

# Magnetic Field Measurements Using a Multichannel Magnetic Probe in TOKASTAR-2<sup>\*)</sup>

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The radial profile of the poloidal field inside the plasma column was measured in TOKASTAR-2 using a multichannel magnetic probe with 10 sensors in the radial direction. The position of the current center and its movement were observed. The oscillation in the plasma radial position was suppressed using the helical magnetic field.

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## 1. Introduction

TOKASTAR-2 is a plasma confinement device comprising two coil systems, one is for the tokamak and the other is for the stellarator [1]. These two coil systems can be operated independently. The TOKASTAR-2 coil system contains eight toroidal field (TF) coils ( $N_{TF} = 50$  turns each), three-block ohmic heating (OH) coils (central solenoid with  $N_{OH1} = 84$  turns and upper and lower coils with  $N_{OH2} = 22$  turns each), a pair of pulsed vertical field (PVF) coils ( $N_{PVF} = 20$  turns each), a pair of vertical field (VF) coils ( $N_{VF} = 100$  turns each), two outboard helical field (HF) coils ( $N_{HF} = 98$  turns each), and four additional helical field (AHF) coils ( $N_{AHF} = 126$  turns each). The coil configuration is shown in Fig. 1. The tokamak plasma is generated using the TF, OH, and PVF coils. The duration and peak value of the plasma current of the tokamak discharge were increased by adjusting the vertical magnetic field, including the capacitance of the capacitor in the PVF coil circuit [2]. The plasma position was measured with a high-speed camera in the tangential direction; however, details were unclear because the field of view was limited. In this study, we measured the poloidal magnetic field inside the plasma column in order to measure the radial distribution of the plasma current density, evaluate the effect of the superimposed helical magnetic field on the tokamak and optimize the tokamak discharges.

## 2. Method

The radial profile of the poloidal magnetic field was measured using a multichannel magnetic probe (MMP) with 10 sensors in the radial direction. The sensor array was inserted into a glass tube jacket of outer diameter

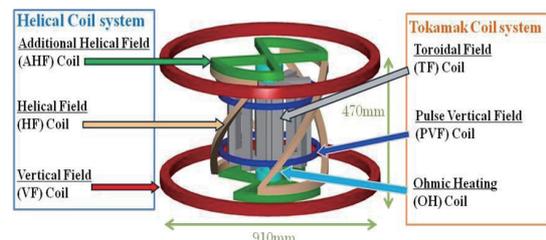


Fig. 1 Coil configuration of TOKASTAR-2.

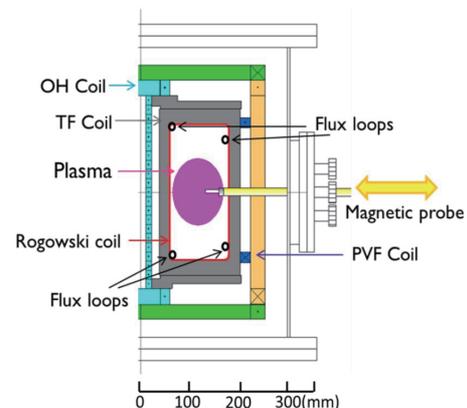


Fig. 2 Cross section of the TOKASTAR-2 and the MMP insertion position.

6 mm. The location of the MMP is shown in Fig. 2. When the MMP was inserted at the maximum position, the innermost coil (Coil 1) was located 75 mm from the center of the device. The distance between adjacent coils was 10 mm and  $NS$  was  $8.83 \times 10^{-5} \text{ m}^2$  in this coil. The  $NS$  denotes the product of the number of turns  $N$  and the effective coil area  $S$ . The material of the coil bobbin was alumina. The magnetic field distribution was obtained by numerically integrating the voltage of the measuring coils.

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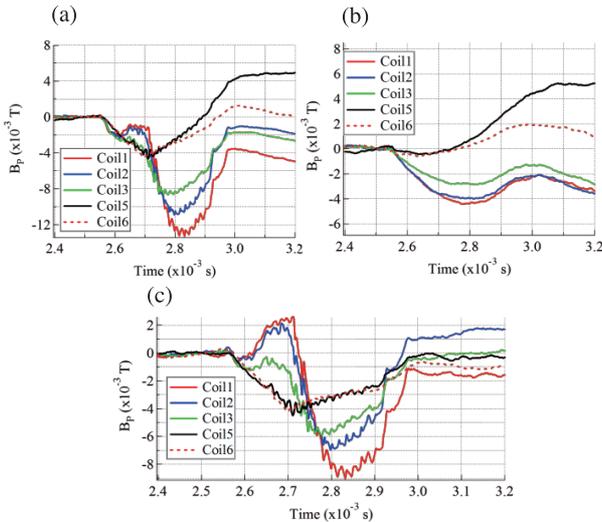


Fig. 3 (a) Total magnetic field obtained using the MMP. (b) Background magnetic field. (c) Magnetic field generated by the plasma current.

In this study, the poloidal magnetic field generated by the plasma current and the total magnetic field were used to determine the plasma center position. The poloidal magnetic field generated by the plasma current was obtained by subtracting the field without the plasma current and with the same OH and PVF coil currents from the field with the plasma current as follows:

1. Obtain the voltage at each position using the 10 coils for the tokamak discharge.
2. Obtain the voltage at each position using the 10 coils for the same OH and PVF coil currents without the plasma current.
3. Subtract the voltage without plasma from the voltage with plasma to obtain the magnetic field using only the plasma current.
4. The resulting voltage was numerically integrated to obtain the poloidal magnetic field.

Figure 3 shows the components of the magnetic field. The total magnetic field is shown in Fig. 3 (a). The background magnetic field is shown in Fig. 3 (b). The magnetic field generated by the plasma current is shown in Fig. 3 (c). For the innermost channel (Coil 1), the peak magnetic field was  $-9 \times 10^{-4}$  T, whereas the peak background magnetic field was  $-4.5 \times 10^{-4}$  T.

### 3. Experimental Results

To measure the poloidal magnetic field distribution in the entire plasma, the MMP was inserted at the maximum position. Coil 1 was located at  $R = 75$  mm, where  $R$  is the distance from the center of device, and Coil 10 was located at  $R = 165$  mm. Figure 4 shows the time evolution of the plasma current and the total poloidal magnetic field measured by the MMP. Figure 5 shows the total magnetic

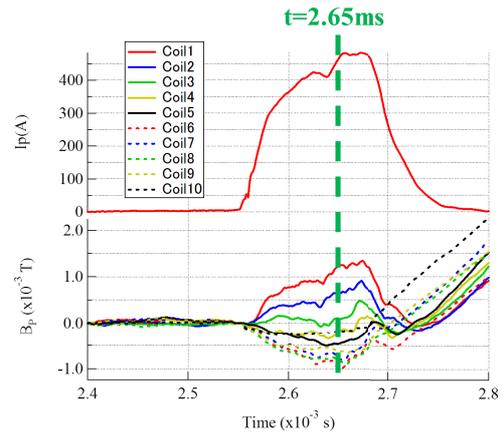


Fig. 4 Plasma current and poloidal magnetic field measured by the MMP inserted at the maximum position.

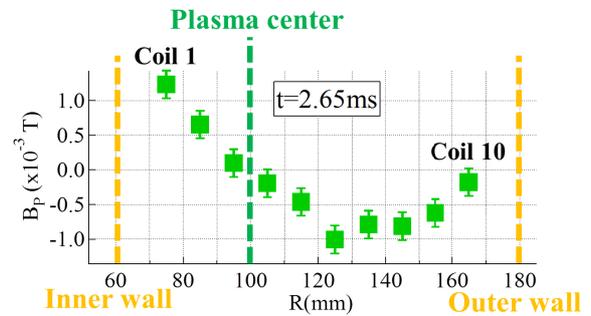


Fig. 5 Magnetic field distribution at  $t = 2.65$  ms in the plasma shown in Fig. 4.

field distribution in the radial direction at the peak of the plasma current ( $t = 2.65$  ms). The charging voltage of the capacitor banks for each coil was 1 kV for TF, 2 kV for OH, and 0.42 kV for PVF (the charging voltage of PVF was optimized).

In Fig. 5, the sign of the poloidal field is inverted near  $R = 100$  mm. Therefore, it is inferred that the plasma center is located at this position. The peak plasma current of the discharge shown in Fig. 4 was lower than the current of typical discharges ( $> 800$  A) in TOKASTAR-2 because of the insertion of the MMP.

Therefore, to obtain data for plasmas with higher plasma current, experiments were conducted under the condition that the insertion of Coil 1 was limited to  $R = 125$  mm. Figure 6 shows the time evolution of the plasma current and the poloidal magnetic field generated by the plasma current. Figure 7 shows the radial profiles of the magnetic field generated by the plasma current ( $t = 2.6 - 2.9$  ms). The gas was changed from helium to nitrogen. Consequently, higher plasma current with better reproducibility was obtained with nitrogen in TOKASTAR-2. Charging voltages were the same as those in the previous experiment. The optimum PVF voltage value for extending the plasma duration in nitrogen discharges was the same.

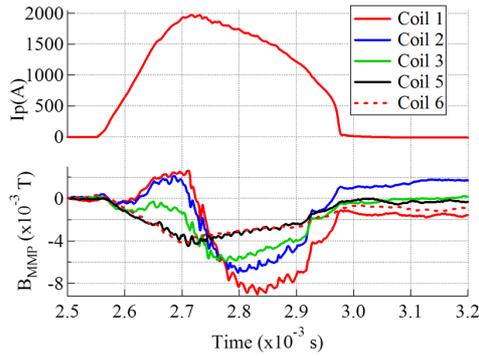


Fig. 6 Plasma current and poloidal magnetic field measured using the MMP at 50 mm outward from the most inserted position.

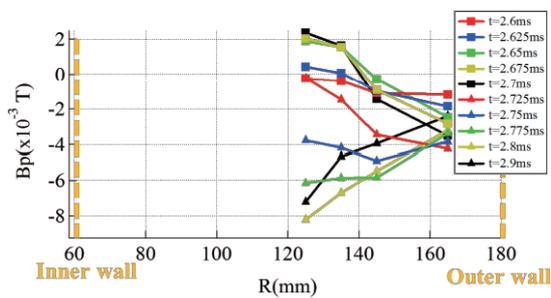


Fig. 7 Magnetic field distribution for  $t = 2.6$ - $2.9$  ms in the plasma shown in Fig. 6.

As shown in Fig. 6, the peak value of the plasma current increased from 500 A to 2000 A, and the plasma current duration increased from 0.2 ms to 0.4 ms.

The total magnetic field measured by the MMP (not shown) was negative for all channels during this discharge, and hence the plasma center position cannot be determined by the null point of the MMP signals, as shown in Fig. 5. Instead, the plasma center position was inferred using an analytical solution for the magnetic field generated by the ring current. The Z-component of the poloidal magnetic field at point  $(R, Z)$  generated by the ring current  $I$  at  $(R_0, 0)$  is

$$B_Z(R, Z) = \frac{\mu_0 I}{2\pi} \frac{1}{\sqrt{(R_0 + R)^2 + Z^2}} \times \left[ K(k) + \frac{R_0^2 - R^2 - Z^2}{(R_0 - R)^2 + Z^2} E(k) \right], \quad (1)$$

$$k = \frac{2\sqrt{R_0 R}}{\sqrt{(R_0 + R)^2 + Z^2}}. \quad (2)$$

In particular, on the equator plane  $Z = 0$  on which the MMP coils are located

$$B_Z(R, 0) = \frac{\mu_0 I}{2\pi R_0} \left[ \frac{K(k)}{1 + R/R_0} + \frac{E(k)}{1 - R/R_0} \right], \quad (1')$$

$$k = \frac{2\sqrt{R/R_0}}{1 + R/R_0}. \quad (2')$$

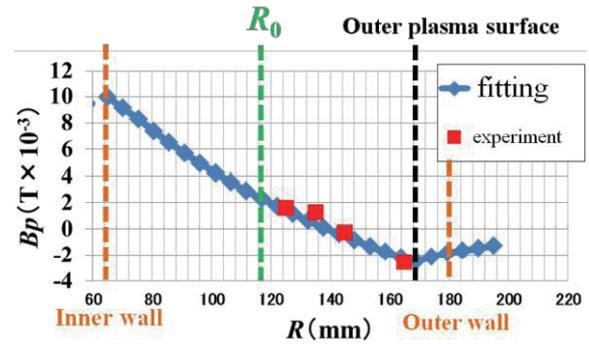


Fig. 8 Example of the analysis in which the dataset at  $t = 2.65$  ms in Fig. 7 was fitted. The inferred plasma center position is  $R = 117$  mm.

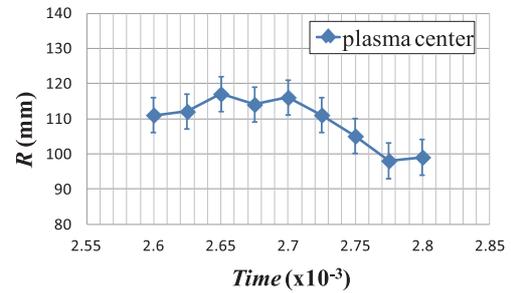


Fig. 9 Time evolution of the inferred plasma center position for the discharge shown in Fig. 6.

Note that the above equation is valid only for the region outside the plasma column. For the region inside the plasma column, the following equation is used in place of eq. (1')

$$B_Z(R, 0) = \frac{\mu_0 I(r)}{2\pi R_0} \left[ \frac{K(k)}{1 + R/R_0} + \frac{E(k)}{1 - R/R_0} \right] + \frac{\mu_0}{4\pi R_0} \int_r^a \left[ \ln \left( \frac{8R_0}{r'} \right) - \frac{3}{2} \right] j(r') 2\pi r' dr', \quad (3)$$

where  $r = |R - R_0|$  is the minor radius of point  $(R, Z)$  and  $I(r)$  is the plasma current within  $r$ . The second term in eq. (3) is the vertical field generated by the plasma current outside  $r$ .

Figure 8 shows an example of the analysis in which the dataset at  $t = 2.65$  ms in Fig. 7 was fitted. Figure 9 shows the time evolution of the inferred plasma center position. The plasma center moved outward temporarily during the current ramp-up phase.

Next, to observe the effect of the helical field, an external helical magnetic field was applied to the tokamak plasma. The coil current values were 1 A for VF, 25.51 A for HF, and 22.83 A for AHF. These values were determined so that the helical coil creates closed magnetic surfaces. The current in these coils was driven by steady-state power supply and remained nearly constant during tokamak discharges.

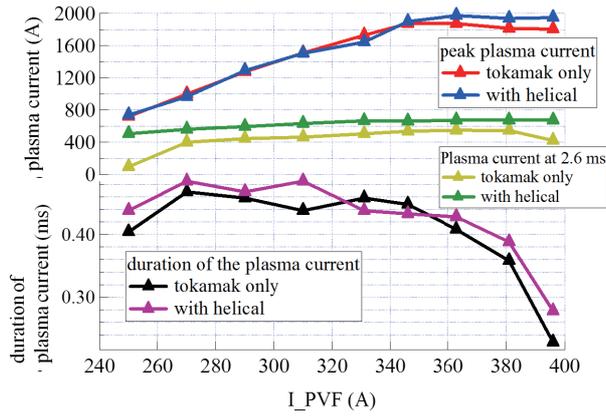


Fig. 10 Effect of helical field on the plasma current (peak value and value at  $t = 2.6$  ms) and duration of the plasma current.

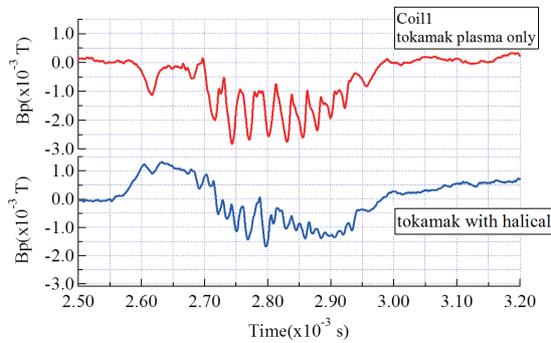


Fig. 11 Poloidal magnetic field at MMP Coil 1 for PVF coil current of 250 A (minimum value in Fig. 10).

Figure 10 shows the plasma current (peak value and value at  $t = 2.6$  ms) and the duration of the plasma current as a function of the peak PVF coil current. The peak plasma current increased by applying the helical field when the PVF current value was large, whereas the plasma current value at  $t = 2.6$  ms increased for a wide range of PVF current values. In general, the plasma current duration increased.

Figure 11 shows the poloidal magnetic field at MMP Coil 1 for PVF coil current of 250 A (minimum value in Fig. 10). In this weak vertical field region, a large oscillation was observed in the magnetic field, as shown in the top waveform. This oscillation was suppressed by applying the helical field, as shown in the bottom waveform. The inferred plasma center position is shown in Fig. 12. The oscillation of the plasma center in the radial direction was also suppressed by applying the helical magnetic field. The cause of the oscillations was not identified, but the horizontal position instability caused by the weak or high  $n$ -index vertical magnetic field is a potential candidate.

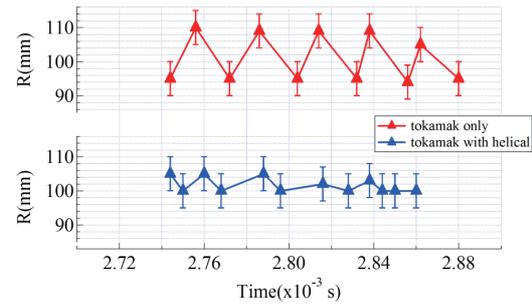


Fig. 12 Inferred plasma center position in the radial direction without (top) and with (bottom) helical field.

## 4. Summary and Future Plan

The radial profile of the poloidal field inside the plasma column was measured in TOKASTAR-2 using a multichannel magnetic probe (MMP) with 10 sensors in the radial direction. The plasma center position was estimated as the point where the total poloidal field crosses zero for maximum insertion of the MMP. The peak value of the plasma current and plasma current duration increased when the MMP was pulled 50 mm radially outward from the most inserted position. In this case, because the plasma center was located outside the range covered by the MMP coils, the plasma center position was inferred using an analytical solution for the magnetic field generated by the ring current. Results showed that the plasma center moved outward temporarily during the current ramp-up phase. Oscillation in the plasma radial position was observed for weak vertical fields. The oscillation was suppressed by applying the helical magnetic field. This suggests the stabilization effect of the helical field on the radial plasma movement [3]. In the future, we plan to study this phenomenon in detail by evaluating the effective poloidal field generated by the helical field.

The signal-to-noise ratio in the obtained data is insufficient for precisely analyzing the plasma center and current profile. To evaluate the NS required for an adequately high signal-to-noise ratio, a test MMP with NS of  $7.5 \times 10^{-4} \text{ m}^2$  was constructed and tested, and the result showed that the measurement noise sufficiently decreased. We plan to develop a new MMP that will have spatial resolution similar to the old MMP ( $\sim 10$  mm) and NS similar to the test MMP ( $\sim 7.5 \times 10^{-4} \text{ m}^2$ ) to obtain a more accurate poloidal field distribution.

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