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Modelling of Reversed Shear Scenarios in KSTAR

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1. Introduction

The research objectives of the KSTAR tokamak are (i) to extend present stability and performance boundaries of tokamak operation through active control of profiles and transport, (ii) to explore methods to achieve steady state operation for tokamak fusion reactors using non-inductive current drive and (iii) to integrate high performance and steady state operation as a step toward an attractive tokamak fusion reactor [1]. In order to achieve these research objectives, it is essential to develop high performance steady state scenarios in which a dominant fraction of the plasma current is driven by bootstrap current that alleviates the requirement on the externally driven non-inductive current. From the decades of experiments, it is well-known that the reversed shear scenario with internal transport barrier (ITB) helps to drive high fusion performance together with high fraction of bootstrap current. The characteristics of the ITB is sensitively depends on the shape of the q-profile [2].

In this paper, predictive modelling of the reversed shear scenario is performed in KSTAR. Firstly, the possibility of the production of reversed q-profile is investigated using heating and current drive systems which are currently planned in KSTAR. Secondly, optimal experimental conditions for the reversed shear scenario are discussed which exhibits high non-inductive current fraction together with high fusion performance.

2. Modelling of Reversed Shear Scenarios in KSTAR

The predictive modelling is performed with ASTRA code [3] employing the Weiland transport model [4]. The NBI heating package [5] is embedded in ASTRA for the calculation of the heating and current drive by the NBI system in KSTAR. CURRAY is employed to calculate the ICRH/FWCD and LSC is used to calculate LHCD. A model developed by Kim [6] is employed for the calculation of the bootstrap current in the plasma. No models for MHD activities are included in the simulations. The Weiland transport model is employed for the predictive simulation with ASTRA to calculate temperature profiles, which is a fluid model based on the ion temperature gradient (ITG) and the trapped electron mode (TEM). The simulation is performed until the plasma reaches steady state conditions where the current density profile is fully equilibrated. The electron density profile (n_e) and radiation profile (P_{rad}) is taken from a typical improved H-mode discharge at ASDEX Upgrade (pulse 17870) and multiplied by constant values which are apt to KSTAR plasma conditions. Initial current density profile and boundary condition for ion and electron temperatures are also taken from the same discharge and multiplied by constant values. In ASTRA, the momentum equations are not solved, however the Weiland model uses the velocity shear in the computation of the transport coefficients. Hence for the toroidal velocity v_{tor}^{sim}, $v_{tor}^{sim} = cT_i^{sim}$ is used. The heat diffusivities are defined as the sum of the neoclassical and turbulent contributions, the poloidal rotation is assumed to be neoclassical [7]. The effective ion charge (Z_{eff}) is assumed to be constant at 2.0.

Firstly, predictive modelling is performed for the second phase of the KSTAR operation. Plasma current is 1 MA, toroidal magnetic field is 2 T and pulse duration is 300 s. All three beam sources are applied with a total heating power of 8.1 MW operated at 120 kV for Deuterium. A heating power of 1.5 MW out of 3 MW is used from 38 MHz of ICRH system. All heating power of 3 MW is applied from 5 GHz of LHCD system. The calculated ion and electron temperature profiles are shown in figure 1 (a). The Weiland model predicts that an ITB is formed in the ion channel around $\rho_{tor} = 0.3$. It corresponds to the location of the minimum q-value (q_{min}) (see figure 1 (e)). Heat conductivity is close to neoclassical inside the ITB and $R/L_{Ti} > 10$ for $4.5 < \rho_{tor} < 7.5$. Very high fusion performance is obtained in this reversed shear scenario with an ITB. The confinement enhancement factor ($H_{98}(y, 2)$) is 1.92 and normalised beta (β_N) is 4.47, corresponding normalised fusion gain ($\beta_N H_{98}(y, 2)/q_{95}$) is 0.53 which is much higher than those of ITER reference scenario (0.2) and advanced scenario (0.15). The density profile is shown in figure 1 (b). It is rather peaked and line average density is 57% of the Greenwald density. Current density profiles are presented in figure 1 (c). Off-axis LHCD plays a dominant role to produce the reversed current density profile. In this simulation, the fraction of the non-inductive current drive is more than 100%; bootstrap current fraction is 67%, NB current fraction 39% and LH current fraction 33%, which results in a negative ohmic current drive. q_{min} is higher than 1.5 as shown in figure 1 (e), desirable for avoiding the (3, 2) neoclassical tearing mode (NTM).

Secondly, predictive modelling is performed for the third phase of the KSTAR operation. Plasma current is 2 MA, toroidal magnetic field is 3.5 T and pulse duration is 300 s. NBI system is upgraded to a total heating power of 16.2 MW from six beam sources (two neutral beam boxes) operated at 120 kV for Deuterium. 38 MHz of ICRH system is upgraded with a heating power of 6 MW and 5 GHz of LHCD system with 5 MW. The calculated ion and electron temperature profiles are shown in figure 1 (a). The Weiland model predicts that a weak ITB is formed in the ion channel around ρ_{tor} = 0.2. This also corresponds to the location of q_{min} (see figure 1 (e)). Heat conductivity is close to neoclassical inside the ITB, however R/L_{Ti} > 10 is only observed for 0.7 < ρ_{tor} < 0.8. Although the ITB is weak and narrow, still high fusion performance is obtained in this scenario. The confinement enhancement factor ($H_{98}(y, 2)$) is 1.78 and normalised beta (β_N) is 3.37, corresponding normalised fusion gain is 0.46. The density profile is the same as that of 1 MA / 2 T case but the multiplication factor is higher (see figure 1 (b)). The line average density is 41% of the Greenwald density. In this scenario, off-axis LHCD also plays a role to produce the reversed current density profile, however not enough to raise $q(0)$ and q_{min}; q_{min} is 1.35. Moreover, as the ITB is located in the centre, bootstrap current is higher in the centre which moves the location of q_{min} towards the centre of the plasma. The fraction of the non-inductive current drive is more than 100%; bootstrap current fraction is 53%, NB current fraction 32% and LH current fraction 34%, which also results in a negative ohmic current drive.

5. Conclusions

Predictive modelling of reversed shear scenarios is performed at KSTAR. The results exhibit that reversed q-profiles are able to be established using the present heating and current drive system in KSTAR. Very high fusion performances together with high bootstrap fractions are obtained in both 1 MA / 2 T and 2 MA / 3.5 T cases. However, it is necessary to further develop ways to make broader ITB with optimal location of q_{min} and to compensate overdrive of NB current in the centre of the plasma. Applying ECCD is one of possibilities. Balanced NBI is under consideration in KSTAR to avoid overdrive of the central NB current.

	1 MA / 2 T	2 MA / 3.5 T
$H_{98}(y, 2)$	1.92	1.78
β_N	4.47	3.37
$H_{98}(y, 2)\beta_N / q_{95}^2$	0.53	0.46
IBS (%)	67	53
INB (%)	39	32
ILH (%)	33	34

Table 1. Fusion performance and current drive fractions in reversed shear scenarios

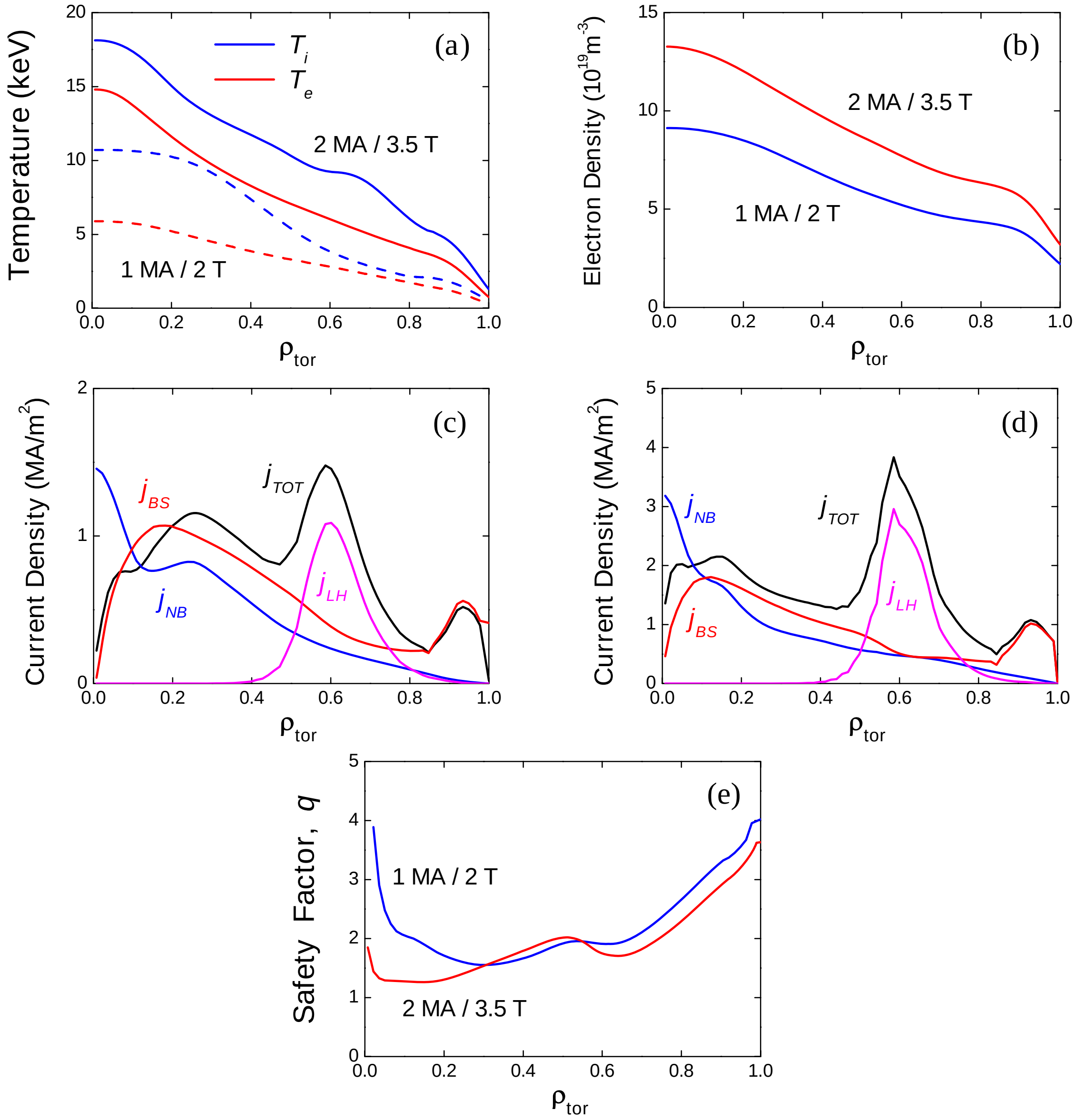

Figure 1. (a) Ion and electron temperature profiles, (b) density profiles, (c), (d) total, bootstrap, NB and LH current density profiles and (e) q-profiles for 1 MA / 2 T and 2 MA / 3.5 T reversed shear scenarios in KSTAR

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