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A New Mass Spectrometer for Upper Atmospheric measurements in the Auroral Region

Utah State University RESEARCH FOUNDATION

Space Dynamics LABORATORY Utah State University Research Foundation

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Research Objectives

- Develop a mass spectrometer capable of measuring densities of ions and neutral particles in the mesosphere/lower thermosphere (MLT)
- Demonstrate instrument performance with a laboratory prototype instrument
- Obtain high sensitivity to allow for high resolution spatial profiling of atmospheric species of interest using time-of-flight mass spectrometry (TOF-MS)

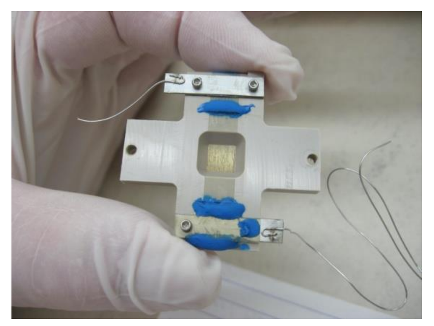
Introduction

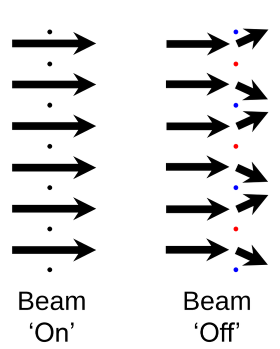
Last year at the AGU fall meeting we presented a mass spectrometer instrument concept for making measurements in the MLT. Continued instrument design and research during the past year has resulted in a laboratory prototype axially sampling time-of-flight mass spectrometer (TOF-MS). The TOF-MS is inherently adaptable and can be configured to detect ions or neutral particles. The TOF-MS is intended for use on sounding rocket missions and we have submitted two proposals that plan to employ the TOF-MS to make *in-situ* measurements of ambient ions and neutral particles in the polar MLT. **M**ass **S**pectrometry of the **T**urbopause **R**egion (MSTR) proposes four sounding rocket flights at different seasons of the year to measure the density of several neutral species from 70-120km to enhance our understanding of the MLT, particularly in the turbopause region. **ROCK**et-borne **ST**orm **E**nergetics of **A**uroral **D**osing in the **E**-region (**ROCK-STEADE**) proposes one sounding rocket flight with a varied instrument suite to investigate the ionosphere-thermosphere energy transfer process during an aurora. **ROCK-STEADE** will use two TOF-MS instruments, one each to measure ions and neutral particles from 100-170km.

Mass spectrometry in the MLT is challenging, due to the high speeds and elevated pressures encountered on sounding rocket flights. Sampling the undisturbed atmosphere generally requires cryogenics to eliminate the bow shock that forms on the ram side of the instrument. In addition, several methods of vacuum pumping are available to maintain suitable operating pressures inside the TOF-MS. These methods include barium loaded getter tubes, miniature turbo pumps, and basic cryogenic pumping. Because it is capable of making fast, accurate measurements the TOF-MS has the potential to greatly aid in enhancing our understanding of the MLT.

Electronics

Bradbury-Nielsen gate (BNG)

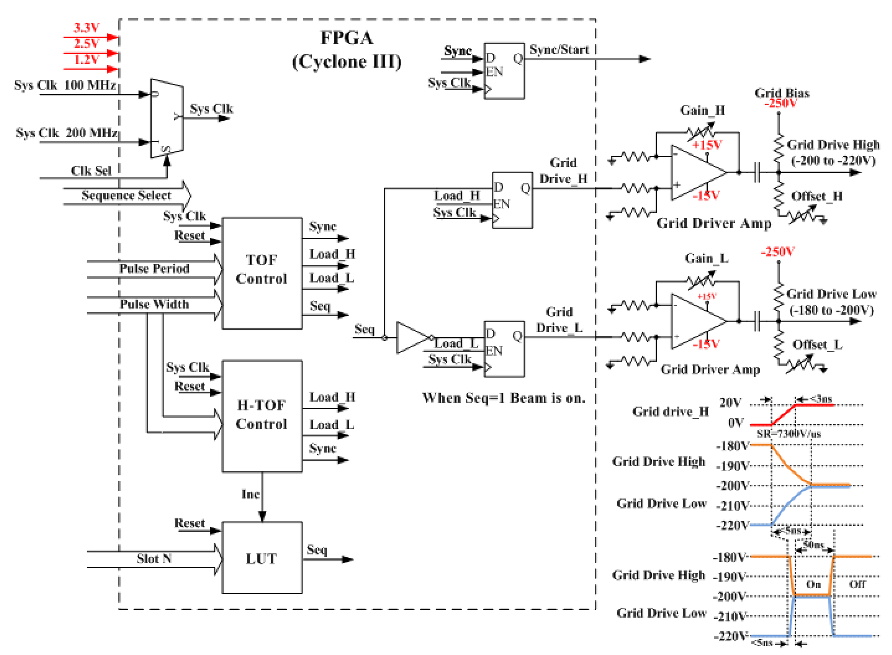


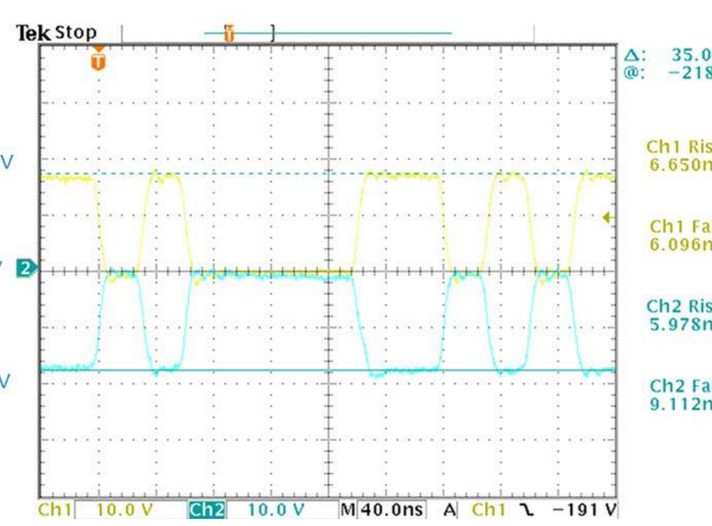


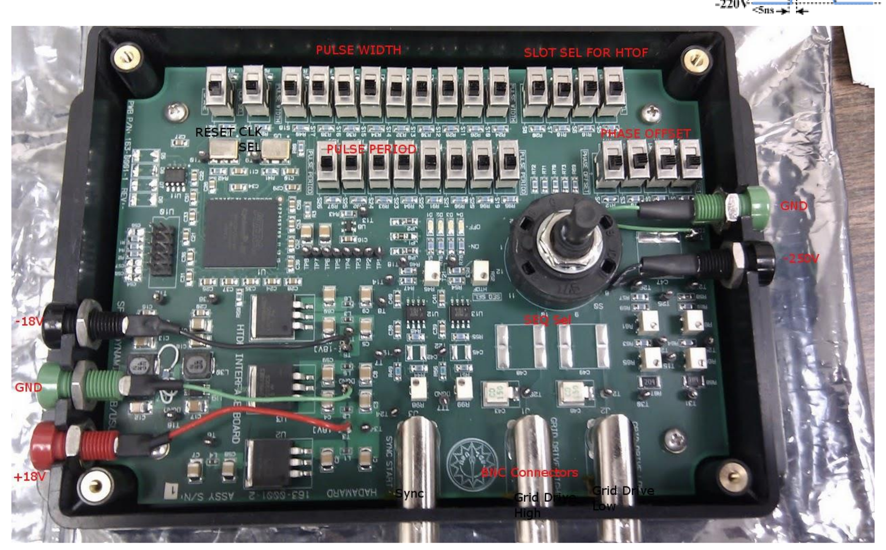
- Two sets of interleaved wires, used to modulate incoming ions
- For beam "on" both sets of wires are set at the acceleration potential, V_{acc}
- For beam "off" every other wire is at $V_{acc} \pm V_{mod}$
- Wires are 10 µm gold plated tungsten with average wire spacing of 75 µm
- Pulse rise time ~5 ns

Control board

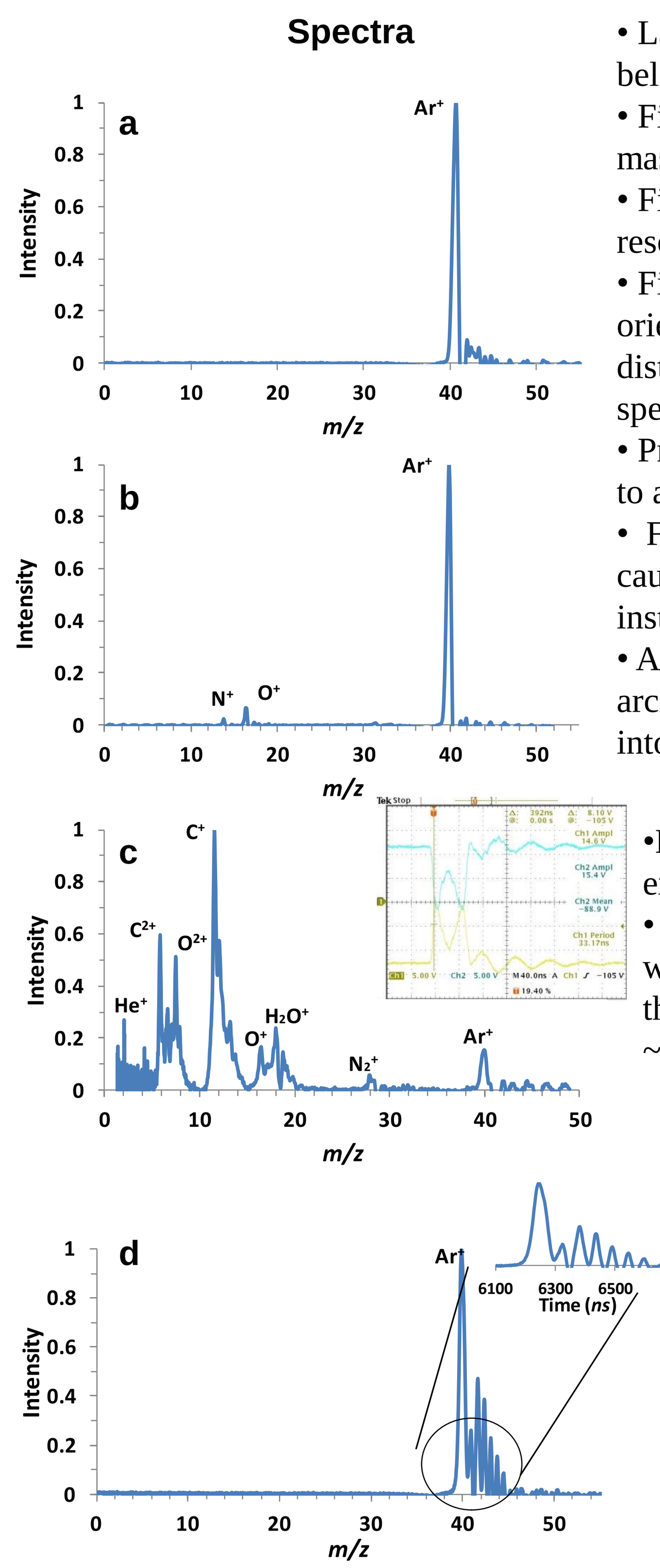
- Mode select allows TOF-MS to operate in conventional TOF-MS, multiplexing Hadamard Transform (HT) TOF-MS, beam "on," or beam "off" mode
- Provides the TOF-MS with modulated drive voltages to pulse the ion beam, along with a start of sequence pulse coincident to the first pulse of each of the TOF or HT-TOF sequences to trigger data collection
- Because of design challenges due to required large drive amplitudes (~40 V differential), large negative bias voltage (-200 V), and fast rise/fall times, selected FPGA (Altera Cyclone III, EP3C5F256C6N) for its fast switching speed and adequate memory to hold several Hadamard sequences of different lengths.
- Pulse rise/fall times of ~5 ns with 20 V range





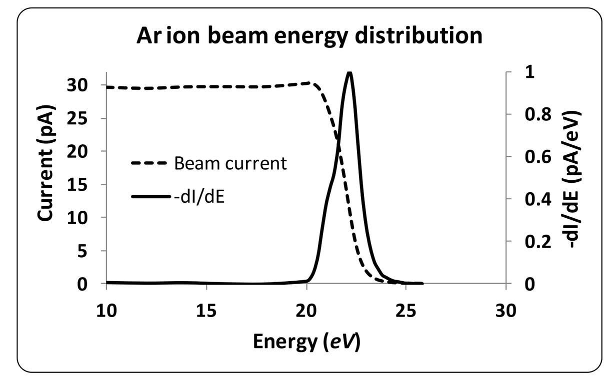


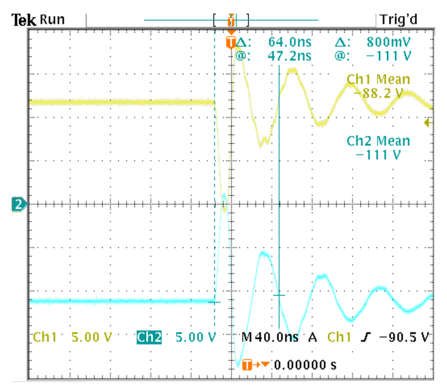
Laboratory Prototype



- Laboratory prototype TOF-MS placed in ion optics test chamber (see figure below) Nov. 28, 2011, spectra obtained the next day in conventional TOF mode
- Figure a) obtained from 122 eV Ar^+, 222 seconds integration time. SNR = 648, mass 40 resolution = 56 at FWHM
- Figure b) obtained with ion gun velocity filter off. Ar^+ SNR = 646, mass 40 resolution = 63 at FWHM
- Figure c) obtained by chamber backfill with various gases, with instrument oriented toward ion gauge. Peak shifting due to "hot" ions with large energy distribution. Peak "doubling" due to problems with modulation pulses, but spectra obtained nonetheless (see inset for modulation voltage plot).
- Pressure for during data collection for figure c) was ~10^{-4} torr, corresponding to a mean-free-path ~5x the length of the instrument.
- Figure d) obtained from 122 eV Ar^+ over 6.27 hrs. Signal after Ar^+ peak is caused modulation pulse. Ion velocity distribution and broadening due to instrument contribute to a signal spread of ~50 ns
- After less than 24 hrs of initial pumpdown, TOF-MS experienced only one arcing incident in nearly 19 hours of continuous operation at pressures ranging into the 10^{-4} torr range

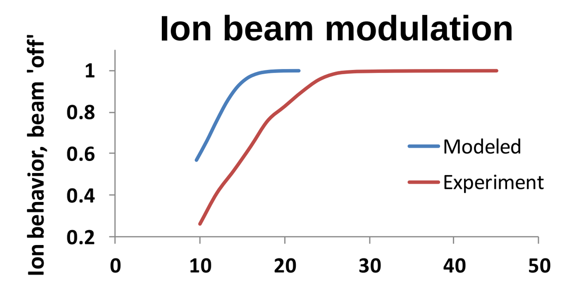
- Energy of Ar^+ ions used in experiment peaks at around 22 eV.
- Acceleration potential of 100 V was used in the TOF-MS, giving the Ar^+ beam a final energy of ~100 eV.



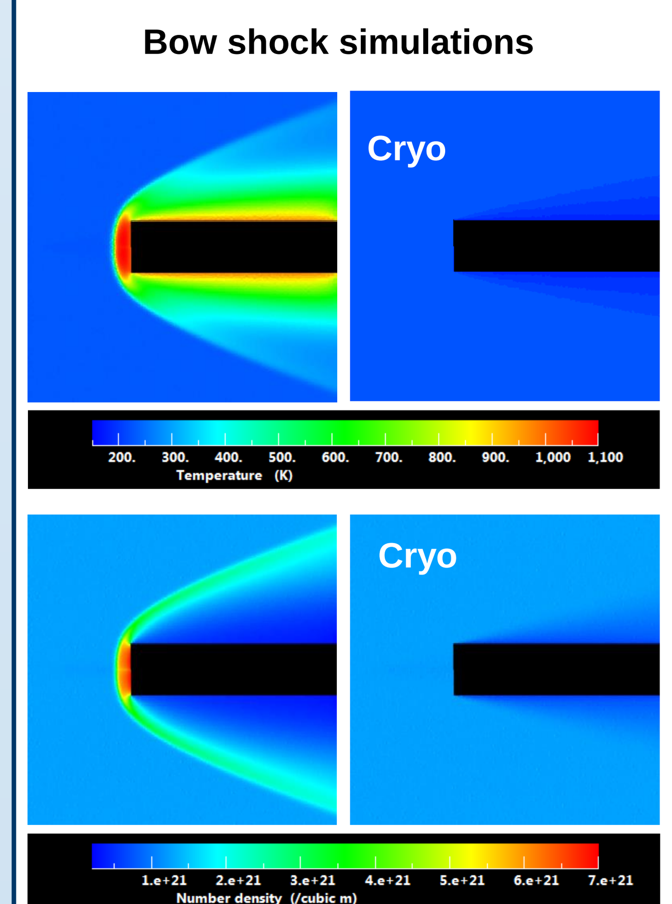


- Figure at left shows the BNG modulation waveform that was used to collect the mass spectrum shown in Figure d)
- Magnified spectrum (inset) shows oscillations due to beam modulation

- Experiments show the required BNG voltage to deflect ions in beam "off" state
- Counts were integrated over a period of 10 seconds at various BNG modulation voltages and compared to the total number of counts collected during the same time period with no modulation voltage applied

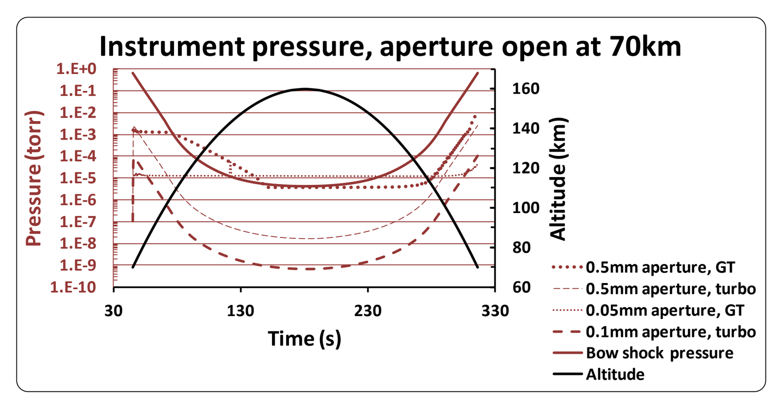


Bow Shock Elimination and Vacuum Pumping Options

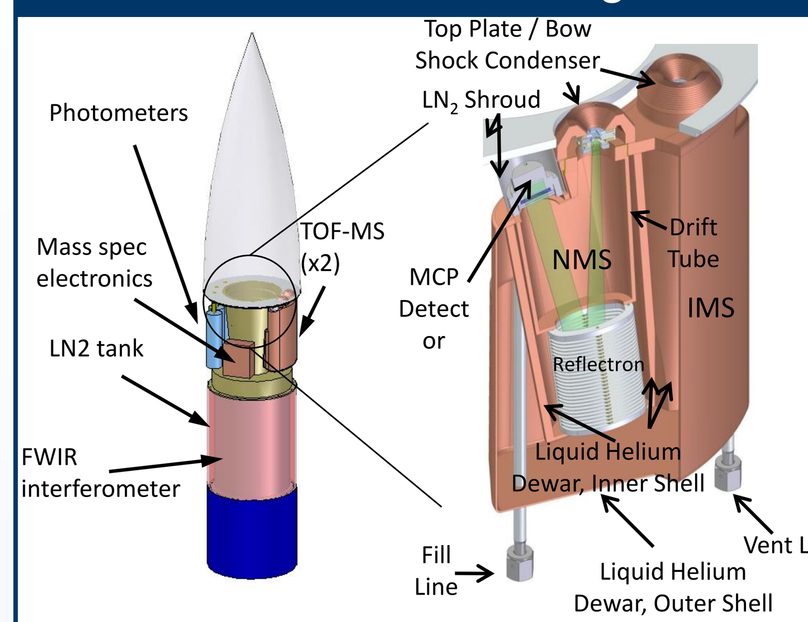


- High-speed rocket flight through the MLT normally causes a region of enhanced density and pressure, called a bow shock, on the ram side of the rocket (or payload)
- Bow shock can interfere with direct sampling of ambient atmosphere
- Below 25 K, (nearly) all incident gas molecules are adsorbed on a copper surface (Brown et. al.)
- Both **MSTR** and **ROCK-STEADE** will employ cryo-cooled front plates to enable direct atmospheric sampling by eliminating the bow shock
- Figure below shows simulated instrument pressure
- Mean-free-path requirement (~10x drift tube length) is met at 3×10^{-5} torr

- Barium loaded getter-tubes can be used as an inexpensive pumping method
- Aperture size can be tailored for the specific mission and pressure requirements

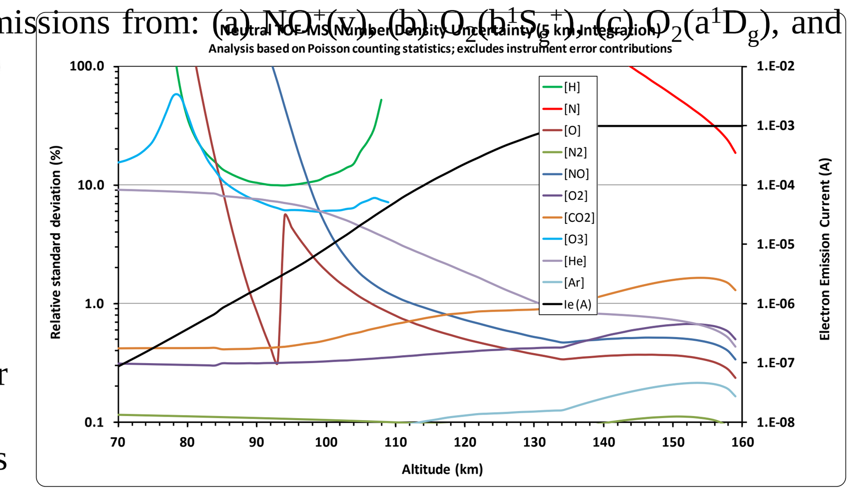


ROCKet-borne STorm Energetics of Auroral Dosing in the E-region (ROCK-STEADE)



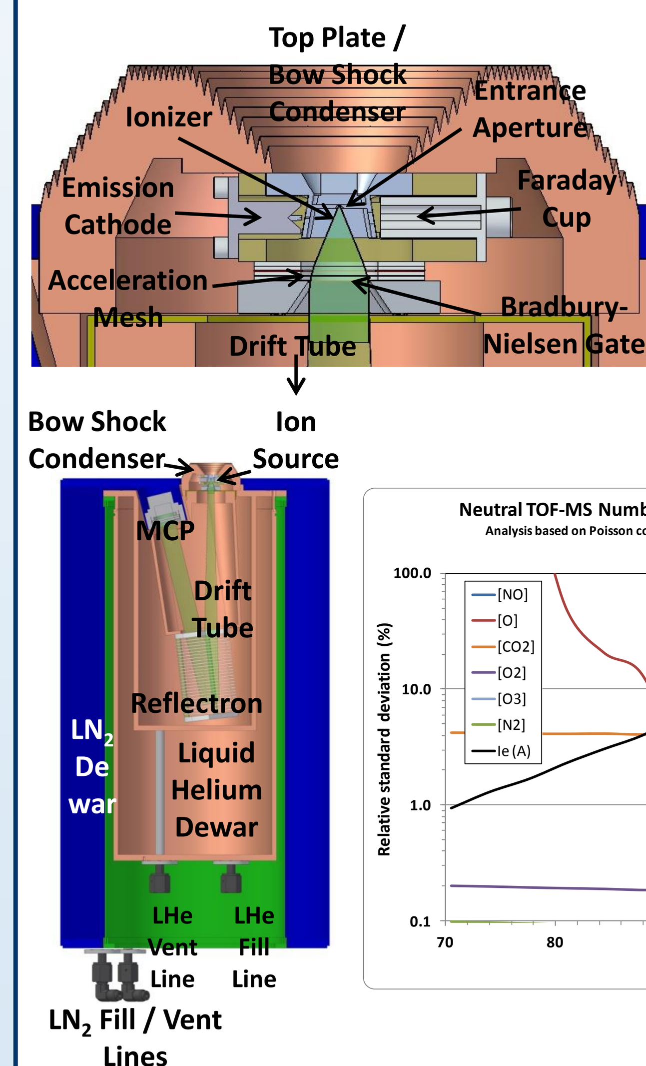
Science Questions

- What are the energy characteristics of the auroral particle precipitation?
- What is the total ionization rate from auroral particle precipitation?
- What are the E-region kinetic temperature and neutral/ion/electron concentrations?
- What are the excitation and loss mechanisms responsible for auroral emissions from: (a) $NO^+(v)$, (b) $O_2(b^1\Sigma_g)$, (c) $O_2(a^1\Delta_g)$, and (d) NO(v)



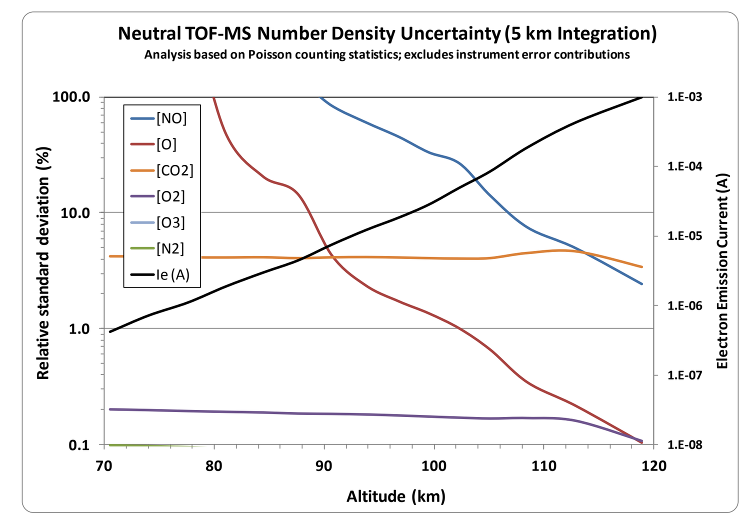
- **ROCK-STEADE** will consist of one sounding rocket launch
- Instrument suite includes a Field-Widened interferometer, four photometers, and two TOF-MS instruments
- One TOF-MS will be configured to measure neutral particles while the other will be configured to measure ions
- TOF-MS measurements will begin at about 70 km, and will measure neutrals: N_2, O_2, O, CO_2, NO, H, O_3 and ions: N_2^+, N^+, O_2^+, O^+, NO^+

Mass Spectrometry of the Turbopause Region (MSTR)



Science Questions

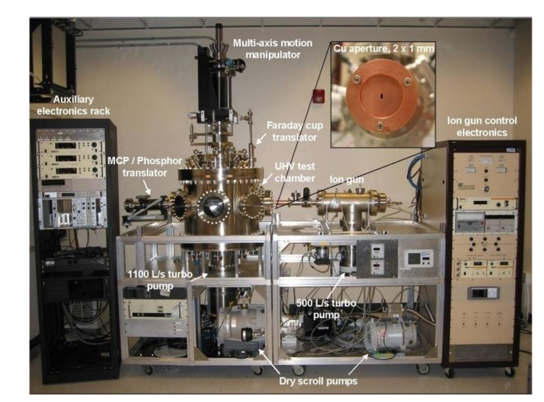
- Turbopause Altitude and Structure: What is the altitude at which the atmosphere turns from well mixed to diffusive equilibrium? At what rate do the major species mixing ratios fall off with altitude near the turbopause?
- Comparison of measured CO_2 profiles with those retrieved by IR radiometry: Are observed CO_2 profiles in agreement with profiles obtained by a developmental simultaneous Temperature-CO_2 retrieval with SABER data?
- Transport of NO across the turbopause: How strong is the descent ove the polar night? How much NO is transported downward across the turbopause?



- **MSTR** will consist of four sounding rocket launches at different times of the year in order to make observations of equinox, summer and winter solstice conditions and near-polar night
- Each rocket will carry one TOF-MS instrument
- Overall goal is to measure volume densities of CO_2, O_2, N_2, O, and NO as a function of altitude from 70 to 120km
- Modeling indicates the ability to measure CO_2 and O_2 with less than 10% relative standard deviation

Conclusions and Future Work

- Good resolution is achieved with the linear TOF-MS instrument
- For situations with high UV flux, a reflectron design can be incorporated to reduce background
- Testing of the TOF-MS will continue in the SDL ion optics facility
- Beam modulation improvements will enable collection of cleaner spectra
- Several options are available for maintaining suitable pressures inside the instrument, including cryo-pumping, barium loaded getter tubes combined with properly tailored aperture sizes, and miniature turbo pumps



References and Acknowledgments

Brown, R.F., D.M. Trayer, and M.R. Busby, *Condensation of 300--2500 K Gases on Surfaces at Cryogenic Temperatures.* Journal of Vacuum Science and Technology, 1970. **7**(1): p. 241-246.

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