BEEPS Mass Spectrometer Redesign

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Introduction

- The B-field Electrostatic Energetic Particle Spectrometer (BEEPS) is a two-stage instrument.
- The first stage is an electrostatic analyzer that filters ions by their energy to charge ratio.
- It works by applying a voltage to the inner sphere R_1 and grounding R_2.
- The second stage is a mass spectrometer.
- Ions are separated by a toroidal magnetic field created by 15 permanent wedge-shaped magnets.
- Between stage 1 and stage 2 there is a post acceleration voltage V_{PA} that makes all ion energies entering stage 2 uniform.
- Originally designed to separate protons from heavier ions, changes were done so that it can distinguish between O^+ and N_2^+.

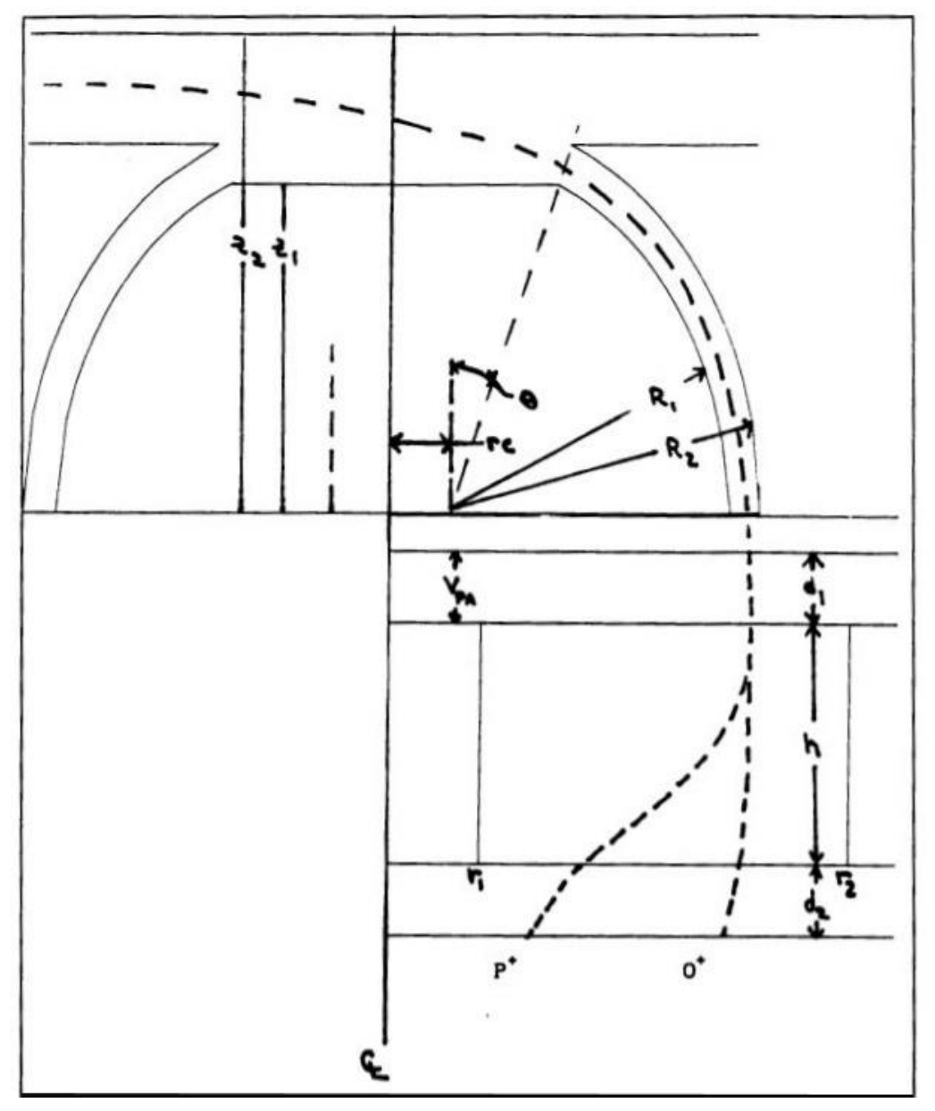

Figure 1. A rough sketch of the original BEEPS. The concentric spheres create the "stretched" electrostatic analyzer. The magnetic wedges are of height h [1].

Motivating Science

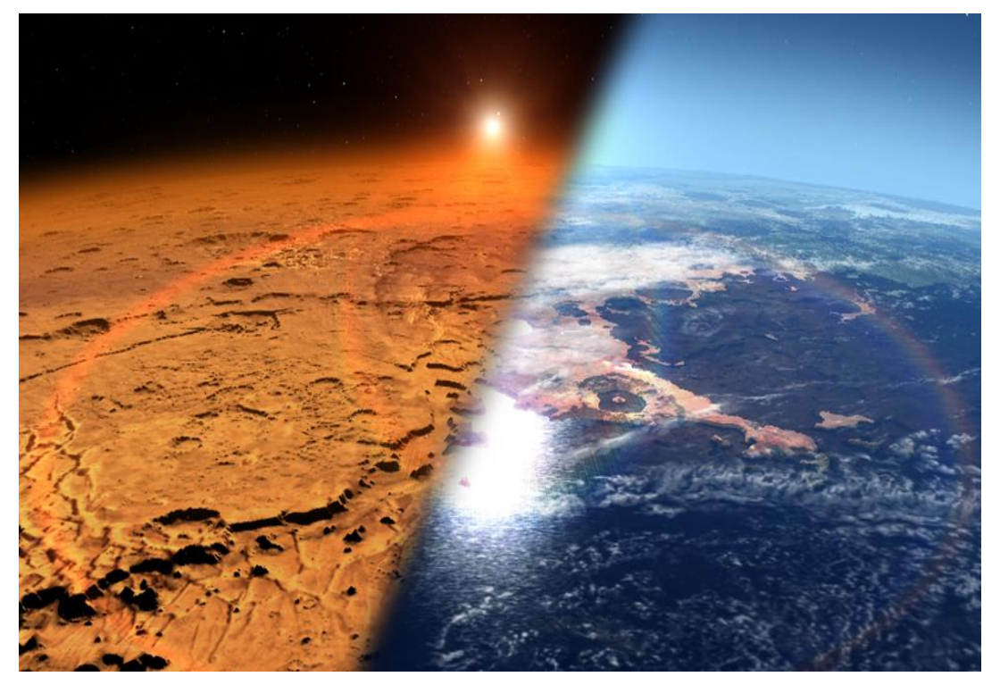

Figure 2. An artist depiction of Mars before and after its atmosphere was lost to space [2].

- Ion upflow is the movement of ions in the ionosphere into higher altitudes.
- The upflow of ions can increase the density in a region causing drag on satellites and thus orbital decay.
- Ion upflow can also lead to ion outflow, the escape of ions from the atmosphere.
- It has long been theorized that solar wind driven ion outflow was a source of Mars atmosphere decay.
- The dominant species above the ionosphere F-region has long been understood to be O^+ and H^+.
- In 2015, the sounding rocket mission RENU2 recorded emissions from both ground and flight sensors of N_2^+ in the region [3].
- This is significant because the mass of N_2^+ is roughly twice O^+.

Analytical Solutions

- Using the Lorentz Force a deflection distance for a charged particle in B of length h is $\delta r = (\frac{\sqrt{2m^3E}}{qB})(1-\sqrt{1-(hqB)^2/2m^3E}$.
- Based on total ion deflections the inner and outer radii of the magnetic wedges, r_1 and r_2, were chosen to be 5 mm and 40 mm.
- Wedge angle $\emptyset_{mag}$ is based on the maximum strength for the smallest volume.
- With this geometry it is given by $1 = \frac{\emptyset_{mag}}{2(24-\emptyset_{mag})}\ln\left(\frac{r_2}{r_1}\right)\frac{r_2+r_1}{r_2-r_1}$ [1].
- The most efficient wedge angle is then $\emptyset_{mag}$ = 10.3 °.

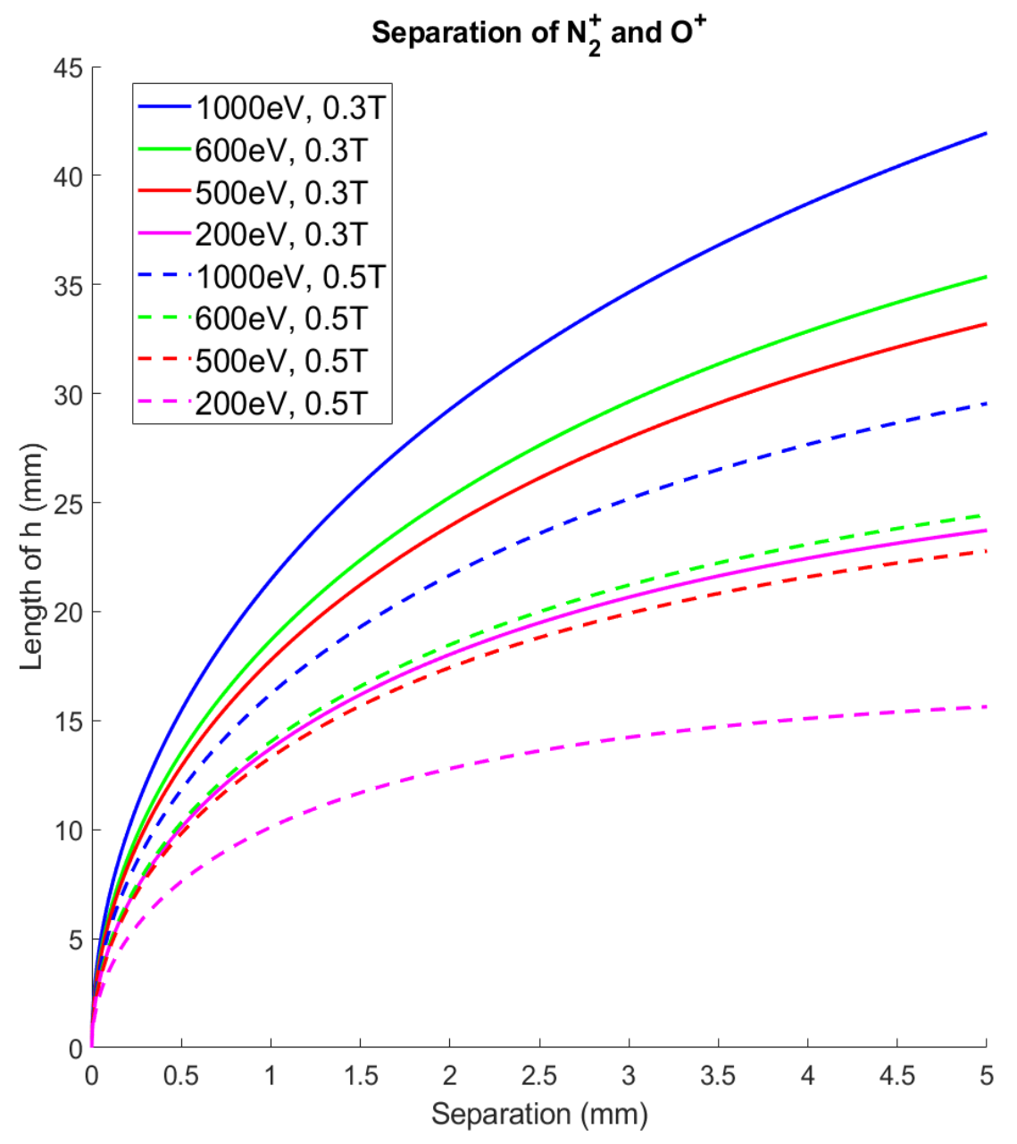

Figure 3. Estimated separation of O^+ and N_2^+. Increasing B increases separation. Increasing E decreases separation.

- Using the Lorentz force, Newtons 2nd law, and centripetal acceleration, the electrostatic analyzer voltage for a charged particle E is $V = 4\frac{R_2-R_1}{R_2+R_1}\cdot\frac{E}{q}$.

3D Modelling

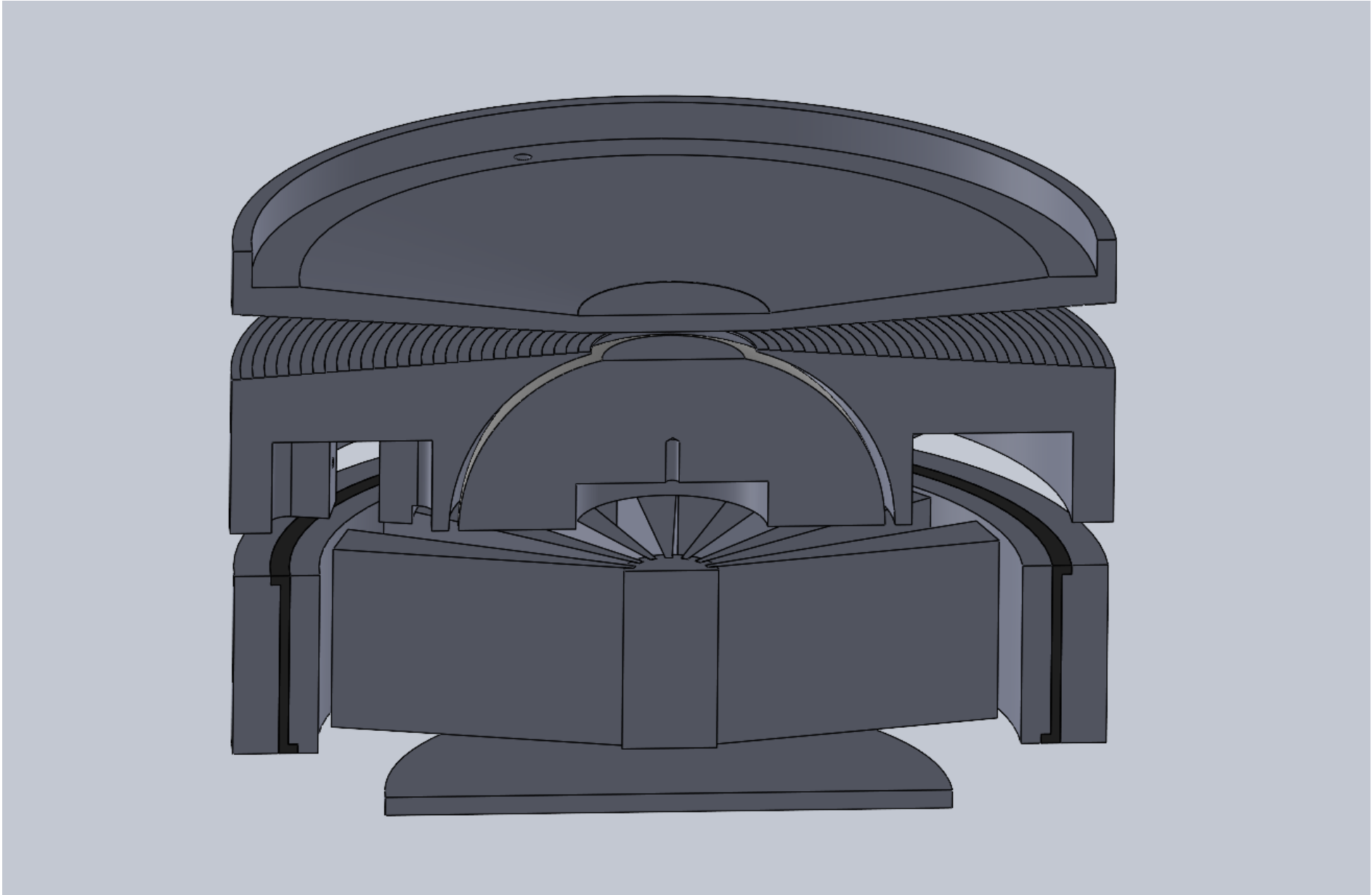

Figure 4. A section view of the redesigned BEEPS 3D model. The top section is the analyzer, the middle the mass spectrometer, the bottom the MCP (40mm).

- A 3D model of the modified magnetic section was created using the original BEEPS drawings as a source.
- The 15 magnetic wedges are held in place by an aluminum center piece and are surrounded by 3 shells.
- After particle simulations the final length of the magnetic section is 22.3 mm.
- With a R_1 of 28.1 mm and R_2 of 29.5 mm, the analyzer is roughly twice the size of the original BEEPS.
- For simplicity in modelling parameters the "stretched" top hat analyzer was changed to a more standard top hat analyzer, reducing the ion beam focus and making the instrument less accurate.
- The bottom cylinder of Figure 4 is the microchannel plate (MCP).
- The MCP is stacked on top of the anode and provides a gain of $5 \cdot 10^5$, making measuring the ion flux possible.
- largest limiting factor to the original beeps was the MCP diameter (40mm) and magnet strength.

Magnetic Field Modelling

- The 3D model was imported to ANSYS Maxwell, an electromagnetic field solver.
- Magnetic materials were modeled to estimate the strongest magnetic field in the gap.
- The strongest field is estimated to be 690mT using Alliance N-45M Neodymium Iron Boron. See Figure 5.
- The ideal area for particle flight is between 15 mm and 35 mm where the field is relativity uniform.
- The field leakage from the instrument is small, roughly 600 times less than the field inside. See Figure 6.
- The field will then have a minimal affect on the ions outside.

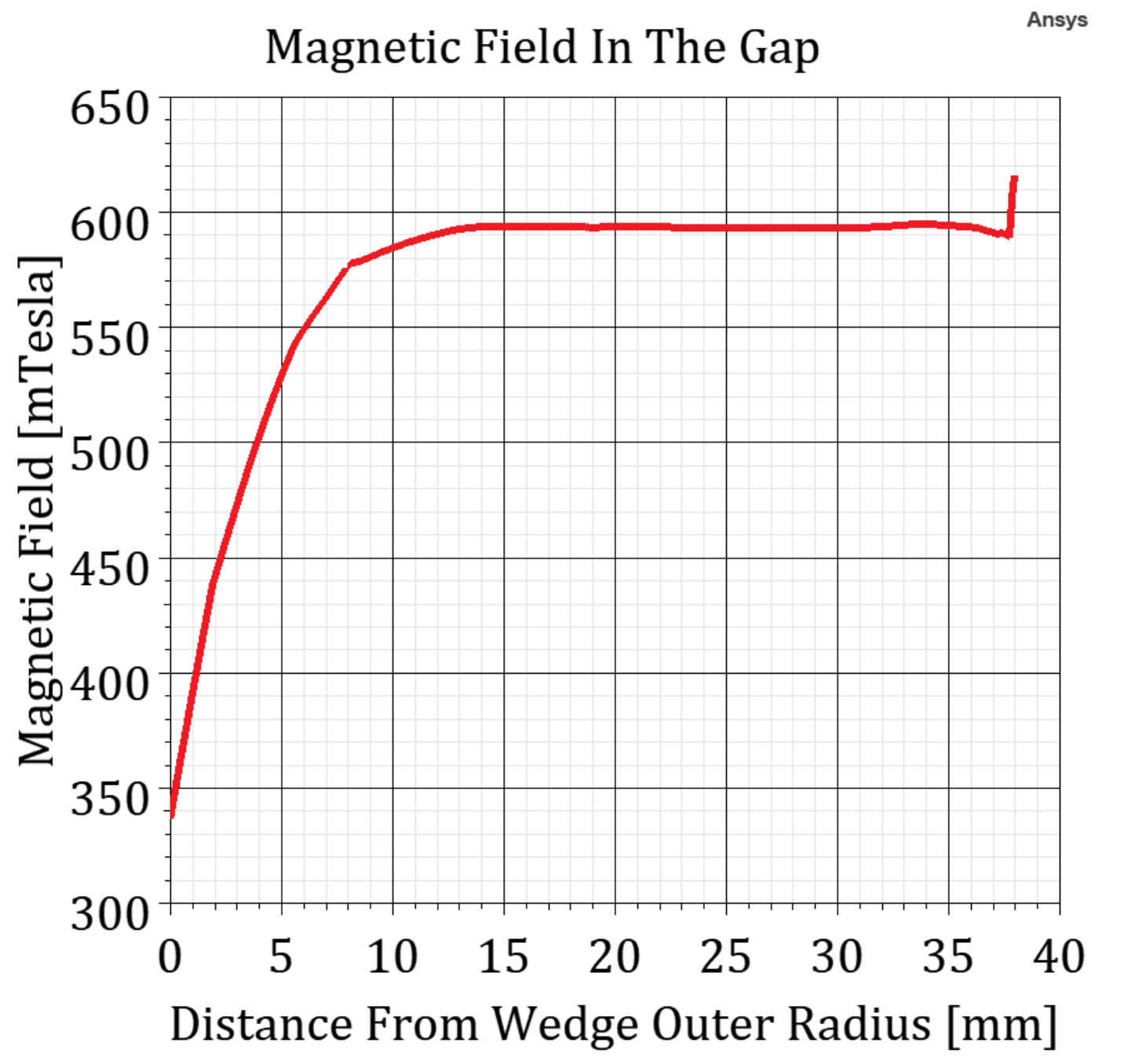

Figure 5. The magnetic field in the gap vs. the distance from the outer edge of the wedge r_2. About 2mm of each 40mm wedge is inside the center piece.

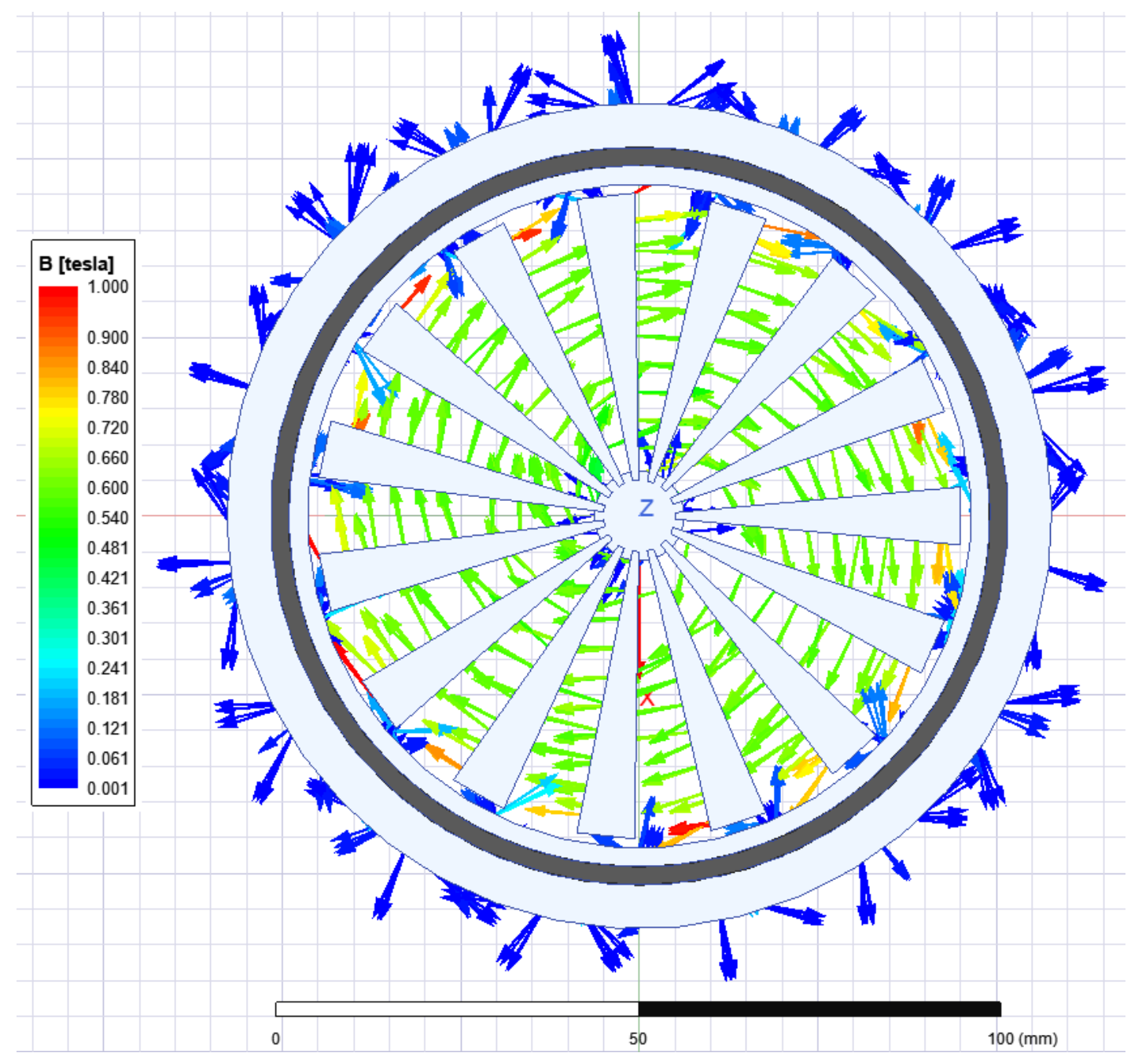

Figure 6. The magnetic field modelled with N-45M. Looking down a clockwise field is created, deflecting ions towards the center.

Particle Simulations

- The 3D model was imported to SIMION, an ion optics simulation that calculates ion trajectories in electromagnetic fields.
- A cone beam with a half angle of 10° made up of O^+ and N_2^+ at 5eV was used to test both their separation distances and individual distributions. See Figure 7.
- Particles were accelerated by V_{PA} to 500eV, 600eV, 700eV, and 800eV.
- The distance between the magnetic section and the MCP was varied based on best distribution.
- Particles that cross the center of the MCP are "bad" particles as they land in the wrong pitch angle bin.
- Simulations estimate the best length of the magnetic section to be 22.3mm and that a 40mm MCP can be used.

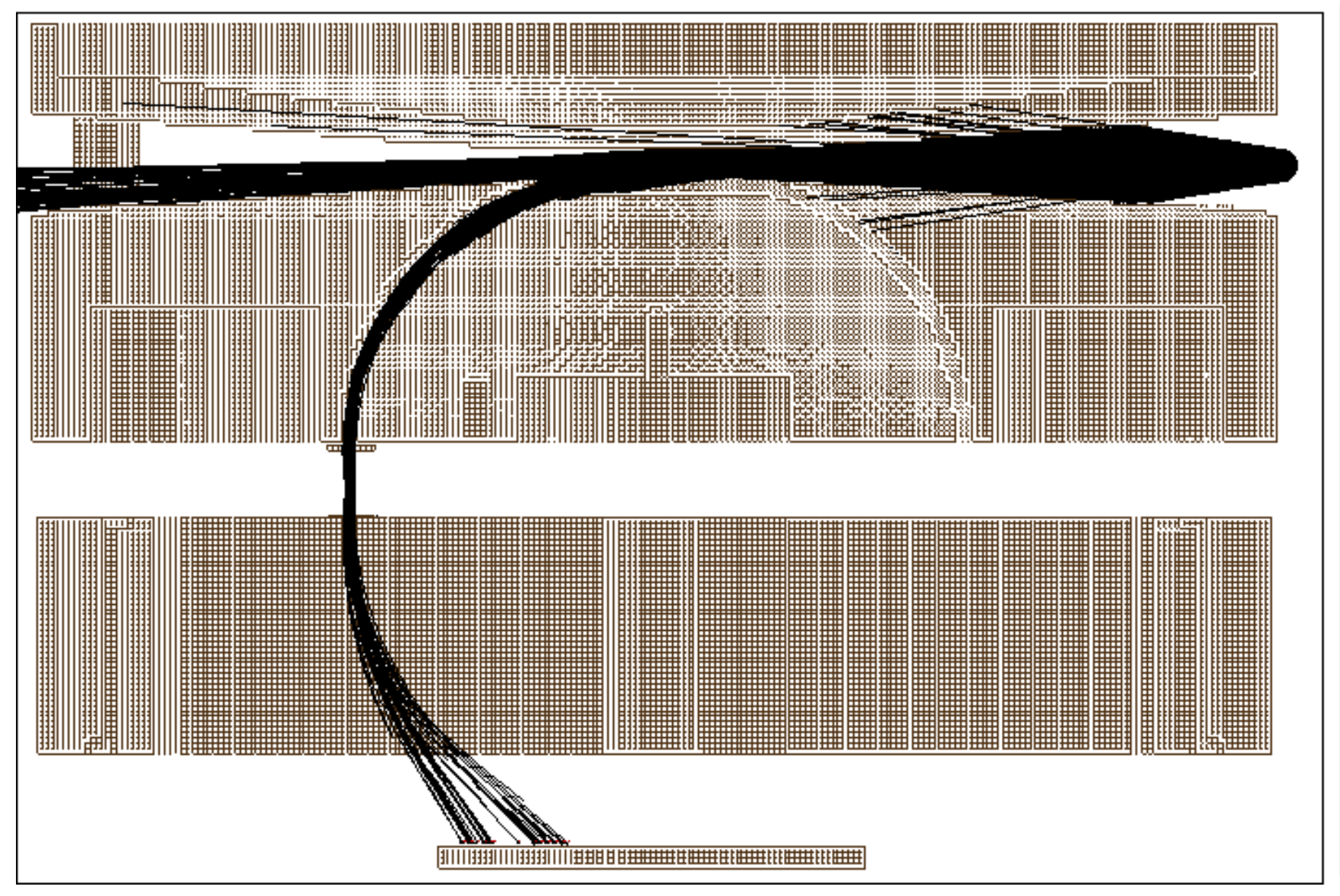

Figure 7. A SIMION simulation with particles accelerated to 800eV. Trajectories can be seen in black. The particles of the correct energy are deflected through the electrostatic analyzer. Between stage 1 and 2 they are accelerated to a higher energy. They are then separated by mass, with N_2^+ to the left and O^+ and to the right.

Figure 8. A different angle of particle trajectories. Particles that do not fly over the center of the instrument pass through.

Results

- Particle simulations estimate that both the separation of the ions and the width of their distributions decrease as the accelerating potential increases.
- The separation between distributions is estimated at 3.4mm, 2.4mm, 1.4mm, and 1.2 mm for particles with a post acceleration energy of 500eV, 600eV, 700eV, and 800eV, respectively.
- Assuming the O^+ and N_2^+ anodes must be a minimum of 5 mm apart, the collection percentages are 95.8%, 91.7%, 82.3%, and 74.2% for 500eV, 600eV, 700eV, and 800eV, respectively.

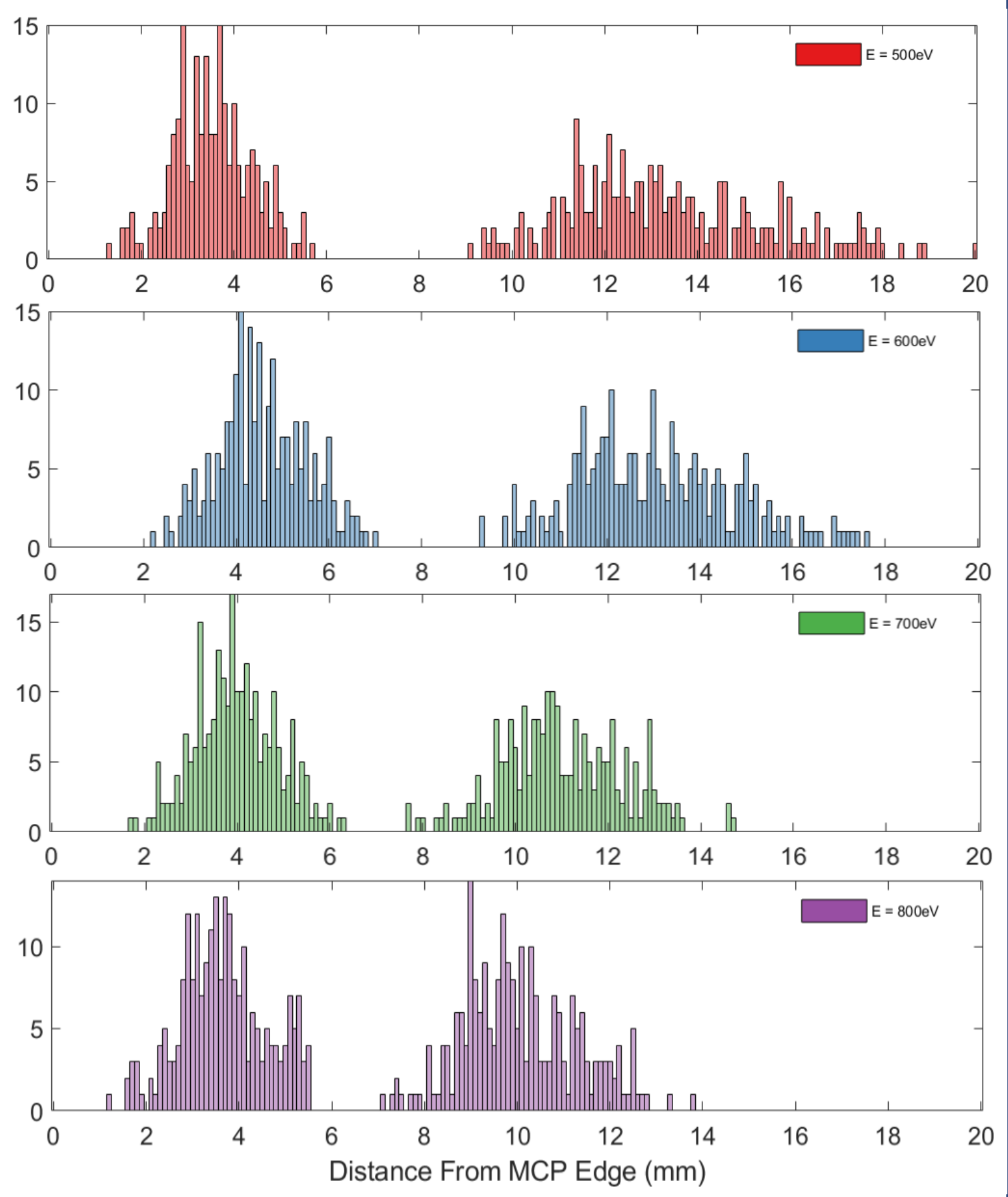

Figure 9. Histograms of ion distributions and their distance from the edge of the MCP, with N_2^+ to the left and O^+ to the right. The 500eV O^+ distribution is considered too large, with particles crossing the MCP center.

Conclusions

- Modifications to the BEEPS design were done so that it could distinguish between O^+ and N_2^+. Changes include doubling the electrostatic analyzer radii and more than doubling the length of the magnetic section.
- The key reason this can be achieved is advancements in magnetic material that allow for a stronger field with the same volume.
- Enough particle deflection was estimated that a 40 mm MCP could be used in place of the originally assumed necessity of a 75 mm MCP.
- Distributions were estimated to have no overlap but to lack separation greater than 3.4 mm.
- Based on the separation distances and the distribution widths , the best post accelerated energy is 600eV with 91.7% of its particles captured using a 5 mm spacing between anodes.

Future Work

- A more advanced particle simulation is needed before further development of the BEEPS can be done.
- A simulation with a sweeping R_1 voltage using an ion beam with a range of particle energies would correctly simulate how the instrument functions in real time.
- Simulations should include particle beams from every angle to help determine its geometry factor.
- Modifications in the wedge angle may be necessary to maximize ion flux with respect to ion deflection.

References

[1] Lynch, Kristina Anne, "Fine structure of auroral particle acceleration" (1992). Doctoral Dissertations. 1681. https:// scholars.unh.edu/ dissertation/1681

[2] Brown, K. NASA's Maven reveals most of Mars' atmosphere was lost to space. *NASA* (2017). Available at: https://www.nasa.gov/press-release/nasas-maven-reveals-most-of-mars-atmosphere-was-lost-to-space. (Accessed: 1st April 2022)

[3] Ellingsen, P. G., Lorentzen, D., Kenward, D., Hecht, J. H., Evans, J. S., Sigernes, F., and Lessard, M.: Observations of sunlit N_2^+ aurora at high altitudes during the RENU2 flight, Ann. Geophys., 39, 849–859, https://doi.org/10.5194/angeo-39-849-2021, 2021.