Construction and Plasma Initiation of the Tokamak-Helical Hybrid Device TOKASTAR-2

Koki OKANO, Kozo Yamazaki, Hideki ARIMOTO, Tetsutarou OISHI, Kazuhisa BABA, Makoto HASEGAWA and Tatsuo SHOJI

Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603 Japan

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TOKASTAR, a hybrid magnetic configuration between tokamak and stellarator, has been proposed for the study of magnetic confinement optimization. The construction of the small device named TOKASTAR-2 was started in April 2008, and completed in March 2009. As a preliminary experiment, spatial distribution of electron temperature (T_e) and electron density (n_e) are measured in a simple toroidal magnetic field configuration. Initial ECH plasmas with $T_e \sim 10\,\mathrm{eV}$, $n_e \sim 10^{16}\,\mathrm{m}^{-3}$ are confirmed. In the preliminary experiment of ohmic heating plasma production, plasma current (I_p) of 25 A is observed. The plasma equilibrium is calculated by the TOSCA code, and the magnetic flux surface and optimal vertical field coil currents are clarified for the future experiment.

Keywords: TOKASTAR, tokamak-stellarator, ECH (electron cyclotron heating) plasma, OH (ohmic heating) plasma, Plasma current, one-turn voltage, TOSCA code

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1. Introduction

TOKASTAR [1, 2] is a hybrid magnetic configuration concept between tokamak and stellarator. A miniature experimental machine C-TOKASTAR (TOKASTAR-1) was constructed with a pair of helical coil and without toroidal coil systems, and the basic magnetic surface properties have been investigated experimentally [3]. Based on this experiment, we constructed a new hybrid machine TOKASTAR-2. This machine is characterized by the outboard helical coil system added to the tokamak device. The coil configuration of TOKASTAR-2 is shown in Fig. 1. Four kinds of coils are prepared. Eight toroidal field (TF) coils generate toroidal magnetic field strength of ~ 1 kG at plasma center ~ 12 cm. Ohmic heating (OH) coil can drive plasma current up to ~ 1 kA in the center of the toroidal device. Two outboard helical field (HF) coils form helical magnetic field, which are located symmetrically outside the TF coils. The $N = 1$ or 2 mode perturbation can be made by these HF coils. TF coils, OH coils and HF coils are in the vacuum chamber. A pair of vertical field (VF) coils is installed outside the chamber to suppress the outward plasma expansion.

The microwave generator having 2.45 GHz and 2 kW pulsed magnetron oscillator was prepared for ECH (electron cyclotron heating) plasma generation. Several 200 μF-5 kV capacitors are utilized to energized pulsed current to each coil system. Table 1 shows basic machine parameters of TOKASTAR-2.

Figure 2 shows a picture of machine core installed inside the vacuum chamber, and a picture of the external appearance of the whole device is shown in Fig. 3.

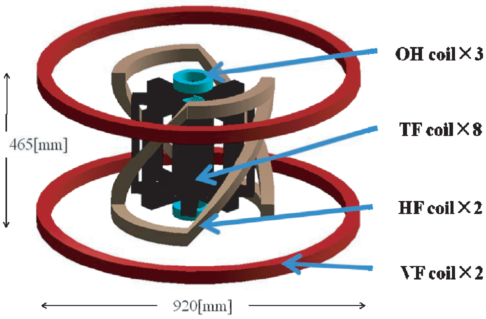

Fig. 1 Coil configuration of TOKASTAR-2.

Table 1 Basic machine parameters of TOKASTAR-2.

Toroidal magnetic field	B_t	~0.1[T]
Major radius of plasma	R_p	~0.1[m]
Minor radius of plasma	a_p	~0.04[m]
Microwave injection power	P_{ECH}	~2[kW]
Plasma current (expected)	I_p	~1[kA]

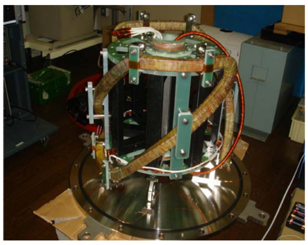

Fig. 2 Machine core.

Fig. 3 External appearance.

author's e-mail: yamazaki@ees.nagoya-u.ac.jp

Langmuir probes were prepared to analyze plasma temperature (T_e) and density (n_e), and Rogowski coil was prepared to measure plasma current (I_p). One-turn coils and saddle coils were installed inside machine core to measure the magnetic flux.

First step of experiment is to produce an ECH toroidal plasma in a simple toroidal magnetic field. Second step is tokamak plasma confinement experiment with ~ 1 kA plasma current. Third step is outer helical field application to tokamak plasmas. The goal of TOKASTAR-2 experiments is to investigate the effects of outboard helical field application to tokamak, for example, to check the change of MHD modes and plasma transport properties compared to those of pure tokamak and stellarator.

2. Measurement of Initial Plasma Parameter

ECH helium plasma generation in a simple toroidal field system was attained, with duration of several milliseconds. Spatial distribution of T_e and n_e were measured by the electrostatic double-probe method. Figure 4 shows the location of measurement probes. The calculation of T_e and n_e has been done from the current-voltage characteristic of the probe.

Typical plasma with $T_e \sim 10$ eV and $n_e \sim 10^{16}$ m^{-3} is produced near TF coil center (point P shown in Fig. 4). As for the temporal variation of n_e distribution, it is observed from the ion-saturation current measurement that the plasma is initiated inside the torus, moves outward, and then returns back inward as shown in Fig. 5. This behavior corresponds to the movement of ECR (electron cyclotron resonance) layer, which is discussed in the other paper [4].

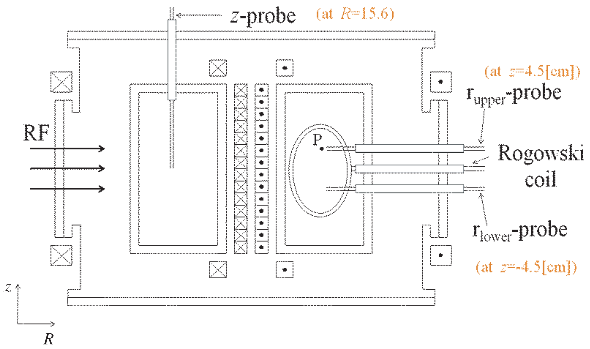

Fig. 4 Location of measurement probes.

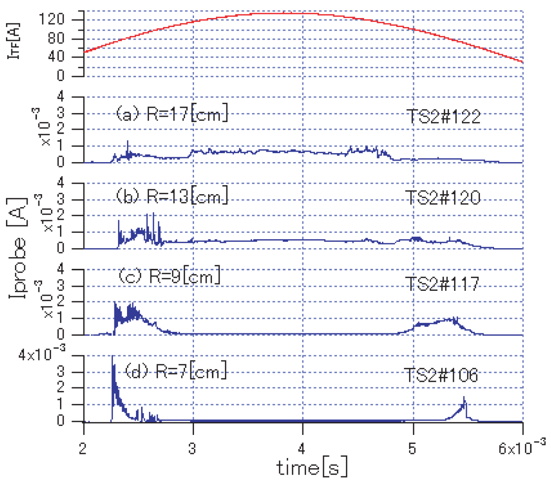

Fig. 5 Time traces of TF coil current and four signals of probes at different positions.

3. Test of OH Plasma Production

Plasma OH current drive was attempted in preparation for the generation of tokamak plasma. Figure 6 shows the discharge timing of TF and OH coils. The OH coil current is started at the time when the TF magnetic field strength at the plasma center is nearly 0.0875 T (first EC resonant magnetic field strength).

Figure 7 shows measured plasma currents (I_p) and one-turn voltage (V_{loop}), with static vertical field coil current I_{VF}(DC) of 0, 10, 20 and 30 A.

Plasma current on the order of 10 A are observed corresponding to OH coil current rising phase. Measured waveforms of I_p are varied depending on static I_{VF}.

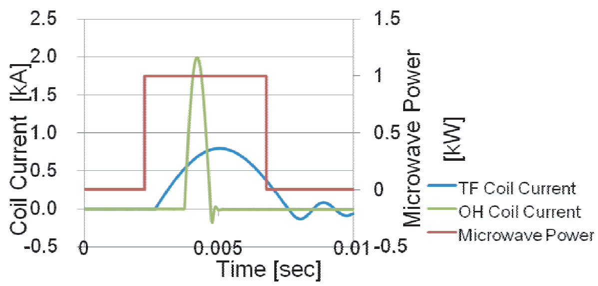

Fig. 6 Discharge timing of coils.

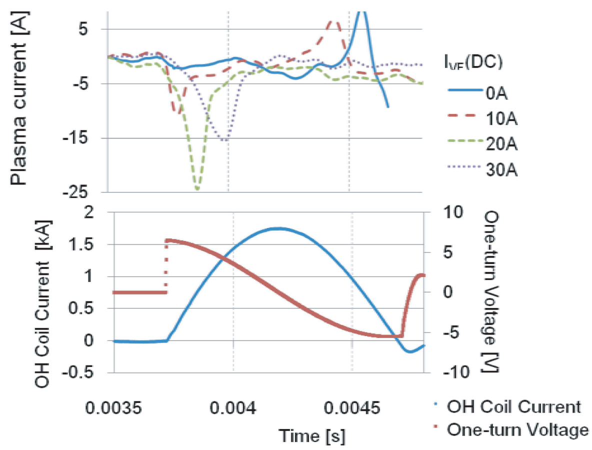

Fig. 7 Measured plasma current I_p and one-turn voltage V_{loop}.

Table 2 Input principal parameters.

Toroidal magnetic field	B_t	0.1[T]
Major radius of plasma	R_p	11[cm]
Minor radius of plasma	a_p	4.5[cm]
Plasma current	I_p	2.5[kA]

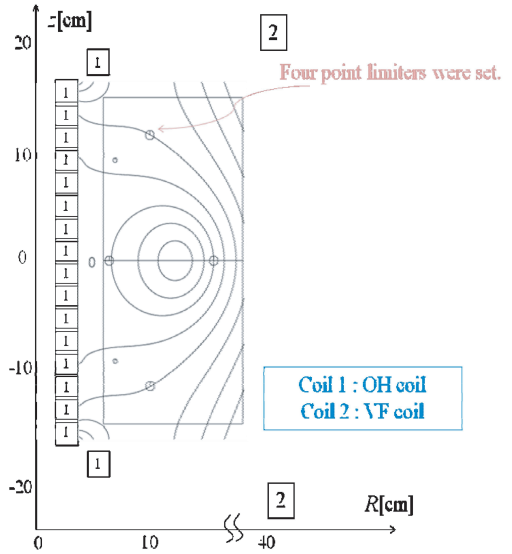

Fig. 8 An example of magnetic flux surface.

4. Equilibrium Analysis Using TOSCA Code

TOSCA [5] is a free-boundary equilibrium analysis code which is suitable for the designs of tokamak experiments. It can calculate the best current of poloidal coils given to achieve goal plasma parameters. In this code the Grad-Shafranov equation for tokamak plasma is solved, which is digitizing 129×257 meshes.

Input principal plasma parameters in TOKASTAR-2 are set as shown Table 2.

Figure 8 shows an example of magnetic flux surface in TOKASTAR-2. Coils are divided into twenty blocks as shown in this figure. The configuration and the turn number of the OH coil system (shown as #1 block of coils in the figure) were designed to minimize the vertical error field near the plasma region. In the calculation, four limiter points are defined. In the actual device, stainless-steel limiter plates are installed as limiters.

Calculated one-turn voltage is shown in Fig. 9. Compared to the measured value shown in Fig. 4, the calculated one-turn voltage is approximately two times larger. It is suggested that the eddy current on the vacuum chamber due to the OH current change might reduce one-turn voltage.

Optimal VF coil currents are calculated, for the future large plasma current experiment, as shown in Table 3. This is the case when the plasma current of 2.5 kA is assumed.

It is found from this table that VF coil current should

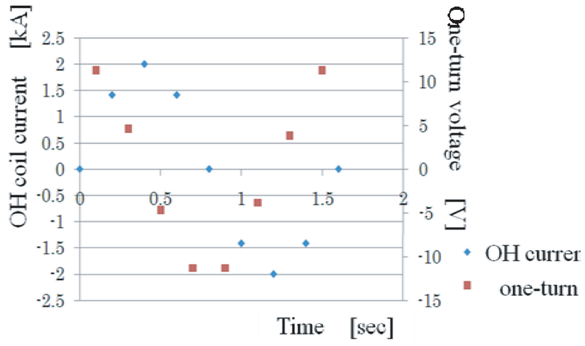

Fig. 9 Calculated OH coil current and one-turn voltage.

Table 3 Required VF coil current for 2.5 kA plasma current sustainment.

OH current [AT]	VF current [AT]
-2000	5845
-1414	5270
0	3576
1414	1911
2000	1218

be controlled corresponding to the change in the OH coil current, because large OH current might induce vertical error field. In the real experiment, the effect of eddy current on the vacuum vessel is also important.

In the present experiments, small plasma current ($\sim$25 A) was observed as shown in Fig. 7, and the required equilibrium vertical filed for this discharge is $\sim$1 G ($I_{VF} \sim$ 0.5 A). Even if the plasma minor radius was reduced to $\sim$1 cm, the required field is $\sim$2 G ($I_{VF} \sim$ 1 A) which is twenty times lower than the real experiments. The inverse vessel eddy current induced by the pulsed OH current might create large inverse vertical field, and large vertical field application is required. The details of this eddy current analysis and measurement will be carried out in the near future.

5. Summary

The new machine TOKASTAR-2 is constructed for the optimization of tokamak stellarator hybrid configuration. Initial ECH plasmas with $T_e \sim 10$ eV, $n_e \sim 10^{16}$ m^{-3} are confirmed by the Langmuir probe method.

In the preliminary OH plasma production, plasma current of $\sim$25 A is observed. Experiments of kA plasma current production in TOKASTAR-2 will be carried out in the near future.

Acknowledgement

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