CHOPPING HIGH INTENSITY PROTON BEAMS USING A PULSED WIEN FILTER

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Abstract

Chopping high intensity beams at low energies poses substantial challenges. A novel E×B chopper system for proton beams of up to 200 mA and repetition rates of 250 kHz is being developed for the Low Energy Beam Transport (LEBT) section of the accelerator driven neutron source FRANZ [1]. It consists of crossed electric and magnetic fields which require carefully matched deflection forces to avoid aberrations and the loss of cylindrical beam symmetry in the chopper. Numerical studies for the field design and their effects on beam transport are presented. The status of the hardware development is reported.

INTRODUCTION

The chopper uses a Wien filter-type E×B configuration combining a static magnetic deflection field with a pulsed electric compensation field to deliver 50 to 100 ns proton pulses [2]. The setup minimizes the risk of voltage breakdowns and provides secure beam dumping outside the transport line.

BEAM DYNAMICS AND MATCHING OF DEFLECTION FORCES

In order to prevent beam aberrations and emittance growth, careful matching of electric and magnetic deflection forces is required.

Longitudinal Field Shaping

The Wien condition demands that the integral of the electric and magnetic deflection forces cancels out to zero, so that the beam is transmitted in forward direction.

For a simple magnetic dipole with flat pole shoes and an electric deflector with circular-shaped plates the corresponding forces satisfying the Wien condition are shown in Fig. 1. The fields were computed using *CST EMS*. As expected, the electric forces dominate in the center and the magnetic forces in the outer region.

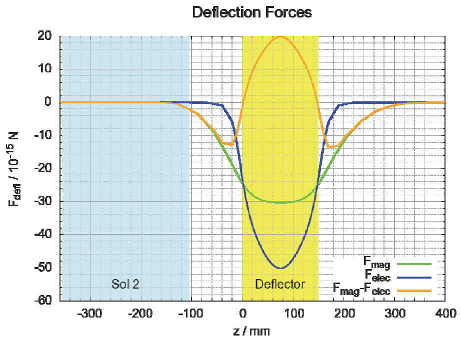

Figure 1: Deflection forces along the chopper axis z for the locally mismatched case.

The local force mismatch leads to a horizontal movement of the center particle. This is illustrated in Fig. 2 for on-axis protons with an energy of 120 keV passing through the chopper. The global matching of the deflection forces using the Wien condition eliminates the momentum offset behind the chopper, but cannot prevent a position offset of the transmitted particles.

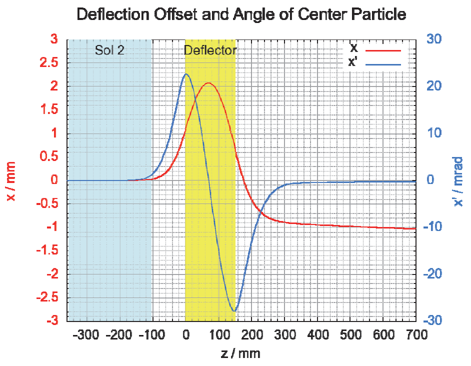

Figure 2: Horizontal movement of the center particle along the chopper axis z for the locally mismatched case.

To reduce this movement, it is necessary to match the shape of magnetic and electric forces by shimming the poles and installing shortening tubes. An optimized geometry is shown in cross-sectional view in Fig. 3. The maximum particle position and momentum while moving along the chopper is reduced from 2.1 mm and −27.9 mrad (as in Fig. 2) to below 0.1 mm and −0.7 mrad.

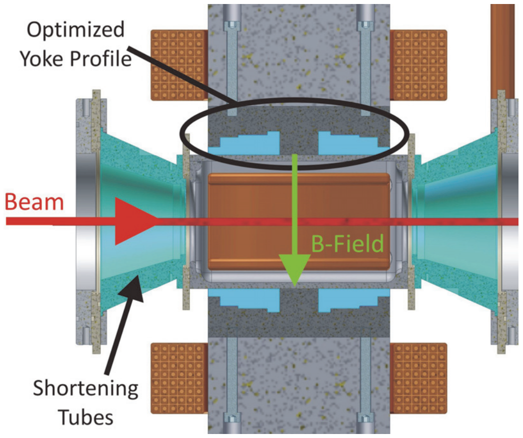

Figure 3: Longitudinal pole contour and magnetic shortening tubes. Complete dipole shown in Fig. 10.

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Transverse Field Shaping

For realistic beam sizes additional effects of crossed electric and magnetic fields have to be considered. In order to investigate these effects, numerical studies were conducted using the PIC code *Bender* developed at IAP. A KV input distribution was matched into the chopper system using two solenoids. The output of a simulation with a 120 keV, 50 mA proton beam transported through static chopper fields is shown in Fig. 4.

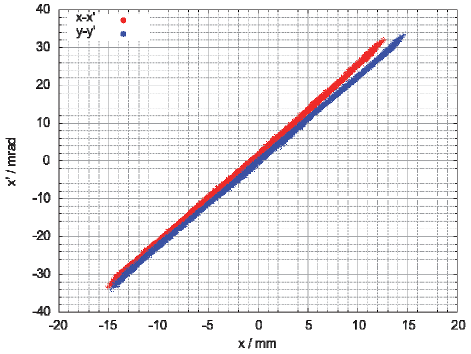

Figure 4: Transverse phase space distributions for longitudinally optimized pole profile.

The beam ellipses in the x-x' and y-y' planes are tilted against each other. Additionally, position and momentum offsets are reduced, but the absolute values of x_{max} and x_{min} vary by more than 2.5 mm leading to the loss of the initial cylindrical beam symmetry. This asymmetric focusing behavior is displayed in Fig. 5. Single particles were tracked from different horizontal input positions through the chopper. The center particle remains on-axis due to efficient longitudinal matching of the deflection forces. However, the particles with positive input positions are bent towards the center, while the particles with negative input positions are not.

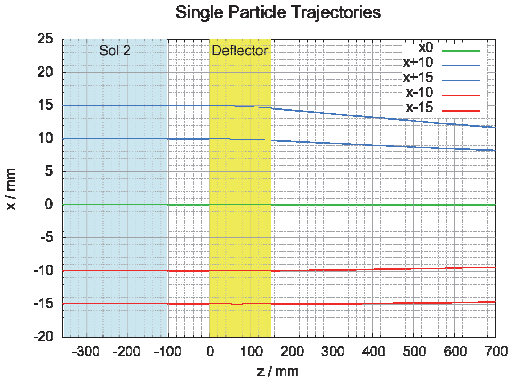

Figure 5: Asymmetric focusing behavior in the horizontal plane.

This behavior results from the superposition of two effects. First, deviations from ideal fields for the given geometry result in higher electric and lower magnetic field integrals for off-axis particles. This leads to a force mismatch bending both, right and left off-axis particles, into negative x-direction.

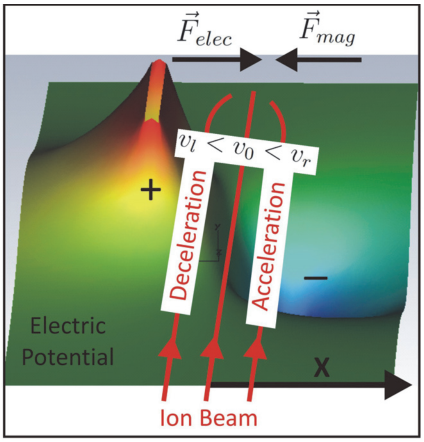

Figure 6: Horizontal focusing effect in a Wien filter due to velocity change in the electric potential.

The second effect is the Wien focusing effect [3]. The longitudinal velocity v_z inside the electric deflector depends on the horizontal position x of the incoming proton with mass m_p, charge q and input energy qU_{ac}. Assuming a constant electric field E_x, i.e. linear potential between the deflection plates, and a symmetric voltage distribution one can directly calculate the particle velocity in the deflector:

$$v_z(x) = \sqrt{\frac{2q(U_{ac}+E_x\cdot x)}{m_p}} .$$

This changes the Lorentz force for the off-axis particles leading to a focusing effect in the horizontal plane as illustrated in Fig. 6.

The superposition of both effects results in the asymmetric focusing of Fig. 5. For the particles with positive positions (depicted in blue) both effects add up, while for the particles with negative positions (depicted in red) the effects partially compensate, nearly canceling out the net effect.

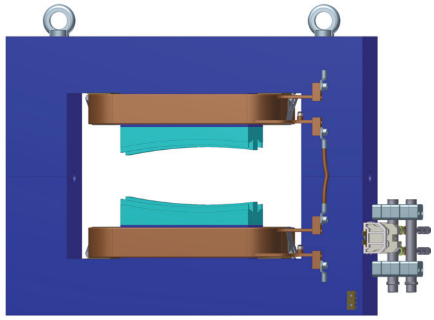

Figure 7: Drawing of chopper dipole with tilted and curved poles.

To minimize this unwanted beam behavior, optimization of the transverse pole contour is required. To correct the horizontal field inhomogeneities, a parabolic pole shape can be used. In addition, the poles have to be tilted to partially shift the focusing effect from the horizontal to the vertical plane. A typical pole shape taking both effects into account is depicted in Fig. 7.

The output of a transport simulation using the same beam input parameters as for Fig. 4, but the new magnetic field, is reproduced in Fig. 8. The transversely optimized pole shape leads to a reduction of cylindrical asymmetry with similar phase space distributions in the two transverse projections. A small mismatch between the beam diameters in x- and y-dimension remains.

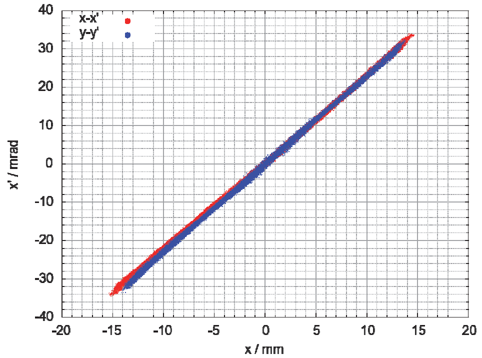

Figure 8: Transverse phase space distributions for longitudinally and transversely optimized pole profile.

For a quantitative evaluation the percentage deviation of the Twiss parameters of the horizontal plane (x-x’) compared with those of the vertical plane (y-y’) are plotted in Fig. 9. Three different magnetic field scenarios are shown. Case 1 is the mere dipole with flat poles and without shortening tubes (fields like in Fig. 1). Case 2 has the longitudinally optimized pole profile shown in Fig. 3, while in case 3 the pole is also optimized transversely (Fig. 7). For comparison the deviation of the Twiss parameters behind an 80 cm drift is also calculated. In addition, the pink-colored dots show the relative horizontal offset (mean x-position ⟨x⟩ normalized by the horizontal beam radius r_x).

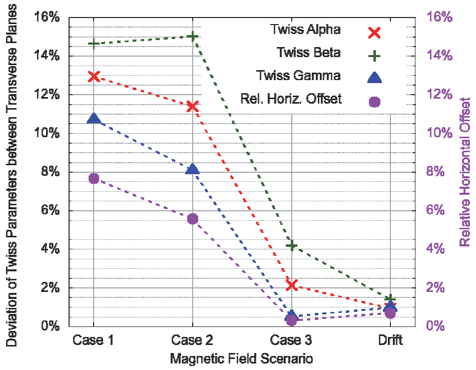

Figure 9: Comparison of Twiss parameters between transverse planes and relative horizontal offset for different magnetic field scenarios.

For the longitudinally and transversely optimized fields of case 3 the deviation between the two planes decreases reducing the cylindrical asymmetry. Also, the relative horizontal offset vanishes. For this magnetic field scenario the aberrations due to the mismatch of deflection fields are minimized, so that the emittance growth through the chopper is now dominated by space charge effects and dynamic effects resulting from the non-ideal primary voltage pulse for the electric deflector.

HARDWARE DESIGN

The 15 cm long chopper dipole (Fig. 10) has been manufactured recently. It has alterable pole plates to adapt the pole shape and match the magnetic and electric deflection forces. The typical B-fields are below 100 mT.

Figure 10: Manufactured chopper dipole with flat poles.

The electric field is driven by a HV pulse generator developed at IAP providing ±6 kV at a repetition rate of 250 kHz. The deflector plates have to be designed carefully in order to tackle the issues of field quality, cooling and spark prevention. A prototype deflector chamber has been manufactured and successful chopping of a 15 keV helium beam with the required repetition rate was already demonstrated [4].

CONCLUSION

The study of beam dynamics in crossed electric and magnetic fields shows that longitudinal and transverse optimization of the pole contour in combination with shielding tubes is required to match the deflection fields, to minimize aberrations and to preserve the cylindrical beam symmetry.

A special H-type dipole magnet with alterable pole plates was designed and manufactured. The HV pulse generator driving the electric field is operational.

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