A White Paper to the NSF Engineering Directorate

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

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29 September 2014
Abstract

The field of low temperature plasmas (LTPs) represents a vital area of interdisciplinary research and one that offers extraordinary societal benefit. The field of LTPs, as a discipline, has grand-challenge level scientific questions with a dynamic range that is perhaps greater than any other field of physical science. At the same time, the world-wide high-technology infrastructure is facilitated by the role that LTPs play in fields as diverse as microelectronics fabrication and nanoscience to medicine. Despite these scientific challenges and proven societal benefits of LTPs, federal support for this important area of research has been lacking. The US leadership role in this critical area is at risk. This white paper discusses the current scientific challenges of LTPs in the context of the extremely large dynamic range and intellectual diversity of the field, and the vital role that LTPs play in technology development. Comparisons are made to international activities in LTPs. A strong case is made in favor of the unique role of LTPs in science and engineering, and the need for a commitment to long-term support to build upon the current success of the field. This in turn will ensure the development of the field and sustained societal benefit. We propose that the Engineering Directorate of the National Science Foundation establish a program in Low Temperature Plasma Science and Engineering (LTPSE). This program would fund a broad science and technology program in LTPs with an annual solicitation, and provide support for early career researchers, graduate students, and small businesses.
Introduction to Low Temperature Plasmas

Low temperature plasmas (LTPs) are the plasmas associated with electron-volt (eV) science and technologies. Plasmas are ionized gases (and sometimes liquids) composed of neutral particles, radicals, excited states, ions, and electrons. LTPs have characteristic electron temperatures of a few eV to 10 eV with fractional ionizations that 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 boundary layers (sheaths) of LTPs to energies of tens to hundreds of eV enables activation of surface modifying processes such as sputtering, etching, and deposition. With such properties, LTPs are essential to technological devices ranging from etching and deposition of materials in microelectronics fabrication to surgical instruments.

LTPs are also typically non-equilibrium, implying that the electron temperature $T_e$ is much higher than the ion temperature $T_i$, which in turn is higher than the gas temperature $T_g$. Due to the partially ionized nature of LTPs, although some of the particles are extremely energetic (i.e., electrons and 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 the beneficial plasma-surface interactions which deposit and remove materials 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 led to the emerging 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 and plasmas in bubbles in liquids, now being investigated for chemical processing and medical applications. [5]

This white paper is a review of the scientific and technological challenges of LTPs, their societal and economic impact, and their specific international competitiveness issues. We present a case in favor of this dynamic and critically important area of research that deserves sustained federal support. We therefore propose the establishment of a Low Temperature Plasma and Engineering (LTPSE) Program in the NSF Engineering Directorate.

Societal Impact

The field of LTPs harbors fundamental scientific issues that are intellectually challenging and rewarding. In spite of these scientific challenges, LTPs have already delivered enormous societal benefits. Addressing those science challenges will enable this record of societal benefit to continue and expand. Here are examples of the societal impact of LTPs.

The entire current and future information technology 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 used in LTP lighting sources.[6] If we did not have efficient LTP lighting sources, we would require

| LTPSE Challenge – Advanced Diagnostics: | Interrogation of dynamic and structured plasmas over an extremely broad 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 is needed to non-intrusively probe LTPs. New diagnostic methods are required to keep pace with the evolution of the needs of the LTP community.

Figure 1 – Laser induced fluorescence (LIF) measurements of the electron density above a magnetic cusp. (Ref: J. E. Foster, University of Michigan; E. Barnat, Sandia National Labs. [22])
more than 30 additional 1-GW electrical power plants in the US. Renewable energy sources such as solar cell arrays, cannot be economically produced without deposition and etching by LTPs.[7] These plasma processes also enable production of more advanced computers and microprocessors that can be 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 rely on propulsion from LTP thrusters.[9] A vast array of other technologies also would not exist, at least economically, without LTPs, including liquid crystal display (LCD) panels, mass produced polymer sheets, IR-filtering glazing on windows, hardened metals for human implants, 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] There is an entirely new field of medicine where atmospheric pressure plasmas are applied directly to human tissue for wound healing and cancer treatment – plasma medicine.[3]

It is true that modern society would not be as advanced if it were not for LTPs – imagine what high technology would mean if microelectronics were limited to early 1990s technologies, if jet engines had not advanced since the days of the Boeing 707, and advanced human prosthesis and implants were still objects of research. As seen from the broad range of applications, it is amply evident that LTPs have had and continue to have deep societal impact.

Economic Impact

The tremendously positive 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 therefore quantifying the impact on economic competitiveness is difficult. This exhaustive economic analysis was, however, performed for Germany.[11] The study is ten years old and so the numbers are conservative estimates of the minimum economic impact of LTPs, since the technology fields enabled by LTPs have significantly expanded in the last ten years. To provide estimates of the impact of LTPs on US economic competitiveness, we will use Germany as a benchmark. Germany has 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. The GDP for Germany in 2007 was $3.32 Trillion and that of the US was $13.81 Trillion, a ratio of 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 to the German economy (US: $266 billion) with an estimated annual growth of 10%. We note that with annual growth of 10% since 2004, the estimated impact on the US economy would be in excess of $650 billion today. This is clearly a conservative estimate. The information technology industry in the US that is enabled by LTPs alone contributed nearly $1 Trillion ($954 billion) to US GDP in 2012.[13]
Other examples of the economic impact of LTPs come from the surface treatment industry that processes a tremendous amount of plastics and polymers for personal care products, medical products, adhesives and packaging using atmospheric pressure corona plasmas. The estimated worldwide market for flexible packaging treated by corona plasmas is about $70 billion with a US market of about $25 billion/year.[14] Water treatment facilities worldwide use LTP based ozonizers which have a market of about $740M. The global market for physical vapor deposition (PVD) coatings, a technology dependent on LTPs, will exceed $20 billion/year in 2014.[15]

Scientific and Technological Challenges

It is also true that LTPs have been the source of many of the fundamental physical 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 scientific 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 [16] and appear in Appendix A. Several of the current scientific and technological 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 DOE 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 [17] and the DOE Workshop [16]. These reports described the unifying scientific 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 Bound ed Systems (http://doeplasma.eecs.umich.edu) in August 2009 with a 5-year grant period. This is only the second federally funded center devoted to the science or technology of LTPs. The first was the NSF-ERC for Plasma Aided Manufacturing (1998-2003). The fundamental science issues addressed by the center revolve around 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, 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. The center’s grant period will end this year.

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

**Funding of LTP Science**

It is ironic that a field such as LTPs that has delivered such significant societal benefits and has many science challenges yet to be addressed has also historically been so poorly funded by the federal government for fundamental research. It is true that industry funds its own R&D in LTPs for specific product development purposes. University researchers do often receive support from industry to aid in applied plasma-based technology development. However, research involving fundamental principles of LTPs that underlie and whose mastery is necessary for the technology development is rarely funded by industry. Supporting 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 perhaps the NSF/DOE Partnership 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 in the fundamentals of LTPs. Considering only regular and CAREER grants (excluding, for example, small grants for student travel to conferences), over the past five years, NSF has averaged funding only 2 LTP proposals per year from the NDPPS. There is no formal SBIR/STTR support for LTPs in the NDPPS. It should be noted that essentially all fields 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 field of plasmas that does not have such a home agency or program.

The DOE-OFES should be congratulated for its willingness to include LTPs in their prior 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. However, the LTP center’s grant period ends this year. It has impacted a limited subset of the LTP community and focused on a subset of the diversity of LTP topics. Currently there is no plan to continue the LTP center program at DOE as priorities in the OFES are reassessed.

**LTPSE Challenge – Plasma Interaction with Soft and Living Matter:** 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, and HIV therapy, to name a few. Knowing where and how various reactive species are formed is critical for controlling their production efficiency and plasma composition, thereby effectively enabling control of the plasma interaction with soft and living matter.

![Figure 4 – Plasma interaction with cells, activation of reactive-oxygen-species (ROS) production pathways and deactivation on anti-oxidant system. (Ref: M. Keidar, George Washington University.)](image-url)
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 volatile organic compounds (VOCs) 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 VOCs from the exhaust. The deliverable of such a project is an assessment of the efficiency of plasma remediation of the VOCs from the exhaust. It is typically not within the statement of work of such a project to investigate fundamental plasma transport or any other fundamental properties of plasmas. 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 federally-funded recurring program focused on LTPs. At one time, LTPs were actively but indirectly supported by the NSF Engineering Directorate through programs in chemical and electrical engineering that welcomed proposals emphasizing LTPs. The program in electrical engineering and one of the programs in chemical engineering stopped their active support of LTPs about 10-12 years ago. This lack of formal support for LTPs has become more critical by the recent decision by the CBET (Chemical, Bioengineering, Environmental and Transport Systems) program not to formally solicit proposals focusing on LTPs. This has nearly terminated the formal support of LTP applications in Engineering. CBET will now only formally consider plasma proposals that are directly related to combustion systems though submission of individual LTP focused proposals discussed with program managers are sometimes encouraged. LTP-focused proposals submitted to the Engineering Directorate are now most often transferred to the NDPSS. For all practical matters, this leaves the NSF Engineering directorate with no formal support for LTPs in spite of the exceedingly vital role that LTPs play in the science and technology infrastructure of the US.

Dynamic Nature of LTPs

LTP science and engineering (LTPSE) 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 past five years, in spite of there still being many scientific and technological challenges in low pressure plasmas, much of the research in LTPSE has transitioned from

LTPSE 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 science. The limits of scaling have yet to be reached. With charged particle densities as high as \(10^{15-10^{17}} \text{cm}^{-3}\) 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 extremely small scales.

Figure 5 - Micro-plasmas tens of µm in size fabricated using photolithographic techniques are the basis of advanced displays and lighting. (Ref: D. Go, Notre Dame University; J. G. Eden and S.-J. Park, University of Illinois. [23])
sustaining plasmas at lower pressures to uses of plasmas at higher pressures of 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.[18] 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 at best a small profile five years ago. This rapid transition of motivating applications is a hallmark of LTPs and, in part, is why LTPs are so impactful in investigating the science and developing the technologies resulting in societal benefit.

LTPSE 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$_3$F$_8$/O$_2$/CO$_2$/N$_2$). The bounding surfaces to these plasmas range from silicon 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.

**Workforce and International Competitiveness**

In the post WWII years, the majority of advances in the science of LTPs and development of LTP technologies came from the US. It is questionable whether that is true now. International conferences at which members of the LTP community report on their results (e.g., the US-based Gaseous Electronics Conference and Gordon Conference on Plasma Processing Science, as well as the 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 several decades. This has occurred at a time when US support for LTPs has diminished. For example, there are multiple LTP focused 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 and continues to have 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 and technology in Europe, Japan, and Korea far exceed that of the US.

The United Kingdom (UK) stands out as an example of the European investment in basic research in LTPs that greatly exceeds that in the US. The UK equivalent of the NSF, the Engineering and Physical Sciences Research Council (EPSRC), has a designated home for LTPs as a research area under Lasers and Plasmas.[19] Major EPSRC investment in LTPs in recent years includes at least three major multi-year grants each in excess of $3M. The EPSRC portfolio of active LTP projects is about $5M/year shared among 16 universities ($310k/university/year) which does not include equipment which is funded by a different mechanism. These figures also do not include funded projects in which LTPs are a key technological enabler and research funds are used to characterize known plasma properties, but not to seek new plasma knowledge (e.g., nanomaterials). In addition to the funding for basic research, EPSRC provides funds for doctoral research student training programs (typically 30-50 PhD students per program). Using a conservative estimate of 40 PhD traineeships worth a US equivalent of $40k/year (stipend, benefits, indirect and tuition), this adds an additional $1.6M/year investment by EPSRC for a total of $6.6M/year devoted to basic research in LTPs. On a per capita basis, the UK-EPSRC investment in basic research in LTPs translates (excluding equipment) to a US-NSF equivalent of $33M/year.[20] As a final note, it is important to recognize that basic research in LTPs in Europe is also funded through the European Research Council and the European Cooperation in Science and Technology (COST) program.[21] There are at least two COST programs now based on LTPs that involve UK researchers. Therefore the $6.6M/year figure of UK funded research in basic LTPs ($33M/year NSF equivalent) is a lower bound.

The end result is that the demographics of the LTP academic community in the US lack a critical cadre of early career investigators – a situation that largely results from limited funding opportunities. Within ten years, a significant number of the leading LTP researchers in US universities will have retired with there being few early career faculty members to take their place. Although Europe also has a similar number of retirements, 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 LTPSE 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 to-
ward other areas. A program devoted to LTP would help myself and other early career researchers interested in LTP a great deal.”

The Innovation Pipeline in LTPs – Small Businesses and Large Industries

The importance to LTPs to US industry is immense. The need for innovation in these industries to remain internationally competitive has never been greater. The path to that innovation begins in universities where future employees of those industries learn the fundamentals and investigate the basic principles of the field. Dr. Richard Gottscho, Executive VP for Global Products at Lam Research, attributes the continuing innovation of the high technology industries dependent on LTPs to the education and training of its early career employees supported, in part, by NSF programs. “The world-leading competitiveness of the American Semiconductor Equipment Industry relies heavily on a steady-influx of top-notch technical talent from American Universities. While hiring smart people is most important, smart people with a basic education in low temperature plasma physics and chemistry enables a faster ramp to ingenuity and innovation. At a time when Foreign governments are investing more in basic low temperature plasma science precisely to take away the American position, the need for talented students, schooled in the fundamentals has never been greater.”

Large companies were once small companies, arguably the source of some of our most innovative technologies. In addition to the human resources that NSF support of LTPs provides, many high-tech start-up companies rely on the SBIR program to transition scientific possibilities into new product offerings. Unfortunately, there is no formal solicitation for SBIR/STTR support in LTPs from the NSF. The inherent discipline in the SBIR Phase I application process provides the structure to explain, validate, plan, and most importantly create a market-driven business model for new concepts. Companies that succeed in getting SBIR Phase II funding are ready for outside investment. In fact, many angel investors and almost all venture capital firms will only consider investing in a startup once a Phase II SBIR has been awarded. The LTP field has and continues to present great entrepreneurial opportunities due to the close link to marketable societal benefit, and the relatively low capital investment. One of the rate limiting steps has been the lack of the dependable, recurring SBIR support that an LTPSE program at NSF would provide.

Dr. Randy Cooper, CTO of NeoTech Aqua Solutions that develops LTP based technologies, has seen SBIR/STTR support as being critical to the success of his company. “The STTR contracts NeoTech Aqua Solutions (called Ultraviolet Sciences at that time) was awarded were instrumental in the development of our water purification equipment...These contracts also supported a Master's student, a Ph.D. student, and a Post-Doctoral Fellow, who have gone on to develop new, innovative applications themselves using LTPs. We, our customers, and our community have benefited greatly from the investment made into LTP research...” Dr. Gary S. Tompa, President of Structured Materials Industries (SMI) also
comments on the benefits to the competitiveness of small businesses provided by LTPSE funding. “This is an area that is underserved at this time – the science of such plasmas is not well understood and the breadth of the realms to which this technology can beneficially be applied are only beginning to be realized...We believe the proposed initiative...is very much at the core of what should be done to rapidly bring this technology to fruition...The program outlined will help the industry in general and to a great extent the small business community. The program will generate technology advances which are capitalized on both by large and small businesses alike. In fact universities are the springboard of inventiveness and entrepreneurship – students and recent graduates are the engine of small progressive startup companies.” Dr. Bob Gray, General Manager of EP Technologies LLC, states, “Cold plasma technology has the potential to provide breakthroughs in critical human health issues...Small companies such as EP Technologies which drive this application work are dependent upon Federal Government support to enable ‘high risk’ development of concepts into commercialized products...”

Proposed Program in Low Temperature Plasma Science and Engineering in the NSF Engineering Directorate

There are common high level scientific challenges throughout the field of LTPs. These were well articulated by the DOE LTP workshop (see Appendix A) and are highlighted in the text boxes. These common scientific and technological challenges to some degree unite the field. However, unlike other fields of plasma science, there is not a single grand discovery scientific challenge (e.g., magnetic reconnection, HED equation of state) that captures the majority of the field. In this sense, LTPSE is an interdisciplinary field of technology linked by shared scientific challenges. However, the interdisciplinary nature of LTPs has resulted in the absence of a home of LTPs in any federal agency, including the NSF. For example, EPA may welcome a subset LTPs that addresses the technology of plasma removal of pollutants, but would likely not support the plasma technologies of microelectronics fabrication, and would also likely not support the fundamental underlying science.

Given these unique set of conditions, we confidently state the following:

- A common discovery scientific 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 $10^5$, motivating applications from healthcare to nanoscience), it is not possible to distill this intellectual diversity into a narrowly defined scientific or technological challenge that covers the entire field and which an applications-driven federal agency will support.

- Society and plasma science are better served by capitalizing on the dynamic nature and intellectual diversity of LTPs through the establishment of an LTPSE program in the NSF Engineering directorate having a broad annual solicitation and by allowing the current scientific and technological challenges to be defined by the proposers.
The proposed program will accomplish the following:

- Advance the science of LTPs.
- Enable fundamental investigations in LTP science and engineering by establishing and maintaining the infrastructure, both equipment and human, that in turn facilitate researchers to engage in more focused applied research desired by other federal agencies and companies.
- Correct an imbalance in US research capabilities and address critical workforce issues.
- Enable CAREER, SBIR and STTR opportunities to be well supported in LTPs.
- Enable important leveraging of opportunities with US start-up companies and established industries.

We propose that the NSF Engineering Directorate establish a formal, separately funded program in low temperature plasma science and engineering (LTPSE). The LTPSE program would have an annual solicitation with a broad call for proposals addressing the science and technology of LTPs. The program would be funded at a sufficient level to capitalize on the proven potential of the field by addressing the scientific challenges and technology development that so quickly result in societal benefit, and to regain US international leadership in the field. The program would invest in the human resources required to maintain and increase the vitality of the field in academics, national laboratories, and industry by support of students, early career researchers, and small businesses. We propose that the LTPSE program be phased in over a 3-year period to provide overlapping sets of 3-year grants where in the steady state 1/3 of the grants are re-competed every year. We propose this mode of operation to continue for five years, after which the NRC would evaluate the impact of the program. A successful evaluation would then continue and possibly increase support for LTPSE within the NSF.

References

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Appendix A: Prioritized Science Challenges from the DOE Workshop “Low Temperature Plasma Science: Not Only the Fourth State of Matter but All of Them” [16]


Priority 1: Predictive control of plasma kinetics

Plasma kinetics underlies 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 brings about 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 ionized 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 boundary 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 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 scientific and technological challenges in developing the experimental and computational techniques required to span these very large dynamic ranges.