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Particle-loss Control Modeling for ECRH Breakdown in QUEST

Ryota YONEDA[1], Kazuaki HANADA[2]
[1]*IGSES Kyushu University, Kasuga 816-8580, Japan*
[2]*RIAM Kyushu University, Kasuga 816-8580, Japan*

Abstract
A combinative investigation of RF-induced breakdown experiments with altering magnetic configuration and a point model of hydrogen ionization was carried out. For positive and negative n-index configurations, the results showed different behavior from each other. Conventional mechanism of breakdown phase can be applied for the negative n-index configuration. In the other hand, in cease of positive n-index, it was indicated that trajectory of confined electrons enhances breakdown more likely.

1. Introduction

RF-induced breakdown will be applied in ITER [1]. For ITER, the electric field that applied to bring to ionization of prefill gas and current drive should be less than 0.3 V/m. Since the superconducting coil and thick vacuum vessel limit the maximum toroidal field. Meanwhile for spherical tokamaks (STs), it is also important to cause breakdown and start-up of the plasma without using center solenoid (CS). In STs, the space for CS is basically limited because of its unique design and that requires another power source to initiate plasma. Electron cyclotron resonance heating (ECRH) has been intensively developed to ionize and to start-up plasma. Such non-inductive plasma experiments with ECRH have been investigated broadly in STs.

The Tokamak discharge can be divided into three procedures: (1) plasma breakdown phase, (2) plasma formation phase (3) plasma current start-up phase. In this study, we focus on the first breakdown phase and give quantitative investigation how breakdown of plasma can be affected by the initial magnetic configuration. Let us start with the conventional breakdown mechanism. The process of breakdown has been simply illustrated as a competition between plasma production and particle-loss [2]. The difficulty to evaluate breakdown in detail comes from its complex, one has to take into account such effect of single particle collision-less heating, neutral particle elastic and inelastic collisions, Coulomb collisions, grad B drifts and $E\times B$ drifts. Therefore, some parameters must be chosen to examine breakdown. Typical duration for particle-loss (τ) was set for that purpose during this study. A combinative investigation of RF-induced breakdown experiments with altering magnetic configuration and a point model of hydrogen ionization has been performed to evaluate τ.

2. Experimental Apparatuses

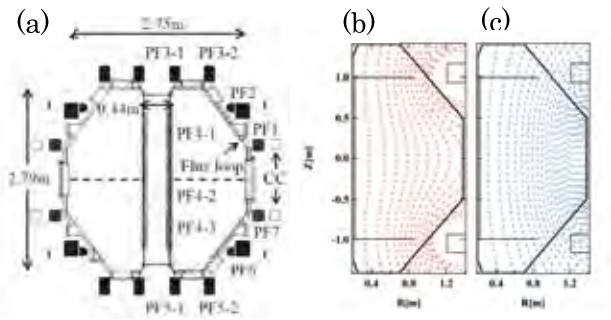

Figure 1. (a) Cross-sectional side view of QUEST (b) Positive n-index configuration (c) Negative n-index configuration.

QUEST is a middle-sized ST with R=0.64 m, a=0.40 m, and toroidal magnetic field B_T<0.25 T. It is equipped with electron cyclotron wave at frequency of 2.45 GHz and 8.2 GHz. For each frequency RF power that injected was set to approximately 10kW to minimize the power-dependent effect. Magnetic configuration of positive and negative n-index at electron cyclotron

resonance (ECR) layer can be controlled in combination with poloidal field (PF) coils. Figure 1 shows the schematic view of QUEST including PF coils. All experiments were performed on QUEST.

3. Point Model of Hydrogen Ionization

Theoretical interpretation of the breakdown phase is based on the Townsend avalanche. Ionization by electrons that accelerated in the applied electric field has to overcome the loss electrons that caused by such as drift loss and direct loss along with magnetic field lines. Thus, the relation between production and disappearance of particles is expressed as below,

$$n_e = n_{e0}[(\tau_{ion}^{-1} - \tau_{loss}^{-1})\mathrm{t}] \qquad (1)$$

where τ_{ion}^{-1} is the ionization rate, τ_{loss}^{-1} is the loss rate and n_{e0} is the initial density of free electrons. It was discussed that the dominant loss comes from the direct loss along with magnetic field lines [2]. Therefore, the expression can be written as,

$$n_e = n_{e0}\exp\left[v_\varphi(\alpha - L^{-1})\mathrm{t}\right] \qquad (2)$$

where v_φ is the thermal velocity, α is the Townsend's first coefficient and L is the connection length. Here, based on the model above, a point model that includes possible reactions of hydrogen such as ionization, excitation and recombination. Table 1 denotes the reactions implemented in the model. In this manner, we can rewrite the expression and constitute a point model [3],

$$\frac{dn_e}{dt} = \sum_{j<k}\sum_{i} \epsilon_{jk}^{i} k_{jk}^{i} n_j n_k - \frac{n_e v_\varphi}{L} \qquad (3)$$

where ϵ_{jk}^{i} is the number of lost or gained electron at each reaction, k_{jk}^{i} is the reaction rate of reaction i between j and k, n is the population density. The point model allows to describe α in more detail. Here, typical duration for particle-loss is set as $\tau = L/v_\varphi$. Then, $v_\varphi = C_s = \sqrt{k_B T_e/m_i}$. C_s is the ion sound velocity. Assuming that escaping electrons' velocity is governed by the motion of following ions. The developed point model requires initial parameters of electron temperature and density of free electrons. These were measured by the diverter probe during experiments. Note that the point model includes the collisionality between neutrals and electrons since reactions on Table 1 are implemented.

Table 1. Implemented reactions of point model.

Electron Collisions with H, H^+		
(1) Excitation	$e + H \rightarrow e + H^*(n = 2,3)$	R1
(2) Ionization	$e + H \rightarrow e + H^+ + e$	R2
(3) Recombination	$e + H^+ \rightarrow h\nu$	R3
Electron Collisions with H_2, H_2^+ and H_3^+		
(4) Dissociation	$e + H_2 \rightarrow e + H + H$	R4
(5) Ionization	$e + H_2 \rightarrow e + H_2^+ + e$	R5
(6) Dissociative Ionization	$e + H_2 \rightarrow e + H^+ + H + e$	R6
(7) Dissociation	$e + H_2^+ \rightarrow e + H^+ + H$	R7
(8) Dissociative Recombination	$e + H_2^+ \rightarrow H + H$	R8
(9) Dissociative Recombination	$e + H_3^+ \rightarrow H_2 + H$	R9
(10) Dissociative Recombination	$e + H_3^+ \rightarrow e + H^+ + H + H$	R10

4. Experimental Results and Discussion

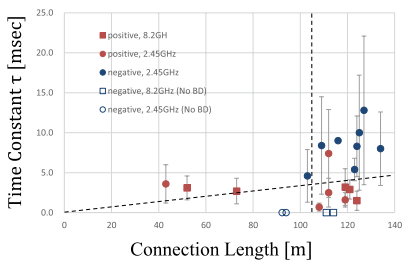

Figure 2. Evaluated τ with different n-index

Experiments were demonstrated with altering magnetic configuration to quantitatively investigate τ. For each discharges, after RF power turns off, exponential fitting for H_α signal decay was calculated to evaluate τ. Figure 2 shows results with different magnetic configuration and frequency. The dotted line in lateral direction is estimated τ from the point model. And the vertical dotted line shows breakdown threshold of L from the model. Results with negative n-index are consistent with the conventional interpretation of breakdown. In the other hand, with positive n-index, it suggests that the existence of confined electrons in breakdown phase. More detail will be discussed in the presentation.

Reference

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