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Measurements of the Heating Beam Deposition Profile in TFTR

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Abstract

The calculated heating-beam deposition profile is experimentally verified for a variety of target plasma densities for the first time. The calculation of the heating-beam deposition is found to be consistent with the measurement for the discharges without MHD activity. It is also demonstrated that the radial electron flux is unchanged from the ohmic phase to the initial auxiliary heating phase (≤ 100 msec).

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The beam deposition profile of neutral-beam-heated tokamak plasmas is important for understanding particle and heat transport. If the particle transport is based on a diffusive process, the electron particle balance equation in a neutral-beam-heated plasma is as follows:

$$\frac{\partial n_e(r, t)}{\partial t} = -\nabla \cdot \Gamma_e(r, t) + S_b(r, t) + S_w(r, t)$$

where $S_b(r, t)$ and $S_w(r, t)$ are source of electrons from the heating beam and the wall, respectively, and $\Gamma_e(r, t)$ is a radial electron flux which is a function of the electron diffusion coefficient $[D_e(r, t)]$ and the convection velocity $[v_p(r, t)]$.^{1,2} In order to solve for $\Gamma_e(r, t)$, it is essential to have precise values of $S_b(r, t)$ and $S_w(r, t)$ together with the measured electron density $[n_e(r, t)]$. In this paper, the increase in the number of electrons based on the calculated^{3,4} heating-beam deposition profile is compared with the measured electron density for the first time. The study shows that the calculation is consistent with the measurement within the measurement error for the initial heating phase (≤ 100 msec). In particular, the initial rate of rise of $n_e(0)$ is found to be a good measure of the central beam deposition rate. The dependence of the heating beam deposition profile on the target plasma density ($\bar{n}_{et}$) is also demonstrated in this letter. In the course of this study, it was demonstrated that $\Gamma_e(r, t)$ is unchanged from the ohmic phase to the initial auxiliary heating phase (≤ 100 msec after the start of neutral-beam injection).

The neutrals (D^0) from the heating beam produce electrons through three different processes and deposit heat in the plasma. These basic processes are

proton ionization, electron ionization, and charge exchange shown as follows:

$$D^0 + D^+ = D^+ + D^+ + e^-,$$

$$D^0 + e^- = D^+ + e^- + e^-, \text{ and}$$

$$D^0 + D^+ = D^+ + D^0 \rightarrow D^+ + D^+ + e^-.$$

The cross-section for each process is well known (within $\pm 20\%$) and the impurity content in the plasma are included in the time-dependent transport code (TRANSP)³ which employs the Monte Carlo method to calculate the electron production rate in each process.⁴ The estimated error in this calculation is $\pm 30\%$. In this study, multi-step ionization processes,⁵ which may be important when the beam voltage and/or target density are high, are not included. Since each heating-beam neutral produces one electron, the rate of rise of the local electron density can be used as a measure of heating-beam deposition rate, if $\Gamma_e(r, t)$ and $S_w(r, t)$ are unchanged.

The experiments were carried out in deuterium plasmas with toroidal magnetic fields of $B_T = 4.8$ T. In TFTR (Tokamak Fusion Test Reactor), the heating beams were arranged tangentially to optimize heating. Deuterium neutral beams with $E_{inj} \leq 110$ keV were injected with a total power of up to 22 MW. For this study, data were restricted to nearly balanced injection, i.e., $|(P_{co} - P_{ctr})/(P_{co} + P_{ctr})| \leq 0.2$, where P_{co} and P_{ctr} are the powers of the neutral beams injected co-parallel and counter-parallel to the plasma current (I_P), respectively. The time-dependent electron density is calculated from the inversion⁶ of the measured line-integral density (10 chords) taking into

account the elongation of the magnetic flux surfaces (as inferred from poloidal field measurements outside the plasma) and a self-consistent Shafranov shift. The absolute and relative error in the determination of local electron density is ± 1.5 and $0.5 \times 10^{18} \text{ m}^{-3}$, respectively. These errors are constant across the profile.

It is instructive to compare the time history of the local electron density in plasmas heated by neutral-beam injection, which both heats and directly fuels the plasma and ion cyclotron radio frequency (*ICRF*)⁷ where no direct fueling is present. First we examine *ICRF* heated plasmas; here, the plasma with $I_p = 1.4 \text{ MA}$ and a minor radius (a) = 0.96 m was heated with 4 MW *ICRF* power. The time history of n_e at $r/a = 0.0, 0.5$, and 1.0 , together with the total stored energy (E_{tot}), electron energy (W_e), and central electron temperature [$T_e(0)$] are illustrated in Fig. 1. Since there is no direct particle fueling, one might expect that the variation of the local n_e is either due to changes in $\Gamma_e(r, t)$ or $S_w(r, t)$. The rise of n_e at the edge [see $n_e(0.9 \leq r/a \leq 1.0)$ in this figure] is the first notable change in the electron density. Following the rapid increase of edge density, an inward propagation of the density rise is noted. As shown in this figure, the local electron density is not perturbed from its value in the ohmic phase until the inward propagation of the edge density has arrived at each radius. The v_p , which is about 10 m/sec near the edge and decreasing to $\sim 5 \text{ m/sec}$ near the center, determined by a time-of-flight method is consistent with the value measured by gas injection in an ohmic plasma for similar plasma parameters.

It is not clear whether the rise of the edge density and its inward propagation is due to $S_w(r, t)$ or density convection. However, if the penetration velocity of the wall neutrals is the sound velocity (which is faster than the time scale of v_p), then $S_w(r, t)$ may not be changed from the ohmic level. As a result of the central heating, $T_e(0)$ is increased from 2 keV to 3.5 keV and the sawteeth are stabilized. The normalized energy confinement time (τ_E/τ_E^L) is 1.1 where τ_E^L is the energy confinement time of L-mode scaling.⁸ This experiment demonstrates that the $\Gamma_e(r, t)$ is not only unchanged, but also insensitive to the change of electron temperature for the initial period (≤ 100 msec) of heating. A saturation of $T_e(0)$ and W_e is observed when the inwardly propagating edge density reaches the center of the plasma. The additional increase of W_e is due to the increase in density near the center.

In a neutral-beam-heated plasma, where direct fueling (S_b) accompanies the deposition of heat, a rise of the local electron density is expected. The time history of the electron density both at the center and edge of the plasma together with E_{tot} , and $T_e(0)$ are shown in Fig. 2. Here, plasmas with two different target densities ($\bar{n}_{et} = 1.5$ and $2.7 \times 10^{19} \text{ m}^{-3}$) at $I_p = 1.5 \text{ MA}$ and $a = 0.9 \text{ m}$ are heated with 18 MW of neutral-beam power (P_B). As indicated in this figure and in contrast to the *ICRF* heating case, the initial slope of $n_e(0)$ is increased as the heating-beam is turned on. A rapid rise in edge density similar to the *ICRF* case is observed. Finally, the rate of rise of $n_e(0)$ is further increased when the inwardly propagating edge density arrives at the center of the plasma in the higher $\bar{n}_{et}$ case (solid line). It was notable

that E_{tot} , and $T_e(0)$ saturate when the inward flow reached the center of the plasma. As $\bar{n}_{et}$ is lowered to $1.5 \times 10^{19} m^{-3}$ (broken line), the slope of $n_e(0)$ increases and the edge density rise is suppressed significantly. The separation between the effect of beam fueling and the edge density convection is not clear. The saturation time of E_{tot} , and $T_e(0)$ is delayed and E_{tot} is higher. As a result, τ_E/τ_E^L for these two discharges was 1.0 (solid line) and 1.2 (broken line) at the time of maximum E_{tot} , respectively. In order to demonstrate the initial rate of rise of the local electron density during the neutral-beam heating period, a comparison between the calculated and measured density is shown in Fig. 3. The target plasma has a low density ($\bar{n}_{et} = 0.8 \times 10^{19} m^{-3}$), $I_P = 1.4 MA$, $P_B = 14 MW$ and $a = 0.9 m$. The achieved τ_E/τ_E^L is two during the neutral beam heating. Here, the calculated S_b is integrated for 50, 100, and 150 msec (shown as histogram in the figure) and compared with the measured electron density at several different radii. As shown in this figure, the rate of rise of the internal local electron density ($r/a \leq 0.5$) is entirely due to the beam fueling while the wall source dominates in the outer region ($r/a \geq 0.5$). The difference between the number of measured and calculated electrons may be a good measure of the wall recycling level. The comparison study was performed for many different beam heated discharges. In general, the measured values are consistent with the calculations within the experimental error unless there was internal MHD activity. Therefore, even in the neutral-beam-heated plasmas, $\Gamma_e(r, t)$ was unchanged from the ohmic value for the initial heating period ($\leq 100 msec$). This result is consistent

with the previously discussed *ICRF* heating case.

The dependence of the heating beam deposition profile on $\bar{n}_{et}$ is illustrated in Fig. 4. Here, the calculated deposition profiles for different $\bar{n}_{et}$ are shown. It is assumed that the outer half of the profile ($0.5 \leq r/a \leq 1.0$) is correct. In order to avoid variations in the initial beam power variation, S_b is integrated from 50 to 100 msec and the profiles are normalized to the peak value. A highly peaked deposition profile is obtained when the heating-beam ($P_B = 22MW$) is injected into a low target density ($\bar{n}_{et} = 0.93 \times 10^{19} m^{-3}$) at $I_p \approx 1.4 MA$ and $a = 0.8 m$. As a result, the achieved τ_E/τ_E^L was three and the density profile was highly peaked. The profile broadening correlates with increasing $\bar{n}_{et}$ as shown in this figure.

In summary, the calculation of heating-beam deposition in a tokamak plasma is consistent with the measured value over a wide range of plasma discharges without internal MHD activity. In general, $\Gamma_e(r, t)$ is unchanged by the auxiliary heating, at least for the initial heating period ($\leq 100 msec$). The dependence of the heating-beam deposition on target plasma density are also demonstrated.

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Figure 1 Typical time histories of local electron densities together with the E_{tot} , W_e and $T_e(0)$ for an *ICRF* heated plasma at $I_P \approx 1.4$ MA with $P_{rf} = 4$ MW.

Figure 2 The time history of electron density at the center and edge of the plasma together with $T_e(0)$, and E_{tot} for two different target plasma densities at $I_P = 1.5$ MA with $P_0 = 18$ MW. Broken line - $\bar{n}_{et} = 1.5 \times 10^{19} \text{ m}^{-3}$. Solid line - $\bar{n}_{et} = 2.7 \times 10^{19} \text{ m}^{-3}$.

Figure 3 A comparison between the measured and calculated density is for several different radii. The histograms represent the integral values of the calculated S_b . The integration time was from the beam turn-on time to 50, 100, and 150 msec. (a) $0.0 \leq r/a \leq 0.1$ (b) $0.3 \leq r/a \leq 0.4$ (c) $0.6 \leq r/a \leq 0.7$ (d) $0.9 \leq r/a \leq 1.0$

Figure 4 The dependence of heating-beam deposition profile on $\bar{n}_{et}$ is illustrated. The normalization values are 0.87, 0.27, and $0.41 \times 10^{19} \text{ m}^{-3}$, respectively.

Figure 1

Figure 2

Figure 3

Figure 4