QUADRUPOLE SLOW-WAVE DEFLECTOR FOR CHOPPING CHARGED-PARTICLE BEAMS*

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Abstract

We introduce a new beam-deflector design for chopping low-energy charged-particle beams, the quadrupole slow-wave deflector (QSWD). This new design integrates the traveling-wave beam deflector, an electrostatic quadrupole, and clearing electrodes into a single compact structure. The four-electrode device performs ion clearing and linear focusing in the quadrupole (or transmit) mode, and also serves as a fast kicker in the deflecting mode. A QSWD operates with a constantly sustained electric field that sweeps off the ions and electrons produced by beam-gas scattering. Thus, a chopper using the QSWD can avoid beam neutralization with consequent emittance growth due to the beam-plasma interaction. We shall present the theoretical studies and the design considerations of the quadrupole deflector. A conceptual design of the chopper for a proposed Long Pulse Spallation Neutron Source (LPSS) at Los Alamos will be given as an example.

Introduction

A typical chopper for low-energy proton or H^- beams uses a fast beam-deflector of slow-wave structure to deflect the unwanted beam to a beam stop. The H^- beam chopper at LAMPF, operating at 750-keV energy is an example[1]. With the advances of the Radio-Frequency-Quadrupole Accelerator (RFQ) and ion source technologies, particles produced in the source can be accepted immediately by an RFQ and accelerated to relatively high energy (2 to 7 MeV) to reduce the phase-space distortion caused by space-charge effects. Thus, beam chopping has to be performed either at a lower energy of some tens of keV between the ion source and RFQ or after the RFQ at an energy of several MeV[2]. An example is found in the LPSS design currently under study at Los Alamos.

Chopping beams at lower energy has the advantages that it is easier to deflect particles and to handle the dumped beam. However, in order to keep the low-energy beam transport (LEBT) distance short to minimize the emittance growth and H^- stripping, the chopper needs to be close to the source. Problems then arise when high vacuum can not be achieved in the deflector region to prevent plasma build up and beam neutralization. Instabilities due to the beam-plasma interaction may occur that limit the beam intensity. Even when the beam can be stably transported, the pulsating field of the deflector can induce strong fluctuations in the plasma and beam neutralization that cause phase-space distortion. An attempt to implement a chopper at 35-keV beam energy at Brookhaven National Laboratory failed for this reason[3]. Our recent computer simulations have evinced this effect[4].

A conceivable solution is to apply a clearing electric field in the deflector region to sweep out the unwanted charged particles. In the following, we shall present a new type of deflector, the quadrupole slow-wave deflector that can be operated with a constantly sustained electric field to minimize the beam neutralization[4]. Although we shall concentrate our discussions on the choppers for proton or H^- beams, the underlying principle should be applicable to all other kinds of charged-particle beams.

The Idea and The Theoretical Study

The idea of a QSWD is to modify one pair of the poles in an electrostatic quadrupole and to use them as the deflector electrodes. To delineate the operational principle, we assume that an H^- beam will be deflected vertically and that the electrodes are oriented in the upright direction. Fig. 1 shows the structure of a QSWD, in which the horizontally deflecting electrodes are the same as those in a normal quadrupole and the vertically deflecting electrodes are made of hyperbolically curved parallel plates connected by coaxial cables behind the ground plate to form a helical slow-wave structure.

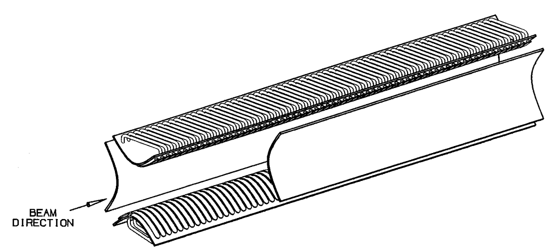

Fig. 1. An illustration of the QSWD structure.

During operation, a dc voltage V is constantly applied to the horizontally deflecting electrodes and the vertically deflecting electrodes are connected to pulsed-power sources. When the pulsing voltages are switched to the ground level, the QSWD functions as an electrostatic quadrupole that focuses the beam in the vertical direction. This constant quadrupole electric field also sweeps off the ions and electrons produced by the beam-gas scattering. When the two slow-wave structures are excited separately, with synchronized pulses of voltage V and $-V$, a deflecting-field pattern with a high dipole component is established as shown in Fig. 2(b).

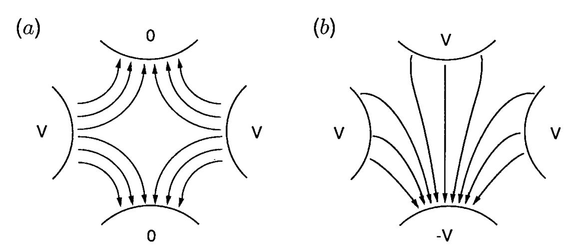

Fig. 2. Schematics of the field configurations in a QSWD: (a) quadrupole mode, and (b) deflecting mode.

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A beam passing through the QSWD will be deflected vertically. The beam chopping can be accomplished by inserting a beam stop, e.g., a metal plate, in the downstream beam-line to stop the deflected beam. Note that since the quadrupole component of the deflecting field converges the beam in the vertical direction and diverges it horizontally, the beam is spread out horizontally on the beam-stop, so that cooling can be handled easily.

We now discuss some of the considerations and theoretical analyses for designing a QSWD. We notice that in order to clear the ions and/or electrons in the beam, the quadrupole field has to be greater than the beam field. Also, we find from the deflecting-field pattern of a QSWD that a beam can be deflected and optimally focused in the same direction and at the same time only when the voltage on the slow-wave structure is higher than or equal to that on the horizontal electrode. Combining these conditions, we obtain a requirement of the minimum voltage for the optimal operation of a QSWD: $V_d \geq Ia^2/(2\pi v\varepsilon_o b^2)$, where I is the beam current, V_d is the deflecting voltage of the slow-wave structure, a is the distance from the central axis to the pole-tips, ε_o is the permittivity of the free space, b is the average beam radius in the channel, and v is the particle velocity. As an example, consider a 100-keV, 20-mA proton beam; if a/b = 2.5, we need $V_d \geq 510$ volts.

Since an exact solution of the time dependent electromagnetic field in the slow-wave structure is difficult to obtain, measurement results and operational experience of the planar coax-plate deflector now in service at LAMPF are used for the purpose of estimation and making approximations in our analysis. The electrodes of the LAMPF planar coax-plate deflector are one-meter long and have a structure similar to those shown in Fig. 1, except that the electrode plates and the ground plates are planar instead of curved. The efficiency was maximized by making the electrode-plates 7.9-mm wide on a 19.2-mm center-to-center spacing. For a separation of 2.8 cm between the deflector electrodes, the bandwidth of the deflector is about 200 MHz corresponding to a rise time about 5 ns. The deflecting electric field measured on median plane is about 94% of that calculated for a continuous pole-face structure using a static-field approximation. Operational experience indicates that the effect of wave dispersion in the slow-wave structure is unimportant. Hence, except for high-frequency operation, one can use the static field computed for an infinitely long smooth pole-face boundary to approximate the field in a QSWD. The approximate electrostatic field for the deflecting mode of a QSWD has been calculated by using a conformal mapping technique[5]:

$$E_x(x,y) = \frac{-\mathrm{sgn}(x)V}{\sqrt{2}a^2}\left[\sqrt{2}x + x\,\mathrm{sgn}(y)\Gamma\cos\psi + y\Lambda\sin\psi\right], \quad (1)$$

and

$$E_y(x,y) = \frac{V}{\sqrt{2}a^2}\left[\sqrt{2}y - y\Lambda\sin\psi + y\,\mathrm{sgn}(y)\Gamma\cos\psi\right], \quad (2)$$

where $\Gamma = \rho + \rho^{-1}$, and $\Lambda = \rho - \rho^{-1}$,

$$\rho = \frac{\left(\sinh^2 q\cosh^2 q + \sin^2 p\cosh^2 p\right)^{1/4}}{\left(\cos^2 p\cosh^2 q + \sin^2 p\sinh^2 q\right)^{1/2}},$$

$$\psi = 0.5\tan^{-1}\left(\sin p\cos p\,\mathrm{csch}\,q\,\mathrm{sech}\,q\right) + \left(\pi/4\right),$$

$p = \pi(x^2 - y^2)/(4a^2)$, and $q = \pi xy/(2a^2)$.

To track the motion of the deflected beam, we have developed an envelope-tracking program that uses a set of semi-empirical envelope equations and a particle simulation code utilizing the electric field given in Eqs. (1) and (2). We observe good agreement between the envelope tracking and the particle simulation for a KV beam.

A Design Example: Application to the Chopper for LPSS

In the design of LPSS, an upgrade to the front end of LAMPF linac is planned that utilizes an RFQ to replace the injector, the LEBT line, and the first tank of the linac. Such a reconfiguration, however, requires replacement of the chopping function that provides the appropriately time structured H^- beam to the LANSCE accumulator ring. Chopping (removal of 25% of the beam at a 2.8-MHz rate) is currently accomplished by a fast-deflector device in the LEBT. With the new configuration, chopping is best accomplished before injection into the RFQ, at a low energy of 100 keV as opposed to the 750-keV energy of the LEBT. At this low energy, a design using a QSWD chopper described below is probably the best choice to avoid difficulties caused by beam neutralization.

For LPSS, the beam condition at the ion source is a 100-keV 15-mA beam with a normalized rms emittance of 0.02π cm mrad and having an envelope of round cross-section with 0.5-cm radius and a divergence of 65 mrad. We use an 18-cm long solenoid with 0.5-T field placed 20 cm in front of the source to focus the divergent beam into the chopper. In the absence of other fields, the beam can be focused to a waist of 0.5-cm radius about 80 cm downstream of the solenoid. The small waist at this point permits adequate separation of the chopped beam at the chopping aperture for a 70-cm deflector length with reasonable voltages.

The maximum voltage of the FET power amplifier now used to drive the slow-wave chopper at LAMPF is about 1 kV. Assuming the same kind of power supply is used in this design, we choose 0.7 kV as the nominal voltage for the deflector and for the electrostatic quadrupole in the QSWD. The energy variation of beam particles caused by this low voltage should be negligible. At a reasonable pole-tip-to-pole-tip distance (6 to 10 cm), the quadrupole gradient is around 1 MV/m^2. For an average beam radius around 1.5 cm, the electric field in the structure should be sufficient to sweep off all the ions and electrons created by gas scattering. The degree of neutralization can be adjusted by varying the QSWD voltage; the consequent shift in the beam-waist position can be corrected by adjustment of the upstream solenoid field. Tracking the envelopes of the deflected beam indicates that, at a deflecting voltage of 0.7 kV and with a chopping aperture between 3 and 4 cm, the length of the deflector should be more than 60 cm. Shorter deflectors or larger separations between the electrodes would require higher voltage to operate the deflector. We chose a 3.5-cm aperture and a 70-cm long deflector. The beam stop is placed 9 cm downstream of the deflector to block the deflected beam. This stand-off distance is chosen to make the transport distance short and to protect the electrodes from being contaminated by the spallation products knocked off from the beam stop by the deflected beam.

Simulation results show that a beam stop located at 1 cm above the central axis should be adequate to block almost all the deflected beam and to let almost all the undeflected beam pass through. An example of particle simulation results is given in Fig. 3 for an initially Gaussian- distributed phase space truncated at three standard deviations. The results of a sensitivity study indicate that the performance of the QSWD is not very sensitive with respect to small variations of beam conditions and to the voltage on the electrodes.

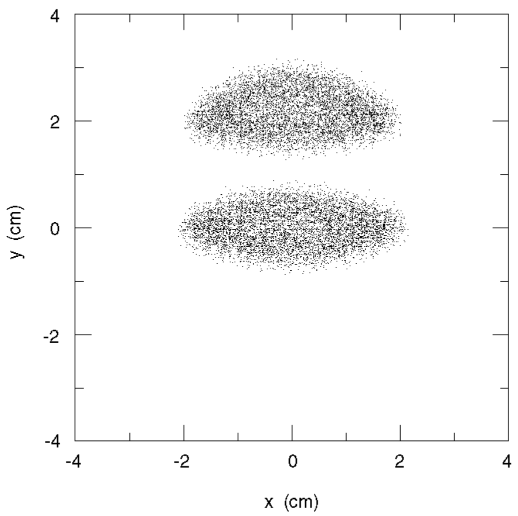

Fig. 3. Simulated beam particle distribution at the beam stop. The upper and the lower distributions correspond to the deflected and the undeflected beams, respectively. Beam particles are assumed to have a Gaussian distribution (truncated at 3-rms) at the entrance to the chopper.

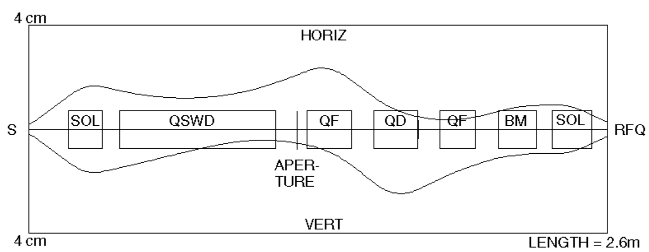

Fig. 4. A design layout showing the beam envelopes and the optical elements from the ion source to the RFQ in the conceptual design for the LPSS chopper.

A possible beam transport system from the chopper to the RFQ is shown in a TRACE2D output in Fig. 4. In this design example, three electrostatic quadrupoles and one magnetic solenoid are used for beam matching purpose. The electrostatic quadrupoles are adopted to minimize the beam neutralization in transport line. The magnetic dipole is inserted for the purpose of merging the H^- and the proton beam-lines before the RFQ.

It should be noted here that, due to the finite mobility of ions in the beam channel, a small amount of neutralization is unavoidable. An accurate estimation is difficult because of the complicated field configuration. A crude estimate shows that for the LPSS parameter range, a vacuum of at least 10^{-5} Torr is needed in the QSWD for the chopper to operate successfully. At this pressure, the beam neutralization is a few percent. Also note that chopping at the end of the QSWD has the advantage of making the LEBT short, but, depending on applications, this may not be the optimum design. Alternatively, one can use focusing devices downstream of the QSWD that amplify the beam deflection.

A similar chopper design with 30-mA beam current and 1-kV QSWD voltage was also studied. In this case, at the entrance of the RFQ, phase-space distortion due to space-charge effect becomes noticeable in the transmitted beam. Operation at higher beam current would require higher voltage on the QSWD, better vacuum, and a shorter matching section before the RFQ. The application of a QSWD can be limited by any of these requirements.

Summary and Conclusions

We have suggested a chopper-deflector that also provides electrostatic focusing to the chopped and unchopped beams for chopping low-energy charged-particle beams utilizing a QSWD. A chopper using a QSWD can avoid the possible beam neutralization and the complications due to the beam-plasma interaction. We have calculated the electrostatic field of the QSWD. Computer programs have been developed for designing a QSWD chopper. An example of a conceptual design for LPSS has been also presented. Theoretical studies show that it is feasible to build such a working device.

Acknowledgments

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