2D-SIMULATIONS OF BREAKDOWN IN TOKAMAK BY COLLISIONAL IONIZATION MODEL

Hiroaki Tsutsui and Ryuichi Shimada
Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology
2-12-1 O-okayama, Meguro-ku, Tokyo 152-8550, Japan

Abstract

Tokamak breakdown processes are studied by self consistent two dimensional computer simulation code. All electromagnetic fields produced by eddy current and plasma current are considered. The ionizations are estimated from the cross sections of elementary processes which strongly depend on the energy of electrons. The density and energy of electrons are determined by conservation laws while the orbit is determined by drift approximation. The good agreements of the computational results and the experiments of JT-60U are obtained.

1. Introduction

In designing the power supply system of a large tokamak, it is important to estimate the breakdown voltage, since the maximum voltage occurs at the breakdown phase.

To evaluate the breakdown voltage, it is necessary to investigate the discharge formation process in the torus configuration. While the discharge formation between the electrodes is described by Townsend's theory [1], no theory exactly describes the torus discharge. In particular, the discharge in the tokamak reactor is characterized by a strong toroidal magnetic field and low gas pressure.

The torus discharge consists of three processes: (1) breakdown process, (2) plasma formation process, (3) plasma current ramping up process. In this study, we restrict our interests to (1) and (2) where casual electrons are accelerated by the electric field and avalanching by the collisional ionization while some electrons vanish due to crashes with the vacuum vessel. Since the orbits of electrons are chiefly determined by the magnetic field, the poloidal magnetic field, which comes from poloidal field (PF) coils or eddy currents on the vacuum vessel, significantly affects the breakdown condition.

In the next section, we discuss the breakdown process in the toroidal system. The simulation model in this study is explained in Section 3. The computation results and comparisons with experiments of JT-60U are shown in Section 4, and summarized in Section 5.

2. Breakdown Process in Toroidal System

In the initial stage of tokamak discharge, the gas in the vacuum vessel consists of few electrons and many neutral molecules of hydrogen. Because the mass of molecules are much larger than that of electrons, we assume the gas is Lorenzian in which the electrons are accelerated by electric field and avalanching by the collisional ionization. This avalanche process modifies the mass conservation law as follows:

$$\frac{dn_i}{dt} = \alpha v_d n_e, \tag{1}$$

$$\alpha \equiv \frac{\sum_j n_j < \sigma_j v_e >}{v_d}, \tag{2}$$

$$v_d \equiv < v_e >, \tag{3}$$

where α is Townsend's coefficient, indices i, j show the species of particles H, H^+, H_2, H_2^+, and <> means the average about the energy of electrons. In this work, we assume that the distribution of electron velocity is shifted-Maxwellian whose average is the drift velocity v_d.

Using the energy loss of Δw_j by one collision, the energy conservation law is written as

$$\frac{d}{dt}(n_e W_e) = \boldsymbol{j} \cdot \boldsymbol{E} - n_e \sum_j \nu_j \Delta w_j, \tag{4}$$

$$\nu_j = n_j < \sigma_j v_e >, \tag{5}$$

where W_e is the averaged kinetic energy of electrons, and ν_j is energy exchange frequency for collision j. In this study, we consider the elementary processes whose cross sections are large and strongly depend on the energy of electrons [2]. By use of Δw_j, the relaxation frequencies for momentum are given as

$$\nu_p^j = \begin{cases} \frac{\Delta w_j}{2W_e} \nu_j & \mathrm{e} \to \mathrm{e}, \\ (1 + \frac{\Delta w_j}{2W_e}) \nu_j & \mathrm{e} \to 2\mathrm{e}. \end{cases}$$

In the quasi-steady state, the momentum conservation law is replaced by the drift equation. The flux of particles $\boldsymbol{\Gamma}$ are expressed by mobility tensor $\boldsymbol{\mu}$ and diffusion coefficient tensor D as follows:

$$\boldsymbol{\Gamma} = \boldsymbol{\mu} \boldsymbol{E} n - \nabla \cdot (Dn). \tag{6}$$

When we choose the direction of magnetic field as z, the mobility tensor is show as

$$\boldsymbol{\mu} \simeq \frac{e}{m} \begin{bmatrix} \frac{\nu_p}{\omega_b^2} & -\frac{1}{\omega_b} & 0 \\ \frac{1}{\omega_b} & \frac{\nu_p}{\omega_b^2} & 0 \\ 0 & 0 & \frac{1}{\nu_p} \end{bmatrix}, \tag{7}$$

which includes the motions along the magnetic field and ExB drift. In this work, the diffusion term is neglected compared with the drift term.

Farady's and Ohm's laws in axisymmetric system are shown as

$$\frac{\partial \psi}{\partial t} + \oint \boldsymbol{E} \cdot d\boldsymbol{l} = V, \tag{8}$$

$$\boldsymbol{E} = \eta \boldsymbol{j}, \tag{9}$$

$$\int G(\boldsymbol{x}, \boldsymbol{x}') j_\phi(\boldsymbol{x}') d^2 x' = \psi(\boldsymbol{x}), \tag{10}$$

where ψ, V, η, $\boldsymbol{j}$ are poloidal flux, external voltage, resistivity and current density, respectively. The function G is Green's function of Grad-Shafranov equation corresponding to the mutual inductance [3].

When the temperature of electrons T_e is assumed to be statinary, the next relations are obtained from Eqs. (4) and (6),

$$E^2 = \frac{m \nu_p(T_e)}{e^2} \sum_j \nu_j(T_e) \Delta w_j. \tag{11}$$

By use of this relation, we obtain the mobility $\mu_\parallel$ and Townsend's coefficient α as functions of the electric field.

We compare our static model with the experiments by use of electrodes [4] in Fig. 1. There are large deviations in the region of weak pressure which is one of the characters of tokamak.

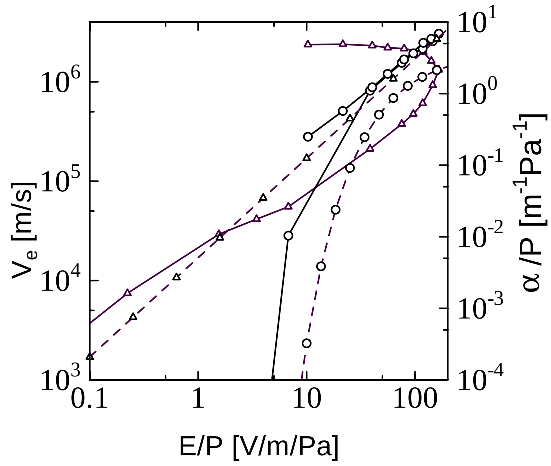

Fig. 1: Velocities (triangles) of electrons and Townsend's coefficients (circles) of hydrogen. Solid lines are results of our static model, dotted lines are that of the experiments.

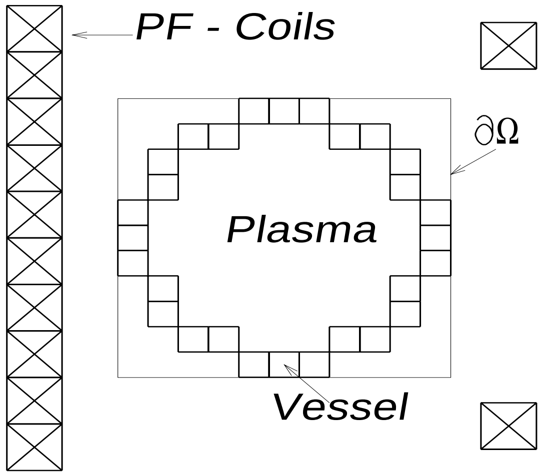

Fig. 2: Cross section of simulation model. $\partial\Omega$ is computational boundary.

3. Numerical Model

The simulation model is depicted in Fig. 2. Since tokamak reactor is axisymmetric, we analyze the two dimensional model on toroidal cross section. The model consists of a toroidal filed coil, poloidal field (PF) coils and the computational region. The PF coil is treated as a co-axial circular one-turn coil with power supply. The computational region are divided into many cells, and every cell is assigned to plasma, vessel or vacuum which has neither electrons nor conductivity. The vacuum vessel is treated as a set of co-axial circular coils similar to PF coils. All physical quantities are determind by Eqs. in Section 2. The flow diagram in our calculation is shown as Fig. 3. In this work, we choose the success of breakdown as the ionization degree of 0.1 where the electron-ion collisions become dominant [5].

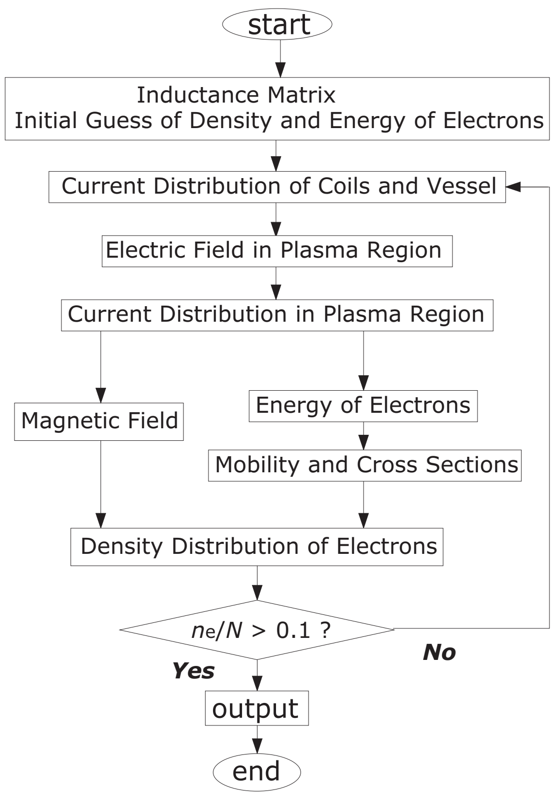

Fig. 3: Flow diagram.

4. Simulations

In this section, we investigate the breakdown conditions for JT-60U and compare them with the results of experiments [6].The parameters used in simulations are listed in Table 1. In this work, the initial degree of ionization is assumed to be 1.0×10^{-10}.

Parameters	Values
Toroidal field at center	3.0 T
Major radius of vessel	3.32 m
Minor radius of vessel	1.7 m
Temperature of neutral gas	423 K
Resistance of vessel	$1.60 \times 10^{-4}\Omega$
Decay time of vessel	15 ms

Table 1: Parameters of JT-60U.

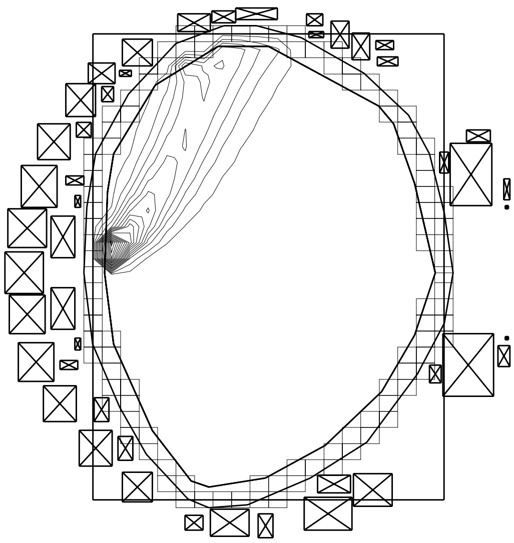

Fig. 4: The distribution of electron density at the breakdown for the initial conditions of $P = 1.0 \times 10^{-2}$ Pa, $n_e(0)/N = 1.0 \times 10^{-10}$.

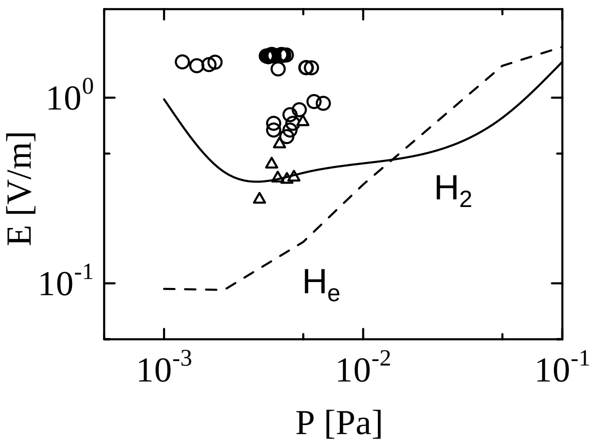

Fig. 5: Border of breakdown for JT-60U. Solid (hydrogen) and dashed (helium) lines are the boundary of breakdown determined by our calculations. Data of experiments by hydrogen are labeled as circles(success) and triangles(fail).

Figure 4 is the distribution of electron density at the breakdown. The position of the largest density is the breakdown region where poloidal field of 30 gauss is the weakest. Next we investigate relations between pressure of neutral gas and electric field for breakdown. The border of breakdown is depicted in Fig. 5. This figure shows our calculations have the qualitative agreement with experiments [6].

Finally we evaluate the breakdown condition by use of helium gas instead of hydrogen because the breakdown voltage of helium is less than that of hydrogen in the experiments by use of electrodes. The results of calculations are also depicted in Fig. 5 which shows helium has advantage over hydrogen in breakdown.

5. Summary and Conclusions

To analyze the breakdown phenomena in the strong magnetic field, we made 2-dimensional simulation code which includes all electromagnetic fields by electric current and depends on the avalanche model. The cross sections in the model are obtained by the energy of electrons whose energy distribution is assumed to be shifted-Maxwellian and determined by the energy conservation law. By use of our code, we have a qualitative agreement of simulations and experiments by JT-60U for the breakdown condition of pressure and electric field. Moreover, the advantage of helium against hydrogen is obtained.

We have to obtain the quantitative agreement including the static electric field by space charge, and should extend this model to the current ramp up phase.

References

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