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THERMAL ANALYSIS OF A COMPACT SPLIT-COAXIAL CW RFQ FOR THE IsoDAR RFQ-DIP

D. Koser*, J. M. Conrad, D. Winklehner, MIT, Cambridge, MA, USA
H. Podlech, U. Ratzinger, M. Schuett, Bevatech GmbH, Frankfurt, Germany

Abstract

The RFQ direct injection project (RFQ-DIP) for the neutrino physics experiment IsoDAR aims at an efficient injection of a high-current H_2^+ beam into the dedicated 60 MeV driver cyclotron. Therefore, it is intended to use a compact 32.8 MHz RFQ structure of the split-coaxial type as a pre-buncher. To determine the thermal elongation of the 1.4 m long electrode rods as well as the thermal frequency detuning of the RF structure at a maximum nominal power load of 3.6 kW, an extensive thermal and structural mechanical analysis using COMSOL Multiphysics was conducted. The water heating along the cooling channels as well as the properties of heat transfer from the copper structure to the cooling water were taken into account, which required CFD simulations of the cooling water flow in the turbulent regime. Here we present the methods and results of the sophisticated thermal and structural mechanical simulations using COMSOL and provide a comparison to more simplistic simulations conducted with CST Studio Suite.

INTRODUCTION

The IsoDAR experiment (Isotope Decay-At-Rest) aims to provide a definitive search for sterile neutrinos by investigating neutrino oscillations through the detection of $\bar{\nu}_e$ disappearance over a short baseline of 16 m from the anti-neutrino source to the detector [1]. To test the sterile neutrino hypothesis with a significance >5σ and distinguish between models with one or two sterile neutrinos with eV-scale mass differences, a kiloton-scale scintillator detector is intended to be used in conjunction with a 50 kiloCurie high-flux anti-neutrino source over the nominal experiment runtime of 5 years. The dedicated anti-neutrino production target for IsoDAR is driven by a high intensity 10 mA, 60 MeV proton beam, producing neutrons in a ^{9}Be target that are captured by a surrounding sleeve of highly pure ^{7}Li. This results in the production of ^{8}Li which undergoes β-decay at rest, with an isotropic $\bar{\nu}_e$ emission at a known energy spectrum.

To overcome the space charge challenges at injection energy and reduce beam emittance growth, the cyclotron-based driver accelerator system is designed to produce a 5 mA, 60 MeV H_2^+ CW beam of molecular hydrogen ions, which is stripped into protons right before the target, effectively doubling the beam current to the nominal value of 10 mA [2]. The beam current requirements for IsoDAR far exceed the present capabilities of commercially available cyclotrons and the therefor developed high-current cyclotron technology would lend itself to a variety of applications beyond neutrino physics, such as the production of radiopharmaceutical isotopes [3].

To significantly increase the injection efficiency into the cyclotron compared to classical LEBT designs, a radio-frequency quadrupole (RFQ) is intended to be used as pre-buncher before the beam is axially injected through an electrostatic spiral inflector into the central region of the cyclotron (see Fig.1) [4]. To position the RFQ as close to the median plane of the cyclotron as possible, the RFQ tank is integrated into the cyclotron yoke and hence needs to be of compact transverse dimension. To achieve this, given the comparatively low operating frequency of 32.8 MHz, a split-coaxial RFQ design is used as depicted in Fig. 2. This offers the advantage that the RF resonance frequency is independent of the transverse resonator dimension, unlike to most other common RFQ resonator types. The basic design properties of the split-coaxial type IsoDAR-RFQ are summarized in Table 1.

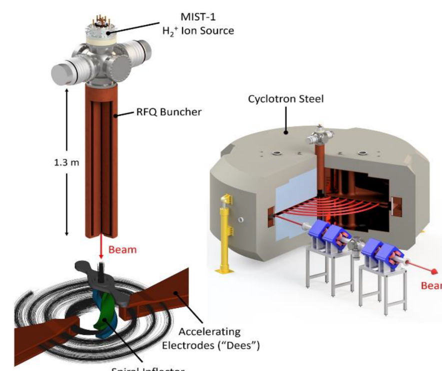

Figure 1: Axial beam injection scheme into the 60 MeV IsoDAR cyclotron.

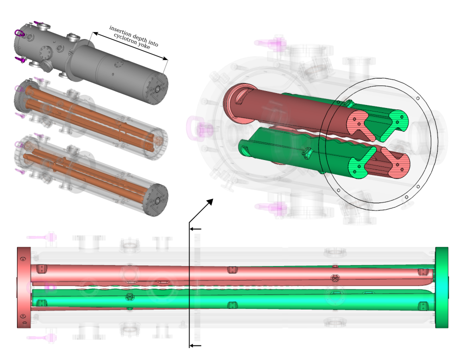

Figure 2: Schematic view of the split-coaxial RFQ design for the IsoDAR RFQ-DIP (the electrodes marked in red and green, respectively, are connected with the same cavity lid).

* dkoser@mit.edu

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Table 1: Design Properties of the IsoDAR-RFQ

RF frequency [MHz]	32.8
design ion	H_2^+
design beam current [mA]	6.5
duty cycle	CW
input/output energy [keV]	15 / ~70
inter-vane voltage [kV]	20
tank diameter [cm]	28
electrode length [cm]	~140
RF power [kW]	3.6
shunt impedance [kΩm]	155

To provide high cooling efficiency, all components of the RFQ structure are directly water cooled and the thermally sensitive electrode rods are made of massive copper, while the tank is made of stainless steel. The technical RFQ design was developed by the Frankfurt (Germany) based company Bevatech GmbH.

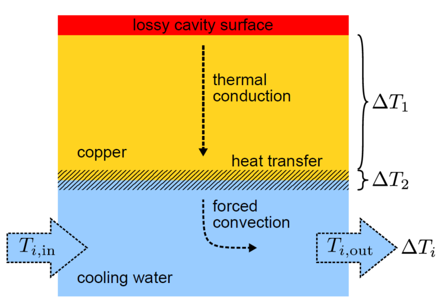
CST SIMULATIONS

As a first step, a thermal analysis was conducted with the CST Studio Suite software, which already had been used for the RF simulations of the RFQ. Since the used CST Thermal Steady State Solver is limited to constant temperature boundary conditions on a volume body, the water heating along the cooling channels as well as the properties of heat transfer from the copper structure to the cooling water were taken into account by applying a semi-analytic model to calculate the boundary temperature at the cooling channel surface of a given channel section (see Fig. 3). The same method was already applied to analyze the thermal problems of the HLI-RFQ at GSI [5].

$$\Delta T_1 = \frac{\dot{Q}_i \, d_{\text{copper}}}{\lambda \, A_i}$$

$$\Delta T_2 = \frac{\dot{Q}_i}{\alpha \, A_i}$$

$$\Delta T_i = \frac{\dot{Q}_i}{\dot{V} \rho \, c_{\text{w}}}$$



$$\rightarrow \boldsymbol{T_{\text{boundary}} = T_{i,\text{in}} + \Delta T_2 + \Delta T_i/2}$$

Figure 3: Simplistic analytic model of heat dissipation by cooling water flow.

The calculated boundary temperatures are depicted in Fig. 4 for an overall CW power dissipation of 3.6 kW (~0.54 kW per electrode), a water flow rate of 8 l/min per cooling circuit and an assumed heat transfer coefficient of 3500 W/m^{2}K. The accordingly simulated temperature distribution is shown in Fig. 5. To simulate the associated thermal deformation, the temperature field was exported to the CST Mechanical Solver and the obtained deformation field was then again imported back into the RF Eigenmode Solver for a frequency sensitivity analysis.

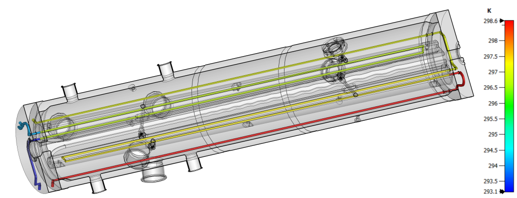


Figure 4: Thermal boundary conditions at the cooling channel surfaces as used for the CST simulations.

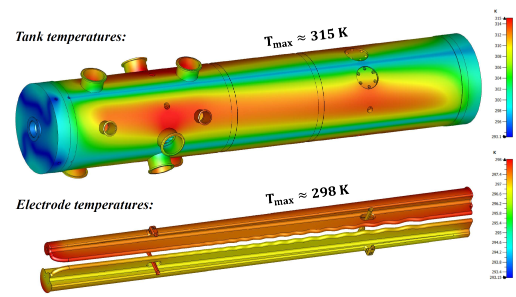


Figure 5: CST simulation results for the temperature distribution at the RFQ tank and at the electrode rods.

Since the electrodes and the tank thermally expand mainly in the longitudinal direction (electrodes by ~ 100 µm and tank by ~ 350 µm), the RFQ resonance frequency is mostly affected by the associated decrease of electric capacitance between the electrode ends and the adjacent tank lids. This leads to a frequency detuning of approximately +24 kHz. The occurring mechanical shift of the modulation cell centers against each other causes a maximum beam phase mismatch of ~2°.

COMSOL SIMULATIONS

To validate the results from the simplistic CST simulations, a more sophisticated thermal analysis using COMSOL Multiphysics was conducted. Using the Nonisothermal Flow multiphysics feauture, the Heat Transfer interface was coupled with a CFD flow simulation, thus allowing for a self-consistent simulation of heat transfer from the structure into the cooling water. For this, no assumption on the value of the heat transfer cofficient has to be made and the local properties of the cooling water flow are taken into account. In the conducted simulations, the differences between laminar and turbulent (k-ω model) flow were investigated.

An improved overall cooling of the RFQ structure and reduced temperatures (see Fig. 6) is a result of turbulent flow mixing the surface fluid layers and hence improving heat transfer, as shown in Fig. 7. The simulated local velocity field of the water flow, as depicted in Fig. 8, lends itself to estimate the effects of erosion corrosion of the copper cooling channel surfaces.

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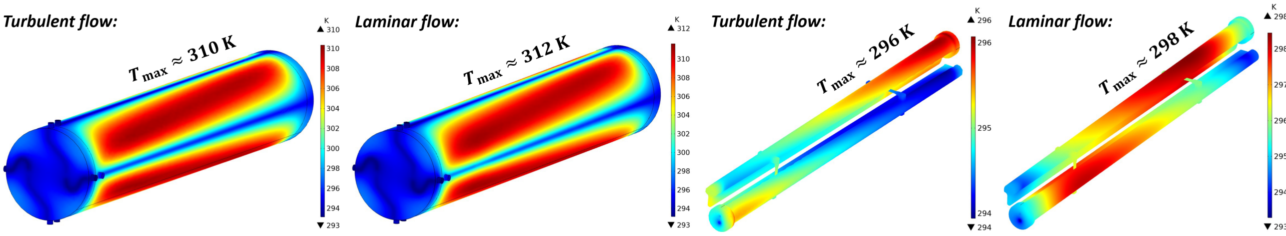

Figure 6: COMSOL simulation results for the temperature distribution at the RFQ tank and at the electrode rods. Turbulent flow yields slightly reduced surface temperatures.

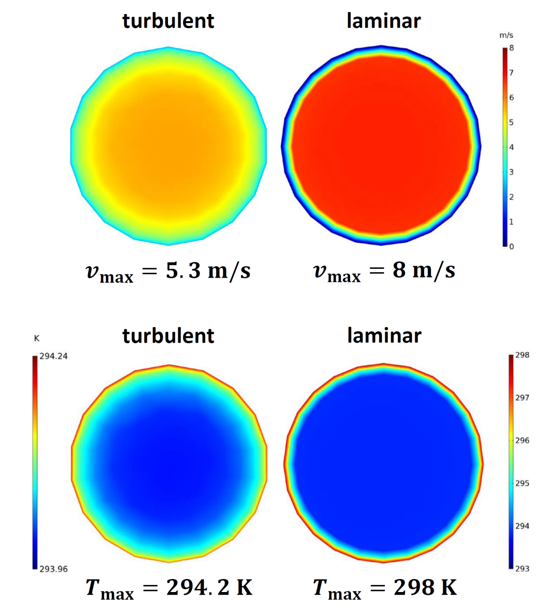

Figure 7: Simulated flow velocity field (*above*) and temperature distribution (*below*) on a cross-sectional profile of a straight cooling channel section for laminar and turbulent flow.

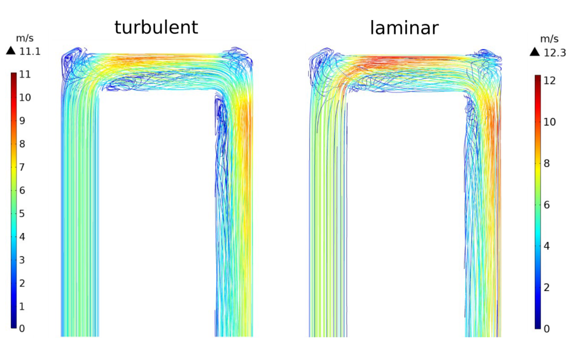

Figure 8: Streamline plot of the water flow around the 180°-bend at the electrode ends, simulated with a turbulent and laminar flow model.

SUMMARY & CONCLUSION

With the proposed cooling concept (all components being directly water cooled) the simulated thermal frequency detuning of the IsoDAR-RFQ of +24 kHz at the nominal CW power dissipation of 3.6 kW is well whithin the tuning range of ±80 kHz of the conceived dynamic movable tuner system. The thermal longitudinal expansion of the copper electrode rods has a negligible influence on the bunching and focusing properties of the RFQ. The thermal analysis was conducted using CST Studio Suite and the results have been validated and are largely consistent with corresponding COMSOL simulations which include CFD simulations of the cooling water flow.

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