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# CURRENT STATUS OF BEAM COMMISSIONING AT THE FRANKFURT NEUTRON SOURCE

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*Abstract*

The Frankfurt Neutron Source FRANZ will be a compact accelerator driven neutron source utilizing the $^7\mathrm{Li}(p,n)^7\mathrm{Be}$ reaction with a 2 MeV proton beam. The 700 keV RFQ has been sucessfully commissioned with a 10 mA proton beam. Conditioning of the subsequent IH-type cavity has been performed up to 10 kW CW. We also report on RFQ emittance measurements performed with a slit grid emittance device. In addition, a fast faraday cup (FFC) was used for bunch shape measurements behind the RFQ.

## 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 thermal spectrum 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 recently. 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-Accelerator end of 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 %.

### *Preparations for* 2 MeV

Radiation safety preparations for 2 MeV beam and neutron operation are under way and will be finished within 2025. A total of six neutron/gamma detectors has been acquired and will be mounted at critical spots around the experimental hall. First activation experiments are planned to be set up on the beamline, once radiation safety regulations are fulfilled.

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## 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 internal triplet lens. 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. Tuning the voltage ratio between RFQ and IH-DTL is the next crucial step towards 2 MeV commissioning.

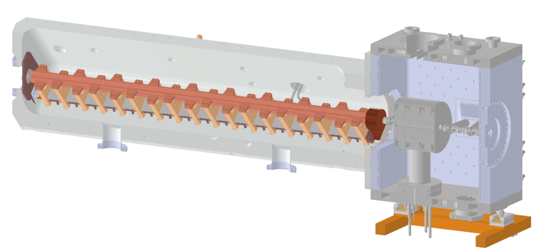

Figure 1: CAD cross-section of the coupled RFQ-IH-DTL cavity. The RFQ is on the left side and the IH-DTL with an internal quadrupole triplet lens is coupled to it on the right.

## RFQ EMITTANCE MEASUREMENTS

In 2024, a series of emittance measurements was performed after the successful commissioning of the 700 keV RFQ beam. A slit-grid emittance measurement device was positioned so that the slit was 705.5 mm behind the RFQ inner wall (see Fig. 2). Due to limited availability of the ion source during the emittance measurement campaign, the measurements were concentrated on measuring the x-plane (horizontal) with only sporadic crosschecks of the y-plane.

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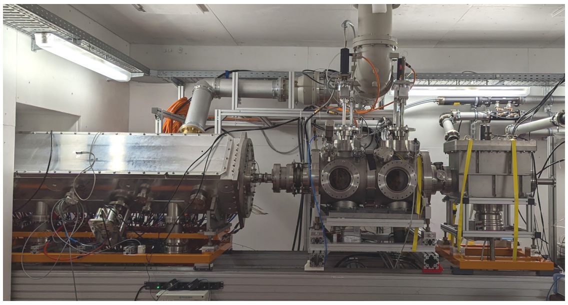

Figure 2: Experimental setup for the emittance measurement behind the FRANZ RFQ. Left to right: RFQ, slit-grid device, beam dump (FDC).

TraceWin/Toutatis simulations of the RFQ and the drift section between the RFQ and slit of the emittance measurement device were performed to compare with emittance measurements. The beam space charge was assumed to be fully compensated for the drift section.

During measurements, several injection settings and RFQ power settings were investigated. Nominal power for stable RFQ operation is known to be 68 kW from commissioning measurements of the RFQ [14] which corresponds to a vane-vane voltage of 60 kV. Overall, the measured emittances as well as the beam orientation in both planes matched well with predictions from the beam dynamics simulations. Due to limited resolution of the measurements, rms emittances could not be reliably calculated from the measurements. However, normalized emittances obtained from measured beam profiles after reduction of noise background retain enough information for evaluation of the RFQ performance and implications of IH-DTL transmission. Since the agreement between measurement and simulations was satisfactory, no issues stemming from a possible mismatch between RFQ and IH are expected for 2 MeV operation.

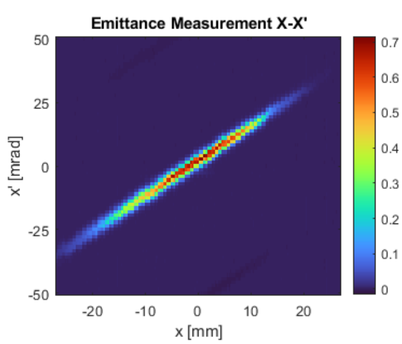


Figure 3: Emittance measurement of the x-x'-plane at RFQ power of $P_T = 72$ kW. Total emittance measured after background cutoff is $\epsilon_{x,n} = 2.53$ mm mrad.

An example for an emittance measurement of the x-plane at 72 kW RFQ power is shown in Fig. 3. The resulting total normalized emittance of this measurement is $\epsilon_{x,n} = 2.53$ mm mrad. The corresponding simulation shown in Fig. 4 has a 99 % emittance of $\epsilon_{n,99\%} = 3.42$ mm mrad with an rms emittance of $\epsilon_{n,rms} = 0.31$ mm mrad. With this result, we feel confident, that the RFQ beam stays well within the acceptance of the subsequent IH-DTL.

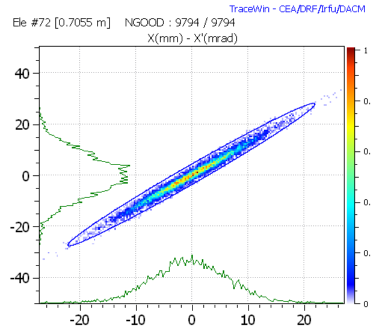


Figure 4: TraceWin/Toutatis simulation of the RFQ beam at nominal operation at the location of emittance measurement. 99 % emittance is $\epsilon_{n,99\%} = 3.42$ mm mrad with an rms emittance of $\epsilon_{n,rms} = 0.31$ mm mrad.

## RFQ BUNCH SHAPE MEASUREMENTS

To validate the longitudinal beam dynamics of the RFQ, dedicated measurements of the bunch shape were performed using a Fast Faraday Cup (FFC) from GSI [15] (a tapered radially coupled variant was used). The FFC was positioned 40 cm behind the RFQ (which was as close as possible) to get sufficiently short bunches for the measurement. The expected bunch shape at the FFC position was simulated with TraceWin based on the RFQ output distribution for comparison. RF interference from the RFQ (175 MHz, 68 kW) had to be suppressed by the use of an additional 5 mm diameter aperture inserted at the RFQ exit.

Bunch shape measurements with the FFC were able to resolve the full bunch shape of the RFQ beam with a measured bunch length of 1.12 ns FWHM (see Fig. 5), which is sufficiently close to the value of 1.17 ns FWHM from TraceWin/Toutatis simulations for the RFQ beam at the FFC position under ideal conditions.

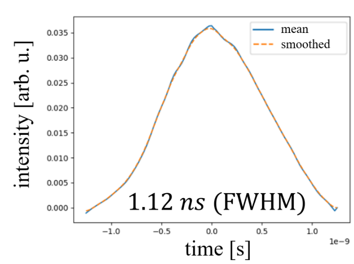


Figure 5: Measured bunch length when evaluated averaged over multiple bunches.

## IH-DTL RF CONDITIONING AND POWER TEST

For LLRF control, in-house custom digital hardware was used. The control system for FRANZ called MNDACS was

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used for RF conditioning of the FRANZ IH-DTL as well. For more details on the software and hardware see [16, 17].

### IH-DTL Coupling

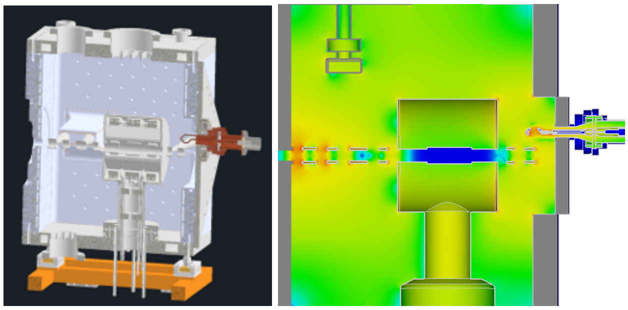

Figure 6: Coupler position (left) and B-field simulated for critical coupling of the IH-DTL (right).

Since the FRANZ IH-DTL was designed to function as part of the coupled RFQ-IH-DTL, where the RF is coupled with a single coupling loop in the RFQ, the IH-DTL has no dedicated flange available for a coupling loop. To overcome this issue, a solution was found by using a very compact 3D printed coupler (see [18]) on the temporary lid on the cavity side port (for RFQ-IH connection). It was found in simulation, that efficient coupling is possible close to the drifttubes (see Fig. 6). Coupling was calculated to allow for a coupling factor of $\beta > 1.5$ to be able to adjust for critical coupling $\beta = 1$ by loop rotation. Final coupling loop orientation was close to the simulated position for $\beta = 1$ within a few degrees. As the cavity was designed and tuned for a resonance frequency of 175 MHz taking into account the steerer body at the entrance of the RFQ, the current configuration with a temporary lid and no steerer body in front of the first drift tube leads to a slightly higher resonance frequency around 176.9 MHz during standalone conditioning.

### IH-DTL Conditioning

For the first conditioning stage, a 500 W CW broadband amplifier was used. Low power conditioning with the small broadband amplifier was done within about 3 days in December 2024, reaching up to 500 W CW. Water cooling was not active for this low power conditioning. Multipacting barriers were observed at powers of 4 – 10 W and (more significantly) around 200 – 300 W. Otherwise, conditioning up to 500 W was uneventful and dominated by rf heating of the cavity and corresponding outgassing leading to a rise in vacuum pressure.

Once the power limit of the small amplifier was reached, the cavity was connected to a Bruker solid-state amplifier, capable of up to 12 kW CW at 175 MHz with a circulator between amplifier and cavity. High power conditioning required about eight days to reach a forward power of 10 kW CW. Above 11 kW, the amplifier shut off consistently, which may be due to the 1.1 % higher resonance frequency of the standalone IH-DTL leading to a slight mismatch in the circulator.

### IH-DTL High Power Test

Finally, after conditioning, the IH-DTL was tested at 10 kW CW for over six hours to confirm the operational stability for FRANZ beam operation in the coming years (see Fig. 7). During this long term test, the cavity temperatures and vacuum pressure were stable and reflected power was also quite stable with exception of one event just before hour 2, where the LLRF control had to shortly interrupt power due to a breakdown event. All in all, the cavity proved capable of sustained operation at 10 kW CW. While the cavity was designed for 60 kW CW operation, operational parameters for FRANZ operations are limited to a duty cycle of < 5 % with the current regulatory limits of $1 \times 10^{12}$ neutrons/s. Operation at maximum allowed duty cycle in this operation mode will amount to an average power load of just 3 kW for the IH-DTL. Higher RF duty factors are expected to become important in a later stage of FRANZ operation with high macro-pulse rates.

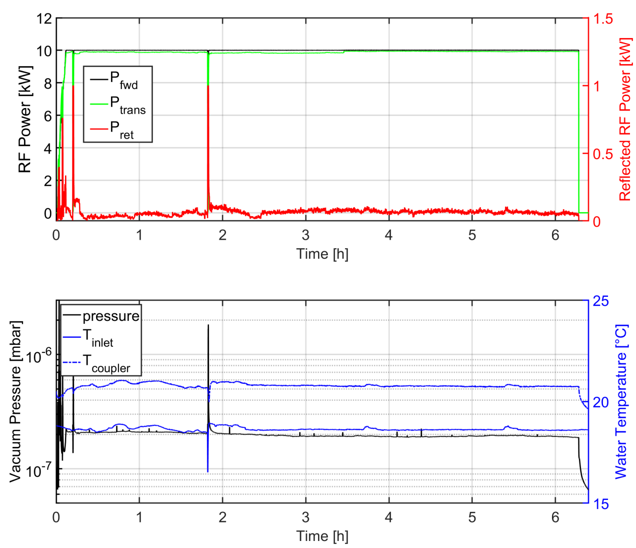


Figure 7: Top: Power plots of final long term CW power test for the FRANZ IH-DTL at $P_f = 10$ kW. Bottom: Cavity vacuum pressure and coupler temperature during long term test indicating stable operation at 10 kW CW.

## CONCLUSION

Beam commissioning at the Frankfurt Neutron Source up to 700 keV was successfully performed and a transmission of 92.7 % was measured for the RFQ. Emittance measurements behind the RFQ agree well with predictions from beam dynamics simulations. RF conditioning of the IH-DTL was finished up to 10 kW CW. Currently, the beamline is being prepared for 2 MeV operation, combining the RFQ and IH-DTL to their coupled state. Tuning of the RFQ-IH-DTL is currently ongoing and RF conditioning is scheduled for summer of 2025. 2 MeV beam operation is planned for the end of 2025 in conjunction with first neutron experiments.

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