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DESIGN OF AN E × B CHOPPER BASED ON PERMANENT MAGNETS*

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Abstract

Chopper systems are typically used to provide beam time structure and ensure the safety of accelerator operations by deflecting the beam away. The reliability of conventional choppers is entirely based on high-voltage (HV) pulsed power supplies. However, when the power supply fails to charge the electrostatic deflection plate, the beam cannot be cut off, and it will enter the downstream accelerator. To meet the strict beam stopping time requirements of the China Initiative Accelerator Driven System (CiADS), novel E × B chopper design has been developed based on a permanent magnet and an electrostatic deflection plate. This design not only ensures the safety of the accelerator but also provides the necessary pulse waveform. The device is small, highly reliable, and suitable for most accelerators. Moreover, beam dynamics simulations have been conducted to evaluate the chopper's influence on beam quality, and its beam cutting capability has been analyzed

INTRODUCTION

To address the challenge of nuclear waste disposal, the Accelerator Driven Subcritical System (ADS) has been proposed as a means of transmuting long-lived nuclides into shorter-lived ones. The Chinese Academy of Sciences has put forward the CiADS project, which is expected to be completed in 2027 [1]. This facility is composed of three main components: a high-power RF superconducting linac, a spallation target made of Liquid Lead Bismuth Eutectic (LBE), and a subcritical reactor. The superconducting linac can operate in either continuous wave or pulsed mode, depending on the requirements of the application. Fig. 1 illustrates the layout of the CiADS facility.

The chopper system is a critical component of the CiADS facility, situated at the low energy transport line (LEBT) at the room temperature front-end, between the last solenoid and the RFQ, as shown in Fig. 1. The chopper plays a crucial role in CiADS by serving as an essential beam-cutting device in case of accelerator failures and trips, while also providing pulse beams for beam commissioning and other terminal purposes. Electrostatic deflectors (electric kickers), magnets (magnetic choppers), or electromagnetic choppers (E × B choppers) can be used to cut the beam. The Frankfurt Neutron Source at the Stern-Gerlach-Zentrum (FRANZ) [2] has designed an E × B chopper based on an electromagnet, which has been successfully commissioned, but there are still some problems that need to be addressed [3]. Firstly, the conventional magnet is still driven by the power supply, which can be avoided by using a permanent magnet. Additionally, the conventional magnets occupy a large space and are difficult to apply to most particle accelerators at present. To overcome these issues, we propose the concept of a compact electromagnetic chopper based on permanent magnets.

In this paper, the structure and parameters of the chopper are introduced, the matching optimization of the magnetic field and electric field on the beam axis has been carried out, in addition, the beam dynamics simulation was performed using TraceWin software, and analyzed the influence of the chopper on the beam.

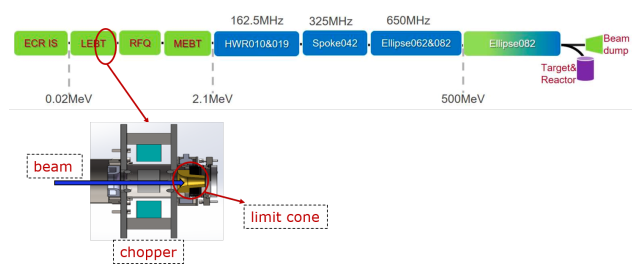

Figure 1: Layout of CiADS.

STRUCTURE OF CHOPPER

The structure of the chopper is illustrated in Fig. 2, which mainly comprises a pair of electrostatic deflection plates symmetrically placed about the Y-Z plane with high voltage applied on both sides, a pair of vertically arranged permanent magnets, a vacuum chamber, and a shielding plate for field optimization. The permanent magnet-based E × B chopper utilizes the force of a permanent magnetic field to deflect the beam. The beam can pass through only when the electric and magnetic fields work in coordination, and when the device does not require beam, reset the current applied to the deflector to zero, and the beam will be blocked by the limit cone. During the accelerator commissioning and pulsed operation, the use of E × B chopper can effectively reduce the duty factor of the power supply and lower the risk of HV breakdown. Futhermore, the system has a compact axial length of 92mm, meeting the design requirements. Compared to the chopper system at FRANZ facility, the

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longitudinal size has been reduced by three times. Due to its compact size, it can be applied to most accelerators.

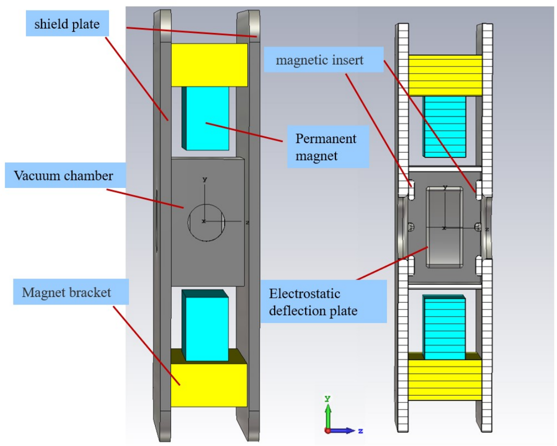

Figure 2: Schematic overview of the structure of the chopper.

FIELD OPTIMIZATION

While the electromagnetic chopper brings many conveniences, its impact on beam quality cannot be ignored. Therefore, field optimization is required to match the magnetic and electric field forces to ensure that the beam can pass through the chopper perfectly without compromising its quality. A particle with a charge of q and a velocity of $\vec{v}_{\mathrm{p}}$ experiences a force in perpendicular magnetic and electric fields:

$$\vec{F} = q\left(\vec{E} + \vec{v}_{\mathrm{p}} \times \vec{B}\right) \tag{1}$$

Due to the non-uniformity of the electric and magnetic fields in the direction of particle motion (z-axis) and based on the directions of the electric and magnetic fields in the chopper, particles can pass through successfully only if th ey satisfy the Wien filter condition [4]:

$$\int q \cdot \left(v_0 \cdot B_y - E_x\right) \mathrm{d}z=0 \tag{2}$$

The non-uniformity of the electric and magnetic fields can cause changes in particle velocity, leading to variations in the deflection angle of particles in the chopper, ultimately affecting the beam quality. Therefore, it is necessary to locally match the electric and magnetic fields in different directions. The simulation code used in this project is CST Studio Suite, which is comprehensive electromagnetic field simulation software. It can simulate and analyze the behavior of electromagnetic fields in detail and supports multiple simulation types, including static, frequency domain, time domain, modal, and optimization.

E_y Optimization

Due to the E_y component of the electric field generated by the electrostatic deflector, the beam will be deflected in the Y direction, resulting in an offset. Therefore, before performing local matching, it is necessary to optimize the deflection plate to minimize the displacement caused by the Ey component. The geometric profile of the electrostatic deflection plate is shown in Fig. 3. where l is the longitudinal length of the electrostatic deflection plate used to adjust the electric field distribution, h is the height of the plate, and $\theta = 2\arcsin\frac{h}{2r}$ is the radian. Both h and *theta* used to adjust the uniformity of the electric field in the y direction and the y-component of the electric field. To decrease the offset further, we have added shielding plates on both sides of the deflector to the X-Y direction. Fig. 4 shows the variation of E_y with z before and after the installation of the shielding plate (x=-10 mm, y=-10 mm), with the center of the deflection plate was chosen as the origin. It can be seen from the figure that the offset (i.e., the integral of E_y along the z-axis) has significantly decreased. However, it should be noted thatdue to the need for overall consideration in the design aspect, the offset is still not zero.

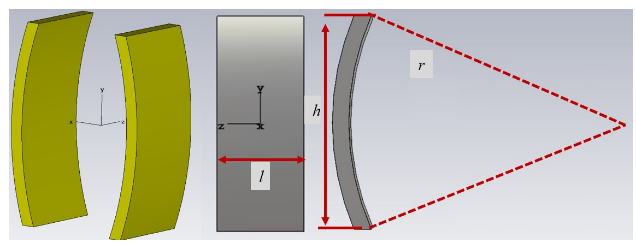

Figure 3: The geometric profile of the electrostatic deflection plate.

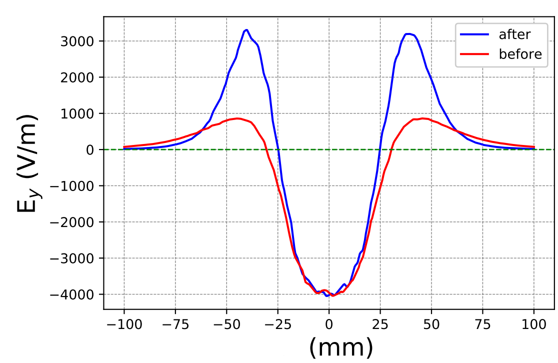

Figure 4: The variation of E_y with z before(red) and after(blue) the installation of a magnetic shielding plate (x=-10 mm, y=-10 mm).

Field Uniformity Optimization

We adjusted the uniformity of the magnetic and electric fields by fixing shims made of soft magnetic material onto the magnetic shielding plate and modifying their shape, size, and position. During CST simulation, we observed that the uniformity of the magnetic (electric) field integration is more sensitive to shims in the vertical (horizontal) direction. In particular, adding shims in the vertical direction has a significant impact on the integral uniformity of the vertical magnetic field. The matching results can be seen in Fig. 5

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and Fig. 6. It can been seen in Fig. 5 that, within the range of -20 mm < y < 20 mm, the difference in the uniformity of magnetic and electric field integrals is less than 1%. For the horizontal direction, a worse uniformity of the E fields was shown in Fig. 6. This result is due to the influence of Wien focusing, where the proton is decelerated when approaching the positive electrode and accelerated when approaching the negative electrode [5]. This change in velocity affects the magnetic field force, so it is necessary to reduce the electric field near the positive electrode and increase it near the negative electrode to ensure that the beam can pass through normally.

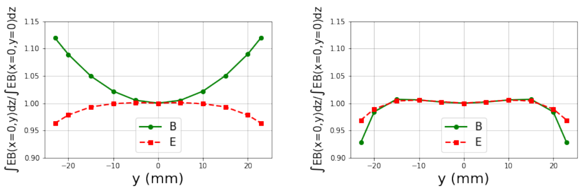

Figure 5: The uniformity of the integration of the magnetic field and electric field in the vertical direction before and after adding the shims.

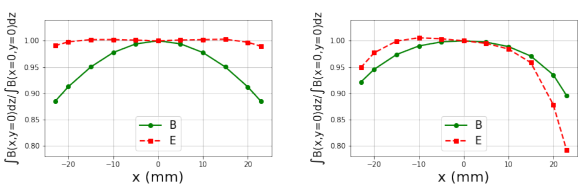

Figure 6: The uniformity of the integration of the magnetic field and electric field in the horizontal direction before and after adding the shims.

BEAM DYNAMIC SIMULATION

Based on the optimized three-dimensional electromagnetic field of the chopper as described above, a beam dynamics simulation of 20 KeV protons was conducted using the Tracewin code. The beam current intensity was 7 mA and the simulation used 10,000 particles.

For this LEBT section, beam matching needs to be performed again after installing the chopper. The phase space distribution of the beam is shown in Fig. 7. The criterion for measuring the quality of beam matching is the mismatch factor [6], which is a measure of the increase in the maximum beam size resulting from a mismatch. Calculation shows that, the mismatch factor without the chopper is $M_{x0} = 5.37 \times 10^{-2}$ and $M_{y0} = 6.56 \times 10^{-2}$, while the mismatch factor with the chopper is $M_{x1} = 5.42 \times 10^{-2}$ and $M_{y1} = 5.46 \times 10^{-2}$. Results indicate that the beam can still be perfectly matched into the RFQ even when the chopper is operating.

As it is necessary to safely stop the beam, a beam cutting capability analysis was conducted on the chopper. Due to the fact that the beam power of the LEBT section is only 140 W, a limit cone is used to block the beam deviating from the chopper. In the current design, the distance from the solenoid exit to the limit cone is 136 mm, and the radius of the limit cone end is 10.43 mm. The simulation results indicate that the limit cone can stop approximately 99.28% of the beam in this configuration. However, if the radius of the limit cone end is reduced to 9.43 mm, about 99.99% of the beam can be stopped.

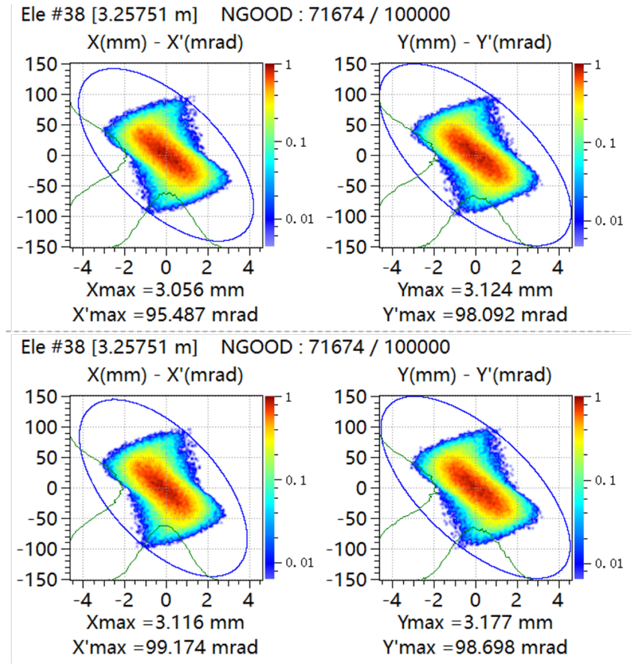

Figure 7: Phase space distribution of beam without (up) and with (below) chopper.

CONCLUSION

Due to the engineering schedule requirement of CiADS, the chopper is currently being mechanically machined. Beam dynamics simulations have shown that, after optimizing the field configuration, the chopper has minimal impact on beam quality and can cut off 99.99% of the beam. The chopper is scheduled to be installed and commissioned online in 2023, and will be used in the LEBT section of the superconducting linac at CiADS in the future.

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