Characteristics of Local Helical Coil System for Dynamic Ergodic Divertor

YUSUKE KIKUCHI, HIROKI KOJIMA, TOMONORI TANIYAMA, MITSUHIRO TOYODA, YOSHIHIKO UESUGI, and SHUICHI TAKAMURA
Nagoya University, Japan

SUMMARY

Heat and particle flux control is one of the most important and difficult problems in steady-state fusion devices. The Dynamic Ergodic Divertor (DED) is an advanced concept in which a rotational perturbed magnetic field is applied to make the tokamak edge magnetic structure stochastic so that it may decrease the heat and particle flux onto the local target in the conventional divertor. This rotational perturbed field is created by two sets of local helical coils (LHC) with a phase difference of 90° in the supplied ac currents. In DED experiments, it is important to study the perturbed magnetic field structure generated by these coil currents. In this paper, a new coil configuration is considered, which has an additional series of return windings so as to improve the mode quality of the rotating helical field (RHF). We obtain the mode structure of RHF using a new Fourier analysis. From this result, we confirm that the parasitic mode of RHF and the coil self-inductance are decreased by the new coil configuration. © 2002 Scripta Technica, Electr Eng Jpn, 139(1): 16–23, 2002; DOI 10.1002/eej.1142

Key words: Local helical coil; mode analysis; tokamak; dynamic ergodic divertor; HYBTOK-II.

1. Introduction

In steady-state operation of magnetically confined fusion devices, it is necessary to control the edge plasma, such as divertor plasma, so as to enhance the confinement properties of the core plasma. The first problem is localization of the heat load from the core plasma to the target plate. The peak heat load in ITER is estimated to be as large as several tens of megawatts per square meter [1]. The second problem imposed by steady-state operation is particle control. It is necessary (1) to control the recycling of fuel particles, (2) to prevent the impurity particles from penetrating into the core region, and (3) to remove helium ash. The Ergodic Divertor (ED) is one scheme for controlling the particle and heat flux in tokamaks. ED makes the tokamak edge magnetic structure stochastic by means of an externally applied magnetic field and creates a more uniform distribution of particles and heat flux to the wall. A large number of studies have been performed in several tokamak devices to investigate this innovative concept for advanced tokamaks. In these experiments, however, a nonuniform distribution of plasma parameters near the perturbation coils was found [2]. This nonuniformity comes from the poloidal nonuniformity of the magnetic structure near the perturbation coils, and it causes localization of the heat load to the wall. This feature of the ED is the main reason that the ED cannot be an option for edge plasma control in ITER.

As an advanced concept of the ED, the Dynamic Ergodic Divertor (DED) has been proposed [3, 4]. In DED a poloidally rotating helical field (RHF) is applied in order to smear out the localized heat flux observed in the ED experiments. In addition, DED has some ability to improve the performance of tokamak discharge. When the edge plasma rotation is generated by RHF, it is possible to control particle recycling at the edge in combination with a pump limiter, and the plasma confinement may be improved by the induced shear flow [5].

A DED experiment is also planned in the TEXTOR tokamak and many theoretical works have been reported [5–7]. Pioneer work on DED has been carried out on a small tokamak device, the CSTN-IV [8], at Nagoya University. Penetration processes and the dynamic behavior of RHF in tokamak plasmas have been investigated. In the case of resistive plasmas (Lundquist number $S \sim 230$), the redistribution of the plasma current due to magnetic field reconnection induced by RHF was predominantly observed [9, 10]. We have started a new DED experiment on a small tokamak device, HYBTOK-II [11, 12] to study the fundamental processes of DED in a higher-temperature region ($S$
compared with CSTN-IV. It is expected that the shielding current against the externally excited RHF around the resonance surface will drive the plasma poloidal rotation.

The characteristics of the DED experiments in HYBTOK-II compared with TEXTOR are as follows: (1) high mode quality of RHF, (2) direct measurements of the perturbation field by magnetic probes in the plasma. In TEXTOR DED experiment, the perturbation coils will be located on the high field side with poloidal coverage of ±60°. These partially located coils will make the poloidal mode spectrum very broad, so that it is difficult to keep the stochastic region narrow at the plasma edge region. In contrast to TEXTOR, the perturbation coils are installed in a poloidally complete region (complete rings) in HYBTOK-II. Therefore, it is expected that the mode quality of RHF is much higher than that of TEXTOR. In addition, it is difficult in large tokamak devices like TEXTOR to measure the magnitude and profile of RHF in a region including the resonance surface using magnetic probes. However, it is possible to insert magnetic probes into the plasma beyond the resonance surface in HYBTOK-II, and these results will give us important information about the interaction between the plasma and RHF around the resonance surface.

For the DED experiment, it is also important to clarify the electrical characteristics of the helical coils, such as the magnetic structure of the RHF and the coil impedance. The fundamental mode number of the RHF is determined by the geometric structure of the helical coils. However, some sideband components around the fundamental mode are also generated due to the toroidal effect, which produce a complicated magnetic structure in the plasma. Since the helical coils are installed outside the vacuum vessel, the RHF is attenuated by the conducting vacuum chamber, and the coil inductance is also affected. It is necessary to evaluate these characteristics experimentally, because a simple analysis of RHF cannot take account of the real structure of the induced eddy current in the vacuum chamber. In this paper we perform a mode analysis of RHF in Section 2, and the frequency dependence of the coil inductance is shown in Section 3. Conclusions of this research are presented in Section 4.

2. Mode Analysis of RHF

2.1 Local helical coil

HYBTOK-II has a major radius of 40 cm and a minor radius of 12.8 cm, and the torus chamber is made of SUS304 with a thickness of 2 mm as shown in Fig. 1. Since it is difficult to install the helical coils in the whole region of the torus chamber due to technical problems (e.g., the observation ports), we have installed two sets (A and B coils) of local helical coils (LHC) at eight odd-numbered toroidal sections among the 16 sections. These two sets of coils are powered independently by IGBT inverter power supplies with a phase difference of 90°.

The externally applied RHF is resonant with the natural helical field with the rotational transform \( q = m/n \), where \( q, m, \) and \( n \) are the safety factor and poloidal and toroidal mode numbers, respectively. A very carefully designed LHC is required to localize the stochastic region of the magnetic field at the plasma edge. In a typical discharge of HYBTOK-II, the \( q \) surface is about 8 at the limiter radius. We have selected \( m = 6 \) and \( n = 1 \) in order to locate the fundamental resonance surface \((m/n = 6/1)\) at the plasma edge. The LHC has six pairs of conductors in the poloidal direction \((m = 6)\) as shown in Fig. 2. The poloidal position and current direction of each coil are chosen such that the toroidal mode number \( n \) is as close to unity as possible. In addition, all windings of the LHC have two turns in order to enhance the magnitude of the RHF.

2.2 Analysis taking the toroidal effect into account

The RHF generally includes spatial sidebands (e.g., \( m \pm 1, m \pm 2, \ldots \)) to some extent in addition to the fundamental mode because of the toroidal effect and the filament feature of LHC. These sideband components have different resonance surfaces at each radial position, and some induced magnetic islands overlap. Therefore, it is important for DED experiments to study the structure of RHF. So far only a few attempts have been made to perform mode analysis taking the toroidal effect and the rotation of the perturbed field into account. In this study, we have
investigated the mode structure along the tokamak magnetic field lines (zeroth order) in order to take the toroidal effect into account. Figure 3 shows the analysis model. The interaction between the plasma and RHF is not taken into account in the present analysis.

The equation of magnetic field lines is

\[ \frac{d\phi}{d\theta} = q \left( 1 - \frac{r}{R_0} \cos \theta \right) \]  

The toroidal angular displacement \( \phi_1 \) between poloidal angle 0 and \( \theta_1 \) is written as

\[ \phi_1 = q_0 \int_0^{\theta_1} \left( 1 - \frac{r}{R_0} \cos \theta \right) d\theta \]  

The correlation \( \Phi(\theta, \tau) \) between two poloidally separated points with a time difference of \( \tau \) is defined by

\[ \Phi(\theta, \tau) = \left( \left\langle B^*_n(0, \phi_0, t) \times B_n(\theta, \phi_0 + \phi_1, t + \tau) \right\rangle \right)_0 \]  

where the asterisk indicates the complex conjugate.

Taking the Fourier transformation of Eq. (3) gives \((m, k)\) spectra of \( \Phi(\theta, \tau) \), where \( k \) is a frequency harmonic number, and the perturbed field \( B_n \) is numerically obtained by the Biot–Savart law taking the real coil configuration into account. On the other hand, the skin effect of the vacuum chamber is taken into account using a transmission function, which is obtained by comparing the magnitude and the phase delay of RHF between the analytical and experimental results. The transmission function is

\[ G(f) = \frac{1}{\sqrt{1 + (f/f_{c1})^2}} \exp \left[ -i(f/f_{c1})^2 \right] \]  

where \( f_{c1} \) and \( f_{c2} \) are the characteristic cutoff frequencies. We have set \( f_{c1} = 3.4 \text{ kHz} \) and \( f_{c2} = 16 \text{ kHz} \) so as to fit the experimental results. In this analysis, we have used a coil current whose amplitude is obtained from Eq. (4) to take the skin effect into account.

2.3 Analysis results

Figure 4 shows the mode spectra of the perturbed field on the magnetic surface of \( q = 7 \). Since the coil current waveform includes odd-numbered harmonics, the mode spectra in the case of \( k = 1, 3, 5 \) are shown in Fig. 4. In the case of the third harmonics \((k = 3)\), the poloidal traveling direction of RHF is opposite to those of the other cases \((k = 1, 5)\). However, the magnitudes of the component of \( k = 3 \) are more than three orders smaller than those of the fundamental component. From these results, we can identify not only the fundamental mode \((m/n = 6/1)\) but also many sideband components. The reason why these sideband components appear is as follows.

The perturbed field is expressed by

\[ B_n(\theta, \phi, t) = e^{i(m \theta + n \phi + k \omega t)} \]  

where \( \omega = 2\pi f_0 \), and \( f_0 \) is the fundamental frequency of the perturbation. From Eqs. (2) and (5) we obtain

\[ B_n(\theta, \phi, t) \sim e^{i \left( m \theta \right)} e^{i \left( n \phi \right)} e^{i \left( \frac{m \theta + n \phi + k \omega t}{f_0} \right)} \]  

Using the modified Bessel function \( I_l \) in the following equation,
The term of exp(nqr \cdot \sin \theta / R_0) becomes
\[ e^{i \nu \sin \theta} = \sum_{l=-\infty}^{\infty} I_l(x) \cdot e^{i \nu l} \] (7)

the term of exp(nqr \cdot \sin \theta / R_0) becomes
\[ e^{i \nu (\frac{-nqr}{R_0}) \sin \theta} = \sum_{l=-\infty}^{\infty} I_l \left( \frac{-nqr}{R_0} \right) \cdot e^{i \nu l} \] (8)

This term expresses the sideband components due to the toroidal effect.

2.4 \( m/n = 0/1 \) mode

From the mode analysis, although the fundamental mode \((m/n = 6/1)\) is found to be dominant, a nonresonant, \( m/n = 0/1 \) parasitic mode is also found. The important point to be noted is that this \( m/n = 0/1 \) mode does not come from the toroidal effect. The origin of this mode is found to be the lack of return windings. The LHC consists of toroidal bars and poloidal joints as shown in Fig. 5, where the current directions of the poloidal joints are changed between sections 6 and 14. This feature of the coil configuration generates a magnetic field with \( m/n = 0/1 \) mode.

2.5 Improvement of local helical coil windings

The magnetic field of \( m/n = 0/1 \) mode is an error field component created by the present LHC windings. Therefore, we should consider the reduction of this mode by modifying the coil configuration so as to cancel the current in the poloidal joints. In addition to improvement of the mode quality, the coil self-inductance is also decreased by reduction of the unnecessary magnetic flux.

To eliminate the effect of this unfavorable coil current, we have installed some additional windings with the current direction opposite to that of the poloidal joints. The configuration of the error correction coil is shown schematically in Fig. 6. The additional return windings are installed on both sides of the coils in which a half helical coil current
(0.5 $I_h$) flows, where $I_h$ is the helical coil current. The mode structures of this coil configuration are shown in Fig. 7. We have confirmed that the coil configuration with the poloidal return windings substantially reduces the intensity of the $m/n = 0/1$ parasitic mode. Since the poloidal joints generate not only the $m/n = 0/1$ mode but also other modes, the intensities of the other modes are also decreased drastically. It should be noted that the intensity of the fundamental mode, $m/n = 6/1$, is not changed.

3. Electrical Characteristics of the Local Helical Coil

3.1 Measurement of the coil impedance

We have installed the LHC with the poloidal joints in HYBTK-II. All the windings except for the return winding of the LHC have double turns. The purposes of the coil impedance measurement are confirmation of the effect of the poloidal return winding and provision of basic data for the evaluation of the energy transfer from the external RHF to the plasma kinetic energy. The latter purpose is discussed below. If the magnetic energy of RHF transfers to the tokamak plasma in the DED experiment, a change of the coil loading resistance is expected. It is possible to evaluate such energy transfers from the characteristics of the coil voltage and current compared with those without the plasma. Therefore, it is necessary to know accurately the coil impedance without the plasma.

The LHC is energized with an inverter power supply, which generates an ac rectangular voltage at a frequency from 1 to 30 kHz. The nominal voltage and current are 600 V and 150 A. The inverter circuit diagram and the coil voltage and current waveforms are shown in Fig. 8. Assuming that the LHC is a series circuit consisting of a resistance and an inductance, the coil inductance is calculated from
the coil voltage at the time when the coil current is equal to zero. However, the waveform of the voltage is changed, as shown in Fig. 8(b) (see “Change of the voltage”). Therefore, we have evaluated the coil impedance using another bipolar power supply, which generates a sinusoidal voltage. The result is shown in Fig. 9, where we can determine the resistance and inductance change with the driving frequency due to the skin effect of the vacuum chamber and cable of LHC. First, we have compared vacuum chambers made of SUS 304 and Pyrex glass with the same diameter to investigate how the skin effect of stainless steel affects the coil loading impedance. The experimental results indicate that the skin effect of the vacuum chamber does not affect the coil impedance. Second, when we evaluate the coil self-inductance, the skin depth of the cable, that is, how the current flows in the cable, must be considered. At 1 kHz, the current flows over the cable conductor, because the skin depth (2.1 mm) is wider than the radius of the cable (1.6 mm). The internal inductance of the coil is gradually decreased with the driving frequency, because the current channel width becomes narrower than the radius of the cable at 10 kHz, where the skin depth is about 0.65 mm.

It is also found that the coil external inductance is reduced due to the return windings. The return windings make it possible to improve the mode quality of RHF and to reduce the driving voltage of the inverter power supply. In our DED experiment, due to the limitation of the ac supply voltage of the inverter (600 V), reduction of the coil self-inductance can extend the operation region of the coil current. In fact, the driving voltage can be reduced by about 20% when the return windings are installed.

3.2 Reproduction of the waveforms of the voltage and current

We have reproduced the waveforms of the coil voltage and current using the Laplace transformation given by

$$I(t) = \frac{V_0}{R} \left[ u(t) \left( 1 - e^{- \frac{R}{L} t} \right) - 2n \left( t - \frac{T}{4} \right)^n \left( 1 - e^{- \frac{R}{L} \left( t - \frac{T}{4} \right)} \right) \right] + \ldots$$

(9)

where $u(t)$, $V_0$, $R$, $L$, and $T$ are a step function, the coil voltage, the coil resistance, the coil inductance, and the period of the current, respectively. At 5 kHz, comparisons of the current calculated from Eq. (4) with the experimental waveforms are shown in Fig. 8(b); good agreement between the experiments and calculations is obtained.

3.3 Measurement of the RHF in a vacuum

We measured the RHF in a vacuum using a small magnetic probe. The magnetic probe is inserted into the vacuum chamber using a linear motion feed-through. The radial profile of the poloidal component of RHF is shown in Fig. 10.

For comparison with the experimental results, we calculated the magnetic field generated by $m$ helical windings wound on a circular cylinder. The poloidal component of the RHF inside the LHC is expressed by [13]

$$B_y = \frac{2N\mu_0J\sigma r}{\pi r} \sum_{p=0}^{m} K_N'(N\alpha r) L_N(N\alpha r) \cos N(\theta - \alpha)$$

(10)

Fig. 9. Frequency dependence of LHC resistance and self-inductance.

Fig. 10. Radial distribution of helical magnetic field in vacuum.
where \( J, r_c, I_N, K_N, \) and the prime represent the coil current, the location of the coil, the Bessel function of order \( N, \) and the differential with respect to the radial position, respectively. Then \( \alpha = n/mR_0, \) and \( N = (2p + 1)m \) for integral \( p. \) In the case of \( p = 0 — \) the fundamental mode — the approximate solution of the poloidal component of RHF is

\[
B_\theta \propto r^{m-1}
\]

Comparison between the experimental and analytical results reveals some discrepancy near the location of LHC due to the limitations of the multipole approximation. In addition, the calculation of the RHF using the Biot–Savart law does not agree with the experimental results near the LHC. From Fig. 10, deep inside the vacuum chamber, the attenuation of the experimentally observed \( B_\theta \) gradually becomes weaker than that given by the approximate solution. However, it can be concluded that the LHC generates predominantly a magnetic field which has the \( m = 6 \) mode.

4. Conclusions

We have installed a local helical coil which generates a rotating helical field for the Dynamic Ergodic Divertor experiment in a small tokamak device, HYBTOK-II. We have performed a mode analysis of the rotating helical field, taking the real coil configuration and the toroidal effect into account. From this analysis, it is found that a parasitic mode \((m/n = 0/1)\) is created by the poloidal joints of local helical coils. By modifying the coil configuration, the mode purity of the rotating helical field is greatly improved and the coil self-inductance can be reduced. The present work will be useful to future DED experiments in some tokamak devices.

REFERENCES

3. Finken KH, Wolf GH. Background, motivation, concept and scientific aims for building a dynamic ergodic divertor. Fusion Eng DES 1997;37:337.
Yusuke Kikuchi (student member) received his B.E. degree in electrical and electronic engineering from Ibaraki University and M.E. degree in energy engineering and science from Nagoya University in 1999 and 2001, and presently is a Ph.D. student there.

Hiroki Kojima (student member) received his B.E. degree in electrical engineering and M.E. degree in energy engineering and science from Nagoya University in 1998 and 2000, and presently is a Ph.D. student there.

Tomonori Taniyama (student member) received his B.E. degree in electrical engineering and M.E. degree in energy engineering and science from Nagoya University in 1999 and 2001, and presently is with Hitachi System and Service Co.

Mitsuhiro Toyoda (student member) received his B.E. degree in electrical engineering from Nagoya University in 2000, and presently is an M.E. student there.

Yoshihiko Uesugi (member) received his D.Eng. degree in plasma science from Nagoya University in 1983 for work on excitation of lower hybrid waves and its diagnostic. He has been an associate professor in the Center for Integrated Research in Science and Engineering, Nagoya University, since 1996, and has been working on fusion plasma science, basic plasma engineering and its applications.

Shuichi Takamura (member) received his D.Eng. degree in plasma science from Nagoya University in 1973 for work on linear and nonlinear interactions between RF electric fields and ion waves. He has been a professor in the Department of Energy Engineering and Science, Graduate School of Engineering, Nagoya University, since 1988, and has been working on fusion plasma science, basic plasma engineering and its applications.