Designing a Sine-Coil for Measurement of Plasma Displacements in IR-T1 Tokamak

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Abstract. A method for the measurement of the plasma position in the IR-T1 tokamak in toroidal coordinates is developed. A sine-coil, which is a Rogowski coil with a variable wiring density is designed and fabricated for this purpose. An analytic solution of the Biot–Savart law, which is used to calculate magnetic fields created by toroidal plasma current, is presented. Results of calculations are compared with the experimental data obtained in no-plasma shots with a toroidal current-carrying coil positioned inside the vessel to simulate the plasma movements. The results are shown a good linear behavior of plasma position measurements. The error is less than 2.5% and it is compared with other methods of measurements of the plasma position. This method will be used in the feedback position control system and tests of feedback controller parameters are ongoing.

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INTRODUCTION

In several configurations of magnetically confined plasmas, the position of the plasma column is a major determinant of plasma behavior for controlling the plasma equilibrium. Several methods are employed for displacement measurements, such as optical and magnetic methods. For the magnetic method, almost it is used sine-coil. The Ampere's theorem and the Biot–Savart law are well known tools used to calculate magnetic fields created by current distributions [1-4]. The former is often used in high-symmetry problems of magnetisms. At first section of this work, an analytic solution of the Biot–Savart law, which is used to calculate magnetic fields created by toroidal current-carrying coil positioned inside the vessel to simulate the plasma movements, is presented.

In the second section a sine-coil, which is a Rogowski coil with a variable wiring density is designed and fabricated for measurement of no-plasma shot experiments with circle coil of radius R = 0.45 m. The last section contain experiments on the ohmically heated air core tokamak IR-T1 with a major radius R=0.45 m and a minor radius a = 0.125 m measurement of plasma position with the sine-coil. The vacuum chamber is a stainless steel welding structure with two toroidal breaks and a minor radius b= 0.15 m.

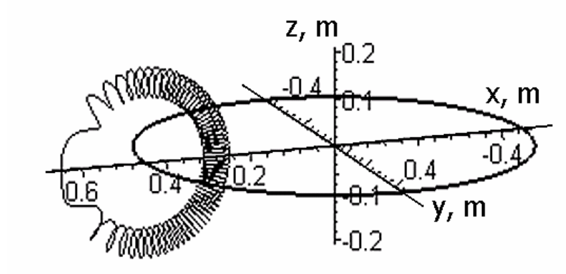

FIGURE 1. Toroidal structure of plasma current and sine- coil.

ANALYSIS AND RESULTS

Now we try to use the Biot-Savart law to calculate the field in the toroidal coordinate of the circular wire coil of radius r = 0.45 cm as shown in figure 1. According to Maxwell equation the magnetic field, B, is given by $\vec{\nabla}\times\vec{B}=\mu_0\vec{J}$, since the $\vec{\nabla}.\vec{B}=0$ and using expression of $\vec{\nabla}.(\vec{\nabla}\times\vec{F})=0$, we can write $\vec{B}=\vec{\nabla}\times\vec{A}$, where J is current density and A is vector potential so that the above expression yields,

$$\vec{A}(\vec{r})=\frac{\mu_0}{4\pi}\int\frac{J(\vec{r}^{\,'})}{\left|\vec{r}-\vec{r}^{\,'}\right|}dv' \tag{1}$$

and by defining $\vec{J}(\vec{r}')dv'=\vec{I}dl$, B(r) leads to,

$$\vec{B}(\vec{r})=\frac{\mu_0 I}{4\pi}\oint_c\frac{d\vec{l}\times(\vec{r}_2-\vec{r}_1)}{\left|\vec{r}_2-\vec{r}_1\right|^3} \tag{2}$$

This equation has been solved using a numerical method, and the topology of the whole magnetic fields calculated. Figure 2 shows the circular wire used for our calculation.

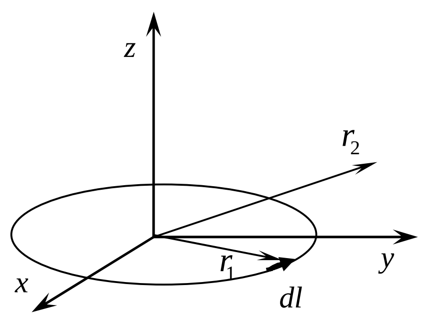

FIGURE 2. An electrical current I flows in the wire. The magnetic field is created at point r_2.

For using the Biot-Savart law in numerical calculation according to simulated coil and tokamak structure, we defined equation parameters as below,

$$dl=[-0.45\sin(u),+0.45\cos(u),0] \tag{3}$$

$$r_1=[0.45\cos(u),0.45\sin(u),0] \tag{4}$$

$$r_2 = [x, y, z] \tag{5}$$

$$p = [\,0.45\cos(u)\,z,\ 0.45\sin(u)\,z,\ -0.45\sin(u)\,(y-0.45\sin(u)) - 0.45\cos(u)\,(x-0.45\cos(u))\,] \tag{6}$$

$$q = (|x-0.45\cos(u)|^2 + |y-0.45\sin(u)|^2 + |z|^2)^{(3/2)} \tag{7}$$

$$S = \left[\frac{0.00004500000000\ \cos(u)\,z}{(|x-0.45\cos(u)|^2 + |y-0.45\sin(u)|^2 + |z|^2)^{(3/2)}},\ \frac{0.00004500000000\ \sin(u)\,z}{(|x-0.45\cos(u)|^2 + |y-0.45\sin(u)|^2 + |z|^2)^{(3/2)}},\ \frac{1}{10000}\frac{-0.45\sin(u)\,(y-0.45\sin(u)) - 0.45\cos(u)\,(x-0.45\cos(u))}{(|x-0.45\cos(u)|^2 + |y-0.45\sin(u)|^2 + |z|^2)^{(3/2)}} \right] \tag{8}$$

where $\vec{P} = d\vec{l} \times (\vec{r}_2 - \vec{r}_1)$, $q=(\vec{r}_2 - \vec{r}_1)^3$ and S is integrand of magnetic field components $[B_x, B_y, B_z]$ under parameter of u which varies from 0 to 2π, and electric current is 1×10^3 Amps. The magnetic field calculated in mid-plane of toroidal current-carrying coil for high field side and low field side is shown in figure 3. Now, a sine-coil, which is a Rogowski coil with a variable wiring density is designed and fabricated for measurement of position of current-carrying coil as illustrated in figure 1. The equation of path for this coil with respect to a reference point in lab introduced as below,

$$R\{\, a + b\cos(m\theta)\sin(\theta)\,,\ a + b\cos(m\theta)\cos(\theta)\,, b\sin(m\theta)\,\} \tag{9}$$

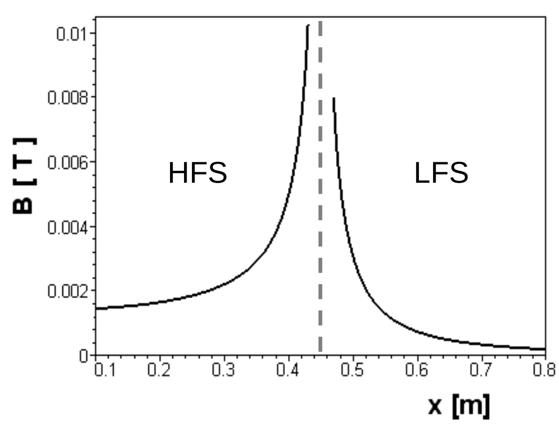

FIGURE 3. The magnetic field calculated in mid-plane of current-carrying coil, high field side and low field side, R=0.45 m according to figure 1.

The flux induced in the sine-coil from current coil calculated with $\Phi = \oint \vec{B}.\vec{n}ds$ is shown in figure 4. Here we defined a parameter for radios of each turn of sine-coil surface as v, which varied from 0 to 0.005 meters and parameter of t, that varied from 0 to 2π, the area with low number of turns. The flux calculated at the mid-plane strongly depends on the position of the wire loop inside the sine-coil as shown in Figure 5. The curve shows a linear behavior inside the sine-coil from R=0.25 m to R= 0.59 m.

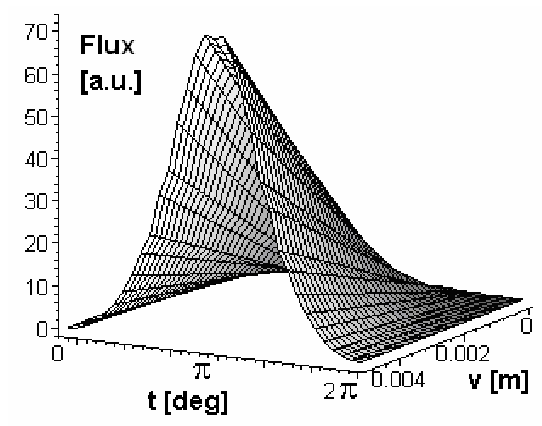

FIGURE 4. The flux induced in the sine-coil from current loop in surface of coil in the all points.

The result has been investigated for measurement of current carrying coil position with respect to sine-coil position. In this calculation, we fixed the sine-coil position and moved the current coil in the R direction. The results of flux calculation by Biot-Savart law is compared with experimental data (figure 6). They show a good agreement with theory.

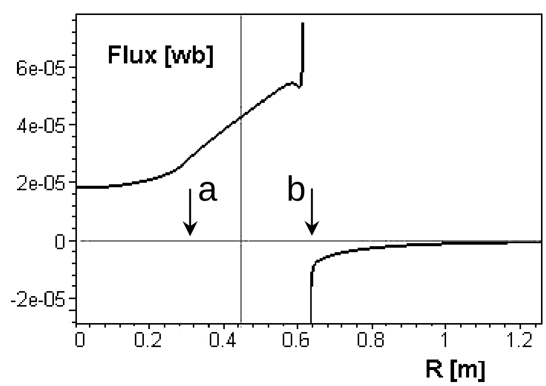

FIGURE 5. The flux induced in sine-coil in the mid-plane of current wire according to figure 1 configuration, the radius of sine-coil here is r=0.17 m. "a" and "b" indicate the sine- coil limits, and dash line indicates the current loop position.

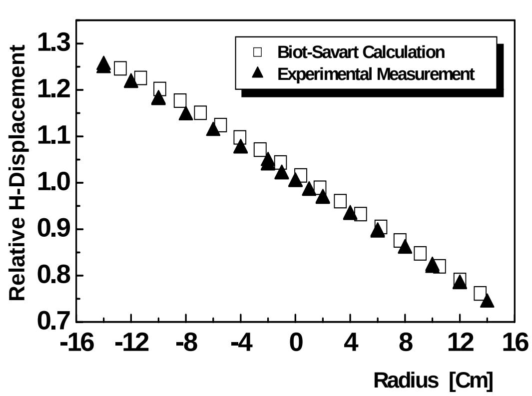

FIGURE 6. Comparison of calculations with actual plasma position. The rectangle and the triangle symbols show the Biot Savart law calculation and the measurements with the sine-coil, respectively.

The signal induced from plasma current in Sine-coil and Rogowski coil is shown in figure 7. The plasma displacement can be determined as the ration of the sine-coil signal and the plasma current measured by the Rogowski coil. The result is shown in figure 8.

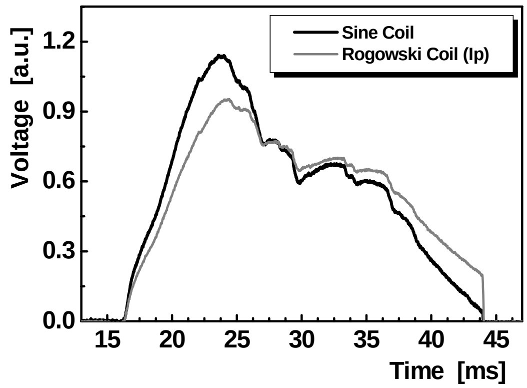

FIGURE 7. The signal induced from plasma current in Sine-coil and Rogowski coil.

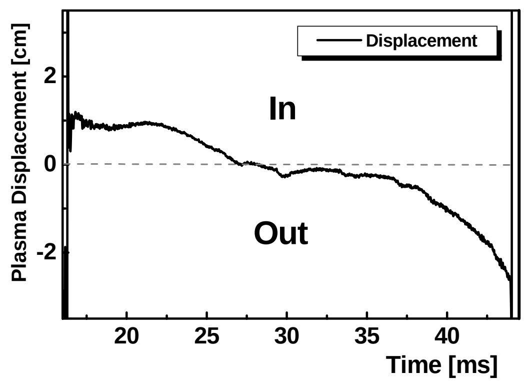

FIGURE 8 The plasma displacement measured by this signals.

In conclusion, comparing the results of the model experiment with the equation (4) we conclude that the sine-coil can be exploited for measurement of plasma displacement in the IR-T1 tokamak. The error is less than 2.5% and it has been compared with other methods of measurements of the plasma position. In addition, this method will be used in the feedback position control system and tests of feedback controller parameters.

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