Final Report

DOE Award Number:	Supplement to DE-SC0001923 (ARRA funds for capital equip.)
Awarded to:	Trustees of Tufts College
Project Title:	**Supplement:** "Improved Optical Diagnostic and Microwave Power Supply" *for "Instabilities in Nonthermal Atmospheric Pressure Plasma"*
Principal Investigator:	Jeffrey Hopwood, Professor and Chair Electrical and Computer Engineering Department
Report Date:	May 30, 2011
Project Period:	August 15, 2010 through August 14, 2011

I. Executive Summary

This supplemental program "Improved Optical Diagnostic and Microwave Power Supply" has funded the purchase of laboratory instrumentation to enhance the main DOE project, "Instabilities in Nonthermal Atmospheric Pressure Plasma." The main program's goals include a scientific study of the plasma physics causing large-area plasmas to become unstable at atmospheric pressure. These fundamental scientific discoveries will then allow for the design of controllable cold plasma sources capable of materials processing, including photovoltaic devices, at one atmosphere. This leads to lower costs of energy production. This final report describes *only* the completion of the supplement. A high-speed spectroscopic camera capable of diagnosing plasma fluctuations and instabilities on time-scales of 2 ns was specified, purchased, installed and tested at the Tufts University Plasma Laboratory. In addition, a 30 watt microwave power system capable of producing short pulses of power in the 0.8 – 4.2 GHz bands was specified, purchased, installed and tested. Scientific experiments are continuing under the funding of the main grant, but a few preliminary examples of scientific discoveries made using these items are included in this report.

II. Accomplishment of Goals and Objectives

The following two experimental laboratory systems were installed at the Tufts University Plasma Laboratory: (1) an intensified CCD camera and imaging spectrograph, and (2) a 0.8 – 4.2 GHz pulsed microwave power system. These items are shown in Table I below.

Table I: Supplemental Equipment Request

Description	Supplier	Est. Cost
iCCD camera	Princeton Instruments (Trenton, NJ)	$30,550
+controller		$12,400
Imaging spectrograph		$10,550
Gratings, mounts, software		$3,930
SUBTOTAL		$57,430

Description	Supplier	Est. Cost
0.8-4.2 GHz amplifier	Amplifier Research (Souderton, PA)	$21,500
RF signal generator	Agilent Technologies (Santa Clara, CA)	$24,560
Pk & Ave Power Sensor (2)	Agilent Technologies	$6,082
RF Power Meter	Agilent Technologies	$7,485
SUBTOTAL		$59,627

The above systems were purchased using competitive quotes as required. The goals for the purchase and implementation are shown in Table II. All schedules were met, as indicated.

Table II. Achieved Schedule of Implementation

Days	*-60*	*0*	*60*	*120*	*180*	*240*
Quotes	xxx(completed)					
Order		xxx(completed)				
Installation (amp)			xxxxxxx(completed)			
Installation (iCCD)				xxxxxx(completed)		
Test and verify					xxxxxx(completed)	
Science experiments						xxxxxx→on-going

III. Summary of Project Activities

The iCCD camera and imaging spectrograph system were tested using a linear plasma generated in the test chamber shown in Figure 1. The spectroscopic image in Figure 2 shows the spatially resolved image of the spectrum of a 0.15 atm argon plasma operating at approximately 1 watt of power at 900 MHz. A series of filaments is visible in the image (y-direction) and the infrared argon emission spectrum is recorded (x-direction). This linear plasma is relatively small compared to the lab's current state-of-the-art (20 mm vs. 150 mm), nonetheless, the capabilities of the diagnostic tool are demonstrated.

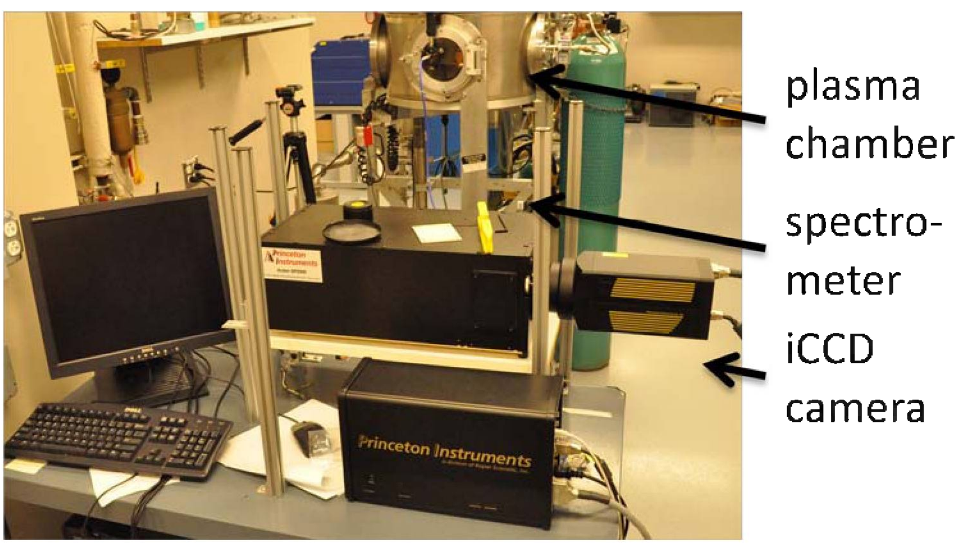

Figure 1. Imaging spectrometer in the process of diagnosing a linear plasma

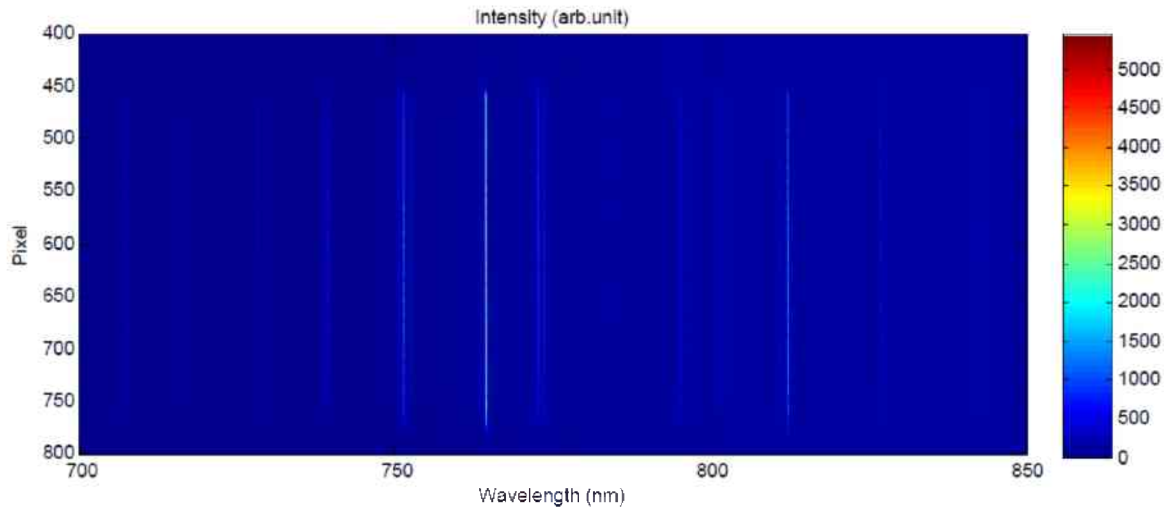

Figure 2. Spatially-resolved infrared emission spectrum from a 20-mm linear microplasma array (1 pixel = 50 μm)

After wavelength and emission intensity calibration, it is possible to extract the spatially-resolved excitation temperature within this microplasma array using the Boltzmann method. These preliminary data are shown in Figure 3 in which the image is zoomed to 1.5 mm. Each microplasma filament is marked by an increase in the integrated emission intensity (*top*). The Boltzmann plot of these emission intensities – along with measurements of the 420-nm band intensities (not shown) – provides the somewhat surprising spatially-resolved excitation temperature (*bottom*). It is interesting that the excitation temperature is lower *inside* the intense microplasma region. We are continuing our investigation of this preliminary observation.

As a second demonstration of the installation and integration of equipment from this supplement, we present the pulsed microwave power system in Figure 4. In this example, the system is used to pulse power into a single microplasma thus causing a transition of the discharge from a resonator-stabilized mode to a high-intensity discharge similar to an arc. The microwave resonator is physically forbidden from supporting an arc, so the arc discharge attaches to an earthed electrode intentionally positioned several millimeters below the resonator. A time-sequence from the iCCD camera spans 500 μs and shows the propagation of the glow discharge toward the ground electrode (Figure 5). The images were taken in the repetitive pulsed mode and stitched together, so each image is not the successor to the previous event, but rather the image from a subsequent pulse-induced instability.

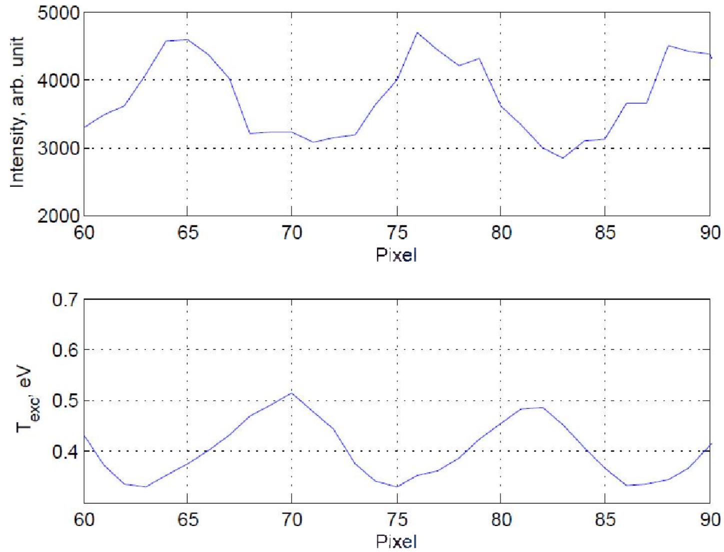

Figure 3. Integrated emission intensity shows three of the numerous microplasmas within the 20-mm array (top). The Boltmann plot of line emission intensities yields the excitation temperature in the vicinity of these microplasmas (bottom). ***Note:*** *1 pixel = 50 microns.*

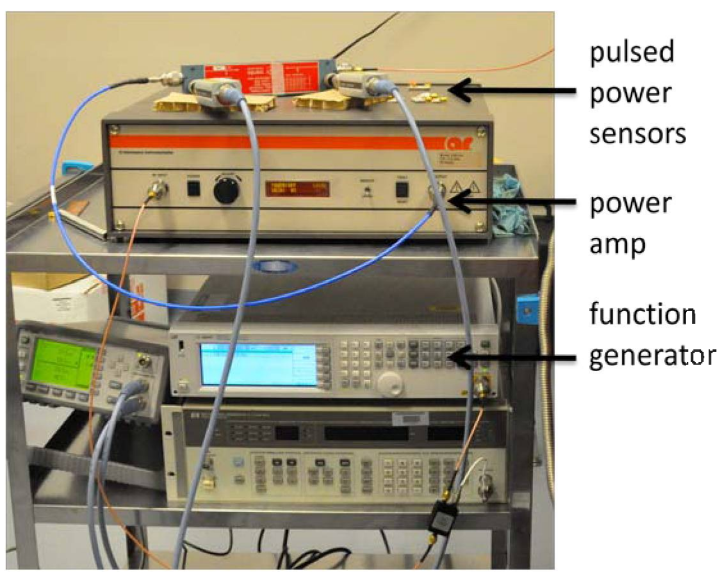

Figure 4. Pulsed microwave power system

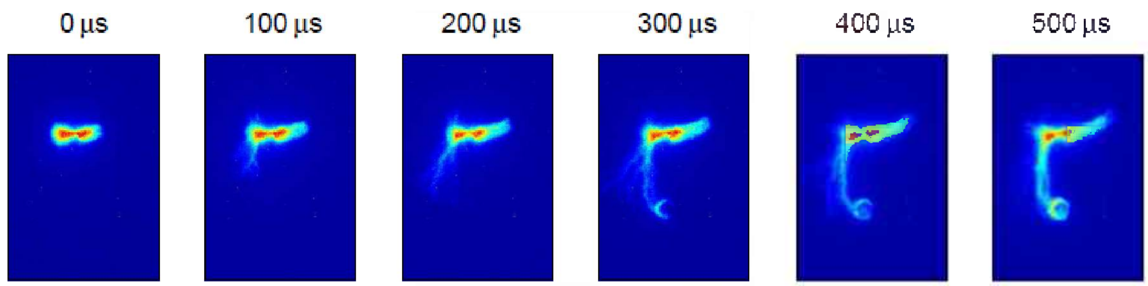

Figure 5. A time-sequence of images from a pulsed microplasma (approximately 200 µm in diameter) as the discharge propagates toward a grounded electrode (bottom center, visible for t>300µs)

IV. Publications and Technology Transfer

The following publications have been made possible in part by this supplemental grant to-date:

"Internal structure of 0.9 GHz microplasma," Naoto Miura and Jeffrey Hopwood, *Journal of Applied Physics*, accepted for publication April 14, 2011.

"Stable linear plasma array at atmospheric pressure," Chen Wu, Alan R Hoskinson, Jeffrey Hopwood, submitted to *Plasma Sources Science and Technology* (March 29, 2011).

V. Costs

This DOE ARRA grant (Tufts DEZ003) is under spent by $6652.50 primarily due to the substitution of one of the originally budgeted items: An Agilent Technologies N5181A microwave signal generator ($15,637) was substituted for the Agilent Technologies E4428C signal generator specified in the original proposal ($24,560). The former instrument was selected due to its superior pulse generation capabilities – short microwave pulse generation is the principal goal of the purchased RF generator system. The $9k savings was partially offset by a price increase in the Princeton Instruments spectrometer and iCCD camera. The original budgeted cost of $57,430 had increased to $60,750 in the time between grant preparation and ordering. Other variations to the anticipated budget were due to the competitive bidding process which reduced the cost of some items as outlined below:

Instrument	Original quote	Actual	Difference
RF generator	$24560	$15637	($8923)
Spectrometer/CCD	$57430	$60750	$3320
Power sensors	$6082	$5142	($940)
Power meter	$7485	$5988	($1497)
Power coupler	$0	$1157	$1157
			($6883)

The remaining small discrepancy is due to variance in the charges of miscellaneous items such as shipping and freight charges. These cost under-runs have been reported and deobligation of funds is in progress.

VI. Summary

All goals of the ARRA supplemental grant to DE-SC0001923 have been met. The systems are installed and contributing to the scientific goals of the main grant. This document serves as the final report on the ARRA supplement only, and is not the final report for the on-going grant DE-SC0001923.

Reported and Signed,

Jeffrey A. Hopwood
Tufts University
Principal Investigator