北海道大学工学部研究報告
第176号（平成8年）

Bulletin of the Faculty of Engineering
Hokkaido University, No. 176 (1996)

Analysis for halo current induced during plasma quench

Tomoaki HINO

(Received October 9, 1995)

Abstract

The expression for the halo current induced during the plasma quench phase is analytically obtained. The numerical calculation shows that the highest value of the halo current in the present large tokamaks is approximately 20 % of the plasma current. For the reduction of the halo current, the edge cooling due to the active impurity generation or emission from the wall is adequate, in addition to the enhancement of the wall resistance in the halo current loop by the use of insulators.

1. Introduction

It is known that the halo current is induced during the plasma or the current quench phase in the large tokamaks such as JT-60U and JET [1, 2]. Since the halo current flows along the poloidal direction, it can be regarded that this current is generated to conserve the diamagnetic toroidal flux. The eddy or shell current is induced along the toroidal direction during the current quench phase to conserve the poloidal flux due to the plasma current. Since the halo or the eddy current causes a large electromagnetic force, the failure of the divertor wall or the first wall may take place. In particular, if the wall elements with active cooling structures is ruptured, the serious accident such as the loss of coolant accident would be occurred.

It was observed that the graphite wall tiles were ruptured by the electromagnetic force due to the halo current in JT-60U [1]. In JET, the halo current as high as 20 % of the plasma current was measured [2]. Since the evaluation for the halo current is very important for the designs of in-vessel components, the analysis for the halo current is required and then the method to reduce the halo current has to be developed.

In this note, we first analyze the halo current induced during the plasma quench phase by using the induction equation. The numerical examples for a tokamak and a helical device are given and the magnitudes of the halo currents are discussed. Finally, several schemes for the reduction of the halo current are suggested.

[1]Department of Nuclear Engineering, Hokkaido University, Kita-13, Nishi-8, Kita-ku, Sapporo, 060 Japan
[2]National Institute for Fusion Science, Furo-cho, Chikusa-ku, Nagoya, 464-01 Japan

2. Analysis for halo current

The halo current, I_h, is described by the following induction equation if the couplings with the surrounding conductors are ignored.

$$\frac{d}{dt}(L_h I_h) + R_h I_h = -\frac{d}{dt}\Phi, \tag{1}$$

where $L_h \simeq \mu_0 a^2/2R$ is the self inductance, a the plasma radius, μ_0 the permeability, R the major radius, R_h the resistance of the halo current loop and Φ diamagnetic toroidal flux. It is assumed that the major radius remains the same, e.g., the vertical disruption be considered, but the plasma radius decreases as follows,

$$a = a_0(1 - t/\tau_d), \tag{2}$$

where a_0 is the plasma radius before the disruption, τ_d the plasma quench or the current quench time. The moving velocity of the plasma column then becomes $v_d = a_0/\tau_d$ and the width to be scrapped off by the wall $\Delta = v_d t$. The resistance of the halo current loop consists of the plasma resistance, R_p, and the wall resistance, R_w. The resistance of the halo current loop is given by

$$R_h = \frac{l_p \eta_p + l_w \eta_w}{2\pi R \Delta}, \tag{3}$$

where l_p is the poloidal length in the region of the halo plasma, l_w the poloidal length in the wall region, η_p the plasma resistivity and η_w the resistivity of the wall material. For the evaluations both for L_h and R_h, it is presumed that the halo current is induced along the poloidal direction in the entire torus as shown in Fig. 1. The width and the thickness of the halo current channel are $2\pi R$ and Δ, respectively.

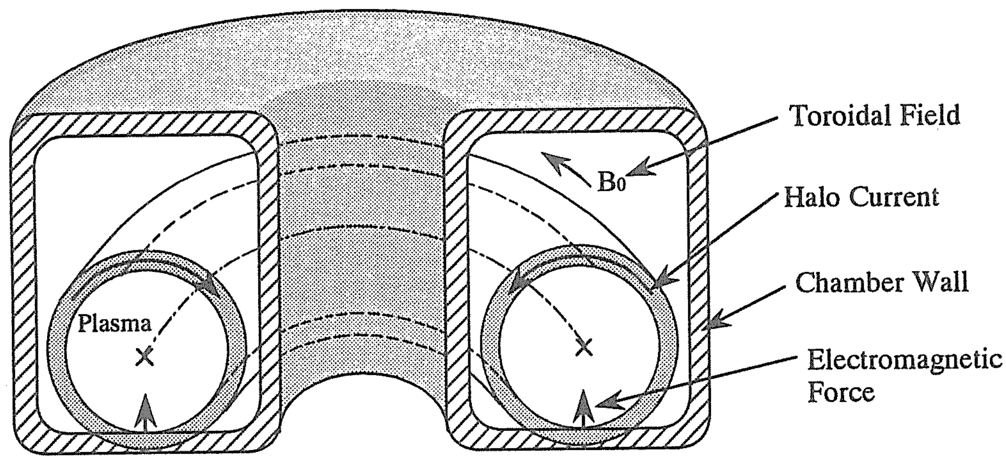

Fig. 1 Halo current induced during plasma quench phase.

The expressions of l_p and l_w are obtained for the geometry shown in Fig. 2. In the case that the plasma radius is much longer than the scrapped depth, $a \gg \Delta$, the value of θ in Fig.

2 is approximated as $\theta \simeq \sqrt{\Delta/a}$. Then, l_p and l_w are given by

$$l_p \simeq 2\pi(a + \frac{\Delta}{2}) - 2\sqrt{a\Delta} \simeq 2\pi a, \tag{4}$$

$$l_w \simeq 2\sqrt{a\Delta}. \tag{5}$$

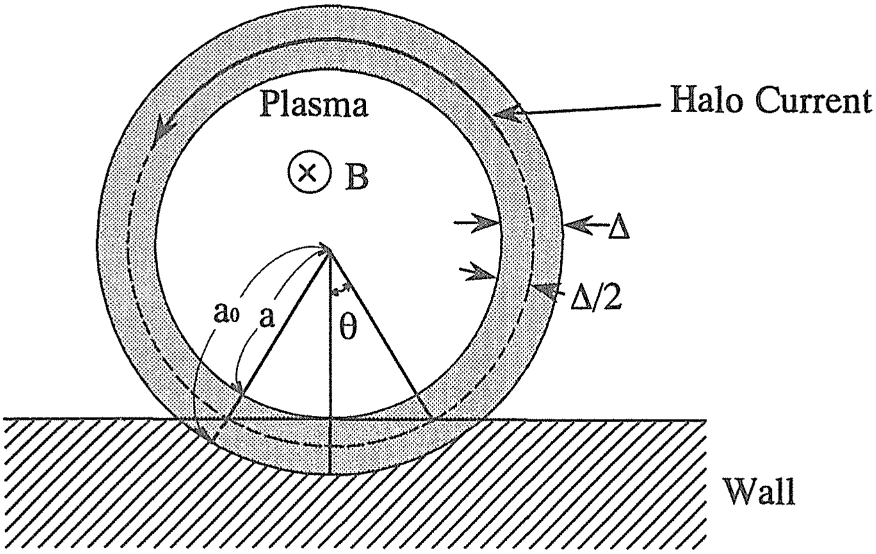

Fig. 2 Geometry used for calculation of the resistance of current loop.

Since the plasma resistivity is expressed as $\eta_p = 5\text{x}10^{-5} Z_{eff} \ln\Lambda / T_e^{3/2} \simeq 10^{-3} Z_{eff} / T_e^{3/2}$ [Ω−m] and the wall resistivity 1.4×10^{-5} [Ω−m] in the case of the isotropic graphite, the resistance of the halo current loop in Ω becomes

$$R_h \simeq \frac{10^{-3} Z_{eff}}{T_e^{3/2}} \frac{a}{R\Delta} (1 + 4.5 \times 10^{-3} \frac{T_e^{3/2}}{Z_{eff}} \sqrt{\frac{\Delta}{a}}), \tag{6}$$

where T_e is the electron temperature of the halo plasma and Z_{eff} the effective atomic number.

In Eq. (1), the change of the self inductance is given as $(dL_h/dt)/L_h = -2(a_0/a)/\tau_d$. The change of the diamagnetic toroidal flux becomes $-d\Phi/dt = 2(a_0/a)\Phi_0/\tau_d$. Here, Φ_0 is the initial value of the diamagnetic toroidal flux,

$$\Phi_0 = \pi a_0^2 \Delta B, \tag{7}$$

where $\Delta B = B_0 - B$, B_0 the toroidal magnetic field in the vacuum and B the toroidal magnetic field in the plasma. Since the plasma pressure, p, is approximated as $p \simeq B_0 \Delta B / \mu_0 = (B_0^2 / 2\mu_0)\beta$, we have

$$\Delta B = \beta \frac{B_0}{2}, \tag{8}$$

where $\beta = p/(B_0^2/2\mu_0)$ is the beta value. In Eq. (8), it is assumed that the plasma pressure is constant. From Eqs. (7) and (8), the change of the diamagnetic toroidal flux becomes

$$-\frac{d\Phi}{dt} = \frac{\pi a_0^2 B_0 \beta}{\tau_d}. \tag{9}$$

Then, from Eqs. (1), (6) and (9), the induction equation for the halo current is approximated as

$$\frac{dI_h}{dt} \times \frac{I_h}{\tau_h} = \frac{\beta A^2 q I_p}{\tau_d}, \tag{10}$$

where $A = R/a_0$ is the aspect ratio, $q = (a_0/R)(B_0/B_p)$ the safety factor, $B_p = \mu_0 I_p / 2\pi a_0$ the poloidal magnetic field and I_p the plasma current. The resistive time constant of the halo current loop, τ_h, is given by

$$\tau_h^{-1} = \frac{1.6 \times 10^3 Z_{eff}}{a_0 \Delta T_e^{3/2}} \left(1 + 4.5 \times 10^{-3} \frac{T_e^{3/2}}{Z_{eff}} \sqrt{\frac{\Delta}{a_0}}\right) - \frac{2}{\tau_d}. \tag{11}$$

In Eqs. (10) and (11), it is presumed that $a \simeq a_0$. The solution of Eq. (10) then becomes

$$I_h = \beta A^2 q I_p \frac{\tau_h}{\tau_d} (1 - e^{\frac{-t}{\tau_h}}), \tag{12}$$

where

$$\left(\frac{\tau_h}{\tau_d}\right)^{-1} = \frac{1.6 \times 10^3 Z_{eff}}{a_0 \Delta T_e^{3/2}} \left(1 + 4.5 \times 10^{-3} \frac{T_e^{3/2}}{Z_{eff}} \sqrt{\frac{\Delta}{a_0}}\right) \tau_d - 2. \tag{13}$$

In the device without plasma current such as a helical device, the halo current is also induced during the plasma quench phase. The halo current in the currentless device is given by

$$I_h = \frac{2\pi}{\mu_0} \beta B_0 R \frac{\tau_h}{\tau_d} (1 - e^{\frac{-t}{\tau_h}}). \tag{14}$$

Since the plasma quench time in the helical device is longer than that of the tokamak disruption, the halo current is much smaller, compared with the case of a tokamak device.

3. Estimation of halo current

Based on the expressions for the halo current, we here estimate the value of the halo current. For the case of tokamak, it is assumed that $a_0 = 1$ m, $\Delta/a_0 = 0.1$, $Z_{eff} = 6$, $q = 2$ and $A = 3$. If the electron temperature in the halo plasma, T_e, is lower than approximately 260 eV, the resistance due to the graphite wall becomes much smaller than that of the halo plasma. Then, the resistive time constant of the halo current, τ_h, is roughly proportional to $T_e^{3/2}$ in this case. The current quench time in the large tokamaks is of order of 10 ms. Although the beta value at the edge plasma is small, the value at the core plasma may exceed about 10 %. For the case with $\beta = 10$ % and $\tau_d = 10$ ms or 20 ms, the ratio of the halo current to the plasma current, I_h/I_p, is plotted to the electron temperature of the halo plasma in Fig. 3. This ratio has a value as high as approximately 0.2 when $\beta = 10$ % and $T_e = 50$–60 eV. In the case of JET, the highest halo current induced was also 20 % of the plasma current [2] .

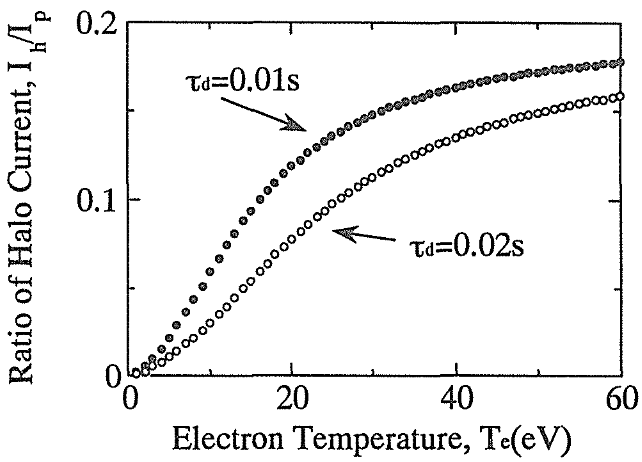

Fig. 3 Ratio of halo current to plasma current for the case that $A=3$, $q=2$, $a_0=1$ m, $\Delta/a_0=0.1$, $Z_{eff}=6$ and $\beta=10$ %

The halo current increases as both the electron temperature and the beta value. Since the beta value and the electron temperature increase as the decrease of the plasma radius during the plasma quench, the halo current shall increase as the progress of the plasma quench and has a maximum in the end of the plasma quench. The electromagnetic force per unit poloidal length, thus, becomes highest in this phase. When $I_p=5$-20 MA and $B_0=5$T, the highest electromagnetic force is estimated as (5-20)x10^5 kg/m.

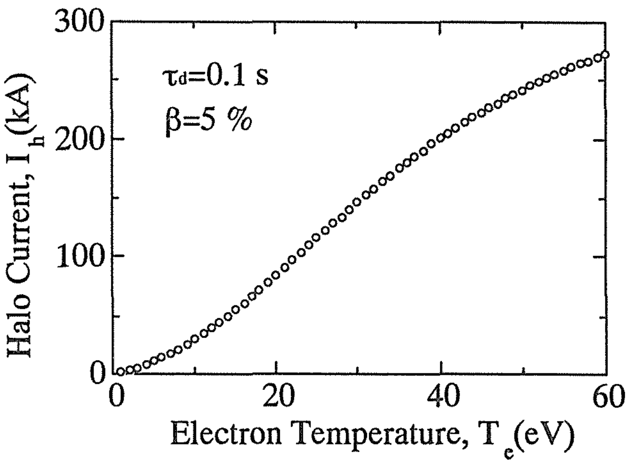

Fig. 4 Halo current induced in currentless plasma. Here, $B_0=$ 4T,$R=4$ m, $a_0=1.5$ m, $\Delta/a_0=0.1$, $Z_{eff}=6$ and $\beta=5$ % and $\tau_d=100$ ms.

In the helical device, the plasma quench time is much longer than that of the tokamak. For the case that $a_0=1.5$ m, $\Delta/a_0=0.1$, $Z_{eff}=6$, $R=4$ m, $\beta=5$ % and $\tau_d=100$ ms, the halo current is plotted to the electron temperature in Fig. 4. The halo current induced in this case is as high as ~250 kA if $T_e \lesssim 50$ eV. Compared with the case of the tokamak, the halo current of the helical device is a few times smaller.

4. Discussion and summary

The halo current may be reduced by decreasing the electron temperature of the halo plasma since the halo current is roughly proportional to $\tau_h/\tau_d \sim T_e^{3/2}/Z_{eff}\tau_d$. When the vertical disruption takes place, the plasma column collides with the walls. If the impurity emission largely occurs, the edge temperature can be significantly reduced. For this purpose, the active impurity generation or emission such as the scheme to use solid target evaporator [3] or gas impurity injection is suitable. For example, if the edge temperature is reduced from 50 eV to 10 eV, the halo current is three times decreased. In addition, the heat load to the wall is reduced due to the radiation of the impurity. In the scheme of solid target evaporators, the use of beryllium or boron is adequate since these materials contribute to the wall conditionings for next discharge shots [3] .

The other approach is to enhance the wall resistance of the halo current loop. The halo current shall be induced in the divertor wall and/or the first wall. If the insulators between the wall tiles are placed along the toroidal direction, the halo current is very largely reduced. For example, when the resistance of the wall is 1 Ω, the ratio of the halo current to plasma current becomes of order of 10^{-6}.

In summary, the halo current was analyzed based on the induction equation. The numerical calculation showed that the halo current can be as high as approximately 20 % of the plasma current. The electromagnetic force due to the halo current becomes of order of 10^6 kg/m in the fusion experimental reactor. For the reduction of the halo current, the edge cooling due to the active impurity generation is suitable. The use of the insulators between the wall tiles along the toroidal direction is also quite effective.

Acknowledgement

The author thanks Prof. T. Yamashina, Hokkaido University for his encouragement.

References

[1] L. Rossi, E. Deksnis, P. Lomas, E. Martin, R. Mohanti, M. A. Pick and G. Saibene, Fusion Technology 1992 Vol.1(1993) 353.
[2] M. Saidoh, J. Plasma and Fusion Research 71(1995) 372.
[3] T. Hino and T. Yamashina, Fusion Eng. and Design 24(1994) 425.