

# COOLING SKID, THERMAL CHARACTERIZATION AND SIMULATIONS FOR THE ARGITU RFQ AT ESS-BILBAO

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## Abstract

The ARGITU RFQ at ESS-Bilbao is a 352.2 MHz, 4-vane RFQ that will accelerate protons from 45 keV to 3.0 MeV. The RFQ is a 3.1 meters long structure machined in OFHC copper of high purity, and no brazing has been used to assemble the vanes that conform each of the four segments. The cooling of the structure is carried out by cooling channels that runs longitudinally along the vane tips and transversal in the vacuum grid region. In a first stage, the RFQ will operate at a maximum duty cycle of 1 %, and for this stage a first version of the water cooling skid has been designed, built and tested. The vane cooling channels in this setup runs in series from segment to segment allowing a simpler design. A dedicated chiller that provides great stability and control has been integrated in the system, as well as water flow and temperature valves and sensors monitored using IO link technology. The cooling water skid, the tests performed with the RFQ and their correlation with FEM simulations are described in this paper. The dynamic tuning of the RFQ during conditioning and operation are also described.

## INTRODUCTION

The ESS-Bilbao RFQ is the first accelerating structure of the ARGITU neutron source and the HiCANS platform project [1–3]. The RFQ is 3.1 m long, machined in OFHC copper. It is an assembly of four segments of approximately 800 mm length, each one assembled using rubber gaskets instead of brazing to facilitate any replacement in case of damage. It will accelerate protons from 45 keV to 3.0 MeV at a frequency of 352.2 MHz [4, 5]. The RFQ has been fabricated, assembled and tested at low RF power. The tuning, including cooling water in the process, has also been finished [6]. The next commissioning stages require conditioning with RF power and beam. The initial configuration for HiCANS platform project first stages will be limited to low duty cycles below approximately 1 %, because power couplers at this stage do not have active cooling [7]. This reduced duty factor relaxes the average thermal load, but it does not remove the need for a stable and well-characterized water-cooling system.

RF power losses produce thermal deformation and therefore a change of resonant frequency and field profile. Conversely, changes in cooling-water temperature or flow modify the temperature field in the vanes and body, and can be used to compensate frequency drift. For this reason, cooling specifications define not only water flow and temperature magnitudes, but also stability requirements. The present



Figure 1: ESS-Bilbao RFQ connected to the cooling skid during the first water-cooling and frequency characterization campaign.

work focuses on the cooling implementation for HiCANS-platform specifications, the technology used for this and on the first measurements of RFQ frequency as a function of the water-cooling conditions.

## RFQ COOLING SETUP

The RFQ body includes several families of machined cooling channels. Channels type 1 run close to the vane tips and are the most effective ones for frequency control; channels type 2 are placed in the external vane region; and channels type 3 cool the vacuum-grid region. The full RFQ cooling specification gives nominal flow rates of 3.3 l/min per type 1 channel and 6 l/min for type 2 and type 3 channels, with a total RFQ-body flow, excluding tuners, couplers and pickups, of about 437 l/min [4, 5]. In the setup for HiCANS-platform, the cooling skid is simplified with a single chiller and a common inlet water temperature. Type 1 and 2 channels are connected in series, whereas type 3 channels are arranged in parallel between segments to minimize temperature gradients caused by coolant heating. This arrangement reduces the number of independently controlled circuits and is adequate for the low-duty-cycle commissioning phase.

Figure 1 shows the RFQ and the cooling skid. The system includes the SMC chiller, piping, manual flow adjustment elements, SMC PF3W7 flow-temperature sensors and the corresponding EPICS monitoring and control. The sensors validation campaign showed temperature stability below approximately  $\pm 0.1$  °C at fixed set points and good flow stability for the sensors. The flow and temperature-meter sensors are connected to the control system directly via IO-link technology, without needing a PLC.

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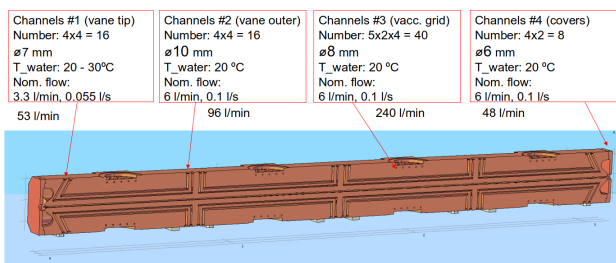


Figure 2: Simplified RFQ model showing the cooling channels distribution and the water flows requirements.

## STABILITY MEASUREMENTS

The cooling skid system was connected to the RFQ as described in Figs. 1 and 3. A SMC chiller has been used, along with IFM and SMC sensors (models PF3W704, PF3W720, and PF3W740) to monitor pressure, temperature, and flow rates. Testing was conducted over a three-hour period at a constant inlet pressure of 6 bar. With the chiller set points ranging from 15 °C to 35 °C. Both temperature and flow rate stability remained within requirements, as illustrated in Fig. 4.

## FREQUENCY MEASUREMENTS

A preliminary characterization of the RFQ frequency response has been carried out with the complete cooling circuit installed. The cavity frequency was measured with a ZVH device and monitored together with EPICS cooling variables. The chiller set point was varied from 20 °C to 30 °C in steps of 1 °C; each step was held long enough for the sys-

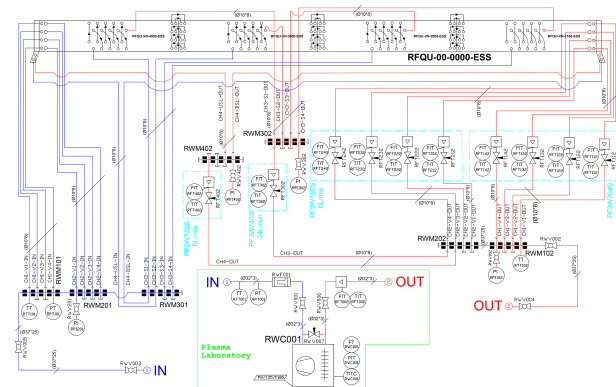


Figure 3: P&ID diagram of the HiCANS-platform RFQ cooling system, including chiller, flow-temperature sensors and channel distribution.

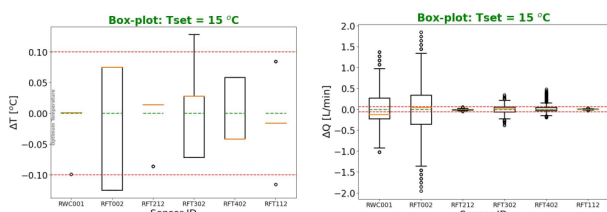


Figure 4: Statistics of the temperature and flow measurements for different sensors during a 3 hours test.

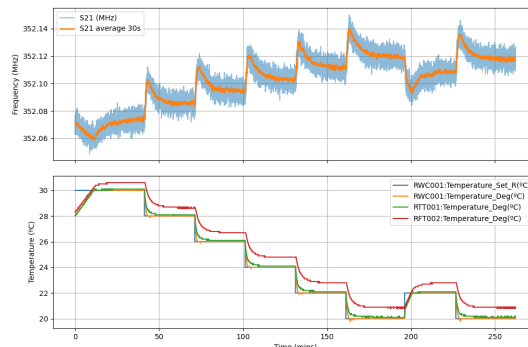


Figure 5: Measured RFQ frequency during a sequence of water-temperature set point changes from 20 °C to 30 °C.

tem to approach steady state. Figure 5 shows a representative sequence. The frequency follows the water-temperature changes with a slow thermal transient and reaches a new quasi-steady state after about 10 min to 15 min.

The steady-state detuning is approximately linear in the measured temperature range. With the present series-connected layout, the measured slope is about  $-4$  kHz/°C. This value is much smaller than the sensitivity expected when the vane-tip channel temperature is changed independently while the other channels remain fixed. In the present configuration all channel families share the same inlet water, with the same temperature, so part of the deformation produced near the vane tips is compensated by the deformation of the external body and lobe region. This thermal compensation is useful for stable operation but reduces the tuning authority of the single-chiller configuration. A second SMC chiller has already been added to the system, to use for high power conditioning if necessary. With two chillers, different water circuits can be used for channels type 1 and for the rest, increasing the frequency-changing performance of the system.

Transient response has also been investigated, as it is the basis for dynamic control. An example is shown in Fig. 7. For a positive temperature step of 3 °C, the chiller outlet

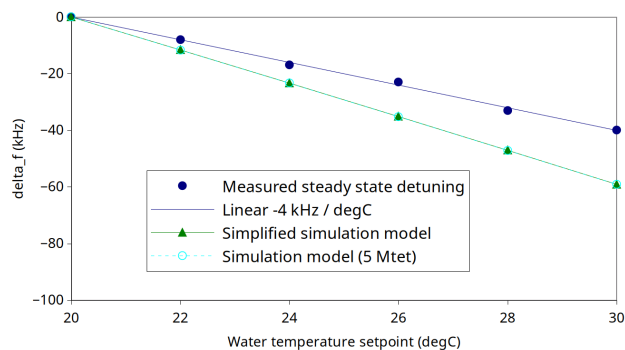


Figure 6: Steady-state frequency shift as a function of water temperature. The measured RFQ slope is about  $-4$  kHz/°C, while a simplified FEM model of the detuning gives about  $-6$  kHz/°C.

temperature increases gradually and the RFQ frequency has an initial overshoot of 40 kHz, until a steady state consistent with the measured steady-state slope is achieved. Cooling transients after a reduction of set point are faster in the absence of RF power, because the chiller removes heat more rapidly than it can heat the full water volume and RFQ copper body. These transient measurements will be fitted to compact response functions for later use in RFQ frequency-control simulations.

## THERMO-MECHANICAL AND RF SIMULATIONS

The frequency measurements were compared with FEM simulations performed with ELCANO. The model represents one longitudinal quarter of the RFQ and couples heat transfer, mechanical deformation and RF eigenfrequency calculations in static and transient regimes. The simulation chain applies the cooling-water temperature as a boundary condition, computes the copper temperature distribution, deforms the RFQ mesh, and finally evaluates the change of eigenfrequency. Figure 8 shows the simplified geometry and the RF mesh used in the calculation. Although not all RFQ geometry details are included (inter-segment deviations, intrinsic deformations, different water temperature or water flow for channels in different quadrants), the agreement is sufficient for a first predictive model and supports the use of this numerical framework to extrapolate the behavior to RF-power conditions.

## IMPLICATIONS FOR RFQ OPERATION

For the first RF power conditioning stage, the measured low sensitivity of the single-chiller configuration is advantageous because small setpoint or flow perturbations will not produce large instantaneous frequency excursions. However, the same compensation that improves passive stability also limits active tuning authority. During operation with higher RF power, thermal detuning and detuning-dependent power deposition will need to be evaluated with the RF field present. The present measurements provide the zero-power baseline for that next step, where independent control of

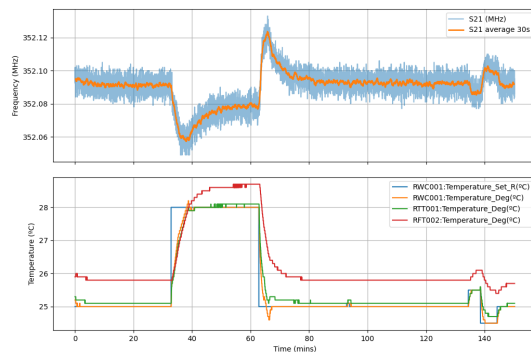


Figure 7: Transient frequency shift for step-up and step-down changes in the chiller temperature set point.

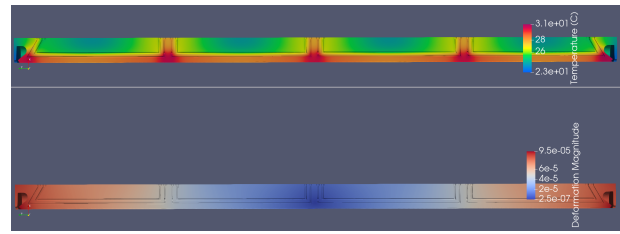


Figure 8: Temperature and deformation maps for the simplified model used for coupled thermal, mechanical and RF frequency calculations.

different channel families, active RF feedback and a refined model will be needed. The present work validates the instrumentation and the modelling procedure needed to build that model.

## CONCLUSIONS

The cooling skid has been installed and tested with the complete RFQ body. Temperature and flow sensors have been integrated into the EPICS monitoring system, and the first zero-power frequency characterization has been performed. The agreement between measurements and simulations provides a validated starting point for RF power conditioning studies. Future work will include measurements with RF power, identification of transient response functions and extension of the control model to higher-duty-cycle operation.

## REFERENCES

- [1] M. Pérez, F. Sordo, I. Bustinduy, J. L. Muñoz, and F. J. Villacorta, “ARGITU compact accelerator neutron source: a unique infrastructure fostering R&D ecosystem in Euskadi”, *Neutron News*, vol. 31, no. 2-4, pp. 19–25, 2020. doi:10.1080/10448632.2020.1819140
- [2] Paulin, Mariano Andrés *et al.*, “The HERMES reflectometer at the JULIC neutron platform”, *EPJ Web Conf.*, vol. 286, p. 03003, 2023. doi:10.1051/epjconf/202328603003
- [3] J. Baggemann *et al.*, “High power target for the high brilliance neutron source”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 1069, p. 169912, 2024. doi:10.1016/j.nima.2024.169912
- [4] I. Bustinduy and J. L. Muñoz, “ESS-Bilbao RFQ Technical Design Report”, ESS-Bilbao, Internal report, 2015.
- [5] J. L. Muñoz, I. Bustinduy, I. Rueda, and D. de Cos, “Development of the radio frequency quadrupole proton linac for ESS-Bilbao”, in *EPJ Web Conf.*, vol. 231, p. 02001, 2020. doi:10.1051/epjconf/202023102001
- [6] J. L. Muñoz, I. Bustinduy, D. Fernandez-Cañoto, and e. a. Garmendia, “ARGITU RFQ bead-pull tuning and RF tests at ESS-Bilbao”, presented at IPAC’26, Deauville, France, May 2026, paper THP4030, this conference.
- [7] J. L. Muñoz *et al.*, “Power couplers conditioning and multipacting simulations for the ESS-Bilbao ARGITU RFQ”, presented at IPAC’26, Deauville, France, May 2026, paper MOP7012, this conference.