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Topical Review

The 2017 Plasma Roadmap: Low temperature plasma science and technology

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Abstract

Journal of Physics D: Applied Physics published the first Plasma Roadmap in 2012 consisting of the individual perspectives of 16 leading experts in the various sub-fields of low temperature plasma science and technology. The 2017 Plasma Roadmap is the first update of a planned series of periodic updates of the Plasma Roadmap. The continuously growing interdisciplinary nature of the low temperature plasma field and its equally broad range of applications are making it increasingly difficult to identify major challenges that encompass all of the many sub-fields and applications. This intellectual diversity is ultimately a strength of the field. The current state of the art for the 19 sub-fields addressed in this roadmap demonstrates the enviable track record of the low temperature plasma field in the development of plasmas as an enabling technology for a vast range of technologies that underpin our modern society. At the same time, the many important scientific and technological challenges shared in this roadmap show that the path forward is not only scientifically rich but has the potential to make wide and far reaching contributions to many societal challenges.

Keywords: plasma, low-temperature plasma, roadmap

(Some figures may appear in colour only in the online journal)

Contents

Introduction

Journal of Physics D: Applied Physics published the first Plasma Roadmap in 2012 [1]. This first-of-its-kind Roadmap shared the individual perspectives of 16 leading experts in the various sub-fields of low-temperature plasma science and technology. The intent of the Roadmap was on one hand to provide insights to research needs and opportunities in the complex multidisciplinary research field of low temperature plasmas. On the other hand, the intent was also to establish a respected and research community driven reference to guide decisions on investments in the field. The 2012 Plasma Roadmap has been impactful in meeting these goals and was recently selected for IOP Publishing's Special Edition of 50 years of JPhys series as one of the most influential papers of this era [2]. Based on this success, the editors and editorial board decided to periodically update the Roadmap, and this 2017 Plasma Roadmap is the first such update. The format of the Roadmap remains the same, although an important change from the 2012 edition is that each section is now written by two authors to stimulate discussions on the subtopic with the intent to provide broader perspectives.

Low temperature plasmas (LTP), ionized gas (or sometimes liquid), represent a unique state of matter composed of neutral atoms and molecules, radicals, excited states, ions and electrons. Low temperature plasmas, the topic of this Roadmap, have characteristic electron energies of a few eV to 10 eV with ionization degrees that are typically small, but can reach tens of percent in arc discharges. These energetic electrons can efficiently generate radicals, charged species, excited states and photons. Space charge sheaths at the boundary of plasmas, particularly at low pressure, accelerate and deliver fluxes of ions to surfaces with adjustable energies ranging from a few to hundreds of eV. These ion fluxes enable surface modification by sputtering, etching, activation and deposition that are essential to technological devices ranging from the etching and deposition of materials in microelectronics fabrication to medical implants.

While many successful industrial applications of plasma are based on arc, microwave and inductively coupled plasma discharges that operate close to thermal equilibrium [3, 4], the majority of low temperature plasmas significantly deviate from thermodynamic equilibrium, with the electron temperature T_e being much higher than the heavy particle temperature and gas temperature T_g. LTP sources can produce a chemically rich environment at close to room temperature both at reduced and at ambient pressures, a unique condition that enables the delivery of highly reactive plasma species in a non-destructive and beneficial way to even extremely heat sensitive 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 nanometer resolution in the fabrication of microprocessors [5]. This beneficial contact with surfaces now extends to liquids, organic tissues and wounds, which led to the emerging field of plasma medicine [6]. LTPs may also non-destructively and beneficially interact with surfaces internal to the plasma, such as in a particle or aerosol-laden *dusty* plasma which enabled, for example, nanomaterial synthesis [7]. LTPs can also be generated and sustained within liquids and bubbles in liquids, now being investigated for chemical processing, medical applications and in the context of environmental stewardship [8]. These are just a few examples that illustrate the extraordinary societal benefit of low temperature plasmas.

The field of low temperature plasmas is exceptionally interdisciplinary with grand-challenge level scientific questions that have a dynamic range that is perhaps greater than any other field of physical science. The LTP discipline brings together many different research fields, such as electrodynamics, fluid dynamics, heat transfer, statistical physics, thermodynamics, atomic and molecular physics, material and surface science, chemistry, chemical engineering, electrical engineering, and recently even biology and medicine. While the field is extremely diverse in its applications and related science, common to all subfields is the requirement to control and understand non-equilibrium plasma kinetics and the interactions of plasmas with matter.

To capture the evolution of the field, the topics discussed in the 2017 Plasma Roadmap somewhat differ from the prior edition. For example, the topic of 'Plasma Agriculture and Innovative Food Cycles' has been added, a field which has recently emerged from the growing plasma medicine community. We added the sections 'Plasmas in Analytical Chemistry' and 'Plasma Metamaterials and Plasma Photonic Crystals' in recognition of the research activity in these areas. In addition to adding sections, we also reorganized sections to capture the important topics of plasmas in the areas of energy, flow control and material processing and synthesis. While we do not have a separate section on plasma catalysis, this topic is of growing interest for the plasma community and is covered in the sections related to environment and energy.

In addition to the application motivated sections, we added several sections dealing with fundamental plasma science, including the important topics of transport in plasmas and plasma theory. Many fundamental questions in LTP science remain unsolved. Examples of these questions include the dominant mode of energy transfer and chemical reaction processes in transient plasmas, the mechanisms and origins of the formation of complex self-organizing structures in plasmas and the physical and chemical interaction of plasmas with materials and liquids. In recognition of its importance in the development of accurate models and predictive based modeling tools, we also included a section titled 'Plasma Chemistry: Mechanisms, Validation and Distribution'

While the scientific and technological advances highlighted in the Roadmap are testimony to the innovativeness of our field, the number of research groups working in more fundamental areas that enable these advances is decreasing. There are many root causes for this trend, one being that funding is increasingly being focused on applications with there being less investment in developing the fundamental plasma models, computational techniques and algorithms and diagnostics needed to support the application driven advancements of the field. If this trend continues unabated, the health of the low temperature plasma field is at risk. The enviable track record of the low temperature plasma field in the development of plasmas as an enabling technology for a vast range of technologies shows that the support of fundamental research in the past has paid off.

The field of low temperature plasmas depends on nurturing and supporting new generations of scientists and engineers involved in plasma science, modeling and diagnostics. The training of this next generation of scientists and engineers in the fundamentals of plasma science becomes an increasingly challenging task particularly in view of the growing interdisciplinary nature of the field. As the field moves forward and the technological advances emerging from the field continue to provide societal benefit, we should also continue to make investments in the fundamentals of plasma science that underpin this technological advancement, and enable the career advancement of the next generation.

Peter J Bruggeman, Uwe Czarnetzki and Mark J Kushner
Editors of the 2017 Plasma Roadmap

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12. Aerospace applications: propulsion and flow control

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Low temperature plasmas in the aerospace industries have a long history in materials processing, beacons, communication, re-entry physics, hypersonic flow and plasma aided combustion. Although the high temperature exhaust of both turbines and chemical rockets contain ionized gas, it took the development of electric propulsion (EP) and flow control (FC) to emphasize the importance of LTPs to energize a gas for the purposes of generating a force which translates to controlling motion. In EP, this force, carried by ions, is the primary thurst to accelerate a vehicle in space. FC is an atmospheric process in which the force transferred from ions or deposited as heat in the flow over an airfoil enables the modification of the flight characteristics of an aircraft. To the degree propeller and turbine blades are also airfoils, FC may extend well beyond airplanes. Although EP and FC operate in different environments, they share the same goal of using plasma generated forces as a momentum transfer mechanism to affect flight characteristics.

Electric propulsion

Status. The biggest difference between EP and chemical propulsion is not necessarily the state of the matter expelled to generate thrust, but the power source. Contrary to chemical propulsion, in which the energy is stored in the propellant chemical bonds, EP relies on external energy sources. Separating the source and the propellant allows for very large power densities, which translates into a high propellant exhaust velocity. The latter is responsible for the low propellant mass consumption of EP devices [115]. Although electric (or 'plasma') thrusters deliver a low thrust, they are the best options for various types of spacecraft manoeuvres and missions, such as orbit transfer, trajectory correction and interplanetary missions.

The development of EP dates back to the 1960s. Since then, EP has evolved gradually, with the emergence of many architectures and the use of EP on hundreds of satellites and space probes. However, the full potential of EP has only just begun to be realized. The increase in the available power on-board spacecraft has accelerated the development of all-electric communication satellites, while realizing ambitious missions. The recent trend in access to space, which combines the constellations of small satellites, as well as micro- and nanosatellites, requires the development of efficient miniaturized EP systems.

The most advanced technologies are the gridded ion engine and the Hall thruster [1]. Ion engines deliver a high exhaust velocity, but the thrust is limited. Hall thrusters offer a larger thrust-to-power ratio [115]. Numerous studies are aimed at improving performance and capabilities. For instance, the development of the Hall thruster configuration termed 'magnetic shielding' has led to a drastic improvement in thruster lifetimes [115, 116]. Likewise, the wall-less configuration may potentially provide a means for reducing the wear of the Hall thruster assembly [115]. In parallel, several new cathode-less concepts have emerged in recent years to offer simple, reliable and low-cost solutions for small and micro-satellites, such as the PEGASES thruster, the ECR thruster, the Vacuum-Arc Thruster and liquid-fed Pulsed Plasma Thruster [115, 117].

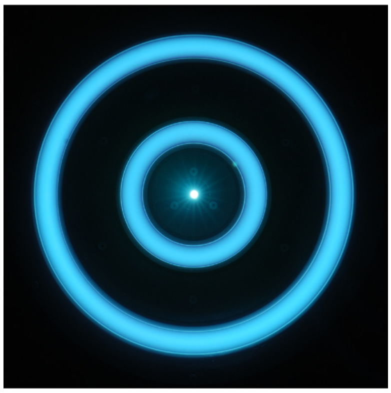

Figure 22. Front view of the 10 kW class X2 two-channel nested Hall thruster with its centered-mounted cathode firing with xenon at full power in dual channel configuration. Image courtesy of Ray Liang, reproduced with permission.

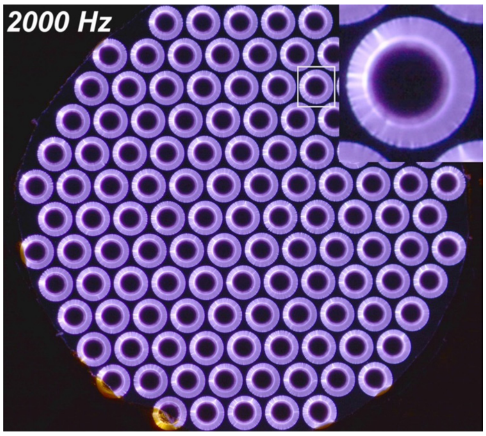

Figure 23. Front view of the plasma actuated grid composed of 1.8 mm diameter holes.

Current and future challenges. Near-term challenges can be categorized by the EP system input power. Long life span, high-power thrusters (>20 kW) are needed for propelling large spacecraft and interplanetary probes. A promising approach is the nested-channel Hall thruster, see figure 22, in the magnetic shielding configuration [115]. The architecture was validated at 20 kW and present research is aimed at operating above 100 kW [115]. In the MW power range, studies on magneto-plasma dynamic devices and on the VASIMR rocket must be pursued. In addition to a high-thrust level, dual-mode capability is also of relevance to optimize mission profiles. Concerning low-power engines, 1–100 W, efficient and compact sources are required for small satellites. Miniaturization of existing flight-proven architectures is one means of achieving this [118]; another is the development, optimization and qualification of cathode-less systems. Another critical aspect of EP is identifying alternative propellants to xenon to reduce the overall cost of EP while prolonging the mission duration.

Advances in science and technology to meet challenges. From a fundamental viewpoint, an in-depth study of the physics of LTP discharges, the core of EP devices, is necessary. Priority must be given to electron transport, turbulence and confinement in magnetized discharges. A better grasp of plasma-wall interaction is also necessary to refine sheath models and to better assess wear processes. This requires accurate data on material properties, such as secondary electron emission and sputtering yields. Theory and experiments must be combined with sophisticated computer simulations. The development of powerful 3D codes with predictive capabilities has become a necessity. From a more technological standpoint, two aspects are relevant: the manufacturing of new materials, which includes cathode emitters, to extend both thruster lifespan and operating envelope and the improvement of power supplies in terms of efficiency and mass. Finally, yet another critical point is the influence of ground-test facility effects on performance. Diagnostic standardization and direct testing in space for miniature plasma thrusters may provide answers.

Flow control

Status. Electrical discharges for aerodynamic applications have been widely studied during the last three decades. Starting from the 1990s, research has been conducted on thermal plasmas to modify transonic and supersonic flows occurring around vehicles or projectiles [119]. Since 2000, research has focused on surface non-thermal plasma for the control of subsonic airflows [120–122]. In aeronautical applications, the aim can be, for instance, to reduce skin-friction drag during cruise flight conditions. There are several types of laboratory-scale plasma actuators, the most common being a surface dielectric barrier discharge (SDBD). When a SDBD is powered by ac voltage, an electrohydrodynamic force is produced, resulting in an electric wind-based wall jet. SDBDs can produce forces up to 400 mN m^{-1} and electric wind velocities up to 10 m s^{-1} in atmospheric air. If instead the HV has a nanosecond repetitively pulsed waveform, then gas heating results in a pressure wave of a few kPa per mJ cm^{-1} [123]. In both cases, energy is transferred to the flow either as heat or force. When a SDBD is mounted onto a profile wall, one of the two phenomena can modify the boundary layer, resulting in the control of the whole flow around the profile body. Over the last 15 years, SDBD have been successfully demonstrated in most aerodynamic conditions of interest to academic and industrial research, up to Reynolds numbers of a few million. However, although SDBD plasma actuators can operate in cruise flight conditions, so far their development has remained in the laboratory research phase.

Current and future challenges. The main challenge for using plasma actuators in real aeronautical applications is to demonstrate their capability to control airflow at high Reynolds numbers. The main advantage of SDBDs is their ability to operate at a wide range of single or multiple frequencies. The ac SDBD is a linear electromechanical converter since the temporal behaviour of the electric wind follows any HV waveform. The SDBD is thus a multi-frequency actuator with a short response time, which is useful for efficient real-time closed loop airflow control. However, the use of SDBDs is limited to the control of subsonic airflows, because they are usually employed in simple geometries and at the centimetre scale. Since near-wall flows can be controlled with little energy if directed with precision at the proper location and at the right time, one can imagine new plasma actuator designs, such as matrices of densely packed surface micro-plasmas, which can deposit energy at any location on the wall, at any time. The result is a multi-scale spatio-temporal actuator.

Advances in science and technology to meet challenges. The first advance needed for using plasma actuators in real aeronautical applications is efficient, high Reynolds number CFD models to determine how, where and when to act on the wall. Ideally, a self-consistent plasma model including air chemistry should be coupled to a DNS fluid mechanical model, which is computationally expensive because the time and space scales are very different in plasma physics and fluid mechanics. The second advance is to find new applications for plasma actuators. On the one hand, because plasma actuators cannot operate in the rain, use at ground level (on the blades of a wind turbine or on the surface of medium altitude unmanned aerial vehicles for instance) has many challenges outside very dry locations. Besides, discharges in atmospheric air produce unwanted ozone. On the other hand, because electrical discharges can be sustained in severe pressure and temperature conditions, plasma actuators may be well suited for applications in engines and, more generally, in process systems engineering. Indeed, since the electrohydrodynamic force becomes a dominant fluid force at small scales, we can anticipate new actuator designs applied to small-scale devices. For instance, a new actuator based on a plasma actuated grid composed of millimetre-scale holes, see figure 23, has been recently investigated for mixing enhancement. Promising results have been obtained for velocities up to 60 m s^{-1} and this new actuator may be very useful for enhancing combustion inside engines. Also, plasma gas micro-pumps installed in micro-channels could be effective tools in microfluidics. As for liquids, a new avenue of research could be opened with electroaero-microfluidics. Another advance would be plasma actuators as a laboratory tool for fundamental research in fluid mechanics. Indeed, no other actuator has similar spatio-temporal flexibility, making the plasma actuator an efficient tool for manipulating and understanding turbulence and stability phenomena.

Concluding remarks. EP and FC remain two very active fields of research that combine the physics of plasmas with high-tech applications. Although EP is increasingly used for satellites, there remains a great need for the development of new devices able to deliver very low, as well as very high, thrust. On the contrary, FC has not yet reached industrial maturity and future works will aim at validating the plasma actuator concept in real conditions of use.