

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 $3.0 \times 10^{18} \text{ m}^{-3}$ 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 $3.0 \times 10^{18} \text{ m}^{-3}$ 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.

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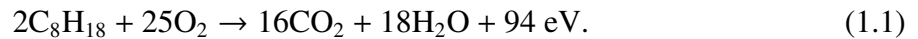
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Chapter 1

Introduction

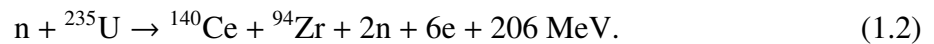
1.1 Energy production [1–3]

Energy demands for our lives and industries increase with increasing in population. The primary fossil fuels such as coal, natural gas, and oil have been utilized for many years in the world. It is relatively easy to produce energy from the fossil fuels, though there are problems such as much greenhouse gas emissions and the exhaustion of reserves. Dominant is this process in burning the fossil fuels:



The averaged energy is approximately 0.9 eV per atom concerned with this reaction.

Nuclear reaction has a great advantage in the energy production and the reduction of greenhouse gas emissions. In general, it is more difficult to produce energies by means of nuclear reaction than by the fossil fuels. There are two types energy production methods by nuclear reaction, that is, nuclear fission and nuclear fusion. Let us consider the nuclear fission. Nuclear fission reactions of the uranium isotope ^{235}U through slow neutron impacts occur in nuclear reactors. Uranium is splitted into, for instance, cesium, zirconium, and neutron:



The total masses of the initial and final states are 236.053 u and 235.832 u, respectively, where $u = 1.660539 \times 10^{-27}$ kg is the atomic mass unit. This difference in mass, 0.221 u, is released as the energy of 206 MeV. The averaged energy is 0.88 MeV per nucleon of the uranium. Thus, the energy gain is much larger than that of the fossil fuels. This method has crucial concerns for the safety and same problem as the fossil fuels like low reserves.

There is considerable interest in the electric generation by a nuclear fusion in respect of fuels reserves, the safety, and low CO₂ emissions. Nuclear fusion process for future power plant is that two light nuclei merge to form a heavier nucleus, and the total masses of the final state is slightly less than that of the initial state. This difference in mass is released as the energy. The reactions related the fusion power plant are given below,

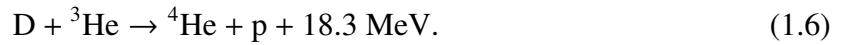
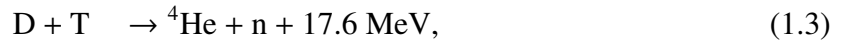


Fig. 1.1 shows them reaction rates as a function of ion temperature. Among others, the deu-

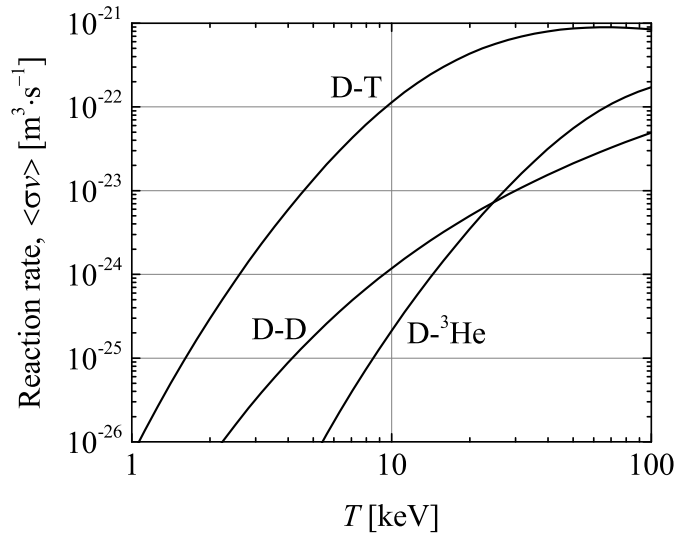


Figure 1.1: Reaction rates $\langle\sigma v\rangle$ for D – T, D – D, and D – ${}^3\text{He}$ reactions as a function of ion temperature.

terium (D) and tritium (T) reaction is most expected for the future fusion reactor because D – T reaction rate is largest in the whole ion temperature. However, this reaction requires a much higher temperature than that of a regular life (typically $T > 10$ keV). It was proposed that high temperature plasmas are generated and confined by the magnetic field. This method has enormous reserves. D is easily extracted from the sea. Because T is virtually absent in the earth, this is supplied by the nuclear fusion reaction between lithium and neutron:



where lithium is in the blanket surrounding the region of D-T reactions.

1.2 Fusion reactor

It has found to be the most promising confinement method that the plasma is confined by a magnetic configuration with a torus shape as shown in Fig. 1.2 (a). Magnetic fields for a plasma confinement consist of a toroidal and a poloidal fields. In the absence of a poloidal field, charged ions and electrons are separated by a curvature and $\text{grad}B$ drifts, resulting in outward drift of the charged particles. For this reason, in general, the magnetic field line has a helical shape around the torus due to the combination of the toroidal and poloidal fields, and the plasma has nested toroidal magnetic flux surfaces as shown in Fig. 1.2 (b).

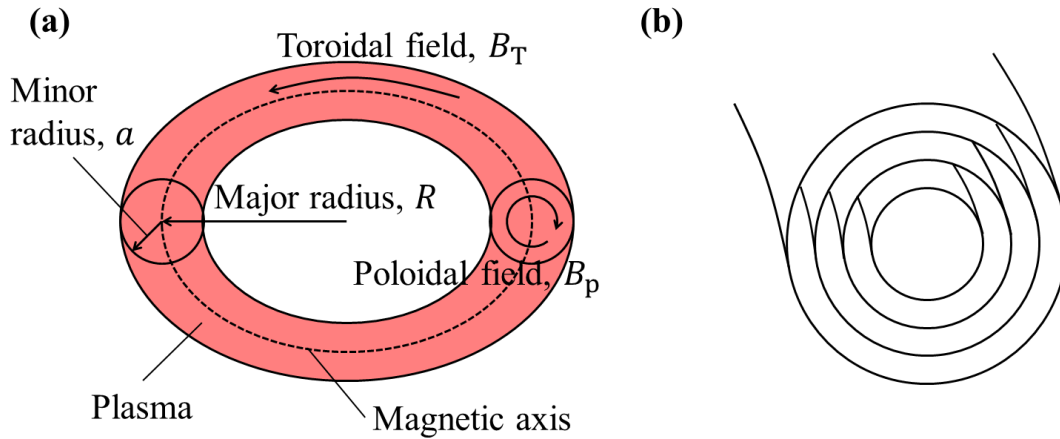


Figure 1.2: (a) Magnetic configuration with a torus shape and (b) nested toroidal magnetic flux surfaces.

There are two types of method to generate the poloidal field: tokamak (by a plasma current) and helical (by external helical coils). As shown in Fig. 1.3, in the tokamak device, the toroidal field is generated by the toroidal field coils (TFC), and the poloidal field is generated by a plasma current in the toroidal direction. The plasma current is induced through magnetic induction by changing the current of the central solenoid coils at a constant rate. In the helical device, the toroidal field is also generated by TFCs, and the poloidal field is produced by a external helical field coils (HFC). Both of them have a helical field line (HFL).

Shown in Fig. 1.4, as examples of tokamak device, are ITER, KSTAR, and JT-60SA. ITER

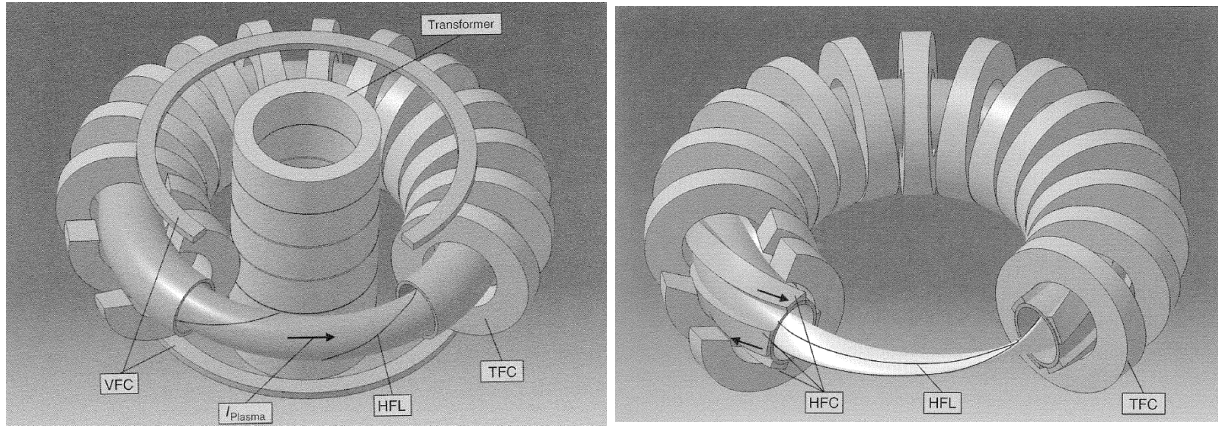


Figure 1.3: Schematic view of tokamak device on the left and helical device on the right [3].

is the largest superconducting tokamak, which is now under construction in Cadarache, France. This project aims at demonstrating the scientific and technical feasibility of fusion reactors as an energy production. KSTAR is fully superconducting tokamak in Daejeon, Korea. JT-60SA is one of the largest superconducting tokamak, which is now under construction in Ibaraki, Japan. This project is intended to contribute to the early realization of fusion energy by supporting the exploitation of ITER and research towards DEMO reactor by addressing key physics issues. In Chap. 2, JT-60SA device will be introduced in more detail.

As examples of helical device, Heliotron J, large helical device (LHD), and WENDEL-STEIN (W7-X) are shown in Fig. 1.5. Heliotron J is the experimental reactor in the institute of advanced energy of Kyoto university introduced in Chap. 4 in more detail. LHD is the superconducting helical machine in the national institute for fusion science (NIFS). LHD project aims for fusion-plasma confinement research in a steady-state machine [8]. W7-X is one of the largest fusion experimental reactor of the stellarator type. W7-X project aims at investigating the suitability of this type for a power plant [9].

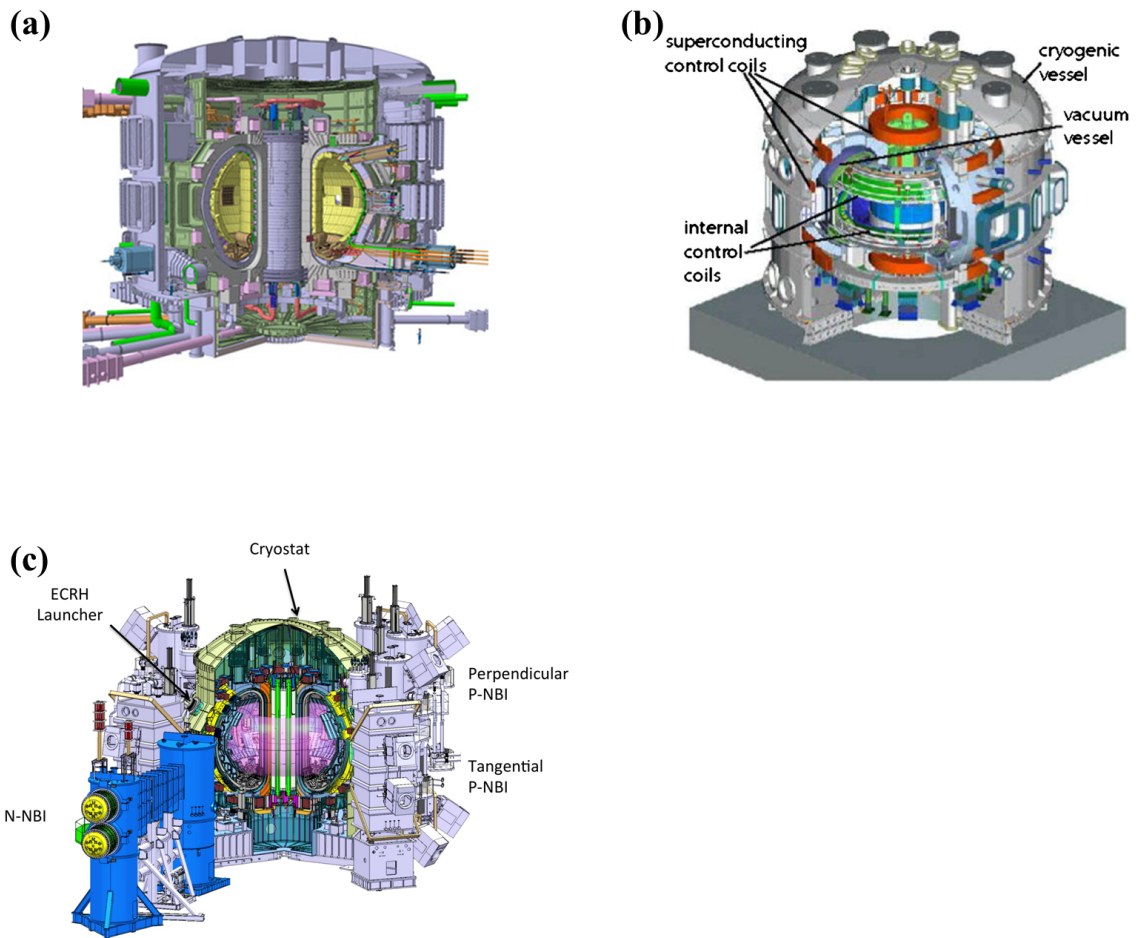


Figure 1.4: Schematic view of (a) ITER [4], (b) KSTAR [5] and (c) JT-60SA [6]. These diagrams are not drawn to same scale.

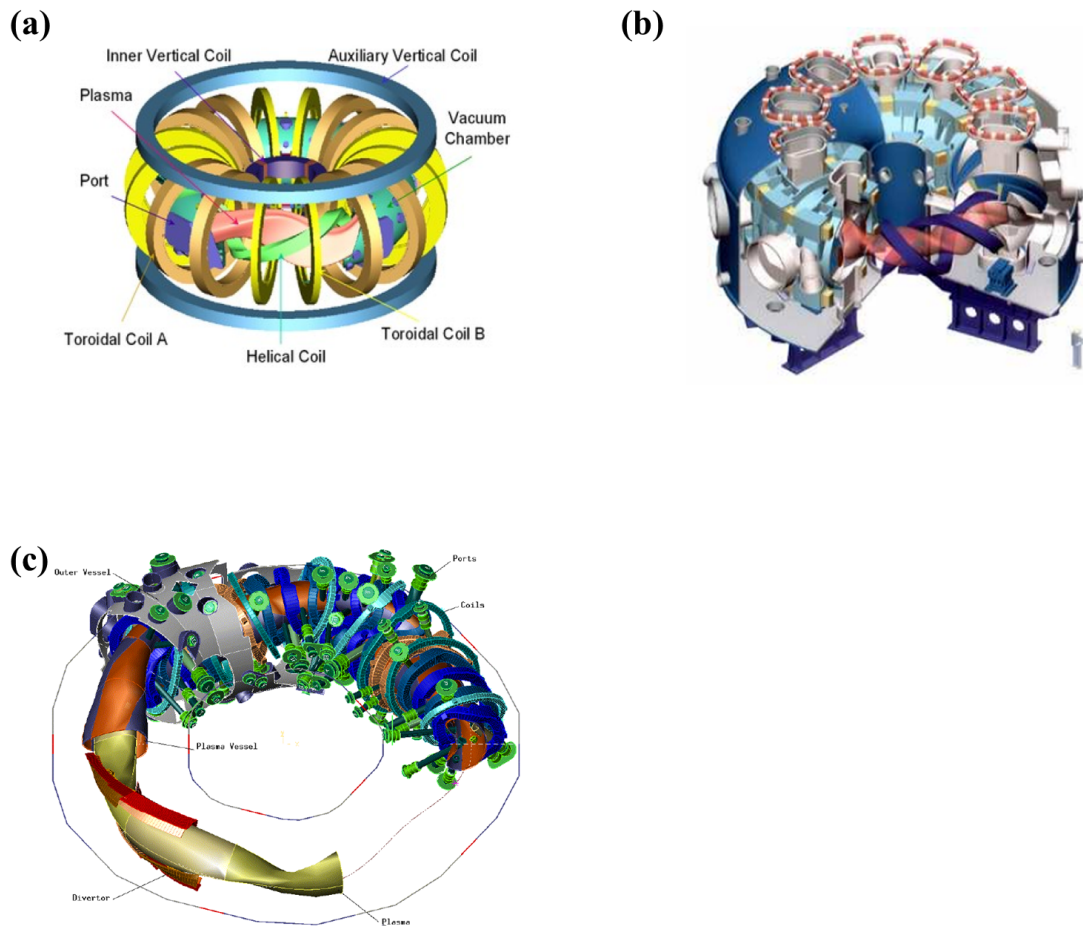


Figure 1.5: Schematic view of (a) Heliotron J [7], (b) LHD [8], and (c) W7-X [9]. These diagrams are not drawn to same scale.

1.3 Plasma start-up

Since the the creation of the plasma is a starting point for the fusion plasma, a reliable plasma start-up is significant. 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. Discussed, in this chapter, are the ohmic heating plasma start-up and electron cyclotron resonance heating assisted plasma start-up for tokamak devices, and the plasma start-up using NBI for helical devices. In this thesis, successful plasma start-up or burn-through is defined as follows: the electron temperature is high enough so that impurity radiation is no longer a larger fraction of the total power loss from the plasma. This criteria is generally satisfied $T_e > 100$ eV.

1.3.1 Ohmic heating (OH)

OH is the conventional method to generate the plasma. 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, $E = V_L/2\pi R$, 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 . The plasma is ohmically heated by this current. The heating power is given as $P_{OH} = R_p I_p^2$, where R_p is the electrical resistance of the plasma. Because the electrical resistance decreases with increasing the electron temperature, $R_p \propto T_e^{-3/2}$, OH is effective at low temperatures.

The plasma start-up by OH has been investigated in a number of tokamaks. Shown in Fig. 1.6 [10] are the time evolutions of the plasma current, the loop voltage, and the D_α emission during OH discharge in the DIII-D tokamak. As the loop voltage is reduced from ~ 5 V to ~ 2.6 V ($E \sim 0.25$ V $\cdot$ m $^{-1}$), the plasma current decreases and the peak of D_α is delayed. The completion of breakdown is convenient to define as occurring the peak of D_α emission, though it is conventionally defined as follows: the electron-ion collision frequency is greater than the collision frequency of electron-neutral. The breakdown time, τ_{bd} , is plotted as a function of the applied electric field, E in Fig. 1.7 [10]. τ_{bd} exponentially increases with decreasing E field. The lower limit of E is obtained to be 0.25 V $\cdot$ m $^{-1}$. The breakdown time has also been

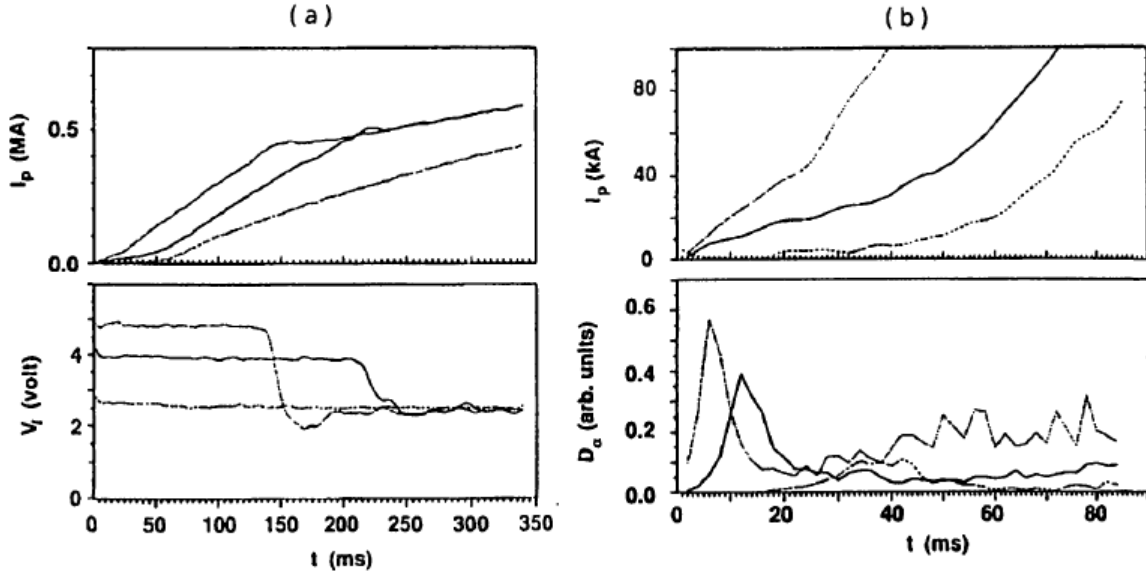


Figure 1.6: Effect of varying the loop voltage on (a) the plasma current evolution and (b) the D_α emission during low voltage Ohmic start-up [10].

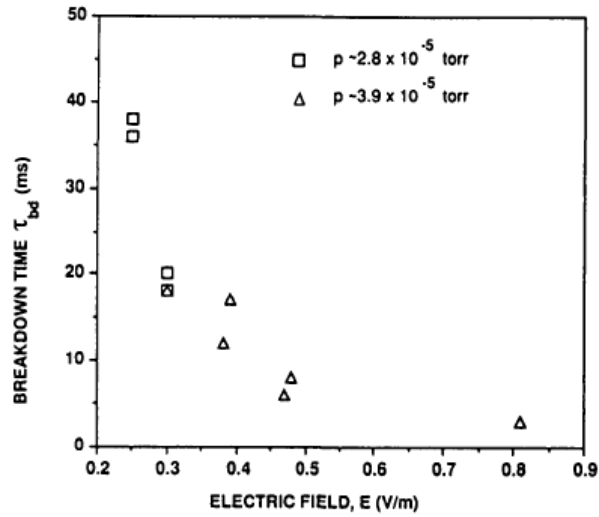


Figure 1.7: Dependence of the breakdown time τ_{bd} on the applied electric field E (at $R = R_0$) during Ohmic start-up [10].

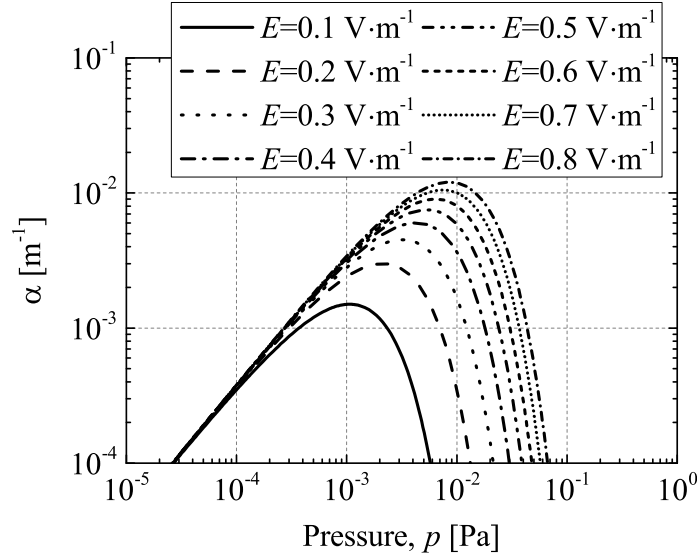


Figure 1.8: Townsend's first coefficient, α , for various electric fields as a function of gas pressure.

theoretically investigated from the analysis of the OH start-up in the DIII-D tokamak. This is given by

$$\tau_{\text{bd}} = \frac{\ln\left(\frac{n_{\text{bd}}}{n_{\text{e0}}}\right)}{v_e \left(\alpha - \frac{1}{L_{\text{eff}}} \right)}, \quad (1.8)$$

where n_{bd} is the electron density at breakdown, n_{e0} is the initial electron density, and v_e is the electron velocity. Electrons are produced through ionizations of hydrogen gas by electron impacts. α (Townsend's first coefficient) is ionizations per meter along its path and it is well approximated by

$$\alpha = Ap \exp\left(-\frac{Bp}{E}\right), \quad (1.9)$$

where $A = 3.91 \text{ m}^{-1} \cdot \text{Pa}^{-1}$ and $B = 94.0 \text{ V} \cdot \text{m}^{-1} \cdot \text{Pa}^{-1}$ for hydrogen, and p is the gas pressure. As shown in Fig. 1.8, α decreases with decreasing E . L_{eff} is the effective connection length which is the distance from the avalanche region to the vessel wall along the magnetic field lines [10].

The effective connection length is evaluated by

$$L_{\text{eff}} \approx \frac{0.25aB_T}{B_{\text{err}}}, \quad (1.10)$$

where a is the plasma minor radius, B_T is the toroidal magnetic field, and B_{err} is the error field. The error field shortens the connection length. The longer L_{eff} (less B_{err}) is better for breakdown.

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 $0.3 \text{ V} \cdot \text{m}^{-1}$. Figure 1.9 shows the simulated breakdown time as a function of pressure for various error fields using the ITER parameters ($B_T \sim 5 \text{ T}$ and $a \sim 2 \text{ m}$). There are the upper and lower pressure limits. From the point of view of the physical process, the upper pressure limit can be understood such that electrons are not accelerated sufficiently to ionize the hydrogen gas due to the high collisionality. In the case of the lower pressure limit, electrons rarely collide with the hydrogen gas due to the low collisionality. In such a low pressure range, runaway electrons must be considered. Production of runaway electrons is anticipated at gas pressures below $2.0 \times 10^{-3} \text{ Pa}$ in the gray area. Prompt breakdown, $\tau_{\text{bd}} < 20 \text{ ms}$, is required to ensure the reliable plasma current rise in the initial discharge phase [11]. Breakdown might be restricted in the narrow range of pressure, $2.0 \times 10^{-3} \text{ Pa} < p < 3.8 \times 10^{-3} \text{ Pa}$. Moreover, this range depends strongly on the error field strength. At error field strengths above 4 mT, breakdown would not occur. Thus, the limitation in the applied electric field makes it difficult to generate the plasma.

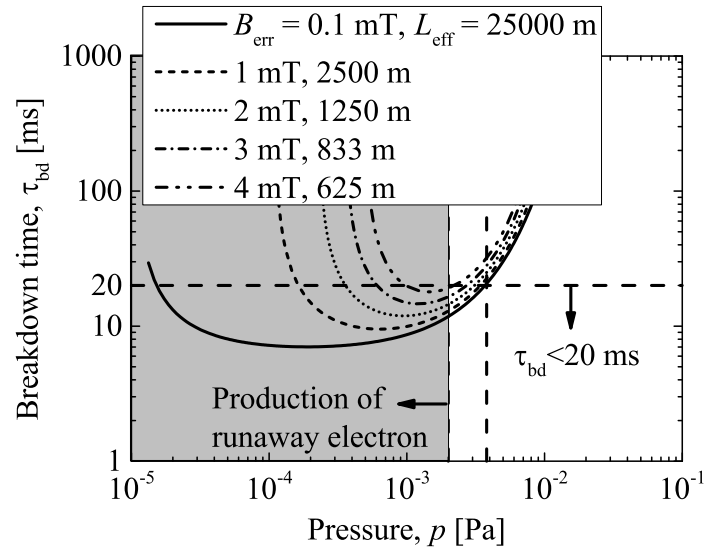


Figure 1.9: Simulated breakdown time for various error fields as a function of gas pressure of the hydrogen gas on ITER.

1.3.2 Electron cyclotron resonance heating (ECRH) assisted start-up

ECRH assisted plasma start-up was proposed for a reliable plasma start-up, because ITER has the constraint on the applied electric field, $E < 0.3 \text{ V} \cdot \text{m}^{-1}$. ECRH assisted plasma start-up with a low electric field was demonstrated on normal conducting tokamaks such as DIII-D [12] and JT-60U [13], and on the superconducting tokamaks such as Tore Supra [14] and KSTAR [15]. As shown in Fig. 1.10, the ECRH assisted plasma start-up has been performed on JT-60U [13]. Although the applied loop voltage is normally approximately 25 V on JT-60U, it is successfully reduced from 25 to 4 V ($E = 0.26 \text{ V} \cdot \text{m}^{-1}$) with the 200 kW of fundamental ordinary mode (O1-mode) ECRH from the low field side (LFS). O-mode wave is accessible to the resonance.

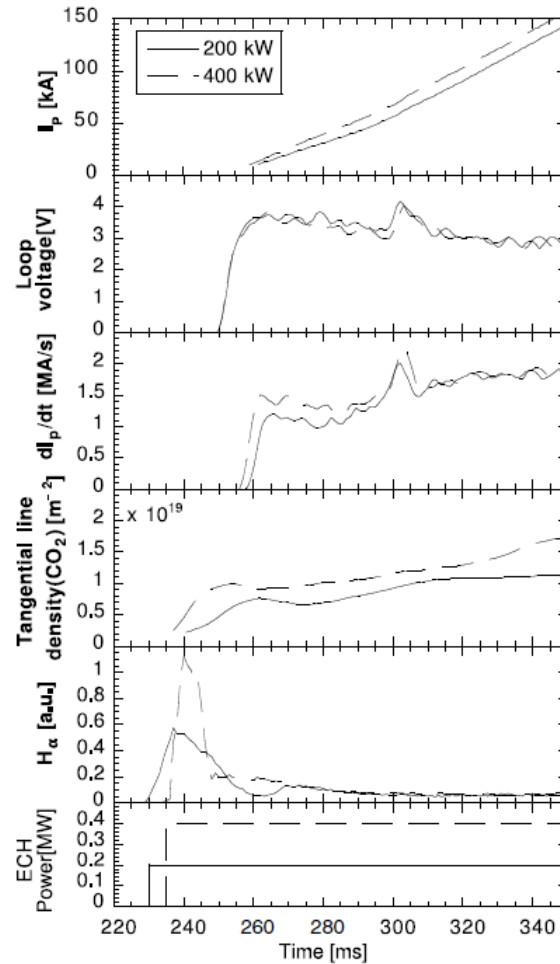


Figure 1.10: Example of the successful ECRH assisted plasma start-up on JT-60U [13].

Although the single pass absorption of O-mode wave is quite lower than that of extraordinary mode (X-mode), the absorption efficiency becomes high due to multiple reflections. Figure 1.11 shows a schematic view of the absorption scenario for O-mode injection from the LFS [13]. The O-mode wave passes through the electron resonance layer with low absorption. The rest of the wave is reflected and de-polarized at the inner wall, resulting in the appearance of the X-mode. The resultant X-mode is reflected and converted to an electron Bernstein wave (EBW), which has much higher absorption efficiency than that of the electron cyclotron wave. This mechanism makes it possible to start up the plasma by the O-mode injection. On KSTAR, 350 kW of X2-

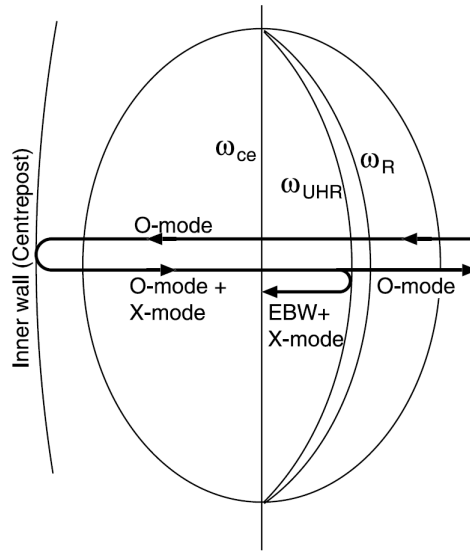


Figure 1.11: Schematic representation of the absorption scheme for low field side O-mode injection [13].

mode ECRH assisted plasma start-up with a low loop voltage of 2.0 V ($E = 0.24 \text{ V} \cdot \text{m}^{-1}$) was obtained, which is shown in Fig. 1.12. X-mode wave is accessible to the resonance only in the case of the second harmonic. For the case of the second harmonic resonance, the operating magnetic field strength can be reduced by half compared with the fundamental ECRH, leading to high beta. Both O1-mode and X2-mode ECRH assisted plasma start-up from the LFS are planned situation in ITER.

In order to analyze the ECRH assisted plasma start-up, a zero-dimensional (0-D) model has been developed for various tokamaks. This model, which describes ECRH assisted plasma start-up at ISX-B, was proposed by Kulchar *et al.* [16], and more advanced models were developed

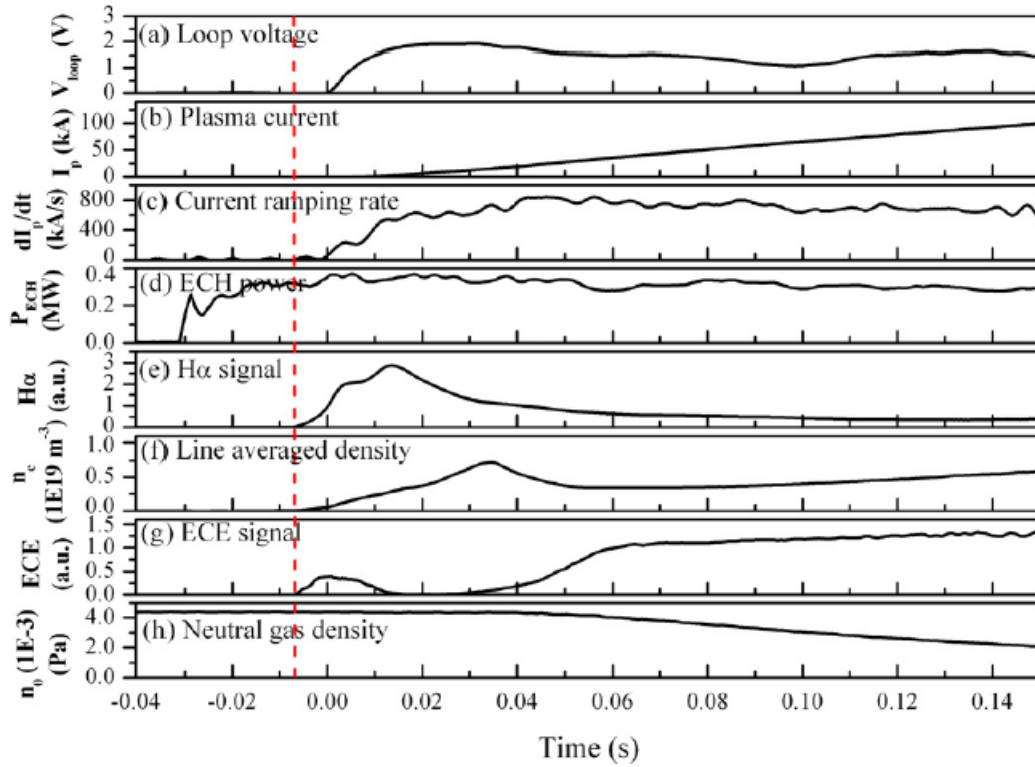


Figure 1.12: Example of the successful ECRH assisted plasma start-up on KSTAR [15].

by Lloyd *et al.* [11], Bae *et al.* [17], Kim *et al.* [18, 19], and Goswami [20]. 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. For instance, shown in Fig. 1.13 is the 0-D model result for the KSTAR tokamak. Left top figure shows the applied loop voltage, and right top and left bottom figures show the time evolution of the electron density, the electron temperature, and the plasma current. The dependence of the plasma start-up on the error field strength, the impurity contents, and the initial neutral gas pressure is analyzed by investigating the time evolutions of the main variables such as the electron density, the electron temperature, and the plasma current.

JT-60SA also has the limitation of the applied electric field ($E < 0.5 \text{ V} \cdot \text{m}^{-1}$) for breakdown due to the usage of superconducting coils. The simulated breakdown time is plotted as a function of gas pressure in Fig. 1.14. It is found that breakdown might be limited in the narrow range of pressures, $3.3 \times 10^{-3} \text{ Pa} < p < 9 \times 10^{-3} \text{ Pa}$, and $B_{\text{err}} < 3 \text{ mT}$. In JT-60SA, the X2-mode

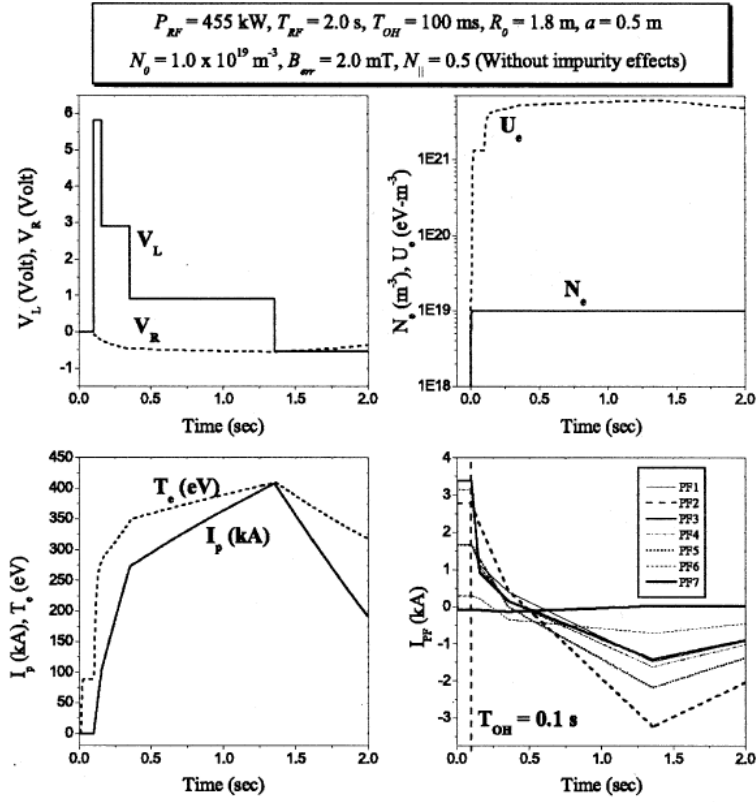


Figure 1.13: 0-D model simulation results of KSTAR [17].

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.

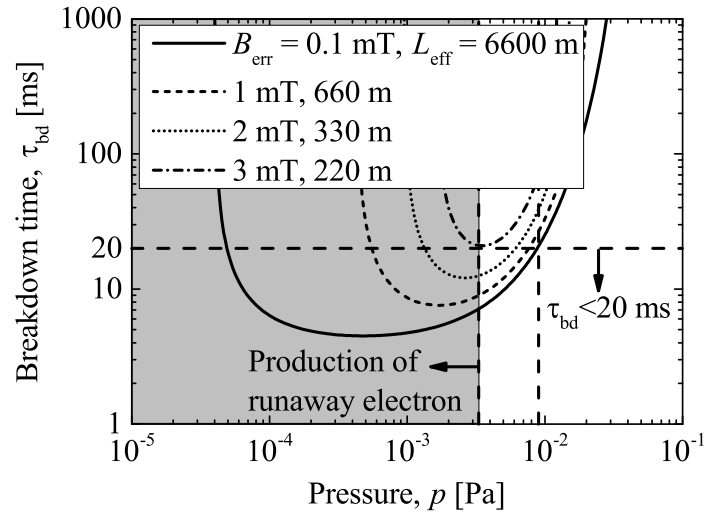
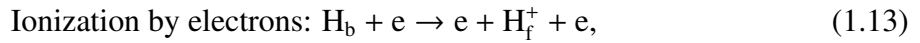
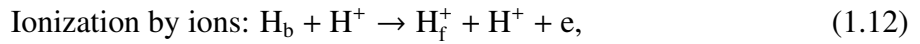
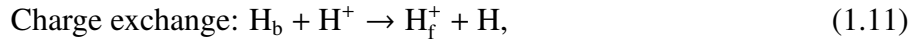


Figure 1.14: Simulated breakdown time for various error fields as a function of gas pressure of the hydrogen gas on JT-60SA.

1.3.3 Plasma start-up using neutral beam injection (NBI) [21,22]

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 was successfully demonstrated in LHD [23] shown in Fig. 1.15. In this experiment, only the neutral beam (co-tangential hydrogen beams, the beam energy is 97 keV, and the port-through input power is approximately 1.6 MW) is applied for the plasma start-up. These injected atoms are ionized through the collisions with the plasma, resulting in the formation of fast ions. Main processes are as follows:



where H_b and H_f^+ represent the neutral beam atom and the resulting fast ion, respectively. The fast ions are confined by the magnetic field because the magnetic field basket is initially formed by the TFCs and HFCs. The energy of these fast ions is then transferred to the electrons and ions through Coulomb collisions. Thus, after the onset of the NBI, the electron density gradually increases to about 10^{18} m^{-3} due to the ionization of the prefill gas. Puffing the additional gas raises the electron density and the stored energy. It was found that there is a proper gas puff timing, i.e. the gas puff earlier than 0.8 s is not effective for increasing the plasma density.

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 ($T_e < 10 \text{ eV}$) of the NBI plasma start-up. As shown in Fig. 1.16 (a), it takes approximately 4 s to break down the plasma. Due to the cooling capacity of the wall opposite to the neutral beams, the plasma start-up by NBI must be achieved in less than 0.4 s. This indicates that the plasma start-up by NBI might be difficult in W7-X. In Fig. 1.16 (b), the dependence of the start-up time on the initial electron density is shown. At initial electron densities above $1.2 \times 10^{16} \text{ m}^{-3}$ for the H_2 gas pressure of $p_{\text{gas}} = 5 \times 10^{-7} \text{ mbar}$, the plasma start-up time could be less than

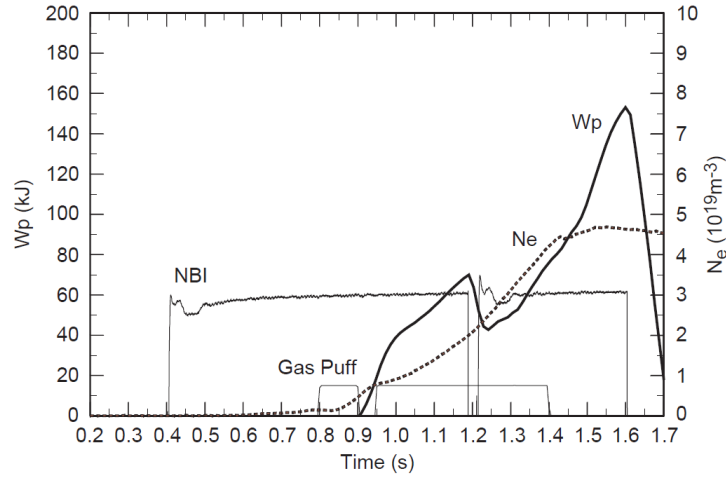


Figure 1.15: Example of the successful NBI plasma start-up on LHD [23].

0.4 s. This implies that the seed plasma generated by 2.45 GHz microwaves, which is achieved in Heliotron J [25], could be effective for a reliable plasma start-up.

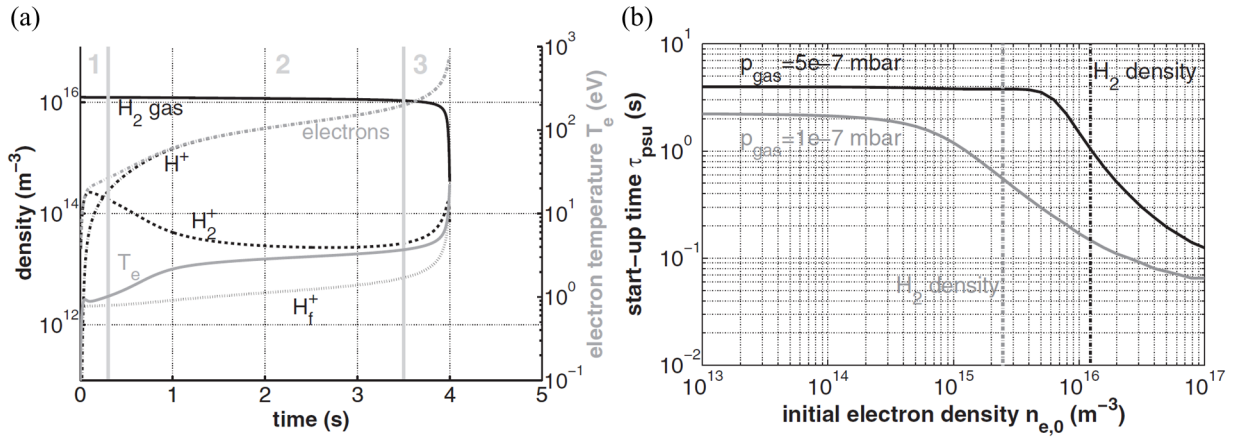


Figure 1.16: 0-D model simulation results of W7-X [24]: (a) simulated time evolution of NBI plasma start-up and (c) dependence of the start-up time on the initial electron density.

Because the plasma start-up using only NBI is possible in LHD, few studies have attempted in LHD to investigate the NBI plasma start-up with the assistance of seed plasma generated by microwaves. In Heliotron J, the NBI plasma start-up has been done with the aid of the seed plasma generated by 2.45 GHz microwaves [25]. This study is considered to contribute to the analysis of the plasma start-up by NBI in W7-X

1.4 Composition of this thesis

The purposes of this thesis are to examine how much ECRH power is required the plasma start-up in the JT-60SA device, and to clarify 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.

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Chapter 2

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

2.1 JT-60SA device

The JT-60SA project has been implemented jointly by Europe and Japan since 2007 [1, 2]. This project is intended to contribute to the early realization of fusion energy by supporting the exploitation of ITER and research towards DEMO by addressing key physics issues. The JT-60SA tokamak is now under construction in JAEA. This facility is expected to finish its construction phase in 2019 and then start plasma experiments.

In Fig. 2.1, the schematic view of the JT-60SA tokamak is shown. JT-60SA tokamak mainly consists of vacuum vessel, cryostat, 18 toroidal field (TF) coils, 4 central solenoid (CS) coils, and 6 equilibrium field (EF) coils, all coils of which are made of superconducting materials such as Nb₃Sn and NbTi for a steady-state operation. Planned are a 10 MW N-NBI and 24 MW P-NBI for heating, current drive, and momentum-input, and a 7 MW ECRH system with multi frequency (110 GHz and 138 GHz) gyrotrons for heating and current drive as well as for plasma start-up. Totally, the power of 41 MW is prepared.

In the JT-60SA tokamak, the toroidal electric field for plasma breakdown is limited up

$0.5 \text{ V} \cdot \text{m}^{-1}$ due to the utilization of the superconducting coils. This may make it difficult to start up plasmas if the wall is not in good condition, that is, the incorporation of impurities such as carbon and oxygen is concerned.

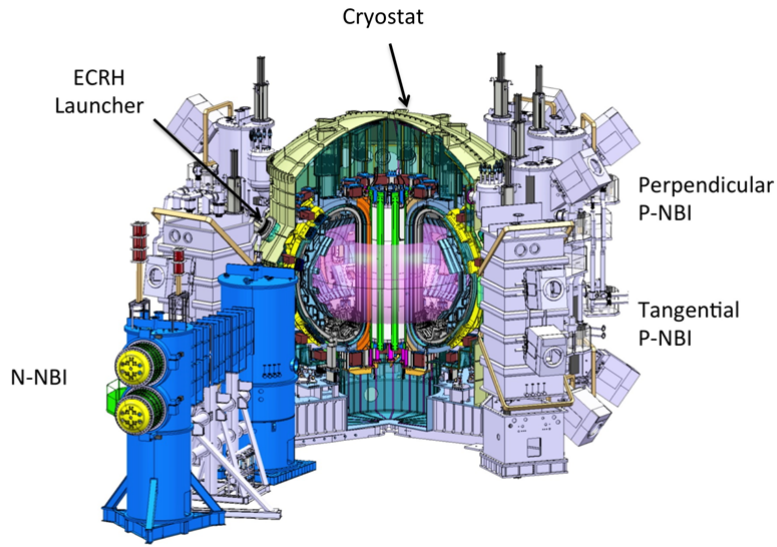


Figure 2.1: Schematic view of the JT-60SA tokamak [3].

2.2 0-D model equations

The ECRH pre-ionization effects are theoretically investigated by a 0-D model [4–7] to examine the conditions for a reliable start-up in JT-60SA. 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%.

2.2.1 Particle density equations for electrons and deuterium atoms

Consider the following simple plasma start-up processes in which electrons are produced only by the deuterium atom ionizations by electron impacts:



and lost by the particle confinement. Therefore, the electron density n_e is described by the following equation:

$$\frac{dn_e}{dt} = n_D n_e \langle \sigma_{e,D}^{\text{ion}} v_e \rangle - \frac{n_e}{\tau_p} \quad (2.2)$$

where n_D is the deuterium atom density, the particle confinement time τ_p is considered as 100 ms, and $\langle \sigma_{e,D}^{\text{ion}} v_e \rangle$ is the coefficient rate for deuterium atom ionization by electrons, given by a fitting function

$$\langle \sigma_{e,D}^{\text{ion}} v_e \rangle = \frac{2 \times 10^{-13}}{6 + T_e/13.6} \sqrt{\frac{T_e}{13.6}} \exp\left(\frac{-13.6}{T_e}\right), \quad (2.3)$$

where T_e is the electron temperature in electron-volts.

We assume that the total number of particles are conserved,

$$\frac{dn_D}{dt} = -\frac{dn_e}{dt} \quad (2.4)$$

The impurity density assumed to be much smaller than the hydrogen density.

2.2.2 Energy density equations for electrons and deuterium ions

Next, let us calculate the electron and bulk ion temperatures. The electron and ion temperatures are determined by the energy density equations for electrons and bulk ions. The energy density equation for electrons requires to take into account the nine terms: (1) ECRH, (2) OH, (3) deuterium ionization and radiation power loss, (4) the equilibrium power transferred from electrons to bulk ions due to the Coulomb collisions, (5) impurity radiation power loss, (6) bremsstrahlung power loss, (7) the direct power loss due to the error field, (8) the power loss

due to $\text{grad}B$ and curvature drift, and (9) the energy confinement power loss.

$$\frac{dU_e}{dt} = p_{\text{ECRH}} + p_{\text{OH}} - p_{\text{IONIZ}} - p_{\text{EQU}} - p_{\text{IRAD}} - p_{\text{BREM}} - U_e (\nu_{\text{eff}} + \nu_{\text{dr}} + \nu_{\text{E}}), \quad (2.5)$$

where $U_e = 3n_e T_e / 2$ is the electron energy density and $U_i = 3n_i T_i / 2$ is the ion energy density. Here p_{ECRH} is the absorbed ECRH power density. Because the electron density and temperature vary with time, the ECRH power absorption efficiency will be mentioned in Discussion.

The ohmic heating power density p_{OH} is given by $p_{\text{OH}} = I_p^2 R_p / V_p$, where R_p is the plasma resistance, and V_p is the plasma volume.

The ionization and radiation loss p_{IONIZ} is given by

$$p_{\text{IONIZ}} = \frac{V_n}{V_p} n_D n_e \langle \sigma_{e,D}^{\text{ion}} \nu_e \rangle W_D, \quad (2.6)$$

where V_n is the volume occupied by deuterium atoms, V_p is the plasma volume, and W_D , the total energy lost per ionization, is considered to be 30 eV.

The equilibration loss transferred from electrons to ions p_{EQU} is given by

$$p_{\text{EQU}} = 7.75 \times 10^{-34} (T_e - T_i) \frac{n_e \ln \Lambda}{T_e^{3/2}} \times \left(\frac{n_{D^+}}{2} + \sum_I \frac{n_I \langle Z^2 \rangle_I}{A_I} \right), \quad (2.7)$$

where $\ln \Lambda$ is the Coulomb logarithm, n_{D^+} is the hydrogen ion density, and A_I is the impurity ion mass number (See Appendix D).

The line radiation loss through the interaction between electrons and impurity ions p_{IRAD} is given by

$$p_{\text{IRAD}} = n_e n_I \times 10^f, \quad (2.8)$$

where $f = -33.93 + 4.888Q - 2.432Q^2 + 0.3697Q^3$ for the carbon impurity and $f = -34.06 + 4.194Q - 1.827Q^2 + 0.2467Q^3$ for oxygen impurities with $Q = \log T_e$. The impurity density n_I is treated as $n_I = f n_e$, where f_I is the ratio of the impurities to the electron density.

The bremsstrahlung power loss p_{BREM} is given by

$$p_{\text{BREM}} = 1.53 \times 10^{-38} n_e T_e^{1/2} \left(n_{D^+} + \sum_I n_I \langle Z^2 \rangle_I \right), \quad (2.9)$$

where $\langle Z^2 \rangle_I$ is the mean-square charge.

In the initial phase, the error field causes direct connection of the field lines to the vacuum chamber wall; consequently, the electrons escape from the plasma along the field lines. The error field loss rate ν_{err} is given by

$$\nu_{\text{err}} = \left(\frac{\delta B}{B} \right) \left(\frac{v_e}{a} \right) \left(1 - \frac{I_p}{I_c} \right), \quad (2.10)$$

for $I_p < I_c$ and by $\nu_{\text{err}} = 0$, for $I_p > I_c$, where v is the electron velocity along the magnetic field from the plasma center to the outside of the plasma, and I_c is the critical current, $I_c = 4\pi a \delta B / \mu_0$. Here, we assume the electron velocity as the electron thermal velocity.

The drift loss rate due to $\text{grad}B$ and curvature drift [8], ν_{dr} , is given by

$$\nu_{\text{dr}} = 4.95 \times 10^{-9} \frac{T_e}{a R_0 B}. \quad (2.11)$$

Here ν_E is the energy loss rate given by the empirical law based on neo-Alcator scaling.

The energy density equation for bulk ions requires to take into account the three terms: (1) the equilibrium power transferred from electrons to bulk ions due to the Coulomb collisions, (2) the charge exchange power loss, and (3) the energy confinement power loss.

$$\frac{dU_i}{dt} = p_{\text{EQU}} - p_{\text{CX}} - U_i \nu_E, \quad (2.12)$$

The charge exchange loss between hydrogen atoms and hydrogen ions p_{CX} is given by

$$p_{\text{CX}} = \frac{V_n}{V_p} e n_{D^+} n_D (T_i - T_D) \langle \sigma_{D^+, D}^{\text{cx}} \nu_{D^+} \rangle, \quad (2.13)$$

where T_D is the temperature of deuterium atoms, and $\langle \sigma_{D^+, D}^{\text{cx}} \nu_{D^+} \rangle$ is the rate coefficient for

charge exchange,

$$\langle \sigma_{D^+, D}^{cx} \nu_{D^+} \rangle = 1.066 \times 10^{-14} T_i^{0.327}. \quad (2.14)$$

2.2.3 Electric circuit equation

Induced in the plasma is a loop voltage by changing the current in the CS coils, which makes the plasma current. The equation for the plasma current is described by the electric circuit equation:

$$\frac{dI_p}{dt} = \frac{V_L - I_p R_p}{L}, \quad (2.15)$$

where V_L is the applied loop voltage, and L is the plasma inductance,

$$L = \mu_0 R_0 \left(\ln \frac{8R_0}{a} - 1.75 \right). \quad (2.16)$$

Although the plasma inductance is a strong function of the current profile and varies rapidly with time as the current channel forms, for simplicity, we assume a flat current profile and treat the plasma inductance as a constant. The plasma inductance is $L = 4.67 \mu\text{H}$ for $R_0 = 2.97 \text{ m}$ and $a = 1.18 \text{ m}$.

2.3 Results

2.3.1 Simulation results for JT-60SA

We calculated plasma start-up using the 0-D model with the JT-60SA parameters as shown in table 2.1. Figure 2.2 shows the temporal behavior of the loop voltage and absorbed ECRH power. The ECRH power was turned on at $t = 0.0$ s; that is, it was applied before the loop voltage is turned on. The loop voltage of approximately 9 V, which corresponds to 0.5 Vm^{-1} , was applied from $t = 0.05$ s to 0.15 s. We scanned the initial electron temperature and density in the range of $T_e = 0.1 - 2.0$ eV, from $n_e = 1.0 \times 10^{15}$ to $1.0 \times 10^{17} \text{ m}^{-3}$ and confirmed that these changes have little impact on the temporal behavior of the main variables.

Table 2.1: JT-60SA parameters for the 0-D model calculation.

Plasma minor radius	1.18 m
Plasma major radius	2.97 m
Error field, B_{err}	1.0 mT
Carbon impurity fraction, n_C/n_e	0.1%
Oxygen impurity fraction, n_O/n_e	0.1%

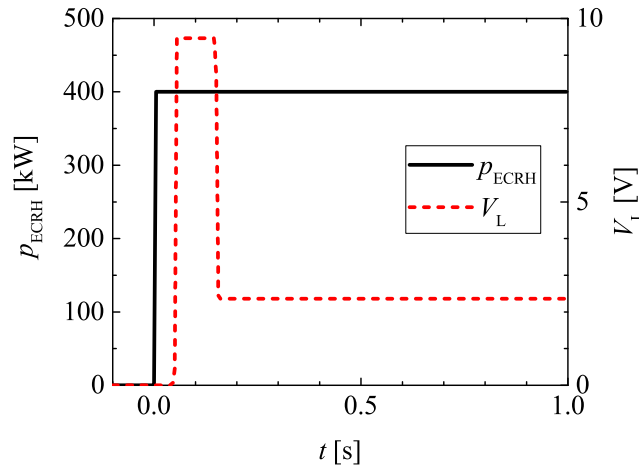


Figure 2.2: Temporal behavior of the loop voltage and the absorbed ECRH power.

We assume the following initial parameters as shown in table 2.2: an electron density of $1.0 \times 10^{16} \text{ m}^{-3}$, a neutral density of $3.0 \times 10^{18} \text{ m}^{-3}$, electron and ion temperatures of $T_e = 1.0$ eV and $T_i = 1.0$ eV, respectively, carbon and oxygen densities of 0.1% of the electron density, and

an absorbed ECRH power of $p_{\text{ECRH}} = 400$ kW. In this paper, we define successful start-up as occurring when the electron temperature becomes sufficiently high, so that p_{IRAD} is no longer a large fraction of the total power loss from the plasma. This generally applies when $T_e > 100$ eV.

Table 2.2: Initial conditions for the 0-D model calculation.

Electron temperature, T_e	1.0 eV
Ion temperature, T_i	1.0 eV
Plasma current, I_p	0 A
Hydrogen atom density, n_H	$3.0 \times 10^{18} \text{ m}^{-3}$
Electron density, n_e	$1.0 \times 10^{16} \text{ m}^{-3}$

Figure 2.3 shows the temporal behavior of the electron and neutral densities, the electron and ion temperatures, and the plasma current in a successful start-up. The electron density rises promptly to near $3.0 \times 10^{18} \text{ m}^{-3}$, and the neutral density decreases with increasing electron density. These electrons are produced by pre-ionization using ECRH.

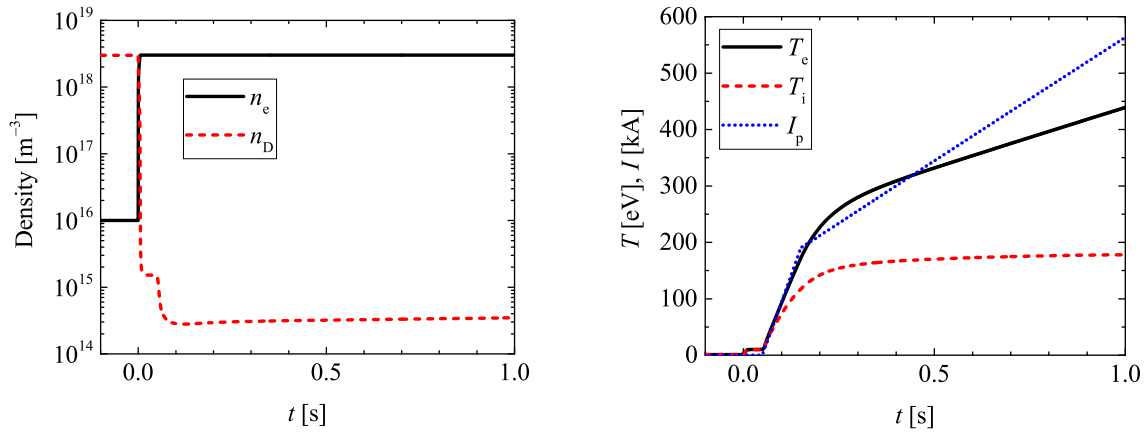


Figure 2.3: (a) Time evolutions of electron and neutral densities for a successful start-up. Absorbed ECRH power is $p_{\text{ECRH}} = 400$ kW and (b) Time evolutions of electron and ion temperatures and current for a successful start-up. Absorbed ECRH power is $p_{\text{ECRH}} = 400$ kW.

In contrast, when the ECRH power is reduced to 100 kW, the discharge fails. Figure 2.4 shows the temporal behavior of the electron and neutral densities, electron and ion temperatures, and plasma current in an unsuccessful start-up. In the initial phase, the line radiation power due to impurity ions, ionization power, and equilibration power are the dominant losses in the

electron energy density equation. In this case, the plasma cannot overcome the radiation barrier. Although the electron density reaches near $1 \times 10^{18} \text{ m}^{-3}$, the electron temperature remains approximately 2 eV. Despite applied the loop voltage, the plasma current does not increase due to the high resistivity.

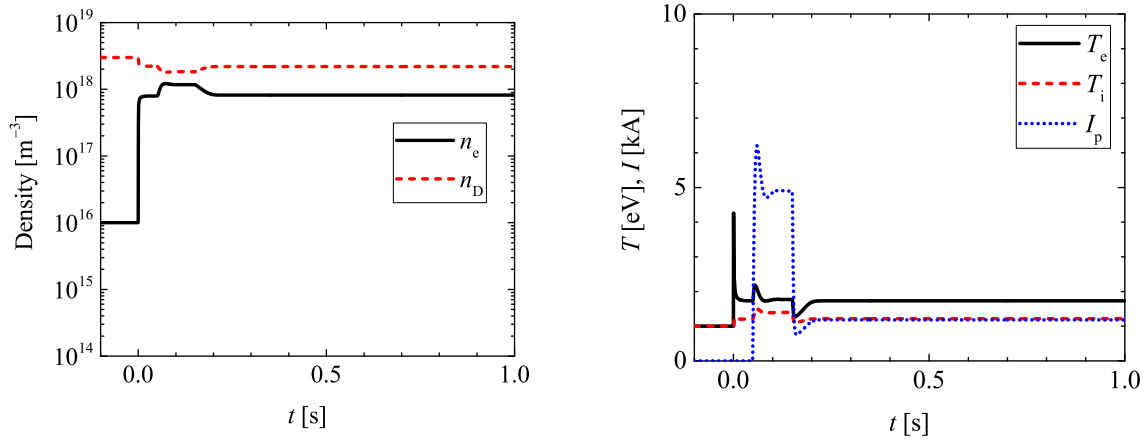
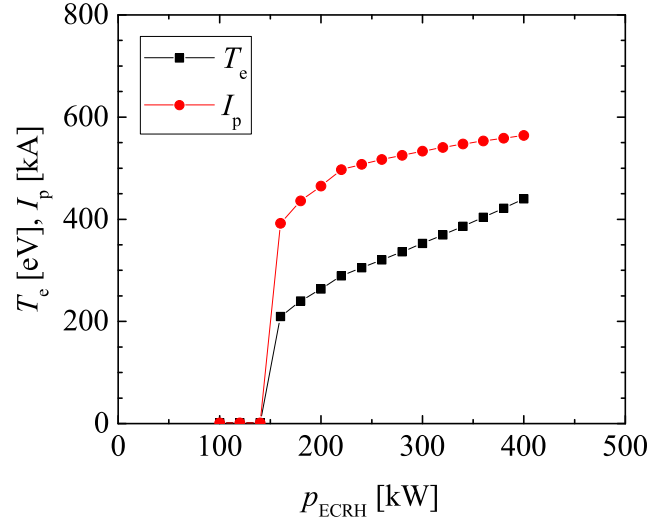
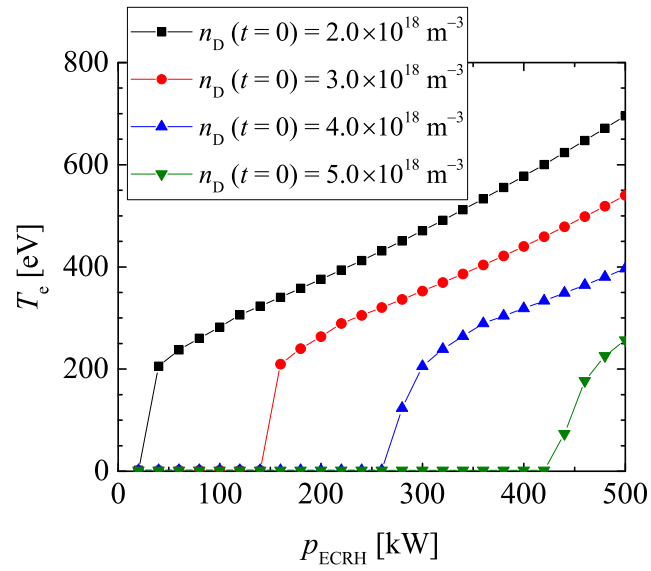


Figure 2.4: (a)Time evolutions of electron and neutral densities for a unsuccessful start-up. Absorbed ECRH power is $p_{\text{ECRH}} = 100 \text{ kW}$ and (b)Time evolutions of electron and ion temperatures and current for a unsuccessful start-up. Absorbed ECRH power is $p_{\text{ECRH}} = 100 \text{ kW}$.

Figure 2.5 shows the dependence of the electron temperature and plasma current at $t = 1.0 \text{ s}$ on the absorbed ECRH power. The initial conditions are an electron density of 10^{16} m^{-3} and a neutral density of $3.0 \times 10^{18} \text{ m}^{-3}$. The carbon and oxygen densities are the same as that shown in Fig. 2.3. The figure reveals a threshold in ECRH power for successful start-up; an ECRH power of approximately 150 kW is required when the initial neutral density is $3.0 \times 10^{18} \text{ m}^{-3}$.

Figure 2.6 shows the electron temperature at $t = 1.0 \text{ s}$ versus the absorbed ECRH powers. The initial neutral density was scanned from $2.0 \times 10^{18} \text{ m}^{-3}$ to $5.0 \times 10^{18} \text{ m}^{-3}$. More ECRH power is required as the initial neutral density increases because the radiation power loss increases. Below the threshold power, the radiation barrier cannot be overcome, and the electron temperature remains as low as 1 eV.

Impurities have an important role in plasma start-up. Figures 2.7 show the electron temperature at $t = 1.0 \text{ s}$ for various ratios of impurities to the electron density. The ratios of carbon and oxygen impurities to the electron density were varied between 0.0% and 1.5%. The effect of carbon impurities is slightly larger than that of oxygen impurities. When the carbon impurities

Figure 2.5: Electron temperature and plasma current at $t = 1.0$ sFigure 2.6: Electron temperature at $t = 1.0$ s for a neutral density of $2.0\text{-}5.0 \times 10^{18} \text{ m}^{-3}$

were more than 0.5% of the electron density, the required ECRH power was more than 300 kW. Suppression of oxygen and carbon impurities would be useful to ensure successful start-up and reduce the required ECRH power. Nevertheless, this required ECRH power is considered to be overestimated. In the 0-D model, spatially-uniform plasma is assumed. The radiation power from the impurity such as carbon and oxygen is localized in the edge region since it has a peak at electron temperatures below 100 eV. For a more quantitative and detailed analysis, 1-D model is discussed.

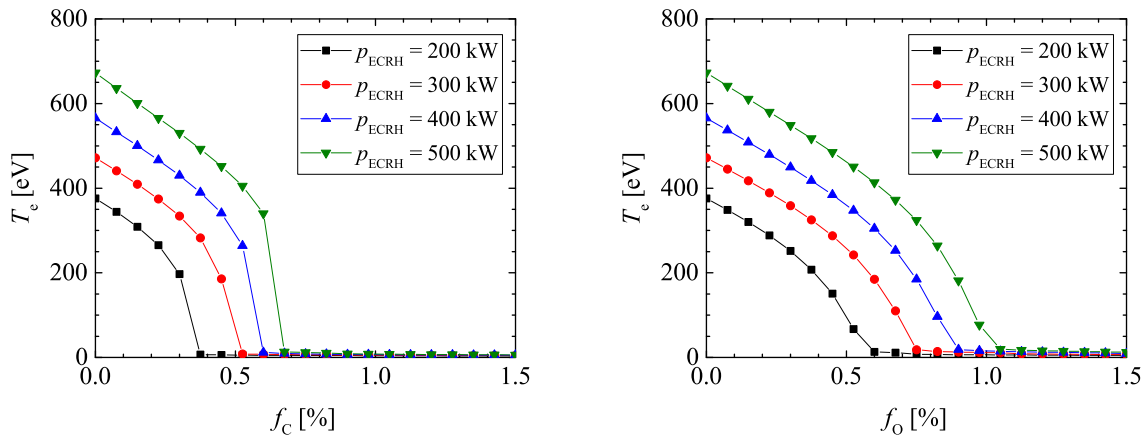


Figure 2.7: (a) Electron temperature as a function of fraction of carbon impurities for an absorbed ECRH power of 200-500 kW and (b) Electron temperature as a function of fraction of oxygen impurities for an absorbed ECRH power of 200-500 kW

2.3.2 Comparison with experimental data for JT-60U

We calculated the plasma start-up in JT-60U by using the 0-D model and compared it with the experimental results. We assumed a major radius of $R_0 = 3.05$ m, a minor radius of $a = 0.72$ m, a self-inductance of $5.49 \mu\text{H}$, an initial electron density of $1.0 \times 10^{16} \text{ m}^{-3}$, and no impurities. Two types of start-ups were calculated: ECRH-assisted start-up with an ECRH power of 950 kW (from $t = 0.23$ s), a loop voltage of 4 V ($t = 0.25 - 0.35$ s), and an initial neutral density of $0.64 \times 10^{18} \text{ m}^{-3}$; and OH start-up with a loop voltage of 25 V ($t = 0.25 - 0.33$ s) without ECRH power, and with an initial neutral density of $1.4 \times 10^{18} \text{ m}^{-3}$. Figure 2.8 shows the calculated temporal behavior of the plasma current. In the ECRH-assisted start-up, the plasma current

increased to nearly 0.07 MA at 0.4 s. In the OH start-up, the plasma current increased to nearly 0.26 MA at 0.4 s. The numerical simulation qualitatively reproduced the time evolution of the experimental results [9] in both cases.

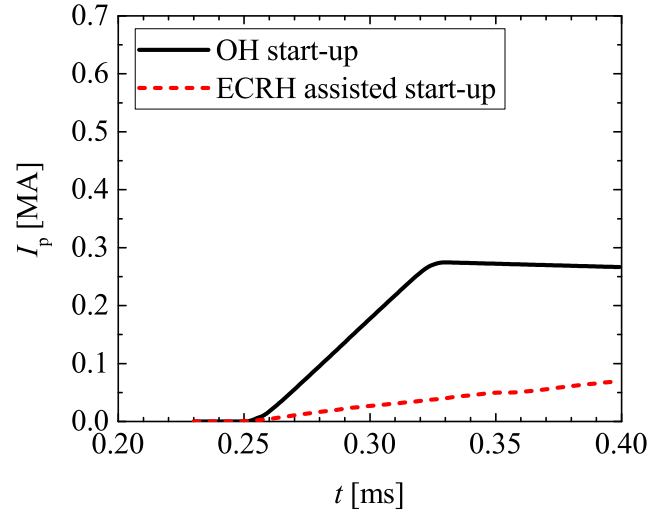


Figure 2.8: Temporal behavior of the plasma current for JT-60U.

2.4 Discussion

Using JT-60U parameters, simulated plasma currents are approximately half of those in the experimental results described in [9]. The plasma current ramp-up rates are calculated to be 4.3 MA/s for the OH start-up and 0.5 MA/s for the ECRH assisted start-up. Since the actual plasma has a radial structure and the electron temperature is higher than that of the simulated at the core region, the plasma resistivity is considered to be lower than that of the simulated one. Let us evaluate the plasma current under the assumption that the plasma resistivity is negligibly small. The plasma current ramp-up rate is approximated by

$$\frac{dI_p}{dt} \sim \frac{V_L}{L} = \begin{cases} 4.6 \text{ MA/s,} & \text{for the OH start-up,} \\ 0.73 \text{ MA/s,} & \text{for the ECRH assisted start-up.} \end{cases} \quad (2.17)$$

Although the plasma current ramp-up rates slightly increase, this assumption does not explain completely these difference. A self-inductance of $3.0 \mu\text{H}$ can reproduce the experimental results, However, in this case the minor radius has to be set at 1.9 m because the major radius remains virtually unchanged. This difference might be considered to be due to the eddy current flowing along the vacuum vessel.

The basic assumption of this model is that all of the injected ECRH power is absorbed into the plasma. These calculation results correspond to the O1-mode ECRH 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.

The calculations taking into account the 2nd harmonic ECRH absorption efficiency has been attempted. Simulation results indicate that even 10 MW could not start up the plasma. This is considered to be due to the radial structure of the plasma. The deposition profile of the ECRH must be included into the model because the ECRH power is localized at the resonance layer.

2.5 Summary

We investigated the effects of ECRH pre-ionization on plasma start-up using the JT-60SA parameters and a 0-D model. 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 $n_D = 3.0 \times 10^{18} \text{ m}^{-3}$. Since all of the injected ECRH power is assumed to be absorbed into the plasma, this result is considered to correspond to the O1-mode ECRH assisted plasma start-up from LFS. 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.

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Chapter 3

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

3.1 Introduction

As discussed in Chap. 2, 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. Therefore, we develop a 1-D model that includes a radial transport to study 2nd harmonic X-mode ECRH assisted plasma start-up in JT-60SA.

3.2 1-D model equations

In the 1-D model, we assume that the plasma is cylindrically symmetrical from the initial start-up phase, as shown in Fig. 3.1. This model comprises energy transport equations for electrons and hydrogen ions, particle transport equations for electrons and hydrogen atoms, and a toroidal current equation. These equations are numerically solved by Crank-Nicolson method with a time step $\Delta t = 1.0^{-6}$ s (See Appendix B).

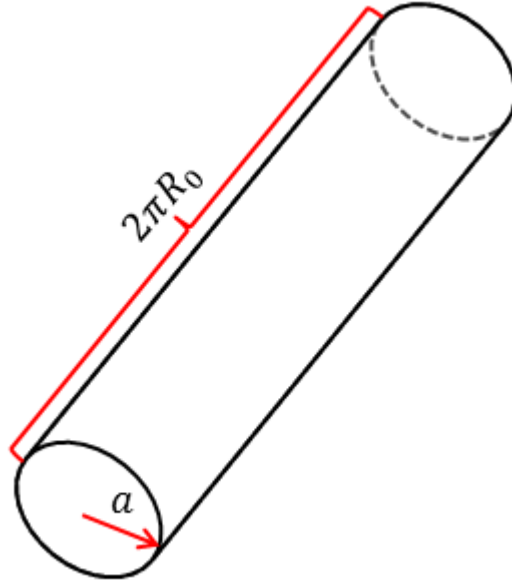


Figure 3.1: Cylindrically symmetrical plasma.

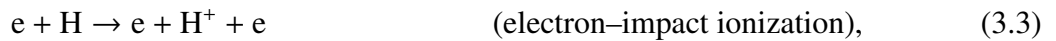
3.2.1 Particle transport equations for electrons and hydrogen atoms

The particle transport equations for electrons and hydrogen atoms are

$$\frac{\partial n_e}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r D_e \frac{\partial n_e}{\partial r} \right) + n_H n_e \langle \sigma v \rangle_{e,iz} + n_{H^+} n_H \langle \sigma v \rangle_{i,iz} - n_{H^+} n_e \langle \sigma v \rangle_{rec}, \quad (3.1)$$

$$\frac{\partial n_H}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r D_H \frac{\partial n_H}{\partial r} \right) - n_H n_e \langle \sigma v \rangle_{e,iz} - n_{H^+} n_H \langle \sigma v \rangle_{i,iz} + n_{H^+} n_e \langle \sigma v \rangle_{rec}, \quad (3.2)$$

where D_e and D_H are the particle diffusivities for electrons and hydrogen atoms, respectively. Because these diffusivities have not been experimentally investigated as well as the thermal diffusivities of electrons and ions, we assume spatially uniform diffusivities of $D_e = D_H = 1.0 \text{ m}^2 \text{ s}^{-1}$. In the initial plasma start-up phase, after plasma density is formed, whether the plasma starts up or not is determined by power balance of electron. Therefore, no parallel transport loss terms such as error field and drift loss are included in 1-D model. The numbers of electrons and hydrogen atoms vary via the reactions [1]:





The cross sections for these reactions are $\langle\sigma v\rangle_{\text{e,iz}}$, $\langle\sigma v\rangle_{\text{i,iz}}$, and $\langle\sigma v\rangle_{\text{rec}}$, respectively.

The boundary conditions for electron and hydrogen atom densities are given by

$$\left. \frac{\partial n_{\text{e}}}{\partial r} \right|_{r=0} = 0, \quad n_{\text{e}} \big|_{r=a_{\text{p}}} = n_{\text{eb}}, \quad (3.6)$$

$$\left. \frac{\partial n_{\text{H}}}{\partial r} \right|_{r=0} = 0, \quad n_{\text{H}} \big|_{r=a_{\text{p}}} = n_{\text{Hb}}, \quad (3.7)$$

where n_{eb} and n_{Hb} are the fixed boundary electron and hydrogen atom densities.

3.2.2 Energy transport equations for electrons and hydrogen ions

The electron and ion temperatures are determined by the following energy transport equations for electrons and ions:

$$\begin{aligned} \frac{\partial U_{\text{e}}}{\partial t} = & \frac{1}{r} \frac{\partial}{\partial r} \left(r n_{\text{e}} \chi_{\text{e}} \frac{\partial T_{\text{e}}}{\partial r} \right) + p_{\text{ECRH}} + p_{\text{OH}} - p_{\text{IONIZ}} - p_{\text{EQU}} - p_{\text{BREM}} \\ & - p_{\text{IRAD}} - U_{\text{e}} (\nu_{\text{err}} + \nu_{\text{dr}}), \end{aligned} \quad (3.8)$$

$$\frac{\partial U_{\text{i}}}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r n_{\text{i}} \chi_{\text{i}} \frac{\partial T_{\text{i}}}{\partial r} \right) + p_{\text{EQU}} - p_{\text{CX}}, \quad (3.9)$$

where n_{e} is the electron density, T_{e} is the electron temperature, n_{i} is the ion density, T_{i} is the ion temperature, $U_{\text{e}} = 3n_{\text{e}}T_{\text{e}}/2$ is the electron energy density and $U_{\text{i}} = 3n_{\text{i}}T_{\text{i}}/2$ is the ion energy density. Electrons are assumed to be heated by ECRH (p_{ECRH}) and by OH (p_{OH}) and to lose energy through ionization and radiation (p_{IONIZ}), the equilibration energy transferred from electrons to ions (p_{EQU}), bremsstrahlung due to hydrogen ions (p_{BREM}), the interaction between electrons and impurity ions (p_{IRAD}), and direct power loss due to the error field and grad B and curvature drift. Ions are heated only by the equilibration energy transferred from electrons to ions (p_{EQU}) and lose energy by charge exchange between hydrogen atoms and hydrogen ions (p_{CX}). All these channels are discussed later in more detail.

Note that the thermal diffusivities, χ_{e} and χ_{i} in the plasma start-up phase are not investigated

experimentally and theoretically. Here, we use the Bohm diffusion [2, 3] to calculate thermal diffusion and assume that the thermal diffusivity is uniform within the plasma. The electron and ion thermal diffusivities are given by

$$\chi_e = \chi_i = \chi_{\text{Bohm}} = \frac{1}{16} \frac{T_e^{\text{res}}}{B_T^{\text{res}}}, \quad (3.10)$$

where T_e^{res} and B_T^{res} are the electron temperature and toroidal magnetic field at the electron cyclotron (EC) resonance position, respectively.

In this model, we assume that the ECRH power density is a Gaussian centered on axis, and is absorbed in a single-pass through the plasma. The absorbed ECRH power density is given by

$$p_{\text{ECRH}} = p_{\text{ECRH}}^{\text{I}} (1 - f_O e^{-\tau_O} - f_X e^{-\tau_X}), \quad (3.11)$$

$$p_{\text{ECRH}}^{\text{I}} = p_0 \exp \left\{ - \left(\frac{r}{r_w} \right)^2 \right\}, \quad (3.12)$$

where $p_{\text{ECRH}}^{\text{I}}$ is the injected ECRH power density, r_w is the e-folding radius of the EC beam, p_0 is determined as the volume integral of Eq. (5) equals to the injected total EC power, f_O and f_X are the fractional powers for the ordinary mode (O-mode) and extraordinary mode (X-mode), respectively, and τ_O and τ_X are the optical depths for the O-mode and X-mode, respectively. The optical depths [4] for second-harmonic ECRH are expressed by

$$\tau_{O, X} = 4\pi^2 \frac{R_0}{\lambda} \frac{T_e}{m_e c^2} \alpha n_{\perp O, X} \frac{\left[(S - D - n^2) (P - n_{\perp O, X}^2) \right]^2}{D^2 (P - n_{\perp O, X}^2)^2 + n_{\parallel}^2 P (S - n^2)^2}, \quad (3.13)$$

where R_0 is the major radius of the plasma, λ is the free-space wavelength of RF waves, $\alpha = n_e/n_c$, $n_c = m_e \epsilon_0 \omega^2 / e^2$ is the cut-off density, and S , D , and P are the components of the dielectric tensor in the cold-plasma dispersion relation. The components of the dielectric tensor are

$$S = 1 - \frac{\omega_{pe}^2}{\omega^2} \left(\frac{\omega^2}{\omega^2 - \omega_{ce}^2} \right) = 1 - \alpha \left(\frac{N^2}{N^2 - 1} \right),$$

$$D = -\frac{\omega_{pe}^2}{\omega^2} \left(\frac{\omega \omega_{ce}}{\omega^2 - \omega_{ce}^2} \right) = -\alpha \left(\frac{N}{N^2 - 1} \right),$$

$$P = 1 - \frac{\omega_{pe}^2}{\omega^2} = 1 - \alpha, \quad (3.14)$$

where N is the harmonic number. Here, n is the refractive index, $n_{\parallel}$ is the parallel component of the refractive index, and $n_{\perp}$ is the perpendicular component of the refractive index, which is given by

$$n_{\perp O, X}^2 = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}, \quad (3.15)$$

where the plus and minus signs correspond to the O-mode and X-mode, respectively, and $A = S$, $B = -(S + P)(S - n_{\parallel}^2) + D^2$, and $C = P((S - n_{\parallel}^2)^2 - D^2)$.

The OH power density p_{OH} is given by $p_{OH} = \eta_{\parallel}^{(NC)} J_p^2$, where $\eta_{\parallel}^{(NC)}$ is the neoclassical resistivity and J_p is the plasma current density.

The ionization and radiation loss p_{IONIZ} [5] through electron–hydrogen atom collision is given by

$$p_{IONIZ} = n_H n_e S W_H, \quad (3.16)$$

where n_H is the hydrogen atom density, W_H is the total energy loss per ionization and radiation is considered to be 30 eV, and S is the coefficient rate for electron ionization and is given by

$$S = \frac{2 \times 10^{-13}}{6 + T_e/13.6} \sqrt{\frac{T_e}{13.6}} \exp\left(\frac{-13.6}{T_e}\right). \quad (3.17)$$

The equilibration energy transferred from electrons to ions p_{EQU} [6] is given by

$$p_{EQU} = 7.75 \times 10^{-34} (T_e - T_i) \frac{n_e \ln \Lambda}{T_e^{3/2}} \left(\frac{n_{H^+}}{A_H} + \sum_I \frac{n_I \langle Z^2 \rangle_I}{A_I} \right), \quad (3.18)$$

where $\ln \Lambda$ is the Coulomb logarithm, n_{H^+} is the hydrogen ion density, A_H is the mass number of hydrogen, n_I is the impurity density, $\langle Z^2 \rangle_I$ is the mean-square charge, and A_I is the impurity ion mass number. The impurity density n_I is treated as $n_I = f_I n_e$, where f_I is the ratio of impurity density to electron density.

The bremsstrahlung power loss due to hydrogen ions p_{BREM} [5] is given by

$$p_{\text{BREM}} = 1.53 \times 10^{-38} n_e T_e^{1/2} n_{\text{H}^+}. \quad (3.19)$$

The interaction power loss between electrons and impurity ions including line radiation, radiative recombination radiation, dielectronic recombination radiation, charge exchange recombination radiation and bremsstrahlung p_{IRAD} [6] is given by

$$p_{\text{IRAD}} = n_e n_{\text{I}} \times 10^f, \quad (3.20)$$

where $f = -33.93 + 4.888Q - 2.432Q^2 + 0.3697Q^3$ for carbon impurities and $f = -34.06 + 4.194Q - 1.827Q^2 + 0.2467Q^3$ for oxygen impurities with $Q = \log_{10} T_e$.

The charge exchange power loss between hydrogen atoms and hydrogen ions p_{CX} [5] is given by

$$p_{\text{CX}} = \frac{3}{2} e n_{\text{H}^+} n_{\text{H}} (T_i - T_0) S_{\text{CX}}, \quad (3.21)$$

where T_0 is the temperature of thermal hydrogen atoms, and S_{CX} is the rate coefficient for charge exchange, which is given by

$$S_{\text{CX}} = 1.066 \times 10^{-14} T_i^{0.327}. \quad (3.22)$$

In the initial start-up phase, the poloidal error field causes electrons to escape directly from the plasma along the magnetic field lines and in the direction of the first wall. We assume that electrons escape at the hydrogen ion sound speed because of the ambipolar potential. When the magnetic field generated by the plasma current exceeds the error field, the error field loss becomes negligible: we define this current as the critical current. The error field loss rate ν_{err} [2, 6] is assumed to be

$$\nu_{\text{err}} = \begin{cases} \frac{C_s}{L_f} \left(1 - \frac{I_p}{I_c}\right), & \text{for } I_p \leq I_c, \\ 0, & \text{for } I_p > I_c, \end{cases} \quad (3.23)$$

where I_p is the plasma current, I_c is the critical current, $I_c = 4\pi a B_{\text{err}}/\mu_0$, C_s is the hydrogen ion sound speed, and L_f is the effective connection length. These quantities are given by

$$C_s = \sqrt{\frac{T_e + T_i}{m_H}}, \quad (3.24)$$

$$L_f = 0.25 \times a \frac{B_T}{B_{\text{err}}}, \quad (3.25)$$

where m_H is the hydrogen ion mass (1.67×10^{-27} kg), and B_{err} is the error field.

The drift loss rate due to grad B drift and curvature drift, ν_{dr} [7], is given by

$$\nu_{\text{dr}} = \begin{cases} \frac{2T_e}{3aR_0B_T} \left(1 - \frac{I_p}{I_c}\right), & \text{for } I_p \leq I_c, \\ 0, & \text{for } I_p > I_c. \end{cases} \quad (3.26)$$

The boundary conditions for electron and ion temperatures are

$$\left. \frac{\partial T_e}{\partial r} \right|_{r=0} = 0, \quad T_e|_{r=a_p} = T_{\text{eb}}, \quad (3.27)$$

$$\left. \frac{\partial T_i}{\partial r} \right|_{r=0} = 0, \quad T_i|_{r=a_p} = T_{\text{ib}}, \quad (3.28)$$

where T_{eb} and T_{ib} are constants.

3.2.3 Toroidal current equation

The toroidal current equation [8] is derived from the Maxwell equations and Ohm's law and is expressed as

$$\mu_0 \frac{\partial I_p}{\partial t} = 4\pi S \frac{\partial}{\partial S} \left(\frac{1}{\sigma_{\parallel}^{(\text{NC})}} \frac{\partial I_p}{\partial S} \right), \quad (3.29)$$

where $I_p(S, t)$ is the plasma current inside the magnetic surface, S is the poloidal cross-sectional area of the plasma ($S = \pi r^2$), and $\sigma_{\parallel}^{(\text{NC})} = 1/\eta_{\parallel}^{(\text{NC})}$ is the neoclassical conductivity.

The boundary conditions are given as

$$I_p(0, t) = 0, \quad (3.30)$$

$$\left. \frac{\partial I_p}{\partial S} \right|_{S=\pi a_p^2} = \frac{V_L - I_p R_p}{L}, \quad (3.31)$$

where V_L is the applied loop voltage, R_p is the plasma resistance, and L is the self-inductance. This self-inductance is the sum of the external inductance L_e and internal inductance L_i , which are defined as

$$L_e = \mu_0 R_0 \left(\ln \frac{8R_0}{a_p} - 2 \right), \quad (3.32)$$

$$L_i = \frac{\mu_0 R_0 l_i}{2}, \quad (3.33)$$

respectively, and where l_i is given by

$$l_i = \frac{2\pi \int_0^{a_p} B_p^2(r) r dr}{\pi a_p^2 B_p^2(a_p)}, \quad (3.34)$$

with $B_p(r)$ being the poloidal magnetic field at r produced by the plasma current inside r .

3.3 Results

3.3.1 Simulation results for JT-60SA

We used the 1-D model to simulate plasma start-up for the JT-60SA configuration. Figure 3.2(a) shows the temporal behavior of the loop voltage V_L and injected ECRH power P_{ECRH}^I . A loop voltage of approximately 9 V, which corresponds to an electric field of approximately $0.5 \text{ V}\cdot\text{m}^{-1}$, is applied starting at $t = 0.00 \text{ s}$ for OH and is maintained for 0.1 s. To assist plasma heating, the second-harmonic X-mode ECRH is switched on at $t = 0.01 \text{ s}$ (i.e., 0.01 s after the loop voltage is switched on). Although the minor radius of the plasma actually evolves over time, we assume a constant minor radius ($a = 1.18 \text{ m}$) in this simulation and further assume that the plasma develops only within this radius. This model does not describe the physical process of the early breakdown phase, i.e., the Coulomb phase. In the Coulomb phase, the electron–ion collision frequency is greater than the collision frequency of electron–hydrogen atom and molecule [9]. The Coulomb phase is considered to last for such a short time that we can simulate after the Coulomb phase. Assuming an initial electron temperature of approximately 1 eV leads to an initial electron density of approximately $0.002n_H(t = 0)$ [9]. The initial ion temperature starts at room temperature, and there is no initial plasma current. Carbon and oxygen are considered as major impurities because the first wall in the vacuum vessel of JT-60SA will be covered with graphite tiles. The JT-60SA parameters and initial conditions are shown in Tables 3.1 and 3.2. For successful plasma start-up, the electron temperature must be sufficiently high so that p_{IRAD} is no longer a large fraction of the total power loss from the plasma; this generally occurs for $T_e > 100 \text{ eV}$ [10, 11]. In addition, since the plasma must expand outward sufficiently, we define successful plasma start-up to be when the electron temperature at half radius ($\rho = r/a = 0.5$) exceeds 100 eV at $t = 0.15 \text{ s}$.

Figure 3.2 shows the time evolution of loop voltage and injected ECRH power [Fig. 3.2(a)], electron and hydrogen atom density at $\rho = 0$ [Fig. 3.2(b)], ECRH absorption efficiency [Fig. 3.2(c)], electron temperature at $\rho = 0$ [Fig. 3.2(d)], and plasma current [Fig. 3.2(e)], and Fig. 3.3 shows the radial profile of electron density [Fig. 3.3(a)], electron temperature [Fig. 3.3(b)], and current density [Fig. 3.3(c)] for a successful plasma start-up. When the loop voltage is switched on, the electron density exhibits a flat profile, following which the profile peaks be-

Table 3.1: JT-60SA parameters for the 1-D model calculation.

Plasma minor radius	1.18 m
Plasma major radius	2.97 m
EC frequency & mode	110 GHz 2nd X-mode
EC beam radius at EC resonance position	5 cm
Fraction power for O-mode, f_O	0.00
Fraction power for X-mode, f_X	1.00
Error field, B_{err}	1.0 mT
Carbon impurity fraction, n_C/n_e	0.1%
Oxygen impurity fraction, n_O/n_e	0.1%

Table 3.2: Initial conditions for the 1-D model calculation.

Electron temperature, T_e	1.0 eV
Ion temperature, T_i	0.03 eV
Plasma current, I_p	0 A
Hydrogen atom density, n_H	$3.0 \times 10^{18} \text{ m}^{-3}$
Electron density, n_e	$0.002n_H(t = 0)$

cause of ECRH injection. Electron density is observed to increase from the center and diffuse outward. Furthermore, positive feedback forms between ECRH absorption efficiency and electron temperature. Once the plasma is heated with the help of positive feedback, the electron temperature rises drastically 10 ms after ECRH injection. ECRH absorption efficiency eventually reaches approximately 100%, at which point the spatial profile of electron temperature forms a peak. As the electron temperature increases, low resistivity prevents the current density from penetrating into the core; consequently, a hollow current density profile forms. In this case, at $t = 0.02$ s, the plasma is fully ionized, and at $t = 0.15$ s, the electron temperature reaches approximately 1.5 keV, and the plasma current is approximately 150 kA.

Understanding which processes are important in the initial plasma start-up phase is vital. Figure 3.4 shows the time evolution of electron density, temperature, and plasma current [Fig. 3.4(a)] and the various power terms at $\rho = 0$ [Fig. 3.4(b)] in the initial start-up phase. The dominant physical process depends on the phase. Electron and ion density gradually increase due to OH; therefore, the dominant processes are ionization loss (IONIZ) and equilibration loss (EQU) due to energy transferred from electrons to ions through collisions. After ECRH onset, electron density increases promptly, and ECRH absorption power density slightly increases; however, the ECRH absorption power is mainly consumed by ionization and equilibration loss,

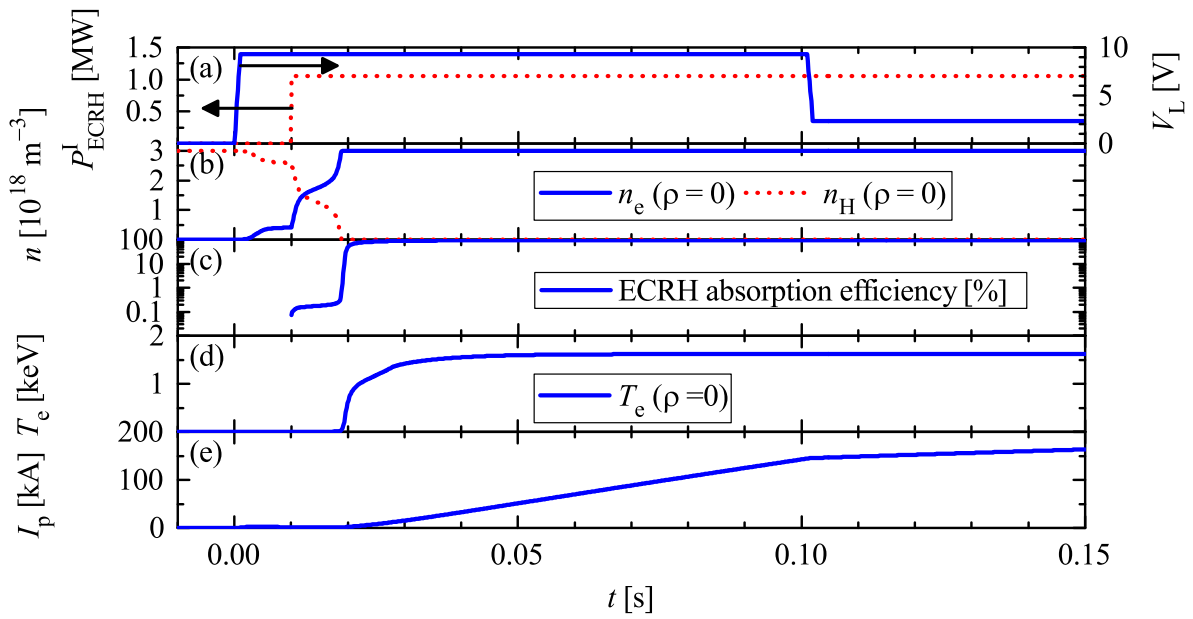


Figure 3.2: Time evolutions of (a) loop voltage and injected ECRH power, (b) electron and hydrogen atom density at $\rho = 0$, (c) ECRH absorption efficiency, (d) electron temperature at $\rho = 0$, and (e) plasma current for a successful plasma start-up. The parameters are $P_{\text{ECRH}}^I = 1.05$ MW, $n_{\text{H}}(t = 0) = 3.0 \times 10^{18} \text{ m}^{-3}$, and $B_{\text{err}} = 1.0$ mT.

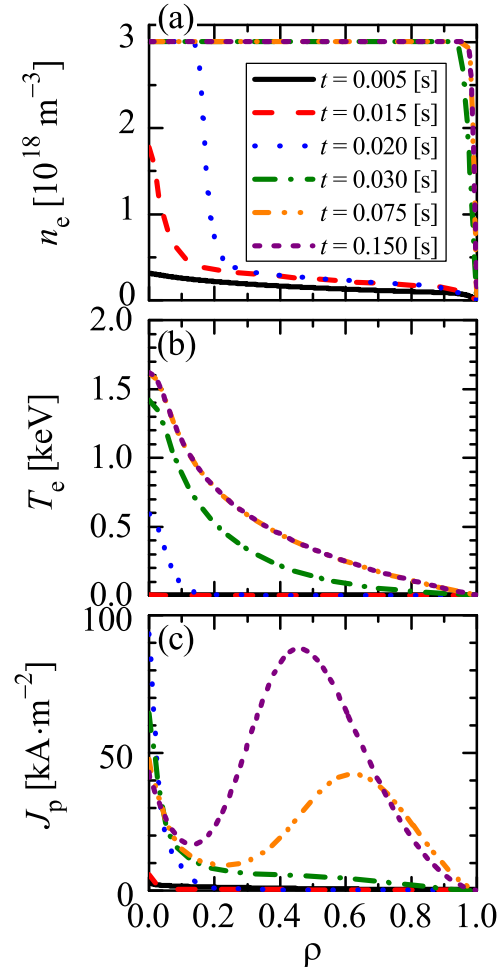


Figure 3.3: Radial profiles of (a) electron density, (b) electron temperature, and (c) current density for a successful plasma start-up. The parameters are $P_{\text{ECRH}}^{\text{I}} = 1.05 \text{ MW}$, $n_{\text{H}}(t = 0) = 3.0 \times 10^{18} \text{ m}^{-3}$, and $B_{\text{err}} = 1.0 \text{ mT}$.

and the electron temperature remains approximately 5 eV. Because of positive feedback between ECRH absorption efficiency and electron temperature, the latter rises drastically starting at $t \sim 0.019$ s. Thermal conduction loss (COND) becomes the dominant process after the electron temperature rise. Due to increase in electron temperature, the error field (ERROR) and drift loss (DRIFT) drastically increases and the interaction power loss between electrons and impurity ions (IRAD) peaks at $t = 0.019$; however, these terms are not dominant process. Therefore, plasma start-up is considered to depend weakly on error field and impurity concentration. At $t = 0.028$ s, the plasma current exceeds the critical current $I_c \approx 12$ kA, and then these error field and drift losses vanish. Thus, during current ramp-up phase, the thermal conduction loss is the dominant process.

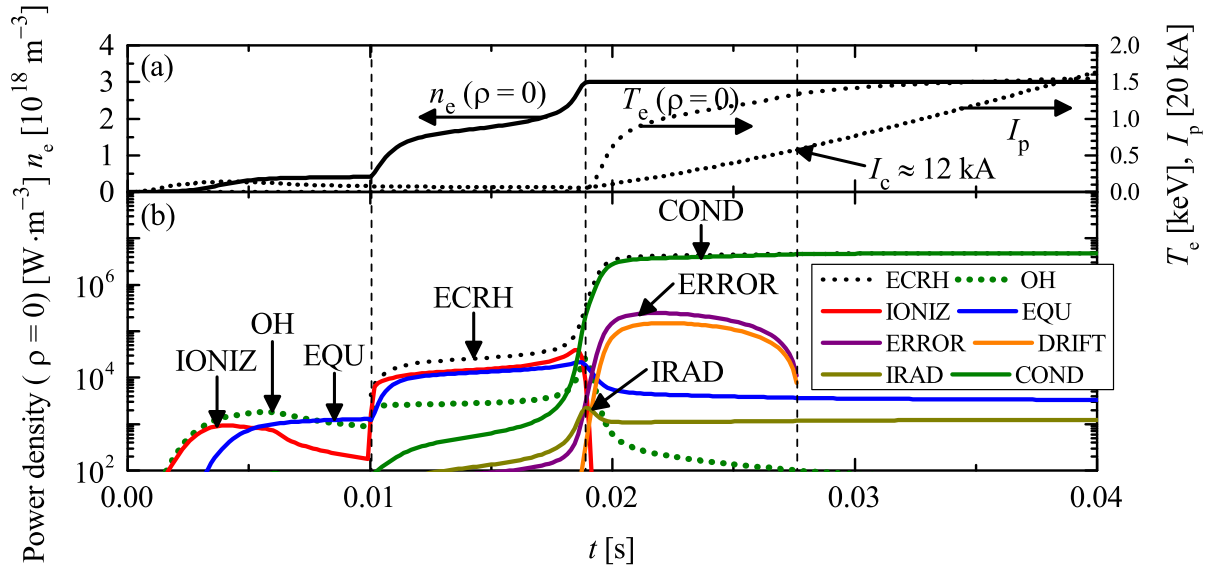


Figure 3.4: Time evolutions of (a) electron density, electron temperature at $\rho = 0$, and plasma current, and (b) power source and loss terms for electron energy density at $\rho = 0$ for a successful plasma start-up. The parameters are $P_{\text{ECRH}}^I = 1.05 \text{ MW}$, $n_H(t = 0) = 3.0 \times 10^{18} \text{ m}^{-3}$, and $B_{\text{err}} = 1.0 \text{ mT}$. IONIZ is ionization and radiation power loss through electron–hydrogen atom collision. IRAD is the interaction power loss between electrons and impurity ions. COND is the thermal conduction loss.

3.3.2 Parameter dependence on plasma start-up

Figure 3.5(a) shows the electron temperature at $\rho = 0.5$ and $t = 0.15$ s as a function of ECRH power for several initial hydrogen atom densities $n_H(t = 0) = 1.0, 2.0, 3.0, 4.0,$ and $5.0 \times 10^{18} \text{ m}^{-3}$. Figure 3.5(b) shows the threshold ECRH power as a function of initial hydrogen atom density $n_H(t = 0) = 1.0 - 10.0 \times 10^{18} \text{ m}^{-3}$. Upon increasing the ECRH power, the electron temperature rises drastically at a specific ECRH power, as can be observed in Fig. 3.5(a). This means that a threshold ECRH power exists for plasma start-up. As shown in Fig. 3.5(b), this threshold ECRH power increases sub-linearly with the initial hydrogen atom density: $P_{\text{ECRH}}^{\text{TH}} \sim 0.6\{n_H(t = 0) - n_H^{\text{TH}}\}^{0.8}$, where $n_H^{\text{TH}} \sim 1.05 \times 10^{18} \text{ m}^{-3}$ is the threshold density. This result is attributed to the power losses due to ionization and equilibration becoming dominant in the power balance; the power loss through these processes increases with the number of electrons and hydrogen atom ions. These results also suggest that about 1 MW of ECRH power is required for plasma start-up for $n_H(t = 0) = 3.0 \times 10^{18} \text{ m}^{-3}$, an error field of approximately 1 mT, and an EC beam radius of approximately 5 cm. As is apparent from Fig. 3.5(b), no ECRH power is required for plasma start-up when the initial hydrogen atom density is less than the threshold density. However, another physical process may be important for such a low initial hydrogen atom density. Note that below the initial hydrogen atom density of $1.7 \times 10^{18} \text{ m}^{-3}$, the applied electric field for plasma start-up exceeds the Dreicer electric field. Under these conditions, plasma start-up is restricted by the generation of runaway electrons that cause a direct power loss, thereby leading to high electron power loss.

Figure 3.6 shows the electron temperature at $\rho = 0.5$ and $t = 0.15$ s as a function of ECRH power for the error field B_{err} , of 1.0, 5.0, and 10.0 mT. ECRH power is required for plasma start-up even for no error field ($B_{\text{err}} = 0$ mT) because the IONIZ and EQU power loss processes are the dominant power loss processes during the initial plasma start-up phase. The threshold ECRH power increases with increasing error field because the error field power loss itself increases; hence, the plasma current takes longer to exceed the critical current. This is especially prominent in the case of low initial hydrogen atom density start-up because the ionization and equilibration power losses are relatively low.

Figure 3.7 shows the electron temperature at $\rho = 0.5$ and $t = 0.15$ s as a function of injected ECRH power for several carbon impurity concentrations. In Fig. 3.7, the decrease in the

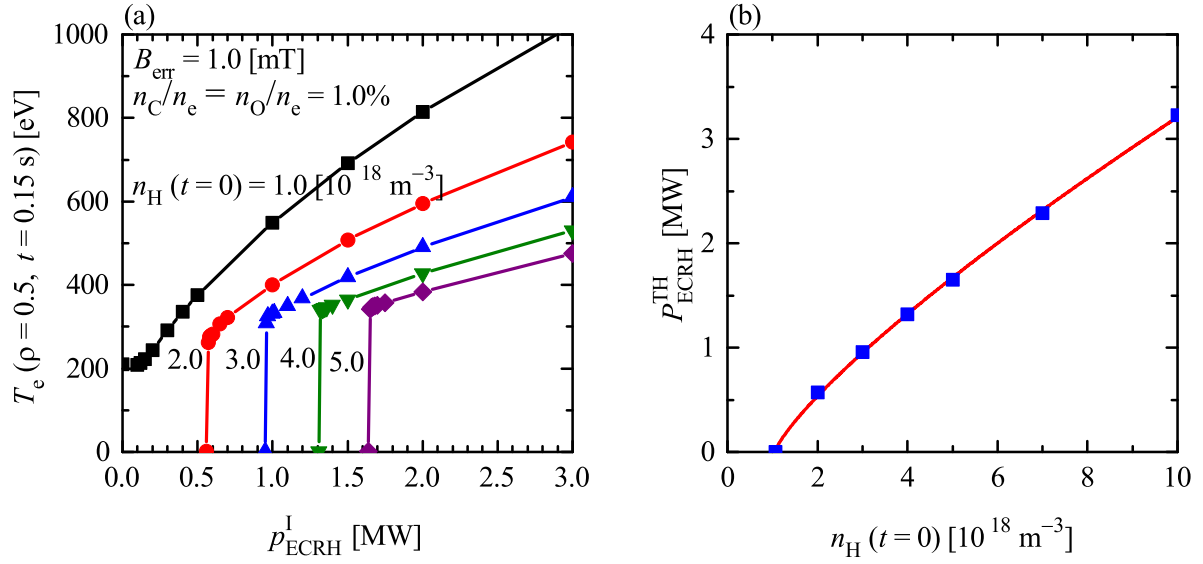


Figure 3.5: (a) Electron temperature at $\rho = 0.5$ and $t = 0.15$ s as a function of injected ECRH power and for several initial hydrogen atom densities of $n_H(t=0) = 1.0, 2.0, 3.0, 4.0$, and $5.0 \times 10^{18} \text{ m}^{-3}$. (b) Threshold ECRH power as a function of initial hydrogen atom density.

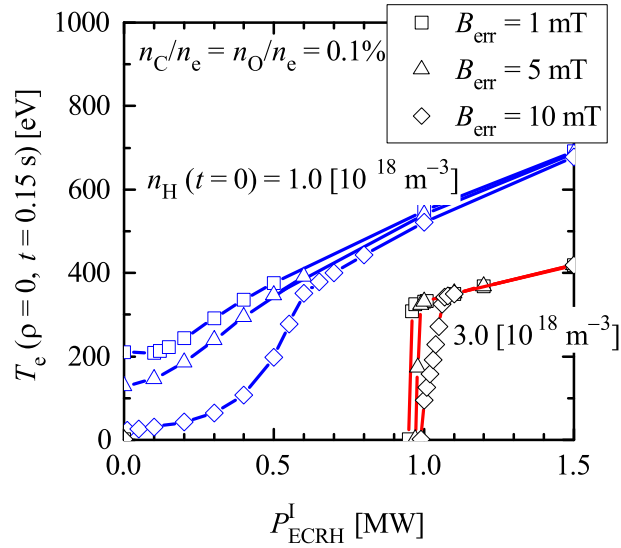


Figure 3.6: Electron temperature at $\rho = 0.5$ and $t = 0.15$ s as a function of injected ECRH power and for several error fields $B_{\text{err}} = 1.0, 5.0$, and 10.0 mT.

electron temperature at $\rho = 0.5$ is due to the increase in power loss by radiation from carbon impurities. In the case of the low initial hydrogen atom density $1.0 \times 10^{18} \text{ m}^{-3}$ and low carbon impurity concentration 0.1%, ECRH power is not required to start up the plasma; however, the greater carbon impurity concentration 5.0%, plasma start-up requires an ECRH power of approximately 100 kW. In the case of the initial hydrogen atom density of $3.0 \times 10^{18} \text{ m}^{-3}$, the threshold ECRH power increases with increasing the carbon impurity concentration. Suppressing the density of carbon impurities would be useful for successful start-ups and to reduce the required ECRH power.

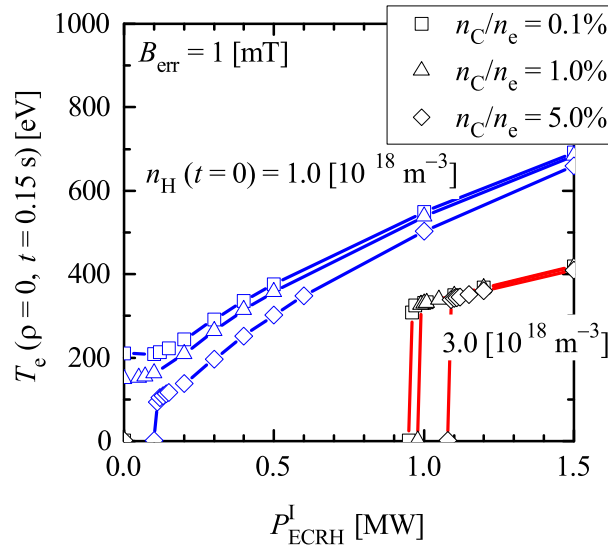


Figure 3.7: Electron temperature at $\rho = 0.5$ and $t = 0.15 \text{ s}$ as a function of injected ECRH power and for several carbon impurity ratios n_C/n_e .

3.3.3 Comparison with simulation and experimental data for JT-60U

To validate the 1-D modeling proposed in this paper, we compare the JT-60U experimental result with the simulation results of 1-D model. The parameters of this experiment are as follows: 110 GHz second-harmonic X-mode 800 kW, EC beam radius of 6.5 cm, error field of approximately 3 mT, and initial hydrogen atom density of approximately $3.0 \times 10^{18} \text{ m}^{-3}$. According to Kajiwara et al. [12], second-harmonic X-mode 800 kW ECRH assisted plasma start-up could

initiate the plasma, whereas a 400 kW one could not. Figure 3.8 shows the time evolution of second-harmonic X-mode 800 kW ECRH assisted plasma start-up shot (E038049) and the simulation results of 1-D model of initial hydrogen atom density $0.8 \times 10^{18} \text{ m}^{-3}$. Since the assumed density is lower than the experimental one, the treatment of hydrogen atom transport is the subject of further study. In this experiment, the measurements of electron temperature, electron density, and plasma current density profile were not performed. 800 kW ECRH was injected at $t = 230 \text{ ms}$ and an approximately 4 V of the applied loop voltage was switched on at $t = 250 \text{ ms}$. The simulated plasma current qualitatively reproduced the time evolution of the experimental result. However, the simulated plasma current differs in quantity from the experimental result. It may be due to the effects of the eddy current of vacuum vessel. Plasma breakdown occurs at the time of the onset of loop voltage ($t = 250 \text{ ms}$) judging from the H_α line emission. The time of increase in the simulated electron density agrees with this H_α line emission.

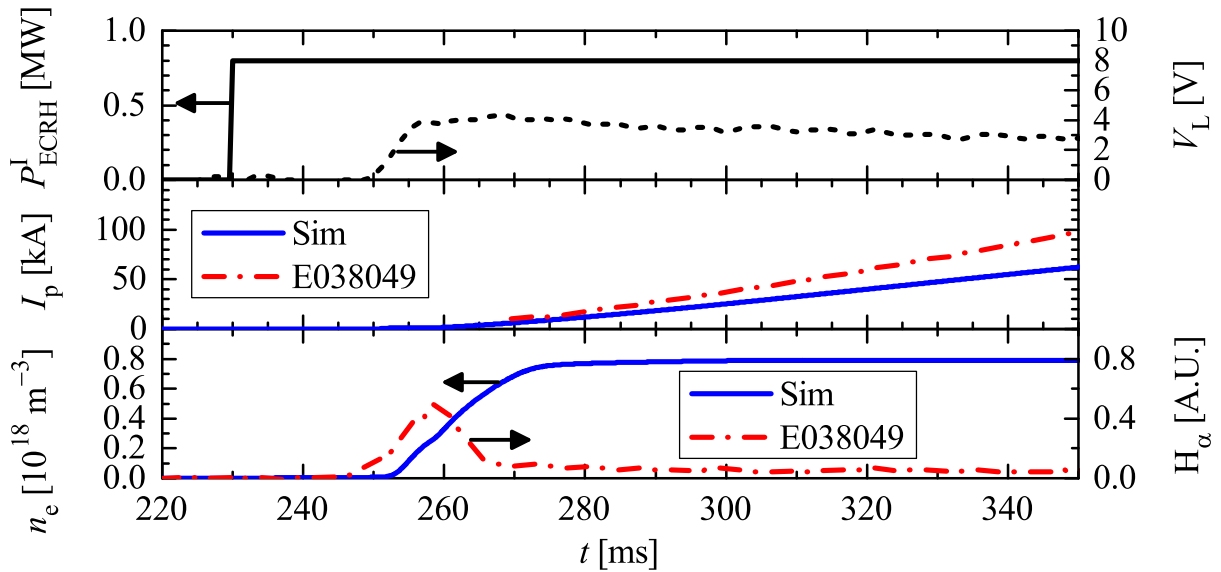


Figure 3.8: Time evolution of second-harmonic 800 kW ECRH assisted plasma start-up shot (E038049) and the simulation results of 1-D model.

3.4 Discussions

We have previously studied the plasma start-up in JT-60SA by the 0-D model [13] as shown Fig. 3.9. Herein, we assumed that the ECRH power was uniformly absorbed within the plasma, and the absorption efficiency was assumed to be 100%. The result showed that approximately 200 kW of ECRH power is required for plasma start-up for an initial hydrogen atom density $n_H(t = 0) = 3.0 \times 10^{18} \text{ m}^{-3}$ and that required ECRH power of the 0-D model is less than that of the 1-D model. This is because single-pass absorption rate is included in the 1-D model. The ECRH global absorption efficiency is quite low ($\sim 0.1\%$) in the initial plasma start-up phase, resulting that ECRH absorption power density is lower at the resonance position than that of 0-D model although ECRH power deposition profile is localized at this position.

In the 1-D model, the plasma is considered to occupy a cylinder just from the onset of the loop voltage. During the initial start-up phase, however, the magnetic field lines are actually open. During this phase, power loss along the magnetic field lines is considered to be the dominant form of power loss. Although it is natural to consider and include the formation of a plasma equilibrium, this question is not answered in this study because it makes the model excessively complicated. To compensate for this, we introduced into the 1-D model a direct loss term that is due to the error field. This power loss becomes negligibly small when the poloidal magnetic field generated by the plasma current exceeds the error field. A more quantitative estimate must include the plasma equilibrium.

In addition, the thermal and particle diffusivity during the initial plasma start-up are not investigated experimentally and theoretically; instead, we adopt a spatially uniform diffusivity. As shown in Fig. 3.10, we studied the effect of diffusivity on the threshold ECRH power by varying the ratios $\chi_e/\chi_{\text{Bohm}}$, $\chi_i/\chi_{\text{Bohm}}$, and D_e, D_H from 0.5 to 2, where χ_{Bohm} is the Bohm diffusivity. The results indicate that the threshold ECRH power is nearly independent of diffusivity. The insensitivity of particle diffusivity may be attributed to the fact that the effect of particle diffusion is weaker than that of particle source terms just after ECRH is switched on because in this phase the electron density has already reached around $2 \times 10^{18} \text{ m}^{-3}$ as shown in Fig. 3.2. The thermal diffusivity is also not dominant because in this phase the dominant processes of power loss are ionization and equilibration losses as shown in Fig. 3.4.

We now consider hydrogen atom transport. Generally, hydrogen atom diffusion is closely

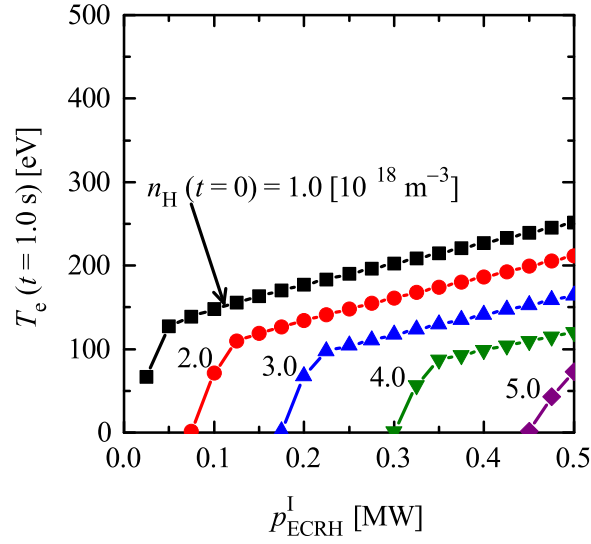


Figure 3.9: Electron temperature at $t = 1.0$ s as a function of injected ECRH power and for several initial hydrogen atom density $n_H(t = 0) = 1.0, 2.0, 3.0, 4.0,$ and $5.0 \times 10^{18} \text{ m}^{-3}$ by 0-D model.

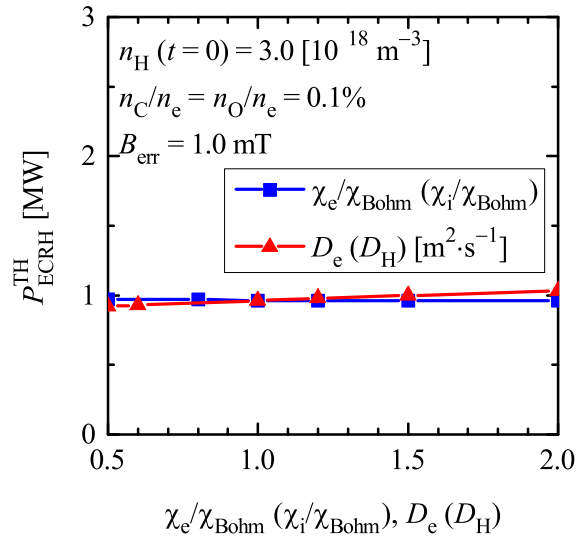


Figure 3.10: Thermal diffusivity and particle diffusivity vs. threshold ECRH power. The parameters are $n_H(t = 0) = 3.0 \times 10^{18} \text{ m}^{-3}$, $n_C/n_e = n_O/n_e = 0.1\%$, and $B_{\text{err}} = 1.0 \text{ mT}$.

related to collisions between electrons, hydrogen ions, and hydrogen atoms. During the initial plasma start-up phase, the hydrogen atom density profile is mainly determined by the ionization of hydrogen atoms rather than by diffusion. Furthermore, hydrogen atom motion is independent of magnetic field line. However, because simulations using Monte-Carlo methods (e.g., the AURORA code [14]) take too long to calculate the time-evolution and an estimate of the threshold ECRH power, this study is left for a future study.

3.5 Summary

At JT-60SA, we plan to apply a 110 GHz second-harmonic X-mode ECRH to assist plasma start-up because the applied toroidal electric field is limited to $0.5 \text{ V}\cdot\text{m}^{-1}$. 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. In addition, we used the 1-D model to investigate the effects of second-harmonic X-mode ECRH assisted plasma start-up.

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 ECRH absorption efficiency and electron temperature. Subsequently, power loss due to the thermal conduction loss becomes dominant. Power losses due to error and drift depends weakly on the plasma start-up because 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 $n_H(t = 0) = 3.0 \times 10^{18} \text{ m}^{-3}$ 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.

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Chapter 4

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

4.1 Introduction

In a number of stellarator/heliotron devices, plasmas are initiated by the ECRH, which limits the operating magnetic field strength. As introduced in Chap. 1, proposed and demonstrated to mitigate this limitation of the field strength was plasma start-up using NBI, which is useful for beta scaling and high beta experiments. In LHD, the plasma start-up by only NBI was demonstrated [1]. This plasma start-up was analyzed by the 0-D model, which is composed of the time dependent particle density equations for fast hydrogen ions and bulk hydrogen ions, and energy density equations for electrons and bulk ions [2]. In W7-X, the plasma start-up by NBI was investigated particularly during the breakdown phase using the 0-D model, where hydrogen molecule and helium atom are included [3]. In Heliotron J device, the NBI plasma start-up was demonstrated with the assistance of the seed plasma generated by 2.45 GHz microwaves [4]. Because the seed plasma is considered to be initially existed from the calculation start time, the 0-D model for the breakdown phase in W7-X must be improved to deal with the burn-through phase. In this chapter, for this purpose, some improvements of the 0-D model are introduced.

4.2 Heliotron J device

Heliotron J device is one of the stellarator/heliotron devices, which consists of $L = 1/M = 4$ helical coils, two types of toroidal coils, and three types of vertical coils [5, 6]. The plasma has a major radius $R = 1.2$ m and a averaged minor radius $\langle a \rangle = 0.1 - 0.2$ m, where the operating magnetic field is $B < 1.5$ T, the rotational transform is $\iota(0)/2\pi = 0.53$ (standard configuration). These are shown in Table 4.1. Shown in Fig. 4.1 is the Heliotron J device from the top view including heating, gas puff, and diagnostics systems for the NBI plasma start-up and the basic parameters. In this experiment, two types of heating systems are used, one is 2.45 GHz magnetron for the generation of a seed plasma and the other is the neutral beam injection (P-NBI: BL1 for counter-tangential hydrogen beams, BL2 for co-tangential hydrogen beams) system for the plasma heating. The interaction length of the neutral beams with the plasma, L , is approximately 1.6 m. There are three types of fueling gas species: hydrogen, deuterium, and helium. Deuterium is used for the prefill and main gas puff.

Table 4.1: Basic parameters of Heliotron J device.

Plasma major radius, R	1.2 m
Plasma minor radius, a	0.1 – 0.2 m
Vacuum chamber volume, V_v	2 m ³
Magnetic field, B	< 1.5 T
Rotational transform, $\iota(0)/2\pi$	0.53
ECH 70 GHz	< 0.4 MW
NBI < 30 kV	< 800 kW $\times$ 2
Interaction length, L	1.6 m
Beam species P_j	0.6 : 0.3 : 0.1
ICRF 19 – 23 MHz	0.4 MW $\times$ 2
Fueling gas	H ₂ , D ₂ , and He

4.3 Typical wave form of the NBI plasma start-up

Typical wave form of NBI plasma start-up in Heliotron J is shown in Fig. 4.2. In order to produce a seed plasma, the 2.45 GHz microwaves with the power of 12 kW is applied on at $t = -200$ ms before the NBI, the duration of which are a few hundred milliseconds. The line averaged density of the seed plasma is measured around $6 \times 10^{17} \text{ m}^{-3}$ by means of the

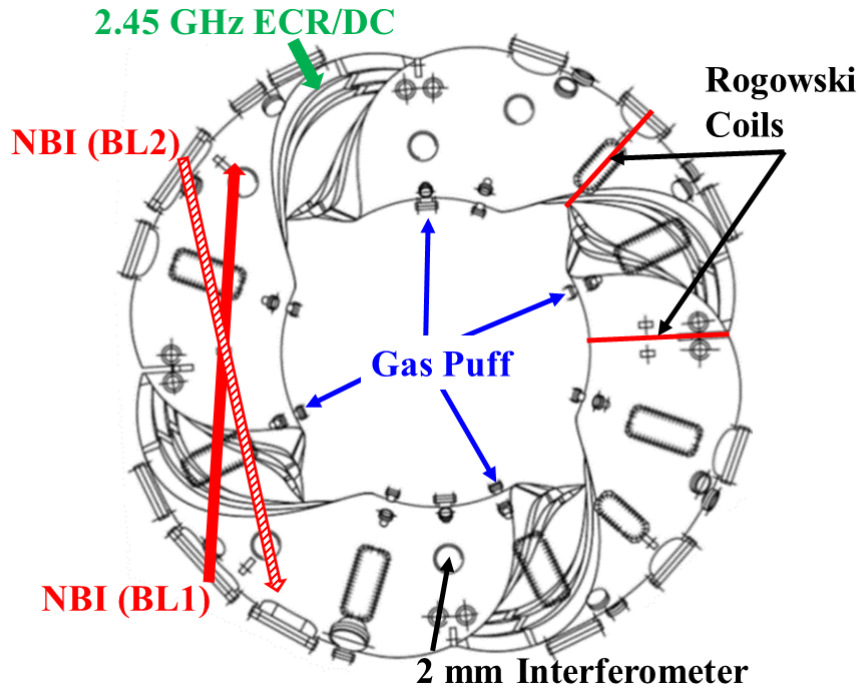


Figure 4.1: A schematic view of the Heliotron J from the top.

interferometer. Then, the NBI with the power of 350 kW is switched on at $t = 195$ ms, where the fast hydrogen beams are ionized via collision and charge exchange process with the target plasma resulting in fast hydrogen ions. The fast hydrogen ions are confined in the magnetic field and heat the electrons/ions through the Coulomb collisions. The main gases are puffed at $t = 210$ ms after the NBI for the density build-up. The prompt increase in the electron density is observed. After an approximately 10 ms from the increase in the electron density, the stored energy measured by the Rogowski coils increases.

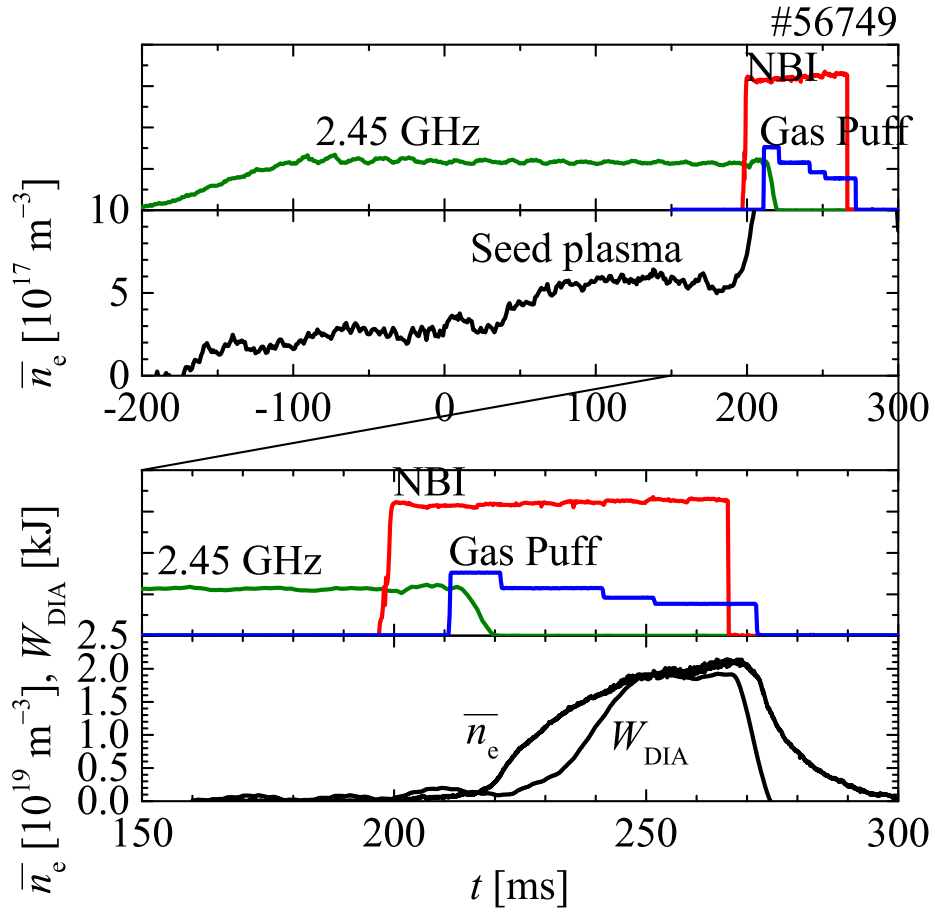


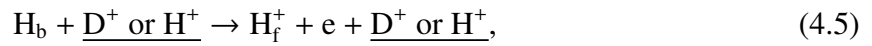
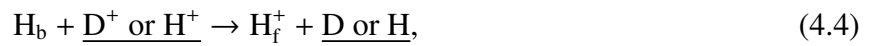
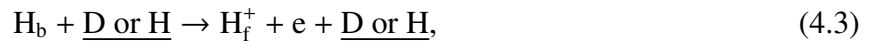
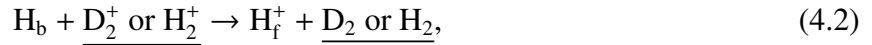
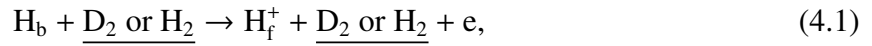
Figure 4.2: Typical wave form of NBI plasma start-up in Heliotron J.

4.4 0-D model equations

The 0-D model for NBI start-up is comprised of the time dependent particle and energy density equations: density equations for fast hydrogen ions from the NBI, density equations for deuterium and hydrogen molecules, deuterium and hydrogen molecular ions, deuterium and hydrogen atoms, and bulk deuterium and hydrogen ions, and energy density equations for bulk electrons and ions. These equations are solved by the fourth-order Runge-Kutta method so as to suppress the calculation error within 1%.

4.4.1 Particle density equations for fast hydrogen ions from NBI

In Heliotron J, due to the use of the positive ion sources of NBI, the neutral beams comprise of not only full energy component, $E_{b1} = 25$ keV, but also half, $E_{b2} = 12.5$ keV, and third energy component, $E_{b3} = 8.3$ keV. When high-energy neutral beams are entering into the plasmas, the neutral beams are ionized through charge exchanges of neutral beams with ions and background neutrals and ionizations of neutral beams by ions and electrons as follows:



Therefore, the neutral beam decay length, λ_{bj} is given as

$$\begin{aligned} \frac{1}{\lambda_{bj}} = & [D_2] \sigma_{bj, D_2}^{\text{ion}} + [D_2^+] \sigma_{bj, D_2^+}^{\text{cx}} + [D] \sigma_{bj, D}^{\text{ion}} + [D^+] \left(\sigma_{bj, D^+}^{\text{cx}} + \sigma_{bj, D^+}^{\text{ion}} \right) + n_e \frac{\langle \sigma_{bj, e}^{\text{ion}} | v_{bj} - v_e | \rangle}{v_{bj}} \\ & + [H_2] \sigma_{bj, H_2}^{\text{ion}} + [H_2^+] \sigma_{bj, H_2^+}^{\text{cx}} + [H] \sigma_{bj, H}^{\text{ion}} + [H^+] \left(\sigma_{bj, H^+}^{\text{cx}} + \sigma_{bj, H^+}^{\text{ion}} \right) \end{aligned} \quad (4.7)$$

where j denotes the beam energy species, a squared bracket, $[x]$, means the density of x , v_{bj} is the beam velocity, and v_e is the electron thermal velocity. $\sigma_{bj,a}^{\text{ion}}$ and $\sigma_{bj,a}^{\text{cx}}$ are the cross sections of ionization and charge exchange of neutral beams by species a , respectively, which are shown in Fig. 4.3. The beam cross section for deuterium species is assumed to be same as that for hydrogen species. The dominant beam ionization is the charge exchange by deuterium or hydrogen ion because the beam energy range is around 10 – 30 keV.

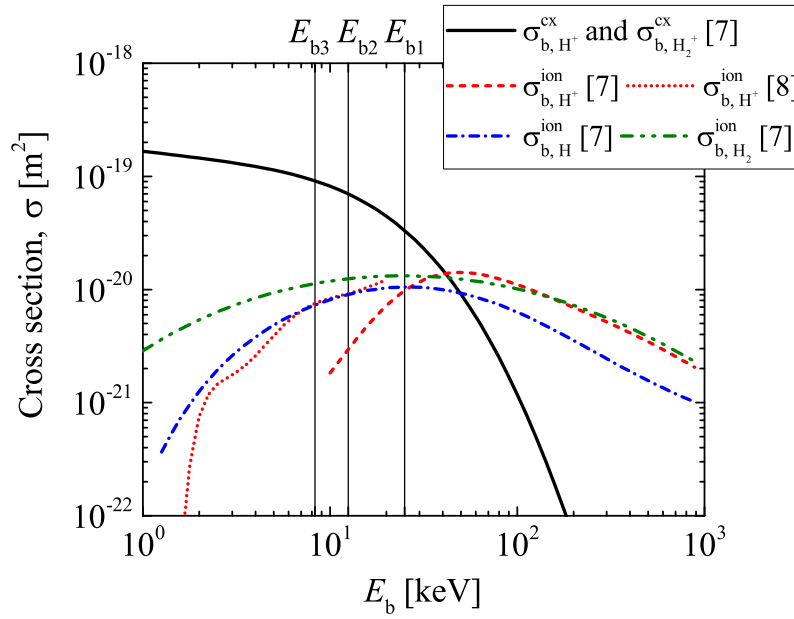
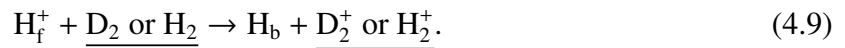
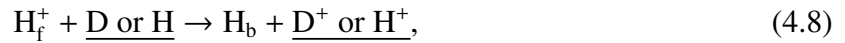


Figure 4.3: Beam cross sections for various charge exchange and ionization processes as a function of beam energy [7, 8].

Fast hydrogen ions are produced by the ionization of hydrogen beams as mentioned above, and lost by the charge exchange between neutral beams and background neutrals:



The time for charge exchange of fast hydrogen ions with deuterium molecules in the initial

start-up phase is

$$\tau_{\text{CX}} = \frac{1.0 \times 10^3}{[\text{D}_2]\sigma_{\text{f, D}_2}^{\text{cx}} v_{\text{f}}} [\text{ms}] \quad (4.10)$$

$$\approx 0.1 - 1 [\text{ms}], \quad (4.11)$$

where the deuterium molecule density is of the order of $10^{16} - 10^{17} \text{ m}^{-3}$, the cross section for charge exchange between fast hydrogen ion and deuterium molecule is approximately $5 \times 10^{-20} \text{ m}^2$, and the velocity of fast hydrogen ion is approximately $2.2 \times 10^6 \text{ m} \cdot \text{s}^{-1}$. The slowing-down of the fast ions is neglected because the slowing-down time, τ_{se} , is much larger than the time for charge exchange (See Appendix D). According to the calculation using the zero-dimensional Fokker-Planck equation, the loss time including the charge exchange loss and the direct loss of fast hydrogen ion is estimated to be $\tau_{\text{loss}} = 6.1 \text{ ms}$ in standard magnetic configuration [9]. The direct loss time of fast hydrogen ion is the same order of the loss time. In this simulation, the direct loss can be neglected. The density equations for fast hydrogen ions are

$$\begin{aligned} V_{\text{p}} \frac{d[\text{H}_{\text{fj}}^+]}{dt} = & \frac{P_{\text{bj}}}{eE_{\text{bj}}} \left\{ 1 - \exp\left(-\frac{L}{\lambda_{\text{bj}}}\right) \right\} - V_{\text{D}}^{\text{i}}[\text{H}_{\text{fj}}^+][\text{D}]\sigma_{\text{fj, D}}^{\text{cx}} v_{\text{fj}} - V_{\text{H}}^{\text{i}}[\text{H}_{\text{fj}}^+][\text{H}]\sigma_{\text{fj, H}}^{\text{cx}} v_{\text{fj}} \\ & - V_{\text{D}_2}^{\text{i}}[\text{H}_{\text{fj}}^+][\text{D}_2]\sigma_{\text{fj, D}_2}^{\text{cx}} v_{\text{fj}} - V_{\text{H}_2}^{\text{i}}[\text{H}_{\text{fj}}^+][\text{H}_2]\sigma_{\text{fj, H}_2}^{\text{cx}} v_{\text{fj}}, \end{aligned} \quad (4.12)$$

where V_{p} is the plasma volume, P_{bj} is the beam power, E_{bj} is the beam energy, e is the elementary charge, L is the interaction length of neutral beams with the plasma, V_a^{i} are the volumes occupied by species a inside the plasma, and $\sigma_{\text{fj, } a}^{\text{cx}}$ is the cross sections of charge exchange of fast hydrogen ions with species a , which is shown in Fig. 4.4. The first term on the right hand side represents an ionization of neutral beams, and the other terms a charge exchange loss of fast hydrogen ions. The initial conditions for fast hydrogen ion densities are

$$[\text{H}_{\text{fj}}^+]_{t=t_0} = 0, \quad (4.13)$$

where t_0 is the calculation start time.

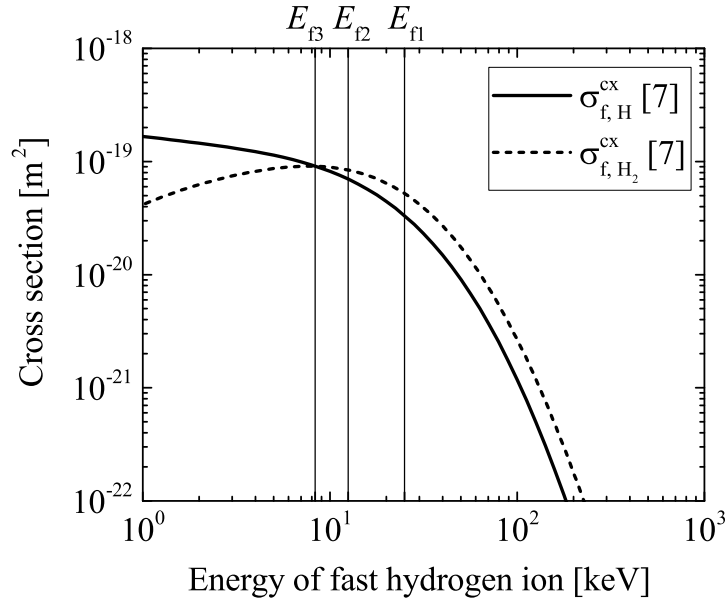


Figure 4.4: Cross sections for charge exchange between fast hydrogen ion and hydrogen atom and molecule as a function of energy of fast hydrogen ion [7].

4.4.2 Particle density equation for deuterium molecules

In Heliotron J, the vacuum vessel is filled by deuterium molecules due to the prefill gas. These deuterium molecules entering the plasma are ionized or dissociated by electrons or fast hydrogen ions, and then the deuterium molecular ions or deuterium atoms are produced as follows:



Estimated, by the following manner, is the neutral screening effect, which is shown in Fig. 4.5. The penetration length of deuterium molecules into the plasma, l_{D_2} , is estimated with a density decay equation, in which the profiles of the electron density and temperature are taken into account (See Appendix C). The volume occupied by deuterium molecules inside the plasma is

calculated as

$$V_{D_2}^i = 2\pi R \left\{ \pi a^2 - \pi (a - l_{D_2}) \right\}, \quad (4.18)$$

and the total volume occupied by deuterium molecules inside the vacuum vessel is

$$V_{D_2}^t = V_{D_2}^i + V_o. \quad (4.19)$$

The density equation for deuterium molecules is given as

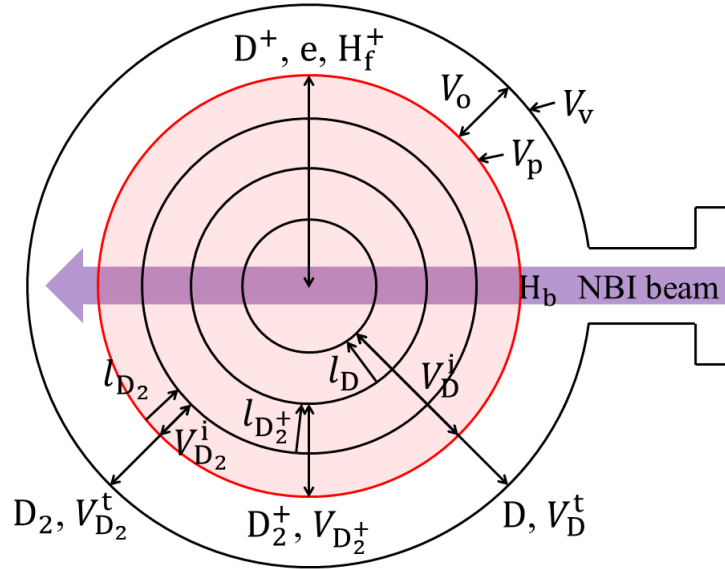


Figure 4.5: A schematic diagram of NBI plasma simulation model.

$$\begin{aligned} \frac{dV_{D_2}^t[D_2]}{dt} = & Q_{GP} + \alpha_{\text{plasma}} \left(\frac{V_{D_2}^t[D_2^+]}{\tau_p} + \frac{1}{2} \frac{V_D^t}{\tau_D} + \frac{1}{2} \frac{V_p[D^+]}{\tau_p} \right) \\ & - V_{D_2}^i n_e[D_2] \left(\langle \sigma_{e, D_2}^{\text{diss}} v_e \rangle + \langle \sigma_{e, D_2}^{\text{ion}} v_e \rangle \right) \\ & - V_{D_2}^i [H_{fj}^+][D_2] \left(\sigma_{fj, D_2}^{\text{cx}} + \sigma_{fj, D_2}^{\text{ion}} \right) v_{fj} \end{aligned} \quad (4.20)$$

where Q_{GP} is the influx of a gas puff, α_{plasma} is the recycling rate, τ_p is the particle confinement time, and τ_D is the residence time of deuterium atoms. The first term on the right hand side represents the main gas puff, the second the generation of deuterium molecules from deuterium

molecular ions, deuterium atoms, and deuterium ions, the third the dissociation and ionization of the deuterium molecules by electrons, and the last the charge exchange and ionization of deuterium molecules by fast hydrogen ions. The initial condition for deuterium molecule density, $[D_2]_{t=t_0}$, is of the order of 10^{15} m^{-3} from the experimental data.

4.4.3 Particle density equation for deuterium molecular ions

The deuterium molecular ions are produced in the deuterium molecules region as follows:



and then they enter into the plasma with decaying due to the processes as follows:



The mean free path of deuterium molecular ions is

$$\lambda_{D_2^+} = \frac{\nu_{D_2^+}}{n_e \left(\langle \sigma_{e, D_2^+}^{\text{dis}} \nu_e \rangle + \langle \sigma_{e, D_2^+}^{\text{dis, rec}} \nu_e \rangle \right)}, \quad (4.26)$$

and the penetration length of deuterium molecular ions into the plasma, $l_{D_2^+}$, is

$$l_{D_2^+} = \begin{cases} a - l_{D_2} & \text{for } l_{D_2} + \lambda_{D_2^+} > a, \\ \lambda_{D_2^+} & \text{for } l_{D_2} + \lambda_{D_2^+} \leq a. \end{cases} \quad (4.27)$$

The volume occupied by deuterium molecular ions is given as

$$V_{D_2^+} = 2\pi R \left[\pi a^2 - \pi \left\{ a - (l_{D_2} + l_{D_2^+}) \right\}^2 \right]. \quad (4.28)$$

The density equation of deuterium molecular ions is

$$\begin{aligned} \frac{dV_{D_2^+}[D_2^+]}{dt} = & V_{D_2}^i n_e [D_2] \langle \sigma_{e, D_2}^{\text{ion}} v_e \rangle + V_{D_2}^i [H_{fj}^+] [D_2] \left(\sigma_{fj, D_2}^{\text{cx}} + \sigma_{fj, D_2}^{\text{ion}} \right) v_{fj} \\ & - V_{D_2^+} n_e [D_2^+] \left(\langle \sigma_{e, D_2^+}^{\text{dis}} v_e \rangle + \langle \sigma_{e, D_2^+}^{\text{dis, rec}} v_e \rangle \right) - \frac{V_{D_2^+}[D_2^+]}{\tau_p}, \end{aligned} \quad (4.29)$$

where the first term on the right hand side represents an ionization of deuterium molecules by electrons, the second a charge exchange and an ionization of deuterium molecules by fast hydrogen ions, the third a dissociation and a dissociative recombination of deuterium molecular ions by electrons, and the last a confinement particle loss. The initial condition for deuterium molecular ion density is given by

$$[D_2^+]_{t=t_0} = \frac{\langle \sigma_{e, D_2}^{\text{ion}} v_e \rangle}{\langle \sigma_{e, D_2^+}^{\text{dis}} v_e \rangle + \langle \sigma_{e, D_2^+}^{\text{dis, rec}} v_e \rangle} [D_2]_{t=t_0} \quad (4.30)$$

by assuming that the density equation for deuterium molecular ions is in a steady-state condition at the calculation start time, and shown in Fig. 4.6.

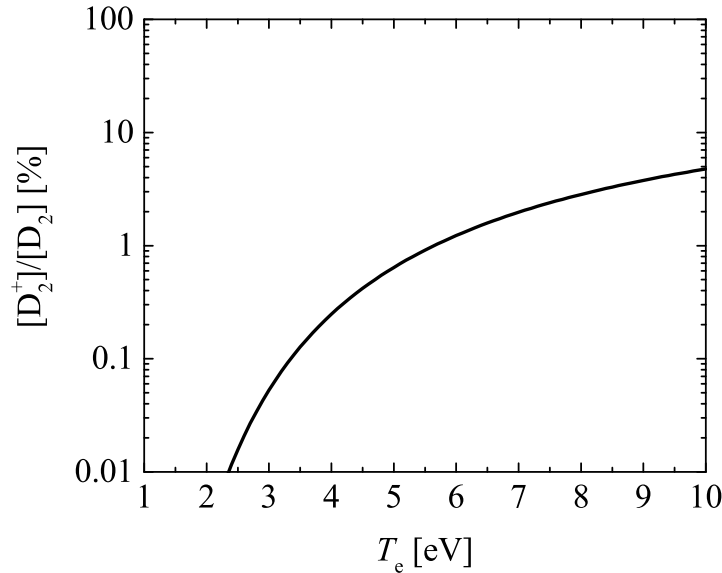


Figure 4.6: Fraction of deuterium molecular ion density to deuterium molecule density as a function of electron temperature.

4.4.4 Particle density equation for deuterium atoms

Deuterium atoms are produced in deuterium molecules and deuterium molecular ions regions:



and lost by



The mean free path of deuterium atoms is also given by

$$\lambda_D = \frac{v_D}{n_e \langle \sigma_{e, D}^{\text{ion}} \rangle + [H_{fj}^+] (\sigma_{fj, D}^{\text{cx}} + \sigma_{fj, D}^{\text{ion}}) v_{fj}} \quad (4.37)$$

and the penetration length of deuterium atoms into the plasma, l_D , is

$$l_D = \begin{cases} a - (l_{D_2} + l_{D_2^+}) & \text{for } l_{D_2} + l_{D_2^+} + \lambda_D > a, \\ \lambda_D & \text{for } l_{D_2} + l_{D_2^+} + \lambda_D \leq a. \end{cases} \quad (4.38)$$

The volume occupied by deuterium atoms inside the plasma is

$$V_D^i = 2\pi R \left[\pi a^2 - \pi \left\{ a - (l_{D_2} + l_{D_2^+} + l_D) \right\} \right] \quad (4.39)$$

and the total volume of deuterium atoms is

$$V_D^t = V_D^i + V_o. \quad (4.40)$$

The density equation for deuterium atoms is given by

$$\begin{aligned} \frac{dV_D^t[D]}{dt} = & V_{D_2}^i n_e [D_2] 2 \langle \sigma_{e, D_2}^{\text{dis}} v_e \rangle + V_{D_2^+} n_e [D_2^+] \left(\langle \sigma_{e, D_2^+}^{\text{dis}} v_e \rangle + 2 \langle \sigma_{e, D_2^+}^{\text{dis, rec}} v_e \rangle \right) \\ & - V_D^i n_e [D] \langle \sigma_{e, D}^{\text{ion}} v_{\text{ion}} v_e \rangle - V_D^i [H_{fj}^+] [D] \left(\sigma_{fj, D}^{\text{ex}} + \sigma_{fj, D}^{\text{ion}} \right) v_{fj} - \frac{V_D^t[D]}{\tau_D}, \end{aligned} \quad (4.41)$$

where the first term on the right hand side represents the dissociation of deuterium molecules by electrons, the second the dissociation and dissociative recombination of deuterium molecules by electrons, the third the ionization of deuterium atoms by electrons, the fourth the charge exchange and ionization of deuterium atoms by fast hydrogen ions, and the last the particle loss due to the residence time. Assuming a steady-state condition as well as the deuterium molecular ion, the initial condition for deuterium atom density is given as

$$[D]_{t=t_0} = \frac{\langle \sigma_{e, D}^{\text{ion}} v_e \rangle}{\langle \sigma_{e, D}^{\text{ion}} v_e \rangle + \frac{V_v}{V_p} \frac{1}{n_{e,t=t_0} \tau_D}} \left(\frac{2 \langle \sigma_{e, D_2}^{\text{dis}} v_e \rangle}{\langle \sigma_{e, D}^{\text{ion}} v_e \rangle} + \frac{[D_2^+]_{t=t_0} \langle \sigma_{e, D_2^+}^{\text{dis}} v_e \rangle + 2 \langle \sigma_{e, D_2^+}^{\text{dis, rec}} v_e \rangle}{[D_2]_{t=t_0} \langle \sigma_{e, D}^{\text{ion}} v_e \rangle} \right) [D_2]_{t=t_0}, \quad (4.42)$$

where the seed electron density is set as an initial condition for the electron density, $n_{e,t=t_0}$, and the degree of dissociation of deuterium molecules, $[D]/([D] + 2[D_2])$, is shown in Fig. 4.7.

4.4.5 Particle density equation for bulk deuterium ions

The deuterium ions are produced by the dissociative ionization of deuterium molecules by electrons, by the dissociation of deuterium molecular ions by electrons, by the ionization of deuterium atoms by electrons, by the charge exchange between fast hydrogen ions and deuterium atoms, and by the ionization of deuterium atoms by fast hydrogen ions as follows:



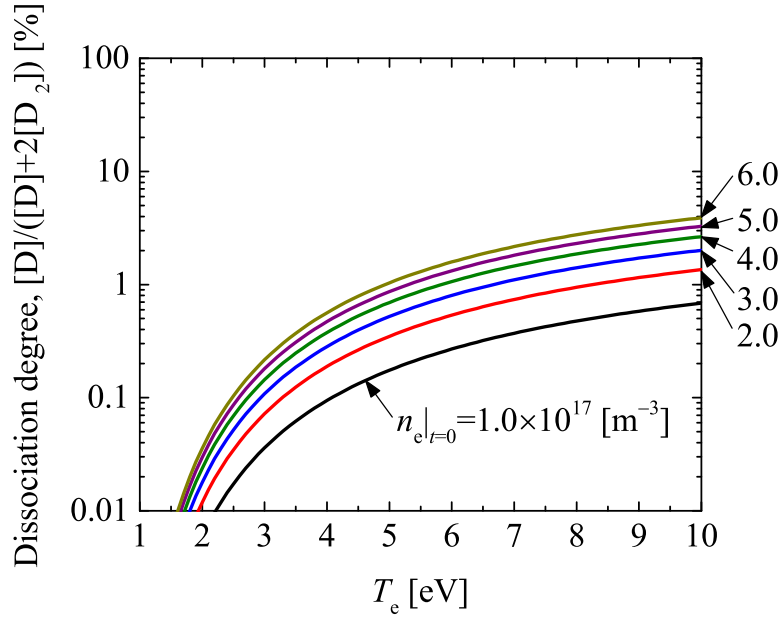


Figure 4.7: Degree of dissociation of deuterium molecules as a function of electron temperature for several seed electron densities of $n_{e|t=0} = 1.0, 2.0, 3.0, 4.0, 5.0, \text{ and } 6.0 \times 10^{17} \text{ m}^{-3}$.



They are lost by the recombination of deuterium ions with electrons, by the charge exchange of deuterium ions with deuterium molecules, and by the particle confinement loss as follows:



Thus, the density equation for bulk deuterium ions is given as

$$\begin{aligned} V_p \frac{d[\text{D}^+]}{dt} = & V_{\text{D}_2}^i n_e [\text{D}_2] \langle \sigma_{\text{e}, \text{D}_2}^{\text{dis, ion}} v_e \rangle + V_{\text{D}_2^+} n_e [\text{D}_2^+] \langle \sigma_{\text{e}, \text{D}_2^+}^{\text{dis}} v_e \rangle \\ & + V_{\text{D}}^i n_e [\text{D}] \langle \sigma_{\text{e}, \text{D}}^{\text{ion}} v_e \rangle + V_{\text{D}}^i [\text{H}_{fj}^+] [\text{D}] \left(\sigma_{fj, \text{D}}^{\text{cx}} + \sigma_{fj, \text{D}}^{\text{ion}} \right) v_{fj} \\ & - V_p n_e [\text{D}^+] \langle \sigma_{\text{e}, \text{D}^+}^{\text{rec}} v_e \rangle - V_{\text{D}_2^+}^i [\text{D}^+] [\text{D}_2] \langle \sigma_{\text{D}^+, \text{D}_2}^{\text{cx}} v_{\text{D}^+} \rangle - \frac{V_p [\text{D}^+]}{\tau_p}. \end{aligned} \quad (4.50)$$

According to the quasi-neutrality condition, the initial condition for deuterium ion density is

$$[D^+]_{t=t_0} = n_{e,t=t_0} - [D_2^+]_{t=t_0}. \quad (4.51)$$

4.4.6 Particle density equations for hydrogen molecules, hydrogen molecular ions, hydrogen atoms, and bulk hydrogen ions

Hydrogen molecules are entering through the NBI line and by NBI, which does not interact with the plasma particles. Therefore, the density equation for hydrogen molecules is given as

$$\begin{aligned} \frac{dV_{H_2}^t[H_2]}{dt} = & C_d (n_{BL} - [H_2]) + \alpha_{beam} \frac{P_{bj}}{2eE_{bj}} \exp\left(-\frac{L}{\lambda_{bj}}\right) \\ & + \alpha_{plasma} \left(\frac{V_{H_2}^+[H_2^+]}{\tau_p} + \frac{1}{2} \frac{V_H^t}{\tau_H} + \frac{1}{2} \frac{V_p[H^+]}{\tau_p} \right) \\ & - V_{H_2}^i n_e [H_2] \left(\langle \sigma_{e, H_2}^{diss} v_e \rangle + \langle \sigma_{e, H_2}^{ion} v_e \rangle \right) \\ & - V_{H_2}^i [H_{fj}^+] [H_2] \left(\sigma_{fj, H_2}^{ex} + \sigma_{fj, H_2}^{ion} \right) v_{fj} \end{aligned} \quad (4.52)$$

where C_d is the conductance coefficient between the vacuum vessel and the neutral beam (NB) line, n_{BL} is the density in the NB line, and α_{beam} is the recycling rate of the NBs.

The density equations for hydrogen molecular ions, hydrogen atoms and bulk hydrogen ions are almost the same as those of deuterium.

4.4.7 Energy density equations for bulk electrons and ions

The energy density equation for bulk electrons is

$$V_p \frac{dU_e}{dt} = P_{fj \rightarrow e} - P_{ion, dis} - P_{equ} - P_{conf}^e, \quad (4.53)$$

where $U_e = 3n_e T_e / 2$ is the energy density of electrons. Electrons are heated only by fast hydrogen ions through Coulomb collisions ($P_{fj \rightarrow e}$). The heating power of electrons by fast

hydrogen ions is

$$P_{fj \rightarrow e} = \frac{V_p e^3 \ln \Lambda}{4\pi \epsilon_0^2} \frac{n_e [H_{fj}^+]}{m_e v_{fj}} F\left(\frac{v_{fj}}{v_e}, \frac{m_e}{m_{fj}}\right), \quad (4.54)$$

where

$$F(x, \beta) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-\xi^2) d\xi - \frac{2x}{\sqrt{\pi}} (1 + \beta) \exp(-x^2). \quad (4.55)$$

Here $\ln \Lambda$ is the Coulomb logarithm, ϵ_0 is the permittivity of free space, m_e is the mass of electrons, and m_{fj} is the mass of fast hydrogen ions.

Electrons lose energy via ionization and dissociation processes of molecules, molecular ions, and atoms for deuterium and hydrogen ($P_{\text{ion, dis}}$).

$$\begin{aligned} P_{\text{ion, dis}} = & V_{D_2}^i n_e [D_2] L_{D_2} + V_{D_2^+}^i n_e [D_2^+] L_{D_2^+} + V_D^i n_e [D] L_D \\ & + V_{H_2}^i n_e [H_2] L_{H_2} + V_{H_2^+}^i n_e [H_2^+] L_{H_2^+} + V_H^i n_e [H] L_H, \end{aligned} \quad (4.56)$$

where L is the electron cooling rate as shown in Fig. 4.8. Here, the electron cooling rates for hydrogen and deuterium species are assumed to be same. Electrons lose energy due to the Coulomb collisions with bulk ions, i.e. the equilibration process. The equilibration energy transferred from electrons to bulk ions (P_{equ}) is

$$P_{\text{equ}} = V_p 7.75 \times 10^{-34} (T_e - T_i) \frac{n_e \ln \Lambda}{T_e^{3/2}} \left(\frac{[D^+]}{A_{D^+}} + \frac{[H^+]}{A_{H^+}} \right) \quad (4.57)$$

where T_i is the ion temperature, and A_{D^+} and A_{H^+} is the mass number of deuterium and hydrogen ion, respectively.

The electron confinement power loss (P_{conf}^e) is

$$P_{\text{conf}}^e = \frac{V_p U_e}{\tau_e}, \quad (4.58)$$

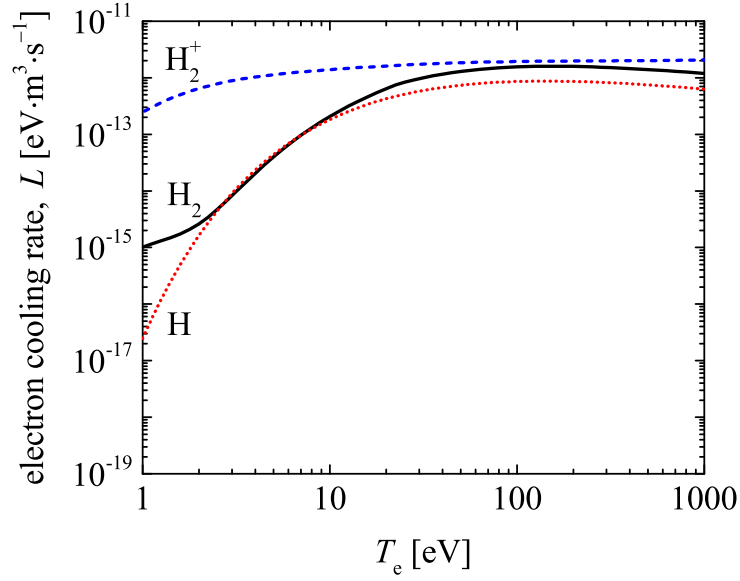


Figure 4.8: Electron cooling rate of hydrogen molecules, hydrogen molecular ions, and hydrogen atoms.

where the electron confinement time, τ_e , is assumed to be equal to the particle confinement time, τ_p , in this model.

The energy density for bulk deuterium and hydrogen ions is

$$V_p \frac{dU_i}{dt} = P_{fj \rightarrow i} + P_{\text{equ}} - P_{\text{cx}} - P_{\text{conf}}^i, \quad (4.59)$$

where $U_i = 3n_i T_i / 2$ is the energy density of bulk ions which include the deuterium and hydrogen ions, that is, $n_i = [D^+] + [H^+]$.

Bulk ions are heated by fast hydrogen ions through the Coulomb collisions ($P_{fj \rightarrow i}$). The heating power of bulk ions by fast hydrogen ions is

$$P_{fj \rightarrow i} = \frac{V_p e^3 \ln \Lambda}{4\pi \epsilon_0^2} \left(\frac{[D^+]}{m_{D^+}} + \frac{[H^+]}{m_{H^+}} \right) \frac{[H_{fj}^+]}{v_{fj}}, \quad (4.60)$$

where m_{D^+} and m_{H^+} are the mass of deuterium and hydrogen ion, respectively.

Bulk ions are also heated by electrons through the equilibration process (P_{equ}).

Bulk ion energy is lost by charge exchanges between bulk ions and deuterium and hydrogen atoms (P_{cx}).

$$\begin{aligned}
 P_{cx} = & V_D^i \frac{3}{2} [D^+][D] (T_i - T_D) \langle \sigma_{D^+, D}^{cx} \nu_{D^+} \rangle \\
 & + V_H^i \frac{3}{2} [D^+][H] (T_i - T_H) \langle \sigma_{D^+, H}^{cx} \nu_{D^+} \rangle \\
 & + V_D^i \frac{3}{2} [H^+][D] (T_i - T_D) \langle \sigma_{H^+, D}^{cx} \nu_{H^+} \rangle \\
 & + V_H^i \frac{3}{2} [H^+][H] (T_i - T_H) \langle \sigma_{H^+, H}^{cx} \nu_{H^+} \rangle,
 \end{aligned} \tag{4.61}$$

where T_D and T_H are the deuterium and hydrogen atom temperatures.

The bulk ion confinement power loss (P_{conf}^i) is

$$P_{conf}^i = \frac{V_p U_i}{\tau_i}, \tag{4.62}$$

where the bulk ion confinement time τ_i is also assumed to be equal to the particle confinement time τ_p in this model.

4.4.8 Particle density equations for impurities

A schematic diagram of impurity simulation model is shown in Fig. 4.9. Estimation of penetration length of impurities is the same method as the deuterium molecules, molecular ions, and bulk ions. Density equations for impurity particle are given as follows.

$$\frac{dV_I^{0t} n_I^0}{dt} = V_I^{1+} n_e n_I^{1+} R_{1 \rightarrow 0} - V_I^{0i} n_e n_I^0 S_{0 \rightarrow 1+} + \sum_{j=1}^z \frac{V_I^{j+} n_I^{j+}}{\tau_p}, \tag{4.63}$$

$$\begin{aligned}
 \frac{dV_I^{1+} n_I^{1+}}{dt} = & V_I^{0i} n_e n_I^0 S_{0 \rightarrow 1+} + V_I^{2+} n_e n_I^{2+} R_{2 \rightarrow 1+} - V_I^{1+} n_e n_I^{1+} S_{1 \rightarrow 2+} - V_I^{1+} n_e n_I^{1+} R_{1 \rightarrow 0} \\
 & - \frac{V_I^{1+} n_I^{1+}}{\tau_p},
 \end{aligned} \tag{4.64}$$

$$\begin{aligned} \frac{dV_I^{j+} n_I^{j+}}{dt} = & V_I^{(j-1)+} n_e n_I^{(j-1)+} S_{(j-1)+ \rightarrow j+} + V_I^{(j+1)+} n_e n_I^{(j+1)+} R_{(j+1)+ \rightarrow j+} - V_I^{j+} n_e n_I^{j+} S_{j+ \rightarrow (j+1)+} \\ & - V_I^{j+} n_e n_I^{j+} R_{j+ \rightarrow (j-1)+} - \frac{V_I^{j+} n_I^{j+}}{\tau_p} \quad (j = 2, 3, 4, \dots, z-1), \end{aligned} \quad (4.65)$$

$$V_I^{z+} \frac{dn_I^{z+}}{dt} = V_I^{(z-1)+} n_e n_I^{(z-1)+} S_{(z-1)+ \rightarrow z+} - V_I^{z+} n_e n_I^{z+} R_{z+ \rightarrow (z-1)+} - \frac{V_I^{z+} n_I^{z+}}{\tau_p}, \quad (4.66)$$

where $S_{j+ \rightarrow (j+1)+}$ is the ionization rate coefficient of impurity from charge state $j+$ to $(j+1)+$ and $R_{(j-1)+ \rightarrow j+}$ is the recombination rate coefficient of impurity from state $(j-1)+$ to $j+$ [10]. We assume that once the impurity ions come out of the plasma and reach the vessel wall, they are recycled to a neutral impurity [11].

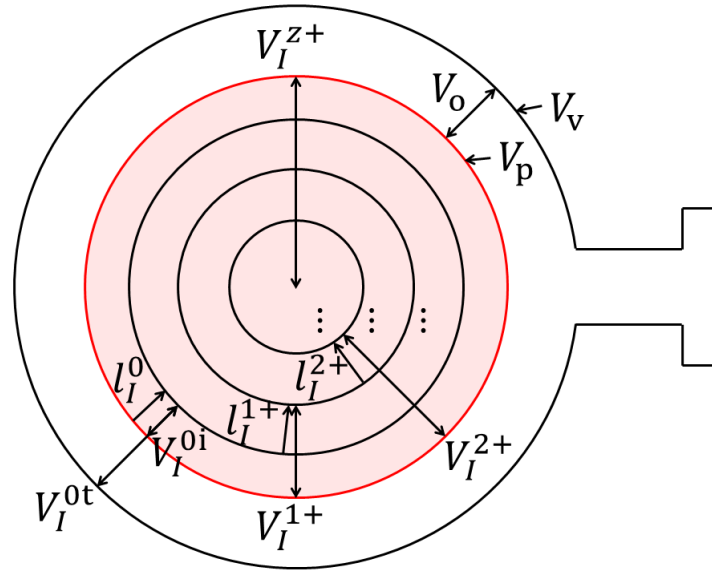


Figure 4.9: A schematic diagram of impurity simulation model.

4.5 Results

4.5.1 Simulation results

Shown in Fig. 4.10 are the time evolutions of (a) the NBI power and main gas puff, (b) the electron density, (c) the densities for fast hydrogen ion from NBI, deuterium molecule, deuterium molecular ion, and deuterium ion, and (d) the electron and ion temperatures for a with density build-up case. NBI power of 350 kW is applied at $t = t_{\text{NBI}} = 194$ ms for the generation of fast hydrogen ions and then the main deuterium gas is puffed at $t = t_{\text{GP}} = 218$ ms for a density build-up. Set, as an initial electron density, is the seed plasma density of $6.0 \times 10^{17} \text{ m}^{-3}$, which is greater than the threshold seed density for NBI plasma start-up. In this case, fast hydrogen ions are sufficiently produced mainly by $\text{H}_b + \text{D}^+ \rightarrow \text{H}_f^+ + \text{D}$ and $\text{H}_b + \text{e} \rightarrow \text{e} + \text{H}_f^+ + \text{e}$. The electron density gradually increases before the main gas puff because deuterium and hydrogen molecules are ionized or dissociated by the electrons, which are heated nearly 100 eV by fast hydrogen ions. In this phase, the heating power of electrons by fast hydrogen ions is a few kilowatts because of low electron density as shown in Fig. 4.11. However, this heating power leads to around hundreds kilowatts after the main gas puff as the electron density drastically increases. These processes are described in Fig. 4.12. As explained above, (1) production of fast hydrogen ions, (2) electron heating, and (3) ionization and dissociation of the deuterium gases are important. Because the process (1) increases with increasing the process (3), these processes create a positive feedback loop resulting in a successful plasma start-up.

For no density build-up case, shown in Fig. 4.13 are the time evolution of (a) the NBI power and main gas puff, (b) the electron density, (c) the densities for fast hydrogen ion from NBI, deuterium molecule, deuterium molecular ion, and deuterium ion, and (d) the electron and ion temperatures. As the seed electron density is low, (1) production of fast hydrogen ions remains low, resulting in the low (2) electron heating. (3) ionization of Deuterium molecules weakly proceeds in such a low electron temperature. In this case, (4) the charge exchanges between fast hydrogen ions, and deuterium and hydrogen molecules occur. Thus, the density build-up fails because no positive feedback loop is created.

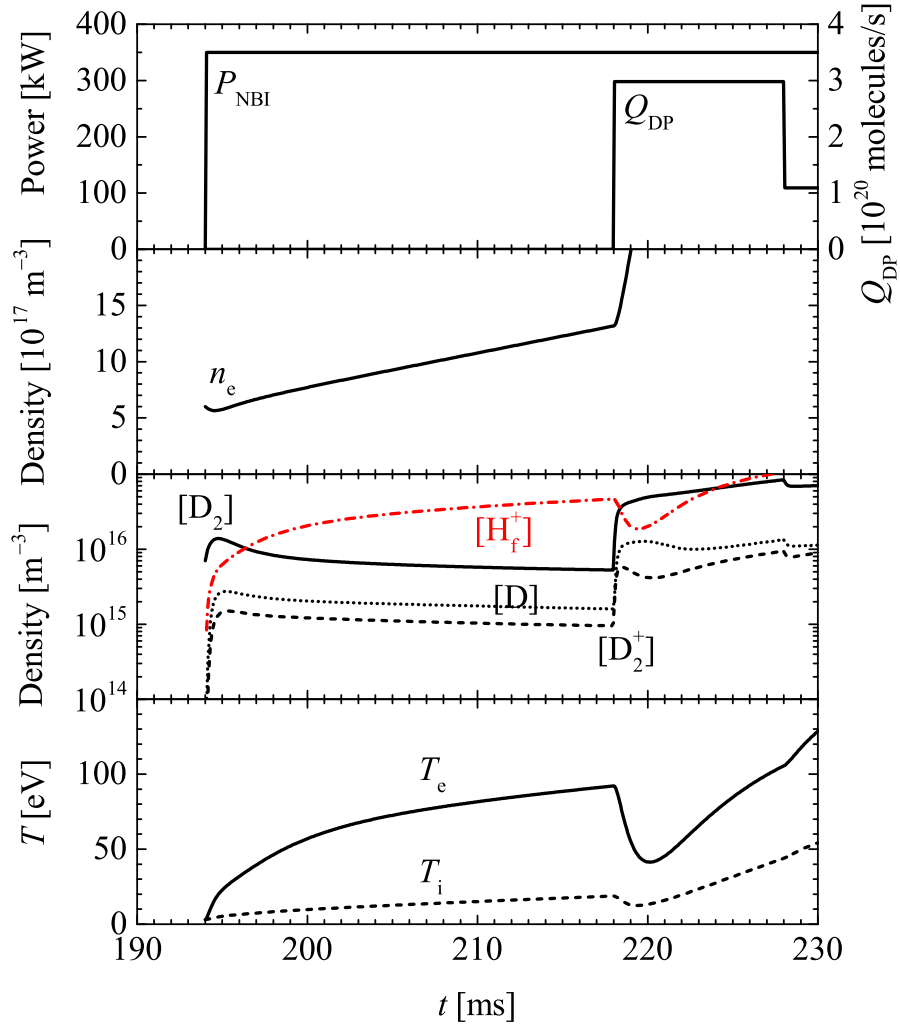


Figure 4.10: Simulation time evolution of (a) NBI power and main gas puff, (b) electron density, (c) densities for fast hydrogen ion from NBI, deuterium molecule, deuterium molecular ion, and deuterium ion, and (d) electron and ion temperatures for the successful start-up case.

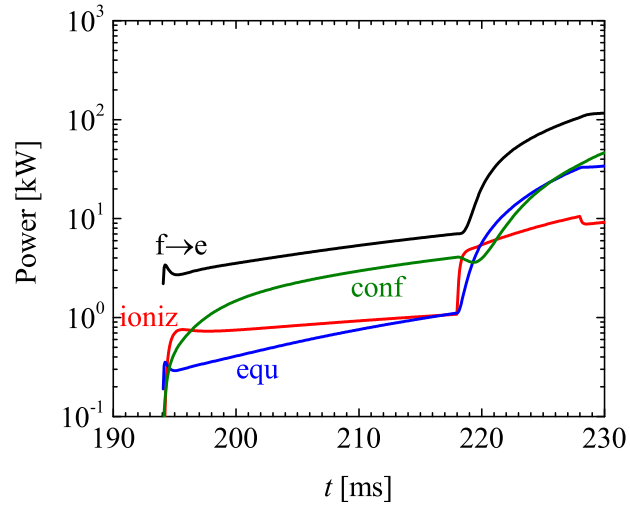


Figure 4.11: Simulational time evolution of the electron heating power by fast hydrogen ions ($f \rightarrow e$), ionization power loss (ioniz), equilibration power loss (equ), and confinement power loss (conf) for the successful start-up case.

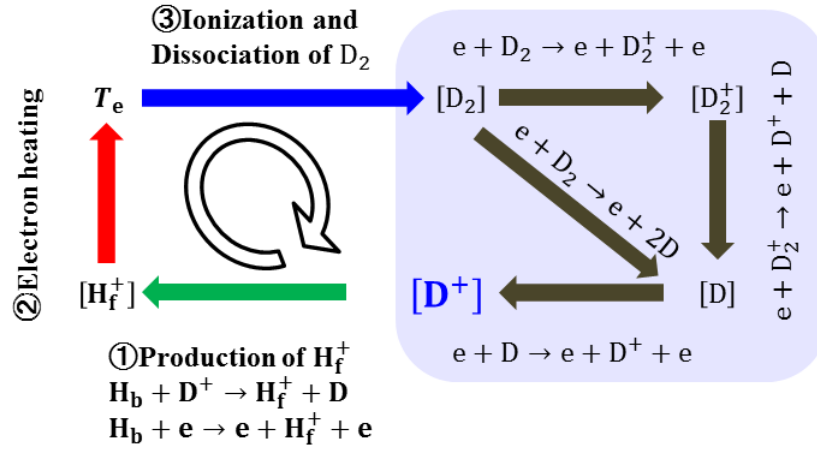


Figure 4.12: Dominant physical processes for the successful start-up case.

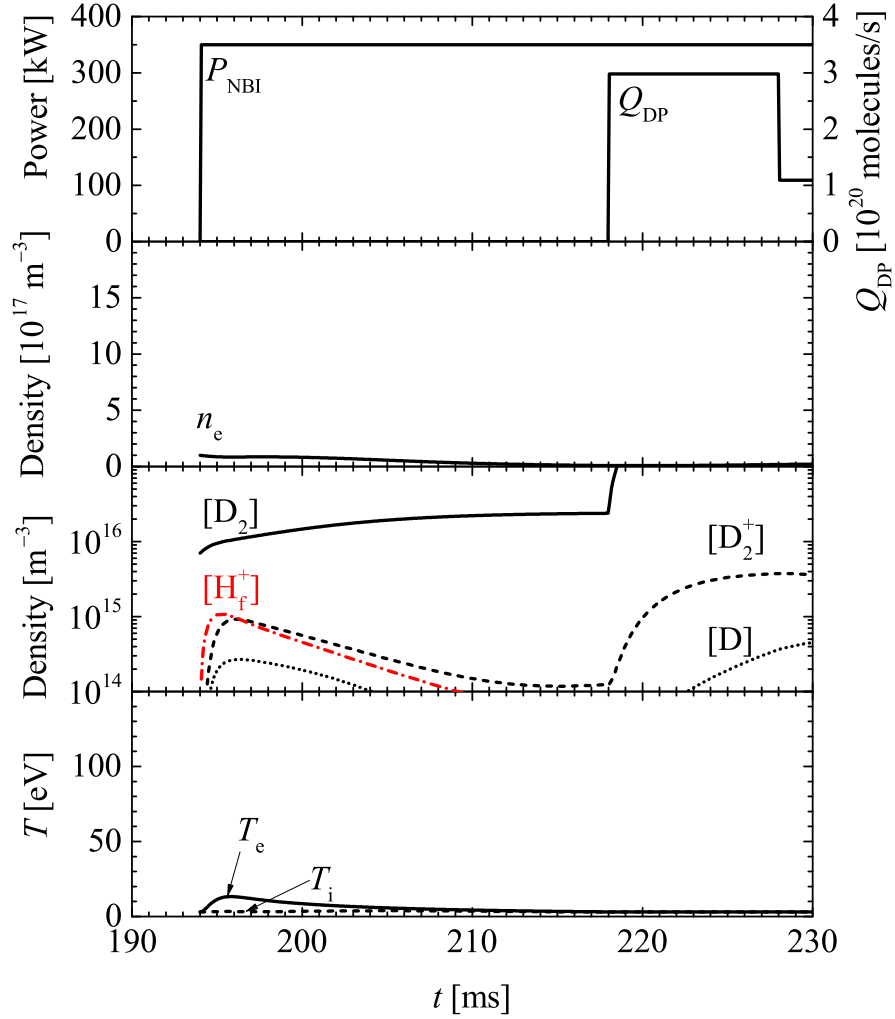


Figure 4.13: Simulation time evolution of (a) NBI power and main gas puff, (b) electron density, (c) densities for fast hydrogen ion from NBI, deuterium molecule, deuterium molecular ion, and deuterium ion, and (d) electron and ion temperatures for the unsuccessful start-up case.

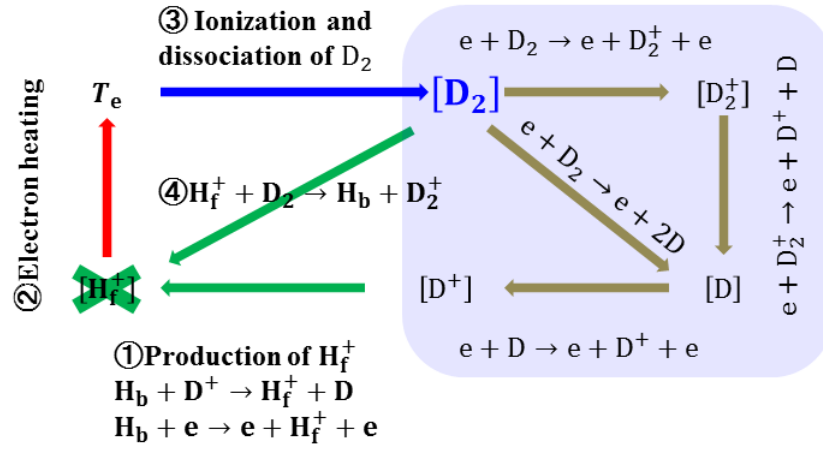


Figure 4.14: Dominant physical processes for the unsuccessful start-up case..

4.5.2 Comparison with experimental data

In order to validate this model, comparisons with the experimental data are conducted. Figure 4.15 shows the time evolutions (#56749) of (a) the NBI power and main gas puff, (b) the electron density, and (c) the stored energy, (d) the CIII emission, and (e) the OV emission for experiment and simulation. The electron density starts to increase just after the main gas puff, and the rise in the stored energy delayed a few milliseconds from that in the electron density. These time evolutions are reproduced in the simulation. The simulated peak of the OV emission (278 nm, $1s^22s3p \rightarrow 1s^22s3s$) almost agrees with the experimental results, indicating that the electron temperature after gas puff is reproduced in the simulation.

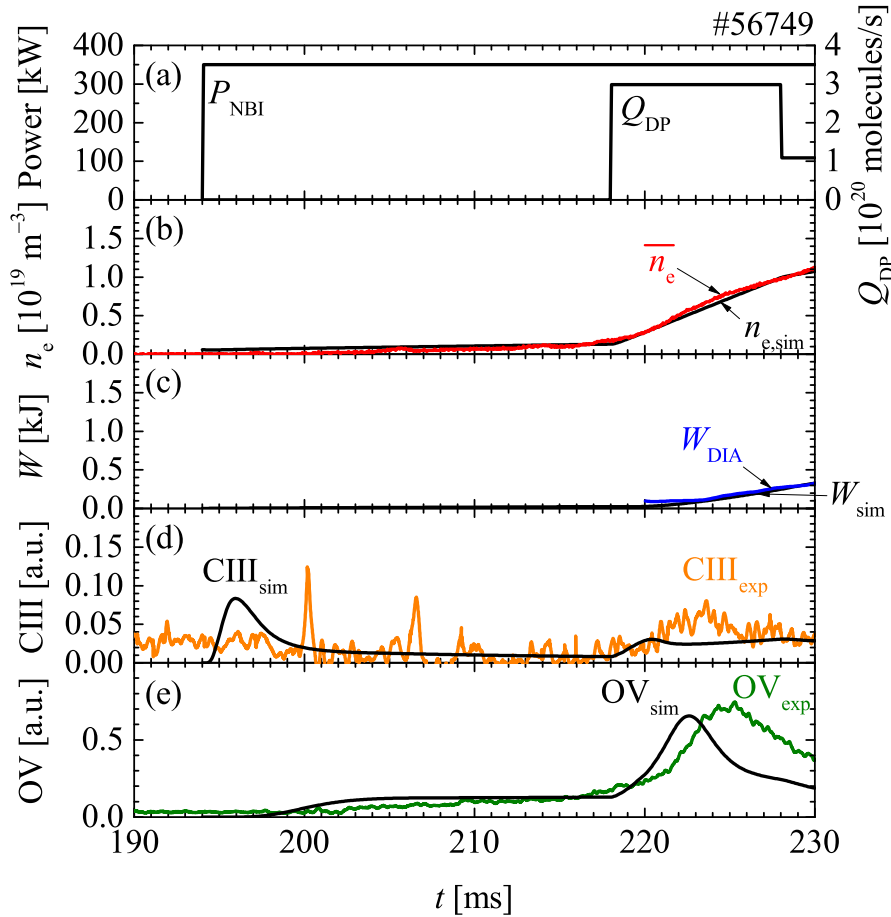


Figure 4.15: Time evolution (#56749) of (a) the NBI power and main gas puff, (b) the electron density, (c) the stored energy, (d) the CIII emission, and (e) the OV emission for the experiment and simulation.

Shown in Fig. 4.16 is the dependence of the electron density after the main gas puff at $t = t_{\text{GP}} + 10$ ms on the seed plasma density before the NBI, where red open circles and blue crosses show the cases with and without density build-up in the experiments. The threshold in the seed plasma density for the density build-up is considered to be in the shaded area, which area was not measured in the experiments. This is due to the difficulty in the control of the pre-filled gas pressure. The simulated dependence is indicated as black closed circles. This reproduces the tendency of the experimental dependence. The physical processes in the initial start-up phase were mentioned in previous section.

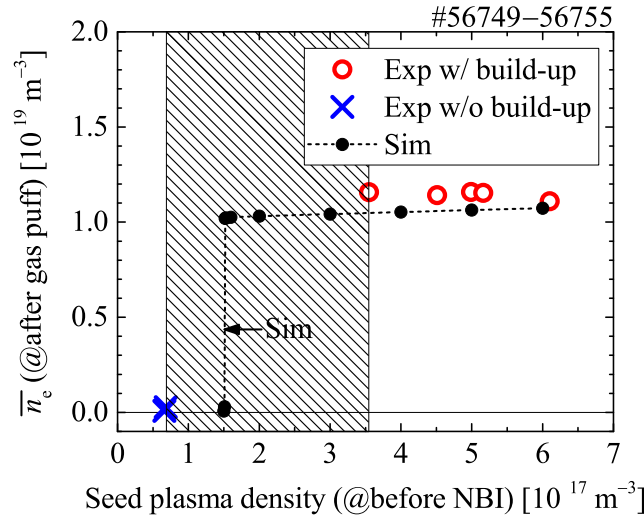


Figure 4.16: Dependence of the electron density after gas puff at $t = t_{\text{GP}} + 10$ ms on the seed plasma density.

The dependence of the electron density after the main gas puff at $t = t_{\text{GP}} + 10$ ms on the difference time between the main gas puff and the NBI, $\Delta\tau = t_{\text{GP}} - t_{\text{NBI}}$, is shown in Fig. 4.17. The density build-up fails for the case of the early puff, which corresponds to $\Delta\tau = -2$ ms. In this case, the main gases are puffed before the electron temperature reaches to enough temperature to ionize the main gas puff. This tendency is also reproduced by the simulation, which is shown as black closed circles. In Fig. 4.18, the dependence of the fast hydrogen ion density and the electron temperature at gas puff timing on $\Delta\tau$ is shown. The fast hydrogen ion density at gas puff timing increases with increasing $\Delta\tau$. The electron temperature at gas puff also increases. The electron temperature must be enough high to ionize the main gas puff.

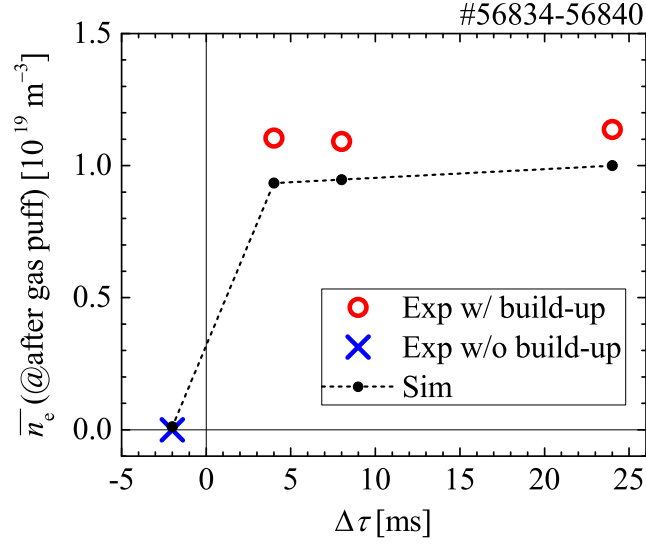


Figure 4.17: Dependence of the electron density after gas puff at $t = t_{\text{GP}} + 10$ ms on the difference time between the main gas puff and the NBI, $\Delta\tau = t_{\text{GP}} - t_{\text{NBI}}$.

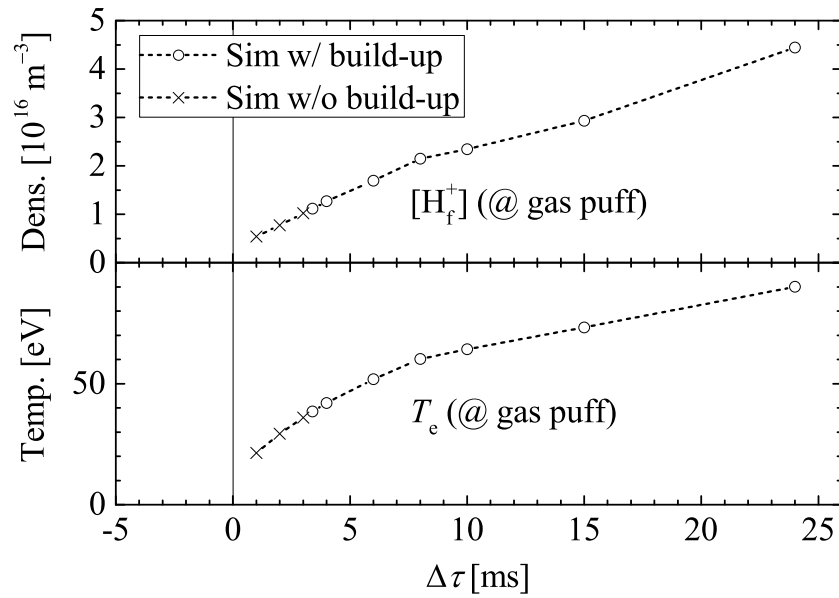


Figure 4.18: Dependence of the fast hydrogen ion density and the electron temperature at gas puff on the difference time between the main gas puff and the NBI, $\Delta\tau = t_{\text{GP}} - t_{\text{NBI}}$.

Figure 4.19 shows the dependence of the electron density and the stored energy build-up rates on the NBI power. The stored energy build-up rate is almost zero below the NBI power of approximately 200 kW. However, the electron density build-up rate gradually decreases with decreasing the NBI power. In such a low NBI power, the breakdown occurs and then the electron density increases. The burn-through is not achieved because of low input power. This is also reproduced by the 0-D model. For the unsuccessful start-up case, the physical processes are considered to be that the less NBI power, the less fast hydrogen ions are produced, resulting the low electron temperature.

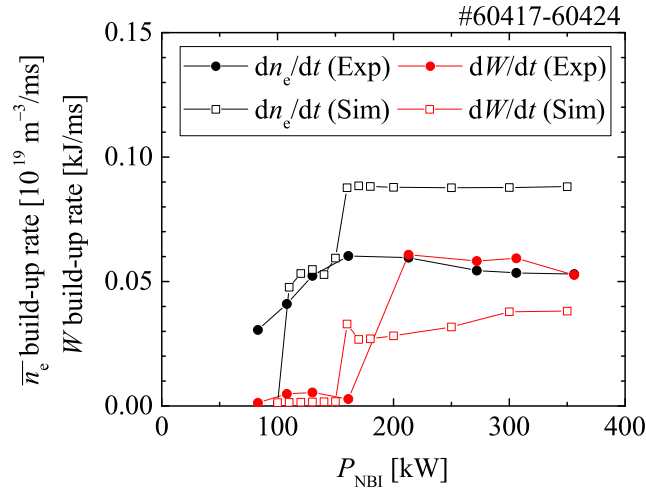


Figure 4.19: Dependence of the electron density and stored energy build-up rate on the NBI power.

4.6 Discussions

The 0-D model analysis was carried out until the electron density reaches $1 \times 10^{19} \text{ m}^{-3}$, and reproduced the time evolution of plasma start-up well. Comparisons with the experiment result are made through the end of the NBI as shown in Fig. 4.20. The time evolution of the electron density is reproduced in the 0-D model simulation quite well, and that of the stored energy in the simulation is reproduced within a factor of 2. This difference is considered to be due to the change in the confinement time. The dependence of the electron density and the stored

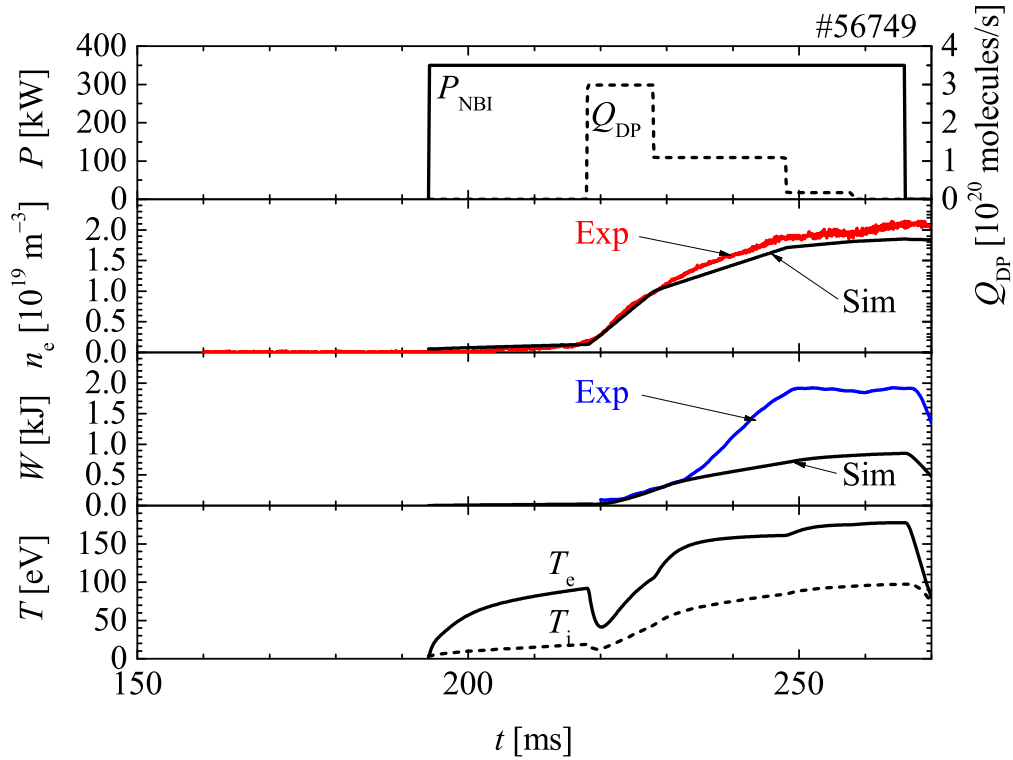


Figure 4.20: Time evolution of NBI plasma start-up (#56749).

energy at $t = 230 \text{ ms}$ on the particle and energy confinement time is shown in Fig. 4.21. The electron density is nearly independent of the confinement time because the particles, which go out of the plasma, return back to the plasma again. The stored energy strongly depends on the confinement time as it does not occur such a process as concerns the stored energy.

In Heliotron J, the seed plasma density of approximately $1 \times 10^{17} \text{ m}^{-3}$ is required to build up the high density plasma using the NBI with the beam energy of 25 keV. In order to assess

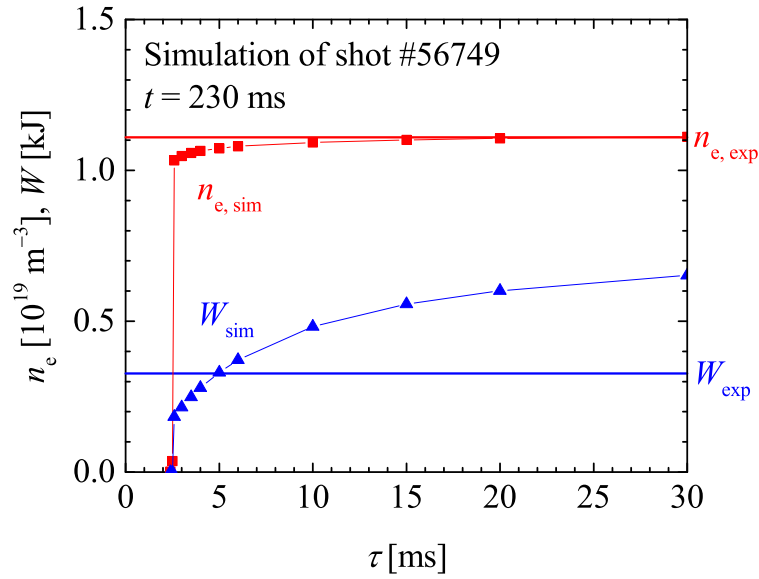


Figure 4.21: Dependence of the electron density and the stored energy at $t = 230$ ms on the confinement time.

how much the seed plasma density is required by changing the beam energy, the 0-D model analysis is conducted though the maximum beam energy in Heliotron J is 30 keV. The threshold densities of the seed plasma are plotted as a function of beam energy in Fig. 4.22. This analysis indicates that the threshold density almost linearly increases with increasing the beam energy. This tendency can be explained as follows. The productions of fast hydrogen ions As shown in Fig. 4.3, the beam cross sections decrease with increasing the beam energy, resulting in a lower production of fast hydrogen ions. Furthermore, from Eq. 4.54, the electron heating by fast hydrogen ions decreases with a rise in beam energy.

Consider plasma start-up without a seed plasma. The dependence of the plasma start-up time on the interaction length of the NBs with the plasma, L , is shown in Fig. 4.23 though the actual interaction length in Heliotron J is approximately 1.6 m. The plasma start-up time, $\tau_{\text{start-up}}$, is defined as the time from the NBI switch on until the electron temperature reaches 100 eV. The injected NBI power is 1.6 MW, which is the maximum value of Heliotron J NBI system. The plasma start-up time considerably decreases with increasing the interaction length. Although plasma start-up without a seed plasma is expected for the interaction length $L = 1.6$ m, the plasma start-up time $\tau_{\text{start-up}} = 93$ ms exceeds the NBI pulse duration available

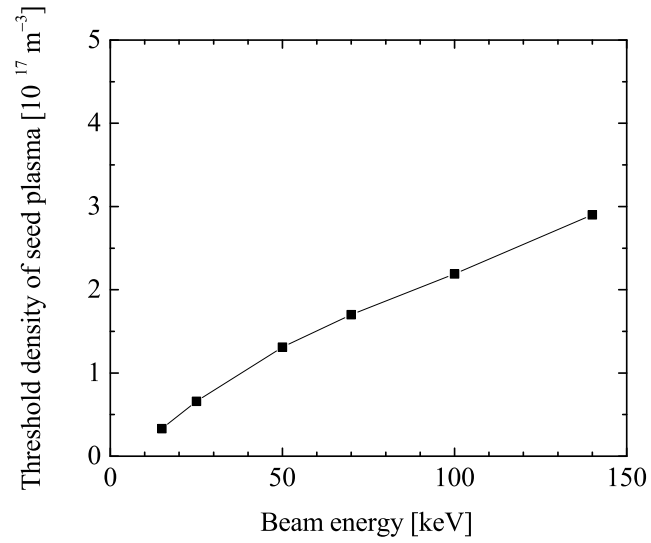


Figure 4.22: Dependence of the threshold density of seed plasma on the beam energy.

in Heliotron J and the impurities such as carbon and oxygen will likely be incorporated into the plasma. Therefore, the seed plasma might be necessary for the plasma start-up in Heliotron J.

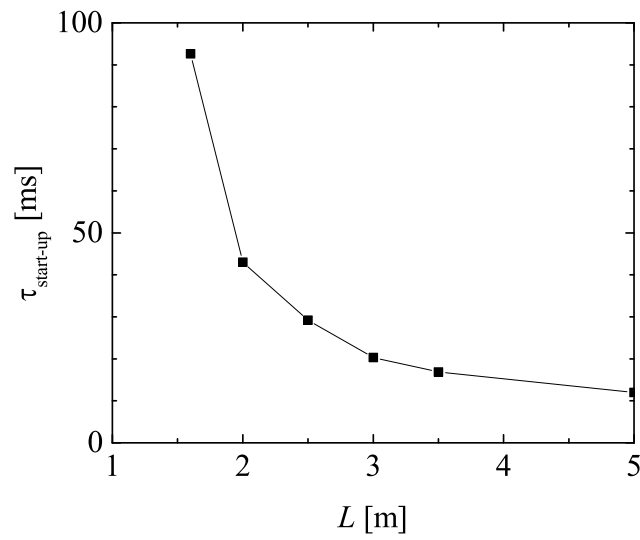


Figure 4.23: Dependence of the plasma start-up time, $\tau_{\text{start-up}}$, on the interaction length of the NBs with the plasma, L . Injected NBI power is 1.6 MW.

4.7 Summary

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 $1.0 \times 10^{19} \text{ m}^{-3}$. 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. Simulated results are as follows:

1. The dominant processes in the NBI plasma start-up in Heliotron J are that the production of fast hydrogen ions, the electron heating, and the 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.
2. For a low seed plasma density case, because the production of fast hydrogen ions is kept low, the 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. Comparisons with the experiments are as follows:

1. The 0-D model reproduces the time evolution of the electron density and the stored energy quite well.
2. The tendency of the dependence of the density build-up on the seed plasma density are reproduced in the simulation though the measurements in shaded area in Fig. 4.16 was not done. These measurements might be needed the control of the pre-filled gas pressure or the 2.45 GHz microwaves power.

3. 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 become enough high to ionize the main gas puff.
4. 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.

In W7-X, the plasma start-up using perpendicular NBI is planned. Due to the cooling capacity of the wall opposite to NBs, it is found that the plasma start-up by NBI alone might be difficult. The seed plasma generated by 2.45 GHz microwaves could be effective for a reliable plasma start-up. This work is considered to contribute to the analysis of the plasma start-up by NBI in W7-X.

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Chapter 5

Summary

A reliable plasma start-up is an 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 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 $n_D = 3.0 \times 10^{18} \text{ m}^{-3}$.
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 $n_H = 3.0 \times 10^{18} \text{ m}^{-3}$ 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 ionizations 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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Appendix A

ECRH absorption efficiency

A.1 Hot plasma dielectric tensor

From the kinetic theory, the hot plasma dielectric tensor $\overleftrightarrow{\epsilon}^{(\text{hot})}$ is calculated as follows [1]:

$$\epsilon_{xx} = S^h = 1 - \frac{\omega_p^2}{\omega^2} \frac{e^{-b}}{b} \sum_{N=-\infty}^{+\infty} N^2 I_N(b) [-\zeta_0 Z(\zeta_N)], \quad (\text{A.1})$$

$$\epsilon_{xy} = -\epsilon_{yx} = iD^{(h)} = -i \frac{\omega_p^2}{\omega^2} e^{-b} \sum_{N=-\infty}^{+\infty} N [I'_N(b) - I_N(b)] [-\zeta_0 Z(\zeta_N)], \quad (\text{A.2})$$

$$\epsilon_{xz} = \epsilon_{zx} = n_z n_x \eta^{(h)} = -\frac{1}{2} n_z n_x \frac{\omega_p^2}{\omega \omega_{ce}} \frac{v_{th}^2}{c^2} \frac{e^{-b}}{b} \sum_{N=-\infty}^{+\infty} N I_N(b) [\zeta_0^2 Z'(\zeta_N)], \quad (\text{A.3})$$

$$\epsilon_{yy} = S^{(h)} - 2n_x^2 \tau^{(h)} = S^{(h)} + n_x^2 \frac{\omega_p^2}{\omega^2} \frac{v_{th}^2}{c^2} e^{-b} \sum_{N=-\infty}^{+\infty} [I'_N(b) - I_N(b)] [-\zeta_0 Z(\zeta_N)], \quad (\text{A.4})$$

$$\epsilon_{yz} = -\epsilon_{zy} = i n_z n_x \xi^{(h)} = \frac{i}{2} n_z n_x \frac{\omega_p^2}{\omega \omega_{ce}} \frac{v_{th}^2}{c^2} e^{-b} \sum_{N=-\infty}^{+\infty} [I'_N(b) - I_N(b)] [\zeta_0^2 Z'(\zeta_N)], \quad (\text{A.5})$$

$$\epsilon_{zz} = P^{(h)} = 1 - \frac{\omega_p^2}{\omega^2} e^{-b} \sum_{N=-\infty}^{+\infty} I_N(b) [\zeta_0 \zeta_N Z'(\zeta_N)]. \quad (\text{A.6})$$

A.2 Warm-plasma dielectric tensor

For the case of the fundamental ECRH, the hot plasma dielectric tensor is approximated as follows [2, 3]:

$$\varepsilon_{xx} = \varepsilon_{yy} = 1 - \frac{\omega_p^2}{2\omega^2} \left[\frac{\omega}{\omega + \omega_{ce}} - \frac{R}{\Delta\sqrt{2}} Z(\zeta_1) \right], \quad (\text{A.7})$$

$$\varepsilon_{xy} = -\varepsilon_{yx} = -i \frac{\omega_p^2}{2\omega^2} \left[\frac{\omega}{\omega + \omega_{ce}} + \frac{R}{\Delta\sqrt{2}} Z(\zeta_1) \right], \quad (\text{A.8})$$

$$\varepsilon_{xz} = \varepsilon_{zx} = -\frac{\omega_p^2}{4\omega\omega_{ce}} \frac{n_x}{n_{\parallel}} Z'(\zeta_1), \quad (\text{A.9})$$

$$\varepsilon_{yz} = -\varepsilon_{zy} = i\varepsilon_{xz}, \quad (\text{A.10})$$

$$\varepsilon_{zz} = 1 - \frac{\omega_p^2}{\omega^2} \left[1 + \frac{\omega^2}{4\omega_{ce}^2} \frac{n_x^2}{n_{\parallel}^2} \frac{x}{R} Z'(\zeta_1) \right]. \quad (\text{A.11})$$

A.3 Perpendicular electron heating rate

From the quasi-linear Vlasov equation [4], the change rate in distribution of electron is given as

$$\begin{aligned} \frac{\partial f_e}{\partial t} = \frac{\pi e^2}{4m_e^2} \sum_{N=-\infty}^{+\infty} \left\{ \frac{1}{v_{\perp}} \frac{\partial}{\partial v_{\perp}} \left[N\omega_{ce} |A|^2 \delta(\omega - N\omega_{ce} - k_{\parallel}v_{\parallel}) \left(\frac{N\omega_{ce}}{v_{\perp}} \frac{\partial f_e}{\partial v_{\perp}} + k_{\parallel} \frac{\partial f_e}{\partial v_{\parallel}} \right) \right] \right. \\ \left. + \frac{\partial}{\partial v_{\parallel}} \left[k_{\parallel} |A|^2 \delta(\omega - N\omega_{ce} - k_{\parallel}v_{\parallel}) \left(\frac{N\omega_{ce}}{v_{\perp}} \frac{\partial f_e}{\partial v_{\perp}} + k_{\parallel} \frac{\partial f_e}{\partial v_{\parallel}} \right) \right] \right\}, \quad (\text{A.12}) \end{aligned}$$

where

$$A = v_{\perp} E^{-} e^{i\theta} J_{N-1} \left(\frac{k_{\perp} v_{\perp}}{\omega_{ce}} \right) + v_{\perp} E^{+} e^{-i\theta} J_{N+1} \left(\frac{k_{\perp} v_{\perp}}{\omega_{ce}} \right) + 2v_{\parallel} E_{\parallel} J_N \left(\frac{k_{\perp} v_{\perp}}{\omega_{ce}} \right), \quad (\text{A.13})$$

where $E^{\pm} = E_x \pm iE_y$, and the angle θ is between the static B field and the wave vector k .

Maxwellian electron distribution is maintained during the electron cyclotron heating because the electron-electron collision frequency is of the order of μs . Maxwellian electron dis-

tribution is given by

$$f_e(v) = n_e \left(\frac{m_e}{2\pi T_e} \right)^{3/2} \exp\left(-\frac{m_e v^2}{2T_e}\right). \quad (\text{A.14})$$

A plasma in the form of plane is assumed as shown in Fig. A.1, then the electron density, temperature, and the magnetic field are a function of position, x . For the fundamental resonance,

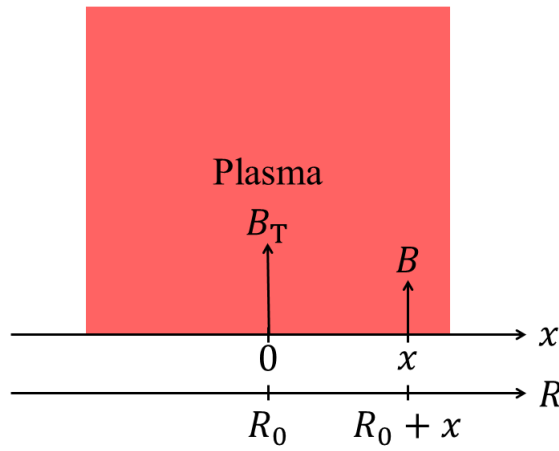


Figure A.1: Plasma in the form of plane. Electron density, temperature, and magnetic field vary with position, x .

$N = \pm 1$ is considered here. Thus, the change rate in distribution of electron becomes

$$\begin{aligned} \frac{\partial f_e}{\partial t} = & -\frac{\pi e^2 n_e(x)}{4m_e \omega T_e(x)} \left[\frac{m_e}{2\pi T_e(x)} \right]^{3/2} \left\{ \frac{1}{v_\perp} \frac{\partial}{\partial v_\perp} \left[\omega_{ce}(x) |A|^2 \delta\left(\frac{\omega x}{R} - k_\parallel v_\parallel\right) \exp\left(-\frac{m_e v^2}{2T_e}\right) \right] \right. \\ & \left. + \frac{\partial}{\partial v_\parallel} \left[k_\parallel |A|^2 \delta\left(\frac{\omega x}{R} - k_\parallel v_\parallel\right) \exp\left(-\frac{m_e v^2}{2T_e}\right) \right] \right\}, \quad (\text{A.15}) \end{aligned}$$

where

$$A = v_\perp \left[E^- + \frac{v_\parallel k_\parallel}{\omega_{ce}} E_\parallel \right]. \quad (\text{A.16})$$

By integrating over the velocity space, the perpendicular electron heating rate per unit volume and time is given by

$$\begin{aligned} \frac{d^2 W_{\perp}}{dt dV} &= \int_0^{\infty} \int_{-\infty}^{\infty} \frac{1}{2} m_e v_{\perp}^2 \frac{\partial f_e}{\partial t} 2\pi v_{\perp} dv_{\parallel} dv_{\perp} \\ &= \frac{\pi \epsilon_0 \omega_p^2 \omega_{ce}}{\omega^2} \frac{R}{\Delta} \frac{\exp\left(-\frac{x^2}{2\Delta^2}\right)}{\sqrt{2\pi}} \left| E^{-} + \frac{n_x}{n_{\parallel}} \frac{\omega}{\omega_{ce}} \frac{x}{R} E_{\parallel} \right|^2, \end{aligned} \quad (\text{A.17})$$

where Δ is the spatial width of the resonance,

$$\Delta = \sqrt{\frac{k_{\parallel}^2 R^2 T_e}{m_e \omega^2}} = n_{\parallel} R \sqrt{\frac{T_e}{mc^2}}. \quad (\text{A.18})$$

This heating occurs only within a distance of the order of Δ . Based on the theory of the propagation of electromagnetic waves, we obtain

$$E^{-} + \frac{n_x}{n_{\parallel}} \frac{\omega}{\omega_{ce}} \frac{x}{R_0} E_{\parallel} = \frac{-i E_y 2 \sqrt{2} \Delta \left(1 - \frac{\alpha}{2} - n_{\perp}^2\right) (1 - \alpha) - n_x^2}{\alpha R_0 Z(\zeta_1) (1 - \alpha - n_x^2)}. \quad (\text{A.19})$$

Thus, the perpendicular electron heating rate per unit volume and time is represented by

$$\frac{d^2 W_{\perp}}{dt dV} = \frac{\epsilon_0 \omega}{\alpha} \frac{\sqrt{2} \Delta}{R} |E_y|^2 \left[\frac{\left(1 - \frac{\alpha}{2} - n_z^2\right) (1 - \alpha) - n_x^2}{1 - \alpha - n_x^2} \right]^2 \text{Im} \left(\frac{1}{Z(\zeta_1)} \right). \quad (\text{A.20})$$

A.4 Optical thickness for the perpendicular injection

By integrating the absorption coefficient along the ECRH wave path, one obtain the optical thickness as follows:

$$\tau = \frac{(2\pi)^2 R n_z^2 T_e}{\alpha \lambda n_x mc^2} \frac{\left[\left(1 - \frac{\alpha}{2} - n_z^2\right) (1 - \alpha) - n_x^2 \right]^2}{(1 - \alpha - n_x^2)^2 + (1 - \alpha) n_z^2}. \quad (\text{A.21})$$

The optical thickness of the X-mode and the O-mode for the fundamental are given by

$$\tau_X = \frac{\pi^2 R}{\lambda} \frac{T_e}{m_e c^2} n_{\parallel}^2 \alpha^{-1} (2 - \alpha)^{3/2} (1 + \alpha)^2, \quad (\text{A.22})$$

$$\tau_O = \frac{\pi^2 R}{\lambda} \frac{T_e}{m_e c^2} \frac{\alpha \sqrt{1 - \alpha}}{1 + n_{\parallel}^2 (1 - \alpha)}. \quad (\text{A.23})$$

The optical thickness of the X-mode and the O-mode for the second harmonic is represented by

$$\tau_{O, X} = \frac{\pi^2 R}{2} \frac{T_e}{\lambda m_e c^2} \alpha n_{\perp O, X} \frac{\left[(S - D - n^2)(P - n_{\perp O, X}^2) \right]^2}{D^2 \left(P - n_{\perp O, X}^2 \right)^2 + n_{\parallel}^2 P (S - n^2)^2}. \quad (\text{A.24})$$

Appendix B

Numerical Treatment

B.1 Particle transport equation

The simplified particle transport equation in cylindrical polar coordinates is given

$$\frac{\partial n}{\partial t} = \frac{\alpha}{\rho} \frac{\partial}{\partial \rho} \left(\rho \frac{\partial n}{\partial \rho} \right) + s, \quad (\text{B.1})$$

where α is a constant value, s is a particle source term, and $\rho = r/a_p$ is a normalized minor radius.

Consider Eq. (B.1) with θ -implicit method [7]. We obtain

$$A_j n_{j-1}^{k+1} + B_j n_j^{k+1} + C_j n_{j+1}^{k+1} = D_j, \quad (\text{B.2})$$

$$A_j = -\frac{\theta \alpha \Delta t \rho_{j-1/2}}{\rho_j (\rho_{j+1/2} - \rho_{j-1/2}) (\rho_j - \rho_{j-1})}, \quad (\text{B.3})$$

$$C_j = -\frac{\theta \alpha \Delta t \rho_{j+1/2}}{\rho_j (\rho_{j+1/2} - \rho_{j-1/2}) (\rho_{j+1} - \rho_j)}, \quad (\text{B.4})$$

$$B_j = 1 - A_j - C_j, \quad (\text{B.5})$$

$$D_j = s_j \Delta t + \frac{(1 - \theta) \alpha \Delta t \rho_{j-1/2}}{\rho_j (\rho_{j+1/2} - \rho_{j-1/2}) (\rho_j - \rho_{j-1})} n_{j-1}^k + \frac{(1 - \theta) \alpha \Delta t \rho_{j+1/2}}{\rho_j (\rho_{j+1/2} - \rho_{j-1/2}) (\rho_{j+1} - \rho_j)} n_{j+1}^k$$

$$+ \left\{ 1 - \frac{(1-\theta)\alpha\Delta t\rho_{j-1/2}}{\rho_j(\rho_{j+1/2} - \rho_{j-1/2})(\rho_j - \rho_{j-1})} - \frac{(1-\theta)\alpha\Delta t\rho_{j+1/2}}{\rho_j(\rho_{j+1/2} - \rho_{j-1/2})(\rho_{j+1} - \rho_j)} \right\} n_j^k, \quad (\text{B.6})$$

where k and j represent the mesh points of time and space, respectively, as shown in Fig. B.1, and θ is the implicitness parameter ($\theta = 0.5$ represents the Crank-Nicolson method).

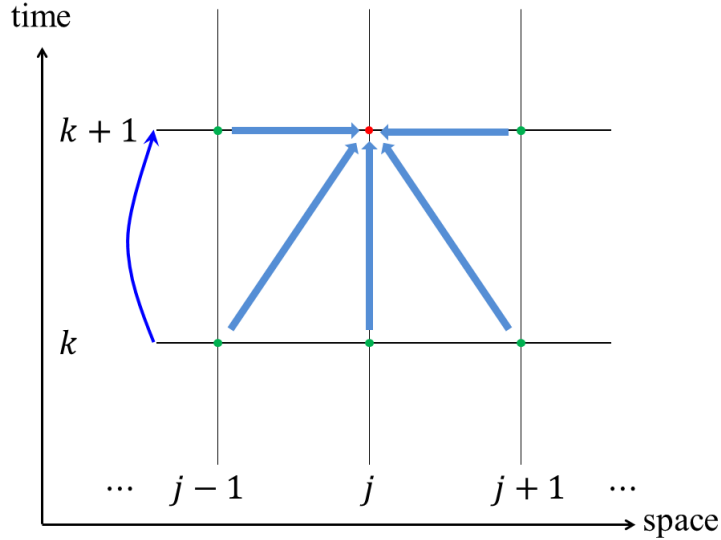


Figure B.1: Finite difference grid in Eq. (B.2). k and j represent the mesh points of time and space, respectively.

B.2 Energy transport equation

The simplified energy transport equation in cylindrical polar coordinates is given

$$\frac{\partial U}{\partial t} = \frac{\beta}{\rho} \frac{\partial}{\partial \rho} \left(\rho n \chi \frac{\partial T}{\partial \rho} \right) + p, \quad (\text{B.7})$$

where $U = 3nT/2$ is the energy density, β is a constant value, χ is the thermal diffusivity, and p is the heating power. By applying the θ -implicit method to Eq. (B.7), we obtain

$$A_j T_{j-1}^{k+1} + B_j T_j^{k+1} + C_j T_{j+1}^{k+1} = D_j, \quad (\text{B.8})$$

$$A_j = -\frac{\theta\beta\Delta t\rho_{j-1/2}\chi_{j-1/2}n_{j-1/2}^{k+1}}{\rho_j(\rho_{j+1/2} - \rho_{j-1/2})(\rho_j - \rho_{j-1})}, \quad (\text{B.9})$$

$$C_j = -\frac{\theta\beta\Delta t\rho_{j+1/2}\chi_{j+1/2}n_{j+1/2}^{k+1}}{\rho_j(\rho_{j+1/2} - \rho_{j-1/2})(\rho_{j+1} - \rho_j)}, \quad (\text{B.10})$$

$$B_j = \frac{3}{2}n_j^{k+1} - A_j - C_j, \quad (\text{B.11})$$

$$D_j = p_j\Delta t + \frac{(1-\theta)\beta\Delta t\rho_{j-1/2}\chi_{j-1/2}n_{j-1/2}^k}{\rho_j(\rho_{j+1/2} - \rho_{j-1/2})(\rho_j - \rho_{j-1})}T_{j-1}^k + \frac{(1-\theta)\beta\Delta t\rho_{j+1/2}\chi_{j+1/2}n_{j+1/2}^k}{\rho_j(\rho_{j+1/2} - \rho_{j-1/2})(\rho_{j+1} - \rho_j)}T_{j+1}^k \\ + \left\{ \frac{3}{2}n_j^k - \frac{(1-\theta)\beta\Delta t\rho_{j-1/2}\chi_{j-1/2}n_{j-1/2}^k}{\rho_j(\rho_{j+1/2} - \rho_{j-1/2})(\rho_j - \rho_{j-1})} - \frac{(1-\theta)\beta\Delta t\rho_{j+1/2}\chi_{j+1/2}n_{j+1/2}^k}{\rho_j(\rho_{j+1/2} - \rho_{j-1/2})(\rho_{j+1} - \rho_j)} \right\} T_j^k, \quad (\text{B.12})$$

where $n_{j-1/2}^{k+1}$, n_j^{k+1} , and $n_{j+1/2}^{k+1}$ are calculated from the particle transport equation.

B.3 Toroidal current equation

Now, the simplified toroidal current equation in cylindrical polar coordinates is given

$$\frac{\partial I}{\partial t} = \gamma\Psi \frac{\partial}{\partial \Psi} \left(\eta(T) \frac{\partial I}{\partial \Psi} \right), \quad (\text{B.13})$$

$$(\text{B.14})$$

where γ is a constant value, $\Psi = \pi r^2 / \pi a_p^2 = \rho^2$ is the cross-section area of normalized by πa_p^2 , and η is the neo-classical conductivity which is given as a function of electron temperature.

Using θ -implicit method, we can write Eq. (B.13) as

$$A_j I_{j-1}^{k+1} + B_j I_j^{k+1} + C_j I_{j+1}^{k+1} = D_j, \quad (\text{B.15})$$

$$A_j = -\frac{\theta\gamma\Delta t\Psi_j\eta_{j-1/2}^{k+1}}{(\Psi_{j+1/2} - \Psi_{j-1/2})(\Psi_j - \Psi_{j-1})}, \quad (\text{B.16})$$

$$C_j = -\frac{\theta\gamma\Delta t\Psi_j\eta_{j+1/2}^{k+1}}{(\Psi_{j+1/2} - \Psi_{j-1/2})(\Psi_{j+1} - \Psi_j)}, \quad (\text{B.17})$$

$$B_j = 1 - A_j - C_j, \quad (\text{B.18})$$

$$\begin{aligned}
D_j = & \frac{(1-\theta)\gamma\Delta t\Psi_j\eta_{j-1/2}^k}{(\Psi_{j+1/2}-\Psi_{j-1/2})(\Psi_j-\Psi_{j-1})}I_{j-1}^k + \frac{(1-\theta)\gamma\Delta t\Psi_j\eta_{j+1/2}^k}{(\Psi_{j+1/2}-\Psi_{j-1/2})(\Psi_{j+1}-\Psi_j)}I_{j+1}^k \\
& + \left\{ 1 - \frac{(1-\theta)\gamma\Delta t\Psi_j\eta_{j-1/2}^k}{(\Psi_{j+1/2}-\Psi_{j-1/2})(\Psi_j-\Psi_{j-1})} - \frac{(1-\theta)\gamma\Delta t\Psi_j\eta_{j+1/2}^k}{(\Psi_{j+1/2}-\Psi_{j-1/2})(\Psi_{j+1}-\Psi_j)} \right\} I_j^k. \quad (\text{B.19})
\end{aligned}$$

Appendix C

Density decay of hydrogen molecules

The length how much hydrogen molecules penetrate into the plasma is calculated by the density decay equation [8]. The hydrogen molecules entering the plasma from the plasma edge are decayed through the following reaction:



The density decay equation for hydrogen molecules are represented by

$$\frac{d[\text{H}_2]}{dt} = -n_e[\text{H}_2] \left(\langle \sigma_{\text{e}, \text{H}_2}^{\text{diss}} v_e \rangle + \langle \sigma_{\text{e}, \text{H}_2}^{\text{ion}} v_e \rangle \right) - [\text{H}_f^+][\text{H}_2] \left(\sigma_{\text{f}, \text{H}_2}^{\text{cx}} + \sigma_{\text{f}, \text{H}_2}^{\text{ion}} \right) v_f. \quad (\text{C.5})$$

Consider a hydrogen molecule with the thermal velocity, v_{D_2} , from the plasma edge position, a_p . The density of hydrogen molecules at the position, r , is given as

$$[\text{H}_2](r) = [\text{H}_2](a_p) \exp \left[-\frac{1}{v_{\text{H}_2}} \int_{a_p}^r \left\{ n_e(r) \left(\langle \sigma_{\text{e}, \text{H}_2}^{\text{diss}} v_e \rangle + \langle \sigma_{\text{e}, \text{H}_2}^{\text{ion}} v_e \rangle \right) + [\text{H}_f^+](r) \left(\sigma_{\text{f}, \text{H}_2}^{\text{cx}} + \sigma_{\text{f}, \text{H}_2}^{\text{ion}} \right) v_f \right\} dr \right]. \quad (\text{C.6})$$

Shown in Fig. C.1 is the normalized hydrogen molecule density, $[H_2](r)/[H_2](a_p)$, as a function of position, r . The penetration length, l_{H_2} , is the distance where this normalized density drops to $1/e$, and its maximum value is $l_{H_2} = a_p$.

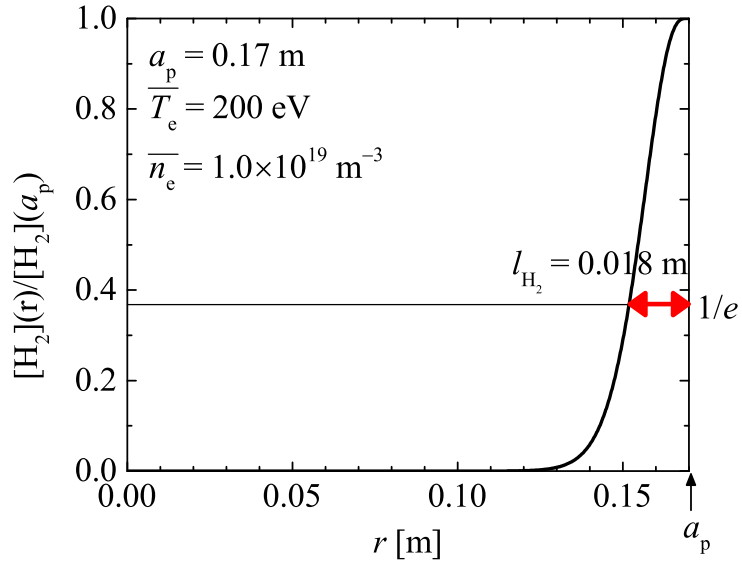


Figure C.1: Normalized hydrogen molecule density as a function of position, r . Assumed electron temperature and density profiles are $T_e = 2\bar{T}_e[1 - (r/a_p)^2]$ and $n_e = 4\bar{n}_e[1 - (r/a_p)^6]/3$, where $\bar{T}_e = 200$ eV and $\bar{n}_e = 1.0 \times 10^{19} \text{ m}^{-3}$.

Appendix D

Coulomb collision

D.1 Fokker-Planck coefficients

Consider a test particle with charge Ze , mass of m , and velocity of $\mathbf{v}$ interacts with a field particle with charge $Z_j e$, mass of m_j , and velocity of $\mathbf{v}_j$ via the Coulomb force over the distance of r in laboratory system. Rosenbluth potentials are defined as

$$H_j(\mathbf{v}) = \left(1 + \frac{m}{m_j}\right) \int \frac{f_j(\mathbf{v}_j)}{|\mathbf{v} - \mathbf{v}_j|} d\mathbf{v}_j, \quad (\text{D.1})$$

$$G_j(\mathbf{v}) = \int f_j(\mathbf{v}_j) |\mathbf{v} - \mathbf{v}_j| d\mathbf{v}_j, \quad (\text{D.2})$$

where the subscript j denotes the field and test particles, respectively [9, 10]. $f_j(\mathbf{v}_j)$ is a velocity distribution for the field particles. Here, we adopt a Maxwellian distribution such as

$$f_j(\mathbf{v}_j) = \frac{n_j}{\pi^{3/2} v_{Tj}} \exp\left(-\frac{v_j^2}{v_{Tj}^2}\right), \quad (\text{D.3})$$

where n_j is the density of the field particle and $v_{Tj} = \sqrt{2T_j/m_j}$ is the thermal velocity of the field particle.

By substituting the Maxwellian distribution, these potentials are obtained as

$$H_j = \left(1 + \frac{m}{m_j}\right) \frac{n_j}{v} \Phi\left(\frac{v}{v_{Tj}}\right), \quad (\text{D.4})$$

$$G_j = n_j \left\{ \frac{v^2 + v_{Tj}^2/2}{v} \Phi\left(\frac{v}{v_{Tj}}\right) + \frac{v_{Tj}}{2} \Phi'\left(\frac{v}{v_{Tj}}\right) \right\}, \quad (D.5)$$

where

$$\Phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy, \quad (D.6)$$

$$\Phi'(x) = \frac{2}{\sqrt{\pi}} e^{-x^2}, \quad (D.7)$$

is the error function and its differential, respectively.

The average change rates in parallel velocity of a test particle, in squared parallel velocity, and in squared perpendicular velocity with the Maxwellian field particles are given as

$$\frac{\langle \Delta v_{\parallel} \rangle}{\Delta t} = - \left(1 + \frac{m}{m_j} \right) \frac{A_D}{v_{Tj}^2} \Psi\left(\frac{v}{v_{Tj}}\right), \quad (D.8)$$

$$\frac{\langle (\Delta v_{\parallel})^2 \rangle}{\Delta t} = \frac{A_D}{v} \Psi\left(\frac{v}{v_{Tj}}\right), \quad (D.9)$$

$$\frac{\langle (\Delta v_{\perp})^2 \rangle}{\Delta t} = \frac{A_D}{v} \left\{ \Phi\left(\frac{v}{v_{Tj}}\right) - \Psi\left(\frac{v}{v_{Tj}}\right) \right\}, \quad (D.10)$$

where

$$\Psi(x) = \frac{\Phi(x) - x\Phi'(x)}{2x^2}, \quad (D.11)$$

$$A_D = \frac{n_j Z^2 Z_j^2 e^4 \ln \Lambda}{2\pi \epsilon_0^2 m^2}. \quad (D.12)$$

D.2 Equilibration power

When there are two different temperature particle species, a heat exchange occurs. This heat exchange power is called as the equilibration power.

The change rate in energy of a test particle colliding with the Maxwellian field particles is

$$\frac{\langle \Delta E \rangle}{\Delta t} = \frac{1}{2} m \frac{\langle (v + \Delta v)^2 - (v)^2 \rangle}{\Delta t} \quad (D.13)$$

$$=mv\frac{\langle\Delta v_{\parallel}\rangle}{\Delta t} + \frac{1}{2}m\left(\frac{\langle(\Delta v_{\parallel})^2\rangle}{\Delta t} + \frac{\langle(\Delta v_{\perp})^2\rangle}{\Delta t}\right) \quad (\text{D.14})$$

$$= -\frac{m^2 A_D}{2m_j v} \left\{ \Phi\left(\frac{v}{v_{Tj}}\right) - \left(1 + \frac{m_j}{m}\right) \frac{v}{v_{Tj}} \Phi'\left(\frac{v}{v_{Tj}}\right) \right\}. \quad (\text{D.15})$$

Equilibration power due to the Coulomb collisions transferred from Maxwellian test particles to Maxwellian field particles per unit volume is given

$$p_{\text{EQU}} = \int_0^{\infty} \frac{\langle\Delta E\rangle}{\Delta t} f 4\pi v^2 dv \quad (\text{D.16})$$

$$= \frac{nn_j Z^2 Z_j^2 e^4 \ln \Lambda}{(2\pi)^{3/2} \epsilon_0^2 m_j m} \frac{T - T_j}{\left(\frac{T_j}{m_j} + \frac{T}{m}\right)^{3/2}}, \quad (\text{D.17})$$

where T is the temperature of Maxwellian test particles and T_j is the temperature of Maxwellian field particles.

For electron-ion collisions, the equilibration power transferred from electrons to ions per volume are

$$p_{\text{EQU}} = 7.61 \times 10^{-34} (T_e[\text{eV}] - T_i[\text{eV}]) \frac{n_e \ln \Lambda}{T_e^{3/2}[\text{eV}]} \left(\frac{Z_i^2 n_i}{A_i}\right) [\text{eV} \cdot \text{s}^{-1} \cdot \text{m}^{-3}], \quad (\text{D.18})$$

where T_e is the electron temperature, T_i is the ion temperature, n_e is the electron density, n_i is the ion density, Z_i is the charge of ion, and A_i is the atomic mass of ion.

D.3 Heating power by fast hydrogen ions

The change rate in total energy of the Maxwellian field particles collided with a test particle is

$$\frac{\langle\Delta E_j\rangle}{\Delta t} = -\frac{\langle\Delta E\rangle}{\Delta t} \quad (\text{D.19})$$

$$= \frac{m^2 A_D}{2m_j v} \left\{ \Phi\left(\frac{v}{v_{Tj}}\right) - \left(1 + \frac{m_j}{m}\right) \frac{v}{v_{Tj}} \Phi'\left(\frac{v}{v_{Tj}}\right) \right\}. \quad (\text{D.20})$$

The heating power into the Maxwellian field particles collided with monoenergetic test particles per volume is

$$p = n \frac{\langle \Delta E_j \rangle}{\Delta t} \quad (D.21)$$

$$= \frac{nm^2 A_D}{2m_j v} F\left(\frac{v}{v_{Tj}}, \frac{m_j}{m}\right), \quad (D.22)$$

where

$$F(x, \beta) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-\xi^2) d\xi - \frac{2x}{\sqrt{\pi}} (1 + \beta) \exp(-x^2). \quad (D.23)$$

The heating power into Maxwellian electrons and ions by the monoenergetic fast hydrogen ions per volume are calculated

$$p_{f \rightarrow e} = \frac{e^3 \ln \Lambda}{4\pi\epsilon_0^2} \frac{n_e}{m_e} \frac{n_f}{v_f} F\left(\frac{v_f}{v_{Te}}, \frac{m_e}{m_f}\right) [\text{eV} \cdot \text{s}^{-1} \cdot \text{m}^{-3}], \quad (D.24)$$

$$(D.25)$$

and

$$p_{f \rightarrow i} = \frac{e^3 \ln \Lambda Z_i^2}{4\pi\epsilon_0^2} \frac{n_i}{m_i} \frac{n_f}{v_f} F\left(\frac{v_f}{v_{Ti}}, \frac{m_i}{m_f}\right) [\text{eV} \cdot \text{s}^{-1} \cdot \text{m}^{-3}] \quad (D.26)$$

$$\approx \frac{e^3 \ln \Lambda Z_i^2}{4\pi\epsilon_0^2} \frac{n_i}{m_i} \frac{n_f}{v_f} [\text{eV} \cdot \text{s}^{-1} \cdot \text{m}^{-3}], \quad (D.27)$$

respectively. Plotted, in Fig. D.1, is the values of $F(x, \beta)$ as a function of x for the collisions of fast hydrogen ions with electrons, hydrogen ions, and deuterium ions. As the electron temperature increases, this value of F decreases from 1.0 to 0.0. Because the velocity of fast hydrogen ions are much larger than the bulk ions in Heliotron J, $F(v_f/v_{Ti}, m_i/m_f)$ is estimated to be approximately one.

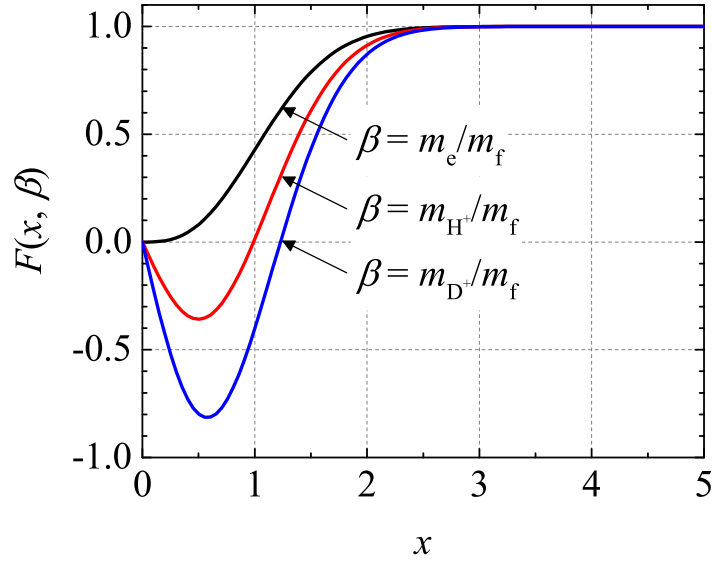


Figure D.1: Values of $F(x, \beta)$ as a function of x for the collision of monoenergetic fast hydrogen ions with Maxwellian electrons (black line), hydrogen ions (red line), and deuterium ions (blue line).

D.4 Slowing-down time of fast hydrogen ions

The slowing-down time for a test particle colliding with Maxwellian field particles is given by

$$\tau_s = - \frac{v}{\frac{\langle \Delta v_{\parallel} \rangle}{\Delta t}}, \quad (\text{D.28})$$

$$= \frac{v_{Tj}^2 v}{\left(1 + \frac{m}{m_j}\right) A_D \Psi\left(\frac{v}{v_{Tj}}\right)}. \quad (\text{D.29})$$

Now let us consider that the velocity of a test particle is much larger than the thermal velocity of field particles. By using a asymptotic expansion for Ψ , the slowing-down time is

$$\tau_s = \frac{3 \sqrt{\pi} v_{Tj}^3}{2 \left(1 + \frac{m}{m_j}\right) A_D}. \quad (\text{D.30})$$

The slowing-down time of fast hydrogen ion is given

$$\begin{aligned}\tau_{\text{se}} &= \frac{3(2\pi)^{3/2} \epsilon_0^2 m_f T_e^{3/2}}{e^4 \sqrt{m_e} \ln \Lambda} \frac{1}{n_e} \\ &= 3.16 \times 10^{16} \frac{T_e^{3/2} [\text{eV}]}{n_e [\text{m}^{-3}]} [\text{ms}],\end{aligned}\tag{D.31}$$

and shown in Fig. D.2. The slowing-down time is around 5 – 15 ms when the electron temperature drastically increases to around 100 – 200 eV after the onset of the NBI.

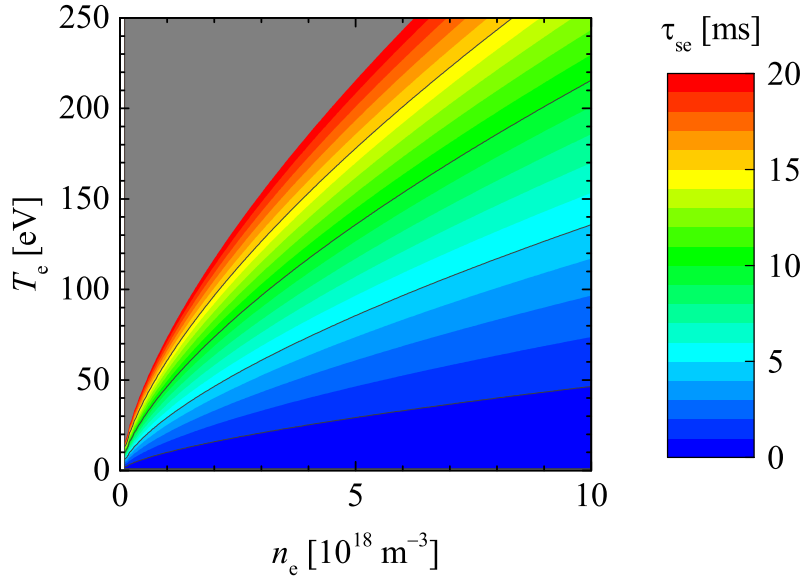


Figure D.2: Contour plot showing the slowing-down time as a function of electron temperature and electron density.

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Achievements

Awards

1. Best presentation award, K. Hada, J.H. Lee, H. Lee, S. Endo, T. Kajiwara, F. Okino, Y. Machida, L. Jiao, S. Aoyagi, M.E. Wijaya, R. abdullah, and Q. Zhang, “Hour-by-Hour Simulation of an Energy-Independent Office Building”, GCOE Group Research Presentation on 3rd August of Kyoto University Global COE Program, August 3, 2012, Kyoto, Japan

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1. T. Maekawa, S. Ide, K. Kajiwara, K. Nagasaki, A. Isayama, and K. Hada, “将来の大型超伝導トカマク装置に向けたプラズマ着火・立ち上げ研究の現状 (Recent Research Activities on Breakdown and Start-up towards Future Superconducting Large Tokamaks)”, J. Plasma Fusion Res. Vol. **87** No.10 (2011) 671-681 (解説記事).
2. K. Hada, K. Nagasaki, K. Masuda, R. Kinjo, S. Ide, and A. Isayama, “Analysis of ECRH Pre-Ionization for Plasma Start-Up in JT-60SA”, Plasma and Fusion Research Vol. **7** (2012) 2403104 (Reviewed).
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2. K. Hada, K. Nagasaki, K. Masuda, R. Kinjo, S. Ide, and A. Isayama, “Plasma startup using ECRH preionization in JT-60SA”, Korea-Japan Workshop on Physics and Technology of Heating and Current Drive, Kyoto, Japan, December 6, 2011
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5. K. Hada, K. Nagasaki, K. Masuda, R. Kinjo, S. Ide, and A. Isayama, “One-Dimensional Analysis of ECRH Assisted Plasma Start-up in JT-60SA”, US-Japan RF Heating Physics Workshop, Nara, Japan, December 11, 2012
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2. 羽田和慶, 長崎百伸, 増田開, 諫山明彦, 井手俊介, “JT-60SA における ECRH を用いた予備電離に関する解析”, モデリング・シミュレーションサブクラスターおよび定常運転・制御サブクラスター, JAEA システム計算科学センター, 2011 年 1 月 13 日
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