P09

The Particle-loss Control of RF-induced Breakdown with Tokamak Magnetic Structure in QUEST

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Abstract
Understanding of plasma breakdown process in tokamak magnetic configuration has a difficulty because of its sudden occurrence and nonlinearity. Especially in RF-induced breakdown, it is not fully investigated and stays on empirical knowledge. A combinative investigation of RF-induced breakdown experiments with altering magnetic configuration and a point model of hydrogen ionization was performed. The results showed that electron temperature required for breakdown must reach 4.0 to 6.0 eV.

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. The understanding of this mechanism to acquire the plasma discharge has a difficulty because of its sudden occurrence and nonlinearity. In tokamaks operation, breakdown of plasma is the first step of the tokamak plasma build-up. Here, the definition of breakdown is the condition that plasma discharge is achieved and sustained, not when the ionization of gas is enhanced. Later it will be discussed more in detail that breakdown is electron avalanche as a result of competition of plasma particle production and loss. The conventional way to get breakdown in tokamak is to apply toroidal electric field by changing coil current of center solenoid (CS) coil in time, which accelerate electrons. This method is called inductive breakdown. In future large tokamaks such as ITER[1] and JT60-SA[2], there is a concern to realize promising plasma breakdown and start-up[1,3]. Superconducting coil system and thick vessel set a limitation to the maximum toroidal field to make an inductive breakdown of plasma in those tokamaks. In this way, inductive breakdown has to be carefully handled. As for ITER, the maximum electric field must be less than 0.3 V/m and its plan employs additional radio frequency (RF) power injection to support inductive breakdown[1]. This RF power injection is one non-inductive method for breakdown and start-up. RF-induced breakdown is realized with different mechanism with inductive one. The mechanism is called electron cyclotron resonance heating[4] (ECRH). Non-inductive start-up experiments with ECRH have been demonstrated in many tokamaks: DIII-D, MAST, LATE and TST-2. Breakdown conditions for inductive plasma start-up have been also investigated because it was one critical issue for ITER design. Consequently, there remain no technical problems to realize a reliable breakdown in ITER with ECRH assist[1]. However, the nature of RF-induced plasma breakdown in a tokamak type of magnetic configuration is not fully understood and stays on empirical knowledge. Experiments on particle loss scheme with RF-induced plasma after breakdown has been reported showing good agreement with theory[5]. By applying particle loss scheme onto breakdown phase, therefore, the conditions and optimization of RF-induced breakdown will be discussed in this paper.

2. Point model of hydrogen-plasma

Plasma breakdown mechanism in magnetic structure of tokamaks is simply described that it is a competition between the particle production and loss of plasma. We can simply express the relation between electron production and loss as,

$$\frac{dn_e}{dt} = n_e(\tau_{\text{ion}}^{-1} - \tau_{\text{loss}}^{-1}),$$

where τ_{ion}^{-1} is the production rate via ionization and τ_{loss}^{-1} is the loss rate. For ionization rate τ_{ion}^{-1}, it is usually referred as Townsend first coefficient α. We propose a new approach to build up a model that derives α in time as a result of overall reactions such as ionization, recombination and excitation. Following the database of reaction rate[6], the model developed solves particle balance equations in time. The particle balance equation is described as below,

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

where, ϵ_{jkp}^{i} is number of lost or gained particles, k_{jk}^{i} is reaction rate for reaction i between j and k,

n_p is population density[7]. 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}. The accelerated electrons at ECH layer by RF are assumed to be governed by ambipolar diffusion and this mechanism results in that electrons practically move along magnetic field lines at the ion sound velocity C_s. By introducing the loss term due to electron movement parallel to the magnetic field, the point model of hydrogen ionization is modified. For the electron density, the particle balance equation is described as,

$$\frac{dn_e}{dt} = \sum_{j<k}\sum_{i} \epsilon^i_{jkp} k^i_{jk} n_j n_k - \frac{n_e C_s}{L},$$

where, L is the connection length of magnetic line of force.

3. Experimental Apparatus (QUEST)

Q-shu Univ. Experimental Steady-State Spherical Tokamak (QUEST) is a medium-sized spherical tokamak at Kyushu University. Outer diameter of the vacuum vessel is 2.74m, inner diameter is 0.44m and its height is 2.8m as shown in Fig. 1. Flat divertor plates are set at ±1m from the mid-plane. A Langmuir probe array is located in radial direction on upper diverter plate. As for RF system, one 2.45 GHz system up to 50kW, two 8.2GHz Klystron systems up to 400kW. 2.45 GHz system is mainly used in wall conditioning with low injection power. The 8.2GHz systems are used for plasma heating and current drive. RF injected from both RF systems was propagating as O-mode in the experiments. Experiments are performed with different n-index configuration by controlling PF coils: positive and negative n-index configuration.

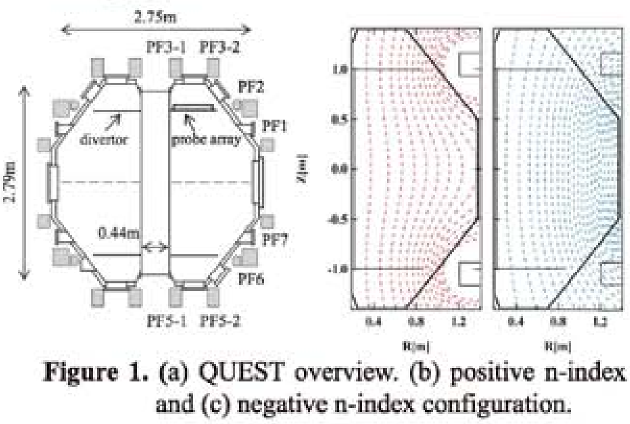

Figure 1. (a) QUEST overview. (b) positive n-index and (c) negative n-index configuration.

4. Experimental Results and Discussion

The experiments of RF-induced breakdown were carried out with different RF frequencies of 2.45 GHz and 8.2 GHz. Both for 2.45GHz and 8.2GHz, there were no effects on the RF injection power, however, clear thresholds of breakdown existed on L. They were 110m for 2.45GHz and 85m for 8.2GHz respectively. In these conditions, direct loss along magnetic field lines is superior and breakdown conditions were highly sensitive with L. On the other hand, for positive n-index, there were no dependence on both RF injection power and L, and breakdown was always obtained.

To compare the conditions with negative n-index configurations whether breakdown of plasma was acquired or not, the electron temperature T_e and the electron density n_e of the divertor probe were investigated. since the electron temperature and density have no strong tendency against the connection length, one can estimate that even if the connection length is shorter than the threshold where the breakdown was not achieved, there must be plasma almost the same values with them. Typically, T_e = 2.0 ~ 4.0 [eV] and n_e = 1.0 ~ 2.0×10^{15} [m^{-3}] for 2.45 GHz and T_e = 4.0 ~ 5.0 [eV] and n_e = 1.0 ~ 3.0×10^{15} [m^{-3}] for 8.2GHz. Based on these parameters, the point model calculation was performed to illustrate breakdown occurrence.

In Fig. 2, comparisons between the modeling threshold of electron temperature for breakdown

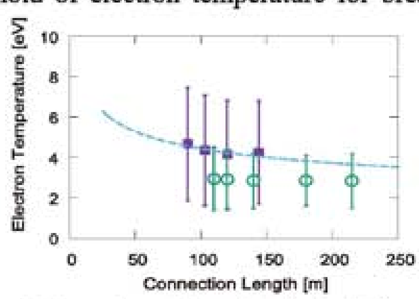

Figure 2. Experimental results for both frequencies with negative n-index. ○: 2.45GHz and ■ : 8.2GHz. Dashed line: modeling result of minimum T_e of breakdown.

and experimental results is shown. The shorter L becomes; the higher electron temperature must be achieved for breakdown. In practical, the injected RF power cannot heat electrons up and Townsend avalanche could not have obtained. It also presents that breakdown of plasma requires electron temperature approximately from 4.0 to 6.0 eV.

Reference

[1] R. Toschi, IAEA-CN-53/F-I-2 225 (1991).
[2] K. Hada, Plasma Fusion Res. 7, 1 (2012).
[3] J. Stober, Nucl. Fusion 51, 83031 (2011).
[4] V. Erckmann, Plasma Phys. Control. Fusion 36, 1869 (1994).
[5] S. Nakao, Phys. Lett. A 96, 405 (1983).
[6] J. R.K. Janev, ELEMENTARY PROCESSES IN HYDROGEN-HELIUM PLASMAS (Springer-Verlag, Berlin, 1987).
[7] T. Wauters, Plasma Phys. Control. Fusion 53, 125003 (2011).