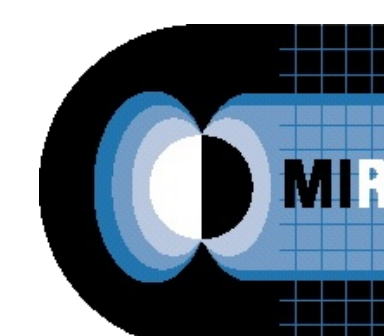


# First Flight of the Thermal Ion Gated Time of Flight (TIGTOF)

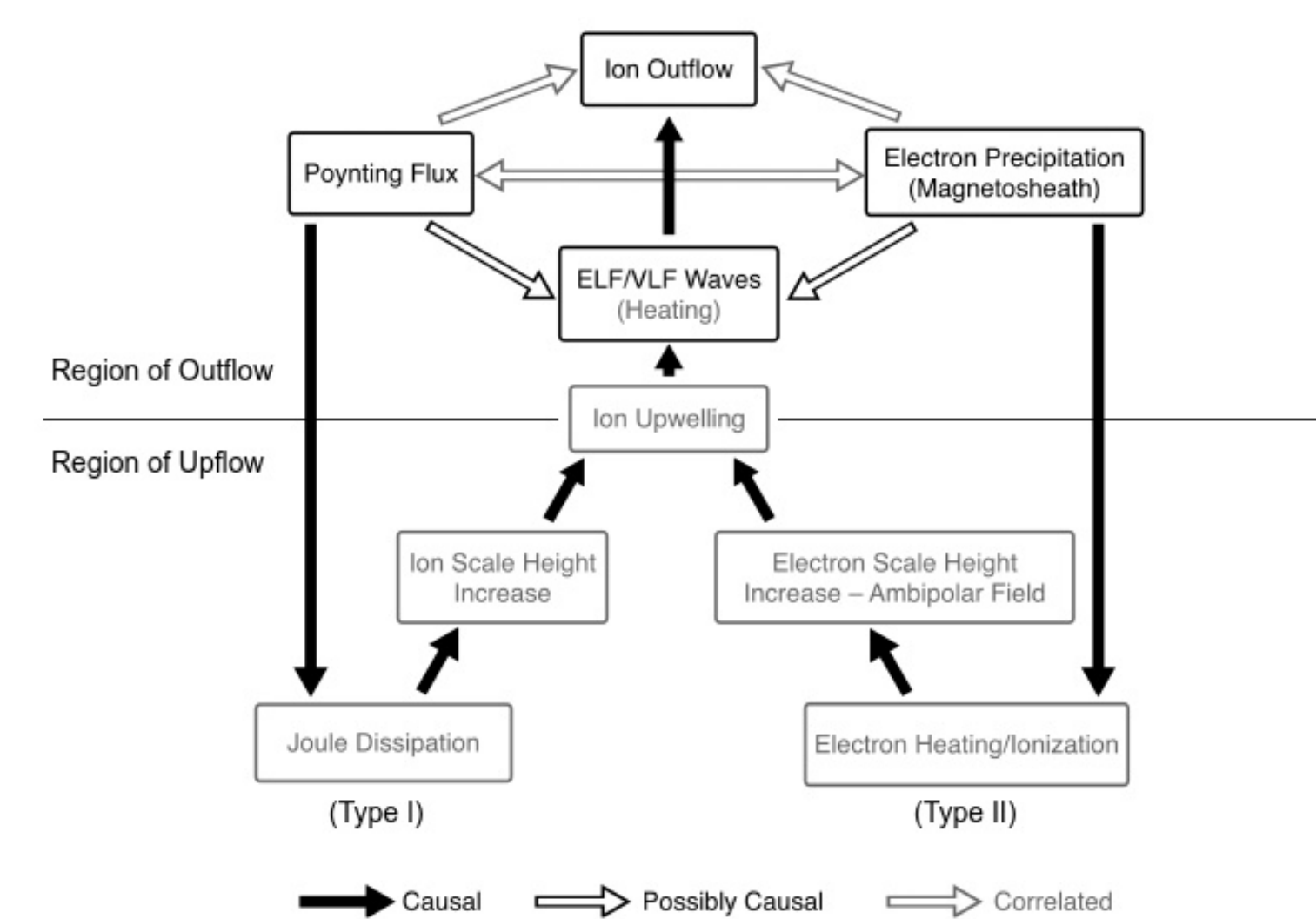
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## Abstract

The escape of atmospheric particles at high latitudes is a well documented process called ion outflow. On Earth, outflowing O<sup>+</sup> is most commonly observed, followed by significant populations of heavier molecular (e.g. N<sub>2</sub><sup>+</sup>) ions. Although we can measure upflow on Earth, we lack the basic data necessary to fully understand the role that differing ion masses play in the upflow process. The Thermal Gated Ion Time of Flight (TIGTOF) is being developed to measure in-situ particle fluxes in the cusp-region ionosphere, and will allow us to:

- 1.) examine the role of molecular ions in ion upflow processes, and
- 2.) ultimately provide a proper characterization of the energy budget as input to ionosphere-thermosphere coupling models.

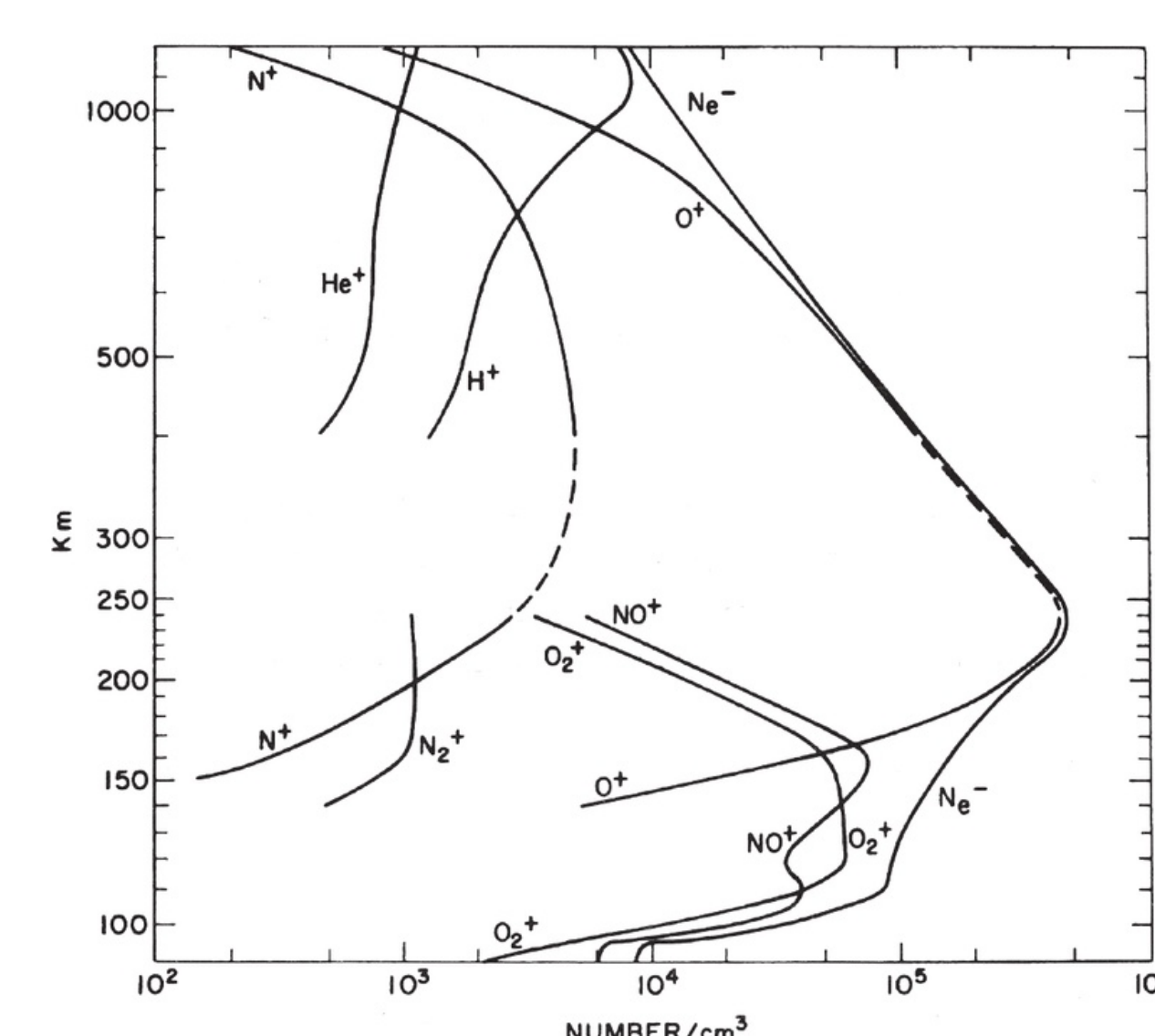
## Science Background



Ion outflow is a two-stage process through which atmospheric particles gain energies necessary to escape Earth's gravitational field. The first stage of ion outflow is called upflow in which ions are lifted from 100 - 250 km up to 500 - 600 km. There are two types of ion upflow: Type I is the ionospheric convection known as Joule heating, and Type II is driven by soft electron (~ 100s of eV) precipitation.

The second stage is called outflow, during which particles are lifted from 500 - 600km and higher. Upflowing particles must receive additional energization in order to achieve escaping velocity. In the absence of this additional energization, particles may return to lower altitudes (downflow).

Figure adapted from Strangeway et al. 2004.

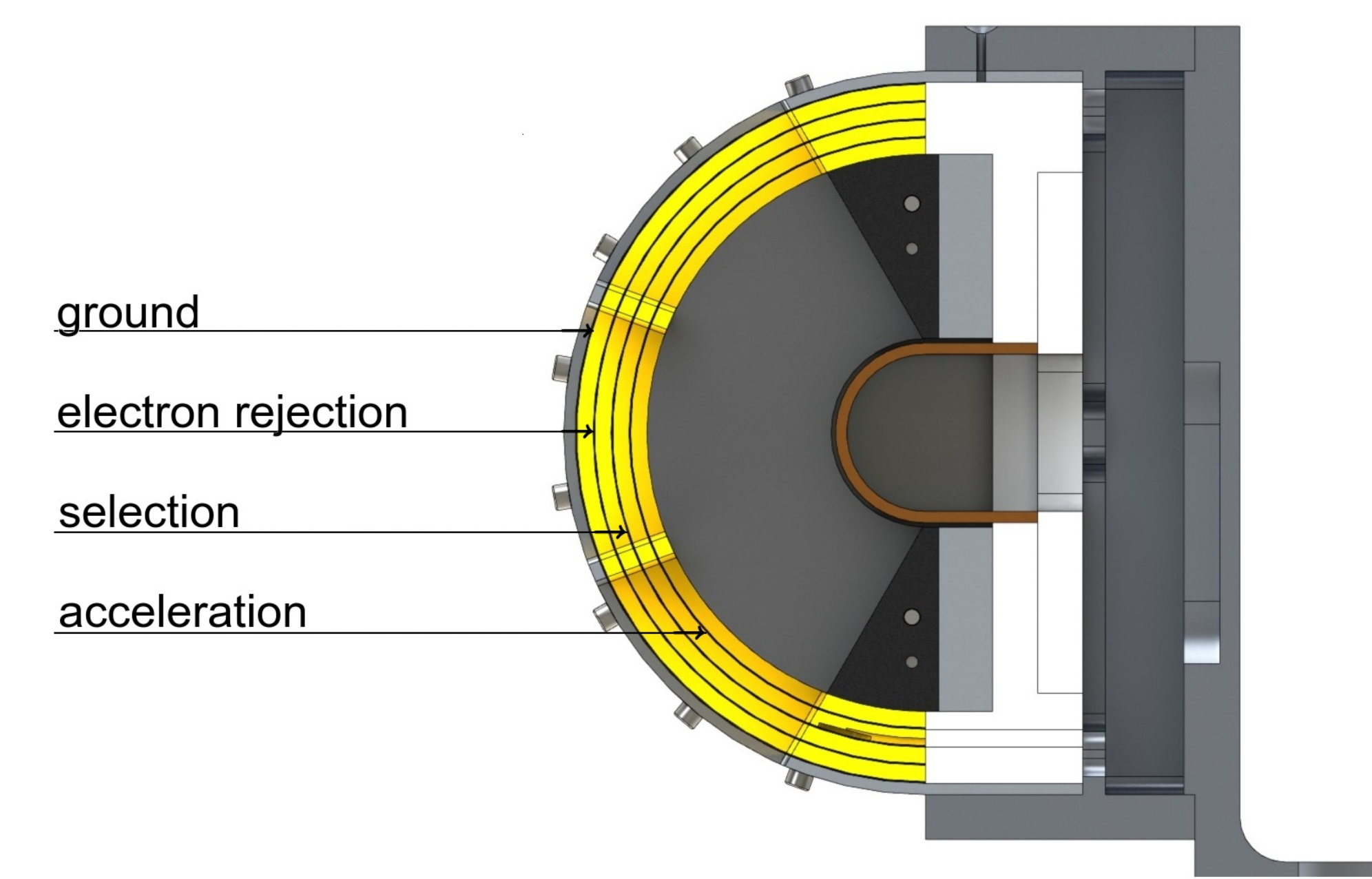


Precipitating electrons associated with Type II ion upflow couple energy most efficiently between ~ 230 - 250 km, where the primary constituents of Earth's atmosphere are O, O<sub>2</sub>, and N<sub>2</sub>. Low collision rates at these altitudes gravitationally stratify the atmosphere, resulting in O<sup>+</sup> being the dominant ion species with a significant N<sub>2</sub><sup>+</sup> population also present. Ground and in-situ observations have predominately shown O<sup>+</sup> to be the dominant upflowing particle species at sounding rocket (~ hundreds of km) and satellite (~ thousands of km) altitudes (Shelley et al. 1972, Waite et al. 1985, and Yau et al. 1985). The processes which produce the observed preferential upflow of O<sup>+</sup> over N<sub>2</sub><sup>+</sup> are not well understood and require further investigation.

Figure adapted from Johnson et al. 1969.

## TIGTOF v.1

TIGTOF is a Retarding Potential Analyzer (RPA) that utilizes a gated Time of Flight (TOF) method to measure ion mass and relative number densities of particle species within a population. TIGTOF's ability to distinguish between three distinct mass regimes, protons, heavy ions (e.g. O<sup>+</sup>, 16 amu), and heavier molecular ions (e.g. N<sub>2</sub><sup>+</sup>, 28 amu), will be crucial for understanding the impact of increased mass throughout the magnetosphere.

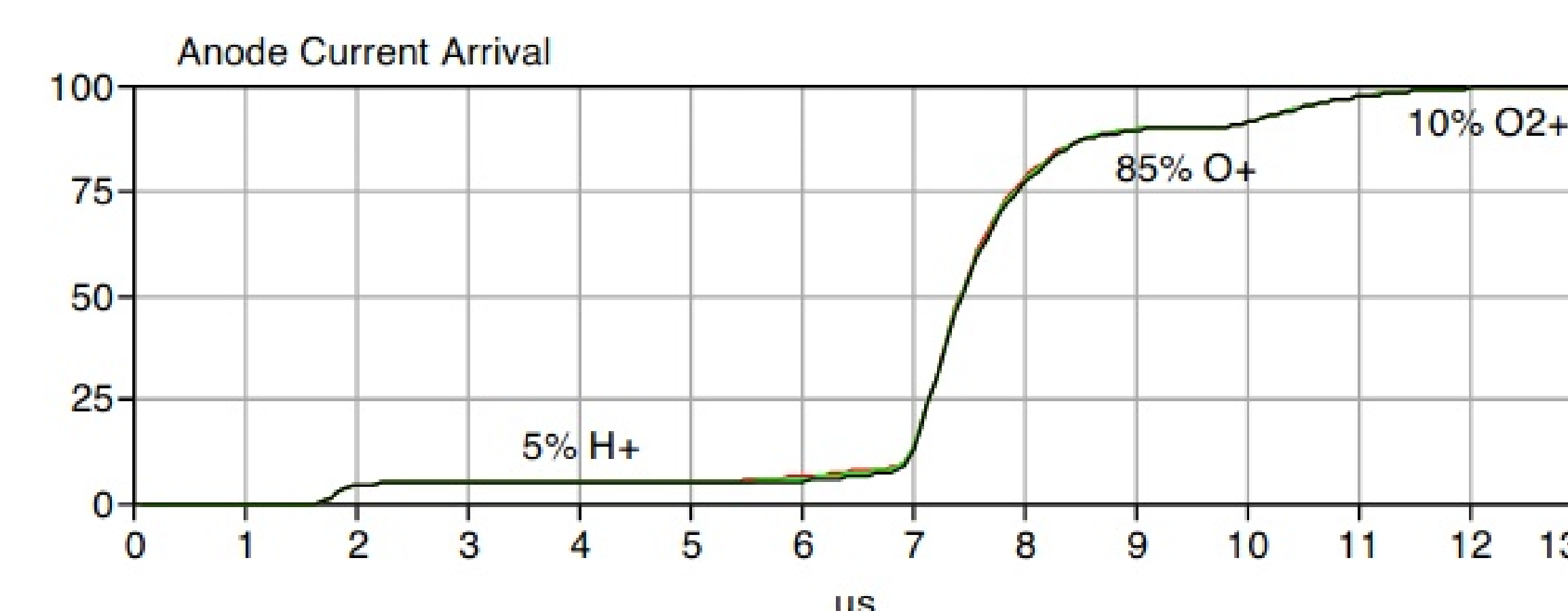


## Flight

A prototype of this version of TIGTOF (v.1) was flown on the Cusp Region EXperiment (CREX-2) sounding rocket in December 2021. Thus far, analysis of CREX-2's flight data has shown that:

- 1.) Modeled fits to the flight data are inconsistent during the initial and final stages of the flight (possibly correlated to higher ram velocities on the upleg and downleg) but are somewhat consistent during the majority of the flight.
- 2.) The observed time of flight delay for O<sup>+</sup> is higher than can be accounted for by timing errors and/or mechanical tolerances. The reason for this is currently unclear. There may also be some surface charging effects that are not accounted for.
- 3.) The numerical model does not account for the physical "wrinkles" in the screen material, which could introduce additional errors into the time of flight calculations.

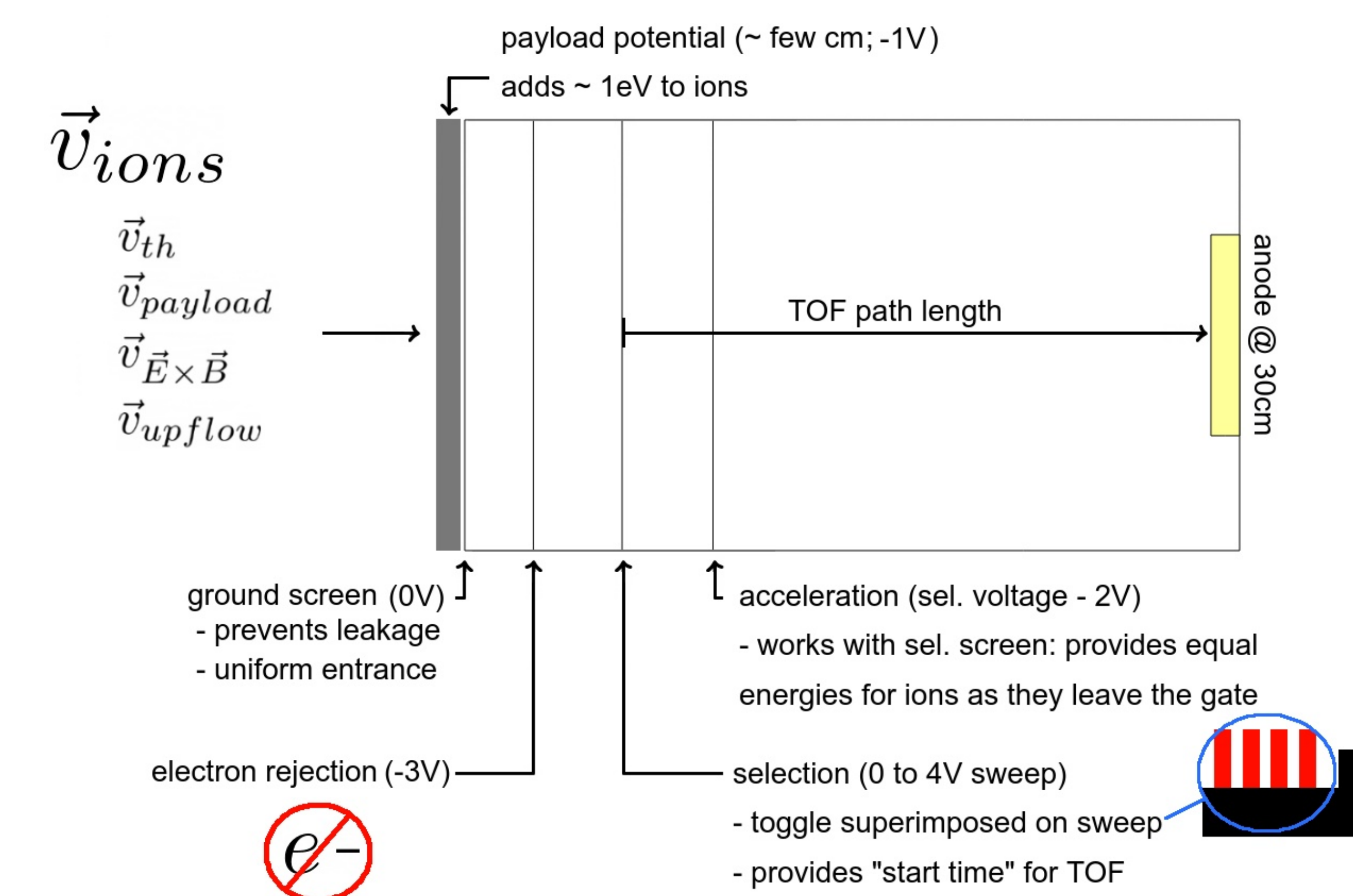
NET: implementing an overall larger TIGTOF; i.e. with a larger entrance area and longer time-of-flight path, would provide better signal and better time-of-flight resolution, thus compensating for the observed issues. Further analysis of the CREX-2 flight data is planned and should provide the information necessary to redesign TIGTOF.



At the anode, the collected charge produces a waveform derived from the combination of arrival times for each mass group, with smaller ions arriving at the anode first. The CREX-2 simulations show that the resulting waveform consists of three distinct peaks determined by the TOF of each mass. Increasing the TOF path length will increase TIGTOF's resolution (i.e. increasing the distance between these peaks).

## TIGTOF v.2

TIGTOF is being redesigned based on the CREX-2 flight data. We have decided to implement an overall larger geometric factor to provide improved TOF resolution. The curved screens (originally designed to accommodate a large range of ram entrance angles into the instrument's aperture) will be replaced with flat, rectangular ones since the angular field-of-view can be drastically reduced for a TIGTOF that is ram-facing, which will be the case for RENU3.



TIGTOF's gated TOF is controlled by the four screens across the aperture (Figure not to scale):

- 1.) ground: provides uniform entrance field to incident ions.
- 2.) electron rejection: repels electrons; accelerates ions.
- 3.) selection: determines admitted minimum energy of particle.
- 4.) acceleration: accelerates ions toward the anode.

The delay between the opening of the TOF gate and the arrival of particles at the anode provides the TOF. Combining the measured TOF with the TOF path length gives the velocity of the measured ion; comparison with the admitted energy yields ion mass.

There are 5 main contributions to the ion velocity at the entrance screen:

- 1.) Thermal velocity ~ 500 - 1000 m/s. Assumed isotropic.
- 2.) Payload velocity ~ 1000 to 2500 m/s.
- 3.) Ionospheric convection (ExB) drift velocities ~ few hundred m/s.
- 4.) Ion upflow/downflow ~ typically a few hundred m/s.
- 5.) Payload plasma potential ~ 2000 to 4000m/s for O<sup>+</sup>

## Acknowledgments

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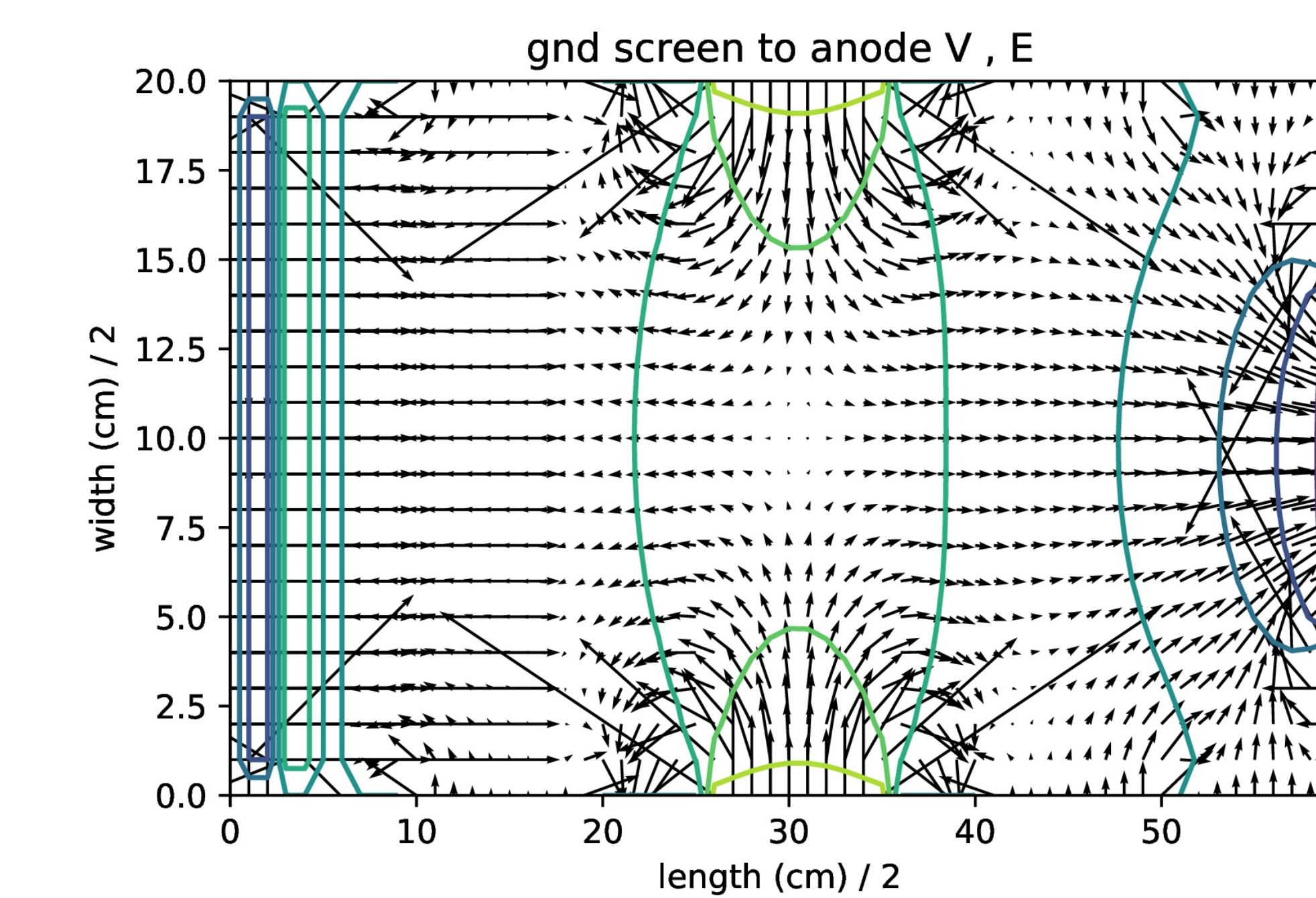
Support for RENU2 was provided at the University of New Hampshire by NASA award NNX13AJ94G.

RENU3 is funded by NASA grant 80NSSC21K0972.

## Model Results

We have been developing a numerical model part of this effort to guide TIGTOF's v.2 redesign. The model utilizes a "relaxation method" to calculate the electric potential and electric field inside TIGTOF (resulting from the biases applied to the 4 screens, walls, and anode). The inclusion of Einzel lenses improve focusing of ion paths toward the anode and introduce another source of voltage into the model. The electric field vectors provide information about the paths that particles (ions) will follow to arrive at the central anode. This method is applied iteratively until the absolute error (i.e. the absolute difference between successive iterations) is minimized below a specified threshold (1e-4).

The goal is to focus the trajectories of incident ions toward a smaller anode area to reduce anode capacitance.



The dimensions of TIGTOF v.2 have been changed to maximize TOF resolution. Further, a 10x10 cm entrance aperture with a 30 cm length would make TIGTOF v.2 the same size as a 1U cubesat. Since TIGTOF does not use high-voltage and does not require any deployments, its simplicity, compact size, and light weight would make TIGTOF v.2 an ideal cubesat instrument.

## Summary

TIGTOF v.1 was flown on CREX-2 in 2021. We are developing an improved instrument (TIGTOF v.2) based on this flight data. TIGTOF v.2 will be included in the Rocket Experiment for Neutral Upwelling (RENU3) sounding rocket payload in 2024. The improved instrument will have a longer TOF path length (to improve mass resolution), and flat screens (easier to install, and less prone to the wrinkling that introduces error into the TOF calculations). Additionally, a numerical model is being developed to guide the redesign effort.

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