DESIGN AND OPTIMIZATION OF A LOW FREQUENCY RF-INPUT COUPLER FOR THE IsoDAR RFQ*

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Abstract

The Isotope Decay-At-Rest experiment (IsoDAR) is a proposed underground experiment which is expected to be a definitive search for sterile neutrinos. IsoDAR uses an especially designed low frequency spilt-coaxial radio frequency quadrupole (RFQ) to accelerate H_2^+ ions directly from the ion source into the main cyclotron accelerator. This paper mainly focuses on the design and optimization of a low frequency (32.8 MHz) RF-input coupler for the IsoDAR RFQ. Starting with a basic design, we determine its appropriate position for this coupler in the RFQ. Finally, we optimized the design to lower the input power without compromising the coupling efficiency.

INTRODUCTION

The planned Isotope Decay-At-Rest (IsoDAR) is an underground experiment that is expected to be a definitive search for sterile neutrinos. The details of the IsoDAR experiment can be found in [1–3]. In summary, IsoDAR produce 10 a mA of protons at 60 MeV by accelerating H_2^+ ions inside a compact cyclotron. These protons produce electron-antinutrinos ($\bar{\nu}_e$) while interacting with a special target and disappearance of $\bar{\nu}_e$ would signal the existence of additional sterile neutrinos. We plan to use a spilt coaxial radio frequency quadrupole (RFQ) to accelerate H_2^+ ions directly from ion source into the cyclotron using a spiral inflector. The detail design parameters for the IsoDAR RFQ can be found in [2]. The important parameters for the IsoDAR RFQ are listed in Table 1.

Table 1: RFQ Parameters

Parameter	Value	Unit
Ion type	H_2^+	q/A = 1/2
Frequency	32.8	MHz
Input energy	15	keV
Output energy	70	keV
Beam current	10-20	mA
Duty factor (CW)	100	%
Total RF input power	≤ 10	kW
Length	1378.69	mm
Number of active couplers	1	NA

An RF input-coupler is a device that transmits the electromagnetic power from an RF-source to an RF-cavity and a particle beam. In addition to its main function of transferring RF power, an RF coupler also works as a vacuum barrier between inside and outside the cavity, and thermal barrier between room and cryogenic temperature. The input-couplers can be divided into two categories based on the geometry of their cross-sections: Coaxial couplers and waveguide couplers. Both of these coupler types have their own advantages and disadvantages, the details of which can be found in [4,5]. In general coaxial couplers are preferred at lower frequencies (< 500 MHz) and waveguide couplers are preferred at higher frequencies (> 500 MHz) [6]. Since the operating frequency of the IsoDAR RFQ is very low (32.8 MHz), we chose a coaxial loop coupler. This paper mainly focuses on the design and optimization of an input power coupler for the IsoDAR RFQ.

DESIGN OF RF-INPUT COUPLER

Designing a robust RF-input coupler is a complicated process; a full electromagnetic (RF) field calculation should be performed with a multiphysics package such as COMSOL [7] or CST [8]. In addition, other physical parameters such as total power, required number of couplers, operational frequency, mode of operation, vacuum and RF-window design, coupling type, thermal- and, multipacting effect [9,10] and cooling system have to be taken into account.

The fundamental requirements for the IsoDAR input coupler are listed in Table 2. Based on these requirements, We prepared an initial design which was based on the IFMIF/EVEDA 50 Ω loop coupler [11]. The current optimized design has a slightly different loop shape (L-shaped) than that of original IFMIF loop coupler as shown in Fig. 1(a). This optimized design has a coupler port diameter of 100 mm to incorporate a larger loop length which helps to enhance coupling efficiency. In addition, larger port helps to incorporate cooling system inside the loop.

Table 2: Coupler Parameters

Parameter	Value (Nominal)	Unit
Frequency	32.8	MHz
Operating power	≤ 10	kW
Coupling type	Inductive (loop)	NA
Input impedance	50	Ω
Coupling port diameter	≈ 100	mm

While designing an RF-input coupler, the thermal- (heating), and multipacting effects are the most important parameters. We plan to minimize the thermal heating by employing

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* Work supported by NSF grants PHY-1505858 and PHY-1626069, as well as the Heising-Simons Foundation.

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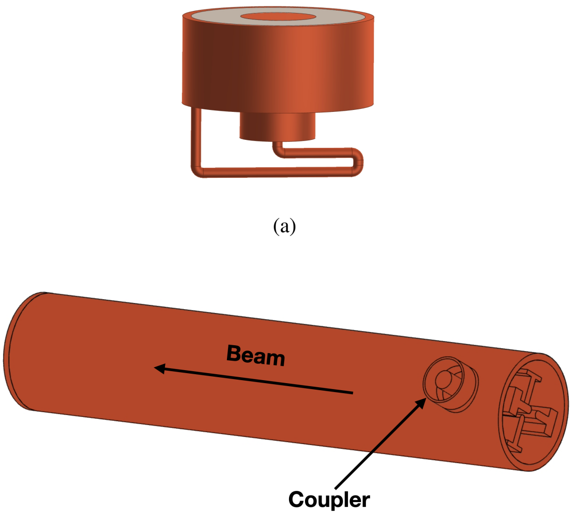


(a)

(b)

Figure 1: CAD design of (a) a loop coupler, and (b) the IsoDAR RFQ tank showing the position of this loop coupler.

an effective cooling system through the hollow loop and supress the multipacting effects, which occur at the inner surface from the material having a high Secondary Electron Yield (SEY) (> 1) by applying a thin (~ nanometers) coating material having a low SEY such as titanium nitride (TiN) as has been shown in [11, 12]. The remainder of the paper will focus on the mechanical and RF design.

POSITION FOR THE LOOP COUPLER

The loop coupler has to be placed at the position where the value of magnetic field is maximum to get the best coupling efficiency. We used COMSOL simulations to find the longitudinal and azimuthal position for the loop coupler in the RFQ, which showed that the magnetic field is maximum near the two ends of RFQ. Since the downstream of the RFQ is embedded inside the cyclotron yoke by design, the only choice to place the input coupler is the upstream region of RFQ. In this region, we found that maximum value of the magnetic field can be found between 115 mm and 135 mm along the z-axis and hence we placed the coupler at 125 mm. Similarly, we also determine the azimuthal position by evaluating the contour plot for the norm of magnetic field in the X-Y plane at the longitudinal position of 125 mm. The plot showed the higher value of magnetic field just above the horizontal vanes and hence we placed the loop coupler at this position. A CAD model showing both the longitudinal and radial position of the loop coupler in the IsoDAR RFQ is shown in Fig. 1(b).

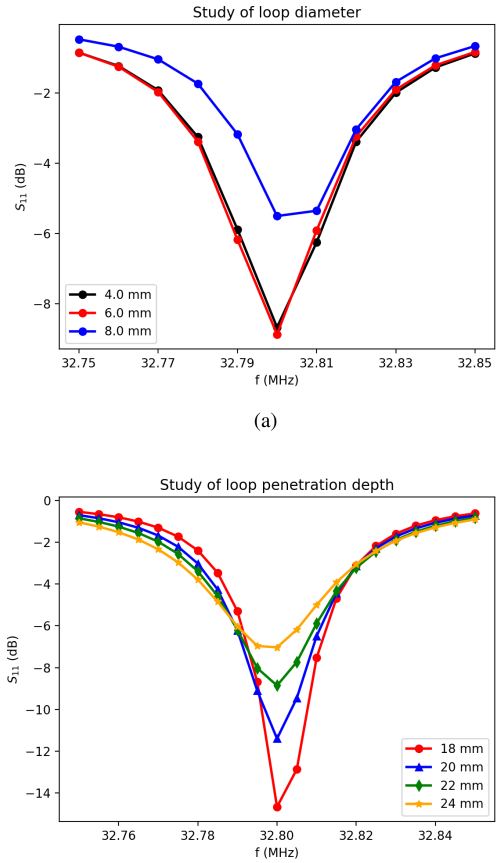
After determining the coupler type, loop shape, and its appropriate position, we optimized the design of loop coupler which we present in the following section.

OPTIMIZATION OF LOOP COUPLER

The optimization of the loop coupler involves determining its appropriate diameter, penetration depth: radial distance between the inner surface of the RFQ tank and the mid surface of the lower loop diameter, and orientations to minimize RF input power and signal reflection. The reflection coefficient S_{11} measures the amount of signal reflection. The lower the value of S_{11}, the better would be the signal transmission and also the lower input power. The maximum value of S_{11} (dB) is zero, which indicates full reflection.

Loop Diameter and Penetration Depth

To find the appropriate dimension of the loop diameter, we ran COMSOL simulations and studied the variation of the reflection coefficient S_{11} with its diameter by fixing the penetration depth to 22.0 mm and a loop angle to 0°. Fig. 2(a) shows a comparison of S_{11} with frequency for three different loop diameters, where the black, red, and blue curves represent loop diameter of 4.0 mm, 6.0 mm, and 8.0 mm, respectively. Simulations showed that the value of S_{11} is mostly the same for 4.0 mm and 6.0 mm, and we obtained more reflection in the case of 8.0 mm loop diameter which is due to the small radial gap between the lower loop surface and base of RFQ electrode. We choose the diameter of 6.0 mm rather than 4.0 mm to ease the machining and to increase water flow through the loop.



(a)

(b)

Figure 2: Plot showing the variation of S_{11} with frequency with different (a) loop diameters, and (b) penetration depths.

After choosing a 6.0 mm loop diameter, we analyzed the variation of S_{11} with its penetration depth. COMSOL simulation showed that the value of S_{11} (dB) increases with the larger penetration depth as shown in Fig. 2(b), where red, blue, green, and orange curve represent corresponding plots for penetration depth of 18 mm, 20 mm, 22 mm, and 24 mm, respectively. Because of the limited radial gap between vane and RFQ tank, we could not further reduce the penetration depth, however 18 mm is sufficient to meet our targeted operating power.

The increase in reflection coefficient with higher penetration depth is due to increase in the amplitude of surface electric field at the loop lower surface due to a narrow gap between loop coupler and RFQ vane, which may lead to RF breakdown. Kilpatrick has developed an empirical formula [13]: f[MHz] = $1.64 \cdot E_k^2 e^{-8.5/E_k}$, where E_k in MV/m is the Kilpatrick limit of the electric field before RF breakdown. This formula provides a conservative estimation of breakdown voltage as the practical value is much higher than this value [14]. For 32.8 MHz, the value of one Kilpatrick limit is 7.743 MV/m, and in our case simulations showed that the maximum is well below this conservative limit.

Loop Rotation

The final step of the optimization was to determine the appropriate orientation of the loop coupler inside the RFQ. Accordingly, we studied the variation of the S_{11}-parameters by rotating the coupler from 0° to 360° in clockwise direction, where 0° corresponds to L-shaped, Fig. 1(a), and 180° corresponds to mirror L-shaped. The COMSOL calculations show that the reflection coefficient is lowest, i.e. critically coupled, at 30° and 330° (see Fig. 3(b)), however we need the value of coupling factor slightly above $\beta \geq 1$. Therefore, an angle around 25° – 35° is likely to be suitable for operation. Figure 3 (bottom) depicts the variation of S_{11} at the loop angle of 0°, where the resonant frequency is slightly off from the design frequency of 32.8 MHz.

Thus, we optimized the input coupler in terms of its diameter, penetration depth and the loop rotation. The optimized design has a diameter of 6.0 mm, penetration depth of 18 mm and loop orientation of 0°. After optimizing the loop coupler, we have calculated the input power required to operate IsoDAR RFQ using this coupler, which we discuss in the following section.

INPUT POWER CALCULATION

To calculate the required input power for the RFQ, we compared the simulated amplitude of the electric fields at a point (10 mm, 10 mm) in the XY plane, along z-axis between two COMSOL solvers; Electrostatic and Eigen-mode. The electric fields for the Electrostatic solver was evaluated using the 22 kV inter-vane voltage (obtained from the RFQ Beam dynamics code PARMTEQM) while for the Eigen-mode solver, we varied RF input power via the loop coupler until we get the same amplitude of the electric fields at the same location. Simulations showed that the required input power is about 4 kW.

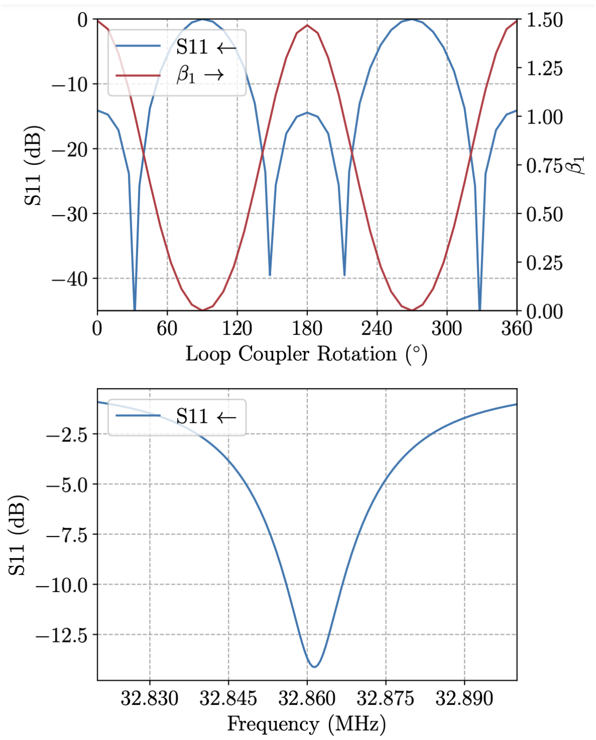


Figure 3: Variation of S_{11} with loop orientation (top), and frequencies at loop angle of 0° (bottom).

SUMMARY AND FUTURE WORKS

In this paper, we described the design and optimization of a low frequency RF-input coupler for the IsoDAR RFQ. We designed the L-shaped coaxial loop coupler whose optimal position for placement was found to be at 125 mm from the entrance flange of RFQ. Then we presented the optimization technique we employed to determine its appropriate diameter, penetration depth and loop orientation. The optimized design has a diameter of 6.0 mm, penetration depth of 18 mm, and loop orientation of ≈ 35°. Finally, we found that the power required for this coupler to produce the same electromagnetic field as generated in the electrostatic approximation by an inter-vane voltage of 22 kV is approximately 4 kW.

ACKNOWLEDGEMENTS

This work was supported by NSF grants PHY-1505858 and PHY-1626069, as well as the Heising-Simons Foundation. D. Winklehner was supported by funding from the Bose Foundation.

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