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APPLICATION NOTE

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"A new gating technology exclusive to the highly advanced PI-MAX4 ICCD camera platform... combines the higher sensitivity of the conventional image intensifiers used in traditional ICCD cameras with the ability to deliver <500 picosecond resolution."

<500 Picosecond Gating Augments Studies of Atmospheric Pressure Plasma Jets

Advances in Scientific Intensified CCD Camera Technology Enable New Investigations of Non-Thermal APPJs

Introduction

Non-thermal 'atmospheric pressure plasma jets' (APPJs) hold great promise for innovative applications in material processing and biomedicine/healthcare because of their ability to generate plasmas that are not confined between electrodes[1]. Produced using one of several different experimental setups (e.g., a number of jet configurations are based on dielectric barrier discharge, or DBD), fed with pure rare gases (helium, neon, or argon), and excited by pulsed high voltages, all non-thermal APPJs exhibit a unique feature: they are not continuous media but actually consist of 'plasma bullets' traveling at high velocity in ambient air[1].

The growing utilization of these low-temperature APPJs during the past several years has led to the desire to better understand the physical phenomenon of the plasma bullets (spatio-temporally localized luminous effects) in the effluent of the jets[2]. Imaging studies of a cold APPJ in an argon atmosphere performed with a high-speed intensified CCD (ICCD) camera, for example, have shown that plasma bullets can have a propagation velocity of up to 20 kilometers per second[2]. The appearance both of the plasma bullets as well as the spatio-temporal evolution of the generation zone of metastable argon atoms can be explained by the effect of a self-propagating ionization front[2].

It is important to note that non-thermal APPJs can propagate over rather long distances; however, their diameters are limited to only a few millimeters[1]. While this spatial coverage is sufficient for small-scale applications, a more efficient solution for large-scale applications is to organize several plasma jets in 1D or 2D arrays operating simultaneously from a unique power supply[1].

This application note will provide an overview of non-thermal APPJ experimental setups for single-jet and multiple-jet studies in addition to the newest relevant imaging technology.

Single-Jet Studies

A typical non-thermal APPJ experimental setup comprises a glass tube with two external electrodes of certain length (along the axis of the tube) with a gap between them. Plasma is formed in the flowing rare gas (often helium). Plasma packages travel within the tube and outside in the air, where they form bullets even though there is no external field. The apparent speed of visible plasma packages, ionization fronts, and plasma bullets is much greater than the speed of the flowing feed gas[3].

ICCD cameras enable researchers to observe the development of plasma bullets in cold APPJs by tracing the formation of plasma packages as a discharge close to the instantaneous cathode, following their motion between and inside the electrodes up to their emergence at the edge of the glass tube, and then capturing the formation of a plasma bullet. Inside both electrodes, plasma is concentrated close to the walls and is bright, while outside it is located at the axis[3]. See Figure 1.

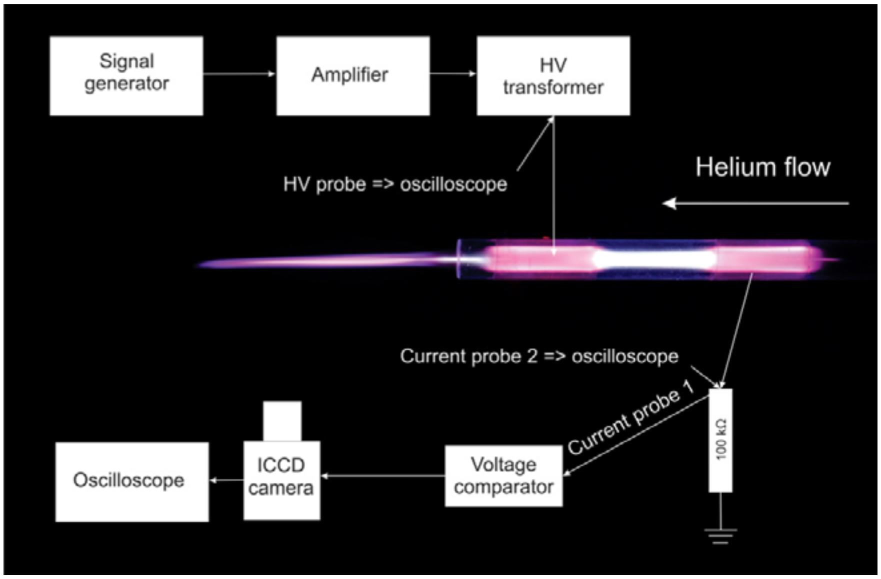


Figure 1.
A typical non-thermal APPJ experimental setup[3].

Low-temperature APPJs offer controllability of a variety of agents (e.g., radicals, ions, UV, and electric fields) and do not cause thermal damage to heat-sensitive biological systems, which makes them suitable for biomedical applications such as sterilization, treatment of mammalian and cancerous cells, blood coagulation, wound healing, and dental treatments[4].

The photograph in Figure 2, for example, shows a plasma generated in the root canal of a tooth using the non-thermal APPJ device depicted in Figure 3.

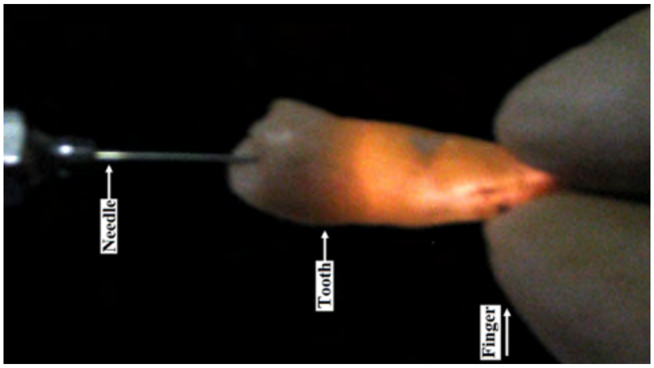
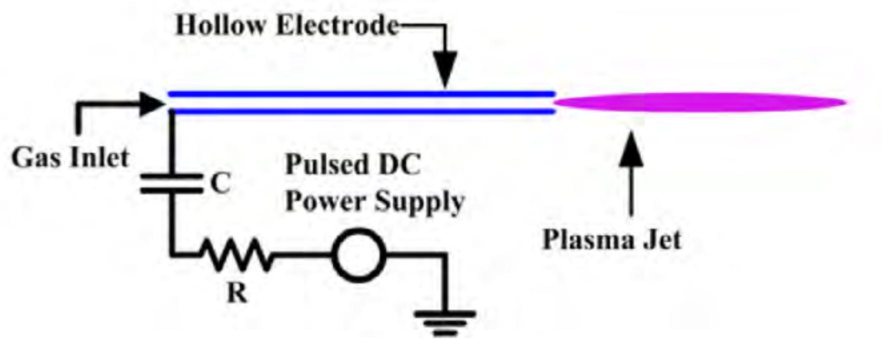


Figure 2.
Photo of a plasma generated in the root canal of a tooth using a non-thermal APPJ device based on a single-electrode (SE) configuration[5].

Figure 3.
Schematic of a non-thermal APPJ device based on a single-electrode configuration[5].



Because of the narrow channel geometry of a root canal, which typically has a length of a few centimeters and a diameter of one millimeter or less, the plasma generated by a traditional jet is not efficient enough to deliver reactive agents into the root canal for disinfection. To achieve better killing efficacy, a plasma needs to be generated inside the root canal, whereupon reactive agents, including short-lifetime species such as charged particles, could play a role in killing bacteria[5]. Utilizing the device shown in Figure 3, a cold plasma could be generated inside a root canal (Figure 2).

Multiple-Jet Studies

Generating multiple non-thermal APPJs in order to cover larger treatment areas has recently become desirable; however, since the interaction between neighboring jets cannot be avoided it is therefore imperative to elucidate the physical processes that occur between jets[1]. It could also be of interest to produce an interaction between two or more of these small-diameter jets impacting the same location of a target to increase the deposited dose of plasma, or to finely tune the composition of the reactive species using a different gas mixture feed in each jet[1].

Material processing and chemical decontamination, as well as biomedicine/healthcare, are among the fields that could benefit from the use of multiple low-temperature APPJs. Figure 4 shows an experimental setup utilized to perform a comprehensive study of the physical properties of the interaction between two microplasma jets produced in helium and counter-propagating in ambient air[1].

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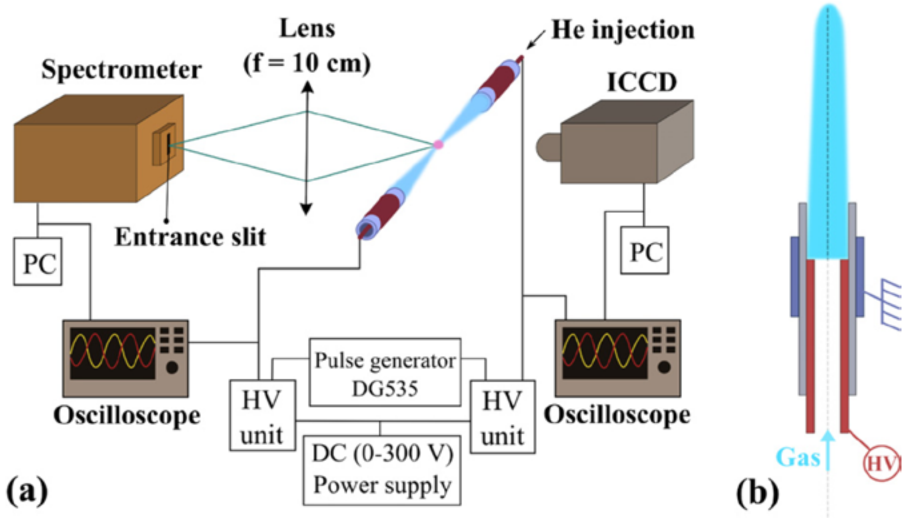
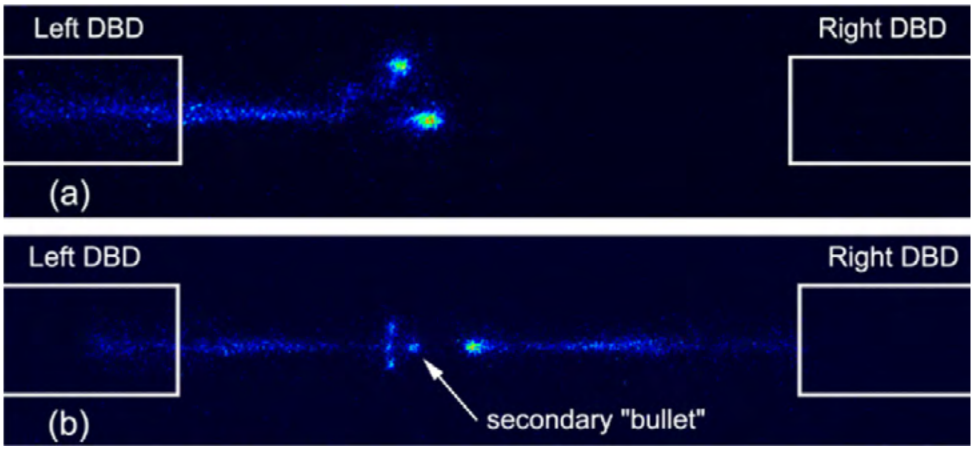
Figure 4.
Experimental setup: (a) general arrangement… the HV units are two 'homemade' high-voltage, pulse-forming units; (b) details of the DBD devices[1]. Courtesy of Dr. Vincent Puech.



In this study, the spatio-temporal evolution of plasma emission was investigated using an advanced ICCD camera (Princeton Instruments PI-MAX®3:1024i) that permits exposure times as short as 0.39 nanoseconds with a fully integrated high-voltage controller. Spectroscopic measurements were made with a 750 mm focal length spectrometer (Princeton Instruments Acton SP 2750i) equipped with three different gratings, allowing the researchers to study plasma emissions in the wavelength range from 190 to 900 nanometers.

Figure 5 presents two 'snapshots' (exposure times: 5 nanoseconds) of the microplasma jets propagating in ambient air as they arrived in a turbulent area.

Figure 5.
(a) Two counter-propagating helium flows and only one plasma jet; (b) two counter-propagating helium flows and two counter-propagating plasma jets. A 'secondary bullet' emerges in (b). Images acquired with a 16-bit, precision-gated Princeton Instruments ICCD camera. Gray level intensity has been converted into false colors[1]. Courtesy of Dr. Vincent Puech.



A fascinating feature of the interaction between the two counter-propagating plasma jets is the sudden occurrence of a secondary glow discharge at later times (see Figure 6).

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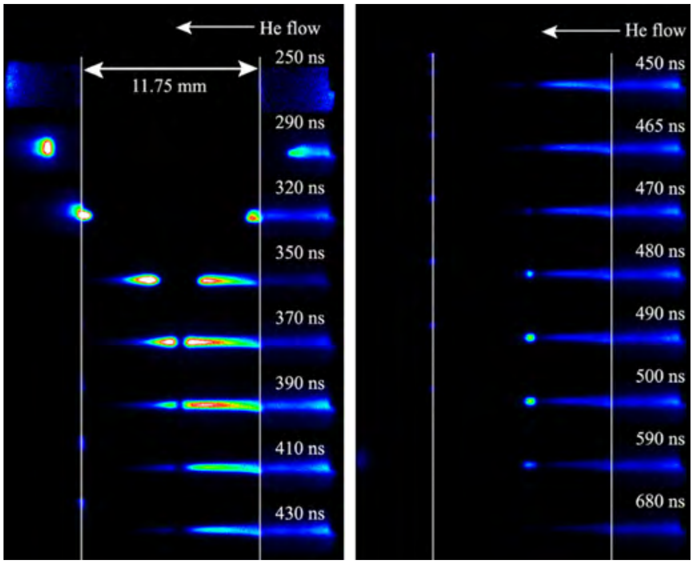

Figure 6.
Images (false color, exposure times: 0.95 nanoseconds) of the dynamics of the propagation of two counter-propagating microplasma jets acquired with a 16-bit, precision-gated Princeton Instruments ICCD camera. Helium was fed only through the device on the right, so as to avoid hydrodynamic instabilities[1]. Courtesy of Dr. Vincent Puech.

The body of data collected reveals that the plasma bullets, which constitute the jets, interact with each other from the time they leave the nozzle of their respective devices. This interaction results in a decrease in the velocity of both plasma bullets. More important, the ignition of a 'secondary' discharge, a pink glow, suddenly appears in the small space between the jets where no bullet propagation occurs (Figure 7).

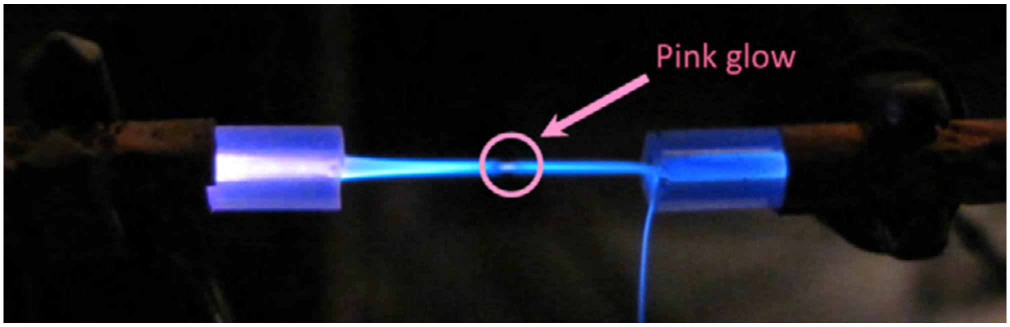

Figure 7.
Digital photography (true color) of the colliding microplasma jets showing the secondary pink glow in between the two DBDs[1]. Courtesy of Dr. Vincent Puech.

Based on current measurement analysis, correlated with optical emission spectroscopy and high-speed digital photography observations, it is suggested that this transient pink glow is attributable to a secondary negative glow induced by the sudden reversal of the potential of the plasma columns, instantaneously correlated with the voltage reversal of the DBD electrodes, while the floating potential of the previously dark zone remains almost unchanged[1].

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New Imaging Technology for Time-Resolved APPJ Studies

Recently, Princeton Instruments introduced a new gating technology exclusive to the highly advanced PI-MAX4 ICCD camera platform that combines the higher sensitivity of the conventional image intensifiers used in traditional ICCD cameras with the ability to deliver <500 picosecond resolution.

By utilizing state-of-the-art electronics and fiberoptically bonding the intensifier to the CCD sensor, this new picosecond gating technology enables PI-MAX4 cameras (see Figure 8) to gate conventional image intensifiers, which normally achieve ~2 to 3 nanosecond gating, at <500 picoseconds without sacrificing quantum efficiency (QE).

Figure 8.
The PI-MAX4:1024i ICCD camera utilizes a conventional image intensifier fiberoptically bonded to an interline-transfer CCD and runs at near video rates (26 frames per second).

An integrated programmable timing generator, SuperSynchro, built into these cameras makes them perfect for single- and multiple-jet studies. Furthermore, the latest Princeton Instruments LightField® 64-bit data acquisition software, available as an option, affords complete control over all PI-MAX4 hardware features via an exceptionally intuitive user interface. LightField provides automatic defect correction, precision exposure control, and a host of innovative functions for easy capture and export of non-thermal APPJ imaging and spectral data.

Summary

The Princeton Instruments PI-MAX4 family, the new benchmark for ICCD camera performance, combines the advantages of picosecond gating with the high QE of conventional image intensifiers fiberoptically coupled to scientific-grade sensors. These cameras are well suited for the latest studies of non-thermal APPJs as well as numerous other time-resolved imaging and spectroscopy applications.

Low-temperature APPJs are quickly gaining popularity in areas such as biomedicine/healthcare, material processing, and chemical decontamination. Myriad single-jet and multiple-jet setups each provide their own distinct advantages for various practical applications across these diverse realms. As researchers' efforts to characterize and develop non-thermal APPJs become even more refined, highly advanced scientific ICCD cameras will play an increasingly critical role in such endeavors.

Acknowledgements

Princeton Instruments wishes to thank Dr. Vincent Puech (Laboratoire de Physique des Gaz et des Plasmas, CNRS & Univ. Paris-Sud, Orsay, France) for his contributions to this application note.

Resources

For more information about the Princeton Instruments PI-MAX4 family of cameras, please visit: **http://www.pi-max4.com**

To learn about the research of Dr. Vincent Puech, please visit:
http://www.lpgp.u-psud.fr/~puech/

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