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
(Received 9 December 2009 / Accepted 23 April 2010)

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 \( T_e \sim 10 \text{ eV}, n_e \sim 10^{16} \text{ m}^{-3} \) 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.

© 2010 The Japan Society of Plasma Science and Nuclear Fusion Research

Keywords: TOKASTAR, tokamak-stellarator, ECH (electron cyclotron heating) plasma, OH (ohmic heating) plasma, Plasma current, one-turn voltage, TOSCA code
DOI: 10.1585/pfr.5.S2037

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 \sim 1 \text{ kG} \) at plasma center \sim 12 \text{ cm}. Ohmic heating (OH) coil can drive plasma current up to \sim 1 \text{ 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 \mu \text{ F}-5 \text{ 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.

**Table 1 Basic machine parameters of TOKASTAR-2.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal magnetic field</td>
<td>( B_t \sim 0.1 \text{[T]} )</td>
</tr>
<tr>
<td>Major radius of plasma</td>
<td>( R_p \sim 0.1 \text{[m]} )</td>
</tr>
<tr>
<td>Minor radius of plasma</td>
<td>( a_p \sim 0.04 \text{[m]} )</td>
</tr>
<tr>
<td>Microwave injection power</td>
<td>( P_{\text{ECH}} \sim 2 \text{[kW]} )</td>
</tr>
<tr>
<td>Plasma current (expected)</td>
<td>( I_p \sim 1 \text{[kA]} )</td>
</tr>
</tbody>
</table>

Fig. 1 Coil configuration of TOKASTAR-2.

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 $\sim 1$ 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].

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. 4 Location of measurement probes.](image)

![Fig. 5 Time traces of TF coil current and four signals of probes at different positions.](image)

![Fig. 6 Discharge timing of coils.](image)

![Fig. 7 Measured plasma current $I_p$ and one-turn voltage $V_{loop}$.](image)
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 $\times$ 257 meshes.

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

<table>
<thead>
<tr>
<th>Toroidal magnetic field</th>
<th>$B_t$</th>
<th>0.1[T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius of plasma</td>
<td>$R_p$</td>
<td>11[cm]</td>
</tr>
<tr>
<td>Minor radius of plasma</td>
<td>$\alpha_p$</td>
<td>4.5[cm]</td>
</tr>
<tr>
<td>Plasma current</td>
<td>$I_p$</td>
<td>2.5[kA]</td>
</tr>
</tbody>
</table>

![Fig. 8 An example of magnetic flux surface.](image)

Table 2 Input principal parameters.

![Fig. 9 Calculated OH coil current and one-turn voltage.](image)

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

<table>
<thead>
<tr>
<th>OH current [AT]</th>
<th>VF current [AT]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2000</td>
<td>5845</td>
</tr>
<tr>
<td>-1414</td>
<td>5270</td>
</tr>
<tr>
<td>0</td>
<td>3576</td>
</tr>
<tr>
<td>1414</td>
<td>1911</td>
</tr>
<tr>
<td>2000</td>
<td>1218</td>
</tr>
</tbody>
</table>

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 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 (~ 25 A) was observed as shown in Fig. 7, and the required equilibrium vertical field for this discharge is ~ 1 G ($I_{VF}$ ~ 0.5 A). Even if the plasma minor radius was reduced to ~ 1 cm, the required field is ~ 2 G ($I_{VF}$ ~ 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 $T_e$ ~ 10 eV, $n_e$ ~ $10^{16}$ m$^{-3}$ are confirmed by the Langmuir probe method.

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

Acknowledgement

The authors would like to thank Dr. K. Shinya for allowing us to use TOSCA code.


