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Award Number: W81XWH-10-1-0923

TITLE: Light Weight Portable Plasma Medical Device - Plasma Engineering Research Laboratory

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CONTRACTING ORGANIZATION: Texas A&M University, Corpus Christi
Corpus Christ, TX 78412-5503

REPORT DATE: October 2011

TYPE OF REPORT: Annual

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;
Distribution Unlimited

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE
October 2011

2. REPORT TYPE
Annual

3. DATES COVERED
1 October 2010 – 30 September 2011

4. TITLE AND SUBTITLE
Light Weight Portable Plasma Medical Device - Plasma Engineering Research Laboratory

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W81XWH-10-1-0923

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Texas A&M University, Corpus Christi
Corpus Christ, TX 78412-5503

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

We have established a state-of-the-art plasma research facility which is capable of conducting various interdisciplinary research projects. We have completed the setup of a direct current atmospheric resistive barrier cold plasma system, setup of a 13.56 MHz radio frequency dielectric barrier plasma system, setup of a laser induced breakdown plasma experimental system, setup of a plasma shadowgraphy diagnostics system and setup of an optical emission spectroscopy diagnostics as planned. The setup of a 900 MHz/2.45 GHz wave plasma system and the setup of a two color laser interferomtery diagnostics are currently in progress. We have also constructed a preliminary plasma source for the biological testing and preliminary results are reported.

15. SUBJECT TERMS
Plasma, laser, shadowgraphy, bacteria, cancer

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					USAMRMC
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
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INTRODUCTION

The project entitled - Lightweight Portable Plasma Medical Device – Plasma Engineering Research Laboratory has made significant progress meeting the proposed milestones. The project has two objectives, in which the objective 1 is to develop a plasma research facility and establish a range of experimental plasma systems and diagnostics. The objective 1 has 7 proposed tasks that are aimed to be completed in year 1 (Oct 2011), in which 5 tasks are completed and the results and progress are reported and two tasks are in progress and expected to be completed by next quarter. The project's second objective is to develop a prototype of a portable plasma source for biomedical applications such as sterilization, infection treatment and cancer treatment. The objective 2 was proposed to start at the beginning of year 2 of the project, however the PI and research team has developed a test portable plasma source and tested on a few bacterial and cancer cells and promising results are obtained. The PI has established the Plasma Engineering Research Lab (PERL) with a state-of-the-art facilities and equipment obtained through this grant funding as well as several donations from the university and the community. The PI has mentored 15 undergraduate students and 2 graduate students to perform various research projects. Several of these students have presented their work at various conferences and symposiums and few of those presentations has received best paper award. The PI has mentored a visiting scientist and a postdoctoral research associate. The PI and the research team are preparing two journal manuscripts which are to be submitted in the upcoming weeks. The PERL has received a great visibility in the university campus as well as in the state.

BODY

Table 1. The Project Objectives and Tasks

Task	Proposed Milestones	Base Line Plan Date
Objective 1: Establish Plasma Engineering Research Lab		
1	Setup a direct current - atmospheric - resistive barrier cold plasma system	26 OCT 2011
2	Setup a 13.56 MHz radio frequency dielectric barrier plasma system	26 OCT 2011
3	Setup a 900 MHz/2.45 GHz wave plasma system	26 OCT 2011
4	Setup a laser induced breakdown plasma experimental system	26 OCT 2011
5	Implement plasma shadowgraphy diagnostics Setup	26 OCT 2011
6	Implement a two color laser interferomtery diagnostics setup	26 OCT 2011
7	Implement a optical emission spectroscopy diagnostics setup	26 OCT 2011
Objective 2: Develop Portable Plasma Source		
8	Design phase: Design an optimized portable plasma source system	26 OCT 2012
9	Construction phase: Construct the portable plasma source based on the design analysis and utilizing the existing resources and knowledge gained from objective 1.	26 OCT 2012
10	Testing and characterization phase: Portable plasma source will be tested and characterized for its operating parameters and plasma parameters.	26 OCT 2012
11	Biological testing: In-vitro biological testing.	26 OCT 2012

I. OBJECTIVE 1: ESTABLISH PLASMA ENGINEERING RESEARCH LAB

1. Setup a direct current - atmospheric - resistive barrier cold plasma system

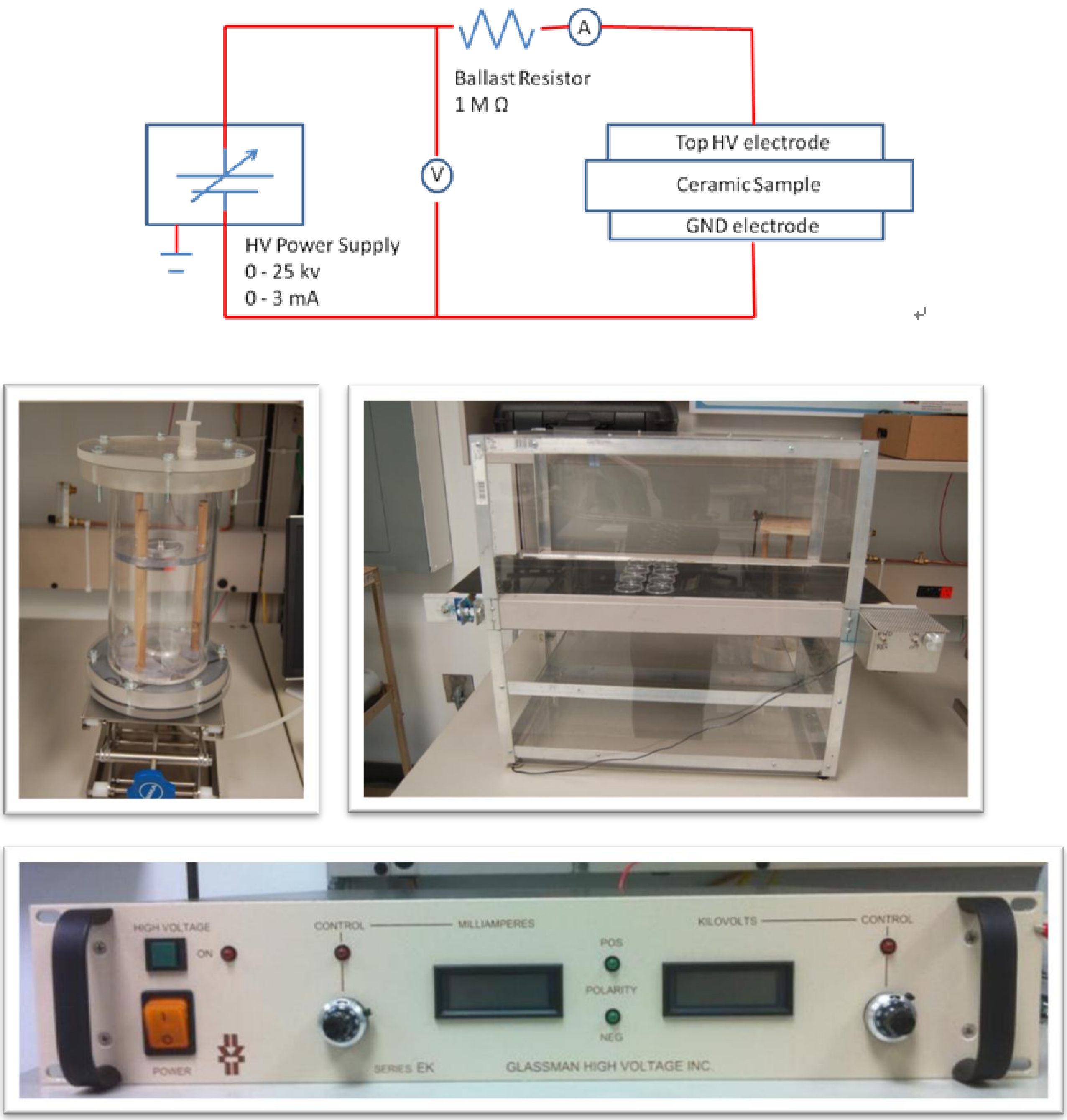
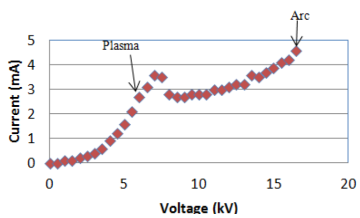
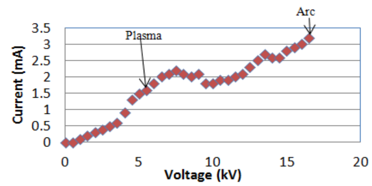
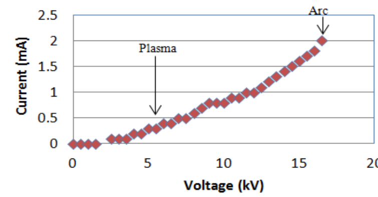


Figure 1. DC atmospheric pressure resistive barrier discharge

We have completed setting up the direct current atmospheric - resistive barrier cold plasma system. The DC power supply was acquired and atmospheric pressure plasma in air and helium has been experimented. A Mechanical Engineering Undergraduate Student is assisting on setting up the atmospheric Pressure resistive barrier discharge.







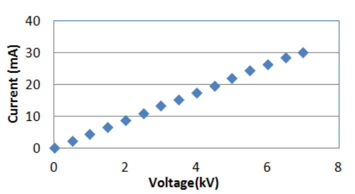


Fig.5– Moist Trial 1 of TAMUCC Stoneware

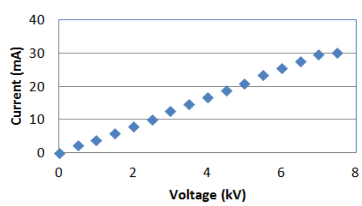


Fig. 6– Moist Trial 2 of TAMUCC Stoneware

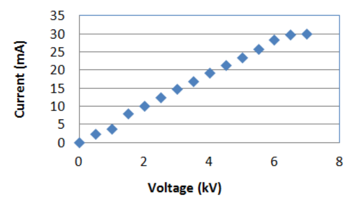


Fig. 7 – Moist Trial 3 of TAMUCC Stoneware

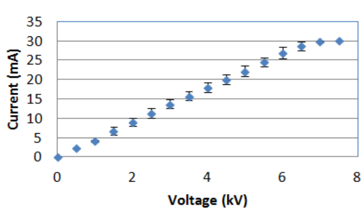


Fig8. – Moist Average of TAMUCC Stoneware

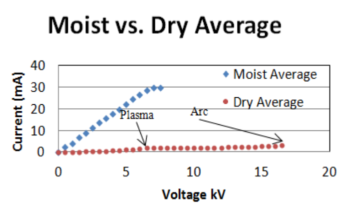


Fig.9 – Dry and Moist Average of TAMUCC Stoneware

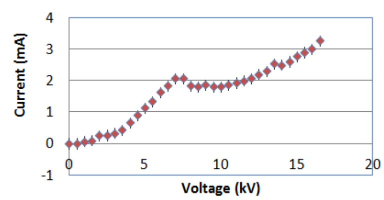


Fig.4– Average Dry Trial of TAMUCC Stoneware

Figure 2. The V-I characteristics of the resistive barrier DC plasma characteristics

The direct current resistive barrier discharge has been developed and tested for its voltage and current characteristics for different experimental conditions of the resistive barrier. The dryness and the moisture content of the resistive barrier has been varied and the VI characteristics and plasma parameters were diagnosed. The results are reported as technical report and presented in the key research accomplishments section.

2. Setup a 13.56 MHz radio frequency dielectric barrier plasma system

Figure 3. Setup a 13.56 MHz radio frequency dielectric barrier plasma system

We have completed the setup of a RF system that generates atmospheric pressure plasma at a low temperature. Currently a Hispanic Minority Mechanical Engineering Undergraduate student is assisting on setting up the experiment and collecting data. The data has been presented in a recent LSAMP conference and IEEE ICOPS conference.

Atmospheric pressure cold (non-thermal) plasmas have become increasingly prevalent within many research and industrial applications due to their range of reactive gas species produced that can be controlled and used in vast areas of application. In addition, the atmospheric plasma systems do not require expensive vacuum systems for their operation and generate a range of reactive ion species concentrations. This experimental research is being carried out to characterize and quantify the concentrations of the reactive ion species and other residual gases in order to theoretically extrapolate radial and axial distances. A set of gas flow rates were tested at fixed RF powers range from 60 W to 180

W. Through proportionally increasing oxygen gas flow rate and applied RF power the amount of reactive ionized species are quantified and characterized. The experiment is also extended to various axial distances and the measured decay of reactive ion species which provides the required treatment distances based on the application treatment requirements.

The chemical characterization of the atmospheric pressure diffused plasma source was performed. The results confirm that the plasma source generates required amount of Nitrous Oxide gases that are the primary reaction agents to induce several healing mechanism in the human body.

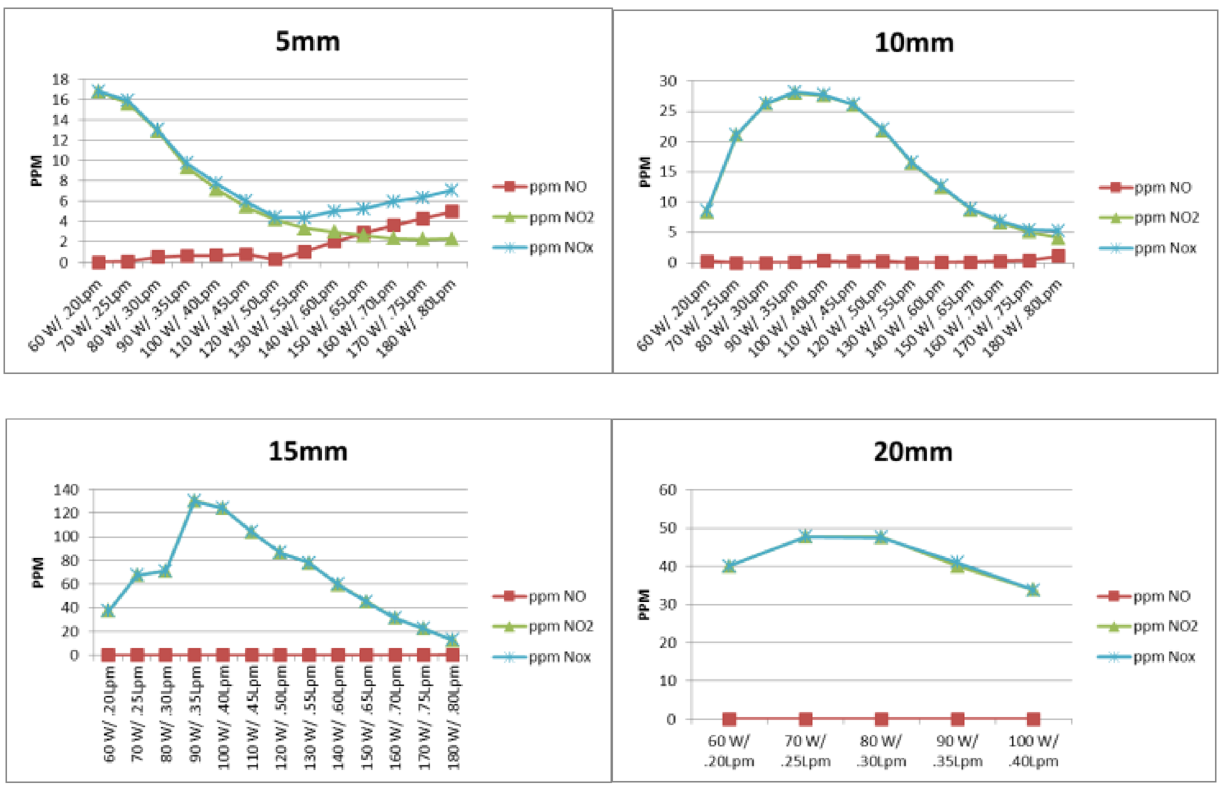


Figure 4. ppm at varying distances of Surfx® – Atomflo™ AH-250C - Testo-350 Diagnostics, Acquisition Software and Plasma Data Comparison

3. Setup a 900 MHz/2.45 GHz wave plasma system

The design of a 2.45 GHz microwave plasma system is currently in progress.

4. Setup a laser induced breakdown plasma experimental system

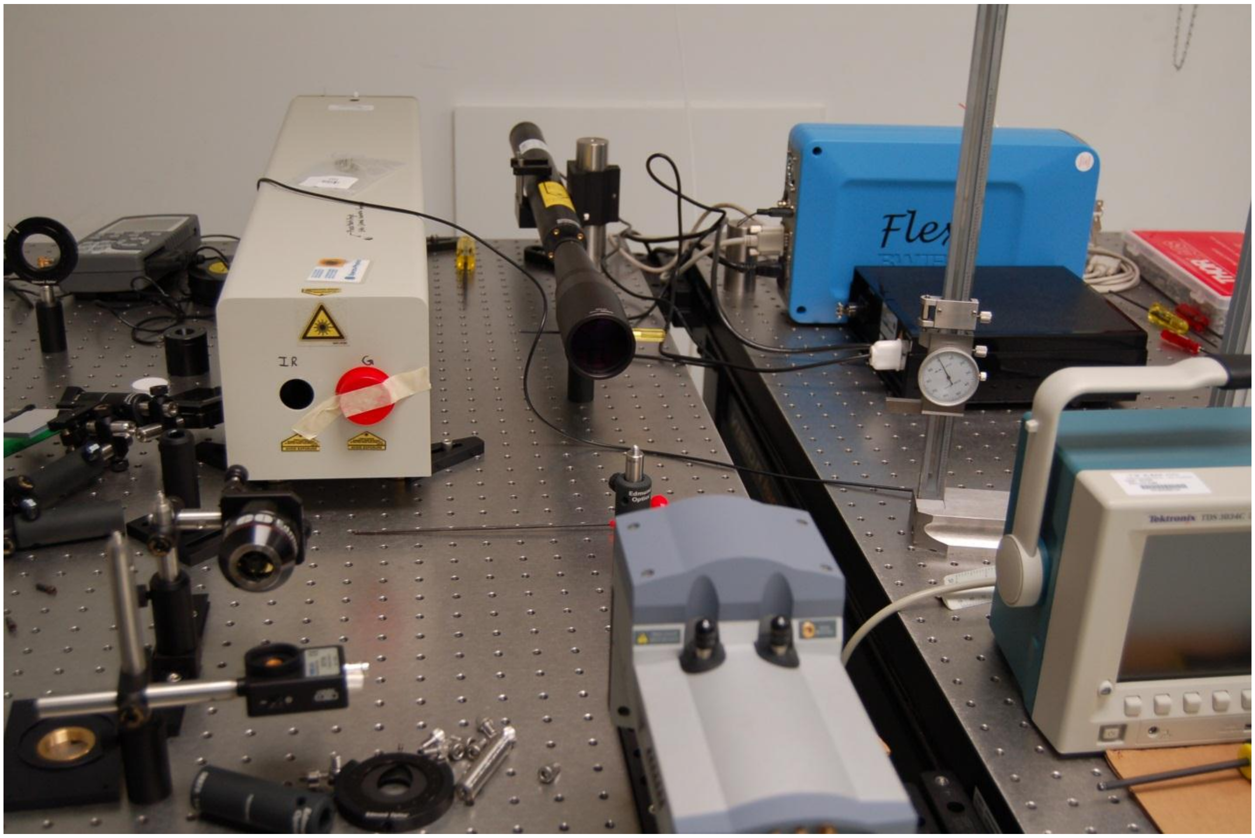


Figure 5. Setup a laser induced breakdown plasma experimental system

The picture of the experimental setup is shown in Fig. 5. In this experiment, a pulsed Nd:YAG laser (Spectra-Physics, Indi 40), with a 1st harmonic at λ = 1064 nm, 1.165 eV per photon and a 2nd harmonic at λ = 532 nm, 2.33 eV per photon is used. The laser output is a circular beam of 1-cm cross section diameter with Gaussian distributed beam intensity and 1.0 mrad beam divergence. The full-width at half maximum (FWHM) of the laser pulse is 6 ± 1 ns, with a 1-ns rise/fall time and a maximum available laser output energy of 450 mJ at 1-20 Hz rep rate. The laser outputs both 1st and 2nd harmonic laser beams simultaneously and in order to study the infrared laser induced plasma the 532 nm 2nd harmonic crystal generator was detuned and a dichromatic mirror separates any minimal 532 nm laser output from the 1064 nm pump laser. The laser output beam energy is controlled using a variable attenuator and each laser pulse is sampled through an IR beam sampler and the laser output energy is measured using laser energy meter (Coherent, FieldMax II). In this experiment, all IR optical components are specially coated, with 98% transparency at 1064 nm. The IR beam is then reflected by a high damage threshold (20 J/cm2)

IR coated kinematic mirror (TECHSPEC) in order to obtain a top-down configuration for the IR beam to enter the plasma chamber. The 1-cm-diameter IR beam is then passed through a 1064 nm transmission coated 3-cm-diameter Zinc Selenide window. The laser beam was focused by using a high-power handling (500 MW/cm2) objective lens mounted inside the plasma chamber. The objective lens (Thorlabs, LMH-5X-1064) has an effective focal length of 40-mm, with a 10-mm entrance aperture and a 0.13 NA. Due to its short focal length, the objective lens is mounted inside the plasma chamber using an adjustable length holder, so that the laser-induced plasma will be positioned at the cylindrical chamber air and visible through side windows for diagnostics. The space between the entrance IR window and the objective lens is maintained at the same pressure as that of the chamber pressure in order to avoid differential pressures acting on the objective lens. Great care was taken to position the objective lens together with the plasma chamber precisely in the line of sight with the IR laser beam. In addition, using the laser energy meter, it is found that the laser beam experiences a 5% loss as it passes through the coated IR optics, including the attenuator, beam sampler, mirrors and windows. The laser energy available immediately after the objective lens corresponding to a 300 ± 5 mJ laser output was measured by the Coherent FieldMax II energy meter to be 285 ± 5 mJ, corresponding to the measured incident laser energy on the focal spot, in agreement with the analytical estimate. A high-speed (<2-ns rise time) visible photodetector (Thorlabs, DET10A/M) mounted with collection optics is used to detect and observe the laser breakdown visible spark. The photodetector is connected to a high speed 2.5 GS/S oscilloscope to monitor the laser induced plasma emission. The plasma chamber was made from stainless steel and flushed several times before finally filling with dry air (< 10 ppm water) to the desired pressure ranging from 2000 Torr to 100 mTorr. Optical view ports on both sides of the cell are made of 3-cm-diameter by 5-mm-thick sapphire windows. The view ports enabled observation of the interior at right angles to the cell axis which is coincident with the direction of the laser beam, as well as for diagnosing the plasma. The chamber pressure was measured precisely by a pressure gauge with a pressure controller–readout (MKS Instruments, 910-11 and PDR 900-11). The gas flow through the chamber was regulated by a needle valve in the gas line and another valve in the pumping line. For one set of experiments on determining the effects of removing micro dust particles of diameters ≥ 0.1 μm on the breakdown threshold of dry air, we have inserted a filter capsule in the incoming gas line and cleaned residual dust on window and lens surfaces by means of an aerosol jet. The filter houses a dual-pleated polytetrafluoroethylene (PTFE) filtering element with ≤ 0.1−μm pore size.

5. Implement plasma shadowgraphy diagnostics Setup

We have completed the laser focused plasma and the shadowgraphy diagnostics together. We have obtained very good results and he is working on two journal manuscripts based on the results.

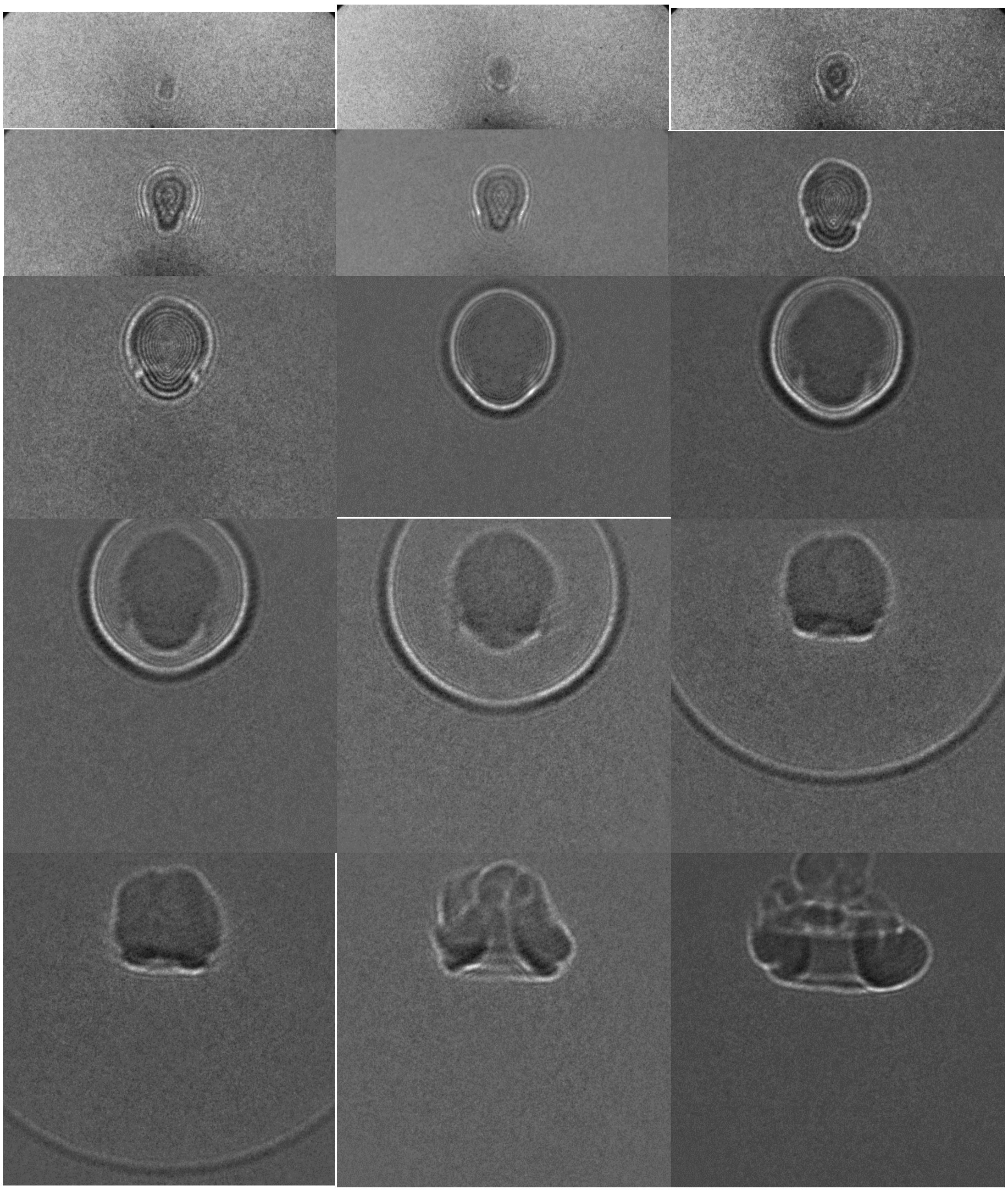


Figure 6. Shadowgrams of the laser induced plasma in air

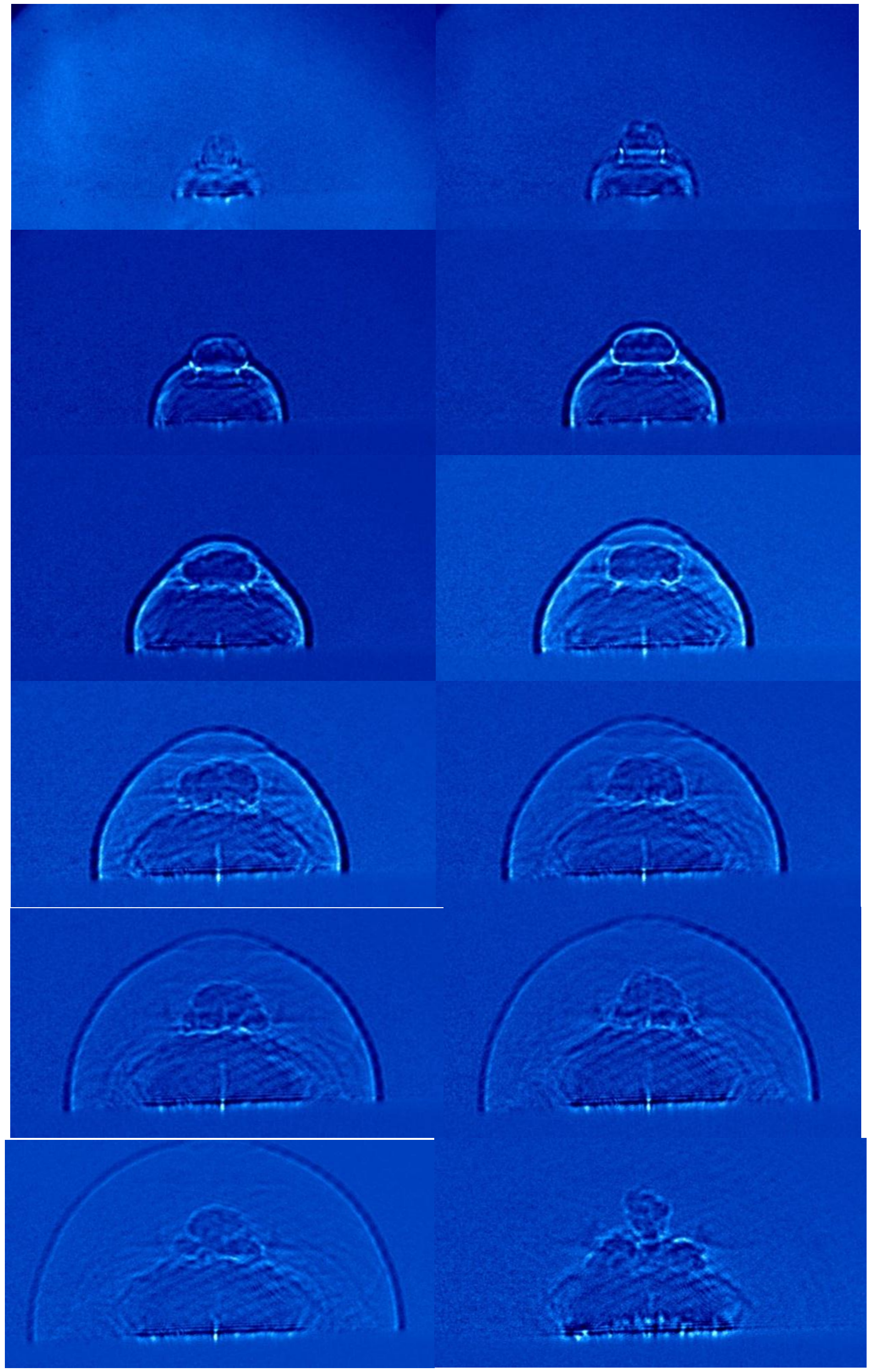


Figure 7. Shadowgrams of the laser induced plasma at air target interface

6. Implement a two color laser interferomtery diagnostics setup

The setup of a two color laser interferomtery diagnostics is in progress.

7. Implement optical emission spectroscopy diagnostics setup

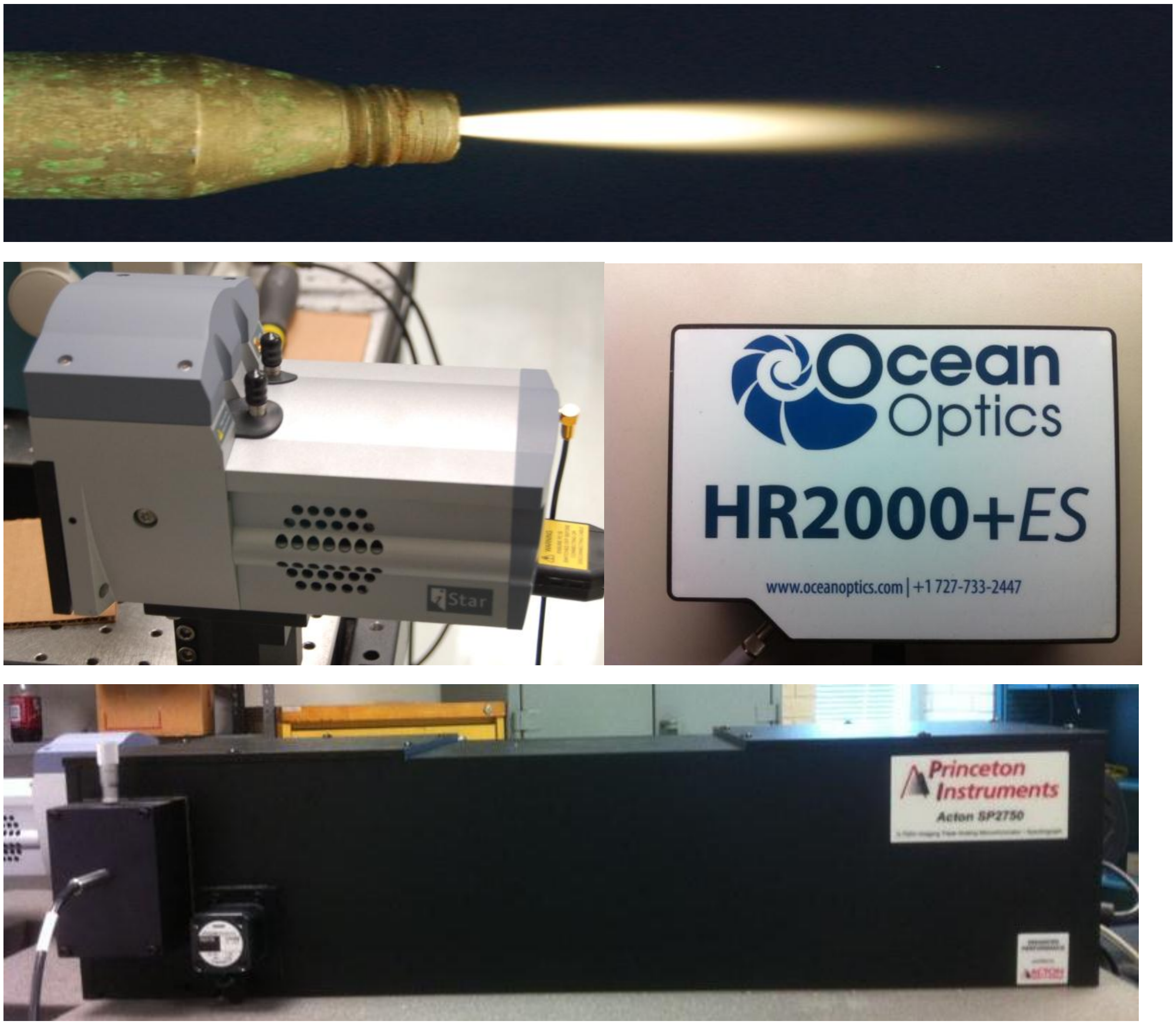


Figure 8. Optical emission spectroscopy diagnostics setup

The OES diagnostic setup is used as shown in Fig. 8 to measure the rotational Trotand vibrational Tvib temperatures of the laser induced plasma. A high resolution narrow band 0.01 nm resolution monochromator Acton Research, model ARC-SP-2758 is used. The monochromator has a multiple grating option, which gives the flexibility of choosing the resolution and wavelength range. A holographic grating of 68_68 mm, 2400 grooves/mm, optimized for the entire visible wavelength range is used to acquire emission spectrum. The plasma emission is acquired by a collecting lens f 10 and sent to a fast gating Andor iStar ICCD ANDOR, DH 734 through a high-quality 200–800 nm fiber-optic bundle. The Andor iStar ICCD detector is integrated with an Acton SpectraPro 2750 spectrograph system. This system has a near-Lorentzian slit function with a halfmaximum width of 0.2 nm when the grating density is set to 1200 lines/mm. The UV excimer laser is synchronized with the gated ICCD in such a way that the spectral emissions from the laser induced plasma are acquired at different plasma lifetimes ranging from 45 ns to 100 micros with a gating time of tg=45 ns for time windows t_100 ns and tg =100 ns for time windows t 100 ns. The spectral emission signal strength of the laser induced plasma spark is very weak due to small plasma dimension and short gating times of 45–100 ns. In order to obtain good signal strength and spectral profile, 2000 laser shots are used at each acquisition time and the laser is operated at 1 Hz to maintain the same laser energy output.

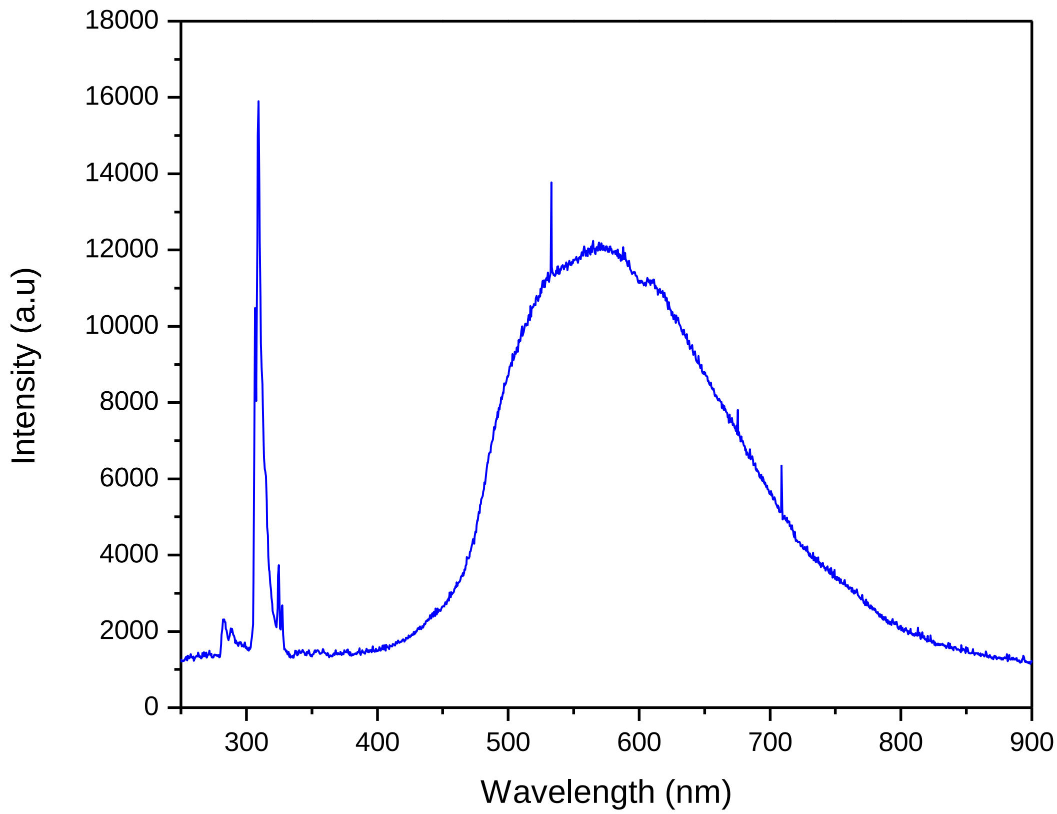


Figure 9. Optical emission spectrum of air plasma

II. Objective 2: Develop Portable Plasma Source

The following tasks under the objective 2 will be completed in the next project year as per the proposed milestones. The tasks under the objective include:

- 8. Design phase: Design an optimized portable plasma source system
- 9. Construction phase: Construct the portable plasma source based on the design analysis and utilizing the existing resources and knowledge gained from objective 1.
- 10. Testing and characterization phase: Portable plasma source will be tested and characterized for its operating parameters and plasma parameters.
- 11. Biological testing: In-vitro biological testing.

The team has developed a preliminary testing prototype and its efficacy was also tested on few bacterial lines and some cancer cell lines and the results are very promising.

KEY RESEARCH ACCOMPLISHMENTS

The project has met the project deadlines for majority of the proposed tasks under the Objective 1 during this year and some has made progress ahead of the project deadlines in some tasks under objective 2. The status and remarks of the project milestones are given below.

Table 2. Status and remarks of the project milestones

Task	Proposed Milestones	Base Line Plan Date	Status/Remark
I. Objective 1: Establish Plasma Engineering Research Lab			
1	Setup a direct current - atmospheric - resistive barrier cold plasma system	26 OCT 2011	Completed
2	Setup a 13.56 MHz radio frequency dielectric barrier plasma system	26 OCT 2011	Completed
3	Setup a 900 MHz/2.45 GHz wave plasma system	26 OCT 2011	In Progress
4	Setup a laser induced breakdown plasma experimental system	26 OCT 2011	Completed
5	Implement plasma shadowgraphy diagnostics Setup	26 OCT 2011	Completed
6	Implement a two color laser interferomtery diagnostics setup	26 OCT 2011	In Progress
7	Implement a optical emission spectroscopy diagnostics setup	26 OCT 2011	Completed
II. Objective 2: Develop Portable Plasma Source			
8	Design phase: Design an optimized portable plasma source system	26 OCT 2012	In Progress
9	Construction phase: Construct the portable plasma source based on the design analysis and utilizing the existing resources and knowledge gained from objective 1.	26 OCT 2012	In Progress
10	Testing and characterization phase: Portable plasma source will be tested and characterized for its operating parameters and plasma parameters.	26 OCT 2012	In Progress
11	Biological testing: In-vitro biological testing.	26 OCT 2012	In Progress

REPORTABLE OUTCOMES

A. MENTORING

The PI is dedicated to mentor students of diversity and underrepresented minority groups.

The PI has mentored the following scientists in the research

Dr. Zhen Ma

Dr. Kenneth Williamson

The PI has mentored the following Graduate Students

Heather Anderson

Anudeep Reddy Kandi

The PI has mentored the following Undergraduate Students

Eduardo Valdez

Francisco Rodriguez

Bokang Yang

Thurman Walling

James Shames

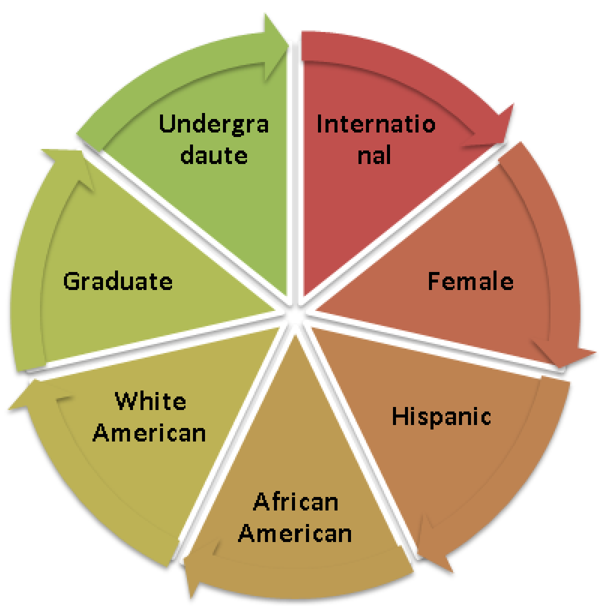
Isaac Colmenero

Kim Pham

Megan Norfolk

Jennifer Anderson

Amanda Whitmill



B. CONFERENCE PUBLICATIONS

1. Norfolk, M., Thiyagarajan, M., waldbeser, l., whitmill, A. (2011). Apoptosis and Autophagy in Cancer Cells Induced from Non-Thermal Ionized Plasma. San Jose, California: SACNAS National Conference.

2. Valdez, E., Thiyagarajan, M. (2011). Characterization of Diffused Atmospheric Pressure Cold Plasma System for Surface Modification. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium (Best Paper Award).

3. Vidal, G., Thiyagarajan, M., Pam, H. (2011). Cold Plasma Inactivation of E. coli and S. aureus on Solid Surfaces for Infection Treatment. San Jose, California: SACNAS National Conference.

4. Ausland, J., Thiyagarajan, M., Vidal, G. (2011). Deactivation of Escherichia coli using a Novel Cold Plasma Technology and its effect on the bacterial growth. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium.

5. Yang, B., Thiyagarajan, M. (2011). Electrical Conductivity Characterization of Novel TAMUCC Stoneware Ceramic at Various Experimental Conditions. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium.

6. Hes, J., Thiyagarajan, M., Branecky, C., Ramon, R. (2011). Electrical Conductivity Measurements and Analysis of Ceramic Materials at Various Moisture Conditions. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium.

7. Anderson, H., Thiyagarajan, M., Vidal, G., Pam, H. (2011). Non-Thermal Plasma Decontamination of E. Coli and S. Aureus – Research and Review. San Jose, California: SACNAS National Conference.

8. Ramon, R., Thiyagarajan, M. (2011). Portable Plasma Disinfection Conveyor System. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium.

9. Norfolk, M., Thiyagarajan, M. (2011). Pre-programmed Cell Death in Acute Monocytic Leukemia Cancer Cells Induced by Nonthermal Ionized Plasma. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium (Best Paper Award).

10. Valdez, E., Thiyagarajan, M. (2011). Reactive Gas Species Characterization of Diffused Atmospheric Pressure Cold Plasma System. San Jose, California: SACNAS National Conference.

11. Pam, H., Thiyagarajan, M., Vidal, G., Alison, D., Mott, J., Buck, G. (2011). Sterilization of Escherichia coli and Staphylococcus aureus Microorganism using a Novel Cold Plasma Technology. San Jose, California: SACNAS National Conference.

12. Pham, H., Thiyagarajan, M., Vidal, G., Buck, G., Mott, J. (2011). Sterilization of Staphylococcus aureus using a Novel Cold Plasma Technology and its effect on the bacterial growth. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium.

13. Rodriguez, F., Thiyagarajan, M., Yang, B., Williamson, K. (2011). Surface Energy Modification using Atmospheric Pressure Cold Plasma System. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium.

14. Thiyagarajan, M. (2011). Materials Engineering Course Design and Improvement for Effective Research Based Learning Environment. Corpus Christi, TX: TAMUCC 1st Faculty Symposium: Course Design for the Millennial Student.

15. Thiyagarajan, M. (2011). Portable Plasma Biomedical Device for Cancer Treatment. Irvine, California: ASME Emerging Technologies - 6th Frontiers in Biomedical Devices Conference.

16. Thiyagarajan, M. (2011). Portable Plasma Medical Device for Infection Treatment and Wound Healing. Irvine, California: ASME Emerging Technologies - 6th Frontiers in Biomedical Devices Conference.

17. Thiyagarajan, M. (2011). Effects of Cold Plasma and Treatment of Leukemia Cancer Cells. Marseille, France: International Conference on Medical Physics and Biomedical Engineering.

18. Thiyagarajan, M. (2011). Effects of Plasma Treatment on E. Coli, S. Aureus and N. Meningitidis Microbes. Marseille, France: International Conference on Medical Physics and Biomedical Engineering.

19. Thiyagarajan, M. (2011). Characterization of Reactive Gas Species in Diffused Atmospheric Pressure Cold Plasma System. Paris, France: International Conference on Applied Chemistry and Chemical Engineering.

20. Thiyagarajan, M., waldbeser, l. (2011). Effective Non-Thermal Plasma Induction of Apoptosis in Leukemia Cancer Cells. Chicago, IL: 38th IEEE International Conference on Plasma Science (ICOPS) and 24th Symposium on Fusion Engineering (SOFE).

21. Thiyagarajan, M. (2011). Experimental Study of Shock Wave Discontinuities and Interactions with Laser Induced Plasmas. Chicago, IL: 38th IEEE International Conference on Plasma Science (ICOPS) and 24th Symposium on Fusion Engineering (SOFE).

22. Thiyagarajan, M. (2011). High Power Pulsed Laser Induced Breakdown Plasma at Gas-Solid Interface. Chicago, IL: 18th IEEE International Pulsed Power Conference.

23. Thiyagarajan, M. (2011). Plasma Treatment on E. Coli, S. Aureus, N. Meningitides for Food Industries. Paris, France: International Conference on Food Engineering and Biotechnology.

24. Thiyagarajan, M., waldbeser, l. (2011). Portable Plasma Torch on E.Coli, S. Aureus, N. Meningitidis and other Clincal Isolates. Chicago, IL: 38th IEEE International Conference on Plasma Science (ICOPS) and 24th Symposium on Fusion Engineering (SOFE).

25. Thiyagarajan, M., waldbeser, l. (2011). Treatment of Cancer Cells using a Pulsed Power Plasma Source. Chicago, IL: 18th IEEE International Pulsed Power Conference.

26. Thiyagarajan, M. (2011). Report on Portable Plasma Bio-Medical Device and Characterization. Omaha, Nebraska: Telemedicine and Advanced Technology Research Center - Midwest Technology Exchange Conference.

27. Whitmill, A., Thiyagarajan, M., waldbeser, l. (2011). Effects of Non-Thermal Ionized Plasma on THP-1 Acute Monocytic Leukemia Cells. Ithaca, NY: National Conference on Undergraduate Research (NCUR).

28. Whitmill, A., Thiyagarajan, M., waldbeser, l. (2011). Induction of Apoptosis in Leukemia Cells by Non-thermal Ionized Plasma. Prairie View, TX: 7th Annual LSAMP Conference (Best Paper Award).

29. Valdez, E., Thiyagarajan, M. (2011). Reactive Gas Species Characterization of Diffused Atmospheric Pressure Cold Plasma System. Prairie View, TX: 7th Annual LSAMP Conference.

30. Whitmill, A., Thiyagarajan, M., Waldbeser, L. (2011). Effects of Ionized Plasma on THP-1 Acute Monocytic Leukemia Cells. Corpus Christi, TX: 2011 Annual McNair Symposium.

31. Whitmill, A., Thiyagarajan, M., waldbeser, l. (2010). Effects of Ionized Plasma on Acute Monocytic Leukemia Cells. (pp. 74). Canyon, TX: 8th Annual Pathways Research Symposium.

32. Thiyagarajan, M., Hardeman, K., Waldbeser, L. S. (2010). Effects of Plasma Treatment on E. Coli, S. Aureus, N. Meningitidis and Other Clinical Isolates. (2010th ed., vol. 7, pp. 131). Anaheim, CA: 2010 SACNAS National Conference (Best Paper Award).

33. Walling, T., Thiyagarajan, M. (2010). Nitrogen Oxides and Light Wavelengths Produced by a Portable Plasma Device. (pp. 56). Canyon, TX: 8th Annual Pathways Research Symposium.

34. Thiyagarajan, M., Whitmill, A., waldbeser, l. (2010). Effects of Non-Thermal Ionized Plasma on Human Leukemia and Lymphoma Cells. (vol. 7, pp. 82). Anaheim, CA: 2010 SACNAS National Conference.

35. Whitmill, A., Thiyagarajan, M., waldbeser, l. (2010). Effects of Non-Thermal Ionized Plasma on Human Leukemia and Lymphoma Cells. (pp. 8). Texas: 10th Annual Research Symposium, South Texas Sigma Xi.

36. Walling, T., Thiyagarajan, M. (2010). Nitrogen Oxides and Light Wavelengths Produced by a Medical Treatment Device. (pp. 41). Texas: 10th Annual Research Symposium, South Texas Sigma Xi.

C. JOURNAL MANUSCRIPT SUBMITTED

Optical breakdown threshold investigation of 1064 nm laser induced air plasmas

We present the theoretical and experimental measurements and analysis of optical breakdown threshold for dry air by 1064 nm infrared laser radiation and the significance of the multiphoton and collisional cascade ionization process on the breakdown threshold measurements over pressures range from 10 Torr to 2.5 atmospheres. Theoretical estimates of the breakdown threshold laser intensities and electric fields are obtained using two distinct theories namely multiphoton and collisional cascade ionization theories. The theoretical estimates are validated by experimental measurements and analysis of laser induced breakdown process in dry air at a wavelength of 1064 nm by focusing 450-mJ max, 6 ns 75 MW max high-power 1064 nm IR laser radiation onto a 20-μm-radius spot size that produces laser power densities up to 3 – 6 TW/cm^2, well above the threshold power flux for air ionization over the pressures of interest ranging from 10 Torr to 2.5 atm. The measured breakdown threshold laser intensities and electric fields are compared with classical and quantum theoretical ionization models as well as with 193 nm, shorter laser wavelength. A universal scaling analysis of the breakdown threshold measurement results provided a direct mechanism to compare breakdown threshold values over wide range of frequencies ranging from microwave to ultraviolet frequencies. Comparison of 1064 nm laser-induced effective field intensities for air breakdown measurements with data calculated based on the collisional cascade and multiphoton breakdown theories is used successfully to determine the collisional microwave scaled portion. The measured breakdown threshold 1064-nm laser field intensities are then scaled to classical microwave breakdown theory after correcting for the multiphoton ionization process for different pressures.

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I. INTRODUCTION

Laser induced plasmas are of significant interests in a large domain of research and industrial applications in the field of science and technology.[1,2] Laser-produced plasmas are widely used in laser ablation,[3] micromachining,[4] photochemistry,[5] laser fusion,[6] flow control,[7-9] drag reduction in supersonic and hypersonic flows,[10,11] ignition of combustion gases,[12] thrusters in space applications,[13] and laser-initiated switching applications.[14] This paper examines the air breakdown threshold by multiphoton and cascade ionization process at 1064 nm infrared (IR) wavelength laser radiation over a wide pressure ranges and the results are compared with previously published air breakdown threshold measurements carried out at microwave frequencies and at 193 nm ultraviolet (UV) wavelength.[15]

Laser-induced breakdown can be described as the formation of an ionized gas or plasma during or by the end of the laser pulse. The experimental condition that is usually used is the detection of a glow or flash in the focal region for 10%–50% of the laser firings.[16] As described by Raizer,[16] the photon-initiated electron cascading plasma process initiates when a pulsed laser beam is focused to a small volume, which produces a very sudden temperature rise in the medium at that point. If the electric field of the laser radiation in the focal region becomes greater than that of the binding electrons to their nuclei, it will trigger breakdown of the air molecules and produce ionization of the gas. Following the initial breakdown cascade effect takes place due to the increased plasma density and the medium becomes opaque to the laser beam leads to further energy absorption. During the rising phase of the laser pulse, primary and secondary electrons are created by several mechanisms, such as, multiphoton ionization (MPI),[17-19] free electrons in the air at room temperatures, and the inverse bremsstrahlung absorption or cascade ionization process, which corresponds to an ionizing collisional cascade (CC) evolution.[20,21]

For the MPI process, a neutral atom absorbs enough laser photons within a quantum lifetime of the excited state[18] [$\tau \approx h/\varepsilon_\gamma$ = 3.5 $\times 10^{-15}$ s (at 1064 nm)] to raise it from the ground state to the ionization level or above. When enough atoms are ionized, it can produce an observable flash.[18] For a cascade ionization process, a few initial electrons in the breakdown region are required, which could be created by a process such as MPI of the gas species or the presence of dust or the creation of electrons at the ambient gas temperature. These electrons then gain energy by absorbing laser energy and undergoing elastic collisions with neutral atoms. After accumulating energy slightly higher than the ionization potential of the gas, the electron may ionize an atom by inelastic collisions producing two electrons of low energy; these are then available for the process to be repeated.[21]

These two ionization mechanisms, Multiphoton ionization and Collisional Cascade ionization, differ fundamentally and are described by different theories that are necessary to understand the experiments at 1064 nm with higher laser energies otherwise stated higher photon flux in comparison with previously reported 193 nm UV laser breakdown experiments.[15] In the previous 193 nm UV laser breakdown threshold study, a 180-mJ, 20$\pm$2 ns, 10 MW UV laser beam with a photon flux of 1.75 $\times 10^{17}$ photons per pulse was focused to a 30-μm spot size to create optical breakdown.[15] In this paper, we report measurements and analysis of 1064 nm IR laser breakdown threshold experiments in which a 450-mJ, 6-ns laser beam with a photon flux of 1.3 – 2.4 $\times 10^{18}$ photons per pulse was focused to a 20-μm spot size to create optical breakdown. It was reported that the photon energy of the 193 nm laser is 6.42 eV suggesting approximately 3 photons to be absorbed with in the photon excitation life time of 6.5 × 10^{-16} seconds for ionization of air with an ionization energy of 15.6 eV further illustrating the significance of multiphoton ionization at the 193 nm UV laser radiation.[15] Similar theory is extended to the 1064 nm, in which the photon energy of the 1064 nm laser is 1.165 eV suggesting approximately 14 photons to be absorbed within the photon excitation life time of 3.5 × 10^{-15} seconds for ionization of air. It shows that, for the multiphoton ionization of air at 1064 nm it requires approximately 5 times more (5×) photons than at 193 nm, however the photon excitation life time is 6 time longer (6×) at 1064 nm than at 193 nm suggesting a potential contribution of multiphoton ionization even at 1064 nm in addition to the cascade collisional ionization process at varied pressures especially at low collision or collision less pressures. In general, the cascade theory best describes the breakdown at high pressures (>100 torr) and long laser pulse lengths (>10 ns). On the other hand, the MPI theory alone should best describe the breakdown at lower pressures, in the millitorr regime where the electrons are more collision less, and for shorter pulse lengths (<1 ns) where the cascade process cannot develop.[21]

We report measurements and analysis of air breakdown processes, in this paper, by focusing a 1064 nm 250-450-mJ, 6 ns, 42 – 75 MW high-power IR laser radiation onto a 20-μm-radius spot size ($r = f\alpha/2$, where f = 4 cm is the focal length and α = 1 mrad is our laser beam divergence) that produces laser power densities up to 3 – 6 TW/cm^2, well above the CC threshold power flux for air ionization at this wavelength that is 10^{10} W/cm^2.[22] The breakdown threshold is measured and compared utilizing classical[23] and quantum theoretical ionization models.[17,18] The measurements and analysis of the 1064 nm infrared laser induced optical breakdown results extended to photon energies (eV), multiphoton ionization threshold intensities (W/cm^2) for corresponding photon excitation lifetimes (seconds), collisional cascade laser breakdown threshold intensities (W/cm^2), breakdown electric field and effective electric field and compared with 193 nm ultraviolet laser radiation. In addition, our investigation of the breakdown threshold field intensities for air using 1064 nm laser radiation is extended to correlate the corresponding threshold field requirements by using high-power microwave radiation by means of "universal plot".[23,24] A universal scaling analysis of these results allows one to predict aspects of high-power microwave air breakdown based on measured laser breakdown observations. The high-power microwave breakdown threshold has been investigated experimentally and computationally.

The theoretical air breakdown threshold estimation for 1064 nm at 760 Torr in comparison with 193 nm are presented in Section II, the experimental and diagnostics setup are presented in Section III, experimental results are discussed in Section IV, and a summary is presented in Section V.

II. THEORETICAL AIR BREAKDOWN THRESHOLD ESTIMATION

A. Multiphoton ionization

The breakdown threshold based on the quantum MPI processes is derived by Nelson.[17,25] In MPI, a neutral atom absorbs enough laser photons within the quantum excitation lifetime to raise it from the ground state to the ionization level or above. If enough atoms are ionized, it may produce a visible flash.[21] The interaction laser intensity threshold I_0 is written in terms of flux density as

$$I_0 = h\nu c N_0, \tag{1}$$

with $N_0 = 2(2\pi)^3 \times 137 \times (1/\lambda)^3$. Therefore, the breakdown threshold laser intensity can be defined as

$$I_{B(\mathrm{MPI})} = SI_0, \tag{2}$$

where S is the MPI coefficient, which is the ratio of ionization potential, U_i, of the gas (15.6 eV for air)[23,24,26] to the photon energy, ε_γ, of the laser beam (ε_γ = 1.24/ λ (eV), where λ is the vacuum wavelength in micrometers). With ε_γ = 1.165-eV photon energy for the 1064 nm laser radiation, it requires approximately S = 14 photons to be absorbed within the quantum excitation lifetime $\tau \approx h/\varepsilon_\gamma$ = 3.5 $\times 10^{-15}$ s in order to ionize the air molecules. Thus, the breakdown laser intensity threshold value for 760-torr air at 1064 nm laser radiation is $I_{B(\mathrm{MPI})}$ = 4.42 $\times$ 10^9 W/cm^2. The corresponding rms breakdown electric field is obtained from[16]

$$E_{B(\mathrm{MPI})} = 1.94 \times 10^4 \sqrt{I_{B(\mathrm{MPI})}} \quad \text{V/cm}, \tag{3}$$

where $I_{B\,(\mathrm{MPI})}$ is expressed in MW/cm^2 and we obtain $E_{B(\mathrm{MPI})}$ = 1.3 $\times$ 10^6 V/cm.

Similarly, it was reported that the multiphoton ionization theory was applied to193 nm laser radiation in which a 6.42-eV photon energy requires S = 3 photons to be absorbed within the quantum excitation lifetime $\tau \approx h/\varepsilon_\gamma$ = 6.5 $\times 10^{-16}$ s in order to ionize the air molecules and the estimated laser intensity threshold value for 760-Torr air ay 193 nm laser radiation was reported as $I_{B(\mathrm{MPI})}$ = 8.73 $\times$ 10^{11} W/cm^2,[15] which is approximately two orders of magnitude higher compared to that of 1064 nm. The corresponding rms breakdown electric field at 193 nm was reported as $E_{B(\mathrm{MPI})}$ = 18 $\times$ 10^6 V/cm,[15] which is an order of magnitude higher compared to that of 1064 nm estimates. It is evident that, it requires lesser laser intensity at the focal volume for a 1064 nm laser compared to a 193 nm laser in order for an optical breakdown formation as the breakdown threshold intensity I_B is inversely proportional to the cube of the laser wavelength for the multiphoton ionization process.

B. Collisional cascade ionization

The theory of Collisional Cascade (CC) ionization phenomena in air was reviewed by Kroll and Watson,[18] based on the data obtained by MacDonald.[23] In the cascade ionization process, a few initial free electrons are assumed to be present in the focal region, and these electrons then gain energy by absorbing laser energy upon elastic collisions with neutral atoms. After a cascade that accumulates energy slightly higher than the ionization potential of the gas, the electron may ionize an atom by inelastic collisions producing two electrons of low energy; these are then subjected to the collisional process and are repeated. If enough atoms are ionized within the laser pulse period, breakdown is observed as a bright spark.[18] Based on this theory, the threshold power flux for breakdown is given by[18]

$$I_{B(\mathrm{CC})} = 1.44 \times 10^6 (p^2 + 2.2 \times 10^5 \lambda^{-2}) \quad \mathrm{W/cm^2}, \tag{4}$$

where p is the pressure in atmospheric pressure units and λ is the radiation wavelength in micrometers. Although this theory is primarily based on observations at microwave frequencies, and as well as pressures below atmospheric conditions, it can also be scaled to 1064 nm-wavelength laser frequencies.[24] Assuming that there are no dust particles (r $\sim$ 1−2 μm) nor significant water vapor in the air the cascade ionization theory predicts a breakdown flux intensity threshold value for 1064 nm wavelength of $I_{B(\mathrm{CC})}$ = 2.8 × 10^{11} W/cm^2 corresponding to $E_{B(\mathrm{CC})}$ = 10.3 × 10^6 V/cm.

Similarly the collisional cascade microwave breakdown theory was also extended to previously published 193 nm laser breakdown of air at 760 Torr and the estimated breakdown flux intensity threshold value was reported to be of $I_{B(\mathrm{CC})}$ = 8.5 × 10^{12} W/cm^2 corresponding to $E_{B(\mathrm{CC})}$ = 56 × 10^6 V/cm, at 760 Torr air and assuming that there are no dust particles ($r \sim 1-2$ μm) nor significant water vapor in the air.[15] These breakdown threshold estimates at 193 nm is approximately one order of magnitude higher compared to that of 1064 nm. It is evident that, it requires lesser laser intensity at the focal volume for a 1064 nm laser compared to a 193 nm laser in order an optical breakdown formation as the breakdown threshold intensity I_B is inversely proportional to the square of the laser wavelength for the collisional cascade ionization.

Based on the breakdown threshold electric field estimates, it can be inferred that for an optical breakdown of air at 760 Torr using 193 nm laser radiation the multiphoton ionization process contributes to approximately 25% of the total breakdown threshold and the reaming 75% is contributed by the collisional cascade ionization process whereas by using the 1064 nm laser radiation the multiphoton ionization process contributes to approximately 10% of the total breakdown threshold and the remaining 90% is contributed by the collisional cascade ionization process. These MPI contributions at 1064 nm can be further higher at lower pressures where collisions are low, which is of interest in this paper.

The Fig. 1. illustrates the comparison of the breakdown threshold estimates of the 1064 nm and 193 nm laser radiations based on the collisional cascade microwave breakdown theory for a wide range of pressures in a universal plot of effective electric field plotted as a function of pressure normalized by diffusion lengths. In this case, the estimated values for 193 nm is obtained with a diffusion length of 12 μm[15] and for 1064 nm the experimental diffusion length is of 8 μm. The solid line in Fig. 1. is the classical microwave breakdown theory for 2.8 GHz with a diffusion length of 0.2 cm[23] and the region of interest and study for this paper is highlighted in the graph representing the pressure regime of interest, ranging from 10 Torr to 2000 Torr (~2.5 atmospheres). It can be observed that the trend of breakdown threshold as a function of pressure for 1064 and 193 nm for dry air are similar for vacuum pressures and up to 100-125 atmospheres, and beyond which the significant differences in the trend can be observed.

III. EXPERIMENTAL SETUP

The schematic diagram of the experimental setup is shown in Fig. 2. In this experiment, a pulsed Nd:YAG laser (Spectra-Physics, Indi 40), with a 1^{st} harmonic at λ = 1064 nm, 1.165 eV per photon and a 2^{nd} harmonic at λ = 532 nm, 2.33 eV per photon is used. The laser output is a circular beam of 1-cm cross section diameter with Gaussian distributed beam intensity and 1.0 mrad beam divergence. The full-width at half maximum (FWHM) of the laser pulse is 6 ± 1 ns, with a 1-ns rise/fall time and a maximum available laser output energy of 450 mJ at 1-20 Hz rep rate. The laser outputs both 1^{st} and 2^{nd} harmonic laser beams simultaneously and in order to study the infrared laser induced plasma the 532 nm 2^{nd} harmonic crystal generator was detuned and a dichromatic mirror separates any minimal 532 nm laser output from the 1064 nm pump laser. The laser output beam energy is controlled using a variable attenuator and each laser pulse is sampled through an IR beam sampler and the laser output energy is measured using laser energy meter (Coherent, FieldMax II). In this experiment, all IR optical components are specially coated, with 98% transparency at 1064 nm. The IR beam is then reflected by a high damage threshold (20 J/cm^2) IR coated kinematic mirror (TECHSPEC) in order to obtain a top-down configuration for the IR beam to enter the plasma chamber. The 1-cm-diameter IR beam is then passed through a 1064 nm transmission coated 3-cm-diameter Zinc Selenide window. The laser beam was focused by using a high-power handling (500 MW/cm^2) objective lens mounted inside the plasma chamber. The objective lens (Thorlabs, LMH-5X-1064) has an effective focal length of 40-mm, with a 10-mm entrance aperture and a 0.13 NA. Due to its short focal length, the objective lens is mounted inside the plasma chamber using an adjustable length holder, so that the laser-induced plasma will be positioned at the cylindrical chamber air and visible through side windows for diagnostics. The space between the entrance IR window and the objective lens is maintained at the same pressure as that of the chamber pressure in order to avoid differential pressures acting on the objective lens. Great care was taken to position the objective lens together with the plasma chamber precisely in the line of sight with the IR laser beam. In addition, using the laser energy meter, it is found that the laser beam experiences a 5% loss as it passes through the coated IR optics, including the attenuator, beam sampler, mirrors and windows. The laser energy available immediately after the objective lens corresponding to a 300 ± 5 mJ laser output was measured by the Coherent FieldMax II energy meter to be 285 ± 5 mJ, corresponding to the measured incident laser energy on the focal spot, in agreement with the analytical estimate. A high-speed (<2-ns rise time) visible photodetector (Thorlabs, DET10A/M) mounted with collection optics is used to detect and observe the laser breakdown visible spark. The photodetector is connected to a high speed 2.5 GS/S oscilloscope to monitor the laser induced plasma emission. The plasma chamber was made from stainless steel and flushed several times before finally filling with dry air (< 10 ppm water) to the desired pressure ranging from 2000 Torr to 100 mTorr. Optical view ports on both sides of the cell are made of 3-cm-diameter by 5-mm-thick sapphire windows. The view ports enabled observation of the interior at right angles to the cell axis which is coincident with the direction of the laser beam, as well as for diagnosing the plasma. The chamber pressure was measured precisely by a pressure gauge with a pressure controller–readout (MKS Instruments, 910-11 and PDR 900-11). The gas flow through the chamber was regulated by a needle valve in the gas line and another valve in the pumping line. For one set of experiments on determining the effects of removing micro dust particles of diameters $\geq 0.1\ \mu$m on the breakdown threshold of dry air, we have inserted a filter capsule in the incoming gas line and cleaned residual dust on window and lens surfaces by means of an aerosol jet. The filter houses a dual-pleated polytetrafluoroethylene (PTFE) filtering element with $\leq 0.1-\mu$m pore size.

IV. EXPERIMENTAL MEASUREMENTS, RESULTS, AND DISCUSSION

In general the breakdown threshold is defined as the minimum laser energies or intensities at which 10-50% of the laser pulses resulted in a visible optical breakdown.[24] Similarly, in this experimental study, the breakdown threshold is defined as the minimum laser intensity at which the air breakdown with a visible spark is observed for 50% of the laser pulses. The occurrence of breakdown was detected by observing a visible spark at a right angle to the laser beam direction using a high-speed (<2-ns rise time) visible photodetector (Thorlabs, DET10A/M) while gradually increasing the intensity for each laser pulse. The measurements were made in dry air (< 10-ppm water) at room temperature. The primary measurement is the incoming laser energy with the corresponding intensity at the focal spot and is then calculated. In this paper, the focal length f of the objective lens used is 4.0 cm, and the diameter d of the unfocused laser beam used is 1.0 cm, with a laser beam divergence α of 1.0 mrad. Following standard optical focal theory, the minimum focal volume is assumed to be cylindrical[24] with a corresponding radius of $r_0 = f\alpha/2 =$ 20 μm and an axial length (depth of focus) of $l_0 =$ 0.414 $(\alpha/d)f^2$ = 66 μm. The characteristic diffusion length is obtained by[23,24,27]

$$\left(\frac{1}{\Lambda}\right)^2 = \left(\frac{\pi}{l_0}\right)^2 + \left(\frac{2.405}{r_0}\right)^2, \quad (5)$$

which yields a value of Λ = 8 μm. This value for plasma diffusion length is close to the $2r_0/6-(\mu$m) value used in previous longer wavelength (10.6-μm) air breakdown laser experiments.[28] Another aspect when comparing the pulsed 1064 nm laser breakdown data to the steady-state continuous wave (CW) microwave breakdown case is that, although the laser energy is pulsed (6 ns), there are many oscillations (1.7×10^6 cycles) in the electric field within a single pulse. The threshold breakdown in air using a focused laser radiation is independent of pulse length and can be treated as if in steady state if the number of cycles contained within the pulse is more than 10^6.[24] The breakdown threshold laser intensity at the focal minimum is determined by

$$I_B = \frac{1}{\pi}\left(\frac{W_B}{r_0^2\tau_p}\right), \quad (6)$$

where W_B is the minimum laser pulse energy at which the breakdown is observed, r_0 is the focal spot radius, and τ_p is the FWHM of the laser pulse. In our experiment, we have measured the breakdown threshold for air at pressures ranging from 10 to 2000 torr (~2.5 atm). Fig. 3. shows the measured breakdown threshold energies W_B (mJ) and from which the derived breakdown threshold laser intensities I_B (W/cm^2) for different pressures. The 1064 nm I_B value for dry air at 760 Torr was measured to be 2×10^{11} W/cm^2, which is close to the theoretical estimates. It is evident that at laser frequencies, higher energies are required at low collisional pressures than at higher collisional pressures. From I_B, the breakdown threshold electric field E_B is determined using $E_B = 1.94 \times 10^4 \sqrt{I_B}$ with I_B is in MW/cm^2. In Fig. 4., the solid squares show the measured breakdown electric field in air for various pressures. The E_B value for dry air at 760 torr was measured to be 8.8 × 10^6 V/cm, which is close to the theoretical estimates, and it is observed that E_B decreases for pressures ranging from 10 torr to 2.5 atm, which is expected in our regime where the laser frequency ω is much higher than the electron collision frequency $\upsilon_c (\omega \gg \upsilon_c)$. It indicates that for such high-frequency wave fields, there are many oscillations of the electric field per collision. It is therefore convenient to make use of the concept of effective electric field for energy transfer. The effective electric field appears in the form[23,24]

$$E_{\text{eff}} = E_B \left(\frac{\upsilon_c^2}{\upsilon_c^2 + \omega^2} \right)^{1/2}. \tag{7}$$

The effective electric field represents the effectiveness of the electric field in coupling its energy to the electron with the field multiplied by the factor $(\upsilon_c^2/(\upsilon_c^2 + \omega^2))^{1/2}$. For our experimental conditions, $\omega/\upsilon_c \gg 1$, and thus

$$E_{\text{eff}} \approx E_B \left(\frac{\upsilon_c}{\omega} \right). \tag{8}$$

The electron collision frequency is determined by $\upsilon_c = \beta \times 10^9 p$, where p is in torr.[23,24,26] The parameter β depends on the gas used, with a value of 5.33 for air data. The effective electric field E_{eff} is shown in Fig. 4. (solid circles) as a function of pressures ranging from 10 torr to 2.5 atm, and it is observed to increase within the pressure range, which means that the effectiveness of energy coupling through electron collisions is higher above atmospheric pressures when compared to partial vacuum conditions.

It has been observed by Stricker[24] that, at 1.064-μm laser wavelengths, for gas pressures above few hundred Torr and for pulse lengths in the 10^{-9}–s range, gas breakdown is best described by the cascade ionization processes.[21] However, at lower pressures the 1064 nm laser wavelength laser radiation can also play a role through multiphoton ionization. Using the concept of effective electric field, the comparison of 1.06-μm laser-induced breakdown data for air with scaled calculations based on the CC theory was done effectively when compared with microwave data and shows good agreement.[24] The laser-induced breakdown data are effectively compared with the microwave data using a universal plot that has $E_{\text{eff}}\Lambda$ as the ordinate plotted as a function of $p\Lambda$. The 2-D universal plot represents all four laser breakdown parameters including pressure, frequency, diffusion length, and electric field.

The experimental values of $E_{\text{eff}}\Lambda$ obtained from our measured dry-air breakdown data without any gas filters are compared with typical microwave CW data for air is shown in Fig. 5. The solid curve shows the typical microwave CW data at 2.8 GHz with 0.2 cm diffusion length and the dashed curve shows the classical cascade breakdown theory [equation (4)] extended to 1064 nm laser radiation wavelength. According to this theoretical result, the breakdown threshold for air at 1064 nm-wavelength radiation converges with the microwave breakdown data at above atmospheric pressures and deviates significantly for very low pressures. However, for low pressures, the medium becomes less collisional, and the MPI process will dominate over the collisional breakdown process, although the MPI process is a weak function of pressure $p^{-1/3}$.[27] In Fig. 5, the triangles show the measured breakdown data for air from 10 torr to 2 atm. In order to compare it with the collisional microwave breakdown, the 1064 nm laser-induced breakdown data, where MPI processes play a role at lower pressures, a correction for the MPI process as a function of pressure is necessary. From the measured breakdown data, the portion of MPI effects as a function of pressure $p^{-1/3}$ is eliminated by correcting with a multiplicative factor $E_B \times [(E_{B(CC)}(p) + E_{B(MPI)}(p))/E_{B(CC)}(p)]$, where the terms are given by Eqs. (3) and (4) as a function of pressure, and the results are shown by circles in Fig. 5. The corrected CC data shift to a much higher value at lower pressures where the MPI process is significant compared to that in higher pressures where collisional processes dominate. This means that a higher electric field is required in order to obtain breakdown at lower pressures without the influence of MPI processes. The breakdown threshold values were then multiplied by a scaling factor of 2.1 in order to scale with the microwave breakdown plot to examine the overall trend of the data as pressure is varied. The scaled data are shown by squares in Fig. 5. Similar scaling values were used in 1.06-μm laser breakdown experiment at above atmospheric pressures (1 – 50 atm) in order to compare the scaled results with microwave breakdown data. In which the multiphoton ionization process was ignored due to the high collisional pressures and dominating collisional cascade ionization process. In our case sub-atmospheric pressures are studied and the 2.1 scaling factor can also be due to the fact that larger spatial wavelength averages of the microwave breakdown data are on the order of several centimeters, whereas the localized laser focus diameter is 20 μm. Another possibility for the factor is the presence of microscopic dust particles on the order of several micrometers in size, which has been shown to reduce breakdown for shorter laser wavelengths but does not influence the longer wavelength microwave breakdown.[28] In order to investigate the effect of dust on the breakdown threshold, consequently, on the scaling factor, we have carried out a set of similar breakdown threshold measurements with a 0.1-μm dual-pleated PTFE filter inserted in the incoming gas pipeline. In laboratory air, the average size of dust particles is about 1–2-μm diameter,[28] and therefore, filtering dust particles of 0.1 μm or larger diameter will rid our system of them if present. The result of the breakdown threshold measurements as a function of pressure range from 10 torr to 2.5 atm is shown in Fig. 6. With the filter present, the minimum pressure at which the breakdown was observed is 15 torr, whereas without the filter, the minimum breakdown pressure is 10 torr. As expected, the breakdown threshold for dry air as a function of pressure increases somewhat at lower pressures with the 0.1-μm filter. After correcting for the MPI process from the measured breakdown threshold values (triangles) that are then given by circles, we then multiply the result by a scaling factor of 1.74 in order to fit the measured data with the microwave breakdown curve, as shown in solid squares. It is evident that the presence of dust particles does play a role in the breakdown threshold values at lower pressures, as observed in our case. The scaling factor can also be attributed to the wide differences in frequencies between the microwave and laser frequencies. The resulting IR laser pressure scaling agrees well with the average microwave curve. In our experiment, the overall pressure variation of the scaled data is in good agreement with the classical microwave breakdown results. It should also be noted that the microwave cascade curve is an average and subject to a range variation about the plotted values. The important aspect is that the pressure scaling of laser and microwave cases is similar over a wide range of pressures, as well as at lower pressures where a correction of the MPI process is necessary.

The measured 1064 nm optical breakdown threshold electric fields and corresponding effective electric fields for pressures range from 10 Torr to 2.5 atm is compared with the 193 nm laser breakdown measurements in Fig. 7. It can observed that the breakdown electric field required for air breakdown in the pressure regime of interest at 1064 nm is approximately an order of magnitude less than that of at 193 nm. The effective electric fields for both laser wavelengths appear very close suggesting that for the same amount of effective coupling of the laser energy on to medium (gas) it requires less amount of laser intensity when an infrared 1064 nm laser radiation is used compare to an ultraviolet 193 nm laser radiation.

V. SUMMARY

The theoretical estimates of the 1064 nm air breakdown threshold laser intensities and breakdown electric fields are obtained using multiphoton ionization and collisional cascade ionization theories at 760 Torr and at other pressures and compared with breakdown threshold estimates for 193 nm laser radiation. Based on the multiphoton ionization theory the estimated breakdown threshold for 1064 nm laser intensity at 760 Torr is $I_{B(\mathrm{MPI})}$ = 4.42 × 10^9 W/cm^2 and the estimated breakdown threshold electric field is $E_{B(\mathrm{MPI})}$ = 1.3 × 10^6 V/cm. Based on the estimates it is observed that the breakdown threshold estimates for 1064 nm is one or two orders of magnitude lower in comparison with breakdown threshold estimates for 193 nm. This observation of low breakdown threshold at 1064 nm is explained through several aspects, including the longer photon excitation lifetimes to absorb the required number of photons, inverse proportional relationship between the breakdown threshold intensities and electric fields with laser wavelength powers. It is estimated that, for the 1064 nm laser breakdown at 760 Torr, multiphoton ionization process contributes to ~10% and collisional cascade ionization process contributes to the remaining ~90% of the total ionization mechanism.

The theoretical breakdown threshold estimates are validated by 1064 nm experimental laser breakdown threshold measurements. A 250-450-mJ, 6 ns, 42 – 75 MW high-power 1064 nm Nd:YAG laser with 1 cm beam diameter and 1.0 mrad beam divergence is focused onto a 20-μm-radius spot size in dry-air using an objective lens for pressures ranging from 10 torr to 2.5 atm, where multi-photon and CC processes are significant, have been carried out. The breakdown threshold laser energies for various pressures are measured and from which the corresponding laser breakdown threshold intensities, breakdown electric fields and effective electric fields are obtained. The measured breakdown threshold field intensities are scaled to the classical microwave theory by correcting for MPI processes at various pressures. The MPI processes were observed to be dominant at pressures below 100 torr where the plasma is less collisional, whereas the cascade ionization process dominates for pressures above 100 torr up to 2.5 atm. Based on the breakdown measurements and comparing with the classical and quantum theories, 88% of the total ionization mechanism is carried out by the cascade ionization process, and 12% of the ionization process is carried out by the MPI process at p = 760 torr. The MPI-corrected measured breakdown threshold data were scaled and fitted the CC microwave breakdown measurement pressure variation well. A scaling factor of 2.1 is used to scale the 1064 nm breakdown threshold data after correcting multiphoton ionization process on to the classical microwave breakdown theory. The effect of the presence of sub-micron particles on the breakdown threshold was carried out with 0.1-μm filtered air and the measurements show that slightly higher breakdown field is required especially at lower pressures and in close agreement with microwave measurements when scaled with a scaling factor of 1.74, indicating that small sub-micron dust particles can reduce breakdown threshold at laser wavelengths.

ACKNOWLEDGEMENTS

This work was partially supported by the College of Science and Engineering at the Texas A&M University-Corpus Christi, Texas Research and Development Fund (TRDF) and the Department of Defense (DOD)/Army grant (W81XWH-10-1-0923) administered by the U.S. Army Medical Research & Materiel Command (USAMRMC) and the Telemedicine & Advanced Technology Research Center (TATRC), at Fort Detrick, MD. The authors would like to thank Uma Magesh and Kenneth Williamson for assistance.

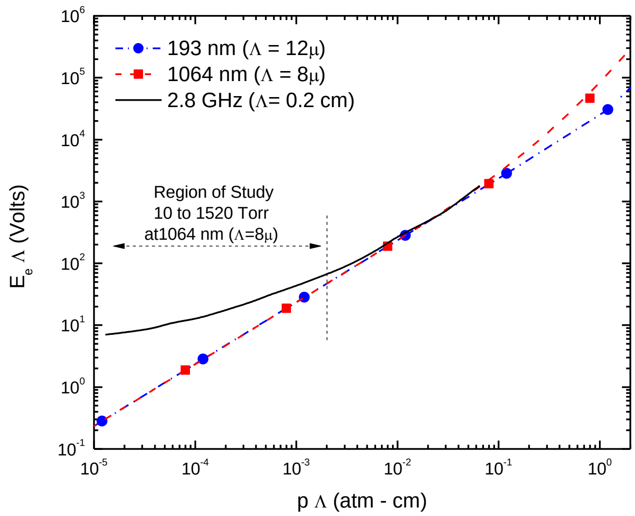

FIG. 1. Universal plot of microwave breakdown theory at 2.8 GHz with Λ = 0.2 cm (solid line) extended to laser breakdown at λ = 1064 nm with Λ = 8 microns (square, dash) and λ = 193 nm with Λ = 12 microns (circles, dash-dot-dash).

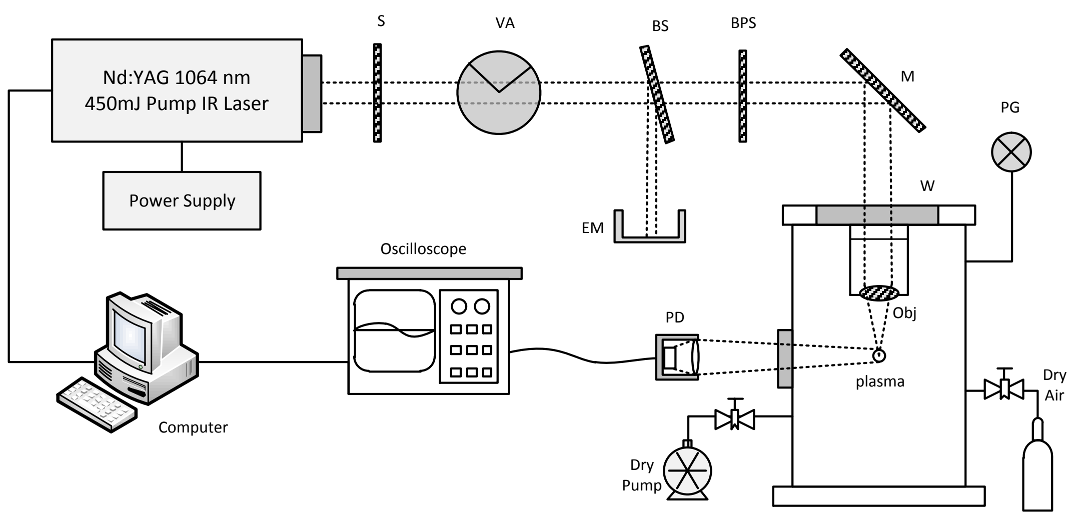

FIG. 2. Schematic of the experimental and diagnostic setup of 1064 nm laser-induced air plasma. S – Shutter. VA – Variable Attenuator. BS – Beam Sampler. EM – Energy Meter. BPS – Beam Profile Sampler. M – Mirror. W – Window. PG – Pressure Gauge. Obj – Objective Lens. PD – Photo Detector.

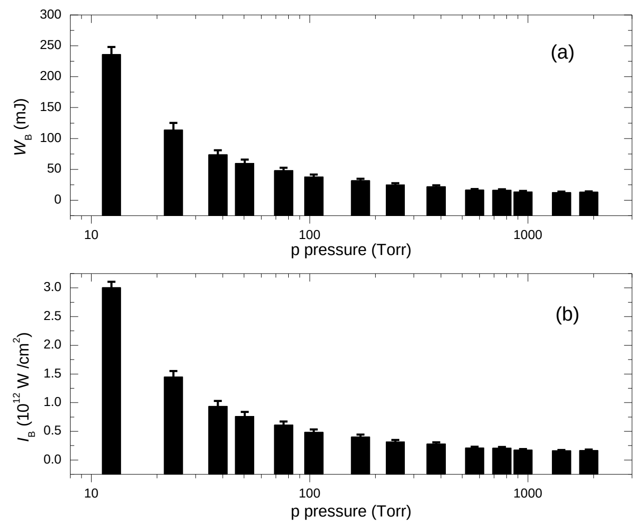

FIG. 3. Breakdown threshold measurement results. (a). Measured 1064 nm air breakdown threshold laser energies as a function of pressure. (b). Breakdown threshold 1064 nm laser power intensities at the focal volume derived from breakdown threshold laser energy as a function of pressure.

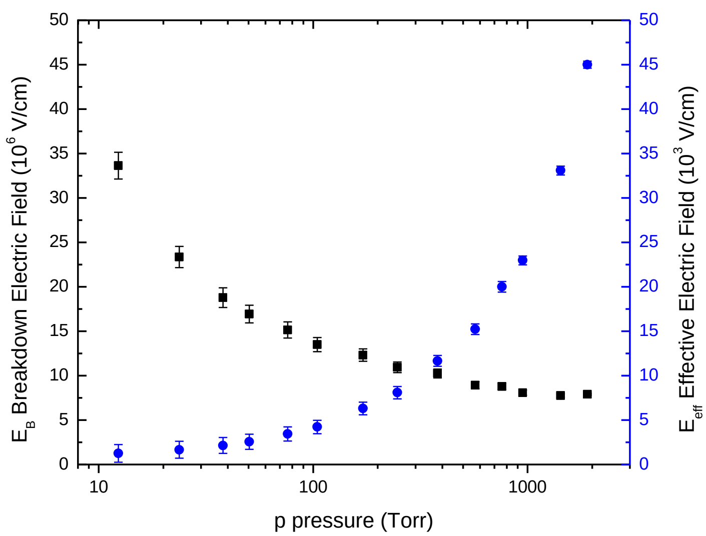

FIG. 4. Measured breakdown threshold electric field E_B and effective electric field E_{eff} plotted as a function of pressure p in Torr.

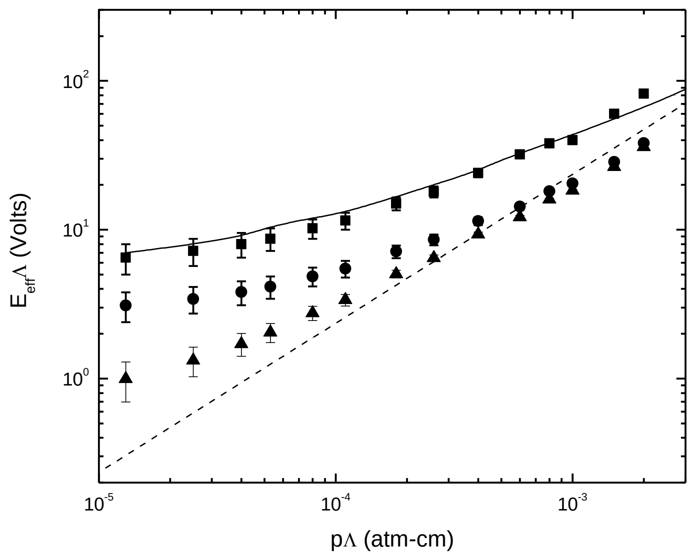

FIG. 5. Universal plot of (triangles) experimental 1064-nm laser breakdown threshold fields in dry air (without gas filter) compared with (solid line) microwave theory. (Dotted line) Microwave theory extended to λ = 1064 nm. (Circles) MPI-corrected breakdown threshold data. (Squares) Data in circles scaled by a factor of 2.1.

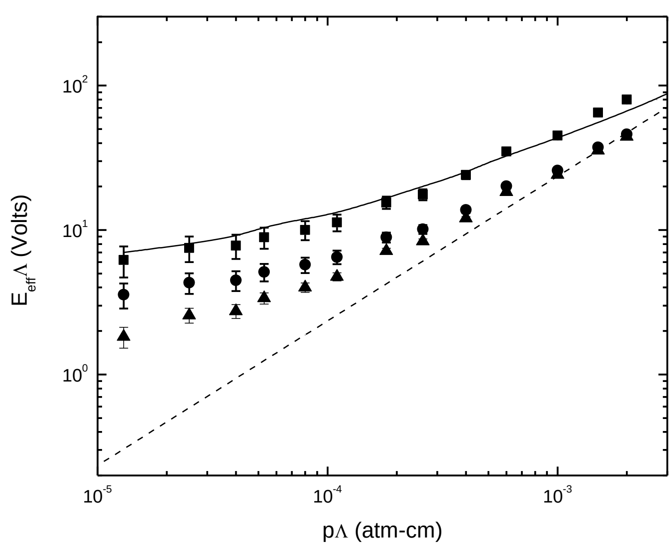

FIG. 6. Universal plot of (triangles) experimental 1064-nm laser breakdown threshold fields in dry air (with 0.1-μm filter) compared with (solid line) microwave theory. (Dotted line) Microwave theory extended to λ = 1064 nm. (Circles) MPI-corrected breakdown threshold data. (Squares) Data in circles scaled by a factor of 1.74.

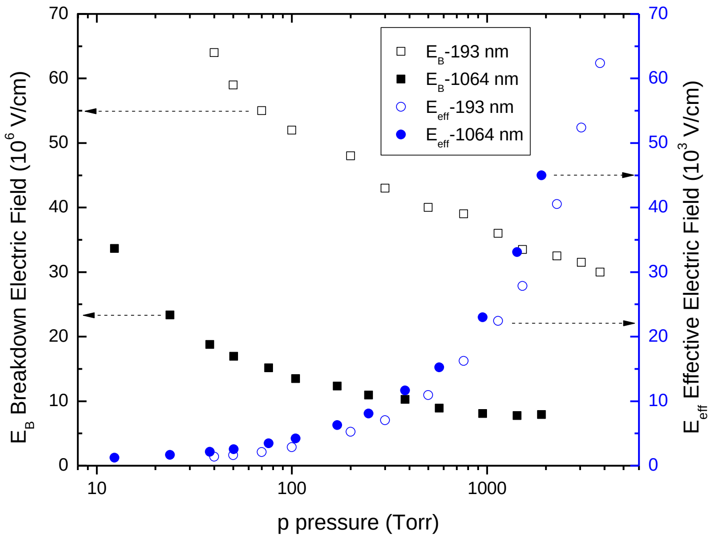

FIG. 7. Measured 1064 nm laser air breakdown threshold electric fields (solid squares) and effective electric fields (solid circles) in comparison with measures 193 nm laser air breakdown threshold electric fields (line squares) and effective electric fields (line circles).

CONCLUSION

The PI and the research team have completed majority of the proposed tasks on or before the deadline and the tasks that are in progress will be completed in the upcoming weeks. The Project also made significant progress on the tasks under objective 2 well ahead of the milestone deadline and will be expected to complete in the upcoming project year. The research outcomes are demonstrated. The research team has been taking initiatives for the future research work on animal testing and is aiming to request additional funding from funding agencies.

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APPENDIX

Dr. Magesh Thiyagarajan

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Education

PhD, University of Wisconsin - Madison, 2008.

MS, University of Tennessee - Knoxville, 2004.

BS, University of Madras - India, 2001.

Diploma in Computer Applications, TATA Infotech, India, 2000.

Licensures and Certifications

Disbursement of Funds, TAMUCC. (2010 - Present).
Biological Defense Safety Program and Technical Safety, TAMUCC. (2010 - Present).
CITI Collaborative Institutional Training Initiative - Responsible Conduct of Research, CITI. (2010 - Present).
TRIZ (Innovative way for new ideas). (2009 - Present).
Six-Sigma Green Belt Certification, General Electric Compmany (GE). (2008 - Present).
Intellectual Property for Technologists, General Electric Company (GE). (2008 - Present).
Hiring the Right People, General Electric Company (GE). (2008 - Present).
Entrepreneurial Business Program Certification, School of Business, University of Wisconsin-Madison. (2007 - Present).

Professional Employment

Assistant Professor of Engineering - Director of Plasma Engineering Research, Texas A&M University - Corpus Christi. (July 2009 - Present).
Direct the Plasma Engineering and Science Research Projects
Mentor interdisciplinary students to carry out research
Lead the research on portable plasma based biomedical device for combat care application
Lead the research on Bacterial deactivation mechanisms through cold plasma
Lead the research on treatment of cancer cells through cold plasma

Lead Engineer, General Electric Company (GE). (March 2008 - June 2009).
Key Lead on Plasma Medicine and Plasma Sterilization of Medical Devices.
Task leader and key contributor for large scale waste gasification project.
Extensive engineering, R&D and process control in optical data storage project.
EIT – Electrical Impedance Tomography for brain and lung strokes.
Technology, market research, fetched government proposals for a total of

Research Fellow, University of Wisconsin – Madison, WI. (June 2004 - February 2008).
Laser and RF Plasmas for Industrial and Military Applications
The principal focus of my research is to design, implement, diagnose and characterize the laser induced plasmas for advanced industrial and military application.
Proposed and written a research proposal and received a competitive grant
Designed and built experimental setups to characterize high power 10 MW UV laser focused plasma in the presence of dielectric window materials for micro machining.

Collaborated with MIT and Texas Tech University research groups for optimized results.
Supervised and guided undergraduate and graduate research assistants.

Teaching Assistant, University of Wisconsin – Madison, WI. (August 2004 - June 2006).
Taught Electric Circuits Laboratory Course – for four semesters with class strength of 30.
Organized tutorials to clarify course material. Wrote instruction manual to help students use software and hardware in a better way. Class scored 7% higher in final than any of the professor's former classes.
Exceptional student feedback for all four semesters.
Received the Honorable mention for exceptional teaching performance during 2004 – 05.
Received the Best Teaching Assistant Award for the 2005 – 06 academic year.

Scientific Consultant, ASI Technology Corporation. (June 2003 - June 2004).
Designed and developed a novel plasma Stealth antenna prototype for military applications.

Scientific Consultant, Michael Grace Grant. (August 2002 - June 2004).
Developed a 25 kV High-Voltage experimental plasma ball lightning system

Research Assistant, University of Tennessee – Knoxville, TN. (August 2002 - May 2004).
Developed an effective biological plasma decontamination system- Patent Pending.
Presented research results to funding sources and fetched for further research.
Designed a commercial model of the plasma decontamination unit.

Project Coordinator, Engineering Enterprises. (August 2001 - June 2002).
Designed Analog and Digital IC circuit design using TTL and LSI chips.
Team Leader: Designed and implemented a Transistor Curve Tracer project.

Intern, General Electric Company – Alstom. (2001).

Professional Memberships

Louis Stokes Alliances for Minority Participation
McNair Scholars Program
American Society of Mechanical Engineers
Sigma Xi
Toastmasters International Club
MIT Entrepreneur Club
Eta Kappa Nu
Tau Beta Pi
Institute of Electrical and Electronics Engineers
Nuclear and Plasma Sciences Society

TEACHING

Teaching Experience

ENGR 2322, MATERIALS SCIENCE
ENTC 3410, MATERIAL SCIENCE
ENTC 4496, DIS: Design and Fabrication of Conveyor System with Variable Speeds

Non-Credit Instruction

Plasmas in the Engineering & Science Field, Presented to the Introduction to Engineering Class - Fall 2010. (October 2010).

Plasmas in the Engineering & Science Field. (October 2009).
Introduction to Plasma Science and Engineering, Freshman Seminar Series. (October 2009).

Teaching Awards and Honors

NSF Travel Award for ASEE Integrating Sustainability in Engineering Courses workshop, NSF. (2010).
Best Teaching Assistant Award, Dept. of Electrical Engineering, Univ. of Wisconsin Madison. (2005).
University of Madras Gold Medalist, University of Madras. (2001).

SCHOLARLY AND CREATIVE ACTIVITIES

Publications

Refereed

Conference Proceedings

Anderson, H., Thiyagarajan, M., waldbeser, l., Gonzalez, X., Norfolk, M., Whitmill, A. (2011). Apoptotic Behavior in THP-1 Acute Monocytic Leukemia Cancer Cells Induced by Nonthermal Plasma. College Station, TX: 9th Annual Pathways Research Conference.

Ausland, J., Thiyagarajan, M., Vidal, G. (2011). Deactivation of Escherichia coli using a Novel Cold Plasma Technology and its effect on the bacterial growth. College Station, TX: 9th Annual Pathways Research Conference.

Yang, B., Thiyagarajan, M. (2011). Electrical Conductivity Characterization of Novel TAMUCC Stoneware Ceramic at Various Experimental Conditions. College Station, TX: 9th Annual Pathways Research Conference.

Norfolk, M., Thiyagarajan, M., waldbeser, l., Gonzalez, X., Anderson, H., Whitmill, A. (2011). Nonthermal Ionized Plasma Induction of Pre-programmed Cell Death in Acute Monocytic Leukemia Cancer Cells. College Station, TX: 9th Annual Pathways Research Conference.

Kandi, A., Thiyagarajan, M., Williamson, K. (2011). Optical Characterization and Diagnostics of High Power 1064 nm Infrared Laser System. College Station, TX: 9th Annual Pathways Research Conference.

Pham, H., Thiyagarajan, M., Vidal, G., Buck, G., Mott, J. (2011). Sterilization of Staphylococcus aureus Microorganism using a Novel Cold Plasma Technology. College Station, TX: 9th Annual Pathways Research Conference.

Rodriguez, F., Thiyagarajan, M., Yang, B., Williamson, K. (2011). Surface Energy Modification using Atmospheric Pressure Cold Plasma System. College Station, TX: 9th Annual Pathways Research Conference.

Valdez, E., Thiyagarajan, M. (2011). Surface Modification using Diffused Atmospheric Pressure Cold Plasma System. College Station, TX: 9th Annual Pathways Research Conference.

Norfolk, M., Thiyagarajan, M., waldbeser, l., whitmill, A. (2011). Apoptosis and Autophagy in Cancer Cells Induced from Non-Thermal Ionized Plasma. San Jose, California: SACNAS National Conference.

Valdez, E., Thiyagarajan, M. (2011). Characterization of Diffused Atmospheric Pressure Cold Plasma System for Surface Modification. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium (Best Paper Award).

Vidal, G., Thiyagarajan, M., Pam, H. (2011). Cold Plasma Inactivation of E. coli and S. aureus on Solid Surfaces for Infection Treatment. San Jose, California: SACNAS National Conference.

Ausland, J., Thiyagarajan, M., Vidal, G. (2011). Deactivation of Escherichia coli using a Novel Cold Plasma Technology and its effect on the bacterial growth. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium.

Yang, B., Thiyagarajan, M. (2011). Electrical Conductivity Characterization of Novel TAMUCC Stoneware Ceramic at Various Experimental Conditions. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium.

Hes, J., Thiyagarajan, M., Branecky, C., Ramon, R. (2011). Electrical Conductivity Measurements and Analysis of Ceramic Materials at Various Moisture Conditions. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium.

Anderson, H., Thiyagarajan, M., Vidal, G., Pam, H. (2011). Non-Thermal Plasma Decontamination of E. Coli and S. Aureus – Research and Review. San Jose, California: SACNAS National Conference.

Ramon, R., Thiyagarajan, M. (2011). Portable Plasma Disinfection Conveyor System. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium.

Norfolk, M., Thiyagarajan, M. (2011). Pre-programmed Cell Death in Acute Monocytic Leukemia Cancer Cells Induced by Nonthermal Ionized Plasma. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium (Best Paper Award).

Valdez, E., Thiyagarajan, M. (2011). Reactive Gas Species Characterization of Diffused Atmospheric Pressure Cold Plasma System. San Jose, California: SACNAS National Conference.

Pam, H., Thiyagarajan, M., Vidal, G., Alison, D., Mott, J., Buck, G. (2011). Sterilization of Escherichia coli and Staphylococcus aureus Microorganism using a Novel Cold Plasma Technology. San Jose, California: SACNAS National Conference.

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Rodriguez, F., Thiyagarajan, M., Yang, B., Williamson, K. (2011). Surface Energy Modification using Atmospheric Pressure Cold Plasma System. Corpus Christi, TX: Sigma Xi 11th Annual Undergraduate Research Symposium.

Thiyagarajan, M. (2011). Materials Engineering Course Design and Improvement for Effective Research Based Learning Environment. Corpus Christi, TX: TAMUCC 1st Faculty Symposium: Course Design for the Millennial Student.

Thiyagarajan, M. (2011). Portable Plasma Biomedical Device for Cancer Treatment. Irvine, California: ASME Emerging Technologies - 6th Frontiers in Biomedical Devices Conference.

Thiyagarajan, M. (2011). Portable Plasma Medical Device for Infection Treatment and Wound Healing. Irvine, California: ASME Emerging Technologies - 6th Frontiers in Biomedical Devices Conference.

Thiyagarajan, M. (2011). Effects of Cold Plasma and Treatment of Leukemia Cancer Cells. Marseille, France: International Conference on Medical Physics and Biomedical Engineering.

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Thiyagarajan, M. (2011). Experimental Study of Shock Wave Discontinuities and Interactions with Laser Induced Plasmas. Chicago, IL: 38th IEEE International Conference on Plasma Science (ICOPS) and 24th Symposium on Fusion Engineering (SOFE).

Thiyagarajan, M. (2011). High Power Pulsed Laser Induced Breakdown Plasma at Gas-Solid Interface. Chicago, IL: 18th IEEE International Pulsed Power Conference.

Thiyagarajan, M. (2011). Plasma Treatment on E. Coli, S. Aureus, N. Meningitides for Food Industries. Paris, France: International Conference on Food Engineering and Biotechnology.

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Whitmill, A., Thiyagarajan, M., waldbeser, l. (2011). Effects of Non-Thermal Ionized Plasma on THP-1 Acute Monocytic Leukemia Cells. Ithaca, NY: National Conference on Undergraduate Research (NCUR).

Whitmill, A., Thiyagarajan, M., waldbeser, l. (2011). Induction of Apoptosis in Leukemia Cells by Non-thermal Ionized Plasma. Prairie View, TX: 7th Annual LSAMP Conference (Best Paper Award).

Valdez, E., Thiyagarajan, M. (2011). Reactive Gas Species Characterization of Diffused Atmospheric Pressure Cold Plasma System. Prairie View, TX: 7th Annual LSAMP Conference.

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Walling, T., Thiyagarajan, M. (2010). Nitrogen Oxides and Light Wavelengths Produced by a Portable Plasma Device. (pp. 56). Canyon, TX: 8th Annual Pathways Research Symposium.

Thiyagarajan, M., Whitmill, A., waldbeser, l. (2010). Effects of Non-Thermal Ionized Plasma on Human Leukemia and Lymphoma Cells. (vol. 7, pp. 82). Anaheim, CA: 2010 SACNAS National Conference.

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Luo, S., Thiyagarajan, M., Scharer, J. (2006). Diagnostics and Simulation of High pressure Argon and Nitrogen Plasma. Traverse City, Michigan: 33rd International Conference on Plasma Science, IEEE Proceedings of Plasma Science.

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Scharer, J., Thiyagarajan, M., Luo, S. (2005). Efficient Creation of Laser Initiated, RF Sustained Atmospheric Pressure Range Plasmas. Monterey, California: 32nd International Conference on Plasma Science, IEEE Proceedings of Plasma Science.

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Thiyagarajan, M. (2005). Plasma Decontamination & Sterilization of Biological Agents. Tulsa, Oklahoma: SHPE National Conference.

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Thiyagarajan, M., Alexeff, I. (2004). Ambient Pressure Resistive Barrier Cold Plasma Discharge for Biological and Environmental Applications. Baltimore, Maryland: 31st International Conference on Plasma Science, IEEE Proceedings of Plasma Science.

Alexeff, I., Thiyagarajan, M. (2004). An Experimental Model of Ball Lightning. Baltimore, Maryland: 31st International Conference on Plasma Science, IEEE Proceedings of Plasma Science.

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Thiyagarajan, M., Alexeff, I., Paremswaran, S. (2003). Characteristics of the Steady-State Atmospheric Pressure DC Discharge. Seol, South Korea: 30th International Conference on Plasma Science, IEEE Proceedings of Plasma Science.

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Thiyagarajan, M., Alexeff, I., Parameswaran, S., Beebe, S. (2005). Atmospheric Pressure Resistive Barrier Cold Plasma for Biological Decontamination. (21st ed., vol. 33). IEEE Transactions on Plasma Science.

Alexeff, I., Parameswaran, S., Thiyagarajan, M., Grace, M. (2004). An experimental study of ball lightning. (3rd ed., vol. 32). IEEE Transactions on Plasma Science.

Non-Refereed

Periodicals

Thiyagarajan, M., Walling, T., Chirinos, F., Chatham, G., Pekshev, A. (2010). Local firm eyes mass production - Technology speeds the healing process, can sterilize surfaces. Corpus Christi, TX: Caller Times. www.caller.com/news/2010/feb/22/plasma/

Research Reports

Thiyagarajan, M. (2010). Plasma Engineering and Science Research - TAMUCC. Engineering Research in Texas.

Thiyagarajan, M. (2010). Experimental Investigation of Air Plasma & Nitrogen Oxide Characteristics of Plasma. (vol. 2010). Texas: Texas Higher Education Coordinating Board.

Thiyagarajan, M., Walling, T., Elias, C. (2010). Report on Experimental Measurements of Spatially Resolved NOX Concentration from Plason Plasma Device. Plasma Technologies.

Presentations

Thiyagarajan, M. (Author & Presenter), Salazar, A. (Author), Gloria, J. (Author), Ramon, R. (Author), "Plasma Assisted Automatic Food Processing Unit," Coastal Bend Business Plan Competition, Coastal Bend Business Innovation Center, Corpus Christi. (December 2010).

Thiyagarajan, M. (Author & Presenter), "Sustainable Energy Research Program on Liquid Fuel Production through Innovative Plasma Processing of Low Ranking Coal," TAMUS - 2012 Federal Initiative Proposals, TAMUS, TAMUCC. (October 25, 2010).

Thiyagarajan, M. (Panelist), Pezold, F. L. (Panelist), Lyle, S. D. (Panelist), Lyle, C., Martin, G., Murphy, O., "SBIR/STTR Panel Discussion," SBIR/STTR Workshop, Coastal Bend Business Innovation Center, Texas A&M University Corpus Christi. (September 24, 2010).

Thiyagarajan, M., "Plasma Research at PERL TAMUCC," Office of Strategic Research Development Team visits the PERL lab, PERL, TAMUCC. (November 24, 2009).

Thiyagarajan, M., "Plasma Research at PERL, TAMUCC," TAMUS Chancellor Dr. Mike Mckinney visits PERL Plasma Lab, PERL - TAMUCC. (November 5, 2009).

Thiyagarajan, M., "Plasma Research Overview at PERL," Lieutenant Governor David Dewhurst visits Plasma Lab, TAMUCC, PERL ST 221, TAMUCC. (October 20, 2009).

Thiyagarajan, M., "FI2011 - Plasma Research Proposal," TAMUS Feeral Initiative Team visits PERL Plasma Lab, TAMUCC, PERL, TAMUCC. (October 12, 2009).

Thiyagarajan, M., "Plasma Research at PERL TAMUCC," Drexel University - Technology Team visits Plasma PERL lab, PTI - TAMUCC, PERL TAMUCC. (September 24, 2009).

Contracts, Grants and Sponsored Research

Grant

Thiyagarajan, Magesh (Principal), "Fundamental Research on Electrochemical Effects of Using Non-thermal Non-equilibrium Microwave Plasmas on Low-rank Coal Particles," Sponsored by NSF-DOE, Federal

Thiyagarajan, Magesh (Principal), "Plasma Assisted Microbial Decontamination for Food Product Processing Industries," Sponsored by Research Enhancement Grant, TAMUCC, Texas A&M University-Corpus Christi

Thiyagarajan, Magesh (Principal), "Plasma Engineering Research," Sponsored by TAMUS - 2011 Federal Initiative, Federal

Thiyagarajan, Magesh (Co-Principal), Chattam, Gary (Principal), "Universal Atmospheric Contaminant Scrubber for Submersibles," Sponsored by NAVY - Small Business Innovative Research (SBIR), Federal

Thiyagarajan, Magesh (Principal), "Lightweight Portable Plasma Medical Device," Sponsored by DOD - USAMRAA, Federal. (September 2010 - September 2013).

Thiyagarajan, Magesh (Principal), "Cold Plasma & NOx Induced Apoptosis Research on Various Human Cell Structures Aimed for Skin Cancer Treatment," Sponsored by Texas Research Development Fund (TRDF), State. (September 2010 - September 2012).

Thiyagarajan, Magesh (Principal), "Experimental Investigation of Air Plasma & Nitrogen Oxide (NO) Characteristics of Plasma Medical Manipulator Using Gas Chromatography and Optical Emission Spectroscopy," Sponsored by Texas Research Development Fund (TRDF), State, (December 2009 - September 2011).

Thiyagarajan, Magesh (Co-Principal), Waldbeser, Lillian S (Principal), "The Effect of Non-thermal Plasma on Human Leukemia and Lymphoma Cells," Sponsored by University Research Enhancement Grant, Texas A&M University-Corpus Christi (September 2010 - August 2011).

Thiyagarajan, Magesh (Principal), Chen, Lea-Der (Co-Principal), Tintera, George Dunkin (Co-Principal), Balasubramanya, Mirley (Co-Principal), "Collaborative Research: Improving Student Reflection and Metacognitive Thinking: A Texas Collaborative for Faculty Development (IMRT)," Sponsored by NSF - TUES, Federal (December 2010).

Thiyagarajan, Magesh (Principal), "Sustainable Energy Research Program on Liquid Fuel Production through Innovative Plasma Processing of Low-Ranking Coal," Sponsored by TAMUS - 2012 Federal Initiative, Federal (October 2010 - December 2010).

Thiyagarajan, Magesh (Co-Principal), Um, Dugan (Principal), Karayaka, Hayrettin (Co-Principal), Simionescu, Petru-Aurelian (Co-Principal), "CNS - CISE - Research Experiences for Undergraduates Sites (Computer Sci. & Engg)," Sponsored by NSF - REU, Federal, (September 2010 - December 2010).

Thiyagarajan, Magesh (Principal), Tintera, George Dunkin (Co-Principal), Fernandez, John D (Co-Principal), Balasubramanya, Mirley (Co-Principal), "Collaborative Research: Improving Student Reflection and Metacognitive Thinking: A Texas Collaborative for Faculty Development," Sponsored by NSF – CCLI Phase 2, Federal (February 2010 - December 2010).

Thiyagarajan, Magesh (Principal), "Atmospheric Pressure Cold Plasma Source for Teaching - Instructional and Research Applications related to Material Science," Sponsored by Higher Education Fund (HEF), State (January 2010 - July 2010).

Thiyagarajan, Magesh (Principal), "Pre-proposal - Lightweight Portable Plasma Medical Device," Sponsored by DOD (USAMRMC), Federal (2009).

Sponsored Research

Thiyagarajan, Magesh (Principal), "High Voltage Direct Current Large Volume Cold Plasma Source System – Plasma Engineering Research Lab," Texas A&M University-Corpus Christi, (August 2009 - September 2009).

Scholarly and Creative Awards and Honors

Outstanding Islander - Texas A&M University Corpus Christi, TAMUCC. (2011).
Best Research Paper Award - "Effects of Plasma Treatment on E. Coli, S. Aureus, N. Meningitidis and Other Clinical Isolates", National SACNAS Conference 2010. (2010).
Coastlines - TAMUCC Monthly Newsletter - Features Plasma Lab Research and Scholarly Activity, Texas A&M University Corpus Christi. (2010).
Campus News - TAMUCC - "Dr. Magesh Thiyagarajan Receives Department of Defense Research Grant for Plasma-Biomedical Engineering Research", Texas A&M University Corpus Christi. (2010).
Texas A&M University Corpus Christi - Facebook Page - Features DOD Research Grant Award for Plasma - Biomedical Engineering Research, TAMUCC. (2010).
The Islander Magazine - Spring 2010 - Dr. Magesh Thiyagarajan and the Plasma Engineering Research Lab is featured in the cover story - Page 14, Texas A&M University Corpus Christi. (2010).
Caller Times - News Paper Features a Cover Story on Research at Plasma Lab, Caller Times News Media. (2010).
QEM Travel Award for NSF-MRI Workshop, Quality Education for Minorities (QEM). (2010).
Who's Who in America - 2010, Marquis Who’s Who. (2009).
The Islander Magazine - Fall 2009 - Featured Plasma Engineering Research Lab, TAMUCC. (2009).
Lt. Gov. David Dewhurst visits Plasma Research Lab, TAMUCC. (2009).
Vilas – Dissertator Fellowship Award, Univ. of Wisconsin - Madison. (2008).
Dissertator Travel Fellowship Award, Dept. of Electrical Engineering, Univ. of Wisconsin Madison. (2007).
Vilas – Dissertator Fellowship Award, Univ of Wisconsin - Madison. (2007).
Best Paper Award, SHPE - Society of Hispanic Professional Engineers. (2005).

IEEE - Graduate Fellowship Award, IEEE – NPSS (Institute of Electrical and Electronics Engineering). (2004).
The Citation Award for Professional Promise, University of Tennessee - Knoxville. (2004).
Best Project Award, University of Madras. (2001).

SERVICE

Department

Committee Member, Faculty Search Committee - Assistant Professor of Mechanical Engineering. (January 2011 - Present).
Committee Member, Faculty Search Committee - Associate Professor of Mechanical Engineering. (January 2011 - Present).
Committee Member, Engineering Technology ABET Re-Accreditation Review. (September 2009 - Present).
Attendee, Meeting, Industrial Advisory Board IAB. (October 2010).
Faculty Mentor, SACNAS Conference Booth - TAMUCC - Computing Sciences and Engineering Representative. (September 2010 - October 2010).
Committee Member, Engineering Education Program Coordinator II Search Committee. (August 2010 - September 2010).
Committee Member, Lab Coordinator II – Search Committee. (August 2010 - September 2010).
Committee Member, Engineering Labs and Machine Shop Reorganization. (May 2010 - September 2010).
Faculty Advisor, Brochure Design and Development for Mechanical Engineering and Engineering Technology (EET & MET) Programs. (November 2009 - April 2010).
Committee Member, Faculty Search Committee - Assistant Professor of Mechanical Engineering. (October 2009 - February 2010).
Committee Member, Engineering Technology Curriculum Review. (October 2009 - January 2010).
Committee Member, Faculty Search Committee - Associate Professor of Mechanical Engineering. (October 2009 - January 2010).

College

Faculty Advisor, ASME - Engineering Seminar Series. (October 2010 - Present).
Committee Member, Physics Faculty Search Committee. (September 2010 - Present).
Committee Member, S&T College Scholarship Committee. (August 2009 - Present).
Tour Guide Engineering Research Labs and Facilities, Associate Dean of Engineering Search. (February 2010).

University

Faculty Mentor, Louis Stokes Alliance for Minority Participation (LSAMP) Program. (August 2010 - Present).
Student Org Advisor (Professional Org), ASME-TAMUCC - American Society of Mechanical Engineers - TAMUCC Professional Engineering Chapter. (February 2010 - Present).
Faculty Mentor, McNair Scholars Program. (November 2009 - Present).
Committee Member, South Texas Engineering Alliance. (September 2009 - Present).
Committee Member, TAMUCC & Del Mar Community College Memorandum of Understanding (MOU) – Articulation Agreement for Mechanical Engineering. (July 2010 - January 2011).
Faculty Mentor, TAMUCC Booth - Austin Engineering Expo. (October 2010).
Program Organizer, 1st Coastal Bend Business Plan Competition - 2010. (January 2010 - March 2010).
Attendee, Meeting, CEO Breakfast - TAMUCC Student Research Representative. (March 2010).

Conference-Related, 7th Annual Texas A&M University System Pathways Student Research Symposium - Judge. (November 2009).
Guest Speaker, Community College STEM Conference - PERL Research Demonstration. (October 2009).
Committee Member, Texas A&M University System Engineering Program Meeting, Dallas, TX. (October 2009).

Professional

Committee Member, Del Mar College Engineering and Engineering Technology Advisory Committee. (February 2010 - Present).
Reviewer, Book, Statics and Strength of Materials, Mott, Pearson. (2010 - Present).
Reviewer, Grant Proposal, Coastal Bend Innovation Center. (2009 - Present).
Committee Member, TAMUCC Engineering Summer Camp Judge. (July 2010).
Reviewer, Journal Article, Journal of Optical Communications. (2009).
Committee Chair, General Electric - Newcomers Club. (2008 - 2009).
Reviewer, Conference Paper, 7th Annual TAMU System Pathways Symposium. (November 2009).
Officer, Vice President, IEEE - Madison WI Chapter. (2004 - 2005).

Public

Committee Member, Innovation Academy Mentors. (December 2010 - Present).
Collaborator, Plasma Technologies Inc - Community Entrepreneurial Technology Development and Validation. (July 2009 - Present).
Guest Speaker, Plasma Lab Tour - Victoria County Outreach program. (November 2010).
Guest Speaker, SBIR/STTR Workshop Panel - Coastal Bend Innovation Center. (September 2010).
Guest Speaker, Plasma Lab Tour for Innovation Academy Students. (August 2010).
Member, Coastal Bend Business Plan Competition. (January 2010 - March 2010).
Program Organizer, Costal Bend Engineering Week Competition. (November 2009 - March 2010).
Committee Member, Science Fair Judge - School of Science and Technology Corpus Christi. (January 2010).
Guest Speaker, IDEA Public School - PERL Research Demonstration. (October 2009).

Service Awards and Honors

Semi-Finalist of the Coastal Bend Business Plan Competition, Coastal Bend Business Innovation Center. (2010).
American Society of Mechanical Engineers Membership Approved, TAMUCC. (2010).
Who's Who in America - 2011, Marquis. (2010).
Panelist - SBIR/STTR Workshop, Coastal Bend Business Innovation Center. (2010).
Best Business-Technology Plan - GE Growth Competion, General Electric Company (GE). (2008).
Best Business Plan Award - Plasma Devices, Burrill Business Plan Contest - Univ. of Wisconsin Madison. (2006).
Best Business Plan Award - Plasma Devices, Wisconsin Governor Business Plan Contest. (2006).