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A 2D semi-analytical model for Faraday shield in ICP source

L.G. Zhang, D.Z. Chen*, D. Li, K.F. Liu, X.F. Li, R.M. Pan, M.W. Fan

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, Hubei 430074, PR China

HIGHLIGHTS

- In this paper, a 2D model of ICP with faraday shield is proposed considering the complex structure of the Faraday shield.
- Analytical solution is found to evaluate the electromagnetic field in the ICP source with Faraday shield.
- The collision-free motion of electrons in the source is investigated and the results show that the electrons will oscillate along the radial direction, which brings insight into how the RF power couple to the plasma.

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ABSTRACT

Faraday shield is a thin copper structure with a large number of slits which is usually used in inductive coupled plasma (ICP) sources. RF power is coupled into the plasma through these slits, therefore Faraday shield plays an important role in ICP discharge. However, due to the complex structure of the Faraday shield, the resulted electromagnetic field is quite hard to evaluate. In this paper, a 2D model is proposed on the assumption that the Faraday shield is sufficiently long and the RF coil is uniformly distributed, and the copper is considered as ideal conductor. Under these conditions, the magnetic field inside the source is uniform with only the axial component, while the electric field can be decomposed into a vortex field generated by changing magnetic field together with a gradient field generated by electric charge accumulated on the Faraday shield surface, which can be easily found by solving Laplace's equation. The motion of the electrons in the electromagnetic field is investigated and the results show that the electrons will oscillate along the radial direction when taking no account of collision. This interesting result brings insight into how the RF power couples into the plasma.

1. Introduction

ICP sources have been used in various fields of application such as material technology, space thrusters, accelerators, and fusion research [1–4]. In the latter field, RF sources, when compared to a filamented arc source, have fewer parts and are in principal maintenance free due to the absence of filaments, which is of particular importance for fusion reactors where remote maintenance is required in a radioactive environment. For these reasons, and based on the related progress made by IPP Garching, the RF-driven ion source has been selected as the reference source for the ITER neutral beam injectors since 2007 [5,6]. Faraday shield is a thin copper structure with a large number of slits, as shown in Fig. 1(a), which is used to protect the ion source against erosion in ICP sources [7]. The slit on the Faraday shield is the channel through which the RF power is coupled into the plasma, hence the Faraday shield has a great influence on the electromagnetic field distribution, and consequently on the plasma excitation. Recent studies [7–9] show that the Faraday shield can also eliminate capacitive coupling.

However, the complex structure of the Faraday shield as well as the skin effect due to the high frequency make it hard to evaluate the RF electromagnetic fields. At frequency of 13.56 MHz the skin depth in copper is only 35.3 μm while the whole source might be as large as several hundred mm, thus a great large number of cells would be required in 3D finite element analysis which would result an unacceptable computation resource requirement. Perhaps it is because of this reason, only the ICP model without Faraday shield, as shown in Fig. 1(b), is discussed in most studies [10–12].

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* Corresponding author.
E-mail address: dzhchen@mail.hust.edu.cn (D.Z. Chen).

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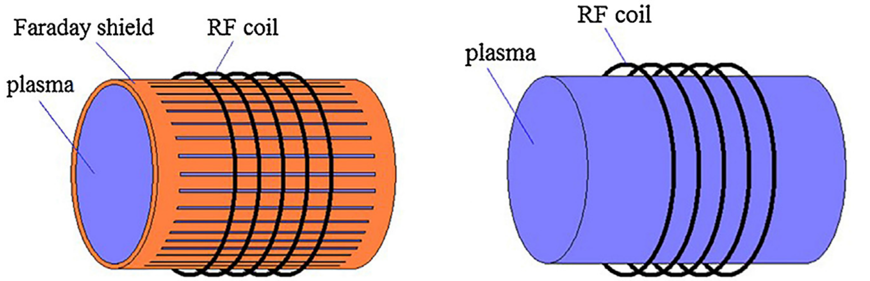

(a) ICP model with Faraday shield (b) ICP model without Faraday shield

Fig. 1. ICP model with and without Faraday shield.

Obviously, ignoring the influence of the Faraday shield will not give an exact understanding of the ICP source.

To study the electromagnetic field in the ICP source with the Faraday shield, we established a 2D model on the assumption that the Faraday shield is sufficiently long and the RF coil is uniformly distributed, and the copper is considered as ideal conductor with infinite conductivity. Under these assumptions, the paper discusses the solution of the electric field and the magnetic field, respectively. FEA result of the 2D model is also given to confirm the analytical result. Then, the motion of the electrons in the electromagnetic field is investigated. As usual, a 2D model won't give all the details exactly but indicates the most important physical essence of an ICP source with Faraday shield.

2. 2D model of the ICP source with Faraday shield

A typical ICP source includes an insulation cylinder with a sparse RF coil wounded around outside to excite plasma inside the cylinder. The Faraday shield is located inside the cylinder close to the wall to protect it against erosion from plasma. As the insulation cylinder has little influence on the electromagnetic field, it is not shown in Fig. 1(a). Since the frequency is about a few MHz, the magnetic field generated by the coil cannot penetrate the conductor so the slits on the Faraday shield is the only way for RF power coupling into the source. In order to simplify the analysis, a sufficiently long ICP source with Faraday shield is considered, and the RF coil is supposed uniformly distributed. These assumptions leads to a 2D model, as shown in Fig. 2. The plasma will not be taken into account in this paper.

2.1. Electromagnetic field without Faraday shield

Firstly, consider the electromagnetic field with no Faraday shield. In this case, concerning the frequency of a few MHz, the displacement current can be neglected, thus the magnetic field $\boldsymbol{H}$ is uniform inside the source with only axial component:

$$\boldsymbol{H} = H_0 \boldsymbol{e}_z \tag{1}$$

where $H_0 = \frac{NI}{l}$, N is the number of turns, l is the actual length of the coil, and I is the driving current.

The electric field $\boldsymbol{E}$ contains both the azimuthal component E_ϕ and the axial component E_z. The azimuthal component E_ϕ is generated by the changing magnetic fields which can be obtained according to Faraday's law,

$$\oint_C \boldsymbol{E} \cdot \mathrm{d}\boldsymbol{l} = -\mathrm{j}\omega \int_S \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{S} \tag{2}$$

Considering (2) and $\boldsymbol{B} = \mu_0 \boldsymbol{H}$, it is easy to get

$$E_\phi = \frac{1}{2} \mathrm{j}\omega\mu_0 H_0 r \tag{3}$$

where ω is the angular frequency of the exciting current, and μ_0 is the permeability of vacuum.

For an actual device, the spiral structure of the coil must be considered as show in Fig. 3. Coil current produces a voltage between its ends,

$$V = -N \cdot \mathrm{j}\omega \int_S \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{S} = N E_{\phi m} \cdot 2\pi R \tag{4}$$

where R is the radius of the coil and $E_{\phi m}$ is the azimuthal component of the electric field at the inner surface of the coil. The coil voltage

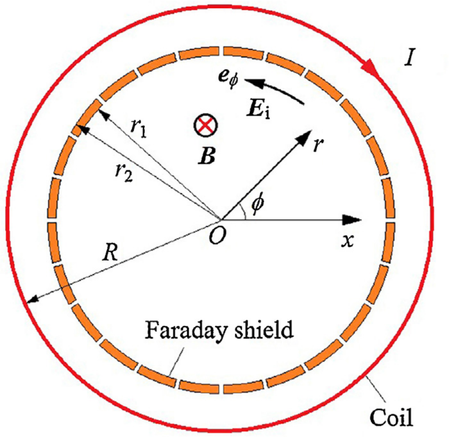

Fig. 2. 2D model of the ICP source with Faraday shield.

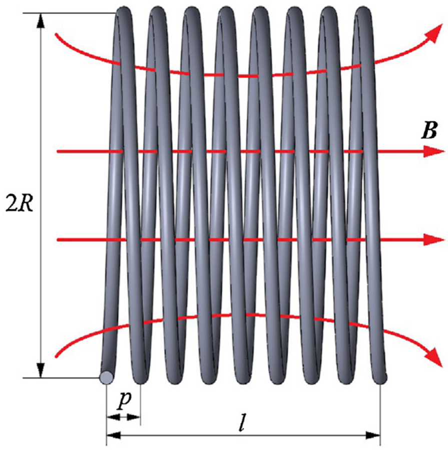

Fig. 3. Spirality of the RF coil.