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Advanced Physics and Plasma Control with Segmented In-vessel Control Coils in the KSTAR Tokamak

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Abstract

In-vessel coils are to be used for the fast plasma position control, field error correction (FEC), and resistive wall mode (RWM) feedback stabilization in the Korea Superconducting Tokamak Advanced Research (KSTAR) device. Recently, a new configuration that incorporates toroidal segmentation concept, has been adopted. The new coil system is found to allow a wider range of plasma control flexibility satisfying the KSTAR advanced physics requirements for the plasma position and FEC/RWM control capability, in addition to engineering advantages. Here, we report physics and engineering analyses for the new in-vessel control coil system and explore new physics issues using the in-vessel control coils.

Keywords:

control-coil, field-error-correction, resistive-wall-mode, KSTAR

1. Introduction

During the design phase of the Korea Superconducting Tokamak Advanced Research (KSTAR) device [1], the plasma magnetics control has been considered as one of the important requirements for advanced tokamak (AT) operations. Here, the magnetics control implies control of plasma equilibrium parameters by magnetic means, and it includes control of plasma position, current and shape, compensation of non-axisymmetric error field due to many sources (including misalignment of superconducting coils), and resistive wall modes (RWM) control. In-vessel copper coils have been suggested to be used for the fast vertical and radial plasma position control, field error correction (FEC), and RWM feedback stabilization in the KSTAR device. In the earlier version of the in-vessel coil system design (Fig. 1(a)), the plasma position control is to be realized by using two pairs of inner control (IVC for vertical position control and IRC for radial position control) coils while both the error field compensation and RWM control are to be realized by utilizing the picture-frame shaped FEC/RWM coils.

Recently, a significant change has been made to the previous design. A new configuration of in-vessel coils, in which all in-vessel coils are unified into a single set by adopting the concept of segmented coil system, has emerged. Several advantages, particularly in engineering aspects, have been identified by the adoption of this new type of in-vessel control coil design. From the physics point of view, the new coil system has been also found to allow a wider range of plasma control capability, including the possibility of helical resonant field generation for tearing mode and plasma rotation control,

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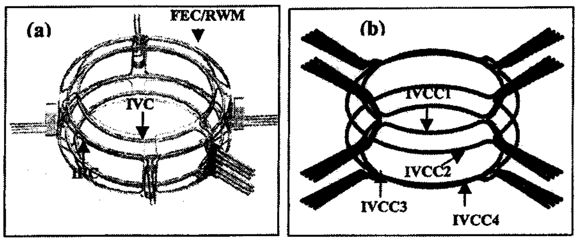

Fig. 1 Schematic diagrams of the design of (a) the former KSTAR in-vessel coil (IVCC) system, and (b) the present KSTAR IVCC system.

in addition to the plasma position and FEC/RWM control capability. In the present paper, the recent design progress of the KSTAR in-vessel control coil (IVCC) system is reported. The design features of IVCC are described in Sec. **2**. Then, relevant physics considerations and the results of preliminary engineering analyses are presented in Secs. **3** and **4**, respectively. A summary and some future works are given in Sec. **5**.

2. New Design Scheme of KSTAR in-Vessel Control Coil System

Figure 1(b) shows the present design of the in-vessel control coil system in KSTAR. Sixteen toroidally segmented coils, which are located in the same positions as in the former two IVC and two IRC coils in Fig. 1(a) (four toroidally segmented coils at each position), replace the old IVC, IRC, and FEC/RWM coils. Thus, the former FEC/RWM coils are eliminated in this new design. Each segmented coil can be easily inserted into the vacuum vessel through three NBI-type ports and one RF port from outside of the vacuum vessel for installation, as shown in Fig. 2.

The new IVCC system should simultaneously control the plasma position and FEC/RWM. Therefore, the connection method of the segmented coils to duplicate the functions of the former in-vessel coils is an important design consideration. Figure 3 represents the cross sectional view of segmented coils and shows the connection method. Each coil has eight conductor bars and is divided into an IC part, which functions like the former IVC or IRC coils, and an FEC/RWM part, which plays the role of former FEC/RWM coils. The IC parts of the IVCC1 and IVCC4 coils consist of six conductor bars while those of IVCC2 and IVCC3 are comprised of four conductor bars. The FEC/RWM parts of all the coils consist of two conductor bars. The IC parts of the coils are serially connected to adjacent coils by joining them externally to complete the former IVC coils using

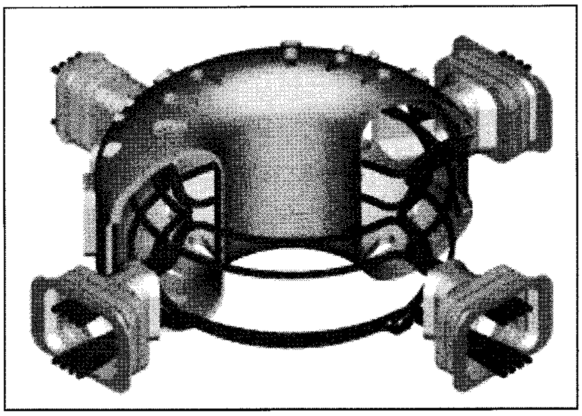

Fig. 2 Configuration of the KSTAR vacuum vessel and IVCC.

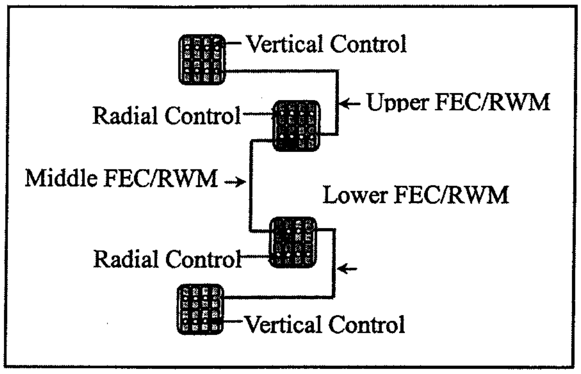

Fig. 3 Cross sectional view of segmented coils and the connection scheme for field error correction (FEC) and resistive wall mode (RWM) control.

IVCC1 and IVCC4, and the former IRC coils using IVCC2 and IVCC3. One of the FEC/RWM parts of the upper IVCC2 is connected to that of upper IVCC1 to form an upper FEC/RWM coil. The other FEC/RWM part of the upper IVCC2 is connected to that of IVCC3 to form a middle FEC/RWM coil. The lower part is a mirror configuration of the upper FEC/RWM coil connection. Figure 4 shows detailed combinations of coil connection for position control and FEC/RWM control.

The segmented configuration of IVCC has significant advantages in engineering aspects. They include: (1) enhancement of the coil system reliability with no welding or brazing points inside the vacuum vessel, which results in removing the possibilities of major accidents such as cooling water leakage or coil destruction due to weak mechanical strength in weak

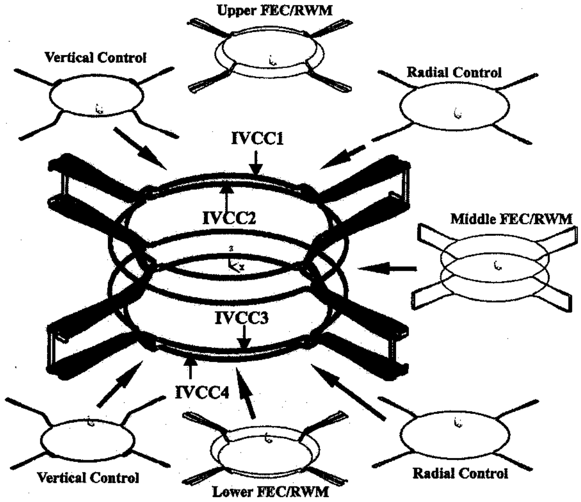

Fig. 4 Combination of KSTAR IVCC for position control and FEC/RWM control.

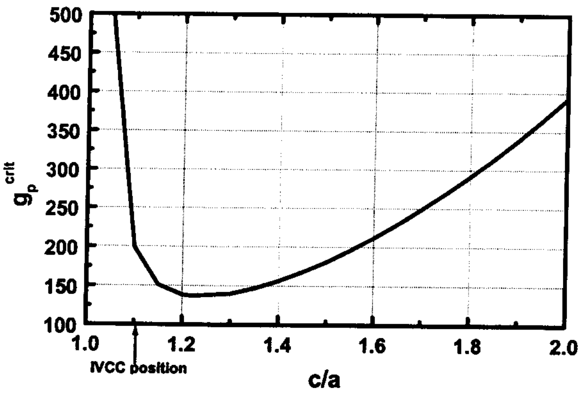

Fig. 5 Critical gain as a function of feedback coil position (a : plasma minor radius, c : radial position of feedback coils).

points, (2) simplification in fabrication and installation owing to the coils being able to be fabricated outside the vacuum vessel and installed after device assembly, (3) easy repair and maintenance of the coil system, and (4) substantial saving in in-vessel space by the reduction of two coil sets to one.

3. Physics Requirements

The relevant physics issue of KSTAR IVCC is that it should be capable of controlling (1) unstable vertical movements inherent to elongated plasmas, (2) rapid radial position adjustment to provide effective antenna-plasma coupling, (3) resistive wall modes, and (4) the compensation of non-axisymmetric error fields.

The power supply requirements for the control of vertical and radial motions are not changed significantly from the previous design values because the locations of segmented control coils coincide with the former IVC and IRC locations. The maximum feedback currents and voltages for vertical position control (IC parts of IVCC1 and IVCC4) and for radial position control (IC parts of IVCC2 and IVCC3) are 42 kA-turns and123 V/turn, and 22 kA-turns and 52 V/turn, respectively. These values are the same as those reported in ref. 2.

There is a considerable reduction of required currents for both error field correction and RWM control by the adoption of the new design concept owing to the change of coil positions (closer to plasma boundary). In the assessment of possible error fields in KSTAR, various possible sources of error fields, such as misalignment during coil installation, coil winding irregularities, bus lines, and vacuum vessel welding have been considered. When the permeability of the welded vessel joints is 1.10 and the standard deviation of misalignment is 2 mm, the maximum current needed to correct the error fields below the critical value of locked modes (FEC/RWM parts of all the coils) has been estimated to be about 13 kA-turns, which is about half the value obtained for the previous design. In addition, it is found that the dominant harmonic of error fields generated from segmented IC connection is $(m, n)=(1, 4)$ component and negligibly small (≤ 0.07 gauss/kA). Meanwhile, the calculation of required currents for RWM control has been investigated using a cylindrical model [3]. A proportional-integral-differential (PID) control law has been applied in this study. Figure 5 shows the critical gain over which the RWM is stable, as a function of feedback coil position. In the present design of IVCC, it is shown that the RWM can be suppressed with proportional gains larger than 200. The required feedback coil current is estimated to be about 2.4 kA-turns under the assumption of 5 gauss of RWM amplitude. There is a reduction of a factor of three compared with the feedback current requirement from the old version of FEC/RWM coils.

Besides the duplication of functions of former in-vessel coils, there are other interesting physics possibilities to be explored by using the new IVCC design. By applying a helical magnetic perturbation, magnetic islands can be generated on some rational surfaces, which will then act to drag locally the plasma flow. A local flow shear can be thus generated around some rational surfaces, which is well-known to be able to suppress local turbulent fluctuations. It is, however, noted that the islands can act negatively by providing a seed for the neoclassical tearing modes or by destabilizing the RWM by the reduction of plasma rotation. A more careful study is thus necessary to see whether this scheme can be used effectively for the control of local flow shear and related turbulent transport. Other possibilities are the control (suppression or generation) of tearing modes, and initiation of static magnetic islands at the plasma edge for impurity control

4. Preliminary Engineering Analysis

Mechanical stress analyses for several possible worst case scenarios have been carried out in the case of IC connection to design support structures. The number of vertical supports used in the analyses for IVCC1 and IVCC4 is twelve (three per segment) and that of IVCC2 and IVCC3 is sixteen (four per segment). One inter-segment joint is located at every circular-to-straight transition part where two adjacent segments meet each other. The allowable peak equivalent stresses for the conductor and case material are 218 and 207 MPa, respectively. The calculated maximum peak stress on the conductor material of IVCC2 and IVCC1 are 123 and 147 MPa, respectively. But those on case material reach up to 249 MPa for IVCC2 and 340 MPa for IVCC1. These results show that the stress on case material of the circular part of IVCC1 exceeds for several worst cases. Although increasing the number of the IVC vertical supports is considered to resolve this problem, there is little choice to increase the number of supports due to the limited in-vessel space. Thus, it is necessary to compromise the case thickness and material selection. From the analyses of time delay and amplitude reduction of feedback currents based on the solutions of a set of circuit equations, the maximum allowable case thickness has been found to be 4 mm.

Another important design issue comes from the dual function configuration, meaning non-uniformity and non-axisymmetry of currents in the coil system. Thus, mechanical and thermal effects of the configuration should be carefully investigated. The electromagnetic load calculation has been completed for the mechanical stress analysis of the segmented coils. As in the case of the IC connection, the maximum load distribution is located at the circular-to-straight transition part, whose absolute maximum value reaches up to 72 kN/m in radial direction, 59 kN/m in toroidal direction, and 99 kN/m in z-direction. On the basis of this calculation, a detailed three-dimensional analysis is now in progress and will be reported in a future publication.

5. Summary and Future Works

A new scheme based on toroidal segmentation of coils has been adopted in the design of KSTAR IVCC system for the control of vertical and radial plasma position, compensation of error fields, and control of RWM. It has been found that the new design scheme has many outstanding advantages not only in engineering aspects but also in physics point of view. Combining distinct plasma control activities with different time scales in a single coil system is not straightforward and requires extensive research works. From physics viewpoint, the development of optimal IVCC operation scenario under the consideration of relationship between error fields and RWM control is in progress. The possibility of using IVCC for the control of tearing modes and the plasma rotation will be investigated in the future. Detailed engineering design of the IVCC system, including mechanical and thermal stability analyses of the coils, design and analysis of support structures, coil feed-through, and development of coil baking scenario, is in progress and will be reported in the near future.

Acknowledgement

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