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Energy Balance Development for RF-induced Plasma Breakdown in QUEST

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Abstract
Plasma breakdown by radio frequency (RF) is a common method to plasma devices. In the QUEST spherical tokamak, we employ electron cyclotron resonance heating (ECRH) to initiate plasma, which is RF injection in EC frequency range (2.45, 8.2 and 28GHz). Illustration of RF-induced plasma breakdown requires particle and energy balance equation together for detailed description. In this study, we discuss the development of energy balance equation to investigate experimental observations of RF-induced breakdown in QUEST.

1. Introduction

When electric field is applied to partially ionized gas, electrons are accelerated and collide with neutrals for further ionizations. Repetition of this process yields current, and plasma discharge is achieved. In tokamak operations, breakdown of plasma is the first step of the plasma build-up. Here, the definition of breakdown is the condition that plasma discharge is achieved and sustained. The conventional way to obtain breakdown in tokamak is to apply toroidal electric field E_ϕ by changing coil current of center solenoid (CS) in time, which accelerates electrons. This method is called inductive breakdown. Breakdown conditions for inductive plasma start-up have been intensively investigated because it was one critical issue for ITER design [1]. It is well described that the minimum E_ϕ for inductive breakdown is governed by prefill gas pressure and connection length. ITER plan employs multi-pole field null configuration and additional radio RF power injection to support inductive breakdown by pre-ionization, because of the difficulty to supply sufficient E_ϕ[2]. Intensive studies had promoted in many devices to obtain reliable breakdown with ECRH [3]. Consequently, there remain no technical problems to realize a reliable breakdown in ITER with ECRH-assist [1]. Besides, in spherical tokamaks (STs) with low aspect ratio of plasma, the space for CS is technically limited and operation without CS is the important issue. CS-less design can directly contribute to enhancing its compactness and cost-effectiveness. For this purpose, non-inductive plasma current start-up experiments with ECRH have been demonstrated in STs with external vertical field B_v: MAST, CDX-U, LATE TST-2 and QUEST. Experiments on CDX-U and DIII-D show a parameter scan of plasma current I_p with different B_v, RF power and neutral pressure. In the experiments, I_p changes proportionally to RF power, inversely to neutral pressure and B_v. They also present that confined electrons in open field are important in breakdown phase. This indicates magnetic configuration and strength of B_v play essential roles in RF-induced breakdown. In QUEST, the importance of incubated electrons due to magnetic configuration has been also confirmed by experiments and a modeling that lifetime of electrons highly contributes to breakdown occurrence [4]. In the modeling previously developed only solves particle balance equations in time. Therefore, in this study, we discuss development of energy balance equations to include RF power dependence.

2. Particle and Energy Balance Equations

The model we developed in this paper is based on the Townsend avalanche theory. In this model, plasma breakdown is achieved when the ionization rate of neutral hydrogen atoms and molecules caused by electron impact exceeds the loss rate of electrons. Therefore, we can simply express the relation between electron production and loss as,

$$\frac{dn_{\mathrm{e}}}{dt} = n_{\mathrm{e}}(\tau_{\mathrm{ion}}^{-1} - \tau_{\mathrm{loss}}^{-1})$$

where τ_{ion}^{-1} is the ionization rate and $\tau_{\mathrm{loss}}^{-1}$ is the loss rate. Hence, electron density is,

$$n_{\mathrm{e}} = n_{\mathrm{e0}} \exp[(\tau_{\mathrm{ion}}^{-1} - \tau_{\mathrm{loss}}^{-1})t],$$

where n_{e0} is the initial density of electrons. For ionization rate τ_{ion}^{-1}, it is usually referred as Townsend first coefficient α. We propose a different approach to evaluate RF-induced breakdown by building up a model that derives α in time as a result of overall reactions such as ionization, recombination and excitation. Following the database of the reactions [5], the model developed solves particle balance equations in time. The particle balance equation [6] is described as below,

$$\frac{dn_p}{dt} = \sum_{j<k} \sum_i \epsilon_{jkp}^i k_{jk}^i n_j n_k - \frac{n_p}{\tau_{\mathrm{loss}}},$$

where, ϵ_{jkp}^i is the number of lost or gained, k_{jk}^i is reaction rate for reaction i between j and k, n_p is population density. The first term of the right hand side of the equation stands for the production of particles and the second is the loss term represented by τ_{loss}.

Energy balance equations accompanied with particle balance [6] is written as,

$$\frac{3}{2}\frac{dn_p T_p}{dt} = \sum_{j<k} \sum_i \epsilon_{jkp}^i E_{jkp}^i k_{jk}^i n_j n_k + \sum_j E_{jp} k_j^{\mathrm{el}} n_j n_p + P_{\mathrm{RF},p},$$

where T_p is Maxwellian temperature, E_{jkp}^i the corresponding energy change for involved populations. k_j^{el} is the elastic collision reaction and $P_{\mathrm{RF},p}$ is the RF power coupled to plasma. In the equation, the first term in the right hand side stands for inelastic collisions and the second for elastic collisions.

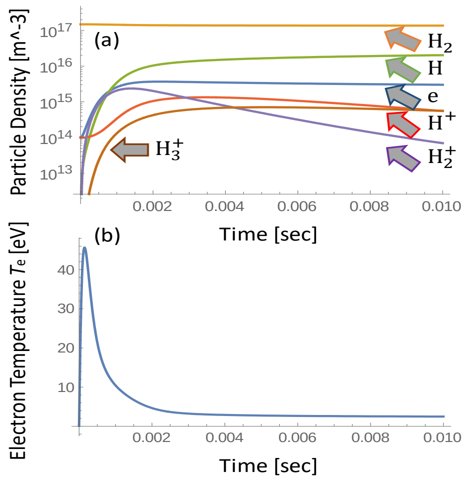

Figure 1. Modeling results of particle and energy balance equations. (a) Hydrogen particle density and (b) electron temperature in time.

3. Simulation Results and Discussion

Firstly, in Fig.1, we demonstrated a simulation by ignoring elastic collisions for simplicity. We assumed that power absorption to plasma occurs a cylindrical EC resonance layer, which is reasonable for RF-induced breakdown in tokamak magnetic configurations. Electron density and temperature become steady after the rapid increase at 1ms. These observations are consistent with experimental results. Description in detail will be given in the presentation.

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