Designing an Optical Column for use with Ionic Liquid Ion Sources

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September 22, 2021

1 Introduction

In previous work, we have used a Wien Filter to filter out unwanted species and obtain only fully accelerated monomers from an ionic liquid ion source beam. However, a maximum of 11% of fully accelerated monomer particles make it through the filter. This mostly occurs due to a large beam radius and steep half angle, which causes particles to be over/ under-deflected. Filter performance is greatly affected by beam half angle and beam cross-sectional diameter at the point of entry in to the Filter. The beam half-angle is determined by the transverse velocity component of the particles i.e. how fast the particles are travelling outwards, perpendicular to the beam travel direction. The aim of the current study is to reduce beam half angle and cross-sectional diameter as much as possible. The smaller these parameters, the better the filter performance.

In order to reduce these two parameters a setup known as an einzel lens needs to be placed between the emitter and the Wien Filter. This lens both focuses i.e. reduces the beam diameter and collimates i.e. reduces the transverse velocity of particles. One can then obtain a beam with a smaller diameter and a shallower half angle resulting in a higher current density and a greater percentage of fully accelerated monomers exiting the Wien filter.

Previous reports used magnets with a surface Gauss of 8,340 G to generate a field strength of 500 mT at the centre of the filter. Due to manufacturing limitations that were not known at the time, the current report studies magnets with a rated surface Gauss of 5,000 G.

This report first briefly characterises the ion beam being studied in section 2, before moving onto summarising the design of the Wien Filter and the electric and magnetic fields generated in section 3 and their effects on an incident beam of particles in section 4. A more detailed study of beam parameters and Filter design were carried out in a previous study.

The report then proposes a design for an Einzel Lens in section 5, to be placed before the Wien Filter, that can both collimate and focus an incident beam of particles, in the hope of increasing the number of particles exiting the Wien Filter. The study focuses on increasing this number as much as possible in sections 6, and section 7 where the Einzel Lens is used together with the Wien Filter. And finally, some closing remarks and avenues for further research are explored in section 8 Note that COMSOL Multiphysics is used for all simulations and every figure in this report has been generated using this software.

2 Beam Parameters

Beam parameters for fully accelerated monomers 1-ethyl-3-methylimidazolium tetrafluoroborate ($\mathrm{EMI-BF_4}$) as used in this study are highlighted below:

$$\mathrm{V_0} = 1000\ \mathrm{V}$$

$$\mathrm{m_1} = 111\ \mathrm{amu}$$

$$\alpha = 18\ ^{\circ}$$

where $\mathrm{V_0}$ is the emission voltage of particles i.e. the voltage at the ionic liquid ion source emitter needle, $\mathrm{m_1}$ is the mass of monomer $\mathrm{EMI^+}$ (in atomic mass units) and α is the beam half-angle at the point of emission. The velocity of the emitted particles is calculated as follows:

$$\mathrm{v} = \sqrt{\frac{2\mathrm{qV_0}}{\mathrm{m_1}}}$$

where q is the charge of an electron. Using this equation the velocity of these fully accelerated monomers is $41,696\ \mathrm{ms^{-1}}$.

The beam has a parabolic position distribution of particles. This means that particle numbers decrease in a parabolic fashion as one moves outwards, perpendicular to beam travel. COMSOL does not natively allow particle beams with parabolic distributions to be emitted from a point source. To fool the software, the beam is released from a small geometric circle with a 0.01 mm radius which essentially acts like a point source. For the following studies a beam of 1000 particles with the aforementioned parameters are used.

3 Wien Filter Geometry and Fields

The proposed Wien Filter design consists of 2 electrodes generating a static, vertical electric field and 2 permanent magnets generating a static, horizontal magnetic field. This setup is encased inside an iron yoke and two aperture plates, placed in the path of the beam, one for entrance and one for exit. This geometry is shown by figure 1, where the electrodes are coloured gold, iron yoke light grey, magnets teal and aperture plates black.

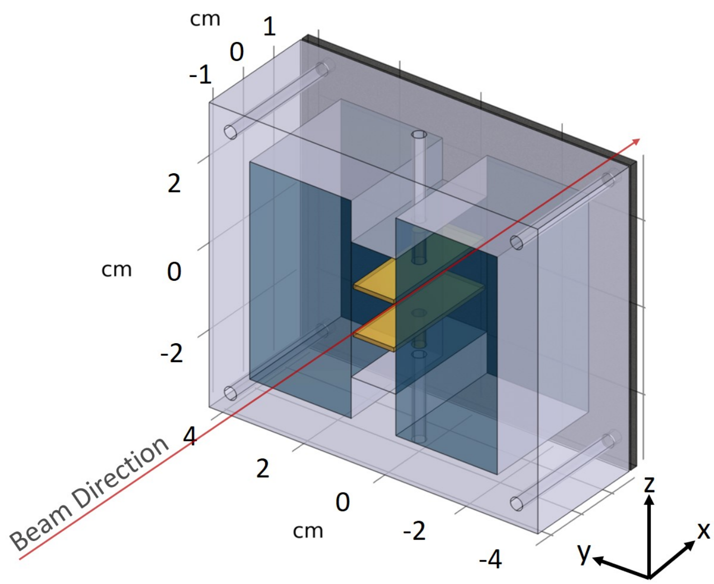

Figure 1: Three-dimensional translucent orthographic projection of the proposed Wien Filter design. The iron yoke is coloured light grey, permanent magnets teal, electrodes gold and aperture plates black with beam direction shown by the red arrow. Note the entrance aperture has been omitted for clarity.

Note that the entrance aperture plate has been removed to aid visibility. Beam direction is in the x-axis as illustrated. The Wien Filter has been discussed extensively in the previous report however to provide a quick summary it features two N52 Neodymium permanent magnets, two electrostatic deflectors and two aperture plates made of Stainless Steel 301, and an iron yoke made of Steel 1018. The yoke has a y-axis width of 80 mm, a z-axis height of 70 mm, and an x-axis length of 30 mm. The aperture plates are 1 mm in thickness with a gap of 0.5 mm between the yoke and the plates themselves. This takes the Wien Filter to a total x-axis length of 33 mm. The electrostatic deflectors are 30 mm in x-axis length and 10 mm in y-axis width, they are spaced 10 mm apart in the z-axis. This gives the beam a volume of 10 x 10 x 30 mm to travel through inside the filter.

The filter lets particles with a velocity $v = \frac{E}{B}$, where E = electric field strength and B = magnetic field strength, escape while it causes deflection, in the z-axis, for all other particles. Previously, magnets with a surface Gauss of 8,340 G were used to generate a magnetic field strength of 500 mT at the centre of the filter. However, due to manufacturing limitations, in this report we use magnets with a surface Gauss of 5,000 G. Figure 2 (a) shows the resulting magnetic fields from COMSOL in the yz plane. It can be seen that despite using magnets with a surface Gauss of 500 mT, a field strength of roughly 200 mT is generated at the centre of the filter. Consequently, the electric field strength necessary to isolate fully accelerated monomers is also reduced. It was found by trial and error that a single EMI$^+$ emitted in the x-axis will pass straight through the filter if a potential difference of 62.6 V was maintained between the electrodes. The generated electric field in the yz plane can be seen in figure 2 (b).

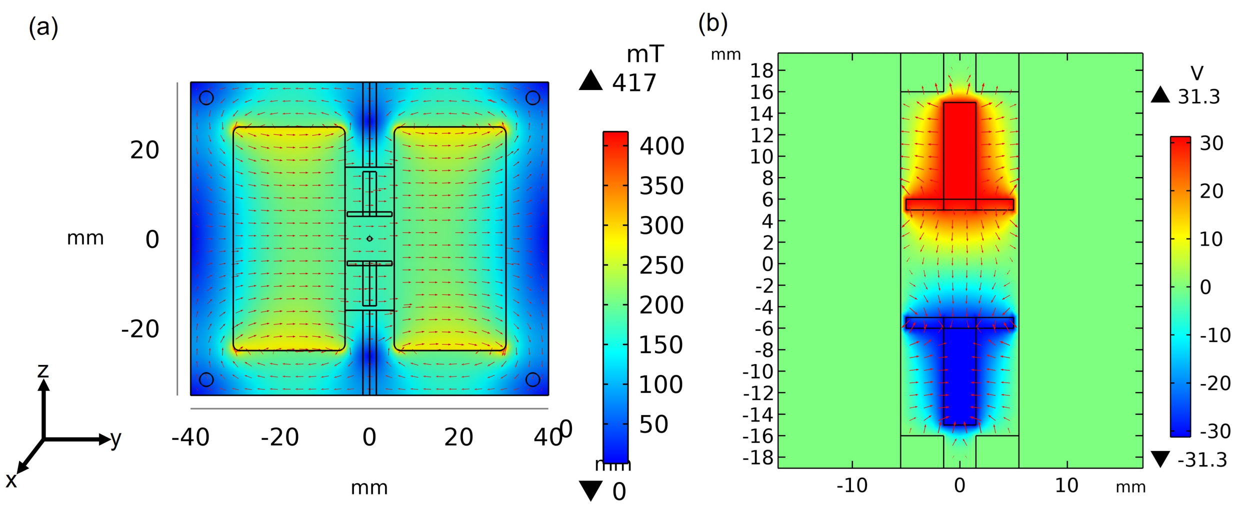

Figure 2: (a) Magnetic field lines generated by permanent magnets with a rated 5,000 G surface Gauss and (b) Electric field lines generated by electrodes with an applied potential difference of 62.6 V between them.

4 Particle Tracing using only the Wien Filter

Figures 3 (a - c) show the results of a particle tracing study conducted using only the Wien Filter and fully accelerated EMI$^+$ monomers with mass 111 amu and emission voltage 1000 V, with a velocity of $41,696$ ms^{-1}, given by the equation in section 2.

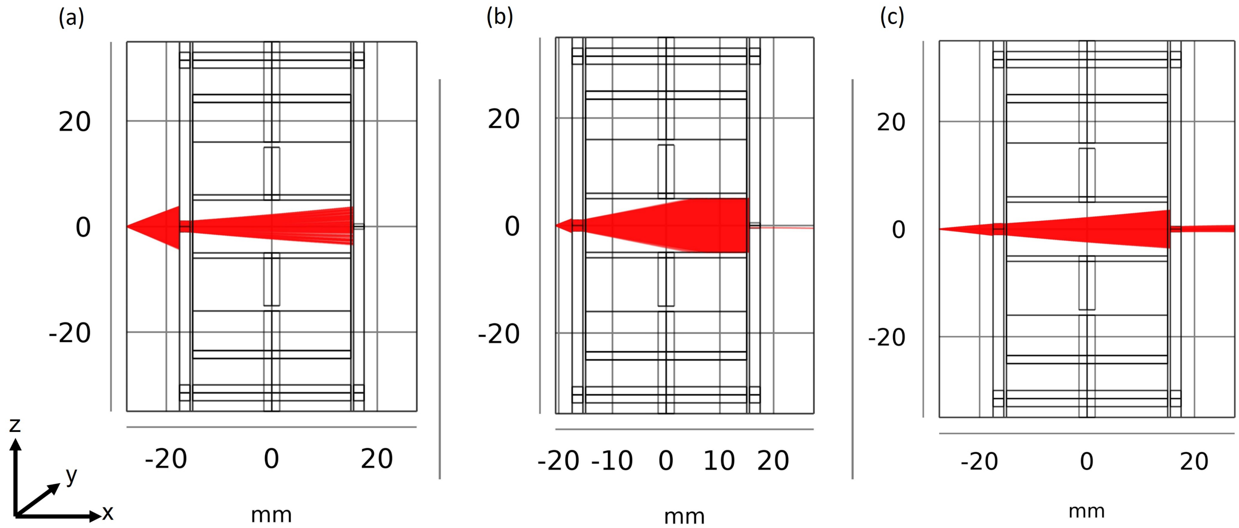

Figure 3: Particle trajectories of a parabolic beam of fully accelerated EMI$^+$ monomers released from a geometric circle with radius 0.001 mm and beam half angle (a) 18 degrees 10 mm upstream from filter, (b) 18 degrees and 3.078 mm upstream from filter, and (c) 5.71 degrees and 10 mm upstream from filter.

Figure 3 (a) shows the results of a beam with a typical half angle of 18 degrees, released 10mm upstream from filter entrance. A large part of the emitted beam simply does not enter the filter and none of it escapes, due to the very steep half angle producing a large cross-sectional diameter at the point of entry to the filter.

This can be corrected for by moving the beam source closer to the filter. The results of this are shown by figure 3 (b) where the beam still has a half angle of 18 degrees but is now 3.078 mm upstream from the filter entrance. This allows a majority of the beam to enter the filter, however very little of it, only 2 particles in fact, escape the filter and are detected 10 mm downstream from the filter.

Figure 3 (c) shows particle tracing tracing results for a beam that is placed 10 mm upstream from the filter but the half angle has been manipulated such that the cross-sectional diameter of the beam, at the point it enters the filter, matches the diameter of the entrance aperture, which is 2 mm here. The half-angle obtained, via simple trigonometry, is 5.71 degrees. Particle retention is still unsatisfactory with only 27 particles escaping the filter.

It is obvious that beam half angle needs to be reduced in order to increase particle retention numbers. This can be done, as previously discussed, by placing an Einzel Lens before the Wien filter.

5 Einzel Lens Geometry and Materials

An orthographic projection of a basic Einzel lens design is shown in figure 4.

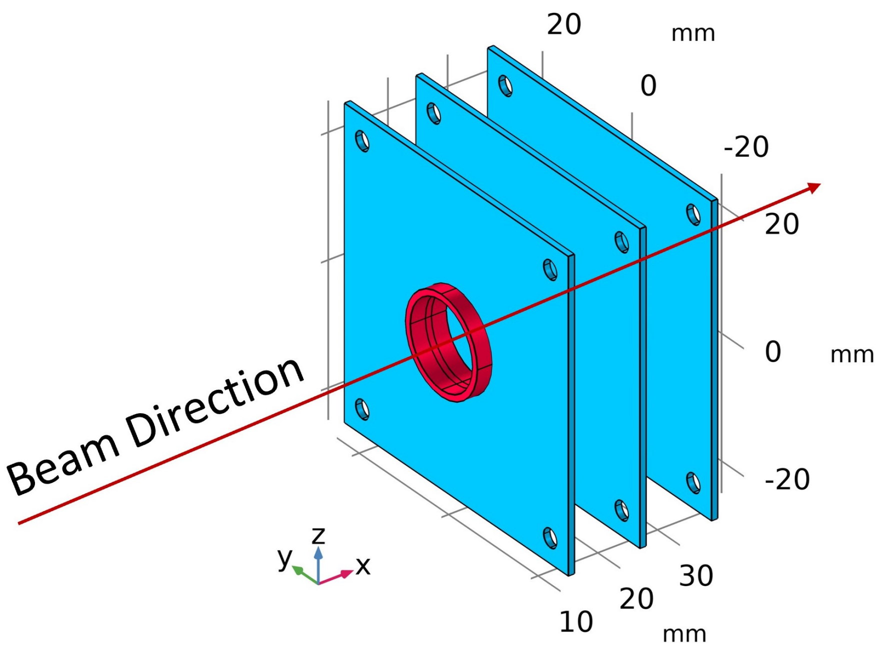

Figure 4: Three dimensional orthographic projection of the basic Einzel Lens set up. There are three lenses coloured red, and three lens holders coloured blue. Beam direction is in the positive x-axis.

The setup consists of three lens holders coloured blue, each of thickness 1 mm, and width and height of 50 mm. Each of these holders has a hole in the centre to accommodate the lens cylinders, of length 6 mm in figure 4, coloured red. The lens holes are of radius 8 mm. Each lens holder also has four screw holes, placed in each corner, of radius 1.5 mm, the centres of which are placed 4 mm away from the edges. The screw holes are there to accommodate macor or alumina rods that can be used to mount the setup in a vacuum chamber. The lens holders are placed equidistant from each other so that they hold the lens cylinders in the centre. In figure 4, each lens has an inner radius of 7 mm and each lens is 1 mm thick, giving a total radius of 8 mm.

The setup is 30 mm in length and 50 mm in width and height. These are constraints imposed due to the practicalities of fitting the Einzel Lens in a vacuum chamber. Therefore, the separation distance between each lens cylinder is given by subtracting from the total length, which is 30 mm here, the lengths of the three cylinders and dividing the resulting value by two, to obtain the lengths of the two lens gaps. The entire setup uses stainless steel 310, polished smooth and with no other surface treatments.

Figure 5 shows the same lens setup but in the xz and yz planes, for better clarity. Again, beam direction is in the positive x-axis.

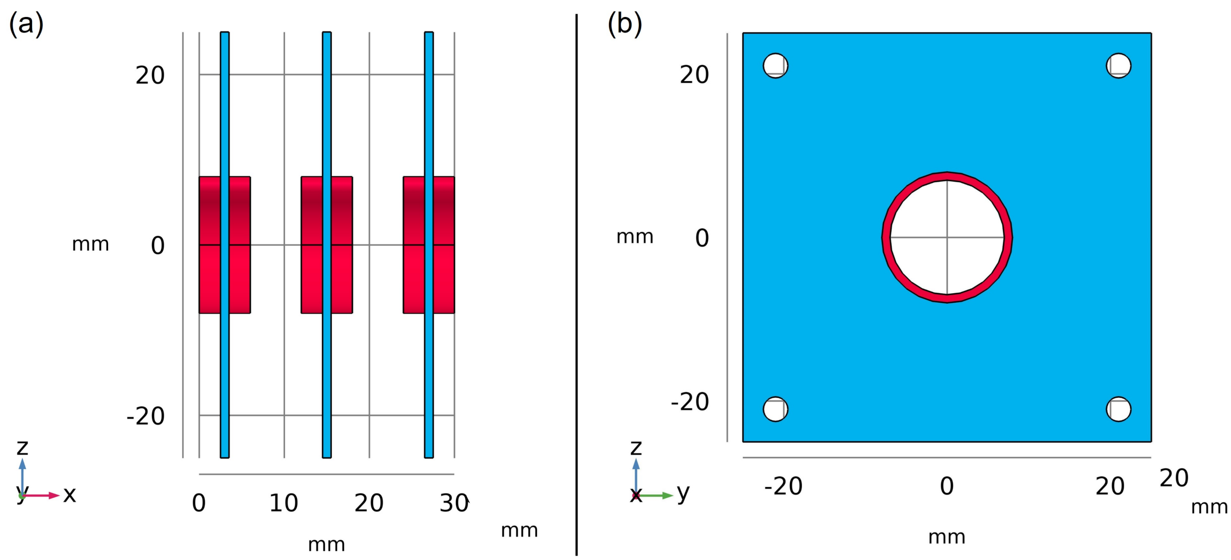

Figure 5: Orthographic projection of einzel lens setup in (a) xz and (b) yz planes, where beam travel is in the x-direction. The lens cylinders are coloured red and the lens holder plates are coloured blue. The lens cylinders are 6 mm in length here.

6 Einzel Lens Fields and Particle Tracing Simulations

A three-lens electrostatic Einzel lens, which is being used here, has an applied voltage V_{lens} at the lens in the centre and ground applied to the outer two lenses. V_{lens} is determined by the kinetic energy of the particles one wishes to focus. Here we are using particles that have been accelerated to 1000 V and therefore V_{lens} must not be greater than 1000 V. We can now run a particle tracing simulation with the lens design shown in figure 5. A particle emission source is placed 10 mm upstream from the einzel lens setup. The emission source itself is a geometric circle with a radius of 0.01mm, as discussed before. The source emits 1000 particles simultaneously with mass 111 amu and charge q, accelerated to 1000 V, with a parabolic position distribution and a half-angle of 18 degrees. Particle-particle interactions are not considered in these simulations.

The particle tracing results are shown in figure 6 (a) and the electric potential generated by the lens is shown in figure 6 (b).

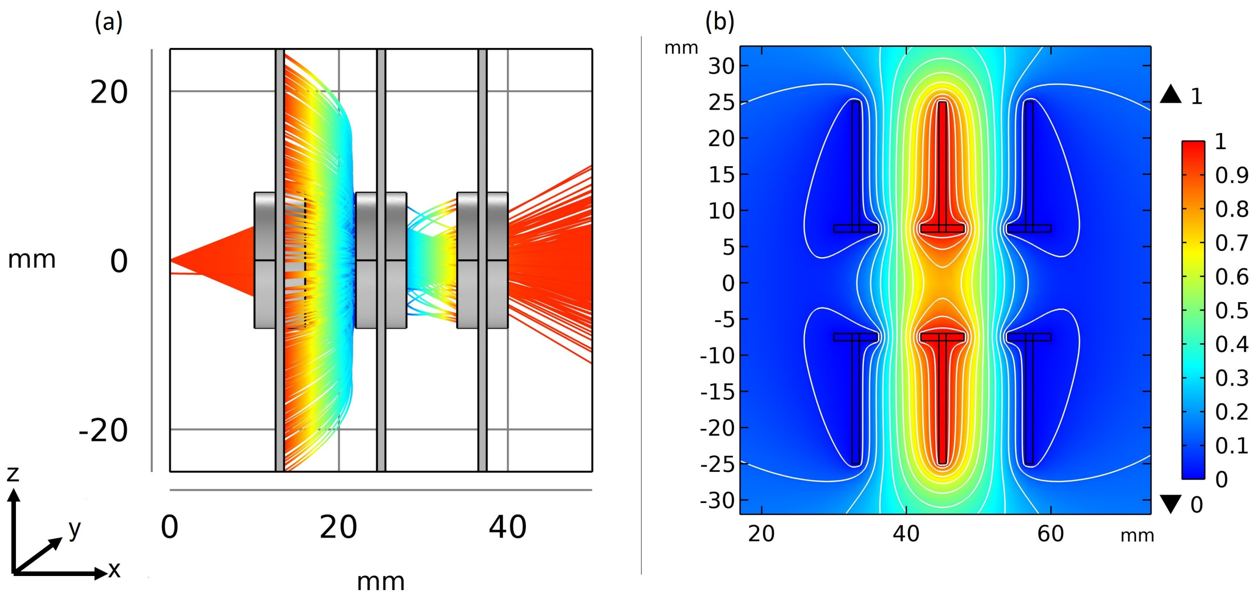

Figure 6: Electric potential diagram obtained from COMSOL with a potential of 1000 V applied to the lens in the centre and 0 V at the outer two lenses.

A particle counter is placed 10 mm downstream from the lens setup. For an emission of 1000 particles, only 534 particles make it out of the lens. The rest, as can be seen, simply bounce off the edges of the cylinders. Additionally, note that this lens has been entirely unhelpful in reducing beam half angle.

We now increase the radii of the lens cylinders, from 8 mm to 15 mm, in an attempt to observe the effect of lens radius on particle trajectories. Figure 7 (a) shows the particle tracing results. Indeed, this larger radius enables 100 % particle retention as all 1000 particles make it out to the other side. It can also be noted that the lens does make an attempt to collimate the beam as the half angle is much reduced, albeit with a penalty of a very large beam diameter. This behaviour can be understood by looking at the field diagrams for this lens, shown by figure 7 (b). A larger lens radius reduces the electrostatic potential in the centre of the lens. This ultimately leads to shallower particle deflection, resulting in a larger beam diameter with greater collimation.

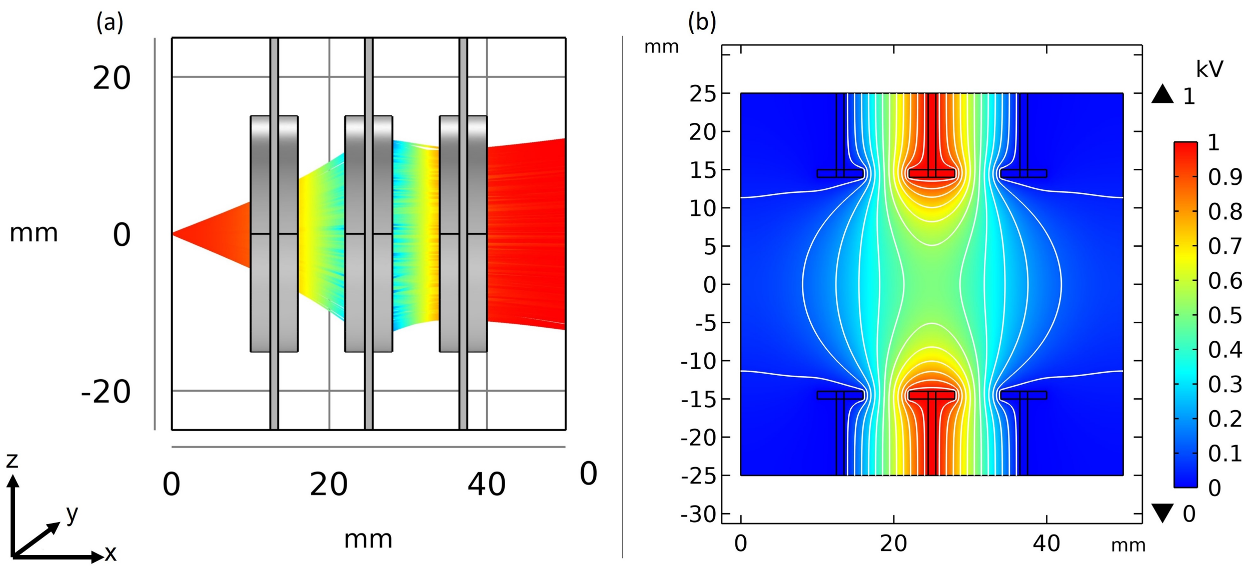

Figure 7: Particle Tracing simulation results obtained from COMSOL. The colour spectrum shows kinetic energies of particles. A larger lens radius of 15 mm means no particles bounce off.

We can increase the voltage applied at the central cylinder from 1000 V to 1400 V, in an attempt to reduce beam diameter at the exit. The particle tracing results from this can be seen in figure 8 (a) with figure 8 (b) showing the electric fields generated. While this certainly reduces the beam diameter at this larger lens size, it also shoots off particles at large inflections. Particle retention is still good with 933 particles making it out of a 1000.

While increasing lens radii improves collimation it leads to large beam diameters. Increasing the voltage at the central lens does not alleviate the problem satisfactorily either.

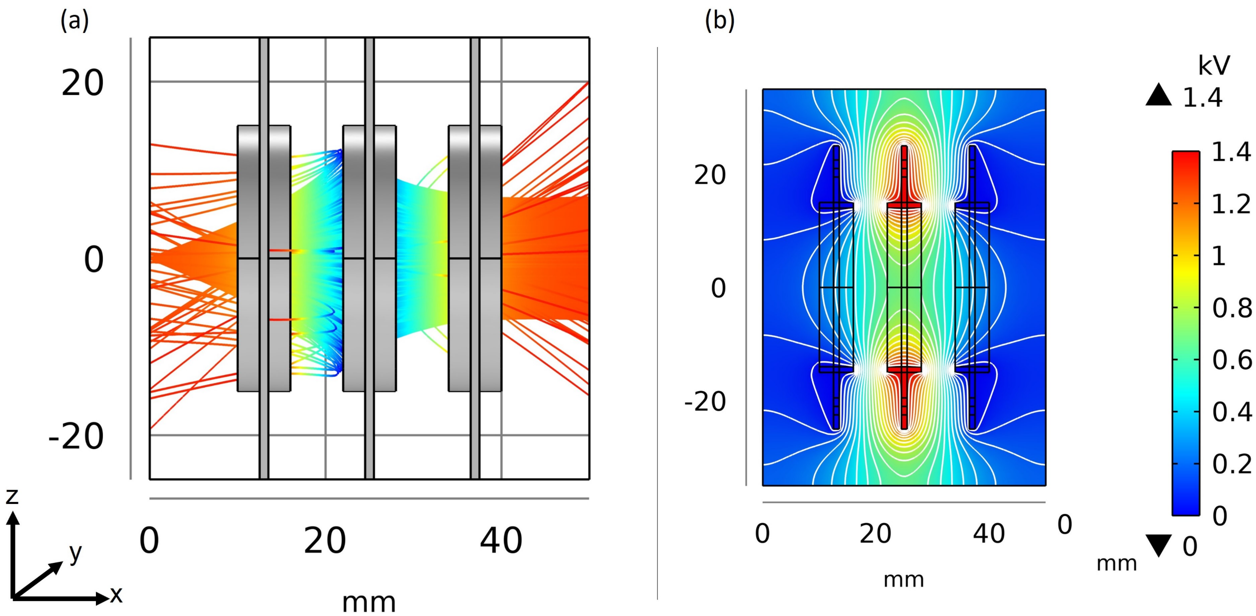

Figure 8: Particle Tracing simulation results obtained from COMSOL. The colour spectrum shows kinetic energies of particles. A higher voltage of 1400 V at the central lens reduces beam diameter but also shoots off particles with large inflection angles.

Therefore, for the rest of this report, we will revert to using a lens radius of 8 mm with a voltage of 1000 V applied at the second lens. However, in order to catch the particles that were bouncing off the second lens, we will increase the length of the second lens from 6 mm to 26 mm and completely remove the first and third lens so that we are only left with the apertures in the lens holders, 1 mm thick each. The particle tracing results are shown in figure 9 (a) and the electric fields generated are shown in figure 9 (b).

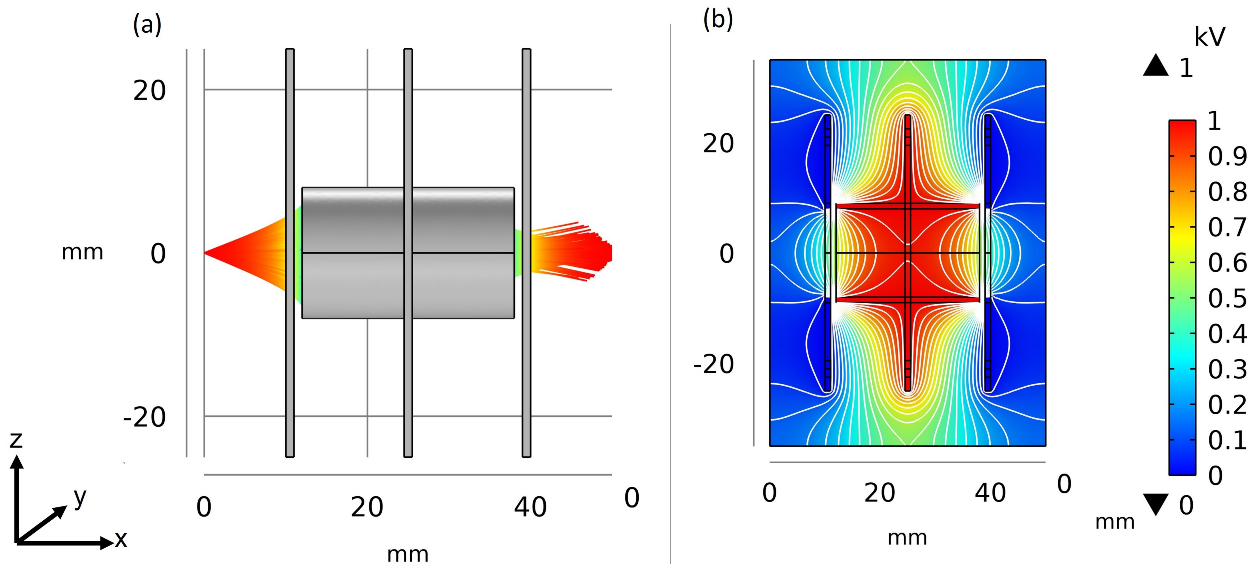

Figure 9: Particle Tracing simulation results obtained from COMSOL. The colour spectrum shows kinetic energies of particles. A longer central lens at 1000 V captures all of the particles, collimates, and focuses the beam, however, shoots some particles with large inflection angles at the end.

We can see that this setup does in fact capture all incident particles, collimates and focuses the beam. Particle retention is good with 732 particles making it out of the exit.

This setup however shoots off some particles with large inflections at the exit. There are a few ways to eliminate this. Firstly, the third lens aperture could be made smaller, so as to act as a limiting aperture. However, closer inspection of the particle tracing reveals that most of these offshoot particles emerge farther downstream than we can put the last lens without disrupting the electric field lines in the central lens too much.

Secondly, particles being shot with large inflections like this are indicative of a field strength too strong. This could be alleviated by either reducing the applied voltage at the second lens or increasing lens diameter slightly. The latter option would both decrease field strength and potentially allow greater numbers of particles to exit the lens. For the reasons discussed, we will proceed with the third solution: increasing lens diameter from 8 to 9 mm. The particle tracing results are shown in figure 10 (a) and the electric fields generated are shown in figure 10 (b).

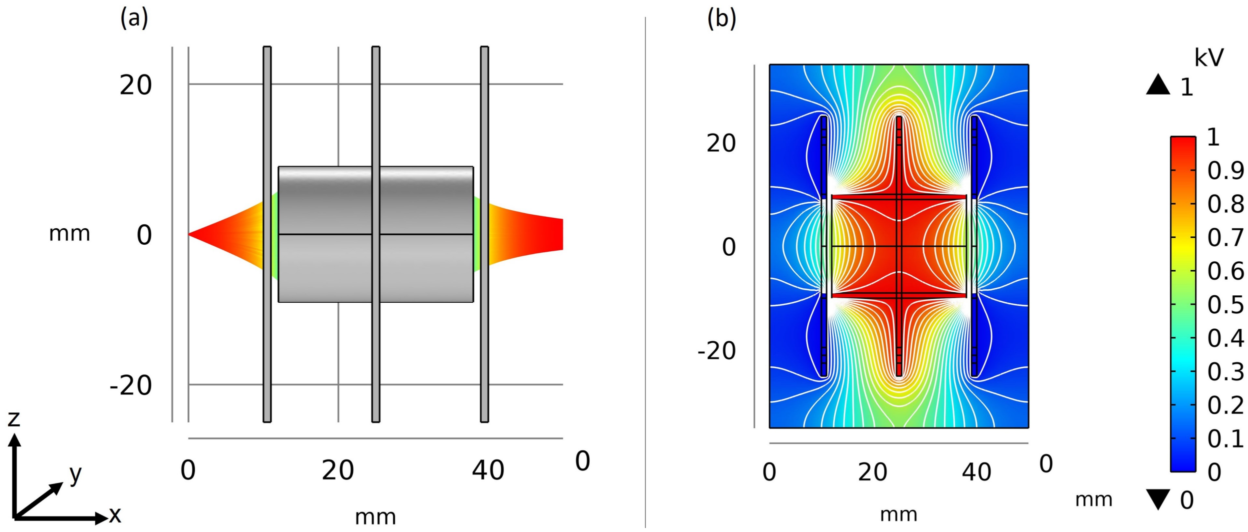

Figure 10: Particle Tracing simulation results obtained from COMSOL. The colour spectrum shows kinetic energies of particles. Lens radii have been increased to 9 mm with a central lens length of 26 mm. This set up is effective as a collimating and focusing Einzel lens.

This set up collimates and focuses the beam effectively, with 735 particles making it out and will hence be used with the Wien Filter for further simulations. Figures 11 (a) and (b) show Poincaré maps placed right at the entrance of the Einzel lens and 10 mm downstream from the lens setup, respectively.

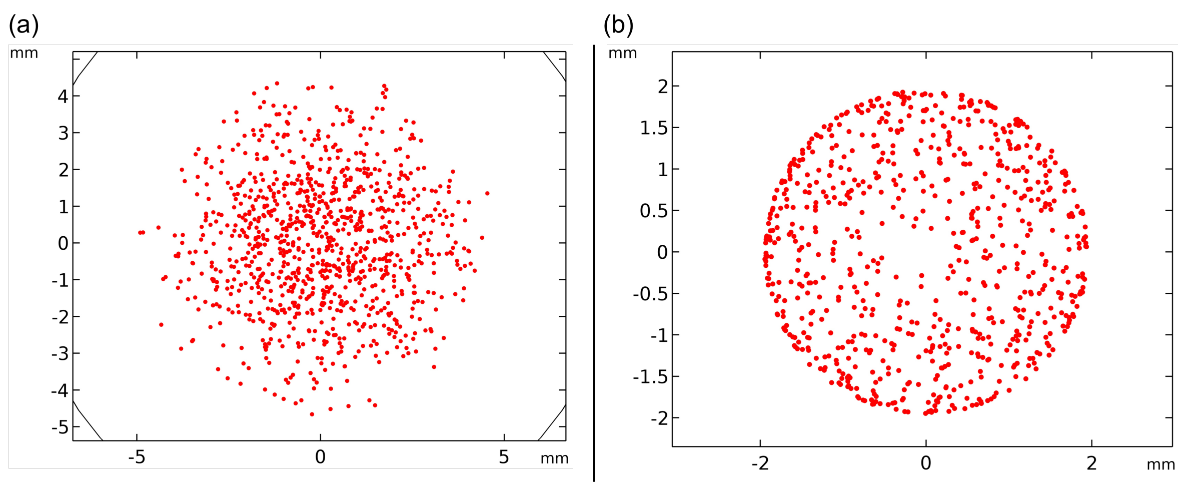

Figure 11: Particle Tracing simulation results obtained from COMSOL. The colour spectrum shows kinetic energies of particles. Lens radii have been increased to 9 mm with a central lens length of 26 mm. This set up is effective as a collimating and focusing Einzel lens.

We can see that beam diameter at the entrance to the Einzel lens is roughly 5 mm and roughly 2 mm at the exit. We also note that the beam has a parabolic position distribution at the entrance but a concave distribution at the exit. Nonetheless, this set up now needs to be tested with a Wien Filter.

7 Particle Tracing With Einzel Lens and Wien Filter

We now proceed to run particle tracing studies with both an Einzel Lens and a Wien Filter.

We do this in three separate studies: with a 5 mm, 10 mm, and a 15 mm gap between the Einzel Lens and the Wien Filter. We still use a conical fully accelerated beam of 1000 EMI$^+$ monomers with a parabolic position distribution and a half angle of 18 degrees, placed 10 mm upstream from the Einzel Lens entrance. We use the Einzel Lens setup depicted in figure 9 and the Wien Filter setup depicted in section 3 for all three studies in this section.

Figure 12 shows particle tracing results when the distance between the Einzel Lens and Wien Filter is 5 mm.

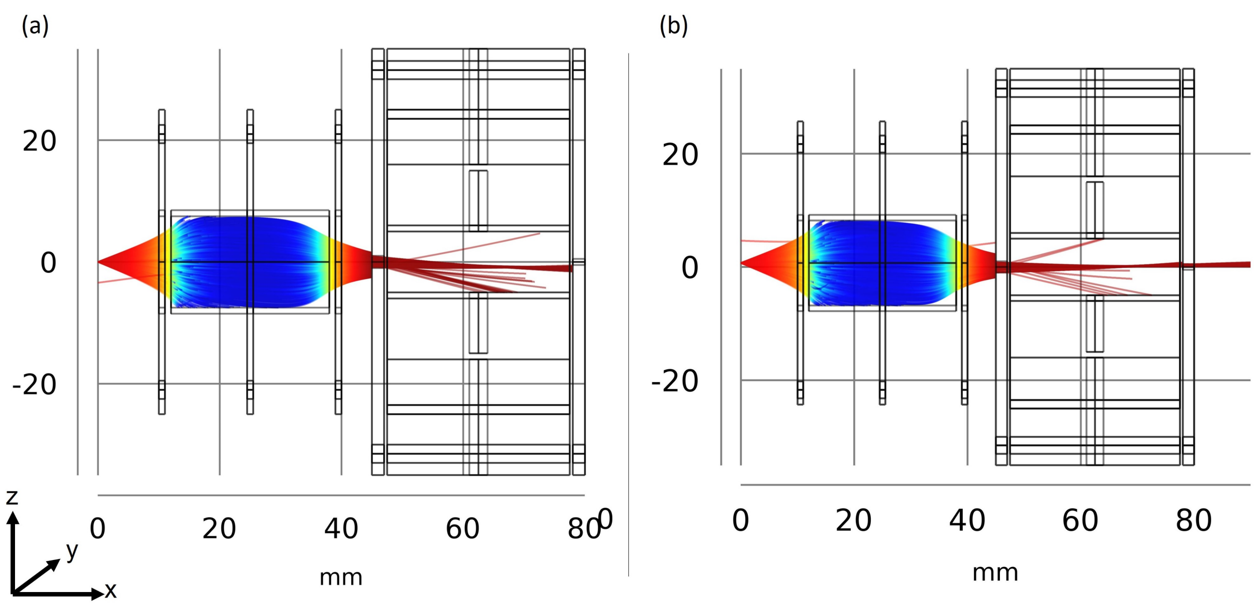

Figure 12: Particle trajectories of a parabolic beam of fully accelerated EMI$^+$ monomers released from a geometric circle with radius 0.001 mm and beam half angle 18 degrees with a 5 mm gap between the lens and filter (a) without a z-offset and (b) with a z-offset of 0.7 mm.

The beam deflects down in the z-axis before it even enters the filter, as is visible in figure 12 (a). This is believed to be caused by magnetic field lines leaking out of the Wien Filter, from the very strong permanent magnets inside. Due to this, very little of the beam enters the filter and none makes it out. This can be resolved by moving both beam emission and the Einzel Lens up in the z-axis. Figure 12 (b) shows the results when Einzel Lens and beam emission source are moved up 0.7 mm in the z-axis. Most of the beam can now be seen entering the filter with a measly 27 particles making it out.

Figure 13 (a) shows particle tracing results when the distance between the lens and the filter is increased to 10 mm and there is no z-offset, while figure 13 (b) shows particle tracing with a 0.7 mm offset in the z-axis. Still, no particles make it out in figure 13 (a) while only 58 make it out in figure 13 (b). Particle retention is again poor but still improved from earlier results in figure 3, when the Wien Filter was being used without an Einzel Lens, and in figure 12, when the distance between the lens and filter was 5 mm.

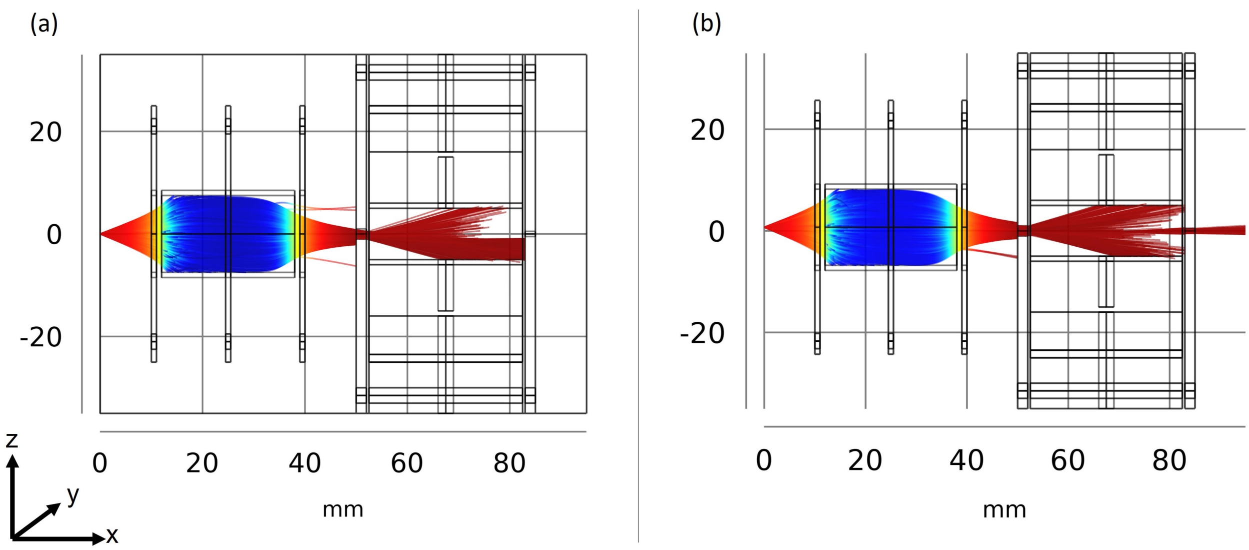

Figure 13: Particle trajectories of a parabolic beam of fully accelerated EMI$^+$ monomers released from a geometric circle with radius 0.001 mm and beam half angle 18 degrees with a 10 mm gap between the lens and filter (a) without a z-offset and (b) with a z-offset of 0.7 mm.

Figure 14 shows particle tracing results when the distance between the Einzel Lens and Wien Filter is increased still to 15 mm with figure 14 (a) showing results without any z-offset and figure 14 (b) showing results with a 0.7 mm z-offset as done previously. As before, no particles escape the filter without the offset while a poor number of 15 particles escape with the z-offset.

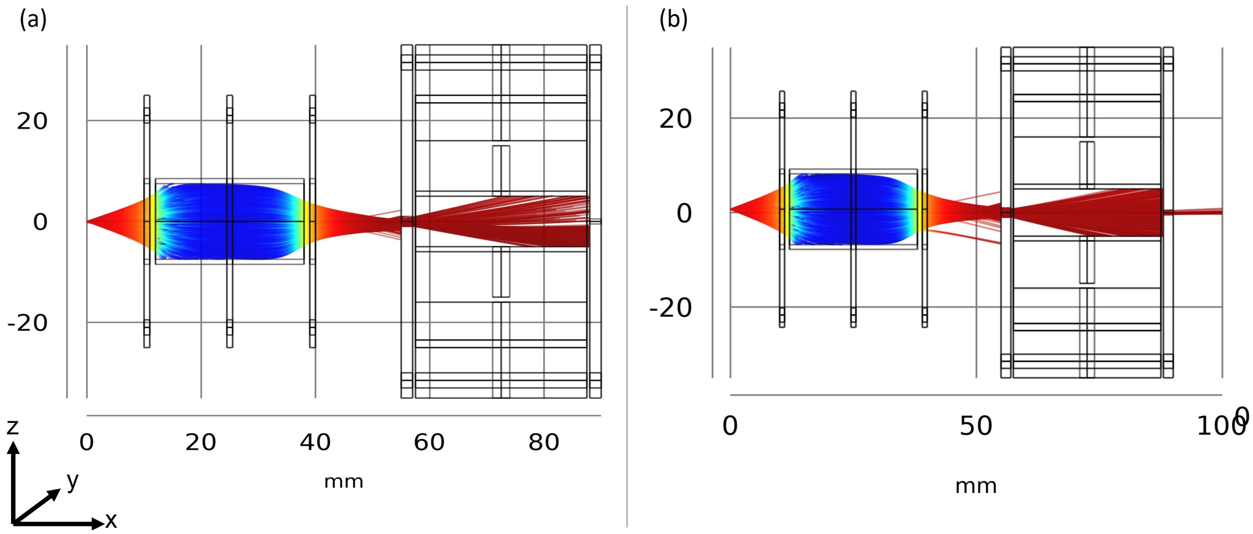

Figure 14: Particle trajectories of a parabolic beam of fully accelerated EMI^+ monomers released from a geometric circle with radius 0.001 mm and beam half angle 18 degrees with a 15 mm gap between the lens and filter (a) without a z-offset and (b) with a z-offset of 0.7 mm.

8 Summary and Further Work

This report hopes to have served as a useful extension to a previous, albeit more detailed, study that only explored the use of a Wien Filter. A brief overview of the proposed design for a Wien Filter that uses permanent magnets and electrostatic deflectors to generate perpendicular magnetic and electric fields was given. It was found that magnets with a rated surface Gauss of 5,000 G will only generate roughly 200 mT at the centre of the filter and an electric potential difference of 62.6 V will suffice to isolate fully accelerated $EMI - BF_4$ monomers that are travelling paraxially through the centre of the filter.

Filter performance was further briefly evaluated using a conical beam of fully accelerated EMI^+ monomers with a parabolic position distribution, released from an ionic liquid ion source of $EMI - BF_4$. Out of a beam of 1,000 particles with a half angle of 5.71 degrees, only 27 make it out of the filter. In order to increase this number a design for an Einzel Lens was also proposed that uses three electrostatic lens, placed one after another, where the outer two are at ground and the central lens has a potential difference of 1000 V applied to it. A lens radius of 9 mm, and eliminating the first and second lens entirely, leaving only the apertures in the holder plates, and making the central lens 26 mm long, were found to result in a beam that had a cross-sectional diameter of 2 mm, 10 mm downstream from the lens. When the Wien Filter is placed here, out of 1,000 incident particles, only 58 make it out of the entire setup.

In summary, using an Einzel Lens before a Wien Filter certainly improves particle retention, albeit still remaining hopelessly poor. It is believed that the primary cause of this is the very steep beam half angle. Here we propose two potential solutions. An Einzel Lens will typically either collimate a beam or focus it, but not both. This is especially true for beams that enter with steep half angles, as in this report. Therefore, adding in a second Einzel Lens could potentially prove fruitful, where one lens focuses and the other collimates. This would require the addition of at least two more lens cylinders to the current design, one that is at a voltage, and one at ground. Alternatively, one could simply increase the length of the current Einzel Lens setup where the central lens could simply be made longer. This would allow for a lower voltage at the central lens and could therefore reduce the beam half angle.