Model Analysis on Plasma Start-Up for Toroidal Fusion Devices

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Abstract

A reliable plasma start-up is significant for both tokamak and helical devices because the the creation of the plasma is a starting point for the fusion plasma. In tokamak devices, plasma start-up assisted by electron cyclotron resonance heating (ECRH) under a low electric field condition has been proposed to ensure the reliable plasma start-up. In JT-60SA tokamak ($R = 2.96$ m, $a = 1.18$ m, $B_T = 2.25$ T), which is now under construction in JAEA, the toroidal electric field for breakdown is limited up to $0.5 \text{ V} \cdot \text{m}^{-1}$. This may make it difficult to start up the plasma if the vacuum chamber wall is not in good conditions. We have studied the plasma start-up assisted with ECRH using a zero-dimensional (0-D) model, which consists of five temporal equations: the density equations for electrons and deuterium atoms, the energy density equations for electrons and bulk ions, and the electric circuit equation. This calculation shows that the ECRH is effective for plasma start-up under the low electric field condition in JT-60SA. An absorbed ECRH power of 150 kW is required to start up the plasma for the initial neutral density of 3.0×10^{18} m^{-3} and there is a threshold in ECRH power for a successful start-up. The threshold depends on the initial neutral density and greater ECRH power is required as the initial neutral density increases. Analyses of the plasma start-up assisted by a second harmonic extraordinary mode (X2-mode) ECRH have been attempted. It has been concluded that the deposition profile of the ECRH has to be included into the model for this analysis. Therefore, we develop a one-dimensional (1-D) model including a radial structure to study X2-mode ECRH assisted plasma start-up in JT-60SA. The 1-D model is composed the same equation system as the 0-D model, and included the radial transport. It is found that the ECRH power of around 1 MW is required to start up the plasma under the expected conditions such as the initial neutral density of 3.0×10^{18} m^{-3} and the error field of about 1 mT. This estimate of ECRH power is less than that of the planned ECRH system. In helical devices, plasma production is conventionally initiated by the ECRH, which limits the operating magnetic field strength. Proposed is a plasma start-up using neutral beam injection (NBI), which mitigates the limitation in the magnetic field strength. In Heliotron J, the plasma start-up by NBI has been done with the assistance of the seed plasma generated by 2.45 GHz microwaves. To clarify the physical processes in the initial start-up phase, we have developed a 0-D model, which comprises of time-dependent particle and energy balance equations for fast hydrogen ions from NBI, molecules (D_2 and H_2), molecular ions (D_2^+ and H_2^+), bulk ions (D^+ and H^+), and electrons. The dominant processes in Heliotron J are production of fast hydrogen ions, electron heating, and ionizations and dissociations of the deuterium gases. For a high seed plasma density case, these processes form a positive feedback loop, meaning that plasma start-up would not occur, otherwise. The 0-D model analysis is validated by the experimental data in Heliotron J such as the time evolution of the electron density, the stored energy, and the OV emission. The dependence of the plasma start-up on the seed plasma density and the NBI power is also investigated in the simulation.

1 Introduction

Energy demands for our lives and industries increase with increasing in population. There is considerable interest in the electric generation by a nuclear fusion in respect of fuels reserves, the safety, and low CO2 emissions. It has found to be the most promising confinement method that the plasma is confined by toroidal and poloidal magnetic fields which form a magnetic configuration with a torus shape. There are two types of method to generate the poloidal field: tokamak (by a plasma current) and helical (by external helical coils). Since the the creation of the plasma is a starting point for the fusion plasma, a reliable plasma start-up is significant for both tokamak and helical devices. In these fusion reactors, the understanding of physical processes in the initial start-up phase and modeling techniques are necessary for a reliable plasma start-up.

Ohmic heating (OH) is the conventional method to generate the plasma for tokamak devices. A loop voltage, V_{L}, is applied to the torus gas inside the vessel through magnetic induction by varying the current of the central solenoid coils. A small amount of free electrons in the gas are accelerated towards the toroidal direction by the electric field, $E = V_{\mathrm{L}}/2\pi R$, and collide with the neutral gas. More electrons are newly produced via ionization processes. Consequently, the avalanche breakdown occurs, leading to the generation of the plasma current, I_{p}. In ITER, superconducting coils are utilized for a steady-state operation. Due to the use of superconducting coils, the electric field for breakdown is limited to $0.3\ \mathrm{V \cdot m^{-1}}$. Under this limitation, breakdown might be restricted in the narrow range of pressure, 2.0×10^{-3} Pa $< p < 3.8 \times 10^{-3}$ Pa. At error field strengths above 4 mT, breakdown would not occur.

Electron cyclotron resonance heating (ECRH) assisted plasma start-up was proposed for a reliable plasma start-up, because ITER has the constraint on the applied electric field, $E < 0.3\ \mathrm{V \cdot m^{-1}}$. ECRH assisted plasma start-up with a low electric field was demonstrated on normal conducting tokamaks such as DIII-D [1] and JT-60U [2], and on the superconducting tokamaks such as Tore Supra [3] and KSTAR [4]. For instance, the ECRH assisted plasma start-up has been performed on JT-60U. Although the applied loop voltage is normally approximately 25 V on JT-60U, it is successfully reduced from 25 to 4 V ($E = 0.26\ \mathrm{V \cdot m^{-1}}$) with the 200 kW of fundamental ordinary mode (O1-mode) ECRH from the low field side (LFS). On KSTAR, 350 kW of X2-mode ECRH assisted plasma start-up with a low loop voltage of 2.0 V ($E = 0.24\ \mathrm{V \cdot m^{-1}}$) was obtained. In order to analyze the ECRH assisted plasma start-up, a zero-dimensional (0-D) model has been developed for various tokamaks such as ISX-B, KSTAR, JET, and ITER [5–8]. The 0-D model basically consists of particle density equations for electrons and neutral atoms, energy density equations for electrons and ions, and an electric circuit equation, which are solved for a spatially uniform plasma.

JT-60SA also has the limitation of the applied electric field ($E < 0.5\ \mathrm{V \cdot m^{-1}}$) for breakdown due to the usage of superconducting coils. In JT-60SA, the X2-mode ECRH assisted plasma start-up has been proposed for a reliable plasma start-up. There has been little study done concerning on how much ECRH power is required for a reliable plasma start-up and on the dominant physical processes in JT-60SA. This thesis presents the model analysis of the ECRH assisted plasma start-up in JT-60SA.

In stellarator/heliotron devices, ECRH has been conventionally employed for the plasma start-up. This method limits the operating magnetic field strength. For beta scaling and high beta experiments, the plasma start-up using NBI was proposed. The plasma start-up by the NBI alone (co-tangential hydrogen beams, the beam energy is 97 keV, and the port-through input power is approximately 1.6 MW) was successfully demonstrated in LHD [9]. In W7-X, NBI is planned for the plasma start-up. Nevertheless, W7-X has only the perpendicular injection NBI system, the interaction length of which is generally shorter than that of the tangential injection. The 0-D model was developed to evaluate the breakdown phase ($T_e < 10$ eV) of the NBI plasma start-up [10]. This indicates that the plasma start-up by NBI might be difficult in W7-X, and a seed plasma before the NBI could be effective for a reliable plasma start-up. In Heliotron J, the NBI plasma start-up has been done with the aid of the seed plasma generated by 2.45 GHz microwaves [11]. This study is considered to contribute to the analysis of the plasma start-up by NBI in W7-X

This thesis aims at examining how much ECRH power is required the plasma start-up in the JT-60SA device, and clarifing the dominant physical processes in the initial start-up phase in the JT-60SA device and the Heliotron J device.

This thesis is organized as follows. In Chap. 2, the zero-dimensional (0-D) model is introduced and applied to the JT-60SA device. Hydrogen atoms, hydrogen ions and electrons are dealt with in this model. The plasma start-up assisted with the ECRH is investigated under the assumption that all of the ECRH power is absorbed into the plasma. In order to include the absorption efficiency of ECRH into the model, we have developed the one-dimensional (1-D) model, which has a radial structure. In Chap. 3, the 1-D model is described in detail. The physical processes in the initial start-up phase are discussed. The dependence of the ECRH plasma start-up on the initial hydrogen gas pressure, the error field, and the impurities such as carbon and oxygen are also examined. To validate the 1-D model analysis, a comparison with experimental results in JT-60U is made. In Chap. 4, the NBI plasma start-up in Heliotron J is investigated by the 0-D model. The 0-D model is improved, that is, the dissociation process of hydrogen and deuterium molecules is considered and the neutral screening effect is included. This model calculation is compared with the various experimental conditions. Finally, the summary and the conclusion are shown in Chap. 5.

2 Zero-dimensional (0-D) model analysis of ECRH assisted plasma start-up in Tokamaks

We investigated the effects of ECRH pre-ionization on plasma start-up using the JT-60SA parameters and a 0-D model. The 0-D model consists of five temporal equations: the density equations for electrons and deuterium atoms, the energy density equations for electrons and bulk ions, and the electric circuit equation. These equations are solved for spatially-uniform plasma. In this model, we assume that the major and minor radii remain constant and all of the injected ECRH power is absorbed. These equations are numerically solved by the fourth-order Runge-Kutta method so as to suppress the calculation error within 1%.

The calculation shows that the ECRH power is effective for plasma start-up under low loop voltage conditions. An absorbed ECRH power of 150 kW is required to start up the plasma for $n_D = 3.0 \times 10^{18}$ m^{-3}. This result is considered to correspond to the O1-mode ECRH assisted plasma start-up from LFS because the O1-mode ECRH assisted plasma start-up has much high absorption due to the appearance of the X-mode wave and the EBW.

It is found that there is a threshold in ECRH power for a successful start-up. The threshold depends on the initial neutral density, and greater ECRH power is required as the initial neutral density increases. In addition, it also depends on the carbon and oxygen impurity densities because the radiation loss increases with increasing impurity densities. This implies that for a reliable start-up, it is important to control the neutral density and reduce the impurity densities. The radial profile has to be included because the impurity radiation power is localized in the edge region.

The calculation using the JT-60U parameters qualitatively reproduces the time evolution of the experimental data. The difference between the simulation and experimental data is thought to be due to the eddy current flowing along the vacuum vessel.

The analysis of the ECRH plasma start-up including the absorption efficiency has been attempted. It is concluded that the 0-D model must be included the ECRH deposition profile for the analysis of the plasma start-up assisted by the 2nd harmonic X-mode ECRH.

3 One-dimensional (1-D) model analysis of ECRH assisted plasma start-up in Tokamaks

The 0-D model is not sufficient for investigating the 2nd harmonic X-mode ECRH plasma start-up because it lacks a radial structure, radial transport, and the localization of ECRH power. We developed a 1-D model of plasma start-up for the JT-60SA configuration to understand the physical processes involved in the initial start-up phase and to estimate how much ECRH power is required for plasma start-up. This model comprises same equation system as the 0-D model.

The 1-D model allows us to investigate the localization of EC power and the time evolution of electron density, electron temperature, and current density profile. When using the 0-D model, it is difficult to investigate second-harmonic X-mode ECRH assisted plasma start-up in a large device, such as JT-60SA, because during the initial plasma start-up phase, the absorption efficiency is relatively low, and EC power is localized at the EC resonance; these effects are not included in the 0-D model.

This calculation provides an insight into the physical processes, which are important during the initial plasma start-up phase. After the onset of OH, ionization and equilibration are the dominant power loss processes because of the increase in the number of electrons and ions. After the onset of ECRH, positive feedback develops between the ECRH absorption efficiency and the electron temperature. Subsequently, power loss due to the thermal conduction loss becomes dominant. Power loss due to the error field and drift depends weakly on the plasma start-up because the electron temperature at the core reaches about 1 keV before the magnetic field lines close. The impurity radiation power loss peaks at this time, which suppresses the density of carbon impurities would be helpful for successful start-ups and to reduce the required ECRH power.

The results of this calculation indicate that the plasma start-up is restricted to low prefill pressure without ECRH and that an ECRH threshold power exists for successful plasma start-up. In other words, an ECRH power of approximately 1 MW is required for plasma start-up for $n_{\mathrm{H}}(t = 0) = 3.0 \times 10^{18}$ m^{-3} in the current design (with an error field of approximately 1 mT and an EC beam radius of approximately 5 cm). This estimate of ECRH power is less than that of the planned ECRH system. The results of the present study indicates that with increasing initial hydrogen atom density, greater ECRH power is required for plasma start-up. This result is attributed to the effects of power loss from ionization and equilibration. The required ECRH power thus depends weakly on direct power loss caused by the error field and impurity radiation loss by carbon. These results imply that controlling the initial hydrogen atom density, suppressing the error field by using the Error Field Correction Coil (EFCC) to control the magnetic field, and reducing the impurity density are all useful for reliable plasma start-up.

4 0-D model analysis of NBI plasma start-up in Heliotron devices

In Heliotron J, NBI plasma start-up have been done with the aid of the seed plasma generated by 2.45 GHz microwaves. A 0-D model has been developed for the understanding of physical processes in the density build-up phase. The 0-D model analysis is conducted less than the electron density of around 1.0×10^{19} m^{-3}. This model is composed of time dependent particle and energy balance equations for fast hydrogen ions from the NBI, molecules (H_2 and D_2), molecular ions (H_2^+ and D_2^+), bulk ions (H^+ and D^+), and electrons. Included, into the 0-D model, were the neutral screening effects, enabling us to analyze the density build-up phase.

The 0-D model has been clarify the physical processes in the initial start-up phase in Heliotron J. The dominant processes in the NBI plasma start-up in Heliotron J are that production of fast hydrogen ions, electron heating, and ionizations and dissociations of the deuterium gases. It is noted that these processes create a positive feedback loop, resulting in a successful density build-up. Conversely, once this positive feedback loop is interrupted, the density build-up fails. For a low seed plasma density case, because production of fast hydrogen ions is kept low, electron heating remains low. In this case, the charge exchanges between fast hydrogen ions and the neutral molecules occur, resulting in loss of the fast hydrogen ions. Then, the positive feedback loop is not formed.

The validation of 0-D model analysis is conducted with the NBI plasma start-up experiments in Heliotron J. The 0-D model reproduces the time evolution of the electron density, the stored energy, and the OV emission quite well. The tendency of the dependence of the density build-up on the seed plasma density are reproduced in the simulation. However, the seed plasma density of $1 - 3 \times 10^{17}$ m^{-3} was not measured. These measurements might be needed the control of the pre-filled gas pressure or the 2.45 GHz microwaves power. The early gas puff does not lead to the successful density build-up. This tendency is also simulated by the 0-D model. For the early gas puff case, the density build-up fails because the electron temperature does not becomes enough high to ionize the main gas puff. The simulated dependence of the electron and the stored energy build-up rates on the NBI power agree with those of the experiments. For the case of below the NBI power of 200 kW, the lower productions of fast hydrogen ions are obtained, resulting in a lower electron temperature. Thus, the density build-up fails.

5 Summary

A reliable plasma start-up is important issue for tokamak and helical devices since the creation of the plasma is a starting point for a fusion plasma. In this thesis, simulation analyses are conducted for the plasma start-up assisted by ECRH on JT-60SA and for the NBI plasma start-up on Heliotron J.

In JT-60SA tokamak, it has been found that the only OH is difficult to start up the plasma. We investigate the effects of the ECRH assisted plasma start-up using the 0-D model, which consists of five temporal equations: the density equations for electrons and deuterium atoms, the energy density equations for electrons and bulk ions, and the electric circuit equation. The calculations show that the ECRH assist is effective for plasma start-up. Under the assumption that the all of the ECRH power is absorbed in the plasma, simulation results are as follows:

1. An absorbed ECRH power of 150 kW is required to start-up plasma for $n_{\rm D} = 3.0 \times 10^{18}$ m^{-3}.
2. The threshold ECRH power for a successful plasma start-up is observed.
3. The dependence of the plasma start-up on the initial neutral density and the impurity densities such as carbon and oxygen are large.
4. For the analysis of 2nd harmonic ECRH assisted plasma start-up, the deposition profile of the ECRH must be taken into account.

For this purpose, we have developed the 1-D model of plasma start-up for the JT-60SA configuration to understand the physical processes involved in the initial start-up phase and to estimate how much ECRH power is required for a 2nd harmonic ECRH assisted plasma start-up. Simulation results are as follows:

1. Approximately 1 MW ECRH is required to start up the plasma for $n_{\rm H} = 3.0 \times 10^{18}$ m^{-3} in the current design (with an error field of approximately 1 mT and an EC beam radius of approximately 5 cm). This ECRH power is less than the planned one in JT-60SA.
2. The required ECRH power increases with increasing the initial hydrogen atom density. This is due to the power loss from ionization and equilibration. Controlling the initial hydrogen atom density is important.

3. The required ECRH power depends weakly on direct power loss caused by the error field and impurity radiation loss by carbon. This indicates that suppressing the error field by using the error field correction coil (EFCC) to control the magnetic field and reducing the impurity density are helpful for a reliable plasma start-up.

The physical picture of X2-mode ECRH assisted plasma start-up on JT-60SA is obtained in the present work. It is our expectation that this model analysis provides fundamental understandings on the X2-mode ECRH assisted plasma start-up on a large tokamak device like ITER.

In Heliotron J, the plasma start-up by NBI has been done with the assistance of the seed plasma generated by 2.45 GHz microwaves. A 0-D model has been developed for the understanding of physical processes in the density build-up phase. This model consists of time dependent particle and energy balance equations for fast hydrogen ions from the NBI, molecules (H_2 and D_2), molecular ions (H_2^+ and D_2^+), bulk ions (H^+ and D^+), and electrons. The neutral screening effects are included into this model. Simulation results are as follows:

1. Production of fast hydrogen ions, electron heating, and ionizatoins and dissociations of the deuterium gases are dominant processes in the density build-up phase. For the case of successfully density build-up, these processes form a positive feedback loop. In the case of unsuccessful density build-up, this positive feedback loop is not created.
2. The 0-D model reproduces a time evolution of the electron density, the stored energy, and the OV emission quite well.
3. The early gas puff, which does not build up the plasma, is reproduced by the 0-D model.
4. The simulated dependence of the electron and the stored energy build-up rates on the NBI power agree with those of the experiments.

In W7-X, the plasma start-up using perpendicular NBI is planned. This work will contribute to the analysis of the plasma start-up by NBI on W7-X.

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