Modelling of ICRH-heated Ramp-up Phases at ASDEX Upgrade in KSTAR Experimental Conditions

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1. Introduction

Steady state operation of a fusion device is one of key issues to develop an economically viable fusion power plant. This issue is more critical for the tokamak-based fusion power plant due to the inherent pulsed operation property of tokamaks. In this context, one of research objectives of the KSTAR tokamak is set to establish a steady state operation scenario as a step toward an attractive tokamak fusion reactor [1]. ITER also sets one of its goals to build up steady state operation scenarios with Q = 5 at reduced plasma current. The hybrid mode or reversed shear mode can be considered as strong candidates for the steady state operation scenario. It usually exhibits high bootstrap current owing to high plasma pressure compared with conventional ELMy H-modes. Together with external current drive, fully non-inductive current drive is achievable by this high fraction of bootstrap current. The very core of a subject in hybrid modes and reversed shear modes is how to produce and sustain a flat or reversed q-profile. Generally, these q-profiles are able to be formed by preheating in the plasma current ramp-up phase using external sources. The preheating in the plasma ramp-up phase increases the plasma conductivity and subsequent reduction of the diffusion of the Ohmic current into the centre of the plasma comes up with the flat or reversed q-profile. Apart from NBI (Neutral Beam Injection), ECH (Electron Cyclotron Heating) and LHCD (Lower Hybrid Current Drive), the effect of ICRH (Ion Cyclotron Resonance Heating) for the preheating has not been investigated systematically in tokamak devices. In this paper, predictive modelling of ramp-up scenarios with ICRH is performed using the ASTRA code [2] to investigate the effect of ICRH on the evolution of the q-profile during the current ramp-up phase at ASDEX Upgrade in preparation of KSTAR steady state operation scenario development.

2. Modelling of ICRH-applied Ramp-up Phases at ASDEX Upgrade

The predictive modelling is performed with the ASTRA code. CURRAY [3] is embedded in ASTRA for the calculation of the heating and current drive by ICRH/FWCD and the NBI heating package [4] is employed to calculate the NBI heating and current drive. A model developed by Sauter [5] is employed for the calculation of the bootstrap current in the plasma. No models for MHD activities which could influence on the evolution of q-profile are included in the simulations. The GLF23 transport model [6] is employed for the predictive simulations with ASTRA to calculate the anomalous heat transport. The simulation is performed based on a typical improved H-mode discharge at ASDEX Upgrade (pulse 17870) which exhibits low magnetic shear plasmas. The plasma current is 1 MA and the toroidal magnetic field is 2.1 T with $q_{95} = 3.8$ at low triangularity ($\delta \sim 0.2$) and moderate density ($<n_e>/n_{GW} \sim 0.4$). This discharge uses only NBI for the external heating and current drive. The first beam source with the beam power of 2.5 MW is applied at 0.3 s during the current ramp-up phase to raise the electrical conductivity and delay the penetration of the inductive current towards the centre of the plasma. The transition from limiter to lower single null divertor configuration takes place at 0.5 s and the plasma enters into the H-mode regime. At 1s, when the current flat top phase begins, an off-axis tangential beam source is applied to the plasma. This experimental recipe keeps the central safety factor $q(0)$ close to 1 and creates a low central magnetic shear.

In this study, three different simulations are performed to investigate the effect of ICRH on the evolution of the q-profile. First, one simulation is executed using the GLF23 model to reproduce the original discharge. Second, the other simulation is done assuming that ICRH with 1 MW heating power at 36.5 MHz, (0π)-phasing is provided at 0.5 s after the first NBI to help delay the current penetration. Last, another simulation is performed assuming that ICRH with 2 MW heating power is provided at 0.5 s. All the simulations start at 0.4 s using the initial conditions from the experiment. For the simulations, electron density profiles (n_e) are taken from experimental measurements. The radiated power is calculated including bremsstrahlung, cyclotron and line radiation. The toroidal velocity is assumed to be zero and the poloidal rotation is assumed to be neoclassical. The effective ion charge (Z_{eff}) is assumed to be constant at 2.0.

The time evolutions of the central q-value ($q(0)$) and the central electron temperature are compared in figure 1 (a) and (b), respectively among the three simulations. As shown in the figures, $q(0)$ begins to increase as the ICRH is turned on at 0.5 s corresponding with the

increase of the central electron temperature. It is more emphasised if the heating power is increased. However, $q(0)$ values from ICRH-applied cases drop faster than that of the NBI only case and eventually they become lower than that of the NBI only case after 0.9 s. This can be explained by that the reduction of Ohmic current in the core region is compensated by the increase of bootstrap current and NB driven current in the core region due to increase of the electron temperature by applying ICRH. The q-profile and temperature profiles are compared at the beginning of the current flattop phase (1.05 s) in figure 1 (c) and (d), respectively. As shown, the q-profiles are almost the same, while temperature profiles are rather different. The plasma parameters are compared at 1.05 s for the three simulations in table 1. As shown in the table, by applying higher ICRH during the current ramp-up phase, normalised beta as well as non-inductive current drive fractions can be improved.

	NBI only	1 MW ICRH	2 MW ICRH
$H_{98}(y, 2)$	1.05	0.80	0.97
β_N	1.27	1.34	1.38
IBS (%)	14	15	16
INB (%)	19	20	21
INI (%)	33	35	37

Table 1. Comparisons of confinement enhancement factor, normalised beta, bootstrap current fraction, NB driven current fraction and non-inductive current fraction at 1.05 s

3. Summary and Discussions

The predictive modelling is performed with the ASTRA code for the current ramp-up phase to investigate the influence of ICRH on the evolution of q-profile. As more ICRH power is applied to the plasma, higher plasma performance can be achieved. However, the effect on the q-profile is negligible. It is identified that the reversed shear plasma cannot be obtained with the present setting of ICRH. Negative current drive at the centre of the plasma could be an option to establish a reversed shear plasma. Since the plasma size of ASDEX Upgrade ($R = 1.65$, $a = 0.5$) is very similar to that of KSTAR ($R = 1.8$, $a = 0.5$), the simulation result and its application to experiments can give a strong feedback to establish steady state operation scenarios in KSTAR, particularly during the current ramp-up phase.
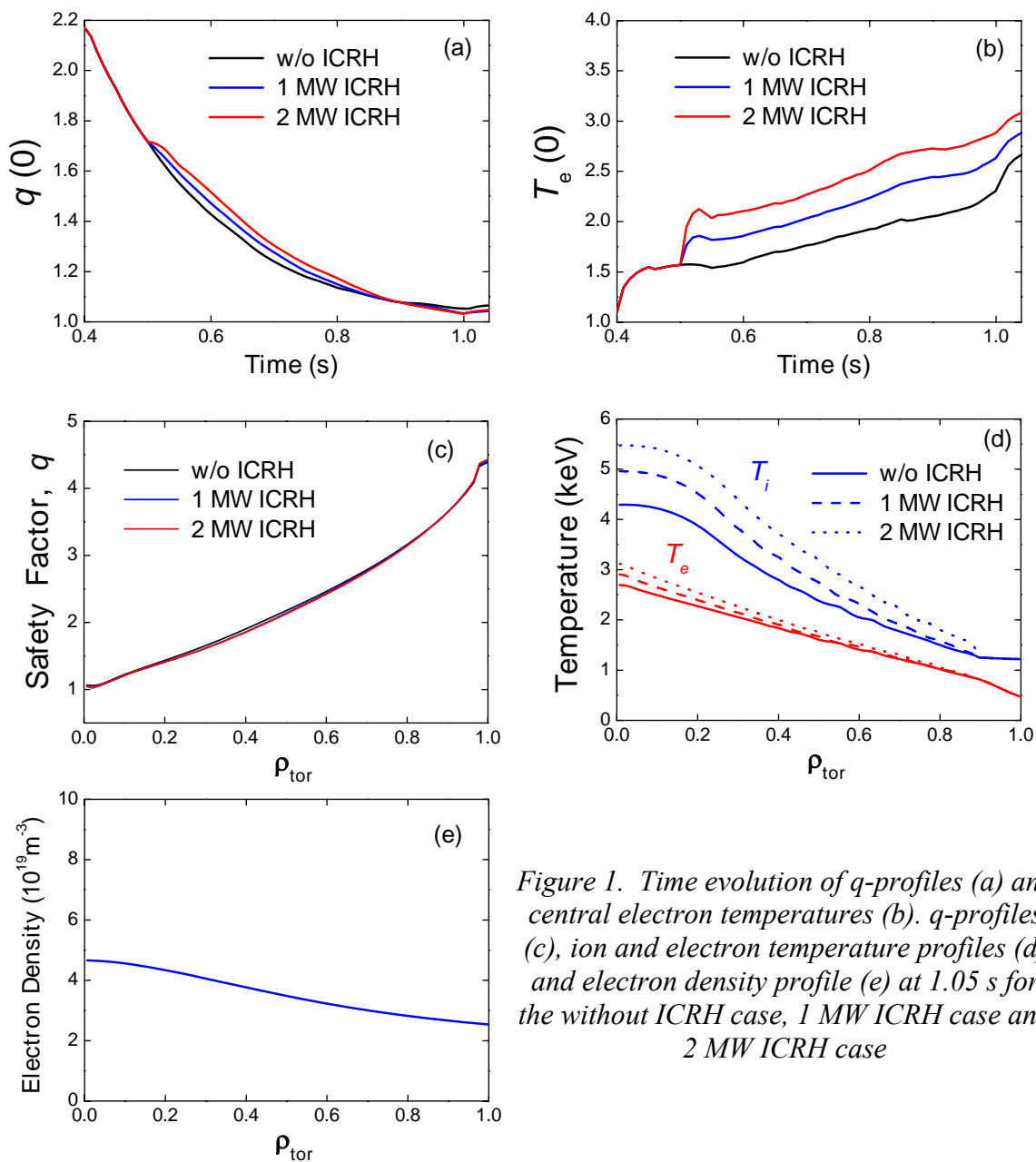
Figure 1. Time evolution of q-profiles (a) and central electron temperatures (b). q-profiles (c), ion and electron temperature profiles (d) and electron density profile (e) at 1.05 s for the without ICRH case, 1 MW ICRH case and 2 MW ICRH case

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