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Review

1995–2005: A Decade of Innovation in Low Temperature Plasma and Its Applications

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Abstract: Scientific breakthroughs tend to come in spurts when unique societal, economical, and political circumstances conspire (knowingly or unknowingly) and create an environment ripe for creativity. The field of low temperature plasma (LTP) recently experienced such an upheaval, which this paper attempts to relate in some details. There have been “roadmap” papers published before, which look towards the future of the field, but all roads start somewhere and even “new” roads are often paved over older roads that were discovered and traveled by early pioneers. With the sharp decrease in funding for fusion research in the USA in the early 1990s the plasma science community was faced with a dire situation that threatened to choke off plasma physics advances. However, in the background and far from the visibility accorded to fusion research, a few laboratories were quietly engaged in innovative research that in due time revolutionized the LTP field and breathed new life into plasma science. Groundbreaking applications of LTP were investigated that until today constitute most of the LTP research activities. These innovations spanned a wide spectrum that included the invention of novel devices, improvement of existing ones, and the deployment of these devices to areas ranging from industrial to biomedical applications. These efforts turned out to have impactful scientific and societal implications. In this paper plasma sources and applications developed during this uniquely innovative decade are briefly discussed.

Keywords: low temperature plasma; dielectric barrier discharge; plasma jet; cells; biomedical applications; combustion; reactive species

1. Introduction

Although scientific investigations of the fourth state of matter, plasma, first took place in the 19th century, the field only established itself as a genuine field of study in the early decades of the 20th century. The need to understand fundamental physics of plasma (arc physics, spark discharge physics, etc.) and its early applications, such as in radio communications/wave propagation and later (in the 1960s and 1970s) in the manufacture of semiconductor devices, gave the field a great impetus during those early years. In addition, the quest to build a controllable and efficient fusion reactor brought major attention and funding to plasma physics research. However, in the 1980s it became clear that the goal to achieve a viable fusion reactor to produce electricity is a very long term and extremely difficult proposition and some of the challenges, especially in materials and in the control of plasma disrupting instabilities, seemed almost unsurmountable. The effect of this was devastating to the fusion research community in the United States, where a sharp decrease in funding caused the shutdown of many facilities and experimental reactors. On the other hand, work in the field of low temperature plasma (non-thermal discharges with energetic electrons but gas temperature of few hundreds degrees or less) was mostly concerned with: (1) low pressure (much below 1 torr) discharges and the understanding/improvement of reactors (capacitively coupled and inductively coupled) used for semiconductors applications; (2) high pressure (up to one atmosphere) discharge applications such

as for ozonizers, electrostatic precipitators, and corona discharges used for printing. However, this state of affairs changed drastically in the early 1990s when three groups (one in Japan, one in France, and the third in the USA) started reporting their work on easily and practically generating relatively large volume, atmospheric pressure, low temperature, diffuse plasmas in a stable and controllable manner [1–3]. This caused a burst of research activity on this topic in laboratories in many countries. Figure 1 is a general illustration of how a large volume diffuse plasma looks like.

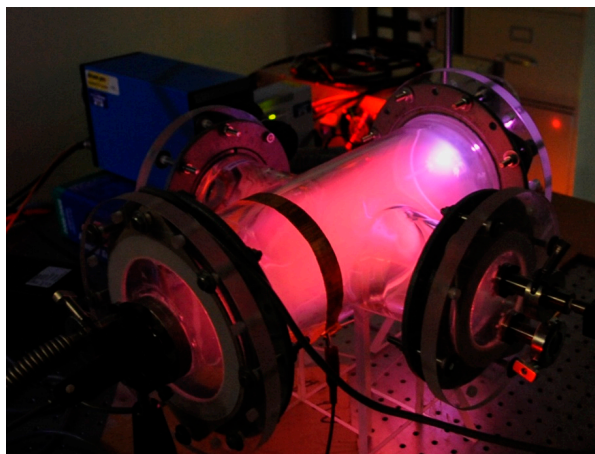


Figure 1. Photograph showing a diffuse low temperature plasma (gas is air at 3 Torr).

A most noteworthy and highly impactful research program was a Multi-University Research Initiative (MURI) program funded by the US Air Force Office of Scientific Research (AFOSR) which sought to develop methods to generate air plasma with electron densities equal or greater than 10^{13} cm^{-3} at low power budgets. A consortium of US universities was involved in this work, which included Stanford University, Princeton University, Ohio State University, the University of Tennessee, and Old Dominion University. A book on non-equilibrium atmospheric pressure air plasma, edited by K. Becker et al. and published by IoP in 2005, was one of the results of this endeavor and a proper culmination to the decade we are discussing here [4]. Some of the most prominent early researchers in LTP and air plasma chemistry, including U. Kogelschatz, E. Kunhardt, A. Garscadden, R. Vidmar, and Y. Akishev (to name just a few) contributed chapters to this book. Also, the first ever book chapter discussing early groundbreaking work (from 1996 to 2004) of the emerging field of the biomedical applications of atmospheric pressure LTP (e.g., plasma medicine) was published in this book (chapter sections written by M. Laroussi and E. Stoffels). It is of note to mention here that the main interest of AFOSR at the time was to use non-equilibrium air plasma for radar applications, such as cloaking or using plasma as a microwave reflector (plasma mirror), etc. However, unexpected spin-offs emerged from various contributors to this program and others; most prominent amongst them is the use of atmospheric pressure LTP for biomedical applications, plasma-assisted combustion by nanoseconds pulsed discharges, and plasma actuators for aerodynamics applications [5–8]. In addition, new devices or improvement of existing ones were proposed, amongst them the use of nanoseconds high voltage pulses to drive DBDs (instead of sinusoidal voltages) [9–11], the resistive barrier discharge (RBD) which allowed the use of DC or 50/60 Hz voltages (instead of kHz frequencies) [12] and the development of low temperature plasma jets, which are today used extensively in biomedical applications [13]. Other noteworthy developments unrelated to the AFOSR program were the emerging field of dusty plasma [14], and the development of high power impulse magnetron sputtering (HiPIMS) [15,16]. It is remarkable that all these fascinating developments occurred within one decade, starting around 1995 and lasting to around 2005. Of course some great work has been done since then but most of it was enabled by, or the product of, or an extension of the discoveries and breakthroughs established during that rather exceptional decade. In this paper brief descriptions of some of the major developments mentioned above are presented. This is far from being an exhaustive coverage as many applications

are not included, such as plasma display panels, chemical applications (removal of volatile organic compounds, CO₂ reforming, plasma catalysis, etc.), surface and material processing (including plasma nanotechnology), propulsion (plasma thrusters), etc. These have also experienced noteworthy recent advances and have been reviewed by colleagues who are much more expert in these topics than the author of this paper.

2. Novel Sources of Non-Equilibrium Atmospheric Pressure Plasmas

2.1. The Pulsed Dielectric Barrier Discharge (P-DBD)

The first discovery that a plasma discharge can be generated at atmospheric pressure using dielectric barriers that cover two electrodes was made by Theodose du Moncel in 1855 [17]. This was followed by a device developed by W. von Siemens in 1857 that used a dielectric barrier discharge (DBD) configuration to generate plasma in air to produce ozone [18]. Plasmas in DBDs are generally generated by using high AC voltages in the kHz range [19–21]. However, in the early 2000s the use of nanoseconds wide repetitive high voltage pulses was introduced [9–11]. These narrow pulses allow for a better control of the electron energy distribution function (EEDF) and produce an enhanced chemistry as compared to the use of AC power. Nanoseconds pulses were previously used for low pressure discharges in gas lasers, but they were employed to improve the performance of DBDs and to generate atmospheric pressure low temperature plasma with enhanced gas phase chemistry only in the late 1990s/early 2000s [9–11]. This improvement, again, came out of the research work conducted under the AFOSR MURI program mentioned above.

2.2. The Resistive Barrier Discharge

Conventionally, the generation of uniform and diffuse plasma at atmospheric pressure using DBDs requires the use of high AC voltages with frequencies in the kHz range. This necessitated voltage amplifiers that work in the audio frequency range (kHz). To extend the frequency of operation to the line frequency (50 or 60 Hz) a few ideas were proposed. One that gained traction (i.e., is used today in industrial applications) was based on the use of a high resistivity layer/film to cover at least one electrode [12]. This allowed the use of high voltages with frequencies all the way down to DC, which eliminated the need for the kHz amplifier, therefore simplifying the system and making it more economical [12]. The RBD was used in several applications including the cleaning of air flows in heating, ventilation and air conditioning (HVAC) systems and in biomedical applications [22,23].

2.3. Microdischarges

Paschen law dictates that the breakdown voltage of a gas is a function of the pressure-electrodes gap product (p.d). There is a value of (p.d) at which the voltage is minimal. To operate a discharge at higher pressures (up to atmospheric pressure) requires that the gap distance d be small. These types of discharges with very small gap distance (micrometers to millimeters) are referred to as microdischarges or microplasmas. The concept of microdischarge was first reported by White A.D. in 1959 [24]. However, extensive research into the physics and applications of microdischarges was only carried out in the past 25 years with noteworthy advances during the decade discussed in this paper. These include the breakdown of the conventional (p.d) scaling at very small dimensions and the influence of boundary-dominated processes. Interested readers can consult the following review papers and references therein for detailed discussion of these plasma discharges [25,26]. Applications of microdischarges range from Excimer UV generation, to lighting, to environmental applications.

2.4. Non-Equilibrium Atmospheric Pressure Plasma Jets (N-APPJs)

Various material processing applications require the plasma (thermal or non-thermal) to be delivered to a target located at a distance away from the plasma source. This is also true for medical applications where the target can be a patient. However, until the early 2000s no source existed that

can deliver an atmospheric pressure plasma jet safely, at biologically tolerable temperatures (less than 40 °C). Such source should also be electrically safe and operate within acceptable thresholds of UV emissions. The first such source was the “plasma pencil”, a device capable of launching a plume of low temperature plasma in ambient air and can be applied to soft tissues without inducing any electrical or thermal damage [13]. The plasma pencil was first reported in an Applied Physics Letters paper in 2005 and was developed under an AFOSR grant. Another device that was proposed around that time is the kINPen, which was developed in Germany [27]. Figure 2 shows three examples of N-APPJs. The plasma pencil, the kINPen, and other plasma jets that came after were all extensively used in various biomedical applications including in wound healing and the destruction of cancer cells and tumors [28]. Also of note was the discovery that the plasma plumes emitted by N-APPJs were enabled by guided ionization waves known as “plasma bullets”. This discovery was independently made in Germany (University of Wuppertal) and the USA (Old Dominion University) on a low frequency RF-driven jet and on the repetitively pulsed (ns to μ s pulses) plasma pencil, respectively [29,30].

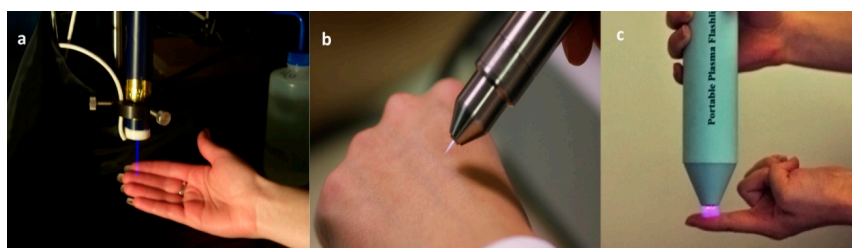


Figure 2. Three examples of non-equilibrium atmospheric pressure plasma jets (N-APPJs). (a) Plasma pencil (Old Dominion University, USA); (b) kINPen (INP, Germany); (c) Plasma “flashlight” (HUST, China).

2.5. High Power Impulse Magnetron Sputtering (HiPIMS)

High power impulse magnetron sputtering generates highly ionized plasma by applying power in short pulses with power densities in the $\text{kW}\cdot\text{cm}^{-2}$ at the target. The pulse lengths range from 10 to 200 μ s at duty cycles of only few percent. This may not exactly fit in the category of low temperature plasma applications but has been a prominent research topic within the LTP community, mostly for plasma material processing. HiPIMS was first introduced in 1999 [15,16]. High-quality films have been deposited using this kind of discharge, leading to superior materials property [31].

3. Select New Applications of Low Temperature Plasma

As mentioned above in this paper, the decade from 1995 to 2005 witnessed the emergence of some exciting new applications of LTP. It is not the purpose of this paper to cover all of them but to present a few that became major foci of research activities in the past decade. To date interest in these applications seem to steadily grow as a greater number of labs and investigators enter the field.

3.1. Biomedical Applications of LTP

It is without a doubt that the biomedical application of LTP attracted the highest interest and energized the field like no other application did. This application emerged in the mid-1990s when atmospheric pressure LTP was shown to have strong bactericidal effects [5,6]. AFOSR became very interested and started a research program in 1997 that aimed at developing and testing LTP devices for decontamination/sterilization purposes and to be used for the disinfection of wounds and to accelerate the wound healing process. By the early 2000s work on mammalian cells was carried out which showed that LTP can affect cell functions in a sub-lethal way [32]. Until 2005 only very few investigators were involved in this groundbreaking work (mostly in the USA and the Netherlands), but shortly after that the LTP research community realized the implications of this work and a number of laboratories in the USA, Europe, and Asia started similar programs. What happened in the next few years following

2005 may be described as a research “fever” or “rush” when many laboratories suddenly (and maybe surprisingly) made biomedical applications of LTP a priority over their traditional research endeavors. The field grew exponentially and became known as “Plasma Medicine” [33]. However, after this initial rush the research community realized the complexity and the myriad of possible physical and biochemical effects involved in plasma–cell/tissue interaction, and consequently adopted a more sober and long-term view of the field. Today, LTP-based biomedical research covers several applications ranging from decontamination, to wound healing, to dentistry, to dermatology/cosmetics, and to cancer treatment. The first clinical trials on wound healing took place in Germany in 2010 [34], and preliminary small scale humans trials on cancer took place more recently in Germany and the USA. Presently the field of plasma medicine remains very active with some dedicated research centers and institutes in several countries, a number of dedicated conferences and peer reviewed journals. It is important to note here that the introduction of LTP to biomedical research has permitted the building of fundamental scientific knowledge concerning the interaction of plasma with soft matter (including cells, tissues, etc.). This knowledge was simply missing prior to the 1990s. Much more work still remains to be done, but today (the end of the second decade of the 2000s) we know quite a bit more about what happens to biological cells and tissues when they are exposed to cold plasma. This includes greater knowledge and better understanding of the variety of the biochemical pathways whereby plasma affects cells and how deep plasma species penetrate skin and the underlying tissues [35].

3.2. Plasma Interaction with Liquids

Investigations on the interaction of LTP with liquids have been flourishing in the present decade mainly because of their strong relevance to medical applications. However, early work (supported by AFOSR) started already in the late 1990s and early 2000s with experiments on plasma in and on top of liquids, especially water [36–39]. The chemistry at the plasma–liquid interface plays a crucial role and determines what happens in the liquid bulk. For information on more recent work the reader is referred to reviews [40–42].

LTP produces reactive oxygen species (ROS) such as O , O_2^- , $O_2(^1\Delta)$, OH , H_2O_2 , and nitrogen reactive species (RNS) such as NO , NO_2 . When these interact with biological media the concentrations and fluxes of these species play a crucial role in the biological outcomes. Many of these species are produced in the gaseous phase and at the gas–liquid interface. In complex liquid media (media containing amino acids, carbohydrates, etc.) the plasma-produced ROS and RNS generate long-lived species such as hydrogen peroxide (H_2O_2), nitrites (NO_2^-), nitrates (NO_3^-), peroxynitrite ($ONOO$), and organic radicals (ROO). These species are known to have impactful chemical and biological effects. Applications range from environmental use, such as water treatment, to medical applications since cells and tissues are usually covered by biological fluids. Of particular note is the relatively recent use of plasma activated media (PAM) or plasma activated liquids (PAL) to kill cancer cells [43,44].

3.3. Electromagnetic Waves Interaction with Atmospheric Pressure LTP

Studies of the interactions of EM waves with plasma go back to the 1930s. Most of these studies concern collisionless or low collisional plasmas. Atmospheric pressure plasmas are highly collisional and LTP has a low degree of ionization making the collision frequency much greater than the plasma frequency. This results in a very different interaction than for the case of low collisional plasmas [45]. One of the research programs supported by AFOSR in the 1990s (plasma ramparts program) had the aim of studying the absorption and reflection of microwaves by low temperature air plasmas [46]. This knowledge is useful in radar applications and also for plasma diagnostics such as microwave interferometry and microwave scattering. Microwave interferometry has been used for many decades as a method to accurately measure the electron number density in low pressure plasma. In this case the phase shift undergone by a wave crossing a plasma is linearly related to the electron number density of the plasma. However, in highly collisional plasmas (as is the case for atmospheric pressure) this is no

longer true. The relationship between the phase shift and the electron density for highly collisional uniform plasma was derived in a paper published in 1999 [47]:

$$N_e = 38.6 \nu_c (f_o \Delta\Phi/d)^{1/2} \quad (1)$$

where N_e is the electron density, ν_c is the collision frequency, f_o is the microwave frequency, $\Delta\Phi$ is the phase shift and d is the plasma thickness. Unlike the low collisional case where the electron density depends on the first power of the phase shift (linear), Equation (1) shows that in the highly collisional case it depends on the square root of the phase shift. This also implies that for atmospheric pressure plasmas it is better to use a higher frequency microwave interferometer in order to resolve small changes in phase.

3.4. Dusty Plasmas

The study of dusty plasma has its roots in astrophysics as it relates to studies of the dynamics of cosmic plasma environments, such the rings of Saturn [48]. Its industrial relevance became clear when the cause of some fatal defects in semiconductor devices was found to be due to dust settling on wafers under/after plasma exposure [49]. The field, also referred to as “complex plasma”, witnessed an expansion of interest in the 1990s and onward. Some of the main issues were related to understanding the interactions between charged dust particles, phase transition, self-organization, pattern formation, dust acoustic-waves/shocks, etc. [50]. Knowledge gained from dusty plasma studies is useful for the study of crystallization, defect propagation, etc. Of note is a collaboration between the German Space Agency (DLR), the Russian Space Agency, the Max-Planck Society, and the Russian Academy of Science, which resulted in a highly successful science experiment on board of the International Space Station (ISS), named “Plasma Crystal” [51]. Here the spatial and temporal distribution of charged dust microparticles was studied under a zero gravity environment.

3.5. Plasma-Assisted Ignition and Combustion

Studies on using non-equilibrium plasmas to aid ignition and combustion of fuel/air mixtures have been going on for a few decades. However, intense investigations were carried out starting in the late 1990s [7,52,53]. These investigations aimed at elucidating the plasma-assisted ignition and plasma-assisted combustion processes and optimizing the plasma operating parameters to improve the process. The goals include reducing the ignition delay time, igniting supersonic flows, flame stabilization, sustaining combustion of lean mixtures, etc. This knowledge can help improve the efficiency and stability of various industrial applications including that of aircraft engines, gas turbines, and internal combustion engines. One of the noteworthy improvements was the use nanoseconds pulsed discharges. For more details the reader is referred to references [52–54].

4. Conclusions

The advancements achieved in the field of low temperature plasma during the decade between 1995 and 2005 had been truly remarkable given the relatively modest funding available to the early investigators in this research area. Innovative and unexpected applications emerged that introduced LTP technologies to other disciplines such as aerodynamics control, combustion, and biomedicine. These innovations were initially introduced by only a few investigators but in due time a sizable international community formed that brought a critical mass to the field. Today, the majority of the research activities in LTP are in large part extensions and/or expansions of the ideas first introduced in that uniquely productive decade. The reader can also learn about future possibilities and where the field may be heading to by consulting the following references [55,56].

As mentioned in this paper AFOSR played a key role in the United States in funding and promoting scientific research on non-equilibrium low temperature plasma and many of the spectacular developments in the field during the 1990s and early 2000s were accomplished under programs funded

by this research office. This support allowed keeping the US in the forefront of the field and as a hot bed of new concepts, new applications and breakthroughs, which since then have been emulated by plasma science laboratories from around the world. Conventional wisdom would dictate that such research should have also been supported and promoted by agencies and foundations the mission of which is fundamental science. However, unfortunately, in the US, only minimal support was accorded by such agencies/foundations to LTP research during the defining decade discussed in this paper. This was mostly because there was no independent LTP program/directorate at these institutions. This resulted in the scattering of LTP research proposals around several internal directorates which had only marginal interest in the field.

To conclude, it is interesting to note that the decade discussed in this paper spans the last few years of the last century and the first few years of the 21st century, a transition time that brought about change and upheaval to various human activities, including noteworthy advances and innovations in the field of low temperature plasma and its truly remarkable applications.

Conflicts of Interest: The author declares no conflict of interest.

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