§21. Global particle balance study in long-pulse discharges by NBI

Nakamura, Y., Noda, N., Takeiri, Y., and LHD experimental Group G1, G2

We have proceeded the development of plasma heating systems (ECH, NBI, ICH) for obtaining a steady state currentless plasma in the superconducting helical device (LHD), which is greatly suitable to study the physics and technologies for steady state operation. After the LHD machine has completed, we tried promptly to sustain a high temperature plasma by ECH and NBI. In the second experimental campaign, we have achieved a long-pulse discharge with the duration of 22 s by NBI alone. In the longest discharge, the plasma density was kept almost constant at around 3 x 10^{18} m^{-3} and the plasma temperature (electron and ion) of around 1keV was sustained up to the end of the discharge. We observed no impurity accumulation and no radiation collapse during the discharge.

In order to extend the discharge duration towards steady state operation, it is most important to investigate the particle balance in the long-pulse discharge. Therefore we have studied the global particle balance by estimating the gas sources and sinks. The wall particle loading rate during the discharge can be described by

$$\Gamma_{\rm wall} = \Gamma_{\rm puff} + \Gamma_{\rm NBI} + \Gamma_{\rm NBI}^{\rm gas} - \frac{dN_{\rm D}}{dt} - \frac{dN_0}{dt} - \Gamma_{\rm pump} \qquad (1)$$

where $\Gamma_{\rm puff}$ is the gas puff fuelling rate, $\Gamma_{\rm NBI}$ is the energetic beam particle fuelling rate, $\Gamma_{\rm NBI}^{\rm gas}$ is the cold particle fuelling rate from gas in the beam line, dN_D/dt is the neutral loss rate due to plasma formation, dN_0/dt is the neutral gas buildup rate, $\Gamma_{\rm pump}$ is the pump exhaust rate and $\Gamma_{\rm wall}$ is the wall pump rate. This type of particle balance has been used for many other tokamak discharges. As an example, we present the particle balance at 10 s after the initiation of the long-pulse discharge in Fig. 1. Since the external gas puffing was performed only in the startup phase, $\Gamma_{\rm puff} = 0$. $\Gamma_{\rm NBI}$ is calculated to be 0.127 Pam^3/s from the beam parameters (E_b = 66 keV, P_{in} = 660 kW) including the shine-through particles. The neutral gas flux ($\Gamma_{\rm NBI}^{\rm gas}$) from the beam duct is estimated to be 0.037 Pam^3/s from the pressure measurement in the beam drift tube. The neutral loss rate due to plasma formation is estimated as the rate of change in the hydrogen inventory. In this analysis we assume $Z_{\rm eff} = 1$ and flat density profiles typical of long-pulse modes. With these assumptions, the hydrogen inventory is roughly equal to the electron inventory, which can be estimated as the product of the line averaged electron density and the plasma volume (V_p), i.e. $N_D \approx N_e \approx \bar{n}_e V_p$. The contribution of this term to the particle balance is very small because the electron density is almost constant during the discharge. Since the divertor pressure decreases abruptly with the initiation of discharge and it is kept almost constant at the low level of 10^{-4} Pa, dN_0/dt = 0. The particle exhaust by a pumping system (pumping speed of 75 m^3/s) is not so large ($\Gamma_{\rm pump}$ = 0.004 Pam^3/s) because the divertor pressure is very low as indicated above. The wall pump rate, $\Gamma_{\rm wall}$, can be readily calculated to be 0.154 Pam^3/s from the eq. (1). Here, if we exclude the shine-through particles, which may be absorbed in the NBI armor tiles, from the particle balance, the net beam particle fueling rate for plasma production is 0.048 Pam^3/s since the shine-through power of NBI is about 65 % of the injection power because of low plasma density. The wall pump rate becomes to be 0.075 Pam^3/s. As you can see in Fig. 1, it is found that the major external particle sources originate from the beam particles and the gas flow from the beam line and the wall acts as a main particle sink. On the other hand, we should estimate the total amount of recycling particles from the wall. If we define $\Gamma_{\rm wall} = N_D/\tau_p^*$, where $\tau_p^* = \tau_p / (1-R)$, τ_p is the particle confinement time and R is the recycling coefficient, and $\tau_p \approx \tau_E$ (~ 0.1 s), one finds that R = 0.95 in case of excluding the shine-through particles. Assuming that the divertor particle flux is homogeneous along the divertor leg trace, we can estimate the total particle flux ($\Gamma_{\rm div}$) to the divertor from the measurement by a divertor probe array and $\Gamma_{\rm div}$ = 0.607 Pam^3/s. As a result, one should note that the particle source for plasma formation almost originates from the recycling particles in the long-pulse discharge.

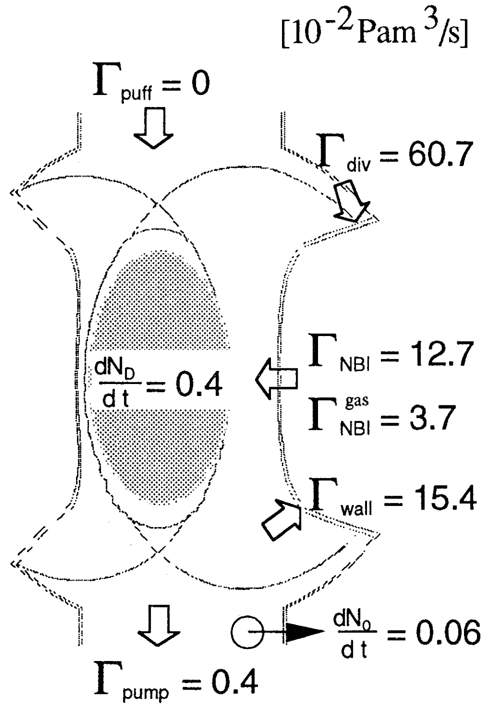

Fig. 1. Schematic view of global particle balance in long pulse discharge by NBI.