Ion Beam Transport Simulations for the 1.7 MV Tandem Accelerator at the Michigan Ion Beam Laboratory

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Abstract

The Michigan Ion Beam Laboratory houses a 1.7 MV tandem accelerator. For many years this accelerator was configured to run with three ion sources: a TORoidal Volume Ion Source (TORVIS), a Duoplasmatron source and a Sputter source. In this article we describe an application we have created using the SIMION® code to simulate the trajectories of ion beams produced with these sources through the accelerator. The goal of this work is to have an analytical tool to understand the effect of each electromagnetic component on the ion trajectories. This effect is shown in detailed drawings. Each ion trajectory simulation starts at the aperture of the ion source and ends at the position of the target. Using these simulations, new accelerator operators or users quickly understand how the accelerator system works. Furthermore, these simulations allow analysis of modifications in the ion beam optics of the accelerator by adding, removing or replacing components or changing their relative positions.

1. Introduction

The Michigan Ion Beam Laboratory (MIBL) is part of the Department of Nuclear Engineering and Radiological Sciences of the University of Michigan. The main instruments in the laboratory are a 400 kV ion implanter manufactured by National Electrostatics Corporation (NEC), a 1.7 MV tandem accelerator manufactured by General Ionex Corporation and a 3 MV tandem accelerator manufactured by NEC (recently installed). The facility is

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Keywords: education; educational aids; electrostatic accelerators; beams in particle accelerators; computer modeling and simulation

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primarily used to conduct material surface modification by ion implantation and radiation damage [Naab et al. (2011)]; and surface composition and structure interrogation through ion beam analysis.

The laboratory has the goal of developing an analytical tool to diagnose ion beam trajectories through these accelerators. In a previous article, we described the simulation of ion trajectories through the 400 kV ion implanter [Naab et al. (2013)] using SIMION® 8.0 [Manura and Dahl (2008)]. In this article, we describe the simulation of ion trajectories through the 1.7 MV tandem accelerator using the same code.

To help the readers, Table 1 has the list of the most used acronyms in this article.

<table>
<thead>
<tr>
<th>Acronyms</th>
<th>Meaning</th>
</tr>
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<tbody>
<tr>
<td>BPM</td>
<td>Beam Profile Monitor</td>
</tr>
<tr>
<td>CEC</td>
<td>Charge Exchange Canal</td>
</tr>
<tr>
<td>EC</td>
<td>Extraction Cup</td>
</tr>
<tr>
<td>ECC</td>
<td>Extraction Cup Canal</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
</tr>
<tr>
<td>HEM</td>
<td>High Energy Magnet</td>
</tr>
<tr>
<td>HET</td>
<td>High Energy Tube</td>
</tr>
<tr>
<td>HVT</td>
<td>High Voltage Terminal</td>
</tr>
<tr>
<td>IEAS</td>
<td>Ion Extraction and Acceleration System</td>
</tr>
<tr>
<td>LEM</td>
<td>Low Energy Magnet</td>
</tr>
<tr>
<td>LET</td>
<td>Low Energy Tube</td>
</tr>
<tr>
<td>MIBL</td>
<td>Michigan Ion Beam Laboratory</td>
</tr>
<tr>
<td>TEQ</td>
<td>Triple Electrostatic Quadrupole</td>
</tr>
<tr>
<td>TORVIS</td>
<td>TORoidal Volume Ion Source</td>
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</table>

2. General description of the accelerator

For many years, before the installation of the 3 MV tandem accelerator, the 1.7 MV tandem accelerator was configured as shown in figure 1(a). Figure 1(b) shows the application of the simulation to the 1.7 MV accelerator with all the electrodes/poles that produce the electric/magnetic fields to accelerate and transport the ion beam from an ion source to the target/sample.

The accelerator had two injection beamlines. One contains the TORVIS (T) source [Sundquist et al. (1995)] and the other contains the Sputter (S) [Middleton (1983)] or Duolam (D) [Lejeune (1974)] sources. In each of these injection beamlines, einzel (E) and gridded (G) lenses were used to focus the beam coming out of the ion sources at the charge exchange canal (CEC) of the high voltage terminal (HVT) in the accelerator tank. The low energy bending magnet (LEM) and sets of steerers (yS and xyS) were used to align the ion beam direction with the CEC.

In the accelerator tank the ions reach the desired energy. The voltage of the HVT is positive to attract the negative ions injected into the accelerator tank through the low energy tube (LET) and repel the positive ions through the high energy tube (HET).

The high energy bending magnet (HEM) bends the beam into the chosen experimental beamline. The triple electrostatic quadrupole (TEQ) focuses the beam at the position of the beam profile monitor (BPM) in each of the beamlines. Finally, the beam drifts to reach the target/sample (Ta). The direction of the beam is aligned with the target using the steerers (XYS) in each beamline.

The accelerator had three experimental beamlines: one of them for ion beam analysis (IBA), a second one for radiation damage by ion irradiation (II) and a third one for irradiation accelerated corrosion experiments (IAC). Only two of these beamlines are shown in figure 1(b).

3. Description of the simulation application

In the simulation application (figure 1(b)), only the electrodes/poles producing electric/magnetic fields are drawn, as they affect the trajectory and energy of the ions in a confined region of the space. Each component has been drawn according to its specifications using geometry files in SIMION® [Manura and Dahl (2008)].
In the simulation the ion trajectory starts at the aperture of a source. The initial conditions of the ions (energy and divergence) are used as inputs, and depend upon the source extraction voltage and the reported divergence of the ion beam coming out of the source.

![Diagram of the accelerator and SIMION® application](image)

**Fig. 1.** (a) 3D drawing of the accelerator. (b) 3D drawing of the SIMION® application developed to simulate ion trajectories. The insets show in more detail some of the components. The geometry of the LEM and HEM poles are identical, their orientations are opposite. The inset labeled ‘EQ’ shows one electrostatic quadrupole. The beam trajectory corresponds to protons at 2 MeV on the target.

A voltage is assigned to the electrodes of each component to calculate the electric or magnetic field in the volume of the component where the beam goes through. These voltages are adjusted manually to achieve the desired effect (beam direction, beam energy or focused beam position).

The ions injected in the LET have negative charge (atom with one extra electron) up to the HVT. In the CEC the
ions become positive. Different positive charge states can be assigned to the ions coming out of the CEC. The position where the ion becomes positive and the ion final charge state is programmed in SIMION® using a LUA file [Manura and Dahl (2008)].

3.1. Ion initial conditions for each ion source


![Fig. 2. Ion extraction and acceleration system of the TORVIS. (a) Schematic reproduced from figure 1 in Sundquist et al. (1995). (b) Drawing done with SIMION®. The H⁻ initial energy is 1.8 keV and the H⁺ energy at the exit of this system is 34.4 keV.](image-url)

Figure 2(a) shows a schematic of the TORVIS and its ion extraction and acceleration system (IEAS). The inset labeled ‘Ex’ in figure 1(b) is a 3D drawing of the IEAS of the source done with SIMION® that does not include the source body or aperture. Figure 2(b) shows a 2D view of the same system, the voltage of each electrode in operation conditions, some equipotential lines along the system, and the H⁺ ion trajectories. The potential difference between the source body or aperture and the first electrode downstream from the source, the extraction cup (EC), is 1.8 kV. As the beam is extracted through the aperture of the source it is focused in the extraction cup canal (ECC) and diverges afterwards [Alton (1981)]. The divergent beam from the ECC is nearly equivalent to have a virtual point object at the end of the ECC close to the source emitting ions with 1.8 keV initial energy (see figure 2(b)). This assumption is validated by the schematics in figures 7a, 10, 12 in Alton (1981). The electrodes EC and EL1 form a gap lens; and the electrodes EL1, EL2 and EL3 an einzel lens. The beam is focused at the right end of the EL3 electrode where there is a hollow cylinder (represented by dashed lines) that, in practice, reduces the conductance of the system to avoid H₂ gas flowing downstream from the IEAS into the acceleration tubes. The final three electrodes of the system are R1, R2 and R3 that form a short acceleration tube. In the simulation, the initial H⁺ energy is 1.8 keV and the H⁺ energy at the exit of the IEAS is 34.4 keV. The voltage values used in the simulation for each electrode are the same values used in practice to maximize the beam current from the source. We observe in figure 2(b) that the simulation reproduces the focal point at the position of the hollow cylinder to maximize the current output from the source.

In the case of the Duoplasmatron source (used to produce helium ion beam) the IEAS is simpler than for the TORVIS. As shows figure 1 in Lejuene (1974), the body of the source is at the same voltage than the extractor. This voltage determines the energy of the ions coming out of the source, which in our laboratory is typically 18 kV. The
ions are extracted through a very small aperture (0.015” in diameter). The source is set to extract He$^+$ ions. At 6 cm downstream from the source there is an einzel lens (see component labeled ‘E’ in figure 1(b)) that focuses the beam in a charge exchange system, a Na oven, where the He$^+$ ions are converted to He$^-$ ions. Figure 3 shows the simulation of helium ion trajectories from the source aperture through the einzel lens and the oven canal (represented by dashed lines). The oven canal is located 55 cm downstream from the einzel lens. In the simulation, the voltage of the einzel lens middle electrode to focus the beam in the oven canal is 15.3 kV. In practice, the value of the einzel lens voltage to maximize the beam current through the oven canal is about 16.2 kV, showing a very good agreement with the value of the simulation.

![Fig. 3. Simulation of helium ion trajectories from the Duoplasmatron source. The initial condition of the beam is a point source emitting ions at 18 keV with maximum divergence of 3°. Equipotential lines in the einzel lens are shown. The trajectory lines change color where the ions change their charge state inside the oven canal. In this figure, the scale in the vertical direction is increased by a factor of 2.](image)

In the case of the Sputter source, similar to the TORVIS, negative ions are extracted from the source and there is no need to have a charge exchange system after the source. The process of producing negative ions with the Sputter source [Middleton (1983)] is completely different from the processes for both the TORVIS and the Duoplasmatron source. But the ion optic of the Sputter source, for the purpose of the simulation, is very similar to the optic of the Duoplasmatron source, shown in figure 3; only a few changes have to be made. The initial conditions are a point source at 10 cm from the einzel lens emitting ions at 30 keV with maximum divergence of 3°. Since the ions extracted from the Sputter source are negative, the polarity of the middle electrode of the einzel lens is negative to properly focus the beam downstream.

3.2. Ion injection into the acceleration tubes

After the ion beam is extracted from an ion source, it is injected in the acceleration tube and focused in the CEC in the HVT. The two injection beamlines are similar (see figure 1).

For the TORVIS, it was mentioned in the previous section that the beam is focused before the exit of the IEAS (see figure 2(b)). Then the Y steerer (yS), the bending magnet (LEM) and the XY steerer (xyS), shown in figure 1(b), are used to align the direction of the beam with the CEC in the HVT. Each of these components is very simple. A steerer produces a region of uniform electric field to change the direction of the beam by a small angle on the order of 1°. A bending magnet produces a region of uniform magnetic field where the ion beam is bent, in our case, by an angle of 30°. A gridded lens (see ‘G’ labeled component in figure 1(b)) is used to focus the beam in the CEC. Figure 4 shows a 2D drawing of this lens. A gridded lens is formed with two grounded cylindrical electrodes and a metallic mesh in between. The metallic mesh is biased to a positive voltage to focus the negative ion trajectories at the desired location. The voltage applied to the gridded lens in the simulation to focus the 34.4 keV H$^-$ beam in the HVT canal is 6.0 kV. The value used in practice is about 6.5 kV.

For the Duoplasmatron source, it was mentioned in the previous section that the ion beam extracted from the source is focused in the Na oven canal with an einzel lens. After that, the beam is focused in the CEC in the HVT in a similar way as explained for the TORVIS. In this case, the gridded lens voltage in the simulation to focus the beam in the HVT canal is 3.3 kV. The value used in practice is about 3.0 kV.

For the Sputter source, the beam is injected in a similar way as that for the TORVIS and Duoplasmatron sources. For many years we used the Sputter source to produce iron beam with an extraction voltage of -30 kV and a power supply for the einzel lens of -20 kV. Under this condition, it was impossible to focus the beam between the einzel lens and the gridded lens. As an example: according to the simulations, the voltage required to focus a 30 keV negative ion beam from the Sputter source at the position of the Na oven canal (as in figure 3) between the einzel
and gridded lenses is -26.5 kV. Then, the combined effect of both lenses was used to focus the beam in the HVT canal (see figure 5). The negative power supply of the einzel lens was set at the maximum voltage to minimize the beam divergence of the beam coming out of the source and the gridded lens voltage adjusted to focus the beam in the HVT canal.

![2D drawing of the gridded lens showing equipotential lines and the lens focusing effect on negative ion trajectories.](image)

Fig. 4. 2D drawing of the gridded lens showing equipotential lines and the lens focusing effect on negative ion trajectories.

![Simulation of a 30 keV Fe⁺ beam from the Sputter source to the HVT. To focus the beam in the HVT canal, the voltage to the einzel lens middle electrode is -20 kV and to the gridded lens 3.4 kV. In practice, the gridded lens voltage was about 3.8 kV.](image)

Fig. 5. Simulation of a 30 keV Fe⁺ beam from the Sputter source to the HVT. To focus the beam in the HVT canal, the voltage to the einzel lens middle electrode is -20 kV and to the gridded lens 3.4 kV. In practice, the gridded lens voltage was about 3.8 kV.

![Side view of the acceleration tubes with hydrogen ion trajectories. Top: shows equipotential lines and tubes focusing effect. Bottom: shows nitrogen gas scattering effect. In this figure, the scale in the vertical direction is increased by a factor of 1.3.](image)

Fig. 6. Side view of the acceleration tubes with hydrogen ion trajectories. Top: shows equipotential lines and tubes focusing effect. Bottom: shows nitrogen gas scattering effect. In this figure, the scale in the vertical direction is increased by a factor of 1.3.

When a -30 kV power supply was installed to replace the -20 kV power supply of the einzel lens, the beam was first focused in between the einzel and gridded lenses using the einzel lens with a voltage of -26.5 kV and then focused in the CEC using the gridded lens. In practice, we did not observe an improvement in the transmitted current through the CEC.

### 3.3. Ion acceleration to MeV energies

The ions are accelerated to MeV energies in the acceleration tubes. Figure 6 shows the acceleration tubes drawn with SIMION® together with equipotential lines along the low and high energy tubes and hydrogen ion trajectories. In the simulation, the hydrogen ion trajectory changes color where the ion changes charge state from -1 to +1. The point where the ion changes charge state was chosen arbitrarily inside the HVT canal, and to be more realistic, it could be programmed to be at a different point inside the canal for each ion. In the top of figure 6, a focusing effect by the acceleration tubes can be observed; the beam size at the exit of the HET is smaller than at the entry of the
LET. In the bottom of figure 6, the simulation includes the ion scattering due to the nitrogen gas leaked into the canal [Jacob et al. (2000)]. In practice, the total scattering angle is the result of multiple small collisions between the ion and the gas atoms along the HVT canal. In the simulation, the ion direction is changed only once at the same point where it changes its charge state and the scattering angle is chosen randomly between 0 and 0.5° [Jacob et al. (2000)].

3.4. Beam focusing in the experimental beamlines

The divergent beam coming out of the acceleration tubes is bent into one of the experimental beamlines with the HEM and focused with the TEQ at the position of the BPM (see figure 1(b)). A 3D drawing of the TEQ done with SIMION® is shown in figure 7. The first and third quadrupoles focus the beam in the horizontal direction and the second quadrupole focuses the beam in the vertical direction. This effect is achieved by the electrode voltage configuration shown at the bottom of figure 7. The absolute voltage of all the electrodes in the first and third quadrupole is the same. The absolute voltage of all the electrodes of the second quadrupole is also the same, but different to the absolute voltage of the first and third quadrupoles.
Figure 8 (left) shows a picture of the BPM signal on the oscilloscope screen for a 2 MeV proton beam focused at the position of the BPM, where the FWHM of each signal (X and Y directions) is about 3 mm. Figure 8 (right) shows the simulated proton distribution along the horizontal direction (X) of a 2 MeV proton beam focused at the position of the BPM. The proton distribution is fitted with a Gaussian function with a FWHM of 2.7 mm that is in good agreement with the measured value. A similar distribution was obtained in the vertical direction (Y) with the same FWHM.

The most common beams produced in MIBL with the 1.7 MV accelerator during the last few years were 2 MeV He\textsuperscript{++} for ion beam analysis; and 2 MeV H\textsuperscript{+}, 3.2 MeV H\textsuperscript{+} and 5 MeV Fe\textsuperscript{++} for ion irradiations. For all these beams, the simulation and used-in-practice voltages of the TEQ to focus the beam at the BPM position are compared in Table 2.

Table 2. Comparison between the TEQ voltages in the simulation (first value) and used in practice (value in parentheses). X and Y represent the horizontal and vertical directions. The voltage unit is kV.

<table>
<thead>
<tr>
<th>Source</th>
<th>Ion beam</th>
<th>Focus in X</th>
<th>Focus in Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>TORVIS</td>
<td>H\textsuperscript{+} at 2 MeV</td>
<td>13.1 (13.5)</td>
<td>16.0 (16.5)</td>
</tr>
<tr>
<td>TORVIS</td>
<td>H\textsuperscript{+} at 3.2 MeV</td>
<td>21.9 (22.5)</td>
<td>26.3 (25.5)</td>
</tr>
<tr>
<td>D</td>
<td>He\textsuperscript{++} at 2 MeV</td>
<td>5.9 (6.3)</td>
<td>7.3 (6.6)</td>
</tr>
<tr>
<td>S</td>
<td>Fe\textsuperscript{++} at 5 MeV</td>
<td>15.7 (16.2)</td>
<td>19.1 (19.2)</td>
</tr>
</tbody>
</table>

3.5. Beam steering and rastering

In practice, the beam direction is adjusted in several places along the beam trajectory from the ion source to the target using steerers (see figure 1(b)). The steerer is formed by a pair of parallel plates that produces an electric field perpendicular to the beam direction. Thus, the steerer deflects the beam in horizontal or vertical direction depending on the orientation of the plates. Although, the steerers were included in the simulation application there is no need to use them therein since all the components are perfectly aligned. But the simulations can be used to estimate what degree of misalignment is able to correct a steerer.

The steerer plates can also be used to raster the beam over the target by applying a time-dependent voltage to the plates. The result of an ion beam passing through the raster system is a uniform ion distribution over the surface of the sample. This effect is simulated in our previous work in Naab et al. (2013) and shown in figure 8.

Table 3. Comparison of the gridded lens voltages.

<table>
<thead>
<tr>
<th>Source</th>
<th>Ion beam</th>
<th>Simulation</th>
<th>Practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>TORVIS</td>
<td>H\textsuperscript{+} at 34.4 keV</td>
<td>6.0 kV</td>
<td>6.5 kV</td>
</tr>
<tr>
<td>D</td>
<td>He\textsuperscript{+} at 18 keV</td>
<td>3.3 kV</td>
<td>3.0 kV</td>
</tr>
<tr>
<td>S</td>
<td>Fe\textsuperscript{+} at 30 keV</td>
<td>3.4 kV</td>
<td>3.8 kV</td>
</tr>
</tbody>
</table>

4. Discussion

In the section “Ion initial conditions for each ion source” we show that the simulation done for the TORVIS source using the same electrode voltages than in practice reproduces well the focal point at the position of the hollow cylinder to maximize the current output from the source (figure 2(b)). In the case of the Duoplasmatron source, the simulation voltage of the einzel lens middle electrode to focus the beam in the Na oven canal agrees within ~6% with the value used in practice.

In the section “Ion injection into the accelerator tubes” we compare the simulation and used-in-practice voltages of the gridded lens to focus the beam in the CEC of the HVT for ion beams produced with each of the sources. The data are summarized in Table 3 and the agreement is within ~12%.

Table 2 shows that the agreement between the TEQ voltages in the simulations and used in practice is within ~11%.

Finally, in the section “Beam focusing in the experimental beamline” we show that the beam FWHM at the BPM position obtained in the simulation and in practice differ by ~10%.
5. Conclusion

The simulation application for the 1.7 MV accelerator is completed. The visual interface of the application allows for rapid understanding of the effect of each component on the ion beam trajectories. The parameters for each component in the simulation agree within ~10% with the parameters used in practice. The agreement between these values is related to the similarity between the real component shape and the drawing done with SIMION® to calculate the electric/magnetic field affecting the trajectories of the ions.

Using these simulations, new accelerator operators or users quickly understand how the whole machine works. Furthermore, these simulations allow the analysis of potential modifications in the ion beam optics of the accelerator by adding, removing or replacing components and changing their relative positions.

References