HIGH POWER CONDITIONING AND FIRST 2 MEV BEAM RESULTS OF THE COUPLED RFQ-IH-DTL FOR FRANZ

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Abstract

The Frankfurt Neutron Source FRANZ is a compact-accelerator driven neutron source based on the $^7Li(p,n)^7Be$ reaction using a 2 MeV proton beam. Following successful stand-alone RF conditioning of the IH-DTL up to 10 kW cw, the coupled RFQ-IH-DTL cavity was assembled, tuned and conditioned up to 200 kW. First beam experiments have been performed, demonstrating proton acceleration to 2 MeV. We report on the high-power conditioning, coupling and LLRF tuning procedure, as well as initial beam commissioning results.

INTRODUCTION

The Frankfurt Neutron Source (FRANZ) is a compact accelerator driven facility originally initiated in the early 2000s [1–6]. It is designed to provide a 2 MeV proton beam for neutron production via the $^7\mathrm{Li}(p,n)^7\mathrm{Be}$ reaction [7]. The produced neutrons with a kinetic energy around 30 keV can be used for a number of experiments in the fields of applied physics and experimental astrophysics [8].

Beam Commissioning Progress

Significant progress on the driver linac was made in recent years. The commissioning of the new CHORDIS ion source [9, 10] in late 2020 was a first milestone. Since the CHORDIS ion source only provides a 35 keV proton beam, an electrostatic post-accelerator was developed and commissioned at IAP to reach the desired beam energy of 60 keV [11]. After stable operation was confirmed, the Low Energy Beam Transport line (LEBT) was commissioned and the 60 keV beam was transported up to the point of injection into the RFQ in late 2021. Following a redesign of the RFQ electrodes for 60 keV [12, 13], new electrodes were delivered and mounted in the RFQ in summer 2023. The RFQ was then tuned, conditioned and commissioned with a 10 mA proton beam until the end of 2023. Emittance measurements and bunch shape measurements of the 700 keV proton beam behind the RFQ followed in 2024, reporting a RFQ transmission of 92.7 % [14, 15]. In 2025, the RFQ and IH-DTL were combined to form a coupled RFQ-IH-DTL cavity. The cavity was commissioned with beam in late 2025 with a measured beam energy of 1.9 MeV. The results of the cavity tuning and beam commissioning are reported here.

The Coupled RFQ-IH-DTL

To reduce space requirements and save the need for a second high power amplifier, the FRANZ main accelerator cavity was designed as a coupled RFQ-IH-DTL which consists of a 700 keV four-rod RFQ and a short 1.3 MV IH-DTL with an internal triplet lens [6]. The cavities are coupled inductively by a large coupling flange at the meeting point of the two cavities (see Fig. 1). Due to this fixed coupling, the RF phase between RFQ and IH-DTL is locked and had to be carefully considered during the RFQ beam dynamics design to ensure the correct phase relation between the last cell in the RFQ and the first gap in the IH-DTL. Due to this setup, the voltage ratio between the IH-DTL and the vane-vane voltage of the RFQ is directly dependent on the coupling strength between the two cavities. After the redesign of the RFQ for 60 keV, the ideal ratio was calculated to be

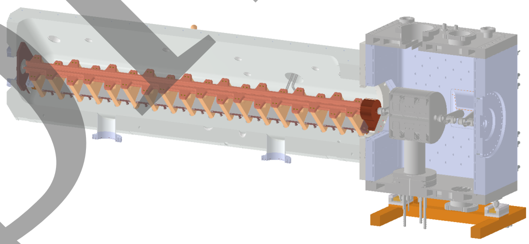

Figure 1: CAD cross-section of the coupled RFQ-IH-DTL cavity. The RFQ is on the left side and the IH-DTL with an internal quadrupole triplet lens is coupled to it on the right.

$$\frac{U_{0,IH}}{U_{RFQ}} = \frac{2.06\,\mathrm{MV}}{60\,\mathrm{kV}} = 34.34 \tag{1}$$

to match the beam dynamics simulated. To reach this ratio, both cavities have to be tuned to a frequency close to the common frequency of 175 MHz so that the correct coupling is achieved [6]. In practice, this tuning was only possible with an extensive bead pull measurement campaign.

BEAD PULL MEASUREMENTS

In contrast to typical bead pull measurements for single cavities, where usually only the relative voltage distribution withing the cavity is of interest, for the coupled RFQ-IH-DTL, two calibrated bead pull measurements are required. The RFQ vane-vane voltage U_{RFQ} is measured perpendicular to the RFQ vanes. To ensure a homogeneous field

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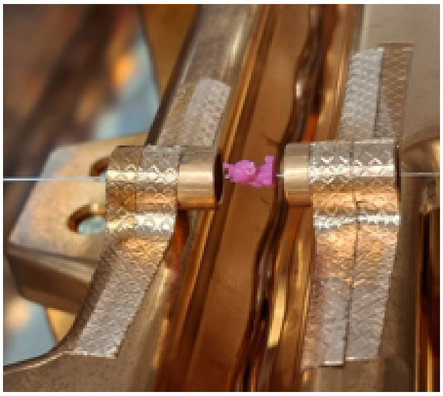

Figure 2: Copper tubes on top of the RFQ electrodes for the measurement of the vane-vane voltage.

distribution for this measurement, temporary copper tubes were attached to the top RFQ vanes with conductive copper tape (see Fig. 2). This way, a well defined gap voltage, which in good approximation is equal to the RFQ vane-vane voltage, can be measured. The IH-DTL voltage distribution is measured on the beam axis as usual.

To be able to calculate a voltage ratio between the two measurements, there are basically two possible strategies: (A) both measurements are performed with the same or sufficiently identical beads. (B) the bead constants need to be known for both measurements. Since the RFQ voltage is much lower in comparison to even the smallest gap voltage in the IH-DTL, strategy (B) was chosen to be able to tune the bead characteristics for each measurement. The bead constants were measured in a well known cavity (MYRRHA CH2) in combination with CST simulations of that cavity.

The voltage ratio was tuned by changing the RFQ tuning plate heights of the last two tuning plates to adjust the RFQ resonance frequency while using the IH-DTL plunger tuner to readjust the RFQ-IH-DTL resonance frequency to 175 MHz. This way, the coupling between the two cavities was adjusted until the desired voltage ratio was reached. The analysis was performed with UNICORN, a python based bead pull analysis tool currently in development. One of the final bead pull measurements is shown in Fig. 3, where both the IH-DTL and the RFQ measurements with the corresponding integration boundaries for voltage calculation are shown. Figure 4 shows the RFQ and IH-DTL plunger tuner positions for different voltage ratios after final tuning of the cavities.

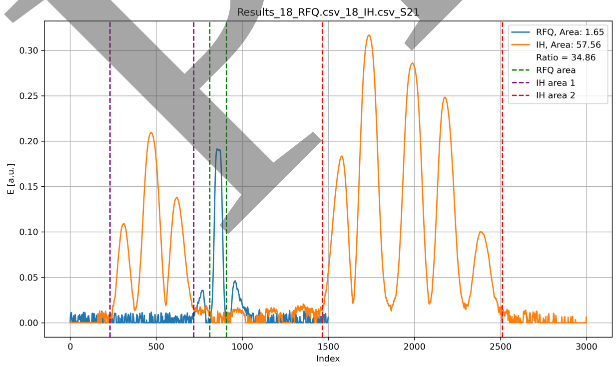

Figure 3: Bead pull measurement data for IH-DTL (orange line) and RFQ (blue line) at a voltage ratio of $U_{0,IH}/U_{RFQ} = 34.8$. The integration boundaries for voltage calculation are marked by the dashed lines.

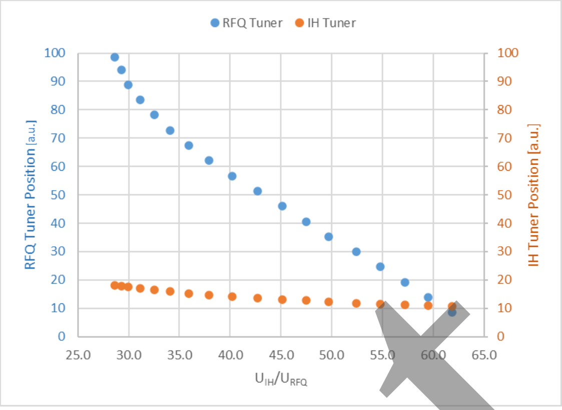

Figure 4: RFQ and IH-DTL tuner positions for different voltage ratios U_{IH}/U_{RFQ} at a fixed operation frequency of 175 MHz.

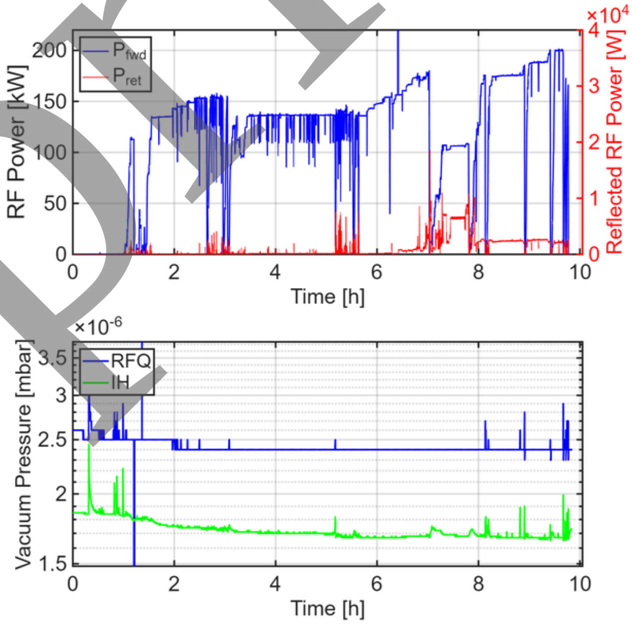

Figure 5: Plot of RFQ-IH-DTL conditioning data from 2 Dec 2026, reaching a forward power of 200 kW in preparation for beam commissioning.

HIGH POWER CONDITIONING

After the RF tuning of the cavities was finalized, the combined RFQ-IH-DTL cavity was attached to the main amplifier (Thomson 250 KW tube amplifier) via rigid coaxial lines. LLRF control and overall accelerator control are achieved with in-house developed hardware and control system software [16, 17]. Over the course of about six weeks (Oct to Dec), the cavity was gradually conditioned up to 200 kW. At lower powers up to about 30 kW, conditioning was performed at 100 % duty cycle to reduce the conditioning time.

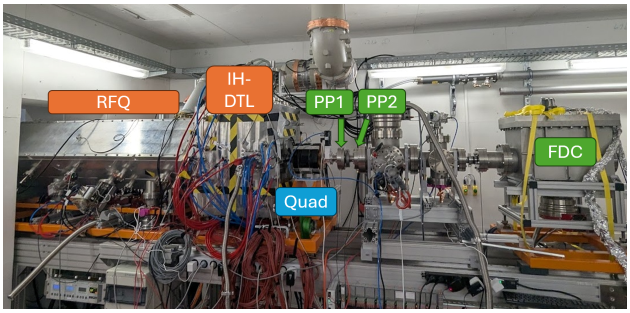

Figure 6: The FRANZ beamline for first 2 MeV measurements. Phase probes positions (PP1 and PP2) are marked as well as the Faraday Cup beam dump (FDC).

Multipacting was mostly observed at powers below 500 W (see [18]). For higher powers, the duty cycle was gradually reduced to reduce the impact of thermal effects on cavity operation. The final conditioning power was sustained at 2 % duty cycle (see Fig. 5), sufficient for beam operation at an ion source duty cycle of 1 % as the standard operating parameters for the CHORDIS ion source at FRANZ. For 2 MeV beam operation, a power requirement of about 165 kW was estimated, which was later confirmed by beam measurements.

BEAM ENERGY MEASUREMENTS

Following the successful conditioning of the cavity with sufficient overhead, the beamline was set up for first beam commissioning measurements. For these first measurements, a short beam diagnostics section was set up (see Fig. 6) [19]. The section consists of a quadrupole triplet lens directly behind the IH-DTL exit, two phase probes, diagnostics chambers with screen and camera diagnostics and finally a Faraday Cup beam dump for current measurements.

An example of the measurement signals for beam energy and beam current is shown in Fig. 7. The phase difference between the two phase probes was measured with a Analog Devices AD8302 phase detector connected to the two phase probes. The beam energy was then calculated from the drift between the two phase probes. After first successful beam measurements in Dec 2025 confirming successful acceleration, a dedicated measurement campaign for the beam energy was carried out in the beginning of March 2026, where a wide range of RF power settings and RFQ tuner positions were investigated (see Fig. 8). The corresponding beam currents for that measurement are shown in Fig. 9. The resulting maximum beam energy measured is 1.905 MeV at a forward power of $P_F = 195$ kW, whereas a more stable operating point with the highest beam current is found at 1.89 MeV at a forward power of $P_F = 165$ kW.


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Diagram1: Ch1,Ch2,Ch3,Ch4

Meas Res
Meas 1
Amplitude 5.6917 V
Max 6.0016 V
Meas 2
Max 6.0016 V

V1 -6.3 mV
V2 6.0016 V
ΔV 6.0079 V
☑ Track waveform

V1 334.98 mV
V2 1.46109 V
ΔV 1.12611 V
☑ Track waveform

Horizontal
Res: 4 ns / 250 MSa/s
RL: 1 MSa RT
Scl: 400 µs/div
Pos: 136 µs
Trigger Normal
A: Analog edge
Lvl: 1.2 V

Ch1Wfm1
Pos: 0.04 div
Off: 0 V
Scl: 400 mV/div
Cpl: DC 1MΩ
Dec:High | TA: Off
Bw: Full

Ch2Wfm1
Pos: -2 div
Off: 800 mV
Scl: 1 V/div
Cpl: DC 1MΩ
Dec:Sa | TA: Off
Bw: 5 MHz

Ch3Wfm1
Pos: -4 div
Off: 0 V
Scl: 2 V/div
Cpl: DC 1MΩ
Dec:Sa | TA: Off
Bw: Full

Ch4Wfm1
Pos: -4.06 div
Off: 0 V
Scl: 1 V/div
Cpl: DC 1MΩ
Dec:Sa | TA: Off
Bw: Full

Figure 7: Phase probe (yellow) and FDC signal (green) of the 1.9 MeV beam behind the RFQ-IH-DTL from measurements on 3 March 2026 with a peak current of 6 mA.

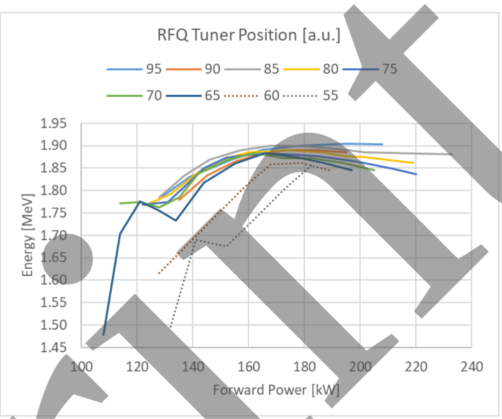

Figure 8: Proton beam energy measured at forward powers between 102 kW and 233 kW for different RFQ tuner positions (which corresponds to different $U_{0,IH}/U_{RFQ}$). The dashed lines indicate measurements with too little RFQ voltage due to a very high voltage ratio.

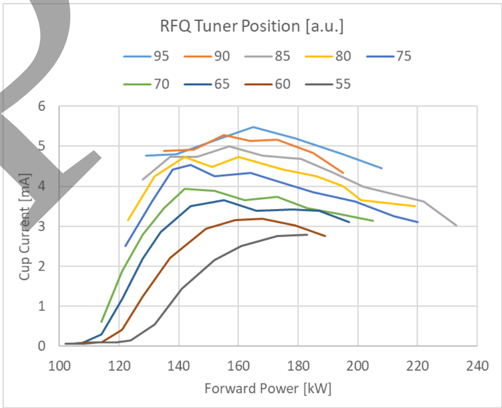

Figure 9: Proton beam current measured at forward powers between 102 kW and 233 kW for different RFQ tuner positions (which corresponds to different $U_{0,IH}/U_{RFQ}$).

CONCLUSION

Beam commissioning at the Frankfurt Neutron Source up to 1.9 MeV was successfully performed and beam currents up to 6 mA have been measured. This marks an important milestone as the FRANZ accelerator now provides a high current proton beam sufficient to produce neutrons with a neutron target. Currently, the beamline is being prepared for pulse shape measurements and emittance measurements. First neutron experiments are contingent on authorization by radiation safety authorities, the process is ongoing.

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