A New Electron Source for Laboratory Simulation of the Space Environment

Linda Habash Krause[1], Daniel Everding[2], Matthew Bonner[2], and Brian Swan[3]

1. NASA Marshall Space Flight Center, ZP13
2. University of Alabama, Huntsville, Department of Physics
3. University of Alabama, Huntsville, Center for Space Plasma and Aeronomic Research

We have developed a new collimated electron source called the Photoelectron Beam Generator (PEBG) for laboratory and spaceflight applications. This technology is needed to replace traditional cathodes because of serious fundamental weaknesses with the present state of the art. Filament cathodes suffer from numerous practical problems, even if expertly designed, including the dependence of electron emission on filament temperature[1], short lifetimes[2] (~100 hours), and relatively high power[3] (~10s of W). Other types of cathodes have solved some of these problems, but they are plagued with other difficult problems, such as the Spindt cathode's extreme sensitivity to molecular oxygen[4]. None to date have been able to meet the demand of long lifetime, robust packaging, and precision energy and flux control. This new cathode design avoids many common pitfalls of traditional cathodes. Specifically, there are no fragile parts, no sensitivity to oxygen, no intrinsic emission dependencies on device temperature, and no vacuum requirements for protecting the source from contamination or damage.

Recent advances in high-brightness Light Emitting Diodes (LEDs) have provided the key enabling technology for this new electron source. The LEDs are used to photoeject electrons off a target material of a low work-function, and these photoelectrons are subsequently focused into a laminar beam using electrostatic lenses. Electron energy is controlled by the voltage on the lenses, whereas the electron flux is controlled by the brightness of the LEDs. Key features include low power (~1 W), low source voltage (~5 V), long lifetime (~ 100,000 hours), and temperature independence over the range T= -30° C to + 55° C. Particle trajectory modeling shows that with a single set of lenses, the cathode can produce a laminar beam with an energy range from 0.4 eV to 30 keV. The acceleration voltage of the instrument is set by the upper limit of the desired energy range. Because the Geosynchronous Earth Orbit (GEO) charging electron population is on the order of 10s of keV in energy, the new electron source is ideally suited to simulate a GEO charging environment in the laboratory.

The PEBG works by illuminating a target material and steering photoelectrons into a laminar beam using electrostatic lenses (Figure 1). Figure 2 shows assembled and exploded views of the basic structure of the cathode. The instrument consists of a base assembly (housing one electronics board), a target disc which serves as the electron emitting plate, an inner electrostatic lens, an LED board, an outer case, and an aperture endcap with a guard ring. A Teflon insert electrically isolates the inner lens from the case and aperture endcap. The lens has its own endcap welded to the cylinder with an aperture in the center surrounded by six sockets arranged in a concentric ring. Figure 3 shows a photograph of the inside of the PEBG. One LED fits snuggly into each of the six sockets and is oriented toward the emitter plate. The emitter plate is biased negatively with respect to the case (usually at vehicle common), and the inner lens is fixed at a potential which is a fraction of the negative voltage placed on the emitter plate. This voltage configuration eliminates the need for an external lens to produce a laminar beam, demonstrated with computer simulations for beam energies from 0.4 eV through 30 keV. The beam energy is then controlled by the voltage on the two biased electrodes, whereas the flux is controlled by the brightness of the LED photon source. Our emission target is made of Lanthanum Hexaboride (LaB_6), which has a workfunction of 2.5 eV. Thus, we have chosen LEDs with a peak wavelength at 450 nm, corresponding to 2.75 eV per photon. PEBG current is controlled by the brightness of the LEDs, whereas the energy is controlled by the voltages placed across the electrostatic lens assembly.

Preliminary calculations were performed to gauge a baseline intensity of electron flux which could be expected with this cathode design. The calculations were performed with a configuration of six LEDs at 450 nm. The six LEDs produce a total 3.0 W of optical power (according to the manufacturer's specifications.) Each 450 nm photon contains 2.75 eV of energy, so the photon emission rate was calculated to be 6.8×10^{18} electrons/second, and with the experimental value of 0.8 for the target quantum efficiency, this corresponds to a photoejected electron current of 0.8 A. This is the emission rate off of the plate, but the current exiting the cathode still needed to be determined. This was accomplished by modeling the electron trajectories using SIMION, often used for modeling electrostatic lens systems[5]. Since the workfunction of LaB6 is 2.5 eV, the maximum photoelectron energy should be around 0.25 eV. Model calculations were performed to ascertain the relationship between electrode voltages and beam energy, information critical for the design of the electronics. Results are shown in Figure 4. The upper panel shows the evolution of a sample electron's energy as it propagates along the beam axis. For an emitter plate voltage of -5V, a cylinder voltage of -4V, and a guard ring at chamber ground, the resulting beam energy is 2.8 eV. Note that the beam energy is relatively uniform beyond 5 cm from the emitter plate. The laminar flow and the uniform beam energy make this simple electrode configuration an attractive design. The simulation shows that ~75% of the generated particles escape the instrument, resulting in a net current of 0.6 A for the six LEDs.

Initial Results: Dimmer Circuit Linearity and Beam Current

LEDs require a fairly precise operating voltage and current, and the standard way to acheive dimming is through Pulse Width Modulation (PWM) of the power feeding the diodes. Once we built a dimmer circuit designed to power the PEBG LEDs, we performed an experiment to gauge the amount of photocurrent emitted from a single ultra-bright blue LED (wired in series with two others) as a function of the duty cycle of the signal feeding the controlling electronics. The signal was provided by a laboratory function generator in TTL mode set at 1,000 Hz. The signal's duty cycle was altered using a built in duty cycle modulator. The photocurrent measurements were made with a laboratory photodiode with an accompanying picoammeter. The power supplied to the circuit was provided by a programmable current/voltage controlled power supply (in this setup, the power supply was set to 5V and was in current-controlled mode).

The triple LED series was controlled by an LM3500 integrated circuit, capable of supporting 2-6 ultra-bright blue LEDs. The duty cycle output from the function generator was fed into the SHUTDOWN pin of the LM3500 to accomplish the PWM of the LEDs. The LEDs themselves are Royal Blue XLAMP light emitting diodes produced by Cree; each has an operating forward voltage of 2.85V and an optimal forward current of 350 mA. The uncovered LED was placed 4 cm from the collecting photodiode; the remaining two LEDs were covered with opaque tape for safety reasons. The photodiode was constantly illuminated by the uncovered LED and the incoming duty cycle was altered to acquire desired data. Figure 5 shows the relationship between the photocurrent and the duty cycle of the PEBG's dimmer circuit. Figure 6 shows the impact of duty cycle on the power sourced to the LEDs.

Initial beam current tests were performed for a prototype model using low-brightness UV LEDs, and results have indicated an 80% quantum efficiency of LaB6 when operated under vacuum ($P < 10^{-5}$ Torr). The maximum current we were able to produce was 0.25 mA, far below from what we expect when we incoporate the super-bright blue LEDs. Combining our experimental results with our theoretical calculations, we find that this design enables 0.1 A of electron current per LED to be emitted in a collimated beam. The UV LEDs used in the prototype model were much larger (physically) than the super-bright LEDs, which are approximately 3mm on a side, and it is conceivable to incorporate 20 or more LEDs in a single housing. Delivery of the engineering model which will house the blue LEDs is expected 15 June, 2012. Details of these experiments and results will be presented at the conference and in the final paper.

Similar Technologies

Ultraviolet light has been used to generate electrons within a laboratory for decades[6]. UV LEDs are even being used in some low current variations of this new style of cathode[7]. For the final paper, a brief survey of modern cold cathodes will be presented.

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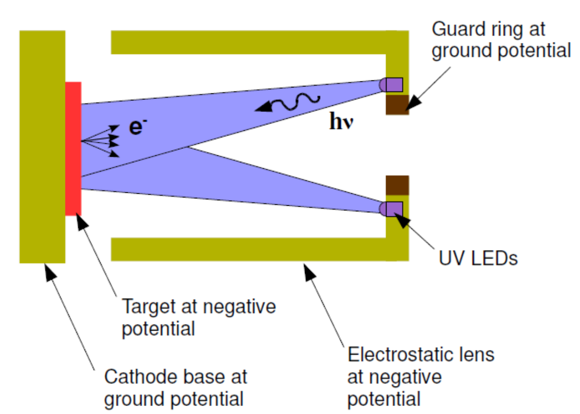


Figure 1. Blue or UV LEDs illuminate a target to photoeject electrons, then accelerated with electrostatic lenses.

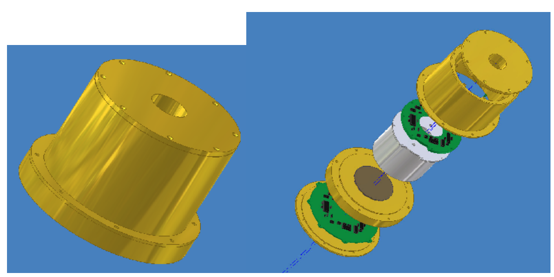


Figure 2. Assembled (left) and exploded (right) views of the PEBG.

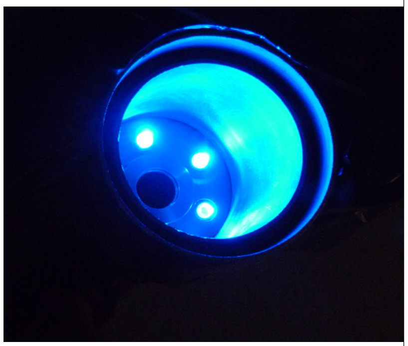


Figure 3. With the base and target sub-assembly removed, we can see the 450-nm LEDs illuminated. The inner lens is isolated electrically from the outer case, which is nominally held at spacecraft frame potential (in space) or at the vacuum chamber wall potential (in the lab).

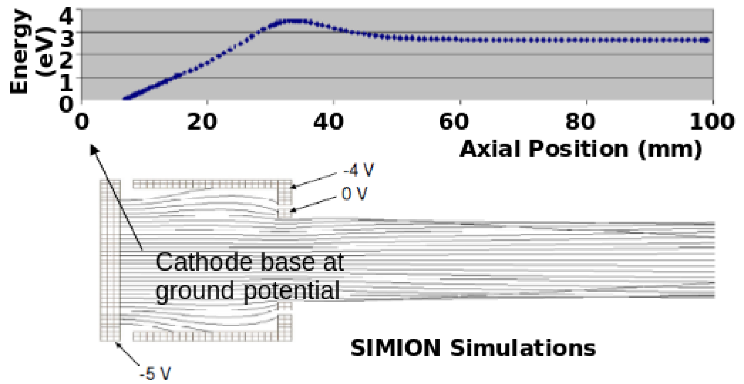


Figure 4. SIMION simulations show a laminar, monoenergetic electron beam for a -5V target and a -4V lens configuration, resulting in a 2.8 eV electron beam. Simulations have show laminar beams for energies from 0.4 eV to 30 keV with one set of lenses.

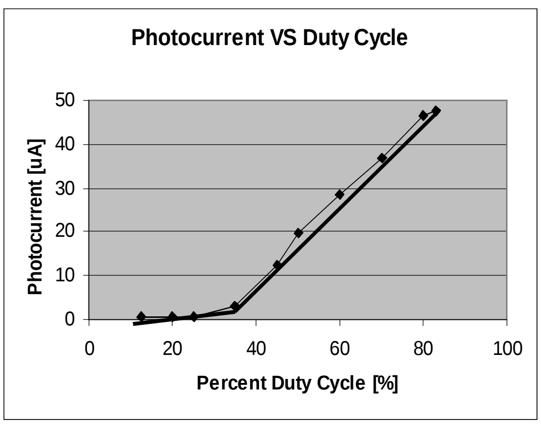


Figure 5. Calibration of the LED brightness as a function of duty cycle from the dimmer circuit. Note that the output is roughly linear (with an offset) from 40% to 80%.

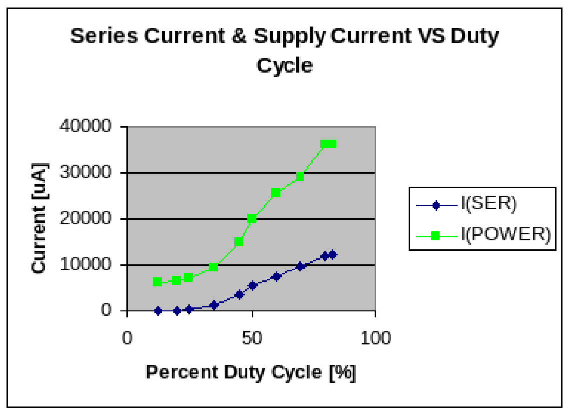


Figure 6. Current through the series of LEDs is compared with current sourcing the LEDs as a function of duty cycle.

A New Electron Source for Laboratory Simulation of the Space Environment

Linda Habash Krause[1], Daniel Everding[2], Matthew Bonner[2], Abigail Taylor[3], and Brian Swan[4]

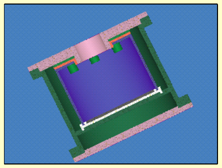
1. NASA Marshall Space Flight Center, ZP13
2. University of Alabama, Huntsville, Department of Physics
3. St. Mary's College of Maryland, Department of Physics
4. University of Alabama, Huntsville, Center for Space Plasma and Aeronomic Research

Abstract –We propose to develop a new collimated electron source called the Ultraviolet Cathode (UVC) for spaceflight. This technology is needed to replace traditional cathodes because of serious fundamental weaknesses with the present state of the art. Recent advances in UV Light Emitting Diodes (LEDs) have provided the key enabling technology for this new electron source. The device is powered by a dimmer circuit that adjusts the brightness of the LEDs. This aspect was tested in a photodiode experiment to record the current produced by the LEDs. The previously space-qualified UV LEDs are then used to photoeject electrons off a target material, and these photoelectrons are subsequently focused into a laminar beam using electrostatic lenses. Electron energy is controlled by the voltage on the lenses, whereas the electron flux is controlled by the brightness of the LEDs. Key features include low power (~1 W), low source voltage (~5 V), long lifetime (~ 100,000 hours), and temperature independence over the range T= -30° C to + 55° C. Particle trajectory modeling shows that with a single set of lenses, the cathode can produce a laminar beam with an energy range from 0.4 eV to 30 keV. The acceleration voltage of the instrument is set by the upper limit of the desired energy range. We are developing the cathode for operation from 0.4 eV to 30 eV.

Introduction and Motivation

- Cathodes are needed on spacecraft for a variety of experimental and operational applications.
- Traditional cathodes suffer from unpredictable temperature dependence, short lifetimes, and high power. Newer field-emission cathodes are hyper-sensitive to O2.
- UVC will PWM the LEDs to control the brightness (thus electron beam current), whereas lens voltages will control electron beam energy. This decouples beam current from the energy, something which is not possible with present-day cathodes.
- Enables CubeSat missions; enables cathode operation between balloon altitudes and ionosphere ("ignorosphere")
- It would also make a nice addition to MSFC's Low Energy Electron and Ion Facility (LEEIF) used for calibration of flight instruments. Precision electron spectrometers are increasing in demand for observations of turbulence in the solar-terrestrial environment, and the UVC could be operated in a high-frequency pulsing mode.

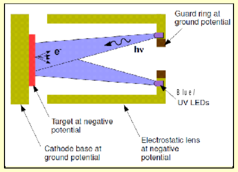
Concept Design



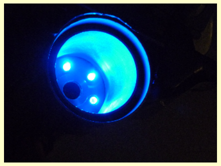
3D Cut-Away of UVC

Recent advances in Light Emitting Diodes (LEDs), both in higher optical intensities and shorter wavelengths, have provided key enabling technologies for this new electron source. These advanced LEDs, ranging from short blue (λ ≈ 450 nm) to near ultraviolet (λ ≈ 260 nm), are used to photoeject electrons off a target material, and these photoelectrons are subsequently focused into a laminar beam using electrostatic lenses. Electron energy is controlled by the voltage on the lenses, whereas the electron flux is controlled by the brightness of the LEDs

Potential target materials were selected based on robustness and work function (Φ). Two materials, Al 6061 (Φ=4.08 eV) and LaB_6 (Φ=2.5 eV), were the initial selections for a target material, both known for their resilience and relatively low work functions. Unfortunately, neither of these materials performed as desired due to their low quantum efficiencies. Additional research is being made into alternate semiconductor materials, with emphasis on cesium based surfaces with high quantum efficiencies.



Theoretical Concept for UVC



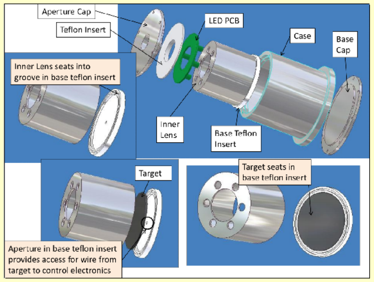
Prototype with Blue LEDs

Potential light sources were selected for their photon energy and brightness. Chief among these were the ultraviolet LEDs with photon energy near 4.5 eV, more than enough to photoeject electrons from the potential target materials.

LED Type	FW Current (mA)	FW Voltage (V)	Wavelength, λ (nm)	Viewing Angle, θ (°)	Optical Power (μW)
Ultraviolet	20.0	6.2	270	7.0	600
Violet	20.0	3.3	405	20.0	155
Royal Blue	350.0	2.85	450	140	500,000

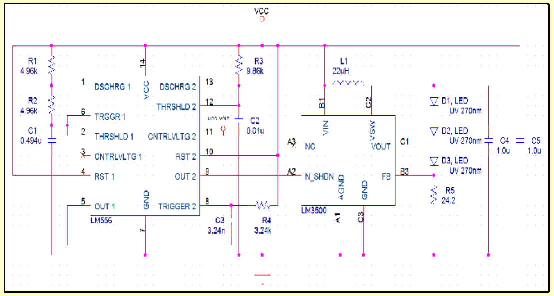
There were a number of challenges to the design that needed to be taken into account. LEDs run efficiently only over a small range of currents or voltages, so operating the device demands precise current and voltage control. Because of its planned use aboard a rocket, the design needed to insure a high level of stability against vibrations (insert stuff about shear, stress, oscillations, etc).

Mechanical Design



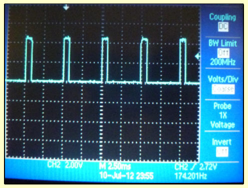
The instrument consists of a base assembly (housing one electronics board), a target disc which serves as the electron emitting plate, an inner electrostatic lens, a second electronics board with LEDs, an outer case, and an aperture endcap with a guard ring. One UV LED fits into each of six sockets in the inner lens and is oriented toward the emitter plate. The emitter plate is biased negatively with respect to the case (at vehicle common), and the lens is fixed at a fraction of the negative voltage placed on the emitter plate.

Circuit Design



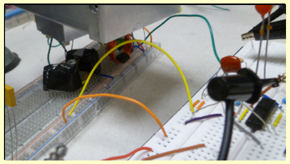
LED Dimmer Circuit Diagram

The dimmer circuit uses an LM556 astable multivibrator / pulse width modulator (PWM) to generate a pulse train for an LM3500-21 LED driver. The 3500 is an 8 pin integrated circuit (IC) that provides both regulated current and regulated voltage to a string of LEDs. Additionally, the 3500 alters the brightness of the LEDs when the duty cycle of the 556 pulse train is changed. When the pulse is low, the 3500 shuts off current to the LEDs; when the pulse is high the 3500 provides current to the LEDs. The longer the pulse is high, the brighter the illumination.

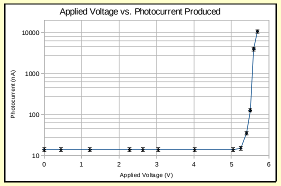


Trace of 556 Output Signal

Photodiode Experiment



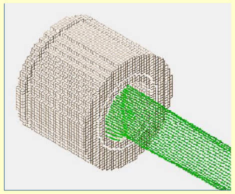
Photodiode Experimental Set-up



Graph of Applied Voltage vs Photocurrent

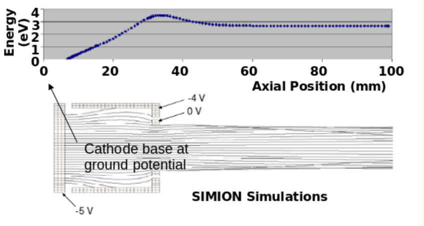
To test the LED dimmer circuit, a photodiode was placed over one of the UV LEDs and the other two were covered completely. The circuit was connected to a power source and the photodiode was wired to an ammeter. Power was applied and the photocurrent output from the LED was measured. The circuit behaved mostly as expected. Increasing the voltage applied to the PWM increased the duty cycle of the square wave output of the astable multivibrator. This in turn increases the amount of time the LM3500 is "on" and summarily increases the brightness of the UV LEDs. There was no significant photocurrent until the applied voltage reached around 5.25 V, but after that threshold the photocurrent increased very quickly.

Simulation Results



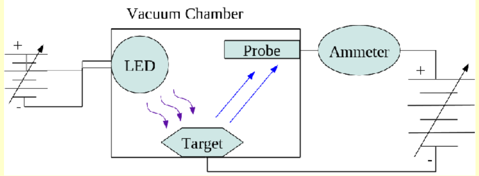
Isometric view of the UV Cathode. The aperture is encircled by a concentric guard ring which is electrically isolated from the rest of the aperture plate. The guard ring is fixed to a common potential with the experiment chamber (or space vehicle frame), the emitter plate is biased negatively with respect to the guard ring, and the cylinder is fixed at a potential which is a fraction of the negative voltage placed on the emitter plate. This voltage configuration eliminates the need for an external lens to produce a laminar beam. The electron trajectories, shown in the figure on the left, were calculated using SIMION, with the method and details results explained below.

To examine the cathode's effects on lower-energy photoelectrons, we ran our SIMION simulations with an initial photoelectron energy of 0.1 eV. The upper panel describes the electron energy of one of the beam's electrons, and the lower panel illustrates the laminar flow out of the cathode. For an emitter plate voltage of -5V, a cylinder voltage of -4V, and a guard ring at chamber ground, the resulting beam energy is 2.8 eV. Note that the beam energy is relatively uniform beyond 5 cm from the emitter plate.



SIMION computations of electron trajectories have thus shown that an aperture with area approximately 50% of the emitter plate yields a transparency of approximately 70% of the emitted electrons.

Planned Experiments: Target Quantum Efficiency Determination and Electron Beam Calibration



Preliminary calculations were performed to gauge a baseline intensity of electron flux which could be expected with the low-current version of the cathode design. The calculations were performed with a configuration of six LEDs at 260 nm. The six LEDs consumed power of 0.78 W to produce 1.2 mW of optical power (according to the manufacturer's specifications.) Each 260 nm photon contains 4.8 eV of energy, so the photoelectron emission rate was calculated to be 1.5×10^{15} electrons/second, corresponding to a photoejected electron current of 0.24 mA. The issue, however, is that the photoejection quantum efficiency of the target material still needs to be determined at this wavelength. The experiments planned for the summer will ascertain the QEs of both Al and LaB6, and then a net electron gun efficiency can be quantified and calibrated.

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