Final Report: DE-SC0002588:

Plasmas in Multiphase Media:
Bubble Enhanced Discharges in Liquids and Plasma/Liquid Phase Boundaries

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Executive Summary

In this research project, the interaction of atmospheric pressure plasmas with multi-phase media was computationally investigated. Multi-phase media includes liquids, particles, complex materials and porous surfaces. Although this investigation addressed fundamental plasma transport and chemical processes, the outcomes directly and beneficially affected applications including biotechnology, medicine and environmental remediation (e.g., water purification). During this project, we made advances in our understanding of the interaction of atmospheric pressure plasmas in the form of dielectric barrier discharges and plasma jets with organic materials and liquids. We also made advances in our ability to use computer modeling to represent these complex processes. We determined the method that atmospheric pressure plasmas flow along solid and liquid surfaces, and through endoscopic like tubes, deliver optical and high energy ion activation energy to organic and liquid surfaces, and produce reactivity in thin liquid layers, as might cover a wound. We determined the mechanisms whereby plasmas can deliver activation energy to the inside of liquids by sustaining plasmas in bubbles. These findings are important to the advancement of new technology areas such as plasma medicine.

Comparison of Actual Accomplishments to Goals and Objectives of Project

The original project had two objectives – 1) investigation of the role of bubbles in liquids on electrical breakdown and the propagation of plasma streamers and 2) investigation of the interaction of atmospheric pressure plasmas with liquid layers. During the time of the project, the sub-fields of plasma medicine, plasmas on liquids and plasma jets have burgeoned to the point of nearly dominating the field of low-temperature plasma as a whole. As a result, the focus of our investigation was less on the role of bubbles in breakdown and propagation of streamers and more on interactions of atmospheric pressure plasmas with liquid layers and interfaces, and organic materials. These interfaces include liquids exposed to the atmosphere and the liquid interface in bubbles. These activities included investigation of the plasma sources that are used in these plasma-liquid-organic interactions. During the project period, we made many new discoveries in how atmospheric pressure plasmas and plasma sources interact with complex surfaces, liquids and inside bubbles. We also quantified the fundamental operating properties of the two main plasma sources used for atmospheric pressure plasma interactions with liquids and complex organic surfaces – plasma jets and dielectric barrier discharges.

Products Developed Under the Award

The primary work produce resulting from this grant are refereed journal articles, conference proceedings and presentations, seminars and symposia. A list of publications and presentations that acknowledge support from the DOE under this grant are listed in Appendix A. The products include:

	Number:
Refereed Journal Articles	19
Book Chapters	1
Conference and Workshop Presentations	
Invited with Proceedings	6
Invited with Abstracts	22
Contributed with Proceedings	4
Contributed with Abstracts	24
Invited Symposia, Seminars, Short Courses	15

Summary of Project Activities

The project activities addressed computational investigations of a comprehensive range of topics addressing plasmas interacting with liquids, bubbles in liquids, and the response of liquid and organic materials to the delivery of activation energy by atmospheric pressure plasmas. Our computational investigations also addressed the plasma sources used in these processes. The major findings are discussed in the accompanying journal articles included as Appendix B. The findings are briefly summarized here.

(Note: In the following, [JA-x] refers to the xth entry in the listing of journal articles appearing in Appendix A.)

[JA-1] One of the major outcomes of atmospheric pressure plasmas interacting with organic and semi-insulating materials, such as thin liquid layers, is the delivery of electric fields into the materials due to the impact of the plasma ionization wave on the surface. In this article, we discuss the mechanisms of electric field delivery to individual components of cells under the skin.

[JA-2] Sustaining plasmas in bubbles is a means of producing reactive species inside liquids. Applications include purification of water and chemical processing. In this project, we collaboratively investigated the synergistic effects of plasmas in bubbles and the resulting stability of the bubble.

[JA-3,4] It is commonly assumed that the ions striking surfaces in atmospheric pressure plasmas have low energies. In this work, we computationally demonstrated that under select conditions, pulses of high energy ions can be delivered to organic surfaces. We examined the distribution of ion energies delivered to flat polymer surfaces and small particles suspended in air. These results have potentially important implications for the use of atmospheric pressure plasmas to treat organic materials and liquid surfaces.

[JA-5,12,15] The delivery of atmospheric pressure plasmas into the human body in the context of plasma medicine is challenging. In the treatment of lung tissue, the plasma may be guided by the branching of the bronchial tubes. In these papers we investigated the mechanisms whereby atmospheric pressure ionization waves can be guided by tubular, branching structures, and how plasmas can be induced in neighboring tubes. We determined scaling laws for the manner in which the plasmas can split and be reformed during their travel through the tubes.

[JA-6,9,13] Atmospheric pressure plasmas in the form of ionization waves in dielectric barrier discharges (DBDs) are used in the treatment of wounded skin. In these studies, we quantified the manner of delivery of activation energy (e.g., ion, photons, radicals) by DBDs into small wounds in skin. We numerically demonstrated the spreading of plasma on the surface of skin and into small wounds. We estimated the rate of sputtering of cellular membranes by these atmospheric pressure plasmas, and how the delivery VUV photon fluxes, ions and radicals depend on the topography of the wound.

[JA-7] Plasma treatment of porous materials is of interest in the functionalization of tissue scaffolding for tissue engineering. The goal in this treatment is to have atmospheric pressure plasmas penetrate into randomized structures, usually moisture or liquid covered dielectrics, to functionalize the surface with desired chemical properties. In this paper, we investigated the mechanisms whereby plasmas can penetrate deeply into such highly porous materials.

[JA-8] The code *nonPDPSIM* used during this project was employed in a collaborative experimental investigation of plasma jets for purposes of code validation. The modeling platform reproduced experimentally observed distributions of excited states in atmospheric pressure plasma jets.

[JA-10] One of the ways to deliver activation energy from atmospheric pressure plasmas jets into the human body is the use of endoscopes – flexible tubes that are inserted into the lungs, esophagus or rectum. These tubes have circuitous paths which take turns of differing radii of curvature which makes delivery of the plasma questionable. In this project, we investigated how atmospheric pressure ionization waves propagate through bending dielectric tubes. We quantified the charging mechanisms of the inside surfaces of the tubes and how that affects the path the plasma takes. We made predictions of the properties of the jet that emanates from the tube.

[JA-11] The *2012 Plasma Roadmap* is a comprehensive projection of the direction the field of low temperature plasmas will take in the next 5+ years. The principle investigator was a contributor to the roadmap in the area of plasma modeling.

[JA-14] In previous work, we determined the ability of atmospheric pressure plasmas to deliver pulses of energetic ion fluxes to solid and liquid surfaces. In this investigation, we proposed a method to control those ion energies through the use of porous membranes. By varying the dielectric constant and the diameter of the pores of the membranes, one can control the distribution of ion energies penetrating through the pores to the underlying surface.

[JA-16] Sustaining plasmas in bubbles in liquids is an extremely promising method to deliver radicals into the interior of liquids. In this collaborative study, the mechanisms for producing radicals and excited states by atmospheric pressure plasmas in bubbles in water were investigated. Quantitative comparisons were made to experiments performed by collaborators.

[JA-17] The majority of atmospheric pressure plasmas in contact with liquids are in the form of plasma jets. In order to increase the area of the liquid being treated, bundles of plasma jets are often used. Experimentally, it is observed that the plasma jets mutually interact. In this project, we computationally investigated the mechanisms whereby small arrays of plasma jets interact through electrostatic, photolytic and hydrodynamic mechanisms. We found that the diffusion of ambient air into the jets will preferentially quench outer jets in the bundle and intensity the interior jets.

[JA-18] In most cases of atmospheric pressure plasmas treating human tissue, the tissue is covered by a thin layer of a water-like liquid. The active species produced by the plasma must penetrate through the liquid layer before reaching the underlying tissue. In this investigation, we modeled micro-plasma-streamers as produced by dielectric barrier discharges and their interaction with thin layers of water. We quantified the mechanisms whereby the plasma produced reactive species are filtered and transformed by the water layer before reaching the underlying tissue.

[JA-19] It is often the case that small wounds in skin treated by plasma are filled with a liquid. The electrical properties of the liquid and the shape of the wound affect the dynamics of the plasma and can feed-back to the plasma properties. In this investigation, we modeled the interaction of plasma streamers as produced in dielectric barrier discharges with small wounds of different sizes filled with liquids having different dielectric properties. We quantified how these properties affect the delivery of electric fields to structures in the liquid resembling blood platelets and to cells below the liquid.

Computer Modeling

This project involved the use and improvement of the modeling platform *nonPDPSIM*. This modeling platform was largely developed, validated and released to collaborators prior to the start of this grant. As such we refer the reader to the authors' prior publications, available at http://uigelz.eecs.umich.edu for a detailed description of the algorithms and validation of *nonPDPSIM*. During this grant we improved and refined those algorithms. These mathematical algorithms and solution methods have been peer reviewed through these many publications. We include a brief description of the algorithms here.

The model, *nonPDPSIM*, is a multi-fluid hydrodynamics simulation in which transport equations for all charged and neutral species and Poisson's equation are integrated as a function of time. The fundamental equations for charged species that are solved are,

$$-\nabla \cdot \varepsilon \nabla \Phi = \sum_j N_j q_j + \rho_s \quad , \tag{1}$$

$$\frac{\partial N_j}{\partial t} = -\nabla \cdot \vec{\phi}_j + S_j \quad , \tag{2}$$

$$\frac{\partial \rho_s}{\partial t} = \sum_j - q_j (\nabla \vec{\phi}_j + S_j) - \nabla \cdot (\sigma(-\nabla \Phi)) \quad , \tag{3}$$

where *ε, Φ, ρ_s,* and *σ* are the permittivity, electric potential, surface charge and conductivity of solid materials; and for species *j*, N_j, ϕ_j, S_j and q_j are density, flux, source function and charge. Poisson's equation (Eq. 1), transport equations for conservation of the charged species *j* (Eq. 2) and the material and surface charge balance equation (Eq. 3) are simultaneously integrated using a sparse-matrix and Newton iteration technique.

Updates of the charged particle densities and electric potential are followed by an implicit update of the electron temperature by solving the electron energy conservation equation,

$$\frac{\partial \varepsilon}{\partial t} = \vec{j} \cdot \vec{E} - \nabla \cdot \left(-\kappa \nabla T_e + \varepsilon \vec{\phi}_e \right) - \sum_i \Delta \varepsilon_i k_i N_i \tag{4}$$

where the average electron energy $\varepsilon = \frac{3}{2} k T_e$ for electron temperature T_e, ϕ_e is the Scharfetter-Gummel form of the electron flux, $\vec{j} = q\vec{\phi}_e$ is the total electron current in electric field $\vec{E}$, and κ is the electron thermal conductivity. The summation is over electron collisions with species having density N_i and rate coefficient k_i resulting in change in electron energy $\Delta\varepsilon_i$. The electron transport coefficients and rate coefficients for bulk electrons as a function of T_e are obtained by solving Boltzmann's equation for the electron energy distribution (EED). Rate coefficients are obtained by solving Boltzmann's equation and creating look-tables that provide rate and transport coefficients as a function of T_e = (2/3)ε, where ε is the average electron energy. Poisson's equation (Eq. 1) is solved throughout the entire the computational domain (except in metals where the potential is specified as a boundary condition). Continuity equations for gas phase charged and neutral particles are only solved in the plasma regions including liquid. Equation (3) for surface and volume charges is solved on and inside all non-metallic materials.

Photo-ionization by streamer generated radiation producing electrons ahead of the avalanche front is critical to the propagation of positive streamers. Our approach to photoionization is based on line-of-sight propagation of UV ionizing radiation generated by high lying excited states that are produced largely in the high E/N in the avalanche front. The UV radiation is absorbed (without producing ionization) over a specified mean-free-path which determines its extent beyond its origin. Photoionization occurs by absorption of UV radiation by selected species. The source term in Eq. 2 includes these photoionization processes which are computed using a Green's functions. The rate of photoionization given by

$$\frac{\partial N_i^+(\vec{r})}{\partial t} = \sum_j \int N_j(\vec{r}\,') A_j G_j(\vec{r}, \vec{r}\,') \sigma_{ij} d^3 \vec{r}\,' \quad , \tag{5a}$$

$$G_j(\vec{r},\vec{r}') = \frac{exp\left(-\sum_k \int_{\vec{r}'}^{\vec{r}} N_k(\vec{r}'')\sigma_{kj} d\vec{r}''\right)}{4\pi|\vec{r}-\vec{r}'|^2} \quad . \tag{5b}$$

In these expressions, excited state N_j emits a photon at location $\vec{r}'$ with a rate given by Einstein coefficient A_j and ionizes species N_i with cross section σ_{ij} at location $\vec{r}$. In traversing the plasma the photons are absorbed by species N_k with cross section σ_{kj}. The function $G_j(\vec{r},\vec{r}')$ is the probability of survival of the emitted photon and divergence of its flux between emission and ionization.

The model is executed on an unstructured mesh. All Laplacian operators are formulated using conservative finite volume techniques. For example, for node *i* and flux ϕ,

$$-\nabla \cdot \phi_i = -\frac{1}{V_i}\sum_{k=1}^{n} \frac{A_{i,k}\phi_{i,k}}{|\vec{r}_i - \vec{r}_k|} \tag{6}$$

where $\phi_{i,k}$ the flux between nodes *i* and *k* defined as being positive if directed away from *i*, $\vec{r}_i$ is the spatial location of node *i*, $A_{i,k}$ is the area of the face between the volume cells centered on nodes *i* and *k*, and V_i is the volume of the cell for node *i*. The system of equations for charged particle transport and Poisson's equation is integrated in time using an implicit Newton's method with numerically derived Jacobian elements . The resulting sparse matrix was solved using the numerical package *dslucs*, obtained from the SLAP Sparse Matrix Library or in parallel using the Intel Math-Kernal-Library (MKL). The matrix solver uses a biconjugate gradient spare matrix solution technique with incomplete LU factorization for preconditioning.

The transport of secondary beam-like electrons emitted from the surfaces are tracked using an electron Monte Carlo Simulation (eMCS). The fundamentals of the eMCS will briefly be described. The computational mesh employed in the plasma hydrodynamic portion of the model is unstructured. As such, it is computationally expensive to locate particles in the mesh during the eMCS to accumulate statistics at nodes in the mesh; or to obtain mesh quantities, such as electric fields and collision frequencies, required to advance the trajectories of the pseudoparticles. As these assignments and interpolations would otherwise be responsible for the vast majority of the computer time spent in the eMCS, the following methodology was used.

The advancement of trajectories in the eMCS is performed on a Cartesian mesh (CM) which is over-layed onto the unstructured hydrodynamics mesh (UM). The CM overlays only that portion of the UM in which beam electron transport is expected to be important, a choice refined by iteration and experience. The resolution of the CM is chosen to be fine enough to capture the small scale features of the UM. As the number of arrays in the eMCS which are indexed on the CM is small, there is not a large computational penalty to having a fine enough resolution in the CM to capture the resolution of UM.

At the beginning of the eMCS, Green's functions are developed for interpolation of quantities from the UM to the CM, and vice-versa. To interpolate from the UM to a node in the CM, the nearest nodes from the UM in each of the four Cartesian quadrants centered on the node in the CM are located. Quantities on the UM in adjacent quadrants are interpolated to the axes of the CM; and those axial quantities are then interpolated to the central CM node. To interpolate from the CM to a node in the UM, the mesh cell in the CM containing node in the UM is located. The four vertices of the cell in the CM then provide values to perform a 2-dimensional interpolation to the node in the UM. As such, the ideal spacing of the CM is to have a single node from the UM in each cell of the CM. In practice, this is not possible and so search algorithms are employed to locate the appropriate vertices in the CM and nodes in the UM to facilitate use of the Green's functions.

The electric potentials produced in the fluid module are interpolated to the CM. Based on incident ion fluxes and secondary electron emission coefficients, electron pseudoparticles are released with an energy of 4 eV from nodes on surfaces in the UM. These pseudoparticles are weighted by the magnitude of the local ion flux, the secondary electron emission coefficient and the number of particles released at each node. The weighting of each pseudoparticle has units of electrons/s. Using the Monte Carlo techniques, the trajectories of the secondary beam electrons and their progeny are integrated as a function of time. Pseudoparticles (and their progeny) are tracked until they hit boundaries, move out of the confines of the CM or fall below a specified energy thereby joining the bulk electron distribution. The weightings of these latter pseudoparticles are summed into sources S_i for electrons and are included in Eq. 1. The trajectories of the beam electrons are sampled with each move of the pseudoparticles, binning them in energy and location on the CM to produces spatially dependent electron energy distributions, $f(\varepsilon,\vec{r})$ having units of electrons-cm^{-3}eV^{-1}. When convolved with electron impact cross sections, source functions having units cm^{-3}s^{-1} are produced which then contribute to S_i for the appropriate species. These source functions are then interpolated onto the UM.

The fluid averaged advective velocity is obtained by solving a modified form of the compressible Navier Stokes equations in which source terms for momentum imparted from the electric field are included. In doing so, we assume that the pressure is sufficiently high and the rate of momentum transfer is sufficiently large that little momentum is instantaneously stored in the electrons and ions. As such, the electron and ion momentum sources instantaneously appear in the fluid equations. The equations we solve for the fluid averaged advective velocity, $\vec{v}$, are

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \vec{v} , \qquad (7)$$

$$\frac{\partial \rho \vec{v}}{\partial t} = -\nabla P - \nabla \cdot \rho \vec{v}\vec{v}_i - \nabla \cdot \bar{\bar{\tau}} + \sum_i q_i N_i \vec{E} , \qquad (8)$$

$$\frac{\partial \rho c_p T}{\partial t} = -\nabla \cdot \left(-\kappa \nabla T + \vec{v} c_p T\right) - P(\nabla \cdot \vec{v}) + \left(\bar{\bar{\tau}} \cdot \nabla \vec{v}\right) - \sum_i \Delta h_i S_i + \sum_i \vec{j}_i \cdot \vec{E} , \qquad (9)$$

$$\frac{\partial \rho c_p T_m}{\partial t} = -\nabla \cdot \left(-\kappa_m \nabla T_m\right) , \qquad (10)$$

where ρ is the total mass density (including charged species), T is the gas temperature, P is the thermodynamic pressure (ideal gas behavior), $\bar{\bar{\tau}}$ is the viscosity tensor, κ is the thermal conductivity, c_p is the heat capacity, and Δh_i is the heat of formation for reaction i having source function S_i. Eqs. 7-9 are solved throughout the plasma volume. Eq. 10, with the subscript m denoting non-plasma materials, is solved only in solids and non-plasma gases. The last term in

Eq. 8 accounts for momentum imparted from the electrostatic field $\vec{E}$ where the sum is over all charged species having density N_i and charge q_i. The last term in Eq. 9 accounts for Joule heating due to acceleration of ions in the electrostatic field having current density j_i.

Ion energy and angular distributions (IEADs) to surfaces are computed using the Plasma Chemistry Monte Carlo Module (PCMCM) in *nonPDPSIM*. The PCMCM is executed on a Cartesian mesh that overlays a subset of the computational domain. Pseudo-particles representing ions are launched from sites within the PCMCM mesh with weightings proportional to their rate of generation by electron impact and heavy particle reactions. Pseudo-particles are also launched from the boundaries of the PCMCM mesh in proportion to the entering fluxes of ions. Monte Carlo techniques are used to advance their trajectories in time varying electric fields while accounting for elastic and inelastic collisions. The energy and angles of particles as they strike surfaces are recorded over a predetermined period of time to provide IEADs as a function of location on the polymer surface and time. Electric potentials as a function of position computed on the unstructured mesh are interpolated onto the rectilinear structured mesh that overlays the unstructured mesh to enable the Monte Carlo algorithms to more rapidly execute. As the filament evolves, snapshots of electric fields are transferred to the PCMCM to produce a time sequence of the IEADs to the surface. The time interval between export of the electric fields to the PCMCM as well as the mesh resolution were extensively parameterized to insure that the IEADs were not sensitive to these values. In the end, the typical resolution for structured PCMCM meshes were 0.5-1 μm.

In modeling the interaction of atmospheric pressure plasmas with liquids, we used two approaches. The first method considered the liquid as a non-plasma-penetrating dielectric. In the second method, we treating the water in the same way we treated gas phase plasmas. In extending *nonPDPSIM* into the liquid phase, we attempted to make a minimum of limiting assumptions. The numerical mesh is divided into zones which are specified as being gas or liquid. Computationally and algorithmically, the liquid zone is treated identically to the gas phase. The same equations (e.g., Poisson's, transport and energy conservation, radiation transport) are solved in the liquid as in the gas. In order to properly include the larger dielectric constant of the liquid, an atomic polarizability is specified for each species so that the number density weighted polarizability yields the proper dielectric constant. Transport coefficients for neutral and charged species, and absorption cross sections, are determined by the local densities on a mesh-point-by-mesh-point basis.

The rate of transport of gas phase species into the liquid is determined by Henry's law considerations. Henry's law states that at a constant temperature and at equilibrium, the density of a gas dissolved in a liquid, water in this case, is proportional to the partial pressure of the gas in the vapor phase. A larger Henry's law constant indicates a greater likelihood that the species in contact with water will dissolve into the liquid. For example, H_2O_2 and HNO_3 are quickly solvated in water, while the solvation process for NO and O_3 is slow. Henry's law was implemented into *nonPDPSIM* in the following manner. The interface between the gas and liquid phases is located by determining liquid mesh points, j, that have gas phase mesh points i as at least one neighbor. For diffusive transport from the gas into the liquid, the diffusion coefficient between i and j is given by

$$D_{ij} = D_i\left(\frac{hn_i - n_j}{hn_i}\right) \tag{11}$$

Where D_i is the diffusion coefficient in the gas phase, n_i and n_j are the densities of the species in the gas and water, and h is Henry's law constant. This effectively shuts off diffusion into the water when the equilibrium density at the surface is reached.

Due to their higher potential energies, we assumed that all ions, as well as electrons, and pass directly into the liquid. That is, the liquid mesh point having a gas phase mesh point as a neighbor receives charged species with a rate of diffusion (or drift in the electric field) given by their gas phase transport coefficients. For these species the diffusion coefficient for transport into the liquid is given by the gas phase values. For transport of the charged species out of the liquid into the gas, the liquid transport coefficients are used, which effectively traps the charged species in the liquid. From a practical perspective, the diffusion out of the water of dissolved gas phase ions or electrons is highly unlikely since their rates of solvation or charge exchange are large.

The exception to these practices is the evaporation of the liquid. We do not explicitly address the surface tension of the liquid-gas interface. Instead, we assume that the gas phase density of liquid vapor at the liquid surface is given by its saturated vapor pressure, which is 27 Torr at 300 K for water. The corresponding vapor density is then used as a boundary value for diffusion of the liquid vapor from the interface into the gas.

Appendix A – Publications and Presentations Acknowledging DOE Support

(Note: A subset of these publications and presentations were co-sponsored by DOE Grant DE-SC0001939.)

Refereed Journal Publications

1. N. Y. Babaeva and M. J. Kushner, "Intracellular Electric Fields Produced by Dielectric Barrier Discharge Treatment of Skin", J. Phys. D **43**, 185206 (2010).
2. B. S. Sommers, J. E. Foster, N. Yu. Babaeva and M. J. Kushner, "Observations of electric discharge streamer propagation and capillary oscillations on the surface of air bubbles in water", J. Phys. D. **44** 082001 (2011).
3. N. Y. Babaeva and M. J. Kushner "Ion Energy and Angular Distributions onto Polymer Surfaces Delivered by Dielectric Barrier Discharge Filaments in Air: I. Flat Surfaces", Plasma Source Sci. Technol. **20**, 035017 (2011).
4. N. Y. Babaeva and M. J. Kushner "Ion Energy and Angular Distributions onto Polymer Surfaces Delivered by Dielectric Barrier Discharge Filaments in Air: II. Particles", Plasma Source Sci. Technol. Plasma Source Sci. Technol. **20**, 035018 (2011).
5. Z. Xiong and M. J. Kushner, "Ionization Wave Splitting at the T-Junction of a Dielectric Channel", Trans. Plasma Sci. **39**, 2320 (2011).
6. N. Y. Babaeva and M. J. Kushner, "Dynamics of Dielectric Barrier Discharges Over Wounded Skin", Trans. Plasma Sci. **39**, 2964 (2011).
7. M. Wang, J. E. Foster and M. J. Kushner, "Plasma Propagation through Porous Dielectric Sheets", Trans. Plasma Sci. **39**, 2244 (2011).
8. B Niermann, T Hemke, N Y Babaeva, M. Boke, M. J. Kushner, T Mussenbrock, and J Winter, "Helium Metastable Dynamics in Sheath or Bulk Dominated rf Micro-plasma Jets", J. Phys. D. **44**, 485204 (2011).
9. N. Yu. Babaeva, N. Ning, D. B. Graves and M. J. Kushner "Ion Activation Energy Delivered to Wounds by Atmospheric Pressure Dielectric Barrier Discharges: Sputtering of Lipid-like Surfaces", J. Phys. D. **45,** 115203 (2012).
10. Z. Xiong and M. J. Kushner, "Atmospheric pressure ionization waves propagating through a flexible high aspect ratio capillary channel and impinging upon a target", Plasma Sources Sci. Technol. **21** 034001 (2012).
11. S. Samukawa, M. Hori, S. Rauf, K. Tachibana, P. Bruggeman, G. Kroesen, J. Ch. Whitehead, A. B. Murphy, A. F. Gutsol, S. Starikovskaia, U. Kortshagen, J.-P. Boeuf, T. J. Sommerer, M. J. Kushner, U. Czarnetzki and N. Mason, "The 2012 Plasma Roadmap (Review Article)", J. Phys. D: Appl. Phys. **45**, 253001 (2012).
12. Z. Xiong, E. Robert, V. Sarron, J-M. Pouvesle and M. J. Kushner. "Dynamics of Ionization Wave Splitting and Merging of Atmospheric Pressure Plasmas in Branched Dielectric Tubes and Channels", J. Phys. D. **45**, 275201 (2012).
13. N. Y. Babaeva and M. J. Kushner, "Reactive Fluxes Delivered by Dielectric Barrier Discharge Filaments to Slightly Wounded Skin", J. Phys. D. **46**, 025401 (2013).
14. N. Yu. Babaeva and M. J. Kushner, "Control of Ion Activation Energy Delivered to Tissue and Sensitive Materials In Atmospheric Pressure Plasmas Using Thin Porous Dielectric Sheets", J. Phys. D. **46**, 125201 (2013).

15. Z. Xiong, E. Robert, V. Sarron, J.-M. Pouvesle and M. J. Kushner, ”Atmospheric Pressure Plasma Transfer Across Dielectric Channels and Tubes”, J. Phys. D. **46**, 155203 (2013).
16. W. Tian, K. Tachibana and M. J. Kushner, “Plasmas Sustained in Bubbles in Water: Optical Emission and Excitation Mechanisms”, J. Phys. D. **47**, 055202 (2014).
17. N. Yu. Babaeva and M. J. Kushner, “Interaction of Multiple Atmospheric Pressure Micro-plasma Jets in Small Arrays: He/O_2 Into Humid Air”, Plasma Source Sci. Technol. **23**, 015007 (2014).
18. W. Tian and M. J. Kushner, “Atmospheric pressure dielectric barrier discharges interacting with liquid covered tissue”, J. Phys. D. **47**, 165201 (2014).
19. N. Yu. Babaeva, W. Tian and M. J. Kushner “The Interaction Between Plasma Filaments in Dielectric Barrier Discharges and Liquid Covered Wounds: Electric Fields Delivered to Model Platelets and Cells”, to be published in J. Phys. D.

<u>Book Chapters</u>

M. J. Kushner and M. Kong, “Fundamentals of non-Equilibrium Plasmas” in Plasma Medicine: Applications of Low-temperature Gas Plasmas in Medicine and Biology”, ed. M. Laroussi, M. G. Kong, G. Morfill and W. Stolz (Cambridge, United Kingdom, 2012).

<u>Invited Conference and Workshop Presentations with Proceedings</u>

1. M. J. Kushner “Fundamentals of Gas Phase Plasmas for Treatment of Human Tissue”, MMVR18/NextMed (Medicine Meets Virtual Reality Conference), Newport Beach, CA, February 2011.
2. Zhongmin Xiong, Natalia Yu. Babaeva, Wei Tian and Mark J. Kushner, “Interaction of High Pressure Plasmas with their Boundaries: Channels, Tubes, Liquids and Tissue”, 30^{th} Int. Conf. on Phenomena in Ionized Gases, Belfast, N. Ireland, Sept. 2011.
3. S-H. Song , M. D. Logue , Y. Zhang , P. Tian and M. J. Kushner, “Control of Electron, Ion and Photon Distributions in Low Pressure Plasmas Using Pulsed Power”, XXI Europhysics Conference on the Atomic and MolecularPhysics of Ionized Gases, Viana de Castelo, Portugal, July 2012.
4. J. P. Booth, N. Sirse, P. Chabert, P. Indelicato, A. Surzhykov and M. J. Kushner, “Dynamics of Cl_2 Inductively Coupled Plasmas: The Role of Electronic and Vibrational Excitation”, 10^{th} Frontiers in Low Temperaure Plasma Diagnostics, Rolduc, Kerkrade, The Netherlands, April 2013.
5. J. P. Booth, P. Chabert, N. Sirse, P. Indelicato, A. Surzhykov and M. J. Kushner, “Optical Diagnostics of Low-Pressure Plasmas Sustained in Halogen Gases”, 31^{st} International Conference on Phenomena in Ionized Gases, Granada, Spain, July 2013.
6. M. J. Kushner, “Plasma-Surface Interactions with Complex Materials: Inorganic, Liquid and Organic (Living) Surfaces”, 8^{th} International Conference on Reactive Plasmas, Fukuoka, Japan, (Plenary), February 2014.

<u>Invited Conference and Workshop Presentations with Abstracts Only</u>

1. N. Yu Babaeva, Y. Yang, and M. J. Kushner, “Plasma Sources at the Extremes: Large Areas to Liquid Densities", 6th Asia-Pacific International Symposium on the Basics and Applications of Plasma Technology, Hsinchu City, Taiwan, December 2009.
2. N. Yu Babaeva and M. J. Kushner, “Modeling DBD-Plasma Surface Interactions”, AFOSR Plasma Actuator Workshop, Gainesville, FL, February 2010.

3. M. J. Kushner, “Controlling the Properties of Low Temperature Plasmas: The Role of Modeling in Investigating the Science and Developing the Technology”, APS Division of Atomic, Molecular and Optical Physics Annual Meeting, Houston, TX, May 2010.
4. N. Yu. Babaeva and M. J. Kushner, “A Computational Study of Interactions of Multiple Plasma Filaments in DBDs with Human Skin”, IEEE International Conference on Plasma Science, Norfolk, VA, June 2010.
5. M. J. Kushner and N. Yu. Babaeva “Plasmas in Bubbles in Liquids and Streamers Intersecting with Liquids”, 20th European Conference on the Atomic and Molecular Physics of Ionized Gases (ESCAMPIG), Novi Sad, Serbia, July 2010.
6. Y. Yang, N. Yu. Babaeva, S-H. Song, J Shoeb and M. J. Kushner, “Controlling Plasmas for Nanofabrication and Plasma Treatment of Living Tissue”, 18th International Vacuum Congress, Beijing, China, August 2010.
7. N. Yu Babaeva and M. J. Kushner, “Models for the Interaction of Dielectric Barrier Discharges With Exposed Cells and Tissues Under Liquids”, 3rd International Conf. on Plasma Medicine, Griesfwald, Germany, September 2010.
8. M. J. Kushner, “The Role of Modeling in Developing New Plasma Technologies: Microelectronics to Plasma Medicine and Liquids”, 63rd Gaseous Electronics Conference, Paris, France, October 2010. (Plenary)
9. N. Yu. Babaeva, S-H. Song, J. Shoeb, M. Wang, J.-C. Wang, and M J. Kushner, “Controlling Plasma Sources: Nano to Bio.” 57th American Vacuum Society International Symposium, Albuquerque, NM, October. 2010.
10. N. Yu. Babaeva, Z. Xiong, W. Tian and M. J. Kushner, “Fundamentals of Plasma Tissue Interactions: Control and Delivery of Radicals, Ions and Electric Fields”, 1st International Symposium of Plasma Biosciences, Seoul, Korea, August 2011.
11. M. J. Kushner, “Accomplishing the Difficult with Atmospheric Pressure Plasmas: High Value Depositon (and NBC Cleanup)”, DARPA Workshop on Atmospheric Pressure Weakly Ionized Plasmas for Energy Technologies, Flow Control and Materials Processing, Princeton, New Jersey, August 2011.
12. N. Yu. Babaeva and M. J. Kushner, “Challenges in Modeling of Plasma Interactions in Medicine and Biology: What Insights Can You Expect?”, 58th American Vacuum Society International Symposium, Memphis, TN, October. 2011
13. N. Yu. Babaeva, Z. Xiong, W. Tian, N. Ning, D. B Graves and M. J Kushner, “Modeling the Interaction of Plasmas with Tissues and Wounds”, Materials Research Spring Symposium, San Francisco, CA, April 2012.
14. N. Yu. Babaeva, Z. Xiong, J. Wang and M. J. Kushner, “Modeling Studies of Microplasmas on and Near Surfaces: Surface Hugging, Crack Penetrating, Endoscopy…and Print Engines”, Workshop on Stability and Instabilities of Microplasmas, Ruhr-Universität, Bochum, Germany, May 2012.
15. M. J. Kushner”, Model Based Design for Non-Equilibrium Plasmas: Reality, Expectation or Fantasy?”, 12th European Plasma Conference: High-Tech Plasma Processing, Bologna, Italy, June 2012.
16. N. Yu. Babaeva, Z. Xiong, E. Robert, V. Sarron, J.-M. Pouvesle, and M. J. Kushner, “Conformal Atmospheric Pressure Plasmas for Biomedical Applications: Along Surfaces, Inside Tubes and Penetrating Cracks”, 4th International Conference on Plasma Medicine,

Orleans, France, June 2012.

17. E. Robert, V. Sarron, L. Brullé, D. Riès, M. Vandamme, S. Dozias, S. Lerondel, A. Le Pape, J.-M. Pouvesle, Z. Xiong and M. J. Kushner, ”Pulsed Atmospheric-pressure Plasma Streams produced by Plasma Gun: characterization and application for tumor treatment”, 4th International Conference on Plasma Medicine, Orleans, France, June 2012.
18. M. J. Kushner, “Low Temperature Plasmas: Photons Matter - Often Ignored but Always There", Gordon Research Conference on Plasma Processing Science, Smithfield, Rhode Island, July 2012.
19. M. J. Kushner, “Model Based Design of Low Temperature Plasma Reactors”, 26th Summer School and International Symposium on the Physics of Ionized Gases, Zrenjanin, Serbia, August 2012.
20. N. Yu. Babaeva, W. Tian, S. Norberg and M. J. Kushner, “Modeling the Interaction of Plasma with Exposed Cells and Cells and Under Liquid”, Plasma-to-Plasma Workshop, Lorentz Center, University of Leiden, Leiden, The Netherlands, January 2013.
21. W. Tian, S. Norberg, N. Y. Babaeva and M. J. Kushner, “Atmospheric Pressure Plasmas Incident onto Thin Liquid Layers”, Workshop on Plasma Surface Interactions, 66th Gaseous Electronics Conference, Princeton, NJ, October 2013.
22. M. J. Kushner, “Plasma Surface Interactions at Inorganic, Liquid and Organic (Living) Surfaces: Differences and Similarities”, Fundamentals of Plasma Surface Interactions Workshop, University of Antwerp, Antwerp, Belgium, November 2013.

Contributed Conference and Workshop Presentations with Proceedings

1. W. Tian and M. J. Kushner, “Investigation of Solvation of Radicals Produced by Microplasmas in Bubbles in Water”, 7th International Workshop on Microplasmas, Beijing, China, May 2013.
2. N. Y. Babaeva and M. J. Kushner, “Interaction of Multiple Atmospheric Pressure Microplasma Jets: He/O_2 into Air”, 7th International Workshop on Microplasmas, Beijing, China, May 2013.
3. W. Tian, S. Norberg, N. Yu. Babaeva and M. J. Kushner, “Plasma Jets and Plasmas on Liquids over Tissue”, 31st International Conference on Phenomena in Ionized Gases, Granada, Spain, July 2013.
4. W. Tian, S. Norberg, N. Yu. Babaeva and M. J. Kushner, “The Interaction of Atmospheric Pressure Plasma DBDs and Jets with Liquid Covered Tissues: Fluxes of Reactants to Underlying Cells”, 21st International Symposium on Plasma Chemistry, Cairns, Australia, August 2013.

Contributed Conference and Workshops Presentations with Abstracts Only

1. N. Yu. Babaeva and M. J. Kushner, “The Interaction of Plasma Filaments in DBDs with Wounded Skin”, IEEE International Conference on Plasma Science, Norfolk, VA, June 2010.
2. N. Yu. Babaeva and M. J. Kushner, “Plasma Filaments in DBDs: Delivery of Radicals and Energetic Ions to Wounded Skin,” Gordon Research Conference on Plasma Processing Science, New London, New Hampshire, July 2010.
3. N. Yu. Babaeva and M. J. Kushner, “Plasma Production in Liquids: Bubble and Electronic Mechanisms”, 63rd Gaseous Electronics Conference, Paris, France, October 2010.
4. N. Yu. Babaeva and M. J. Kushner, “The Consequences of Bubbles in the Electrical

Breakdown of Liquids", 57th American Vacuum Society International Symposium, Albuquerque, NM, October. 2010.

5. N. Y. Babaeva and M. J. Kushner, ""Interaction of Atmospheric Pressure Plasmas with Dry and Wet Wounded Skin", 52nd APS Division of Plasma Physics Meeting, Chicago, IL, Nov. 2010.
6. N. Yu. Babaeva and M. J. Kushner, "Direct and Indirect Treatment of Living Tissue: Dielectric Barrier Discharges vs. Plasma Jets", 38th Int. Conf. on Plasma Science, Chicago, IL, June 2011.
7. Z. Xiong and M. J. Kushner, "Simulation of Atmospheric Pressure Ionization Waves Propagating Through Flexible Capillary Tubes and Impinging onto a Target", 38th Int. Conf. on Plasma Science, Chicago, IL, June 2011.
8. Z. Xiong, N. Y. Babaeva and M. J. Kushner, "Delivering Activation Energy to Surfaces in Atmospheric Pressure Plasmas: Local and Remote", 58th American Vacuum Society International Symposium, Memphis, TN, October. 2011.
9. W. Tian and M. J. Kushner, "Streamer Initiation and Propagation in Water with the Assistance of Bubbles and Electric Field Initiated Rarefaction", 64th Gaseous Electronics Conf., Salt Lake City, UT, November 2011.
10. N. Yu Babaeva and M. J. Kushner, "Control of Ion Activation Energy to Surfaces in Atmospheric Pressure Plasmas Using Porous Dielectrics Films", 64th Gaseous Electronics Conf., Salt Lake City, UT, November 2011.
11. Z. Xiong, K. Takashima, I. V. Adamovich and M. J. Kushner, "Simulation of High Pressure Ionization Waves in Straight and Circuitous Dielectric Channels", 64th Gaseous Electronics Conf., Salt Lake City, UT, November 2011.
12. T. Hemke1, J. Trieschmann, A. Wollny, N. Y. Babaeva, M. J. Kushner, R. P. Brinkmann1, T. Mussenbrock, "Numerical Simulation of a Coaxial Microplasma Jet at Atmospheric Pressure", 39th IEEE Conference on Plasma Science, Edinburg, Scotland, July 2012.
13. E. Robert, V. Saron, D. Ries, S. Dozias, J. -M. Pouvesle, Z. Xiong and M. J. Kushner, "Pulsed Atmospheric Pressure Plasma Streams: Characterization and Role of Critical Experimental Parameters", 39th IEEE Conference on Plasma Science, Edinburg, Scotland, July 2012.
14. W. Tian and M. J. Kushner, "Images and Optical Spectra of Discharges Sustained in Bubbles in Water", Gordon Research Conference on Plasma Processing Science, Smithfield, Rhode Island, July 2012.
15. W. Tian, P. Tian, V. M. Donnelly, D. Economou, D. B. Graves, G. Oehrlein and M. J. Kushner, "Photons: Semiconductor Processing and Plasmas-on-Water", 4th Annual Meeting, DOE Center on Control of Plasma Kinetics, University of Maryland, May 2013.
16. Z. Xiong, E. Robert, V. Sarron, J-M. Pouvesle and M. J. Kushner, "Atmospheric Pressure Plasma Transfer of Jets and Bullets", 4th Annual Meeting, DOE Center on Control of Plasma Kinetics, University of Maryland, May 2013.
17. W. Tian and M. J. Kushner, "The Interaction of Atmopsheric Pressure Plasmas With Liquid Covered Tissues", 40TH International Conference on Plasma Science, San Francisco, CA, June 2013.
18. N. Yu. Babaeva and M. J. Kushner, "Arrays of Atmospheric Pressure Micro-Plasma Jets:

He/O_2 and Ar Jets into Air", 40TH International Conference on Plasma Science, San Francisco, CA, June 2013.

19. S. A. Norberg, E. Johnsen and M. J. Kushner, "Reactive Oxygen and Nitrogen Species (RONS) Produced by Repetitive Pulses in Atmospheric Pressure Plasma Jets", 40TH International Conference on Plasma Science, San Francisco, CA, June 2013.
20. P. Tian, S.-H. Song, M. J. Kushner and S. Macheret, "Properties of Bipolar DC-Pulsed Microplasmas at Intermediate Pressures", 40TH International Conference on Plasma Science, San Francisco, CA, June 2013.
21. W. Tian, S. Norberg, N. Y. Babaeva and M. J. Kushner, "Atmospheric Pressure Plasmas Incident onto Thin Liquid Layers", 66th Gaseous Electronics Conference, Princeton, NJ, October 2013.
22. S. Norberg, A. Schmidt-Bleker, J. Winger, S. Reuter, E. Johnsen and M. J. Kushner, "Controlling Reactive Oxygen and Nitrogen Species (RONS) Production by Atmospheric Pressure Plasma Jets Using Gas Shields", 66th Gaseous Electronics Conference, Princeton, NJ, October 2013.
23. W. Tian and M. J. Kushner, "Atmospheric Pressure Dielectric Barrier Discharge Interaction with Wet Tissue – Modeling Long(er) Term Exposure", 1st International Workshop on Plasma for Cancer Treatment, Washington DC, March 2014.
24. S. Norberg and M. J. Kushner, "Plasma Jet Interactions with Dry and Wet Tissue", 1st International Workshop on Plasma for Cancer Treatment, Washington DC, March 2014

Invited Symposia, Seminar and Short-Course Presentations

1. M. J. Kushner, "Controlling Low Temperature Plasmas: From Nanofabrication to Plasma Medicine", Dept. Mechanical Engineering Seminar, University of Minnesota, January 2011.
2. M. J. Kushner, "Controlling Plasmas and Leveraging Technologies in Plasma Materials Processing: Nanofabrication to Plasma Medicine", Agilent Technologies, Palo Alto, CA, April 2011.
3. M. J. Kushner, "Controlling Low Temperature Plasmas: From Nanofabrication to Plasma Medicine", Electrical Engineering Department Symposium, Clemson University, Clemson, South Carolina, April 2011.
4. M. J. Kushner, "Controlling Low Temperature Plasmas: From Nanofabrication to Plasma Medicine", American Vacuum Society, Michigan Chapter, Ann Arbor, April 2011.
5. M. J. Kushner, "Delivering Activation Energy in Low Temperature Plasmas for Nanofabrication and Plasma Medicine", Chemical Engineering Department Symposium, University of Houston, Sept. 2011.
6. M. J. Kushner, "It is all about Control: Plasmas for Nanofabrication and Plasma Medicine", Applied Physics Program Seminar, University of Michigan, November 2011.
7. M. J. Kushner, "Controlling Fluxes to Surfaces in Atmospheric Pressure Plasmas: Printing, Polymer Processing, Liquids and Medicine", Hewlett-Packard Research Labs, Palo Alto, CA, February 2012
8. M. J. Kushner, "It is all about Control: Plasmas for Nanofabrication and Plasma Medicine", Plasma Physics Division Symposium, Naval Research Laboratory, Washington, DC, February 2012.
9. M. J. Kushner, "It is all about Control: Plasmas for Nanofabrication and Plasma Medicine",

Dept. Seminar, Electrical and Computer Engineering, Michigan State University, February 2012.

10. M. J. Kushner, "Low Temperature Plasmas and Surfaces: Microelectronics, Sterilization, Endoscopy and Printer Engines", Distinguished Lecture Series, University of Toronto, Dept. of Mechanical and Industrial Engr., Toronto, CA, Sept. 2012.
11. M. J. Kushner, "Low Temperature Plasmas and Surfaces: Microelectronics, Sterilization, Endoscopy and Printer Engines", Aerospace and Mechanical Engineering Dept. Seminar, University of Notre Dame, South Bend, IN, December 2012.
12. N. Yu. Babaeva, P. Tian, W. Tian and M. J. Kushner, "Low Temperature Plasmas and Photons (Ever Present, Always Important, Sometimes Neglected): Materials Processing, Plasma Medicine, Liquids", Agilent Technologies, Corporate Seminar, Palo Alto, CA, July 2013.
13. M. J. Kushner, "Atmospheric Pressure Discharges", Summer School on Fundamentals of Low Pressure and High Pressure Plasmas", 21st International Symposium on Plasma Chemistry, Cairns, Australia, August 2013.
14. M. J. Kushner, "Plasma Modeling Techniques", Summer School on Fundamentals of Low Pressure and High Pressure Plasmas", 21st International Symposium on Plasma Chemistry, Cairns, Australia, August 2013.
15. M. J. Kushner, "Low Temperature Plasma-Surface Interactions with Complex Materials: Inorganic, Liquid and Organic (Living) Surfaces", Plasma Physics Seminar, University of Wisconsin, March 2014.