FIRST COMMISSIONING RESULTS OF THE NEW 4-ROD RFQ FOR IMPROVED INJECTOR PERFORMANCE AT HIT

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Abstract

The injector linac of HIT (Heidelberg Ion Beam Therapy Centre) has reliably delivered beam for clinical operation over the past years, but the particle transmission of the RFQ has remained below expectations. To reduce overall treatment times and to provide higher particle intensities for the upcoming Multi-Energy Operation (MEO) mode of the synchrotron, HIT and Bevatech developed a new 4-rod RFQ within an innovation partnership. The new RFQ design provides a substantial transmission margin, with a target value of up to 95%. This was achieved by using realistic particle distributions from the LEBT, implementing full dipole-field compensation and integrating a newly designed and substantially shortened internal rebuncher for improved longitudinal matching into the subsequent IH-DTL. In addition, the RFQ components were manufactured with a dimensional accuracy of 50 µm or better, ensuring field symmetry and close correspondence with the simulated field distribution. The new RFQ is currently being commissioned on our dedicated test bench and results from the factory acceptance tests and the initial beam commissioning will be presented.

INTRODUCTION

The Heidelberg Ion Beam Therapy Centre (HIT) has treated cancer patients with carbon and proton beams since 2009 [1]. With the introduction of helium in 2021, the range of routinely applicable ions for clinical operation was further expanded. The core of the medical accelerator system consists of a compact 7 MeV/u injector linac combined with a 6.5 Tm synchrotron, enabling particle acceleration up to 430 MeV/u. The injector linac comprises a 4-rod radio frequency quadrupole (RFQ, exit energy: 400 keV/u) with an integrated rebuncher and an interdigital H-mode drift tube linac (IH-DTL) [2].

While the linac has reliably supported clinical operations for over 15 years, the existing RFQ has consistently acted as a bottleneck in beam transmission. Originally designed for a normalised rms emittance of 0.125 mm·mrad, it cannot fully accept the actual beams delivered by the ECR ion sources, resulting in significant losses within the RFQ and the subsequent intertank section. These limitations constrain the implementation of advanced clinical concepts such as Multi-Energy Operation (MEO), where higher beam intensities are essential to reduce treatment times and improve therapeutic efficiency.

To address these challenges, HIT initiated a collaboration with Bevatech GmbH to develop a next-generation 4-rod RFQ. The new design (Table 1) is optimised for a normalised rms emittance of 0.25 mm·mrad and is based on extensive beam dynamics studies using RFQGen and TraceWin [3], including full end-to-end simulations up to the IH-DTL exit. The design incorporates longitudinal electric field components at the entrance and exit gaps as well as full dipole compensation [4]. Despite the increased electrode length, the shortened internal rebuncher keeps the total length compact at approx. 1480 mm while improving transverse and longitudinal matching into the IH-DTL. Mechanical tolerances of 50 µm or better were specified to ensure field symmetry and alignment with simulated field distributions.

Simulations predict a transmission efficiency of up to 94%, with output beam parameters closely matched to the acceptance of the downstream intertank section and the IH-DTL. The RFQ operates at an electrode voltage of 70 kV and features optimised RF contacts to minimise power losses and maximise shunt impedance.

Table 1: Main parameters of the new 4-rod RFQ

Parameter	Value
Operating frequency	216.816 MHz
Electrode voltage	70 kV
Electrode length	1380 mm
Number of stems	16
Number of RF cells	205
Ion species	C^{4+}, H_3^+, He^{2+}, O^{6+}
Input energy	8 keV/u
Output energy	400 keV/u
Design emittance (norm., rms)	0.25 mm mrad
Transmission (sim.)	~94%

FACTORY ACCEPTANCE TESTS

The design phase of the project was completed in August 2024 [4], after which the construction phase started. Following copper plating and final assembly, the RFQ was prepared at the manufacturer's facility [5] for factory acceptance tests (FAT). A photograph of the RFQ structure is shown in Fig. 1.

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Figure 1: RFQ structure at the manufacturer's facility [5].

Several aspects were verified during the FAT to assess the vacuum, mechanical and RF performance of the RFQ. All tests were successfully completed, and the results are within specification.

Tolerance Verification

The requirement of 50 µm alignment accuracy arises from the relatively high operating frequency for a 4-rod RFQ (216.816 MHz). Together with the low input energy (8 keV/u), this leads to small modulation wavelengths, especially in the first section of the quadrupole channel and to increased sensitivity to mechanical deviations.

To verify the specified tolerances, the electrode positions were measured using a micrometer gauge and the beam axis was derived. Additionally, a novel optical measurement method using a portable 3D coordinate measuring machine was applied. The overall alignment quality is high (Fig. 2). Only a few measurement points exceed the specified tolerance, but by no more than 10 µm.

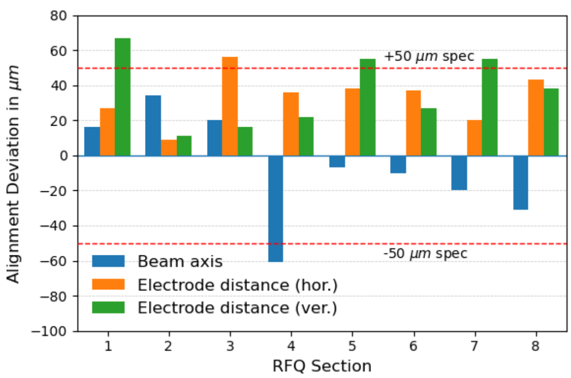

Figure 2: Alignment deviations of the electrodes and beam axis along the quadrupole channel. One section corresponds to two stem spacings.

Field Flatness

The field flatness of the RFQ was evaluated using bead-pull measurements along the 1380 mm long electrodes. Two complementary measurement setups were employed to probe both the field distribution along the electrodes and in the end-gap regions.

For the main measurement, an off-axis bead-pull was performed along the pole tip of the upper electrodes. A cylindrical plastic bead (length 40 mm, diameter 6 mm) mounted on a 0.2 mm wire was moved along the RFQ axis. The induced phase shift was recorded with a vector network analyser. The unperturbed phase served as reference, and the relative voltage deviation $\Delta V/V$ was derived from the measured phase variation. The resulting field profile shows a flatness within $\pm 2.5\%$ over the full length of the structure, fulfilling the design requirements. The final heights of the tuning plates are shown in Fig. 3 in comparison with the initially simulated values, confirming the validity of the RF model.

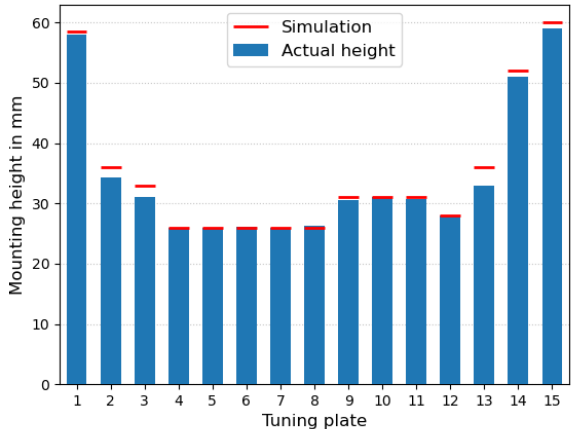

Figure 3: Mounting heights of the tuning plates after field flatness tuning compared to CST Studio simulations [6].

In addition, a second measurement was carried out using a 4 mm plastic sphere to investigate the longitudinal field distribution in the end-gap regions. The bead was moved across the gaps near the RFQ exit. The measured phase variation was significantly smaller ($\approx 3.5°$), as expected for the weaker longitudinal fields in these regions.

The experimental results were compared to CST simulations. A good agreement was found for the second gap, while the first gap showed larger deviations. This is attributed to increased measurement noise and the superposition with quadrupole field components, which complicates the interpretation in this region.

Low-Level RF Measurements

The RFQ tank was designed using CST Studio Suite [6] for a nominal resonance frequency of 216.816 MHz, matching the operational requirements. In addition to the mandatory RF input coupler and tuning plunger, the tank is equipped with three pick-up probes used for measuring the resonance frequency and quality factor. Low-level RF measurements were performed using a vector network analyser.

Measurements of the reflection coefficient (S_{11}) at the input coupler and the transmission coefficients (S_{21}) to the pick-ups showed no unexpected features.

Initial measurements indicated that the resonance frequency needed to be shifted into the controllable range of the tuner. This was achieved by adjusting the outer tuning plates, resulting in a shift towards lower frequencies. After this adjustment, the target resonance frequency was reached within a frequency span of -150 kHz and +524 kHz. The observed asymmetry is favourable, as thermal expansion of the tank during operation is known to lower the resonance frequency.

The reflection coefficient (S_{11}) around the resonance frequency after final tuning was measured. The resonance is located at 216.816 MHz with a return loss of approximately -30 dB, indicating good matching of the input coupler. No parasitic modes are observed in the investigated frequency range.

After optimisation of the electrical contact between the outer stems and the end walls of the tank, a loaded quality factor of Q_L = 1750 was measured. This value is consistent with expectations, taking into account the presence of the input coupler. A summary of the final RF parameters is given in Table 2.

The tank was RF conditioned up to 180 kW within less than one week. Multipactor resonances were observed at RF power levels up to 90 kW. At higher power levels, RF trips occurred only rarely, indicating clean and smooth copper surfaces inside the tank.

Table 2: Final RF parameters of the RFQ from low-level RF measurements and CST simulations

Parameter	Value
Tuner frequency range	216.67–217.34 MHz
Tuner position at 216.816 MHz	~19 mm
Q_0 (unloaded, simulated)	5350
Q_0 (unloaded, measured)	4050–4350
Q_L (loaded, measured)	1750
Shunt impedance (simulated)	33.6 kΩ
Expected RF power loss	146 kW
Coupling factor (pick-ups 1–3)	-50 dB

FIRST BEAM COMMISSIONING

The RFQ was delivered to HIT at the end of March. It was installed and aligned at the dedicated on-site RFQ test bench shown in Fig. 4, which had already been used previously for RFQ qualification measurements. Besides the RFQ itself, the main components are an ECR ion source (Supernanogan [7]), a LEBT including a spectrometer dipole, a triplet, a macro-pulse chopper and a solenoid. Downstream of the RFQ, a ToF line equipped with capacitive phase probes is used for beam energy measurements as well as beam profile and current diagnostics.

During a first commissioning run in May 2026, a 500 µAH_3^+ beam (measured with the analyser cup) was successfully bunched and accelerated through the RFQ and the beam profile was measured 680 mm downstream of the structure using a profile grid (Fig. 5). Further optimisation of the operating parameters is still required. At the present stage of commissioning, no quantitative statement on the transmission can yet be made.

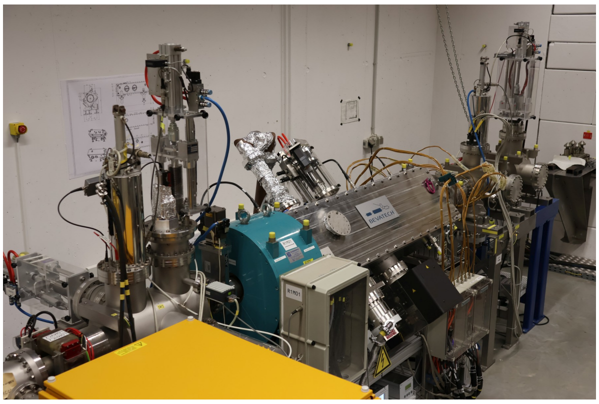

Figure 4: Downstream section of the HIT RFQ test bench with diagnostic chamber, solenoid, RFQ and ToF line.

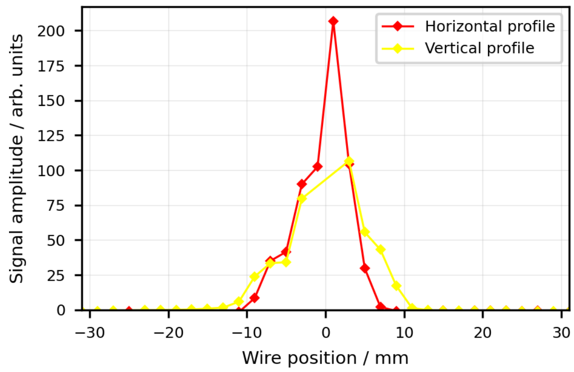

Figure 5: First H_3^+ beam profile measured 680 mm downstream of the RFQ.

CONCLUSION AND OUTLOOK

In collaboration with our industrial partner Bevatech GmbH, a new 4-rod RFQ has been designed and manufactured for the medical treatment facility HIT in Heidelberg. By applying state-of-the-art techniques in design, fabrication and alignment, excellent RF performance has been achieved, with a predicted particle transmission significantly exceeding that of the existing RFQ. The intrinsic limitations of the 4-rod RFQ concept, such as dipole field components and mechanical sensitivity, have been significantly reduced by modern design and manufacturing techniques, enabling efficient operation with improved beam transmission at frequencies above 200 MHz [4, 8].

The RFQ is now ready for detailed measurements of the operating curves for the relevant ion species at our dedicated test bench. These measurements will define the working points and help reduce commissioning time in the accelerator. Installation and commissioning of the RFQ in the linac are planned for the turn of 2026 to 2027.

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