BNG Driver for a Miniaturized Time-of-Flight Reflectron Mass Spectrometer for Upper Atmosphere Composition Measurements

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ABSTRACT

Variations of gas density and composition in Earth's thermosphere and ionosphere are key indicators of interactions between different layers of Earth's atmosphere. The nature of interactions between neutral and ion species in the upper atmosphere is an active area of study in Heliophysics and there is much to learn about the dynamic relationship between the ionosphere and neutral thermosphere. Mass spectrometers are among an array of instruments used to explore Earth's upper atmosphere and other space environments. Mass spectrometers developed for small satellites would potentially dramatically reduce the cost of future missions and provide data with the spatial resolution required for sophisticated studies of complex atmospheric dynamics. 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. This design for a miniaturized time-of-flight (TOF) mass spectrometer (MS) will have a mass resolution and range sufficient for measuring the composition of Earth's thermosphere and ionosphere while operating within the power and space constraints of a CubeSat. The design includes a miniature electronic gating device called a Bradbury-Nielsen gate (BNG). Analysis has shown that the open time for this gating device may significantly degrade the instrument performance and that the gate pulse width should be minimized. This work details the design of an electronic driver for a miniature BNG intended to create gate pulses on the order of nanoseconds.

TIME-OF-FLIGHT MASS SPECTROMETRY

A mass spectrometer is an instrument that determines the composition of a sample of charged particles by measuring the mass-to-charge ratio of the individual particles.[1] TOF-MS works by accelerating charged particles through an electric potential drop. The particles are all given the same increase in kinetic energy, so particles with lower mass experience a larger increase in velocity. The difference in velocities causes the particles separate by mass as they drift through a field free region. The particles' arrival time at a certain location is measured, and the mass-to-charge ratio can be determined using Newtonian physics.[1] The arrival time spectra for a time-of-flight instrument will look like the spectra shown in Figure 1, with the lighter particles arriving first. Distributions in the initial velocity, trajectory, and start times of the particles in each sample affect their arrival times and lead to arrival time distributions of particles for each mass that follow the shape of Maxwell-Boltzmann distributions.
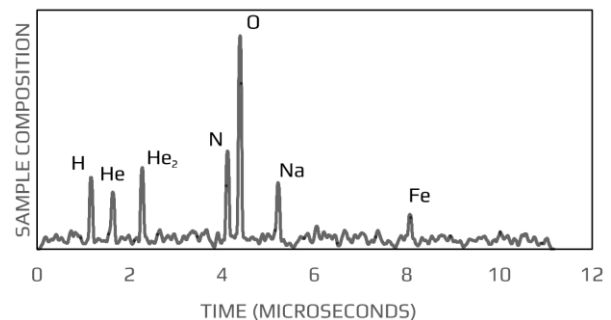

Figure 1: Sample Arrival Time Spectra

TOF-MS Performance

The performance of a mass spectrometer is measured quantitatively by evaluating a property called the mass resolution. This value is measured for some mass value in the measurement range and is calculated using the definition in Equation (1).[1] This compares the mean of the arrival time distribution of a certain particle mass,

"t", to the full width of the distribution peak at half its maximum value, "Δt" (FWHM). The mass resolution value represents the ability of the instrument to create a distinction between each mass value.

$$\frac{m}{\Delta m} = \frac{t}{\Delta t} \qquad (1)$$

MINIATURE TOF-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 2 shows a sample MTOF-MS design to demonstrate the instrument layout.

The aperture will allow samples of ions and neutral particles into the MTOF-MS. It needs to be covered before the MTOF-MS begins to take measurements but will remain open between measurements. The aperture design will limit the number of incoming particles with high off-axis velocity components.
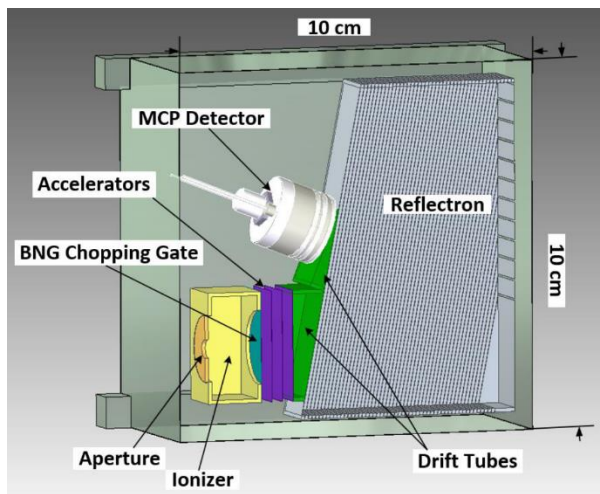

Figure 2: MTOF-MS Instrument Design

The ionizer will be used to positively charge incoming neutral particles. There are several well-known techniques for particle ionization. An efficient, miniaturized ionizer for the MTOF-MS may already be available and will not be a focus of this research. If the design does not include an ionizer, MTOF-MS will still be capable of studying ion composition.

A Bradbury-Nielsen gate (BNG) will be used as an electronic gating device for the MTOF-MS. This design will be based on the use of a miniature BNG fabricated at Space Dynamics Lab.

The drift regions of the MTOF-MS will be field-free regions where the accelerated particles are allowed to separate by mass, as described in the literature. 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.

The reflectron for MTOF-MS will be a series of rings with voltages applied to create a retarding electric field. Voltages on the reflectron rings will be controlled using customized commercial resistor nets.

Additional acceleration grids following the second drift space 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. It has been shown that certain types of MCPs require between 3-5 keV to achieve a consistent efficiency across a range of particle masses.[2]

Charged particles will be detected by a commercially-supplied TOF MCP detector package. The detector will be chosen such that the electrical performance characteristics do not significantly degrade mass resolution and the holding voltages required for the detector plates are within the power constraints of the CubeSat.

BRADBURY-NIELSEN GATES

Time-of-Flight instruments require a gate device to regulate the start time of a sample. TOF-MS designs commonly use BNGs to regulate instrument sampling. A BNG is an electronic gating device made from a plane of evenly-spaced, alternately-charged wires. When the gate is "off", the wires are charged to different voltages, creating an electric field that is perpendicular to the instrument axis. As charged particles fly through the gate, this field deflects their flight away from the instrument axis, keeping them from reaching the detector. When the gate is "on", the wires are all left at the same potential, and particles are allowed to fly into the instrument and reach the detector.[3]

Advantages of Bradbury-Nielsen Gates

Deflection gating can be accomplished using other mechanisms which are easier to fabricate; parallel plate gates have been popular in previous missions flying TOF-MS for this reason. However, BNGs are a superior gating device for miniature TOF-MS. The close proximity of the wires allows them to create stronger, more uniform electric fields at lower voltages, making them more efficient at lower power. The wires are thin and do not require as much space along the axis of the instrument as a parallel plate gate would. Electric field fringing effects, present for both parallel plate and BNG gates, are proportional to the spacing between electrodes and will be much smaller for a BNG.

Fabrication of Miniature Wire Gates

Fabrication techniques for miniature versions of the BNG gate device have already been developed and published. Published techniques for fabricating BNGs have already been verified at Space Dynamics Lab through the successful construction of a miniature BNG.[4]

Effects of Gating on TOF-MS Performance

TOF-MS has historically been limited by the speed of available electronics.[1] An analysis of theoretical flight times for this mini TOF-MS design showed that the gate device pulse width (the amount of time that the gate device is left open for sampling) significantly degrades the mass resolution of the instrument by creating a larger spread in the distribution of arrival times for each particle mass. This additional width can cause the distributions to overlap, leading to lower certainty in the composition measurements.

DESIGN OF BNG DRIVER

This work focuses on an electronic driver for a miniature BNG built at Space Dynamics Laboratory.

Motivation to Improve Gate Performance

Design optimization studies using ideal flight times from a flight time estimation tool for this design show that increasing acceleration voltages will improve the peak resolution and shorten the measurement cycle time of the instrument.[5] However, increased acceleration voltages also results in mean arrival times for each mass that are more closely spaced, such that the spreading effect of the gate pulse width may cause overlaps in the arrival time distributions and reduce the certainty of composition measurements. Therefore, developing a driver to further reduce the open-time of the gate will significantly improve the instrument performance by allowing for higher acceleration voltages.

Design Goals

The following design goals have been developed for the BNG driver.

Table 1: Design Goals for the BNG Driver

Output Property	Previous Driver Result	New Design Goal
Pulse Width	70 ns	< 40 ns
Rise/Fall Times	40 ns	< 10 ns
Gate Voltage Drop	40 V	> 40 V

The driver should apply the shortest possible pulse to each side of the gate; a goal of 40 ns was set in order to improve upon the previous design.

The goal for driver pulse rise/fall times is intended to make the pulse transitions fast enough that the driver can be used for Hadamard Transform sampling techniques.[6]

At this stage in the instrument design, it is unclear how much voltage drop will be needed across the BNG wires in order to efficiently deflect incoming particles when the gate is "off". A goal of greater than 40 volts drop across the wires was set in order to improve upon the previous driver design.

BNG DRIVER DEVELOPMENT

The design of the new BNG driver was accomplished by examining the previous driver design, searching for electronics that could achieve the desired goals, simulating the driver design (including a load representing the mini-BNG), building a verification circuit, and designing a full test board to be used to test the driver on both the representative load and the actual BNGs.

An electronic driver was developed for a linear TOF-MS, with pulse widths around 70 ns and rise/fall times around 40 ns.[7] Examination of the previous design showed that a new design would be needed to achieve the pulse width and voltage drop goals. For the pulse rise and fall times, it is important to note that the original design was capable of faster rise times, but could not achieve these without an undesirable ringing effect caused by op-amp dynamics.

Electronic devices are continuously being improved, and the next stage of the driver design was to search for IC components that could achieve the design goals without undesirable switching dynamics. Few products were available that could tolerate switching voltages over 30 volts and/or switch faster than the output of the previous driver. A Boost Supply High-Side Low-Side MOSFET Driver chip (PN: LTC4446) was examined as a possible switching voltage controller. The IC specifications indicate that it can tolerate up to 120 V above the IC ground voltage and can generate pulse widths down to 25 nanoseconds.

The Driver Circuit Design

The driver circuit portion of the design consists of the Boost Supply MOSFET Driver chip, 2 MOSFET gates (a "top gate" and a "bottom gate"), two logic level inputs, a chip power supply (V_{cc}), and a boost power supply (V_b). A schematic of the driver circuit is shown in Figure 3. Bypass capacitors and a diode are included per manufacturer's recommendations to help handle quickly switching voltages and high currents. The full design includes two driver circuits, one for the "low" side of the gate and one for the "high" side of the gate. The low side of the gate is biased at -75 V (the ground pin is tied to -

75 V) and the high side is biased at 0 V. The output, or "TS" pin, of each driver circuit is connected to one side of a lumped parameter model that represents the BNG. The top gate ("TG" pin) and bottom gate ("BG" pin are connected to the MOSFET gate inputs.
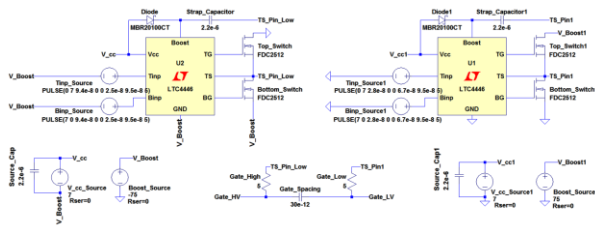

Figure 3: BNG Driver Schematic

The driver works by changing the top and bottom gate inputs to either switch the top gate on (bottom gate off) to tie the output to the boost voltage or the bottom gate on (top gate off) to ties the output to the circuit ground. The timing of the inputs to the "low" and "high" side driver circuits are adjusted to achieve the output waveforms at the gate, shown in Figure 4. The input for each driver circuit is biased to the same voltage as the ground pin for the driver chip.
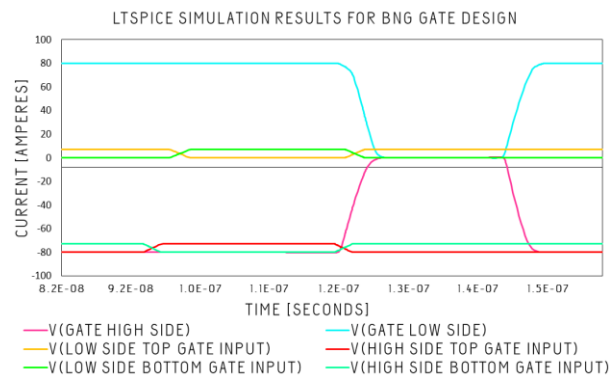

Figure 4: BNG Driver Simulation

Simulating the Driver Performance

The IC was first tested in simulation using one IC, ideal voltage sources, and a lumped parameter model of the BNG. The simulation was later modified to include a driver circuit for each side of the gate. The simulation showed that the chip can produce a 27 ns pulse, with rise/fall times as low as 3-5 ns, depending on the MOSFET chips chosen for the driver circuit. The total possible voltage drop across the gate in the simulation was up to 200 V. The simulation was further modified to include a power supply simulation using a current limited high voltage supply (modeled after a

commercially available unit) for a 150 V drop across the gate and buck regulators for the V_{cc} voltages.

Driver Verification and Test Boards

The successful simulation results led to the development of a driver circuit verification board and a full test board for the design.

The verification board contains only the driver circuit inputs and outputs, and is meant to verify the functionality of one side of the driver circuit alone. The board includes all the components described in the driver circuit, as well as high speed isolators for each input. The isolators will allow the driver circuit verification to be performed at both a zero volt bias and with a negative voltage bias. The driver circuit will be tested with a dummy load similar to the model in the simulation, with the other side of the "gate" tied to ground.

A high level layout of the test board for the BNG Driver is shown in Figure 5. The test board contains a driver circuit for each side of the gate, isolators, a power supply, connections for the test loads, and a daughter board that will be used to control the drivers.
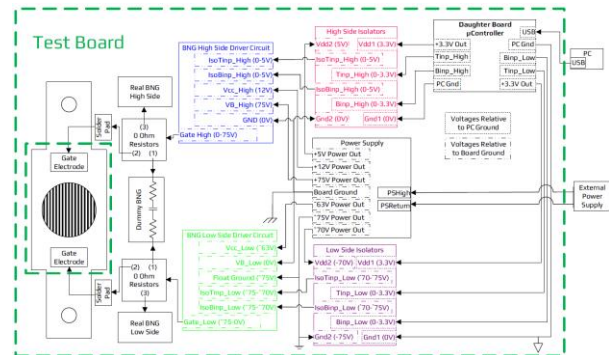

Figure 5: BNG Test Board Layout

The driver circuits are as described in "The Driver Circuit Design" section. Additional resistance and capacitance have been added to the inputs and outputs to help mitigate noise. The high side driver circuit ground is kept at the ground for the board, and the low side driver circuit ground is biased at -75 V and referred to as the floating ground.

A daughter board microcontroller will be attached to the test board so that the driver pulses can be controlled from a PC. The daughter board will supply input signals and power one side of the isolators. The daughter board ground will be tied to the PC ground and isolated from the floating ground and test board ground.

An isolator circuit for each of the four inputs shifts the logic level from 3.3 V to 5 V. The isolators also separate

the grounds on each side so that the 5 V signals can be biased down to the floating ground or at the board ground.

The test board will be capable of driving three different test loads: a dummy load (matching the lumped parameter model from the simulation), a spare miniature BNG mounted directly on the end of the board, and a BNG installed in a linear TOF-MS. The driver board will be tested for each of the three loads individually.

TEST PLAN FOR THE BNG DRIVER DESIGN

Verification Board Test Plan

The verification board will be tested on a dummy load to verify that the driver circuit and isolators operate as expected. Laboratory power supplies will be used to power the circuit, and a function generator will be used to create the control inputs. The output waveform will be measured to determine the rise/fall times, pulse width, and pulse height.

Test Board Test Plan

The test board will be used to verify that the drivers can drive the actual BNG load and test the performance of the new driver on the linear TOF-MS.

First, the test board will be used to drive a dummy load (matching the lumped parameter model from the simulation) to verify that the test board circuit is operating as expected. Second, the spare BNG will be mounted on the test board and connected to the driver outputs. The output waveform will be measured at the gate electrodes (just before the gate wiring begins) to determine the rise/fall times, pulse width, and pulse height applied to the gate. The control signal will be measured at several points to determine the propagation delay from the PC/daughterboard to the gate electrodes. Last, the driver outputs will be connected to the BNG installed in the linear TOF-MS and the output waveform properties will be measured again.

Additional testing of the driver circuit may be done to determine its impact on an ion beam fired through the linear TOF-MS instrument. That information may be used to inform later work on the instrument, including refining the particle definitions for ion optics studies of new designs.

VERIFICATION TEST RESULTS

The verification board has been built and tested using a dummy load and laboratory equipment. Inputs to the verification board were provided by a microcontroller PWM module programmed to operate at 80 MHz and

create two count pulses (25 ns pulse width). The test setup is shown in Figure 6.
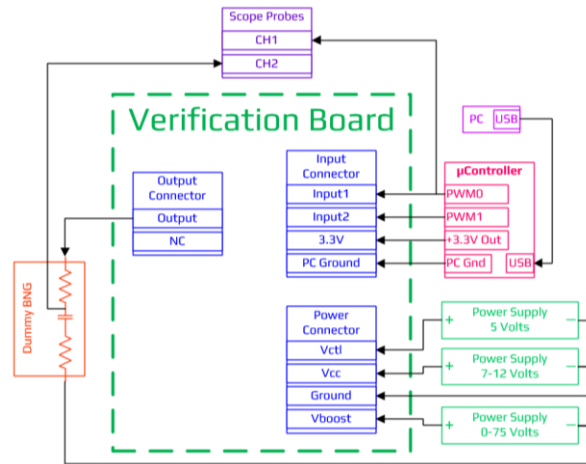

Figure 6: Verification Board Test Setup

Testing performed using this setup yielded the results shown in Figure 7 and Figure 8. The driver output showed that the timing in the circuit simulation is realistic; the board produced pulses of 25-30 ns width with 25-30 ns of propagation delay. This represents a significant improvement in pulse width as compared to the previous driver. However, the voltage swings achieved in test were not as high as those seen in simulation and some undesirable ringing is shown in the driver output.

Limits in the output voltage were determined by increasing the boost voltage until the driver can no longer create output pulses with higher voltage levels than the input. The boost voltage can be increased further in setups where smaller, faster bypass capacitors have been added in parallel to the existing bypass capacitance for the driver chip power, suggesting that higher voltage swings may still be achievable.

Figure 7: Low Side Driver Test Output

Figure 8: High Side Driver Test Output

It is possible that the output ringing is an effect of the measurement equipment rather than the driver output. The equipment used to read the driver output included a moderate bandwidth oscilloscope (100 MHz) and standard passive probes. The probe capacitance is estimated to be about 95 pF and the gate capacitance was measured at 55 pF; the presence of the probe triples the capacitive load on the circuit. Series resistance (around 300 Ω) added to the probe tip showed a significant reduction in the output ringing. The driver output will be further tested using higher bandwidth equipment and active probes to help eliminate the output ringing. Filtering may be used to eliminate any remaining output ringing, although this may affect the timing performance of the driver.

REFERENCES

1. Guilhaus, M., "Principles and Instrumentation in Time-of-Flight Mass Spectrometry: Physical and Instrumental Concepts," Journal of Mass Spectrometry, vol. 30, pp. 1519-1532, 1995.

2. Oberheide, J. and P. Wilhelms and M. Zimmer, "New Results on the Absolute Ion Detection Efficiencies of a Microchannel Plate," Measurement Science and Technology, vol. 8, pp. 351-354, 1997.

3. Bradbury, N.E. and R.A. Nielsen, "Absolute Values of the Electron Mobility in Hydrogen," Physical Review, vol. 49, No. 5, pp. 388-393, 1936.

4. Kimmel, J.R. and F. Engelke and R.N. Zare, "Novel Method for the Production of Finely Spaced Bradbury-Nielson Gates," Review of Scientific Instruments, 2001.

5. Pyle, M.L. and R. Davidson and E. Syrstad and C. Swenson, "Design Analysis and BNG Driver Simulation for a CubeSat Time-of-Flight Mass Spectrometer," UNSGC Fellowship Symposium, May 2015.

6. Zare, R.N. and F.M. Fernandez and J.R. Kimmel, "Hadamard Transform Time-of-Flight Mass Spectrometry: More Signal, More of the Time," Angewandte Chemie, vol. 42, pp. 30-35, 2003.

7. Everett, A. et al, "Characterization of an Axially Sampling Time-of-Flight Mass Spectrometer for Upper Atmospheric Measurements," American Society for Mass Spectrometry Conference Proceedings, Poster Presentation, 2012.