A White Paper to the 2014 FESAC Strategic Planning Panel

A Low Temperature Plasma Science Program: Discovery Science for Societal Benefit

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Abstract

The current status of low temperature plasmas (LTPs) as a research area and technology driver producing societal benefit is discussed. The current science challenges are discussed in the context of the extreme dynamic range and intellectual diversity of the field of LTPs. The case is made that given this extreme dynamic range of science challenges and the broad range of motivating technology areas, it is neither possible nor prudent to define a single science discovery challenge that covers the entire field of LTPs. Given these conditions, we propose that the DOE Office of Fusion Energy Science, perhaps in partnership with the Office of Basic Energy Sciences, fund a broad science program in LTPs having an annual solicitation. The current science challenges would then be defined by the proposers. After a 3-year ramp-up period, the steady state funding level would be $5,000,000/year. Comparisons are made to international activities in LTPs.

Introduction to Low Temperature Plasmas:

Low temperature plasmas (LTPs) are the plasmas of eV physics and eV technologies. LTPs address plasmas whose characteristic electron temperatures are a few to 10 eV and whose fractional ionizations are typically small. Since LTPs have electron temperatures commensurate with the threshold energies of excited states in neutral atoms and molecules, power transfer from electrons to these atoms and molecules efficiently produces activated species (e.g., radicals, excited states, photons). Acceleration of ions in the sheaths of LTPs to energies of tens to hundreds of eV enable activation of surface modifying processes – sputtering, etching, deposition. With such properties, LTPs are often and beneficially used in technological devices, ranging from etching and deposition in microelectronics fabrication to surgical instruments.

LTPs are also typically non-equilibrium, meaning that the electron temperature, T_e, is much larger than the ion temperature, T_i, which is in turn larger than the gas temperature, T_g. Due to the partially ionized nature of LTPs, even though some of the particles are extremely energetic (i.e., electrons and often the ions), the specific energy content of the plasma is low because the energy content is dominated by the far more abundant neutral gas. This situation provides a unique set of conditions wherein plasma species can be non-destructively and beneficially in contact with surfaces. For example, the entire microelectronics industry that forms the technological base of modern society is enabled by beneficial plasma-surface interactions which deposit and remove materi-

Science Challenge - *Advanced Diagnostics:* Interrogation of dynamic and structured plasmas over a broad dynamic range of time (< ns to s) and space (μm to m) is an underlying, cross-cutting challenge in LTP science. Knowing where and how energy is deposited is essential for controlling the production of excited states, chemical reactivity and surface functionality. Since the applications are diverse, a broad range of methods are needed to non-intrusively probe LTPs. New diagnostic methods are needed to keep pace with the evolution of the needs of the LTP community.

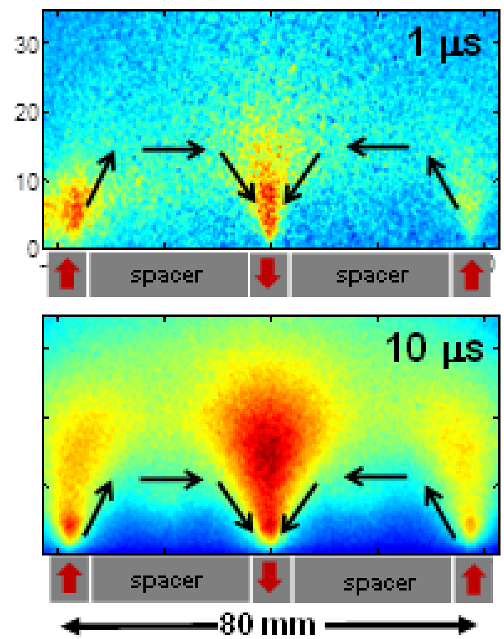

Figure 1 – LIF measurements of the evolution of He excited states above a magnetic cusp.

als with nm resolution in the fabrication of microprocessors.[1] This beneficial contact with surfaces now extends to liquids, such as plasma activated water, which has enabled the new field of plasma medicine.[2,3] LTPs may also non-destructively and beneficially interact with surfaces internal to the plasma, such as in a particle or aerosol laden "dusty" plasma. This is an example of a multi-phase plasma.[4] The concept of multi-phase LTPs extends to plasma sustained within liquids, now being investigated for chemical processing and medical applications. [5]

Science challenge – *Kinetics at Reactive Surfaces*: Understanding the kinetics of chemically reactive LTPs at solid-vapor and liquid-vapor interfaces will required *in situ* "full" characterization (time-resolved electric field, electron density and temperature, gas temperature, species concentrations distributions) of the plasma along with predictive kinetic model development and validation. Applications include biomedical applications, plasma reforming of evaporating liquid fuels and "dry and wet chemistry" plasma materials processing.

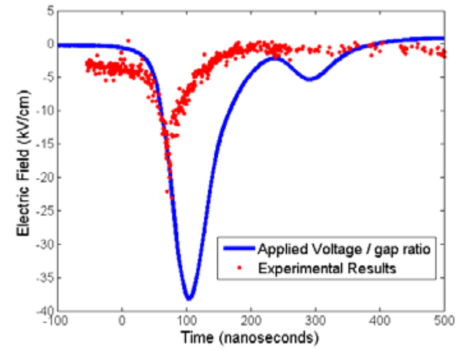

Figure 2a - Time-resolved electric field in a ns pulsed H_2 plasma measured by ps CARS / 4-wave mixing with 0.2 ns resolution.

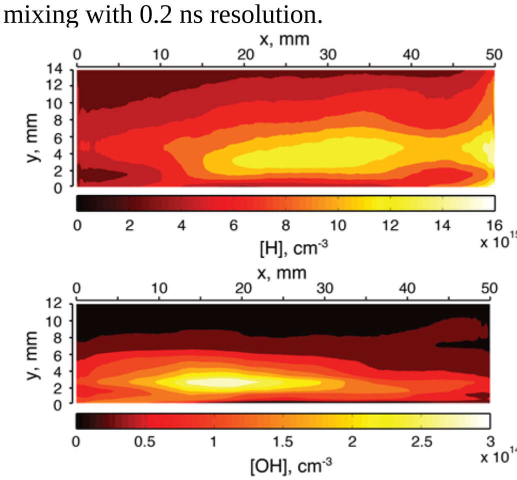

Figure 2b - 2D, absolute distributions of H and OH in ns pulse, surface ionization wave plasmas sustained over liquid water in Ar buffer, measured by LIF / TALIF.

Societal Impact:

LTPs harbor fundamental science issues that are intellectually challenging and rewarding. At the same time, there are enormous and understated societal benefits that are enabled by LTPs. The entire present-day and future information technology (IT) infrastructure owes its very existence to LTPs.[1] In 2012, 12% of the electricity generated in the US was expended by lighting and about 2/3 of that was expended in LTP lighting sources.[6] If not for the efficiencies enabled by these LTP lighting sources, we would require as many as 30 more 1-GW electrical power plants in the US. Renewable energy sources, such as solar cell arrays, could not be economically produced in the absence of deposition and etching by LTPs.[7] These plasma processes also allow ever more advanced computers and microprocessors to be produced and applied to a range of energy-saving control functions. High efficiency jet engines, military and commercial, would not exist in the absence of thermal barrier coatings produced by LTPs.[8] Spacecraft to the outer planets rely on propulsion from LTPs.[9] A vast array of other technologies also would not exist, at least economically, in the absence of LTPs, including liquid crystal display (LCD) panels, mass produced polymer sheets, IR-filtering glazing on windows, hardened metals for human implants and industry, pollution abatement devices and high power lasers. Arrays of micro-plasmas are now used for sterilization and disinfection. The biotechnology and tissue engineering disciplines rely on LTPs for producing biocompatible surfaces.[10] Now, there is an entirely new field of medicine in which atmospheric pressure plasmas are applied directly to human tissue for wound healing and cancer treatment.[3]

It is true that modern society would not be as advanced in the absence of LTPs – imagine what *high technology* would mean if microelectronics were limited to early 1990s technologies, jet engines had not advanced since the days of the Boeing 707 and advanced human prosthesis and implants were still objects of research. The societal benefit resulting from LTPs is staggering.

Economic Impact:

Although the solicitation for white-papers did not ask for an assessment of the impact of the activity on economic competitiveness, the impact of LTPs on economic competitiveness is undeniable through the technologies that are uniquely enabled by LTPs. An exhaustive analysis of the impact of LTPs on the US economy has not been performed and so quantifying the impact on economic competitiveness is difficult. This exhaustive economic analysis was, however, performed for Germany.[11] This study is 10 years old and so the numbers are conservative estimates of the minimum impact of LTPs since the technology fields enabled by LTPs have significantly expanded in those 10 years. To provide guidance, we will highlight the impact of LTPs on economic competitiveness in the US by analogy to Germany, a highly technologically developed western economy that in many ways resembles that of the US. We will quote figures for Germany and in parenthesis include estimates for the US based on the ratios of 2007 Gross Domestic Product (Germany GDP = \$3.32 Trillion, US GDP = \$13.81 Trillion, ratio = 4.2).[12] Based on the 2004 study, 70,000-80,000 jobs in Germany (US: 290,000-330,000) can be directly attributed to plasma technologies. There are 500,000 jobs in Germany (US: 2,080,000), or 7% of the manufacturing workforce, enabled by plasma technologies. This represents \$64 billion (US: \$266 billion) to the German economy with an estimated annual growth of 10%. The conservatism of this estimate is indicated by the fact that the information technology industry in the US which is enabled by LTPs contributed nearly \$1 Trillion (\$954 billion) to US GDP in 2012.[13]

Science Challenge – *The Gas phase – Liquid phase Plasma Interface.* The manner in which a plasma transitions between the gas phase and the liquid phase is poorly understood. Understanding these complex processes at atmospheric pressure will required a coupled experimental and modeling approach. This science challenge is one of the highest priorities of the LTP field.

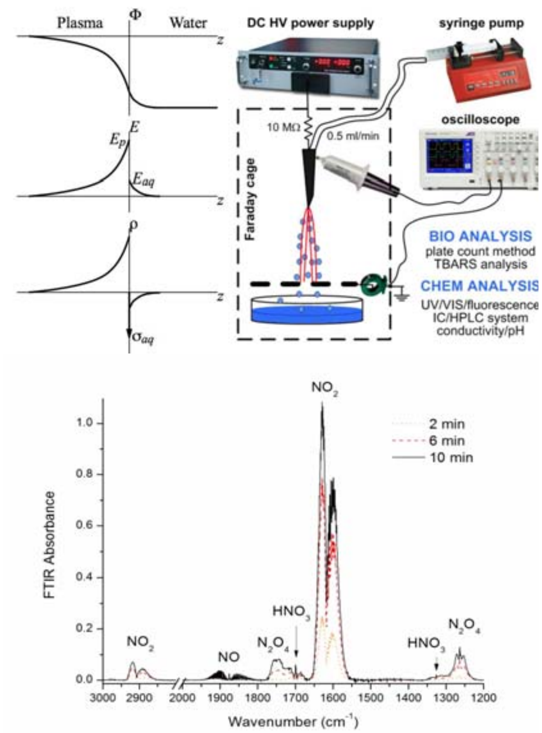

Figure 3 - (top left) Anticipated charge densities, electric fields, and potentials near the plasma-water interface. (top right) Experimental system investigating plasma-water droplet interactions using electrospray and pulsed/transient streamers and sparks. (bottom) FTIR spectrum of gas phase species from air plasma.

Science Challenges:

It is also true that LTPs have been the source of many of the fundamental principles that form the basis of other fields of plasma physics. For example, the fundamental concepts of electron and ion transport, cyclotron resonance, electromagnetic wave interactions with plasmas, electrical probes, interferometric diagnostics, charged particle distribution functions, high energy beam produced plasmas, laser-induced-fluorescence, radiation transport in plasmas and non-ideal plasmas were all first developed (and continue to be developed) in the context of LTPs. The field of LTPs continues to hold extreme science challenges, largely centered on the control of power through the plasma for the selective production of excited states, ions, photons and surface reactivity. These prioritized science challenges were summarized in the DOE Workshop report *Low Temperature Plasma Science: Not Only the Fourth State of Matter but All of Them* [14] and appear in Appendix A. Several of the current science challenges are discussed in the text boxes appearing throughout this document.

In acknowledgment of the importance of LTPs, the Department of Energy Office of Fusion Energy Sciences (OFES) opened the 2009 competition for Plasma Science Centers to LTPs. In responding to the call for proposals, the LTP community very seriously considered the recommendations of the Decadal

Plasma 2010 report *Plasma Science: Advancing Knowledge in the National Interest* [15] and the DOE Workshop [14] which speak to the unifying science challenges of obtaining a predictive capability for the reactive, multi-species, multi-phase and bounded systems encountered in LTPs. OFES initiated the Plasma Science Center for ***Predictive Control of Plasma Kinetics: Multi-Phase and Bounded Systems*** in August 2009 with a 5 year grant period. (See the *Center* website at *http://doeplasma.eecs.umich.edu* .) The fundamental science issues addressed by the *Center* revolve about control of the distributions of energetic particles in LTPs. LTPs interact with atoms and molecules for the purpose of producing excited states, radicals and photons, with surfaces for the purpose of beneficially modifying their properties, and with dust particles in multi-phase plasmas. These interactions ultimately depend on the shape and evolution of the charged particle (electron, positive ion and negative ion) velocity distributions, $f(\vec{r},\vec{v},t)$. Due to the partially ionized nature of LTPs, these velocity distributions are dominantly non-Maxwellian. As a result, there is an opportunity to uniquely craft $f(\vec{r},\vec{v},t)$ to achieve a desired rate of interaction. In fact, lying at the very heart of advancing LTP science is the ability to predictably control and shape $f(\vec{r},\vec{v},t)$ for beneficial interaction with atoms, molecules, and solid-and-liquid phases. Obtaining this predictive control is an incredibly challenging goal, *a grand challenge,* considering the extreme diversity and complexity of the field. The *Center* has made considerable progress towards this goal.

Science Challenge – *Plasma Interaction with Soft Matter (cells):* Interaction of low-temperature plasmas with living organisms is the foundation of the rapidly emerging plasma medicine field. Plasma interactions with cells lead to activation of various pathways forming a solid basis for plasma application in cancer therapy, wound healing, HIV therapy etc. Knowing where and how various reactive species are formed is critical for controlling their production efficiency and plasma composition effectively enabling control of the plasma interaction with soft matter.

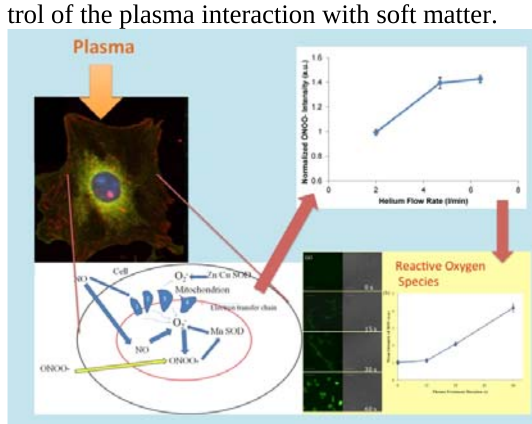

Figure 4 – Plasma interaction with cell, activation of reactive-oxygen-species (ROS) production pathways and deactivation on anti-oxidant system.

Due to the extreme dynamic range of LTPs (discussed below), there is no single overriding science challenge, beyond perhaps control of $f(\vec{r},\vec{v},t)$, that unites the field. There are, however, highly linked and intermeshing sets of science challenges that provide a broad front with which the science frontiers in LTPs are advanced. A subset of these science challenges are described in the text boxes.

Funding of LTP Science:

It is ironic that the field of LTPs that is so important to the well-being of society and harbors so many science challenges has historically been so poorly supported by the Federal government for fundamental research. It is true that industry does fund its own R&D in LTPs for specific product development purposes. University researchers often do get support from industry to aid in that very applied, plasma based technology development. However, research into the fundamental basic principles of LTPs that underlie and whose mastery is necessary for the technology development is rarely funded by industry. Supporting that fundamental research is the role of the Federal government. *However, to date, there has never been a Federal agency with a recurring program of broadly funding fundamental research in LTPs*. The exception is the *NSF/DOE Partnership in in Plasma Science (NDPPS).* However the number of awards made by the *NDPPS* in the LTP area is quite small and not sufficient to maintain research into the fundamentals of LTPs. It should be noted that essentially all subfields of plasmas that are covered by the *NDPPS except for LTPs* have another agency or program that provides the majority of their funding. LTPs is the only subfield of plasmas that does not have such a home agency or program.

The OFES should be congratulated for its willingness to include LTPs in the call for plasma science centers in response to the *Plasma 2010 Decadal Report*, and for funding the LTP *Center*. The LTP *Center* has been extremely impactful and productive in its research. Although the Co-PIs of the *Center* are extremely grateful for this support, the LTP *Center* is of a finite duration, reaches a limited subset of the LTP community and is focused on a subset of the diversity of LTP topics.

There certainly is funding by the Federal government in areas that include LTPs. This funding comes from the Department of Defense, DOE Office of Basic Energy Sciences, Environmental Protection Agency and NASA, among others. With very rare exceptions, this funding is for very specific applications which in many cases just happen to be satisfied by an LTP. For example, the EPA may have a solicitation for ways to clean aromatic-hydrocarbons (AH) from smokestacks using any technique - typically referred to as *best-available-technology (BAT)*. A researcher proposes and is funded to investigate methods to use plasmas sustained in the smokestack as a *BAT* to remove AHs from the exhaust. The deliverable of such a project is an assessment of the efficiency of plasma remediation of the AH from the exhaust. It is typically not within the statement of work of such a project to investigate fundamental plasma transport. Some fundamental investigations are no doubt performed in such projects as necessary to satisfy the statement of work and deliverables. However, such fundamental research is at best a minor by-product of the highly applied and technology oriented project. With the exception of the small number of grants provided by the *NDPSS*, there is no recurring program in the Federal government whose focus is LTPs. This situation has become more critical by the recent decision by the Engineering Division of NSF to terminate the vast majority of support of LTP applications. Prior to this decision, applications that involved LTPs were considered by the CBET (Chemical, Bioengineering, Environmental and Transport Systems) program. CBET will now only consider plasma proposals that are directly related to combustion systems.

Science Challenge – *Scaling and Miniaturization for Microplasmas:* Significant advancements have been made in the miniaturization of plasma devices to the scale of µm's, yet understanding plasma behaviors at these scales is a broad challenge for LTP plasma science. The limits of scaling have yet to be reached. With charged particle densities as high as 10^{15}-10^{17} cm^{-3} possible, the impact of pushing plasma dimensions to sub-µm scales could be profound. At these scales, the surface-to-volume ratio is extremely large, and surface processes can dominate plasma behavior. Yet, there is still much that can be learned about how electron emission (secondary, field, metastable), recombination, and charging processes interact with the discharge under such confinement, requiring new diagnostics and modeling techniques capable of probing such extreme scales.

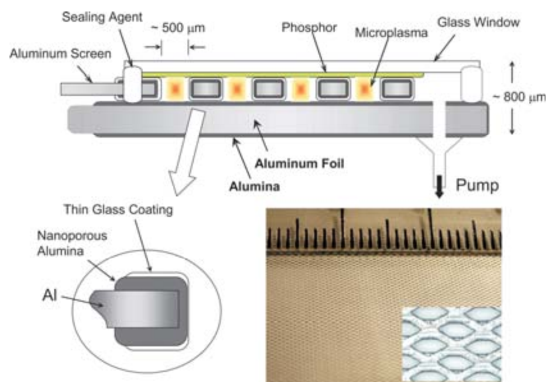

Figure 5 - Micro-plasmas tens of µm in size are the basis of advanced displays and lighting. [17]

Dynamic nature of LTPs:

LTP science is exceedingly dynamic. Although the very basic and fundamental science issues are longer lived, their context rapidly changes in response to how societal benefit is best produced. For example, during the 5½ years since the original LTP *Center* proposal was written, the main focus of LTP science has transitioned from sustaining plasmas at lower pressures to uses of plasmas at higher pressures up to 1 atm (and including liquids). This transition has been motivated, in part, by advances in the use of LTPs in material processing and human healthcare. This transition is described in the recently published *Plasma Roadmap*.[16] These motivating applications very often include multiphase systems and the interaction of atmospheric pressure plasmas with liquids. Although the fundamental science issue of controlling of $f(\vec{r},\vec{v},t)$ persists, the current context is transitioning to atmospheric pressure systems, an operating regime that had little mention in the original proposal of the LTP *Center*. This rapid transition of motivating applications is a hallmark of LTPs and, in part, is why LTPs have been so impactful in investigating the science and developing the technologies that result in societal benefit.

LTP science also covers an enormous dynamic range of operating conditions. For example, typical areas being investigated by the LTP community span a range of 10^9 in pressure (< 1 mTorr, as might be used in plasma etching, to liquid densities, as used in environmental applications and healthcare), 10^9 in spatial scale (nm, plasma transport in nano-porous material, to meters, flat panel display deposition) and 10^{12} in time (10s ps for formation of space charge layers in streamers to minutes in plasma surface interactions). The plasma chemical systems of interest number in the hundreds or even thousands, ranging from rare gases as used in displays to the multi-component gas mixtures used in microelectronics processing (e.g., $Ar/C_5F_8/O_2/CO_2/N_2$). The bounding surfaces to these plasmas range from Si surfaces to living tissue. The motivating applications range from healthcare to spacecraft propulsion. This dynamic range of scientific investigation and applications is likely unique in plasma science and perhaps unique across the physical sciences.

Science Challenge – *Controlling Plasma Reactivity for Nucleation of Nanomaterials:* Nucleation of nanoparticles having predictable properties is a critical challenge in LTP science. The size, shape, composition, crystallinity, and surface chemistry of the nanoparticles acutely depend on control of plasma produced reactivity including reactant fluxes, electron density, and temperatures (neutral, ion, and electron). Developing control schemes for nanophase plasmas coupled to nanoparticle production for use in electronics and optoelectronics (LEDs, solar cells) is a high priority science challenge.

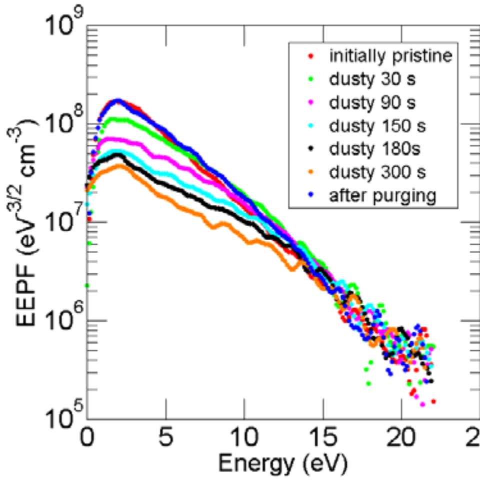

Figure 6a – Electron probability distributions in an 80 mTorr Ar/SiH_4 plasma with a growing inventory of nucleating nanoparticles.

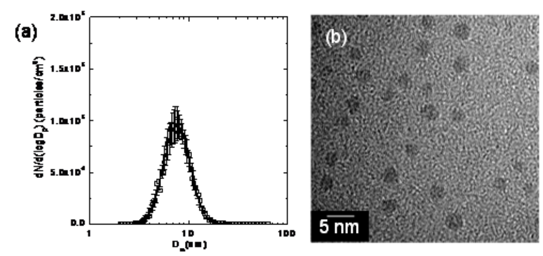

Figure 6b (left) On line aerosol mobility measurements and (right) carbon nanoparticles nucleated from ethanol vapor in an atmospheric pressure microplasma.

Workforce and International Competitiveness:

In the post WWII years, the worldwide center of LTP science was clearly in the United States. The majority of advances in the science of LTPs and development of LTP technologies came from the US. It is questionable whether that is now true. International conferences at which the LTP community reports their results (e.g., the Gaseous Electronics Conference, International Symposium on Plasma Chemistry) were once dominated by US researchers. These conferences are now dominated by European and Asian researchers. This situation has resulted from very deliberate investments by the governments of, for example, Germany, France, the Netherlands, Belgium, Italy, Portugal, Japan, China and Korea in the fundamentals and applications of LTPs over a period of decades where the US support for LTPs has diminished. For example, there are multiple research Centers in Germany (perhaps 4) with funding levels that exceed that of the DOE LTP *Center*. A similar situation exists in France where there are national initiatives in the underlying LTP science for plasma medicine and materials processing. Japan has had multiple national initiatives in LTP topics ranging from materials processing to microplasmas, and now plasma medicine. It is telling that smaller economies such as those of the Netherlands, Portugal and Belgium that have relatively limited ability to make investments in science and technology have chosen to make significant investments in LTPs. The per capita investment in LTP science technology in Europe, Japan and Korea far exceed that of the US.

The end result is that the demographics of the LTP academic community in the US lack a cadre of *early career* investigators – a situation that largely results from limited funding opportunities. Within 10 years, a significant fraction of the leading LTP researchers in US universities will have retired with few *early career* faculty to take their place. In Europe there are similar retirements taking place; however, there is also a cadre of *early career* faculty members to take their place. The UK, France, the Netherlands, Belgium, Germany, Italy, Portugal, Japan, Korea and increasingly China have all made deliberate investments in LTP science and technology by hiring *early career* professors at their leading institutions – and provided a funding source to nurture their careers. When contacted about this white paper, one of the few assistant professors in the US with a background in LTPs replied, "*My own experience is that I would prefer to spend most of my time working in the LTP field, but a lack of grant support has pushed me toward other areas. A program devoted to LTP would help myself and other early career researchers interested in LTP a great deal.*"

Science Challenge – *Predictive Control of Electron Kinetics Including Collective Effects*: Being able to predictably control velocity and energy distributions $f(\vec{r},\vec{v},t)$ based on fundamental understanding of the coupling of electromagnetic energy into low temperature plasmas underlies our ability to advance the field, control plasma chemistry and utilize LTPs for societal benefit. For example, nearly all high technology semiconductor materials processing relies on bringing to the surface a carefully crafted set of plasma produced, energy selected fluxes of ions, electrons and reactive neutral species.

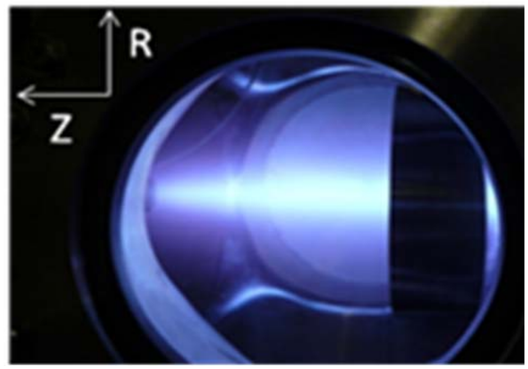

Figure 7 – Magnetized LTP in Xe that for control of $f(\vec{r},\vec{v},t)$ which separates "hot" electrons from cold electrons with a magnetic filter. Anomalous transport due to instabilities may affect the efficiency of the magnetic filter.

Proposed Program in *Low Temperature Plasma Science*:

There are high level common themes and science issues that permeate through LTPs, and these were well articulated by the LTP workshop (see Appendix A) and are highlighted in the text boxes. These are common discovery science challenges that to some degree unite the field. However, unlike other subfields of plasma science, there is not a single grand discovery science challenge (e.g., reconnection, HED equation of state) that captures the majority of the field. Given these unique set of conditions, we can state the following with confidence:

- *A common discovery science challenge in LTPs is controlling the flow of power through the plasma to produce desired excited states, chemical reactivity and surface functionality.*
- *However, given the extreme intellectual diversity that defines the field of LTPs (dynamic ranges of 10^9, motivating applications from healthcare to nanoscience), it is not possible to distill this intellectual diversity into a narrowly defined scientific challenge that covers the entire field.*
- *Society and plasma science are better served by capitalizing on the dynamic nature and intellectual diversity of LTPs through funding a general LTP science program having a broad annual solicitation – and let the current science challenges be defined by the proposers.*
- *The proposed program will not only address an imbalance in US research capabilities and critical workforce issues, it would also enable crucially important leveraging with, for example, US start-up companies and established industries. The proposed LTP program will enable fundamental investigations in LTP science, establishing and maintaining the infrastructure, both equipment and human, that in turn enables research groups to engage in more focused applied research with companies.*

We propose that the DOE Office of Science through the auspices of the Office of Fusion Energy Science (OFES), perhaps in partnership with Basic Energy Sciences (BES), become the home agency for low temperature plasmas (LTPs). In this role, the OFES would sponsor a general low temperature plasma science program having an annual solicitation with a broad call for proposals addressing the science of LTPs, with motivation by society benefiting technologies. The program would be funded at a minimum level of $5,000,000/year in the steady state. For an average annual grant of $125,000 - $150,000 per principle investigator, 35-40 projects could be continuously supported. Assuming 3-year grants, the program would ramp up from $1,670,000 in year 1, to $3,340,000 in year 2 and $5,000,000 in year 3. This would phase in over-lapping sets of 3-year grants in the steady state where 1/3 of the grants are recompeted every year. We propose this level of funding for 5 years after which the LTP program will be evaluated. A successful evaluation would then increase funding to $7,500,000 over the next 3 years.

The current LTP Plasma Science *Center* has been exceedingly successful due to the collaborations that all of the co-PIs of the center take part in. Every member of the *Center* collaborates with other members in some form. The impactful, discipline-leading research performed by the *Center* has largely resulted from the benefits of these collaborations. It is our recommendation that some form of *center-like* research be retained in the proposed LTP program. At one extreme, this could take the form of a formal center operating as the current *Center* operates. At the other extreme, the LTP program could be operated as a research collective with annual meetings where the currently funded PIs and invited guests share their results and formalize potential collaborations.

Science Challenge – *Coupled Interactions of Ions, Electrons, Photons, and Neutral Species with Surfaces Immersed in Plasmas:* The interactions between charged and neutral species and photons with semiconductor, insulator, and metal surfaces have recently been found to be more complex than was previously realized. Polymer surfaces can be degraded by simultaneously impinging ions and ultraviolet (UV) photons. The probability for UV-induced photoemission of electrons from surfaces is a strong function of the nature of the surface, which is a dynamic function of charged and neutral species impingement. Under the right conditions, highly anisotropic etching of nano-scale features can be obtained with in-plasma photo-assisted etching. Such synergies are also believed to be important in atmospheric pressure plasmas used for medical and materials processing applications. Understanding and controlling these linkages is a daunting science challenge.

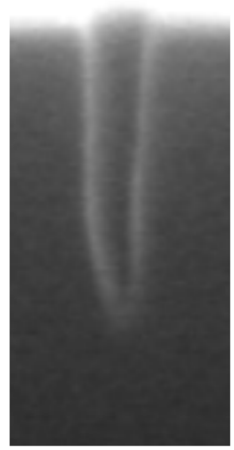

Figure 8 – Micrograph of a 150 nm deep hole etched into silicon in a chlorine microwave plasma when photo-assisted etching dominates.

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Science Challenge – *Development of Next Generation Plasma Sources:* Novel plasma sources with controllable properties can extend plasma enhanced manufacturing processes to a broader range of applications with greater societal impact. Plasma sources from mTorr to atmospheric pressure must be developed based on fundamental understanding at the kinetic level of heating mechanisms, plasma-wave interactions and sheath dynamics.

Figure 9a - Atmospheric pressure plasma hydroxyl generator for environmental and medical applications utilizing VHF ballasting.

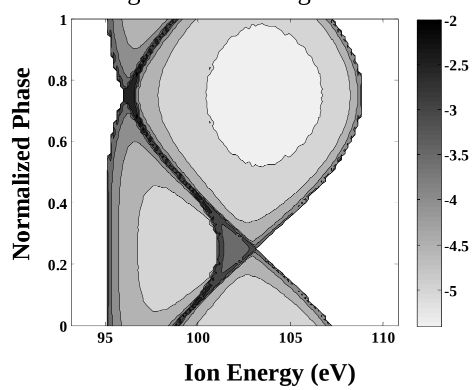

Figure 9b - Theoretical ion energy control using phase-locked harmonic power delivery for next generation electronic devices.

Appendix A: Prioritized Science Challenges from the DOE Workshop "Low Temperature Plasma Science: Not Only the Fourth State of Matter but All of Them" [14]

http://science.energy.gov/~/media/fes/pdf/about/Low_temp_plasma_report_march_2008.pdf

Priority 1: Predictive control of plasma kinetics

Plasma kinetics underlie the fundamental means of transport in and utilization of LTPs, and the generation of chemically reactive species. These kinetic processes are ultimately expressed in the ability to craft and control the distributions of velocities and energies of electrons and ions; and, in some cases, neutral particles that originate as ions. The character of these distributions will determine the efficiency with which power is transferred from electromagnetic and electrostatic fields to atoms, molecules and surfaces; and the selectivity with which excited, chemically active species and surface structures are produced. Being able to predictably control velocity and energy distributions based on fundamental understanding of the coupling of electromagnetic energy into low temperature plasmas underlies our ability to advance the field, control plasma chemistry and utilize LTPs for societal benefit. For example, the entire world-wide informational technology infrastructure is predicated on bringing to the surface a carefully crafted set of plasma produced, energy selected fluxes of ions and reactive neutral species.

Priority 2: Collective behavior and nonlinear transport

The non-equilibrium and partially ionized nature of LTPs produce unique collective behavior and nonlinear transport rarely found in other fields of science and plasma physics. For example, the ability to change the degree of ionization by many orders of magnitude in a few ns at temperatures of only a few eV is a highly nonlinear process that is only approached in extremely high energy density physics. The non-equilibrium nature of LTPs with their broad array of positive and negative ions of varying mass and transport coefficients, neutral particles and electrons provides for a rich possibility of waves and instabilities not encountered in other plasma systems or otherwise in nature. Extending and improving our knowledge base of these non-linear processes and collective effects will enable us to customize, for example, extremely large area quiescent plasmas for material processing, controlling plasma chemistry for producing of selected species or optimize the efficiency of combustion for high utilization of fuel by creating radicals of critical densities in specified locations.

Priority 3: Interfaces and multiple phases in plasmas

A unique attribute of LTPs is their ability to interact with multiple phases: solid, liquid and gas. At one extreme, plasmas in liquids are being developed as surgical instruments. At the other extreme, low pressure plasmas are being used to create nano-crystals of unique composition, morphology and properties. Plasmas interacting with surfaces are now the basis of microelectronics fabrication. In some cases, such as micro-discharges, the electrons in the solid material confining the plasma may merge with the electrons in the plasmas. In all cases, there is a phase boundaries with which plasma activated species (ions, radicals, electrons) either pass through or interact with. The means of generating and optimizing plasmas in contact with multiple phases based on fundamental science principles, particularly those in liquids, is now beyond our abilities. LTPs provide a unique opportunity in which nano-particles of sufficient density and critical composition could create a new class of meta-materials.

Supporting Priorities: Cross cutting and facilitating science and technology: Diagnostics, Modeling and Fundamental Data

Making science advances in each of the scientific priorities listed above requires that there be an available and evolving state-of-the-art foundation in diagnostics and modeling supported by a robust knowledge base of fundamental data (e.g., electron impact cross sections). The diagnostics and models must both be able to resolve multiple phenomena on extremely disparate time and spatial scales. The disciplines providing the fundamental data supporting these activities must have the ability to rapidly, accurately and inexpensively produce, assess, catalogue and make available to the community these data. Although diagnostics, modeling and fundamental data are couched here as supporting priorities, they also hold extreme science and technology challenges in developing the experimental and computational techniques required to span these very large dynamic ranges.