Design and Analysis of Conical-Backed Two-Arm Archimedean Spiral Antennas for Improved Antenna-Plasma Coupling In Tokamak Fusion Reactors

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Abstract: The research explores strategies to optimize antenna-plasma coupling in tokamak fusion reactors. The focus is on utilizing a conical-backed two-arm Archimedean spiral antenna design to enhance interaction efficiency within the constraints of Steady-state superconducting tokamak (SST-1) environments. The intended antenna setup is designed to function within the frequency spectrum spanning from 0.1 to 1.0 GHz. While conventional spiral antennas typically rely on vertical or horizontal baluns for excitation, this novel design employs direct feeding via a coaxial cable, integrating a planar feeding section meticulously optimized to ensure broad-spectrum input impedance matching. Simulation results clearly demonstrate that the proposed antenna design inherently resonates at 0.65 GHz, exhibiting a reflection coefficient of -22.99 Db. The study aims to contribute insights into improving the effectiveness of antennas for plasma coupling in fusion energy research.

Index Terms: Antenna-Plasma coupling, Tokamak, SST-1, Fusion reactors, Conical-backed and Impedance matching

I. Introduction

Within the realm of tokamak fusion reactor development, effective antenna-plasma coupling stands as a crucial component for achieving efficient energy transfer and containment of the plasma. The swift advancement of wireless technology is driving the appeal for compact, planar, and wideband antennas, addressing diverse communication needs. Moreover, a multitude of radio services, such as broadband satellite communication, mobile systems, ground-based, and airborne direction-finding, demand antennas that are compact, wide-ranging, and circularly polarized. Traditional spiral antennas find extensive application in various fields requiring broad bandwidth and circular polarization patterns. Yet, the standard feeding configuration for spiral antennas is centrally positioned, necessitating a balun and an impedance matching network, which expands into the z-axis [1]. This approach's primary drawback lies in the enlarged antenna size due to feeding, imposing additional design limitations unsuitable for cutting-edge portable communication devices. This feeding method has been extensively researched previously [2], [3].

Using border feeding to design a spiral antenna is a technique that comes with the trade-off of limited bandwidth [1], [5-7]. The fully planar spiral antenna described in [1] is fed from the edge using a Marchand balun, which complicates the design and enlarges the antenna. A balun is required to connect the balanced two-arm spiral antenna to the unbalanced coaxial cable. The CPW-fed antenna has garnered significant attention due to its advantageous characteristics, ease of fabrication, integration with MMICs, simplified single-layer metallic configuration, low radiation loss, and reduced dispersion compared to a Microstrip feed [4]. A CPW-powered dual-arm spiral antenna with two distinct feeding methods is proposed in [5, 6]. In [7], a new CPW-fed spiral antenna with three arms is introduced, featuring an in-depth exploration of the CP bandwidth. Yet, the antenna's size is double that of the conventional model and the spacing between its arms are too narrow, imposing additional constraints on the fabrication process.

The study's primary objective is to contribute novel insights and methodologies for enhancing the performance of antennas within the challenging operational environments of fusion reactors. Through rigorous analysis, the research aims to uncover strategies that not only bolster antenna effectiveness but also promotes stability and reliability in plasma containment and energy transfer processes. The spiral antenna proposed in this paper is specially demonstrating impedance matching. It is a conical-backed dual-arm Archimedean spiral antenna, optimized using CST-MWS software, yielding results such as reflection coefficient, VSWR, Z-matrix, efficiency, gain, etc.

After the opening remarks, this paper is structured into four main sections. Section II provides a detailed explanation of the antenna design, while section III offers an analysis of the simulated results for the proposed antenna structure. Section IV summarizes the findings and presents concluding remarks.

II. Proposed Antenna Design and Analysis

The spiral antenna is tailored for compatibility and analysis within the SST-1 Tokamak. The SST-1's opening port stands at a height of 280 mm. to accommodate larger diameters, a limitor is positioned at the space's rear, constraining diameter expansion due to spatial limitations. Opting for geometric simplicity is preferred to mitigate complexity and associated costs. Meeting these criteria is best achieved through the use of a spiral structure, which naturally offers broad bandwidth and circular polarization capabilities. This paper introduces a two-arm conically backed Archimedean spiral antenna distinguished by its innate resonance. Significantly, it avoids external matching techniques like baluns, stub tuners, or phase shifters. Instead, a central transition section, integrated with a 50-ohm coaxial transmission line, enables self-sufficient impedance matching. For achieving high gain and a unidirectional radiation pattern, a metallic disc supports the spiral, designed conically to minimize pattern tilt and improves symmetry around the bore sight. The spacing between the spiral arms is maintained to prevent arcing between them. Air breakdown due to atmospheric pressure typically occurs at 30 kV/cm. breakdown transpires only when such an electric field is present, necessitating a significant voltage to establish said filed. In the actual scenario, the tokamak contains no air and operates at extremely low pressure, devoid of atmospheric conditions.

The proposed antenna design utilizes conical-disc backed spiral antenna structures to optimize coupling with plasma, enhancing tokamak system performances. The conical shape boosts impedance bandwidth and radiation pattern, whereas the disc backing enhances antenna impedance matching and radiation efficiency. The spiral structure is fine-tuned for optimal interaction with the tokamak plasma. Figure 1 represents the basic structure of two-arm Archimedean spiral antenna.

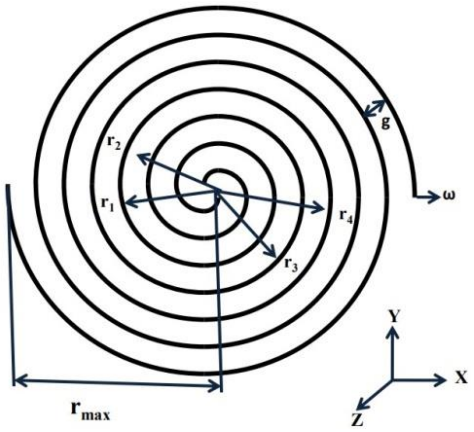


Figure 1: Two-arm Archimedean spiral antenna

Figure 1 depicts the geometry of the proposed antenna, comprising two Archimedean spiral equations as given below:

$$r_1 = a\Phi + b_1$$

$$r_2 = a\Phi + b_2 \quad (1)$$

Here r_1 and r_2 denote the inner and outer radii of the spiral structure, respectively. "a" represents the growth rate, whereas b_1 and b_2 denote the distance from the starting point of the spiral to the origin. The gap width, g is defined as $b_2 - b_1$.

The second spiral undergoes a 180-degree rotation, with its trace defined by,

$$r_3 = a(\Phi - \pi) + b_1$$

$$r_4 = a(\Phi - \pi) + b_2 \quad (2)$$

The dimension of the feed line, ω is contingent upon the growth rate, α determined by,

$$\omega = (a * \pi) - g \quad (3)$$

The count of turns, denoted as "N" is estimated by,

$$N = \frac{r_{max} - g}{\omega + g} \quad (4)$$

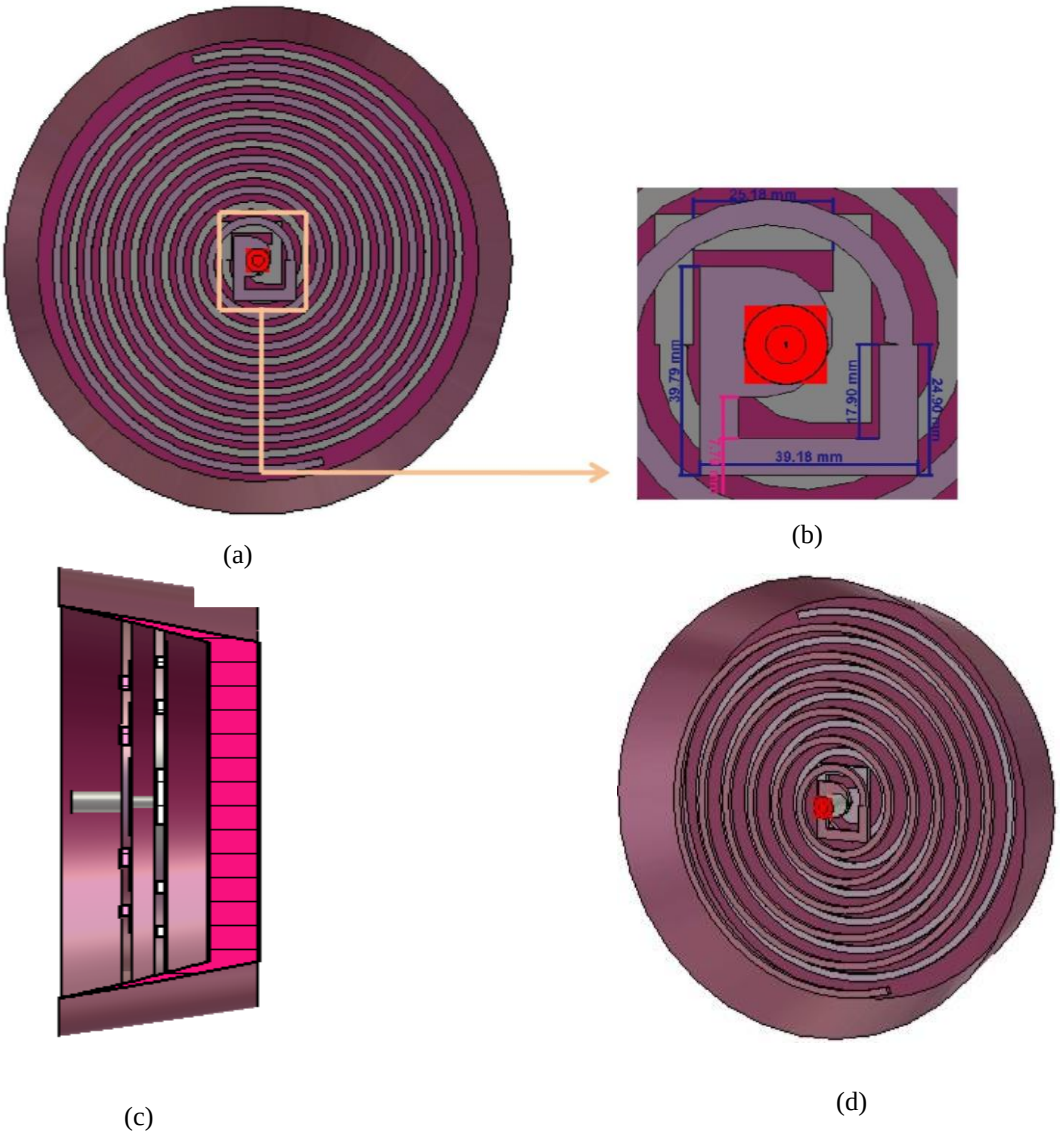
r_{max} signifies the utmost extent from the center to the periphery of the spiral, whereas "g" denotes the gap width. The lowest operational frequency can be estimated using the equation employed for conventional spiral antennas [3].

$$f_{low} = \frac{c}{2 * \pi * r_{max}} \quad (5)$$

Where "c" represents the speed of light

III. Results and Discussions

The proposed antenna design is subjected to numerical modeling and simulation through the utilization of the CST microwave studio software. Employing the finite integration technique (FIT) to solve Maxwell's equations [8], the software offers thorough analysis. Figure 2 depicts the schematic arrangement of the modeled antenna structure. (a) Shows the front view of the design. (b) Shows the zoom in view of the feeding design. (c) Shows the top view of the conical backed cavity. (d) Represents the perspective view of the structure.



(a) (b) (c) (d)

Figure 2: illustration of the cavity-backed spiral antenna design, featuring (a) the frontal view, (b) a close-up of the feeding section, (c) a side view of the conical cavity, and (d) a perspective rendering of the structure.

The antenna design is customized to comply with SST-1 port space limitations and is subsequently simulated using CST-MWS. Based on the simulation outcomes, the antenna exhibits natural resonance around 0.65 GHz, showcasing a reflection coefficient of -22.99 dB. The antenna prototype displays a unidirectional radiation pattern across the frequency range, with broadside gain surpassing 20 dBic for this particular design. A waveguide port is selected at the spiral's center to facilitate coaxial feeding for both arms. The calculated scattering parameters of the suggested antenna array, expressed via the reflection coefficient, are depicted into the subsequent segment.

a) Reflection Coefficient

This indicates that the antenna attains ideal impedance matching precisely at the designated 650 MHz frequency, with a reflection coefficient of -22.99 dB as shown in figure 3. This value indicates minimal signal power reflection, with the majority being either transmitted or absorbed by the system.

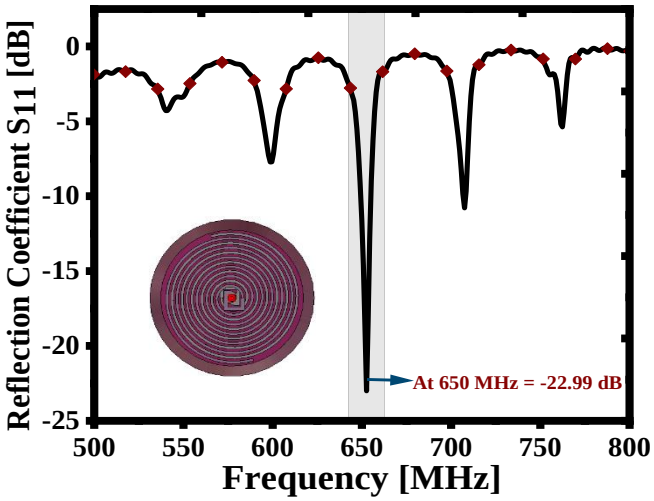


Figure 3: simulated S_{11} of conical-backed archimedean spiral antenna

b) Voltage standing wave ratio (VSWR)

At 650 MHz frequency, the antenna demonstrates a VSWR value close to (VSWR>2), signifying a nearly ideal impedance match amid the antenna and the transmission line as illustrated in figure 4. A VSWR value approaching 1 indicates a minimal signal reflection, enhancing power transfer efficiency. These outcomes suggest the system is finely tuned, optimizing signal integrity, and mitigating losses attributable to signal mismatch.

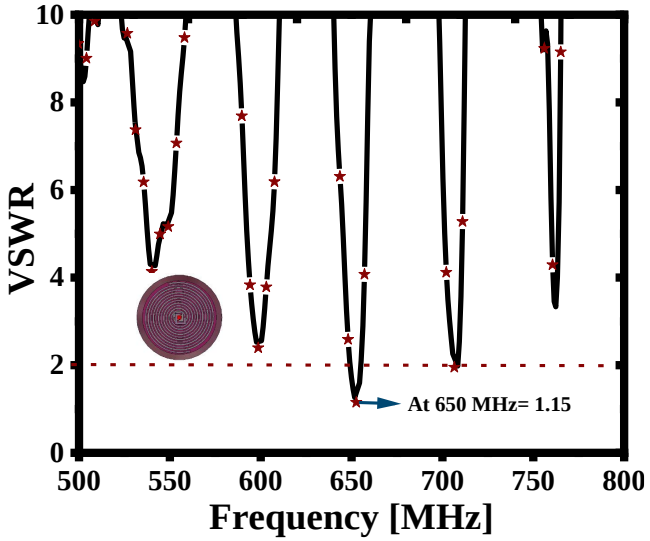


Figure 4: VSWR of conical-backed archimedean spiral antenna

c)Z-matrix

Obtaining a result where the impedance magnitude is close to 50 ohm, with a small imaginary component, signifies a well-matched antenna system (figure 5). This indicates that antenna efficiently absorbs and radiates electromagnetic energy, minimizing signal reflections and losses. Additionally predominant real impedance helps in maximizing power transfer from the transmitter to the antenna, enhancing overall system performance.

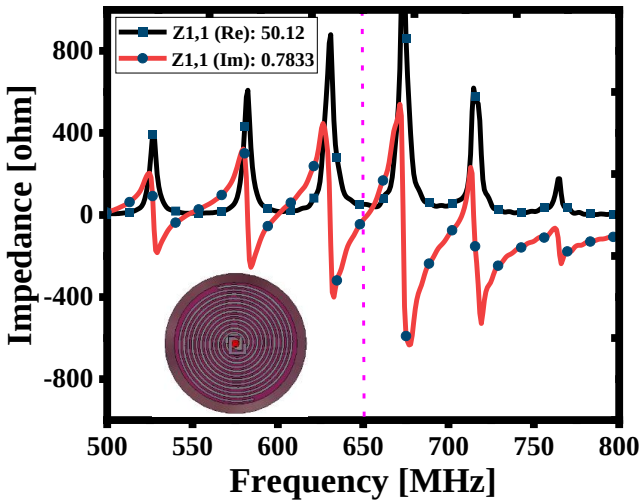


Figure 5: Z-matrix of conical-backed archimedean spiral antenna

d) Gain

A gain of 23.03 dBic is achieved as shown in below figure 6. This gain value indicates that the antenna efficiently directs the radiation power in a specific direction, enhancing signal strength and communication range.

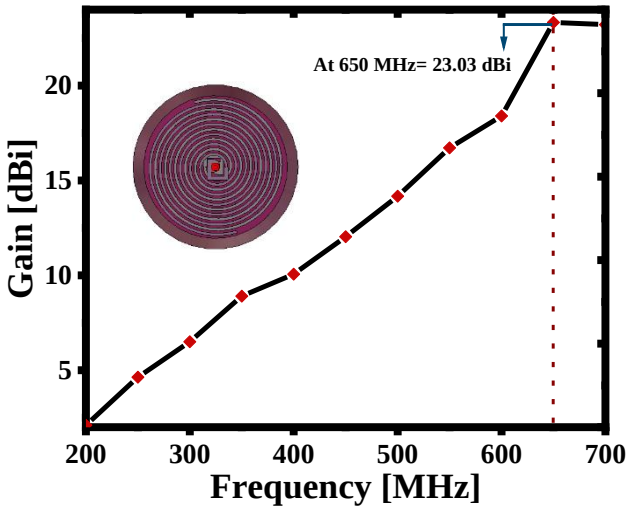


Figure 6: Gain of conical-backed archimedean spiral antenna

e) Radiation and Total efficiency

This high efficiency indicates that the antenna effectively converts input power into radiated electromagnetic energy with minimal losses. Achieving over 90 efficiency (in figure 7) means that the majority of the power supplied to the antenna is successfully radiated, leading to improves performance and reduced energy waste.

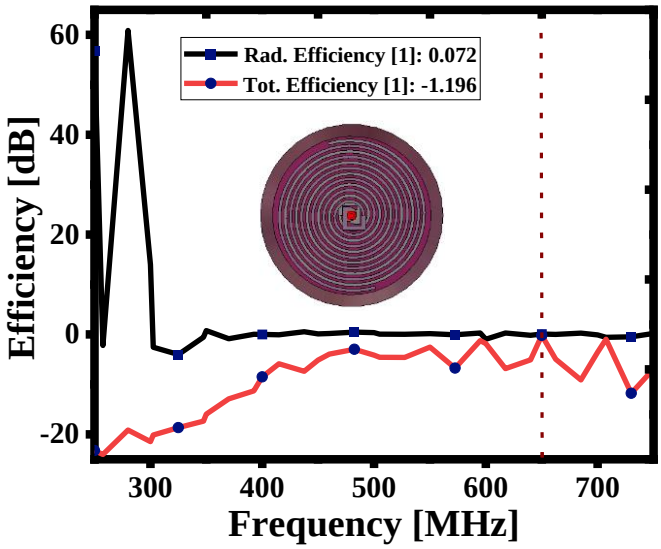


Figure 7: Efficiency of conical-backed archimedean spiral antenna

f) Directivity

A directivity of 19.05 dB (as shown in figure 8) indicates that the antenna effectively concentrates its radiated energy in a specific direction, enhancing its ability to transmit and receives signal over greater distances with higher precision.

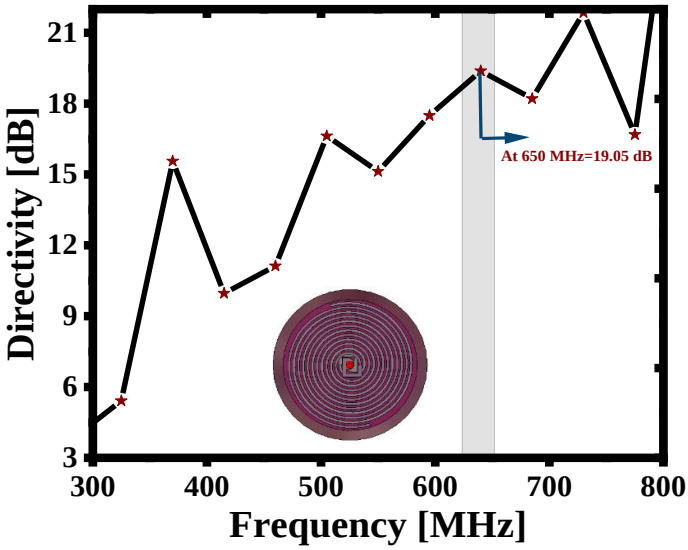


Figure 8: Directivity of conical-backed archimedean spiral antenna

g) Surface current distribution

This central feed point ensured that more current flows at the core of the spiral, gradually decreasing as it moves outward along the arms. This distribution is crucial for the efficient operation of the antenna, as the central feed maximizes the excitation of the spiral arms, leading to improved radiation characteristics and overall performance. The enhanced current at the center supports strong electromagnetic field generation, contributing to the antenna's high efficiency and directivity. Figure 9 depicts the current distribution along the spiral arms.

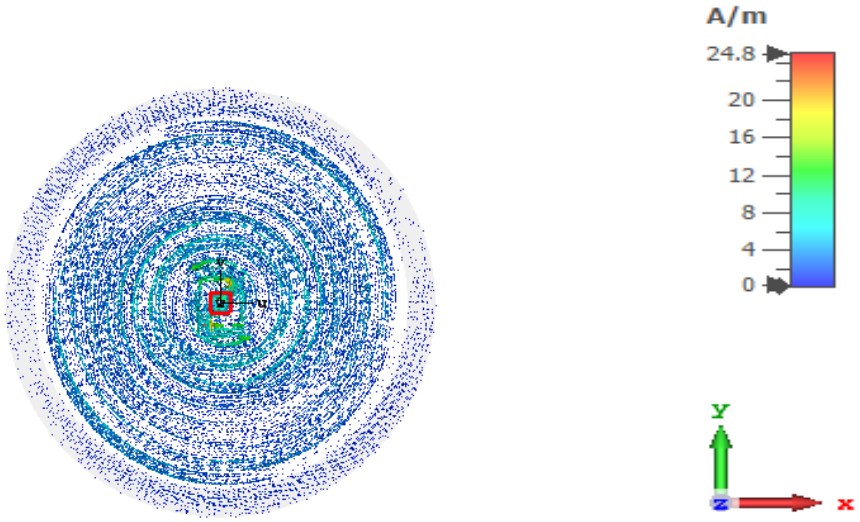


Figure 9: current distribution of conical-backed archimedean spiral antenna

h) Radiation Pattern

The radiation pattern of the spiral antenna is unidirectional, achieved through the use of conical-backed cavity. This configuration directs the radiated energy predominantly in one direction, enhancing the antenna's performance for applications requiring focused signal propagation. The cavity backing effectively minimizes radiation in unwanted directions, thereby improving the gain and ensuring that the energy is concentrated where it needed the most. Figure 10 (a) represents the 1-D polar graph and 10(b) shows the 3-D representation of the radiation pattern.

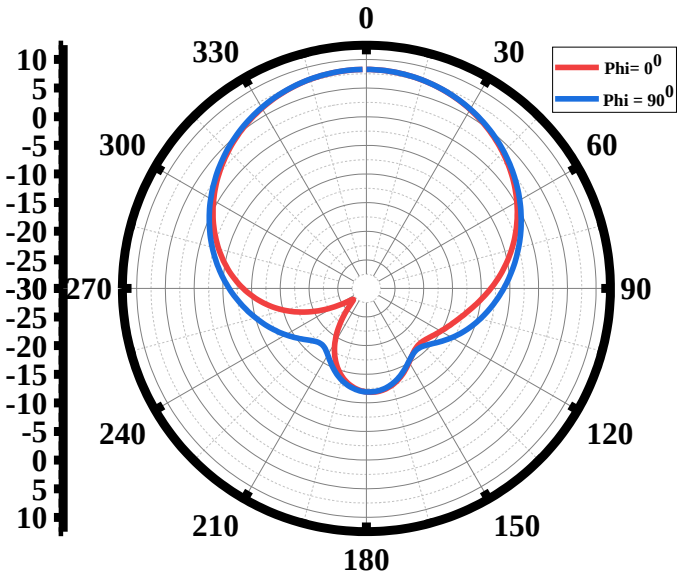


Figure 10(a): 1-D Polar graph of conical-backed archimedean spiral antenna

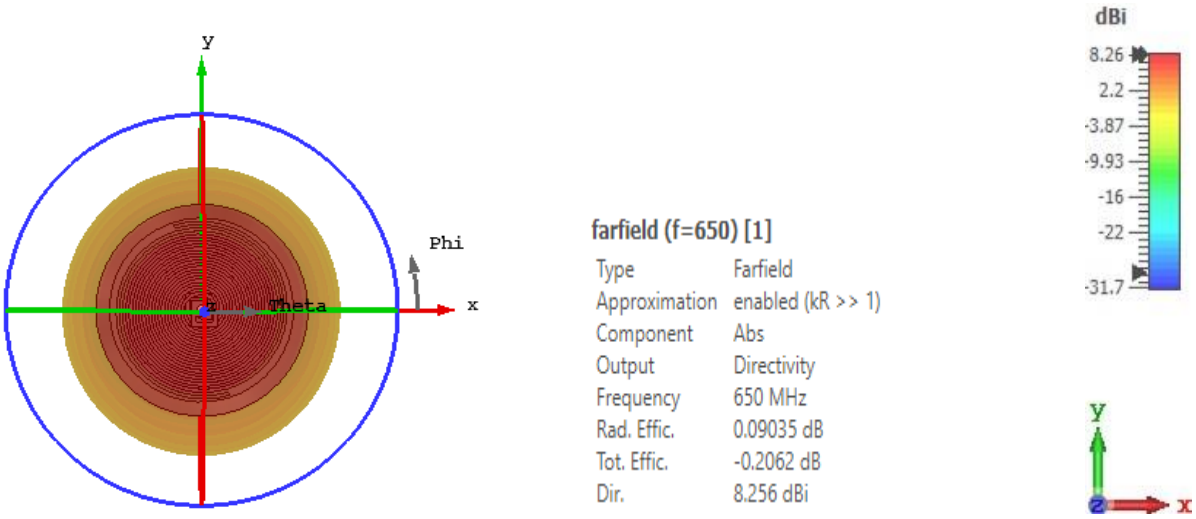


Figure 10(b): 3-D graph of conical-backed archimedean spiral antenna

Table 1: Result of the proposed cavity backed archimedean Spiral Antenna

Antenna Profile	**Compact size and simple(Conical cavity)**
Reflection Coefficient	-22.99 dB
VSWR	1.15
Efficiency	High (> 90%)
Impedance Matching	Z1,1 (Re)= 50.12 Z1,1 (Im)= 0.7833
Radiation Pattern	unidirectional
Gain	23.03 dBi
Directivity	19.05 dB

IV. Conclusion

The research explores the utilization of conical-backed two-arm Archimedean spiral antennas for enhancing antenna-plasma coupling in tokamak fusion reactors, with a focus on achieving optimal performance within the space constraints of the SST-1 reactor. The targeted frequency for operation is set at 650 MHz, aligning with the operational requirements of the fusion reactor. By employing a coaxial feed with a characteristic impedance of 50 ohms, the reflection coefficient is achieved at an impressive -22.99 dB, indicating excellent impedance matching. Additionally, the VSWR is measured at 1.15, indicative of minimal power loss due to impedance mismatch. The antenna demonstrates a substantial gain of 23.03 dBi, ensuring efficient power transfer between the antenna and the plasma. Moreover, the achieved Z-matrix indicates a real impedance of 50 ohms and an imaginary impedance of 0.7833, further corroborating the antenna's suitability for plasma coupling. Through meticulous consideration of dimensions to accommodate space constraints, the study highlights the efficacy of conical backed two-arm Archimedean spiral antennas in facilitating robust antenna-plasma interaction within tokamak fusion environments.

Data Availability

All the related data provided in the article.

Conflicts of Interest

The authors declare no conflicts of interest that could influence the objectivity and impartiality of the research.

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