1.06 m) and downstream (X=1.72m).



FIG. 3 Energy balance between electrons and ions.

Around 6 mtorr, it is found that $T_e$ and $T_i$ become almost equal, which indicates that the temperature relaxation process between electrons and ions gives the essential role for the decrease in $T_e$, which is denoted as path 4 in the energy balance as shown in Fig. 3. Both ionization and radiation processes are not effective for the electron cooling at $T_e$ of less than 5 eV. $T_i$ is determined by the energy balance between the energy gain from electrons with the temperature relaxation
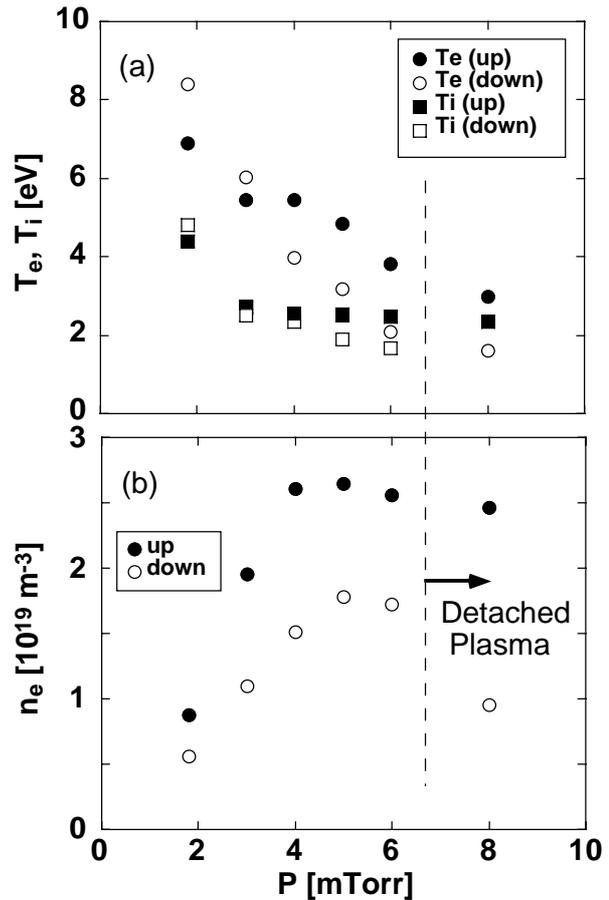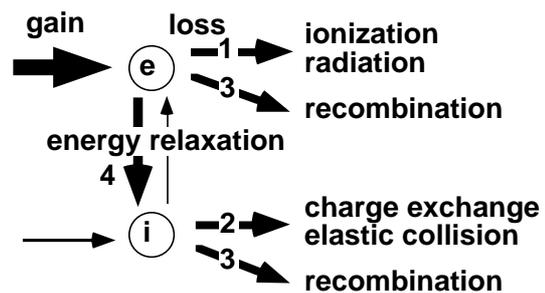
process and the energy loss to neutrals due to the charge exchange process, which is one of the reasons why the reduction of $T_i$ is smaller than that of $T_e$. Such a tendency of $T_i$ on $P$ was also confirmed with the ion sensitive probe measurement. Above $P \sim 6$ mtorr, both $T_e$ and $T_i$ are likely to decrease in the downstream. Unfortunately, the intensity of HeII is too weak to measure $T_i$ in the detached plasma region. Moreover, $T_e$ by the probe measurement is also doubtful in the detached plasma region because there is a large drop of $T_e$ along the magnetic field. In the detached recombining plasma, the analysis of continuum and a series of line emissions from highly excited levels can give $T_e$ of less than 0.5 eV[3]. However, there are a lot of discussion on the temperature measurement in the detached recombining plasma region. It is necessary to continue to carry out the research on the temperature measurement in the detached plasma region.

In this detached helium plasma regime, we can summarize that the electron-ion temperature relaxation process is a key to decrease $T_e$ along the magnetic field to a temperature less than 1 eV, where the radiative and three body recombination occur, leading to the detached plasmas.

## (b) Ion Heating Associated with Radial Plasma Potential Profile

Anomalous heating of ions was clearly observed at relatively low gas pressure $P$ around 1 mtorr. Figure 4 shows that the dependence of $T_i$ on the discharge current $I_d$ as a parameter of the neutral pressure $P$. $T_i$ is found to be dramatically increased at $P \sim 1.2$ mtorr to be compared
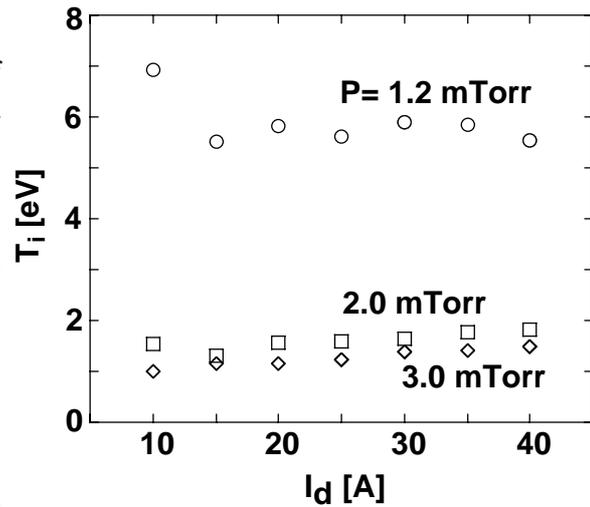


*FIG. 4 Dependence of ion temperature $T_i$ on the discharge current $I_d$ as a parameter of the neutral gas pressure P at upstream ( X = 1.06 m ) .*



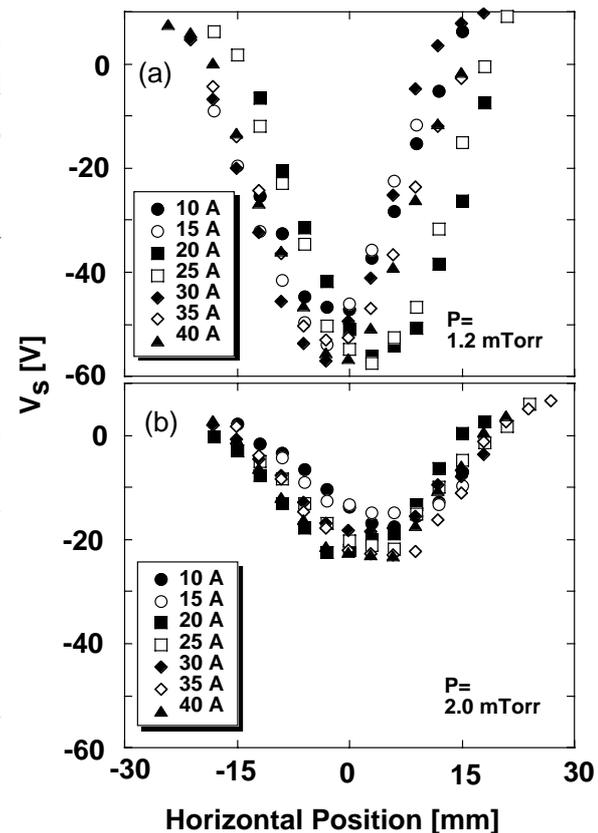*FIG. 5 Horizontal profiles of plasma potential $V_s$ as a parameter of the discharge current $I_d$ at upstream ( X =1.06 m) . (a):the neutral pressure P~1.2 mtorr, (b):P~2.0 mtorr.*

with $T_i$ at $P \sim 2.0$ mtorr and 3.0 mtorr, weakly depending on $I_d$. $n_e$ is roughly proportional to $I_d$. It is quite difficult to explain the increase of $T_i$ at $P \sim 1.2$ mtorr by only taking account of the energy balance mentioned in the previous section. Figure 5 shows the horizontal profiles of plasma potential $V_s$ for several $I_d$'s. The $V_s$ profiles at $P \sim 1.2$ mtorr are found to be much more hollow in comparison with those at $P \sim 2.0$ mtorr, which may be associated with the discharge electron current flowing across the magnetic field.



*FIG. 6 Dependence of ion temperature $T_i$ on the radial electric field $E_r$. The fitting curve is shown as $T_i = aE_r^2 + b$ where $a=3.5\mathrm{x}10^{-7}$ and $b=1.0$.*

Reduction of $P$ makes an enhancement of the radial electric field $E_r$. When an ion is produced due to ionization in this plasma potential well, the ion can be accelerated by the $E_r$. The excursion length $L$ of the ion across the magnetic field is expressed by $L = 2E_r/(\omega_{ci}B_z)$ where $\omega_{ci}$ is ion cyclotron frequency. Therefore, the energy gain from the potential well can be estimated to be $q E_r L$, which is proportional to $E_r^2$. Figure 6 shows the ion temperature $T_i$ as a function of averaged $E_r$ obtained from Fig. 5. The ion temperature $T_i$ is found to be proportional to the square of $E_r$, which is in a fairly good agreement with the fitting curve in Fig. 6 calculated by taking account of the ion motion in the potential well. This result indicates that the radial electric field induced by the electron current across the magnetic field can directly heat up ions in addition to the ion-electron temperature relaxation process.

### 4. Summary

We have done the ion temperature measurement by detecting Doppler broadening of HeII as well as the ion sensitive probe in the NAGDIS-II device to understand the energy balance between electrons, ions and neutrals in relation to detached plasmas. Moreover, ion heating associated with the radial potential well was also investigated.

### Reference

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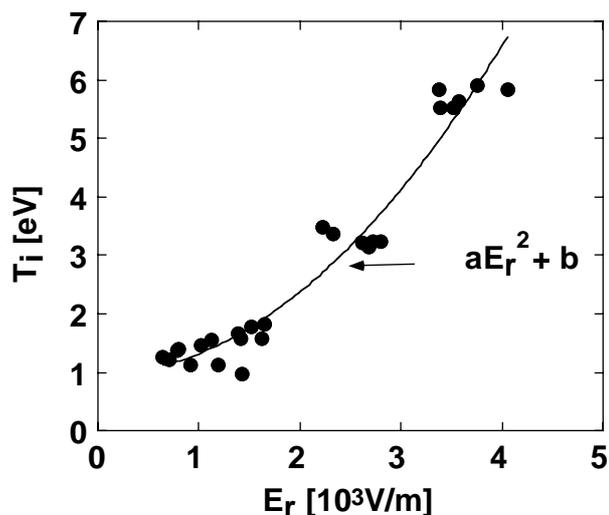[4] N. Ohno et al., Contrib. Plasma Phys. **36**, 339 (1996).