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The Simulational Study on the KSTAR Operation Modes

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Abstract

Adaptability of the advanced tokamak operation modes in KSTAR tokamak is investigated by computing self-consistent MHD equilibria and current density profiles using ACCOME. It is shown that KSTAR heating and current drive system based on multiple technologies(neutral beam, ion cyclotron and lower hybrid system) are adequate to study the wide range of advanced tokamak physics.

1. Introduction

The KSTAR(Korean Superconducting Tokamak Advanced Research, [1]) device ($R_0 = 1.8m$, $a = 0.5m$, $\kappa = 2$, $\delta = 0.8$, $B_T = 3.5T$, $I_p = 2MA$) is being constructed to study advanced tokamak plasma for pulse length up to 300 seconds. The KSTAR tokamak will be a versatile facility capable of operating in the wide range of advanced tokamak operating modes. The auxiliary systems will provide heating and current drive capability as well as the flexibility in the control of current density and pressure profiles, to access the regimes of improved performance.

Several advanced plasma configurations and operation modes in baseline and upgrade phases have been identified [2] through a MHD equilibrium and power balance study. These configurations require the control of current density profile as well as the pressure profile, and it is important to assure that these configurations can be actually achieved with the heating and current drive system under design.

The self-consistent analysis of the MHD equilibrium and the current distribution is necessary since the currents and the MHD equilibrium strongly depend on each other. In this work, we analyze three reference modes of non-inductive operation for their adaptability in KSTAR using ACCOME [3]; baseline reference mode, upgrade reference mode, and reverse shear mode. The ACCOME code is a simulation model for the computation of self-consistent MHD equilibria in the presence of current density source terms due to neutral beam injection(NBI), fast wave in the ion cyclotron range of frequencies(ICRF), lower hybrid(LH) wave, ohmic electric fields, and bootstrap current effect. The results illustrate the variety of current drive applications for NBI, ICRF fast wave(FWCD) and lower hybrid wave(LHCD), ranging from use as a source of central current drive to a mechanism for off axis current drive control. It is important to note that the density and temperatures are assumed in ACCOME calculation and that no transport calculation is performed to determine the heating power necessary to achieve a particular equilibrium pressure. Thus, the quoted values of neutral beam and rf powers refer to the required current drive power. The required heating powers for the assumed equilibrium pressures are determined through the transport calculation using WHIST [4]. WHIST solves the flux-surface-averaged 1-D transport equations which are coupled with the 2-D equilibrium solution of Grad-Shafranov equation.

2. Numerical Results

In ACCOME model calculations, the toroidal magnetic field was $B_0 = 3.5\ T$, the electron density was assumed to be the form, $n_e(\psi) = n_e(0)(1-\psi)^{\alpha_n}$, and the electron and ion temperatures to be the form, $T_j(\psi) = T_j(0)(1-\psi)^{\alpha_{T_j}}$. Here ψ is a normalized poloidal flux function. The neutral beam injection was modeled with 3 beam lines and 3 deuterium sources at each beam line. A beam energy was 120 KeV and tangency radius was 1.65 m. The LHCD parameters are as follows. The wave frequency is 3.7 GHz, and the parallel refractive index is $n_{||} = 2.0 \sim 4.0$ for the forwarded power and $n_{||} = -7.8 \sim -6.3$ for the reverse power. These parameters correspond to a grill phasing between adjacent waveguides of $80° \sim 140°$. The finite poloidal extent of the LH grill is modeled by launching three 'bundles' of rays from vertical positions in the poloidal plane of $(-2.0, 0, 0.2)\,m$. The FWCD parameters were wave frequency, $f = 38\ MHz$, toroidal width of antenna strap, $0.1\ m$, and antenna strap radius, $0.53\ m$. Seventeen poloidal modes ($-8 \leq m \leq 8$) were used to represent the semi-spectral solution for the electric field E in the full-wave ICRF code, and a single toroidal mode($n_\phi = 18$) of the antenna current strap was used. The bootstrap current is evaluated based on the Hirshman-Sigmar moment approach of the neoclassical theory [5].

2.1 Baseline Reference Mode

A baseline mode is the plasma configuration expected with the initial heating system, 8 MW NBI, 6 MW FWCD, and 1.5 MW LHCD. It is characterized by parameter values corresponding to plasma current, $I_p = 1.5\ MA$ with the standard monotonically increasing q profile. Fully non-inductive current drive operation with pulse length of 300 s will be possible. Fig. 1 shows ACCOME calculation with $n_e(0) = 0.7 \times 10^{20}\ m^{-3}$, $\alpha_n = 0.5$, $T_e(0) = T_i(0) = 8\ KeV$, and $\alpha_{Te} = \alpha_{Ti} = 1.0$. The volume-averaged β_t and β_p are $1.76\ \% and 1.4\%$, respectively, with $< n_e >= 3.9 \times 10^{19}\ m^{-3}$, and $< T_e >=< T_i >= 3.1\ KeV$. The plasma current is 1.56 MA with fast wave driven current, $I_{FW} = 0.09\ MA$, neutral beam driven current, $I_{NB} = 0.74\,MA$, bootstrap current, $I_{BS} = 0.38\,MA$, and lower hybrid wave driven current, $I_{LH} = 0.35\ MA$. For a reduced density of $n_e(0) \leq 0.7 \times 10^{20}\ m^{-3}$, the initial current drive power would be sufficient to drive a 1.5 MA. With higher density, the initial current drive power is not sufficient to drive fully non-inductive plasma current of 1.5 MA. The off-axis LH current drive tends to broaden the current density profile, raising up q_0 above unity(1.05).

2.2 Upgrade Reference Mode

A upgrade reference mode is a standard high-β tokamak discharge with a monotonic q profile and $\beta_N (\equiv \frac{\beta}{I_p/aB_0})$ close to the first-stability limit given by the ballooning mode. A full non-inductive current drive will be possible with a full KSTAR compliment of heating and current drive systems, 20 MW NBI, 12 MW FWCD, and

4.5 MW LHCD. Fig. 2 shows ACCOME calculation with $n_e(0) = 1.1 \times 10^{20}\ m^{-3}$, $\alpha_n = 0.5$, $T_e(0) = T_i(0) = 13\ KeV$, and $\alpha_{Te} = \alpha_{Ti} = 1.0$. β_t and β_p are calculated as 4.0 % and 1.8 %, respectively, with $< n_e >= 6.2 \times 10^{19}\ m^{-3}$, $< T_e >=< T_i >= 5.0\ KeV$, $P_{NB} = 18\ MW$ and $P_{FW} = 3.0\ MW$. The plasma current of 2.18 MA can be provided with $I_{FW} = 0.14\ MA$, $I_{NB} = 1.39\ MA$ and $I_{BS} = 0.65\ MA$. Thus the upgraded current drive power would be adequate to drive 2.0 MA of fully non-inductive plasma current. The value of on-axis safety factor, q_0, is less than one because of the highly peaked nature of the fast wave driven current density profile. The FWCD power is absorbed via electron Landau damping(ELD) and transit time magnetic pumping(TTMP) near the plasma center. The value of q_0 can be controlled by reducing the FWCD power and using LHCD power.

2.3 Reverse Shear Mode

The reverse shear mode is one of the advanced configurations being considered in KSTAR tokamak. With a high bootstrap current, the current profile is naturally hollow and leads to the negative magnetic shear configuration. This configuration has been thought to be promising since it produces high β_N due to high-n ballooning stability and enhanced confinement due to suppression of anomalous transport mechanism such as ion temperature gradient driven mode and trapped electron mode [6]. Model results from ACCOME are shown in Fig. 3. The parameters used were, $n_e(0) = 1.7 \times 10^{20}\ m^{-3}$, $\alpha_n = 0.5$, $T_e(0) = T_i(0) = 14\ KeV$, and $\alpha_{Te} = \alpha_{Ti} = 1.0$ with $P_{LH} = 4.5\ MW$. The current density profiles in Fig. 3(a) correspond to a total LHCD current of 0.39 MA, $I_{BS} = 1.86MA$ and $I_p = 2.25MA$. The bootstrap current fraction is high with $I_{BS}/I_p = 82.7$ %. By by taking credit for high bootstrap current generation, the entire plasma current could be driven with 4.5 MW of LHCD power alone. The total current density is hollow due to the large fraction of bootstrap current. The bootstrap current fraction and the shape of bootstrap current density depend sensitively on the shape of pressure profiles. For a good alignment of the bootstrap current profile, control of the bootstrap current profile through active control of the pressure profile is necessary. In Fig. 3, negative current drive using NBI or FWCD can be used to optimize the q profile for MHD stability. The safety-factor $q(\psi)$ is shown in Fig. 3(b). The β_t and β_p are 6.7% and 2.9 %, respectively. The value of β_N is 5.2 and the discharge is in the second stability regime. These types of high bootstrap current equilibria are unstable to low-n external kink modes, owing to the large bootstrap current densities in the plasma periphery. The low-n kink mode stability would have to be ensured by a conducting shell or feedback stabilization. However, LHCD power at high $n_{||}$ can be used to drive a reverse current, thus cancel large bootstrap current densities at that location and possibly stabilize the external kink mode.

3. Comparative Study

The comparative study has been done to assure that the equilibrium pressures for three operation modes described above can be actually achievable using the transport code, WHIST. In WHIST, the transport model of net radial particle and energy flux for the main plasma is described as the combination of full neoclassical and anomalous transport. The anomalous transport coefficients are forced to follow the ITER-H mode energy confinement scaling formula with a confinement inhancement factor (H_f). The power depositions and driven-currents of incident neutral beams and rf waves in the plasma are modeled using the semi-analytical formulae and described in tail in Ref.[4]. Fig. 4(a) shows the time-evolution of applied auxiliary heating powers in case of the baseline mode. I_p is ramped up from 100 kA to a flattop maximum of 1.5 MA in 4 seconds. The initial heating and current drive powers drive the 100 % non-inductive plasma current of 1.5 MA and produce β_t = 1.73% with H_f = 0.68, shown in Fig. 4(b). In Fig. 5(a), the time evolution of those corresponding to the upgrade mode is shown. I_p is ramped up to 2.0 MA at the flattop phase. The upgrade heating and current powers produce β_t = 4.05% with H_f = 1.07 at I_p= 2.0 MA (Fig. 5(b)). Fig. 6(a) and (b) show the time evolution of applied auxiliary heating powers and β_t corresponding to the reverse shear mode: β_t = 6.5% with H_f = 1.7 at the flattop current phase of I_p= 2.0 MA.

4. Summary

In summary, three KSTAR operation modes are analyzed with a current drive/MHD equilibrium model, ACCOME and a transport model, WHIST. It was shown that the initial heating and current drive power(8 MW NBI, 6 MW FWCD, and 1.5 MW LHCD) is sufficient to drive the fully non-inductive plasma current of 1.5 MA and the upgrade system(20 MW NBI, 12 MW FWCD, and 4.5 MW LHCD) is adequate to produce tokamak discharges that will be of interest for the advanced tokamak study and demonstration.

Acknowledgments

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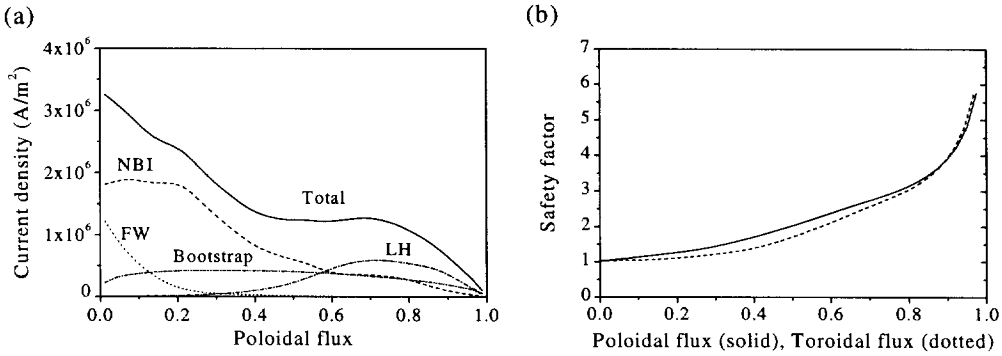

Figure 1: Result for baseline reference mode. (a) Current density profiles (A/m^2) versus poloidal flux. (b) Safety factor q versus poloidal flux(solid) and toroidal flux(dotted).

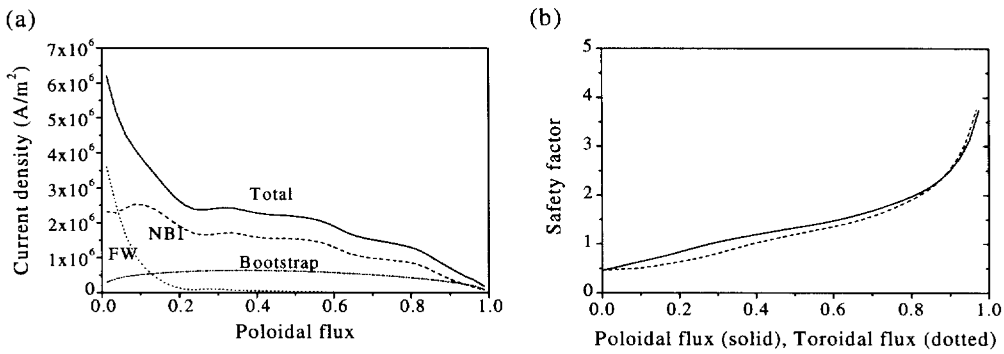

Figure 2: Result for upgrade reference mode. (a) Current density profiles (A/m^2) versus poloidal flux. (b) Safety factor q versus poloidal flux(solid) and toroidal flux(dotted).

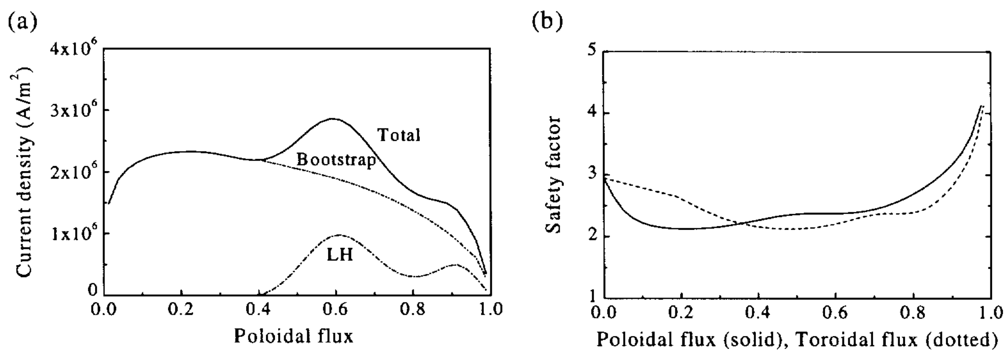

Figure 3: Result for reverse shear mode. (a) Current density profiles (A/m^2) versus poloidal flux. (b) Safety factor q versus poloidal flux(solid) and toroidal flux(dotted).

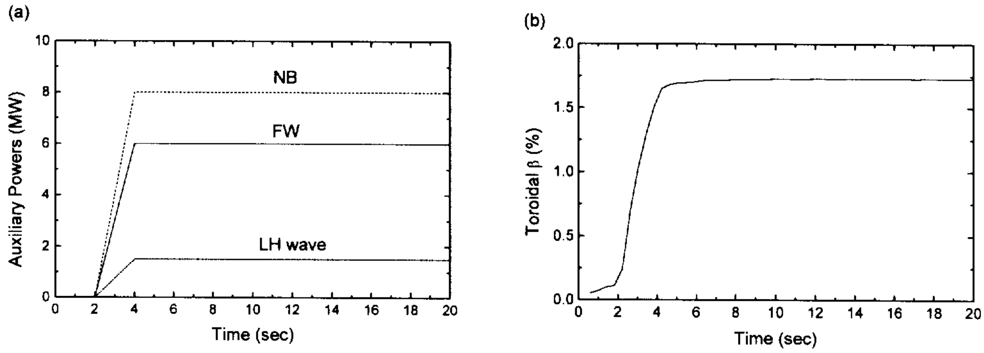

Figure 4: Result for baseline reference mode. Time evolution of (a) auxiliary heating powers and (b) toroidal beta.

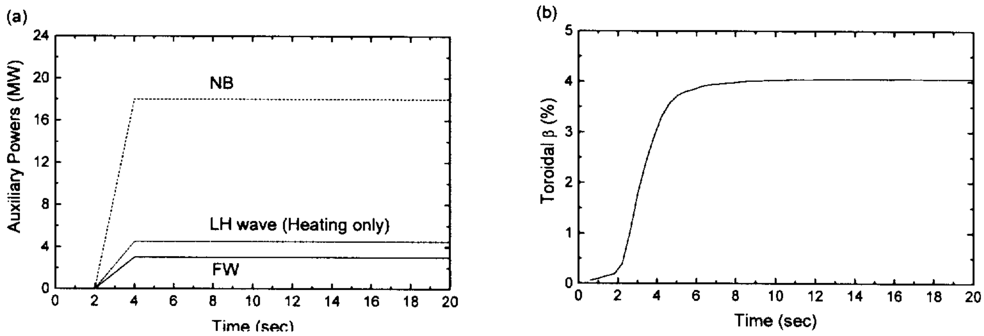

Figure 5: Result for upgrade reference mode. Time evolution of (a) auxiliary heating powers and (b) toroidal beta.

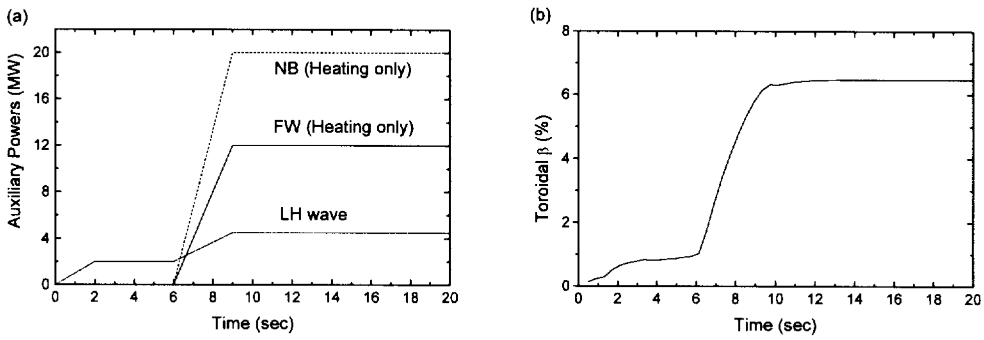

Figure 6: Result for reverse shear mode. Time evolution of (a) auxiliary heating powers and (b) toroidal beta.