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Versatile controllability of non-axisymmetric magnetic perturbations in KSTAR experiments

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HIGHLIGHTS

- A newly upgraded In-Vessel Control Coil(IVCC) system has been installed in KSTAR.
- The system consists of broadband power supplies and a current connection patch panel.
- The system has been confirmed for various dynamic demands of 3D magnetic field configurations.
- It can help expand understanding of the 3D tokamak physics.

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ABSTRACT

A newly upgraded IVCC (In-Vessel Control Coil) system equipped with four broadband power supplies, along with a current connection patch panel, are introduced with a discussion of their capabilities on various KSTAR experiments. Until the 2014 KSTAR experimental campaign, the non-axisymmetric field configuration could not be changed in a shot, let alone the limited number of accessible configurations. With the installation of the new power supplies, such restrictions have been greatly reduced. Based on the 2015 KSTAR run-campaign, this new system was confirmed to easily cope with various dynamic demands for toroidal and poloidal phases of the 3D magnetic field in a shot. With newly equipped magnetic sensors, this enables us to extend the operational options and further explore the 3D physics for tokamak plasmas.

1. Introduction

The tokamak is an axisymmetric device in principle, but in practice has some discrepancy in symmetry due to inherent defects that result from the manufacturing and assembling the toroidal field coils. This small error field can cause various damaging effects on tokamak plasmas. To compensate this incongruity, new coils whose currents are not evenly distributed are employed, known as field error correction (FEC) coils [1–4].

While many researchers have put a lot of time and effort into making the tokamak plasma more axisymmetric, another option for advanced plasma operation using a non-axisymmetric field on tokamak devices, has been on the rise in the last decade. In particular, it has been found that using FEC coils to produce a deliberately non-axisymmetric perturbed field can suppress the edge localized modes (ELMs), a transient event that releases almost 20% of the plasma stored energy to the walls in high confinement plasmas, called an H-mode [5,6]. Among many attempts to avoid or minimize the ELMy effect, using resonant magnetic perturbation (RMP) to apply a non-axisymmetric field is one of the most effective methods in current tokamak experiments [7,8], although a theoretical model or the explanation of the mechanism involved has not been completely established.

The KSTAR (Korea Superconducting Tokamak Advanced Research) tokamak [9] also has a module equipped for FEC in the in-vessel control coils (IVCCs) which have a picture-framed segment with external connection circuits to provide capabilities, as illustrated in Fig. 1 [3]. Besides the FEC, the purposes of the IVCCs are to achieve control of the vertical and radial plasma positions, field error correction and resistive wall mode (RWM) stabilization. Since it has been determined that KSTAR tokamak has extremely low level of intrinsic error field [10], it is possible to obtain the purest plasma response to externally driven non-axisymmetric fields in the KSTAR tokamak plasma. That is, the KSTAR tokamak is a suitable device for studying the effect of a 3D magnetic field on tokamak plasmas. Indeed, using the FEC coils, the ELM response

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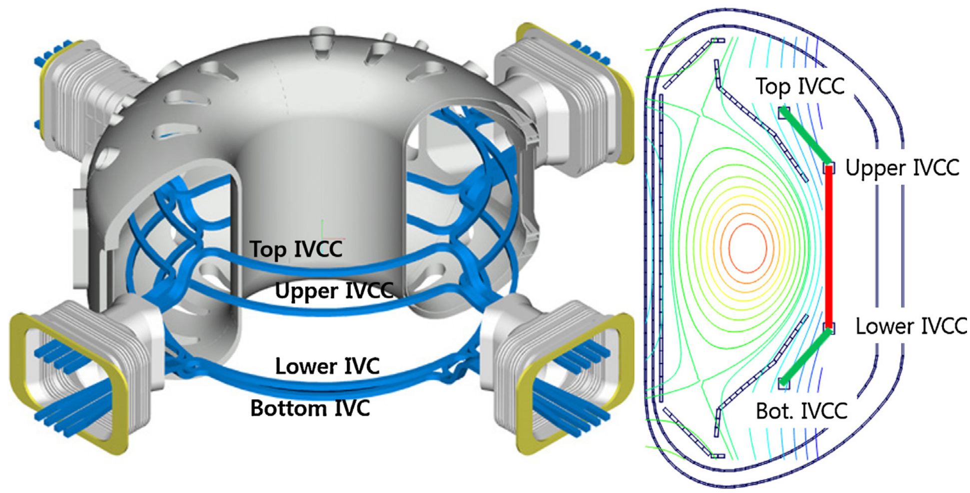

Fig. 1. 3D(left) and cross-sectional (right) views of in-vessel control coils (IVCCs) in the KSTAR tokamak.

produced by the 3D magnetic field has been studied in KSTAR for many years. By making n (toroidal mode number) = 1 and n = 2 magnetic field configuration, some impressive physical indication of ELM suppression have been observed [8,11], However, to conduct flexible experiments to investigate the physical feature intensively, the present limited features of the power source and the difficulty in changing the current configuration should be improved. For this purpose, we have installed new broad-band power supply systems with an IVCC patch panel system to provide various magnetic configuration setups. The basic functionalities of this flexible 3D field control system have been verified in the 2015 KSTAR campaign.

The remainder of this article is organized as follows. The newly installed power supply system as well as the patch panel system is described in Section 2, with emphasis on the flexibility of the magnetic configuration. This is followed in Section 3 by a review of the integrated operation process for plasma experiments in the 2015 KSTAR campaign. The final part, Section 4, discusses the role of the upgraded system in the tokamak plasma study.

2. New installed IVCC system in KSTAR

2.1. Broad-band power supply

In 2015, a total of 5 identical power supplies (P/Ss) were installed in the IVCC system. 4 P/Ss are used for the non-axisymmetric physics study and are called IPS(In-vessel control coil power supply), while remaining P/S is allocated for plasma radial control by connection to the IRC (In-vessel radial control coil). Each power supply has two stacks which can be operated as even currents in the parallel operation mode, and can be controlled individually in the private operation mode. In the parallel operation mode, the IPS can be operated with ±5 kA, ±500 V limit. Since 2 turns-coils are connected to the IPS, the maximum achievable current on the IVCC is 10 kA. The broad-band operating capacity, from 1 kHz to DC, is the most important change in this new equipment, which is equipped with a 10 kHz switching frequency. Though the IPSs can be operated continuously, the overall system including the current path has 20 min-duty cycle at full power operation, due to the capability of the IPS output cable to the IVCC. That is, 15 min is required to relax the rising temperature on the cable produced by 5 min of operation, which is the longest designed pulse length of the KSTAR tokamak [9]. The circuit diagram and a 3D feature of a single P/S are provided in Fig. 2.

2.2. Patch panel for 3D field configuration

If each IVCC can be operated individually with its own power supply, there can be many kinds of perturbed magnetic configuration, combining the current (or radial magnetic field) direction of each of the coils. We can make n = 1 or 2 field configuration for each of the row-coils, and its toroidal peak angle can be varied independently. The kinds of possible configurations, however, have been limited by the number of power supplies or their functionality. To minimize the required number of IPS for a specific magnetic configuration, we introduced a patch panel as seen in Fig. 3. The current path between the coil segments can be routed physically on this patch panel. By changing the setup of patch panel, we can also control the current direction as a characteristics of the new power supplies (i.e. −5kA to 5kA in the parallel operation mode or −2.5kA to 2.5kA in the private operation mode). Through combinations of the patch panel setup and the currents on the power supplies, we can configure the toroidal phase (or the peak angle of magnetic perturbation on the toroidal circumstance) of the row-coils. Focusing on the connectivity between the IPS and the IVCC, the series of patch panels used in the 2015 KSTAR experimental campaign are shown in Fig. 4 with their defined names.

In the figure, the picture-frame of coils are simplified with three rows of a four column table. The color in the box denotes the connected IPS number and the sign (+/−) indicates the current direction on the coils when a positive current flows in the IPS: '+' denotes the current which takes an outward direction in the radial magnetic field (B_r). Though some configurations have the same functionality, each designed configuration has its own property for its feature, For example, we can make an identical n = 1 perturbation field using only the middle coils in STD-N1D, STD-N1E, STD-RWM in Fig. 4, but they can be distinguished as the additional field perturbation of n = 1 on top, n = 1 on bottom, or n = 2 on middle coils, respectively. It is assumed that the side-band effect for higher n-mode is ignorable in these configurations.

3. IPS current control by plasma control system

In KSTAR experiments, the plasma control system (PCS) provides real-time controllability based on a PID feedback loop for discharged coil currents, to create and sustain a tokamak plasma [12,13]. The IPS current operation is also integrated in the PCS as a means of adjusting the IPS input voltage, i.e., the demanded IPS currents are translated to the command of the IPS input voltage in the PID feedback loop. In the translation, the PID gain parameters are