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UPGRADE AND COMMISSIONING OF THE 60 KEV LOW ENERGY BEAM TRANSPORT LINE FOR THE FRANKFURT NEUTRON SOURCE FRANZ

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Abstract

The Low Energy Beam Transport line (LEBT) for the Frankfurt Neutron Source (FRANZ) has been redesigned to accommodate a 60 keV proton beam. Driven by a CHORDIS ion source, operating at 35 kV, a newly designed electrostatic postaccelerator has beeen installed to reach the desired beam energy of 60 keV. Additional upgrades to the beamline include two steerer pairs, several optical diagnostics sections and an additional faraday cup. We present the results of beam commissioning up to the point of RFQ injection. Emittance measurements were performed to prepare matching to the RFQ and improve the beam dynamics model of the low energy beamline. Due to the successful operation of the beamline at 60 keV, retrofitting of the RFQ for the new energy has been initiated.

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].

Figure 1: Photograph of the current FRANZ LEBT beamline (Aug. 2022).

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. After stable operation was confirmed, the Low Energy Beam Transport line (LEBT), see Fig. 1, was commissioned and the beam was transported up to the point of injection into the RFQ-Accelerator. This presents an important milestone for the initial beam commissioning of the FRANZ facility. Meanwhile, emittance measurements to further improve an efficient injection into the RFQ are well under way. We will present the recent progress since ca. 2019 and show a path to operation for first experiments with neutrons within the next two years.

RECENT DEVELOPMENTS

In recent years, the FRANZ project faced some delays in commissioning. Failure to reach the designated RFQ injection energy of 120 keV with protons posed a significant hurdle for the project. As a consequence, the RFQ injection energy was reduced to 60 keV, necessitating a redesign of the RFQ electrodes, as well as the desire to acquire a reliable ion source for operation. A turning point was reached, when the decision landed on the well known CHORDIS ion source which was provided to IAP by GSI Darmstadt. Since then, several adjustments and upgrades to the high voltage terminal and LEBT have been made.

CHORDIS Ion Source

The CHORDIS ion source is a filament driven volume type ion source [9, 10] (see Fig. 2). Plasma confinement is realized with a permanent magnet multi-cusp field. When operated with hydrogen gas at an extraction voltage of 35 kV, the CHORDIS produces up to 60 mA of total beam current with a proton fraction of typically 45 %, the rest being H_2^+ and H_3^+.

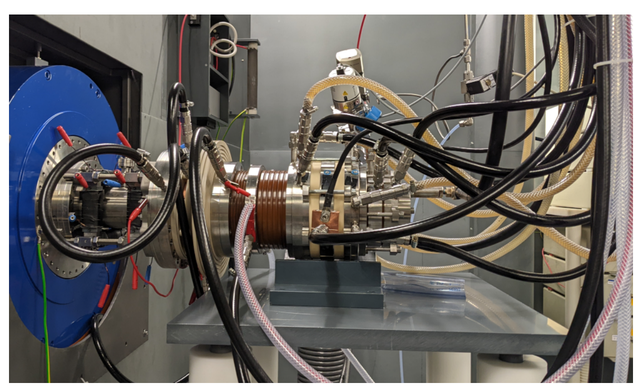

Figure 2: CHORDIS ion source mounted at the FRANZ high voltage terminal complete with electrostatic post-accelerator and steerer pair. The first solenoid of the LEBT can be seen on the left side (blue casing).

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The CHORDIS ion source was commissioned at the FRANZ terminal in August to November of 2020 and has worked reliably since then. While maximum beam currents of up to 60 mA were reached during initial commissioning and first experiments, a more moderate operation mode at 30 mA was used for most of the beam commissioning of the LEBT and will also be used for first experiments with the RFQ in 2023. The ion source is operated in pulsed operation, currently at 10 Hz with a pulse lenght of 500 µs to 1 ms.

Steerers

The original LEBT for FRANZ relied on a mechanical adjustment mechanism to adjust the center position and tilt of the ion source. No additional steerers were installed. This system was replaced by two pairs of xy-steerers to account for mechanical requirements of the new ion source+post-accelerator concept and to provide a more flexible beam adjustment system. The first steerer pair is positioned behind the ion source and post-acccelerator to allow for corrections of the beam immediately after extraction. To ensure efficient injection into the RFQ, an additional steerer pair was installed in front of the last LEBT solenoid.

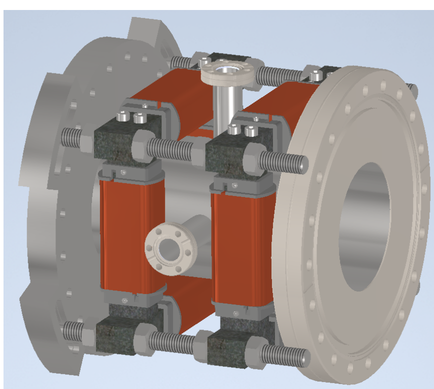

Figure 3: CAD Layout of the newly developed steerer pair with beam pipe.

These steerers were designed and manufactured in house at IAP in 2021 (see Fig. 3). Using a 1.8 mm diameter copper wire with 120 windings per coil, each steerer can produce up to 23 mT, yielding an effective 2.5 mTm. For a 60 keV proton beam, that corresponds to a deflection of up to 66 mrad, which is much more than would realistically be needed in any situation predicted for the LEBT.

Electrostatic Post-Accelerator

To reach the desired proton beam energy of 60 keV, an additional electrostatic post-accelerator was needed, as the CHORDIS is only designed for 35 kV. The post-accelerator was also designed and manufactured in-house at IAP from 2020 to 2021 [11]. The design consists of a wide acceleration gap and an additional screening electrode, that is shielded on both sides by ground electrodes (see Fig. 4).

In July 2021, the post-accelerator was mounted to the beamline and tested to hold 60 kV in the acceleration gap

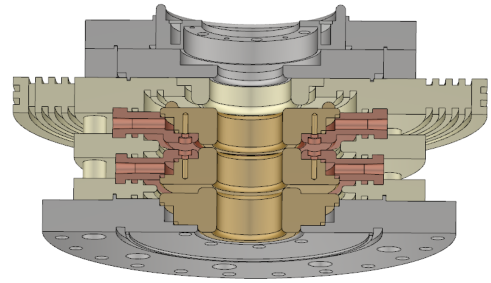

Figure 4: CAD Layout of the newly developed electrostatic post-accelerator. Beam direction is from top to bottom.

with no issues. During operation, an effective potential difference of 25 kV is needed in the acceleration gap. Allowing for higher stable voltages in the gap helps to prevent a cascade event in case of high voltage breakdown in the extraction system of the ion source. Beam operation with the post-accelerator resulting in a total proton beam energy of 60 keV has been successfully commissioned in October 2021.

RF Amplifier Conditioning

Using the FRANZ RFQ prototype cavity [2], the main 250 kW 175 MHz rf amplifier for the FRANZ linac has been conditioned up to 60 kW in continuous wave operation [12].

Control System Software

A new control system software was developed during the commissioning phase. This new control system is based on Java, ZeroMQ and REST, providing efficient data collection and a versatile driver system and web interface [13].

BEAM COMMISSIONING

Beam commissioning of the FRANZ LEBT started in mid 2020 despite the obvious challenges presented at that time. The commissioning can be summarized by the following milestones:

- 11/2020: First 35 keV proton beam.
- 10/2021: Fist 60 keV proton beam.
- 11/2021: 60 keV emittance measurement.

After the operation of the CHORDIS ion source in combination with the post-accelerator has proven stable in several experiments and continuous operation, the final design and ordering of the RFQ electrodes could be completed in 2022. A delivery of the RFQ with new electrodes is expected in late 2022. Following rf conditioning of the RFQ, beam commissioning with a final proton energy of 700 keV is planned. Upon success, the IH-DTL will be mounted and commissioning of the RFQ-IH-DTL combination [6] will be started. We are optimistic to get to the final energy of 2 MeV in 2024.

Optical Beam Diagnostics

As part of the recent commissioning efforts, additional diagnostics were desired to enable an improved beam dynamics model of the LEBT. To this end, a total of six camera

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modules were mounted into vacuum in the diagnostics tank (D1) behind the first solenoid of the LEBT [14]. Using these cameras, the beam induced fluorescence (BIF) of the residual gas in the chamber can be observed (see Fig. 5). This can be very useful to calibrate beam dynamics simulations using envelope matching with these optical beam measurements.

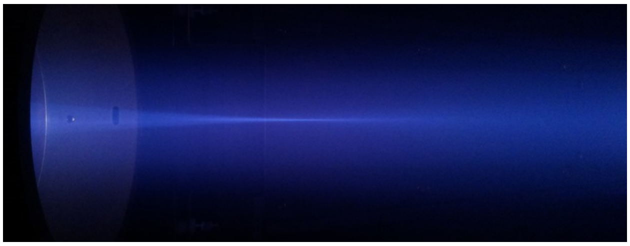

Figure 5: BIF of a 60 keV beam, focusing the proton fraction using the first solenoid, measured in D1.

Additional experiments for optical beam tomography were performed with a system containing ten in-vacuum cameras directly in front of the emittance measurement device behind the LEBT [15, 16].

Beam Dynamics Benchmark

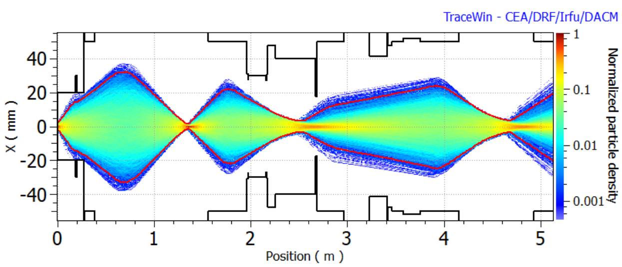

Figure 6: Transverse beam envelope of the proton beam for benchmark LEBT settings.

A beam dynamics model for the FRANZ LEBT was developed using the TraceWin beam dynamics code [17]. To get a model representing the beamline as close as possible, the solenoids were modeled using CST fieldmaps, that were scaled to the initial field measurements of the solenoids. The beam dynamics model was first calibrated using reasonable assumptions for the ion source beam parameters. In the following, the model was refined by matching the measured BIF in D1 with simulated beam envelopes for all three fractions (p, H_2^+ and H_3^+) by adjusting the input beam parameters in the simulation.

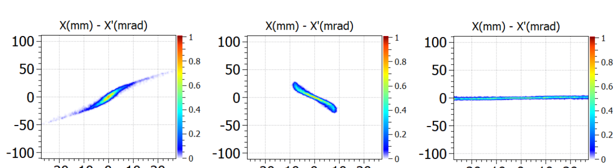

Figure 7: Simulated horizontal phase space particle distribution for comparison with emittance measurement. (left to right): protons, H_2^+ and H_3^+.

The resulting matched beam dynamics model can replicate the beam envelopes for a wide range of solenoid currents for all three fractions. This model was then used to select LEBT settings to benchmark the simulation with emittance measurements at the end of the LEBT. The simulated horizontal beam envelope for one of these settings is shown in Fig. 6. This setting was chosen based on the desire to eliminate as many H_2^+ and H_3^+ ions during beam transport in the LEBT. As a result, while in simulation 98 % of protons are transmitted, only 58 % H_2^+ and 6 % H_3^+ reach the emittance measurement device. The simulated horizontal particle distributions at the position of the emittance measurement are shown in Fig. 7.

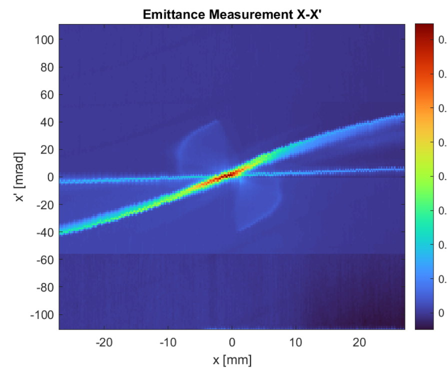

Figure 8: Measured transverse horizontal phase space for a 60 keV beam, based on simulated beam line settings as a benchmark.

A corresponding emittance measurement with the same solenoid settings is shown in Fig. 8. Qualitative comparison shows good agreement between simulation and measurement. Proton and H_2^+ contributions can be identified by comparing Fig. 7 with Fig. 8. As for H_3^+, these are superimposed with a background line of neutral atoms in the emittance measurement.

CONCLUSION

Beam commissioning of the 60 keV proton beam up to the point of RFQ injection has been successful and preparations for RFQ beam tests are under way. More detailed measurements with the explicit goal to evaluate the proton beam emittance, including additional beam collimation for fraction reduction, will be carried out in Q4 2022. With the upgraded RFQ expected in late 2022, we expect proton energies of 700 keV in 2023 and 2 MeV in 2024.

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