Analysis of the Magnetic Field Configuration at the Ohmic Breakdown Phase of a Tokamak

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1. Introduction

One of major methods to initiate the plasma in a tokamak is ohmic breakdown. At the ohmic breakdown phase, toroidal electric fields induced by time-varying current of central solenoids (CS) heat background electrons in the tokamak. Heated electrons ionize neutral gases continuously then breakdown occurs due to avalanche of electrons. During CS current swing, stray magnetic fields which impede the breakdown are produced by eddy currents induced in the vessel and by inherent error fields present in the tokamak. To minimize the stray magnetic fields, field-null region is produced by using appropriate current wave form of poloidal field coils (PFCs). Quality of the field-null region determines whether breakdown occurs or not. Precise estimation of the null quality is needed to develop the optimized ohmic breakdown scenarios.

This research focuses on the development of numerical method to analyze the magnetic field configuration and estimate the null quality precisely. It is essential for the robust breakdown and start-up of fusion devices especially ITER and beyond ITER owing to the low toroidal electric field ($\le 0.3\ \mathrm{Vm^{-1}}$) imposed by terminal voltage limitations on the multi-turn superconducting poloidal field coil system.

2. Methods and Results

Ohmic breakdown of the tokamak can be explained by the Townsend avalanche theory. Townsend first coefficient α which means ionization growth rate is defined as (1), where A and B are coefficients depending on gas species, p is the neutral gas pressure and E is the electric field.

$$\alpha = Ap\exp(-Bp/E) \quad (1)$$

The connection length L is the length of the magnetic field line between intersections with vessel wall surfaces. If we assume drift-free electrons, electrons ionize the neutral gases in the vessel while following the magnetic field line from one wall surface to the other. αL is the average number of ionization reaction by one electron following the magnetic field line before it exits vessel. To sustain the ionization reactions, αL should be larger than 1 as per the Townsend avalanche theory. Generally, two methodologies, “Lloyd condition” and “Field-line-following analysis” are available to analyze the magnetic fields configuration based on the Townsend theory.

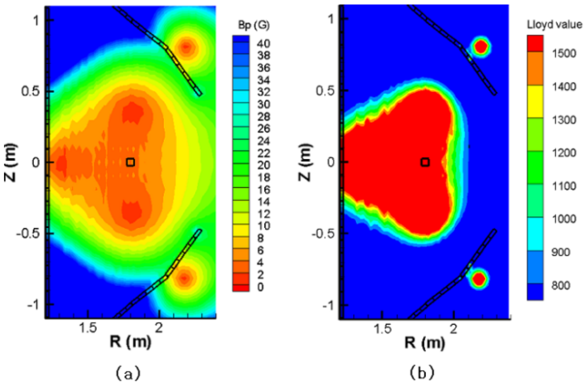
2.1 Lloyd condition

Lloyd condition assumes that magnetic fields are partially homogenous and linear. Under this assumption, connection length L can be considered as effective connection length like (2), where B_T is the toroidal field at the major radius of null region, a_{eff} is the minor radius of the null region and B_P is the magnitude of the poloidal stray field at the null region boundary. In this sense, empirical Lloyd condition (3) is used in many fusion devices to evaluate the possibility of ohmic breakdown.

$$L_{eff} = 0.25 a_{eff} B_T / B_P \quad (2)$$

$$E_T B_T / B_p \ge 1000\mathrm{V/m} \quad (3)$$

Fig 1. shows the ohmic breakdown scenario of the KSTAR device for example. Fig 1. (a) is a contour plot of B_P below 40 G. It shows a very large field-null region represented in red color. Lloyd condition expects that ohmic breakdown will occur at whole null region with the same degree as presented in Fig 1. (b).



(a) (b)

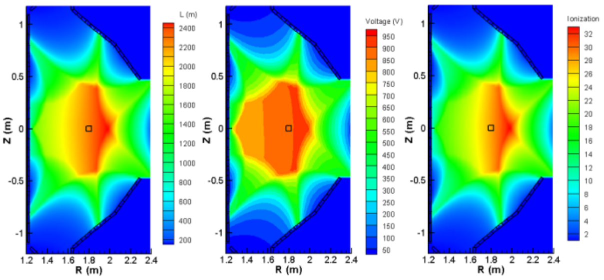
Fig 1. At plasma initiation time (t = 50 ms) of the KSTAR device, contour plots of (a) B_P below 40 G and (b) Lloyd condition value.

2.2 Field-line-following analysis

Although actual magnetic fields configuration at the ohmic breakdown phase is inhomogenous and nonlinear, Lloyd condition doesn't consider this effect. To analyze the detailed and actual magnetic configuration, a field-line-following analysis code is developed. 3-dimensional magnetic field line integration is possible by solving (4) in cylindrical coordinates, where R is a major radius, B_ϕ is the torodial magnetic field.

$$\frac{\partial R}{\partial \phi} = \frac{RB_R}{B_\phi}; \ \frac{\partial Z}{\partial \phi} = \frac{RB_Z}{B_\phi} \quad (4)$$

This developed code can calculate connection length L(=$\int dl$), energy gain of electrons $\int \vec{E} \cdot d\vec{l}$, number of ionization by electron $\int \alpha \, dl$ and other parameters by following the magnetic field lines. Based on these calculations, we can determine if breakdown occurs and find the region where the ohmic breakdown is possible.



(a) (b) (c)

Fig 2. At plasma initiation time (t = 50 ms) of the KSTAR device, contour plots of (a) connection length L(=$\int dl$), (b) energy gain of electrons $\int \vec{E} \cdot d\vec{l}$ and (c) number of ionization $\int \alpha \, dl$ with following the magnetic field lines.

As shown in Fig. 2, the field-line-following-analysis estimates that ohmic breakdown could occur more easily at the outboard rather than the inboard side of the device. This result is different from the estimation by the Lloyd condition described in the previous section.

3. Conclusions

A field-line-following analysis code is developed for analysis of magnetic field configurations at the ohmic breakdown phase of a tokamak. This method can analyze the actual complex magnetic field configuration for the precise estimation of the ohmic breakdown scenarios. This code is applied to the ohmic breakdown scenarios of the KSTAR device and different results from the prediction of the conventional Lloyd condition analysis are observed. The results will be compared with experimental measured data or other simulation results for the validation or verification of the code.

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