TEXAS TECH UNIVERSITY

Center for Pulsed Power and Power Electronics
Department of Electrical and Computer Engineering
Edward E. Whitacre Jr. College of Engineering

APPLICATION FOR 2013 DEIS GRADUATE FELLOWSHIP

SUBMITTED BY

ANDREW STEVEN FIERRO, B.S.C.S., M.S.E.E.

CENTER FOR PULSED POWER AND POWER ELECTRONICS

DEPARTMENT OF ELECTRICAL ENGINEERING

TEXAS TECH UNIVERSITY

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Investigation of pulsed low-temperature plasma through two-photon laser-induced fluorescence and GPU-accelerated simulation techniques

Andrew Fierro, Student Member IEEE

Introduction

It is planned to investigate the formation of pulsed low-temperature plasmas through nonlinear optical measurement techniques and GPU accelerated plasma simulation. Specifically, the ground state atomic densities in pulsed, low-temperature plasmas are difficult to measure with high spatial and temporal resolution. These species are of interest due to the excitation and subsequent emission of energetic photons (hv > 5 eV) in the ultraviolet (UV) and vacuum ultraviolet (VUV) regime that are capable of photoemission from many cathode materials as well as other photoabsorption gas processes (photoionization, photodissociation). Emission of VUV radiation in many gases at atmospheric pressure has been measured [1, 2], implying its impact on pulsed plasma formation. In addition, atomic nitrogen and oxygen are seen as the important species for medical applications [3] and decontamination processes [4] and thus the associated densities of these atoms are vital for the understanding of their biological effects. Typically, the measurement of specific ground state densities is done through optical emission spectroscopy, OES, (a passive technique), however, there is not direct access to the ground state.

Hence it is proposed to utilize the two-photon absorption laser-induced fluorescence (TALIF) to actively probe the atomic ground state population of dissociated nitrogen and oxygen. The use of TALIF to measure atomic oxygen and nitrogen densities was first reported by [5] in a flow discharge. This technique has since been applied in many other experiments. For example, TALIF has been used to study atomic hydrogen ground states in magnetic confinement fusion reactions [6]. The use of TALIF has also become popular for experiments on radio frequency atmospheric pressure plasma jets (APPJ) [7 - 9]. Although APPJs are continuous plasma sources, they use an inert gas (He) with an admixture of oxygen or nitrogen. Thus, this literature provides a valuable reference resource for air discharges. The TALIF technique has been used in pulsed discharges before but mainly to measure atomic oxygen. For instance, the relative density of atomic oxygen was measured in a pulsed dielectric barrier discharge [10]. In addition, the measurement of atomic densities in plasma assisted combustion has been possible with laser-assisted diagnostics [11].

Computer modeling has also recently become another method for determining plasma characteristics [12]. However, many of these computer simulations are based reaction-drift-diffusion [13] due to the complex nature of plasma development inhibiting more accurate approaches. Based on the emergence of computing on graphics processing units (GPU), it is proposed to achieve high performance plasma computation on a desktop PC. Since particle and light interactions (ionization, excitation, dissociation) leading to plasma discharges are inherently statistical and may be fitted appropriately to a numerical solution, a hybrid approach combining Particle-in-Cell (PIC) with Monte Carlo Collision (MCC) methods is proposed. These numerical methods, while capable of providing information not easily obtainable from experimental or other computational methods, needs to be benchmarked through experimental results.

Experimental Setup

Most systems use a Nd:YAG laser to pump a dye laser with a combination of non-linear crystals to achieve the desired laser wavelength of 205 - 225 nm for exciting atomic species. Other non-linear optical effects allow the tuning of laser light and thus the output of a Nd:YAG laser may be tuned from ~200 nm to 1064 nm by use of an optical parametric oscillator (OPO). Some experiments report the ability to measure two-photon LIF with laser

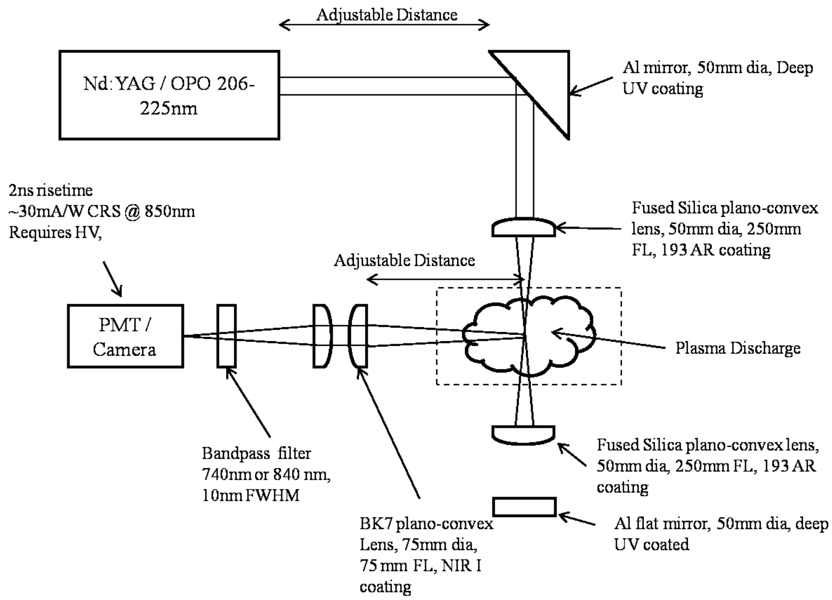

Figure 1: Proposed TALIF experimental setup overview.

energy on the order of 0.15 mJ [8]. Testing at several laser energies will need to be performed to ensure that the measured fluorescence signal scales with the square of the laser intensity. This confirms that the laser is not saturating the pump level and distorting the results.

In the proposed experimental setup, see Fig. 1, the UV laser beam is reflected off an appropriately selected mirror with a UV anti-reflection (AR) coating that has an adjustable distance into the plasma discharge. The adjustable distance provides the ability to measure densities as a function of space. Focusing of the incident laser pulse will provide a small spot (sub-mm) for high spatial resolution and appropriate TALIF signal (as the measured signal is a function of laser intensity). Emission of fluorescent light captured with a NIR-sensitive photomultiplier tube that is perpendicular to the laser light. The adjustable distance from the plasma discharge to the first focusing element is to keep the observed emission in focus. A band pass filter provides the necessary wavelength selection of the fluorescent emission of interest.

A rate equation model was utilized to estimate the measured fluorescent light intensity from an incident laser pulse, see Fig. 2. This model includes laser light characteristics and rates for excitation, quenching, and spontaneous emission as a function of species density in the plasma discharge. It is estimated that 0.04 mW of fluorescent intensity signal will reach the detector with an atomic species density of 10^{14} cm^{-3}. To translate measured signal into absolute atomic densities, a reference discharge must be used in Xenon or Krypton gases [14].

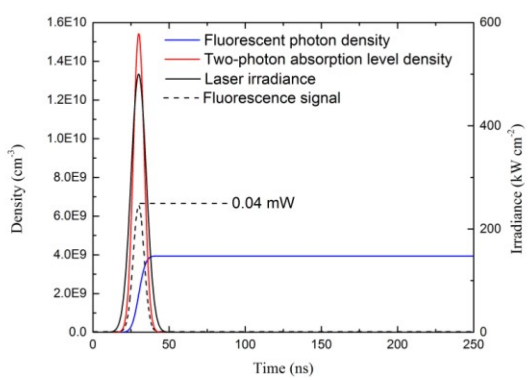

Figure 2: Fluorescent signal estimation for atomic oxygen.

To generate the low-temperature plasma, an existing solid-state high voltage pulser will be used capable of up to 40 kV voltage output with ~100 ns risetimes. Since the low-temperature plasma development is under pulsed conditions, there are timing difficulties that must be considered such as cable length delays and proper triggering. The entire system will be synchronized with a 4-channel low-voltage TTL square pulsed generator.

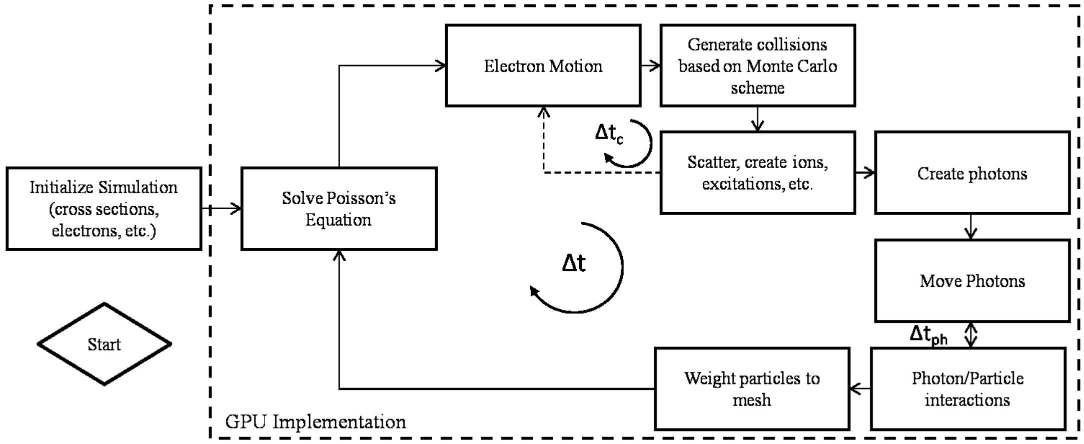

Figure 3: Flow diagram of a GPU-assisted PIC/MCC simulation code.

GPU-Accelerated Simulation

With the advancement of the CPU to multi-core processors, simultaneous thread execution has provided significant speed-up to computational codes. Unfortunately, the particle density (10^5 cm^{-3} – 10^{16} cm^{-3}) present during plasma formation covering a typical cubic-centimeter volume requires considerable computing power that even modern CPUs require hundreds of computational hours to complete for a total run time of several nanoseconds with time steps on the order of picoseconds. In the PIC/MCC method, the determination of collision processes using the MCC method represents the bulk of the computational time since it requires that each particle is evaluated. On a traditional CPU, this algorithm would essentially involve traversing through an electron data structure (tens of millions long, with each element representing many electrons) and performing the necessary computations. Using modern GPUs equipped with the CUDA platform, it is proposed to perform these calculations in parallel thus reducing the computational burden on the CPU. At present, a stand-alone desktop PC 3D CUDA-assisted plasma simulation including many particle and radiation interactions is already under development that is capable of simulating the plasma initiation stage and providing characteristics of the discharge with simulation properties similar to that of the state of the art algorithms ran on high performance clusters, see Fig. 3 for a flow diagram of this plasma simulation code. Furthermore, visualization is achieved with OpenGL rendering.

Preliminary results of the CUDA-accelerated desktop PC code run on a NVIDIA GTX Titan are shown in Figure 4. DC voltage was applied to the left electrode at 10000 V with a ground plane opposite of the needle protrusion. An initial electron population was seeded in the volume with a total number of tracked particles equal to 5 million. A Cartesian mesh was used with a total size of 410^3 that provided a 15 um spatial resolution and occupied ~2.5 GB of

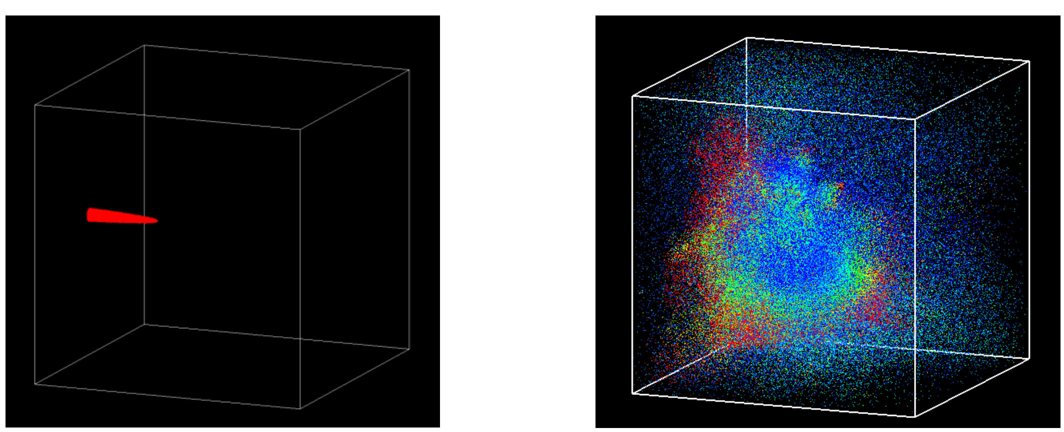

Figure 4: (left) Electrode geometry with ground plane opposite of needle protrusion. (right) Electron distribution (total electrons = 5 x 10^6) after 880 picoseconds, colors indicate particle energy.

memory space. The total run-time for the simulation of 1 ns was about 2 hours. The data indicates that the initial electrons amplify due to ionization processes and move towards the positive electrode. Space-charge generated (not pictured) in the high-field region creates energetic electrons that further enhance the ionization processes.

Resources

Currently, most of the required resources to perform these measurements and computations are available at Texas Tech University. However, it would be necessary to acquire several optical components specific to the transmission of the UV laser beam and measurement of the infrared TALIF signal. These include near-infrared bandpass filters, deep ultraviolet coated mirrors, spherical or cylindrical lenses and optical windows. Funding for these resources would currently be available.

For simulation purposes, initial results have been obtained using a single GPU. It is planned to extend the stand-alone PC version of the code to run on two or more GPU's located in a single machine and is the next logical step before the development of a large cluster-based simulation. As such, a second NVIDIA graphics card will be acquired in the near future.

Conclusions

The outcome of this research would be the investigation of pulsed low-temperature plasma through TALIF measurements and GPU-assisted simulations. In addition to studying plasma formation, the development of an efficient, PIC/MCC code would advance the field of plasma science by demonstrating the effectiveness of CUDA-enabled computing on a desktop PC to a scientific community where even simple simulations typically require the use of high performance computing clusters. The characterization of atmospheric pressure discharges through these methods would further the understanding of mechanisms leading to plasma initiation.

References

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3. Kolb J, Mohamed A, Price R, Swanson R, Bowman A, Chiavarini R, "Cold atmospheric pressure air plasma jet for medical applications," *Appl. Phys. Lett.*, 92, 241501, 2008.
4. Herrmann H, Henins I, Park J, Selwyn G, "Decontamination of chemical and biological warefare (CBW) agents using an atmospheric pressure plasma jet (APPJ)," *Phys. Plasmas*, 6, 2294, 1999.
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10. Ono R, Yamashita Y, Takezawa K, Oda T, "Behaviour of atomic oxygen in a pulsed dielectric barrier discharge measured by laser-induced fluorescence," *J. Phys. D: Appl. Phys.*, 38, 2812, 2005.
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15. Barnat E, Frederickson K, "Two-dimensional mapping of electron densities and temperatures using laser-collisional induced fluorescence," *Plasma Sources Sci. Technol.*, 19, 055015, 2010.

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Prof. Andrea Cavallini
Chair, DEIS Education Committee
DIE Dipartimento di Ingegneria Elettrica
Viale Risorgimento 2, 40136 Bologna, Italy

September 24, 2013

IEEE Dielectrics and Electrical Insulation Society

RE: Nomination Andrew Fierro, Graduate Fellowship

To whom it may concern:

It is my pleasure to write to you in support of Andrew Fierro, currently PhD student in the ECE Dept at Texas Tech University. Please accept this letter of recommendation for Andrew Fierro's research impact in the field of Vacuum Ultra Violet (VUV) radiation studies relating to pulsed atmospheric breakdown. Andrew joined the Center for Pulsed Power and Power Electronics after obtaining his B.S. degree in Computer Science and is currently pursuing his PhD degree in Electrical Engineering (MS ECE in 2011). He is a member of the lab's group studying dielectric surface flashover where he contributes to next generation diagnostics systems for VUV radiation. Andrew has taken graduate classes I taught in Laser Diagnostics, Pulsed Power, Gaseous Electronics, and Plasma Engineering, all advanced classes, and received an A in all of them.

Mr. Fierro has already made significant contributions to uncovering the role of extreme ultraviolet radiation during the rapid formation of electrical plasma; he has authored four peer reviewed journal manuscripts (a fifth one is under review) and contributed eighteen conference presentations/proceedings. Mr. Fierro proposes to develop a CUDA-accelerated advanced 3-dimensional particle simulation for the determination of fundamental characteristics of transient electrical plasma. Applying parallel simulation techniques to plasma kinetics would substantially advance the field of plasma science by demonstrating the effectiveness of CUDA-assisted computing on a desktop.

Mr. Fierro has the right mixture of theoretical background (Computer Science BS and Electrical Engineering MS) and the drive to develop computer models capable of successfully simulating complex phenomena. He is one of the three top PhD students I have advised in my 16 year career.

The proposed measurements contribute to the overall understanding and modeling of pulsed low temperature plasma formation and surface flashover with applications in many fields. At present, we would be able to provide the necessary matching funds for the items needed to conduct the proposed research.

I consider Mr. Andrew Fierro as most deserving of the DEIS graduate fellowship. His proposal "Investigation of pulsed low-temperature plasma through two-photon laser-induced fluorescence and GPU-accelerated simulation techniques" is sound in its suggested approach. The planned work will further push our understanding of low temperature plasma formation and pulsed breakdown in general. As Mr. Fierro's graduate advisor, I will be more than happy to monitor his progress during the award period.

Overall, Mr. Fierro will without a doubt significantly advance the understanding of pulsed low-temperature plasma formation as it relates to many biological and medical applications, and gaseous breakdown in general.

Best Regards,

Dr. Andreas A. Neuber, P.E.
Professor Electrical and Computer Engineering
Phone: (806) 742-1250, Fax: -1281
email: andreas.neuber@ttu.edu
http://www.p3e.ttu.edu

About the Nominator

Dr. Andreas A. Neuber, P.E., Fellow IEEE
Professor, Electrical and Computer Engineering
Texas Tech University
Andreas.Neuber@ttu.edu

Dr. Andreas A. Neuber received the Diploma in physics and the Dr.-Ing. in mechanical engineering degrees from the Darmstadt University of Technology, Germany, in 1990 and 1996, respectively. He was a senior researcher at the institute of Energy- and Power Plant Technology, Darmstadt University of Technology, from 1990 through 1996, in the area of nonlinear laser spectroscopy and chemical reaction kinetics in combustion. In 1996, he joined Texas Tech University, Lubbock, TX, and is currently Professor of Electrical and Computer Engineering. He has published more than 200 journal and conference proceedings papers. His current research interests are high-power microwave breakdown, unipolar surface flashover physics, and explosive-driven pulsed power. Dr. Neuber has served in various capacities on the organizing committees of numerous international conferences, including Technical Program Co-Chairman of the 2002 Power Modulator Conference, Technical Program Chair of the 2003 IEEE International Pulsed Power Conference. He has served as a Guest Editor of the IEEE TDEI for the 2005 and the upcoming 2011 Special Issue on Power Modulators and Repetitive Pulsed Power, and has served as an external readiness review panel member for the US Department of Energy. Dr. Neuber has received the DEIS sponsored William G. Dunbar award at the 2010 IEEE International Power Modulator and High Voltage Conference for "continuing contributions to high voltage research, technology and engineering education".

TEXAS TECH UNIVERSITY

Center for Pulsed Power and Power Electronics
Department of Electrical and Computer Engineering
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September 24th, 2013

RE: Mr. Andrew Fierro, DEIS Fellowship

To whom it may concern,

Please accept this as a letter for Mr. Andrew Fierro's standing in the Electrical and Computer Engineering Department. Mr. Fierro enrolled in graduate school at Texas Tech University in 2010 and completed his Master's degree in Electrical Engineering in December 2011 under advisement from Dr. Andreas Neuber. Currently, he is a member of the Pulse Power lab's group studying dielectric surface flashover.

Mr. Fierro's dedication to his academics and research consistently results in high marks in the classroom and exceptional research contributions including a recent publication in the *Journal of Physics D: Applied Physics*. He has also co-authored several other journal articles and presented at numerous international conferences.

As such, Mr. Fierro is in good standing with the department and qualified for the DEIS fellowship.

Best Regards,

Dr. Michael Giesselmann, P.E.
Professor & Department Chair
Department of Electrical and Computer Engineering
(806) 742 – 3533 - 225
michael.giesselmann@ttu.edu

Research Contributions

Journal

[J1] **A. Fierro**, G. Laity, A. Neuber, “Optical Emission Spectroscopy Study in the VUV-VIS Regimes of a Developing Low-Temperature Plasma in Nitrogen gas,” *Journal of Physics D: Applied Physics*, vol. **45**, 495202, 2012.

[J2] G. Laity, **A. Fierro**, J. Dickens, A. Neuber, K. Frank, “Simultaneous Measurement of Nitrogen and Hydrogen Dissociation from Vacuum Ultraviolet Self-Absorption Spectroscopy in a Developing Low Temperature Plasma at Atmospheric Pressure,” *Applied Physics Letters*, vol. **102**, 184104, 2013.

[J3] G. Laity, **A. Fierro**, L. Hatfield, J. Dickens, A. Neuber, “Spatially Resolved Vacuum UV Spectral Imaging of Pulsed Atmospheric Flashover,” *IEEE Transactions on Plasma Science*, vol. **39**, pp. 2122-2123, 2011.

[J4] G. Laity, A. Neuber, **A. Fierro**, J. Dickens, L. Hatfield, “Phenomenology of Streamer Propagation during Pulsed Dielectric Surface Flashover,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. **18**, pp. 946-953, 2011.

Conference

[C1] **A. Fierro**, J. Dickens, A. Neuber, “Implementation of a 3D PIC/MCC Simulation to Investigate Plasma Initiation in Nitrogen at Atmospheric Pressure,” *66th Annual Gaseous Electronics Conference*, September 30th – October 4th, Princeton, New Jersey, 2013.

[C2] **A. Fierro**, G. Laity, S. Beeson, J. Dickens, A. Neuber, “Study of Low-Temperature Plasma Development Utilizing a GPU-implemented 3D PIC/MCC Simulation,” *IEEE Pulsed Power and Plasma Science Conference*, June 16th – 21st, San Francisco, California, 2013.

[C3] **A. Fierro**, G. Laity, A. Neuber, L. Hatfield, “Photon Emission Dynamics during Low-Temperature Plasma Formation,” *65th Annual Gaseous Electronics Conference*, October 22nd – 26th, Austin, Texas, 2012.

[C4] **A. Fierro**, G. Laity, A. Neuber, L. Hatfield, “Measurements of UV-VUV Radiation Produced from Dielectric Surface Flashover,” *39th IEEE International Conference on Plasma Science*, July 8th – 12th, Edinburgh, United Kingdom, 2012.

[C5] **A. Fierro**, G. Laity, A. Neuber, L. Hatfield, J. Dickens, “Spatially-Resolved Spectral Observations of Pulsed Surface Flashover in a Nitrogen Environment,” *2012 IEEE International Power Modulator and High Voltage Conference*, June 3rd – June 7th, San Diego, California, 2012.

[C6] **A. Fierro**, G. Laity, L. Hatfield, J. Dickens, A. Neuber, “Advanced Imaging of Pulsed Atmospheric Surface Flashover,” *18th IEEE International Pulsed Power Conference*, June 19th - 23rd, Chicago, Illinois, 2011.

Conference Travel

I hereby affirm that, as a US citizen, visa issues will not be an impediment for travel to a DEIS-sponsored conference or to the next CEIDP. The next CEIDP in 2014 will be held in Des Moines, Iowa. If not able to attend this upcoming CEIDP, another option for the International Power Modulator and High Voltage Conference (IPMHVC) which will be held in Santa Fe, New Mexico.

Andrew Fierro

ANDREW S. FIERRO

Education

Texas Tech University January 2012 – Present

- Ph.D. in Electrical Engineering – Center for Pulsed Power and Power Electronics
- Present Cumulative GPA: 4.0
- Expected Graduation Date: May 2015
- Advisor: Andreas Neuber, Ph.D.

Texas Tech University January 2010 – December 2011

- M.S. in Electrical Engineering – Center for Pulsed Power and Power Electronics
- GPA: 4.0
- Graduation Date: December 2011
- Advisor: Andreas Neuber, Ph.D.
- Thesis: "*Investigations of Self-Produced Radiation during Dielectric Surface Flashover*"

Texas Tech University August 2005 – May 2009

- B.S. in Computer Science, minor in Math and Electrical Engineering
- GPA: 3.55
- Graduation Date: May 2009

Work Experience

Texas Tech University Center for Pulsed Power and Power Electronics January 2010 – Present
Graduate Research Assistant

Research and study the plasma processes occurring during the development of a low-temperature plasma under pulsed conditions. Experimental tasks included observation of electrical characteristics, fast-gated visible imaging of streamer formation, and analysis of emission spectra captured with high-speed optical diagnostics including an ICCD or PMT during all stages of breakdown on the nanosecond timescale. In addition, update or write new simulation codes to model emission spectra, kinetic rate equations, and other plasma processes. Large modeling projects include the development of a highly paralleled 3D PIC/MCC model of volume breakdown including many kinetic processes and tracking millions of particles simultaneously on GPU clusters using MPI/CUDA technologies.

Sandia National Laboratories May 2013 - August 2013
Graduate Summer Intern

Acquired experience working on a large software project in development for 5+ years with numerous developers. Main assignment was the implementation of photon processes in a full breakdown simulation. These processes included photoionization, photoexcitation, photoemission. The photons used existing particle framework to enable to incorporation of other photo-processes at the users discretion. In addition, the implementation was verified with analytical rate equations and compared against simple test cases to ensure accuracy.

L-3 Communications May 2009 – January 2010
Graduate Co-op Software Engineer

Tasked with designing software libraries for UNIX/Linux environments as well as Windows using C/C++/Python in a team-oriented environment. Furthermore, assigned to develop unit testing procedures/code and evaluate existing and new software modules and their compliance with unit testing policies. Also was involved with various system administration and development duties for new computer hardware introduced to the lab.

Organizations

- IEEE Student Member
- Nuclear and Plasma Science Society
- Dielectrics and Electrical Insulation Society
- APS Student Member