Neutral Beam Heating and Current Drive System and Its Role in ITER-FEAT Operation Scenarios

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Abstract. The NB H&CD system, providing 33 MW in deuterium beams at 1 MeV from two injectors, in addition to 40 MW RF power, contributes to heating a plasma to sub-ignition through the L-H mode transition followed by finite-Q driven-burn (Q ≥ 10), and achievement of a hybrid operation with an extended-duration (~ 1000 s) or steady-state operation with Q ≥ 5. To achieve such operations, the NB provides non-inductive current drive by injecting the beams tangentially into the plasma with the capability of on- and off-axis current drive. The present engineering design is under the constraints of the beam envelope, vacuum confinement, neutron shielding, tolerances, and clearances required with the toroidal field coils. The on- and off-axis current drive is to be achieved by tilting the beam axis vertically. Each beam axis of the NB injectors can be tilted independently, providing flexibility in the control of heating and the driven current profile.

1. Introduction

The ITER plasma requires an additional heating power of ~ 50 MW to achieve the L-H mode transition, and subsequent finite-Q driven-burn (Q ≥ 10). The Neutral Beam Heating and Current Drive (NB H&CD) system contributes to this requirement by providing 33 MW in atomic deuterium beams at 1 MeV from two injectors, in addition to 40 MW radio frequency (RF) power. The layout design allows for a third injector to reach a total NB H&CD power up to 50 MW, where the total auxiliary power will be increased to ~ 110 MW. Another requirement of ITER is to achieve a hybrid operation extending the pulse duration (~ 1,000 s) and to demonstrate a steady-state operation with Q ≥ 5. To achieve such operations the NB provides non-inductive current drive by injecting the beams tangentially into the tokamak plasma. Since a plasma with negative central shear is considered as an attractive candidate for these operations, the capability of on- and off-axis current drive by the NB has been analysed from both engineering and physics aspects. The paper describes some details of the NB H&CD system and its role in the various operation scenarios.

2. NB H&CD System

The horizontal angle of the tangential injection is defined as a compromise of space limitations around the NB duct, which connects the NB injector to the tokamak vacuum vessel. Another constraint is the beam shine-through to strike the far-side wall between ports. The present engineering design corresponds to a tangency radius of 5.28 m, taking into account the constraints of beam envelope, vacuum confinement, neutron shielding, tolerances, and clearances required between the toroidal field (TF) coils. Thus, the tangency radius is smaller than the plasma major radius. The on-and off-axis current drive is to be achieved by tilting the beam axis vertically. Figure 1 illustrates an elevation view of the NB injector together with the ITER cross section along the beam axis. The beam axis is tilted 2.3° downward to fire the beam close to the plasma axis, then the beam axis can be tilted 1.1° more to reach an off-axis position in the plasma utilising the standard equatorial port without a clash with the TF intercoil structures and PF coils. By tilting the beam source on its support flange, the beam axis can be aimed between two vertical extremes: 0.38 ~ 0.95 m off the plasma equatorial plane at the tangent point, where the beam size is approximately 0.6 m high and 0.4 m wide (elliptic foot print). The plasma equatorial plane including a magnetic axis is

0.50 m above the machine mid-plane, and the beam axis can be changed from z = + 0.15 m ~ - 0.45 m where z = 0 is the machine mid-plane. Each NB injector's beam axis of the NB injectors can be tilted independently, providing flexibility in the control of heating and the driven current profile [1].

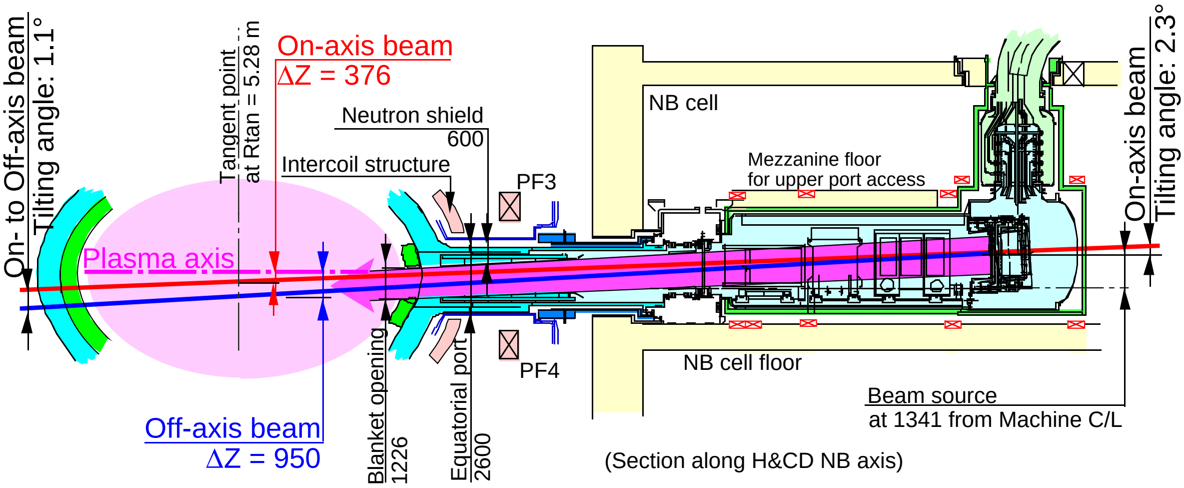

FIG. 1. An elevation view of the NB injector for ITER.

3. Operation Scenarios

Many variants of scenarios are designed for ITER plasma operation. They are classified into three type of scenarios, inductive driven-burn, hybrid driven-burn, and steady-state operations. The inductive driven-burn ($Q \geq 10$) is a nominal scenario which produces a fusion power of P_F = 400 ~ 500 MW with a moderate beta ($\beta_N < 2.0$), reasonable confinement ($H_H \approx 1.0$), and a burn time of 400 s. In the hybrid scenario H&CD power is upgraded to 110 MW, which extends the burn time to 1000 s with $Q \geq 5$, $H_H \approx 1.0$, and $\beta_N < 2.0$. In the steady-state scenario the plasma current is reduced and is supplied non-inductively, and the burn time is extended to ~ 1 hr. The development of ITER steady-state operation scenarios is in progress. At present, a certain range of plasma current is under consideration: low current (I_P ~ 8 MA) with negative shear, and high current (I_P ~ 12 MA) with monotonic q or weak shear profiles. The low current operation requires a challenging H_H and β_N. On the other hand, the high current operation requires modest H_H and β_N, but a large current drive power. In this paper the plasma current is adjusted to I_P = 10 MA as a typical value.

The target plasma has major and minor radii of R/a = 6.2 m/2.0 m, the same as a nominal plasma for the inductive driven-burn operation. The elongation and triangularity are $\kappa/\delta \approx 1.7/0.33$. The flat density and peaked temperature profiles are standard profiles for the inductive driven-burn operation. To enhance a bootstrap current contribution the density profile is modified, as stated below. The average density is fixed to $\langle n_e \rangle \approx 0.7$ in 10^{20}m^{-3} unit. The Greenwald density is n_G = 0.8. The temperature is adjusted so as to produce a fusion power of ~ 400 MW or ~ 500 MW. The plasma is $\beta_N \approx 3.2$, $H_H \approx 1.6$, and Q = 4-5 for the total drive power P_D = 100 MW. The driven current is calculated with the ACCOME code, which has been validated with 0.35 MeV NB in JT-60U experiments [2]. The global NB current drive efficiency is defined as $\gamma_{20} = n_{20}RI_D/P_D$ A/Wm^2.

4. Roles to be played by NB in steady-state operation scenarios

Steady-state operation is the most demanding for the H&CD system and it determines the power requirement and constrains the use of the four H&CD options (NB, IC, EC, and LH).

Weak/moderate/strong negative shear plasmas are investigated here as promising candidates for steady-state operation.

Moderate negative and weak shear / Flat density profile The density and temperature are assumed as shown in Fig. 2 The temperatures are $T_e = T_i$ and $\langle T \rangle = 13.4$ keV. The plasma generates a fusion power $P_F \approx 400$ MW and has $\beta_N \sim 3.2$. Three plasma current profiles are shown in Fig. 3(a). All profiles satisfy $q > 1$, and only Case 2 satisfies $q > 2$. Current profiles are adjusted by NB injection position and its power, and by supplying an additional current in an outer part of plasma region, as shown in Fig. 3(b). The driven currents and NB power are summarised in Table I. The fraction of bootstrap current is moderate, $f_{BS} \approx 35$ %, due to the flatness of density profiles. The required additional current (j_{add}) besides beam-driven (j_{bd}) and bootstrap currents increases from 2.3 MA to 4.2 MA with increasing q_{min}. The NB power reduces from 50 MW to 25 MW. Cases 1&3 use three beam lines with a full NB power, but Case 2 uses two beam lines with reduced power with the help of a large amount of additional current.

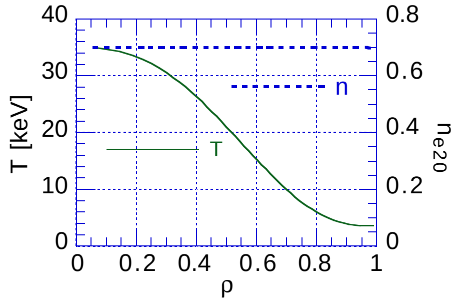

FIG.2. Temperature and density radial profiles.

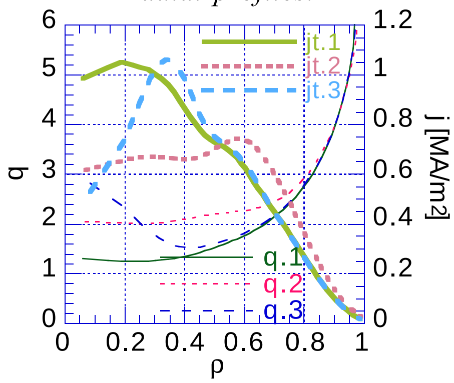

FIG.3(a). Toroidal current density and q radial profiles.

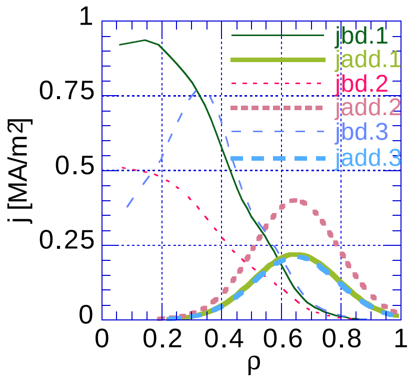

FIG.3(b). Beam driven and additional currents radial profiles.

TAB. I: CURRENTS AND NB PARAMETERS (I_t = 10 MA, $\gamma_{20} \approx 0.39$ A/Wm^2).

	Case 1	Case 2	Case 3
$I_{bd}/I_{add}/I_{bs}$ [MA]	4.58/2.20/3.23	3.20/4.05/3.75	4.44/2.11/3.45
NB position 1/2/3, z[m]	-0.42/0.15/0.15	-0.42/0.15/0.15	-0.42/-0.42/-0.05
Total NB power [MW]	50.8	24.4	49.9
NB power 1/2/3 [MW]	16.9/16.9/16.9	8.1/16.2/0	16.6/16.6/16.6

Moderate negative shear / Rounded density profile The density is slightly modified ($\langle n_{20} \rangle \approx 0.7$, $\beta_N \sim 3.3$, $P_F \approx 500$ MW), as shown in Fig. 4. Two plasma current profiles are shown in Fig. 5(a). Case 1 has $q_{min} < 2$ and Case 2 has $q_{min} > 2$. The beam-driven currents and additional currents are shown in Fig. 5(b), and the results are in Table II. The fraction of bootstrap current increases to $f_{BS} \approx 50$ %, mainly due to a rounded density profile. The required additional current reduces to 1.5/2.6 MA. Case 1 uses three beam lines with a full NB power, and Case 2 also uses three beam lines , but only 57 % of the available power is utilised. The difference observed in bootstrap

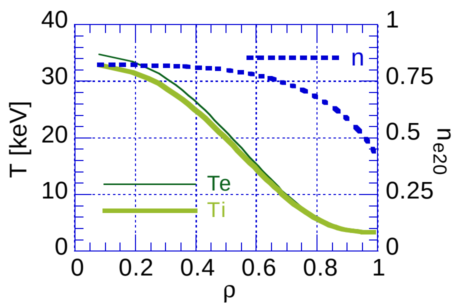

FIG.4. Temperature and density radial profiles.

current comes from the difference in q profile. The higher q in the central plasma region enhances the bootstrap current.

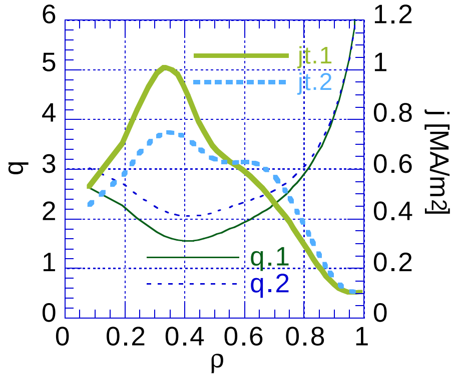

FIG.5(a). Toroidal current density and q radial profiles.

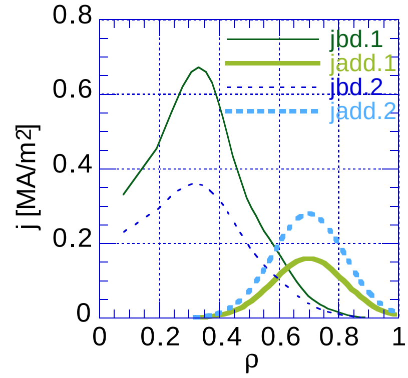

FIG.5(b). Beam driven and additional currents radial profiles.

TAB. II: CURRENTS AND NB PARAMETERS (I_t = 10 MA, $\gamma_{20} \approx 0.33$ A/Wm^2).

	Case 1	**Case 2**
$I_{bd}/I_{add}/I_{bs}$ [MA]	3.84/1.48/4.68	2.22/2.62/5.16
Beam position 1/2/3, z[m]	-0.42/-0.42/0.05	-0.42/-0.42/0.05
Beam power [MW]	50.3	29.0
Beam power 1/2/3	16.8/16.8/16.8	9.67/9.67/9.67

Moderate and strong negative shear / Further modified density profile To increase the bootstrap fraction further and to reduce/avoid the additional current near the plasma edge, the profiles of density and temperature are intentionally modified to generate a steep density gradient at $0.6 \leq r/a \leq 0.8$ (which may need a strong internal transport barrier), as shown in Fig. 6 ($\langle n_{20} \rangle \approx 0.7$, $\beta_N \sim 3.3$, $P_F \approx 500$ MW). Three plasma current profiles for moderate negative shear are shown in Fig. 7(a). The fraction of bootstrap current increases to $f_{BS} \approx 55$ %. The increase of bootstrap current eases the requirement of additional current, which is shown in Fig. 7(b) and Table III. All three cases use three beam lines with a full power of ~ 50 MW. The additional currents now are allowed to be placed at different locations; r/a ≈ 0.75, 0.55, and 0. In the last case, the current in the outer part of the plasma is supplied mainly by a bootstrap current, the three beam lines are placed away from the plasma centre, and the central current can be supplied by EC and/or IC RF drivers. The strong negative shear

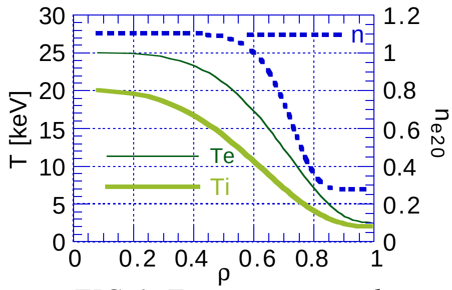

FIG.6. Temperature and density radial profiles.

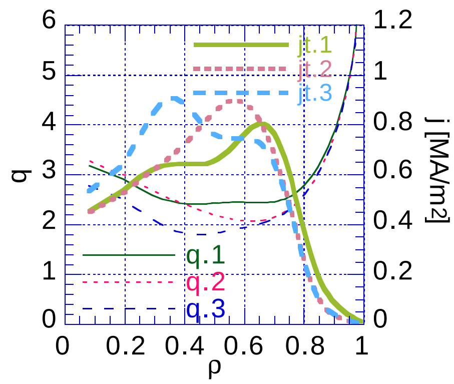

FIG.7(a). Toroidal current density and q radial profiles.

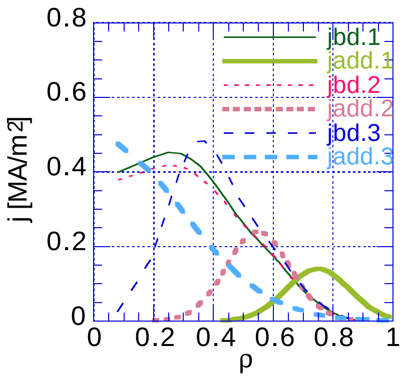

FIG.7(b). Beam driven and additional currents radial profiles.

case is shown in Fig. 8, and the corresponding parameters are listed in Table IV. To reduce the current near the plasma centre, the NB lines are placed away from the centre.

TAB. III: CURRENTS AND NB PARAMETERS (I_t = 10 MA, $\gamma_{20} \approx 0.25$ A/Wm^2).

	Case 1	**Case 2**	**Case 3**
$I_{bd}/I_{add}/I_{bs}$ [MA]	2.98/1.25/5.77	3.03/1.50/5.48	3.11/1.74/5.15
NB position 1/2/3 [m]	-0.42/-0.10/0.15	-0.42/-0.10/0.15	-0.42/-0.42/-0.42
Total NB power [MW]	49.9	50.9	50.1
NB power 1/2/3 [MW]	16.6/16.6/16.6	17.0/17.0/17.0	16.7/16.7/16.7

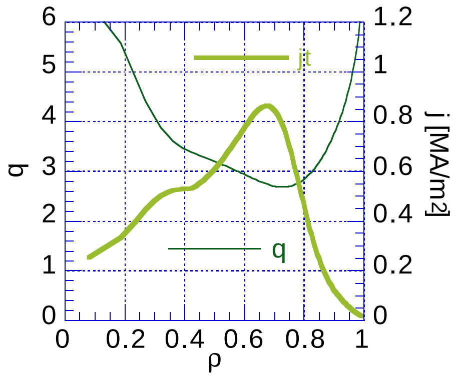

FIG.8(a). Toroidal current density and q radial profiles.

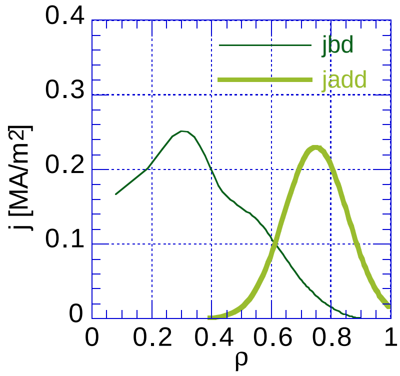

FIG.8(b). Beam driven and additional currents radial profiles.

TAB. IV: CURRENTS AND NB PARAMETERS (I_t = 10 MA, $\gamma_{20} \approx 0.25$ A/Wm^2).

	Case 1
$I_{bd}/I_{add}/I_{bs}$ [MA]	1.57/2.03/6.40
NB position 1/2 [m]	-0.42/0.10
Total NB power [MW]	25.2
NB power 1/2 [MW]	15.9/9.34

5. Summary

1) By tilting the beam source on its support flange, the beam can aim 0.38 ~ 0.95 m off the plasma equatorial plane at the beam tangent point. 2) The NB is able to supply sufficient current density and profile control mainly in an inner part of plasma region ($0 \leq r/a \leq 0.6$) by changing injection position and its power with three beam lines. 3) To cover various scenarios, three beam lines are required, while in certain scenarios with a large fraction of bootstrap current, two beam lines are sufficient. 4) For almost all cases with flat/moderate density profiles for $q_{min} \approx 2$, a certain kind of current driver is required to provide sufficient current in an outer part ($0.5 \leq r/a \leq 0.9$) of the plasma region up to 4 MA, which could be supplied probably by LH waves. 5) The strong internal transport barrier of density in an outer part ($0.6 \leq r/a \leq 0.8$) of the plasma region generates a large fraction of bootstrap current and reduces/eliminates the need of an external current near the plasma edge.

References:

[1] INOUE, T., et al., Proc. 21st Symp. of Fusion Technology, Madrid, Sept., 2000.

[2] OIKAWA, T., et al., Nuclear Fusion, 40 (2000) 435.