§2. Production of NBI Plasmas by Assistance of 2.45GHz Microwave

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In Stellarator/Heliotron (S/H) systems, plasmas can be produced by external heating power without loop voltage. Electron cyclotron resonant heating such as fundamental O-mode or second harmonic X-mode are usually used. While this method is advantageous for high electron temperature plasmas, electron cyclotron resonance layers should be located in the confinement region, which limits operational magnetic field. In LHD, plasmas have been successfully produced only by neutral beam injection (NBI) of the port-through power 1.6 MW, beam energy 97 keV at $n_e \sim 5\times10^{19}$ m^{-3}. The key points for plasma production by NBI is that electron temperature is high enough for background neutral gas to be ionized. Since electrons in NBI startup plasmas are heated through Coulomb collision with injected beam ions, large vacuum volume or high magnetic field is required for long distance so that the beam and neutral particles collide much.

In the medium sized device, Heliotron J, we have successfully demonstrated plasma production by NBI with assistance of 2.45 GHz 5 kW microwaves [1]. Figure 1 shows the time history of an NBI startup plasma. Two tangential (counter- and co-) beamlines of the hydrogen NBI system have been used in Heliotron J (BL1 and BL2, respectively). Each beamline has two bucket-type ion sources, a maximum beam power of 0.7 MW, and an acceleration voltage of 30 keV. 5 kW, 2.45 GHz CW microwaves were generated by a commercial magnetron. This system has been used as a fundamental ECH source for discharge cleaning at a magnetic field around 0.09 T. The TE_{10} mode is transmitted through rectangular waveguides and it is injected into the Heliotron J vacuum chamber directly from the rectangular waveguide. The electric field of the injected waves close to the O-mode is oriented in the horizontal direction. Intense third harmonic ECE signals have been observed during 2.45 GHz microwave injection, indicating the existence of high-energy electrons. Line radiation of Oxygen (OV) is also increased at the initial phase of beam injection, meaning that electrons over the ionization potential 113 eV. The acceleration mechanism of electrons by 2.45 GHz microwaves is yet understood.

The fundamental and higher-harmonic electron cyclotron resonances for 2.45 GHz microwaves are not located in the vacuum chamber during microwave launching. A high electron cyclotron emission (ECE) intensity was observed before NBI; n_e was of the order of 10^{17} m^{-3}. The third-harmonic resonance layer for the ECE with a frequency of 75.5 GHz is located at r/a = 0.3 in the configuration. This phenomenon implies that the 2.45 GHz microwaves generate a low density of energetic electrons (initial plasma). The line-averaged electron density increased immediately after NBI was started and low-density ($\bar{n}_e \approx 0.2\times10^{19}$ m^{-3}) plasmas appeared 10 ms after beam injection. At the same time, the intensity of the oxygen line emission (OV) increased, which reveals that many electrons with energies above the ionization potential (113 eV) were produced in the early phase of beam injection. After that, an additional gas puff increased n_e to over 1×10^{19} m^{-3}.

A low-density plasma was initiated when 2.45 GHz microwaves were turned on. The electron density was measured to be of the order of 10^{17} m^{-3}. The physical process is currently not clear, but lower hybrid waves are possibly excited in the plasma. When 2.45 GHz microwaves were not applied, the line-averaged electron density did not increase above the order of 10^{17} m^{-3} during beam injection. The OV line emission intensity was lower than the resolution limit, indicating that there were few electrons with energies exceeding the ionization potential and that a longer NBI duration is required to sufficiently heat the electrons so that they can ionize the background neutral gas. Therefore, initial plasma generation by 2.45 GHz microwaves strongly assists rapid plasma startup by NBI.

We have been investigating the operation capability of a 2.45GHz magnetron system under high magnetic field circumstance in LHD. We have an experimental plan to study effect of 2.45GHz microwaves on NBI plasma startup, especially the relationship between the power and pulse length of microwaves and the plasma production. We expect that the operational magnetic field regime and reduction of injection beam power can be extended.

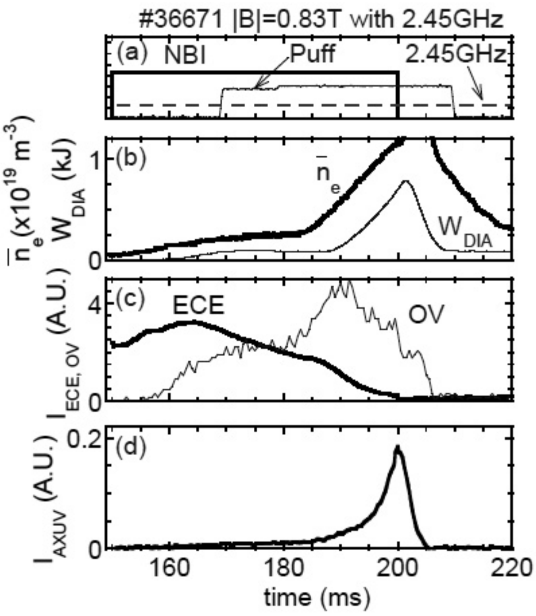

Fig. 1 Time history of NBI startup in Heliotron J. The magnetic field is set as B=0.83 T.

[1] S. Kobayashi, et al., Nucl. Fusion **51** (2011) 062002