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TECHNICAL DESIGN OF AN RFQ INJECTOR FOR THE IsoDAR CYCLOTRON

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Abstract

For the IsoDAR (Isotope Decay-At-Rest) experiment in neutrino physics, a high intensity (10 mA cw) primary proton beam is needed. To generate this beam, H_2^+ is accelerated in a cyclotron and stripped into protons after extraction. An RFQ, partially embedded in the cyclotron yoke, will be used to bunch and axially inject the H_2^+ beam into the cyclotron's central region. The excellent RFQ bunching capabilities will be used to optimize the overall injection efficiency. To keep the setup compact, the distance between ion source and RFQ can be kept very short as well. In this paper, we describe the technical design of the RFQ. We focus on two critical aspects: 1. The use of a split-coaxial structure, necessitated by the low frequency of 32.8 MHz (matching the cyclotron RF) and the desired small tank diameter; 2. The high current, cw operation, requiring a good cooling concept for the RFQ tank and vanes.

INTRODUCTION

Within the framework of the IsoDAR and DAEδALUS "Sterile Neutrino experiments" intense proton driver beams are requested [1]. The first stage is a 60 MeV/amu cyclotron delivering 5 mA of H_2^+- ions, which is equivalent to a 10 mA proton beam [2].

The requested beam current level opens a new chapter of cyclotron technologies: So far PSI (Villligen, Switzerland) is the record holder with a two-staged cyclotron system up to 590 MeV delivering up to 3 mA cw in machine beam times. They use a 12 mA, 760 kV Cockroft Walton electrostatic injector with central, axial injection into the 70 MeV injector cyclotron. Bottlenecks with respect to the beam current increase beyond the 2.2 mA routine level behind the injector cyclotron are significant beam losses at injection into the first cyclotron, as well as the transmission and extraction at both cyclotrons - causing high activation of the equipment.

To alleviate the requirement of very high primary beam currents from the ion source and reduce the massive particle losses in the central region, a novel type of injection, using an RFQ, accelerating protons from 7.5 keV/amu to 35 AkeV inserted into the cyclotron yoke to pre-bunch the beam with high efficiency [3], was proposed by the MIT group (which leads the accelerator design for IsoDAR). This concept had been proposed before in 1981 by RW Hamm [4], but was never realized.

BEVATECH GmbH is collaborating with MIT to develop the technical design of this cw operated RFQ running at 32.8 MHz matching the cyclotron frequency.

DESIGN CHALLENGES

The main challenges in the mechanical RFQ design are:

1. Alignment and stabilization of the quadrupole electrodes positions (±0.1 mm).
2. Suppression of mechanical electrode vibrations (shifting the electrodes' mechanical vibration resonances above 100 Hz).
3. Using metals which allow closed circuit water-cooling at around 0.6 MPa and integration in the typical circuits as used for copper/stainless steel structures.
4. Small outer cavity diameter along the high energy end (below 300 mm).
5. Mechanically well-designed RF tuning options to reach and control the frequency.

Reaching the ultra high vacuum needed for safe RFQ operation (value here) is challenging due to the close coupling with the cyclotron, operating at a higher vacuum level (typical value here). This is mitigated by adding additional turbo-pumps to the RFQ and using metal seals wherever possible.

RF DESIGN

To match the low operating frequency of 32.8 MHz, which is quite unusual for RFQs, the design approach of a split coaxial RFQ which was first proposed in a GSI report in 1979 by R.W. Müller has been followed. Split coaxial RFQs consist of 4 vanes where one pair of vanes is connected to each end lid of the cavity (see Fig. 1). The high electric capacitance of the design reduces the length considerably below $\lambda/4$ and along the full cavity length the vane-vane voltage is constant.

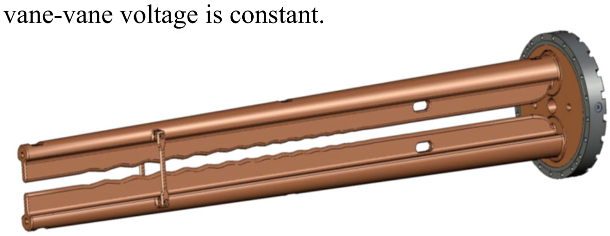

Figure 1: Pair of vanes of the split coaxial RFQ.

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Radio-Frequency (RF) simulations have been performed with CST Microwave Studio to find the right design parameters for:

- Optimized power coupling.
- Geometrical parameters on the frequency.
- Frequency tuning possibilities.

The final RF parameters of the RFQ for the given beam dynamics design from MIT and a matching the electrode modulation can be found in Table 1.

Table 1: CST MWS Design Parameters

Parameter	Value
Frequency	32.9 MHz
Tuning Range*	±270 kHz
Power losses	4.2 kW
Q simulated	2.800
Shunt impedance R_p	4.9 kOhm/m
Total RF power	5.33 kW

The tuning of the RFQ will be performed by cylindrical plungers during operation (see Fig. 2). Nevertheless, to counteract production-related frequency deviations, tuning bodies can be attached to the vanes to optimise the resonance frequency.

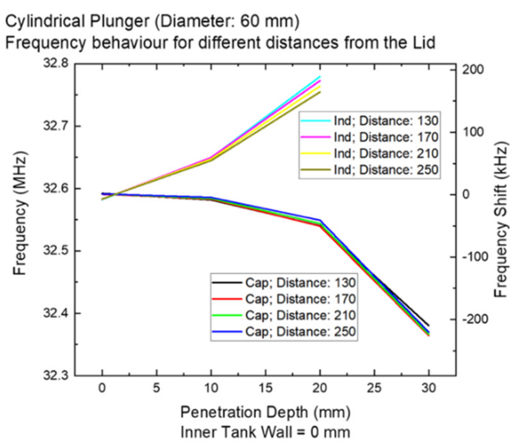

Figure 2: Simulated tuning range for the plungers.

A loop coupler seems to be most appropriate to provide the RF power to the cavity. During the simulations it was found that to provide enough coupling strength a coupler position close to the connected electrodes, where a higher magnetic field will be generated, is preferable.

Another important geometrical parameter is the electrode width profile in z-direction. Besides the possibility to influence the frequency, it has a strong effect on the mechanical stability. The width of the connected ends should be as large as possible. The frequency increases with larger width because of the decrease of inductance (see Fig. 3). On the other hand, the width at the free vane end should be small. A smaller width there increases the frequency because of a decrease of capacitive load. To simplify the production, the width is changed linearly along the tank length.

* Performed with plungers and tuning bodies.

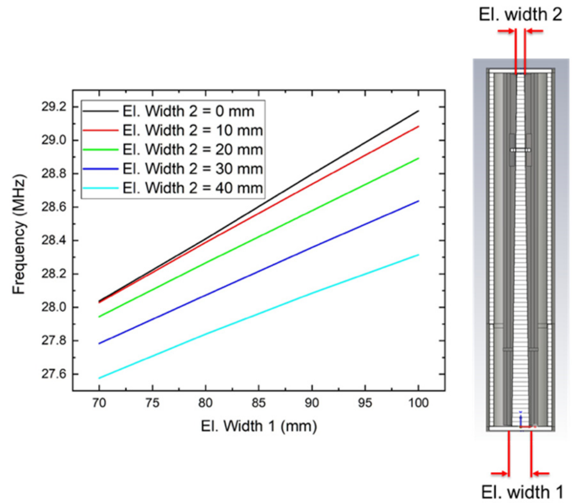

Figure 3: Simulated frequency as function of the electrode width without frequency correction for 32 MHz.

MECHANICAL DESIGN

One main technical challenge is the mechanical alignment and stability of the quadrupole electrodes: They are mechanically fixed and RF-wise grounded at one end only – while their total length is about 1.36 m. A bridging between two electrodes at the same RF potential, as shown in Fig. 4, aligns the electrode pair on identical RF potential against each other, and it is a good remedy for mechanical low frequency electrode vibrations. The stabilizers position along the electrodes is at about 75% of their total length, which is due to the fact that electrodes cross-sectional areas are reduced towards the open ends and due to mechanical vibration considerations.

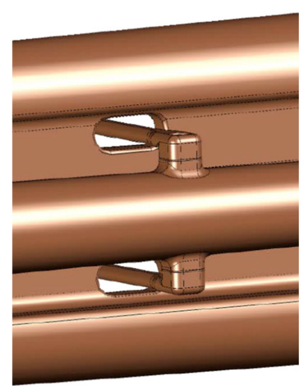

Figure 4: Pair of electrodes with stabilizers and opening in the other electrode pair for the bridging.

The RFQ cavity needs many flanges for vacuum pumping, RF feeding and controls (mounting etc. ee Fig. 5). Stainless steel is proposed for the cavity cylinder as well as the end lids. Welding techniques as well as the CF conflat flange metal sealing technologies are well established. A standard technology to make use of the mechanical properties of stainless steel and of the electrical properties of copper is to galvanically copper-plate the cavity surfaces with at least a few skin depths thickness.

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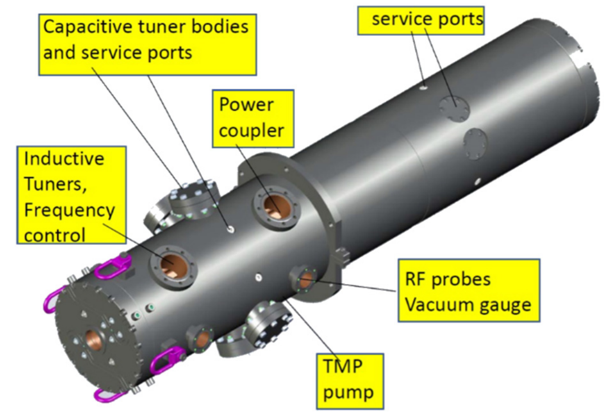

Figure 5: RFQ 3D view and function of flanges.

The electrodes have to carry the main heat load. Therefore, massive copper is preferred in that case which will be treated with deep hole drilling, to provide water cooling channels. No brazing or soldering is foreseen on the copper. Forged E-Cu copper has to be used and no heat treatment is allowed in order to keep the mechanical properties of "hard copper".

The only elements to cause trouble by mechanical vibration resonances are the vanes, as they are rather long and connected to the tank at one end only. The vane stabilizers help to keep the distances between two vanes but cannot fix the vane ends against the cavity walls. Two types of mechanical vibrations are distinguished:

1. Vibrations between vanes on different RF potential, where Lorentz force detuning can happen.
2. Vibrations with only weak coupling to the RF oscillation.

In the first case it is important to shift the resonances high enough (above 50 Hz at least, being the frequency range of typical mechanical excitations by external equipment e.g. vacuum pumps), while in the second case also lower frequencies are tolerable. Simulations have been performed and the 2 lowest vibrational modes are shown in Fig. 6. In any case, it was found the mechanical coupling of two electrodes by the stabilizers will yield an efficient damping of most mechanical resonances.

Result: There are two quarter wave modes which are associated with the choice of a split-coaxial resonator. By coupling two vanes with the stabilizers, the Lorentz force detuning is considerably reduced as opposed to four independently oscillating vanes. The frequencies are as low as 18 Hz and 25 Hz.

Figure 6: Mechanical quarter wave oscillation modes of the vane pairs at 18 Hz and 25 Hz.

During cw operation a power dissipation of about 3.2 kW at the nominal simulated quality factor needs to be considered for cooling. Simulations were carried out for 4.0 kW power dissipation to provide a safety margin. It was found that at nominal operation parameters, the entire tank structure is expanding longitudinally (distance between lids is increasing) as well as a shift of electrodes against each other and a longitudinal expansion of the electrodes themselves can be observed. Overall, these effects lead to an RF detuning of less than 30 kHz and the beam phase deviation due to the thermal electrode elongation amounts to less than 2°. As the thermal effects are dominated by the tank expansion, for the mechanical design it was decided to lower this effect by providing thick copper plating with 1 or 2 mm on the inner tank wall to increase thermal conductivity.

CONCLUSION

Based on the given design requirements, a safe mechanical design for a 32.8 MHz split coaxial RFQ has been suggested and validated. RF simulations to ensure good coupling and tuning possibilities for the RFQ show good results. Mechanical simulations validating stability of the electrodes during operation proved that there is no unexpected cavity detuning which cannot be counteracted. During the cooling simulations it was found that the dominant effect of tank expansion can be counteracted with a thicker copper plating of the tank walls. Currently, an update of the beam dynamics for this RFQ development is in preparation by MIT. After the beam dynamics are finalised, the new electrode modulation will be considered in the final simulation of the vane before the RFQ can be manufactured.

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