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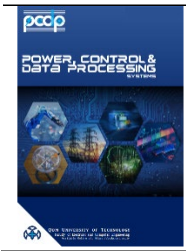

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Simulation Of Ion Beam Interaction of Plasma Focus Device With The Inner Surface of Faraday Cup

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ABSTRACT

One of the important topics in the use of Faraday cup in plasma focus devices is the production of secondary electrons due to the collision of beam particles with the inner surface of the Faraday cup and their trapping in the measurement of particle beam current by the cup. Therefore, in this study, the simulation of the geometrical effects such as the depth and Internal structure of the cup on the production of secondary electrons and the output current of the Faraday cup has been done. The used simulation tool is CST STUDIO SUITE. Based on the simulation results, reducing the aspect ratio leads to an increase in the particle trapping ability, and as a result, the current measured by the Faraday cup is closer to the real current. Furthermore, The Faraday cup current for a cylindrical sample is greater than the actual current and in the ramp example, the Faraday cup current is closer to the actual value.

Keywords: Plasma focus device; Ion Beam; Array Faraday-Cup.

1 Introduction

Plasma focuses devices with different input energies as a source of various types of radiation such as charged particles, soft and hard X-rays, and neutrons have potential applications in many fields [1-4]. Applications of these devices include plasma physics and nuclear fusion research [5-7]. The Faraday cup is one of the important diagnostic tools in plasma focus devices for measuring the current of high-energy ions. The most important challenge in measuring the particle beam current using a Faraday cup is the backscattering of the beam particles from the inner surface of the cup, as well as the production of secondary electrons resulting from the collision of the beam particles with the inner surface of the cup. During the pinch process, the shell electric current converges toward the axis and a narrow column of plasma is formed along the axis. At the moment of column decay, MHD instabilities cause the column to collapse rapidly and create strong induced electric and magnetic fields. The interaction of these fields with heavy ions leads to their intense acceleration. Since the dominant direction of the fields and pressure gradient is along the axis, energetic ions are accelerated and ejected mainly along the axis. Therefore, the angular distribution of ions is anisotropic and the maximum intensity is recorded at an angle of zero degrees (on the axis of the device). The results obtained by Mohanty et al. (2005) using a multi-Faraday cup assembly demonstrate this behavior well and consider the plasma focus device as a directional ion source in which ions have different energy and density ranges at different angles and positions relative to the anode tip [8]. In addition, Sadowski et al. investigated the characteristics of the ion beam in small devices in the energy range of 5-50 kJ and concluded that the ion beam intensity depends on the geometry of the electrodes, the energy of the capacitor bank, the working gas, and the gas pressure [9]. Knowing the ion energy and density distribution is essential for understanding the physics of ion production and acceleration in a plasma focus device. Furthermore, investigating the energy density distribution has a significant impact on these processes in order to optimally utilize the plasma focus device in applications such as material processing and thin film deposition [10-11]. One of the most important beam parameters is the ion flux. For low particle fluxes, their number can be directly obtained by particle counters. However, for high particle fluxes, direct counting of them is associated with a large error. To measure the high flux of ions that have an electrical charge, the simplest and most accurate method is to measure their current using electrical current measuring instruments such as an ammeter. Placing a metal plate in the path of the beam and connecting it by cable to a voltage supply source or, more simply, connecting it to ground, results in the beam current being transferred to the source or ground. The transmitted current is proportional to the beam current, which we can measure by placing an ammeter in series along the current-carrying cable. This metal plate that stops the beam in itself is called a Faraday plate. Another device used to completely stop the beam is the Faraday cup. As its name suggests, this device, made of a conductive metal such as copper or aluminum, is cup-shaped and, by completely stopping the beam and preventing the escape of particles, leads to accurate current measurements [12]. When high-energy ions collide with the metal surface of a Faraday cup, secondary electrons are produced, which lead to a secondary current. If these electrons are not collected in the cup itself or their effect is not modified, they create a net positive charge, resulting in an increase in the Faraday current. Sadeghi et al., numerically showed that for PF devices, particle tracking under electromagnetic fields can predict ion trajectories and angular distributions [13]. Malek studied characteristics of ion beam for various gases in a spherical plasma focus device. He computed the ion beam properties such as flux, fluence and energy using Lee code [14]. Etminan et al., investigated the flux of ion beams in a Mather type (5 kJ) plasma focus device. They used faraday cups array for detector and collect ion signals [15]. Rostamifard et al., studied the characterizations of hydrogen ion beam emitted from MTPF plasma focus device using faraday cup and Lee code. They used a faraday cup detector and time-of-flight (TOF) method for determine the average energy of the hydrogen ion beam [16].

While many studies focus on beam generation, fewer explicitly treat interaction with Faraday cups. The purpose of this paper is to simulate the secondary current of a Faraday cup and to investigate the effect of the cup depth and geometry on the current measurement. To this end, we first describe the physics of the Faraday cup structure, and then proceed to simulate the secondary current of the Faraday cup. CST software is used for this simulation. The simulation results demonstrate the impact of the depth and geometry of the Faraday cup on the secondary electron current.

2 Theory

In general, a Faraday cup (FC) is a beam arrester, electrically isolated from the instrument housing and connected to a current meter. This device is mainly used to measure the beam intensity. The amount of current generated in the Faraday cup depends on various factors, the most important of which are: the number of colliding particles, the degree of ionization of the colliding particles, and the secondary electron efficiency [17]. There is a simple relationship between the electric current of particles and the number of particles, which is shown in equation (1).

$$I_{par} = \frac{N}{t} = \frac{I}{e.Z_{eff}} \quad (1)$$

Where, Zeff is the effective ionization degree, N is the number of particles, t is the time, I_{par} is the particle flux, I is the electric current of the particles, and e is the electric charge. But due to the presence of secondary electrons, the current measured by the Faraday cup is different from the actual current of the particles.

The total electron yield (γ) is the number of electrons emitted from the surface due to the impact of a particle. The angle of impact of the particle is expressed with respect to the surface normal vector and in most experiments the impact is assumed to be perpendicular to the surface (zero impact angle). Factors affecting the yield of electrons emitted from the target surface include: target surface conditions - surface temperature - dependence of the electron yield on particle energy - atomic number of the target surface and the relationship between secondary electron production and particle impact angle.

The number of secondary electrons is calculated by measuring the current. For this purpose, imaginary monitors are placed at different points between the ion source and the Faraday cup and the ion current is calculated. The amount of secondary electron production is obtained from the difference between the actual current and the measured current.

In designing a Faraday cup, several points must be considered, including that the impedance of the desired cup be the same as the impedance of the load transmission line, so that maximum power is transferred from the cup to the line [18]. It should be noted that impedance matching only ensures no power loss and has no effect on other measurement parameters. Impedance matching should be considered as one of the key parameters and the cornerstone of cup design. Considering that the impedance of transmission cables is usually 50 ohms, we try to keep the impedance of the cup as close to this range as possible. Given that the Faraday cup consists of two coaxial cylinders with insulation in between, its resistance can be calculated from the following equation for a coaxial cable:[19]

$$z = \frac{138.2}{\sqrt{K}} \log\frac{D}{d} \tag{2}$$

Where D: inner diameter of the outer cup, d: outer diameter of the inner cup, and K: dielectric constant of the insulation used between the two cups, which for polyethylene is K=2.2. Figure 1 shows the location of the Faraday cup in the plasma focus.

To analyze the Faraday signal based on Figure 1, we consider the following approximations:

- Point source: This means that all ions are emitted from a single point above the anode. In fact, we ignore the dimensions of the narrow plasma compared to the Faraday distance.
- Time-independent: This means that all ions are emitted at the same time, because the lifetime of the narrow plasma (about 100 ns) can be neglected compared to the flight time of the ions to the Faraday detector (about 1 μs).

3 Simulation

To simulate a Faraday cup for a 2.5 kJ plasma, focus device, we need to know the beam and device specifications. Table 1 presents the technical specifications of the device and beam. Considering these parameters, the design is done.

The simulations were performed using CST STUDIO SUITE software and the results are shown below. The aim of this simulation was to determine the number of secondary electrons using the CST code. For this purpose, a source with dimensions of 1 mm was considered at a close distance from the pinch and the total number of ions generated by this source was calculated.

CST STUDIO SUITE offers advanced capabilities for simulating ion diffusion, ion trajectory analysis, ion-surface interactions, and secondary electron emission phenomena. The software enables defining the ion beam as either continuous or pulsed and supports the simulation of both electric and magnetic fields. Importantly, it allows coupling charged particle dynamics with electromagnetic fields, facilitating comprehensive studies of charged particle physics. These features make CST STUDIO SUITE an ideal platform for simulating the physics of Faraday cups. The simulations were conducted using the Charged Particle Dynamics > Accelerator Components > Particle Gun template. Depending on the simulation objectives, three solver options are available: Particle Tracking (PT), Electrostatic (E-static), and Magnetostatic (M-static). The PT solver is predominantly employed because it simultaneously computes particle transport and electromagnetic fields, whereas the E-static and M-static solvers are limited to static field calculations without particle transport.

The simulation workflow initiates with the definition of the geometry in the Modelling tab, followed by specifying the physical parameters in the Simulation tab. Here, particle sources are defined using the Particle Sources module, and electric potentials are assigned via the Electric Potential module. Boundary conditions, background fields, and mesh settings are also configured within this interface. Upon completion of the setup, simulations are executed using the Setup Solver module accessible from both the Simulation and Home tabs. Postprocessing and result analysis are performed in the Postprocessing tab.

In this study, the capacitor is charged to 14 kV, which discharges to generate high-energy ions. For the internal geometry of the cup, a fixed internal diameter of 1 mm and a variable depth from zero to 13 mm were considered. The ratio of the cup's inlet diameter to its depth is defined by the aspect ratio parameter. This assumption is realistic for the focused plasma. However, solving pulsed physics is time-consuming and requires a very powerful computational system. For this reason, continuous physics was used as much as possible. Nevertheless, some studies were solved in a pulsed manner. In this simulation, the geometric specifications of the cup do not change. However, the characteristics of the ion source and the voltage of the electrodes of the focused plasma were redefined for the pulsed mode.

Therefore, changing the aspect ratio results only from changing the cup's depth. The results show that the greater the depth of the cup, the greater the number of secondary particles (Figure 2), but due to the smaller aspect ratio, the more difficult it is for secondary particles to escape, which is due to the increased probability of collision and absorption of these particles into the wall [20]. Depth on the production and confinement of secondary electrons resulting from the interaction of the incident ion beam with the inner graphite surface. As shown in the four models (L = 0 mm, 4 mm, 8 mm, and 13 mm), the cup geometry plays a crucial role in determining the number of secondary electrons that escape from the cup. For shallow depths (L ≤ 4 mm), the beam impacts near the cup entrance, resulting in a higher probability for secondary electrons to exit the cup without being reabsorbed. This leads to a significant increase in the apparent current measured by the Faraday cup due to electron leakage. As the cup depth increases, the internal surface area exposed to the emitted electrons becomes larger, and the likelihood of electron recapture by the walls rises. At a depth of about 8–13 mm, most of the secondary electrons are effectively trapped and reabsorbed, minimizing current overestimation and improving the fidelity of ion beam measurements. Therefore, optimizing the cup depth is essential to achieve a balance between beam acceptance and suppression of secondary electron emission, ensuring higher accuracy in plasma focus diagnostics and ion-beam. The geometry of the Faraday cup plays a critical role in its efficiency and accuracy, particularly regarding secondary electron production. As the depth of the Faraday cup increases, ions and electrons undergo more frequent collisions with the entrance aperture (often referred to as the door) and the internal walls of the cup. These additional interactions lead to an increase in the generation of secondary electrons. However, this increase is not linear; beyond a certain depth, the rate of secondary electron production begins to plateau. This saturation occurs because secondary electrons generated deeper within the cup are increasingly likely to be reabsorbed or scattered before escaping, thereby limiting their contribution to the measured signal. Consequently, optimizing the cup's depth is essential to balance maximizing ion collection efficiency while minimizing secondary electron-induced measurement errors.

Figure 3 illustrates the influence of the Faraday cup depth on the measured beam current and the secondary electron emission (SEE) current. At shallow cup depths ($L < 4$ mm), the measured Faraday current notably exceeds the actual beam current due to the escape of secondary electrons from the cup aperture, which leads to an overestimation of the collected charge. As the cup depth increases, the probability of electron escape decreases because more emitted electrons are reabsorbed by the inner walls, resulting in a lower SEE current. Consequently, the measured current gradually converges toward the true beam current. For depths larger than approximately 8–10 mm, the SEE contribution becomes negligible (< 1 %), and the Faraday current closely matches the real beam value with minimal error. These findings indicate that increasing the cup depth significantly improves measurement accuracy by suppressing secondary electron losses. Therefore, an optimized cup geometry with a depth-to-diameter ratio of about 1:1 is recommended to ensure precise ion-beam current measurements in plasma focus diagnostics.

Figure 4 shows the secondary electron generation for two Faraday cup geometries. As shown in the figure, the secondary current output from the cylindrical sample is higher than that from the inclined surface sample.

The conventional cylindrical geometry has been widely used in plasma discharge systems due to its simple symmetry and well-known electric field distribution. However, it often suffers from strong axial field concentration and enhanced secondary electron emission near the electrode surface, which can lead to non-uniform plasma formation and instability. In contrast, the inclined surface geometry introduces a gradual variation in the local electric field, reducing field crowding and minimizing electron backscattering toward the emission region. This geometric modification can therefore mitigate the effects typically addressed using biased suppressor rings, but without requiring additional electrodes or bias circuits. Moreover, the inclined configuration can improve plasma uniformity, reduce localized heating on the surface, and enhance overall discharge stability. Comparing these two geometries provides valuable insight into whether purely geometric optimization can achieve similar performance benefits to more complex electrical control methods in plasma-base.

The Faraday cup currants from these two geometries are compared in Figure 5. As shown in the figure, the Faraday cup current for the cylindrical sample is greater than the actual current because the secondary outlet current in this geometry causes more error, and in the inclined surface sample, the Faraday cup current is closer to the actual value.

4 Figures

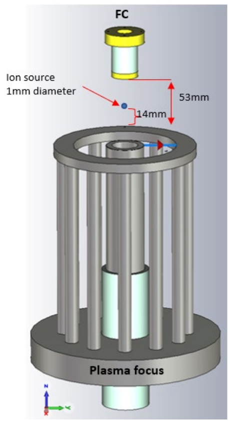

Figure 1: Position of the Faraday cup above the plasma focus and pinch formation

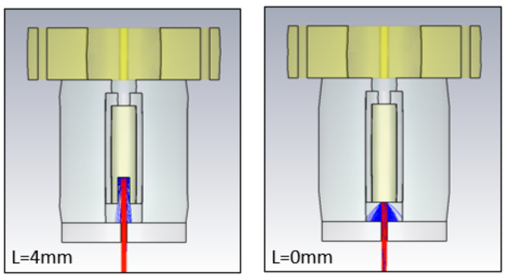

Figure 2: Simulation of the effect of Faraday cup depth (L = 0, 4, 8, and 13 mm) on the generation and confinement of secondary electrons. The results show that as the cup depth increases, the escape of secondary electrons from the entrance aperture is effectively reduced due to enhanced wall reabsorption. Deeper cup geometries therefore minimize secondary electron losses and improve the accuracy of ion beam current measurements.

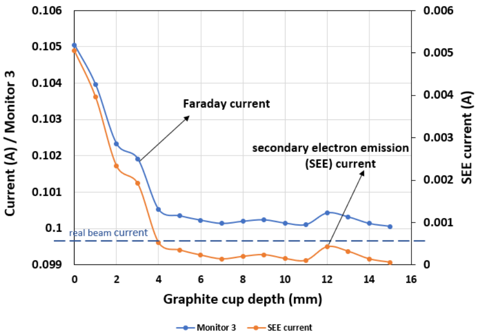

Figure 3: Study of the effect of cup depth on the output current. This figure shows the current measured inside the Faraday cup and the actual beam current. The blue graph is the measured Faraday cup current, which as can be seen, gets closer to the actual value as the cup depth increases. The orange graph is related to the secondary electron measurement efficiency, which according to the figure, gets closer to zero as the cup depth increases, and the Faraday cup current gets closer to its actual value with less error.

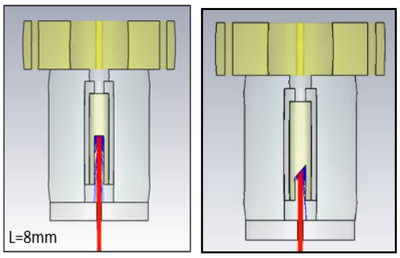

Figure 4: Two examples of Faraday cup geometries: A: Inclined surface B: Cylindrical

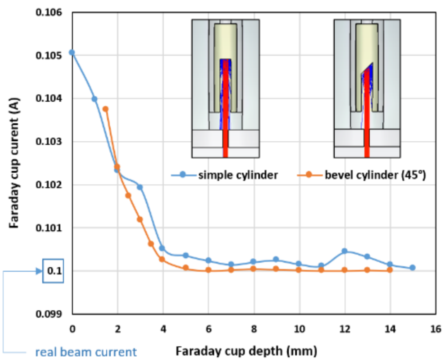

Figure 5: Faraday cup current for two cylindrical and inclined surface geometries

4.1 Tables

Table 1: Technical specifications of the plasma focus and ion beam device

Maximum device energy	2.5 kJ
Total inductance	110 nH
Capacity	22 µF
Maximum capacitor charging voltage	30 kV
Maximum current plasma	80 kA
Pressure	1-3 torr
Cup depth	13 mm
Cup inlet diameter	1 mm
Cup material	Brass- Graphite
Ion Energy	40-150 keV

5 Conclusion

In this research, by simulating the internal structure of the Faraday cup, the effect of the depth and geometry inside the cup on the production of secondary electrons has been studied. For this purpose, various simulations were performed using the CST STUDIO SUITE software. First, the effect of aspect ratio was investigated, and based on simulations, decreasing the aspect ratio leads to an increase in the particle trapping ability, and as a result, the current measured by the Faraday cup becomes closer to the actual current. However, due to the limitation in the dimensions of the Faraday cup, the depth of the cup cannot be chosen to be arbitrarily large, and decreasing the aspect ratio is also possible up to a certain value. In addition, the secondary electron efficiency directly depends on the beam incidence angle, which is why we have the highest secondary electron efficiency in conical cups and inclined surfaces. However, the secondary electron absorption ability leads to the secondary electron efficiency parameter being ignored and to choose the appropriate geometry, we focus only on its electron absorption ability. The closer the current measured by the Faraday cup is to the actual beam current, the greater the absorption ability of that geometry. Therefore, the inclined geometry can be selected as the desired geometry and subsequent simulations can be performed based on it.

Disclosure of Potential Conflicts of Interest

The Authors declare that there is no conflict of interest

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