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EXPERIMENTAL PERFORMANCE OF AN E×B CHOPPER SYSTEM

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Abstract

Beam operation of an $E \times B$ chopper system has started in the Low-Energy Beam Transport (LEBT) section of the accelerator-driven neutron source FRANZ [1]. The chopper is designed for low-energy high-perveance beams and high repetition rates. It combines a static magnetic deflection field with a pulsed electric compensation field in a Wien filter-type $E \times B$ configuration [2]. Helium ions with 14 keV energy were successfully chopped at the required repetition rate of 257 kHz. The maximum chopped beam intensity of 3.5 mA, limited by the given test ion source, 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. 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 experimentally achieved.

INTRODUCTION

A novel $E \times B$ chopper has been commissioned for the LEBT section of the accelerator-driven neutron source FRANZ [1]. The chopper combines a static magnetic deflection field with a pulsed electric compensation field in a Wien filter-type $E \times B$ configuration [2].

Beam pulses of at least a 50 ns flat top length at a repetition rate of approximately 250 kHz are required before the beam is injected into the RFQ. Downstream of the RFQ, a bunch compressor generates 1 ns long pulses [1], thus allowing the energy-dependent measurement of neutron capture cross-sections by the Time-of-Flight (TOF) method.

FIELD OPTIMIZATION

The electric field is generated between two deflection plates made of copper. The longitudinal shape of the plates is adapted to the beam envelope. Shims at the top and the bottom improve the transverse field homogeneity. The deflection plates are mounted on cylindrical insulators. The plates are water-cooled and can be moved horizontally using a customized translator system. A scheme of the electric deflection unit is shown in Fig. 1.

The $E \times B$ concept combines the advantages of magnetic deflection, i.e., stable deflection without risks of voltage breakdown, and of electric deflection, i.e., operation with low power consumption even at high repetition rates. In this setup, however, the beam pulse is exposed to the full electric and magnetic fields.

Therefore, a careful global and local matching of the electric and the magnetic deflection forces is required to avoid beam offsets and to ensure a high beam quality. This is achieved by installing shielding tubes that shorten the magnetic field and by optimizing the pole contour of the dipole in both the transverse and longitudinal directions [2]. A picture of the chopper dipole with the optimized pole shape is shown in Fig. 2.

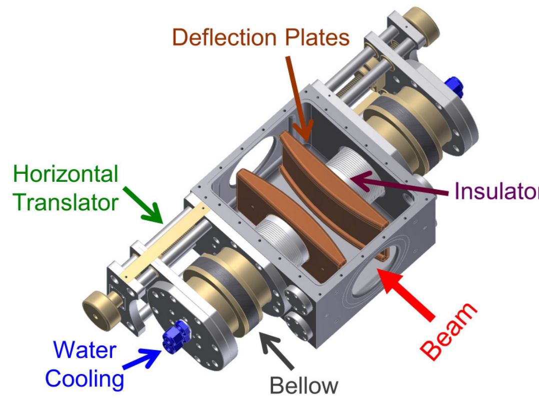

Figure 1: Electric deflection unit of the $E \times B$ chopper.

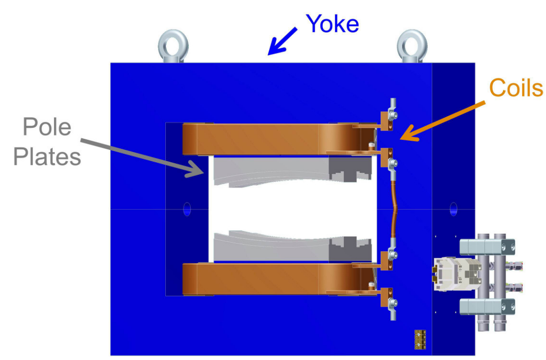

Figure 2: Chopper dipole with transversely and longitudinally optimized pole contour. The beam direction is perpendicular to the plane shown.

BEAM DYNAMICS SIMULATIONS

Beam dynamics simulations using the Particle-in-Cell (PIC) code *Bender* [3] were performed. The simulated pulse shape for 120 keV protons is depicted in Fig. 3. The optimized field setup is used and the measured HV pulse shape is imported into the simulations. The time requirements of at least a 50 ns flat top length and a maximum total length of 350 ns are fulfilled. No significant increase of the pulse length is observed during the transport from the chopper to the RFQ, located 1.5 m downstream. Note that the fall time is slightly larger than the rise time due to the asymmetric shape of the primary HV pulse.

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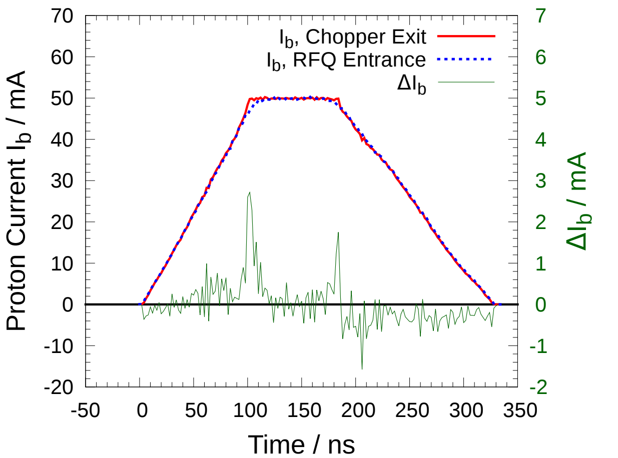

Figure 3: Simulated pulse shape for 120 keV protons behind the chopper (red) and at the RFQ entrance (blue). The difference $\Delta I_b = I_b^{\text{chopper}} - I_b^{\text{rfq}}$ is depicted in green.

BEAM EXPERIMENTS

Experimental Setup

An overview of the FRANZ LEBT section, as used for the experiments presented in this section, is given in Fig. 4. Four solenoids are used for transverse focusing. The chopper is installed between Solenoids 2 and 3 in the center of the LEBT section. The HV pulse generator, which drives the electric deflection fields, is indicated. It uses fast MOSFET technology in the primary circuit, while the high voltage is provided in the secondary circuit by a ferrite transformer core.

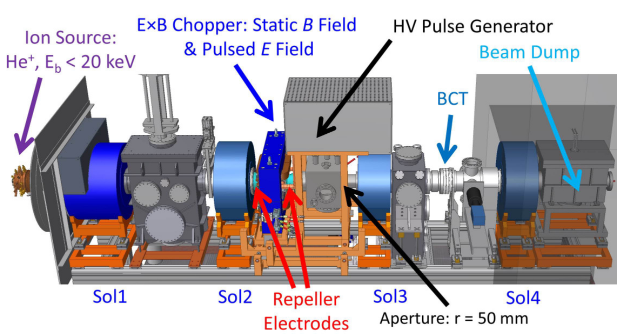

Figure 4: Overview of the FRANZ LEBT section, as used for the experiments presented in this section.

The beam pulse is shaped at a circular aperture with a radius of 50 mm. For the future 120 keV proton beam, a smaller aperture with a 20 mm radius will be employed. For commissioning, a filament-driven volume type ion source was operated with a He$^+$ beam at 14 keV energy. The beam pulse is measured at a fast beam current transformer (BCT) installed between the third and fourth solenoid.

The optimized chopper components were manufactured in-house and by external companies. A photograph of the low-energy line and the $E{\times}B$ chopper after assembly is shown in Fig. 5.

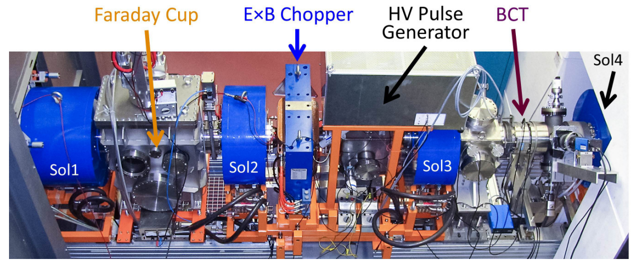

Figure 5: FRANZ LEBT section, including the $E{\times}B$ chopper.

Experimental Results

Beam repetition rates between 103 kHz and 257 kHz can be experimentally achieved for the given setup by adapting the trigger pulse of the HV pulse generator. Measured beam pulses with a 257 kHz repetition rate are shown in Fig. 6.

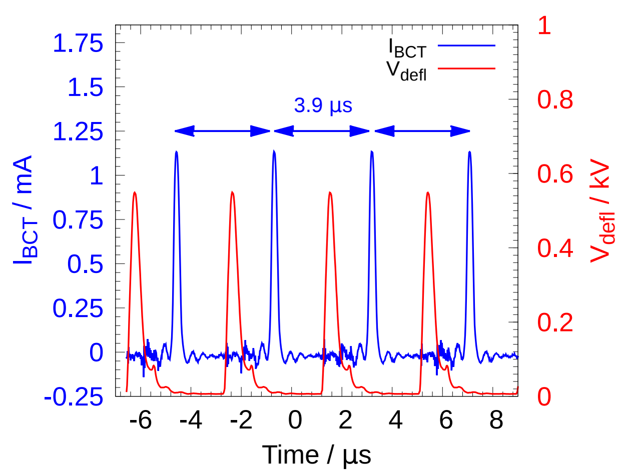

Figure 6: Measured 14 keV He$^+$ beam pulses with a repetition rate of 257 kHz. The signal of the BCT I_{BCT} is depicted in blue and the voltage V_{defl} at the positively charged deflection plate in red. The original BCT data without rf noise correction or baseline restoration are shown.

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 for different experimental setups [4]. A detailed view of a single beam pulse after subtracting the noise that is induced by the HV generator is shown in Fig. 7.

He$^+$ beams with beam currents of up to 3.5 mA, limited by the given test ion source, were successfully transported and chopped. This 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 175 mA.

A characteristic feature of the $E{\times}B$ setup is the necessity to match the magnetic and electric deflection forces. Therefore,

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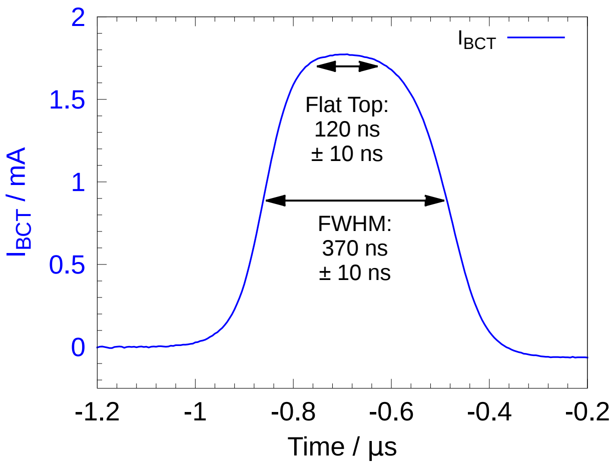

Figure 7: Measured beam pulse.

the behavior of the chopper for different Wien ratios R_{Wien} of the electric to the magnetic field was investigated. For static fields in a hard-edge approximation, the Wien ratio is directly given by $R_{\mathrm{Wien}} = E_x \cdot B_y^{-1}$ [5]. For arbitrary field distributions and time-dependent electric fields, the Wien ratio has to be modified [4]:

$$R_{\mathrm{Wien}} = \frac{\int E_x \,\mathrm{d}z \cdot f_{\mathrm{tof}}}{\int B_y \,\mathrm{d}z}. \quad (1)$$

The time-of-flight factor f_{tof} considers that the finite time of flight through the time-dependent electric field reduces the amplitude of the effective time-averaged electric field [4]. It is especially relevant for low-energy beams.

In practice, the Wien condition is determined by

$$R_{\mathrm{Wien}} = \frac{\int E_x \,\mathrm{d}z \cdot f_{\mathrm{tof}}}{\int B_y \,\mathrm{d}z} = \frac{\int E_{\mathrm{sim}} \,\mathrm{d}z \cdot \frac{V_{\mathrm{meas}}}{V_{\mathrm{sim}}} \cdot f_{\mathrm{asym}} \cdot f_{\mathrm{tof}}}{\int B_{\mathrm{sim}} \,\mathrm{d}z \cdot \frac{I_{\mathrm{meas}}}{I_{\mathrm{sim}}}}. \quad (2)$$

Here, the magnetic field B_{sim} is numerically computed for a coil current I_{sim} and is scaled with the measured dipole current I_{meas}. Then, the electric field E_{sim} is simulated for the given geometry using a static voltage V_{sim} and is scaled with the measured voltage pulse amplitude V_{meas}. The factor f_{asym} corrects a small measured asymmetry between the positive and the negative voltage pulse.

In the experiment, the dipole current was kept constant while the voltage pulse amplitude V_{meas} was increased step by step. The amplitude $I_{\mathrm{BCT}}^{\mathrm{max}}$ and the flat top length t_{flattop} of each beam pulse were measured. The flat top length is defined as the time span between the 98 % values of $I_{\mathrm{BCT}}^{\mathrm{max}}$. Figure 8 shows the measured charge that was transported in the pulse flat top $Q_{\mathrm{flattop}} = I_{\mathrm{BCT}}^{\mathrm{max}} \cdot t_{\mathrm{flattop}}$. It is plotted as a function of the Wien ratio R_{Wien}. For easier interpretation, the Wien ratio is normalized to the calculated velocity v_0 of the 14 keV helium ion beam.

The errors of the Wien ratio are calculated from the uncertainties of each factor in Eq. 2 while the error $\Delta Q_{\mathrm{flattop}}$ is dominated by the time error of $\Delta t_{\mathrm{flattop}} = 10$ ns.

For high electric fields, the magnetic deflection is overcompensated and the beam is swept back and forth over the aperture, generating a double-peak pulse [4]. In these cases, the flat top and maximum current of the higher peak are evaluated.

One can observe how the measured charge in the flat top Q_{flattop} reaches its maximum when the electric and magnetic deflection forces are accurately matched, i.e., close to the theoretically derived Wien condition $R_{\mathrm{Wien}} / v_0 = 1$.

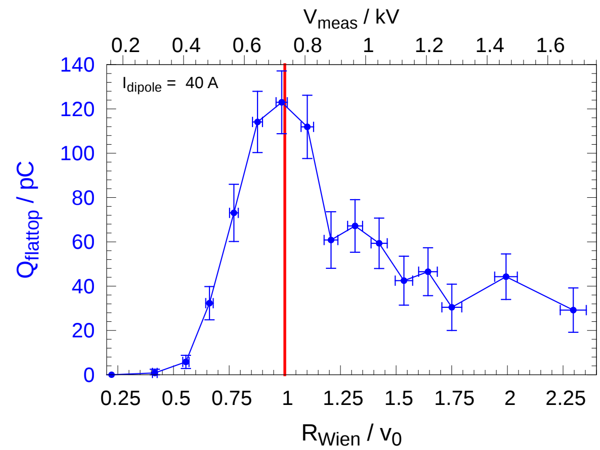

Figure 8: Measured charge in the pulse flat top $Q_{\mathrm{flattop}} = I_{\mathrm{BCT}}^{\mathrm{max}} \cdot t_{\mathrm{flattop}}$ as a function of the Wien ratio R_{Wien}, which is normalized to the velocity v_0 of the 14 keV He^+ beam. The Wien ratio is varied by increasing the HV pulse amplitude V_{meas} while keeping the magnetic deflection field constant.

CONCLUSION

The new $E{\times}B$ chopper for the low-energy line of the FRANZ facility was successfully designed, installed and commissioned with a 14 keV He^+ beam. Repetition rates of 257 kHz and rise times of 120 ns were achieved.

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