§6. Physics of Electron Cyclotron Current Drive and Control of Rotational Transform

Nagasaki, K., Mizuuchi, T., Okada, H., Minami, T.,
Kado, S., Masuda, K., Kobayashi, S., Yamamoto, S.,
Ohshima, S., Sano, F. (IAE, Kyoto Univ.),
Volpe, F. (Columbia Univ.), Cappa, A. (CIEMAT),
Yoshimura, Y., Mutoh, T., Ida, K., Kubo, S.,
Shimozuma, T., Igami, H., Takahashi, H., Motojima, G.,
Mukai, K., Ogawa, K., Toi, K.

Plasma current is not required to sustain plasma equilibrium state in stellarator/heliotron (ST) devices. However, non-inductive current such as bootstrap current which is driven by finite plasma pressure inevitably flows in the toroidal direction, affecting plasma equilibrium and stability through modification of rotational transform profile. Even a small amount of plasma current should be controlled to keep high-performance state and to avoid MHD instabilities. Electron cyclotron current drive provides a useful scheme to control plasma current externally. Recent studies in the Heliotron J device has revealed that ECCD strongly depends on the magnetic configuration and the current drive position[1]. The EC driven current is determined by the Fisch-Boozer effect and the Ohkawa effect, and the current direction is reversed depending on the EC deposition position, indicating that the trapped particle has an important role to determine the EC driven current. Experiments in the Heliotron J also showed that an energetic-ion-driven instability, energetic particle mode (EPM) was completely stabilized by ECCD due to formation of magnetic shear[2]. On-axis ECCD changes the magnetic shear at the radial position where the EPM is excited. The N|| scan experiment shows that there is a threshold of magnetic shear to stabilize the EPM. Both the positive and negative magnetic shear is effective to stabilize the EPM. In this report, we study the effect of ECCD on the LHD plasmas.

In LHD, interesting phenomena were observed so far on the electron temperature profiles in neutral beam current drive (NBCD) and ECCD combined plasmas. The electron temperature is centrally peaked at co-NBCD + co-ECCD and ctr-NBCD + ctr-ECCD, while it is flat in core region at co-NBCD + ctr-ECCD and ctr-NBCD + co-ECCD. The physics mechanism is not clear yet, but the possible reason is the modification of rotational transform or radial electric field formed in core region. In last experimental campaign, a plasma was produced and sustained by NBI at the magnetic configuration of Rax=3.75m and the magnetic field B=-1.375m, where the confinement magnetic field is reversed. 77 GHz EC waves has been applied through 5.5-U port and 2-O ports. NBI #2 (counter direction) and NBI#3 (co direction) were used for an MSE diagnostic. The average electron density is $n_e = 1\times10^{19}$ m^{-3}. The ECCD was applied by 2-O EC waves (horizontal injection), and the oblique launch is possible to control in the co- and counter directions.

The experimental results show that a clear difference is observed in the plasma current, Ip, between co- and counter-ECCD, and the maximum difference in Ip was 10kA. Here NBI#3 drives co-NB current, and NBI#2 does counter-NB current. Figure 1 shows comparison of electron temperature profiles in counter ECCD at t=4.2 sec where the counter-NBCD is applied and at 4.333 sec where the co-NBCD is applied in the discharge #121512. Although the difference in the Te shape is not so clear as in the 16th cycle experiment, it can be seen that the Te profile is centrally peaked for ctr-NBCD + ctr-ECCD at 4.2 sec, and the central Te profile is flat for co-NBCD + ctr-ECCD at 4.333 sec. In the 16th cycle experiment, the NBI drives about 40 kA current during 1.5 sec injection, while the NB current is limited less than 10kA in this experiment. This indicate the change in rotational transform due to non-inductive current affects the core electron confinement. Further study will be performed in the next experimental campaign in order to clarify the role of rotational transform on the core electron confinement and controllability using ECCD.

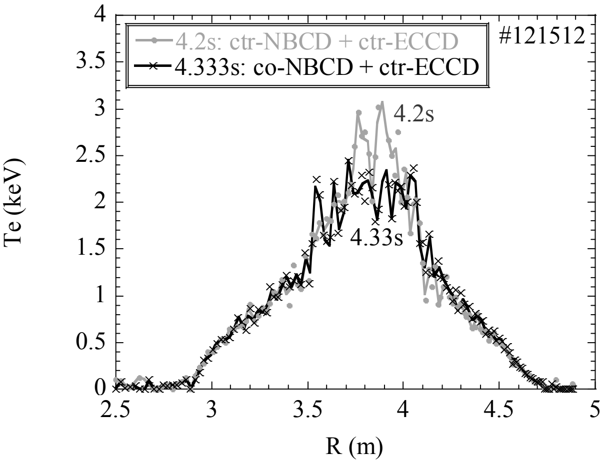

Fig. 1 Electron temperature profile at ctr-NBCD + ctr-ECCD (4.2s) and co-NBCD + ctr-ECCD (4.333s)

1) Nagasaki, K., et al., Nucl. Fusion **51** (2011) 103035.
2) Nagasaki, K., et al., Nucl. Fusion **53** (2013) 113041.