Design Analysis and BNG Driver Simulation for a CubeSat Time-of-Flight Mass Spectrometer

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***Abstract*—Variations of gas density and composition in Earth's upper atmosphere create trajectory and orbit control problems for satellites of all sizes and significantly affect interactions between different layers of Earth's atmosphere. Mass Spectrometers are among an array of instruments used to explore Earth's upper atmosphere and other space environments. Normally, these instruments are substantial in size and deployed on larger satellites and space probes to perform studies of atmospheric properties while in orbit. Data from these studies generally provides information from a specific point in time at a single location. Studies of atmospheric density and composition with multiple locations for each time point could be performed by CubeSat swarms if proper instrumentation were available to fit CubeSat payload restrictions. The proposed miniaturized time-of-flight (TOF) mass spectrometer (MS) will have a mass resolution and range sufficient for measuring the free ion density of Earths ionosphere while operating within the power and space constraints of a CubeSat. This capability can potentially dramatically reduce the cost of future missions while simultaneously enhancing the science return. Elements from existing TOF-MS designs, including the use of spatial focusing, an ion mirror and signal processing techniques, will be used to achieve the desired range and resolution. Optimization of instrument dimensions has been performed to maximize mass resolution. Simulation of an electrical gate driver to minimize particle start time distributions was performed.**

Keywords*—*Low earth orbit satellites, Space technology.

I. INTRODUCTION

ATMOSPHERIC dynamics is an active area of study in NASA's Heliophysics division. Earth's upper atmosphere reacts to various inputs, including solar energy, lower atmosphere disturbances, and diurnal cycles. Reaction to these inputs has been studied by measuring certain atmospheric properties, including local magnetic/electric field strength, temperatures, winds, plasma and neutral densities, and chemical composition. Variation in these properties shows the dynamics of the upper atmosphere and reveals some underlying structures in its behavior, including evidence of feedback reaction to inputs and coupled reactions with geomagnetic activity and lower layers of the Earth's atmosphere. Data sets measuring all of these properties simultaneously on various spatial scales will be required to better understand the feedback and coupling processes. Future studies could improve upon the spatial resolution of atmospheric data by using constellations of small spacecraft with miniaturized instruments. Some instruments, such as Langmuir probes, electric field meters, magnetometers, and drift meters, have already been miniaturized and flown on small spacecraft to measure temperature, electric and magnetic fields, density, winds, and rough composition measurements. Mass spectrometer instruments could be used to accurately measure composition and density, but miniaturized mass spectrometry for CubeSat deployment is still very new. There are many types of mass spectrometers, but not all of them are well suited for CubeSats. Time-of-Flight (TOF) mass spectrometry (MS) could work well for CubeSats because it theoretically can be done in a small space and requires less power than some other techniques.

TABLE I. INSTRUMENT REQUIREMENTS

Primary Instrument Requirements	
Volume	1/2 U (10 cm x 10 cm x 5 cm)
Power Consumption	2 Watts
Instrument Mass	0.65 kg
Altitude Range	250 - 450 km
Operational Life	660 days (1.8 years)
Mass Measurement Range and Resolution	0 - 60 AMU > 50 at 60 AMU
Spatial Resolution	10 km along track sampling
Sensitivity for N_2	$>$ 8e-4 cps/(particles/cm^3)
Secondary Instrument Requirements	
Neutral Temperature Range	200 - 2500 K
Ion Temperature Range	250 - 2300 K
Signal-to-Noise Ratio	> 7
Particle Transmission Efficiency	50%

II. RESEARCH DESCRIPTION

This research project is to design, fabricate, and test a miniaturized TOF-MS instrument to measure composition profiles of the upper atmosphere. The miniature TOF-MS can be flown on a CubeSat, will be able to measure the composition of Earth's upper atmosphere, and will advance space technology by providing accurate, useful measurements with a higher spatial resolution than previous instruments. The technology produced could be useful in other space science applications, but it is targeted for a LEO CubeSat mission from 450-250 km altitude that will demonstrate its capabilities. Primary requirements for the MTOF-MS are listed in Table I. The volume and

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instrument mass requirements flow down directly from 1U CubeSat acceptance requirements; the instrument will be one of many subsystems on a spacecraft with 10 cm^3 dimensions and a maximum mass of 1.33 kg. The power requirement is a portion of the bus power available on a typical CubeSat bus (about 3.5 Watts total). The mass measurements range, mass resolution, and sensitivity requirements are common metrics for evaluating mass spectrometers and will ensure that the MTOF-MS provides quality measurements. The mass range is designed to allow measurement of all of the molecular and atomic species typically found in the thermosphere along with some metallic ions. The mass resolution is a ratio of the average measured mass of a particle species to the full width half maximum of the distribution curve of the mass measurements for that species. This ratio indicates how well the instrument discriminates between the masses in a sample. The sensitivity is a ratio of the particles detected by the instrument vs. the total number of particles that enter the instrument. The spatial resolution requirement states how closely-spaced the along-track measurements should be. This requirement surpasses the spatial resolution required to measure the thermosphere.

Table I also lists secondary requirements for MTOF-MS. The temperature requirements are values predicted by current atmospheric models and will have an effect on the mass resolution and transmission efficiency of the instrument. The signal-to-noise ratio requirement is necessary to ensure the validity of the lower end of the instrument measurement range. Transmission efficiency describes what percentage of the particles will successfully travel through the instrument.

Success of the instrument design will be based primarily on the mass resolution, sensitivity, and measurement cycle time. These metrics are commonly used to describe the performance of mass spectrometers and will best show the advantages of this design. The instrument's performance can be further assessed by comparing the instrument measurements to expected values from atmospheric models and data from a similar instruments. The finished MTOF-MS would be well-suited for deployment on a constellation mission to explore the thermosphere and ionosphere. Given that CubeSats have a lower launch cost and are more easily flown in constellations than sounding rockets or large satellites, this CubeSat instrument could allow for atmospheric studies with better spatial resolution. This spatial resolution would provide data for multi-directional evaluation of aspects of the models which define lateral variations in atmospheric properties.

III. TOF-MS OVERVIEW

Mass spectrometry is a process that determines the chemical composition of a sample. TOF-MS is a well-developed spectrometry technique and the implementation issues affecting resolution, sensitivity, and measurement cycle time are well known. The technique measures the mass-to-charge ratio and quantity of charged particles in a given sample [1, p. 1519]. Particles of varying mass are accelerated through an electric potential. This results in an increase in kinetic energy that causes the velocity of the particles parallel to the potential drop to be inversely proportional to the square root of the mass-to-charge ratio [1, p. 1519]. Higher velocities correspond to lower particle mass. The difference in velocities leads to differences in flight times through a field-free region, or drift region. The particle's time of flight to the particle detector is measured and used to determine the particle mass. The relationship between particle mass and total flight time can be derived using Newtonian physics [1, p. 1520]. Often, ion mirrors, or reflectrons, are incorporated into TOF-MS designs. Reflectrons are made from a series of charged rings or grids which create a retarding electric field. They can be used to redirect the particle flight paths or to correct for initial velocity distributions. Redirecting the particles can allow for longer flight times and better separation of different masses without increasing the length of the instrument [2, p. 182].

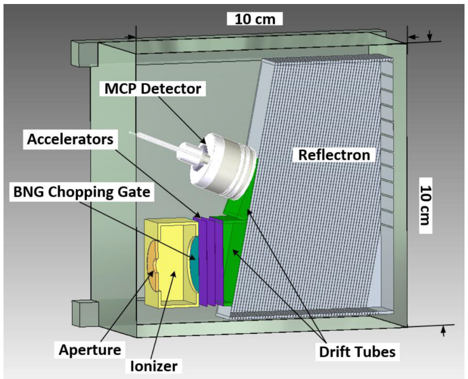

Fig. 1. MTOF-MS Design Layout

IV. MTOF-MS DESIGN

The design of the MTOF-MS will include an aperture, an ionizer device, a gating device, initial and final accelerator grids, drift regions, a reflectron, and a detector device. Figure 1 shows a sample MTOF-MS design to demonstrate the instrument layout.

Particle samples will enter the instrument through the aperture, driven by the satellite ram velocity. The sample then passes through an electron beam ionizer, which will be used to positively charge neutral samples. The incoming particle stream will be regulated using a low-power gating device. Particles will be accelerated using fine accelerator grids and allowed to drift through enclosed, field-free regions where they will separate by mass. There will be two drift tubes, one between the acceleration grids and the reflectron entrance, and another between the reflectron entrance and the MCP detector. A grid-less reflectron will help focus the particles and redirect them towards an MCP detector. Additional acceleration may be required to ensure that particle energies are high enough that the detection efficiency of the MCP device is consistent for all mass values (up to 3-5 keV for certain detectors) [3, p. 353].

V. CHALLENGES TO MASS RESOLUTION

Previous work on TOF-MS mass resolution refinement shows that the following may be challenges to miniaturizing a

TOF-MS instrument: limited drift region length, initial velocity distributions, and gating device pulse width.

The length of drift regions will have significant effects on the resolution of the instrument [1]. The drift region is where the particles separate by mass and the difference in flight times is proportional to the drift region size. Miniature TOF-MS will have much smaller drift spaces than traditional instruments, which will result in smaller arrival time differences between masses.

Particle samples will have a naturally occurring initial velocity distribution that will be visible in the particle detector data and can be mitigated using focusing techniques [4, p. 214]. This initial distribution is a Maxwell-Botlzmann temperature distribution and will cause a distribution in the arrival times for particles of each mass. Arrival time distributions may bleed together if the masses are not sufficiently far apart or if effective focusing techniques cannot be implemented.

The incoming particle stream will be chopped using a low-power gate, but an ideal delta pulse cannot be achieved. Any gating device used for the instrument will be open for a finite amount of time and create a distribution in the start times of the particles. This start time spread will degrade the mass resolution by widening the arrival time distributions for each particle. This effect will be more significant for instruments with smaller total flight times [1, p. 1525].

VI. DESIGN AND ANALYSIS

There are many different methods for improving the performance of a TOF-MS instrument. This research has tested methods using high acceleration voltages and energy focusing techniques based on the instrument dimensions or reflectron. Effort has also focused on a design to minimize the instrument gate pulse width. Focusing of spatial distributions using certain dimension ratios (reported in [5, p. 7-10]) was tested in the design, but was limited by the minimum realistic distance between accelerator grids and required drift spaces that did not fit within the volume constraint. Other methods exist but have not yet been analyzed for this design.

A. *Dimension Optimization*

Calculations from a flight time estimation tool (FTET), developed for design analysis for this project, were used to create a dimension optimization program to determine the highest resolving dimension set which fit within the instrument volume constraint. The FTET was designed to estimate the performance of a single set of instrument parameters by fitting the dimensions within the volume constraint and estimating the idealized particle flight times. The FTET allows for the input of key dimensions such as acceleration potentials, acceleration region lengths, reflectron depth, and reflectron potentials. Additional inputs to the FTET include particle mass, ambient temperature, and satellite ram velocity, all of which will affect the particle flight times. The FTET takes these inputs, calculates the maximum possible dimensions of other components, and finds the theoretical arrival times of a series of particle masses using Newtonian physics. Calculations in the FTET are based on assumptions of ideal electric fields (for the acceleration regions and reflectron) and idealized particle sets (3 standard deviations of the Maxwell-Boltzmann temperature distribution in one dimension with the option to input the gate pulse length as a time-of-birth or starting time distribution).

The flight time and dimension fitting equations developed for the FTET were implemented in a MATLAB optimization program to determine the best dimensions for the instrument. This program iteratively searches for the largest improvement in mass resolution by checking small perturbations for each parameter and updating the operating point to the new set with the best performance. The resolving power of the set was evaluated by taking an offset expression of the mass resolution, referred to as the spacing parameter. The spacing compares the peak width of the largest mass peak to the difference between the average times for the largest and next largest peaks. The peak width is taken to be the arrival times of the largest masses using one standard deviation of initial velocity below and above the average initial velocity. The search ends when a local maxima is reached. The program does not perform an exhaustive search, so several different starting points were chosen to find the best local maxima. The optimization result showed that the reflectron depth should be maximized for the best resolving power, and that increasing acceleration voltage leads to improvement in resolution of the initial distributions as reported in [4]. Testing the optimized dimensions in the FTET revealed that the increased acceleration voltage shortens the measurement cycle time and improves the resolving power of the instrument, but also decreases the separation between mass peaks. Since the instrument gate pulse also significantly widens the arrival time distributions for this instrument, the maximum acceleration voltage will be limited by the size of the gate pulse.

B. *BNG Driver Design and Simulation*

Bradbury-Neilsen Gates (BNGs) have been used often in TOF-MS as particle stream modulators. They are low-power, non-mechanical devices that can effectively divert incoming particles. They consist of a plane of closely-spaced, charged wires that can be charged to two different voltage levels. When the device is powered, an electric field is created between the wires that is perpendicular to the incoming particle stream. This electric field deflects particles away from the instrument detector, effectively turning the instrument off by preventing it from detecting samples [6]. Designs for BNGs on a miniaturized scale have already been published and used as a guide to fabricate miniature BNGs at Space Dynamics Lab [7].

BNGs designed for laboratory instruments with much longer drift spaces and more space between different masses in the spectra do not need to achieve a gate pulse width below 100 microseconds. For this CubeSat-size design, the FTET predicts total flight times of 6-12 microseconds with about 45-100 nanoseconds of separation between arrival peaks. The gate pulse needs to be short enough that it does not cause these closely-spaced mass peaks to overlap. The short drift spaces in this instrument may also mean that the deflecting electric field needs to be stronger to keep particles from impacting

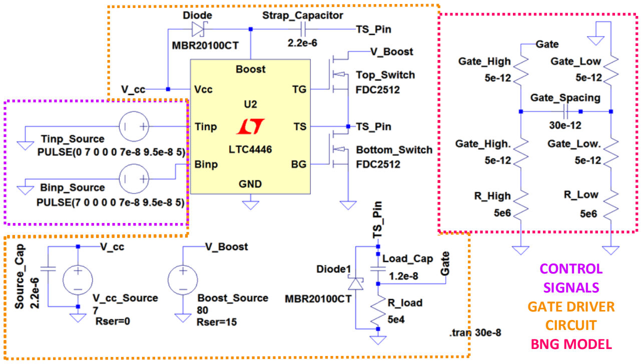

Fig. 2. BNG Driver SPICE Simulation: The control signals are 5V logic signals modeled as square wave inputs (”Control Pulses”). The gate driver circuit in the simulation includes a low-level supply to power the driver chip, a high voltage supply for the gate potential, the driver chip, and connected N-channel MOSFETs driven by the driver chip outputs (”Gate Driver Circuit”). Also shown is the lumped-parameter model of the BNG (”BNG Model”).

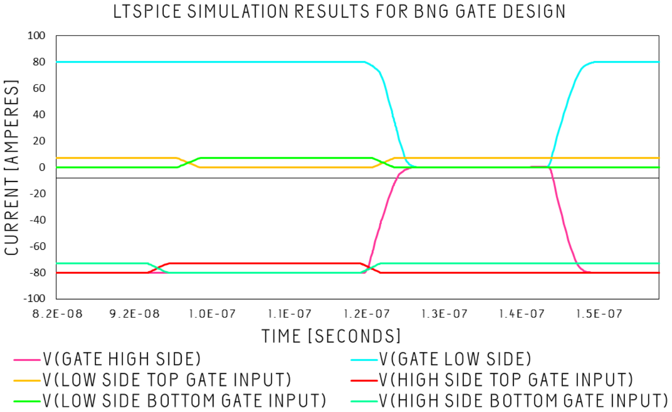

Fig. 3. BNG Driver SPICE Simulation Results: This plot shows the output potential at the gate wires (”Gate High Side” and ”Gate Low Side”) along with the input signals for each side of the driver (”Top Gate Input” and ”Bottom Gate Input”).

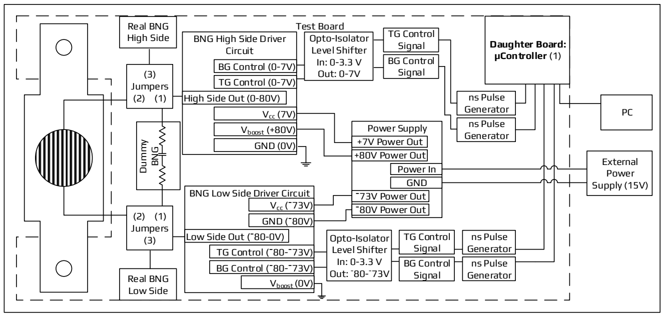

Fig. 4. BNG Driver Test Board Layout

the detector. The predicted mass peak separation served as a guide for the electronics timing for the instrument gate, and the possible need to strong deflecting fields indicated that a high voltage switching device is needed. The switching needs to be as sharp as possible in order to produce clean particle packets.

Devices which can handle high-voltage switching (over 20-30 volts) with nanosecond-scale timing are not as common as lower-voltage switching devices. However, several high-speed boost supply MOSFET drivers were available and capable of switching outputs of 100 volts or higher. One of these driver chips was used to build a gate driver circuit simulation using ideal voltage supplies, simplified control pulses, and a lumped-parameter model of the BNG gate. The simulation schematic is shown in Figure 2. Adjusting the input control pulse timing showed that the gate pulse width would be limited by the propagation delay of the MOSFET driver. Adjusting the model of MOSFET in the circuit showed that the rise/fall time of the gate pulse would largely be limited by the MOSFET rise/fall times.

Results of the gate driver simulation are shown in Figure 3. The simulation showed that a 30 nanosecond pulse can be achieved using a Linear Technology High Voltage High Side/Low Side N-Channel MOSFET Driver. Other manufacturers’devices have similar propagation delays and could produce similar gate pulses. The driver chip ground can be biased to any voltage, so that the gate potential can be centered at a negative voltage in both the ON and OFF states. This means the gate can be used either before or after acceleration.

Design plans for a test board and test plan followed successful simulation of the BNG gate driver circuit. A high-level layout of the BNG Driver test board is shown in Figure 4. The test board contains two boost driver circuits; one for the positively charged side of the gate (or high side), and one for the negative side (or low side). There will also be some supporting electronics, including high speed level shlifters for the gate inputs, high-speed pulse generators to produce precisely timed control pulses, and a microcontroller daughter board to control the pulse generators. The microcontroller will communicate directly with a PC for all tests.

The board includes jumper connections for three tests of the driver. First, the driver will be tested on a dummy version of the gate to show that the electronics perform as expected. This dummy gate will be made from linear circuit components and will resemble the schematic for the lumped-parameter BNG used in the simulation (see Figure 2). Second, the BNG will be tested on a miniature BNG made by SDL, mounted on the test board as shown in the layout. If that test is successful, the driver will be tested a third time on the BNG installed on a sounding rocket TOF-MS instrument, also built by SDL [8]. The instrument test can be used to show what the sample packets it produces will look like. The test board design is capable of supporting all three of the planned BNG driver tests; it has a jumper set so that connections can be switched between the on-board modeled BNG, a spare BNG mounted on the test board, and the external connectors for the instrument mounted BNG.

The test board is designed so it can be placed in the chamber with the sounding rocket instrument. It will be powered by a 15 V DC input and controlled via a USB connection to the daughter board by a regular PC. The 15 V supply will be converted by the test board power supply to the specified high- and low-level voltages for the gate wires. Component selection for the test board electronics is currently underway.

VII. FUTURE WORK

The BNG test board design will be finished and built this summer, and tested using facilities at Space Dynamics Lab. Results of these tests will provide the actual gate pulse width for this instrument. SIMION simulations of the instrument design, including the actual gate pulse width, will be performed to show the expected arrival times of particles. SIMION is a charged particle flight simulation program that is often used to evaluate ion optics problems. These simulations will use particle samples generated to include as many non-ideal distributions and effects as possible. Further work may include integration of some instrument sub-components or development of a signal reading circuit for the MCP detector.

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