Three-Dimensional Analysis of Eddy Current in TOKASTAR-2

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The accuracy of magnetic field analysis including eddy current is important in MHD equilibrium reconstruction of tokamak plasmas. In a small toroidal plasma experimental device TOKASTAR-2, the eddy current calculations were done with an axisymmetric model of the vacuum vessel though its vacuum vessel has periodic three-dimensionality every 90 degrees of toroidal angle due to large horizontal ports. The three-dimensional (3D) eddy current magnetic field is evaluated by 3D magnetic field calculations using ANSYS for the first time in TOKASTAR-2. The results are compared with the conventional axisymmetric magnetic field calculation and measurements using magnetic probes located inside and outside of the vacuum vessel. The resistivity of the vacuum vessel model in ANSYS is modified to reduce the error from the experimental values. Using the developed model, the effect of the presence of the port on the eddy current magnetic field is evaluated. The results show that the toroidal-average of the eddy current magnetic field becomes smaller by presence of the ports but the non-uniformity in the toroidal direction is relatively small. This implies that the effects of the port would be introduced in an axisymmetric model by using poloidally nonuniform resistivity to suppress the eddy current on the midplane.

Keywords: TOKASTAR-2, tokamak plasma, eddy current, 3D analysis, magnetic measurement

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1. Introduction

The TOKASTAR-2 is a small torus plasma experimental device. It can be operated with tokamak, helical, and hybrid configurations. One of the main purposes of TOKASTAR-2 is verification of the stabilization of the tokamak plasma position by helical field [1]. Figure 1 shows magnetic field coils for tokamak operation, together with the vacuum vessel, in TOKASTAR-2. The set of coils consists of three-blocks Ohmic Heating (OH) coils, a pair of Pulsed Vertical Field (PVF) coils, a pair of Shape Control (SC) coils and eight Toroidal Field (TF) coils. In the tokamak operation, these coils are connected to pulsed power supplies with capacitor banks. The toroidal field strength is about 0.1 T and pre-discharge plasma is generated with electron cyclotron resonance heating (ECRH) by a microwave of 2.45 GHz. The OH coils induce a plasma current (~2.2 kA, ~0.5 ms) and the PVF coils and the SC coils form the equilibrium field. The vacuum vessel is in a cylindrical shape with top and bottom flat plates and is made of the stainless steel. The inner radius and the thickness of the side wall are 300 mm and 5 mm, respectively. The thickness of top and bottom plates is 22 mm.

In TOKASTAR-2, a filament current approximation code (FCA code) was developed for determining tokamak plasma positions and shapes [2]. In the FCA code, experimental values of plasma current magnetic fields are given by subtracting calculated vacuum field from magnetic measurements [3]. The vacuum field consists of the coil magnetic field and the eddy current magnetic field. The position and current of the six filaments simulating the plasma current are determined to minimize the error between the experimental and calculated values of the plasma current magnetic field. The filament currents determine the position of the center of the plasma current, and the total flux determines the shape of the plasma. In the calculation

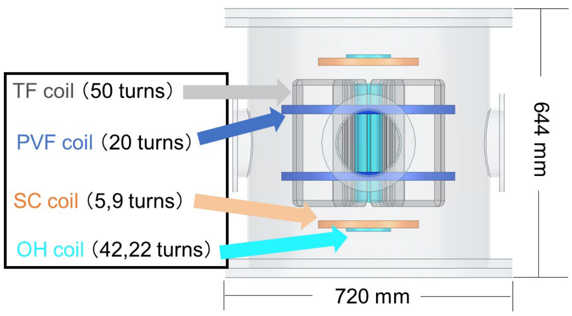

Fig. 1 Coils for tokamak operation and the vacuum vessel in TOKASTAR-2.

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of the plasma position and shape, it is important to reduce the error of the calculated vacuum field. It affects on accuracy of plasma position and shape calculation because the coil magnetic field is about four times larger than the plasma current magnetic field, and the eddy current magnetic field is about two times larger than the plasma current magnetic field in magnetic probes used in the FCA code, in typical cases. Since the vacuum vessel is not isolated toroidally, large eddy current circlulating around the major axis, about several times as large as the plasma current, is driven in the vacuum vessel. The accurate evalution of the eddy current is important in the FCA code analysis. One of the possible causes of the error is that the FCA code does not take into account the three-dimensional (3D) structure of the vacuum vessel because an axisymmetric model of the vacuum vessel is assumed to calculate the eddy current. The 3D calculation of eddy current is possible with the analysis code ANSYS [4] and also with other codes [5]. In this article, 3D calculation of eddy current is conducted using ANSYS to evaluate the effects of three dimensional structure of the vacuum vessel of TOKASTAR-2.

The remainder of this article is organized as follows. In Sec. 2, the magnetic field probes used in this study is described. In Sec. 3, codes for calculating the eddy current are described. In Sec. 4, the results of ANSYS calculations and conventional axisymmetric calculations are compared with the results of magnetic field measurements under no plasma conditions. Based on the results obtained, the vacuum vessel model in ANSYS is modified. In Sec. 5, the effect of the presence of the port on the eddy current magnetic field is evaluated using the developed model. Finally, summary and discussion are given in Sec. 6.

2. Measuring Equipment

In this study, three types of magnetic probes were used.

2.1 Poloidal magnetic probe array

The first type is Poloidal Magnetic Probe array (PMP) [2]. Figure 2 shows the position of PMP. It has total of 16 channel magnetic probes installed along TF coil. The field in the Z and R directions are measured by probes shown in yellow (channels 1, 2, 3, 5, 7, 8, 9, 10, 11, 13, 15 and 16) and blue (channels 4, 6, 12 and 14), respectively. This is used to calculate the position and the shape of the plasma in the FCA code. Therefore it is important to reduce the error of the calculation of coil magnetic field and the eddy current magnetic field at the positions of PMP channels.

2.2 Toroidal magnetic probe array

The second type is Toroidal Magnetic Probe array (TMP). Figure 3 shows the position of TMP. It has total of 8 channel probes measuring the Z component of magnetic field. They are installed on the outer leg of the TF coils, at (R, Z) = (191 mm, 0 mm). The main purpose is obtaining the toroidal distribution of the plasma magnetic field when a helical magnetic field is applied. In this article, it is used to measure the toroidal distribution of the eddy current magnetic fields. In this article, only channels 1, 2, 4 and 5 were used.

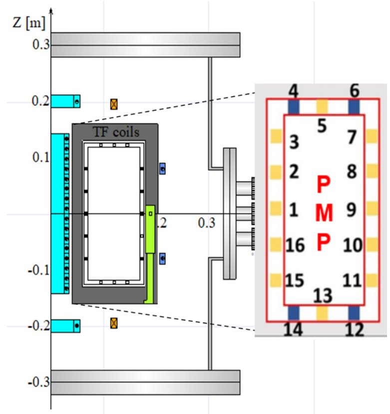

Fig. 2 The position of PMP in the poloidal cross-section. It has 16 channels along the poloidal limiter or the inner surface of a toroidal field coil.

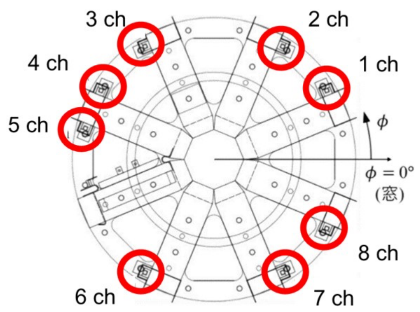

Fig. 3 The position of TMP in the plane view. It has eight channels aligned toroidally.

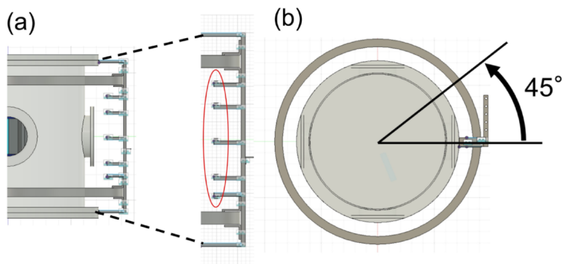

Fig. 4 (a) The position of OMP. It has five channels aligned vertically. (b) Range of motion of OMP in the toroidal direction.

2.3 Outside magnetic probe

The third type is Outside Magnetic Probe array (OMP). Figure 4 (a) shows the position of OMP. This measures the magnetic field in the Z direction. This magnetic probe was fabricated to measure the detailed toroidal distribution of the eddy current magnetic field and then confirm the results of 3D eddy current calculations. The five channels are located separately in the vertical direction at Z = 0 mm, ±100 mm, and ±162.5 mm, while all of them are located at the same radial position of R = 398 mm. It can be moved continuously in the toroidal direction within a range of 45° as shown in Fig. 4 (b). The center of one of the four equatorial ports is located at 0°.

3. Calculation Codes

We use two calculation codes in order to calculate coil and eddy current magnetic field.

3.1 Circuit equation code

The Circuit Equation code (CE) is a code that calculates eddy current flowing in the vacuum vessel, the magnetic field and flux distribution due to eddy current and coil current by inputting the time variation of the coil current for an axisymmetric coil with the model of axisymmetric vacuum vessel. Table 1 shows input and output of circuit equation code.

In CE, the vacuum vessel is approximated as a set of circular filaments and a set of simultaneous differential equations for filament currents is solved. The number of filaments used for modeling the vacuum vessel is 67. Finite cross-sections are considered only for calculating the self-inductance of filaments. The simultaneous differential equation is written as

$$L_{\mathrm{vv}}\frac{d\boldsymbol{I}_{\mathrm{eddy}}}{dt}+R_{\mathrm{vv}}\boldsymbol{I}_{\mathrm{eddy}}+M_{\mathrm{c,vv}}\frac{d\boldsymbol{I}_{\mathrm{coil}}}{dt}=0, \tag{1}$$

where L_{vv} is the inductance matrix of vacuum vessel filaments, $\boldsymbol{I}_{\mathrm{eddy}}$ is the eddy current vector, R_{vv} is the resistance matrix of vacuum vessel filaments, $M_{\mathrm{c,vv}}$ is the inductance matrix between vacuum vessel filaments and the coil currents, $\boldsymbol{I}_{\mathrm{coil}}$ is the coil current vector. The dimension of matrix L_{vv} and R_{vv} is 67×67, that of matrix $M_{\mathrm{c,vv}}$ is 67×4, that of vector $\boldsymbol{I}_{\mathrm{eddy}}$ is 67, and that of vector $\boldsymbol{I}_{\mathrm{coil}}$ is 4 (the OH coil, the upper PVF coil, the lower PVF coil and the SC coil). Note that R_{vv} is a diagonal matrix. The coils and the filament model of the vacuum vessel are shown in Fig. 5.

The CE is included in the FCA code to calculate the eddy current magnetic field. The plasma current is also considered in addition to the coil currents when the CE is used in the FCA code.

3.2 ANSYS

In ANSYS, magnetic field analysis is possible with almost the same input as in the CE. There are three points where it differs from CE. The first point is that coils are not filaments but have finite cross sections. The second point is that ANSYS requires a coil mesh, a vacuum vessel mesh, and a space mesh, as shown in Fig. 6. The number of mesh points is approximately 700,000. The calculation domain

Table 1 Input and output of circuit equation code.

Input	Output
• Coil current value • Coil location • Vacuum vessel model (coordinates, thickness, resistivity)	• Eddy current distribution in vacuum vessel • Coil field, eddy current field

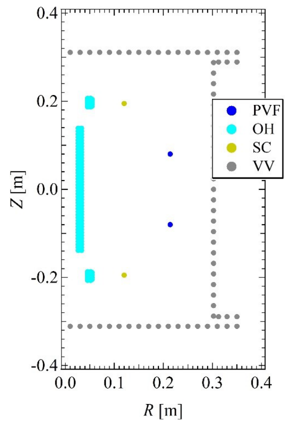

Fig. 5 The coils and the filament model of the vacuum vessel used in the circuit equation code. The size of each symbol does not represent the real cross-section of the filament in the model.

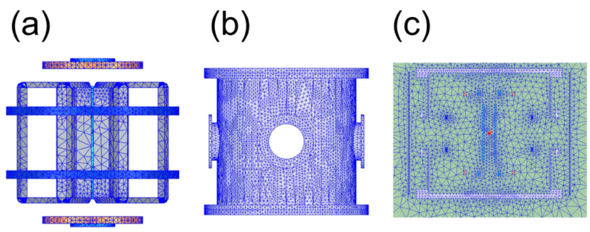

Fig. 6 (a) Coil mesh, (b) vacuum vessel mesh and (c) space mesh in ANSYS.

is a cube with sides of 20 meters centered on TOKASTAR-2. Finally, the biggest difference is that 3D magnetic field analysis is possible. In this study, ANSYS is used only to obtain eddy current magnetic field. It is obtained by subtracting the results without eddy current calculation from the results with eddy current calculation. Since the calculation time of ANSYS is much longer compared to the CE code, it is used only for calculating limited cases and it is not planned to use it for the analysis of experiment data in TOKASTAR-2.

4. 3D Calculation

In order to take into account the 3D nature of the vacuum vessel, a 3D magnetic field calculation was performed using ANSYS. The results were then compared with the

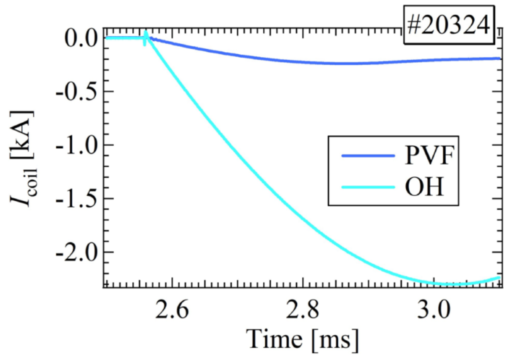

Fig. 7 Waveforms of coil currents used in the analysis; the PVF current coil in dark-blue and the OH coil current in light-blue.

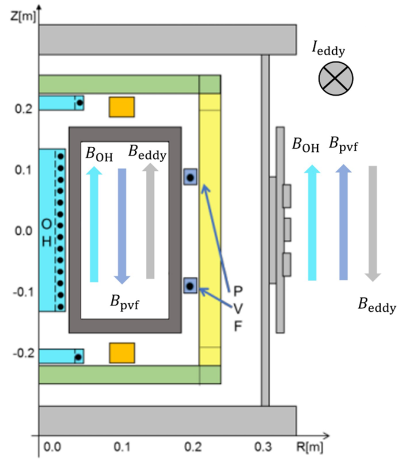

Fig. 8 Direction of the driven current and generated magnetic field in the poloidal cross-section.

results of CE calculations and magnetic field measurement. The PVF and OH coils were energized in the absence of plasma. The waveforms of the coil currents are shown in Fig. 7, which are similar to those in the experiment. In order to compare the total field, the coil magnetic field calculated by CE was added to the eddy magnetic current field calculated by ANSYS. The directions of the driven currents and generated magnetic fields are shown in Fig. 8. The coil currents flow clockwise when viewed from top, so the eddy currents flow counterclockwise. The direction of the eddy current magnetic field is opposite inside and outside of the vacuum vessel. The results are compared at t = 2.8 ms, which is the typical time that the plasma current has its peak in the plasma experiment.

4.1 Results with the original vacuum vessel model

The magnetic fields measured with probes, those calculated with CE and those calculated with ANSYS are shown in Fig. 9 for comparison.

The lower part of Fig. 9 (a) shows the measured and

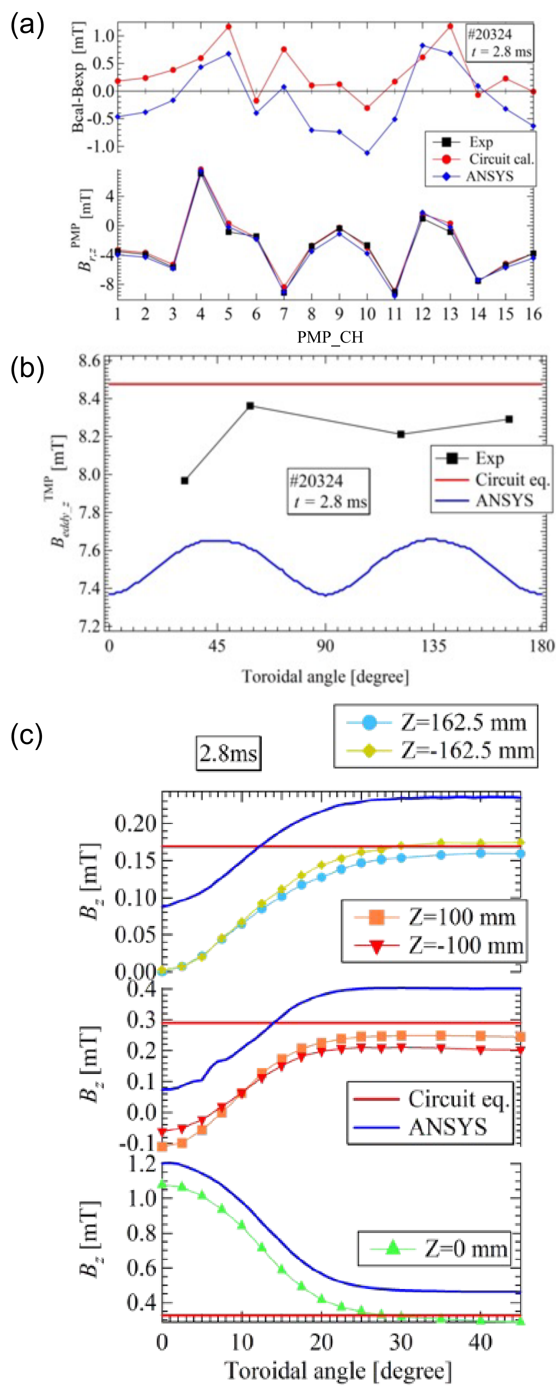

Fig. 9 Experimental and calculated values of vacuum magnetic field with original values of the resistivity of vacuum vessel in (a) PMP, (b) TMP, and (c) OMP. In (a), curves with closed squares, circles and diamonds denote the values measured with PMP, values calculated with CE and values calculated with ANSYS, respectively. In (b), curves with squares denotes the values measured by TMP, while the red and dark-blue curves denote the values calculated with CE and ANSYS, respectively. In (c), results for Z = ±162.5 mm, for Z = ±100 mm and for Z = 0 mm are shown in three panels. Curves with symbols denote values measured with OMP channels, whose positions are shown in legends. The red and dark-blue curves denote the values calculated with CE and ANSYS, respectively.

Table 2 Sum of absolute values of PMP errors in each calculation code.

	Circuit eq.	ANSYS	ANSYS_70%	ANSYS_50%
Error_PMP	6.296 mT	8.219 mT	6.846 mT	6.479 mT

calculated total fields, sum of the eddy current fields and the coil fields, at each channel of PMP, while the upper part shows the error of the calculations, namely difference from the measurement. Figure 9 (b) shows the measured and calculated eddy current magnetic fields at TMP. Figure 9 (c) shows the measured and calculated toroidal angle dependence of the total magnetic field at each channel of OMP. In PMP, errors are larger in ANSYS than in CE for many channels as shown in Fig. 9 (a). The errors are particularly large at channels 8, 9, and 10, which are close to the side wall of the vacuum vessel. In TMP, similar to PMP, errors are larger in ANSYS results than in CE as shown in Fig. 9 (b). In OMP, ANSYS reproduces the toroidal dependence well as shown in Fig. 9 (c); the eddy current magnetic fields change between 0° and about 25° with the similar magnitudes. However, ANSYS results show a larger error, 0.1–0.15 mT, than the CE results in the 30–45° area, where toroidal angle dependance is small and then the effect of three-dimensionality of the vacuum vessel (presence of ports) is considered to be small. These results show that the Z component of the magnetic field calculated with ANSYS is smaller inside the vacuum vessel (PMP, TMP) and larger outside the vacuum vessel (OMP). It implies that the ANSYS calculations underestimate the eddy current magnetic field, which is upward inside the vacuum vessel and downward outside as shown in Fig. 8.

4.2 Modification of the vacuum vessel model

The results of the previous subsection indicate that the eddy current magnetic fields are underestimated in ANSYS with the conditions employed in this study. The reason is not identified yet. In this subsection, attempts are made to improve the underestimation of the eddy current magnetic field by changing the resistivity of the vacuum vessel model.

First, resistivity was changed to 70% and 50% of the original value of 7.2×10^{-7} Ωm, aiming at increasing the eddy current. The results of the analysis are shown in Fig. 10. In TMP and OMP, by reducing the resistivity, the curves of the ANSYS results move vertically and become closer to the experimental values. Note that the shape of the curve is nearly unchanged, though the amplitude (variation along the toroidal direction) become slightly larger with reduction in resistivity. Especially when the resistivity is set to 50%, the calculated values reproduce the experimental values with high accuracy. It is found that the errors were reduced at channels 8, 9, and 10 of PMP, which had large errors in the previous calculations. Table 2 shows

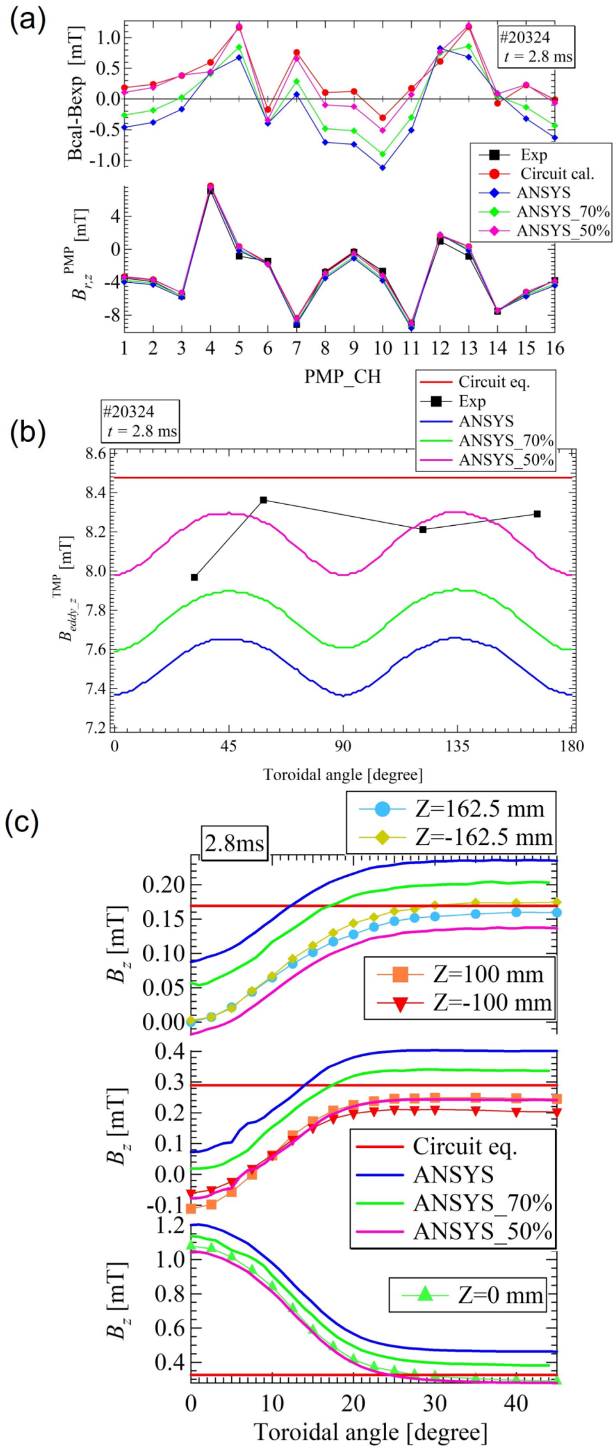

Fig. 10 Results of ANSYS with reduced resistivity of the vacuum vessel; dark-blue, light-green and magenta curves denote results with 100%, 70% and 50% of the original resistivity, respectively. The other curves, showing values measured with probes and values calculated with CE, are the same as those shown in Fig. 9.

the sum of the absolute values of the PMP errors for each calculation code. The error with 50% resistivity is significantly lower than the error with the original value of the resistivity and is close to the error in CE.

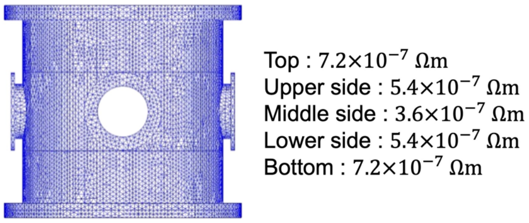

Fig. 11 Vacuum vessel mesh with nonuniform resistivity.

Table 3 Sum of absolute values of PMP errors in each calculation code.

	Circuit eq.	ANSYS	ANSYS_50%	ANSYS_rev
Error_PMP	6.296 mT	8.219 mT	6.479 mT	5.702 mT

The above results show that the error in ANSYS can be reduced by reducing the resistivity. However, the analysis in CE has smaller errors than the analysis in ANSYS. In the calculation model with 50% resistivity, which currently has the smallest error, the error of channels 5 and 13 account for about 40% of the error. These channels are located near the top and bottom of the vacuum vessel of TOKASTAR-2 (see Fig. 2).

In the above analysis, where the resistivity was reduced uniformly, the Z component of the magnetic field was increased in all channels of PMP except for channels 4, 6, 12 and 14 that measure the R-component, and then the errors become larger in some channels though errors in channels 8, 9 and 10 were reduced. Another type of modification of the model was also attempted, where a distribution to the resistivity was introduced so that only the resistivity of the side surface was changed but that of the top and bottom surfaces was left unchanged. Figure 11 shows vacuum vessel mesh with the nonuniform resistivity. The resistivity of the middle part of the side is 50% of the original value, the resistivity of the upper and lower parts of the side is 75% of the original value, and the resistivity of the top and bottom flanges of the vacuum vessel is the same as the original value.

The results of the analysis are shown in Fig. 12. The values obtained with nonuniform resistivity are shown in purple curves (“Ansys_rev”). In PMP, the errors at channels 1, 2, 3, 5, 6, 7, 11, 13, 14 and 15 are smaller in the nonuniform resistivity model compared to the model with the resistivity uniformly reduced to 50%. The sum of absolute values of errors between calculated and experimental values in PMP is lower than in a model with a uniform 50% reduction in the resistivity and also lower than in CE as shown in table 3. In TMP and OMP, there was no significant difference from the model with 50% resistivity except for Z = ±162.5 mm in OMP.

The above results show that ANSYS analysis with the model with a resistivity distribution is able to reproduce the eddy current magnetic field generated in TOKASTAR-2 with good accuracy. However, it should be noted that the error is evaluated only at 2.8 ms for the coil current evolu-

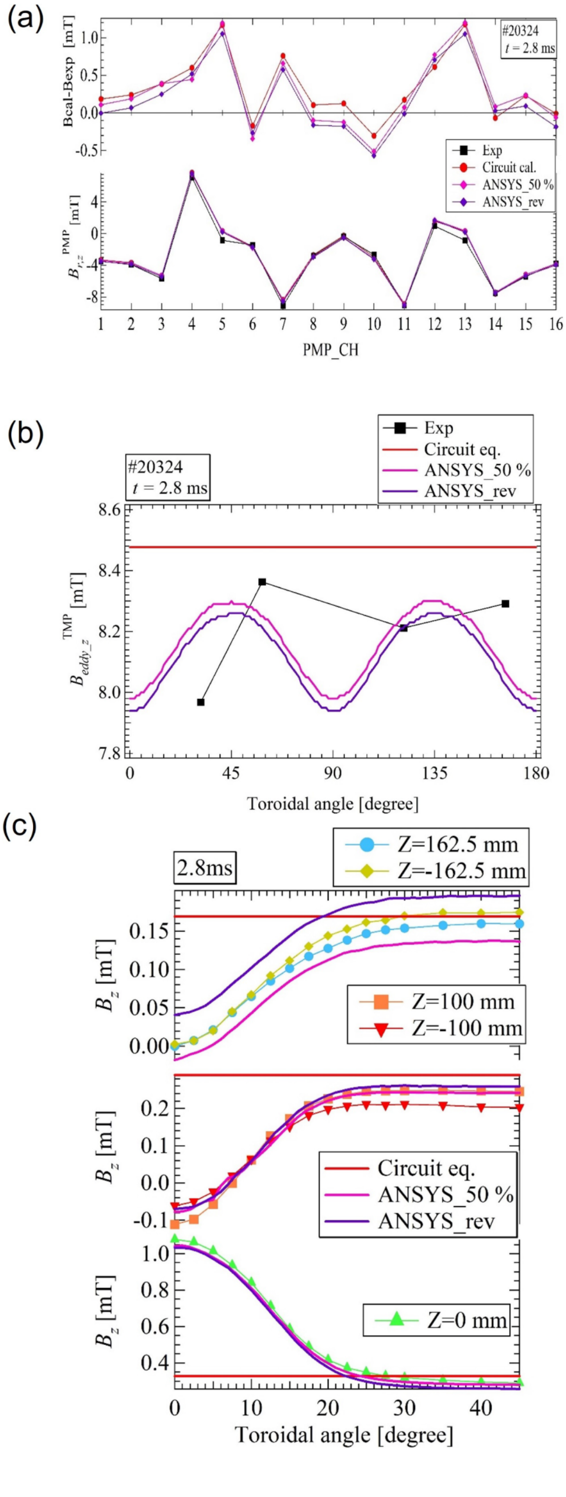

Fig. 12 Results of ANSYS with nonuniform resistivity of the vacuum vessel; magenta and purple curves denote results with 50% of the original resistivity and nonuniform resistivity as shown in Fig. 11, respectively. The other curves, showing values measured with probes and values calculated with CE, are the same as those shown in Fig. 9.

tion shown in Fig. 7. The results do not necessarily mean that the resistivity or thickness of the vacuum vessel wall is different from the designed values, but it is likely that some unidentified and unconsidered effects can be approximately simulated by the change in the resistivity.

5. Evaluation of 3D Eddy Current Magnetic Field

The influence of the ports was evaluated with ANSYS based on the vacuum vessel model with nonuniform resistivity developed in the last section. Comparing Fig. 9 and Fig. 12, it is found that the toroidal dependence of the eddy current magnetic field was hardly changed by the modification of the vacuum vessel resistivity, though its toroidally-averaged value was changed. For instance, the difference between the maximum value and the minimum value along the toroidal direction at the TMP position is 0.30 mT in the original model (in Fig. 9 (b)) and is 0.32 mT in the nonuniform resistivity model (in Fig. 12 (b)); it is only ~9% larger in the latter case. This implies that the 3D effects of the vacuum vessel can be evaluated with the ANSYS based on the vacuum vessel model with modified resistivity. The eddy current was calculated with the vacuum vessel model without ports shown in Fig. 13. The model has no ports but

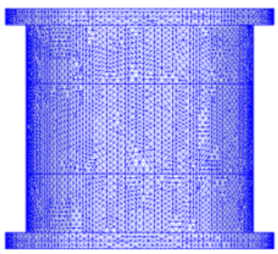

Fig. 13 Vacuum vessel model without ports. The resistivity is the same as that used in the model shown in Fig. 11.

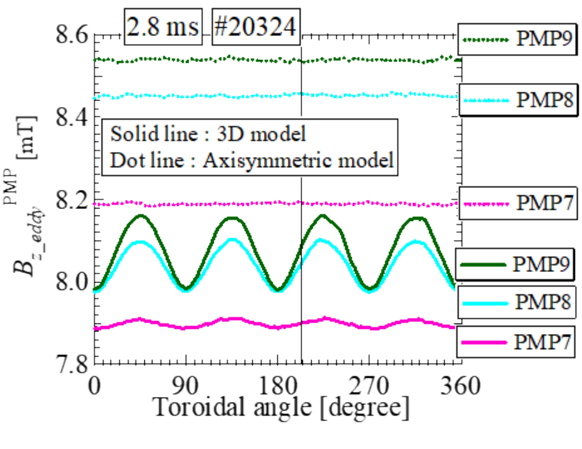

Fig. 14 Toroidal distribution of eddy current magnetic field at channels 7, 8 and 9 of PMP calculated with ANSYS using the model shown in Fig. 13.

has the same nonuniform resistivity as that of the model shown in Fig. 11. The toroidal distribution of the eddy current magnetic field at R and Z of channels 7, 8 and 9 of PMP is shown in Fig. 14. These channels are located at the larger R side of PMP as shown in Fig. 2. In the model with ports, denoted by solid lines, toroidal variation is clearly seen corresponding to the location of ports. The eddy current magnetic field is the lowest at the port center (0°, 90°, 180°, 270°) and the highest between ports. The amplitude is the largest (~0.08 mT) at channel 9, which is located on the midplane. The amplitude at channels 10 and 11 are the same as those at channels 8 and 7, respectively, due to up-down symmetry of the vacuum vessel model and the coil currents. The other channels have lower amplitudes. The results show that the non-uniformity of the eddy current magnetic field in the toroidal direction is relatively small, compared to the errors in PMP shown in Fig. 12 (a). The vertical thin black line shows the toroidal angle of 202.5° where the PMP is located. The PMP is located at the middle point between the peak and the valley, and therefore the magnetic field measured with PMP is close to the average value in the toroidal distribution. On the other hand, the axisymmetric model overestimates the eddy current magnetic field by about 0.1–0.4 mT compared to the 3D model in all three channels. This is observed in all channels including those not shown in Fig. 14. This may be because the toroidal-average of the eddy current is lower near the midplane in the model with ports than in the model without ports.

6. Summary and Discussion

In order to evaluate the effects of ports of the vacuum vessel on the eddy current magnetic fields in TOKASTAR-2, we performed 3D eddy current magnetic field calculations using ANSYS. The ANSYS calculation values were compared with the fields measured by magnetic probes located inside and outside of the vacuum vessel and the fields calculated with the conventional circuit equation code (CE) with an axisymmetric vacuum vessel model, to evaluate the validity of the ANSYS results. The results show that ANSYS underestimates the eddy current magnetic fields and has a larger error than CE in the original vacuum vessel model. The cause of underestimation of the eddy current magnetic fields in ANSYS is not identified yet and will be studied in the future. The error was reduced by reducing the resistivity of the vacuum vessel model to 50% of the original value. The error was further reduced by introducing a distribution of resistivity in the vacuum vessel, where experiment measurements was reproduced with smaller errors than in CE. Modification of the resistivity had only small influence on the toroidal variation of the eddy current magnetic field. Using the developed model, the effect of the presence of the port on the eddy current magnetic field was evaluated. The results showed that the toroidal variation of the eddy current magnetic field is small, but the toroidal-average becomes smaller by presence of the ports. This is thought to be because the presence of the port reduces the eddy currents flowing in the vacuum vessel near the midplane.

As one of possible causes of error in the eddy current calculation, effects of the poloidal plasma limiter [6] and the legs of an assembly of the in-vessel coils including the toroidal field coils [7] are discussed here. These components are made of stainless steel and are not included in the models of CE or ANSYS. The poloidal plasma limiter is mounted to the same toroidal field coil as the PMP. The four legs are apart 90 degrees in the toroidal direction from each other. Since these components have no toroidal loops circulating the major axis, the eddy current generated in these components should be small. Though not large, these components might have some influence. The magnetic field generated by eddy current in the poloidal limiter should be quite localized and it is not adequate to simulate such a field by modification of resistivity of the vacuum vessel. However, the modification of resistivity resulted in reduction of errors in all three types of magnetic probes (PMP, TMP and OMP). This means that the magnetic field simulated by the modification of resistivity is not related to the poloidal limiter. The legs are closer to the bottom channels (12, 13 and 14) of PMP than to the top channels (4, 5, 6). So its effect, in any, should be larger in the bottom channels than in the top channels. However, we can see that no clear difference in errors in these two groups of channels as shown in Fig. 9 (a) for example. This indicates that the legs are not a major source of errors.

For the analysis of experiment data in TOKASTAR-2, fast eddy current calculation by an axisymmetric model is needed. The results of this study show that the effects of the port would be introduced in an axisymmetric model by using nonuniform resistivity. In the future, we plan to create a 2D vacuum vessel model that takes into account the effects of the ports and evaluate the impact of the ports on the plasma position shape calculations.

Acknowledgments

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[1] K. Yasuda *et al.*, Phys. Plasmas **28**, 082108 (2021).
[2] K. Yasuda *et al.*, Plasma Fusion Res. **13**, 3402072 (2018).
[3] R. Ikeda *et al.*, Plasma Fusion Res. **15**, 1303031 (2020).
[4] V. Kindl *et al.*, Fusion Eng. Des. **171**, 112579 (2021).
[5] C. Hansen *et al.*, Phys. Plasmas **24**, 042513 (2017).
[6] K. Muraoka *et al.*, Plasma Fusion Res. **13**, 1402111 (2018).
[7] K. Yamazaki *et al.*, Plasma Fusion Res. SERIES **8**, 1044 (2009).