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Investigation of temporal evolution of runaway electrons beam position in Damavand tokamak runaway discharges

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Abstract

A study on the behavior of runaway electrons beam position in Damavand tokamak has been performed using the current filament model (CFM). The experimental data used in these calculations are based on the measurements obtained from Damavand Tokamak magnetic probes and in all experiments runaway discharges have been used in which most or all of the plasma current is carried by runaway electrons. In the CFM method, the current of the runaway electrons is approximated by a finite number of current filaments, and using the relevant calculations along with the classical method of least squares, the displacement of the runaway electrons beam in the radial and vertical directions in Damavand tokamak is investigated. The most important result obtained from these calculations (in runaway discharges) indicates the displacement of the runaway electrons column in the radial direction and their collision with the external limiter during the most time of plasma presence.

Keywords: Damavand tokamak, runaway electrons, current filament model, magnetic probes, radial displacement

Introduction

The runaway electrons in tokamak machines are particles that move very fast under the effect of acceleration mechanisms so that they are not subjected to any frictional force, which causes them to accelerate to the level of relativistic energies. In Damavand Tokamak, research on runaway electrons is often done in runaway discharges in which the entire discharge current is carried by the runaway electron beam while the ions are cold. The main features of this type of discharge are: (1) the absence or very small number of Mirnov oscillations [1], (2) the occurrence of periodic Parail-Pogutse instability [2], (3) continuous hard X-rays with rapid and repetitive explosions that usually occur simultaneously with moments of parail poguttse instability and voltage spikes [3], and their occurrence in low-density plasmas [4].

One of the important issues in the study of runaway electrons is to obtain the temporal evolution of the beam position of these electrons during the discharge. In this regard, there are various computational and analytical methods that in this study the position of runaway electrons beam using the computational model of the current filament method (CFM) has been investigated.

Introduction of CFM method

In the current filament method, the plasma current is approximated by several wires or filaments carrying the current, i.e., several wires or filaments (e.g. n filament) whose sum of currents is equal to the plasma current and plays the role of the plasma column in the calculations. In the CFM method, the position of the current filaments is constant and their current changes. Therefore, their current is changed so that the difference between the magnetic field and flux measured and calculated has the lowest possible value. The advantage of this method is that since the changes in flux and magnetic field relative to the current are linear, the current of filaments can be determined by classical methods such as least squares. In the laboratory phase, due to the fact that only magnetic probes are installed on Damavand tokamak and there is no flux loop, so it is only possible to use the magnetic field relationship from the current-carrying wire. In the following, the magnetic field resulting from a current-carrying wire is calculated. The magnetic field components R and Z due to a current-carrying wire is calculated from the flux function according to the following equations:

$$B_R = -\frac{1}{R}\frac{\partial \Psi}{\partial z} \tag{1}$$

$$B_z = +\frac{1}{R}\frac{\partial \Psi}{\partial R} \tag{2}$$

The flux function of a current-carrying wire loop is obtained from the following equation:

$$\Psi = \frac{\mu_0 I}{4\pi}\left(\sqrt{(R+R')^2+(Z-Z')^2}\right)\left((2-k^2)K(k)-2E(k)\right) \tag{3}$$

In the above relation, K(k) and E(k) are the elliptic integral relations and (R, Z) and (R´, Z´) are the coordinates of the magnetic probe location and the current-carrying wire, respectively. k is also calculated based on the following equation:

$$k = \frac{2\sqrt{RR'}}{\sqrt{(R+R')^2+(Z-Z')^2}} \tag{4}$$

Now, using equations (1) to (3), the radial and vertical components of the magnetic field resulting from a current filament can be calculated based on the following equations:

$$B_R = \frac{\mu_0 I}{\pi}\frac{(Z-Z')k}{4R\sqrt{RR'}}\left[-K(k)+\frac{R^2+R'^2+(Z-Z')^2}{(R-R')^2+(Z-Z')^2}E(k)\right] \tag{5}$$

$$B_Z = \frac{\mu_0 I}{\pi}\frac{k}{4\sqrt{RR'}}\left[K(k)-\frac{R^2-R'^2+(Z-Z')^2}{(R-R')^2+(Z-Z')^2}E(k)\right] \tag{6}$$

Therefore, the beam of runaway electrons can be approximated by several current filament, and by changing the current intensity of the filaments and finding the state in which the magnetic field measured and calculated on the magnetic probes has the least difference, the current of each filament is calculated. The method most commonly used to determine the current of filaments is the least squares method. After determining the current of filament, the coordinates of the discharge current center can be calculated according to the following equations:

$$R = \frac{\sum_{i=1}^{N} R_i I_i}{I_p} \tag{7}$$

$$Z = \frac{\sum_{i=1}^{N} Z_i I_i}{I_p} \tag{8}$$

Where N is the number of current filaments and R_i and Z_i are the coordinates of the i-th current filament.

Results and discussion

Figures 1 and 2 show the temporal variations of the runaway electrons beam position in the radial and vertical directions that calculated using the current filament model.

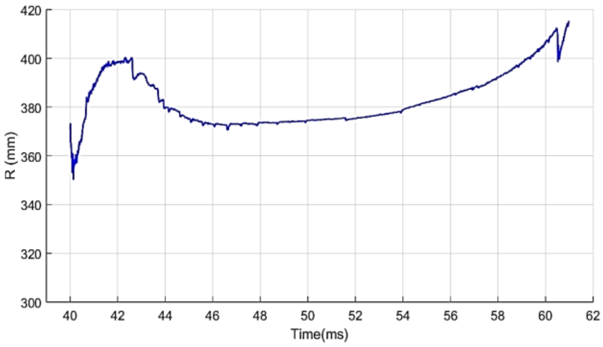

Figure 1. Diagram of the displacement of the runaway electrons beam in the radial direction of the vacuum chamber

Due to the fact that performing stable discharges in tokamak requires a flat toroidal magnetic field and in Damavand tokamak this state is established from 40ms to about 65ms, so the start of discharge time related to the runaway electrons in Figures 1 and 2 is displayed in the range of 40ms to 62ms. As can be seen in the first diagram, the location of the beam moves to the outer wall in the initial moments of plasma and the center of the beam reaches a radius of 38cm, but as the magnetic field resulting from the equilibrium coils increases, the center of the beam is returned to a radius of 36 cm.

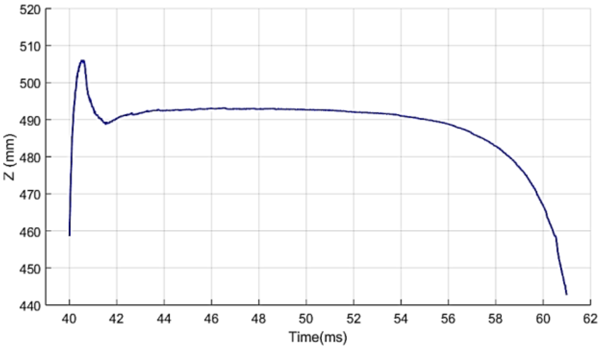

Figure 2. Diagram of the displacement of the runaway electrons beam in the vertical direction of the vacuum chamber

At the final moments of the discharge, due to the reduction of the induced control currents by the passive coils and the presence of the force resulting from the equilibrium coils, the beam of runaway electrons is driven towards the inner wall.

Also, according to Figure 2, the vertical position of the beam remains almost in the center of the chamber and is pushed down to the bottom of the vacuum chamber only at the end of the discharge.

Conclusions

In this study, using the current filament model, the position of the runaway electrons beam for the circular cross-section plasma and in the limiter configuration was investigated. The results showed that the main position variations are in the radial direction and the runaway electrons beam is continuously colliding with the outer wall and the outer limiter slab during the discharge time. Also, the calculations in the Z direction showed that there is no significant displacement of the runaway electrons column in the vertical direction, which indicates the effective presence of magnetic fields from passive coils in the control of the vertical position.

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