31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-2.139 (2004)

Plasma Breakdown Analysis in JFT-2M without the Use of Center Solenoid

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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. On the other hand, the fundamental geometry of a low aspect ratio spherical tokamak (ST), which is very attractive for a possibility of the high beta plasma, is precluded by the presence of a large center solenoid (CS). Therefore, breakdown techniques without the use of a CS have been expected for promising low aspect ratio reactor concepts. Recently, a solenoid-less startup in JT-60U was demonstrated [1] and focused the spotlight of attention, while the solenoid-less startup had been performed in JFT-2M, which is a middle-sized tokamak device with an iron core and ferritic steel boards [2].

To evaluate the breakdown voltage, it is necessary to investigate the discharge formation process in the toroidal configuration. While the discharge formation between the electrodes is described by Townsend's theory [3], the discharge in the tokamak reactor is characterized by a strong toroidal magnetic field and low gas pressure. In the previous work [4], we introduced a collisional ionization model based on elementary processes, and succeeded to explain a breakdown experiment in JT-60U [5] by 2D simulations based on the model.

In the next section, we show a breakdown experiment in JFT-2M. A simulation model of the breakdown process in the toroidal system is explained in Section 3. The computation results and comparisons with the experiments are shown in Section 4, and summarized in Section 5.

2. Breakdown Experiments in JFT-2M

JFT-2M is a middle-sized (R = 1.31 m, a = 0.35 m, $B_{\mathrm{T0}} < 2.2$ T) tokamak device with an iron core, a toroidal gap resistance and ferritic steel boards, and performed the Advanced Material Tokamak EXperiment (AMTEX) program [2] in order to demonstrate compatibility between plasma and the low activation ferritic steel (such as F82H) which is a leading candidate material for a fusion demonstration reactor. JFT-2M has been operating a solenoid-less startup in which only a set of poloidal field (PF) coils are used for the breakdown.

Since the saturation magnetic density of the ferritic steel is about 0.3 T, breakdown voltages were obtained for B_{T0} = 1.6 T, 0.6 T and 0.3 T, in which the breakdown was judged by both D_α signals and a loop voltage drop. Experimental results are

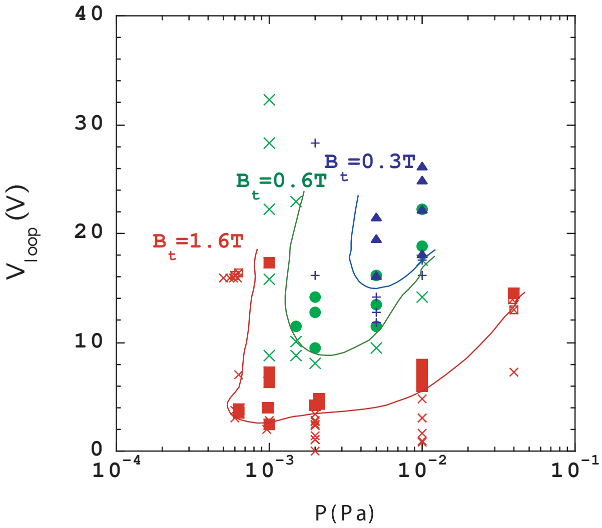

Figure 1. Breakdown tested points in the region of loop voltages and neutral gas pressures in the breakdown experiments for toroidal fields B_T of 1.6 T, 0.6 T and 0.3 T. Fails and Successes at B_T = 1.6 T, 0.6 T and 0.3 T in breakdown are marked with crosses, squares, circles and triangles, respectively.

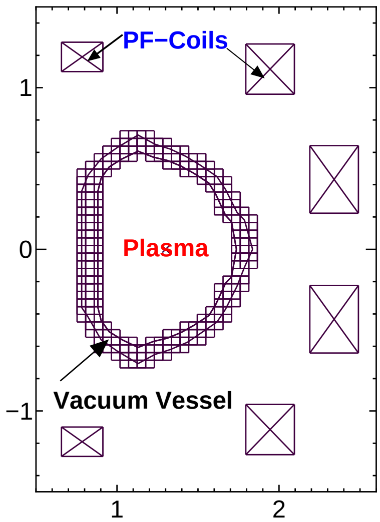

Figure 2. The poloidal cross section of JFT-2M and its simulation model.

summarized in Fig. 1 where peak-applied voltages are plotted as a function of neutral gas (D_2) pressure. Required loop voltages for the breakdown are reduced with a stronger magnetic field which is equivalent to the reduction of error fields. The minimum neutral gas pressure required for breakdown exists. Under the pressure, the required voltage increases abruptly or a breakdown does not occur. This result qualitatively agrees with the experiments of JFT-2 [6] and a conventional breakdown theory [7], while the effect of the ferritic steel is not found.

3. Numerical Model of Breakdown Process

In the previous work, we developed a 2D simulation code [4], and succeeded to explain a breakdown experiment in JT-60U [5]. In this work, we include the effects of the iron core and the toroidal gap resistance into the simulation model. The poloidal cross section of the numerical model is illustrated in Fig. 2. The computational region are divided into many cells which are assigned to either plasma, vessel or vacuum. The vacuum region has neither electrons nor conductivity, while the plasma area is assumed to be filled with many electrons. The vacuum vessel is treated as a set of co-axial circular coils similar to PF coils.

In order to simulate the toroidal insulation, a gap resistance R_G is inserted among coils which simulate a vacuum vessel. A loop voltage V_i in the ith vacuum-vessel coil is given by

$$V_i = R_i I_i + R_{\rm G} \sum_i I_i. \tag{1}$$

According to the measurement of magnetic fields, the iron core scarcely affects a poloidal field in the vacuum vessel. Then the effect of the core can be included as a modification of Green's function (mutual inductance) [8]. Assuming that the iron core is sufficiently fine and long and exists on the z axis, the additional term is given by

$$\Delta G(\boldsymbol{x}, \boldsymbol{x}') = \frac{\mu_0 \chi_{\rm m}}{2} \frac{\pi a^3}{r r'}, \tag{2}$$

where a and $\chi_{\rm m}$ are the radius and the relative permibility of the core, respectively. This term can also keep the Hermitian form of the Green's function, and indicates the flux in the core in the case of $r = r' = a$.

4. Simulations

In this section, we investigate the breakdown conditions for JFT-2M and compare them with the experimental results, which are shown in Section 2. In this work, the initial ionization degree is assumed to be 1.0×10^{-10}, and the threshold of the breakdown is chosen as the ionization degree of 0.1 where the electron-ion collisions become dominant [7].

Using the 2D-simulation code with the modifications for JFT-2M without the ferritic steel, time evolutions of ionization are computed in Fig. 3. Effects of the toroidal gap and the iron core are investigated, and it is found that they are necessary for the breakdown.

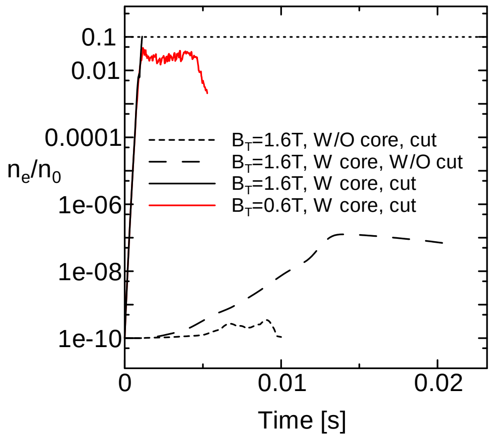

Figure 3. Time evolutions of ionization in three different models; without an iron core and toroidal gap (dotted line), without a gap and with a core (dashed line), with a core and a gap (solid line).

Finally we evaluate the breakdown condition in JFT-2M as shown in Fig. 4. Comparing the simulation with the experiments, the range of neutral gas pressure required for the breakdown is narrow, and the voltages become low, while the effect of toroidal field has not yet obtained numerically. A breakdown happens in closed magnetic surfaces as shown in Fig. 5. Distributions of electron and current densities are not completely overlapped yet. More detailed calculations and investigations of the simulation model are needed.

5. Summary and Conclusions

The breakdown characteristics (voltage and pressure) of JFT-2M were experimentally obtained. Dependences on the toroidal fields were also obtained, and it was confirmed that the breakdown voltage increases with the toroidal field strength, while the effect of

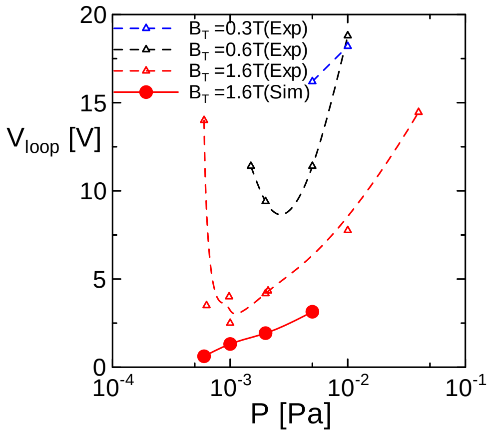

Figure 4. Border of breakdown in JFT-2M. A solid line is the boundary of breakdown for $B_{\mathrm{T}} = 1.6$ T determined by simulations. Data of experiments are labeled as triangles for $B_{\mathrm{T}} = 1.6$ T, 0.6 T, 0.3 T.

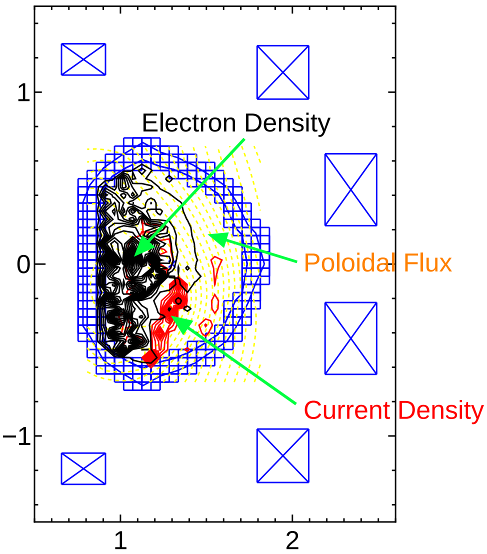

Figure 5. Contours of electron density (black lines), current density (red lines) and poloidal flux (yellow dashed lines) when a breakdown was successful for $B_{\mathrm{T}} = 1.6$ T.

the ferritic steel was not found. Using the simulation code, which can explain a JT-60U breakdown experiment, modified for JFT-2M, the breakdown in JFT-2M is investigated and compared with that of the experiments. The toroidal gap and the iron core are required for the breakdown, while quantitative agreements between the experiments and the simulation were not obtained.

A usual tokamak device has a stray magnetic field produced by the initial exciting current of CS, and its breakdown strongly depends on the stray field. Since the solenoid-less startup, however, has no stray field initially, the formation of closed magnetic surfaces is necessary for the breakdown, whereas the formation process has not yet been cleared. Thus more computations and a further extension of the code including the current ramp-up phase are required.

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