CHOPPING HIGH-INTENSITY ION BEAMS AT FRANZ

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Abstract

The accelerator-driven Frankfurt Neutron Source FRANZ is under construction at the science campus of Frankfurt University. Its Low-Energy Beam Transport (LEBT) line also serves as test stand for transport and chopping experiments with high-intensity ion beams. The high-current proton source was tested successfully with dc currents above 200 mA. The LEBT section consisting of four solenoids and a 250 kHz, 120 ns chopper was successfully commissioned using a helium test beam at low beam currents. Transport simulations including space-charge compensation and measurements are discussed. Simulations and experimental results of the novel LEBT chopper using a Wien-filter type field array and pulsed electrode voltages of up to ±6 kV will be presented.

INTRODUCTION

The "Frankfurt Neutron Source at the Stern-Gerlach-Zentrum" (FRANZ) is under construction in the experimental hall of the *Institut für Angewandte Physik* (IAP) at Frankfurt University [1, 2]. It will deliver neutrons in the energy range of 1 keV to 500 keV, which are especially suited for nuclear astrophysics experiments [3].

The neutrons are produced via the $^7Li(p,n)^7Be$ reaction channel, thus requiring a driver linac delivering a 2 MeV primary proton beam.

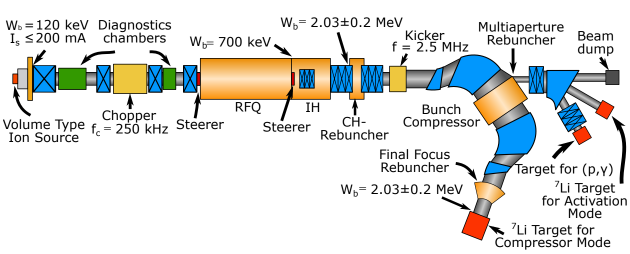

Figure 1: Overview of the Frankfurt neutron source FRANZ.

In the main operation mode, the so-called Compressor Mode, a pulsed high-intensity beam is required for the energy-dependent measurements of neutron capture cross-sections using the time-of-flight method.

ION SOURCE

The primary high-intensity proton beam is generated by an arc discharge driven volume type ion source [4]. Since the ion source cannot be pulsed at the required repetition rate of 250 kHz, it will be operated in dc mode while the beam pulses will be shaped by a chopper in the LEBT section. The design proton current is 50 mA in a first stage, with possible upgrades up to 200 mA.

At the moment, the ion source is undergoing a detailed test program at a dedicated ion source test stand. A proton beam current density of 480 mA/cm^2 was achieved during dc operation using a total arc power of 9.7 kW. For an emission opening radius of 4 mm, a proton current of 240 mA was extracted at 50 keV beam energy. By manipulating the plasma properties, the percentage of the undesired hydrogen fractions, H_2^+ and H_3^+, can be reduced to less than 10 % [5]. First beam emittance measurements show an 89 %-rms emittance of $\epsilon_{\mathrm{rms,\,norm}} = 0.08\,\mathrm{mm\cdot mrad}$ at 52 keV energy and at a normalized beam current of 85 mA [6]. For the future FRANZ operation, a relatively high initial beam energy of 120 keV was chosen to reduce space-charge effects.

LEBT SECTION

In the LEBT line, transverse focusing is provided by four solenoids, allowing space-charge compensated beam transport. An overview of the LEBT section is given in Fig. 3.

The first two solenoids match the beam into the chopper while the remaining two inject the beam into the Radio-Frequency Quadrupole (RFQ). The vertically moveable high-power Faraday Cup, installed at the Diagnostics Chamber 1, is used to measure the beam current and, if required, to stop the beam. The beam pulses that are shaped by the chopper can be measured with a fast Beam Current Transformer (BCT) installed between Solenoids 3 and 4. In addition, a rotating vacuum chamber developed especially for this beamline can be used for beam tomography [7].

Detailed numerical investigations of the LEBT show an efficient matching of the 50 mA dc beam into the acceptance of the RFQ [8]. For these simulations, a fixed space charge compensation of 95 % in front of the chopper and of 0 % behind it was assumed. However, new simulation tools considering a more realistic time-dependent electron production from residual gas ionization and secondary electron production at the metallic walls are under investigation [9].

Figure 2 shows the present status of the LEBT section.

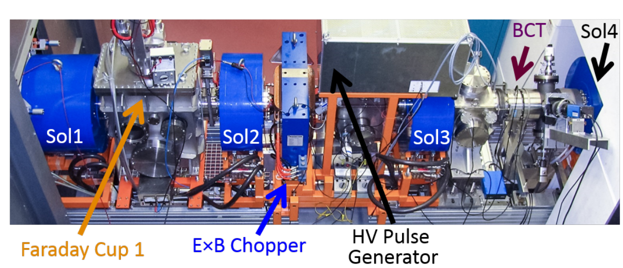

Figure 2: FRANZ LEBT section after assembly.

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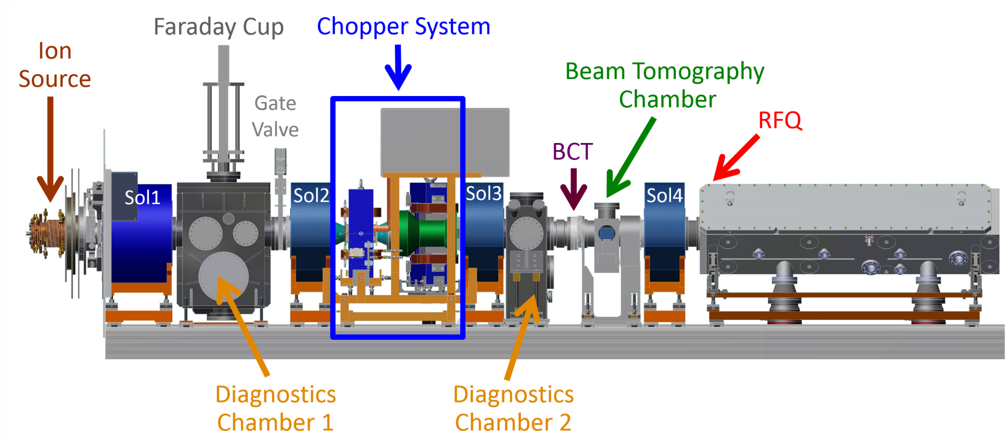

Figure 3: Overview of the LEBT section of FRANZ. The beam travels from left to right. The distance between the entrance of the first solenoid and the end of the fourth Solenoid is 3.5 m. The RFQ length is 1.8 m.

All major components, including the vacuum system, were successfully installed. After assembly, the beamline was commissioned using a low-current He^{+} beam at 14 keV energy that was extracted from a test ion source of the filament-driven volume type.

For commissioning, a Faraday Cup was installed behind Solenoid 4. It will be replaced when the RFQ is delivered. A transmission of (82.7 ± 0.8) % through the complete LEBT section was measured. This was achieved using the test ion source, which produces a beam with significantly larger divergent angles than the future FRANZ ion source.

E×*B* CHOPPER

Concept and Field Optimization

In the Compressor Mode, short pulses in the hundred nanosecond range have to be shaped with a repetition rate of 250 kHz before injection into the RFQ. The pulses are produced by the new *E*×*B* chopper system [10, 11]. It combines a static magnetic deflection field with a pulsed electric compensation field in a Wien filter-type *E*×*B* configuration.

The main components are shown in Fig. 4. The deflection unit consists of a magnetic dipole and electric deflection plates. For a future high-power upgrade, a dedicated beam-separation system will be installed between the chopper and the third solenoid in order to reduce the beam power deposition on the vacuum chamber [12].

The *E*×*B* concept combines the advantages of magnetic deflection, i.e., stable deflection without risks of voltage breakdown even at high beam intensities, and of electric deflection, i.e., operation with low power consumption even at high repetition rates. The Wien-filter field configuration, however, requires a careful local matching of the electric and the magnetic deflection forces to maintain high beam quality [11].

On the beam axis, the deflection forces are matched by longitudinally optimizing the dipole profile and by installing magnetic shortening tubes in front of and behind the dipole. The result is shown in Fig. 5. This assures an unperturbed beam trajectory through the chopper and avoids horizontal deviations or position offsets.

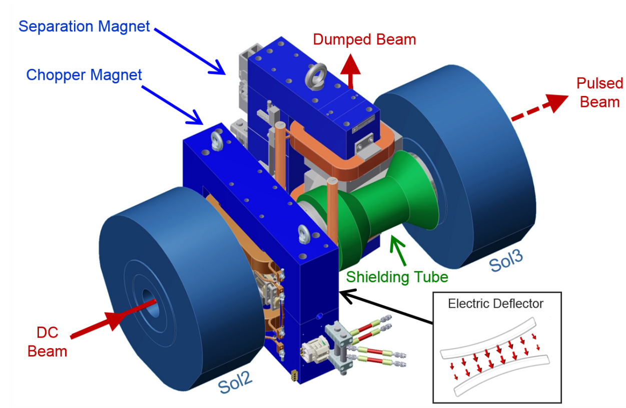

Figure 4: Main components of the *E*×*B* chopper.

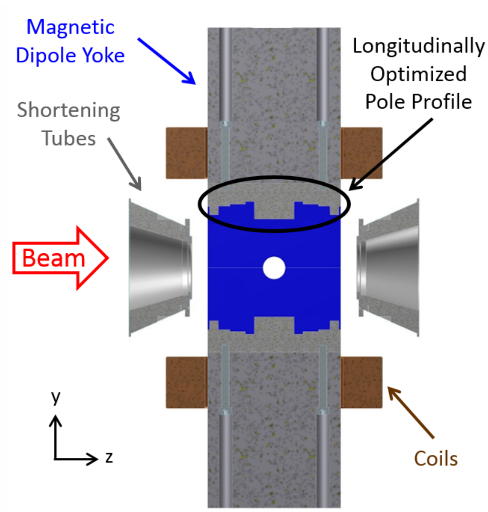

Figure 5: Cross-sectional view of the chopper magnet including shortening tubes and the longitudinally optimized pole profile.

In addition, the deflection forces have to be transversely matched by modifying the horizontal dipole contour. This way, the Wien focusing effect [13] can be equally distributed in both transverse planes, and a given inhomogeneous field distribution can be controlled such that the beam emittance and the cylindrical symmetry is preserved [12]. The transversely optimized pole profile is shown in Fig. 6.

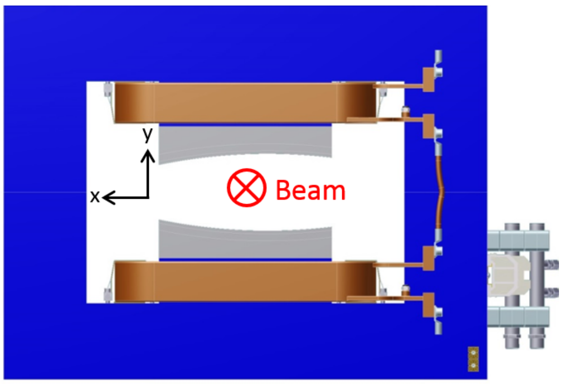

Figure 6: Chopper magnet with transversely optimized pole profile. The dipole yoke is depicted in blue and the exchangeable pole plates in gray. The beam travels perpendicular to the plane shown.

Numerical Simulations

Based on the optimized field configuration, numerical simulations using the Particle-in-Cell code *Bender* [9] were performed. A snapshot of one timestep of a beam shaping simulation is shown in Fig. 7.

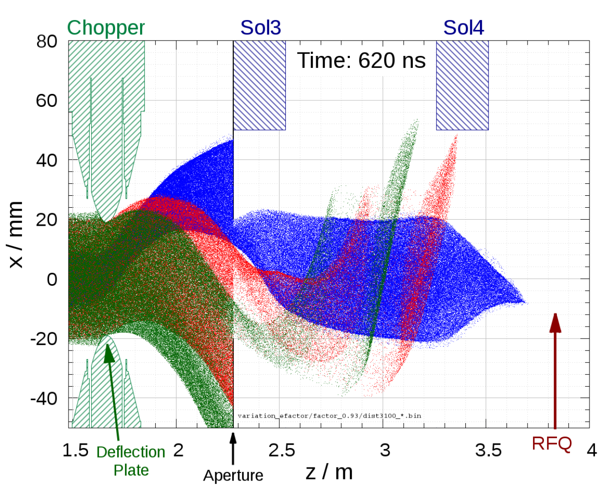

Figure 7: Snapshot of a beam shaping simulation in the $E \times B$ chopper during the fall time of the electric field. Protons are depicted in blue, H_2^+ ions in red and H_3^+ ions in dark green. The beam enters the chopper from the left side. The proton pulse is shaped at a circular aperture with a 20 mm radius.

At first, the incoming dc beam is statically deflected by the magnetic field and dumped at the vacuum chamber. When the HV pulse rises, the resulting electric field compensates the magnetic deflection, thus creating a proton pulse in the forward direction. During the fall time of the HV pulse, the beam returns to its initial position and is again dumped at the vacuum chamber. Behind the chopper, Solenoids 3 and 4 are used for transverse focusing.

The resulting beam pulse at the RFQ entrance is depicted in Fig. 8 for the different hydrogen fractions. An ion source current of 50 mA protons, 5 mA H_2^+ and 5 mA H_3^+ ions is assumed. As required, a flat top length of at least a 50 ns and a total length below 350 ns are achieved for the proton beam. Inside the central 50 ns flat top of the beam pulse, the position offsets in both the x and y directions are below ±0.3 mm.

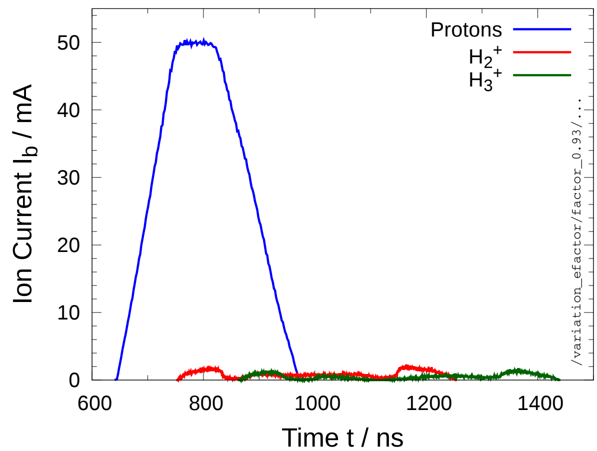

Figure 8: Simulated beam pulse shape at the RFQ entrance for the different hydrogen fractions at a 120 keV energy.

The chopper fields are matched such that the proton pulse maintains its full intensity. In contrast, the vast majority of the H_2^+ and H_3^+ ions are either directly lost at the chopper aperture or gain high position offsets of up to 20 mm (H_2^+) and 40 mm (H_3^+), respectively. This implies that they can be easily collimated before injection into the RFQ resulting in a purified proton beam in front of the RFQ.

In general, an $E \times B$ chopper acts as a pulsed velocity filter so that certain molecular beam fractions or charge states can be automatically separated without using additional equipment in the beamline.

Experimental Results

After manufacture of all components, the $E \times B$ chopper was installed at the beamline and commissioned using the low-current 14 keV He^+ beam. The chopper dipole as well as the electric deflection plates are 15 cm long. The dipole can provide a maximum field on the axis of $B_0 = 130$ mT inside an 11 cm gap. The electric field is driven by a HV pulse generator developed at IAP, which provides electrode voltages of up to ±6 kV with 250 kHz repetition rate. Negatively biased repeller electrodes are installed in front of and behind the chopper to prevent electrons from moving into the deflection area.

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The beam pulses were successfully shaped with the required repetition rate of 250 kHz [10]. A single beam pulse, measured at the fast BCT installed between the third and fourth solenoid, is depicted in Fig. 9. The experimental setup was shown in Fig. 2. The original data from the BCT, without rf noise correction, are shown.

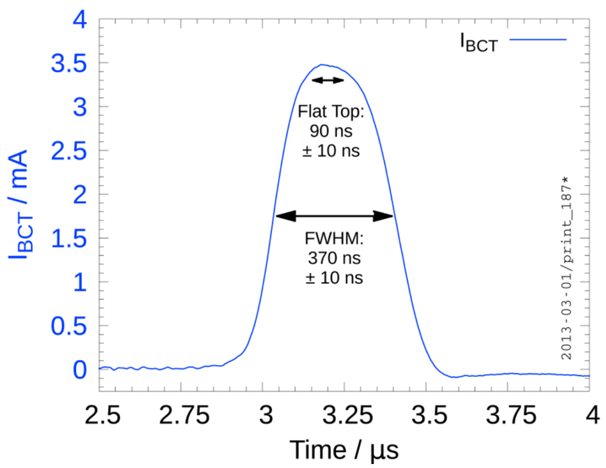

Figure 9: Measured 14 keV helium beam pulse at a 250 kHz repetition rate.

The pulse amplitude of 3.5 mA was limited by the given test ion source. It corresponds to a generalized perveance of $2.7 \cdot 10^{-3}$. For the design species and energy, 120 keV protons, this is equivalent to a beam current of 174 mA.

For different experimental setups, beam pulses with rise times of (120 ± 10) ns, flat top lengths of (85 ± 10) ns to (120 ± 10) ns and Full Width at Half Maximum (FWHM) between (295 ± 10) ns and (370 ± 10) ns were achieved using a circular aperture with a 50 mm radius [12]. For the future proton beam, a smaller aperture with a 20 mm radius will be employed, leading to substantially shorter pulse lengths.

The transmission of the dc beam and the peak transmission of the chopped beam are almost identical. The pulse amplitude, measured at the BCT, was equivalent to (95.2 ± 1.6) % of the maximum transmitted dc current, measured at the Faraday Cup behind Solenoid 4.

The beam pulse, shaped by the chopper in the center of the LEBT section, requires a certain time of flight t_{tof} until it reaches the BCT located at a distance d_{tof} = (1349 ± 2) mm behind the center of the deflection plates:

$$t_{tof} = \frac{d_{tof}}{v_p}. \quad (1)$$

In the nonrelativistic approximation, the particle velocity v_p can be calculated directly from the accelerating voltage V_{acc} using

$$v_p = \sqrt{2 \cdot V_{acc} \frac{q}{m_p}} \quad (2)$$

with the particle charge q and the particle mass m_p.

This can be compared to the measured time of flight, which is given by the time difference between the center of the primary HV pulse and the center of the beam pulse. Figure 10 compares the results for beam energies $W_b = e \cdot V_{acc}$ between 2 keV and 20 keV [12].

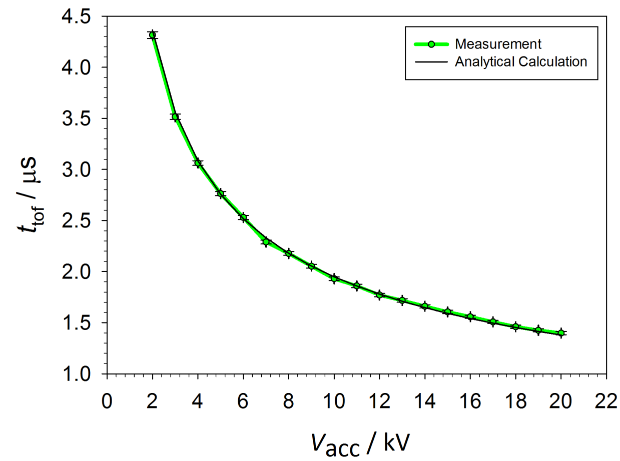

Figure 10: Measured (green) and analytically calculated (black) time of flight between the center of the deflection plates and the center of the BCT for the helium beam pulses as a function of the accelerating voltage V_{acc}.

The indicated error bars for the time of flight t_{tof} in Fig. 10 result from the 5 ns time resolution of the oscilloscope, from possible uncertainties in the extraction voltage and the exact distance as well as from the signal propagation time from the experiment to the oscilloscope.

In general, good agreement between the analytical solution and the measurements can be observed. Consequently, the beam energy can be determined during full operation of the facility. No additional energy or momentum analyzer in the low-energy section is required.

LINAC SECTION

Downstream of the LEBT, a four-rod RFQ will accelerate the beam from 120 keV to 700 keV, while an Interdigital H-type drift tube linac (IH-DTL) will provide the main acceleration to an energy of 2 MeV. The rf frequency is f_{rf} = 175 MHz.

The four-rod RFQ is currently in the final stage of construction (Fig. 11). The IH cavity was successfully manufactured from stainless steel and is now ready for copper plating. First field measurements of the cavity are presented in [14]. After conditioning, both accelerating structures will be coupled in order to be operated with a single rf power amplifier, which significantly reduces the investment costs.

Behind the IH cavity, a Medium-Energy Beam Transport (MEBT) section will match the beam into the acceptance of the bunch compressor. The MEBT section consists of magnetic quadrupole triplets for transverse focusing and a crossbar H-mode (CH) rebuncher cavity [15]. The latter can also be used to provide an energy variation of ±0.2 MeV.

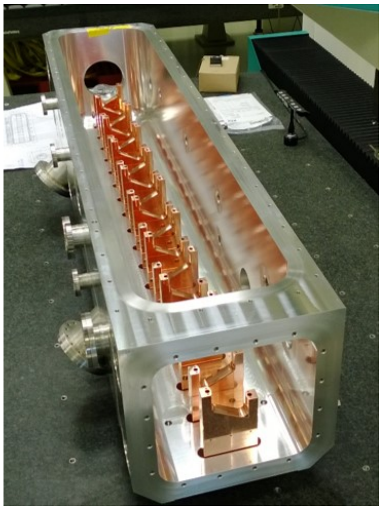

Figure 11: The four-rod RFQ currently under construction.

The bunch compressor is required to form a single high-intensity pulse in front of the neutron production target, allowing for the energy-dependent measurement of neutron capture cross-sections by the time-of-flight method. The bunch compressor is based on the concept by Mobley [16] and was extended to high-intensity beams [17]. It merges nine micro bunches, previously generated in the RFQ bunching section, into a 1 ns long proton pulse. The key components are a 2.5 MHz electric kicker [18], a magnetic ion guiding system [19] and two rf rebuncher cavities [20].

CONCLUSION

The FRANZ facility is under construction at Frankfurt University. The LEBT section, including the novel $E{\times}B$ chopper system, was successfully commissioned using a helium test beam at low beam currents. It is now ready for dc and pulsed operation for the FRANZ facility.

At the same time, the combination of a magnetic LEBT, which allows space-charge compensated beam transport, and a chopper system capable of producing short beam pulses in the hundred nanosecond range represents an attractive test stand for the investigation of low-energy ion beams. Since the chopper system is located in the center of the LEBT section, the longitudinal and transverse properties of the beam pulses can be analyzed before injection into the RFQ.

The beam pulse length as well as the time of flight in the LEBT is considerably lower than the expected rise time for space-charge compensation through residual gas ionization. This allows a dedicated research of longitudinal and transverse space-charge effects including the dynamics of space-charge compensation and electron effects in short pulses.

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