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Construction and test of an ion-gate with high-voltage switch system for single-reflection time of flight measurement

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ABSTRACT
An ion gate and its high-voltage pulse switch system are constructed to produce a few nanosecond pulse beam so that the beam can be used for the time of flight (TOF) measurement. The maximum gating voltages are set to be $\pm 1$ kV to deflect away ion beams of intermediate heavy nuclei such as $^{133}$Cs when the gate is closed. The ion gate was designed by calculating deflection angles analytically and was checked numerically, which were in agreement. On the other hand, the switch system uses a Behlke switch, solid-state high voltage device, for pulse gating and its circuit was designed utilizing an equivalent circuit of the gate. Simulation by LTspice showed that a 10 ns pulse with a peak voltage of 2 kV can be produced if the capacitance of the gate is less than 50 nF. The ion gate was first tested inside the TOF system to ensure that a Cs$^{+}$ beam can be turned on and off in terms of beam arriving at a Faraday cup. The switch was then tested in connection with the gate, and we found that the pulse can be produced and its peak can be controlled by adjusting the capacitance of connection cables so far as its width is kept.

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I. INTRODUCTION
An ion gate (also called the Bradbury–Nielson gate)$^1$ and its high-voltage pulse switch system were designed and fabricated to be used for the time of flight (TOF) measurement of charge-bred ion beams extracted from an electron beam ion source (EBIS). The ion gate deflects the beam away in the closed state and is opened for a few nanoseconds by the switch system to produce a short pulse beam. The TOF system is achromatic with single reflection$^2$ and can be used to quickly monitor the charge state distribution so as to maximize the current of the desired charge-state, which largely depends on charge breeding time by the EBIS. Such a system has been used for the EBIS of Brookhaven National Laboratory for an Au beam.$^3$

An EBIS is under construction for the isotope on line (ISOL) facility of the rare isotope science project (RISP) in Korea$^4$ and will be used for charge-breeding of singly charged isotopes extracted from the ISOL target. To maximize the number of ions in a specific charge state for post acceleration, it will be helpful to measure the charge state distribution within a beam bunch usually with a length of tens of microseconds. The ion gate can select a section of the bunch in the process of searching for an optimal parameter setting of the EBIS. The electron gun can produce a maximum current of 3 A, and a superconducting solenoid is used to produce 6 T for compressing the electron beam up to a radius of 0.5 mm to reach the current density of 500 A/cm$^2$. For intermediate heavy nuclei, the charge bleeding time should be in the range of tens of milliseconds in achieving the mass to charge ratio below 7 considering that the maximum repetition rate conceived is 20 Hz to match with the maximal production rate of isotope beams from the ISOL target.$^6$ The pulse switch for the gate is designed to operate at the same rate to monitor the charge state distribution of each pulse.

The ion gate assembly is located at the entrance of the TOF system to produce a pulse beam as shown in Fig. 1. Also shown is a Cs ion source connected to test the beam gating and pulse beam generation. Ions from the source are mostly Cs$^{+}$, while other singly charged ions of residual gases are also extracted. Considering its mass, Cs$^{+}$ is expected to be the slowest ion produced in large quantity during the test. After charge breeding by the EBIS, the TOF...
system will analyze the charge state distribution in the process of maximizing the ions in the charge state of 27+ as a reference. The flight path of the TOF is roughly 2 m long, and the flight time of $^{133}\text{Cs}^{27+}$ at the energy of 20 keV is around 2.26 $\mu$s. It differs by around 42 ns for the ions with $\Delta q = \pm 1$. Hence, a pulse width of 10 ns is acceptable for identifying the ion currents of different charge states. The TOF is designed to have a mass resolving power ($m/\Delta m$) of 300.

Figure 2 shows the ion gate assembly and its neighboring components. A movable Faraday Cup (FC) is located in front of the gate assembly to measure the total current from the Cs source and sometimes to block the beam without turning off the source. A collimator made of copper is attached to the gate assembly to limit the beam size and also to measure the stray current. A set of electrostatic deflectors in the downstream is used to steer the beam into the reflector, which is an electrostatic mirror as depicted in Fig. 1, so that the beam can be reflected toward a multi-channel plate (MCP, Hamamatsu F12334-11) detector with an effective area of $\phi 20$ mm. A DC beam from the source was first used to check whether the beam can be turned on and off by the gate in terms of beam arriving at the MCP detector.

The switch was designed considering an equivalent circuit of the ion gate assembly. In principle, finite element analysis can be used to accurately estimate the lump circuit of the gate, but a rough estimate of capacitance was thought to be sufficient for designing the switch circuit. The system utilizes a solid-state Behlke device, and its circuit was evaluated using LTspice. Depending on the capacitance of the gate, the pulse shape differs when the switch is turned on. The shape becomes considerably distorted in view of its width when the capacitance is over 50 pF.

II. THE ION GATE

The ion gate system was adopted to produce a high-voltage pulse beam for the TOF measurement with a flight path of 2 m. A deflection plate can be an alternative but at the costs of higher capacitance and longer fringe fields, which can increase the pulse width. The fabricated gate and its design parameters are shown in Fig. 3. The wire made of brass has a diameter of 0.2 mm and is wound on a frame made of Acetal. This method is mechanically simple and vacuum compatible. The winding technique is similar to the one used to fabricate grid wires on the electrodes of an ionization chamber. Small O-rings are used to maintain uniform tension during winding instead of resorting to more sophisticated methods. When the gate is closed to deflect incident ions away, neighboring wires are applied by voltages of opposite polarity. In fact, a simultaneous change in the voltages on two wires to the ground potential allows minimal voltage variation, helping in reducing the pulse width. However, this scheme requires two switches. We chose to use only one switch at the voltage of $-1$ kV, the other wire being kept at 1 kV. When the gate is opened, equipotential on two wires effects the beam focusing but is minor because the beam energy is much higher than the gating voltage.

The deflection angle $\alpha$ by the ion gate can be analytically calculated as follows, where associated geometric parameters are denoted in Fig. 4:

$$\tan \alpha = \frac{\pi}{2 \ln\left(\cot\left(\frac{\mu R}{d}\right)\right)} \frac{V_{\text{wire}}}{E_k/q}$$

When the injection voltage ($E_k$) of $^{133}\text{Cs}^{27+}$ is 20 kV, for instance, the deflection angle is 0.4 mrad. To check with numerical calculation,
FIG. 4. An equipotential map by opposite voltages on neighboring wires of the ion gate. The distance between the wires (d) and the radius of wire (R) are defined.

The electric fields are computed using SUPERFISH\textsuperscript{16} with infinitely long wires in 2D and mid-plane symmetry being assumed. Equipotential lines are plotted in Fig. 4. The deflection angle caused by transverse momentum is calculated with the following relationships:

\[
\Delta p = \int qE_t \frac{dl}{v}, \quad \Delta \theta = \frac{\Delta p}{p},
\]

The deflection angle is calculated to be 30 mrad for Cs\textsuperscript{1+} starting at the center of two neighboring wires with the energy of 20 keV and at ±1 kV on the wires. The ions starting away from the center are deflected by larger angles while the analytical result is 34 mrad. The analytic deflection angles are displayed as a function of incident beam energy at different wire voltages in Fig. 5. A lower energy beam can be handled with a lower gating voltage but is more vulnerable to jitters and electrical noise. Further optimization on beam energy can be investigated using actual beams with the TOF system installed in the EBIS.

The gating of the Cs\textsuperscript{1+} beam was tested in the test stand as shown in Fig. 1 using a FC at the location of the MCP detector.

Two DC power supplies were connected to two wires of the gate. The beam reflection by the reflector was also tested by applying voltages somewhat higher than the beam energy. The reflector is composed of copper plates of 2 mm thick with an aperture of 8 cm. Table I is a summary of test results in which the settings of the TOF system and ion currents measured at the FC are listed showing that the beam gating is done by the applied voltages (V\textsubscript{ion gate}). The beam energy up to 20 keV was checked with the gating voltage of ±1 kV, while lower energy beams were gated using lower voltages. The switch system can be simplified if a lower maximum voltage is applicable.

### III. THE PULSE SWITCH SYSTEM

The switch system is designed based on a commercially available high-voltage Behlke device with an opening time option of 5 ns. The system is composed of two parts: (1) high voltage power supply and (2) pulse switching part using a Behlke switch. The switching part needs to be located near the ion gate to reduce the capacitance of connection cables, while the power supply can be placed away from the beam line so as to reduce radiation exposure. Two parts are then connected by coaxial cables. The opening of the Behlke switch is driven by a trigger (DG646, Stanford Research Systems) with a resolution of 5 ps. The reference signal needs to be accurately synchronized with the beam extraction time from the EBIS.

An equivalent circuit of the ion gate was devised as shown in Fig. 6 considering the capacitance between neighboring wires and with adjacent electrodes on ground potential. In principle, accurate
estimation can be made by finite element analysis including all the nearby components. However, only maximum capacitance, which is crucial in keeping the pulse width, was estimated assuming parallel wire approximation for the gate and considering the capacitance of the vacuum feed through and coaxial cable. A rough estimate was around 20 pF in which capacitance with nearby metallic components is roughly included. All the leads and circuit paths are also designed in view of reducing inductance.

A. Circuit design and simulation using LTspice

The circuit of the switching system was analyzed using LTspice with an equivalent circuit of the ion gate attached, as shown in Fig. 7. Assuming different capacitances of the gate, the circuit design was evaluated for the production of a high voltage pulse, also checking that a drain current of the Behlke switch does not exceed the specified limit of 80 A at a maximum power dissipation of 5 W. The voltages on the two wires are initially set at ±1 kV, and the switch is attached to the wire of negative voltage.

The voltage on the ion gate is monitored at the resistor junction of R3, as indicated in Fig. 7. The drain current flowing through R3 is a parameter determining the voltage shape. The lower resistance allows shorter transient time but at the cost of higher current. A non-inductive ceramic resistor is used to reliably sustain the large current in short time. The voltage and current pulses at two observation points are shown in Fig. 8 for capacitances of 20 pF and 50 pF. The pulse width is widened at 50 pF.

B. Test of the pulse switch

The switch was first tested in connection with circuit boards equivalent to the ion gate for three different values of capacitance in the range of 10–20 pF. The voltage pulses measured are shown in Fig. 9 together with triggering signals. As mentioned, the ion gate

FIG. 7. Circuit diagram of the pulse switch used for the analysis of LTspice. The system is divided into two parts depending on their locations relative to the ion gate.

FIG. 8. Simulated results using LTspice. The pulse voltage on the gate and the current flowing through the resistor indicated in Fig. 7 when $C_p$ is 20 pF (upper) and when $C_p$ is 50 pF (lower).
is effectively opened in terms of beam optics at voltages similar to that of the other wire. When the voltage of the other wire is kept at 1 kV, a clean pulse beam can be produced when the pulse voltage approaches to 1 kV from −1 kV. If the voltage exceeds 1 kV, the produced beam pulse may become wider.

The pulse signals were measured by using an oscilloscope with a bandwidth of over 1 GHz (Lecroy WaveRunner 8000) using a high voltage differential probe. The gate opening synchronizes with a timing signal of the delay generator, as shown in Fig. 9. The Behlke switch opens when a voltage pulse in the range of 3–10 V lasts longer than 50 ns as a trigger pulse, which appears as a delay of gate opening by 50 ns.

The pulse switch with the ion gate was tested as shown in Fig. 10. To measure the pulse voltage using the high voltage probe, the gate is first placed outside of the TOF system. Two different lengths of the coaxial cable between the gate and the switch are tested, and considerably different pulse shapes are observed as shown in Fig. 10 depending on the cable length. An optimal length could be determined with the ion gate installed inside the TOF system for which the voltage pulses can be no longer measured. A notable point is that the beam pulse shape at the MCP detector can be readily controlled by varying the cable length together with different voltage settings on the gate.

The TOF system is shown in Fig. 11 with the gate and pulse switch installed. The Cs ion source is connected to a high voltage platform for the beam extraction and focusing. A vacuum gate valve separates the two systems of the ion source and the TOF to facilitate frequent opening of the TOF during experiments by employing two turbo pumps.

The effect of high voltage pulse switching on the MCP detector was studied with all the TOF components installed. Especially, interference by the high-voltage pulse was checked considering that the MCP detector is located close to the ion gate. An MCP signal induced by the pulse is displayed on the scope together with a trigger signal in Fig. 12. Considerable amount of noise occurs at the MCP detector during the gating, which lasts for hundreds of nanoseconds before decay. However, this noise may not severely interfere with measuring single particle signals by the MCP detector because the flight time of the ions of interest is over 2 μs at a maximum voltage of 20 kV.
IV. SUMMARY

An ion gate and its switch system were constructed to produce required voltage pulses for the TOF measurement. The gate alone was first tested using a Cs\(^{1+}\) beam in the TOF system with a Faraday cup located at the position of the MCP detector. The DC voltages on two wires were controlled to verify the beam gating. The beam focusing and deflection elements of the TOF system were also tested together with the reflector. On the other hand, the switch system was designed based on circuit analysis. The initial test was performed with the switch connected to equivalent circuit boards composed of capacitors and resistors and showed that the measured pulse shapes agree with simulation results by LTspice. The switch was then tested with the gate attached outside of the TOF system. The pulses measured on the scope proved that the peak voltage of 2 kV with a pulse width less than 10 ns can be obtained and can be readily controlled by the length of the connection cable. The pulse shape will be further optimized with beam experiments later. Prior to that, the data acquisition system needs to be prepared for the MCP detector to measure the beam current spectra of different ions in different charge states.

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9. LTspice is freeware compute software produced by Linear Technology.

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