Study on the pre-chopper in CSNS LEBT

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Abstract Physical designing of the pre-chopper in CSNS LEBT is carried out, which includes the deflecting voltage, the length and the width of the deflecting plates, and the gap between the deflecting plates. The most outstanding feature of the design is that both the gap and the width vary with the beam envelope size. So both the requried deflecting voltage and the loaded capacitance are lowered. In order to avoid destruction of the space charge neutralization by the pre-chopper in the whole LEBT, an electron-trapping electrode is arranged to confine the electrostatic field of the pre-chopper to the local area. To examine the reliability of the pre-chopping design in CSNS LEBT, a similar pre-chopping design in ADS RFQ LEBT is set up and an experiment on the pre-chopper is prepared. 3-dimensional simulations are carried out to determine the loaded capacitance and the applied voltage of the electron-trapping electrode.

Key words LEBT, pre-chopper, charge neutralization, deflecting voltage, electron-trapping, loaded capacitance

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1 Introduction

The China Spallation Neutron Source (CSNS) is an accelerator-based high power project currently under R&D in China [1,2]. The accelerator complex consists of an 81 MeV H^- linear accelerator as the injector and a 1.6 GeV rapid cycling proton synchrotron (RCS). The linear accelerator consists of a 50 keV H^- Penning surface plasma ion source, a low beam energy transport line (LEBT), a 3.0 MeV Radio Frequency Quadrupole (RFQ) accelerator, a Medium Energy Beam Transport line (MEBT), an 81 MeV Drift Tube Linear Accelerator (DTL) and a high energy beam transport line (HEBT). LEBT is located between the ion source and RFQ. For CSNS, it mainly serves firstly to match the beam from the ion source into RFQ, and secondly to pre-chop the beam from the ion source into the required beam time structure required by RCS. The H^- Penning surface plasma ion source is chosen for its economy, full satisfaction of the CSNS requirements on the source beam and good collaboration between Rutherford Appleton Laboratory (RAL) and Institute of High Energy Physics (IHEP). For the chosen Penning H^- surface plasma ion sources, the discharging chamber of the ion source is disposed in a 90° deflection magnet with a special magnetic field gradient index (in practice, the magnetic field gradient index n is generally designed to 1), and the ion beam is extracted from a long slit and generally of different emittances from the two transverse phase planes. However, the RFQ is generally designed to accept an axial symmetric input beam with the same beam emittances in the two transverse phase planes. The previous research results [3,4] show that, with three solenoids instead of two, the beam from the ion source can still be matched into RFQ by controlling the coupling and the focusing of the solenoids in LEBT.

As mentioned above, in order to decrease the beam loss during the beam injection process from the linac to RCS, a pre-chopper is arranged in LEBT to pre-chop the beam from the ion source into the required beam time structure required by RCS. The designed beam power for CSNS Phase-Ⅰ is at a comparatively low level of 100 kW, and another chopper will be arranged in MEBT for CSNS Phase-Ⅱ to further sharpen the beam edges left by the pre-chopper during its rising time and falling time, so the requirements of the pre-chopping beam are not so strict. In practice, two kinds of pre-chopping structure are

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generally adopted, namely electrostatic and magnetic structures. For instance, an electrostatic pre-chopper is adopted in LEBT of the Spallation Neutron Source (SNS) [5], while a magnetic alloy (MA) induction cavity as the pre-chopper is adopted in LEBT of the Japan Proton Accelerator Research Complex (J-PARC) [6].

2 Choice of the pre-chopper in CSNS LEBT

Space charge effects are very severe in LEBT since the beam energy is comparatively low. One of the most difficult problems, therefore, is to focus the high-brightness beam extracted from a proton or H^- ion source. The conventional method is to make full use of the effects of charge neutralization, while solenoids are used in LEBT. Judicious use of charge neutralization in the background gas improves the focusing considerably. Even so, some loss of beam current and deterioration of beam quality appears to be unavoidable. In practice, a pressure of the order of 10^{-5} torr is generally kept in the LEBT tube, and about 90% space charge neutralization is usually realized. In this case, higher than 90% beam transmission and lower than 10% beam emittance growth are available.

Obviously, the electrostatic field produced by the electrostatic pre-chopper will destroy the charge neutralization thoroughly by deflecting all ions and electrons generated by the collision between the beam and the background gas. So, unless the space charge neutralization is not needed or the electrostatic field is confined to a very narrow range of the downstream LEBT, the electrostatic chopper cannot be adopted. For example, the length of LEBT is only 12 cm for SNS and in this case no charge neutralization is needed.

In order to avoid destroying the space charge neutralization in LEBT, a MA induction cavity is adopted to pre-chop the beam by modulating the injection beam energy out of the longitudinal acceptance of RFQ for J-APRC. However, due to the high power dissipation of the induction cavity and some other problems, such as high chopping voltage and noise, the pre-chopper has yet to be used, only the chopper in MEBT is used.

The schematic layout of CSNS LEBT is shown in Fig. 1. here, an electrostatic deflector as the pre-chopper is chosen to chop the beam for CSNS, and the deflector is installed downstream in the LEBT, i.e. at the entrance of RFQ.

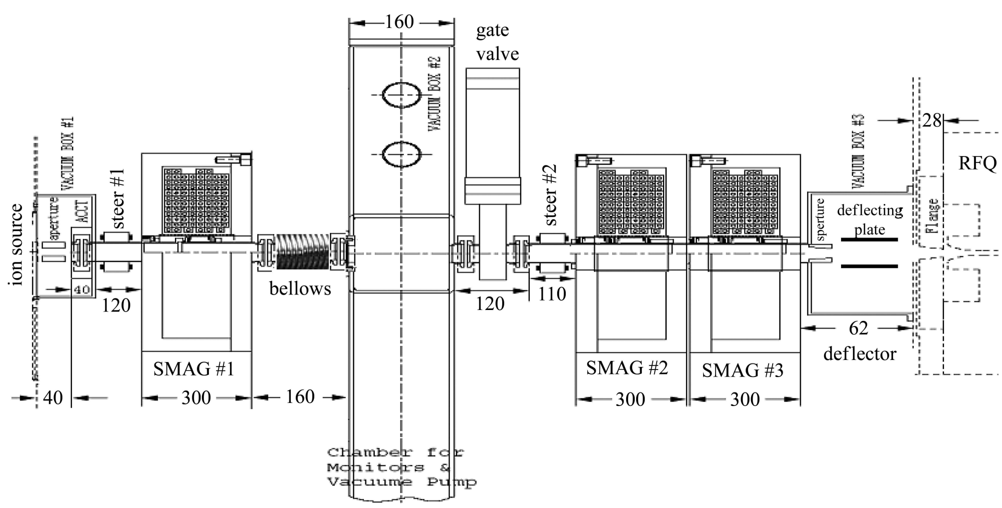

Fig. 1. The schematic layout of CSNS LEBT. An electrostatic deflector as the pre-chopper is located downstream in the LEBT, i.e., at the entrance of RFQ.

3 Physical design of CSNS pre-chopper

From Fig. 1 one can see that, including the width of the flange of RFQ, the longitudinal space for the electrostatic deflector is 90 mm in total. Although the designed width of the flange of RFQ at the outside area is 28 mm, the width of the flange at the central area is 10 mm. So the real longitudinal space for the deflector and other related components is 80 mm.

In order to confine the destruction of charge neutralization caused by the deflector in the local area, a ground potential electrode and an electron-trapping electrode are installed upstream of the deflector. In addition, a beam collimator is installed on the flange of RFQ. The collimator, which is electrically insulated from the flange of RFQ, is split azimuthally into four quadrants, which are also electrically insulated from each other. When the beam is deflecting from the centre, the deposited beam charge and therefore the current will be different for the four quadrants. In Fig. 2, the schematic layout of the deflector and other related components is shown. Sloping deflecting plates are used instead of parallel deflecting plates to decrease the deflecting voltage. For comparison, the beam envelope at a beam current of 40 mA is also shown. As a rough estimate, the required deflecting voltage will decease by about 20%–30% in this way. The gap between the deflecting plates varies from 11.04 mm to 23.28 mm, which has the same variation trend as the beam envelope, and the value is about 1.2 times the beam envelope size. To lower the capacitance between the two plates, the width of the deflecting plates also varies with the envelope size, which is 1.5 times the envelope size. The horizontal length of the deflector is 40 mm, the length of the collimator 6 mm, the length of the ground electrode 3 mm and the length of the trapping electrode 5 mm.

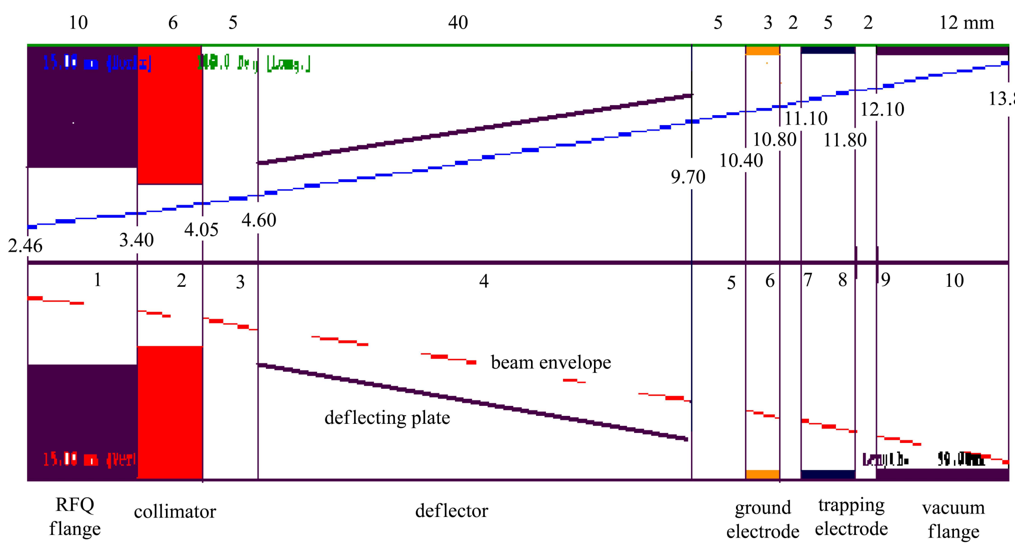

Fig. 2. The schematic layout of the deflector and other related components. For comparison, the beam envelope at a beam current of 40 mA is also shown.

To lower the deflecting voltage and to save the beam target, the chopped beam is designed to lose in the RFQ cavity. To chop the beam thoroughly, it is mecessary to deflect the beam out of the transverse acceptance ellipse of RFQ in phase space, then the beam transmission of RFQ will be zero and it loses completely in the RFQ cavity. Therefore, in this way the deflecting voltage is lowered compared with chopping the beam directly on a beam target located at the front of RFQ. For calculation simplicity, the displacement and the deflecting angle of the beam due to the deflector are calculated by the following equation, got from the parallel plates [7]:

$$x' \cong \frac{VL}{2dV_{\rm a}}, \quad x \cong \frac{VL^2}{4dV_{\rm a}} + x' \cdot L_{\rm drift}, \tag{1}$$

where x' is the deflecting angle at the exit of the deflector, x the displacement at the exit of deflector, V the deflecting voltage, d=30 mm the gap between the plates, L=40 mm the length of the deflector, $V_{\rm a}$=50 keV the beam energy and $L_{\rm drift}$ the drift length after the deflector.

Simulations are carried out to determine the relationship between the RFQ transmission, the displacement and the deflecting angle, and thus the deflecting voltage through the RFQ multi-particle tracking code PARMTEQM. Fig. 3 shows the beam transmission of RFQ versus the deflecting voltage when the beam current is 40 mA. As seen in Fig. 3, the beam transmission of RFQ is zero when the deflecting voltage is 4.5 kV. For this voltage the corresponding displacement and deflecting angle are x=2.46 mm and x'=60 mrad, respectively.

Now that the chopped beam is lost in the RFQ

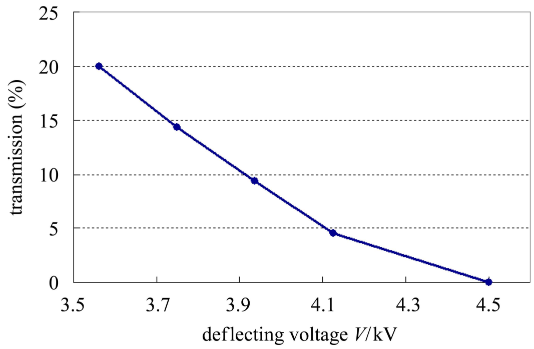

Fig. 3. The beam transmission of RFQ versus the deflecting voltage.

cavity, it must be known how much the total lost beam power is in the RFQ cavity, and what the distribution of the lost beam power is in the RFQ cavity. In Fig. 4, the lost peak beam power versus the RFQ longitudinal position is shown. Most of the lost beam power is deposited at the beginning of RFQ and the largest lost peak beam power is up to 1.8 kW. The total peak power deposited in RFQ is about 2.271 kW compared with the injection beam power of 2.0 kW, so the beam is lost in the RFQ cavity basically without acceleration. Taking the beam duty factor of about 1% and the chopping ration of 50% into account, the average lost beam power is under 12 W. So the lost beam should not have any damage to the RFQ cavity with cooling water. In fact, although the chopped beam is designed to deposit on the beam target for SNS, there is still much beam lost in the RFQ due to the inadequate deflecting voltage. No damage has been found up to now or is foreseen in the future.

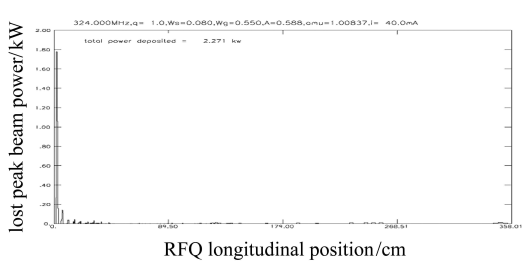

Fig. 4. The lost peak beam power versus the RFQ longitudinal position.

If the rise time of the power supply circuit is not taken into account, the least rise time of the chopped beam pulse is determined by the flight time of the beam particle in the deflecting plates:

$$\tau = L/v = L/\sqrt{E/m}, \quad (2)$$

where v is the particle velocity, E the particle energy and m the particle rest mass. For example, when L=40 mm and E=50 keV, then τ=13 ns. However, if the applied deflecting voltage $V_{\rm apply}$ is larger than the required deflecting voltage $V_{\rm need}$, then the rise time of the chopped beam pulse will be scaled by the following equation:

$$\tau' = \frac{V_{\rm need}}{V_{\rm apply}}\tau. \quad (3)$$

For instance, when the applied deflecting voltage $V_{\rm apply}$=5 kV, the required deflecting voltage $V_{\rm need}$=4.5 kV, τ'=11.7 ns. In practice, a higher output voltage of the power supply is beneficial to the rise time of the beam pulse and therefore it is encouraged.

4 Experimental plan of the pre-chopper in ADS RFQ LEBT

In order to examine the reliability of the above-mentioned pre-chopping design, a similar pre-chopping design in the Accelerator Driven Subcritical Reactor System (ADS) RFQ LEBT is also done. The experiments on the pre-chopper are also being prepared. The design is based on the existing ADS RFQ LEBT layout and the structure of the third vacuum chamber located at the entrance of RFQ. The deflector, the collimator and the electron-trapping electrode are all installed on the existing beam current monitor ACCT housed in the third vacuum chamber. As shown in Fig. 5, the horizontal

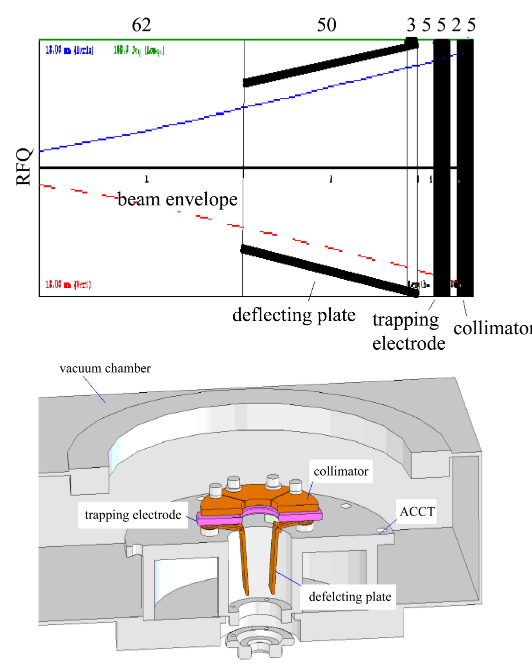

Fig. 5. The layout of the deflector and related components in the third vacuum chamber.

length of the deflector is 50 mm, the gap between the deflecting plates varies from 20.16 mm to 33.84 mm, which is 1.2 times the beam envelope size, and the width of the deflecting plate varies from 25.2 mm to 42.3 mm, which is 1.5 times the beam envelope size.

3-dimension simulations by MAFIA code are carried out to determine the loaded capacitance of the deflector and the least needed voltage for the electron-trapping electrode. As shown in Fig. 6, the simulated components include the deflector and its two legs, the ACCT, the electron-trapping electrode and the collimator. It is very important that the loaded capacitance is known in the design and manufacture of its power supply. The following equation is used to calculate the loaded capacitance:

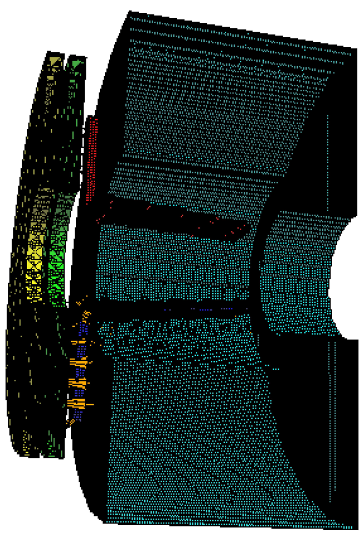

Fig. 6. The cutting view of the simulated 3-dimensional MAFIA volume.

$$W=\frac{1}{2}CV^2. \tag{4}$$

where W is the electric field storing energy, C the loaded capacitance and V the applied voltage on the deflector. The storing electric field energy is about 8.92×10^{-5} J, determined by MAFIA code when the applied voltage on the deflector is 5 kV. From Eq. (4), the loaded capacitance can easily be found as C=7.14 pF.

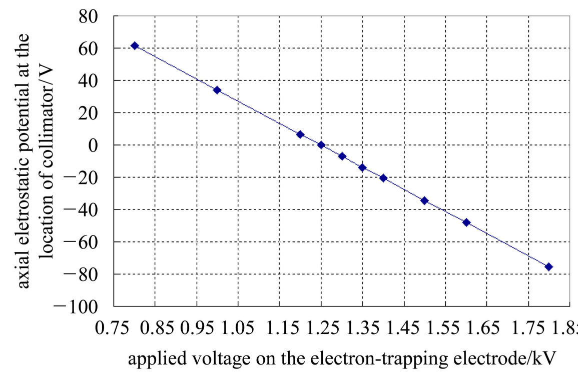

Fig. 7. The axial electrostatic potential at the location of the collimator versus the applied voltage on the electron-trapping electrode.

As mentioned above, the electron-trapping electrode is used to confine the destruction range to the local area. Obviously, when the electrostatic potential on the beam axis is zero or less than zero at the location of the collimator, then the deflector has no side effect on the charge neutralization existing in the long beam transportation line of LEBT upstream of the collimator. Fig. 7 shows the axial electrostatic potential at the location of the collimator versus the applied voltage on the electron-trapping electrode. From Fig. 7 one can see that the electrostatic potential on the beam axis at the location of the collimator is zero when the applied voltage on the electron-trapping electrode is −1.25 kV. Certainly, a negative electrostatic potential is beneficial to the trapping of the ions and hence the charge neutralization. So, in practice, an absolute voltage higher than 1.25 kV will be applied.

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